DISCUSSION OF SUPERCONDUCTING AND ROOM-TEMPERATURE HIGH-INTENSITY ION LINACS

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ABSTRACT

The point of view taken in this discussion is that the basic technology base exists in all essential respects for both superconducting or room-temperature rf linac accelerators and associated power and control systems, and thus a project can make a choice between these technologies on overall system considerations. These include performance, cost, availability, flexibility, and upgradability. Large high-intensity neutron source proposals involving light-ion rf linacs in three categories are reviewed in this context. The categories are cw linacs to high (~1 GeV) and low (~40 MeV) output energy, and pulsed linacs to energy ~1 GeV.

1 BACKGROUND

High-intensity (order 100 mA or greater, and duty-factor of order 10% to fully cw) ion linear accelerators are presently being proposed for a number of applications, all oriented to intense neutron sources. Including are machines for physics research, materials research and development, and the production of special materials. Accelerator-driven transmutation technology (ADTT) is being studied to transmute radioactive waste, produce electricity without a long-term waste legacy (including the use of the thorium fuel cycle), and convert excess plutonium.

1.1 Room-temperature (RT) linac structures

There exists one operating large high-intensity linac – the 1 mA average proton current, 800 MeV linac at Los Alamos, which began operation in 1972. This machine is pulsed, with a duty-factor of 6-12%, and uses room-temperature accelerating structures; an Alvarez drift-tube from 0.75-100 MeV, and the side-coupled structure from 100-800 MeV. As is typical of many accelerators, the structures have been very reliable, as has the facility overall. The main availability loss is from the rf system.

A number of other pulsed, low-duty-factor linacs with room-temperature structures have accelerated peak proton currents of 100 mA or more. The Fusion Materials Irradiation Test (FMIT) prototype room-temperature, cw deuteron RFQ (designed for 100 mA) operated at 50 mA cw, 0.075-2 MeV. H- linacs with RT structures were designed for the Strategic Defense Initiative and low energy prototypes produced pulsed, low-duty factor 100 mA beams of high-brightness.

Extrapolation of the Los Alamos accelerator to the 100 mA, cw class mainly involves engineering to handle the heat load at full cw operation (the required increase of a factor of 4-5 in the number of particles accelerated per bunch has been demonstrated). This engineering has also already been demonstrated for the side-coupled structure in cw applications of electron beams, for example in a microtron developed at Los Alamos, and in research accelerators at CRNL. Engineering for a cw drift-tube linac is also relatively straight-forward, although operating units have not been built and tested. The room-temperature drift-tube and side-coupled linac structures are considered as the conservative reference approach to meeting the requirements of the factory-type applications outlined above.

1.2 Superconducting (SC) linac structures

Superconducting accelerator technology has been studied extensively for nearly three decades. Customer requirements, as always, provided the impetus. As electron accelerators pushed toward ever higher energies, efficient structures in terms of high accelerating gradient and rf power were paramount. High-energy machines are now using SC rf cavities routinely; KEK (32 cavities), DESY (16 cavities), and CERN (28 cavities are the major ones. These machines did much of the pioneering development of SC cavities to high reliability, operating systems.

CEBAF, a high-intensity, medium energy electron machine, made the major commitment to use SC cavities in this parameter regime. At the time, this was a bold step, with a requirement for high availability from a machine that would have 338 cavities and operate at 2° K using a refrigeration plant of unprecedented size. The SC systems at CEBAF have been a major success, with very good availability.

Two future high-energy physics machines have committed to SC rf cavity technology. The LHC will accelerate intense hadron beams, and the TESLA/TTF will accelerate intense electron beams, both at low beam duty factors.

Heavy-ion accelerators were required to have great flexibility to be able to accelerate many different kinds of ions with different charge to mass ratios. Independently-phased short accelerating structures are used to achieve this specification, with a separate rf power amplifier for each structure. The ATLAS machine at ANL was a pioneer in this field, and there are now a number of heavy-ion post-tandem accelerators in routine operation, again with high overall availability.

2 SC RF SYSTEM STATE-OF-THE-ART

This now very considerable *operating* experience base, supplemented by an even larger R&D base around the world, for complete SC rf systems, brings the discussion of the choice of accelerating structure technology to a focus that is the theme and main conclusion of this paper:

The age of adventure (high risk) in SC linacs is over. The technical base is in place, and systems have proved high availability in practice. Therefore, projects can decide to use RT or SC technology on the basis of their performance, cost, availability, flexibility and upgradability requirements.

