SUMMARY OF SESSION 6
WHAT IS SO SPECIAL ABOUT OPERATING BIG SUPERCONDUCTING ACCELERATORS?

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Abstract

Summary of session 6, held at the workshop on accelerator operations at Villars-sur-Ollon, 2001.

1. INTRODUCTION

In this session the specific problems of operating super conducting accelerators were discussed. Reports were given on four big super conducting magnet machines (RHIC, TEVATRON, HERA and LHC) and on the operation of two smaller super conducting linear accelerators (ATLAS and JAERI).

2. CRYOGENICS

Cryogenic systems are common to all these accelerators, whether it be super conducting magnet- or super conduction cavity machines. The cryogenic system is very closely linked to the performance of all these accelerators.

First of all, there is direct link between the cryogenics and the energy deposited by the beam through parasitic mode losses, beam losses, synchrotron radiation and electron cloud.

The field which, can be obtained in Pure Nb super-conducting cavities is directly related to the speed at which the cavities can be cooled down (JAERI).

The correct and fast operation of cryo systems has an important impact on the down time. The recovery from a quench takes typically (depending on the machine) 0.5 to 7 hours if everything works correctly. In the case of wrong or late reactions in the cryo system the recovery time can be days.

The same is true for the recovery after a power cut where the consequences can be even worse, depending on the length of the cut.

This means that a good and fast (direct) communication with the cryogenics operations is indispensable.

3. SAFETY

Cryostats with liquid Helium and/or liquid Nitrogen in the tunnel are potentially dangerous. Super conducting accelerators require special access procedures and adequate operator training.

4. QUENCH PREVENTION AND QUENCH PROTECTION

Magnet quenches do occur from time to time, but if possible, they have to be avoided. Not only do they create down time (0.5 to 7 hrs), but they also result in a severe mechanical shock for the magnet. Specialists are not clear about the number of quenches a magnet can have, but the number is certainly finite. An enormous amount of energy (for the LHC: the equivalent of two big jetliners flying at 900 km/hr) has to be dissipated quickly. A good quench prevention system that dumps the beam before it can provoke a quench is vital. The system has to act fast, -in the LHC the time between failure and beam hitting the magnets varies between 6 and 200 turns, depending on the equipment. All running machines rely on a robust beam-loss monitor system. At the TEVATRON de beam position monitors are also included in the protection system.

The quench protection system itself (the system that deviates the energy once a quench is detected) has to be 100% reliable. On the other hand, it should not be too sensitive in order avoid false quench events (RHIC suffered from this problem in the early stages of ramp commissioning).

It was stressed by all the speakers, representing the super conducting magnet accelerators, that a post mortem system is mandatory. An exact timing in the post mortem is very important in order to establish the right sequence of events and in order to make the right diagnostics.

5. STABILITY AND DYNAMIC EFFECTS

The persistent currents in super conducting magnets cause quit some problems for stability and reproducibility of energy, tune and chromaticity. Reference magnets are used to measure and compensate drifts during injection. Pilot bunches have to be used frequently in order to re-trim the machine and the monitor system has to cover the dynamic range between pilot and production beam. The control system needs very good function editors.

Ramps with super conducting magnets are very slow, so that a tune and chromaticity feedback should not be to difficult to realize.

6. SUPER CONDUCTING CAVITIES

The most predominant characteristic of a supper conducting cavity is its high Q-value (10^9), which means a very narrow resonance line. This makes the tuning of the cavity very critical. It can also lead to mechanical vibrations (ATLAS). The mechanical stress provoked by the high field in the cavity drives it off resonance so that the field disappears. The cavity relaxes and comes back on resonance. This phenomenon creates vibrations in the order of 50 to 100 Hz. A fast feedback can help here.

OPERATIONAL EXPERIENCES DURING RHIC COMMISSIONING: FY2000

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Abstract
During the period between December 1999 and August 2000, the Relativistic Heavy Ion Collider or **RHIC** was brought on line for the first time. RHIC is designed to accelerate Au ions to a momentum of 100 GeV/c per nucleon in two counter-rotating rings with six (6) intersection/collision regions (IRs). The following will describe Operation's experiences by during this period. Topics will include: special methods for independent ring power supply management and control, Operational techniques for utilisation of superconducting (SC) trim and corrector magnets, techniques for crossing transition in an SC collider, techniques for steering in the (IRs) and methods for management of cryogenic and quench protection systems.

1. INTRODUCTION

The RHIC accelerator complex consists of the following components:

- **Injectors:**

Tandem van de Graff, which accelerates Au^{ions} to a momentum of 40 MeV/c per nucleon.

During RHIC operation in FY 2000 it delivered a beam pulse width of 700 μsec and a current is 12 μAmps or approximately 1.5×10^9 Total Au ions per pulse.

AGS Booster, which has a radius ρ of 32 m (104 ft). It collects and accelerates Au^{+32} to a momentum of 430 MeV/c per nucleon. The average intensity was $\cong 1 \times 10^9$ ions per cycle in FY 2000.

The Alternating Gradient Synchrotron or AGS (which is nearly identical to the PS at CERN) has a radius ρ of 128 m (419 ft) collects and accelerates Au^{+77} ions in 4 bunches to 11.24 GeV/c per nucleon. Typical intensity in the AGS was 2×10^9 ions per cycle.

- **Transport lines:**

Tandem to Booster (TTB) line: An 853 m (2800 ft) transport line. Au^{+12} extracted from the Tandem is stripped to Au^{+32} for Booster injection in this line.

Booster to AGS (BTA) transports beam between synchrotrons. It is 61 m (200 ft) long and has a stripping foil, which creates Au^{+77} for injection into the AGS.

The AGS to RHIC (ATR) line transports beam to the X and Y arcs. It has a switching magnet that when commanded to a positive value sends beam down the X arc for Blue ring injection and when negative transports beam to the Yellow ring. There is also a stripping foil, which removes the final electrons from the Au ions for injection into RHIC.

- **ARCs**

The X and Y arcs transport beam from the end of the ATR line into the two RHIC rings. The X arc transports to Blue and the Y to Yellow.

- **RHIC**

A 3.8 km (2.4 mile) circumference accelerator comprised of 2 (two) rings, Blue and Yellow, which accelerates Au^{+79} beam to a momentum of 100 GeV/c per nucleon and collides the two beams at 4 active experimental sites.

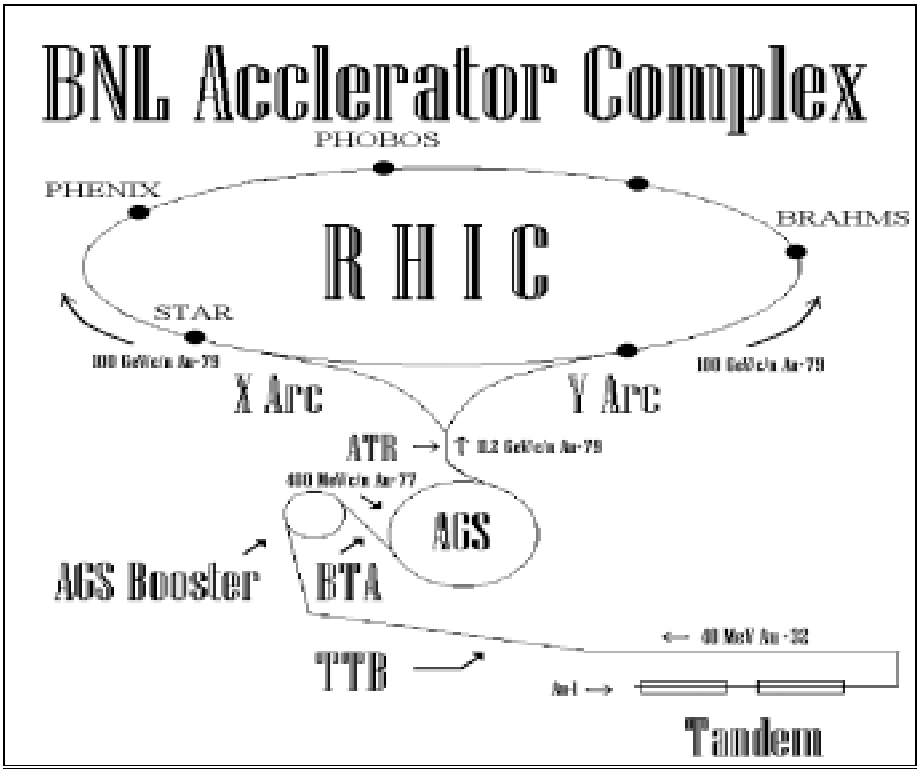


Fig. 1: Representation of Collider Accelerator Complex (not to scale)

During the previous RHIC runs, sextant test and engineering runs, Operations' main concern was with AGS experiments. The main contribution to these runs was to keep the injector on for the RHIC Physicists, while they ran RHIC itself.

During the effort to commission RHIC, Operations was charged with gaining as much hands on experience as possible. To help achieve this, Operations personnel were utilised as 'hands' for commissioning Physicists as much as possible. In doing so, Operators became familiar with nearly all aspects of everyday operation the collider.

2. EARLY COMMISSIONING

During the early stages of the commissioning effort, Operations worked with RHIC Accelerator Physicists and set up the injectors and ATR transport line.

2.1 AGS extraction

AGS extraction was set up such that beam could be delivered to the desired RHIC ring on demand. This required the use of several triggers for AGS extraction equipment. The Blue ring and Yellow ring triggers where set up as on demand, manually activated triggers. A third trigger called *'green'* was used for much ATR commissioning. This triggers extraction every AGS cycle. The AGS has one cycle approximately ever four (4) seconds. When triggering with the green trigger, the beam is transported to a beam dump at the end of ATR, upstream of the arcs.

2.2 ATR setup

Prior to injecting into RHIC, the transport line was set up and studied. Utilising the ATR dump, beam was extracted continuously from the AGS and ATR studied. The first objective was to re-establish transport to the dump (Fig. 2). This had been done previously during the sextant test and engineering run.

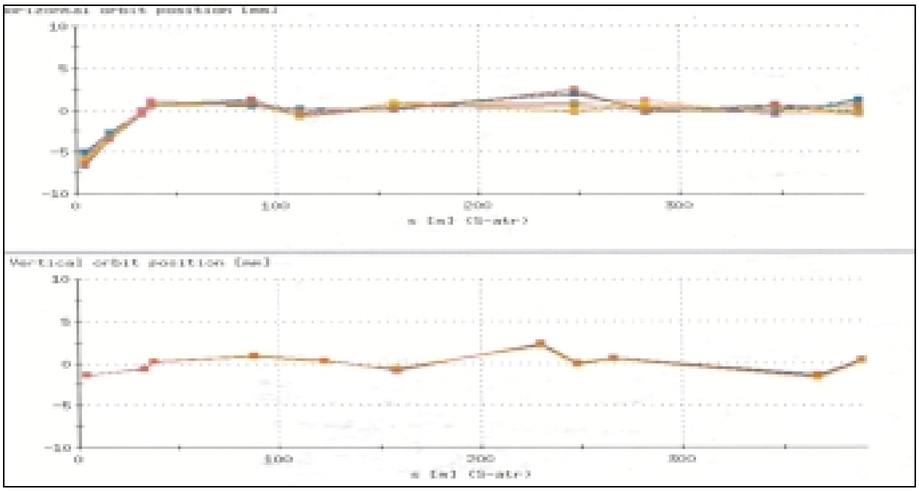


Fig. 2: Beam to AtR dump

Once transported to the dump, beam losses were minimised. Studies dedicated to cross-calibrate Beam Position Monitors (BPMs) to quad centres followed. Operators systematically varied the current for quadrupoles in the line just upstream of each BPM. This exercise was completed for a range of transverse positions incident to the quad. After several sets of data, optical centre was determined and BPM offsets were incorporated into the model for the line. Figure 3 shows a plot of ATR and the Y arc as the arc current was varied, which changes both the dipole and quadrupole strength. Moving a quadrupole in the ATR line produced similar plots.

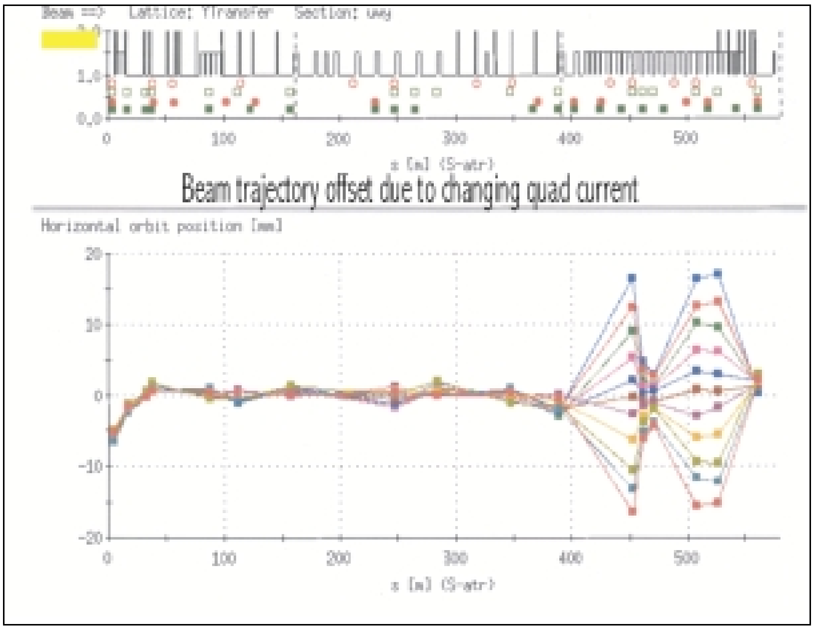
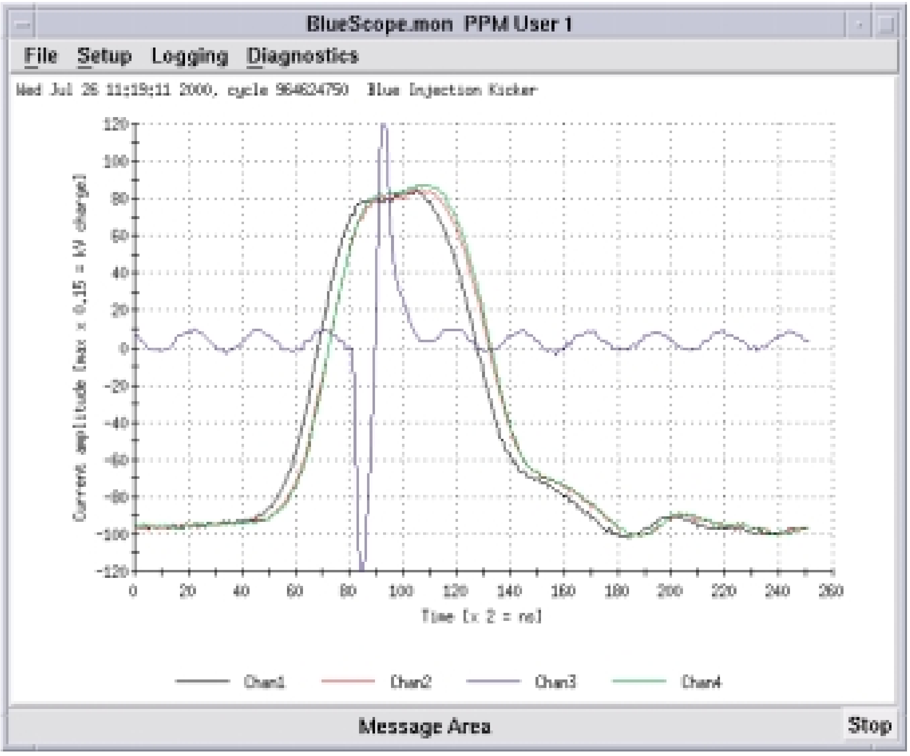


Fig. 3: Trajectory effect of changing the Y arc current

2.3 First RHIC injection

Beam was injected into one ring at a time, first the Blue then Yellow. Since beam has a downward trajectory at the end of the injection arc, it must be kicked upward onto the equilibrium orbit. The first injections were single turn only and done using a corrector dipole to deliver the required diversion. The first turn trajectory was measured and corrected using several methods. The first of these was by ‘hand’. This method had an operator measuring the beam trajectory then changing individual orbit corrector magnets to minimise the divergence from the centre of the beam pipe. Although instructive, this proved to be very tedious and hard to reproduce. In order to close the orbit and circulate the beam, the injection kicker had to be set up. Figure 4 shows the current pulses for three of the four injection kicker modules for the Blue Ring as well as the beam signature on a nearby BPM.



Wed Jul 26 11:19:11 2000, cycle 964624750 Blue Injection Kicker

Fig. 4: Injection kicker and beam signals

Once injection with the injection kickers was established, The magnetic field for injection was adjusted to centre the beam on the ring BMPs. The next objective was to smooth the orbit. The controls for orbit correction allow the choice of any section (local) or the whole accelerator ring (global) for correction. The ‘local’ control was later used to steer the beams onto each other at the Intersections Regions (IRs). Figure 5 top, shows the measured orbit (red) and the corrected orbit (green) for a section of the Yellow ring. Figure 5, bottom shows a detailed view, which could be used for IR steering.

When the orbit correction application produced unexpected results, polarity checks were made on the correctors and several were found to be in the wrong polarity. Several BPM were also wired backwards. Both of these problems were compensated for in the software.

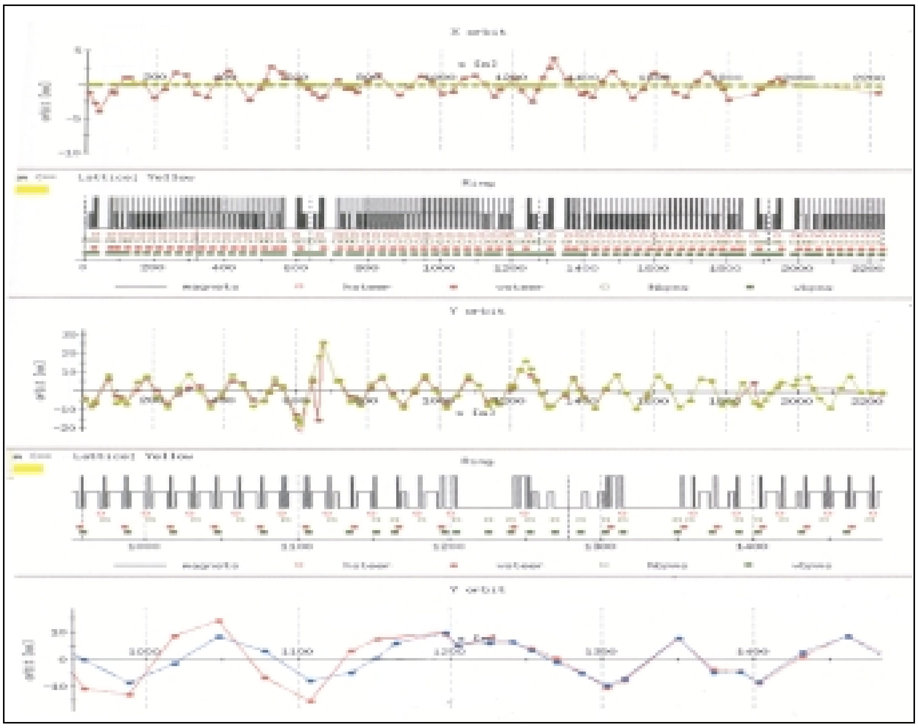


Fig. 5: Orbits

3. CAPTURE AND STORAGE AT INJECTION ENERGY

With beam parameters defined and survival for several seconds achieved, the RF system was brought on and set up. RF experts synchronised the RF systems in the AGS and RHIC so that bunches from the AGS were injected into specific bunches in RHIC. At first, one AGS bunch was injected and stored in each ring. Later 4 bunches were injected then finally 56. Table 1 displays RF harmonics and beam bunches during commissioning period. 4 Booster cycles of 6 bunches each were injected into the AGS. The beam was then de-bunched and adiabatically re-bunched into 4 bunches utilising a specialised RF cavity in the AGS. At extraction in the AGS, bunches are in every 3rd of 12 bunches and extracted into four buckets in RHIC. Bunches are in every 6th bucket in RHIC. Once in routine operation RHIC was filled with 56 bunches (i.e. 14 AGS cycles).

