Analysis of Acceptability of Superconducting Technology on the SNS

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ABSTRACT

Applicability of superconducting technology to SNS baseline design has been investigated throughout the life of the project to date. While use of superconducting magnets has never been seriously considered (parameter space for SNS magnets is completely outside regime where superconductivity is usually applied), the potential benefits of a superconducting linac have led to several careful analyses of this option. The conclusion from each of these investigations has been the same: technical risks of adopting a superconducting linac option are too great for the project to take. While rapid progress is being made in the field, and a different decision could possibly be made were construction to occur five years later than our current schedule, the mandate to complete the SNS on the present timetable precludes this option. A key question is whether the SNS user community would notice a difference in performance were the linac to be superconducting; it is difficult to imagine an answer in the affirmative.

INTRODUCTION

Superconducting technology has made enormous strides in the past fifteen years, much of this advance in fact being driven by needs of large accelerator projects. It is only reasonable to ask, then, whether applying superconductivity to the SNS project could reap any of the benefits of this technology. Two distinct areas exist where such application could occur: magnets and RF structures.

These questions have been revisited numerous times over the course of the project, with arguments and data being updated according to late-breaking developments in the field. To date, however, the results of these analyses have not presented arguments of sufficient strength to merit a change from the original project baseline of remaining with normal-conducting technology.

SUPERCONDUCTING MAGNETS

Superconducting magnets in accelerator application have primarily been in areas where very high fields are required. By using conductor geometry, dipole and quadrupole fields are possible that are significantly above saturation levels in iron, thus significantly optimizing the size and construction costs of rings for very high-energy particles. Rings have been built with dipole fields of 4 to 6 Tesla; the LHC is being designed for even higher fields.

High-field vs Low-field Magnets

The largest application of magnets in the SNS is in the HEBT transport line between the linac and the accumulator ring (AR), in the AR itself, and in the RTBT transport line between the AR and the target. The HEBT magnets must all be of low strength, below 0.3 Tesla in fact, to avoid Lorenz stripping of the negative hydrogen ions passing through them. The AR and RTBT store and transport protons, so this field restriction is not relevant, but the relatively low rigidity of 1 GeV particles does not merit the use of high-field magnets. Various beam-dynamics arguments call for the AR circumference to be as large as practicable, high-field magnets would be of benefit if the arguments were for a smaller, more-compact ring.

Iron-dominated Magnets

Superferric magnets could be considered for SNS applications. In these, the normal iron-dominated magnet design could be employed, but the coils would be replaced by superconducting ones situated inside a cryostat. An option seriously considered for the SSC employed such lower-field superferric magnets. This SSC option was rejected ultimately because of the roughly tripling of the tunnel length that would be required. While large cyclotrons have been built (Michigan State, Texas A&M, for example) with superconducting coils, there is no example in the US of a ring having been built with such magnets. A ring in Dubna, the Nuclotron, employs these magnets, but the design is not directly transferable (beam apertures are vastly different), and there is no base of engineering experience that would give one confidence that a superferric magnet to the SNS specifications could be built to the required reliability standards.

Evaluation

It is quite certain that capital costs for superconducting magnets would be substantially higher because of the complexity of the cryostat design as well as the need for a liquid-helium plant and distribution system for liquid helium. It is not clear that operating costs would be better for the superconducting system: the added staff for the helium plant operation, and higher maintenance costs for the cryogenic magnets would more than compensate for the somewhat lower net power costs.

Of primary concern, however, would be the impact on facility reliability from the higher-maintenance cryogenic production and distribution systems, and the much-more complex magnets.

On the whole, the potential benefit of somewhat-lower power costs are more than offset by higher capital costs, and concerns over meeting the required reliability specification for the SNS.

SUPERCONDUCTING LINAC

The arguments associated with using a superconducting linac for the SNS are complex and most interesting. There are several very strong arguments in favor, as well as some very difficult questions still to be answered that have strongly influenced the SNS project's decision to remain with normal-conducting technology.

Arguments In Favor of Superconducting Linacs

- A superconducting structure consumes significantly less power, leading to a good potential for considerable reductions in the facility power consumption.

