MULTI-STUB SUPERCONDUCTING RF RESONATORS FOR THE ANU HEAVY ION ACCELERATOR

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Abstract

An upgrade of the LINAC at the ANU will rely upon the proven success of Pb/Sn plated split-loop-resonators (SLRs), which perform at accelerating fields of 3.5 MV/m. The SLRs will be combined with 21, two and three-stub resonators, of novel and efficient design. The multi-stub resonators have demonstrated adequate frequency splitting of the accelerating and other modes and feature a demountable stub assembly joint with acceptably low currents. Superconducting RF activity in the last two years has been targeted on improving the performance of the 12 SLRs by re-plating with Pb/Sn and on the optimisation of the two-stub resonator (DVOIKA) using Mafia/MWS software, REF [1,2], in collaboration with FZJ, Juelich. A pre-prototype two-stub resonator was manufactured and is ready for cold test. The development work and current status for DVOIKA cavities is discussed and the extension of these concepts to a three-stub resonator (TROIKA) is flagged.

INTRODUCTION

The acceleration of ions of a wide range of elements to velocities between 1% and 20% of the speed of light, β of .01 and .20, has been a challenge that has spawned a host of technical solutions that increasingly are being developed and refined. The reason for the intense work worldwide in this field is that heavy-ion accelerators are being used in an ever-widening range of fields.

At the Australian National University we have developed, over the years, an accelerator facility used for diverse research. This comprises a 15 million volt electrostatic accelerator, followed by a superconducting linear accelerator (LINAC), which boosts the beam energy further. ANU will develop and construct multi-stub accelerator modules which will make use of the existing infrastructure of liquid He reticulation and beam-lines and will double the capability of the present LINAC [3,4].

The Heavy Ion LINAC is currently equipped with twelve β = .10 SLRs so only ions up to mass ~60 match adequately the resonator electrode separations. The physics program, however, demands heavier ions whose velocities at injection is β = 0.03 to β = 0.06, so resonators for this range must be obtained. A set of resonators matched to of β = 0.06 would extend the accelerator system mass range from the present limit at ~60 atomic mass units (amu) to ~100. A set matched to β = 0.03, would extend the range to ~ 240 amu.

The multi-stub resonators are the natural evolution of inter-digital low β resonators at the heart of the specialized, low velocity LINACs crucial to rare isotope accelerators - the next big step in nuclear science [5]. The two and three stub resonators not only have all the advantages of the inter-digital resonator but also offer substantial improvements in cost and in the accessibility of appropriate technology in Australia.

MODELLING MULTI-STUB RESONATORS

The multi-stub resonator project has built upon successes with fabrication and use of single-stub quarter wave resonators and split loop resonators in our operating LINAC. The project exploits and develops our expertise in coating complex shapes with superconducting films of both niobium and of lead. The innovation of minimising the current in the demountable joint has already been demonstrated in full-scale models of the two-stub and three-stub resonators. These models have also demonstrated control over the frequency splitting of the principal modes enabling exploitation of the accelerating mode. The two-stub resonator is a suitable preliminary step in the conceptual and technical development of the three-stub model and draws upon the precedents of split loop [6] and half wave [7] resonators.

Design Goals

A goal of superconducting cavity design is to achieve the minimum ratios of peak electric and peak magnetic fields, E_p and B_p, to accelerating field E_{acc}. Our goals were the commonly accepted reasonable values [8] of E_p<30-35 MV/m and B_p<60-70 mT and B<1 mT at the demountable RF joint.

The magnetic field in DVOIKA's demountable RF joint is not uniform. It is near zero in the area facing the valley between stubs and reaches the maximum, B_{max}, 90° degrees away. The design goal for magnetic field in DVIOKA's gasket B_{g_max} = 1.7 mT will cause about the same heating effect as in a gasket in uniform field of $B_{g\_uniform}$ = 1 mT. The conductance of heat from the gasket to LHe bath should also be adequate to prevent overheating of the superconducting layer adjacent to the gasket area.

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The conceptual design of the multi-stub resonators has been validated though model tests. It now has to be optimised:

1. to get the most acceleration for the smallest peak surface electric field,
2. to ensure that the peak current density is below the limit of the superconducting film,
3. to adjust the geometry to balance the image currents in the resonator wall, equalise stub to end-plate capacitances
4. to ensure adequate splitting of unwanted principal-modes.
5. to minimise the RF current in the gasket areas.

The next stage of development is to ensure that the stub assemblies are stiff enough that mechanical vibrations do not interfere with operation and that adequate liquid helium cooling can be provided. These issues have been successfully addressed in principle for the $\beta = 0.06$ resonator in recent work [9], but need to be revisited as the design evolves and extended to a $\beta = 0.03$ three-stub resonator and ultimately to a $\beta = 0.01$ version.

