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On the Preference of Cold RF Technology for the International Linear Collider[1]

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Abstract. On August 20th 2004 the International Technology Recommendation Panel (ITRP) released its recommendation that the Linear Collider be based on Superconducting RF Technology. Following a request of the organizers of this conference we will summarise in this article the arguments worked out and presented by the ITRP, which led to this recommendation. The main features of both RF-technologies, the favoured L-band RF system of the superconducting version of the Linear Collider and the X-band-technology anticipated for the normal-conducting alternative will be briefly described

INTRODUCTION

During the last decade considerable effort was made worldwide to develop concepts for a Linear Collider for e^+ - e^- collisions at energies ranging from 500 GeV for initial operation to one TeV and above in a later phase. The scientific case for such a collider with a luminosity above 10^{34} cm^{-2} s^{-1} is described in [1]. The parameters for the Linear Collider were defined by the parameter Subcommittee of the International Linear Collider Steering Committee (ILCSC) in [2]. The luminosity and reliability of the baseline machine should allow the collection of approximately $L_{eq} = 500$ fb^{-1} in the first four years of operation. The polarization of the electron beams should be at least 80% and 50% for positrons. There should be two interaction regions. The energy of the machine should be upgradeable to approximately 1 TeV with the possibility to collect the integrated luminosity of 1 ab^{-1} in about 3 - 4 years.

There are two different approaches, which were made for the next generation of Linear Collider R&D for energies up to 1 TeV by collaborations based in Asia, Europe and the United States. The Japan Linear Collider-X/Next Linear Collider (JLC-X/NLC) design was pushed forward by collaborations centered at KEK and SLAC. It is based on normal conducting RF copper cavities operating at the X-band frequency 11.4 GHz. The TeV Energy Superconducting Linear Accelerator (TESLA) design is based on superconducting cavities fabricated from pure niobium, which are operated at 2 K at the L-band frequency 1.3 GHz. It was pushed forward by the TESLA collaboration, which was centered at DESY [3]. By now both technologies are

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sufficiently well developed to be considered as a successful candidate for the technology of the future Linear Collider.

Therefore the international community had to decide now for one technology and to unite all the tremendous resources available for accelerator R&D to push the development of the chosen technology to maturity in a joint effort. A brief description of these two technologies, of a C-band option and of the 30 GHz CERN project CLIC is given in [4]. The latter may provide a possible technology for a future generation of linear colliders.

In the beginning of last year, the International Committee for Future Accelerators (ICFA) formed through ILCSC the International Technology Recommendation Panel (ITRP) with the charge to choose between the two technologies. The twelve members of the panel, which were called by the community “the wise men,” are from Asia, Europe and North America. They are listed in [5].

The complete explicit charge to the ITRP can be found in [6]. We cite the following sentences from this document: ”On the assumption that a linear collider construction commences before 2010 and given the assessment by the ITRC that both TESLA and JLC-X/NLC have rather mature conceptual designs, the choice should be between these two designs. If necessary, a solution incorporating C-band technology should be evaluated.”

ITRP has interpreted its charge as being to “recommend a technology, rather than choose a design.” The evaluation was carried out at six meetings where presentations about the technologies, visits of the R&D facilities at DESY, SLAC and KEK and meetings with the relevant communities took place. In one meeting also the CLIC R&D program was described:

> “As part of its evaluation process, the ITRP developed a set of criteria that it used to evaluate each technology. The criteria were organized into six major areas:
>
> 1. The scope and parameters specified by the ILCSC
> 2. Technical issues
> 3. Cost issues
> 4. Schedule issues
> 5. Physics operation issues
> 6. General considerations that reflect the impact of the LC on science, technology and society.
>
> The ITRP studied each area to differentiate between the two technologies and to highlight areas that required particular focus. To help with the evaluation, the Panel posed a series of questions to the proponents.”

Since the arguments for the ITRP recommendation refer strongly to the main linac RF systems we will, in the following, give a brief description of the TESLA Test Facility at DESY to illustrate the L-band technology and of the X-band design to illustrate the warm technology. Then we report the ITRP recommendation and the arguments presented in favour of the chosen technology.

The executive summary and the full ITRP report can be found in [7] and [8].

