Superconducting High-Intensity RF Proton Accelerator for Tran.:mutation Technologies*

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Abstract

Superconducting high-intensity RF proton accelerators with CW power of 100-MW can be used for transmutation technologies. Compared to a normal-conducting, room-temperature RF linac, a superconducting linac could offer substantial savings in operational cost. In this paper, we describe the design of such a linac.

INTRODUCTION

High-intensity RF proton accelerators have been proposed for transmutation-technology applications in the last few years [1]. Among these applications are transmutation of waste, neutron-scattering research, and production of tritium. These linacs have nominal output parameters of 100 mA at 1 GeV and must operate with high availability and low beam loss. Operating in a CW mode, they consume hundreds of megawatts of electricity and it is of paramount importance to achieve high power efficiency. Presently these RF linacs are based on room-temperature, normal-conducting technology [2]. Normal-conducting (NC) linacs, though well proven in performance, suffer in efficiency because of the high RF losses in the walls of the copper accelerating structures. A superconducting (SC) linac is an attractive alternative in terms of efficiency because of the insignificant RF loss of the niobium cavities. On the other hand, although SC linacs have been successfully operated for electron beams, an SC proton linac has yet to be built.

We have completed a study to evaluate SC RF linacs for transmutation applications. We have developed an SC RF linac concept that is sufficiently complete to allow us to assess the technical feasibility, technology development requirements, risk factors, and cost. This linac concept is briefly summarized in this paper. A final report is being prepared to document the study in detail [3].

SC RF LINAC DESIGN

Figure 1 shows the SC RF linac design. A normal-conducting injector linac developed at Los Alamos will accelerate the proton beam to 100 MeV [4]. The SC part of the linac starts at 100 MeV and consists of a medium-energy section and a high-energy section. These two accelerator

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sections extend from 100 MeV to 261 MeV and from 261 MeV to 1000 MeV, respectively. In each section, quadrupole doublets are installed between the cryomodules to provide transverse focusing of the beam (Fig. 2). Each cryomodule consists of two 4-cell elliptical SC cavities. In each section, the cavities and cryomodules are identical in design. The cell-shapes in the medium-energy section and high-energy section correspond to β=0.48 and β=0.71, respectively. The power of a 1-MW klystron will be split to supply four cavities.

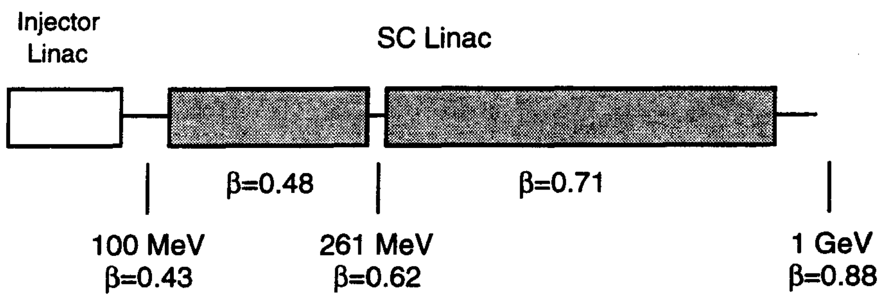

Figure 1: Schematic of SC RF linac.