MAFIA/MWS SIMULATIONS OF DVOIKA CAVITY

For calculations of radio-frequency cavity parameters, two complementary numerical program codes, MAFIA [1] and Micro Wave Studio (MWS) [2], have been used since each program has its own features and simulation accuracies, so the use of two codes provides complementary views.

The main difference between MAFIA and MWS is their mesh generation. MAFIA uses a manual square mesh, which makes spline geometry descriptions inconvenient but allows control of the geometry in important places like the surfaces with the peak fields. MWS has a very powerful automatic geometry generator that allows the creation of very complicate shapes. However, the lack of control over mesh geometry results in too a coarse mesh in high field regions.

RF Losses in Demountable Joints

The proposed multi-stub structures have one joint between the outer wall and the shorting plate and one joint between the tuner plate and the outer wall. These facilitate construction and coating of the resonator surfaces. Multi-stub resonators intrinsically impose minimal currents on these joints and our design allows control even over these. We wish to eliminate electron beam welds because a convenient facility is not locally available and electron beam welding of copper often results in micro-cracks, craters, hidden voids and material projections.

Supporting Stem for DVOIKA

The original role of the supporting stem between the shorting plate and the ends of the stubs, was to lower the quarter wave mode frequency keeping it away from the accelerating mode. A secondary, but important role of the stem is to reduce the current in the demountable joint between the shorting plate and the resonator wall. A straight cylindrical stem succeeded in both respects, however, increasing the diameter of the stem where the stubs meet and decreasing it at the shorting plate, achieved even better attenuation of the gasket current (or magnetic field). Figure 1 shows the larger diameter section of the stem, now a flange of width "TH" with a gap "W" to the resonator wall. The smaller diameter portion of the stem is "H" long.

Keeping the overall dimensions L and D constant while scanning H, TH and W in turn optimises the design.

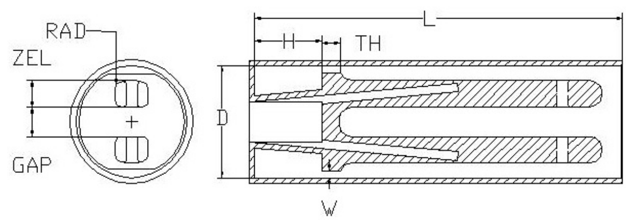

Figure 1: A design of the stem flange.

The mechanism by which the stem flange attenuates the gasket current is not clear. The mirror currents in the wall, due to the two stubs, flows in opposite directions and, in principle, can cancel in the wall without traversing the gasket. In practice though, some small gasket current remains. The stem flange seems to concentrate the current in the can walls well away from the gasket thus reducing the residual gasket current. This effect is strengthened as the gap W is decreased and stub length H is increased.

The target value of $B_g/B_p< 2\%$ is achievable for TH > 30 mm and H > 120 mm. The corresponding distribution of the B-field in RF gasket region is shown in figure 2.

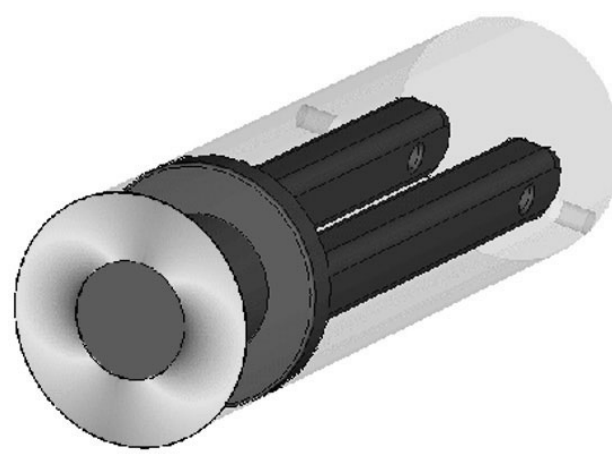

Figure 2: MWS B-field distribution in gasket region with a cylindrical stem flange. The green areas have low magnetic field.

The current distribution around the gasket is a maximum adjacent to the stubs and is small in between the stubs. Mafia simulations confirmed that cuts to edges of the stem flange parallel to the beam axis, do not affect B_g/B_p, as seen in figure 3. Thus the low B field regions of the flange can be cut away to allow better vacuum pumping.

