ACTIVITIES ON THE HIGH CURRENT SC PROTON LINAC FOR THE TRASCO PROJECT

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Abstract

An R&D program, TRASCO, has started in Italy on an accelerator driven system for nuclear waste transmutation. The large flux of spallation neutrons from a high current CW proton linac accelerator is intended to drive a subcritical system to transmute nuclear waste, while producing energy. Our specific task is to develop, together with the national industry, a design of the proton accelerator, along with prototype development for its most critical components.

The present reference design follows from that proposed at Linac'96 and revised at PAC'97. A 1.6 GeV linac, operated at 25 mA, allows to reach 40 MW of beam power. A beam power upgrade is achievable using additional couplers per cavity. This design is based on a normal conductive low energy part, which includes a proton source, a RFQ and a DTL, followed by a three section superconducting linac, at the 352 MHz LEP frequency. The three sections use five cell bi-elliptica1 cavities, designed to match the proton beam at the normalized velocities β=0.5, 0.65 and 0.85.

A design for bi-elliptical (both at the iris and at the equator) cavity geometry has been carried out and a two year R&D activity to be performed by INFN will be dedicated to the fabrication of copper and niobium prototypes of the cavities. The β=0.5 and β=0.65 sections will use thin niobium cavities, copper sprayed for mechanical stability. For the high β section, the sputtering technique will be preferred, in order to reduce the structure costs. A collaboration with CERN is being established to jointly develop a full five cell sputtered cavity for the β=0.85 section, while performing chemical treatments and test on the other prototypes.

In this contribution we present the work that has been curried out so far, including the results from preliminary beam dynamics simulations. A discussion on the expected linac reliability will also be given, on the basis of the parameter choice and of the experience gained with the operation of similar cavities and plants.

Introduction

The generation of a high neutron flux with a broad energy spectrum by means of a high current proton beam impinging on a spallation target opens new perspectives in the use of high energy, high current proton accelerators[1-2]. A CW proton beam power in excess of a few tens of MW could provide the neutron flux to a subcritical nuclear reactor, allowing the design of a new, intrinsically safe, scheme for the nuclear energy production, where the closure of the fuel cycle has been obtained. In the subcritical system the high neutron flux in excess allows the incineration of the nuclear waste (actinides and long lived fission fragments) produced by conventional critical reactors, leaving no substantial amount of radiotoxic waste at the end of the cycle.

The TRASCO Project

TRASCO is a two year, 10 M$, program in which INFN, ENEA and Italian industries, will work on the design of an accelerator driven waste transmutation subcritical system. TRASCO is an Italian acronym for Transmutation (TRASmutazione) of Waste (SCOrie).

This program is in line with the growing European consensus, promoted by Carlo Rubbia through the idea of the Energy Amplifier[2], on a long term reconsideration of the civil use of nuclear power, based on a final solution of the waste accumulation problem. While similar programs are underway in the USA[1] and in Japan[3], in Europe the various national efforts[4] are coordinating through the signature of Memoranda of Understanding, like the one recently signed by INFN, CEA and IN2P3 for a common effort in the accelerator technology development. Another MOU signed with the CERN group led by E. Chiaveri will allow us to use the wide experience gained so far in the production and commissioning of the LEP2 cavities. The cavity prototypes planned for TRASCO will be treated and tested at the CERN premises.

The aim of this preliminary, and short-termed, program is to set the feasibility of a high beam power proton linac based, whenever possible, on established technologies and particularly the "cheap" CERN technology developed for the LEP2 superconducting cavities. This is an extremely attractive option, since it allows the possibility to make use of large and expensive facilities, existing at CERN and at various European companies, for the studies on prototypes.

The low Energy part of the TRASCO Linac (up to 100 MeV)

The low energy section of the machine, up to 100 MeV, is under study by two INFN groups, at the National Laboratories in Legnaro (LNL) and Catania (LNS), in the framework of the collaboration with CEA and IN2P3.

A working prototype of the source is in operation at Saclay, and the main objective of the collaboration is the improvement of the source reliability and availability. A second improved version of the source will be designed and assembled at LNS in the context of the TRASCO program and its collaborations.

