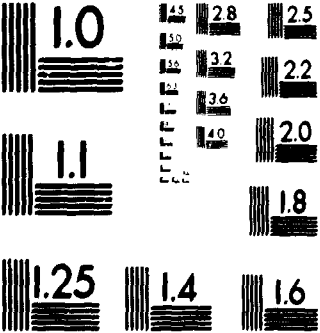
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Contributions to the 12TH INTERNATIONAL CRYOGENIC ENGINEERING CONFERENCE

(Southampton, 12-15 July 1988)

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DELL'ENERGIA NUCLEARE E DELLE ENERGIE ALTERNATIVE
Associazione EURATOM-ENEA sulla Fusione

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(Southampton, 12-15 July 1988)

ENEA - Dipartimento Fusione, Centro Ricerche Energia Frascati

RT/FUS/88/10

Testo pervenuto nel dicembre 1988
Progetto ENEA: Ingegneria del Reattore a Fusione (DC)
Progetto ENEA: Realizzazione Macchina Tokamak FTU (DB)

3/4

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A CONDUCTOR DESIGN FOR NET MACHINE(*)

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The Next European Torus (NET) is a highly demanding machine in all its aspects including the technology to be developed for. In particular, the toroidal field magnet system requires conductors whose performances have to be well advanced in terms of operating current, stability and quench behaviour, mechanical properties and alternating current (ac) losses minimization. In the present paper we present the design of a conductors based on the following criteria: i) use of A-15 superconducting strands (Nb_3Sn or Nb_3Al); ii) cooling by forced flow of supercritical helium); iii) use of composite stabilizing materials in order to reduce ac losses; iv) use of stainless steel as a reinforcing element.

INTRODUCTION

As the present NET specifications call for a toroidal magnetic field of about 5 T on the plasma axis the geometry of the TF coils system will require a maximum magnetic field on the conductor of about 11 T. A superconducting magnet system fulfilling these conditions can be designed on the basis of the present technology choosing one of the two following solutions:

1) a Nb-Ti conductor cooled by means of pressurized superfluid helium at 1.8 K;
2) an A-15 based conductor cooled by liquid helium at temperatures around 4.5 K.

In this paper we will consider only a TF coils designed based on A-15 conductors.

THE TF COIL CONDUCTOR

(a) Layout of the conductor

The design criteria of the proposed conductor are the following:

1) working current I = 16 kA at 4.5 K and 11 T with $I/I_c = 0.5$. The choice of 16 kA as operating current has been mainly dictated by the need of reducing ac losses as they depend on the dimension of the conductor;
2) superconducting strands arranged in a flat cable (Rutherford type) placed symmetrically with respect to the neutral axis in order to minimize degradation effects during winding;
3) stabilizing material made by Cu-CuNi honeycomb structure in order to reduce either ac losses in the stabilizer and losses due to coupling between different strands of the Rutherford cable;
4) cooling by forced flow of supercritical helium at 4.5 K;
5) use of stainless steel as a reinforcing material incorporated in the conductor with the aim also to provide the channels for the liquid helium.

A cross section of the proposed conductor is shown in Fig. 1. The superconducting cable consists of the following sequence of intermediate conductors:

1) multifilamentary wire (A) containing about 400 A-15 filaments ($\phi_{ext} = 0.9$ mm);
2) first level cable (B) consisting of six A wires plus a central dummy copper wire ($\phi_{ext} = 2.7$ mm);

3) Rutherford cable realized by wrapping fourteen B cables around a central insulating ribbon.

The superconductor for the base strand has not yet been chosen, two options being presently under consideration, namely Nb_3Al [1] or Nb_3Sn. The filament diameter has been chosen to be 30 µm, a value which can be reached with the fabrication process of Nb_3Al (jelly-roll method). This is a rather high value if you compare it with the usual Nb_3Sn filament size (~ 5 µm); however we have to say that with this small diameter bridging between adjacent filaments is very likely to occur thus increasing the effective diameter. On the other hand both the adiabatic and the dynamic stability criterion are satisfied by this choice.

<u>(b) Fabrication of the conductor</u>

We can distinguish two main phases in the fabrication of the conductor. First the production of the various components, second their assembly to make the cable.