- The accelerating gradients can be significantly higher than for comparable normal-conducting structures, leading to shorter structures. This can lead to savings in conventional facilities costs and a smaller overall footprint.

- A cryogenic linac structure offers as a matter of course an extremely high vacuum. Vacuum is a concern in the linac, as the fragility of the H^- ion places a requirement on a pressure at least in the mid-10^{-8} Torr range. While achievable in a normal-conducting linac structure, it is not a trivial matter. Pressures higher than this will lead to unacceptable beam losses due to stripping of the H^- ions.

- The design of the superconducting cavity leads to beam apertures which are substantially higher than those for a normal-conducting structure, thus providing significantly higher clearances for beam transmission. This is an important consideration for high-current structures where minimizing beam loss is a strong requirement. Experience, now backed up by good theoretical models, shows that such high-current beams are quite prone to the generation of halo, in which particles can be in orbits that can extend many radii from the beam core. For control of beam loss from scraping of halo on the inside of the accelerator structure, a defining parameter is the ratio between the structure aperture and the core beam radius (containing all but the very weakly-populated halo orbits). For the LANSCE linac this ratio is approximately 6, for the current normal-conducting SNS linac design it is around 15, while for the superconducting APT design this number is in excess of 50. Note that beam losses in LANSCE, which operates at roughly the same power level as SNS, are at a level acceptable for hands-on maintenance, so it is anticipated that the SNS design factor of 15 is sufficiently conservative. Nonetheless, while total beam current in APT is substantially larger than the SNS' (making the beam-loss argument much more compelling), the attractiveness of having such a huge margin of safety that would result from a superconducting design of the SNS cannot be overlooked.

These arguments have been key to driving very substantial efforts in developing of superconducting RF technology. In fact, large-scale applications have been successfully implemented at CEBAF, as well as in accelerating cavities for LEP (CERN) and TRISTAN (KEK). A very substantial development effort is ongoing as well in DESY (Hamburg) for the development of pulsed superconducting cavities for the TESLA project, one of the leading contenders for High-Energy Physics' "Next Linear Collider."

While all of these projects have involved the use of electron beams, a most relevant effort for proton beams has been the superconducting linac design for the APT. The current APT design calls for room-temperature accelerating structures up to 200 MeV, and a superconducting structure from there to the final energy, of 1.0 or upgraded to 1.7 GeV. The R&D efforts for the APT have been addressing some of the thornier issues associated with application of superconducting technology for proton linacs, but it should be noted that in addition there are other issues that must be addressed over and above those being addressed by APT, before this technology can be used in the SNS. Some of the particular challenges are listed below

Arguments Against Use of Superconducting Technology for the SNS Linac

- The SNS linac is pulsed instead of operating in CW mode. All of the currently-operating superconducting RF cavities in the facilities mentioned above operate at 100% duty factor, as will the APT. Only the TESLA R&D program is addressing the issues associated with pulsing superconducting cavities. The very high Q of the superconducting cavities causes problems in stabilization of transient fields during the initial powering at the start of the pulse, leading to a more complex RF and longer filling times. Another concern is that introduction of the high fields in the cavities produces very significant Lorenz forces on the cavities themselves, which can cause distortions of the cavities and change the resonant frequency. This must be dealt with through mechanical stiffeners, and careful resonance tuning control.

- Superconducting cavities are highly sensitive to vibrations, which can make it difficult to remain on resonance. Design requirements call for extremely good mechanical isolation and damping, and current designs, while not completely mitigating the problem, do in fact provide acceptable operation. This is not a serious problem.

- Great increase in complexity of RF system. Control of electric-field gradient levels in the superconducting cavities is substantially more difficult than in normal-conducting structures. In the latter, it is common to provide a single, very large amplifier to drive many cavities, relying on the damping of the copper to produce consistent gradient levels in all of the cells being driven. To achieve the required field stability in a superconducting structure a highly-distributed RF system is required. For instance, while a single klystron in the normal-conducting SNS linac will drive between 40 and 60 cells, a superconducting design would call for driving no more than 5 or 10 cells with a single amplifier. Thus, instead of the 52 klystrons currently planned for the SNS, the RF system would have to have almost 500 amplifiers. Granted, the unit amplifier will be of significantly lower power, but overall reliability in an RF system, according to knowledgeable engineers, is driven more by part count than by system power. The increase by a factor of 10 in part count is most likely to lead to reliability problems.