THE SUPERCONDUCTING RF TECHNOLOGY

The superconducting technology chosen for TESLA uses 9-cell niobium cavities cooled by superfluid He to 2 K and operating at the L-band frequency 1.3 GHz. The design gradient for a 500 GeV collider is 23.5 MV/m and the unloaded quality factor $Q_0 = 10^{10}$. Because of the extremely small RF-power dissipation in the cavity walls the pulse length of the accelerating field can be of the order of 1 ms which results in a high RF to beam power transfer efficiency, allowing a high average beam power while keeping the electrical power consumption within acceptable limits. The primary electric power for the main linac RF and the cryogenic system amounts to 97 MW for the two 250 GeV linacs.

The resulting high beam power of 11.3 MW/beam is an essential ingredient for high luminosity, which is a main requirement for the linear collider. From the above follows an overall primary-to-beam-power conversion efficiency of 23.3%.

Besides the high beam power an extremely small beam size, *i.e.* small emittance, at the interaction point is mandatory for high luminosity. This is favoured by the relatively low RF frequency since the longitudinal and transverse wake-fields in the RF cavities, which can degrade the beam quality by increasing its energy spread and transverse emittance, scale as f^2 and f^3 respectively.

Another advantage of the low RF frequency or large wavelength lies in the correspondingly relaxed alignment tolerances of the cavities which are of the order of .5 mm.

In order to demonstrate the validity of these arguments and the feasibility of an e^+e^- Linear Collider based on superconducting L-Band cavities operated at accelerating gradients near 25 MV/m and to get reliable cost estimates the TESLA Test Facility was set up at DESY in 1993 [9].

The RF System is based on 10 MW RF output power klystrons. The former were already commercially available at the beginning of the TTF. The development of a 10 MW MBK (multi-beam klystron) was then triggered by DESY since the resulting increase in efficiency of the order of 20%, and the reduction of the total number of tubes and hence modulators by the factor two would lead to significant reductions in operating and investment cost for the linear collider.

The first MBK was developed by Thomson (now: Thales) [10]. It has 6 cavities, which are all operated in the fundamental TM 010 mode. There are 7 beams, a central one and 6 peripheral ones. There are two output windows for 5 MW each. The measured efficiency at full power was 65%. The RF pulse duration is 1.5 ms and the max. repetition rate is 10 Hz.

The status of the TH 1801 MBKs manufactured by Thales can be summarized as follows:

- Three klystrons have been manufactured.
- The prototype has been in operation at TTF since May 2000 and has been operated for over 20000 hours.
- Series klystron #1 has been returned to the vendor after ca. 3000h (gun arcing).
- Series klystron #2 has been tested and returned to the vendor.

- Gun arcing has been investigated, the problem is identified and modifications are underway.
- Modified klystron #1 has been re-delivered to DESY Zeuthen in January 2005, and #2 was redelivered to DESY in March 2005.
- More klystrons have been ordered.

In the meantime alternative klystron manufacturers have become interested too in the development of MBKs for a linear collider. The CPI prototype has successfully passed its acceptance test at CPI by the beginning of 2005 and it has been delivered to DESY in March 2005. In contrast to the Thales tube it has only 6 beams. The input and output cavities are operated in the TM 020 mode, the resulting geometry leads to a much smaller current density on the cathode (2.5 A/cm^2). The other parameters are similar as for the Thales tube.

Similarly, also the TOSHIBA multi-beam klystron has made great progress. Its parameters are very similar to the ones of the CPI tube. It has also demonstrated 10 MW output power for 1 ms long pulses and 10 Hz rep. rate. Delivery to DESY in 2005 seems realistic.

The modulators must generate HV pulses up to 120 kV and 140 A. The maximum pulse length is 1.57 ms and the maximum rep-rate is 10 Hz. The voltage droop in the flat top is below 1%. The first three bouncer type modulators with a 1:12 step-up ratio pulse transformer, which were designed and built by FNAL, are still in use at DESY. In the meantime 8 more modulators based on the same principle have been designed and built by joint efforts of DESY and European industry. The leakage inductance of the new pulse transformers has been significantly reduced. Its value is now below 200 μH, which is almost half the value of the first transformers. Accordingly, the pulse rise time to the 98% level decreased from almost 400 μs to below 200 μs. The increased efficiency (65%) of the MBK as compared to the single beam 5 MW klystron (45%) plus a few per cent gain in efficiency resulting from the smaller pulse rise time would lead to a significant reduction of operation cost for the Linear Collider where the average wall plug power for the RF supply is close to 75 MW.