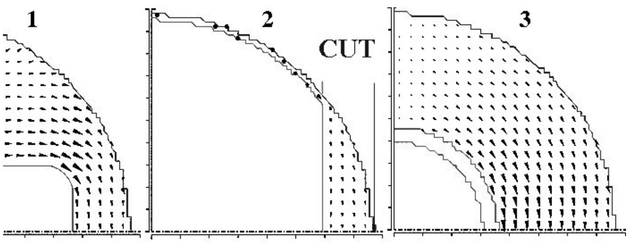

Figure 3: Magnetic fields for a CUT = 10 mm **1**, in the stub region 10 mm from the stem flange, **2**, through the stem flange and **3**, 5 mm from the stem flange and 115 mm from the shorting plate.

In figure 3, view 1 is the magnetic field cross-section 10 mm on the stub side of the stem flange. View 2 is through the flange and view 3 is 115 mm from the flange and 5 mm from the shorting plate. Although a CUT is 10 mm corresponds to the minimum ratio of B_g/B_p = 1.9%, the sensitivity of B_g/B_p to CUT > 10 mm is weak. In the final design, the value of CUT~ 20 mm still keeps B_g/B_p < 2%. The same considerations and features will be incorporated in the TROIKA design.

CAVITY OPTIMIZATION

Peak Surface Electric Field

An important parameter of a superconducting cavity for use in an accelerator is the ratio of peak surface electric field to the accelerating field E_{pk}/E_{acc} because field emission remains the major factor limiting performance. The MWS calculated electric field distribution in DVOIKA is shown in figure 4. The peak surface electric field occurs at the end of the each stub. It depends on the radii of curvature at the end of the stub and on the stub RAD (see figure 1). It also depends on the size of the gap between the ends of the stubs and the tuner plate.

RAD =16 mm produces the minimum in E_p/E_{acc}, 5.0 for MWS simulations or 3.9 for Mafia simulations. For both simulations, increasing RAD from 10 mm to 16 mm resulted in a 15% reduction of E_p/E_{acc}. However increasing RAD >18 mm, causes a rise in E_p/E_{acc} as E_p moves from the ends of the stubs to the region between stubs and beam holes in the can. At radii above 16 mm there is insufficient room in the stubs to adequately radius the edge of the beam holes.

Peak Surface Magnetic Field

The peak surface magnetic field is another important design parameter since it determines the point at which the superconductor goes normal. This design aspect is expressed as the ratio of peak surface magnetic field to accelerating field B_p/E_{acc}. The MWS calculated distribution of magnetic field in DVOIKA is shown in figure 5.

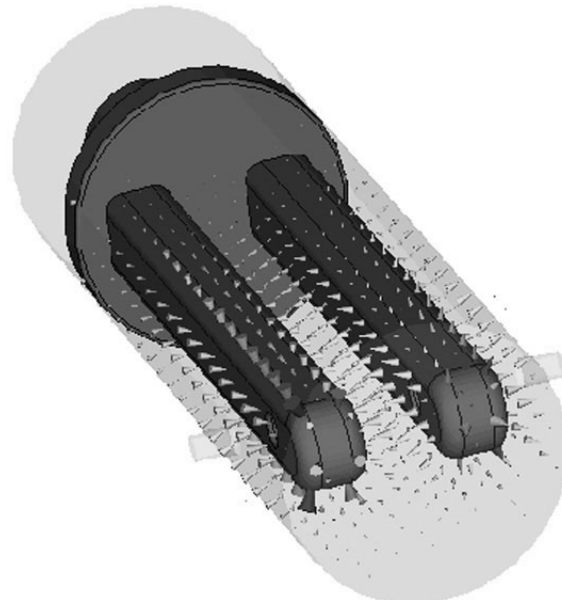

Figure 4: MWS simulation of the electric field distribution in DVOIKA with RAD = 16 mm.

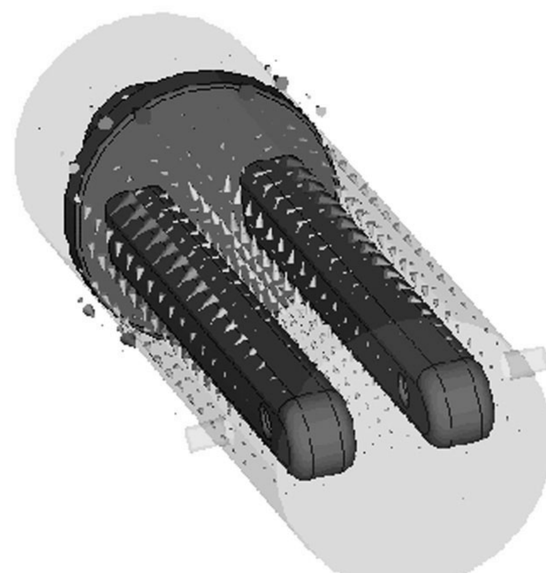

Figure 5: Magnetic field distribution in DVOIKA. MWS simulations for RAD = 16 mm.

