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FETS-FFA RING STUDY

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Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK, providing a proton beam with a power of 0.2 MW. Detailed studies are under way for a major upgrade, including the use of Fixed Field alternating gradient Accelerator (FFA). A proof-of-principle FFA ring, called FETS-FFA is planned to investigate the feasibility of this kind of machine for the required MW beam power. This paper discusses the study of the FETS-FFA ring case.

INTRODUCTION

A major upgrade of the ISIS facility [1], called "ISIS II", is under study and a roadmap has been established [2]. One of the considered options for the proton accelerator is the use of FFA (Fixed Field alternating gradient Accelerator), and more precisely the new concept of VFFA, whose vertical field strength changes exponentially in the vertical direction. This means the equilibrium orbit for different beam momenta shifts vertically. This arrangement has several advantages. First, it brings longitudinal flexibility and so allows beam stacking [3]. It also is more reliable, and more sustainable from an energy consumption point of view, as a whole accelerator system since the main magnets are operated in DC mode. Third, as long as acceleration voltage is sufficient, high repetition rate (more than 100 Hz) can be achieved. Lastly, since the orbit radius is independent of momentum, quasi-isochronism can be achieved for ultra-relativistic particles. The challenges of this type of accelerator are the coupled optics and large vertical magnets.

VFFA is a relatively new concept [4] and no accelerator was constructed. Our plan is to make a prototype model using 3-MeV FETS [5] beam as an injector, accelerating up to 12 MeV beam energy. This paper reviews the study of this prototype ring, called FETS-FFA.

LATTICE DESIGN

In a VFFA, the scaling condition requires magnetic fields that increase exponentially in the vertical direction. In the following, the x-axis is horizontal, the y-axis is vertical and the z-axis is in the longitudinal direction. Magnetic fields are expanded from the ideal mid-plane field (the mid-plane for a VFFA is a zero-displaced plane in the horizontal direction) so that the fields satisfy Maxwell's equations. The variation of the field in the longitudinal direction, which describes fringe fields, is an important feature of FFA optics, and in the initial study we chose to model the magnetic field with a hyperbolic tangent function,

$$g(z) = \frac{1}{2}\left[\tanh\left(\frac{z+M/2}{L}\right) - \tanh\left(\frac{z-M/2}{L}\right)\right], \quad (1)$$

where M is the magnet length and L is a parameter related to the fringe field extent. FODO and FDF triplet lattices have been considered so far, but the triplet solution is currently preferred for its longer straight sections to install cavities, injection and extraction equipment and instrumentation. The lattice parameters are shown in Table 1.

Table 1: Lattice Parameters of FETS-FFA Ring

Parameter	FDF Triplet
Bend angle per cell	36 deg
Cell length	2.50 m
Bd magnet length	0.24 m
Bf magnet length	0.40 m
Space between Bd and Bf	0.08 m
Fringe field extent (L)	0.20 m
Tilt angle (t_f)	0 deg

The geometry of the rings is described by a regular polygon with each side corresponding to a cell, as shown in Fig. 1. The corresponding magnetic field on the closed orbits for extraction energy can be seen in Fig. 2. A bird view of the lattice can be seen in Fig. 3. We notice that the closed orbits of all energies are on top of each other when projected on the horizontal plane, and that the individual orbits do not stay in a horizontal plane.

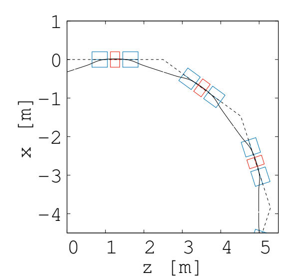

Figure 1: Closed orbits for FDF lattice. The dashed line indicates the polygon with 10 sides. Figure published in [6].

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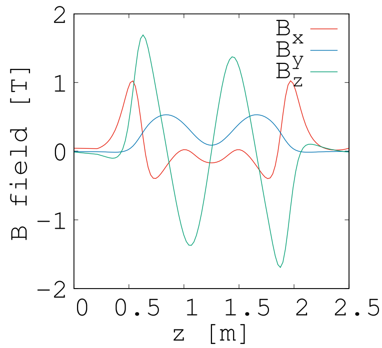

Figure 2: The magnetic fields along the orbit in a cell for 12 MeV beam energy in the FDF lattice. Figure published in [6].