The planned RF distribution system for the linear collider is shown in Fig. 1. The two main arms of the linear waveguide system are connected to the two 5 MW output ports of each MBK. Identical amounts of RF power are branched off by directional couplers and fed to the cavities. The nominal RF power per cavity is 235 kW at full beam current. Each 9-cell cavity has its individual power input coupler. The waveguide system and the klystrons are protected from reflected power by individual circulators at each cavity.

A detailed description of the high power RF system is given in [11].

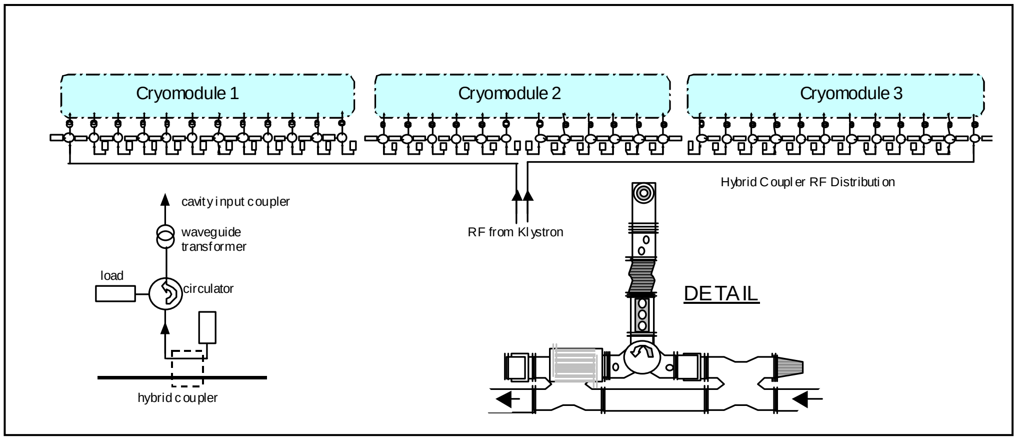

FIGURE 1. RF waveguide distribution foreseen for the linear collider.

During the so-called TTF phase I production methods for superconducting 9-cell cavities operating at gradients above 25 MV/m and for the assembly of cryogenic accelerating modules of 12 m length were successfully established. There are eight 9-cell cavities in a cryogenic module. Stable operation with beam at average gradients close to 23 MV/m in one cryogenic module has been demonstrated. With two cryomodules beam currents of several nC were accelerated up to 270 MeV. In February 2000 first lasing of the SASE (Self Amplified Spontaneous Emission) Free-Electron laser, which was driven by this beam, was achieved [12]. Since 1997 until November 2002, where TTF I operation ended, 15000 hours of beam time were accumulated. During the last two years of TTF I about 50% of the time was allocated to FEL operation including a large percentage of scientific user time. After the end of the very successful operation of the TESLA Test Facility in November 2002, the modification of TTF into a VUV-FEL user facility took place during the years 2003 and 2004. First SASE FEL radiation with this new facility was observed in January 2005. The wavelength of the radiation was 30 nm. The minimum wavelength where saturation can occur in this facility is 6.4 nm. About 35% of the running time will be allocated to users. Based on the same technology the European XFEL project, where a 20 GeV linac will drive an FEL, which will produce radiation with the minimum wavelength in the .085 nm range, will start in 2006 [13].

During the last years significant amelioration of cavity performance has been achieved due to improved welding techniques and stricter Niobium quality control. By the year 2001 the average accelerating gradient had increased from values below 20 MV/m to above 25 MV/m at *Q*-values $>10^{10}$. At the same time the spread in performance was reduced by the factor 3. Presently there are two cryomodules which can be operated at average gradients of 25 MV/m. Further improvement has been achieved by electropolishing of the cavities. After several single cell cavities had reached gradients in excess of 35 MV/m, there are now also several electropolished 9 cell cavities, which have been operated at gradients above 35 MV/m [14]. Some examples are shown in Fig. 2. There are no signs of degradation neither in the cavities nor in the power input couplers. One cavity in the first cryomodule of the newly installed VUV-FEL facility [15] at DESY has reached 35 MV/m with beam.

