A MAGNETIC ALLOY LOADED RF CAVITY SYSTEM FOR EMMA

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Abstract

An RF system using Magnetic Alloy is considered as an option to study the beam dynamics of a linear non-scaling FFAG. Such an FFAG may have many resonances, which affect the beam more when the beam crosses them slowly. The RF system aims at ordinary RF bucket acceleration with an RF frequency sweep of 3 % in 100 turns. The cavity has only 10 cm length to fit in a short straight section. The required RF voltage is 100 kV per turn and each of the three cavities is designed to generate 50 kV.

INTRODUCTIONS

The Electron Model for Many Applications (EMMA)[1] aims to study beam dynamics in linear non-scaling fixed field alternating gradient accelerators (FFAGs). It uses a fixed-frequency 1.3 GHz RF system[2] to accelerate the beam in around 10 turns. This mode of acceleration is typically employed for muon acceleration, [3, 4] where such rapid acceleration is essential and high RF frequencies are necessary.

Due to its usage of linear magnets, a linear non-scaling FFAG such as EMMA crosses a number of linear imperfection resonances, nonlinear resonances, and space charge resonances. The fixed-frequency RF system accelerating in the serpentine mode in EMMA will not permit arbitrarily slow acceleration . A low- and variable-frequency RF system is therefore required to significantly reduce the acceleration rate and to study beam dynamics in EMMA.

In particular, for parameters of the EMMA lattice, one has very good dynamic aperture in the presence of reasonable alignment errors when accelerating in 100 turns, while if acceleration takes 1000 turns, the dynamic aperture is significantly worse and highly sensitive to the alignment errors.

We want the lowest frequency possible so as to be able to vary the RF frequency and to be able to make more turns while accelerating before the RF phase deviates too much. In EMMA, this is about 18 MHz (harmonic 1). We would like to be able to accelerate by 10 MeV in 100 turns, leading to an RF voltage requirement of 100 kV. The cavity must fit in the existing EMMA drifts, meaning that it should be at most about 10 cm long.

There are three different acceleration modes one could imagine using. The simplest is to keep the RF frequency fixed, and use a serpentine acceleration mode as in the existing EMMA ring. Since the RF frequency would be 72 times lower, one would expect acceleration times 72 times longer, and therefore approaching 1000 turns.

One could instead vary the RF frequency to match the time of flight at the beam's current energy. This would allow an arbitrarily long time to be spent accelerating. If one accelerated with a high RF voltage but far off crest, one could have some modest number of synchrotron oscillations during the acceleration cycle. One would have to quickly switch the RF phase near transition (see the time of flight plots in Ref. [5]) to maintain the synchrotron oscillations. Doing anything else could lead to significant bunch lengthening. This mode of acceleration requires approximately an 0.3% variation in the RF frequency.

Another mode of operation is to modify the lattice so that the minimum of the time of flight is well outside the energy range of the machine. This will significantly increase the closed orbit excursion in the machine, but since this experiment would study beams with much smaller emittances than what the main EMMA ring is designed to accept, there should be plenty of horizontal space in the vacuum chamber to accommodate this larger excursion.[5] This mode of operation has longitudinal dynamics which would be similar to what one expects in the machines we are trying to study (where the time of flight dependence on energy is almost completely determined by the velocity variation with energy). Synchrotron oscillations would be stronger than in the previous mode of operation, and one would not have to make a rapid phase change to cross the transition energy. It has yet to be demonstrated that the lattice can be modified in this fashion. This mode of operation would require an RF frequency variation of approximately 3%. While being more challenging to implement than the other modes, this acceleration mode is probably the preferred one.

DESIGN OF LOW FREQUENCY RF SYSTEMS

FT3L MA Cavity

A Magnetic Alloy (MA) loaded cavity is considered for the low frequency RF station. A new material, FT3L, which has two times larger shunt impedance than ordinary magnetic alloy materials, will be used for the cavity cores[6, 7, 8]. Parameters of the RF system are listed in Table 1. As the length of the straight section to install the cavity is only 10 cm, the cavity is very compact as shown in Fig. 1. To operate the cavity at 18 MHz which corresponds to H=1, the MA cores will be of cut core type to reduce the inductance. The size of cores are 27 cm diameter to fit on the table where EMMA magnets are located. Figure 2 shows an FT3L MA core which has 27 cm diameter. The impedance of the cores is about 500 Ω at 18 MHz.

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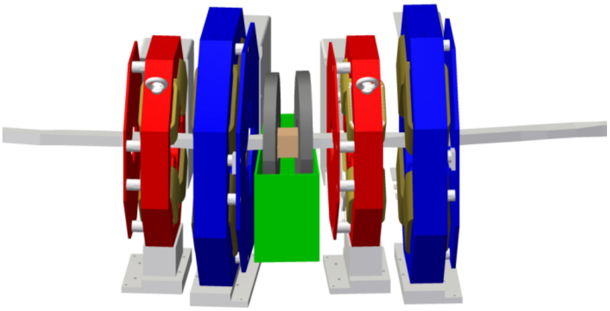

Figure 1: Low frequency RF cavity for EMMA.