The design and development of the CW, 5 MeV, RFQ, similar to the one developed for APT at LANL[5], is considered one of the major technological tasks. An Aluminum full scale prototype of the first section, based on a preliminary design performed at LNL, has been constructed and will be tested in the framework of the collaboration with France to gain experience in view of the final common engineered design. The construction of the first section (up to 2 MeV) of the real RFQ is part of the TRASCO program. A picture of the LNL Aluminum model of the RFQ is shown in Fig. 1.

The medium energy part, up to 100 MeV, is in study by INFN/LNL and CEA/SACLAY, and will take advantage of a contract signed with a qualified industry. This reference option is based on the use of the DTL technology, with the focussing elements incorporated in the accelerating electrodes[6].

An alternative superconducting design is being considered at LNL[7] according to an architecture based on independently phased resonators. This second option is interesting for LNL in view of even other possible applications, as the production of radioactive nuclei to be accelerate in the ALPI booster. This design takes advantage of the wide experience of LNL in the design and operation of low beta superconducting cavities for heavy ions.

Figure 1. The Aluminum model of the RFQ prototype under RF test at LNL.

The High Energy part of the TRASCO linac (100 MeV-1.6 GeV)

The reference linac design for the high energy section of the TRASCO linac has been set in Refs. [8] and [9]. The 25 mA, 100 to 1600 MeV, linac is split three sections, with synchronous cavity β of 0.5, 0.65 and 0.85. The transverse focusing is provided by a periodic doublet lattice, with cell length of 8, 11.2 and 15.3 m, respectively. Figure 2 shows the focussing cell in the three linac sections.

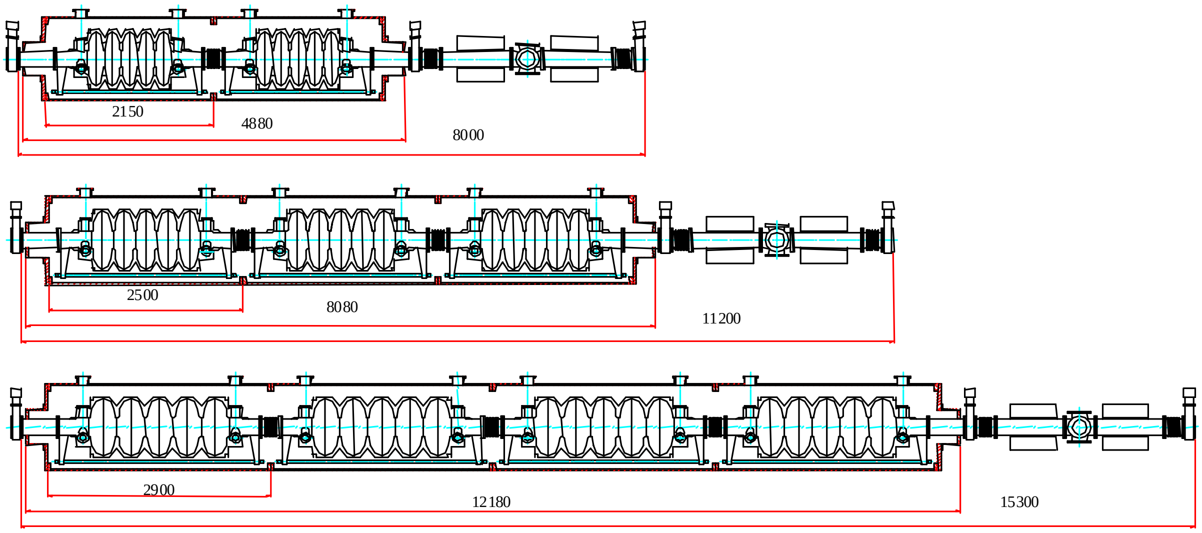

Figure 2: The doublet focussing cells of the three linac sections: above is the β =0.5 section (with two cavities per cryomodule and 8 m of period length), in the middle the β=0.65 section (with three cavities per cryomodule and 11.2 m of period length), at the bottom the β =0.85 section (four cavities per cryomodule and 15.3 m of period length).