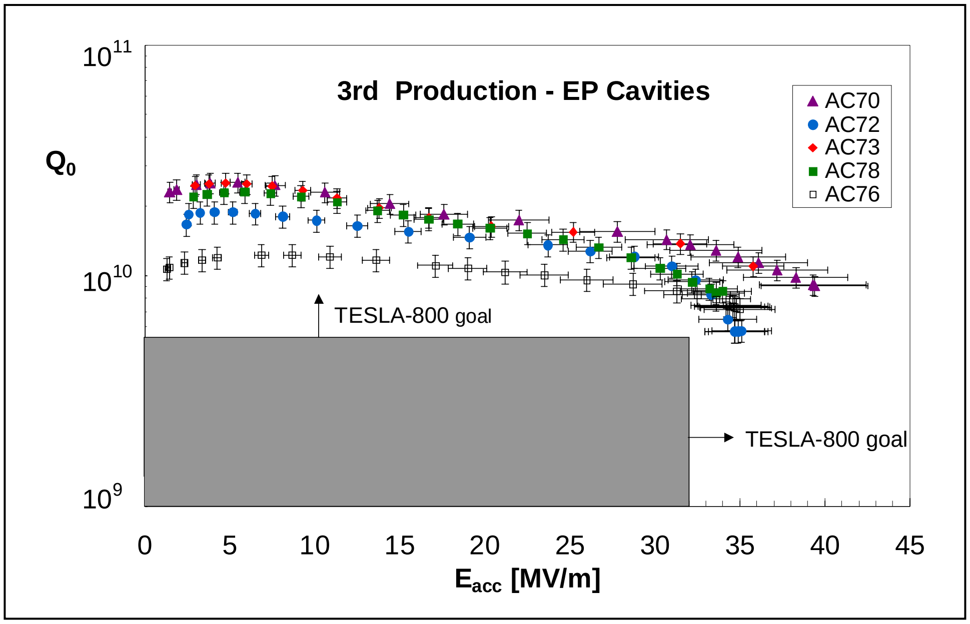

FIGURE 2. Accelerating gradient vs. unloaded quality factor for several 9-cell cavities from the last production series. These cavities have been electropolished. The results, which lie well above 35 MV/m at $Q_0 > 10^{10}$, surpass the requirement for the 800 GeV version of the TESLA linear collider.

With these voltage gradients even the requirements for a 800 GeV version of TESLA are met.

THE WARM RF TECHNOLOGY

The technology of the JLC-X/NLC [4,16] linear collider is based on normal conducting structures made from high quality copper. They are operated at the X-band frequency 11.4 GHz. One advantage of the warm linac technology lies in the fact that there is substantial experience with this technology from the SLAC S-band linac. In addition, at the higher X-band frequency higher voltage gradients can be achieved in the accelerating structures and hence the overall length of the linear collider will be shorter for a given energy. For the X-band structure a loaded accelerating gradient near 50 MV/m is foreseen. (The unloaded gradient is 65 MV/m). This has to be compared with acceleration gradients of 31.1 MV/m for the C-band case at 5.7 GHz and below 20 MV/m at 2.85 GHz. The disadvantages of the high frequency are related to higher energy density in the klystrons and to narrower manufacturing and alignment tolerances, which are in the range of a few μm for the accelerating structures.

The X-band RF system is based on units of two PPM (periodic permanent magnet)-focused klystrons. The output power of each tube is 75 MW for a pulse duration of 1.6 μs. Since long, relatively low power output pulses are optimal from the klystron cost perspective, shorter pulses are needed to power the structures to minimize overall cost.

An RF pulse compression system is used to match these conditions. At least for the initial design the SLED II pulse compression system is pursued. In this system pulse compression is achieved by accumulating and storing the RF power from the klystrons during 1200 ns in a pair of 29 m-long delay lines. Ultimately the stored power is released as a shorter 400 ns pulse and combined with the last 400 ns of the klystron pulse. The anticipated result is a 450 MW pulse of 400 ns duration, which is distributed to 6 accelerating structures. There is a lot of experience with the SLED II system. So far pulses of 240 ns duration and 270 MW power and of 150 ns duration at 480 MW power have been generated at the NLCTA at SLAC.

A possible candidate for a future pulse compression system with increased efficiency, 85% compared to 75% of the SLED II system, is the Delay-Line Distribution System, DLDS. Testing it under realistic conditions would, however, be an expensive project with a duration of several years.