Table 1: RF Harmonics

Machine	Booster	AGS	RHIC
Harmonic	6	12	360
Bunches	6	4	4 (56)

Figure 6 shows the ‘Supercycle’, which defines configuration of the injectors. The graphic shows five (5) Booster Main Magnet current cycles (four (4) with beam and 1 dummy cycle) for every AGS cycle. Each RHIC ring takes as many as 14 Supercycles to fill.

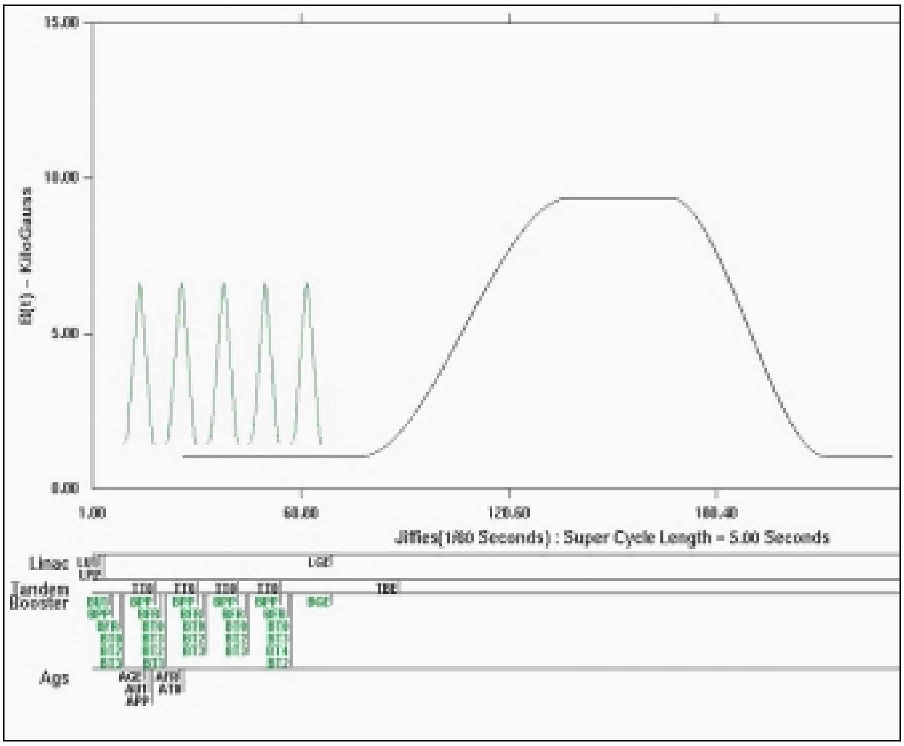


Fig. 6: Depiction of the injectors’ Supercycle

4. ACCELERATION

With beam routinely stored at injection energy, attempts to accelerate the beam were made. The first of these was done with the main magnets ramping to 20 GeV/c/n or just below transition energy (22.9 GeV/c/n). Stopping the ramps at lower energy was done to save time, since a hysteresis correction cycle was necessary after each unsuccessful acceleration attempt. Early in commissioning, resetting the magnets took several minutes (see section on magnet control).

Initial attempts to accelerate were unsuccessful. After observing that the machine was strongly coupled at injection, attempts to adjust the tune produced unexpected results. Upon investigation, a systematic wiring error was found. Several quadrupole shunt supplies were wired backwards. This was corrected, but unfortunately, acceleration continued to elude commissioners. Further investigation and debate prompted commissioning Physicists to suspect that the some of the Chromaticity Sextupoles might also be wired wrong. Investigation proved this suspicion to be correct. Beam was accelerated shortly after this wiring error was corrected.

Later, a system for executing steps necessary to accelerate routinely was developed. It was eventually formalised and incorporated into the ‘Sequencer’. The sequencer is an application designed to sequentially execute commands to control hardware and software. Steps included performing a hysterisis reset, filling the rings, activating RF beam control and activating, acceleration ramp and dumping the beam at the end of a cycle or store. The sequencer proved to be a valuable tool and is presently being expanded upon for use in FY 2001.

Figure 7 Top shows the beam current transformer profiles for the Yellow and Blue rings during an early attempt at acceleration. Beam current for the Yellow and Blue rings are orange and blue respectively. Beam Lifetimes are yellow and green. The bottom shows the radial pick up electrode signals (Blue on the top trace and Yellow on the bottom) as the beam crashed to the inside of the rings. Beam was surviving to $\gamma \cong 12$ at this point.

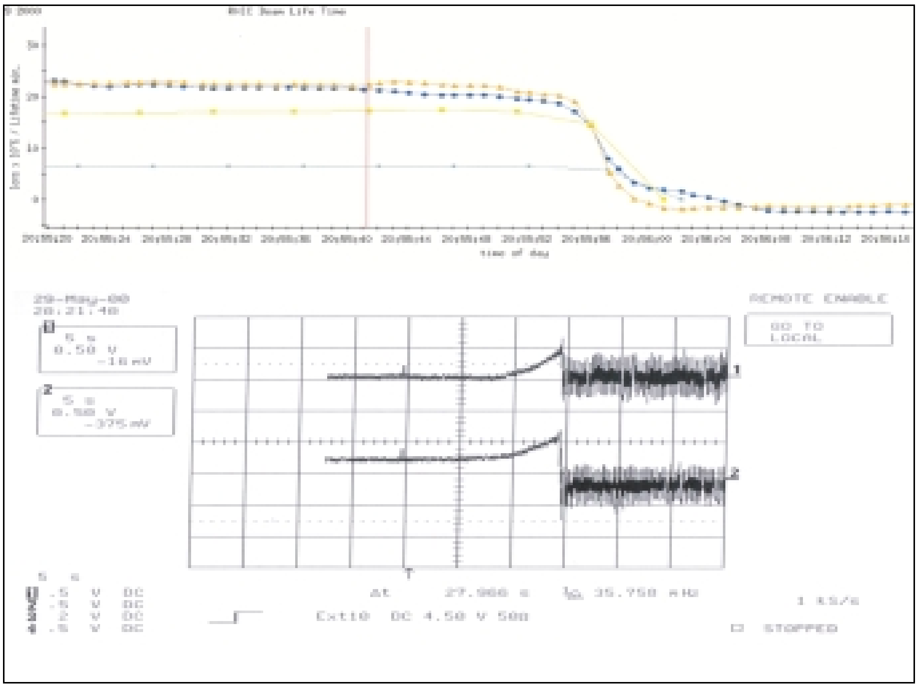
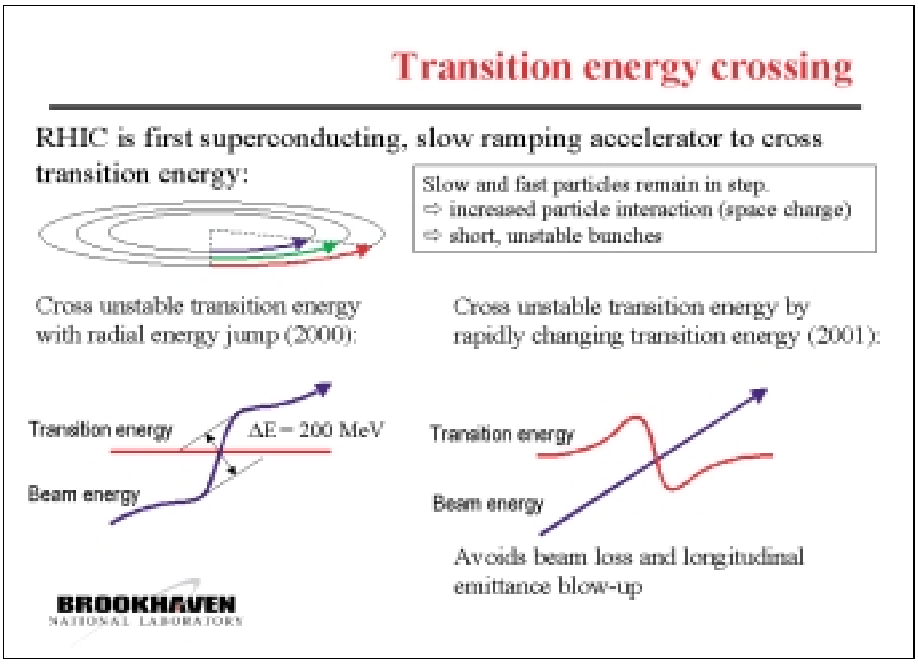


Fig. 7: Early attempt at acceleration

The machines were tuned until acceleration to transition was reproducible when the challenge became crossing a transition with a superconducting machine. This had not been done in a slow ramping superconducting machine before. Since beam is unstable at transition energy, it is desirable to cross through it as quickly as possible. This can be achieved a number of ways. One way is to gradually change the optics of the accelerator for a brief period just prior to transition, and then quickly reverse the distortion, moving the machines through transition as the distortion is removed. This is the preferred method and is achieved utilising a separate set of quadrupoles in the rings specifically designed for this task called ‘gamma jump quads’. During the commissioning efforts, the gamma jump was not available and an alternate method had to be employed. It was dubbed the ‘poor man’s jump’ due to the fact that no specialised (expensive) equipment was needed to create it. Using the poor man’s jump, the energy of the beam is changed rapidly using the RF radial control. The disadvantages of this method include that it is slower than the gamma jump, increasing the time the beam spends at transition and thus beam blow up, and that it utilises much of the beam pipe aperture, increasing the potential for losses. Figure 8 illustrates the gamma jump. The ‘poor man’s jump’ in on the left, the gamma jump on the right.

Figure 9 shows the Yellow ring beam current (blue trace) and a Main Magnet function with a maximum field at $\gamma = 30$. The Black is dipole current and the red the quadrupole current.

In FY 2000 beam final acceleration was $\gamma = 70$. RHIC is scheduled to run at design energy in FY 2001 ($\gamma = 100$).



Transition energy crossing

RHIC is first superconducting, slow ramping accelerator to cross transition energy:

Slow and fast particles remain in step.
⇨ increased particle interaction (space charge)
⇨ short, unstable bunches

Cross unstable transition energy with radial energy jump (2000):

Cross unstable transition energy by rapidly changing transition energy (2001):

Avoids beam loss and longitudinal emittance blow-up

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Fig. 8: Methods for crossing transition

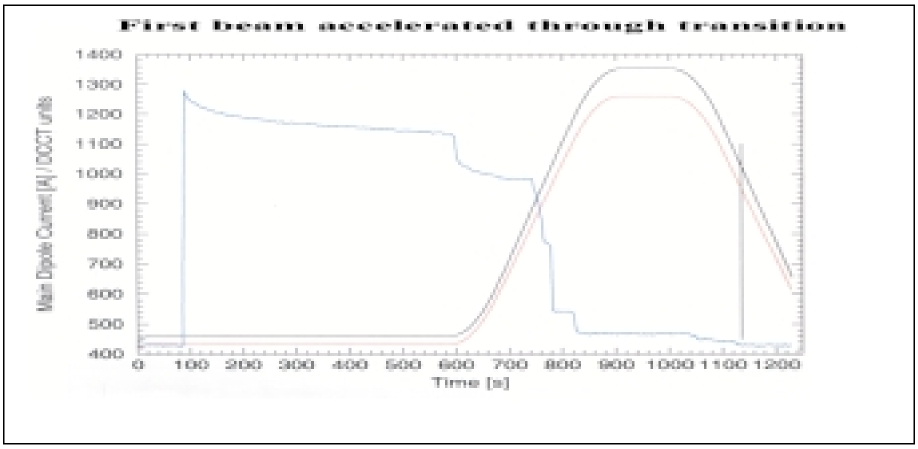


Fig. 9: First beam through transition in Yellow ring

5. COLLISIONS

After accelerated beam was established and stored in both rings simultaneously, the emphasis shifted to establishing collisions. In each IR, the Yellow and Blue beams must change position from the inside ring to the outside or ring RHIC (or visa versa). This is done using specialised dipole magnets, called DX magnets. These magnets are in series with the Blue main dipole bus and bend both beams, causing them to cross. During acceleration, the beams are not coincident transversely or longitudinally. When collisions are desired, i.e. at storage energy, they must be. This is done using the DX and corrector magnets for the transverse planes and by manipulating the RF longitudinally.

RHIC was designed with a Wall Current Monitor (WCM) physically located at the Intersection Point at 4 o’clock. Since the particle bunches have the same charge, they will induce opposite polarity signals on the WCM. Longitudinal bunch alignment can therefore be confirmed by observing that the two WCM cancel (i.e. if both machines have the same current, the signals will be zero). This process was completed in two steps. The first step was to synchronise the RF systems by locking them to the same frequency. In FY 2000, both rings were locked to the Yellow Ring's frequency. By doing this, the respective bunches 'stand still' relative to one another. The second step was to change the relative phase between Yellow and Blue bunches in small steps until they are on top of each other.

Figure 10 shows the process by which the beams were 'synched and cogged'.

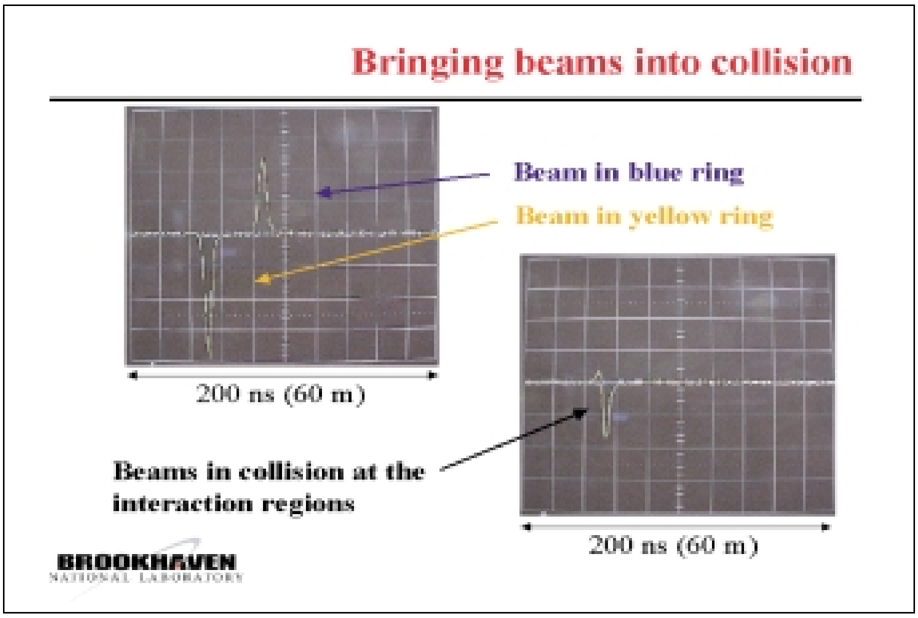


Fig. 10: Left: two bunches, one Blue one Yellow. Right: 'cogged'

With beam cogged and synched, the final step towards collisions was to steer the beams onto each other transversely. There are special BPMs located around the IPs specifically designed for this task. These have both horizontal and vertical plates where as other Ring BMPs are either vertical or horizontal. As previously mentioned, there is a specialised routine in the orbit control application designed specifically for steering the beams in the IRs. Figure 11 shows a sample display of the specialised BPM outputs during tuning for collisions.

While observing the beam position on BPMs, instruments at the IPs were monitored to determine the existence of collisions. These instruments, called 'Zero Degree Calorimeters' (ZDCs) are tungsten sample calorimeters and are positioned at equal distances from and at zero degrees to each experimental IP. With this geometry, incidental events on either detector due to interaction with residual gasses or other obstructions can be excluded and actual collisions detected.

Figure 12 shows the ZDC coincidence rate for STAR, PHENIX, BRAHMS and PHOBOS shortly after the first collisions.

Although the steering algorithm is designed for independent control in the IRs, in practice, when steering for one IR, others were somewhat affected. Operators were careful to record collision rates and BPM positions at all IRs prior to steering anywhere. Once the desired steering was completed, an iterative process of steering and re-steering restored all of the rates.

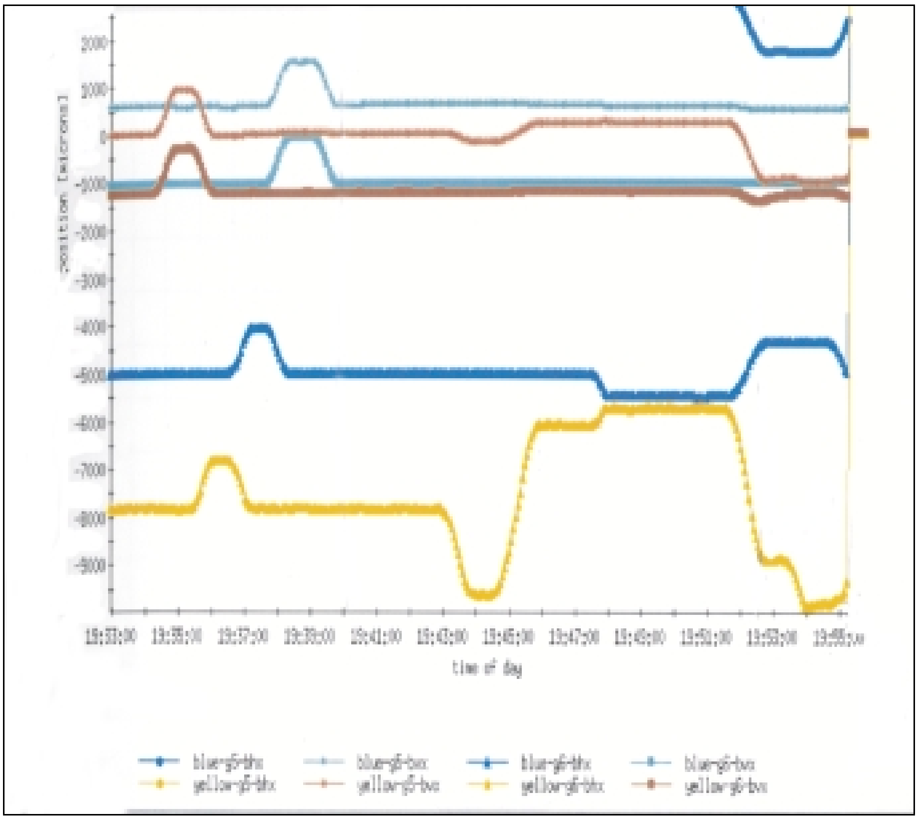


Fig. 11: Steering around the IR at 6 o'clock

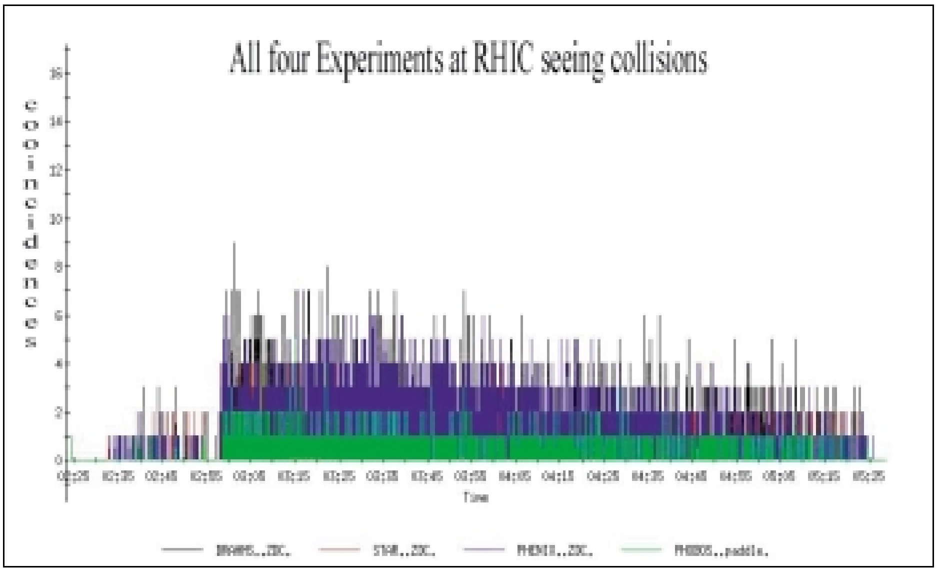


Fig. 12: Collisions with 4 bunches in each RHIC ring

6. MAGNET CONTROL

As mentioned, the RHIC ring is comprised of several different systems of magnets. Each of the systems are controlled and protected in various ways. The main ring magnets are controlled primarily by two applications, one called 'Ramp Editor' and one called 'Ramp Manager'.