1) The fabrication of the Rutherford cable necessitates of a series of sub-cabling phases culminating in the final assembly and flattening around an insulating ribbon. After this the cable must be heat treated in order to allow the formation of the intermetallic A-15. The final product is a very delicate object, owing to the brittleness of the superconductor; and must be handled very carefully. Very large diameter storage drums must be used in order to minimize the degradation of superconducting properties during winding of the magnets.
2) Stabilizing elements have to be realized in such a way that they can assure the necessary stabilization of the superconductor while at the same time the ac losses due to the poloidal variable fields are to be kept at an acceptable level. A feasible solution seems to be the use of Cu-CuNi composites; preliminary fabrication tests have been performed at Europa Metalli-LMI and the cross section of a prototype element showing the typical honeycomb structure is illustrated in Fig. 2. This material is presently under characterization in particular as far as its electrical properties are concerned.
3) The reinforcing material has been chosen to be 316 LN stainless and its procurement in the desired shape should not be difficult.

A schematic diagram of the fabrication process of the whole cable is shown in Fig. 3, There are two critical points: the first is the joining of the superconducting cable with the stabilizer, the second is the further addition of the structure reinforcing material. Low temperature soldering has to be used for joining the rutherford cable to the stabilizer as, owing to the fact that the intermetallic A-15 compound is already formed, any further heating at high temperature has to be avoided in order to not damage the superconducting properties of the Rutherford cable. Particular cure has to be taken in making this soldering because the solder (Pb/Sn or similar) must penetrate as much as possible through the structure of the cable contributing to increase the equivalent resistivity of the system with beneficial effect in reducing the ac losses (see below). The main problem in the addition of the structural material is that the casing has to fulfill a twofold requirement, ensure the necessary mechanical strength and provide the vacuum tight helium channels. Problems arise immediately when we face the necessity of making weldings between the different pieces of the reinforcement structure. It is obvious that the weldings have to meet the same requirements in terms of mechanical strength as the stainless steel while at the same time they have to be vacuum tight.

We are presently making a series of tests on different welding and, although still not conclusive, the results seems to indicate a superior quality of the laser welding. In Fig. 4 a picture of a laser welding on a dummy sample is shown.

STABILITY AND QUENCH BEHAVIOUR

The composition of the ENEA conductor is reported in Table I.

The calculations of stability and quench behaviour have been carried out using a modified version of the 1-D code developed at NBS [2].

As can be seen in Table I, this conductor contains a large quantity of stainless steel. The effect of this metal on the stability (and quench) of the conductor can be large. In fact at 5-10 K the specific heat of SS is one order of magnitude higher than that of copper while its thermal conductivity is two or three orders of magnitude smaller.

Because of this last property of SS and because of the poor thermal coupling between copper and SS, for fast disturbances (up to about 100 ms) the SS is not involved in the heating. On the contrary, for slow disturbances and during a quench, its high thermal capacitance plays a strong role.

The model applied for these calculations consists of:
- a pressure drop of 5 bar that produces a mass flow of 25 g/s;
- a transport current of 16 kA;
- a uniform field of 11.1 T.

We have determined the critical energy E_c (the minimum energy that produces a thermal runaway) by applying pulses of the same duration (0.1 s) on a short length of conductor (1 m) with different amplitudes. Figure 5 shows the wall temperature T_W as a function of time when a pulse smaller or larger than E_c is applied.

Including the thermal capacity of SS E_c is 11 J/kg going down to 4 J/kg when the SS is not considered.

On this basis it seem reasonable to assume that it is the second figure that must be considered for stability. For quench studies, E_c = 11 J/kg must be used.

A pulse larger than E_c produces a quench. Assuming that the current and the field start to decay after 0.1 s with a decay constant of 20 s, Fig. 6 shows the time evolution of the maximum pressure P_M and maximum T_W. Acceptable extreme values are reached.

STRESS ANALYSIS

Figure 7 shows a schematic drawing of the finite element model used to calculate the stress distribution on the ENEA conductor. The distributed load in toroidal direction is 139 MPa and in radial direction is 32 MPa. In Fig. 8 the Von Mises stress are shown. The highest value in the steel is about 360 MPa, in the stabilizing material is about 420 MPa while in the Rutherford cable and in the epoxy is about 120 MPa.

ac LOSSES

ac losses due to the variable poloidal fields have been calculated both for parallel and perpendicular fields. The expressions we have used for hysteresis, coupling and eddy current losses have been extensively discussed in the literature [3] and we present here only the final results. The assumption on the material properties are: i) introduction of solder resistivity (~ 10^{-9} Ωm) which reduce the coupling losses among strands and substrands; ii) complete effectiveness of Cu-Ni double sheet with internal insulating core in decreasing the coupling in the Rutherford cable; iii) negligible losses in the structural parts as a consequence of using the mixed matrix material Cu-CuNi.

