# SUPERCONDUCTING HEAVY ION LINACS*

Jerry A. Nolen
Physics Division, Argonne National Laboratory
Argonne, IL 60439, USA

## Abstract

This paper reviews the present status of superconducting linear accelerators for heavy ions with emphasis on the newest facilities and developments which are in progress at various laboratories around the world. There are currently five routinely operating facilities, two new ones being commissioned, and four new ones under construction. Recent developments, R&D projects, and new concepts related to the technology and applications of superconducting ion linacs are discussed.

## Introduction

Superconducting (SC) rf resonators for accelerating ions with velocities below about 0.5c were developed, beginning about 1970, primarily as the basis for boosters for existing electrostatic accelerators for nuclear physics. Linacs based on this technology have been providing high quality, CW beams for research for nearly two decades now, but methods continue to evolve and improve. SC linacs for highly relativistic particles, which utilize the now-familiar elliptical cavity structures, are not discussed in this paper, but all types of SC rf accelerators are covered in a recent review.[1] There are several other fairly recent reviews which cover the histories and specifics of SC linac facilities and associated technologies[2,3,4,5]. This paper primarily covers developments since the Linac Conference of 1992.

A wide variety of resonator structures have been developed for SC heavy ion linacs. There are quarter-wave, half-wave, helical, and split-ring types, for example. In such a linac there are typically 10's of resonators which are individually controlled and phased to permit tuning over a wide range of velocities and particle types. The resonators are normally cooled with liquid helium at 4.5 K and utilize either niobium or lead as the superconductor. Typical accelerating gradients achieved in practice are 2.5 to 5 MV/m although higher numbers are often observed in off-line tests. An example of a quarter-wave bulk niobium resonator recently developed by INFN Laboratori Nazionali di Legnaro[6] in Italy is shown in Fig. 1.

To date all but one of the SC heavy ion linacs are configured as boosters to electrostatic accelerators to increase the beam energy while maintaining excellent beam quality in both longitudinal and transverse phase spaces. The resonators are packaged in groups of 2 to 8 per cryostat with transverse focusing elements as superconducting solenoids within the cryostats or conventional quadrupoles between cryostats. The configuration of the new booster currently being commissioned at the Department of Physics at JAERI[7] in Japan is illustrated in Fig. 2. A very low beta superconducting linac which accelerates ions directly from an ion source on a high-

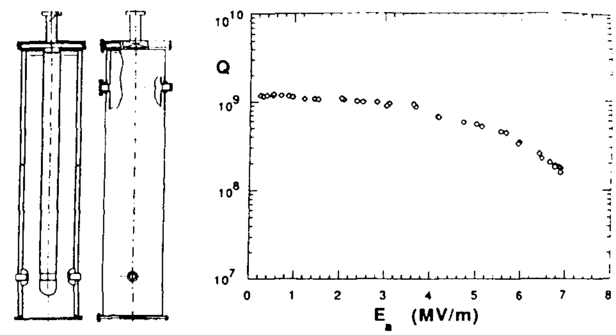


Fig. 1 A bulk niobium 80 MHz superconducting quarter-wave resonator and its measured Q-curve *vs.* accelerating-field gradient.[6]

voltage platform rather from an electrostatic tandem is shown in Fig. 3; this is the Positive-Ion Injector at ATLAS at ANL.[8]

The status of facility upgrades, new facilities, and various technical developments related to SC ion linacs is given below.

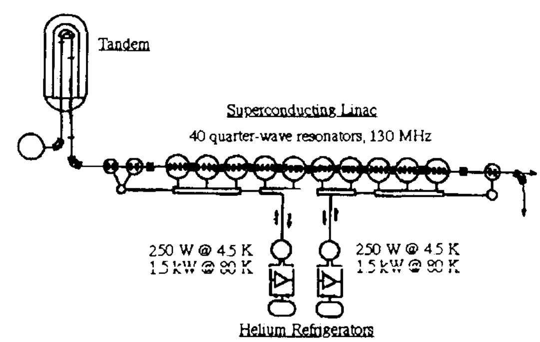


Fig. 2 The layout of the JAERI tandem booster which comprises 40 SC accelerating cavities packaged in 10 cryostats.[7]