This position is synthesized from a number of strong statements [1-3] from operators of SC systems, customers for future projects, and review committees. For example, CEBAF has stated that if an accelerator is the right approach for a project, then a superconducting accelerator will be superior because of lower power cost, lower maintenance, higher availability and lower activation. It has been stated that "the technical and design base is in place in the USA", and "no R&D is required - engineer to success based on demonstrated technology".

It is therefore perhaps of interest to review current high-intensity ion linac projects from the customer point-of-view. Here it is assumed that the technical details are in hand or will be solved by extrapolation of existing technique, so detailed technical explanation is unnecessary except as required to assess the risk level of the extrapolation. More important are the impact of the technology choice on the issues important to the customer - performance, cost, availability, flexibility, upgrade path, and so on.

3 LARGE CW NEUTRON SOURCE PROPOSALS

3.1 Long, high-energy linacs

Accelerators proposed for Accelerator Production of Tritium (APT) and for the various ADTT applications require cw proton currents of tens to a few hundreds of mA, at an output energy of nominally 1 GeV. Low beam loss along the accelerator, nominally less than 1 nA/m/GeV, is required so "hands-on" maintenance can be performed without remote manipulators. Accelerator system availability during scheduled operating time is required to be very high, of order 90%.

Both RT and SC designs are being developed in detail for comparison. The basic SC linac for the APT project is shown in Fig. 1.

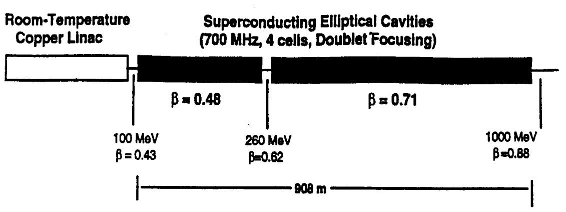

Fig 1 APT SC linac reference configuration. [Courtesy K.C.D. Chan]

The amount of rf power that can be provided to an SC accelerating cavity is limited by sparking, heat load, multipactoring and other technical limits of the input power coupling mechanism, typically a coaxial, electric probe coupler or a waveguide coupler. R&D power limits at present are approaching several hundred kW, but conservative design based on present operational practice places the APT design at 125 kW. The number of cells in each independently-phased cavity is then fixed, here at 4 cells per cavity.

Such short cavities have a very large velocity acceptance, yielding a number of important advantages over typical RT structures that have many cells. Only two different cavity geometries, with design $\beta = 0.48$ and 0.71, are needed for the entire APT SC linac from 0.1-1.0 GeV. Dropout of cavities during operation can be tolerated (with caveats discussed below) by rephasing and power level changes in adjacent cavities. Also, perhaps of relevance to customers where beam power is the most important requirement, SC linacs can more easily be upgraded to higher energy and current as the performance of rf amplifiers, couplers and windows is improved. This is indicated in Fig 2.

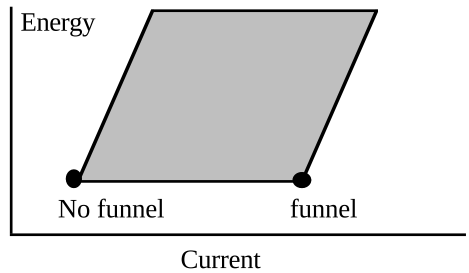

Fig. 2 RT linac performance space is limited to the two dots; if the high-energy portion is properly designed, addition of a funneled low-energy portion could double the beam current and power. The ability of short, independently-phased SC cavities to handle a range of rf power input opens the SC parameter space to the gray area. [From B. Rusnak]

The rf amplifier system arrangement, or architecture, for the SC linac is a key design area. While individual small amplifiers at the level required by one power coupler, or with only one power split to two couplers (total of order 250 kW), the maximum flexibility of the short independently-phased sections is obtained. This would require a large number of amplifiers (at 1 GeV, 100 mA, 400 amplifiers at 250 kW)

Two major system considerations bear on this approach. The most serious is cost. Under a conventional costing approach, rf amplifier cost/watt is thought to scale inversely as the square root of unit size, so a 1 MW unit would have half the cost/watt of a 250 kW unit. This is a large factor and forces selection of large rf units. The other main consideration is the impact on availability of many small amplifiers vs. fewer large ones. The rf system architecture of most of the long high-energy cw linac projects is illustrated in Fig. 3, where the main amplifier output is split 2^n ways, in this case eight.

