CONCEPTUAL DESIGN OF A SUPERCONDUCTING HIGH-INTENSITY PROTON LINAC*

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Abstract

High-intensity continuous wave (cw) proton linacs have been proposed as neutron spallation sources for accelerator transmutation technology applications. These linacs have energies and currents around 1 GeV and 100 mA. Linac designs using room-temperature copper technology require significant microwave power and the cost of operation is high. Superconducting linacs, because of their insignificant wall losses, provide an attractive alternative. Recently, a superconducting design has been developed at Los Alamos National Laboratory (LANL). To make sure the high availability required by the application is satisfied, the design is based on demonstrated superconducting technology. The resulting design reduces power and operating cost, and offers high operational flexibility, high power upgradability, and low beam loss.

Although a superconducting linac offers many advantages for neutron spallation source applications, a proton superconducting linac has yet to be built. Unanswered design feasibility questions concern the multipacting characteristics of elliptical cavities with β (v/c) less than one and the effects of proton beam spill on the long-term superconducting characteristics of niobium. Both issues can be resolved by straightforward tests.

Introduction

High-intensity RF proton linacs have been proposed as neutron sources for research and accelerator-driven transmutation technologies [1]. High-intensity RF proton linacs are attractive alternatives to reactor as a neutron source because linacs can be operated very safely and do not produce high-level radioactive waste. Also, the beam-pulse format of a linac-driven neutron source allows additional flexibility in time-of-flight measurements, which is beneficial for research needs. Projects based on high-intensity proton linacs include the Accelerator Production of Tritium (APT) [2], the European Spallation Source [3], and Accelerator Transmutation of Waste [4]. Each design uses proton linacs with typical beam energy and current of 1 GeV and 100 mA, requiring hundreds of MW of power to operate. These linacs use copper structures operating at room-temperature. Although room-temperature structures have been successfully demonstrated, their cavity resistive power losses are significant, typically more than 25-MW.

Superconducting (SC) RF linacs can be an attractive alternative to room-temperature linacs because of their negligible cavity losses. SCRF linac technology has been under development since the early 1970s. SCRF cavities are now in use in various accelerator centers, including KEK, DESY, CERN, and CEBAF, (recently renamed the Thomas Jefferson National Accelerator Facility) . CEBAF is a notable demonstration of SCRF linac technology [5], with 334 cavities configured similarly to the proton linac needed for neutron source applications. Given the commitments made by LHC and TESLA [6] in SCRF technology, SCRF can be viewed as the future of accelerator technology.

Recently, studies have been completed on use of SCRF linacs to produce high-intensity proton beams [7] [8]. Results from these studies show that the SCRF linac is technically feasible for accelerating high-intensity proton beams. Besides greater power efficiency, the SCRF linac offers high availability and low beam loss, which are important performance requirements for linacs considered for neutron sources. During a recent APT study, an SCRF linac design was developed and its performance investigated [7]. Important technical issues and R&D efforts needed to provide additional information have been identified.

In this paper, the advantages and technical issues of using a high-intensity SCRF linac as the driver for a neutron source will be described using the APT SCRF linac design.

High-Intensity SCRF Linac Design

The APT SCRF linac [7] has been designed with demonstrated SCRF technology. It is intended to show what can be achieved without extensive R&D efforts. The design, therefore, is very conservative.

The baseline room-temperature APT linac design has a low-energy section and a high-energy section [2]. The low-energy section, which brings the beam to 100 MeV, includes an injector, a radiofrequency quadrupole (RFQ) linac, and a coupled-cavity drift-tube linac, and the high-energy section is a coupled cavity linac. In the SCRF design (Fig. 1), the high-energy section is replaced with a SCRF linac. The SCRF linac has two constant-β sections made up of identical cryomodules, where β is the relativistic factor equal to the ratio

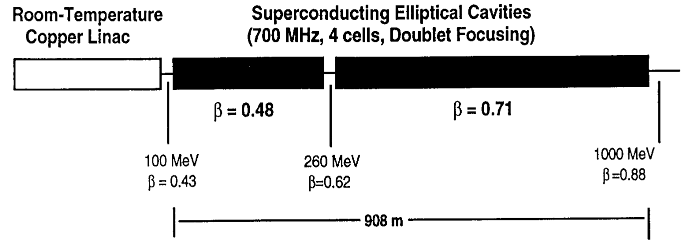

Fig. 1 Schematic layout of the APT SCRF linac

of the beam velocity and the speed of light. Figure 2 shows the two designs of these cryomodules. The cryomodules are separated by doublet quadrupole magnets that provide the transverse focusing. Table 1 summarizes the linac parameters.