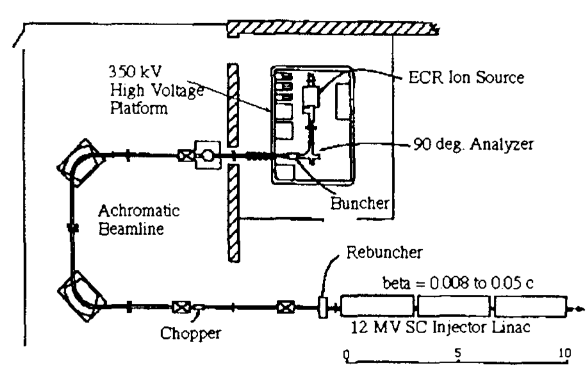


Fig. 3 The configuration of the Positive-Ion Injector at ATLAS which accelerates ions directly from an ion source on a high voltage platform with initial velocities of 0.008c.[8]

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## Facilities with Superconducting Linacs

Reviews such as ref. 4 list the detailed parameters of all existing SC heavy ion linac facilities so the present discussion will be brief and emphasize recent changes.

### Existing Facilities

Since the Saclay SC linac is ceasing operations there are now five operating facilities, all in the United States: ATLAS at Argonne National Laboratory, Florida State University, and Kansas State University based on niobium resonators all fabricated at ANL, and SUNY/Stony Brook and the University of Washington, Seattle based on lead plated resonators. All five facilities have active nuclear and/or atomic physics programs which use the beams from these accelerators.

The new Positive-Ion Injector (PII) at ATLAS has worked well since it was commissioned in 1992; the combination of PII and the original tandem injector delivered the distribution of beams shown in Fig. 4 to users during fiscal year 1993. Uranium beam currents of 5 particle nanoamps are available (see ref. 8 for more details).

The Stony Brook facility has been upgraded significantly during the past couple of years due to a combination of replacing their 16 low-beta split-loop resonators with quarter-wave units and, at the same time, improving the lead plating procedures considerably.[9] The improvement obtained with their new lead alloy plating procedure is discussed in the technology section below.

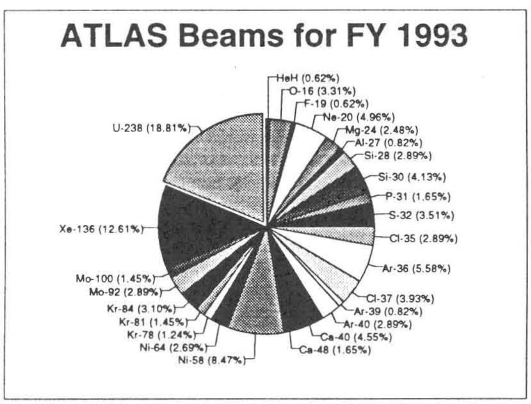


Fig.4 A "PII chart" which shows that ATLAS users extensively utilize the heavy beams made available by the new Positive-Ion Injector which was commissioned in 1992.[8]

### New Facilities

Two new SC heavy ion linacs are being commissioned this year, one in Japan, and one in Italy. In both cases at least some of the niobium resonators were fabricated by industrial companies in their respective countries and not exclusively in national labs or universities as has been the standard procedure for similar heavy ion accelerating cavities elsewhere.

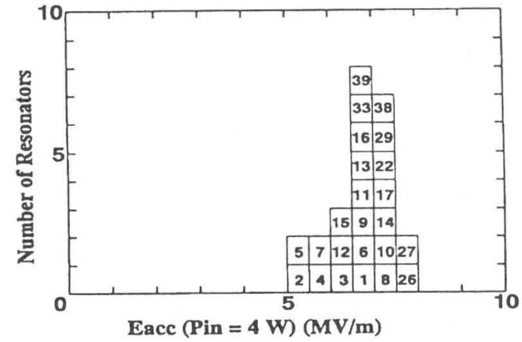


Fig. 5 A histogram of the gradients achieved for the new JAERI resonators in the test stand before installation (at 4 watts input power). At higher powers maximum gradients achieved averaged 10 MV/m.[7]

**The JAERI Tandem Booster.** The new SC booster recently completed at JAERI comprises 40 niobium quarter-wave resonators operating at 130 MHz and designed to add 30 MV to the voltage output of the tandem alone. See Fig. 2 above for the floorplan of the facility. The resonators were fabricated by Mitsubishi Electric Corp. and given final electropolishing and cleaning at JAERI. Very high gradients were achieved during tests of these structures[7] as shown in Fig. 5. Early tests with beam have already achieved 28 MV and accelerated a Ni beam to over 10 MeV/A; details of the early performance are presented in paper TH-24 at this conference.[10]

