LOW FREQUENCY RF SYSTEM FOR THE INDIANA UNIVERSITY COOLER RING

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ABSTRACT

A low frequency rf system working at the orbiting frequencies of particles ($h=1$) has been built at the IUCF Cooler ring. The cavity design features a new ferrite biasing scheme proposed by S. Papureanu and has a wide tuning range. Application of the fundamental mode rf operation in the cooled rf stacking injection is discussed.

MOTIVATION

The Indiana University Cooler is a 3.6 T-m electron-cooled storage ring and synchrotron designed primarily for internal target nuclear physics experiments. Upon its commissioning in 1987, it was equipped with an rf system that covered a frequency range of 6 to 17 MHz and was ferrite-bias tunable for a 2:1 frequency ratio for synchrotron acceleration of $\beta<1$ ion particles. With a ring circumference of 86.8 m, the rf system had to run with modes of harmonic number 6 or higher for a typical proton beam with injection energies from 45 to 200 MeV.

In a ring with electron or stochastic cooling, if the cooling energy is set at the center of the rf bucket, all the beam will eventually converge to a small longitudinal emittance area in the center of the rf bucket due to the combined action of rf and cooling forces. Fig.1 is the computer simulation of the converging process of the beam[1].

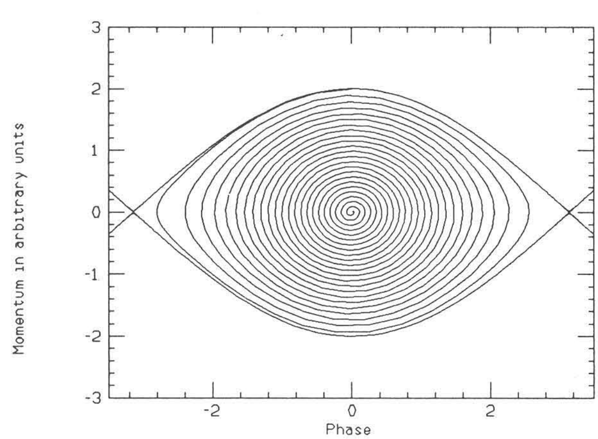

Fig. 1. Computer simulation shows that beam spirals into the center of the rf bucket with combined forces of cooling and rf.

Fundamental mode of rf operation thus has a unique capability to precisely place the beam in a single well defined azimuthal position. This was of particular interest to the cooled rf stacking injection for reasons that will be explained later in this article. Design and construction of a fundamental frequency rf system was thus proposed and accomplished.

THE RF CAVITY

A low frequency limit of 0.5 MHz was chosen to cover most of the beam types and energies that the cyclotron injects into the Cooler. At this frequency range, ferrite-loaded quarter-wavelength coaxial cavity is compact and easy to build.

It is also desired that the cavity has a wide tuning range to follow the synchrotron acceleration of $\beta<1$ particles such as proton and helium. Without a wide continuous frequency coverage, a beam has to be accelerated with a higher harmonic number first and then be rebunched at a lower harmonic number at an intermediate energy. Such a process adds complication to operation and often leads to beam loss.

Ferrite biased tuning is a widely used method to electronically tune an rf cavity. The permeability μ of ferrites decreases as the magnetic field increases. By adding a "biasing" DC or low-frequency magnetic field, the μ or the resonant frequency of the cavity can be changed. This biasing field, however, usually has to be quite strong and must be minimized where the beam goes through. The existing IUCF Cooler PPA cavity (salvaged from the Pennsylvania Proton Accelerator), for example, uses its enclosure as a single turn coil and needs a 4000 A power supply. For the low frequency cavity, an efficient biasing scheme proposed by S. Papureanu was used. The biasing magnet is a quadrupole and is placed outside the ferrite. The field in the center (where the beam line is located) is zero due to quadrupole cancellation. Fig.2 is an illustration of the biasing structure. This approach was first adopted by a cavity design at Max Planck Institute and hence this cavity at the IUCF Cooler was named MPI cavity. With 40 turns of windings on each magnet tip, a 20 A power supply

