SUPERCONDUCTING RF CAVITY FOR HIGH-CURRENT CYCLOTRONS

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Abstract

A novel superconducting cavity is presented for use in high-current cyclotrons. The cavity is an extrusion of a 2-D double-quarter-wave structure, in which the ends of the extrusion are wrapped around and joined so that the cavity has no end perturbations. Power is applied via a linear array of input coupling loops, so that an rf sheet current is launched in a laminar flow that matches the distribution of power coupled to the orbits. Each loop is driven by an independent solid-state rf source. A strategy is presented for using to advantage the independent control of phase and amplitude of the drive array to suppress transient phenomena. Longitudinal modes can be strongly suppressed. These provisions are of importance to suppress rf phenomena that can limit beam current.

INTRODUCTION

A superconducting strong-focusing cyclotron (SFC) is being developed for high-current applications [1]. Our primary motivation in developing the SFC is for its use as a proton driver for ADS fission [2]. Proton beams are used to drive fission in a molten salt core, fuelled entirely from the transuranics extracted from spent nuclear fuel (SNF). One SFC stack can drive 12 80 MW_{th} cores, and destroy all of the transuranics and long-lived fission products produced by a conventional GW_e power reactor. This capability, unique among the many methods for fission, offers the opportunity to close the nuclear fuel cycle and provide a path to green nuclear energy.

The SFC incorporates four innovations. Superconducting quarter-wave cavities are used to provide >20 MV/turn acceleration. The orbit separation is thereby opened so that bunch-bunch interactions between successive orbits are eliminated. Quadrupole focusing channels are incorporated within the sectors so that strong focusing alternating-gradient transport is maintained throughout. Dipole windings on the inner and outer orbits provide enhanced control for injection and extraction of bunches. Finally each sector magnet is configured as a flux-coupled stack of independent apertures, so that any desired number of independent cyclotrons can be integrated within a common footprint.

Preliminary simulations indicate that each SFC should be capable of accelerating 10 mA CW to 800 MeV with very low loss and >50% energy efficiency.

SRF CAVITY FOR ADS

Like all high power cyclotrons the power is delivered to the beam by RF cavities. Conventionally cyclotron cavities are made of copper. Copper cavities have modest Q and therefore dissipate an enormous amount of structure power if driven to produce the >10 MV/m CW needed for the SFC. For example, the four PSI cavities dissipate ~ 2 MW [3], and the ADS with Cu cavities would dissipate 20 MW of power for 40 cavities.

For SFC, it is necessary to use superconducting cavities to reduce losses and make the machine more energy efficient, but there is limited experience with superconducting cavities in cyclotrons, and in stretched geometries. The only previous example that we know is the Triton cavity, a Pb/2%Sn electroplated cavity. These cavities were able to reach 1.1 MV at 5 K with a Q of $1.5*10^8$ [4].

For SFC we will use Nb as the superconducting material. Niobium's T_c is 9.2 K, has critical magnetic field near 150 mT at 4.2 K, and is made in formable sheet.

The limiting criterion for cavity design is the maximum magnetic field at the surfaces. We chose a surface field criterion of 54 mT for design optimization. This choice is comparable to other large cavities [5, 6].

