

Superconducting Accelerators for Nuclear Waste Transmutation

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Abstract—High intensity proton accelerators, with energies in excess of 1 GeV, have been recently proposed for nuclear waste transmutation applications. The large neutron flux, obtained by the spallation target, further multiplied in a subcritical reactor, could open the possibility of closing the fuel cycle in nuclear energy production. This new accelerator application asks for high overall plug efficiency and reliability, together with low particle losses for hands-on maintenance. Superconducting RF technology seems to be the best solution above an energy of 100-200 MeV, for the design of a cost effective machine in terms of both capital and operational costs. In this paper we review the design of the INFN/ENEA TRASCO high-energy accelerator.

I. INTRODUCTION

The possibility of generating 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 produce the neutron flux to a subcritical nuclear reactor, allowing the design of a new, intrinsically safe, scheme for nuclear energy production, where the closure of the fuel cycle has been obtained. In the subcritical system the high excess neutron flux also allows the incineration of 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.

II. 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, in Europe the national efforts are coordinating through the signature of Memoranda of Understanding (MOU), as the one recently signed by INFN, CEA and IN2P3 for a common effort in the accelerator technology development. Another MOU with the CERN group led by E. Chiaveri will allow us to use the experience in the production and commissioning of the LEP2 cavities: the TRASCO prototypes will be treated and tested at CERN.

The aim of our specific effort in this preliminary short-term program is to set the feasibility of a high beam power proton linac based, whenever possible, on 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 section of the machine, up to 6 MeV, is under study by other INFN groups (at LNL and LNS), in the framework of the MOU with CEA/IN2P3. While a working prototype of the source is in operation at Saclay, the design and development of the CW, 6 MeV RFQ, similar to the one developed for APT at LANL, is considered one of the major technological tasks.

The medium energy part, up to 100 MeV, is being studied by INFN/LNL and CEA/SACLAY, and will take advantage of a contract signed with qualified industry.

III. THE TRASCO LINAC DESIGN

The design for the high energy section of the TRASCO linac has been described in [3] and [4]. The 25 mA, 100 to 1600 MeV, 350 MHz linac is split into three sections, with synchronous cavity β values of 0.5, 0.65 and 0.85. Transverse focusing is provided by a periodic doublet lattice, with cell lengths of 8, 11.2 and 15.3 m, respectively. A synchronous phase of 30° was chosen to provide the necessary longitudinal focusing. Table 1 lists the main linac parameters, while Fig. 1 shows the doublet focussing cell in the three sections.

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. $\Delta E/\text{cavity}$ [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/cryom. [kW]	200	500	1000

The additional focusing cells indicated after the plus sign are the needed redundancy required for the linac reliability (discussed in Section III.B)

A. Beam dynamics simulations

Beam losses in a high beam power accelerator should be kept to a minimum, in order to avoid component activation that limits “hands-on” maintenance. Hence, the performance

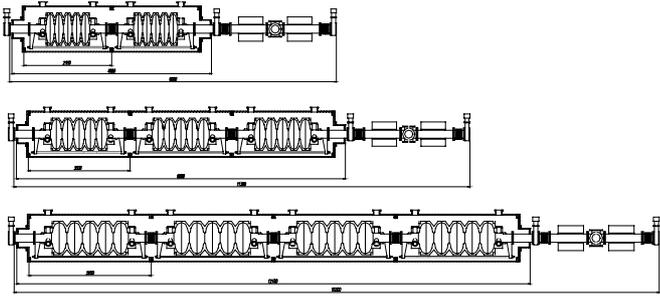


Fig. 1: The doublet focussing cells of the three linac sections: above is the $\beta=0.5$ section (with two cavities per cryomodule and 8 m of period length), in the middle the $\beta=0.65$ section (with three cavities per cryomodule and 11.2 m of period length), at the bottom the $\beta=0.85$ section (four cavities per cryomodule and 15.3 m of period length).

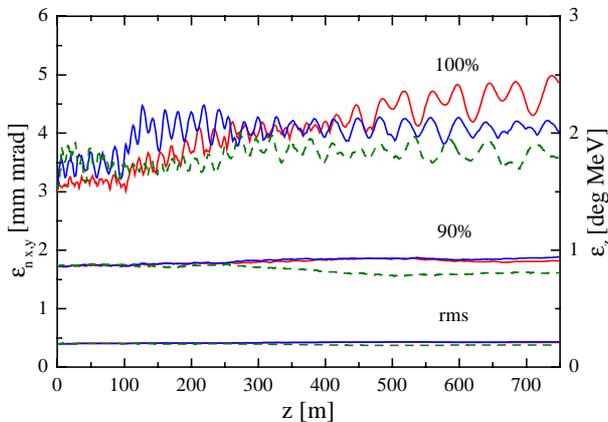


Fig. 2: The rms, 90% and total (100%) emittances along the linac. The solid curves are the transverse emittances, (left axis) and the dashed curve is the longitudinal emittance (right axis). The simulation has been performed with 100,000 particles.