The multiple split at high power has the system advantages noted, but a serious gap exists presently in most projects on the analysis of the required rf field tolerances in each cavity and for the group of cavities powered by a single amplifier, and the effect and control of all of the various errors and operating conditions that the system will be subject to. The tolerances are related to the synchrotron oscillation wavelength; typically, the short cavities will have a loose individual tolerance, while the tolerance for the group powered by one amplifier tightens as more cavities are added. The author is presently building a set of detailed simulation programs that can investigate the detailed design and suitability of rf system layouts.

If a module of cavities driven by one amplifier is short enough (again related to the synchrotron wavelength), failure of a module can be compensated in principle by readjustment of adjacent modules. The APT design

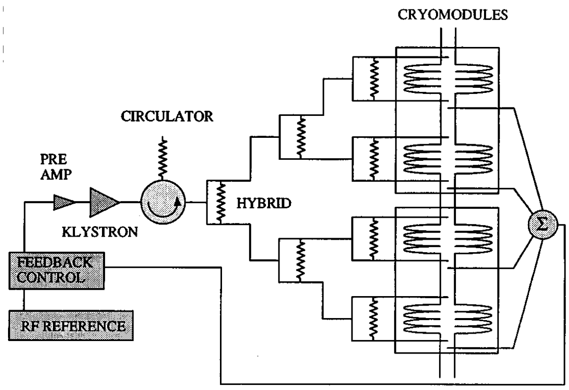

Fig. 3 APT SC RF system architecture. [Courtesy K.C.D. Chan]

includes an additional 5% capacity for this. Availability data from CEBAF and HERA show that the SC components have never been the major cause of unavailability, but rather the rf system components. Again, considerable further analysis is needed to carefully evaluate the readjustment scheme to be sure it is adequate from the beam quality and low beam loss point of view. This is also a goal of the simulation programs under construction.

A major advantage of SC structures is that structure rf power losses are so low that optimization in this respect is not necessary, whereas it is paramount in RT systems. Thus in principle the structure aperture may be larger in an SC system at the same frequency, affording a larger stay-clear factor to help minimize beam loss. Again, considerable work is necessary to better understand in general and in detail how to design linacs for low beam loss.

An area of some uncertainty for the SC approach for high-intensity light ion linacs is the effects that might occur from residual beam loss along the linac, in two areas, both having to do with specific interactions of protons or deuterons with niobium, from which the SC accelerating structures are constructed. The first concerns activation and whether the SC properties would eventually be affected, and the second concerns whether other beam-induced effects might result in conductivity changes of the SC surfaces. Limited tests with beam in actual cavities at SPS and the Los Alamos linac showed no adverse effect. A study [4] of possible radiation effects on niobium found two sets of data, one for niobium-tin which shows early degradation, and another for niobium-titanium which shows almost none. From this, it is concluded that pure niobium should not degrade significantly. Small/thin sample activation and RRR measurements with a proton beam will be made at SATURNE during summer 1996, and single-cavity Q measurements at LANSCE during fall 1996. It is felt that the SC structures will be suitable for intense light-ions, but operating experience over a suitably long period is needed.

The process by which the SC linac has come to be the preferred approach for APT indicates important aspects of the state-of-the-art of SC technology. The choice was made by the customer in an independent review assessment of technical maturity and applicability. There is an important view that SC is a strongly emerging technology that is ultimately the technology of choice for intense light ions, just as it is already the technology of choice for electrons and heavy-ions, and that detailed problems can be worked out. The basic direction was decided at this level. Present more detailed comparison studies have used the following successful approach. First, an ultraconservative RF linac with no optimization was laid out to a point design conceptual level of detail. Second, a point design of an SC linac was done, with similar parameters as the RT linac for easy comparison and with no optimization. The choice between RT and SC technology is made on this basis. This procedure is biased against SC, discussed further below, but in the case of the long cw linac, the cost advantage of SC is large. Optimization then follows, that might include considerable changes in the SC parameters.

The bottom line for the long high-energy cw linac case is a fairly clear and compelling case. The SC approach should result in a saving of ~30% in operating cost, and perhaps some saving in capital cost also, compared to the RT approach. Operational advantages are also seen, in lower beam loss, dimensional stability in operation, adequate availability with ability to handle some failed modules, and flexibility with respect to potential upgrades.

3.1 Short, high-energy linacs

The International Fusion Materials Irradiation Facility (IFMIF) proposal requires cw deuteron accelerator modules at 125 mA to 40 MeV. The output energy is fixed, in order to simulate the fusion neutron spectrum. An international Conceptual Design Activity is in progress. A comparison of RT and SC technology for the 8-40 MeV portion is done by performing a pre-conceptual design of each to comparable detail.

A new SC cavity must be developed for this low-velocity regime. The Toshiba company has proposed [4] a half-wave coaxial resonator candidate shown in Fig. 4, in the cryostat of Fig. 5.