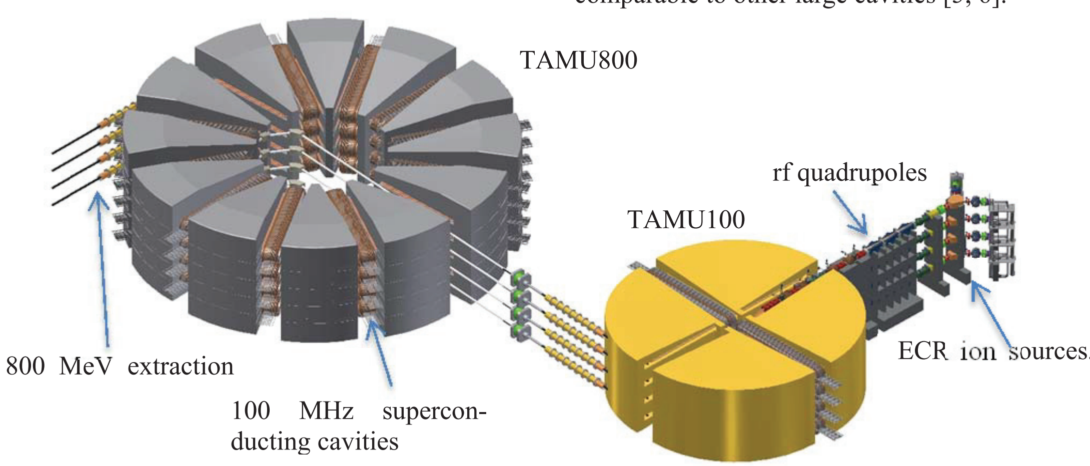

Figure 1. The Strong-focusing cyclotrons, showing the injectors and the main ring for a flux-coupled 4-stack.

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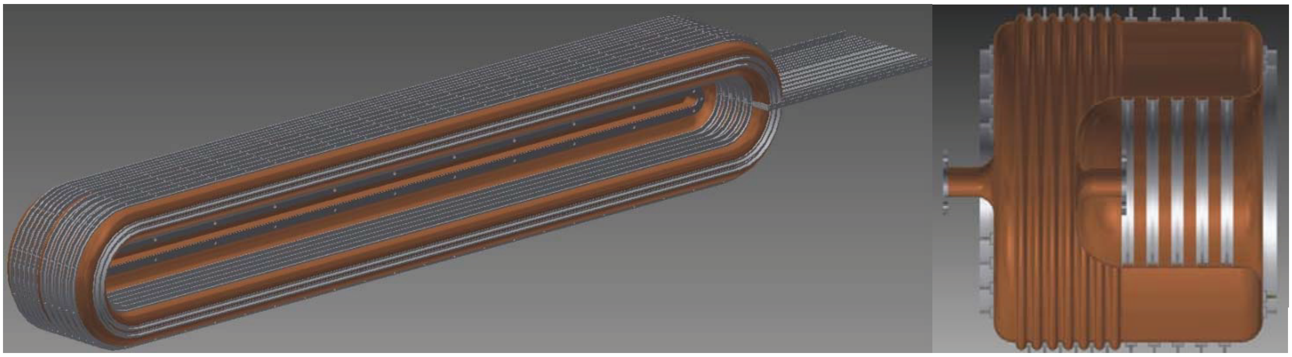

Figure 2: The ADSMS SRF cavity for the 800 MeV cyclotrons. The rounded ends provide a flatter field profile by coupling the magnetic field between the top and bottom half. The 5.58 m width also requires 10 independent power couplers to be distributed across the length, 5 on top and 5 below. On the right is the cross section of the 800 cavity. The undulations reduce multipacting as shown in the paper by [4]. The closed loop cryogenic cooling channels (gray) are also used as the support structure thereby eliminating the need for a pool boiling cryostat.

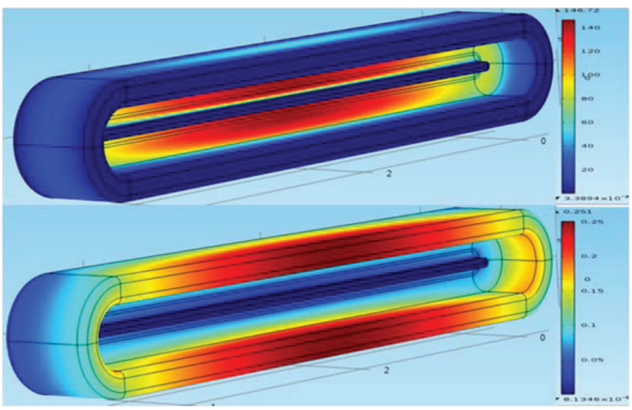

Figure 3: The upper image shows the electric field on the cavity surface. The maximum field on the surface occurs on the iris and reaches 25 MV/m. The bottom image is the magnetic field concentration in the cavity with a maximum surface value of 54 mT.