With these hypothesis the average total losses for a single coil amount to 108 W (1,7 kW for the whole magnet composed by 16 coils).

CONCLUSIONS

The proposed conductor, although certainly an high technology product, seems to be feasible in many of its aspects. In our opinion one of the most critical points is the stress level on the conductor. The results of our calculations suggest the following considerations: a) the stainless steel is everywhere subjected to an acceptable stress; b) the stress applied to the other materials are often beyond their elastic limits; an elastic-plastic analysis is then necessary to determine the correct values of the stress.

FOOTNOTE AND REFERENCES

* Partially supported by Contract N. 181/84-12/FU-NET

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Table I - Conductor composition

Material	Cross-section (mmq)	Weight (kg/m)
Supercond.	22.5	0.18
Copper	196.2	1.75
Cu-Ni	65.6	0.57
Pb-Sn	52.2	0.26
S. Steel	276.0	2.15
Insulation	53.0	0.10
Helium	63.6	0.008
TOTAL	729	5.02

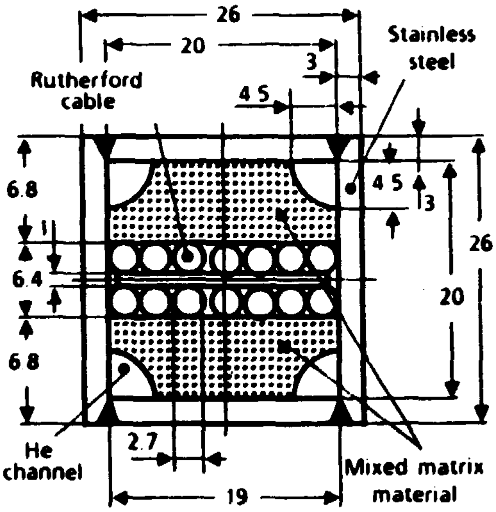


Fig. 1 - Sketch of the ENEA conductor

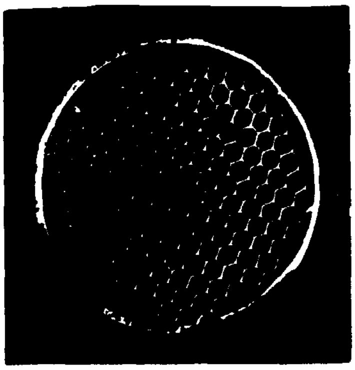


Fig. 2 - Cross section of the proposed Cu-CuNi stabilizer

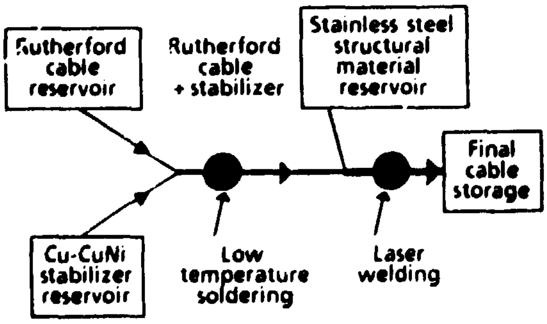


Fig. 3 - Schematic diagram of the conductor fabrication process

Fig. 4 - The conductor dummy sample on which laser welding tests have been peformed

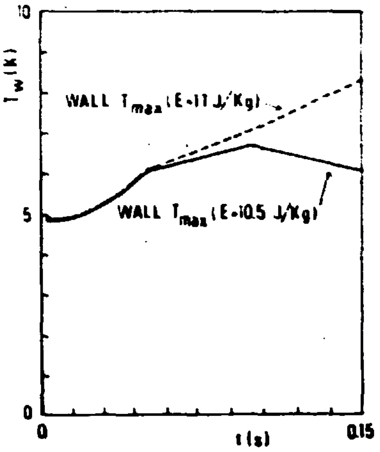


Fig. 5 - Maximum wall temperature T_w as function of time when a pulse of 10,5 J/kg (a) or of 11 J/kg (b) is applied

