LA-UR-02-6684
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Title: **Reliable-Linac Design for Accelerator-Driven Subcritical Reactor Systems**

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Reliable-Linac Design for Accelerator-Driven Subcritical Reactor Systems

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Abstract

Accelerator reliability corresponding to a very low frequency of beam interrupts is an important new accelerator requirement for accelerator-driven subcritical reactor systems. In this paper we review typical accelerator-reliability requirements and discuss possible methods for meeting these goals with superconducting proton-linac technology.

Introduction

High-power proton linacs in the megawatt beam-power range are considered an attractive choice for many applications requiring high average beam power. Applications of proton and deuteron linacs include accelerator-driven subcritical reactors for nuclear-waste transmutation, neutrino factories, fusion-materials studies, and injectors for spallation-neutron sources. Table I presents a survey of high-power linac projects, both proposed and already under construction. Also included are the parameters for the existing 800-MeV LANSCE proton linac, which has operated for almost 30 years.

Table I. High Power Linac Survey (H^+, H^-, D^+).

<table>
<tr><th>Name</th><th>Ion</th><th>Pulse length (msec)</th><th>Rep rate (Hz)</th><th>Duty factor (%)</th><th>I_{bunch} (mA)</th><th>$I_{Average}$ (mA)</th><th>Energy (GeV)</th><th>$P_{Average}$ (MW)</th><th>Start date</th></tr>
<tr><td>LANSCE</td><td>H^+/H^-</td><td>0.625</td><td>100/20</td><td>6.2/1.2</td><td>16/9.1</td><td>1.0/0.1</td><td>0.8</td><td>0.8/0.08</td><td>ON</td></tr>
<tr><td>SNS</td><td>H^-</td><td>1.0</td><td>60</td><td>6.0</td><td>38</td><td>1.4</td><td>1.0</td><td>1.4</td><td>2006</td></tr>
<tr><td>CERN SPL</td><td>H^-</td><td>2.8</td><td>50</td><td>14.0</td><td>22</td><td>1.8</td><td>2.2</td><td>4.0</td><td>?</td></tr>
<tr><td>ESS Short Pulse</td><td>H^-</td><td>1.2</td><td>50</td><td>6.0</td><td>114</td><td rowspan="2">3.75</td><td rowspan="2">1.33</td><td rowspan="2">5+5</td><td rowspan="2">2010</td></tr>
<tr><td>ESS Long Pulse</td><td>H^- or H^+</td><td>2/2.5</td><td>16.67</td><td>4.2</td><td>114/90</td></tr>
<tr><td>FNAL 8 GeV</td><td>$H^+/H^-/e^-$</td><td>1.0</td><td>10</td><td>1.0</td><td>25</td><td>0.25</td><td>8.0</td><td>2.0</td><td>?</td></tr>
<tr><td>KEK/JAERI 400 MeV</td><td rowspan="2">H^-</td><td rowspan="2">0.5</td><td>50/25</td><td>2.5</td><td rowspan="2">50</td><td>0.7</td><td>0.4</td><td>0.28/0.14</td><td>2006</td></tr>
<tr><td>KEK/JAERI 600 MeV</td><td>25</td><td>1.25</td><td>0.35</td><td>0.6</td><td>0.21</td><td>?</td></tr>
<tr><td>TRASCO</td><td>H^+</td><td>CW</td><td>CW</td><td>100</td><td>30</td><td>30</td><td>>1.0</td><td>>30</td><td>?</td></tr>
<tr><td>IFMIF</td><td>D^+</td><td>CW</td><td>CW</td><td>100</td><td>2X125</td><td>2X125</td><td>0.040</td><td>10.0</td><td>2010</td></tr>
<tr><td>KOMAC(KAERI)</td><td>H^+/H^-</td><td>CW</td><td>CW</td><td>100</td><td>20</td><td>20</td><td>0.1(1.0)</td><td>2.0(20)</td><td>2011(?)</td></tr>
<tr><td>ATW</td><td>H^+</td><td>CW</td><td>CW</td><td>100</td><td>45</td><td>45</td><td>1.0</td><td>45</td><td>?</td></tr>
</table>

A historically important high-power proton-linac project (not listed in Table I) is the Accelerator Production of Tritium (APT) project, which took place during the decade of the 1990s. Figure 1 shows a block diagram of the APT linac design [1, 2, 3, 4]. Although the project was cancelled (identified as the backup technology to nuclear-reactor production of tritium in 1998), it established a new technology base for high-current CW proton-linacs. The accelerator used superconducting RF cavities at energies above ~200 MeV with transverse focusing provided by normal-conducting quadrupole doublets between cryomodules. The CW Low-Energy Demonstration Accelerator (LEDA) facility [5] demonstrated the critical low-velocity part of the APT linac, including the DC injector and radiofrequency quadrupole (RFQ) technology at a 100-mA beam current, and a 0.67 MW beam power. High beam availability (90%) was an important feature of the APT design.