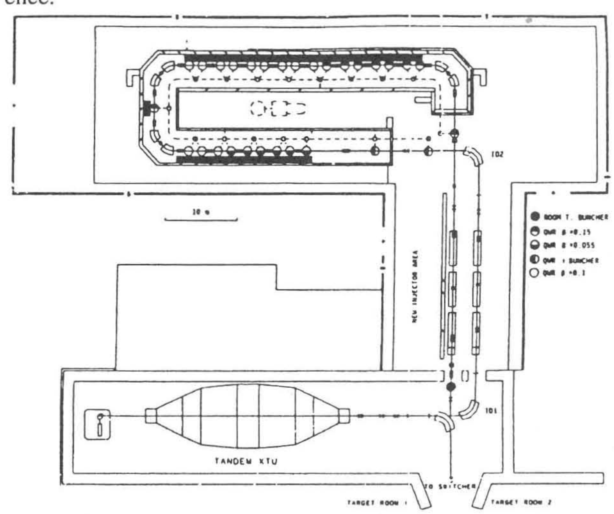

Fig. 6 The floorplan of the ALPI facility at LNL, Legnaro. There are currently 48 intermediate beta resonators installed and commissioning is in progress.

**The ALPI Facility in Legnaro.** The components of phase 1 of the ALPI project are in place and the accelerator is being commissioned. A test nuclear physics experiment was done in May, 1994 with a Ni beam with 12 MV of acceleration by the ALPI booster.[11] Phase 1 uses 48 lead-plated quarter-wave resonators optimized for $\beta_o$=0.11. Phase 2 will add

21 lower beta and 21 higher beta resonators. Some of these new resonators will be bulk niobium structures[6] and others will use copper structures coated with thin niobium films via sputtering.[12] It is the bulk niobium-type of resonator which is being fabricated for ALPI by Italian industry. The physical layout of the ALPI linac relative to the large XTU tandem injector is shown in Fig. 6. An additional proposal to add a SC RFQ and ECR ion source as an alternate injector is also discussed below.

### Facilities Under Construction

There are currently SC heavy ion booster construction projects in progress in Australia, Brazil, and India.

**Australian National University, Canberra.** The initial goal is to install a booster to increase the energy of the 15.5 MV tandem by 6 MV. This will be done by using lead plated resonators which were received from the Nuclear Structure Laboratory in Daresbury, UK, with plans to have beam from this phase by September, 1995. Plans exist to further upgrade the booster voltage to 18 MV during the following couple of years.[13] The Canberra group has been doing development of niobium sputtering methods also.[14]

**Nuclear Science Center, New Delhi.** This institute has plans to add about 16 MV to their 16 MV tandem via a SC booster linac consisting of 32 quarter-wave 97 MHz niobium resonators.[15] There is currently a collaboration between the Nuclear Science Center and the Physics Division of ANL to develop a new structure for this purpose.[16]

There is also an independent, smaller, ongoing development project in Bombay, India. This is a collaboration between BARC and the Tata Institute to produce a few lead-plated quarter-wave resonators of the Seattle type and to install them at the Tata 14 MV tandem.

**University of São Paulo, Brazil.** This group is constructing a SC linac booster for their 9 MV tandem using the existing ANL split-ring resonator, cryostat, and electronic designs.[17] The 14 split-ring resonators for the first stage have already been fabricated in the ANL shops. They could complete the initial project by late 1995 or 1996 depending on the rate of funding for the building and other components.

### Proposed Upgrades

All of the SC heavy ion linacs built to date, except for the new ATLAS Positive-Ion Injector, have been as boosters to electrostatic tandem-type accelerators. However, it is now recognized that tandems are not effective injectors for the heaviest beams such as lead and uranium. The ATLAS PII was the first to replace the tandem as the injector at such a SC linac facility. Others are investigating the use of SC RFQs to address this issue:

**SUNY/Stony Brook Injector.** The concept of a series of independently phased, short SC-RFQ's as the basis for a positive-ion injector to replace the tandem was proposed by a Stony Brook/Legnaro collaboration.[18] A prototype of one short SC-RFQ using a Pb/Sn alloy plated on copper was built and tested.[19] The results were promising, except no attempt was made to phase-lock the resonator. The Stony Brook group does not have funding to pursue this concept at this time, but it is being developed by the Legnaro group.

**ALPI Injector.** This group is pursuing the ECR ion source/SC-RFQ option to replace the XTU tandem as the ALPI injector for heavy beams.[20] Two aluminum cold models have been studied and will be evaluated to select a geometry for a next prototype SC-RFQ study.