Criteria for linac sectioning

The choice of the synchronous cavity β for the three sections determines the linac performance, in terms of acceleration efficiency and beam dynamics behavior. The acceleration efficiency is described by the ratio of the energy gain of a generic particle, ΔW, with respect to that of the synchronous one. This defines the Transit Time Factor (TTF) of a cavity and can be written as:

$$\Delta W = q\Delta V_{acc} = qE_{acc}L_{act}T(\beta,\beta_c)\cos\phi_s$$

where:

$L_{act} \equiv N\lambda\beta_c/2$ is the definition of the active cavity length, E_{acc} is the accelerating gradient for the particle at $\beta = \beta_c$, that is defined as: $E_{acc} \equiv \Delta V_{acc}{}^{\max}/L_{act}$ and ϕ_s is the synchronous phase.

In this definition the transit time factor is normalized to 1 at the nominal particle velocity $\beta = \beta_c$. Note also that the geometrical cell length is not equal to the defined active length of the cell. As a matter of fact, we chose to indicate the β values for the cavities not from the cell to cell distance, but from the behavior of the transit time curve of the whole (end-cell compensated) cavity in the desired energy range, as shown in Figure 3 for the β=0.65 cavity. In particular, the geometrical β values for the three structures are: 0.475, 0.623 and 0.826.

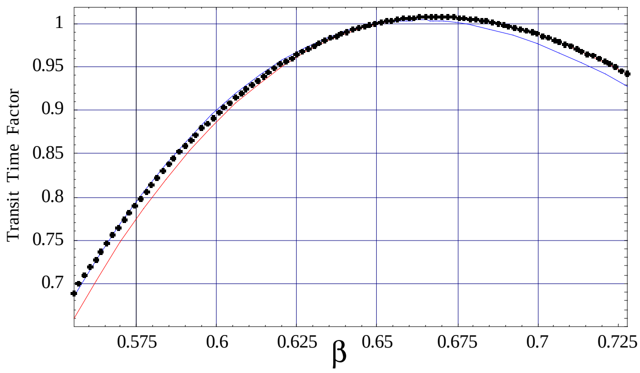

Figure 3: The dotted curve is the transit time curve of the cavity chosen for section II of the linac, as computed from the SUPERFISH fields, the two thin lines are the TTFs for an ideal cavity (sin-like fields) with β=0.652 and 0.648. All the curves are normalized to 1 for a particle with β=0.65.

The procedure for determining the β values and the transition energies of the three sections depends strongly on the operating range allowed by the cavities. Our criteria sacrifice some RF efficiency in the first part of each linac section for improved average (real estate) acceleration gradient. Since the β changes most rapidly at low energies, the initial few cavities in each section are used for velocity matching by operating them at lower RF power than the following. Such an approach allows all section cavities to operate closer to the maximum accelerating gradient (see Fig. 4), while the best klystron efficiency is set for the majority of a section cavities which, in the last part of each section, operate at a constant energy gain. Moreover, the smooth ramping of the effective energy gain at the entrance of each linac section helps the beam matching between the different lattice periods. In the high energy section the energy gain per cavity of 10 MeV and a better packing factor allows a real estate gradient of 2.6 MV/m.

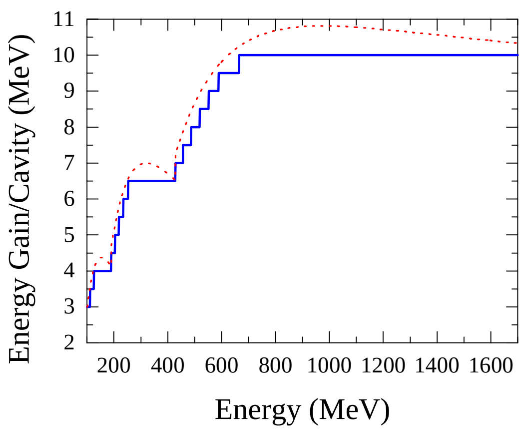

Figure 4: Chosen cavity energy gain vs beam energy (solid) and energy gain corresponding to 16 MV/m peak field (dashed).

Beam dynamics simulations

Beam losses in a high beam power accelerator should be kept to a minimum, in order to avoid component activation and “hands-on” maintenance. Hence, the performance of the linac needs to be validated with simulation codes. The results of extensive simulations, based on a new code[10], were presented at the LINAC 98 Conference[11]. In Figure 5 we show the rms, 90% and 100% emittances for the nominal current of 25 mA, and a typical simulation of 10^5 particles. The two transitions have been used for beam matching across the three sections. With this proper matching procedure the rms emittance growth is limited to below 10% and the total emittance increases by a factor smaller than 2.