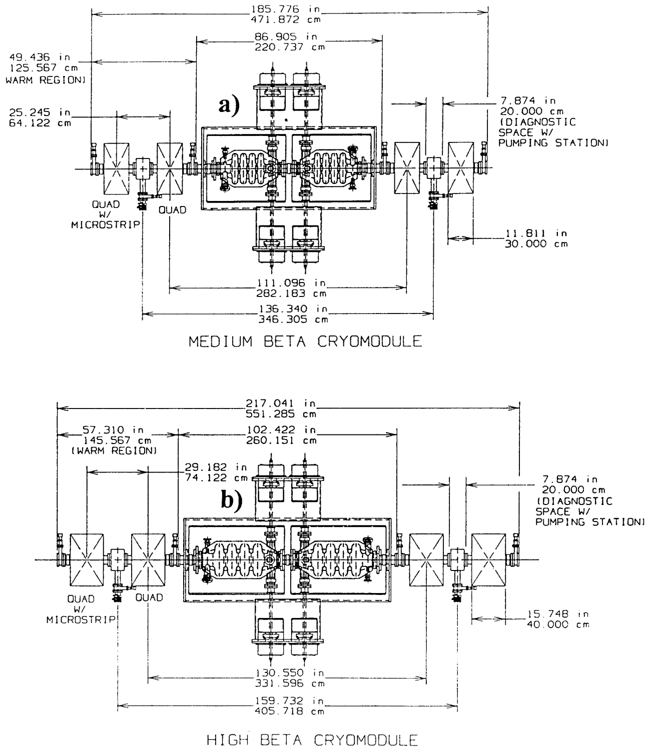

Fig. 2 Layout of a) medium-β section, b) high-β section.

Table 1
Superconducting linac parameters

Beam Current	100 mA
Energy of SC Sections	100 to 1000 MeV
Final Beam Power	100 MW
Cavities per RF Module	4
Cavities per cryostat	2
Cells per cavity	4
RF input couplers/ cavity	2
RF power/ coupler	72 kW and 105 kW
Accelerating gradient, E_0T	4.2 to 5.3 MV/m
Aperture radius	5.0 and 7.5 cm
Nominal operating temperature	2K
Cavity RF power loss (total)	3.17 kW
HOM power (total)	2.98 kW
Static heat leak	4.22 kW
Number of β sections	2
Number of cavities	488
Number of cryostats	244
Number of klystrons	122

RF power is a major design consideration because of the amount needed. Because they cost less per watt of power, larger size RF units are preferred. However, a larger RF unit means further levels of power splitting to reach the lower power level that a power coupler can handle. Too many levels of power splitting can cause difficulties in RF control. Considering the klystron size, the power handling capability of couplers, and RF control, the resultant APT design uses a 1-MW klystron to supply power to four cavities. Each cavity will use two 105-kW power couplers.

To minimize RF power splitting, a power coupler with the highest power carrying capability should be used. A survey of the power carrying capability of existing power couplers (Table 2) showed that a power level between 100 to 150 kW is achievable, consistent with the choice of 105 kW for the APT power coupler. Figure 3 shows a schematic of the power coupler design. A coaxial power coupler has been chosen because it has been used in most SCRF cavities. The coaxial power coupler consists of a 3-1/8" coaxial line with antenna-type termination. To minimize the multipacting caused by gas condensation, the coaxial power coupler is designed for baking. Multipacting limits were investigated by comparing data obtained by Kindermann for the CERN coupler [9] and with the recently-published scaling law [10]. The coupler uses warm windows located outside the cryomodules sufficiently far from the beam to minimize beam-induced window breakdown. The use of two windows provides redundancy for higher availability. The coupling coefficient will be adjustable over 10 dB using a copper-plated stainless steel hydroformed bellows in the outer conductor. The adjustability allows minimization of reflected power during operation.