- Reliability of superconducting RF systems. If one enters the CEBAF control room at any given time during normal operation, and asks the question of how many of the superconducting cavities are off-line, the number is usually about 10%. There are a variety of reasons for a cavity being off-line. In the majority of cases a trip has occurred which requires a simple reset of its amplifier (there are several hundred amplifiers), and could take 5 minutes. In a few cases, a cavity will have experienced a major short-circuit or failure that will require removal of the cryostat and repair of the superconducting structure, which can occur only in a shutdown that typically occurs once per year. In an electron linac, this type of operational situation is completely acceptable. The relativistic electrons are all travelling at the same velocity (c), so there is never a question of phase lag if an accelerating kick is not given to the particles passing through a given cavity. To maintain the total energy through the accelerating structure (typically determined by bending rigidity in a downstream magnet), gradients are adjusted in other cavities to ensure that the integrated energy gain for the whole accelerator remains constant. This is easily done with a feedback system sensing the position of the beam following the above-mentioned bending magnet. In a proton accelerator such as the SNS, the beam is not relativistic, so if a cavity drops out, the beam will arrive at the next cavity later and slower than it should, leading to stability problems. This matter is being seriously addressed by the APT R&D program, it must be solved for acceptable operation of this accelerator. It will require both a significant improvement in the reliability of the overall accelerating systems, and also a system for sensing dropped cavities and automatically re-phasing downstream cavities to compensate for the lack of appropriate energy gain. Beam-dynamics issues associated with a dropped cavity are also being assessed, there could be significant impacts on beam stability and halo formation.

Assessment of Suitability of Superconducting Linac for SNS

An assessment of whether or not the SNS linac should be superconducting should be made on criteria of risk, cost, and impact on main mission. These will be addressed in order.

- Risk

Two main risk factors should be considered: technical and schedule.

Technical Risk

The topics mentioned above must be addressed before it can be said that technical risk of superconducting linac technology is acceptable. While TESLA is addressing the problems associated with pulsing high-power cavities, and APT is focusing on the questions that arise for proton beams, it is clear that an independent R&D effort would be required to combine the results of the first two to provide a solution satisfactory to the SNS. Good progress is being made on both TESLA and APT, however all the answers are not yet all in. By late 1997, TESLA [1] has demonstrated gradients of 16 MV/m in pulsed operation, fill time is about a factor of 10 over normal structure's (500 μs vs 50 μs), and feedback systems seem suitable to handle Lorentz detuning forces. A short section of 7 cavities have been powered in these tests. APT has not yet mounted beam experiments with cavities, but has been doing engineering and physics designs for several years [2].

Of particular concern is the reliability question, and incorporation of proper engineering solutions to ensure that performance of the SNS linac meets the very demanding requirements in this regard. All of the current R&D programs are far away from having satisfactory solutions to this problem.

Assessments by experts as to technical feasibility of a pulsed superconducting proton linac are all positive, for the long run, however all agree that a very significant R&D program is needed before such an option can be endorsed. The ESS project is currently considering very seriously the adoption of superconducting technology [3], however, the schedule for their project is not likely to see a construction start for at least 10 years, it is quite likely that there is sufficient time to successfully answer the outstanding concerns within this time period.

In contrast, the LANSCE linac has been operating for over 20 years, and produces beam of the power and duty factor required for SNS, at close to the required energy. Experience with its performance has proved extremely valuable in developing engineering modifications for improved performance, both in beam loss, stability and reliability. By comparison with a superconducting concept, the current room-temperature design for the SNS linac represents a small extension over existing, proven technology. General assessment of the present SNS design by numerous review teams is that it is mature and conservative, with extremely low technical risk.