of the linac needs to be validated with simulation codes. The results of extensive simulations were presented at the LINAC 98 Conference[5]. In Fig. 2 we show the rms, 90% and 100% emittances for the nominal current of 25 mA, and a typical simulation of 10^5 particles. The transitions have been used for beam matching across the three sections. The rms emittance growth is limited to below 10% and the total emittance increases by a factor smaller than 2.

The ratio of 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 will 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 detail.

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 Drift

Tube Linac (DTL) extension to higher energies is less favorable, due to the required high reliability of the SC linac (explained in the following section).

B. 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), fuel bar poisoning arises: i.e. a new start up procedure needs to be performed and the waste cleaning process is partially lost.

For this reason we are considering a linac design which includes two spare cryomodules for the low ($\beta=0.5$) and intermediate ($\beta=0.65$) 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 ($\beta=0.85$) section. The lengthening due to the contingency hardware is around 80 m, for a new total length of 800 m.

In the case of failure, a spare component will take the place of the faulty, and the beam can be switched again 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.

IV. R&D OF THE TRASCO SUPERCONDUCTING CAVITIES

The SC linac design uses five-cell structures in the three different sections, at synchronous β values of 0.5, 0.65 and 0.85[6]. The choice of the number of cells per structure is motivated by 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 reference 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 Fig. 3. Table 2 reports the geometrical dimensions of the

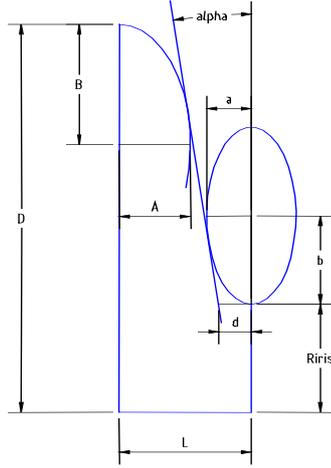


Fig. 3: Reference geometry for the cavity shapes.

internal cells of the cavities. 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 Fig. 3).

The cavity shapes have been extensively investigated with the SUPERFISH and OSCAR2d[7] codes. In Table 2 we report the main electromagnetic characteristics of the three structures. 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 2: 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

TABLE 3: 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

The operating accelerating fields will be 4.6, 5.7 and 6.7 MV/m, respectively. These are values consistent with the CERN operational experience, and the gradient improvements gained through the R&D driven by the Tesla Test Facility

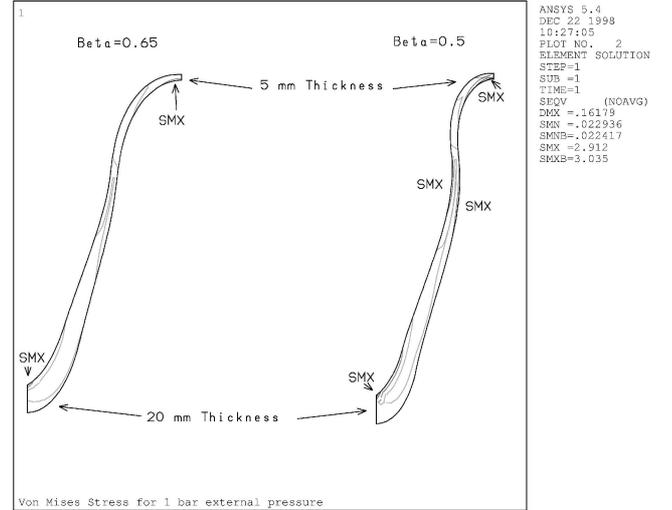


Fig. 4: Stress analysis for the $\beta=0.65$ (left) and $\beta=0.5$ (right) copper sprayed cavities. Units for the stresses indicated in the legend on the right are kgw/mm^2 . The arrows indicate the positions of maximum stresses (SMX).

(TTF) [8] will allow a safety margin for operation and/or a cost reduction by easing the material requirements.

A. Mechanical issues of the structures

The behavior of bulk niobium and copper cavities under vacuum has been investigated with structural analysis tools, in the elastic and in the elastoplastic regimes.

The 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 lowest β cavity was found to be unstable under vacuum and needs a stiffening structure for mechanical stability. Either a standard stiffening structure will be employed or a structural stiffening via copper spraying with a plasma jet (as proposed for the Tesla cavities[9]) will be performed.

