The Indiana University Cooler Injection Synchrotron Rf Cavity*

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Abstract

A small 2.2 Tesla-meter booster synchrotron is under construction at the Indiana University Cyclotron Facility to boost polarized beam performance in the electron cooled Indiana University Cooler Synchrotron. Polarized light proton or deuteron beam from a high intensity polarized ion source will be preaccelerated to 7 and 6 MeV respectively by an RFQ/DTL accelerator. The beams are then debunched to reduce the energy spread and strip-injected into the booster synchrotron. The booster rf system must accomplish the tasks of beam capture and acceleration. At the end of the acceleration cycle, the beam phase needs to be aligned to the Cooler synchrotron rf for bucket-to-bucket beam transfer. A single rf cavity in the ring will provide the necessary rf field to accomplish the above tasks.

I. INTRODUCTION

A ferrite-bias-tuned cavity is designed to provide the rf field of the room sized synchrotron. The cavity needs to be compact and capable of operating in a very wide frequency range to accelerate the low energy ion beams. The biasing scheme produces sufficient bias field with a compact power supply and is capable of compensating driving port impedance variations over a wide frequency range.

II. CAVITY DESIGN

The rf system will be operating at the h=1 harmonic number, which corresponds to a frequency range of 1.2 to 10 MHz in the 17.4 m circumference ring with the required beam types and energies.

While the energy spread of the beam out of the RFQ/DTL is ±1%, a debunching rf cavity in the injection beamline will reduce the beam energy spread to less than ±0.2%. The stripping injection will let the beam coast and fill the entire ring. The longitudinal beam emittance will be about 0.014 eV upon the end of stripping injection and start of rf capture. While such a phase space area can be provided by less than 100 V of cavity voltage, the cavity needs to be able to run at higher voltages to keep the beam inside the reduced moving bucket during acceleration.

During the initial design reviews when the booster output energy for protons was set at 80 MeV, a wide band cavity with 50 Ω resistive gap termination was considered. Such a structure has the obvious advantage of construction and operation simplicity. A tuned cavity, however, has a much higher gap impedance and lowers the rf drive power requirement substantially. At the respecified proton output energy of 200 MeV, the voltage requirement can be more easily attained by a tuned cavity. In addition, in the event of temporary outage of the debunching rf system, the booster can still be kept operational by increasing cavity rf voltage. A tuned cavity design is thus chosen and specified for 500 V operation. A 300 Watt solid state amplifier will be used to drive the cavity with sufficient reserve power.

The tuning of the cavity uses an external quadrupole magnet biasing scheme originated in the Max Planck Institute [1]. A cavity of this type has been in use in the IUCF Cooler synchrotron for the past few years [2] [3].

In this biasing method, a quadrupole biasing magnet and its coils are built completely outside a coaxial cavity and do not see the rf fields. The rf cavity can be built in a straightforward fashion without concerns of disturbances caused by biasing elements. The quadrupole DC magnetic fluxes, on the other hand, penetrate the copper outer conductor of the cavity, providing biasing field to the ferrite rings inside. The symmetry of the quadrupole field provides cancellation of biasing field at the cavity axis, minimizing magnetic disturbance to the beam. In addition, any remnant biasing field slightly off the center are shunted by the ferrite rings which have a relatively high permeability.

Fig.1 is an illustration of the ferrite biasing technique.

The biasing field is predominantly parallel with the rf field in the coaxial structure so the effective rf permeability is determined by $\partial B/\partial H$ [4], with minimum permeability achieved

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near the saturation field of the ferrite.

