A HIGH CURRENT SUPERCONDUCTING PROTON LINAC FOR AN ACCELERATOR DRIVEN TRANSMUTATION SYSTEM

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Abstract

High current CW proton linac accelerators have been recently proposed for a number of applications based on the use of a large flux of spallation neutrons. In this context, an R&D program on an accelerator driven system for nuclear waste transmutation has been recently approved in Italy. Our specific task is to develop, together with the national industry, a design of the high energy part of the proton accelerator, along with prototype development for the most critical components. In this paper we present a revised version of the design proposed at Linac'96, using five cell cavities, rather than the original four cells. This modification, together with a new criterion for using the transit time factor curve for non resonant proton velocities, results in a more modular and efficient design. A 1.6 GeV linac, operated at 25 mA, allows to reach 40 MW beam power. The beam power upgrade is achievable using additional couplers per cavity.

1 PROJECT OVERVIEW

An R&D program has started in Italy on an accelerator driven system for nuclear waste transmutation. In the recently approved two year program, starting in January 1998, two Italian research agencies (INFN and ENEA) will be supported to study, together with other institutions and the national industry, critical components of the accelerator driven system. In the following we present a revised version of the reference design, originally proposed at Linac'96 [1], and the rationale behind the parameter choices.

More generally, a number of applications have been recently proposed for high current proton linacs, including nuclear waste transmutation, energy production by sub-critical reactors, spallation neutron sources and trit-ium production [2]. These applications share in common a number of requirements on the accelerator. A high average current, high energy proton beam is needed. Additional requirements include high wall plug efficiency and low particle losses to guarantee the hands-on maintenance of the system. While these systems differ in the detailed parameters desired, they generally operate in the space charge dominated regime.

A number of accelerator configurations for the system in question have been considered in the literature. While this paper focuses on the superconducting linac option, it is worth mentioning alternatives.

Cyclotrons are presently limited to beams up to 1 MW, and can conceivably be extended up to a few MW. Still, cyclotrons possess the advantage of being compact and so they could be candidates for a demonstration plant.

Room temperature linacs offer a mature technology, but suffer from a much lower RF efficiency and high heat loads in CW operation.

One approach, which relies on well tested technology and provides efficient use of wall plug power, combines a low energy section based on a room temperature linac, and a high energy section based on β-graded superconducting structures.

The low energy section of such a system poses a number of challenges; however, a number of existing technologies address the regime of interest. For instance, proton sources in excess of 100 mA have been demonstrated, RFQs operating with more than 100 mA are operating and DTL structures at high current, up to 200 MeV exist, albeit at low duty cycle.

Here we consider systems with energy greater than 1 GeV and average beam power in excess of 30 MW. Moreover, we address only the high energy section (above 100 MeV) of the system. In the design presented in Section 4 we choose a final beam energy of 1.6 GeV, very close to the Los Alamos APT design [3]. The final choice of beam energy and current is heavily influenced by the specific application and is outside of the scope of the present paper.

The following sections of this paper illustrate the approach followed to design the high energy section from 100 MeV to the target energy of 1.6 GeV.

2 THE 350 MHZ SC LINAC OPTION

The motivation for turning to superconducting technology is twofold: high RF efficiency is readily achieved, which is important for CW operations, and large apertures are possible, which are relevant to minimizing particle loss.

The choice of operating frequency is set by a few general considerations. CERN has operated the LEP2 cavities at 350 MHz, and has added extensive experience at this frequency to the accelerator community. A number of cavity production tools and test stands are available in European companies as a result of the LEP2 development. Additionally, the 350 MHz choice matches existing RFQ and DTL designs.

Frequencies higher than the LEP frequency imply smaller physical dimensions for the cavities and associated components, but require a more complex 2 K cryogenics.

The injection energy of 100 MeV is mainly determin-

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ed by elliptical superconducting cavity constraints. Elliptical cavities for low energies (matched β<0.5) have a short active length and a low accelerating gradient, resulting in a poor "real estate" gradient from an expensive structure. Alternative schemes for the low energy section may allow the extension of the initial section to higher energy (>100 MeV). Nevertheless, elliptical cavities can capture efficiently the 100 MeV beam and higher injection energies have little impact on performance.