Ramp Editor is used to create and load driving functions for the magnet power supplies. The user can define desired characteristics for the ramp and the application then calculates magnet currents using the accelerator model. When designing a ramp, the user can define the machine optics at various values for γ. Each of these segments called ‘Stones’ has editable inputs for all of the magnetic subsystems called ‘Pebbles’. Each Stone is a complete description of the machine. Stones for energies throughout the RHIC cycle are combined and fitted to create a time dependent ramp function. By employing this method the user has the option of either propagating a new setting throughout part, or all of a ramp or of having a change remain in effect for a particular Stone only. An example of a correction that might be propagated throughout a ramp is an orbit correction made at the Stone at injection. Examples of those that it may not be desirable to propagate are IR steering on the Last stone or modified tunes for Stone at transition. Figure 13 shows a sample ramp. Each horizontal line represents a Stone. The stones are fitted together to form a smooth ramp function.

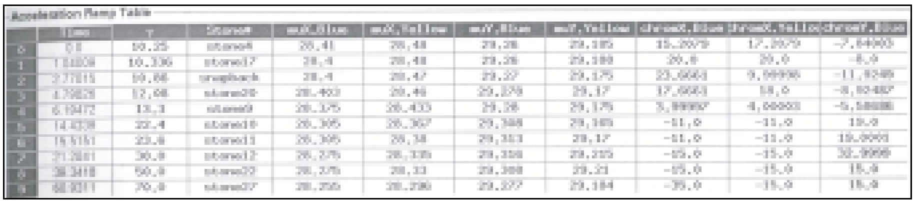


Fig. 13: Stones and Pebbles making up a Ramp

Once a ramp is defined and loaded an application called ‘Ramp Manager’ is used to execute it. The Ramp Manager defines where to ramp to and how fast to ramp. This turned out to be critical since the rate of ramp must be such that the difference between the measured and expected main ring currents must be within tight tolerances or the Quench Protection System will shut the main ring power supplies down. Early in the commissioning effort, this rate was as slow as 2 amps per second, making a ramp to γ = 70 take 1600 seconds or 26 minutes! Ramp times were significantly reduced by the end of the commissioning period. A ramp presently takes approximately 2 minutes.

Ramp Manager was utilised to complete a hysteresis reset. It was determined that the injection field could be reproduced by ramping the magnet from near zero to a value at or above the maximum current for the next cycle, then back to near zero and finally to injection field. At first, this process was quite tedious due to slow ramp rates, but once regular stores were achieved and ramp rates increased, it became less of an issue. Figure 14 illustrates a hysteresis reset. Pilot bunches were utilised to determine if the field was in fact correct. If these pilot bunches, which are low intensity, showed that this was not the case, adjustments were made prior to full injection.

Blue ring was commissioned first because the Intersection Region magnets, which are common to both rings, are controlled by the Blue ring power supply. Because of this, the Blue ring can accelerate beam independently but the Yellow cannot. There were two ‘Ramp Managers’ early in the commissioning effort, one for Yellow and one for Blue magnet control. This allowed one group to work on the magnet power supplies while another could work with beam in the other ring. The two were combined later to form the present Ramp Manager.

Other means of power supply control are available and useful for specific tasks. All of the magnet power supply controls are available via a spreadsheet application called ‘pet’. Control via spreadsheet is most useful when an individual or small group of supplies needs to be manipulated. In practice this was very useful after power supply interlocks. All of the ATR magnets are controlled in this way. Two features designed into the spreadsheet control became useful for performing hysteresis resets for the (warm) magnets in ATR. The first of these features is that, for a given set of parameters, the user is able to associate a value for γ. An operator can change all of the ATR magnets simultaneously by changing the value for γ. When performing the hysteresis reset in ATR, operators would vary γ to complete a cycle similar to that of Fig. 14. Another feature was the use of Stones. To bring supplies on and reset hysteresis, operators had the option of changing ATR to a special Stone that has all zero commands. The method of changing to the 'zero Stone' in ATR was also adopted to expedite personnel access into controlled areas of ATR and RHIC. Since critical devices must to be secured prior to entry and the preferred method of turning off the power supplies is to do it with zero current command, the use of the zero Stone was a nice option.

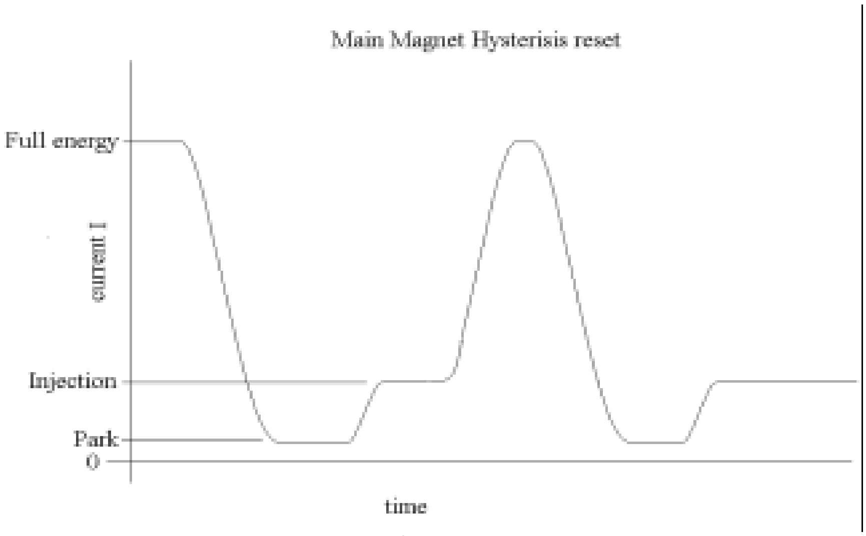


Fig. 14: Example of a Hysteresis reset cycle

In addition to interlock trips, other less obvious modes of failure were encountered. A tool called the Post Mortem Viewer was developed and proved very valuable for diagnosing such failures. It was designed to record magnet functions during each ramp. In the event of Quench Link Interlock, the data is saved into a file for later viewing. Otherwise, the data was overwritten during the next ramp. Figure 15 shows a sample output for the Post Mortem. A full output is comprised of over a thousand plots.

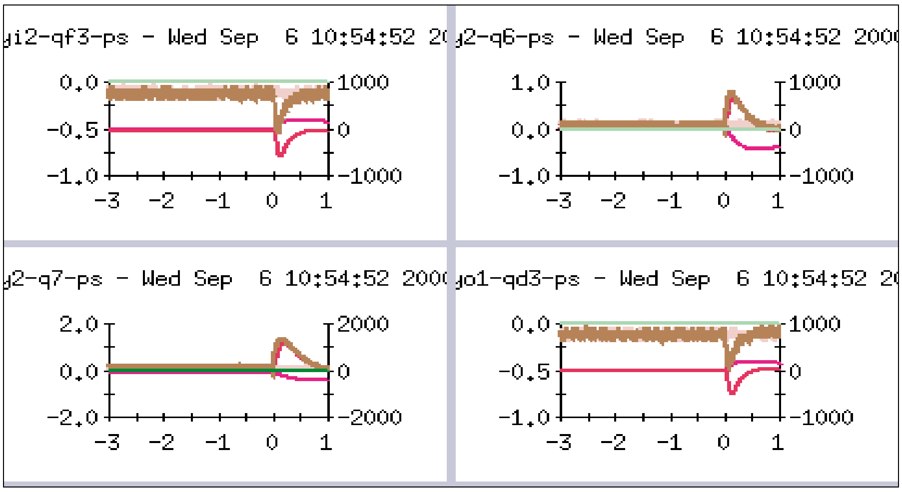


Fig. 15: Post Mortem View Sample graph

Another application called 'PSALL' was available for use. It was similar to the 'pet' version in that the user has control of specific devices. It was arranged so as to be very useful for recovering from quench link interlocks and was widely used in the field by power supply engineers.

7. QUENCH PROTETCTION

During the commissioning run, a major effort was put forth into setting up and understanding the Quench Protection System (QPS). As designed, the QPS monitors the magnets in the RHIC ring, all of which are super-conducting. Cryogen reserve level and flow, magnet voltage, current and temperature are monitored and must be within tight tolerances of predicted values. Early in the commissioning effort, interlocks from the QPS were very frequent, as many as 30 a day. These interlocks were almost exclusively *not* from actual Quenches. Many factors contributed to these interlocks.

An additional set of interlocks was actually implemented during the commissioning effort. Following a corrector magnet failure that was determined to be due to lack of coolant, lead flow indication for these and the ring sextupole magnets was incorporated in the QPS. Interlocks due to low lead flow for these magnets were separated from a main quench interlock system. They would not cause a beam abort or interlock the main ring supply (i.e. pull the Quench Link). A corrector-lead flow interlock would interlock only the supplies affected by the lead indicating low flow. Supplies with common interlocks also share common power supply alcoves in the RHIC ring enclosure. Following the recovery of flow in the lead in question, power supply recovery from a corrector-lead flow interlock was relatively simple. Affected supplies could be reset and brought up individually or in small groups via ‘pet’ or ‘PSALL’ then ramped to the desired value. Effect on the beam due to these trips varied from negligible to drastic depending on the devices that were interlocked.

Unfortunately, the majority of quench link interlocks did cause the beam to be aborted and the Main Ring Power Supply to interlock. The beam would be dumped and the main magnet supply interlocked when any one link in system of permit links (i.e. the Quench Link) failed.

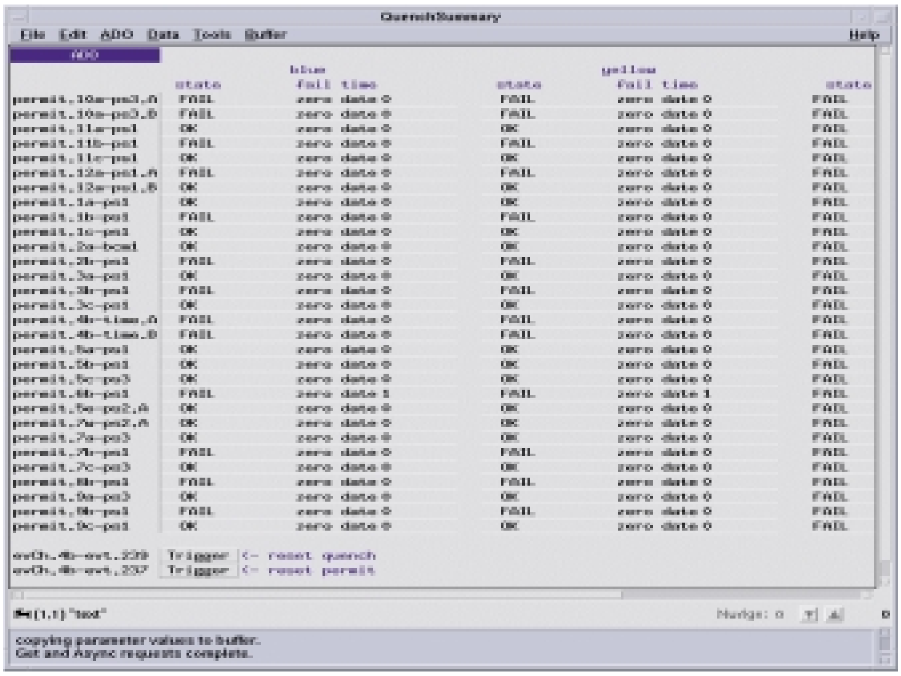
N*early all of the Quench Link failures were NOT due to actual quenches.*

Several items related to the control of the magnets were found to cause interlocks. One of these was related to the Real Time Data Link (RTDL), which contains magnet command and read back information, and runs at 720 Hz. Occasionally, a bad data point on the RTDL would cause the quench link to be pulled. Power supply engineers added additional hardware and software to the systems affected by the RTDL to preserve magnet protection while keeping a single bad data point from causing the link to go down. A second source came from the Wave Form Generators (WFGs), which drive the magnet supplies. Differences between WFG command and WFG read back values often caused the Quench Link to go down. To minimise this problem, WFG software configuration was modified and power supply engineers cleaned up noise on the power supply read back outputs. All of the afore mentioned problems were static, i.e. they were independent of the ramp rate. Others were not.

While investigating possible sources for frequent quench link interlocks, power supply engineers discovered that the main ring sextupoles’ monitoring circuitry was different from the other elements. The voltage for the sextupoles is monitored on the (warm) power supply side of the cables, rather than the (cold) ring side, as is the case for the dipoles and quadrupoles. The calculation used for expected voltage did not take this into account. Modifying the algorithm for the sextupoles eliminated these interlocks.

Another source of trips came when attempts were made to ramp the magnets too fast. The algorithm for main monitoring the magnet was originally set up (or tuned) for a slow ramp rate. Elements to this algorithm needed to be changed (re-tuned) in order to ramp faster.

As each bug became evident and was corrected, quench events went from as many as 20 a day to about one a week. The ramp rate was also increased by more than 10 times. Figure 16 shows the pet page for the Quench Link Summary. A failure of any of these inputs will cause the link to go down.



copying parameter values to buffer.
Get and Async requests complete.

Fig. 16: Quench Link Summary page

8. RUNNING PHYSICS

By the end of the run, RHIC was routinely running for physics at all four experiments in the ring. Stores of many hours were common, some as long as 12 hours. Operations had taken over nearly all of the tasks involved in everyday running of the machine. For example, during the Sextant test, 4 RHIC Physicists were on 3 shifts a day and Operations spent most of the time working with injectors only. By the end of the commissioning run, One RHIC physicist was on during the day and evening, while Operations ran through each night. Figures 17–21 show various parameters for the FY 2000 run.

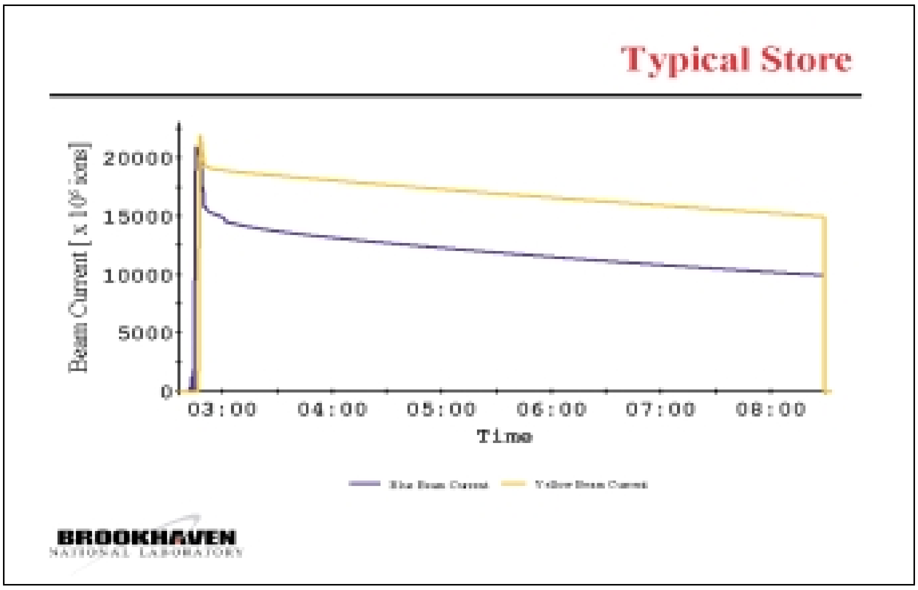
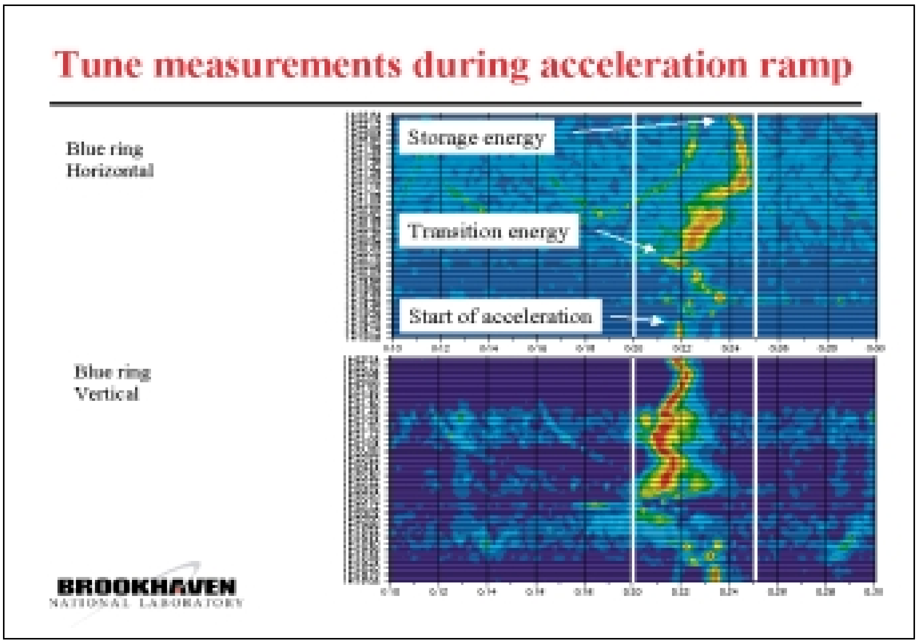