Table 2
Demonstrated power coupler capability with beam

Facility	Frequency (MHz)	Capability (kW)	Current (mA)
CERN	352	60	2-4
KEK (TRISTAN)	508	80	13
DESY	500	100	70
CESR	500	155	110
KEK (AR)	500	168	500

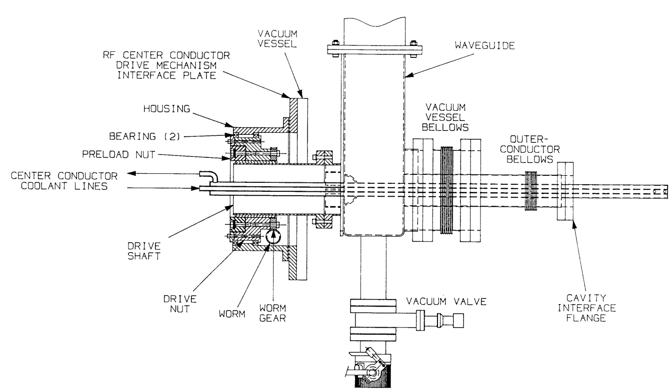

Fig. 3. Schematic of power coupler.

Figure 4 shows the RF system architecture. The power source is a 1-MW klystron at 700 MHz protected by a circulator. It supplies power to four cavities. Cavity field signals from these four cavities are summed and used in feedback control of the klystron. Beam dynamics show that the linac maintains good performance if the amplitude and the phase of the sum of the cavity fields are controlled, respectively, to 1% and 1°; and the fields of individual cavities controlled to 3% and 5°. This RF control specification is expected to be achievable, given experience at CERN and DESY.

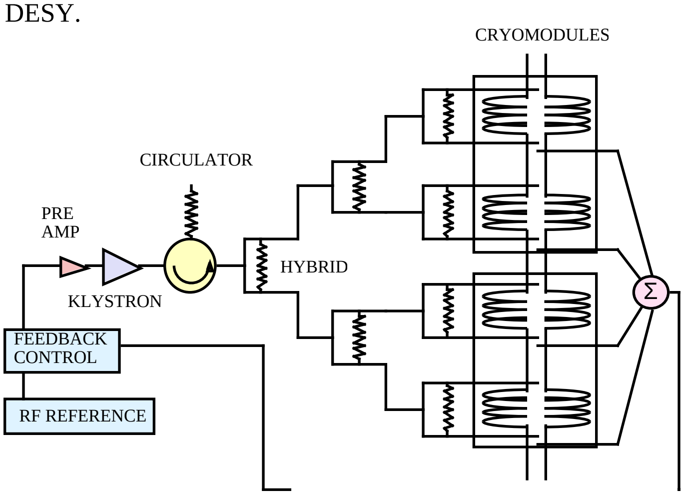

Fig. 4. RF system architecture.

An elliptical cell shape, commonly used in SCRF cavities, will be used here (Fig. 5). Because of the lower β, the cell is significantly shorter than the β=1 elliptical shapes in electron SC accelerators. Although one-point multipacting is not expected for elliptical shape cells, two-point multipacting, particularly for β=0.48, may exist due to shorter cell length. Shorter cell length may also reduce the mechanical rigidity of the cavity structure. Figure 6 shows the cavity design. The cavity will be operated at a gradient of 5 MV/m, corresponding to peak surface field of 16 MV/m. This gradient is well demonstrated in existing SCRF cavities with elliptical cells. At this gradient, field emission and thermal breakdown (quench) are not expected. The cavities will be operated at a temperature of 2-K to minimize cryogenic power and to provide better quench resistance. They will be fabricated with

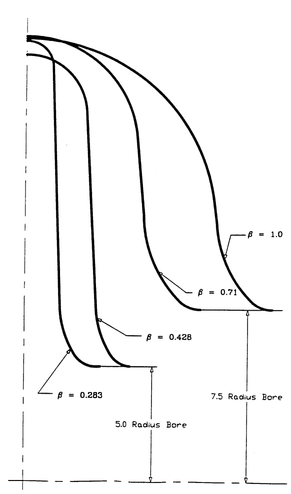

Fig. 5. Shapes of half cells for different β.

solid niobium with an RRR-value of 250. Fabrication and processing procedures will be similar to those used for the CEBAF cavities [11]. In addition, high-pressure rinsing will be used. Heat-treatment is not planned because it is not needed at this field gradient and can reduce the mechanical strength of the niobium.