The ferrite rings used saturate at about 2700 gauss. Assuming an overall air gap of 0.4 cm between the ferrite

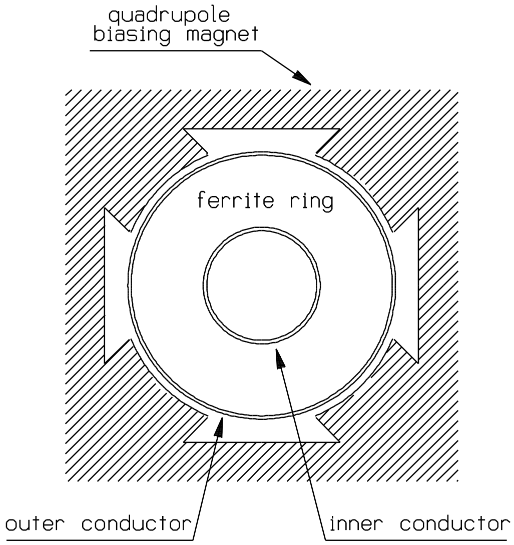

Figure 1. Ferrite ring biasing by external quadrupole magnet.

rings and biasing quadrupole magnet tips, the magnetomotive force (mmf) to drive the ferrite near saturation can be estimated by:

$$NI = \frac{B_s l}{\mu_o} = \frac{0.27\ \mathrm{T} \times 0.004\ \mathrm{m}}{4\pi\times10^{-7}\ \mathrm{H/m}} \simeq 860\ \text{amp-turns} \qquad (1)$$

In practice, the mmf will be achieved by 50 turns of windings on each quadrupole magnet tip driven at 20 A. This current is modest and a small commercial variable power supply can be used.

In this type of cavities, ferrite loss is by far dominant and determines the gap resonant resistance. The ferrite loss, represented by the imaginary part of ferrite permeability, is heavily frequency dependent and also varies with biasing. Fig.2 is a plot of the gap resonant resistance of an IUCF Cooler rf cavity built with the same ferrite materials to be used.

To transfer power efficiently from the amplifier to the cavity, it is important that the driving port of the cavity presents a fixed impedance matching that of the feed transmission line at all frequencies.

The driving port is directly tapped to the center conductor of the cavity, forming a loop enclosing the rf magnetic fluxes at the bottom of the coaxial cavity. Its impedance will normally vary widely with the cavity gap impedance.

For a cavity with heavy capacitive loading, the electrical length of the cavity is much shorter than a quarter wave length. Because the standing wave amplitude along a coaxial cavity axis is sine like and the current amplitude is

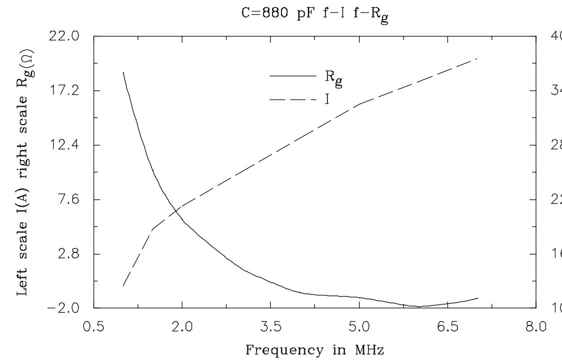

Figure 2. Frequency dependence of IUCF Cooler MPI cavity resonant gap resistance R_g. I is the bias supply current.

cosine like, the voltage distribution is almost linear and the magnetic field is approximately uniform along the axis. Since the power delivered to the driving port equals to the power dissipated on the gap resistance at resonance, the driving loop will see a transformed resistance of :

$$R = R_o \left(\frac{V}{V_o}\right)^2 \qquad (2)$$

where R_o and V_o are gap resistance and voltage, R and V are resistance and voltage at the driving port.

Because of the approximate linear voltage distribution along the cavity axis, a tap to the center conductor has a fixed V/V_o ratio. The driving port impedance therefore is equal to the gap impedance multiplied by a constant fraction. When the resonant gap resistance changes due to frequency dependent ferrite losses, the driving port resistance changes accordingly.

Since the cavity sweeps across the whole operating range in a fraction of a second, it is impractical to mechanically adjust the tap position.

We therefore attempt to change the V/V_o ratio electronically. The voltage at the driving port and at the gap can be expressed by:

$$V = \oint_s \frac{\partial \vec{B}}{\partial t} \cdot d\vec{s}\ ,\quad V_o = \oint_{s_o} \frac{\partial \vec{B}}{\partial t} \cdot d\vec{s} \qquad (3)$$

where s and s_o are the rf magnetic field areas enclosed by the driving loop and the entire cavity respectively.

