Rf Superconductivity Research and Development at Stony Brook*

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(Presented by J.W. Noé)

Abstract

The superconductivity R&D program at Stony Brook is based on an improved lead-on-copper technology applied to various low-frequency (50–300 MHz) low-beta accelerator structures. Current activities include work to enhance the performance of the existing superconducting heavy-ion linac and to beam-test a working prototype superconducting RFQ device.

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Introduction

Rf superconductivity research and development work at Stony Brook dates from 1975, when a collaboration with the Low Temperature Physics group at Cal-Tech was begun to develop and build a superconducting heavy-ion linac at Stony Brook. This accelerator, the first of its type at a University, was dedicated in April 1983 and continues to support a vigorous program of nuclear physics research [1].

Most of the R&D work in the 1975–83 period was concerned with 1) developing support devices and systems such as refrigerators, bunchers, resonator control circuits, beam diagnostic devices, etc. for the linac, and 2) establishing a local technology for plating resonators and assembling cryostat modules in mass production. As the linac construction was completed new programs were initiated in lead-copper technology [2] and in new low-β structures [3, 4]. These overall themes are still the focus of the current efforts, motivated in part by the need to maintain and expand the performance of the installed heavy-ion linac.

For the last ~5 years the Stony Brook rf superconductivity program has proceeded along two parallel tracks. One group has continued to develop the lead-copper technology and to apply this to improving the linac. A second group (which has included from time to time several experienced visitors and several instrumentation students) has worked primarily on a new generation of low-β structures able to both focus and accelerate slow ions.

Lead-copper technology

All of the Stony Brook rf superconductivity work to date has utilized Pb or Pb alloys [2, 5] electroplated on to copper as the superconductor. As discussed by Delayen [6] at an earlier workshop, lead-copper technologies offer many advantages for relatively large low-frequency and low-β structures such as are used in heavy-ion linacs and in proof-of-principle devices like the SRFQ discussed below. This is especially true following various practical improvements by our group over the last several years, which have greatly simplified procedures and provided a more consistently high level of performance.

The advantages of lead-copper include:

- Good cooling, which allows stable operation limited only by available refrigeration.
- Accelerating fields comparable to niobium, for on-line linac operation under similar conditions [7].
- Low fabrication costs, roughly an order-of-magnitude less than bulk or composite niobium.
- Easily applied coatings, even in large complex structures. Coatings are also easily removed with acid and re-applied if necessary.

The main difference between the earlier methods used for the linac construction and those used since 1985 is that the thin (1–2 μm) lead film is now created directly rather than by "chemically-polishing" [6] a thicker (5–10 μm) plated layer. The recent (1991) introduction of an inert (nitrogen) atmosphere for suppressing oxidation during rinsing and drying operations has also been a major step forward.

The current lead-copper plating procedures can be summarized as follows:

- The copper surface is first cleaned and work-hardened by rough mechanical polishing with 600 emery paper. Tumbling can also be used, but the abrasive stones must be tightly packed to avoid micro-craters.
- Where practical the copper surface is next treated for 5 minutes in a brightening agent,

Shipley Chempolish 14. This leaves a clean lustrous surface (featureless at 20,000x in SEM) which can be plated immediately after rinsing in DI water.

- A Pb-Sn alloy is electroplated 1–2 microns thick from a standard commercial fluoborate bath, using the resonator itself as the plating vessel. The tin component is ~2 at%; this seems to give better results than the ~10 at% used in some earlier work [5]. Low currents are used for best uniformity, and the current is reversed for 3 seconds every 12 seconds. The plating anode is typically made from well-cleaned pure sheet lead enclosed in Dynel bags. The bath is circulated for hours through an 0.5 μm filter.
- The plated surface is rinsed very thoroughly (10–30 min) with large volumes of ~10 MΩ–cm DI water filtered to 0.5 μm. No other chemicals are used.
- Drying is done with hot nitrogen gas obtained from LN_2. No solvents are used.
- Chem-polish, rinsing and drying operations are all done in a nitrogen gas atmosphere to prevent oxidation. A flexible membrane cover allows observation and maneuvering of the rinse water and drying gas streams.
- Plated parts are stored under clean nitrogen gas (not in vacuum).