Fig. 17: Beam Current in Yellow and Blue during a typical store



Tune measurements during acceleration ramp

Blue ring
Horizontal

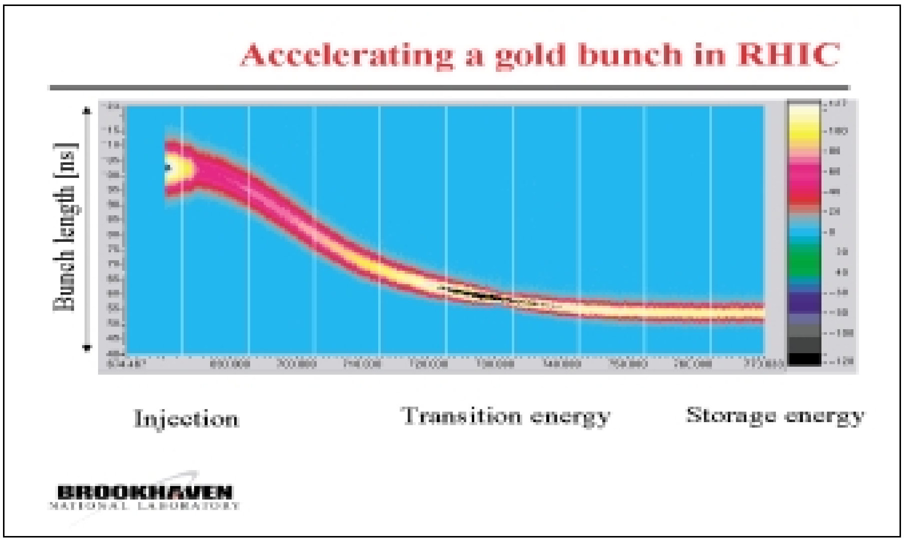
Storage energy

Transition energy

Start of acceleration

Blue ring
Vertical

Fig. 18: Beam tunes during the acceleration ramp



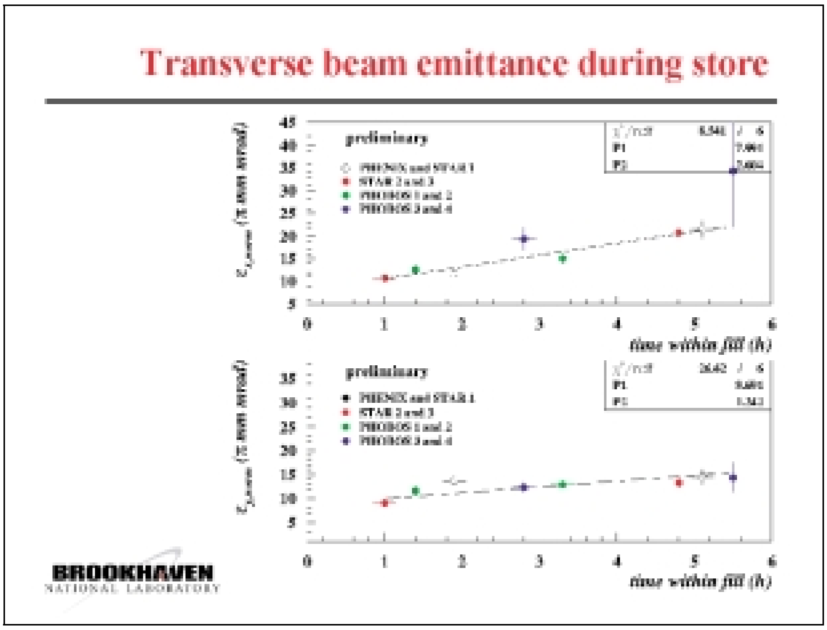
Accelerating a gold bunch in RHIC

Injection

Transition energy

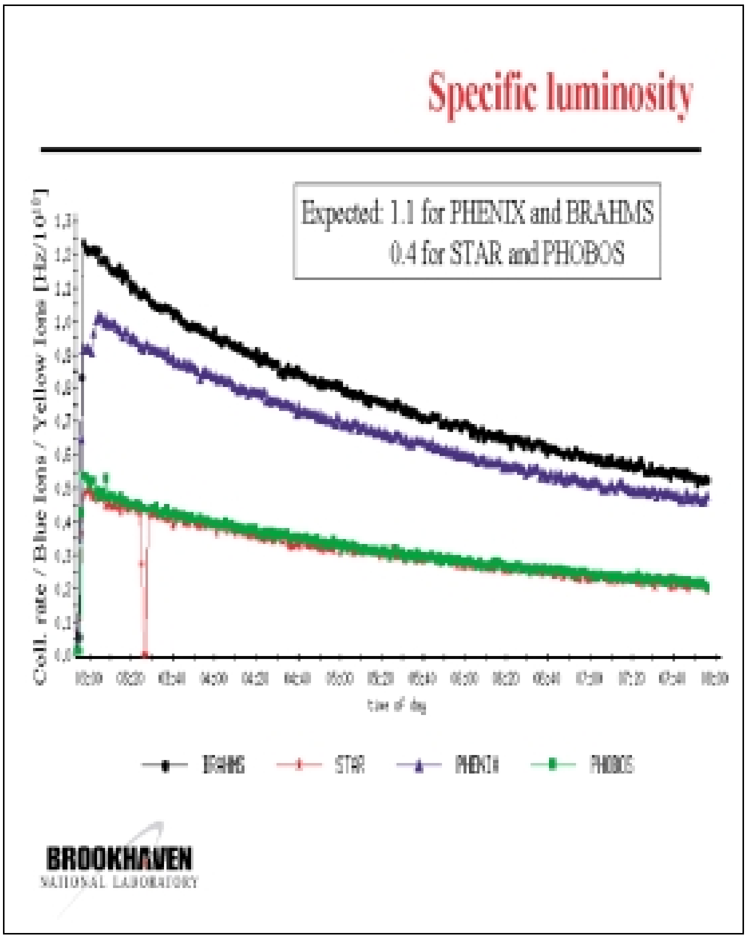
Storage energy

Fig. 19: FY2000 bunch lengths



Transverse beam emittance during store

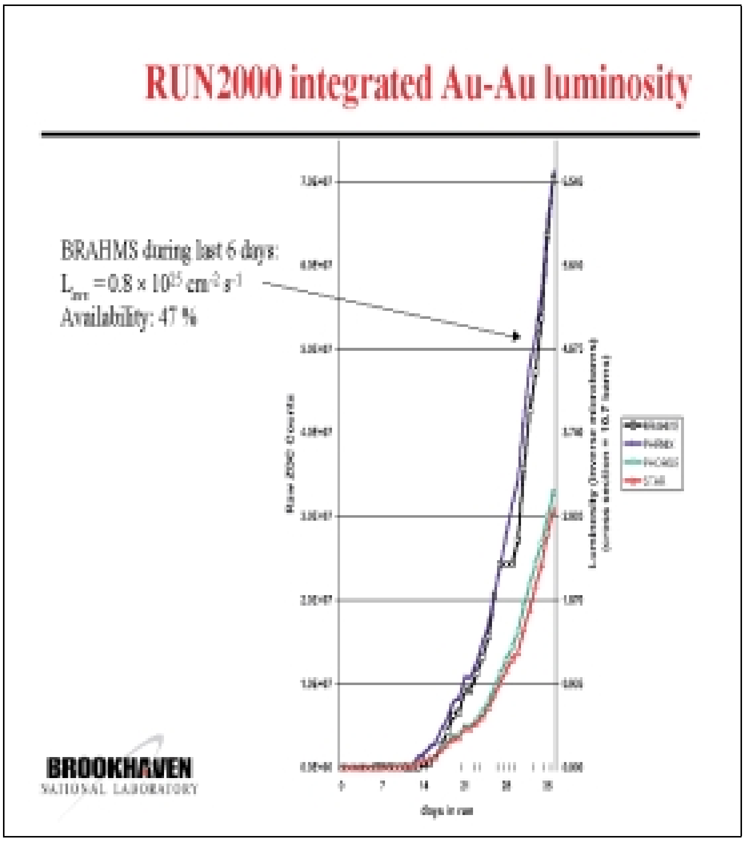
Fig. 20: Emittance vs. time in for a group of stores



Specific luminosity

Expected: 1.1 for PHENIX and BRAHMS
0.4 for STAR and PHOBOS

Fig. 21: Specific luminosity plot during a store



RUN2000 integrated Au-Au luminosity

BRAHMS during last 6 days:
$L_{ave} = 0.8 \times 10^{25}\ cm^{-2} s^{-1}$
Availability: 47 %

Fig. 22: Integrated luminosity for FY 2000 run

9. ACKNOWLEDGEMENTS

The following illustrations were taken from the RHIC logbooks for FY 2001: Figures 2, 3, 4, 5, 7, 9, 11, 12, and 13.

The following illustrations were adapted from a presentation for Quark Matter 2001 by *Dr. Thomas Roser*, Brookhaven National Laboratory: Figures 8, 10 and 17–21.

TOOLS TO CONTROL LARGE SUPERCONDUCTING COLLIDERS

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Abstract
Fermilab's Tevatron accelerator is a cryogenically cooled four-mile ring of superconducting magnets that controls a 980 GeV beam. Superconducting magnets are expensive and take time to replace. To protect the magnets, Fermilab developed Quench Protection and Abort systems. To protect the people who maintain the magnets, Fermilab implemented ODH policies. This paper discusses these problems.

1. INTRODUCTION

Fermilab is a U.S Department of Energy (DOE) research laboratory, operated under DOE contract by Universities Research Association (URA). The Fermilab accelerator complex added the Tevatron, a cryogenically cooled particle accelerator, into its chain of accelerators in 1983. The Tevatron was constructed in Fermilab's Main Ring tunnel, a ring four miles in circumference. The accelerator is a separated function synchrotron that raised the operating energy of Fermilab from 400 GeV to ultimately 980 GeV.

2. IMPACTS

One of the first impacts we saw in operating the new accelerator was that the cycle time increased. The Main ring's cycle time ran at 8 seconds while the Tevatron runs between 60 and 200 seconds depending on the mode of operation. This longer cycle time meant that when tuning you had a much longer wait to find out whether your change was successful. The experimenters didn't mind the slower rep rate because the duty factor in which they received beam increased dramatically with the slower rate (1 second flat top Vs a 23 second flat top).

When tuning the Main Ring it was often quicker to intuitively adjust the tune rather than make a careful calculation of what you wanted changed. But since the Tevatron's tuning rate was so much slower it made more sense to actually figure out how much you wanted to move the beam before making an adjustment. In addition, the sensitivity of the superconducting magnets to beam losses meant you could not use the Main Ring technique of whacking the beam back and forth.

3. CRYOGENIC MAGNETS

The second, and by far the biggest, impact to operating a cryogenic accelerator was that these magnets could easily fail if the conductor went from superconducting to non-superconducting. The Tevatron magnet coils have a cross section of approximately 12 square mm. We run 4380 amps through this conductor. If the coil remains superconducting (no electrical resistance) then everything is fine and happy. But if the coil warms up so that the conductor develops a resistance, that high current will cause the conductor to fail. This is expensive, and worse it takes a week to replace the magnet.

4. PROTECTION & ABORT SYSTEMS

To protect against these kinds of failures, the Tevatron group had to develop a quench protection system to look for magnets that are to go non-superconducting. They came up with the Quench Protection Monitoring system, QPM for short. Some of the requirements for the QPM system were as follows:

- To get rid of the beam (initiate a beam abort) in a safe manner
- To turn off the power supplies and remove the energy from the magnets before the magnet failed
- To monitor itself and ensure that it was always on line and protecting the magnets
- To allow easy troubleshooting
- To quickly show what triggered the quench system. (The QPM contains a circular buffer where measurements of magnet behavior are recorded. When the QPM system senses a quench, the circular buffer is stopped, which allowed us to back up into time and figure out what caused the quench.)

Understanding what causes and, more importantly, how to avoid quenches are vital to Operations. Our biggest quench problem is caused by beam scraping. Uncontrolled beam losses, due to scraping, will warm the Tevatron magnet so that it’s no longer superconductive. In this situation, rather than waiting for a quench, it is preferable to quickly abort the beam into an external dump. Our Abort system has similar requirements to the QPM system:

- When triggered by losses or equipment failure, the abort system fires a set of single-turn kickers that remove the beam safely and quickly
- To quickly diagnose aborts. (Each Beam Position Monitor and Beam Loss Monitor talks to a circular buffer that store positions and losses through out the beam cycle. When the abort fires, all circular buffers for the BPMs and BLMs stop. This allows us to look back at the Tevatron orbit and loss patterns around the entire ring and see what they were doing in small increments before the actual abort occurred.)

5. BENEFITS

One of the positive side effects of the superconducting magnets was that successful operation prevented us from dumping vast quantities of beam on the magnets. The TeV magnets demanded better tuning, and the QPM and Abort systems dumped the beam at spots we specified. As a result, the residual losses in the Tevatron were far lower than during the days when the Main Ring was the final stage of acceleration.

6. ODH PROBLEMS

There are other problems related to superconducting magnets. They require large volumes of internal magnet cryogens. If a cryogenic relief valve opens on one or more of the magnets there is a possibility that the cryogens will displace oxygen in the tunnel, possibly creating an oxygen deficiency hazard (ODH). The whole cryogenic system is considered to be a pressure vessel. (During the Tevatron’s design stage a considerable amount of attention had to be paid to this by various safety committees.) This in turn makes accesses into these beam enclosures complicated. Fixed oxygen alarms were required throughout the Tevatron beam enclosures.

Anyone accessing the Tevatron tunnel is required to take a personal oxygen monitor that will alarm whenever the oxygen levels get below 19.5%. They also must carry a small tank that will give them 5 minutes of air for escape.

A two-man rule became mandatory for all accesses.

The cryogens also required the laboratory’s medical department to certify that all workers who enter ODH enclosures are medically qualified to do so. To this end, a database had to be set up and the Operations Department required use it to check training and medical approval records for every worker before allowing tunnel access.

In addition to all this, moving heavy objects above or around cryogenic components in the tunnel required additional procedures to prevent accidental rupturing of the insulating vacuum or puncturing cryogenic supply lines.

7. OTHER PROBLEMS

1. Four miles takes too long to walk and takes too much time transporting equipment around to complete work, or to interlock, especially when everyone is waiting for beam. So operators and technicians drive the ring in electric golf carts. After a safety analysis was performed and fixed bumpers were added around vulnerable areas to prevent colliding golf carts from rupturing cryo and vacuum systems.
2. Ground faults are much harder to locate unless a cryogenic magnet ruptures its insulating vacuum line and spews its insulation around to be noticed.
3. Vacuum is much harder to leak check in cryogenic magnet systems. The Vacuum technicians need to rely more on time of flight methods for locating vacuum trouble spots. The number of vacuum connections went up a factor of five from the conventional system to the cryogenic vacuum system.
4. If cryogenic magnets warm, cryo-pumping within the vacuum chamber can release contaminates into the vacuum system. These contaminates can then block the smaller apertures in the cryo system causing flow problems. The fix requires a warm up and a decontamination cycle for that part of the ring affected, which typically causes a week down time.
5. We have more rotating equipment, in the form of compressors and expansion engines that require constant attention and higher maintenance.
6. We are more susceptible to power outages. If our cryo equipment is not started within 30 minutes of a site wide power outage or glitch, we are down for a week while we purify and re-cool the ring. Thunderstorms have a much bigger impact on cryogenic accelerators than conventional accelerators.
7. Control software is more complex and sophisticated due to the complexity of cryo systems, power supply systems, and beam tuning controls.
8. Our cryogenic machines use helium for cooling purposes; it is a non-renewable resource. We have developed methods of capturing gas accidentally lost due to quenches and such, but we must be regularly resupplied.

8. RESPONSIBILITES

Operators must be trained to work with the fire department for response to any ODH emergency. This requires being medically approved to use the Self- Contained Breathing Apparatus (SCBA) provided by the Fire Department. In addition to all this, the use of cryogenics requires more training for Operations Department personnel due to its controls system.

9. CONCLUSION

Encourage the development of air temperature superconductors.

Cryogenic machines are much more temperamental than conventional machines. Our system uses helium, which is a non-renewable resource. Cryogenic machines require refrigerators, a cryogenics group for maintenance, sophisticated quench protection systems, more time to replace failed magnets, has a bigger impact on operations due to weather conditions, and a much more complex and expensive set of instrumentation is needed for efficient beam diagnoses. And finally, it takes more time to train operators to deal with cryogenic systems and procedures.

WHO OPERATES CRYOGENICS?

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Abstract
Cryogenics systems are strategic components of superconducting accelerators. To ensure the requested quality of this service the organization of the cryogenic operation must be well incorporated into the global operation policy. This paper aims to define the constraints of the cryogenic operation induced by the cryogenic system itself, and by the interference to other systems. The skills of the operation crew are reviewed and some typical operation activities presented. As the operation of such large systems requires a complex organization with maintenance and cryogenic expert teams, several operational structures will be exposed showing their respective advantages and drawbacks.

1. INTRODUCTION TO A LARGE CRYOGENIC SYSTEM: LHC MAIN RING CRYOGENICS

Eight large cryoplants (Fig. 1) will produce refrigeration for the LHC ring. Each plant normally supplies a whole LHC machine sector of about 3.3 km length via a separate cryogenic distribution line (QRL), with interconnections at every basic machine cell length of 107 meters within the arc.

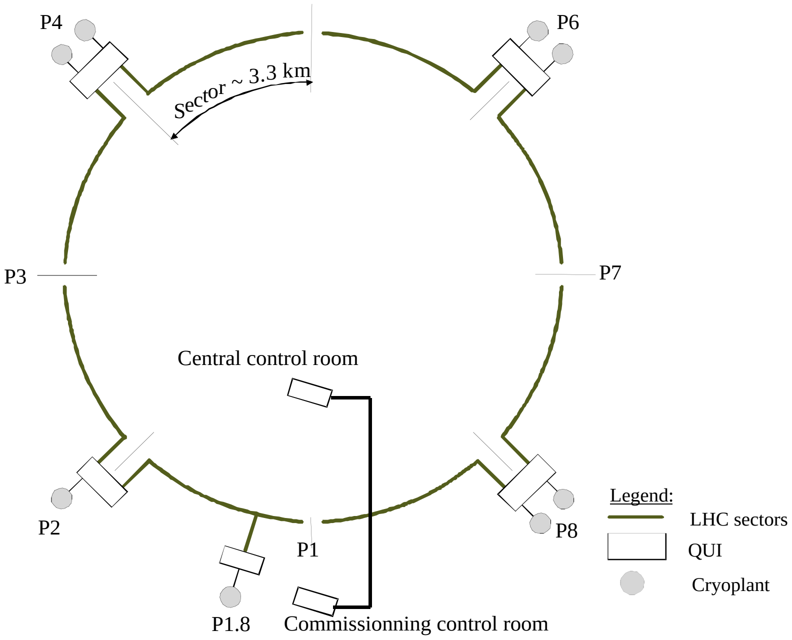

Fig. 1: LHC cryogenic system

The cryogenic system is separated in four distinct entities (Fig. 1). A typical entity is made of (Fig. 1) two cryoplants linked to the distributed cryogenic load located inside the LHC tunnel via a cryogenic interconnection box (QUI) located at a LHC access point (IP).

The 4.5K and 1.8K helium refrigerators constitute a cryoplant and are the main components of the production system. They are delivered and commissionned by industry and integrated by CERN into the cryogenic system of LHC. Figure 2 presents the different components of this system and their interconnections.

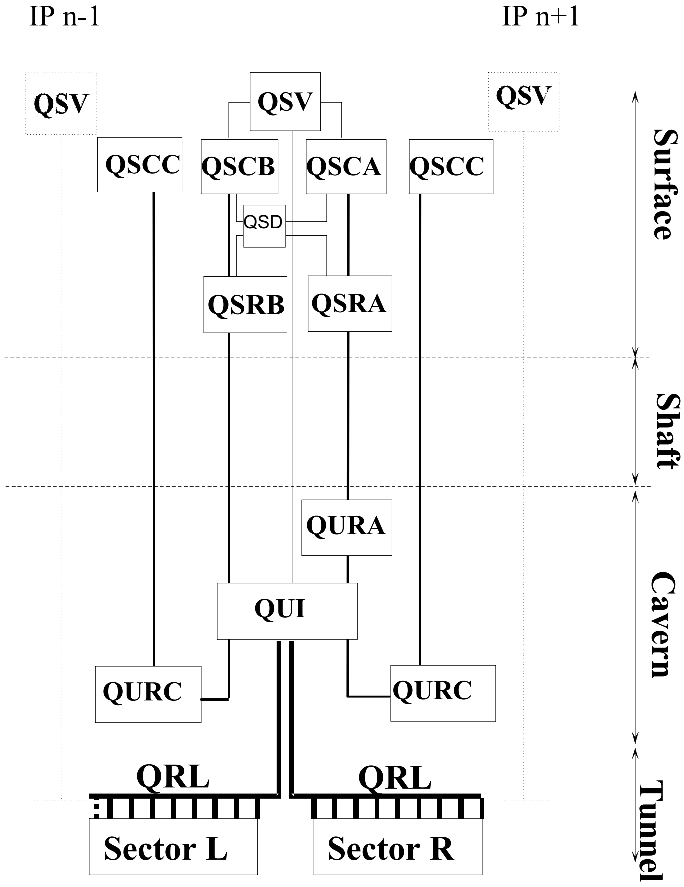

Fig. 2: Typical LHC cryogenic system at one interaction point

The following sets of components constitute a refrigerator and are considered as autonomous cryogenic units: {QSCA, QSRA, QURA} and {QSCB,QSRB}for the 4.5K refrigerator A and B; {QSCC,QURC} for the 1.8K refrigerator; {QUI, QSD, QSV} are the interconnection boxes, the liquid nitrogen storage and the gaseous helium storage connected to the cryoplants.