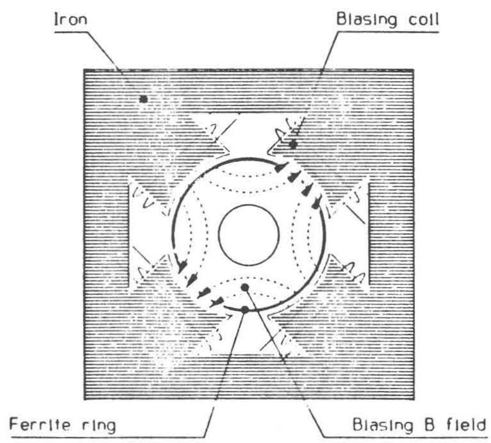

Fig. 2. Principle of ferrite biasing with a quadrupole magnet.

covers a frequency tuning ratio of 7:1, which is more than sufficient to cover the synchrotron acceleration frequency change of $\beta<1$ particles. In Fig.4, the frequency versus current plot of the MPI cavity is shown.

The ferrite rings are stacked with half an inch gaps in between. The enclosure which forms the outer conductor of the coaxial transmission line is made of copper straps instead of solid copper to minimize machining for construction. The spacings between the copper straps allow air flow into the gaps of the ferrites to remove heat buildup. Fig.3 is a cut-away view of the cavity structure.

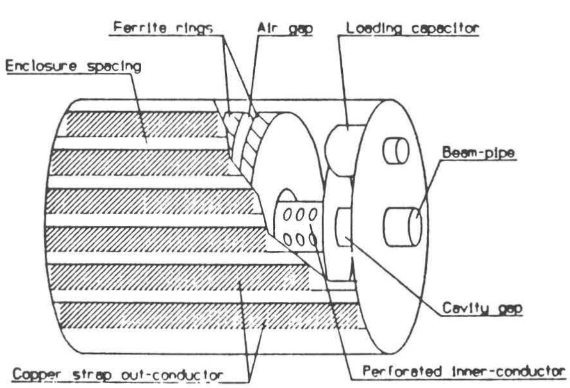

Fig. 3. Cutaway picture of the MPI cavity showing its internal structure.

A 4100 pf variable capacitor is loaded to the gap of the cavity to provide additional tuning range. With 4100 pf of capacitative loading and zero biasing, the cavity resonance is slight below 0.5 MHz.

A cavity merit factor "gap resistance" is defined as R_g as follows:

$$R_g = \frac{V_g^2}{2P} \tag{1}$$

where V_g is the peak rf voltage developed across the cavity gap with a drive-power of P. R_g is thus the equivalent shunt loss resistance across the tank circuit. Fig.4 also shows a plot of R_g at various frequencies.

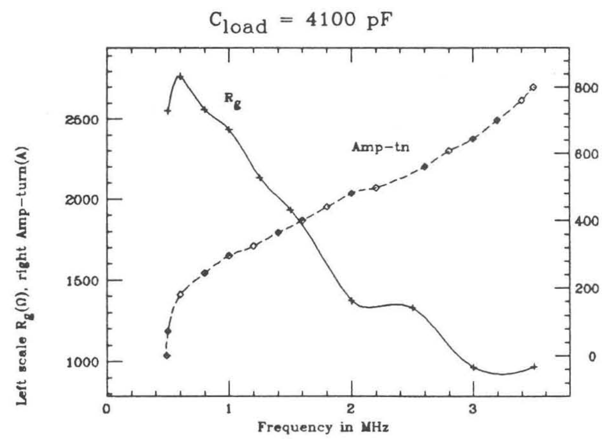

Fig. 4. Bias Ampere-turn and gap resistance versus frequency plot of MPI cavity.