Technical, cost and availability models have been developed in considerable detail and captured in the new ASM system modeling code [4-6] that affords for the first time trade studies within and between the approaches that fully integrate the three aspects. Technical trades include rf frequency, accelerator tanking, and the transition energy around 8 MeV. Availability trades include rf station

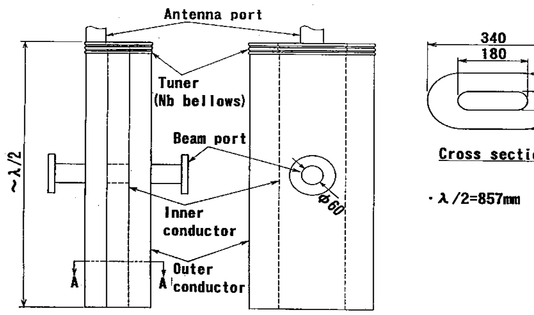

Fig. 4 Toshiba SC β=0.17 cavity schematic, proposed for IFMIF linac.

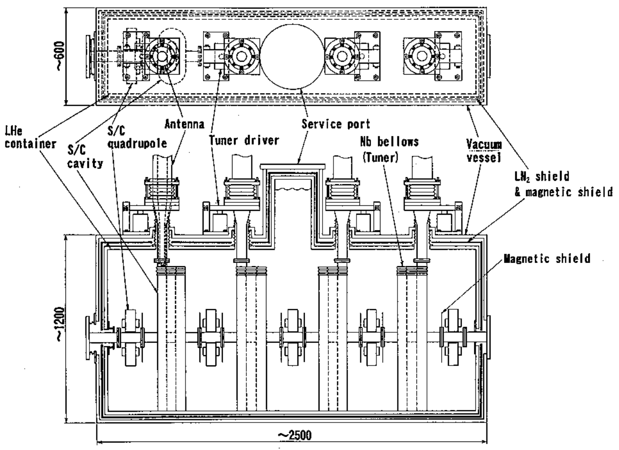

Fig. 5 Toshiba cryounit schematic, proposed for IFMIF linac

failures, injector lifetime, and a detailed availability estimates for all components that are summed to give major subsystem and overall reliability budgets. Cost information is very detailed and linked to the technical and availability information, facilitating trade studies on accelerator gradient, rf technology choice and rf amplifier size.

The result is that the length of the 8-40 MeV linac is about the same for RT or SC. The life-cycle cost is also nearly equal with one major assumption - that large rf amplifiers with power splitting as in Fig. 3 can be used. Thus the usual most important consideration - life-cycle cost - is not available to this project for choice, and it must be made in terms of the other aspects, such as lower beam loss. Presently, a RT 8-40 MeV Alvarez drift-tube linac forms the baseline design for the IFMIF project. More design and prototyping work would be needed before a real choice could be made.

3 LARGE PULSED NEUTRON SOURCE PROPOSALS

Pulsed spallation neutron sources for research using spallation neutrons are being designed by the European Spallation Source (ESS) project, in the US by ORNL with the assistance of several other laboratories, and in Japan by the Japan Atomic Energy Research Institute (JAERI).

The rf linac driver for these sources would accelerate an H- beam for injection into a storage ring. The peak current of order 100 mA is accelerated to nominally 1 GeV. The storage ring features and requirements for the pulsed neutron source time structure rule out a cw beam, requiring instead a beam with a macropulse structure of ~ 1 ms at 50 Hz and a chopped micropulse structure of ~400 ns on and 200 ns off.

The macro- and micro-pulse structure results in less beam-loading in the case of a RT accelerating structure and thus less efficiency and higher cost. On the other hand, the pulsed nature introduces more technical difficulty in achieving the required rf field control in a SC linac. During the buildup of fields in the SC structure, the rf fields produce a radiation pressure called the Lorentz force that mechanically deforms the structure and causes its resonant frequency to change. The mechanical time scale is ~1 ms, similar to the macropulse length. Depending on parameter choices on the loaded quality-factor (Q) of the cavity, microphonic noise may also have to be considered in the control system design, whereas this is not a problem in RT or heavily loaded cw SC structures.

The high loaded Q of SC structures also makes the time required to fill them with rf energy long in proportion to the pulse length. Typically, the filling time is of order 0.14 ms, adding 14% to the required rf power. This factor is sufficient to seriously erode the potential 20-30% cost advantage cited for the cw SC linac.