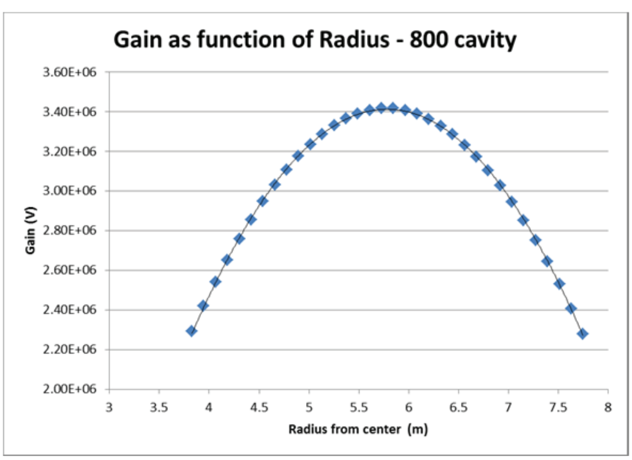

Figure 4: This plot show the voltage gain as a function of the location within the cyclotron. An energy gain of 2.3 MV is achieved at injection and extraction. A maximum gain of 3.4 MV is achieved at the center of the cavity. These gains take into account the transit factor and phase shift.

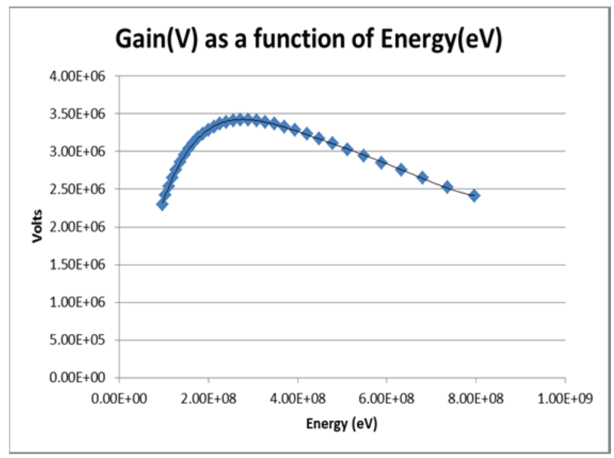

Figure 5: The gain as a function of energy

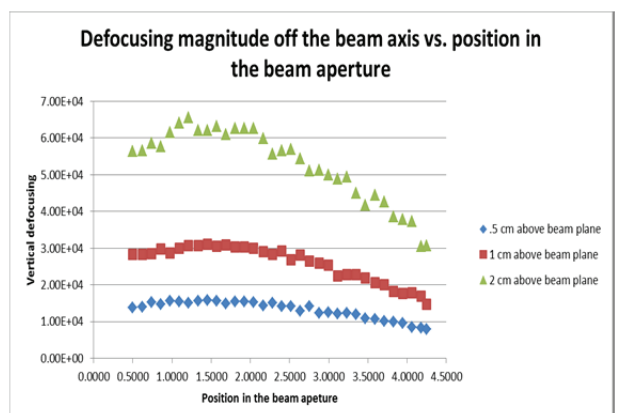

Figure 6: The integrated defocussing effect in Volts of the 800 cavity is shown above for varying distances above the beam plane. Several values are shown as a function of the position within the cavity. Adding 3.327 m to the position indicate the location within the cyclotron.

This cavity has several interesting features compared to other SRF cavities. The first is its sheer size. The slot aperture is 4.75 m across. The central 3.75 m portion is used for the beam orbits. The reason for the additional aperture is to move the lower and the higher order modes further from the resonant frequency and to increase the

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gain. With the modeling that has been accomplished of the cavity, the closest modes (deflecting modes, one horizontal and one longitudinal) occur at 93 MHz and 106 MHz. We are beginning the simulation of an entire beam envelope assembly for one cyclotron.