With the current thin-lead methods typical superconductor performance in actual accelerator environments at 150 MHz and 4.5 K corresponds to a respectable surface resistance R_s of 50–100 nΩ at low rf magnetic fields under 100 G. However R_s invariably increases (Q decreases) at higher fields roughly as $H_s{}^2$. Yogi [8, 6] has shown that this "magnetic Q droop" is especially pronounced in very thin lead surfaces, while thicker surfaces (such as the chemically-polished ones used previously) have a lower limiting magnetic field H_{tr} than thinner ones. These systematics are consistent with the flat high Q curves reported for some especially high-quality thick film surfaces [4, 9]. Hopefully further development work will show the way to combining the simplicity of the present techniques with the potentially flatter $R_s(H_s)$ dependence of the earlier method.

Losses can be further increased by electron field emission. With the current techniques field emission only begins to be significant when peak surface electric fields E_s reach 15–20 MV/m over surface areas of 1–10 cm^2. (In a typical low-β structure this corresponds to accelerating fields $E_a \simeq 3.0$ MV/m.) Extreme measures for dust control (class 100 rooms, etc.) are not needed to achieve these results and might not be practical anyway, since in these low-β accelerators the beam line vacuum and cryostat vacuum are the same. What does seem to be important is starting with a microscopically clean copper surface and thoroughly filtering the plating baths and rinse water.

Multipactoring is potentially more of a problem in lead-copper structures than in niobium because the soft lead surface invariably contains impurities such as hydrocarbon plating bath additives and because wet lead reacts so easily with the atmosphere to form surface insulating layers. Furthermore of course aggressive purification methods (vacuum firing, acid etching) are not possible with lead. Multipactoring tendencies are compounded by geometry in highly-symmetrical structures like the superconducting quarter-wave resonator (QWR). After several years of these difficulties in our retrofit QWR, a Freon-discharge surface-processing method [10] was found that has been universally successful in eliminating multipactoring in all types of lead-copper resonators. The treatment takes only a few minutes and can be done *in-situ* directly in the linac cryostats.

Linac upgrading programs

As originally conceived the 150-MHz superconducting linac was to provide acceleration of ~20 MeV per unit charge from 16 low-β (β=0.055) split-loop resonators (SLRs) in four modules and 24 high-β (β=0.10) SLRs in eight similar modules, all operating at a design accelerating gradient of 3.0 MV/m. (The low-β SLRs are 14 cm in inside length for a total of 2.24 meters and the high-β SLRs are 22 cm long for a total of 5.28 meters. The estimated energy gain further assumes a synchronous phase angle of $\phi_s = -15°$ and an average transit-time factor of ~0.9.) The installed linac did not reach this full energy potential largely because of three significant deficiencies: 1) inadequate delivered cooling of only 3–4 watts per resonator *versus* an expected 6–7 watts; 2) excessive vibration in the low-β SLRs with the full linac in operation, limiting their accelerating fields to ~1.5 MV/m; and 3) inconsistent performance results from the original sequence of high-β SLR platings.

The cooling problem was addressed in 1986 by rebuilding the U-tubes feeding the modules and changing the J–T expander in the helium plant to a Koch-Fermilab wet expander [11]. After these improvements some 6–7 watts per resonator has been routinely available. Further improvement to as much as 9–10 watts per resonator might be possible in the future, since some 40% of the ~500 watt plant capacity is still lost somewhere in the distribution system.

The development of the very rigid superconducting quarter-wave resonator (QWR) in 1983–84 [3, 4] made it possible to deal with the low-β problem by retrofitting $\beta = 0.068$ QWRs into the four low-β modules [12, 13]. The retrofit plan was complicated by the need to fit the taller QWRs into the same cryostat space as occupied by the SLRs. This dictated a more involved cooling system with four small tightly connected helium tanks in place of the previous single large one. Significant capacitive loading in the beam gaps was also needed to keep the resonator height down. This flat gap design and the relatively low β value results in an unusually large E_s/E_a ratio of ~7. On the other hand the massive tapered stem in this QWR gives very great rigidity (Δf < 1 Hz) and a low peak magnetic field of 85 G at 1 MV/m. As part of the retrofit the cryostats are also modified extensively, for example to bring the coupler and tuner motors out of the vacuum space [12].