The tactic of comparing RT and SC linacs with both using the RT parameters is not permissible in this case, because higher accelerating gradients are possible in a SC linac. Operational SC cavity gradients of ~5 MeV/m have been demonstrated, with higher gradients in R&D tests; average gradients of ≥50% of the cavity gradient can be achieved with proper cryostat design. This contrasts with the 1-2 MeV/m RT linac gradients that are forced by rf cost optimization, and means that the SC linac may be nearly half the length of the RT linac, with attendant cost advantages.

The high availability and advantages of lower beam loss, more flexibility and upgrade potential are also factors that positively influence consideration of the pulsed SC linac.

Thus, pulsed spallation neutron sources tend toward the same decision problem as for the short IFMIF linac. The major impetus, a cost advantage of SC over RT, needs yet to be confirmed in detail. Reliability, availability and operability aspects must be integrated with the cost minimization. This could probably be accomplished in a thorough study of about a year in duration, using a tool like the powerful ASM code to capture the data and make the trade studies.

At present, it is not clear that the European and US spallation source studies have the resources to include this careful evaluation of both RT and SC, and RT designs are the baseline. In Japan, however, there is strong interest in the emergence of SC technology and its potential for the future, and the JAERI study, intending to carefully evaluate the SC option, is in a preliminary phase with SC chosen as the baseline. Fig. 6 shows the preliminary point-design layout for the JAERI linac. This facility

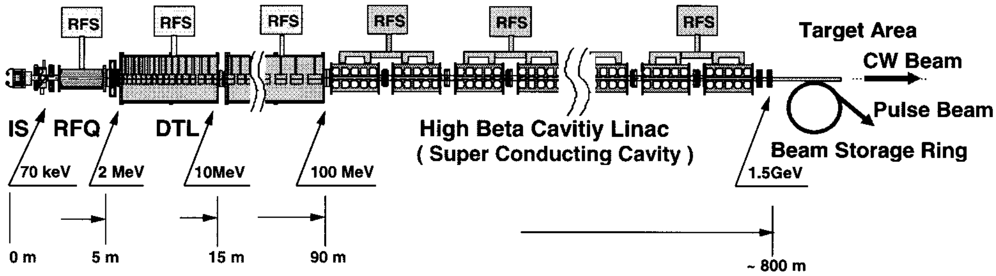

Fig. 6 Preliminary parameters for JAERI proton linac. [Courtesy M. Mizumoto]

may be used in two major phases - the first as a pulsed H- machine for spallation neutron production, and later an expansion to full cw proton capability as a driver for ADTT investigations. It should be noted that the more SC emerges as a technology, the better the potential for further cost reduction.

OVERALL OBSERVATIONS

There are other well-considered ideas for SC approaches, for example by achieving efficiency using SC cavities at the lower end of the current range for long cw linacs, or with SC solenoid focusing and warm accelerating structures at the high current end of the range [7].

The technology base for both room-temperature and superconducting linacs is considered by many to be essentially in place. Many projects, including the high-intensity neutron sources discussed here, could choose either approach and expect that success could be achieved in a well engineered and carefully managed project.

Substantial cost advantage is achieved in a straight-forward manner in a fully cw long high-energy linac.

It appears that cost equality could be achieved in a short cw linac, if large rf amplifiers with power splitting can be used. Evaluation of this question has started under the IFMIF CDA, but requires substantial future effort.

The potential cost advantage of a pulsed long high-energy linac is eroded by the cavity filling time, but enhanced by use of higher accelerating gradient. Thorough design and cost minimization is required.

In that cost might be shown to be about equal, particular attention and thoughtful consideration must be given to the potential operational advantages of SC linacs. Lower beam loss should be assured from the ability to use larger bore apertures, although understanding of beam loss is a very difficult area requiring further work. Dimensional stability, flexibility for continued operation with some percentage of failed units, and upgrade potential are potential advantages of SC technology, as is the strong interest in further development of this emergent technology. As yet, conversion of these aspects to quantitative cost or risk benefits has not been done, although the ASM framework would easily accommodate such a study.

The discussion pointed out several times that rf system issues are actually dominant over the accelerating structure issues. Yet in most projects, very little design and development effort is spent on the rf system. Big cost and operational advantages, and rapid payoff of R&D, could be achieved with the amount of effort that has gone into structure development. For example, most of the rf power (order 80%) goes into the beam in a RT linac, and essentially all of it in a SC linac. An increase in rf amplifier efficiency from ~55-60% as now to 70%, believed possible for klystrons and advanced gridded tubes, would have major impact on operating expenses. Technical questions also need major work; for example whether many-way high power splits will meet the requirements for field control, and evaluation of the integrated system under all operating and fault conditions.

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