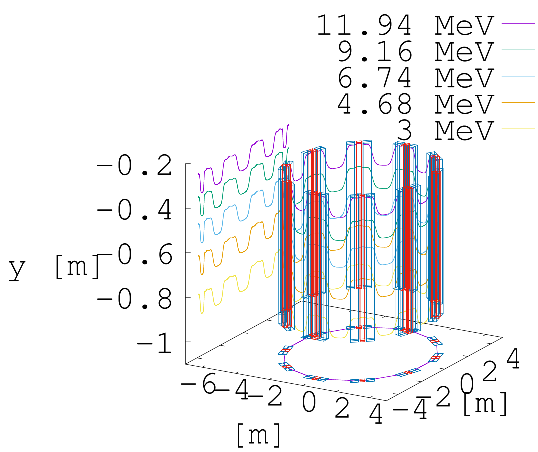

Figure 3: Closed orbits for different momenta in the FDF triplet lattice. The locations of the Bd and Bf magnets are indicated by red and blue boxes respectively. Figure published in [6].

The cell tune is chosen empirically to have a large dynamic aperture, more than 100π mm mrad. The beta-functions are calculated from the eigenvectors according to the Willeke-Ripken formalism [7] and are shown in Fig. 4.

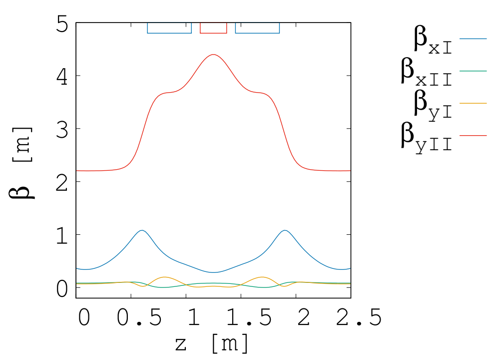

Figure 4: Beta functions β_{xI}, β_{xII}, β_{yI}, β_{yII} according to the procedure by Willeke-Ripken [7]. The magnet positioning is shown at the top, the red box corresponding to the Bd magnet and the blue box to the Bf magnet. Figure published in [6].

ORBIT CORRECTION

In a VFFA, a conventional horizontal orbit corrector using a horizontal dipole magnet would require a large gap, spanning the orbit excursion in the vertical direction, and would be challenging to implement. A double coil design of the main magnets enables horizontal orbit correction. Two pairs of coils, shifted horizontally with respect to their mid-planes, can be excited with different currents. Tuning the currents can enable tuning of the profile of the vertical field along the horizontal direction while main- taining the scaling condition, as shown in Fig. 5. The effect on cell tune is small as shown in Fig. 6. The orbit moves by several centimetres while the variation in cell tune is less than 0.01.

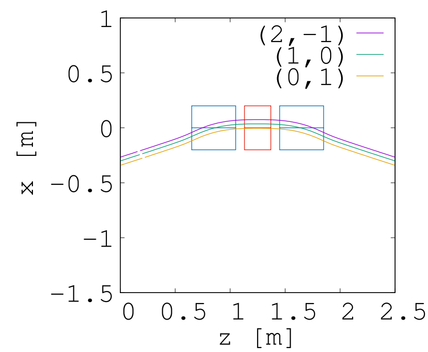

Figure 5: Orbit shift controlled by a double coil design in the FDF triplet lattice. A bracket $(b, 1 - b)$ indicates the relative excitation of outer coil b to inner coil $1 - b$. The total excitation is kept at unity. Figure published in [6].

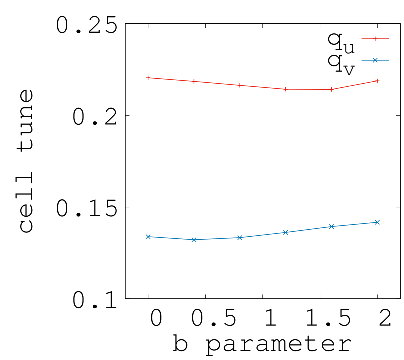

Figure 6: Cell tune shift as a function of relative excitation b parameter of the horizontal orbit control scheme in the double coil design. Figure published in [6].

INJECTION

Injection into FETS-FFA ring is planned using charge exchange injection and phase space painting using pulsed magnets. Extraction is planned using extraction kicker(s) and the septum magnet. For ISIS II, in order to accumulate sufficient intensity, it is expected that phase space painting will be required to reach sufficient beam current. For FETS-FFA ring, it is expected that the intensity limit can be reached with a single injection pulse owing to the high brightness of

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the FETS beam so that phase space painting is not necessary. However, it is desirable to investigate the possibility for painting and low-loss injection in this ring.