Fig. 4 shows a summary of the stress calculations for the two lower β cells under vacuum, when using copper spray stiffening.

B. Cavity prototypes

The construction and test (at room temperature) of a full scale copper prototype of the $\beta=0.5$ five cell cavity (including stiffening elements) is one of the major objectives of the TRASCO program, to determine the fabrication technology and to validate the structural calculations. An agreement with CERN has been established in order to fabricate and test a full $\beta=0.85$ five cell cavity and a single cell test structure (both copper sputtered with Nb), on the basis of our design. The cavities will be ready for tests at CERN in spring 1999.

The Italian company Zanon will build a second copper (that will be sputtered with Nb at CERN) $\beta=0.85$ cavity, a single cell Nb $\beta=0.5$ cavity and a copper model of the five cell structure. These cavities will be tested at CERN.



Figure 5: Preliminary design for the 4.2 K cryostat.

C. Higher order modes and multipactoring

The excitation of higher order modes in the five cell structure can be of some concern due to the very high current foreseen for the linac operation. Even minimal perturbations of the cavity fields could result in beam halo growth, leading to beam losses beyond the threshold of permissible activation of the machine. For this reason we performed a thorough check of the higher mode distribution in the structure using our OSCAR2d code[6]. The analysis of the first (and most critical) band of the $\beta=0.85$ five cell structure shows very low R over Q values for all the high order modes, due to the crossing of the TM011 and TM020 bands. This crossing results in a strong decrease of the shunt impedance of the modes.

The choice of a beam pipe diameter equal to the inner irises diameter helps in reducing the higher order mode excitation of the accelerating structure. In this case the RF field freely propagates out of the cavity for any frequency above the beam tube cut off. For the same reason, no RF field can be trapped in the beam tubes, avoiding the “tube modes” that were measured in the LEP cavities.

We also checked the effect of the main coupler on the on-axis distribution of the electric field. This analysis was performed using the HFSS code on a $\beta=0.85$ structure, with a LEP type main coupler connected to the port. The check was motivated by a possible horizontal test in a LEP-modified cryostat, using the standard LEP couplers and klystrons.

Possible resonant electron loading effects (multipactoring) were investigated with the TWTRAJ postprocessor of the OSCAR2d code, but the low peak magnetic fields and the elliptic shape of the equator resulted in 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, where the resonant condition for one point multipactoring is broken.

D. Preliminary design of the cryomodules

We have started a preliminary design of the cryomodules for the superconducting linac based on the expertise gained in the design of the second and third generation TTF cryostats. The design is still at a preliminary stage, but various solutions have been chosen because of their success in the TTF cryomodule design[10].

Fig. 5 shows a possible preliminary design for the cryostat. The cryostat will have a single thermal shield, made by a self-sustained aluminum sheet or by a thin copper sheet supported by a stainless steel frame. The thermal shield will be cooled by a helium pipe that will be connected through the new “finger-welding” scheme[11] that has been successfully tested at the TTF[8]. This design will reduce production costs and pre-assembly time. The cryomodule will be extremely modular, each module holding a single cavity in a titanium and stainless steel frame.

The other guideline (besides the single shield layout) for the cryomodule design is a cost-effective solution, keeping in mind that extremely low thermal losses are not necessary when operating at 4.2 K. 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 during the assembly phase and to reduce the assembly costs.

IV. CONCLUSIONS

We have summarized here a possible use of superconductivity in linear accelerators planned as drivers for waste incinerators; and outlined the status of the R&D activities for the TRASCO project.

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] 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.
- [4] 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.
- [5] G. Bellomo, P. Pierini, “Beam dynamics in a high current proton linac for nuclear waste transmutation”, in Proc. of the XIX LINAC, Chicago 1998.
- [6] 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, Stockholm, Sweden.
- [7] P. Fernandes, R. Parodi, IEEE Trans. Magn. 24 (1998), p. 154.
- [8] C. Pagani “Developments and achievements at the TESLA Test Facility (TTF)”, These Proceedings.
- [9] S. Bousson et al., “A new fabrication and stiffening method of SRF cavities” in Proc. of the 1998 EPAC, Stockholm, Sweden.
- [10] C. Pagani et al., “Construction, commissioning and cryogenic performances of the first TTF cryomodule”, in Proc. of the 1997 CEC/ICMC, Portland.
- [11] C. Pagani, D. Barni, M. Bonezzi, P. Pierini, J.G. Weisend II, “Design of the thermal shields for the new improved version of the TTF cryostat”, in Proc. of the 1997 CEC/ICMC, Portland.