There is a right (R) and a left (L) hand sector around each refrigeration system,. A sector is composed of different sections namely a regular arc, dispersion suppressors (DS) and long straight sections (LSS) (Fig. 3). The load, per sector, is the QRL, the superconducting magnets, two electrical feed boxes (DFB) controlling the cooling of the magnet current leads, superconducting cavities (at IP4 only) and other cryogenic equipment installed in the long straight sections located near the access points.

The cryogenic equipment installed in the tunnel is fed with helium from the QRL via so-called service modules. About 70% of the cryogenic element are the 107 meters long regular machine cells consisting each of 8 superconducting magnets and their associated QRL and service module. They are 23 such cells and four smaller cells per sector.

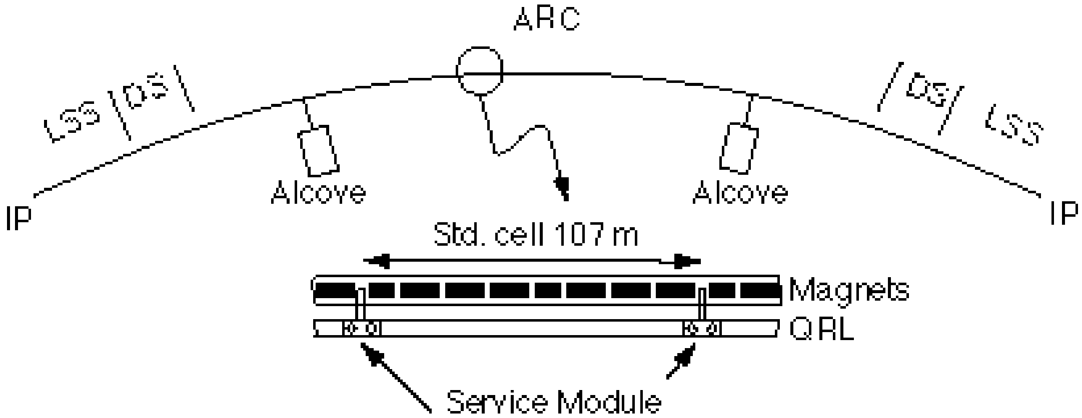

Fig. 3: LHC sector

2. HOW CRYOGENICS INTERACTS WITH OTHER SYSTEMS

2.1 Dependence on utilities (Water, Power, Air, Control)

These utilities are vital for the cryogenic system. They are developed and maintained by dedicated technical groups and a technical control team monitors them. The knowledge of the cryogenic operator about the interface and the nature of the dependence on these systems is fundamental to develop recovery procedures.

2.2 Interaction with other components of the accelerator

Despite of its status of 'service' the cryogenic system will interact strongly with other components of the LHC. These interactions are not just a binary information exchange but reciprocal physical influences (Fig. 4).

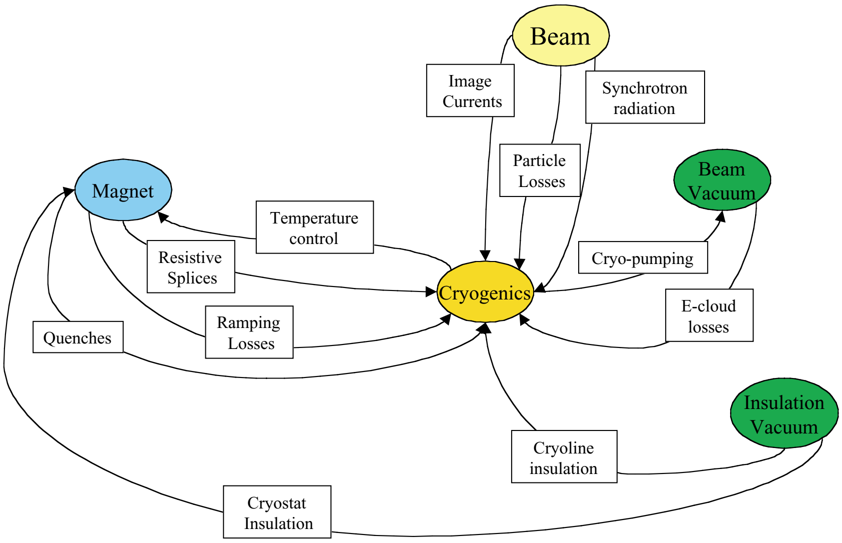

Fig. 4: Interactions with other accelerator components

2.2.1 Vacuum system

Variations of the temperature level in the QRL or in the magnets will induce outgasing in the vacuum system either in the insulation jacket or in the beam pipe depending where the variation is located. The vacuum degradation in the insulation jacket may lead to a large increase of the thermal losses overloading the capacity of the cryogenic system, limit the maximum beam energy and in extreme cases induce a quench. Degradation of the beam vacuum will shorten the beam lifetime and increase the beam losses.

2.2.2 Magnets

The field quality in superconducting magnets depends on the stability of the temperature control in the cold mass. If the temperature drifts out of the superconducting limit 10 mK above the working point, quenches will be induced leading to a beam dump.

2.2.3 Beam

In the previous paragraphs we have seen that the cryogenic system may affect the beam through the vacuum and the magnet. Reciprocally the beams will also have large impact on the cryogenic system. The beam losses in a cold mass may locally overheat the magnet inducing quenches. In normal operation the beam heat load will vary by a factor of 10 within an inner triplet which will impose the use of feed forward loops to avoid step functions in the cryogenic system

3. WHAT MEANS CRYOGENIC OPERATION?

To introduce the different skills developed by the cryogenic operation team, this chapter will review several aspects of typical cryogenic operation tasks.

3.1 Operation without beam

3.1.1 Cool down

This operation will follow the annual technical shutdown. Before start of the cooldown the operation team must complete a checkout of the cryogenic system in collaboration with the maintenance team. This checkout will review the applied maintenance procedure and verify weather each component (mechanical, electrical, control,…) is in operation mode.

Once the checkout completed the production system may start. Then the cooling capacity of the cryoplants can be checked as well as the cryogenic distribution line to avoid the warm up of a entire sector in case of problems.

The cooldown of LHC cryogenic components will last 11 days. During this time the operation team will closely observe the temperature trends, evaluate and correct deviations, identify malfunctions and abnormal heat losses. The operation team will also have to manage the logistics for LN2 and LHe supply delivered to the site by several lorries per day.

3.1.2 Quench recovery

Quenches are considered as normal events in a superconducting machine (1 per week at HERA during the first years of operation). Depending on the extension of a quench (from 1 to 4 cells) the recovery time will last between 3 to 10 hours. It is foreseen to have an automatic quench recovery procedure as it was the case for the LEP quadrupoles. But the operators may reduce the recovery time and the impact of such events by acting on the power capacity of the refrigerators or by giving priorities adapted to the request of the beam operation team.

In addition the cryogenics operators must closely cooperate with the beam operation team to reduce the number of quenches.

3.1.3 Recovery after utilities or cryogenic failures

These events are common in cryogenic operation (four times per cryoplant and year for LEP2). In order to improve the recovery time and the operation efficiency the cryogenic operator will have to:

- Identify the failure
- Cooperate with the utility operation to take the actions reducing the downtime to the minimum (for utility failure)
- Solve the problem by the intervention of the operator himself or requesting the intervention of the cryogenic maintenance team for major cryogenic failures
- Restart the cryogenic system as fast as possible. The cryogenic system acts as a downtime amplifier and the expected downtime for LHC will be 6 hours + 3* (time of the stop duration).
- Report all actions and important issues to prevent new occurrence of identical trouble.

In case of a main (400 kV) power cut, the eight cryoplants will be stopped. One expects that, even with a fully automatic control system, one operator per cryoplant is needed to guaranty a rapid restart. During LEP operation it was noted than after a long period of running at a stable working point such a brutal event has often consequences on minor components of a cryoplant which may impose a restart under degraded conditions.

3.2 Operation with beam

While the accelerator is working with beam, the cryogenic operation team will monitor and optimize the cooling capacity to:

- Improve the stability of the physical cold mass parameters, as a very tight temperature margin (+/–5 mK) has to be guaranteed
- Tune all control parameter to reject any perturbations.
- Check if the temperatures remain within the operational margin to detect and correct malfunctions.
- Reduce the power consumption. (5.5 MW per sector of electrical consumption at nominal)

4. WHO IS IN CHARGE OF THE CRYOGENIC OPERATION?

According to the tasks described in Chapter 4 we can summarize the skills of the operators as follow:

- Understand the cryogenic environment (utilities, control, etc.)
- Understand the interaction with other systems
- Understand the cryogenic system behavior
- Be able to monitor and correct the system with beam operation
- Work out the beam operation period
- Be able to deal with the cryogenic hardware
- Be able to cooperate with the maintenance team

It appears clearly that the creation of a cryogenic operation structure is mandatory.

4.1 The cryogenic operation structure

Figure 5 presents a possible structure for the cryogenic operation:

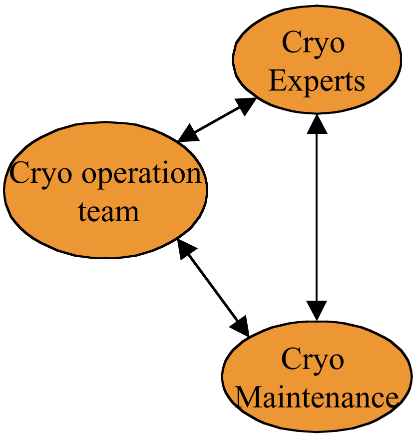

Fig. 5: Cryogenics operation structure

The cryogenic operation team will be in charge of monitoring and optimizing the cryogenic system and the operational procedures for interventions and recovery. It will be the first line intervention on failure. Finally it will coordinate the maintenance and upgrade work with the accelerator operation needs.

The cryogenic expert team is constituted of specialists for the different aspects of the cryogenic system (refrigerators, compressors, process, controls, mechanics, …). This team will support the operation team for optimization and will develop upgrades for continuous improvement of the system. The task of this team is essential for the first years of operation.

The cryogenics maintenance & support teams constitute the second line intervention in case of major failures. They will have to manage all maintenance work with the feedback of the operation team. Moreover these teams will have to implement modifications proposed by the expert team mainly at the beginning of the operation or for later upgrades.

5. INTEGRATION SCENARII

There are several possibilities to integrate the cryogenic operation team in the global operation policy. We consider that the cryogenic expert team and the cryogenic maintenance team shall exist in all cases. Possible solutions with their advantages and drawbacks are presented below.

5.1 Independent cryogenic operation team

The intuitive solution is to create a cryogenic operation team independent of the existing teams for accelerator operation and technical monitoring in charge of the utilities survey.

In this case the cryogenic expertise may be partly incorporated in the operation team. This team will be very efficient in developing better cryogenic operation procedures and will be able to optimize the operation in a shorter time.

The day to day organization will be easier and dedicated to cryogenics and will permit the integration of the operation of other cryogenic systems of the laboratory.

The treatment of the interaction of cryogenics with other components will, however, require a close collaboration with the accelerator operation team which may imply a certain geographical proximity of the teams.

Shift operation will probably be needed for the startup of a machine such as LHC. This will imply a large crew which has to be found in accordance with the human resource policy of the laboratory.

5.2 Integration in the accelerator operation team

In this case the operation of the cryogenic system will be done by the accelerator operation crew.

The advantage is a better coupling between the cryogenic and accelerator operation. All interaction between the cryogenic system and others are mastered by the team. This team can easily develop strategies to limit their impact on the machine behavior.

In addition, cryogenic operation and accelerator operation are sharing human resources.

As the background of the two teams is rather different, an acculturation of the accelerator team to cryogenic problems is needed. For this reason the team will request a stronger expert support during recovery and degraded operation and will mainly depends of the cryogenic expert to establish the procedure, to optimize the cryogenic system and to interact with the maintenance team.

The cryogenic operation is often scheduled out of the normal accelerator operation.

5.3 Integration in a technical monitoring team

In this case the team in charge of monitoring utilities also performs the cryogenic operation.

The first benefit of such a solution will be the good coupling with other technical services, which will imply a better coordination for intervention on utilities reducing the recovery time for such events. The operators' skills and background are quite similar and the training to operate cryogenic systems will be straightforward. In addition, this team will be in direct contact with the accelerator which will be an asset to its motivation and the resources will be shared.

However, as the operators will have many systems to monitor, less attention will be given to the cryogenic system and some degradation may not be recognized. In this case a strong cryogenic expert support will be needed to optimize the cryogenic system. To handle the interaction with other systems, the cooperation will have to include the accelerator team and the cryogenics experts.

5.4 Outsourcing to industry

To face the shortage in human resources, cryogenic operation may be partly or totality outsourced. The problem is to decide what is strategic in the cryogenic operation and cannot be outsourced.

If the operation team is outsourced, the cryogenics will be disconnected from the other operation teams which will imply a strong cryogenics expert support, and an operation interface team which coordinates the activities. With the time the operation expertise may be lost and a strong dependence on the external subcontractor will be created.

Outsourcing should not mean hiring missing staff but procuring a service and the quality estimators of this service are very difficult to establish. Outsourcing of the maintenance is probably easier to follow, as the work can be well defined and controlled by means of a maintenance plan.

6. CONCLUSION

The integration of the cryogenic operation team into the global operational policy must be addressed with caution, and be adapted to the nature of this operation, the human resources and the financial constraints.

The operational structure may change during the lifetime of the accelerator, starting with a strong and dedicated cryogenic operation team and later-on joining other operation teams.

As Cryogenic Operation is a strategic component of a superconducting accelerator such as LHC, the outsourcing of the cryogenic operation is a managerial and political decision which has to be weighted.

7. ACKNOWLEDGEMENTS

I would like to thanks S.Claudet, Ph. Lebrun, L. Tavian, L.Serio for their contribution to this paper and the LEP2 operation crew with whom I have spent seven exciting years running the cryogenic system.

INTERLOCK AND PROTECTION SYSTEMS FOR SUPERCONDUCTING ACCELERATORS: MACHINE PROTECTION SYSTEM FOR THE LHC

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Abstract
The protection of the LHC accelerator has to work under all circumstances, with and without beam. Several sub-systems, such as beam dump systems, beam loss monitors, magnet protection, and powering systems etc. are combined coherently with some dedicated hardware as ‘glue’ to form the machine protection system. The structure, some aspects of the hardware, and in particular the interfaces to the other systems are described.

The impact of the machine protection to commissioning and operation of the LHC has been recently discussed in one half-day session at the LHC Workshop in Chamonix. This write-up is identical to the report by K.H.Mess that is included in the proceedings of the Chamonix workshop [1]. During the session at Chamonix Workshop seven presentations were given that are related to machine protection:

- Mechanisms for beam losses and their time constants, Oliver Brüning.
- Beam losses at HERA - is everything understood? Mark Lomperski (DESY)
- How to use Beam Loss Monitors at the LHC? Helmut Burkhardt
- The Quench Protection System and its interface to Machine Protection, Felix Rodriguez-Mateos
- Architecture of the Machine Protection System, Karl-Hubert Mess
- Information exchange between beam dumping system and other systems, Etienne Carlier
- What data is required to understand failures during LHC operation, Robin Lauckner

The summary of the session is also included in [1].

1. INTRODUCTION

The LHC is a complex accelerator operating close to the limits, both as far as beam energy and beam densities are concerned. Major faults in the complex equipment will result in long repair times. To optimise the operational efficiency of the accelerator, accidents should be avoided and interruptions should be rare and limited to short time. Hence a system is needed that pre-vents dam-age to the magnets, the cables and the power-leads, minimises damage due to irradiation caused by beam losses, and provides the necessary tools to implement a consistent and congruent error and fault tracing, through-out the machine.

Machine protection is not an objective in itself; it is a mean to maximise operational availability by minimising time for interventions and to avoid expensive repair of equipment and irreparable damage. The proposal, presented here, is based on work done for the Tevatron, HERA_p, RHIC and the string tests at CERN [2, 3, 4, 5]. As an evolution of the ideas presented at the Chamonix_X workshop [5] it has been discussed since with numerous colleagues from SL-BI, SL-BT, SL-PC, LHC-ICP, and ST-AA. It has been presented to the DEWG, IWG, and the AIWG working groups as well as to the SL-TC, the TCC, the MAC, and at other occasions.

The interlock and access system for personal safety does in principle not depend on the machine protection system. The two systems are, however, related.

2. THE CHALLENGE

Both, the stored magnetic energy and the energy stored in the beams are unprecedented. Moreover, both systems are coupled. Obviously, faults in the magnet system will in general often result in a beam loss, which in turn may induce quenches. The machine protection system has, however, be made to accept that at times the magnets will be powered, without beam in the machine. The opposite case is not possible.

At nominal operating current, predominately the dipole magnets store a large amount of energy. The LHC magnets are powered separately in each of the eight sectors in order to reduce the energy stored in a particular electrical circuit. Still, the energy in each sector of the LHC amounts to 1.29 GJ, sufficient to heat up and melt 1900 kg of copper [7].

During operation without beam, the large energy stored in the magnets presents the main risk. Various reasons can lead to an uncontrolled energy release. Magnets, superconducting bus bars, current leads, or cryogenic infra-structure could in such a case be destroyed. In case of a failure the magnetic energy has to be extracted. Due to the large inductance a response time in the order of 10 ms to abort the power is acceptable for most elements (such as all superconducting magnets).

Each beam stores energy of up to 0.35 GJ, equivalent to the energy for warming up and melting 515 kg of copper. A sophisticated collimating system protects the magnets from beam losses.

If the operation of the machine becomes unsafe and beam loss has already been observed by the beam loss monitors, or is imminent due to equipment failure, the beams have to be dumped as soon as possible, in order to prevent radiation damage, quenches, and downtime. However, due to the size of the LHC at least 110 µs are required on average to request a beam dump.

The large number of vital components will be a major challenge. More than 8000 superconducting magnets, including about 2000 large dipole and quadrupole magnets, and 6000 corrector magnets, are powered in about 1800 circuits. Several thousand electronic channels may, in case of failure, force a beam dump. To limit the number of superfluous aborts below one per fortnight, the mean time between failure (MTBF) must exceed 100 years for each channel!

The machine downtime depends on the type of faults and their frequency. It could be between two hours and several weeks for one incident. Major accidents may include the partial destruction of a magnet. To warm up the neighbourhood, the repair, and the cool down will require some weeks. Should no spare magnets be available, the repair may last many months.

3. ARCHITECTURE OF THE MACHINE PROTECTION SYSTEM

3.1 General aspects

Some general requirements have to be considered for the machine protection system:

- Protect the machine: In case of fault the necessary steps shall be taken to dump the beam and to discharge the energy stored in the magnets in a safe way.
- Protect the beam: The system shall not generate unnecessary beam dumps.

- Provide the evidence: The system shall help to identify the initial fault, in case of beam dump or power failure.
- Improve the operation: The status of the system must be transparent to the operator at all times.
- Enable tests: Almost all functions must be remotely testable.

This can be achieved by:

- Hardwired abort links protect the equipment (Hard Abort).
- Soft aborts, possibly via computer links, improve the operation efficiency; they may be disabled or may fail.
- The number of channels that may provoke an abort will be minimised.
- The same structure across different sub-systems in the abort chain will be used.
- All inputs can be simulated or bridged. However, in such a case ‘permits’ are also simulated and not passed to destinations outside of the system.