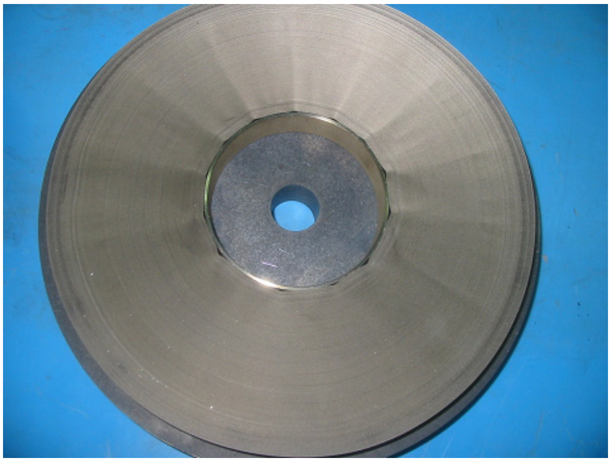

Figure 2: FT3L MA core with 27 cm diameter.[8]

Low Duty Operation

Because the duty factor is low when the low frequency RF is operated in the EMMA, the MA cavity can be operated at a very high field gradient.[9] In particular, low duty factor operation enables air cooling. Because the frequency range of the cavity is affected by the coolant and cavity structure, air cooling is the most suitable option for a frequency higher than several MHz.

Another advantage of a low duty factor is the effective operation of the final stage amplifier. [9] In the frequency range from below 1 MHz to several tens of MHz, vacuum tubes are used. The output power is limited by the anode dissipation in the vacuum tube in high duty factor operation. In the case of pulsed operation, a small vacuum tube can be used to obtain a large output power for a short time. As the average power for EMMA operation is small, the anode power supply for the tube amplifier can be much smaller than that for high duty factor operation. For a synchrotron RF system, the cost of the anode power supply is the most expensive part; that cost can be reduced for low duty factor operation.

Table 1: Main Parameter of EMMA low frequency RF

frequency	18 MHz
frequency sweep	3 %
total RF voltage	100 kV
Number of RF stations	3
Voltage per station	33.3 kV
Length of cavity	10 cm
Number of MA cores	2 per cavity
Size of MA core	27 cm O.D., 10 cm I.D. x 2.5 cm
Cut/un-cut	Cut core
Material	FT3L (13 μm thickness)
Q-value	about 9
Cavity impedance	1 kΩ

Amplifier

The cavity is driven by a push-pull amplifier using two tetrodes 4CW100K tubes. This tube has been used for the PRISM RF system and it has already been confirmed that it can generate about 60 A RF current.[9] Assuming that the floating capacitance in the amplifier and cavity is 80 pF,[10] a cut core configuration is necessary to reduce the core inductance and to resonate at 18 MHz. The expected Q value will be 9. For a slow frequency sweep, the driving current to generate 33 kV would be 33 A ($= 33\mathrm{kV}/1\mathrm{k}\Omega$). Because of the transient effect of the very fast frequency sweep, an RF current about two times larger is necessary as described in the next section. With the RF current available from the 4CW100K vacuum tubes, 33 kV can still be achieved.

TRANSIENT EFFECTS

The "slow" acceleration modes using the low-frequency RF cavity needs 3 % frequency sweep. Because the acceleration will finish in 100 turns, the maximum frequency variation is 97.2 GHz/s, and this means a very rapid frequency sweep. The frequency variation of the typical Rapid Cycling Synchrotron is about 100 MHz/s and the EMMA system requires 1000 times faster variation and the transient effects becomes important.

De-tuning Effects

The basic shape of driving current can be found by modeling the cavity as a parallel RLC circuit. The cavity impedance is given by,

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{j\omega \mathrm{L}} + j\omega C. \qquad (1)$$

In case of high Q cavity, ωL and $\frac{1}{\omega \mathrm{C}}$ are much smaller than the shunt impedance, R, and the circulating current is much larger than that dissipated in the shunt. If the bandwidth of the system is narrower than the frequency sweep range of 0.54 MHz ($= 0.03 \times 18$ MHz), the driving current will be very large. In case of a Q=100 system, the driving current at detuning frequency will be 6 times larger than that at the resonance although Q=9 system needs only 12 % more. Therefore, the tuning circuit will be necessary in case of the high-Q system. The cavity inductance is varying for tuning and given by the RF frequency which is changing very rapidly.

Transient Effects

The transient effects for rapid frequency sweep will cause more significant effects. As the voltage across each circuit element is the same, the total current for the frequency sweep is the sum of the currents in the elements,

$$I(t) = \frac{V(t)}{R} + \frac{1}{L}\int_0^t V(t')dt' + C\frac{dV(t)}{dt}. \qquad (2)$$

When the frequency is swept, the RF voltage is

$$V(t) = V_0 \sin(\omega(t)t). \qquad (3)$$

Assuming the frequency is a linear function of time, $\omega(t) = \omega_0 + \delta t$, the RF phase will be shifted by 180° in 38 turns. This means that a high-Q system of Q$\geq$38 is not very efficient for such a high-speed frequency variation. In the system of Q$\ll$38, the effect is not severe. In case of EMMA beam acceleration, however, the maximum variation will be about two times faster than that for linear sweep. The Q=9 system (the present design of the EMMA low-frequency RF system) may require about two times larger current than that for a slow sweep system. This effect is caused by the integration part in Equation 2. By the effect, the phase of the current which goes thorough the inductance is shifted. To reduce the transient effects, a magnetic alloy-loaded cavity with a relatively low Q ($Q \simeq 9$) will be used.

CONCLUSIONS

A design of a low-frequency cavity to study slow acceleration in a non-scaling FFAGs is presented. Construction and operation of the RF system would be an interesting and rewarding challenge. Furthermore, EMMA provides a unique environment for operating such a cavity since the EMMA repetition rate can be made as low as necessary, permitting air cooling and a smaller power supply for the cavity at this early R&D stage.

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