## Research and Development

In these sections are listed recent developments in the technology of SC linear ion accelerators (limited to heavy and light ions at energies per nucleon less than about 200 MeV). The topics are divided into "Recent Results", for advances which are relatively mature or proven, and "New Concepts and Initiatives", for preliminary or speculative ideas. The number of topics listed here indicates the field is still fertile and not yet fully exploited.

### Recent Results

**Bulk niobium resonator construction.** Most niobium resonators currently in use have solid niobium inner conductors and explosively-bonded copper/niobium sheets for the outer surfaces. The inner structures are typically filled with liquid helium while the outer surfaces are cooled via conduction through the copper sides of the sheets. The Legnaro group has designed annular outer surfaces of bulk niobium sheet with space for liquid helium in the space between, thereby eliminating the need for the bonded laminate. They have had such structures fabricated commercially in Italy, and recent tests have been very promising[6] as indicated in Fig. 1. One advantage of such a fabrication method is the possibility of high temperature treatments which are not possible with the copper laminate material.

A variation on this method developed by K.W. Shepard at Argonne uses a stainless steel outer jacket with small amounts of stainless steel/niobium laminate for hermetic seals at beam and coupling ports.[16] Heat exchanger channels for rapid cooldown of the structure are welded to the stainless steel outer jacket. The structure is practical and cost effective.

**Sputtered niobium films on copper.** It has been shown that thin films (in the microns thickness range) sputtered onto copper structures can produce SC resonators with excellent properties.[21] However, the high-beta structures with simple elliptical cross sections are much easier to coat uniformly than typical low-beta structures. Both the Legnaro and

Canberra groups have been doing R&D on this topic.[12,13] The Legnaro group has demonstrated good Q's and gradients at low rf power into the quarter-wave resonators they tested recently. They are preparing to install some of the $\beta_o$=0.15 sputter coated resonators in ALPI for beam tests very soon. In fact, very soon, ALPI will contain bulk niobium, lead plated, and sputtered niobium resonators all at the same time for comparison. The electrode/resonator geometry developed for making uniform sputtered coatings is shown in Fig. 7.

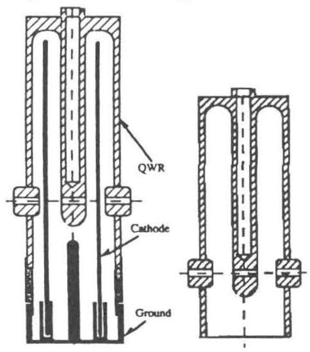


Fig. 7 The electrode and resonator geometry (left) used for sputtering thin niobium films at LNL, Legnaro.[12] The resonator without the electrodes is also shown (right).

**Improved VCX fast tuners.** SC RF structures which otherwise have desirable properties are useless if they can't be phase-locked. The ATLAS fast tuner system,[22] a voltage controlled reactance (VCX) operating at liquid nitrogen temperature, was upgraded a couple of years ago and is now implemented throughout the 3 linacs. The new system can provide up to 30 kVA of reactive tuning, but switches at 25 kHz so that relatively large frequency vibrations (up to 900Hz has been demonstrated) can be compensated without introducing significant phase jitter in the beam.

**High power pulse conditioning.** For niobium resonators which are usually limited in field gradient by electron loading due to field emission, high power pulse conditioning normally improves performance. This limit seems to be mainly determined by the amount of peak rf power available. For example, at ATLAS the full output of a 1500 watt rf amplifier is used for conditioning, whereas at $\beta\sim1$ facilities such as CEBAF 10's of kW are now used.[1] At ATLAS we now have plans to acquire a higher power amplifier with the expectation that higher on-line gradients will be achieved.

**Improved lead-alloy resonator performance.** During the upgrade to replace many split-loop resonators with quarter-wave types and the RFQ test project at Stony Brook improved lead plating procedures were developed.[9] With the recent improvements to the Pb/Sn alloy processing, gradients of 3-4 MV/m have been achieved on-line.