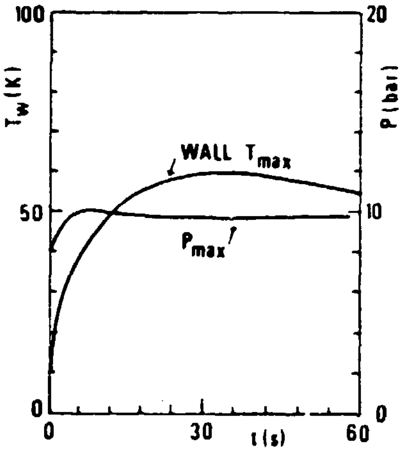


Fig. 6 - Maximum pressure and wall temperature when a pulse of 11 J/kg is applied to 1 m of conductor

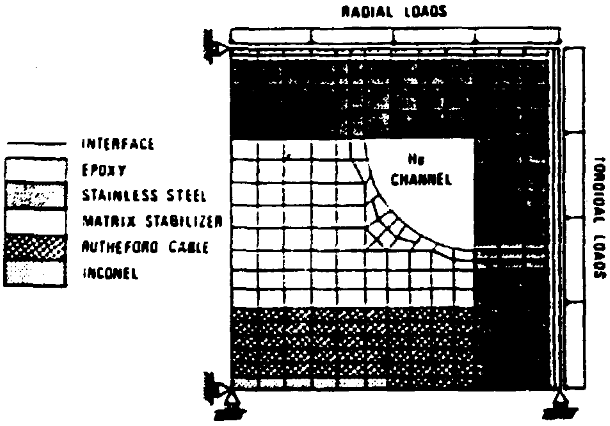
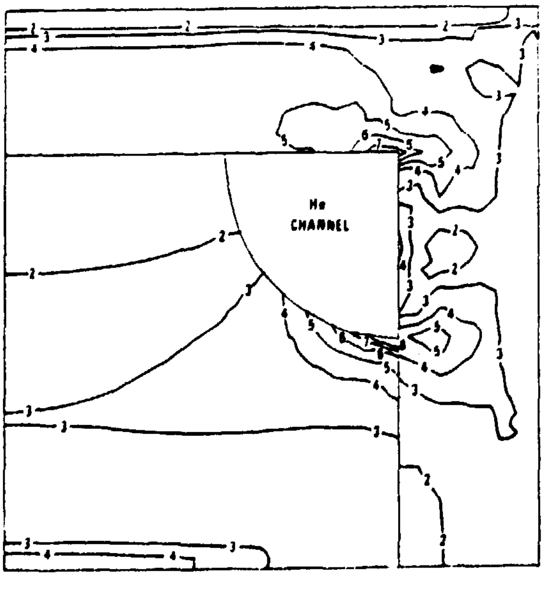


Fig. 7 - Finite element model for stress calculations



Mises equiv. stress I.D. value

2)	6.0×10^7
3)	1.20×10^8
4)	1.80×10^8
5)	2.40×10^8
6)	3.00×10^8
7)	3.60×10^8
8)	4.20×10^8

Fig. 8 - Von Mises stresses

LIQUID NITROGEN COOLING SYSTEM FOR FTU TOKAMAK MACHINE

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In order to reduce the energy consumption and improve the mechanical characteristics of the structural materials, the FTU (Frascati Tokamak Upgrade) machine operates at -196°C. In the following, the cryogenic system of the FTU machine is described.

INTRODUCTION

The basic idea in the design of the FTU (Frascati Tokamak Upgrade) machine is to try to reach a range of plasma parameters of great thermonuclear interest within a reasonable financial effort [1]. In FTU, the good energy confinement properties of a compact tokamak with a medium high toroidal field: 8 T, are combined with the strong plasma heating obtained injecting up to 8 MW of radiofrequency power in the lower hybrid "electron mode" (8 GHz). The main parameters of the FTU machine are resumed in Table I. The basic mechanical structure of the machine is provided by the monolithic toroidal magnet supporting the vacuum chamber and the poloidal field windings. The machine is kept, during operation, at liquid nitrogen temperature: - 196°C, to minimize the power consumption in the magnet coils and the poloidal field windings and to take advantage of the higher mechanical properties of the structural materials (stainless steel and copper) at cryogenic temperature.