Superconducting elliptical cavities similar to those used in relativistic electron accelerators, but compressed longitudinally as required for the lower proton velocities, were designed and built for the APT high-velocity region, $\beta>0.5$ (see Fig.2). These cavities have been successfully tested, providing at 10 MV/m twice the design value of the accelerating gradient [6]. More recently, superconducting spoke cavities (see Fig.3) are being designed and built to operate in the lower velocity range, $0.1<\beta<0.5$ [7]. This latter development allows the use of RF superconducting linac technology for proton kinetic energies above about 5 MeV, which constitutes the majority of the linac for most high-power proton linacs.

During the past decade, worldwide technology developments have made the use of superconducting RF technology more attractive for high-power proton linacs. Advantages of superconducting linacs include lower operating costs, larger affordable bore radius (relaxing alignment, steering, and matching tolerances; reducing beam/loss and radioactivation; easing commissioning, and improving availability), installed redundancy (the linac can continue to operate even if an accelerating module fails), and worldwide industrial capability for fabrication of niobium superconducting cavities and cryomodules. Dramatic progress has occurred in several critical technical areas during the past decade, including higher accelerating gradients, higher power input-power couplers, and operating experience with pulsed electron beams (at the TESLA Test Facility). Furthermore, the performance of superconducting cavities is still improving. During the past 5 years all new high-power proton-linac projects have included superconducting sections. The Spallation Neutron Source (SNS) [8] is scheduled in 2006 to become the first superconducting proton linac.

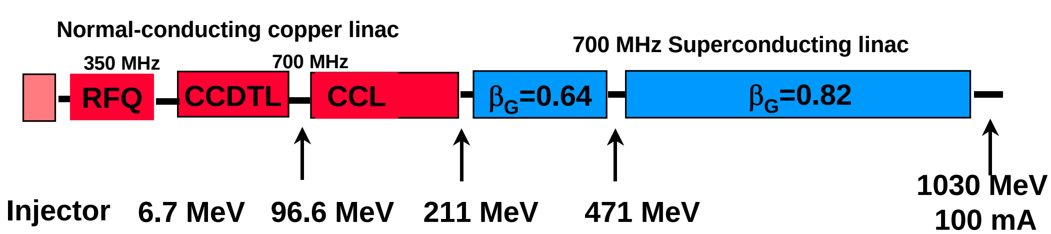

Fig. 1. Block diagram of the APT linac design.

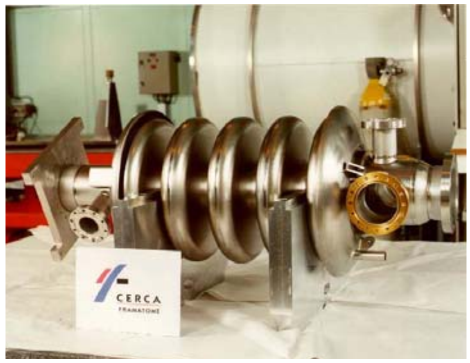

Fig. 2. One of four 5-cell 700-MHz β=0.64 niobium elliptical accelerating cavities built for LANL by CERCA.

Fig. 3. New β=0.175 2-gap 350-MHz niobium spoke accelerating cavity built for LANL by ZANON. The cavity is shown with its end plates removed.

Accelerator Requirements for ATW systems

The beam requirements for an accelerator-driven subcritical reactor system, such as an accelerator transmutation of nuclear waste (ATW) facility [9], vary for different projects. Typical ranges of values are listed in Table II. The last two entries in Table II include approximate requirements for beam reliability (beam continuity) assuming for simplicity that the facility has beam scheduled for 100% of the time. The requirements for the frequency of beam interrupts are specified over two different time durations. These two time durations correspond to different constraints on ATW subcritical systems that deliver power to the grid [9]. First, beam interrupts of duration greater than about a second must be limited, to mitigate the integrated effects of thermal transients in the transmuter (subcritical reactor assembly) that shorten the transmuter lifetime. Second, beam interrupts of duration greater than ~10 minutes must also be limited to avoid long interruptions of power delivered to the power grid. In particular, interrupts of duration greater than ~10 minutes may require even longer (up to several days) transmuter restarts. Fortunately, the transmuter performance is unaffected by interrupts of duration less than about one second, which constitute the majority of accelerator interrupts. The beam-interrupt requirements in Table II must be considered as estimates, since these requirements are not precisely known at this time.