We are evaluating 3 methods to suppress these modes. The first method is to minimize the length of the superconducting portion of the beam pipe; the rest of the tube will be made of Cu-clad stainless steel that will damp the modes strongly. The second method of beam tube mode suppression is to place resistive material in recessed strips in the beam aperture parallel to orbits. The resistive strips would be invisible to the accelerating mode, but would strongly decrease the Q of the beam pipe modes.

The second unique feature is the re-entrant ends of the slot cavity. The rounded ends magnetically couple the top and bottom halves of the cavity. PSI, the highest power cyclotron/accelerator, uses a copper cavity that is of is ~4 times larger in volume and has the standard flat ends. By the boundary conditions the accelerating field must vanish at those faces, which leads to a strong decrease in gradient near the ends. For this reason cavity slot must be about twice the span of the orbits that are accelerated. By adding the rounded ends of the cavity the boundary conditions no longer suppress the accelerating mode at the ends. If a cavity with same side profile (Fig. 2) had flat ends with the same beam aperture, its gain would be ~1.6 MV. With the re-entrant ends the cavity obtains 2.3 MV.

There are five important parameters in the cross section that determine the functionality and performance of the cavity. The first is the accelerating gap, which in principle limits the ultimate gain of the cavity. The gap for the TAMU800 cavity is ~20 cm, which is smaller than dictated by the frequency and transit time. The next parameter that determines the gain is the beam pipe size. A 7 cm beam pipe has been chosen for the RF to ensure there is no chance for large-amplitude beam particles to strike the RF cavity surface. Third, the larger the radius on curve located above the gap and interior iris, the less field enhancement occurs decreasing the surface field maximum of the cavity. Fourth, the width determines the re-entrant end coupling of the cavity. The frequency predominantly determines the overall height and length of the cavity. Because the cyclotron is stacked, having a smaller vertical dimension for the overall cavity is more advantageous than having a horizontally narrow cavity. But the height also determines the coupling between the top and bottom sections, and therefore the gain at injection and extraction. A larger surface area on the lobe ends reduces the peak magnetic field; however if the lobe were expanded, the complexity of machining increased dramatically so it was elected to avoid it.

The result of several rounds of parameter optimizations is the electric and magnetic field distributions shown in Fig. 3. The integrated gain of each orbit in terms of energy/radius can be calculated and is shown in Figs. 4 and 5. The gain is affected by the transit factor and the phase shift of the beam. Fig. 6 shows the integrated defocusing integrated voltage on the beam as function of energy/radius.

The overall cavity height of the cavity is approximately 85 cm tall, 83 cm wide in the azimuthal direction, and 5.6 m deep in the radial direction, with a 4.75 m beam aperture for the approximately 35 beams.

Because of the long slot length, putting all the drive power in one opening would generate a series of unfavorable modes. Therefore a linear array of loop couplers will be used to inject rf power in a distribution that conforms to the power distribution extracted by the orbits. RF drive is supplied to each loop from an independent high-efficiency solid state power source rather than from a single power tube. In total there will be ten 50 kW solid state amplifiers per cavity.

The other critical parameters of each TAMU 800 cavity are as follows: 66 W dynamic heat load at 4.2 K, corresponding to a wall-plug refrigeration load of 23 kW; Q = $3.3x10^9$; and a stored energy of 340 J.

The two cavities for the TAMU100 cyclotron will utilize exactly the same design, but with half the accelerating gap (10 cm), overall azimuthal length (62 cm), and the same radial length. The gap is narrowed to accelerate the low beta protons, and the overall length was reduced to adjust the frequency. This keeps the fabrication of the TAMU 100 and the TAMU 800 cavities essentially the same. The parameters for the TAMU100 cavity are as follows: 129 kV gain at injection, 1.33 MV at extraction, 24 W dissipated at 4.2K, corresponding to 8.4 kW refrigeration load at room temperature, and a Q of $3.14*10^9$.

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