Since the beginning of the 1990s an impressive amount of experience has been obtained at SLAC and KEK in designing and building high power X-band Klystrons. At SLAC 13 XL4 tubes have been built. They reliably generate 50 MW pulses of 1.5 μs duration with 43% beam-to-RF efficiency. For one tube 75 MW at 48% efficiency have even been achieved. Also at KEK two tubes, XB72K-9 and -10 have demonstrated 50 MW pulses of 1.5 μs length. The integrated running time of all these tubes is about 40000 hours. In order to avoid the power consumption of the focusing magnets the development of PPM focused tubes was then started. A SLAC tube called XP 1 has delivered 90 MW for .7 μs and 79 MW at 2.8 μs pulse length with 60% efficiency. Subsequent tubes named PPM-2 and 3, which were designed at KEK have achieved power levels near and above 70 MW for pulse lengths near 1.5 μs (PPM-2) and 65 MW at 1.5 μs (PPM-3) with efficiencies near 55%.

The 75 MW PPM Klystrons require modulator pulses of about 500 kV and 260 A. The conventional line type modulators, which were originally considered, have several drawbacks related to the use of thyratrons, which need frequent tuning and have limited lifetime. Furthermore, a large number of LC-circuits are needed for good flatness of the pulse and the overall efficiency of the modulators is only 50-60%. As an alternative the concept of a solid-state induction-type modulator, where a large number of primary coils wound on Metglas or Finemet cores of toroidal shape are driven in parallel by individual cells of capacitors and IGBT switches, was developed at SLAC and KEK. The relatively low primary voltages (2-4 kV) are summed inductively by stacking the cores on top of each other. The secondary coil penetrates through the central hole of these cores. It is a single loop for the KEK design, at SLAC there are three turns. At SLAC a prototype modulator using a stack of 76 cores was built and tested using three 5045 S-band klystrons as loads. After some improvements the modulator has been moved to the NLCTA to power the SLED II pulse compression system and to demonstrate the JLC-X/NLC baseline X-band RF system. At KEK a prototype to power four klystrons is being built. It has a stack of 160 cores and is designed to produce 1.6 μs long pulses of 500 kV and 2120 A.

The accelerating structures for the X-band main linacs are based on the constant-gradient traveling wave type design. Each unit is .9 m long. The loaded and unloaded accelerating gradients to be maintained are 49.8 MV/m and 64.8 MV/m respectively. The peak fields may become as high as 160 MV/m. To achieve sufficient damping of short- and long-range wake fields, which is a critical issue for these structures, aligning of the structures along the beam with a precision of the order of 10 μm and a combination of detuning and damping are required. The individual cells have to be detuned in such a manner that the Higher-Order-Mode fields integrated over the structure cancel out while the fundamental frequency of each cell has to have the constant value 11.424 GHz. This results in very tight manufacturing tolerances of many of the features (dimensions and alignment) of the individual discs of a few μm or less. Damping is realized by extracting the remaining HOM-power towards manifolds running parallel to the structure.

During high power tests it was found that too large group velocities in the structures do not favour stable RF operation because then, in the case of an RF breakdown, a too large fraction of the incoming RF power would be deposited on the spot where the breakdown occurs and cause damage, rather than being reflected. These problems seem to have been overcome by a new structure design with group velocities in the range of 3%-5% of the velocity of light at the upstream end.

