REMARKS ON LOW β STRUCTURES AND ACCELERATORS USING LEAD TECHNOLOGY*

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Lead Technology, Q, Losses

Although the Pb technology was abandoned about 10 years ago almost everywhere but Caltech, it is still very much alive at least for low β, low frequency structures, and it seems that a majority of superconducting heavy-ion accelerators now in operation, construction or design stage use or are expected to use Pb.

It is very encouraging to know that the Pb technology is still quite far from theoretical predictions, and that there is a lot of room left for improvement. Little fundamental work or great breakthroughs have been achieved since the late 70s on Pb. At that time, it was recognized that the Pb technology was good enough to build a real machine, and all efforts were diverted toward construction which resulted in the Stony Brook booster. Now that Stony Brok is running, and has demonstrated that Pb is a viable superconductor, it is time to pause and explore various directions for improvement.

The last major breakthrough, and probably the one that made the Pb technology viable was the use of slow chemical polishing to remove about half of the 10 μ electrodeposited, leaving a smooth surface and greatly reducing field emission. Unfortunately, the polishing part of the whole process is by far the trickiest and the least predictable. If a plating procedure could be found that would duplicate the polished properties on a plated surface, the Pb technology would be even more attractive. One direction that might be worth exploring is in the preparation of the copper base. The best results obtained on Pb (although at low field) were more than a decade ago on resonators which were first electroplated with Cu. Recently, work was done at the Weizmann Institute, Stony Brook and the University of Washington on plating using warm chemicals; the results seemed encouraging, but since the surfaces were subsequently chemically polished, it is difficult to estimate the effect of using warm chemicals. To our knowledge, no systematic work has been done on using ultra pure chemicals for Pb plating, and it may be the time to do it.

Many things can still be tried to improve the Pb technology. Unfortunately, there is still a certain amount of unpredictability in plating and polishing a resonator, and the variability within a procedure is usually almost as large as it is between different procedures. Furthermore, the correlaion between appearance and performance of a plated surface is still limited, and one must actually do a cryogenic test. All this tells us that doing a conclusive systematic study of the plating process, changing one parameter at a time, might be very time consuming and expensive. In purely economic terms, forgetting the scientific aspect, the point of no return may have been reached or may be reached soon. I hope to be wrong and that somebody will find something simple that will reduce the losses by a factor of 2.

As I said earlier, no fundamental work on the nature of the high field losses in low frequency Pb structures has been done in quite a while, and why they are what they are is still a mystery.

Recent work on quarter-wave resonators indicates that their Q stays constant to higher fields that in split-rings where the Q drops more gradually. One possible explanation is that the quarter-wave has a lower peak magnetic field than the quarter-wave. I am more inclined to think it is due to the absence of a normal current carrying joint. A Pb gasket is presently being developed at ASI for split-rings, and we may be able to answer that question soon.

Losses are, of course, still variable; however, for the most common structures now in operation or development, namely 150 MHz, $\beta \sim$ 0.1, quarter-waves or split-rings, 8 W provide about 0.7 MV. At that level, the Q is already quite field dependent and X-Rays are present.

Half-Wave Resonators

The work done at Caltech over the last two years on structures was on half-wave resonators. Half-waves look similar to quarter-waves, but have two resonant elements instead of one.

The reason half-waves were chosen was mostly of economic nature. The cost of a heavy-ion booster (once the superconductor has been chosen) is almost a linear function of the number of resonators used, irrespective of the nature of the resonator, its or frequency. Although its transit time factor is somewhat more peaked, for the same capital cost, a half-wave would provide about twice the energy gain at less than twice the power dissipation than a quarter-wave. Another advantage is that the currents through the joint at the bottom plate would be almost totally eliminated since the charges would oscillate within that plate. This would allow bringing the bottom plate closer to the drift tube and simplify the frequency tuning.

The resonator which was designed and built, but not yet cryogenically tested, has a frequency of 225 MHz and β =0.16. These parameters were chosen to have a resonator of manageable size. For actual use in boosters, 225 MHz should be reserved for βs higher than 0.2; at lower β the frequency could be 150 MHz.