Table II. Beam Requirements for an ATW

PARAMETER	REQUIREMENT
Energy (GeV)	0.6 – 1.5
Current (mA)	10 - 100
Beam Power (MW)	10 - 100
Linac Beam Loss (W/m)	< 1 W/m required and < 0.1 W/m goal
Beam Interrupts > ~1 s	<100/year≈0.01/hr
Beam Interrupts > ~10 min	<2/year≈0.0002/hr

The actual interrupt spectrum for a modern proton linac like APT is expected to have characteristics similar to that shown in Fig. 4. We note that the two beam interrupt requirements (for 1 sec to 10 min, and >10 min) in Table II lie considerably below, at least an order of magnitude below, the estimated performance levels shown in Fig.4. It should be emphasized that specification of beam-interrupt frequency requirements for accelerator operation has never been done before. Instead, beam availability (ratio of total beam delivery time to scheduled beam delivery time) has been the usual criterion. Modern accelerators can and do achieve high availability; the LANSCE facility achieves about 90% beam availability. But, an order of magnitude or more reduction in the frequency of beam interrupts to meet the ATW specifications would be a challenging new accelerator requirement.

Beam interrupts originate from many subsystems that comprise the overall accelerator system. Achieving a large reduction in the beam-interrupt frequency will probably require some major changes in design and operating philosophy. One idea is to adopt a new design and operating approach with respect to long-duration faults, which is to ride through the faults, rather than the present approach, which is to shut down the beam after each fault [10]. We believe that riding through faults would be most effectively implemented in a superconducting linac. What would be required for a superconducting linac is to leave the beam on after loss of an individual accelerating module. In this context, an accelerating module is defined as a subsystem including one or more superconducting cavities and the RF system that drives them. Based on experience, a failure is more often from some component in the RF system that supplies RF energy to the cavities, rather than the accelerating cavities.

The superconducting linac has several important features that may allow continued operation after a fault. First, the superconducting cavities typically have larger apertures, made economically affordable by the large, orders-of-magnitude reduction in RF power losses. The larger apertures provide extra margin against beam loss, even after faults that may have occurred in upstream beamline elements. Second, short superconducting cavities have a relatively small energy gain, so that loss of an accelerating module has a relatively small effect on the beam energy. The beam-energy reduction associated with loss of a module can be corrected by resetting the parameters of the downstream cavities, provided enough margin is available in the design. To provide this margin, one can install a few percent extra accelerating modules to allow compensation for loss of some modules during operation. After a fault, the downstream cavity parameters can be reset to restore the final energy. In addition, this compensation procedure can be expected to reduce the risk of beam losses that may result from the nonideal conditions caused by the fault. At the end of the run cycle, if not sooner depending on the situation, appropriate repairs would be made to the failed systems without having to shut off the beam. Although there is no obvious reason that this approach could not be made to work, nevertheless, there will be some faults, perhaps including some water, power, or beamline vacuum-system failures, for which shutting off the beam will probably be unavoidable.

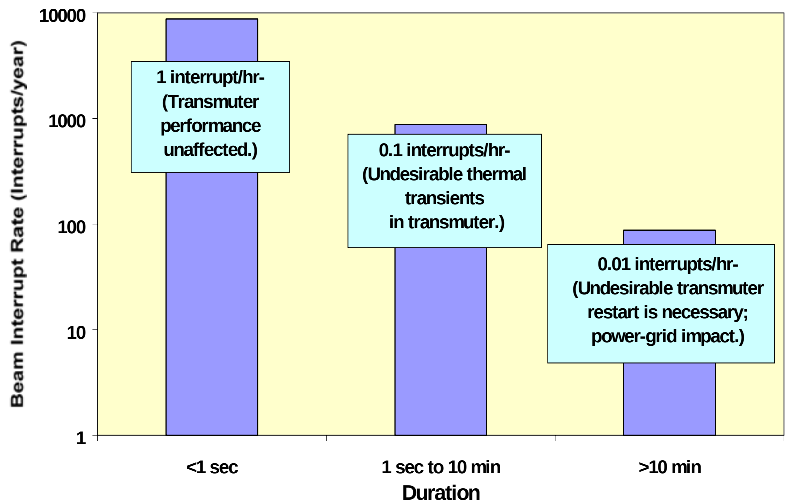

Fig. 4. Anticipated interrupt frequency spectrum for a proton linac like APT or ATW, integrated over three time durations relevant to an ATW system. The impact of the interrupts over each time scale is also described. Beam interrupt requirements must be limited only for interrupts with duration greater than about one second.