3.2 General Architecture

The architecture of the machine protection system is derived from the structure of the LHC and from operational requirements. It consists of a distributed, globally acting Beam Interlock System that informs the Beam Dump System if any unsafe situation is detected, and of locally acting, distributed, Power Interlock Systems. They cause a safe discharge of the energy stored in the magnet system in case of a quench, or other failures. Interfaces between the Power Interlock Systems and the Beam Interlock System ensure the dumping of the beams, if necessary. A Post Mortem System described elsewhere [8] records data from various systems to understand the cause of a fault leading to a beam dump or power abort.

3.3 Architecture of the Power Interlock

The eight sectors in the LHC consist (Version 6.2) of 44 continuous, largely independent cryostats [9], and some warm magnets. Powering of one electrical circuit is al-ways limited to one of those cryostats or half-insertions

The powering system for each electrical circuit includes power converters, (warm) cables from power converters to the current feedthroughs, the current feedthroughs, superconducting bus bars for the current distribution, and finally the superconducting magnets.

In case of a fault in one of the cryostats the energy of some or of all electrical circuits in this cryostat has to be discharged. Each cryostat will have a local Power Inter-lock System. Hence, any cryostat can be powered irrespective of other cryostats. An example of the architecture between IP1 and IP8 is given in Fig. 1.

LHC contains 36 short cryostats requiring one Power Permit Controller (PPC) each, preferentially located close to the power converters. Warm magnets on either side of an interaction point (IP) are treated as if they form an additional ‘continuous cryostat’.

The eight long arc cryostats span the major part of a sector and are electrically fed from both sides. The energy extraction systems for the MQ magnets are in the even points. The MB magnets are discharged at both ends of the arc cryostat. Hence the long arc cryostats need Power Permit Controllers (PPC) on both sides and a communication link in between. The quench detection for main magnets in the arc cryostats comprises about 200 units distributed along the arc.

About 100 power converters installed in the tunnel power the orbit correctors in one sector.

In total, almost 60 Power Permit Controllers (PPC) are required. They will also be connected to the controls network and the timing system.

3.4 Architecture of the Beam Interlock

There will be one Beam Interlock System for the LHC. Right and left from each IP one Beam Permit Controller (BPC) will be installed (see Fig. 1). These controllers are connected to two fast, optical links (Beam Permit Loops) running at 10MHz (see Fig. 2). The two links distinguish between beam I and II. When a link is broken, the corresponding beam is extracted into the beam dump by the Beam Dump System. In addition, a computer connection to the BPC for monitoring, testing and post mortem analysis is required.

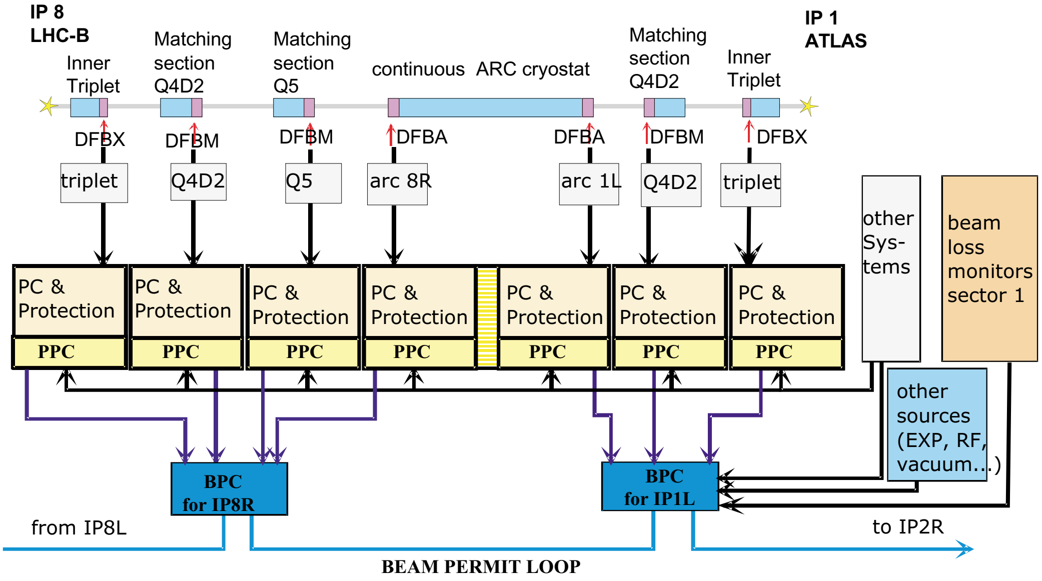

Fig. 1: Power and Beam Protection System between IP1 and IP8

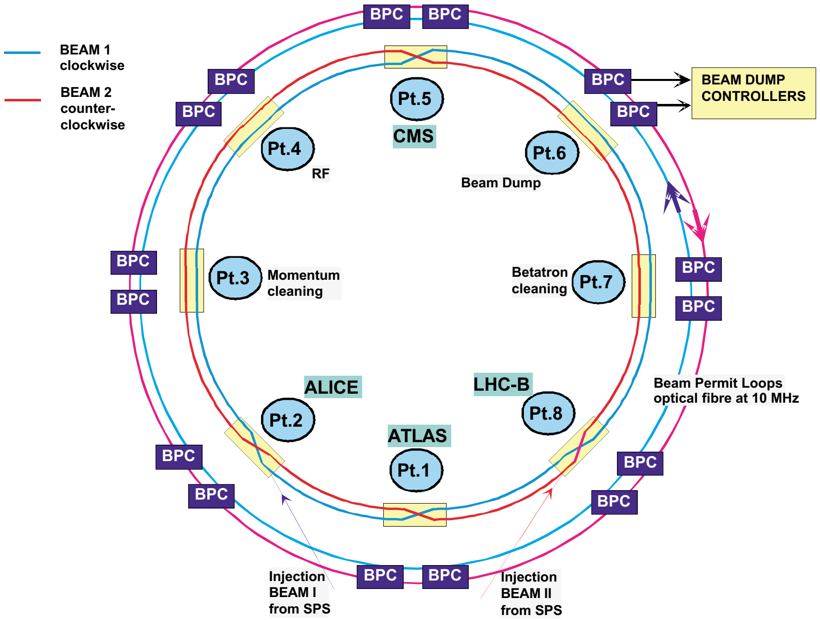

Fig. 2: General layout of the Beam Interlock System

Note that Beam Permission is a necessary but not sufficient condition for beam injection. In order to inject beam, additional conditions have to be met.

Power Permit Controllers report their state to a BPC in the vicinity.

3.5 Inventory of the Machine Protection System

The Machine Protection System consists of:

- 16 Beam Permit Controller BPC,
- global fast links between the BPC and the Beam Dump System,
- a set of 52 (v. 6.2) Power Permit Controller (PPC) for the cryostats,
- some PPC for the warm magnets
- and a computer network connection to each controller.

In addition the Machine Protection System makes use of features provided by the Quench Protection System and Power Control System:

- a set of 8 arc links to collect the quench messages (Quench Loop),
- a set of 8 arc links to fire heaters (Heater Activation Link),
- and field-busses, joining the controls for quench detectors and heater power supplies and the power converters in the arc.

Some details about the Beam Interlock System (BPC and links) and the Power Interlock System (PPC and links) are described below. More information will be presented in a forthcoming report [10].

4. COMPONENTS OF THE POWER INTERLOCK SYSTEM

A Power Permit Controller monitors the powering status of one cryostat. Depending on the cryostat, it monitors the elements in a few electrical circuits for short cryostats, and of some ten electrical circuits in the long arc cryostat. Therefore a modular design is pro-posed. Similar controllers will monitor the powering of all warm magnets in one half-insertion.

An electrical circuit is connected to the PPC through a dedicated channel, identifying the type of the electrical circuit. With respect to the magnet protection, the circuits are divided into two classes:

- Main magnets: Circuits that include magnets with large stored energy. A quench is likely to affect other magnets and electrical circuits. Therefore all magnets in the cryostat will be de-excited (Cryostat Power Abort).
- Other magnets: Circuits that do not include magnets with large stored energy. Normally, a quench of an element in such circuit is contained in that element.

With respect to the impact of a magnet fault to the beams a different distinction has to be applied. Depending on the state of the accelerator, some electrical circuits may not be vital (‘critical’) for machine operation. It would be inappropriate to dump the beams, if such a circuit quits functioning. Hence, some circuits are ‘critical’, i.e. required for beam operation under all circumstances, and some are only sometimes required. Switches set this classification.

4.1 Quench of a main magnet

The electrical circuit to be monitored defines the input and output signals for a given channel. For example a main magnet circuit will have a Quench Loop.

In case of a quench, the loop is opened by the quench detector. Since a main magnet quench will cause a Cryostat Power Abort, the discharge switches extract the energy from the main circuits in this cryostat. In addition the corresponding power converters are switched off by raising the Power

Converter FAST ABORT signal and by removing the corresponding Power Converter PERMIT (constant current outputs). All other circuits of the cryostat are discharged by the PC controller or by a Discharge Switch Trigger command.

The power converter informs the PPC of a fault by dropping the PC OK signal. If the fault requires a fast discharge, the PPC sends in addition a DISCHARGE REQUEST to the PPC (by interrupting a current loop) that activates the discharge switch for this circuit.

In the unlikely and worst case that a discharge switch fails to open after a request (Switch Open Fault), a number of selected heaters will have to be fired by the PPC using the Heater Activation Link.

For the triplet cryostats, the heaters of the MQX magnets are fired in case of a discharge request, since there is no system to extract the energy and the time constants for slow ramp down are too large.

In all cases both signals to the BPC (ALL CIRCUITS OK and CRITICAL CIRCUITS OK) will be switched off.

4.2 Quench of a low energy magnet

Circuits that have little energy stored require only a Quench Loop, a PC OK link, a PC PERMIT link, and a PC ABORT link. If one of the quench detectors for the circuit indicates a quench, it breaks the Quench Loop. The controller switches the power converter off (PC PERMIT, PC ABORT). If the circuit has an extraction resistor, the energy is extracted.

In case of a power converter fault, a signal is transmitted to the controller in order to record the failure.

It is not required to discharge magnets powered in other electrical circuits. In all cases the ALL CIRCUITS OK signal to the BPC is switched off. Internal readable jumper settings determine, whether the electrical circuit in question is considered ‘critical’. If this is the case, also the CRITICAL CIRCUITS OK signal is switched off.

4.3 Interfaces to other systems

In general, the PPC has per electrical circuit the following signals/links:

- one Quench Loop,
- one PC OK input,
- one power permission link (output),
- one PC Fast Abort link (output),
- one PC Slow Abort link (output),
- one Current Low input (I< I_access).

The PPC of the long arc cryostat requires one additional I/O section for the three main magnet circuits with:

- one Quench Loop connecting the PPCs on both sides with all quench detectors for main electrical circuits, and the discharge switches,
- three PC OK inputs,
- three PC PERMIT outputs,
- three PC Fast Abort outputs,
- three PC Slow Abort outputs,
- three Current Low signals (in-put),

- three NO DISCHARGE requests (input),
- three Discharge Switch Open Fault (input),
- three DISCHARGE TRIGGER links. (The second MB discharge switch is operated by the second PPC.)

All electronics of the Power Interlock System is connected to the control system. Status and memory is read-able at any time.

The computer connection to the control system is established via the VME bus, a suitable processor board and VME. It might be considered to employ a local display unit and a keyboard for debugging.

Electronics that is directly connected to the Power Interlock System, like quench detectors, must be connected to the control system, either via Ethernet alone or via fieldbus and Ethernet.

5. COMPONENTS OF BEAM INTERLOCK SYSTEM

The Beam Permit Controller (BPC) combines the messages from different sources to interrupt the 10 MHz pulse trains in the optical fibres of the Beam Permit Loop (BPL) in case of a fault condition. The absence of a pulse train will be interpreted as BEAM DUMP command for the corresponding beam.

The 10 MHz trains are produced in one BPC only (IP6L, set by a jumper). The setting of the jumper (master/slave) is visible at the front panel and readable from the computer. There will be three types of inputs to the BPC. The BPL input will be used to feed the BPL output, unless one of the unconditional inputs indicates a fault condition or one of the conditional inputs does so, provided it is not masked.

All input states and the output state are continuously sampled and stored into a memory as well as displayed life on the front panel.

Table 1: Input signals to the Beam Permit Controller

Name	**Conditional**[a]
RF system	Yes
Loss monitors I	Yes
Loss monitors II	Yes
Beam excursion	Yes
Arc cryostat, All Circuits OK	Yes
triplet cryostat, All Circuits OK	Yes
Q3 cryostat, All Circuits OK	Yes
Q4 cryostat, All Circuits OK	Yes
Q5 cryostat, All Circuits OK	Yes
Q6 cryostat, All Circuits OK	Yes
Q4D2 cryostat, All Circuits OK	Yes
4 spares	Yes
Experiment OK	No
Loss monitors at collimators	No

Name	**Conditional**
Collimators	No
Access system OK	No
Extraction system OK	No
Beam Injection Permit	No
Vacuum valves OK	No
spare	No
arc, Critical Circuits OK	No
triplet, Critical Circuits OK	No
Q3, Critical Circuits OK	No
Q4, Critical Circuits OK	No
Q5, Critical Circuits OK	No
Q6, Critical Circuits OK	No
Q4D2, Critical Circuits OK	No
Warm magnets	No

[a] Preliminary assignment

The control system sets the masks, senses the memory state (frozen or life) and performs the readout. The fail-safe and reliable inputs are described below

Each Power Permit Controller provides two signals to the BPC:

- A fault in one of the main magnets, such as dipole or quadrupole magnet, would always cause a total beam loss. After such fault the signal CRITICAL CIRCUITS OK would disappear, and both beams would be dumped.
- A fault in a corrector magnet, such as a spool piece magnet or orbit dipole corrector, might cause a beam loss. After such fault the signal ALL CIRCUITS OK will disappear. This may imply a beam dump, depending on the machine status.

In case of circulating beams, the breakdown of the BEAM DUMP SYSTEM presents a major hazard. The beams must be dumped, as long as the system is still capable to do so. The signal is unconditional.

Inputs from the LHC experiments are foreseen. The details have still to be discussed.

If the RF system does not work correctly, the beam will debunch. It will not be possible to dump the beam properly without unacceptable beam losses. A signal from the RF system is therefore required to dump the beam if a debunching is to be anticipated or if the feedback is going to fail.

There will be beam loss monitors distributed around the ring, with a set of monitors close to each quadrupole, as well as monitors close to the collimators for beam cleaning. The signature of a beam loss that should request a BEAM DUMP remains to be established.

The input to the Beam Interlock System would be via one of the BPC close to the insertion. It needs to be understood if a link from the alcoves to the BPC is required. Alternatively, the beam loss monitor system might be subdivided into eight sections. In this case one input per octant or sector might be used.

The access system for the protection of people needs to follow the legal requirements. It needs to be completely separate from the Machine Protection System. However, there is an interface between the state of the access sys-tem and the actions to be taken by the Machine Protection System. The Machine Protection System will automatically request a beam extraction in case of an access violation. For safety reasons, a separate link from the access system to the BEAM DUMP SYSTEM is required.

There will be some elements to prevent the accidental injection and circulation of a beam, such as valves in the beam tubes, collimators and some magnets in the transfer line. Such systems are activated if ACCESS to the tunnel or the galleries should be given, or if there is an ACCESS VIOLATION. Considering valves or collimators, an injection can not be allowed unless they are out of the beam.

Two Beam Permit Loops run around the entire accelerator. The signals need to be transmitted as fast as possible to the BEAM DUMP SYSTEMS. The number of access points to the link is limited to 16. Hence, a transmission using optical fibres seems appropriate. The state of these loops is available for local distribution.

All electronics of the Beam Interlock System is connected to the control system. The computer connection to the control system is established via the VME bus, a suit-able processor board and Ethernet. It might be considered to employ a local display unit and a keyboard for debugging. All electronic connected to the computer link has to have a post mortem memory to record all essential signals. The computer link can also provide the machine status and the timing information, as well as operator commands.

6. ACKNOWLEDGEMENTS

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OPERATIONAL CHALLENGES OF HERA'S SUPERCONDUCTING PROTON MACHINE

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Abstract

Compared to its luminosity energy of 920 GeV HERA's superconducting proton machine has a rather low injection energy of 40 GeV. During the cycling procedure of the superconducting magnets eddy currents are induced in the superconducting cables. These persistent currents decay over hours during injection and ramp. The magnetic field components driven by these persistent currents are detrimental to the beam and therefore have to be measured and compensated. In this paper the methods are described to adjust the beam energy, the betatron tunes and the chromaticity both during injection and on the ramp.

1. HERA

HERA, the 'Hadron Electron Ring Accelerator' at DESY, is an electron proton collider for high energy physics. Two rings are placed in one tunnel of 6.3 km circumference. The superconducting proton ring has an injection energy of 40 GeV and a flat top energy of 920 GeV. Typically 100 mA are stored in 180 bunches. In the electron ring (12 – 27.5 GeV) typically 50 mA of either electrons or positrons are stored in 189 bunches with a typical spin polarization of 60%.

In the four straight sections of the HERA ring four experiments are making use of the HERA beams: Both H1 and ZEUS use colliding beams to probe the structure of the proton. Hermes uses the polarized electron beam and a polarized internal gas target to investigate the spin structure function of the proton. HERA-B uses a thin wire target in the halo of the stored proton beam to look for CP-violation.

2. HERA'S SUPERCONDUCTING PROTON MACHINE

Between the injection energy of HERA's proton machine and the flat top energy there is a factor of 23 in energy, and accordingly a factor of 23 in current density in the cables of the main dipoles and quadrupoles. This results in a low current density at injection, which gives much room for persistent currents in the superconducting cables. At 40 GeV the field contribution of the persistent currents to the dipole field is 5×10^{-3}. The persistent currents have decay times of the order of a few hours.

Figure 1 shows the proton energy and beam current from the end of a luminosity run to the beginning of the next run. On the horizontal axis the time is given in hours. It can be seen that it takes approximately 35 minutes to fill the proton machine. After injection energy has been reached, a few low current test injections a needed to adjust parameters like beam energy, betatron tunes, chromaticity and injection orbit. Afterwards HERA is filled with three consecutive fills of the preaccelerator PETRA. Then it takes another 25 minutes to ramp up the beam energy. During injection the field components resulting from the persistent currents are constantly changing. At the beginning of the energy ramp persistent currents are induced again.

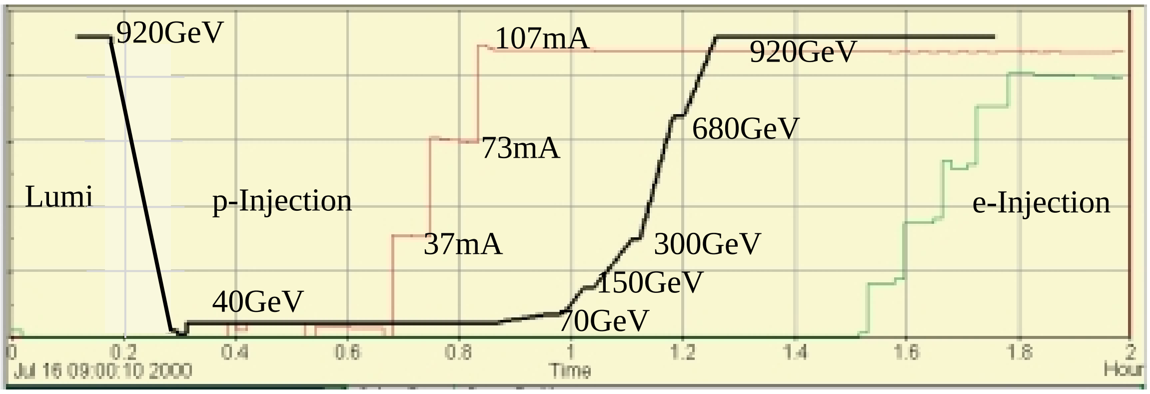

Fig. 1: Data from the HERA archive, showing a refill of the machine from beam dump to luminosity in 2 hours

3. PERSISTENT CURRENTS

Due to the low current density at injection energy there is much room for persistent currents in the cables of the main dipole and quadrupole magnets. Every change in the current driven by the magnet power supply induces magnetic fields in the cables, which then do induce electric eddy currents in the cables. Figure 2 shows a sketch of a strand of superconducting cable with the main current IMAIN, the main magnetic field B and the induced persistent currents I_{PC}.