Due to the wide proton velocity variation from 100 MeV to over 1 GeV, and to the limited velocity acceptance of any resonant accelerating structure, the linac has to be sectioned. Analysis indicates three sections are sufficient to cover the energy range from 100 MeV to 1.6 GeV.

3 OPTIMIZATION CONSIDERATIONS

There are a number of constraints and practical arguments which limit the usable parameter space. A central need is to make the machine cost effective in terms of both capital and operational costs. In general, the capital cost is reduced by decreasing the length of the accelerator, while the operational cost is reduced by having "efficient" acceleration — good RF to beam coupling. Additionally, the RF is a major component of the system cost, and care must be taken to optimally use the klystron's power rating, while saving a proper margin for controls and mismatching.

On the basis of the existing 1.3 MW CW LEP klystron, a nominal power of 1 MW is used for beam acceleration in most of the linac structures. This power feeds four cavities in the high energy section (one cryomodule) and six (two cryomodules) in the intermediate one. For general machine reliability, the first section uses smaller klystrons (500 kW) feeding four cavities (two cryomodules). This scheme is compatible with further current upgrading, based on multiple RF coupler operation.

Efficient use of the cryostats is also demanded because of the capital cost, however beam dynamics considerations affect the arrangement of the accelerating cavities.

A major consideration is the need to keep the beam size well under control, and this implies a limit on the focusing lattice period length. In turn, the focusing period, in combination with the need for warm diagnostic boxes in each cell, sets limits on the cryomodule length. The cost and the added length of the cold/warm transitions require a compact focusing scheme, thus a singlet scheme seems less desirable than a doublet focusing structure.

It is standard practice to use multicell cavities in order to increase the ratio between the active and physical cavity length. The velocity acceptance of the cavities decreases with the number of cells in the structure, and that, in turn, can affect the number of sections needed in the linac for efficient acceleration. Increasing the active cavity length also increases the RF power needed for the beam acceleration, which must be within the limits of the available coupler technology [4].

Five cell cavities represent the best compromise to preserve a three section linac design, while the maximum number of cavities per cryomodule has been limited respectively to two, three and four, on the basis of the focusing scheme outlined above. The considerations presented in this section, combined with basic beam dynamics, and details of the specific system being considered, yield the present reference design.

4 A DESIGN FRAMEWORK

For our design, we assume the parameters and limits given in Table 1. The assumed values for the peak electric field and RF power transmitted through the couplers have been previously achieved CERN test bench values [4]. The nominal current of 25 mA is reachable with a single coupler per RF cavity. To provide a possible beam current upgrade, the cavities will be designed from the beginning with multiple coupler ports, despite the fact that the present design parameters are based on a one coupler solution.

The minimum cavity matched ("effective", not geometric) β has been set to 0.5 based on preliminary electromagnetic and mechanical studies. The reference design of such a cavity, which features an appropriate stiffening structure and an iris radius of 10 cm, has a peak surface to accelerating field ratio of 3.2. For the assumed peak surface field of 15 MV/m and considering the poor packing factor of the active cavity length to the lattice period the average "real estate" accelerating gradient of the low β section is 1 MeV/m.

Table 1: Parameters and limits used for the design of the superconducting linac.

Parameter	Value
Initial Energy	100 MeV
Final Energy	1600 MeV
Beam Current	25 mA
Beam Power	40 MW
Peak Surface Field	≤ 15 MV/m
Minimum Cavity β	0.5
RF Coupler Max. Power	250 kW
Available Power/Klystron	1 MW

The procedure for determining the β values and the transition energies of the sections depends strongly on the operating range allowed by the cavities. Initial studies utilized an operating range which was symmetric in the velocity acceptance curve [1], while present work relies on an asymmetric approach.

The present method sacrifices some RF efficiency in the first part of each linac section for improved average (real estate) acceleration gradient. Since the particle velocity 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 subsequent cavities. Such an approach allows the totality of a section's cavities to operate closer to the maximum accelerating gradient (see Fig. 1), while the best klystron efficiency is set for the majority of a section's cavities which, in the last part of each section, operate at a constant energy gain, independently of the proton velocity.