Three of the four retrofitted modules are now in operation, and the fourth will be installed early next year. QWRs in modules 2 and 3 regularly operate at accelerating fields E_a of 3.0–3.5 MV/m with 6–8 watts dissipation [13]. (Energy gain of 0.51–0.60 MeV per charge at optimum velocity.) Operating fields in the first (prototype) module are not as good, only about 2.0–2.5 MV/m, largely because the plating techniques were not as advanced at the time. The new QWR modules have had an especially favorable impact on linac performance for relatively fast beams like carbon and oxygen, on account of the much broader transit-time factor curve of the 2-gap structure.

When the linac was built up in 1981–83 the copper resonators received from Cal-Tech were immediately plated with lead and installed in cryostats without individual tests. (Some resonators were rejected and replated based on subjective appearance.) The result of this no-test approach was that the average 6-watt accelerating fields in high-β modules 5–9 were significantly lower than in the final three modules 10–12, ~2.1 MV/m *versus* ~2.7 MV/m. All of the best resonators were in these final three modules, but only two resonators out of the 24 exceeded the 3.0 MV/m design goal [1]. (A similar performance up-trend with plating experience has been noted during the recent installation of the Legnaro heavy-ion linac [14].) Thus with the QWR retrofit project nearing completion it was decided to systematically refurbish (replate) all eight high-β modules with the goal of achieving at least 3.0 MV/m in *every* resonator. As the modules are removed some necessary improvements to the rf couplers and the cryostat are also being effected.

First results of the SLR refurbishing program are presented in some detail in a separate paper [15]. These initial results have been quite encouraging, with stable on-line operation at 3.0–3.5 MV/m for 6–8 watts of cooling achieved in all three resonators. (Energy gain of 0.66–0.77 MeV per charge at the $\beta = 0.10$ optimum velocity.) An unexpected result of the thermometry studies [15] is that losses on the outer shell of the SLR from indium joints, couplers, etc. are essentially negligible (only about 5% of total losses). Field emission was also shown not to be a fundamental limitation out to at least 4.0 MV/m. Instead the SLR seems to be limited simply by rapidly increasing cooling requirements as the Q curve falls off with increasing E_a (and H_s). For this reason future efforts will focus mainly on trying to improve the superconductor quality on the high magnetic field portions of the loading arms.

Superconducting RFQ

The advantages of the radio-frequency-quadrupole structure for simultaneous focussing and acceleration of very slow ions ($\beta < 5\%$) are well known. A practical superconducting RFQ (SRFQ) could combine these features with low power consumption, thus allowing straight-forward cw operation at low energy cost. A sequence of short SRFQs could for example efficiently accelerate highly-charged ions from an ECR source up to the minimum velocity of $\beta \simeq 5\%$ needed for a conventional heavy-ion linac [16]. Motivated by these considerations a modest SRFQ development effort has been underway at Stony Brook for several years. The project is in part a collaboration with INFN-Legnaro, which plans such an ECR-SRFQ injector system for its ALPI heavy-ion linac [14].

The concept of a sequence of independently-phased short modular SRFQ devices was introduced by Ben-Zvi in 1989 [17]. This idea was subsequently refined and elaborated by Ben-Zvi, Lombardi and Paul and applied to the specific case of a pre-injector for slow heavy-ions with q/A as small as 1/6 (Pb^{35+}) [16]. It was decided to build and test the third of the six "RFQlets" described in Ref. [16] as a demonstration device. The table below gives the rf properties of the SRFQ, while Fig. 1 shows how it looks.

Experience with the rf design, fabrication and testing of the SRFQ is described in Ref. [18]. The design goal accelerating field of 2.0 MV/m was set by an assumed maximum surface field E_s of 15 MV/m. In the initial tests the resonator easily reached $E_a = 1.3$ MV/m, but above this field was limited by a thermal breakdown attributed to flaws in the copper material (which was not all OFHC type). It is significant however that even at 1 MV/m in these preliminary tests the SRFQ produced substantial acceleration of 0.55 MV per charge for a helium dissipation of only one watt.