The ratio between the beam aperture and the transverse rms beam size is well above 25 all along the linac. This, together with the small number of betatron wavelengths in the linac (few tens), gives us confidence that in this design beam losses in the SC linac would not be a serious problem.

The simulations were performed for a nominal current of 25 mA, the goal being that of a driver for a prototype transmutation plant. An increase of the linac current up to 100 mA has not been studied yet in full details. For currents greater than 50 mA a shorter focussing period should be provided in the first linac section, for example using superconducting quadrupoles in the cryomodules. A DTL extension to higher energies is less favorable, due to the higher reliability of the SC linac, explained in the following.

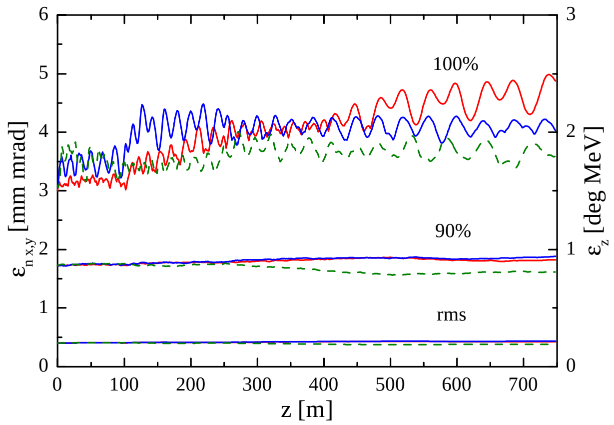

Figure 5: The rms, 90% and total (100%) emittances along the linac The solid curves are the transverse emittances, (left axis) and the dashed curve is the longitudinal emittance (right axis). The simulation has been performed with 100.000 particles.

Reliability of the proposed design

Having assessed that the basic design does not show serious limitations in achieving the objectives for a transmutation plant, we are now planning the inclusion of spare linac focussing cells in order to achieve full reliability in the case of klystron or cavity/coupler faults.

In spite of the demonstrated high reliability of the existing large scale superconducting RF accelerators (LEP, CEBAF, HERA and TRISTAN), a driver for a nuclear waste transmutation plant needs to satisfy the stringent requirements imposed by its specific use. In particular, a beam stop due to any failure of one of its components causes an interruption of the spallation neutron flux sustaining the subcritical system. If this interruption exceeds a fraction of an hour (the exact time depending on the details of the core design), the fuel bar poisoning rises: i.e. a new start up procedure needs to be performed and the waste cleaning process is partially lost.

For this reasons we are considering a linac design which includes two spare cryomodules for the low and intermediate energy sections. These two sections are the most critical, since they need to provide the correct transition energy to the following sections. A 10% spare contingency of three additional cryomodules is planned for the (less critical) high energy section. The lengthening due to the contingency hardware is around 80 m, for a new total length of 800 m. The updated section parameters are presented in Table 1.

Table 1: Summary of the SC TRASCO linac parameters.

	SI	SII	SIII
Section β_c	0.5	0.65	0.85
Section length [m]	96	146	475
Injection Energy [MeV]	100	190	428
Cell period [m]	8.0	11.2	15.3
# focussing cells/section	12+2	13+2	31+3
Max. ΔE/cavity [MeV]	4.0	6.5	10.0
E_{acc} [MV/m]	4.6	5.7	6.7
# cavities/section	24	39	124
# cavities/cryomodule	2	3	4
# cryomodule/klystron	1	1	1
Beam power/cryomodule [kW]	200	500	1000

The additional focusing cells indicated after the plus sign are the needed contingency required for the linac reliability

In the case of failure, a spare component will take the place of the faulty, and the beam will be back on the target in the time required by the reactor design. Some of the components, e.g. the klystrons, can be repaired or replaced during the linac operation, while others, like the cavities or the RF couplers, need to wait for the planned reactor maintenance shutdown.

The best use of these spare components when they are not needed (whether they are kept on or off at all times) needs to be analyzed on the basis of both capital and operational costs.