LIQUID NITROGEN COOLING SYSTEM

Objects

Liquid nitrogen (LN_2) is being used as coolant to take advantage of its high latent heat of vaporization (200 kJ/kg), its relatively low cost (~0.5 $/litre) and ease of handling. To maintain FTU at LN_2 temperature (-196°C), the machine is enclosed by a cryostat.

The design and dimensions of the LN_2 cooling plant have been determined so that it can

- cool the FTU machine within 10 min between 2 successive shots;
- have a flexible system able to automatically exclude each coil from the cooling circuit;
- minimize the number of the pipelines crossing the cryostat wall;
- minimize the nitrogen consumption.

The cooling plant, shown schematically in Fig.1, has been conceived so that it can carry out the following operations.

First cooling down of the machine and control of its temperature

The first cooling down of the machine consists in lowering all the internal components of the cryostat (toroidal magnet, vacuum chamber and poloidal field windings) from room temperature to the required temperature (about -160°C) by spraying liquid nitrogen onto the stainless steel casing of the toroidal magnet. During this phase, it is essential that the thermal gradients between the various components of the machine do not exceed 50°C. To this end, flow pipelines will be installed on the machine to distribute the nitrogen using special sprayers powered by four electromagnetic valves which are automatically controlled to regulate both the temperature and the cooling rate of the machine. Before the cooling of FTU begins, the humidity inside the cryostat and plant circuits is eliminated by a drying process which consists in streaming nitrogen at 80°C for about five days. From 40 to 100 hours is foreseen for cooling the FTU machine, with a nitrogen consumption of 30,000 Nm^3. Successively, a nitrogen consumption of 35 Nm^3/h is expected to maintain the machine at a constant temperature of about -160°C.

Fast cooling between shots and emptying of the poloidal and toroidal windings before each shot.

During an experimental shot undertaken under the operational conditions shown in Table I, the dissipated energy in the poloidal and toroidal windings due to Joule effect is about 200 MJ, corresponded by an average temperature increase of the copper coils of about 15°C. The dissipated energy must be removed within the time (10 min) between two successive experimental shots, and the temperature of the copper coils and structural parts of the machine brought down again to about -190°C. This cooling is effected by pumping liquid nitrogen at a rate of 22700 Nm^3/h into the cooling channels of the coils and by utilizing above all the latent heat of evaporation. A nitrogen consumption of 650 Nm^3 is expected for each fast cooling. The cooling circuit on each coil consists of

- an electromagnetic on-off valve to exclude the circuit when the relative coil has reached the required temperature;
- a filter to avoid the presence of foreign matter in the coil which could damage it;
- a disc with a calibrated hole to regulate the distribution of nitrogen between the coils.

At the end of the fast cooling and before each shot, the excess liquid nitrogen is expelled into the phase separator by utilizing nitrogen gas at a pressure of 6 ate, circulated via a 3500 Nm^3/h pump. .

Pressurization of the cryostat

When the FTU machine has a temperature lower than 0°C, the nitrogen gas inside the cryostat is pressurized at a pressure of 40 mm H_2O. The liquid nitrogen in the storage tanks becomes gaseous in the evaporator and is sent inside the cryostat through an automatic valve. In order to avoid excessive pressure on the cryostat panels, a valve with an adjustable outlet from 40 mm H_2O to 100 mm H_2O, and a calibrated rupture disk at 450 mm H_2O have been installed. The nitrogen consumption foreseen to hold the pressure is 20 Nm^3/h.

Components

The pipelines external to the cryostat for the transfer of the liquid nitrogen or two-phase mixture are in AISI 304 stainless steel and are vacuum insulated.

The characteristics and heat loss of the main components of the plant are given in Table II. During the operational phases, the cooling plant will have a nitrogen consumption, due only to heat loss, from a minimum of 50 Nm^3/h during machine steady state at -160°C to a maximum of 255 Nm^3/h when fast cooling is effected between successive shots. It has not been possible to use exclusively conventional components in realizing the cooling plant: a few modifications, described in the following, have had to be made to adapt them to the plant requirements.

Electromagnetic valves

The automatic on-off valves which exclude the cooling circuit of the coils have been installed inside the cryostat to minimize the number of pipelines crossing it. Normally open electromagnetic valves have been chosen that have to work under temperatures from +50°C to -196°C, in magnetic fields with gradients, intensities and time variations respectively less or equal to 22000 G/m, 1000 G and 360000 G/s. The valves have to have a warning system showing whether they are closed or open and be able to support a maximum pressure of 6 ate. Starting with a normal commercial valve. ENEA and the firms of RIVOIRA and BUSCHJOST have collaborated together to carry out a series of modifications on the coil, on the limit switches, and on the casing of the valve in order to meet the technical specifications. A fatigue test consisting of 20,000 open and closed cycles under operational conditions has been carried out on a prototype and has given positive results.