Schedule Risks

The SNS project is on a very tight timetable. With a line-item construction start authorization in FY99, the clock is definitely running! As stated above, a substantial R&D program would be needed to solve the currently-identified questions relating to a superconducting linac.

An optimistic assessment says that by suitable coordination with APT efforts, an accelerated R&D program for a superconducting SNS linac could be concluded in about a year. Construction of the high-energy portion of the linac would thus be delayed by a year. Considering the much shorter length of this structure, it is just possible that the fabrication time could be shortened so that overall completion date for the project might not be affected.

Against this scenario, one must weigh the risks of the R&D program, whose results are of critical importance before detailed design can occur, as well as the much more complex processes for fabrication and assembly of the cryogenic accelerating modules considering, amongst other things, the need for extreme cleanliness. While much of this could also benefit from APT engineering, there would then be further concerns about the mandated meshing of APT and SNS schedules in order to benefit from this symbiosis.

Evaluation of Risk

While the community believes that a superconducting pulsed linac can be built, eventually, it is quite clear that being able to deliver beams by FY06 from such a structure would entail a high degree of risk. Were the SNS to be on a more relaxed time schedule, it is likely that a much stronger argument for adopting superconducting technology could be made.

- Cost

Capital (Project) Costs

A superconducting design could provide some quite significant savings in some areas, but would also add to capital costs in others. The structure would be shorter, an estimate of reduction by as much as 150 meters in linac length has been made. This would reduce the cost of the linac tunnel substantially. In addition, the cost of the linac itself is likely to be reduced, even though the cost-per-meter of linac structure is considerably higher. Because of lower total power consumption, savings are available as well in the installed electrical facilities.

Areas where costs would increase would include a large cryogenic plant, and distribution system for liquid helium. The linac tunnel will require suitable design for venting of helium gas in the event of a quench, but this should be only a minor cost addition.

RF system costs are difficult to compare. On the one hand, significantly less total RF power is required (•1.5 MW vs • 19 MW), but on the other hand the number of RF amplifiers is probably a factor of 10 higher. While unit costs are substantially lower, total parts count will be much higher. How the net cost comes out is not clear.

Note that project costs must also fund the R&D program, estimated at roughly $13M.

A quick calculation by LANL [4] has indicated that net overall savings to the project could be about $6M.

Operating Costs

Power costs will be quite a bit lower for a superconducting linac. Total draw for the linac systems (including the cryoplant) will drop from 19 MW (peak) to 5 MW (peak), though about 3 MW of this will be continuous for the operation of the cryoplant. A rough estimate of the net power savings [4] would be about $3M per year.

On the other hand, there will be an increase in staff associated with the operations and maintenance of the cryoplant, as well as added technical staff for maintenance of the superconducting structures. A very rough estimate is that an additional 15 people will be needed to handle these functions, pretty much canceling out the savings in power costs.

- Impact on Facility Mission

There are several areas where linac technology could impact the ability of the SNS to satisfy its basic mission, namely to provide a reliable, upgradable platform for neutron sciences. Specifically, how will the Users be impacted by the choice of linac technology?

A positive impact will be that a superconducting linac is more easily interfaced with facility upgrade plans. Because of the highly-distributed RF system, there is almost no added cost for the installation, on Day 1, of RF capability suitable for a full 4 MW of beam power. In addition, because of better vacuum and very large aperture, beam losses will never be a factor in increased current through the linac. This will very much reduce the cost and time to achieve higher beam powers for a superconducting linac.

Negative impacts would be potential problems with reliability of the technology as it now exists. This could be very serious.

One could phrase the question a different way, “Would the Users notice a difference if the linac were superconducting?” In the case of CEBAF, the nuclear physics community clearly benefited from the change from the original normal-conducting design to the superconducting recirculator concept, however the typical SNS User will probably be quite oblivious of whether his neutrons came from protons accelerated in a superconducting linac or a normal-conducting linac. That is, of course, unless one of the structures were substantially more or less reliable than the other!