**Freon conditioning to reduce multipacting.** When first turning on resonators which were not recently conditioned it is normal to experience some degree of mutipacting at low field levels. This is usually eliminated by rf pulse power conditioning, but in some cases it can be persistent or severe. At Stony Brook a procedure of Freon plasma surface treatment has been found to be very effective in eliminating multipacting barriers in their Pb/Sn alloy resonators.[23]

**Characterization of hydride formation.** It has been known for some time that hydride formation on the surfaces of high frequency $\beta\sim1$ resonators under certain circumstances can lead to severe Q-degradation. This phenomenon has been observed to also be a problem in some cases in the types of niobium resonators discussed in this paper.[7] The JAERI group has done a careful job of characterizing this phenomenon as shown in Fig. 8. By cooling quickly through the critical 130-90K temperature range the effect is minimized, but in several severe cases the JAERI resonators have not recovered from the Q-degradation even with several temperature cycles to 100C.

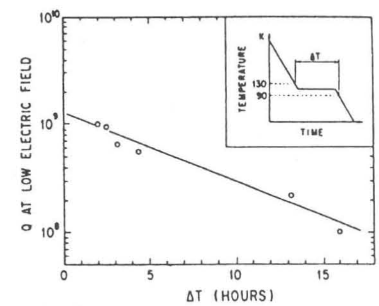


Fig. 8 A graph of data recorded by the JAERI tandem booster group showing the systematics of the Q-degradation phenomenon.

**Cryogenic efficiency upgrades.** To increase cryogenic efficiency and/or capacity several laboratories have incorporated or added wet expansion engines to their helium refrigerator systems. Since the electrical and liquid nitrogen cost to run a SC linac facility of the general types discussed here can be several hundred thousand U.S. dollars per year, careful attention to cryogenic efficiency is prudent. With liquid nitrogen precooling a typical electrical efficiency value with a wet expansion engine (or possibly a double JT-valve as used by CCI, Inc.) is about 1W of refrigeration at 4.5K per 500W of electrical power to the helium compressors. With careful design and using new efficient helium compressors[24] it now seems possible to increase this efficiency to around 1/300.

## New Concepts and Initiatives

**Coupled-cavity development.** In order to improve the cost-effectiveness of 2-gap, quarter-wave resonators, a program to strongly couple pairs of such resonators is in progress by the Argonne/New Delhi collaboration.[16] A superconducting coupling loop would connect the two quarter-wave resonators which would then be excited and controlled as a single, 4-gap resonator. However, since the coupled cavities could be operated in-phase or out-of-phase, the effective transit time curve of the pair is similar to that of a 2-gap cavity rather than a 4-gap type.

**Very low q/m SC linac for radioactive beams.** There is currently world-wide interest in developing facilities capable of producing intense, high-quality radioactive beams for nuclear physics and other applications.[25] One challenge is the acceleration of very low q/m ions from very low energies while maintaining excellent beam quality. SC linacs will almost certainly play an important role in meeting this challenge. R&D is underway at ANL to address these issues.[26]

**Very low-beta, 8-gap SC resonator development.** Related to the radioactive beam post accelerator issues mentioned above is the desire to increase the cost-effectiveness of SC heavy ion linac technology. Preliminary design studies of extending the ATLAS PII 4-gap, low-beta resonators to 8-gap structures was done under a U.S. DOE Small Business Innovative Research Phase 1 grant[27] in an AccSys Technology, Inc. collaboration with K.W. Shepard of ANL. The concept of the proposed structure is shown in Fig. 9 and the beam dynamics studies look very promising.

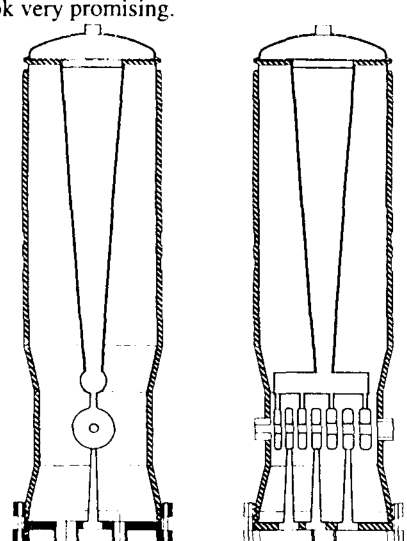

Fig. 9 A schematic drawing of an 8-gap, very-low beta resonator concept. It is a 48 MHz structure and is designed for ions with initial velocities about 0.008c.

**SC RFQ developments.** The development of a high gradient SC RFQ is also in progress as an AccSys/ANL collaboration under a DOE SBIR Phase 2 grant.[28] Such a development could lead to a compact, light-weight, low-energy ion accelerator for medical or industrial applications.

**High brightness SC linacs for light ions.** There have been several studies recently of the issues related to extending the technology associated with the types of resonators discussed here to various high brightness light ion accelerators.[29,30]

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