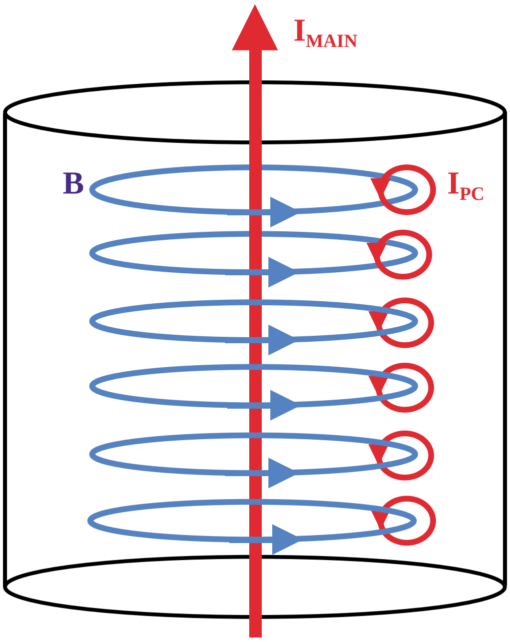

Fig. 2: Sketch of the electric and magnetic fields inside the superconducting cable

As the cable is superconducting, these eddy currents (or persistent currents) decay slowly with typical decay times on the order of hours. Therefore the corresponding magnetic fields (counteracting the main field) decay on the same time scale. For eddy currents perpendicular to the main current the resistance of the superconducting cable is higher than for the main current, as the cable is made up of thousands of small strands. Figure 3 shows a photograph of the cable.

Fig. 3: HERA’s superconducting cable is made up of 24 wires, 1230 filaments each, with a diameter of 14 microns

The field components driven by the persistent currents are mainly dipole and sextupole fields. The contribution of the persistent currents to the dipole field at 40 GeV is 5×10^{-3}, the contribution of the persistent currents to the chromaticity at 40 GeV ($\zeta_{x,PC} = -275$) is about 5 times that of the natural chromaticity ($\zeta_x = -44$) [1].

At the beginning of the proton energy ramp, persistent currents are induced again, leading to nonlinear changes of some field components on the ramp. At higher energies, as the current density in the cable rises, the persistent currents become smaller, until there is no more room for persistent currents in the cables.

4. DIPOLE AND SEXTUPOLE CORRECTION DURING INJECTION AND RAMP

Two HERA dipole magnets (one from each production series) are installed outside the ring, but powered in series with the ring dipoles. In these reference magnets a set of hall probes, NMR probes and rotating coils are used to measure the dipole and sextupole fields during injection and on the first part of the ramp. From 150 GeV on the sextupole component in the dipole magnets becomes so small compared to the main dipole field that the measurement is no longer needed.

From the measured field components corrections are calculated and applied to the horizontal corrector coils and the sextupole magnets in the ring.

5. ADJUSTING THE INJECTION ENERGY

The contribution of the persistent current driven dipole field to the main dipole field at injection energy is of the order of 5×10^{-3} (i.e. 10Γ). Depending on the history of the magnet cycle and the time between the magnet cycle and the injection, the uncorrected dipole field differs from injection to injection. Therefore after each magnet cycle a low current test injection is used to measure the energy of the injected beam relative to the stored beam. If the energy of the injected beam differs from the energy given by the dipole field, the injected bunches will perform synchrotron oscillations around their nominal bunch position. The amplitude of the synchrotron oscillation is measured with a fast beam current monitor and a fast oscilloscope. If the oscilloscope is triggered with the theoretical bunch position, the difference in time between a bunch signal taken a quarter synchrotron oscillation after injection and a signal of the stored bunch is a measure of the energy difference between injected beam and the energy given by the dipole field. With a known calibration factor the dipole field can be adjusted to the energy of the injected bunches. The smallest possible steps in dipole current correspond to relative energy changes of 10^{-4}. In order to avoid hysteresis effects and additional persistent currents in the main dipole magnets, the integral field of all horizontal corrector magnets is used instead with a minimum step size corresponding to a relative energy change of 4×10^{-6}.

For each proton injection the beam energy is adjusted in three steps: First the sum of the field from the reference magnets plus the field from the horizontal correctors is adjusted to the last known good value. Then a test beam with low current is injected; the energy is measured and corrected. Then, as the persistent currents in the reference magnet decay, the horizontal correctors are automatically adjusted to compensate for the changes in dipole field as long as the beam is at injection energy.

6. BETATRON TUNES

As there are no major quadrupole components in the fields driven by the persistent currents, there is no online tune correction at injection. Before beam is injected, the betatron tune quadrupoles are set on the last known good value. After a low current test injection the tunes are adjusted manually. When the beam energy is ramped up, there is a threefold ‘tune controller’: The currents of the tune quadrupoles are changed linearly from file to file (for 40 GeV, 70 GeV, 150 GeV, 300 GeV, 680 GeV and 920 GeV there are files containing all magnet currents for stable operation at these energies). Deviations from the linear behavior are recorded on typical ramps and applied on the following ramps. Last but not least the operator controls the tunes manually.

7. CHROMATICITY

As the sextupole components driven by the persistent current decay during injection, there is an online chromaticity correction using the field data from the reference magnets. First, before injecting beam, the two families of sextupoles are set on the last known good values. After injection of a low current test beam, the chromaticity is adjusted to +3 +/–1 by an automated procedure (change of the rf frequency, measurement of the tune deviation). Then the online sextupole correction keeps the chromaticity constant during injection. When the beam energy is ramped up, persistent currents and therefore sextupole components are reinduced. On the ramp there is a fourfold ‘chromaticity controller’: The currents in the sextupole magnets are changed linearly from file to file. From 40 GeV to 150 GeV the online correction compensates for the nonlinear field changes measured in the reference magnets. From 150 GeV on deviations from the linear behavior are recorded on typical ramps and applied on the following ramps. Last but not least the operator controls the chromaticity manually by looking at the betatron tune spectra. A flat tune peak is a sign for a chromaticity well above +3, which may course bad beam lifetime. A very sharp peak is an indication for low chromaticity approaching zero. Here the chromaticity should be increased immediately to avoid beam instabilities.

8. ACKNOWLEDGEMENT

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OPERATING ATLAS; THE WORLD’S FIRST SUPERCONDUCTING HEAVY-ION ACCELERATOR

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Abstract
ATLAS (Argonne Tandem Linear Accelerator System) has been providing heavy-ion beams for Argonne National Laboratory’s Nuclear Physics Heavy-Ion Program for the past 23 years. Over time we have learned the special needs that this superconducting machine requires, such as; how to cope with power bumps, safety issues involved with cryogens, high-Q resonant cavities, and mechanical vibration. These are just a few of the challenges that must be addressed to operate this superconducting accelerator. This paper shall discuss the nuances that has made ATLAS a world-class accelerator.

1. INTRODUCTION

ATLAS is the world’s first superconducting RF linear accelerator for heavy ions. First beam was accelerated through a portion of the ‘booster linac’ section in 1978. Today ATLAS is a National User Facility. More than 60% of the experiments performed at ATLAS are for groups outside of Argonne National Laboratory. The accelerator operates twenty-four hours a day, seven days a week. Annually ATLAS achieves approximately 6000 hours of beam on target with over 90% reliability.

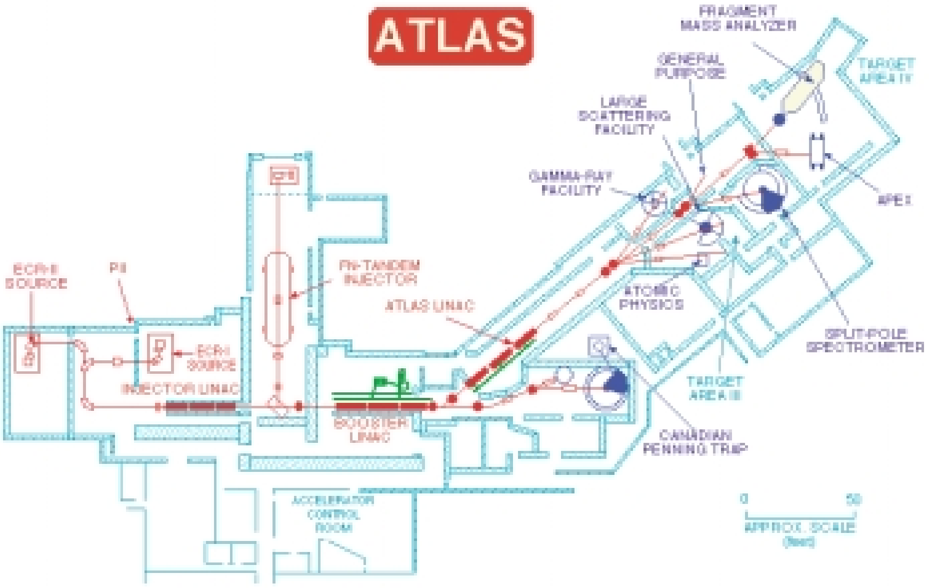

Fig. 1: Layout of the ATLAS Facility

Heavy-ion beams ranging over all possible elements, from hydrogen to uranium, can be accelerated to energies as high as 17 MeV per nucleon and delivered to one of three target areas. The beams are provided by one of two ‘injector’ accelerators, either a 9 million volt (MV) electrostatic tandem Van de Graff, or a 12-MV Positive Ion Injector (PII) comprised of a low-velocity linac and Electron Cyclotron Resonance (ECR) ion source. The beam from one of these injectors is sent on to the 20-MV ‘booster’ linac, and then finally into the 20-MV ‘Atlas’ linac section.

The ATLAS accelerator is constructed with six different superconducting resonator designs. The PII section consists of a range of low velocity (beta = 0.009 – 0.037 c) quarter-wave resonator structures, and the Booster and Atlas sections are comprised of superconducting split-ring resonators with a beta = 0.06 c and 0.105 c. Figure 2 lists the details of each resonator class. There are sixty-four niobium superconducting resonators at ATLAS, housed in fourteen separate cryostats units.

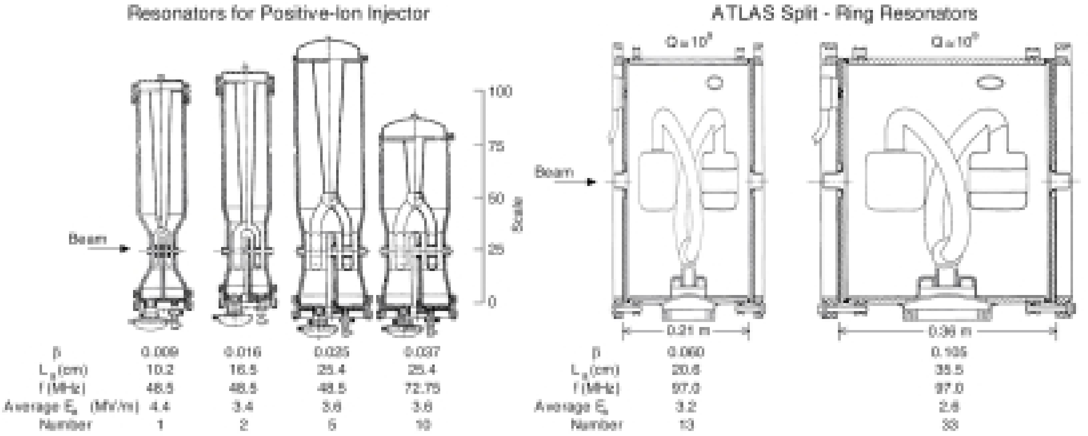

Fig. 2: ATLAS Resonators and their parameters

2. OPERATION ISSUES

2.1 Superconducting Accelerating Resonators

The heart of ATLAS is the superconducting (SC) cavity. The RF linac is based on short, high-gradient SC cavities closely interspersed with short, high field (6-8 T) superconducting solenoids. A benefit derived from a SC linac constructed in this configuration is that the rapid alternation of strong radial and short, high-gradient longitudinal fields maintains the beam quality through the machine [1]. In addition, each accelerating cavity is independently phased. The independent phasing, intrinsic to a SC cavity array, allows the velocity profile to be varied and permits acceleration of a large range of charge-to-mass ratio ions. This makes optimum use of the maximum voltage and enables higher energies for the lighter ions.

Independent phasing also provides the capability to configure the machine in such a way as to compensate for a non-functioning resonator. By the having the ability to skip over a non-functioning resonator, machine reliability is greatly improved. Independently phased resonators are in essence individual accelerators. Each one has to be controlled separately, but must stay phased locked within one degree of each other. The complexity of tuning an accelerator like ATLAS would be very difficult without the use of modern computer systems. In addition, an independently phased array like ATLAS requires many more control elements. When building a control system of this intricacy there must be a high level of reliability if one wants to achieve 6000 hours of beam on target each year.

Because the RF power requirements for SC cavities are low, CW operation is cost effective. The low RF losses of SC cavities also enable large apertures and high field gradients. The accelerating field in these cavities ranges from 2.8 MV/m to as high as 5 MV/m.

Superconducting resonators have several unique characteristics that affect operations. They are vibration, multipacting barriers, and electron loading. The effects of these are discussed below.

2.2 Vibration

In all resonant cavities, ambient acoustic noise will excite mechanical vibration modes that cause fluctuations in the resonator's eigenfrequency. In room temperature resonant cavities these fluctuations are much smaller than the resonator bandwidth and do not affect the RF phase. However, due to the low RF losses in superconducting cavities the bandwidths are typically a few tenths of a hertz. In an accelerator environment it is difficult to reduce the coupled mechanical vibration below a few tens of hertz, therefore some method must be employed to compensate for the eigenfrequency fluctuation. At ATLAS an electronic 'fast tuner' is used to control the RF phase of the resonators. [2]

The fast tuner is mounted on the resonator and is coupled to the cavity's magnetic field. The circuit is based on PIN diodes that switch, at a rate of 25 kHz, between two different impedance states. The eigenfrequency of the resonator changes when the diodes switch from one impedance to the other. The values of the impedances are chosen so that the frequency shift brackets the operating clock frequency. As the resonator's eigenfrequency is driven off the clock frequency by microphonic noise, the feedback on the fast tuner drives the resonator frequency the 180 degrees out of phase with the microphonically induced shift. By switching at a fast rate, the frequency error is corrected to less than 1 degree.

From a daily operation standpoint, this means that one must be aware of where portable mechanical equipment is placed. A vacuum pump or out of balance fan may couple acoustic noise into a resonator and drive the eigenfrequency variations beyond the control of the fast tuner. Even certain modes of refrigeration operation may cause vibration problems. Once these noise sources are recognized they are eliminated and normal operation can resume.

Due to the geometry of the very low beta (.009 c) resonators, a damping device has been developed to reduce the amount of mechanical vibration, thereby reducing the control window of the fast tuner. The damper employs a weight mounted in the inner coaxial line. The pendulum motion of the inner line performs work by sliding the weight on a plate thus damping the amount of mechanical motion. The damper has been installed in three of the lowest beta resonators with the effect of reducing the mechanical vibration amplitude by a factor of six. [3]

2.3 Multipacting Barriers

When a resonator is first cooled down from room temperature, it will not immediately achieve high field gradients. Electrons liberated from the surface at low field levels, typically a few kV/m, traverse to anther surface and liberate secondary electrons. It is possible to establish an 'orbit' of electrons of the right path length so to be in sync with the alternating voltages on the resonator surfaces. These multipacting barriers will inhibit achieving high field levels until emitting objects are sufficiently depleted in that region. This phenomenon is strongly related to the cavity geometry and the cleanliness of the surface. With the application of RF power, and the passage of time, eventually all of the multipacting barriers will go away. To condition the multipacting barriers, ATLAS cavities need anywhere from 1 hour to eight hours, depending on their geometry. Once gone the resonators will operate normally until it is either warmed to room temperature, or has been exposed to poor vacuum conditions. The RF control modules have been designed so that this conditioning process is just a flip of a switch.

2.4 Electron Loading

At high field gradients, the Q of the resonators decreases. Figure 3 illustrates a typical of a resonator Q curve. The high level Q can be increased by pulsing the resonator with short, high power RF. By increasing the Q, the power dissipated into helium is reduced, thereby reducing the overall load on the refrigerator. This conditioning must be repeated from time to time to maintain the lower power losses into the helium system. The ATLAS cryogenic system is designed for an average heat load into the helium of approximately 4 to 6 watts per resonator. Pulse conditioning of

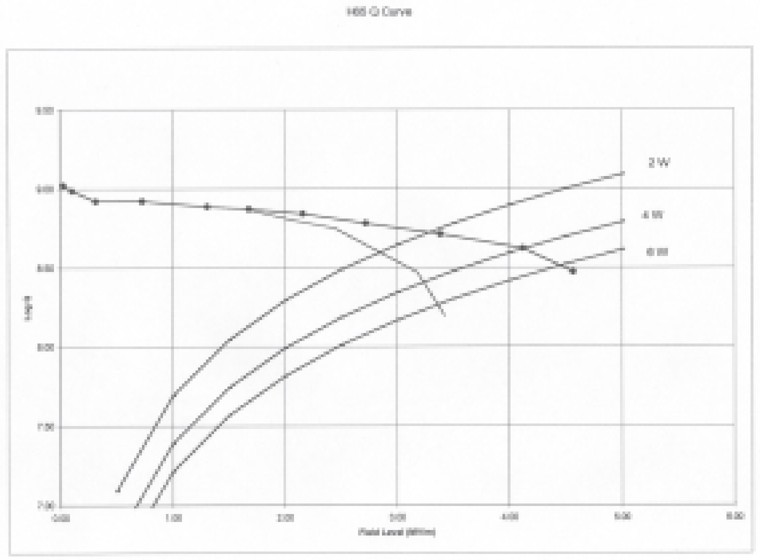

Fig. 3: Typical Q Curve of a Split-ring Resonator. This illustrates the effect of electron loading and the increased load into the helium system.

3. LIQUID HELIUM PLANT

The liquid helium plant is one aspect unique to superconducting machines. At ATLAS, the liquid helium plant is comprised of three separate refrigerators In total, the refrigerators supply 750 watts of liquid helium cooling. This is distributed between fifteen separate cryostat units. Each cryostat has a dewar that holds approximately 50 to 150 liters of liquid helium. Between the cryostat and the helium distribution system, there is an inventory of approximately 3000 liquid liters of helium.

Utility failure at a superconducting machine is not tolerable. Without electrical power, it is not possible to re-liquefy the boil-off gas from the liquid helium. Since the expansion ratio of liquid to gas for helium is approximately 780:1, an over-pressure situation develops rapidly causing helium to vent from pressure relief devices. Without the proper control systems on the helium plant, a short, two-second-power bump can result in the loss of liquid helium inventory.