R&D activities on the TRASCO superconducting cavities

The SC linac design uses five cell structures in the three different sections, at the synchronous values of β=0.5, 0.65 and 0.85[12]. The choice of the number of cells per structure is motivated from a compromise between the structure efficiency and its operating energy range, because the energy acceptance narrows as the number of cell increases. Five cell structures give the highest active length per cavity, compatible with a three section linac design. The efficient energy for such a scheme ranges from 100 MeV to 1.7 GeV.

The cavities have been designed with an elliptical iris and an elliptical equator, on the basis of e.m. and mechanical considerations. A sketch of the geometry is presented in Figure 6. The end cells have been modified with respect to the inner cell geometry in order to achieve field compensation. The magnetic volume reduction needed for compensation is obtained by slightly increasing the angle α, with fixed iris radius (R_{iris}) and d (See Figure 6).

In Table 2 we report the main electromagnetic characteristics of the three structures: the ratio between the peak electric field on the cavity surface with respect to the accelerating field, the ratio of the maximum magnetic field with respect to the accelerating field and the cell to cell coupling. The geometrical parameters of the structures and the operating values for the accelerating gradients in the linac design have been chosen in order to limit the maximum surface electric field below 16 MV/m and the maximum surface magnetic field below 40 mT. A cell to cell coupling of 1.7% has been required to the structure. Table 3 reports the geometrical dimensions of the internal cells of the cavities. The cavity shapes have been extensively investigated with the codes SUPERFISH and OSCAR2d[13].

The operating accelerating fields will be 4.6, 5.7 and 6.7 MV/m, respectively. These are consistent values with respect to the CERN operational experience, and the gradient improvements gained through the R&D driven by the TESLA Test Facility[14] will allow a safety margin for operation and/or a cost reduction by easing the material requirements.

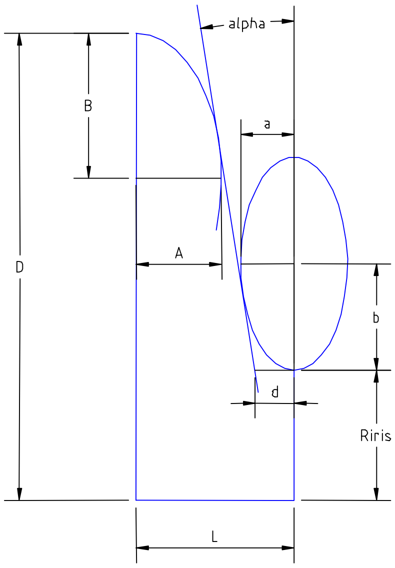

Figure 6: Reference geometry for the cavity shapes.

Table 2: Main e.m. characteristics of the three structures.

β_c	E_p/E_{acc}	B_p/E_{acc} [mT/MVm^{-1}]	Cell to cell coupling [%]
0.5	3.4	8.1	1.8
0.65	2.7	6.5	1.7
0.85	2.3	4.6	1.7

Table 3: Geometrical parameters (in mm) for the internal cell geometry, at the working cryogenic temperature.

β_c	**0.5**	**0.65**	**0.85**
A	47.1	71.6	131.3
B	80.1	121.8	196.9
a	33.4	44.8	35.4
b	60.1	89.6	56.7
d	26.8	32.8	26.8
L	101.1	132.6	175.7
D	392.2	392.7	385.2
R_{iris}	99.4	109.3	114.3

A synchronous phase of 30 degrees was chosen to provide the necessary longitudinal focusing.

Mechanical issues of the structures

The behavior of the bulk niobium and copper cavities under vacuum has been investigated with structural analysis tools, in the elastic and in the elastoplastic regimes. This analysis led to the choice of an elliptical equator, so to achieve a more homogeneous stress distribution along the geometry with respect to the usual elliptical iris and round equator design.

Only the lower β cavities are unstable under vacuum and need stiffening to ensure mechanical stability. The preliminary results obtained recently in France[15] for the structural stiffening of thin niobium cavities via copper spraying with a plasma jet are very promising. In particular, two single cell cavities at 3 GHz made with a RRR=40 niobium sheet of 0.5 mm reached around 30 MV/m of surface peak field. No performance deterioration has been measured after the copper spray deposition.