To be more specific, let us consider how we might respond to four common faults in a superconducting linac. First, consider that during normal operation the detection by installed diagnostics of an incipient RF window problem in the RF drive line between the RF generator and an accelerating cavity. For example, the computer-control system might detect arcing, temperature increase, or vacuum problems. In the conventional operating mode, the machine operators would shut off the beam, and immediately initiate repairs or replacement of components, in this case the widow. This approach could result in a long downtime. The new approach would be to continue beam delivery, detune the cavity to prevent the beam-excited cavity fields from further damaging the window, activate a waveguide switch to isolate the RF window from the RF generator, and then reset the parameters of the downstream cavities to restore the correct final energy. The capability of doing all this very rapidly (<1 msec) to reduce the risk of beam losses during the transient period after detection of the fault would be ideal. But, if the beam apertures are large enough, beam losses that occur before the downstream cavities are retuned might be small, and such a rapid compensation response may not always be necessary.

Second, consider an RF system failure, such as that involving a fault in an RF generator or a circulator. The new approach, similar to that above, would be to continue beam delivery, turn off the RF generator, detune the cavities in that module, and reset the downstream-cavity parameters.

Third, consider a focusing-magnet failure. Other than the potential for infant mortality of a magnet during initial operations, this should be a very rare event. With only a single such failure, the large apertures of the superconducting cavities and solenoid magnets should allow us to continue beam delivery with no other immediate corrective action required. Likewise, a superconducting solenoid-magnet power-supply failure would be irrelevant, if the superconducting magnets operate in persistent mode.

In addition to a new operating philosophy, we would also anticipate a design philosophy with an increased emphasis on high reliability. It would be important for fault reduction to design all systems using more conservative voltages and power levels. Finally, it would be essential to anticipate an active, continuous-improvement program after commissioning, to make high reliability the primary goal for long-term operation.

ATW Design Example

A 1-GeV CW superconducting linac-design concept for an ATW system is shown in Fig. 5 [11, 12]. The 45-mA proton beam is bunched and accelerated to 6.7 MeV by the normal-conducting LEDA RFQ. This is followed by three sections of 350-MHz superconducting spoke resonators corresponding to geometric-β values equal to 0.175, 0.20, and 0.34. The beam energy at the end of the spoke-resonator section is 130 MeV. This is followed by three sections of 700-MHz superconducting 6-cell elliptical cavities corresponding to geometric-β values of 0.50, 0.64, and 0.82. Superconducting solenoid magnets installed in the same cryostats as the superconducting cavities are used for transverse focusing. The design requires maximum accelerating gradients of less than 7.2 MV/m, and a maximum input power-coupler capacity of 250 kW. The design concept uses 220 RF generators, 328 superconducting cavities, and 82 cryomodules. The total length of the linac is 513 m. The estimated power requirements are 96-MW ac-power for the RF system, and 11-MW ac power for the cryogenic refrigerator. The arrangement of cryomodules and accelerating modules is shown in Figs. 6 and 7 for the spoke cavities and the elliptical cavities, respectively. The design specifies one cavity per accelerating module for the spoke cavities and two cavities per accelerating module for the elliptical cavities. These choices are made, anticipating that they will allow continued beam delivery after loss of any accelerating module.

An initial beam-dynamics simulation study [12] with 10,000 macroparticles shows good performance with substantial margin for avoiding beam losses that could cause radioactivation in the accelerator. Fig. 7 shows, as a function of energy, the rms and maximum beam sizes in the simulation together with the aperture radius. The large space between the aperture and the maximum beam size indicates a large margin for beam transport with minimal beam losses, which is ideal for an accelerator design that has good fault tolerance. More study is required for a quantitative assessment of the ability to maintain beam continuity when faults are present.

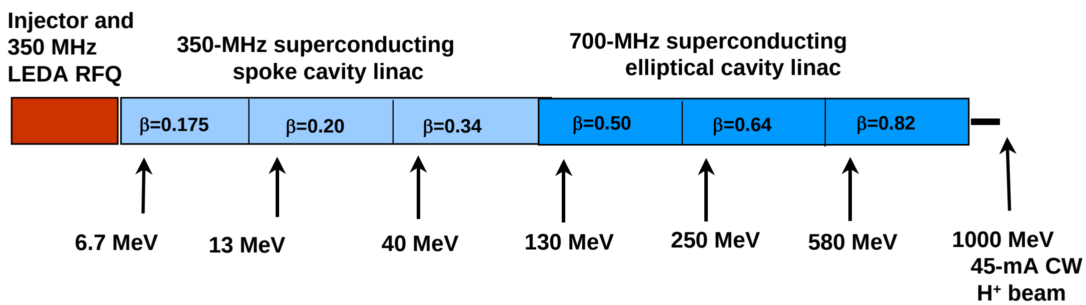

Fig. 5. ATW superconducting linac design concept.