Because the axial current distribution is approximately uniform, we have an approximately uniform *H* field axially. It is only a function of radius, decreasing with the inverse of radius according to Ampere's Law. If the ferrite permeability does not change axially, integration of Eq.3 yields a driving port resonant resistance of:

$$R = R_o \left(\frac{s}{s_o} \right)^2 \qquad (4)$$

which changes with the gap resonant resistance R_o.

If we manage to make the permeability of ferrite rings enclosed by the driving loop different from those in the rest of the cavity, *V/Vo* no longer depends on s/s_o only. Instead, the integration of Eq.3 yields:

$$R = R_o \left(\frac{\mu_d}{\langle\mu\rangle} \right)^2 \left(\frac{s}{s_o} \right)^2 \qquad (5)$$

where $\langle\mu\rangle$ is the average permeability of ferrite rings of the entire cavity and μ_d the average permeability of ferrite rings enclosed by the driving loop.

The V/V_o ratio can therefore be changed by non-uniform axial biasing. The ferrite rings enclosed by the driving loop have adjustable bias strength independent of that for the rest of the cavity. This can be realized by adding trim coils to the quadrupole magnet section that biases the ferrite rings enclosed by the driving loop. The current flowing through the trim coils will have a large effect on the driving port impedance but a small effect on the overall cavity tuning. The trim coil current is pre-programmed as a function of frequency while the main coil current is controlled by the automatic tuning servo loop.

III. CONSTRUCTION

Fig.3 is a sketch of the cavity to be constructed. The ferrite rings are made of Phillips 8C12 material. It has an initial relative permeability of about 800 and saturates at a field of 2700 gauss. The ferrite rings have an inner diameter of 270 mm and outer diameter of 498 mm, with a thickness of 25 mm. The cross section of the cavity will be filled with ferrite, therefore the inner conductor and outer conductor of the coaxial cavity dimensions are about the same as those of the ferrite rings.

Five ferrite rings will be used. Between the ferrite rings, 20 mm spacings provide passage for forced air cooling. Both the inner and outer conductors of the coaxial cavity will have longitudinal slots for air passage.

A 2000 pf variable vacuum capacitor is loaded across the cavity gap to achieve resonance and provide flexibility of variable frequency bands.

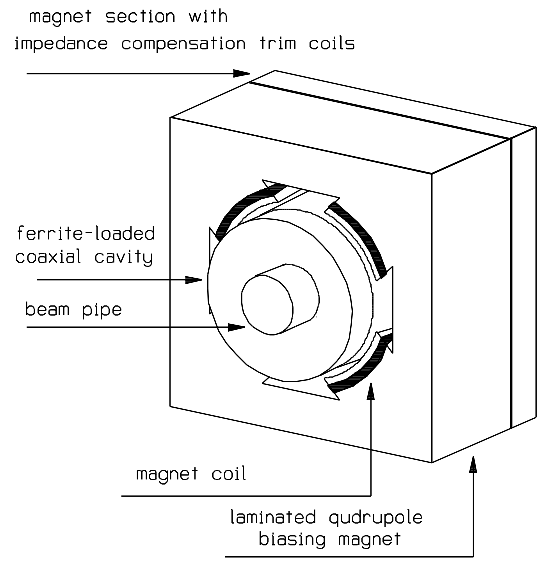

Figure 3. IUCF Cooler Booster Synchrotron rf cavity.

IV. REFERENCES

[1] S. Papureanu, MPI internal publications, MPI, 1989.
[2] R. Pollock, "IUCF Cooler Design Notes", IUCF, 1990.
[3] A. Pei, "A Wide Tuning Range Rf Cavity with External Ferrite Biasing", Proc. PAC 93, p.1421, 1993.
[4] W. Smythe, "Reducing Ferrite Tuner Power Loss by Bias Field Rotation", IEEE Trans. on Nucl. Sci., Vol. NS-30, No.4, p.2173, 1983.