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FFA DESIGN STUDY FOR A HIGH INTENSITY PROTON DRIVER

S. Machida†, ISIS department, STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
On behalf of ISIS-II FFA task team

Abstract

As an option for the proton driver for the next generation spallation neutron source (ISIS-II) at the Rutherford Appleton Laboratory (RAL), a Fixed Field Alternating Gradient Accelerator (FFA) is being considered. A prototype accelerator has been designed, referred to as FETS-FFA, to demonstrate flexible handling of beam repetition for users and high intensity operation with minimum beam loss. FETS-FFA takes the 3 MeV beams from Front End Test Stand (FETS) linac and accelerates them to 12 MeV. FD spiral optics have been adopted as the basic focusing structure, which allows the operating point to be chosen along the diagonal in tune space. Flexible beam repetition will be demonstrated by RF beam stacking at the extraction energy, which enables users to choose different (lower) repetition rates independent of the acceleration cycle. For high intensity beam study, several schemes of injection painting are being considered. At the injection energy, the space charge tune shift can be easily exceed -0.3. This paper discusses the lattice design, while further details of each aspect of the accelerator, including hardware, are presented in separate conference papers.

INTRODUCTION

As an infrastructure of a big science facility, sustainable operation of a particle accelerator becomes a more crucial consideration recently. One of the figure of merit to measure sustainability is energy efficiency. This affects directly the cost of operation and the size of user community which the facility could support.

Fixed Field Alternating Gradient Accelerator (FFA) has potential to be a high power hadron accelerator with, not only sustainable, but also flexible and reliable operation. From the hardware point of view, an FFA is similar to a cyclotron with DC main magnets. Cyclotrons are the most energy efficient accelerators. From the beam dynamics point of view, an FFA is similar to a synchrotron. Time structure of output beams are controlled by an RF accelerator pattern. More flexibilities in RF gymnastics are allowed in an FFA because it is independent of the magnet excitation pattern unlike a synchrotron.

With those potentials of an FFA, the use of an FFA had been proposed several times for a spallation neutron source [1, 2], for an accelerator driven subcritical reactor [3] and for a neutrino factory [4]. However, an FFA accelerator built so far was not designed for the user of high beam power. Experimental demonstration of high power operation is a key milestone for those applications.

As an option for the proton driver for the next generation spallation neutron source (ISIS-II) at the Rutherford Appleton Laboratory (RAL), an FFA is being considered [5]. As the first step, a prototype accelerator has been designed, referred to as FETS-FFA, to demonstrate flexible handling of beam repetition for users and high intensity operation with minimum beam loss. This will be the first FFA aiming for high power operation from the design stage. Note that this demonstrator will not deliver the high beam power in the absolute sense because the beam energy is very low, 12 MeV. However, the space charge tune shift is similar to SNS and J-PARC accelerators, namely around -0.3.

For high power accelerator design, enough space for each system must be allocated. For example, long straight section for injection and extraction is the must to minimise beam loss. In current high power synchrotrons and accumulators, a ring comprises of a few superperiod structure (e.g. 3 or 4) with long straight sections.

An FFA optics, on the other hand, conventionally comprises of many identical focusing cells. It is easy to design and that gives a minimum number of parameters to operate, i.e. strength of focusing and defocusing magnets. It is also believed that a high periodicity lattice reduces the number of systematic nonlinear resonances and maximise dynamic aperture (DA). Since an FFA has all order of multipoles, avoiding systematic nonlinear resonances are particularly important.

High symmetry is, however, not the requirement to make the scaling optics as long as the field profile satisfies the equation.

$$\frac{B_y}{B_{y0}} = \left(\frac{r}{r_0}\right)^k F\left(\theta\right)$$

Any kind of symmetry can be realised by choosing *F(theta)*. We designed 4-fold symmetry lattice before [6]. For FETS-FFA, the optics parameters are further optimised so that 4-fold symmetry lattice with smaller circumference becomes possible. The long straight section is 50% longer than the straight section of the equivalent high symmetry lattice.

4-FOLD SYMMETRY LATTICE

Starting from 16-fold symmetry lattice, some of straight sections are lengthened and the others are shortened to realise 4-fold symmetry lattice with long straight sections. The total circumference is kept the same. The longest straight is 50% longer than the original one. Peak value of beta function becomes large due to modulation in a superperiod. However, it is more in horizontal and not much different in vertical direction. Impact of the beta function increase in horizontal is less because there is huge aperture anyway. On the other hand, vertical beam size determines the magnet aperture. Figure 1 and Table 1 show top view, beta functions of high and superperiod lattices and main parameters.