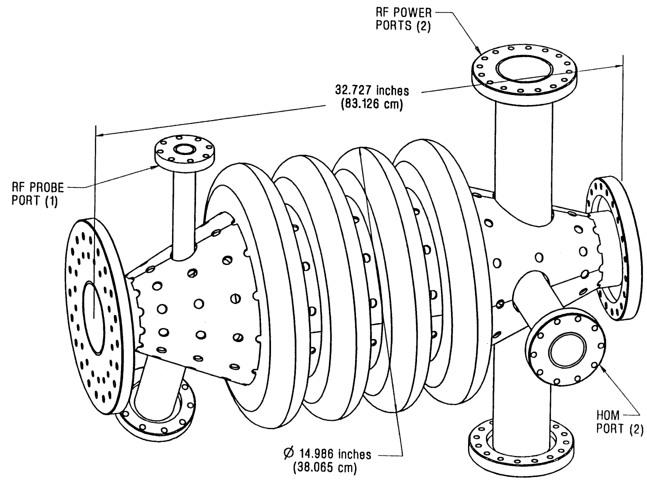

Fig. 6. Schematic of cavity design.

Figure 7 shows the cryomodule design. The cryomodule contains two cavities. Its design is based on the CERN LEP wrapup design [12]. Both a motor-driven tuner and magnetostrictive tuner are included in the design. The cryogenic system is based on the CEBAF cryogenic system, which has demonstrated availability of 97%. To satisfy a higher cooling requirement and to increase the availability of the cryogenic system, three CEBAF units will be used and a liquid helium storage facility will be provided.

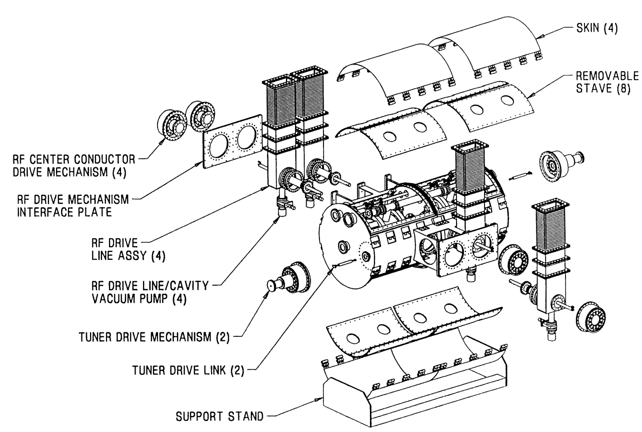

Fig. 7. Medium-β cryomodule.

Because of the power handling constraints of the power coupler, the SCRF cavities have only 4 cells. Their lengths are short compared to room-temperature structures, and have large velocity acceptance as a consequence. Figure 8 shows the transit time of cavities with different numbers of cells when the cavities are used for particle velocity (β) other than the design particle velocity (β_g). The transit time, which is a measure of the efficiency of acceleration, peaks when β is equal to β_g, and decreases when β is change from β_g. Cavities with fewer cells can accelerate efficiently for a wider range of β and have a large velocity acceptance. The efficiency reduction can easily be compensated with a slightly higher gradient. The large velocity acceptance offers availability and upgradability advantages that will be described in the following section.

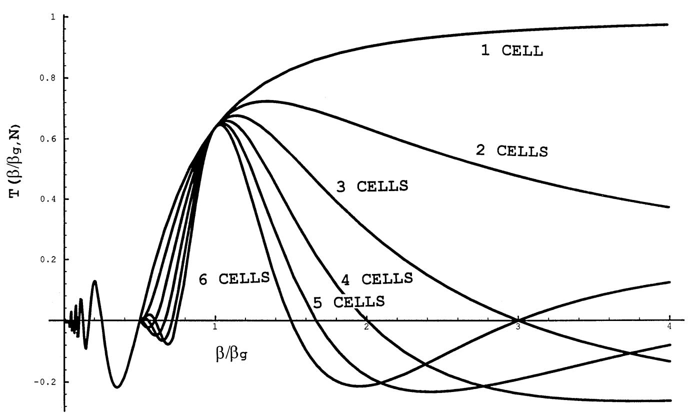

Fig. 8. Transit time factor versus β

Performance Advantages of a SCRF Linac

The performance requirements of a high-intensity proton linac used as a neutron source are the following: high availability over scheduled operation time; low beam loss allowing hands-on maintenance; high power efficiency for low operating cost; and upgradability to higher power level. The APT SCRF linac described here has advantages in satisfying all these performance requirements.