Most of the development effort was on design software for resonators with straight inductors (half-waves and quarter-waves). The design is split in 3 parts: inductor design, drift tube design, and merging of the two. The inductor design software generates all the center conductor profiles with constant peak magnetic field. At every point of every profile, the program generates the required loading capacitance to obtain the wanted frequency, the voltage for a given peak magnetic field, and the shunt impedance. The drift tube design software is more interactive in that the goal is to find the shape of minimum peak electric field and minimum capacitance. In the third part, given the drift tube design, the inductor profile, which maximizes the shunt impedance, is chosen. This profile is design field dependent in that the surface resistance can be field dependent, and the profile which has the highest shunt impedance usually has a high surface magnetic field for a given drift tube voltage.

Following this design, a half-wave copper resonator was built and tested at room termperature, and the design package was found to be very accurate. For example, the frequency was found to be less than 0.5% from the design frequency.

Looking toward the future or toward lighter ions, work is beginning at ASI on a β=0.28, 225 MHz half-wave resonator.

Very low β resonators

Structures with β=0.050 or less tend to be more difficult to build than those of higher β ; at least that was the experience on the Stony Brook booster.

Early this year, under a grant from the NSF, Small Business Innovation Research Program, work began at ASI on a β=0.045, 150 MHz split-ring resonator. This resonator is different from the Stony Brook split-ring in that the inductor cross-section is non-constant, being larger in the stem region than in the drift tube region; and non-circular in regions of high magnetic field. Such a design should greatly improve mechanical stability and reduce the peak magnetic field. In parallel, more theoretical work was done on the electronic stabilization of very low β resonators and on their electromagnetic design.

At a more preliminary stage, work was done, also at ASI, on much lower β resonators (down to β =0.01). These resonators would be two gap structures and would operate in the harmonic region. By alternatively using resonators with slightly different βs so the zeroes of the transit time factor of one resonator corresponds to the maximum of the transit time factor of the other, these resonators would be usable deep inside the harmonic region, with each type of resonator providing a way to traverse the points of no acceleration of the other. These resonators would allow capture of very heavy ions from an electrostatic accelerator, deceleration to low velocities with the ultimate goal being the elimination of the need of an electrostatic accelerator as injector into a LINAC.

Electronic Control

Electronic stabilization of low β structures is now relatively straightforward whether it is done by reactance switching PIN diodes or negative feedback. Both methods now work reliably. The negative feedback stabilization method provides smaller residual phase error and may be more elegant, but, because of the RF power requirement, is limited to mechanically quiet resonators with small energy content.

Although phase stabilization is now very easy , much work remains to be done in integrating all those resonator controllers into a coherent accelerator control system which can handle a new ion species, charge state or output energy almost instantly. Furthermore, bringing up a resonator from first power up to the point where it can be phase locked (multipactor processing, power conditioning, etc.) still requires a lot of operator involvement. The challenge left is not in designing phase stabilization electronics, but designing an integrated booster control system, both in hardware and software, that would allow one or two operators to bring a large number of resonators from first power up through all the stages of processing and conditioning to the point where they are locked with the appropriate amplitude and phase profile through the booster for a given ion species.

Booster design and economics

The numbers that will be quoted are typical for boosters built in the U.S. using the Pb technology. They may be different in other parts of the world or with a different technology, but the relative magnitude and the conclusions should be accurate.

A typical booster costs about $100,000 per resonator. This includes the cost of the resonator, plating, coupler, tuner, stabilization and power electronics, instrumentation, a fraction of the cryostats, stands, vacuum, etc.

The cost of operation of a booster is about $25 per resonator per 24 hour day when run at fairly high power level (8 W). This includes the refrigeration cost, power for electronics, pumps etc., liquid nitrogen, and some manpower.

This indicates that capital costs are of the order of 4000 days running continuously for 24 hours. For average use, this may be 30 years, certainly more than the expected life time of the machine. Even for universities where it is sometimes easier to get construction funds than operating funds, its seems like a very long time.

In that light, it now may be time to stop thinking in terms of resonators and decreasing their power dissipation and more in terms of decreasing capital cost. This probably means trying to reduce the number of resonators to achieve a given capability; in other words, trying to maximize the energy gain out of each resonator.

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