AMPLIFIER, FREQUENCY SOURCE AND CONTROLS

In the $h=1$ mode, sufficient bucket size can be created with a relatively low rf voltage, as[1,2]:

$$\frac{\Delta p_{max}}{p} = \sqrt{\frac{2QeV}{\pi \beta^2 E h \eta}} \tag{2}$$

where Δp_{max} is the maximum momentum deviation from the synchronous momentum p that can be captured by the rf bucket, E the energy of the particle, and η the "frequency slipping factor" defined as $1/\gamma^2 - 1/\gamma_t^2$. γ_t is the "transition γ" of the ring. A ring is isochronous at $E=\gamma_t mc^2$.

A 150 Watt solidstate power amplifier is used to drive the cavity to obtain a gap voltage of 500 Volts peak or higher, sufficient to cover the typical cyclotron beam energy spread of $\Delta p/p = \pm 0.03\%$.

Fig.5 is a block diagram of the IUCF Cooler low frequency rf system. The sweeping frequency source is made of a direct digital frequency synthesizer (DDS) that has sub-microsecond frequency switching speed with phase and amplitude continuity. Automatic tuning is achieved by comparing the phase of the rf drive at the cavity to the phase of rf electric field across the cavity gap. The phase information is used to drive a servo loop that controls a power supply to maintain proper cavity biasing field for correct tuning. Other feedback loops control the amplitude and phase of the cavity.

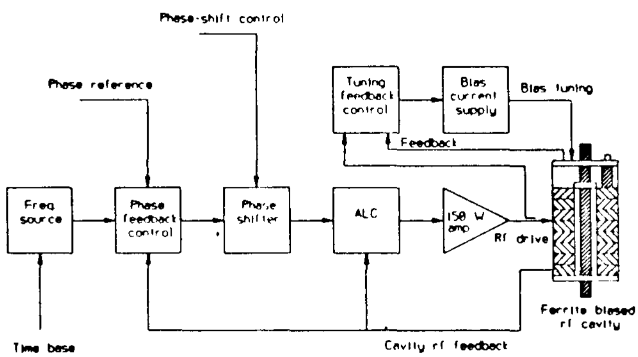

Fig. 5. Block diagram of the IUCF low frequency rf system.

APPLICATION

As an example of the application of the cavity, its use in the multiturn rf stacking injection of the Cooler ring is illustrated as follows.

Detailed description[1,2] of the whole rf stacking process is beyond the scope of this paper so we assume that there already is accumulated beam in the ring. In order for fresh beam injection to occur, a pair of matched kickers must be fired. Because the kickers are placed 180 degree betatron oscillation phases apart, they theoretically only cause a localized orbit distortion in the ring. However, precise matching of kickers is not possible and the stored beam will experience transverse-heating led beam loss while going through the kickers. With the stored beam bunched by electron cooling and the fundamental rf bucket, however, the stored beam can either stay away from the kickers when they fire or go through the kickers at a better behaved time, such as the flattop of the kicker pulse (Fig.6). The kicker firing does need to be synchronized to the rf phase for this operation. Beam experiments showed that with the fundamental frequency bunching, kicker-heating induced beam loss was greatly reduced[3].

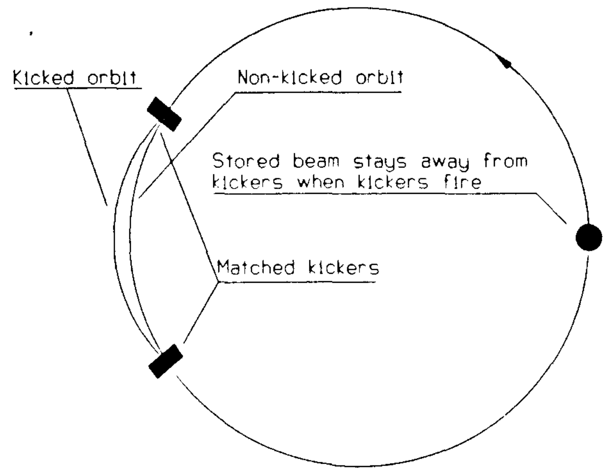

Fig. 6. The low frequency cavity bunches the beam at an azimuthal angle away from the kickers when kickers fire. Lower beam loss can also be achieved by letting beam go through the kickers at the flattop of the kicker pulse.

ACKNOWLEDGEMENTS

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