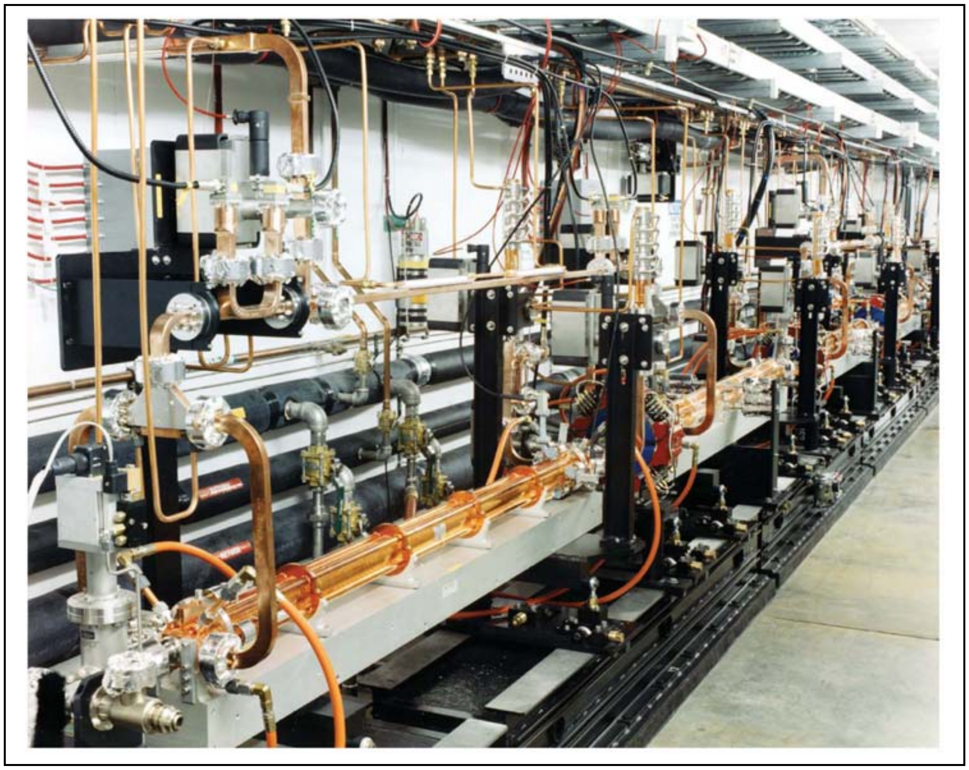

FIGURE 3. High Field Test Stand at NLCTA of SLAC. This picture was taken from [16].

So far the best results have been achieved with a 60 cm, 3% *c* structure, which has been processed to 72 MV/m with 400 ns pulses. At 65 MV/m, the current JLC-X/NLC design gradient, the breakdown rate in the body of this structure meets the goal of < 1 per 10 hrs. A picture of the High Field Test Stand at NLCTA of SLAC is shown in Fig. 3.

THE ITRP RECOMMENDATION

In their report [8] the ITRP members conclude "that each technology would be capable, in time, of achieving the goals set forth in the Parameters Document. The Panel felt that the energy goals could be met by either technology. The higher accelerating gradient of the warm technology would allow for a shorter main linac. The luminosity goals were deemed to be aggressive, with technical and schedule risk in each case. On balance, the Panel judged the cold technology to be better able to provide stable beam conditions, and therefore more likely to achieve the necessary luminosity in a timely manner."

The following explicit statements are directly taken from the executive summary [7] of the ITRP report:

> "We recommend that the linear collider be based on superconducting rf technology. This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both."
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> "Our evaluation process focused on the major acceleration and beam transfer elements of each design. We also examined other critical components, including the damping rings and the positron source. Both technologies had considerable strengths."
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> "The warm technology allows a greater energy reach for a fixed length, and the damping rings and positron source are simpler. The Panel acknowledged that these are strong arguments in favor of the warm technology. One member (Sugawara) felt that they were decisive."
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> "The superconducting technology has features, some of which follow from the low rf frequency, that the Panel considered attractive and that will facilitate the future design:
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> - The large cavity aperture and long bunch interval simplify operations, reduce the sensitivity to ground motion, permit inter-bunch feedback, and may enable increased beam current.
> - The main linac and rf systems, the single largest technical cost elements, are of comparatively lower risk.
> - The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.
> - The industrialization of most major components of the linac is underway.

- The use of superconducting cavities significantly reduces power consumption."

"The choice of the technology should enable the project to move forward rapidly. This will require the engagement of both cold and warm proponents, augmented by new teams from laboratories and universities in all regions."

"The machine will be designed to begin operation at 500 GeV, with a capability for an upgrade to about 1 TeV, as the physics requires. This capability is an essential feature of the design. Therefore we urge that part of the global R&D and design effort be focused on increasing the ultimate collider energy to the maximum extent feasible."

"We endorse the effort now underway to establish an international model for the design, engineering, industrialization and construction of the linear collider."

FINAL REMARKS

Almost immediately after the ITRP decision in favour of the cold technology for the ILC, the international Particle- and Accelerator Physics Communities have started to join their efforts to push the project. In November 2004 the first Global Linear Collider workshop took place at KEK, which was dominated by an extremely constructive spirit of collaboration. The next steps will be the foundation of a Global Design Initiative (GDI) and a common Technical Design Report based on the cold technology.

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