Phase separator

At the outlet of the cooling circuit of the coils, during operation, there is a two-phase mixture of nitrogen (liquid/vapour) which is sent to a separator to divide the two phases so that the liquid can be utilized again and the vapour dispersed into the atmosphere. In order to increase the efficiency of the separation between the liquid and gaseous phases, a special mechanical filter, 0.7x0.9x0.6 m^3 in size and made of 60 suitably shaped plates, has been placed inside the separator.

Main pump and secondary pump

The area available for installing the cooling plant, the operation of the tokakamak machine under shot conditions, and the necessity of minimizing the consumption of liquid nitrogen require the utilization of pumps to circulate the LN_2 with low NPSH and which can operate intermittently. The latter requirement is important for limiting the nitrogen consumption, especially if the time between two successive shots should exceed 10 min.

Sealess pumps manufactured by the firm of CRYOSTAR have been used, immersing the rotating parts completely in LN_2. Some modifications have been carried out on the inlet part of the pump to guarantee the performance conditions shown in Table II. Extensive alternative operation tests have given positive results; in particular, the pumps have been shut down for even up to 60 hours at liquid nitrogen temperature and then put in operation under working conditions without revealing any cavitation.

Control system

The liquid nitrogen cooling plant is one of the subplants under the FTU control system [2] which uses three minicomputers (MICROVAX DEC) acting as plant control units (PCU) connected via Ethernet to a supervisory control unit (SCU) (VAX 730 DEC). Each PCU controls the operations of a set of programmable logic controllers (PLC type NLPC-700 B) which provide a direct control of the activities of each subplant.

The main functions of the PLC regarding the LN_2 plant are

- to accomplish automatically the operational phases described previously;
- to keep the PCU informed on the plant status;
- to allow all the components (valves, pumps, etc.) to be controlled individually.

If the main control (PCU/SCU) is not working, it is possible to operate on the plant from a local console.

CONCLUSIONS

The liquid nitrogen plant was ordered from the firm of RIVOIRA S.p.A. in July 1986. The plant has been completely installed and final testing is under way. The first cooling of the machine at liquid nitrogen temperature is expected to take place in spring 1989.

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2 Berardi, B., Bombi, F., Fermani, G. 'Development status of FTU control system', 14th Symp. Fusion Technol., proc. pp. 1479-1484.