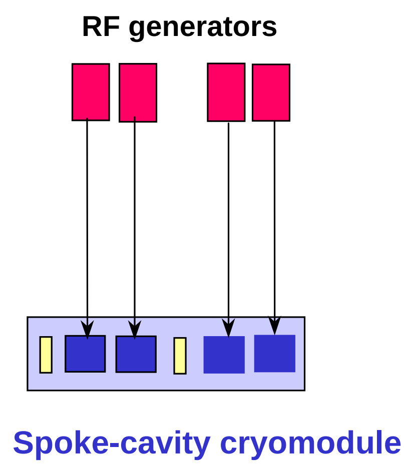

Fig. 6. Block diagram of four spoke-cavity accelerating modules with cavities in one cryostat.

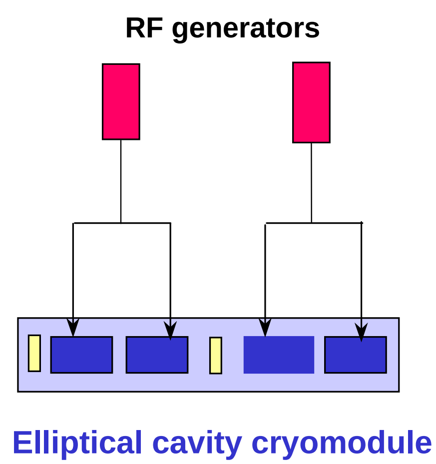

Fig. 7. Block diagram of two elliptical-cavity accelerating modules with cavities in one cryostat.

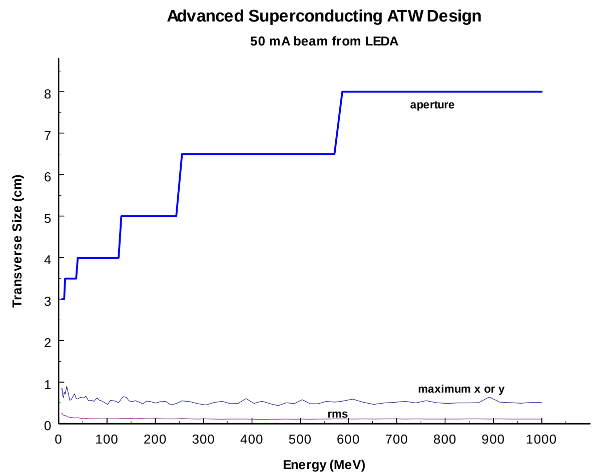

Fig. 8. Beam size (rms and maximum) from multiparticle simulations and aperture radius plotted versus energy for the ATW superconducting linac design concept. (See Ref. [12]).

Necessity for System Optimization

Because of the challenging requirements for accelerator reliability, an overall system optimization should be carried out, including both the accelerator and the transmuter. The question is whether the beam-continuity requirements described in Table II for the accelerator can be relaxed by different transmuter-design choices. To carry out such an optimization, there is information that the transmuter designers need from the accelerator designers, particularly the spectrum of beam interrupts (frequency and duration) that can be expected. Likewise, there is information that the accelerator designers need from the transmuter designers. This includes an acceptable spectrum of beam interrupts for the different transmuter technologies, as well as the important question of what kind of accelerator maintenance schedule is compatible with transmuter operations.

Conclusions

There are many new proton-linac projects proposed for high-power applications. All specify high reliability and low-beam losses as requirements. The recent trend has been to use RF superconducting technology, because of the advantages of lower operating costs, larger affordable bore radius to minimize beam losses, and an installed redundancy so the linac can continue to operate even if an accelerating module fails. The applications for accelerators as drivers for subcritical reactors are particularly challenging because of the stringent requirements on beam continuity. We believe that superconducting linac concepts using short, large-aperture cavities, such as the ATW example presented in this paper, provide the best approach for improving accelerator reliability through a reduction of the frequency of beam interrupts. There can be no doubt that an R&D program will be needed to address these new reliability requirements. In addition, accelerator-driven reactor projects, such as ATW, will need an overall system optimization that includes an exploration of transmuter design options that might relax the accelerator reliability requirements.

Acknowledgments

The author acknowledges helpful discussions with R. Garnett, G. Lawrence, D. Rees, D. Schrage, and R. Sheffield.

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