Frequency f	57.4 MHz
Modulation m	4
Aperture a	15 mm
Overall inner diameter L	55.6 cm
Optimum velocity β_o	0.030
Intervane voltage V^*	420 kV
Energy content U^*	3.9 J
Peak electric field E_s^*	15 MV/m
Peak magnetic field H_s^*	360 G
Geometrical factor Γ	22 Ω

* At the 2 MV/m design accel. field

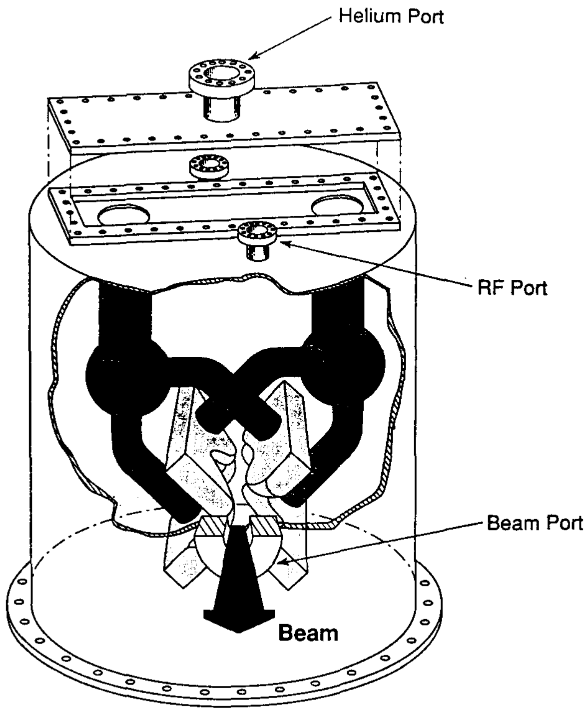

Figure 1: Cut-away view of the prototype superconducting RFQ. The overall diameter is 56 cm.

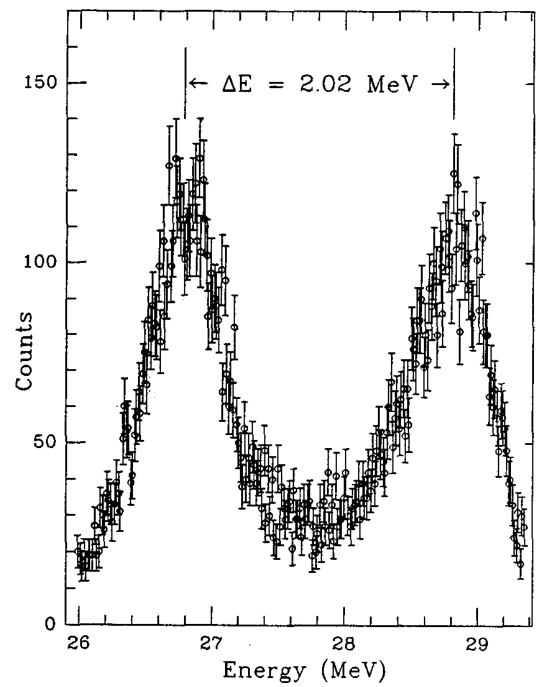

Figure 2: Energy spectrum showing acceleration and deceleration produced by the SRFQ.

The first of a planned series of SRFQ beam tests was recently conducted with $^{35}Cl^{6+}$ beam from the Stony Brook tandem Van de Graaff injector. The 28-MeV energy initially selected corresponds to velocity $\beta = 0.041$, slightly above the anticipated peak of the SRFQ transit-time-factor (TTF) curve. Also the beam charge-to-mass ratio $q/A = 1/6$ matches the design value for this parameter. As the target room chosen for the tests was not on the regular linac injection path, it was not possible to get a cleanly pulsed beam without dark current. Therefore a cw beam was used, averaging over all incident phases. The energy modulation of the SRFQ was measured by scattering beam particles from a gold foil into a surface barrier detector. This energy detector and a sensitive beam viewer were each ~2.5 meters downstream from SRFQ.

Figure 2 shows the resulting pattern of random acceleration and deceleration. (This spectrum is the first reported example of actual beam acceleration by a superconducting RFQ device.) The measured acceleration is consistent with the expected TTF $\simeq$ 0.75 and the separately estimated resonator field of ~0.50 MV/m. The quadrupole component of the resonator field was readily demonstrated in these tests by observing a defocussed beam quickly come to a focus and then become defocussed again as the resonator field was turned up from a low value. In future tests the various focussing and acceleration affects will be studied in more detail as a function of beam velocity.

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