SCRF linacs can achieve high availability because the short cavities have large velocity acceptance. Only two cryomodule designs are needed for the whole high-energy section. The limited number of designs will reduce prototyping efforts and allow provision of ready-to-go spares. Beam dynamics also showed that, because of the large velocity acceptance, the linac is tolerant of single-point failures. The linac can continue to operate with single-point failures such as the loss of cavities, cryomodule, quad magnet and klystron. Operation experience at major SCRF accelerators shows that, as for room-temperature linacs, the RF system is the major source of unavailability. Because the SCRF linac requires 25% less RF power, it can be more reliable than a room-temperature linacs. Preliminary availability estimates of the APT SCRF linac indicate that the required availability is achievable. The present APT SCRF linac design produces 5% extra beam power to cover any unexpected availability shortfall.

SCRF linacs can achieve low beam loss because of their large beam aperture radius. The aperture radii are, respectively, 5 and 7.5 cm for the medium- and high-β sections. These radii are large compared to the typical aperture radius (<2.5 cm) used in the room-temperature structures. The beam size is minimized with strong quadrupole doublet focusing. The SCRF linac achieve ratio of aperture-to-rms beam size as large as 26. The large velocity acceptance of the SCRF linac also allows better tolerance to beam mismatch.

Depending on the design of the room-temperature linac, the required RF power and ac power for a SCRF linac is at least 25% less than for a room-temperature linac. The savings in operating cost will amount to $20 M per year for APT because of the reduced power usage.

Because of the large velocity acceptance in a SCRF linac, beam power can be upgraded by increasing the beam energy, in addition to by increasing the beam current. For the same linac, beam power can be increased by increasing the field gradient, the RF power, and the power coupler capability. The option to upgrade beam power by increasing beam energy is not possible for a room-temperature linac without lengthening the linac, generally requiring extensive facility modification.

Technical Issues

Although a cavity field gradient of 5 MV/m is conservative considering field emission and thermal breakdown limits, multipacting can limit achievement of such a field. Multipacting usually occurs at low field gradient. It depends on the secondary electron coefficient of the cavity surface and satisfaction of resonant conditions. Although multipacting has been eliminated in high-β (β~1) cavities by using elliptical cell shapes, the multipacting property of a medium-β cavity still needs demonstration. The lower-β cell shape is significantly shorter than the β=1 cell shapes (Fig. 5) and its multipacting property may be different. The APT project has designed experiments to investigate multipacting of single-cell lower-β cavities. This information will determine the starting energy of the SCRF linac.

The SCRF linac has been used mainly for electron acceleration. There are few data on the interaction of Nb with proton beam spill. Proton impingement on Nb may cause the Nb to be activated or to lose its superconducting properties. Excessive activation of Nb may prevent timely maintenance and extend the mean time of repairs, reducing facility availability. Proton impingement can cause defects and impurities in Nb and change the thermal and electrical conductivities of the Nb. These changes will be shown as a change of the RRR value of the Nb. It can also change the surface resistivity of the Nb cavities and consequently the Q-values of the cavities. Experiments have been designed to measure these radiation effects. First, experiments are being carried out to irradiate Nb samples with proton beam at Saturne and Brookhaven National Laboratory. The activation of Nb will be measured and compared to other structural materials such as stainless steel, copper, and aluminum. The change of RRR value will be measured as a function of proton fluence to find the change in the bulk thermal and electrical conductivities. Second, a 3-GHz single-cell cavity will be irradiated at cryogenic temperature at LANSCE, Los Alamos

National Laboratory. The changes in the Q-value of the cavity will be measured as a function of proton fluence. The possibility of Q-value recovery by warming to room temperature will also be investigated. The results of this experiment will help in specifying the additional capacity of cryogenic power required to compensate for a decrease in Q-value. A similar experiment has been completed at Saturne recently, although the irradiation was done at room-temperature. There has been no observed decrease of Q-value.

As discussed earlier, power coupler capability is important design information for determining RF architecture. Power coupler design will be developed and tested at a test stand under different operation conditions. The information obtained will be used to optimize linac layout and cost.

Summary

A SCRF design has been developed for a high-intensity proton linac which will be used as the driver for neutron sources. This design is conservative, using current SCRF technologies. As well as lowering operating cost, the design offers performance advantages in availability, beam loss, and upgradability, which are important for the application as a neutron source.

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