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† email address shinji.machida@stfc.ac.uk

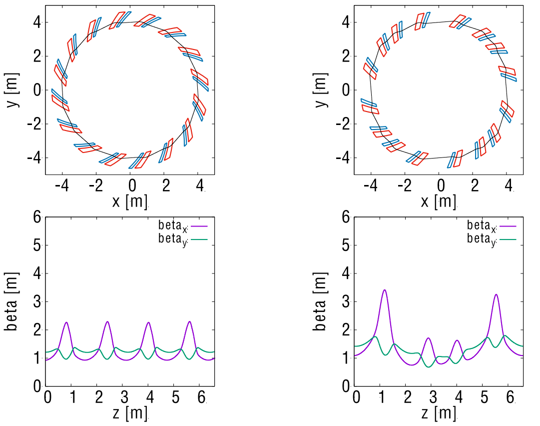

Figure 1: (top) Top view, (bottom) lattice beta function (a quarter) of 16-fold (left) and 4-fold (right) symmetry lattice. Bare tune is fixed at (3.41, 3.39). Red box is Bf (normal bend with focusing) and blue box is Bd (reverse bend with defocusing). Spiral angle is 45 degree for 16-fold symmetry lattice and 30 degree for 4-fold symmetry lattice.

Table 1: Main Parameters

	value	unit
Inj. energy	3	MeV
Momentum	0.075091	GeV/c
Ext. energy	12	MeV
Momentum	0.150541	GeV/c
Cell per s.p.	4	
Spiral angle	30	Degree
Ave rad at inj.	4	m
Long straight	1.54	m
Med straight	0.89	m
Short straight	0.44	m
Nominal tune	(3.41,3.39)	
k-value	7.43	

Tunability and Dynamic Aperture

In order to accommodate large space charge tune shift of around -0.3, the nominal tune is chosen at (3.41, 3.39). From the experience of SNS and JPARC operation, it is suggested that the bare tune should be close to the diagonal line in the transverse tune space. With nonlinear multipoles up to high orders in an FFA, choice of the bare tune needs other considerations. We aim to have flexibility of optics so that the bare tune can be scanned over the integer, from 3 to 4 in both horizontal and vertical direction.

Transverse tune is controlled by two knobs, one is the field index k, we call it k-value, and the ratio of Bd and Bf magnet strength as shown in Fig. 2. In the 16-fold symmetry lattice, there is only one family of Bd and Bf so that the ratio is uniquely determined. In the 4-fold symmetry lattice, magnet strength of 4 doubles in a superperiod is all independent so there are 8 knobs. In fact, optics is determined by the ratio of magnet strength (7 knobs) and the last one is used to scale the orbit depending on the beam momentum.

Without any random errors or misalignment, DA is calculated over the tune space. For high power operation, emittance of horizontal and vertical should be same. We defined DA as the maximum amplitude in equal action for both directions.

At the integer tune of 4, there are many systematic resonances. Another study shows that there is a large vertical tune shift with amplitude. As shown in Fig. 3, DA suddenly decreases above Qy=3.5 toward Qy=4.0.

As shown in Table 2, the target core emittance after painting is 10 pi mm mrad and the physical aperture (vertical) is assumed up to 80 pi mm mrad. In the tune space between 3.0 and 3.5 in both direction, DA is above the physical aperture.

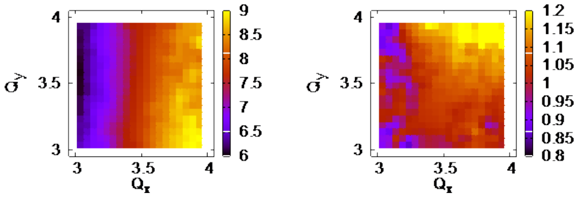

Figure 2: (left) k-value: Increasing k-value from 6 to 9 primarily moves the horizontal tune. (right) Bd/Bf ratio defined by the maximum Bd and Bf among 4 families: Increasing Bd/Bf ratio primarily moves the vertical tune.

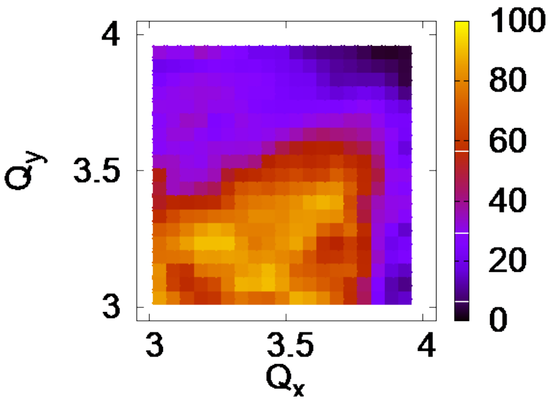

Figure 3: Dynamic aperture. Colour scale on the right is normalise value [pi mm mrad]. There are many systematic nonlinear resonances at tune of 4. Large and positive tune shift with amplitude reduces DA below Qy=4.0.