Injection with a multi-cell scheme is envisaged in the FDF lattice. The proton orbit is bumped onto the foil over 2 cells; H^- ions are brought onto the bumped orbit and then through a thin foil, where the electrons are stripped; and the resultant proton orbit is bumped back onto the closed orbit over 2 more cells. In total 5 cells are required for the injection, out of the 10 cells of the ring.

The effect of foil hits on the beam was estimated. In order to maintain beam maximum amplitude below the 10 µm acceptance of the ring and momentum spread below 0.8% (full range) the injection system should allow at most 10 foil hits in the case of a 20 µg/cm^2 foil.

MAGNET PROTOTYPE

A series of VFFA magnet prototypes are planned to mitigate several risks regarding their designs, tolerances regarding vertical scaling law and manufacturing risks. The magnetic field is also in the superconducting regime, and superconducting-coil-dominated FFAs have never been built either.

To design the magnet, a code based on reversed Biot-Savart principle is used. Starting from a field model with an exponential increase of the field in the vertical direction as required by the vertical scaling law, A 2D-FFT of this field model can then compute point-like pieces of wires at a given distance from the median plane. The wires are then closed into a loop in space to satisfy the continuity of Maxwell equations. An example of the coil configuration using such a method can be found in Fig. 7.

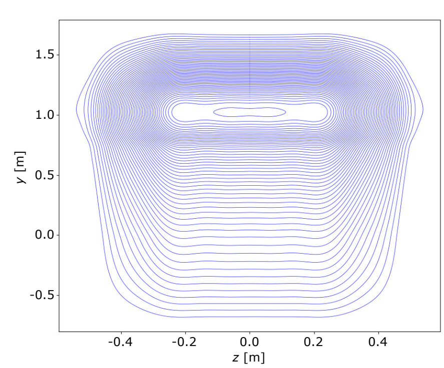

Figure 7: Representation of the coil configuration for the first prototype. The good field region is between y = 0 m and y = 0.6 m.

The resulting field produced by such a coil configuration shows a poor fit of parameters with the initial fringe field model using tanh functions. It leads to significant differences between the field model and the field map, and big changes in closed orbits and tunes. The predictability of the optics of a lattice designed in this field model compare to a real machine is then limited, and more realistic fringe fields is adopted with arc tangent function,

$$g(z) = \frac{1}{\pi}\left[\arctan\left(\frac{z+M/2}{L}\right) - \arctan\left(\frac{z-M/2}{L}\right)\right]. \quad (2)$$

COLLIMATION SYSTEM

Since ISIS-II will be a high-power proton accelerator, a collimation system is essential to protect the various equipments and localise the uncontrolled losses. For general synchrotrons (and hFFAs), horizontal and vertical particle motions are not coupled. In this case, the collimators are placed in the ring in horizontal and vertical plane independently. On the other hand in coupled optics as it is the case in VFFAs, a beam is focused by skew magnetic components, resulting in a coupled motion in transverse phase space. The advantage of this scheme is that the halo particles generated in both directions can be captured by a single-plane collimator. To study the feasibility of single-stage collimator system in FETS-FFA, a particle tracking simulation is applied using 4x4 linear transfer matrix in several FDF lattices with I-shape collimator. To study the feasibility of single-plane collimator system in FETS-FFA, a particle tracking simulation is applied using linear 4 × 4 transfer matrix in several FDF lattices with I-shape collimator. The collimator is placed in the middle of a straight section in the ring. Preliminary results show a strong correlation between the capture efficiency of halo particles and the cell tune.

Several materials have been considered and tungsten has been found to have the best properties among them from thermal and residual dose analysis.

SUMMARY

A roadmap for research, design and construction of a next generation, short pulse neutron source, ISIS II, has been established. A test ring to demonstrate experimentally the features of the VFFA, called FETS-FFA is planned. FODO and triplet lattice configurations are being investigated, with a preference for triplet lattice because of its longer straight sections. Injection with charge exchange is planned and phase space painting is being explored. A magnet prototype to investigate tolerances and manufacturing constraints is under study and the feasibility of a simple collimation system in coupled optics is investigated.

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