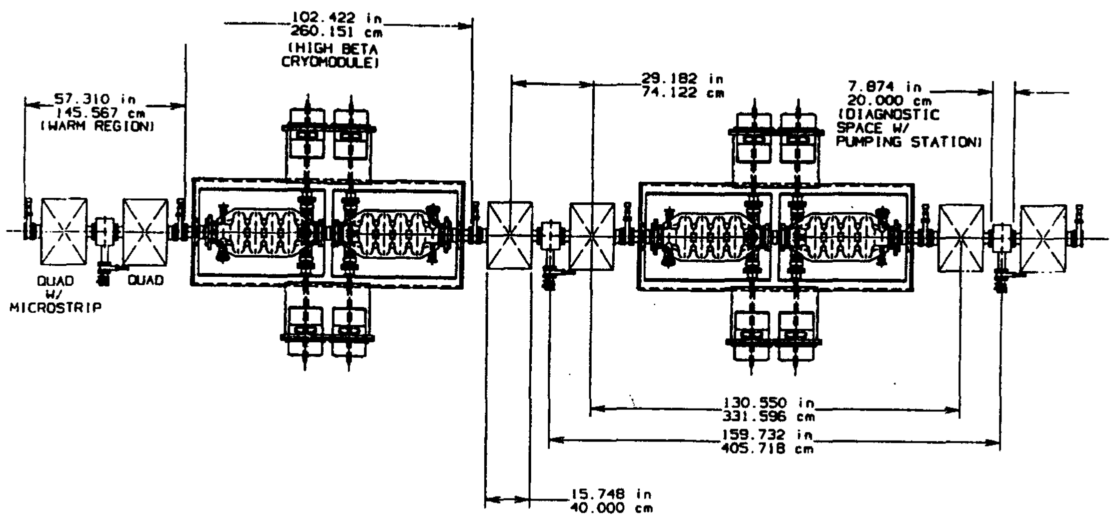

Figure 2: Typical arrangement in the high-energy section

CAVITY FIELD GRADIENT AND POWER-COUPLER

Conservative design parameters and demonstrated SC technologies have been chosen in order to maximize technical feasibility and to minimize technical risk. Such an approach should also minimize the future R&D effort required to develop this SC linac. Our conservatism can clearly be seen in the two critical areas of the design of an SC linac, namely, the cavity field gradient and coupler-power capability. We have chosen a field gradient (E_0T) between 4.2 and 5.3 MV/m. This field gradient has been demonstrated, among other laboratories, at CEBAF at 1.5 GHz [5] and CERN at 350 MHz. It is easily achievable with established cleaning and processing techniques for non-heat-treated niobium with RRR=250 and is extremely conservative with respect to the frontier being explored nowadays at 25 MV/m. We have chosen to feed a cavity with two couplers so that the required power handling capability of each coupler is only 105 kW. This level of power-coupler capability has been demonstrated at CERN [6] and at HERA with beam [7]. Higher power levels have been demonstrated in laboratory tests without beam.

RF SYSTEM AND POWER EFFICIENCY

The design of the RF system was driven by considerations of capital cost, RF control, and power-coupler capability. Capital cost of the RF system dominates the capital cost of the accelerator system and favors larger RF sources. The power from the RF source can be split and distributed to cavities so that power-coupler capability will not be exceeded. However, RF controllability decreases with increasing number of power splitting. The resulted RF-system architecture (Fig. 3) is a compromise between capital cost and RF controllability. For the high-energy section, power from a 1-MW klystron is split among four cavities using three levels of power splitting. A 1-MW klystron is considered reasonable in terms of cost. The power splitting scheme will achieve the required cavity-field control specification of 5% and 3°, respectively, in amplitude and phase.