Orbit Excursion

Orbit moves as accelerated. Orbit excursion from injection to extraction is determined by the k-value and it depends on the bare tune. It is important to know the orbit position inside the magnets for all possible bare tune for magnet design. It is not decided whether the injection orbit radius is fixed for different tune or the extraction orbit radius. It depends how easy to move either injection or extraction system. It also depends the magnet design.

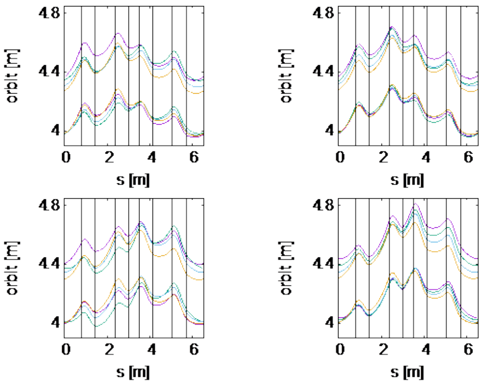

Figure 4: Closed orbit in one superperiod. 4 outer radius curves shows extraction orbits. 4 inner radius curves shows injection orbit. 4 doublet magnet location is indicated by vertical lines. (top left) Qy=3.06, (top right) Qy=3.26, (bottom left) Qy=3.46, (bottom right) Qy=3.76. In each figure, purple line for Qx=3.06, green line for Qx=3.26, blue line for Qx=3.46 and orange line for Qx=3.76.

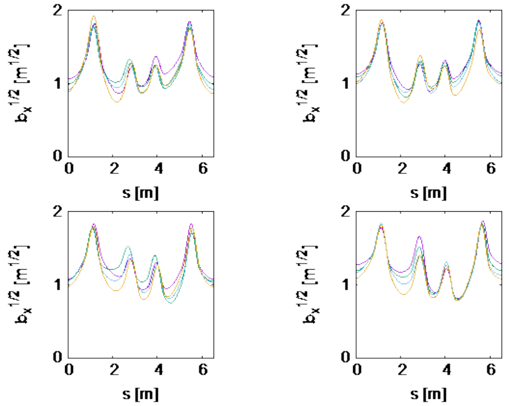

Figure 5: Square root of horizontal beta functions at different operating point. (top left) Qy=3.06, (top right) Qy=3.26, (bottom left) Qy=3.46, (bottom right) Qy=3.76. In each figure, purple line for Qx=3.06, green line for Qx=3.26, blue line for Qx=3.46 and orange line for Qx=3.76.

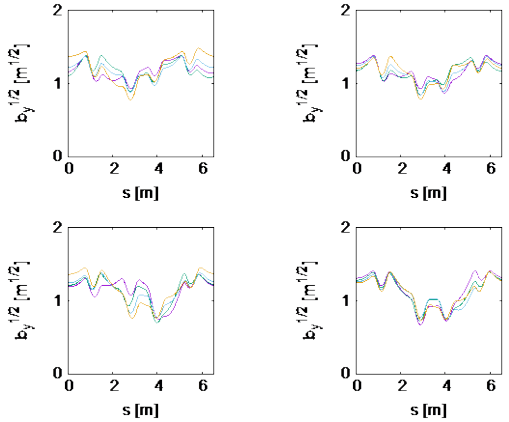

Figure 6: Square root of vertical beta functions at different operating point. (top left) Qy=3.06, (top right) Qy=3.26, (bottom left) Qy=3.46, (bottom right) Qy=3.76. In each figure, purple line for Qx=3.06, green line for Qx=3.26, blue line for Qx=3.46 and orange line for Qx=3.76.

Beam Size

Lattice beta function has a modulation in a superperiod. Peak value is inevitably higher than that of 16-fold symmetry lattice as shown in Fig. 1. When the tune are scanned over the integer, the maximum beta function is constrained in both directions. Figures 5 and 6 show the square root of the beta functions in both directions. It shows a variation of beam size for different bare tune, but not mucy.

Table 2: Aperture Assumption

[pi mm mrad]	**normalised**	**physical**
Core	10	125
Collimator	20	250
Physical aperture	40~80	500~1000

SUMMARY

For the demonstration of a high power FFA, FETS-FFA was design. Lattice with superperiod structure was proposed to ease installation of the key systems such as injection and extraction and to minimise the beam loss. Reduction of symmetry increase beta functions and the beam size. It is, however, mostly in the horizontal direction and the impact on the aperture requirement is minimum because horizontal aperture is already large for orbit excursion. Using 4 families of Bd/Bf doublet focusing cell, the bare tune can be explored in the integer tune. Because of high order multipole, systematic and random nonlinear resonances and DA are concerns. DA calculation shows that more than 100 pi mm mrad (normalised) can be achieved in a large area in tune space.

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