On these basis, we decided to use this technology as the reference one for the lower β cavities, given our low operating peak surface fields (16 MV/m). Figure 7 shows a summary of the stress calculations for the two lower β cells under vacuum, in the case of copper spray stiffening on a 2 mm niobium sheet. The copper thickness ranges from 3 to 18 mm.

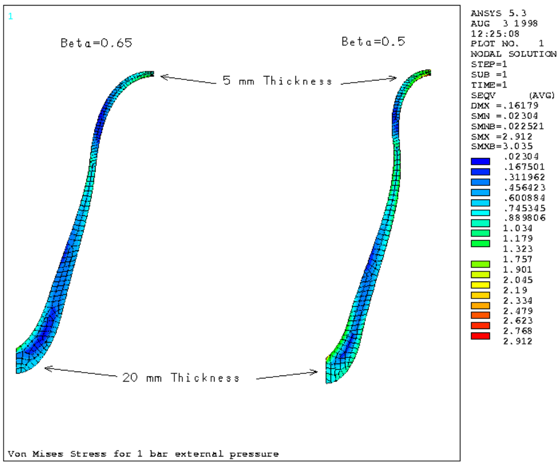

Figure 7: Stress analysis for the β=0.65 (left) and β =0.5 (right) copper sprayed cavities. Units for the stresses indicated in the scale on the right are kgf/mm^2.

Cavity prototypes

The construction and test of prototypes of the cavities with different geometry, required for the three linac section, is one of the important task of the TRASCO program. In particular the two years program on cavity prototypes includes:

- Construction and test of a full β=0.85 five cell cavity. This cavity, now under construction at CERN in the framework of the MOU recently signed, is built according to the TRASCO design and takes advantage of the experience gained at CERN on cavity fabrication, sputtering and test. The cold tests are expected by spring 1999.

- Construction and test of some (4 to 6) single cell cavities, according to the design of the lower beta structures. These cavities are expected to qualify the already mentioned technology[15] of the external copper plasma deposition on a completely treated thin niobium cavity. Reactor grade niobium (RRR=40) of 2 mm thickness has been chosen and ordered for this purpose. On the basis of the experience gained so far[14], we decided to check the niobium sheets with the eddy current technique, to avoid inclusions of foreign materials, and to prefer the electropolishing with respect to the usual BCP (Buffered Chemical Polishing). The 800 ºC heat treatment is foreseen and the final high pressure water rinsing will be applied. This part of the program will be performed with the Italian company ZANON and will use the CERN competencies for chemistry and cold tests.

- Construction and test, with ZANON, of a second full β=0.85 five cell cavity. This cavity should also be equipped with a cryostat and with prototypes of the major ancillary components, as couplers and tuners.

These three objectives are considered particularly important to qualify the chosen technologies and to demonstrate the real cavity performances we can expect. A precise estimation of the linac cost will also be possible after this R&D program.

High order modes and multipactoring

The excitation of high order modes in the five cell structures can be of some concern due to the very high current foreseen for the linac. The analysis of the first bands, performed with the OSCAR2d code[13], shows very low R over Q values for all the high order modes, due to the crossing of the TM011 and TM020 bands. This results in a strong decrease of the shunt impedance of the modes.

The choice of a beam tube diameter equal to the inner irises diameter helped in easing the high order mode behavior of the accelerating structure. The RF field freely propagates through the cavity for any frequency above the beam tube cut off and no trapped “tube modes” are expected.

Possible electron loading effects (multipactoring) were investigated too. As expected the elliptic shape of the equator resulted in a very safe cavity operation. Indeed, the choice of the elliptical equatorial shape gives a stronger longitudinal component of the electric field along the surface, which pushes the electrons strongly towards the cavity equator and brakes the resonant conditions.

Preliminary design of the cryomodules

Based on the expertise gained in the design of the second and third generation of Tesla Test Facility (TTF) cryostats[16] we have started the design of the cryomodules for the superconducting linac. The design is still at a preliminary stage, but various solutions have been chosen because of their success in the TTF cryomodule design.

Figure 8: Preliminary design for the cryostat.