SNS Project Decision Regarding Superconducting Linac

After careful consideration, the first SNS Project baseline, adopted in September 1997 [5], called for a normal-conducting linac. This decision has been revisited several times, as discussed in the following section, and has not been changed. The principal two reasons have been:

- Risk to the project, both technical and schedule. Obtaining the necessary answers from a very aggressive R&D program in a timely fashion is a sine qua non for timely completion of the project. New technology must be developed for this to occur, the risks are high. Again, it should be stated that were the construction schedule for the SNS not so aggressive, a good argument could be made that these risks would probably not be as significant.

- Clear mandates from national committees, the user community and DOE to use conservative, proven technology and designs to ensure the maximum reliability for the facility.

PROCESS FOR ESTABLISHMENT AND VALIDATION OF LINAC TECHNOLOGY

The process of establishing the SNS baseline parameters and technologies began with the series of project Collaboration Meetings, between December 1996 and September 1997. During this time various technology options were examined, including [6]:

a) Full energy, room-temperature linac with accumulator ring,

b) Partial energy, room temperature linac with rapid cycling synchrotron

c) Full energy, superconducting linac with accumulator ring and

d) Induction linac (full energy or with FFAG booster).

The first was selected after substantial discussions, much along the lines (in the case of option c) of the preceding sections of this paper.

The baseline was described in the Pre-CDR document, published in September 1997, and presented to an external Accelerator Review Committee, chaired by Fred Mills in December 1997 [7]. This same committee was asked by DOE to evaluate the process for arriving at the baseline design, and as to whether the baseline design was appropriate for the goals of the project. Though the prime focus of this committee's second report [8] was to assess the relative merits of options a) and b) above, they were presented with rationale for selection of a) over all the others. To quote the committee chairman, "… the Committee believes the technology choices made are reasonable and responsible."

A further description of the technology-choice question was presented in the NSNS Conceptual Design Report [6], which was reviewed by a DOE Committee chaired by Dan Lehman in June 1997. In its report [9], the chair of the Linac subcommittee states, "Normal-conducting RF structures have been selected over superconducting ones, and the committee endorses this choice."

In October 1997, a letter from H. Padamsee to D. Lehman [10] was forwarded to the SNS project for comment. This letter suggested that the project should reopen the question of linac technology. In response [4], A. Jason (LANL) updated the SNS position on the superconducting linac issue, in light of current work on TESLA and APT. The results of this analysis are consistent with the position taken earlier in this current paper.

SUMMARY

A thorough dialog has occurred on the subject of linac technology, extending from the very beginning of the SNS (or NSNS or even prior to that, ORSNS) project. The selection of the normal-conducting design for the linac was made very early on, and has been extensively reviewed and endorsed by both internal and external processes. The rationale for this choice is quite clear: it provides the lowest technical risk, and the highest chance of providing a reliable facility for the neutron sciences community.

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1 "Linear Collider Projects at DESY," R. Brinkmann, EPAC98, p. 53

2 "High Power Proton Linac for APT: Status of Design and Development," G.P. Lawrence, paper MO2002, LINAC98, http://www.aps.anl.gov/conferences/LINAC98/papers/MO2002.pdf

3 “Status of the ESS Design Study,” I. Gardner et al, Vancouver PAC97, p. 988, and “Room Temperature versus Superconducting Pulsed Proton Linacs,” Lecture presented by K. Bongardt, FZ-Juelich, at CERN, Nov 12, 1997.

4 “Superconducting Responses” presentation by A. Jason at NSNS Collaboration Meeting at LBNL, Dec 13, 1997.

5 “NSNS Pre-CDR,” Nov 1996

6 “NSNS Conceptual Design Report” p. 1-45, 1.3.3. Evaluation of Technology Options NSNS/CDR 2/V1

7 “Report of the Committee to Review the Design of the NSNS” F. Mills, chairman, Jan 19, 1997

8 “Report to the DOE on the Validity of Technological Choices in the Design of the NSNS,” F. Mills, chairman, January 28, 1997

9 “DOE Review of the NSNS Project,” June 1997 DOE/ER-0705, p.27

10 Letter from H. Padamsee to D. Lehman, July 2, 1997, private communication