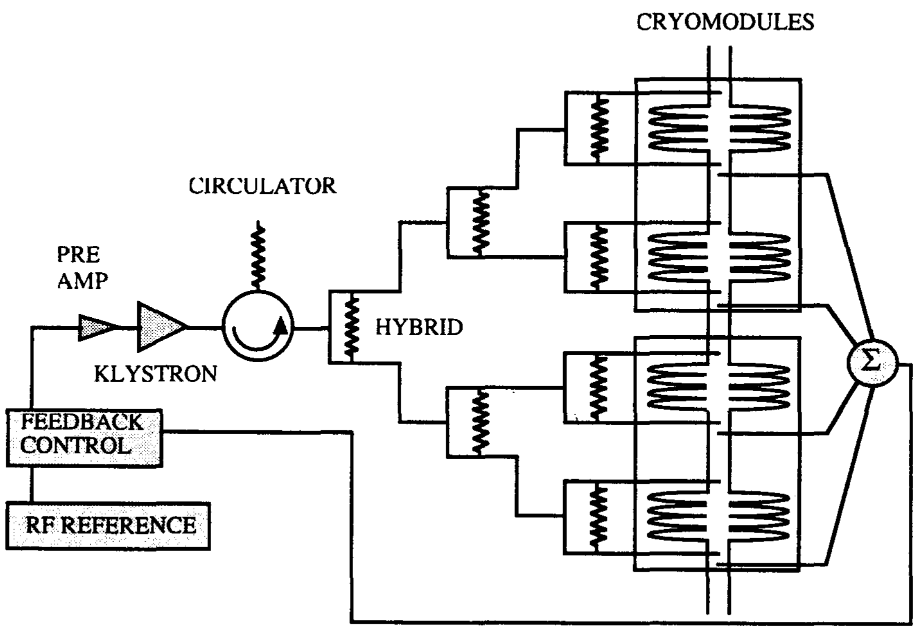

Fig. 3 Schematic of RF-system architecture

Efficiency and lower operating cost are the major advantages of an SC RF linac. In our system, the klystron has an efficiency of 58.5%. Every klystron will be used at its maximum design capacity and therefore, its best efficiency, by adjusting the cavity fields. Assuming a RF distribution loss of 5% and a control margin of 10%, the total RF power and DC power required are 127 MW and 201 MW, respectively. This can be compared to the requirement of 218 and 354 MW for an equivalent NC linac design [8]. The annual savings in operating cost due to the lower electricity consumption are estimated to be at least $20 M.

LOW BEAM LOSS

It is important to minimize beam loss so that hands-on maintenance will not be excluded by high activation of components. We minimize the beam loss in two ways. First, the aperture to rms beam-size ratio has been kept large in the linac. Large aperture radii of 5 and 7.5 cm have been chosen for the medium-energy and high-energy sections, respectively. The beam size has been kept small with strong quadrupole doublet focusing. Particle tracking simulations showed that the aperture to rms beam-size ratio is 19 at 100 MeV and increases to 26 at 1000 MeV. Second, the number of accelerating structure transitions that can lead to beam mismatches, and consequently beam halo, have been kept to a minimum. In the SC linac, the transverse match is maintained by keeping the transverse phase advance constant. The longitudinal match in each section is minimized by maintaining a constant real-estate gradient in each section. Transitions are only found at 100 MeV and 261 MeV. Simulations showed that matching through these transitions can be readily achieved by modifying the accelerating field gradients and quadrupole gradients about these locations.

HIGH AVAILABILITY

Applications require the accelerator to have a high availability (>90%) during scheduled operating time. Preliminary estimates show that this level of availability can be achieved by a combination of a conservative design, redundancy of components, and survival with single-point failures. By using conservative parameters for cavity field gradients and power-couplers, the fault occurrence will be minimized. With only two designs of cryomodules, we can extensively test the prototypes and have spare cryomodules ready to replace failed modules. We have also included redundancy in the refrigerator system by using three smaller units with storage of the liquid Helium. Simulations showed that the system can still operate with minor retuning when there are failures of either a cavity, a cryomodule, or a klystron. Repair can be delayed until scheduled maintenance periods. To further assure that the availability is achieved, we have designed the linac to produce 105 MW of beam power, instead of 100 MW, to compensate for any shortfall of availability.

LARGE VELOCITY ACCEPTANCE AND ITS ASSOCIATED ADVANTAGES

Particle tracking simulations have shown that our SC RF linac has very large velocity acceptance. It has large velocity acceptance because the number of cells is small and the cavities are independently phased. The independent phasing is achieved by adjusting the line lengths between the klystron and the cavities, and the frequency tuning of the cavities. This large velocity acceptance allows the SC linac to operate over a range of energy profiles, consequently adding to the availability and upgrade capability. This flexibility in energy profile is usually lacking in NC proton linacs in this energy range that are built with many cells in one structure. Because of the length of structure, NC proton linacs are designed for a specific energy profile. The energy profile in an NC linac is further restricted because of the high resistive loss when the field gradient is raised.

The flexibility of energy profile provides higher accelerator availability. It allows the SC RF linac to continue operation with failures of a cavity, a cryomodule, or a klystron. In the case that the injected current is reduced, the SC linac can maintain the same output beam power by raising the cavity field gradient and therefore, the output beam energy. The flexibility of energy profile also allows beam-power upgrade possibilities. If additional RF power can be provided, output beam power can be raised by increasing the cavity field gradients of the linac. Considering the upgrade capability of the cavity gradient and coupler, simulations show that a 33% increase in beam power is readily achievable with our design by using this method.

CONCLUSION

Our study shows that a conservative linac design is feasible using demonstrated SC technology. Compared to NC designs, an SC RF linac is very power efficient and therefore, presents significant savings in operating cost. Because of the choice of large apertures and minimum transitions, beam loss should be low. The linac is made up of only two types of cryomodules so that spares can be provided easily. The 4-cell cavities are short and independently phased with a large velocity acceptance. The accelerator system should have the required high availability, be easily upgradable, and flexible to operate.

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