Several measures to ensure a reliable system have been taken. The electrical sub-stations that provide power to the facility have automatic switches that will switch over to a secondary feed line in the event the primary feed goes down. This has reduced most power losses to a manageable duration of anywhere from 1 to 10 seconds. At ATLAS, we have installed Uninterruptible Power Supplies (UPS) on the refrigerator control circuits. These UPS units will allow a power loss of up to 15 to 20 seconds without any adverse affects on the refrigerator system. In addition to the UPS units a Programmable Logic Controller (PLC) system controls the sequence of power-up for the compressors. This controlled re-start is necessary because the start-up current on the compressor motors is large compared to the operating current. If all the compressors were allowed to start at the same time, the current draw would overload the substation.

Even with these measures, an operator must respond to a power bump in a swift and correct manner. There is a ‘Power Bump Procedure’ located at the control console, which must be followed immediately upon a power outage. The average recovery time from a short, 2 second, power loss is from fifteen minutes to one hour. Prior to the installation of the PLC and substation modifications some extended power outages have resulted in a two-week loss of operation.

Contamination of the helium system with air also poses a serious problem. Our refrigerator runs at a positive pressure. This is an advantage in that if there are small leaks in the helium system, air is not draw in. During maintenance periods, care must be taken to maintain the integrity of the helium system. Both operator error and mechanical failures have resulted in air freezing out in the helium plumbing. This can be a very difficult problem to solve. In some cases it is nearly impossible to get enough heat to the plugged area to melt the blockage. Upon melting, other areas in the system are still cold and the contamination may migrate to the cold sections. These incidents must be dealt with on a case-by-case basis.

4. SAFETY

Most of the safety issues are the same whether the accelerator is superconducting or room temperature. However, there is a need for special safety measures due to the use of cryogens at a SC accelerator. Large quantities of liquid helium and liquid nitrogen are being transported through occupied work areas throughout the facility. A catastrophic failure of one of the cryogenic supply lines can result in both an asphyxiation hazard and an egress hazard. The egress hazard comes from condensation in the room becoming so dense that one simply cannot see the escape route through the fog. Escape lanes have been painted on the floor to assist in guidance to the exits. To address the asphyxiation issue, oxygen deficiency monitors have been installed throughout the facility. If there is an alarm on this system loud claxons and flashing lights are activated to notify personnel to evacuate the area. In addition, all accelerator personnel are required to complete a course in cryogenic safety.

5. THE FUTURE

There is currently a proposal at Argonne National Laboratory for a SC accelerator facility that will produce and accelerate unstable nuclei. The Rare Isotope Accelerator (RIA) will take advantage the unique characteristics of SC cavities. The RIA driver accelerator will be capable of producing a 400 Mev per nucleon uranium beam at abeam power of 400 kW. In order to obtain these beam energies and power SC cavity technology is integral. To take advantage of the large acceptance of SC cavities, multiple charge states of uranium will be simultaneously accelerated through the linac. Accelerating 10^{13} uranium nuclei per second to 400 MeV/u requires two stages of stripping. If only one charge state were accepted after each stripping then the intensity at each stage would be reduced by a factor of about five. By capturing and accelerating all of the most populated charge states, the beam intensity will be maintained with only small losses at the final energies. A study has been done at ATLAS to demonstrate this proposal [4].

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JAERI TANDEM BOOSTER AND ITS CRYOGENIC SYSTEM

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Abstract

The JAERI tandem booster linac has been operated for the various experimental programs since 1994. During this seven years, the booster linac worked steadily without serious trouble. However, there are some small problems on the cryogenic system. This paper describes the operational issues on the booster linac and its cryogenic system.

1. INTRODUCTION

The JAERI tandem accelerator facility has a large tandem accelerator and a superconducting booster. The tandem accelerator, of which maximum performance in terminal voltage was 20 MV, was manufactured by National Electrostatics Corporation (NEC) in U.S.A. and started operations for the experiments in 1982. In 1994, the superconducting booster was built for increasing 2 to 4 times the ion beam energy from the tandem accelerator. We have a difficulty with the tandem booster such its cryogenic system loses its stable run sometimes in a few hours after starting the operation of the booster.

2. THE TANDEM BOOSTER

The JAERI tandem booster linac consists of 40 1/4-wavelength type cavities of 130MHz in 10 cryostats, and the total acceleration voltage is 30 MV. There is a buncher with 130 MHz and 260 MHz cavities before the linac, and 60% of the continuous beam becomes available from the two-frequency buncher. A 130 MHz de-buncher is placed after the linac, which is for equalizing spread energy of the accelerated ion beam [1, 2]. Figure 1 shows the schematic diagram of the whole accelerator system, Fig. 2 and Fig. 3 show the cutaway view of the SC cavity and cavity assembled in line, respectively.

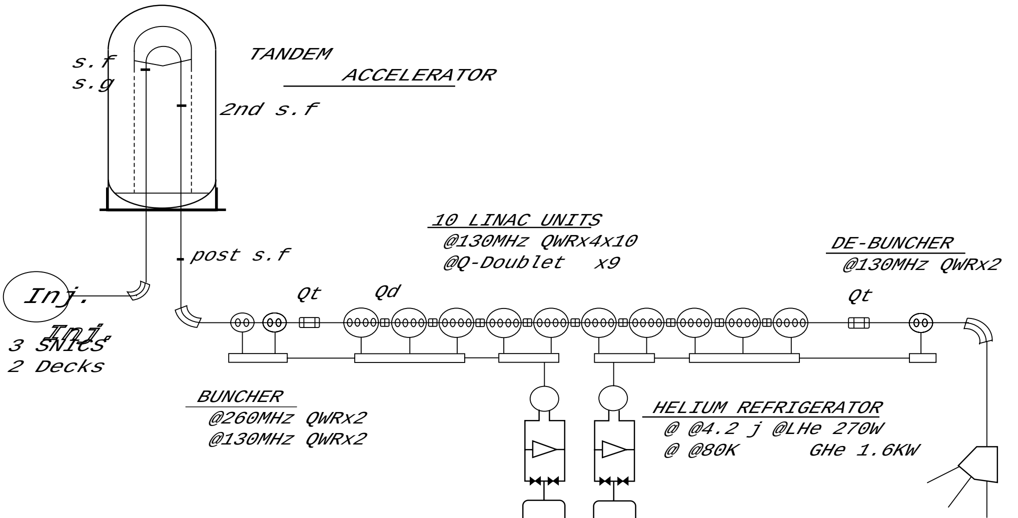

Fig. 1: Schematic diagram of the JAERI tandem accelerator and booster linac facility

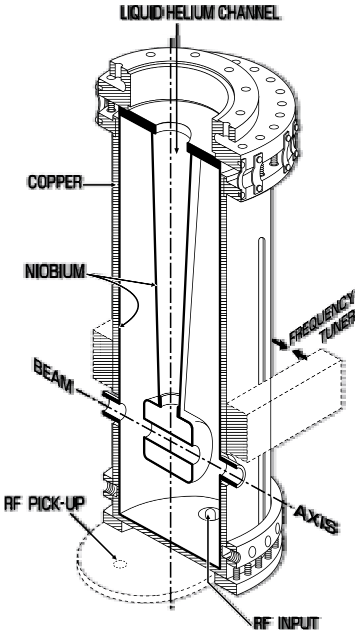

Fig. 2: Cutaway view of the SC cavity

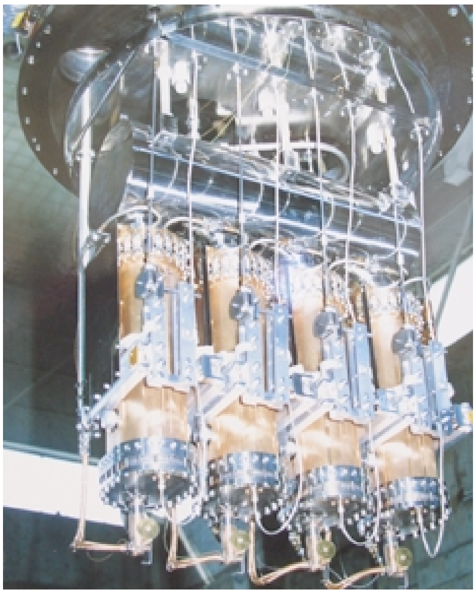

Fig. 3: Cavity assembled in line

3. THE CRYOGENIC SYSTEM FOR THE TANDEM BOOSTER

The JAERI tandem booster is constituted by the accelerating cavities, cryogenic transfer lines and the refrigeration system. The cryogenic system is licensed under the refrigerator safety regulations of the high-pressure gas law in Japan. The cold-box is a model TCF-50 manufactured by Switzerland Suluzer Co. The cold-box has a refrigeration performance to cool down five cryostats (approximately 150W RF load in 20 accelerating cavities) and the thermal load of cryogenic transfer lines and quiescent loss of the whole system. The TCF-50 type cold-box was chosen by their operation records, performances, size and as at many other research institutes. Cold (80K) helium gas is also taken out from the cold-box and returned to the cold-box for cooling radiation shields. It takes three days to cool five cryostats, bunchers and cryogenic transfer lines down to the steady state with full liquid helium. Figure 4 shows the schematic diagram of cryogenic system. Figure 5 shows the He gas flow of the cryostat.

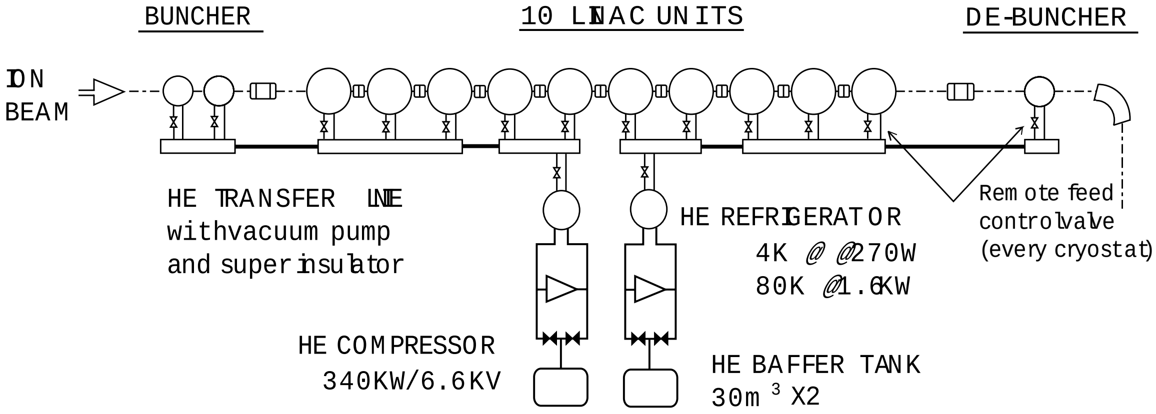

Fig. 4: Schematic diagram of the cryogenic system

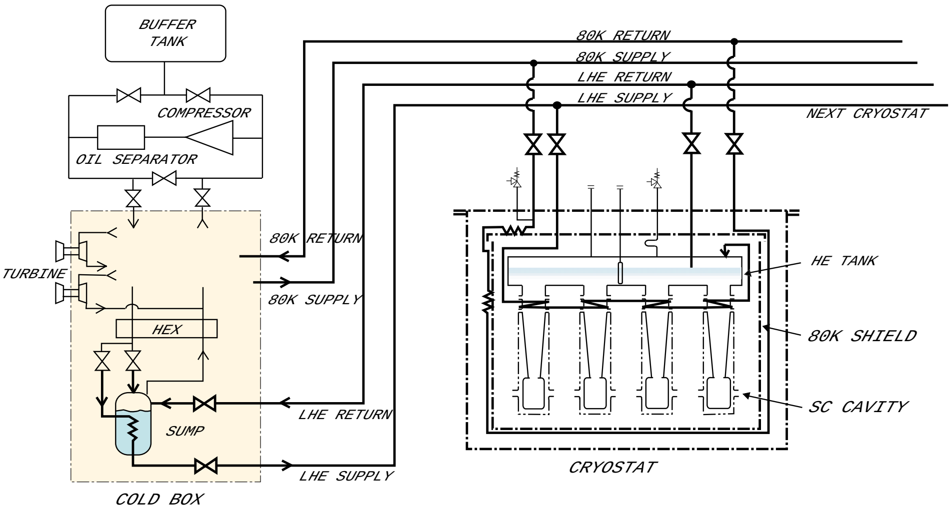

Fig. 5: Schematic diagram of He gas flow

4. OPERATIONAL ISSUES ON THE SUPERCONDUCTING ACCELERATOR

Here, we discuss involved in the operations of the cryogenic system and the superconducting accelerator itself

4.1 The cryogenic system

The main component of cryogenic system is cold box, which produces liquid helium from compressed gas helium. As is described above, the JAERI booster system is regulated by the high-pressure gas law for refrigerators. Under such regulations, it is not allowed to put a reservoir in the liquid helium loop. Gas flow in the cold box always changes quickly with changing thermal load. The time constant of heat exchangers is very long, because there are several large heat exchangers in the cold box. Control of cold box, which has a different time constant, is complicated, because it does not respond immediately to abrupt fluctuation. Control processes of the cold box deviate little by little from an expected series of operations, and eventually loose the stable operation. The pressure supplying liquid to the cryostats changes in such a situation to cause the cavities to deviate their oscillating frequencies. Another reason on instability lies in operation of the pneumatic valves of the cold box. They are operated by using compressed air for the sake of safety in case of a power failure, but the valve control circuits and the mechanical structure are very delicate. Therefore, some valves sometimes get out of control from the control computer. In near future, we will change the control circuits to new reliable ones.

4.2 Acceleration units

JAERI superconducting booster has been running stably during seven years, recently, however, we opened two cryostats because of helium leak from cavity adapter flanges. Indium wires for the vacuum seal were replaced. The leaks were due to frequent thermal cycles. Several thermal cycles have been repeated every year for many reasons such as the legal maintenance of the cryogenic system and the laboratory power stations. In this occasion of opening, we re-tuned the resonant frequencies of the cavities of which natural resonant frequencies had been lowered too much during the thermal cycles. The cavity Q factors have not been degraded very much. However, the Q factors of many cavities built earlier were lower than those made later. Figure 6 shows the result of each Q value. The low Q factors were due to the Q-degradation during slow cool-down through the region of temperature from 130 K to 90 K in which niobium-hydrides precipitate on the niobium cavity surface. We could improve the Q factors by a fast cool-down using a sequential cooling process. The result is shown in Fig. 6 with a different notation.

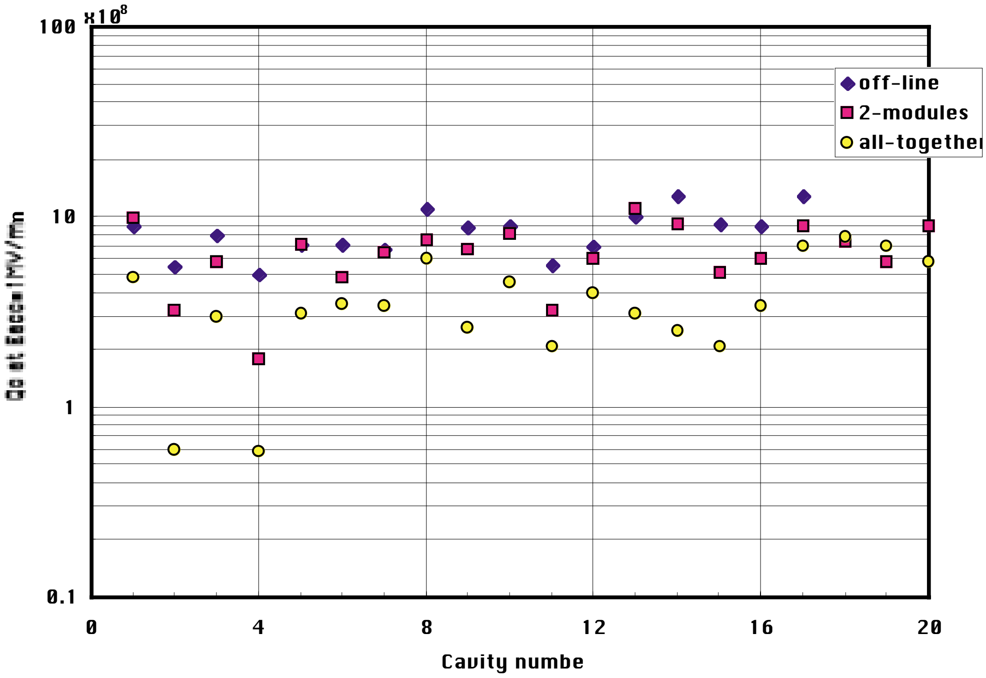

Fig. 6: Q factors under three conditions

4.3 The peculiarity of superconducting linac

To maintain the good condition of the superconducting linac for a long time, we need meticulous handling and considerations of following items; a) vacuum system, b) thermal cycle, c) maintenance and d) Q degradation.

4.3.1 Vacuum system

With respect to the superconducting linac, very strong electrical fields are generated on the surfaces of the acceleration cavities. Therefore, the surface must be protected from any contamination such as micro particles as much as possible. All vacuum components are oil free, and equipped with safety interlocks. Automatic-shut-off valves are inserted between cryostat and main pump, main pump and fore line pump. The main pumps used at JAERI are a magnetically suspended 1,000 L/s turbo molecular pump.

4.3.2 Thermal cycle

Composite materials of niobium-clad copper are used in the cavities, and indium wires for the vacuum seal between flanges. Thermal cycles, then, cause strong stresses between the different materials. We have not experienced serious problems caused by material itself, although we repeated warming-up the cavities several times in a year. It worries us, however, that a big problem may happen in the future. We have to minimize the thermal cycles taking into consideration of the machine time and the power station’s maintenance time.

4.3.3 Maintenance

Opening a cryostat for maintenance has been extremely few, but there have been several times that we had to brake the vacuum until now. The vacuum break has a risk to sprinkle micro particles on the cavity surface. At the vacuum break, dry nitrogen was fed through a very fine filter into the cryostat as slow as possible, because micro-particles might cause electron field emission from the surface of the cavity. In case of opening a cryostat, we used a clean booth.

4.3.4 Q degradation

How to realize and maintain a high Q factor is a big theme for superconducting cavities. With respect to the JAERI's superconducting cavities, very high performances were realized after the improvements of electropolishing and rinsing technology. However, it is uncertain that we will be able to keep their present performances for a long time. If the Q factors decrease, we have no good solution to recover the Q factors. Therefore, the best way to keep the present condition is to protect the cavities against any contamination. Recovering Q factors by a fast cool-down, on the other hand, has a risk of serious damage to the cavities.

4.4 Operations

For the operation of the JAERI tandem booster, it takes about one hour and a half to set the cavities for the beam acceleration. The electric fields of cavities, which give expected ion beam energy, are calculated before starting operation. The RF phase of each cavity is determined by getting the beam phase measured by a beam-bunch phase detector. A heater stabilizes the liquid level in the sump container of the cold box and the total thermal load to the refrigerator is kept constant. A few hours prior to the cavity start-up, the power (approximately as much as the RF power to be inputted) is fed to the liquid helium system using heaters placed in the Dewars of the cryostats. The heater power is decreased with increasing RF input power in order to keep the load to the refrigerator as constant as possible, also. A few hours later from starting the cavities, the operating condition is balanced, and the condition will continue without any handling.

5. ANOTHER TOPIC

A job of exchanging acceleration tubes of the tandem accelerator has been scheduled as an upgrade project of the tandem accelerator. The injection energy to the booster can be increased to make the matching between the tandem and its booster better for very heavy ions. In addition, rare gas ion beams (Ne, Ar, Kr, Xe) are accelerated, and utilized for the various researches. An installation program of RFQ and interdigital-H type linacs may start from the next fiscal year in order to increase species and intensities of ion beams.

6. CONCLUSION

The JAERI superconducting linac has been continued stable operation, therefore, we have some settling problems in the above mentioned. Recovering of the Q factors and maintaining present performances are extremely important subjects of JAERI tandem booster system. We have to find out best solution against these problems.

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