The maximum B field occurs where the stubs meet the stem flange and it is quite sensitive to the size and shape of the conductors and in the stem flange gap geometry. Although the stubs can be made smaller at the beam bore and larger at the base to allow the current to spread over a wider area reducing the magnetic field, this introduces negative effects. Unfortunately, the cylindrical shape of the outer wall does not leave much room to vary the geometry of the stub in the base region. Increasing the cross-section of the stubs, results in a decrease of already limited space for B-field. Another parameter to change to minimise the peak magnetic field is the curvature of the stub. Increasing the radius of the stub RAD not only opens up more space for the B-field but importantly, makes more uniform, the field around the circumference thus lowering the peak field. A typical ratio B_p/E_{acc} of 17.2 mT/MV/m was calculated for RAD = 16 mm with the MWS simulation while the Mafia simulation calculated the ratio as 12.8. For both calculations, increasing RAD from 10 mm to 18 mm produced only a 10% reduction in B_p/E_{acc}. Thus the adopted value of RAD = 16 mm is acceptable.

The results of Mafia and MWS numerical simulations of DVOIKA cavity are summarised in the Table for RAD = 16 mm.

Table 1: DVOIKA RF parameters

	MAFIA	MWS
Frequency, MHz	150	-
Geometry Factor, Ohm	15.7	-
Stored Energy, mJ/(MV/m)^2	-	76
TTF	0.92	-
E_p/E_{acc}	3.9	5.0
B_p/E_{acc}, mT/(MV/m)	12.8	17.2
B at the RF shorting plate gasket joint	1.2 mT	-

MWS gives higher values for the peak fields and even a higher cavity resonance frequency than does Mafia. However, MWS peak field result may not be as reliable due to auto-mesh generation. The main advantage of MWS is its capability for very fast simulations with excellent graphical representation. Therefore Mafia calculations must accompany MWS simulations in order to take into expose artefacts due to the auto-mesh generation.

Cavity Tuning

Frequency tuning is accomplished by deflecting the tuner plate towards the stub ends using a stepping motor driven lever. The same reliable tuner mechanism is employed in ANU QWRs. The device has backlash of about 10 Hz at critical coupling, which is not detrimental to operation. The end plate is less than 0.5 mm and may be deflected up to 2 mm for a tuning range of 40 kHz. A tuning sensitivity of 20 kHz/mm is achieved at tuning gap of 35 mm. For this tuning range and sensitivity the peak magnetic field at the tuner plate joint <1 mT as is the case for the RF gasket joint at the shorting plate.

STRUCTURAL ANALYSES

Instabilities in the electric field amplitude and in the phase due to microphonics are addressed by the RF control system. The resonator's mechanical resonance frequencies must be as high as possible in order to minimise coupling to low frequency ground and machinery vibrations. In DVOIKA, the goal was for the lowest mechanical mode frequency to be > 100 Hz, a commonly accepted reasonable value.

Finite element structural analyses identified the two lowest mechanical modes. One is an axial bending mode of the stubs in which the drift tubes move in the same direction along the beam line. The second is a traverse-bending mode of the stub where the drift tubes move together in a plane perpendicular to the beam axis. Since the stubs themselves and the stem and stem plate are quite stiff, the lowest mode frequencies are dominated by distortion of the shorting plate. By increasing the thickness of shorting plate from 10 mm to 17 mm, the axial mode was raised from 51 Hz to 73 Hz and traverse mode from 53 Hz to 82 Hz. Further increases in the thickness of the shorting plate and/or adding strengthening ribs, can further raise the mode frequencies. An infinitely stiff shorting plate would result in a minimum frequency of 150 Hz.

FUTURE EFFORTS

We continue R&D efforts to develop TROIKA, a three-stub accelerating cavity. In addition, extra work is planned to finalise and optimise the DVOIKA cavity. In particular, significant efforts will be devoted to investigations of multipacting, balancing the forces on the stubs by computing the net electrostatic force on the drift tubes, investigation of and if necessary, correction of beam steering effect.

CONCLUSION

DVOIKA and TROIKA resonators are adopted as the technology of choice in the ANU LINAC upgrade over QWRs because:

i) they have more acceleration per resonator through having two and three active electrodes instead of one as in QWR based resonators,

ii) they have low power losses because of low current in the demountable joints and

iii) they are cheap to manufacture using sputtered niobium instead of electron beam welded niobium or copper.

The resonators will extend the mass range and thus research opportunities for the Heavy Ion Facility at the ANU servicing a national and international community of researchers.

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