TABLE I

Main Parameters of FTU

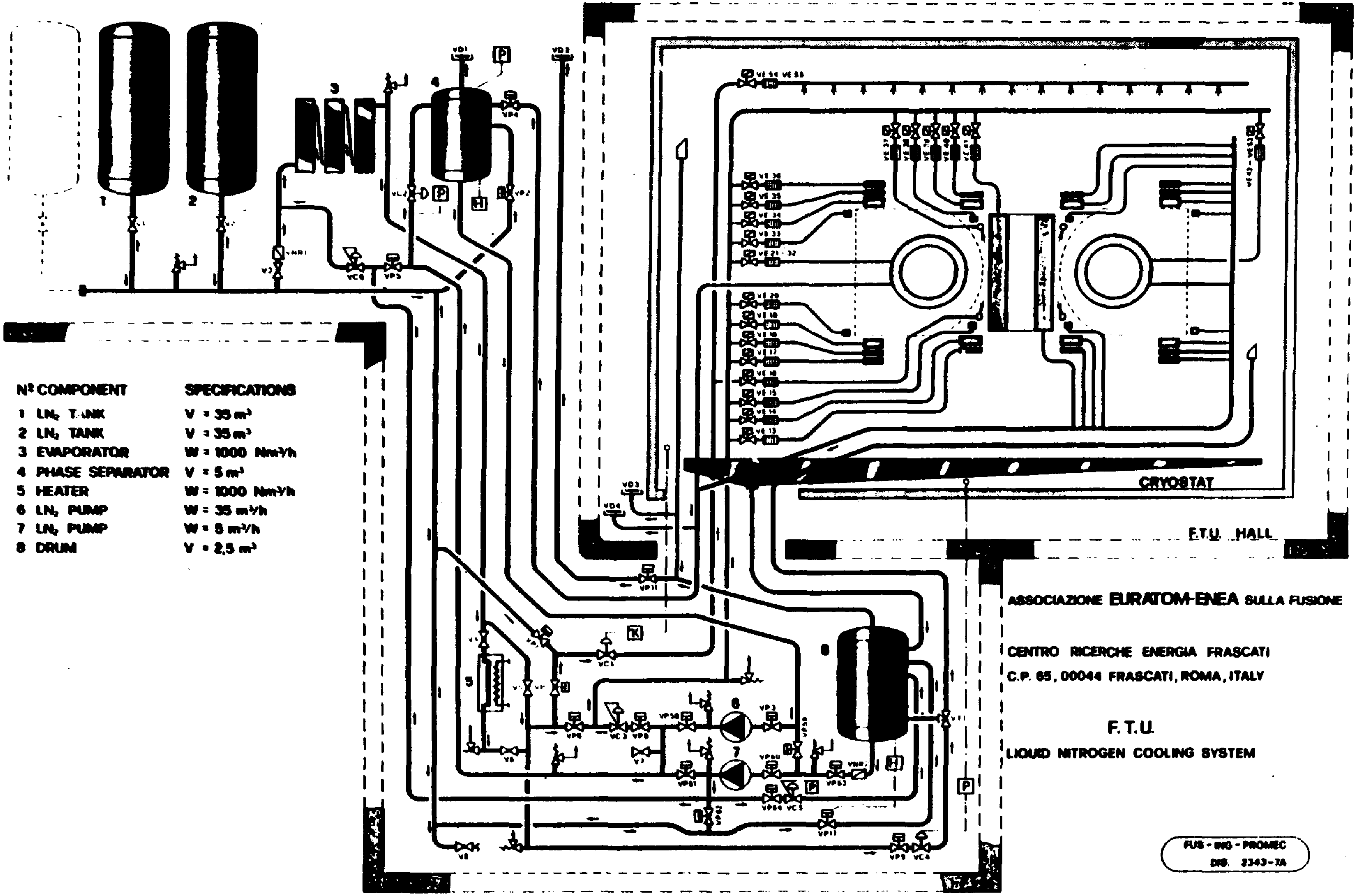
Plasma major radius, R(m)	0.935
Plasma minor radius, a(m)	0.31
Plasma current at q=2.5 (MA)	1.6
Toroidal magnetic field, B_T(T)	8
Toroidal field flattop (s)	1.5
Pulse repetition rate	1 pulse/10 min
Flux swing available (Wb)	6.4
Toroidal magnet weight (t)	55
Load assembly weight (t)	90
Toroidal field power (MW)	120
Toroidal field energy (MJ)	160
Poloidal field power (MVA)	250
Poloidal field energy (MJ)	200
Radio frequency heating	
Power (MW)	8
Frequency (GHz)	8
Pulse duration (s)	1

TABLE II

N°	Components	Specification	Heat Loss (kW)
1/2	LN_2 Tank	35 m^3	0.28
3	Evaporator	1000 Nm^3/h	
4	Phase separator	5 m^3	0.1
5	Heater	1000 Nm^3/h; 80°C	
6	LN_2 (main pump)	35 m^3/h	7.5
7	LN_2 (secondary pump)	5 m^3/h	5.5
8	Drum	5 m^3	0.08
	Superinsulated lines:		
	Lines $\Phi<50$mm	150 m	0.13
	Lines $\Phi>50$mm	110 m	0.19
	Connections $\Phi>50$mm	N° 15	0.03
	Connections $\Phi<50$mm	N° 10	0.03

TABLE III

	Main Pump	Secondary Pump
NPSH (m)	0.6	0.4
Capacity (l/min)	610	98
Head (m. of LN_2 at -196°C)	43.7	89.7



Nº	COMPONENT	SPECIFICATIONS
1	LN_2 TANK	V = 35 m^3
2	LN_2 TANK	V = 35 m^3
3	EVAPORATOR	W = 1000 Nm^3/h
4	PHASE SEPARATOR	V = 5 m^3
5	HEATER	W = 1000 Nm^3/h
6	LN_2 PUMP	W = 35 m^3/h
7	LN_2 PUMP	W = 5 m^3/h
8	DRUM	V = 2,5 m^3

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