The cryostat has a single thermal shield, made by a 1 mm copper sheet supported by a stainless steel frame. The thermal shield are cooled by two symmetrical helium pipes connected through the new “finger-welding” scheme[16] that has been successfully tested at TTF[14]. This design reduce production costs and pre-assembling time.

Following the scheme developed for LEP2 at CERN, the cryomodule will be extremely modular, each module holding a single cavity in a stainless steel frame. The vacuum vessel is open, similar to that one used in the LEP2, with a thin stainless steel sheet closing it, to guarantee easy access. Figure 8 shows the cryostat preliminary design.

Conclusions and Acknowledgments

We have summarized here the major activities on the high current proton linac foreseen for the TRASCO project that has been recently funded in Italy. These activities are at the beginning and the growing interest of the international community suggests that some of them will be modified because of a better coordination between the different subjects and nations involved.

The framework we have recently set through the Memoranda of Understanding signed by INFN with CEA and IN2P3, for a common effort in the accelerator technology development, and with CERN, for cavity development, is a good starting point.

I want to conclude thanking all the members of the TRASCO group for the excellent work done so far, a small part of which I have summarized in this paper.

References

[1] S.O. Schriber, "Survey of Proposed High Intensity Accelerators and their Applications", in Proc. of the 1994 EPAC, p. 213; and M. Promé, "Major Projects for the Use of High Power Linacs", in Proc. of the XVIII LINAC, CERN 96-07 (1996), p. 9.

[2] C. Rubbia, J.A. Rubio, "A Tentative Programme Towards a Full Scale Energy Amplifier", CERN/LHC/96-11 (EET).

[3] N. Akaoka et al., "High Intensity Proton Accelerator for Neutron Science Project at Jaeri", in Proc. of the EPAC 98, Stockholm, Sweden.

[4] See the contributions of M. Salvatores and M. Napolitano at this Workshop.

[5] D. Schrage et al., "CW RFQ Fabrication and Engineering," in Proc. of the LINAC 98, Chicago.

[6] A. Pisent, M. Comunian, G. Fortuna, A. Lombardi, M.F. Moisio "The DTL Approach for a 100 MeV CW Linac" LNL internal note LNL-INFN(REP) 111/96 (1996).

[7] M. Comunian, A. Facco, A. Pisent, "A 100 MeV Superconducting Proton Linac: Beam Dynamics Issues", in Proc. of the LINAC 98, Chicago.

[8] C. Pagani, G. Bellomo, P. Pierini, "A High Current Proton Linac with 352 MHz SC Cavities", in Proc. of the XVIII LINAC, CERN 96-07 (1996), p. 107.

[9] C. Pagani, G. Bellomo, P. Pierini, G. Travish, D. Barni, A. Bosotti, R. Parodi, "A High Current Superconducting Proton Linac for an Accelerator Driven Transmutation System", in Proc. of the 1997 PAC, Vancouver, Canada.

[10] P. Pierini, "A Multigrid-Based Approach to Modeling a High-Current Superconducting Linac for Waste Transmutation", in Proc. of the ICAP 98, Monterey CA, USA.

[11] G. Bellomo, P. Pierini, "Beam Dynamics in a High Current Proton Linac for Nuclear Waste Transmutation", in Proc. of the LINAC 98, Chicago.

[12] D. Barni, A. Bosotti, C. Pagani, P. Pierini, S. Visonà, "SC Beta Graded Cavity Design for a Proposed 350 MHz Linac for Waste Transmutation and Energy Production", in Proc. of the EPAC 98, Stockholm, Sweden.

[13] P. Fernandes, R. Parodi, IEEE Trans. Magn. 24 (1998), p. 154.

[14] C. Pagani "Developments and Achievements at the TESLA Test Facility (TTF)", in Proc. of the 1998 Applied Superconductivity Conference, Palm Desert, CA, USA.

[15] S. Bousson et al., "A New Fabrication and Stiffening Method of SRF Cavities" in Proc. of the EPAC 98, Stockholm, Sweden.

[16] C. Pagani et al., "Construction, Commissioning and Cryogenic Performances of the First TTF Cryomodule", in Proc. of the 1997 CEC/ICMC, Portland and C. Pagani et al., " Design of the thermal shields for new improved version of the TESLA Test Facility (TTF) cryostat", Ibiden.