Moreover, the smooth ramping of the effective energy gain at the entrance of each linac section is expected to help 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 2.5 MeV/m.

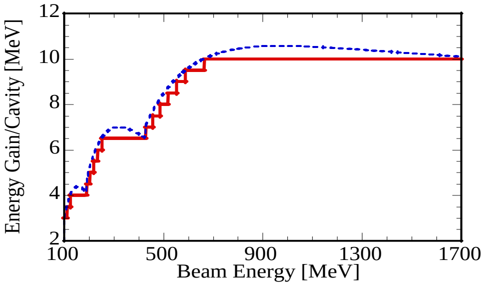

Figure 1: Maximum (upper line) and actual (lower line) energy gain along the accelerator as a function of the beam energy, assuming a peak surface field of 15 MV/m and synchronous phase φ_s= -30°.

In Table 2 we list parameters for the three sections. Note that a shorter lattice period is used at the lower energy ranges, as is required to compensate the effect of transverse RF defocusing.

Table 2: Machine and lattice parameters.

Parameter	**Value**		
Total length	~ 720 m		
Number of cells/cavity	5		
Number of couplers/cavity	1		
Section	**1**	**2**	**3**
Section total length [m]	96	146	475
Injection energy [MeV]	100	190	428
Section period [m]	8	11.2	15.3
# of cavities/section	24	39	124
# of cavities/cryomodule	2	3	4
# of cavities/klystron	4	6	4
Klystron rating (kW)	500	1300	1300
Cavity matched β	0.5	0.65	0.85
Accel. Gradients [MV/m]	4.3	5.4	6.4
Power/coupler [kW] / 25 mA	100	160	250

The linear beam dynamics with space charge has been studied; and a procedure for matching the beam between the linac sections has been devised. The matching of the short period FODO structure of the DTL to the long period doublet structure in the SC linac is still under investigation.

A lattice, consistent with the above machine parameters is shown in Fig. 2. The maximum needed quadrupole integrated strength is approximately 1.6 T, which is achievable within the 60 cm reserved for each quadrupole in the 3 m intermodule section. A normalized emittance of 1 π mm-mrad (transverse) and 1 π deg-MeV (longitudinal) has been assumed [3], and a constant synchronous phase of -30° has been used along the linac.

5 R&D PROGRAM

On the basis of the present reference design, the objective of the two year program, for the high energy part of the linac, is to develop the technology of the most crucial components, while finalizing the design of the machine.

We plan to develop, together with the industry, Nb single cell cavities at the lowest beta, to be measured at CERN, and a complete five cell copper structure for mechanical and RF warm tests. A complete copper, Nb sputtered, cavity at the highest beta is also planned; the R&D on single cells being in progress at CERN [5].

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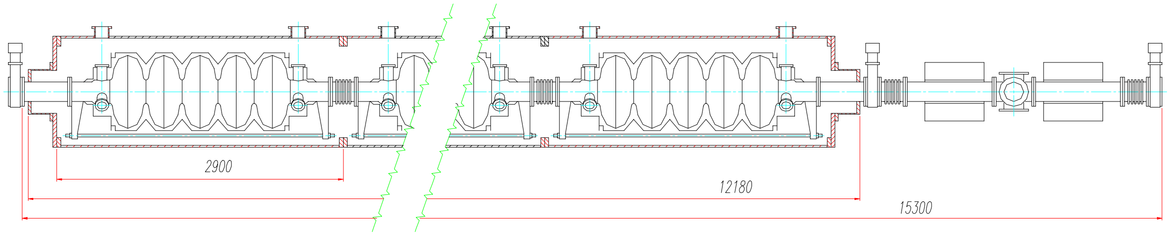

Figure 2: Layout of the basic cell in the high energy section (the low and intermediate energy sections differ only in the cryomodule length). The 3 m intermodule distance accomodates the quadrupole doublet, steering magnets (not shown), and a diagnostic and pumping box. The beam pipe aperture is maintained at 20 cm or greater throughout the linac.