ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRAI01

DEVELOPMENTS AND PROSPECTS OF FFAS AT RAL

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on behalf of the FFA task team,

Abstract

A Fixed Field Alternating Gradient Accelerator (FFA) can offer several advantages for use as a proton driver for high power beam applications. In particular, control of the pulse structure can be easily done by RF gymnastics. A FFA is a sustainable (energy efficient) and reliable accelerator with the main magnets with DC operation. We will discuss the development of a FFA physics design for ISIS (spallation neutron and muon source) upgrade and its proto-type status.

INTRODUCTION

Studies are in progress to upgrade ISIS, the UK's spallation neutron and muon source, in a plan referred to as ISIS-II. The beam power of the proton driver is in the range 1.25 to 2.5 MW with a beam energy of 1.2 GeV. That level of beam power has already been achieved at PSI in Switzerland, SNS in the US and J-PARC in Japan and is therefore not seen as a major challenge. However, beam power is not the only figure of merit for future proton drivers. There are some other essential factors we must take into account.

The most important consideration is sustainability, a feature that becomes increasingly relevant of late. Without assuring a good measure of sustainability, we cannot operate the facility. At the present time a cyclotron is the most energy efficient accelerator. Another key factor is reliability of operation. Even if an accelerator has a state-of-the-arc design, users will hesitate to use it if it frequently breaks down. An accelerator like a cyclotron using DC magnets is robust and its robustness can be an important contributor to the reliability.

More specifically, in the spallation neutron community, accelerator-based facilities should have two features: capacity and capability. Capacity means that a facility can comfortably deal with the large number of experiments that is essential to meet or expand demand from the scientific community. Capability means that a facility can provide bespoke experiments. For example, it can provide flexible operation such as high peak current with low repetition or low peak current with high repetition depending on users' requests.

As a candidate for a future high power proton driver a cyclotron has many attractive features The only caveat is that it is not a pulsed machine, whereas neutron users need pulsed protons. A synchro-cyclotron is an option, or a Fixed Field Alternating Gradient Accelerator, FFA [1-3]. However, people are not easily convinced about the idea because no high power FFA exists. To show viability and convince the community that an FFA can provide the high power beams required, a project RAL has in mind to design and construct a small-scale demonstrator of an FFA-based high power machine [4]. Referred to as FETS-FFA, the ring will use the existing Front End Test Stand (FETS) as its injector. Since an FFA is a pulsed accelerator like a synchro-cyclotron, there are many challenges that are similar to those in a high intensity synchrotron. Table 1 shows the main parameters of FETS-FFA. The average current is about three orders of magnitude higher than any existing fixed-field accelerating ring.

Table 1: FETS-FFA Main Parameters

Parameter	Value
Beam energy	3 – 12 MeV
Average radius	4 – 4.2 m
Repetition rate	100 – 120 Hz
Number of protons per pulse	3×10^{11}
Average current	about 5 mA
Space charge tune shift	about -0.25

BEAM DYNAMICS ISSUES OF THE HIGH POWER BEAMS

This paper considers four topics that are of importance in the realisation of a high power FFA.

FD Doublet Spiral Lattice

We know that the operating tune should be close to the diagonal line in tune space. In other words, both horizontal and vertical tunes should be similar in a high power synchrotron. Radial sector FFAs use the field index k and the strength ratio of normal bend Bf and reverse bend Bd, which changes the flutter factor. However, the reverse bend makes the circumference larger. Spiral sector FFAs eliminate the reverse bend so that the circumference is smaller.

However, they do not provide full tune control because of the loss of flutter factor control. The idea of an FD spiral lattice was introduced a few years ago [5]. We keep the reverse bend for full control of tune, but make the strength of the reverse bend a minimum by having vertical focusing from the spiral angle as well.

In FETS-FFA, we choose the nominal tunes to be similar in both horizontal and vertical planes with values (3.41, 3.39). We have full control of tune at least as large as an integer to optimise high power operation by changing the field index k and Bd/Bf ratio. The directions of tune change under variations in each parameter are shown in Fig. 1.

We found that an FD doublet spiral lattice behaves like a triplet focusing with one focusing and one defocusing magnet. It is interesting to see that there is smooth transition from FD doublet radial sector optics (FD doublet) to spiral sector optics (DF doublet) through FD spiral optics (DFD triplet) as shown in Fig. 2.

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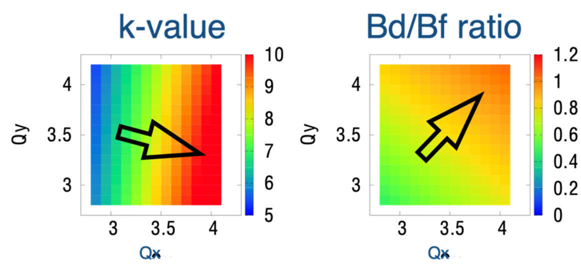

Figure 1: Direction of tune change when k increases (left) and of tune change when Bd/Bf ratio increases (right).

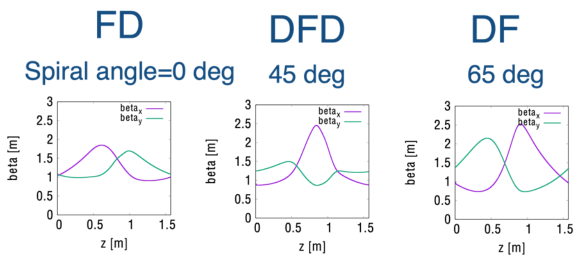

Figure 2: Radial sector optics (left), FD spiral sector optics (middle), and spiral sector optics with only Bf (right).

Lattice with Superperiod

One of the advantages of an FFA compared with a cyclotron is that we can make the magnets smaller by squeezing the orbit excursion from injection to extraction. Increasing the number of cells per ring increases the field index k, hence the orbit excursion becomes smaller. On the other hand, the same total circumference is made up of more straight sections and each of them becomes shorter. A long straight section is always preferred for handling high power beams at injection and extraction, and for RF cavities, collimation, etc. A compromise is to introduce a superperiod structure so that some straight sections become longer for some requirements.

We designed a lattice with 16-fold symmetry first. This gives a reasonably large field index k, making the orbit excursion less than half a metre. On the other hand, the straight section is less than a metre, which may be enough but it is better if we can create longer straight sections. Now we shorten some of the straight sections and lengthen others keeping the total circumference the same. Four FD doublet magnets are excited independently to minimise modulation of the lattice beta functions. Figure 3 (bottom) shows the lattice from such optimisation. We have 4 long straight sections that are over 50% longer than the original length. Some of the straights have to be shortened, but it should not be a problem.

Reducing the symmetry increases the number of systematic resonances. For example, if we make a 5-fold symmetric lattice out of a lattice with 15-fold symmetry, there will be a systematic 3rd order resonance within the possible operating tune region, that is 3.33 between 3.0 and 3.75. However, if we make a 4- or 8-fold symmetric lattice out of a lattice with 16-fold symmetry, systematic resonances up to 5th order will always be outside the operating tune region. Table 2 summarises the location of systematic resonances for lattices with different symmetries.

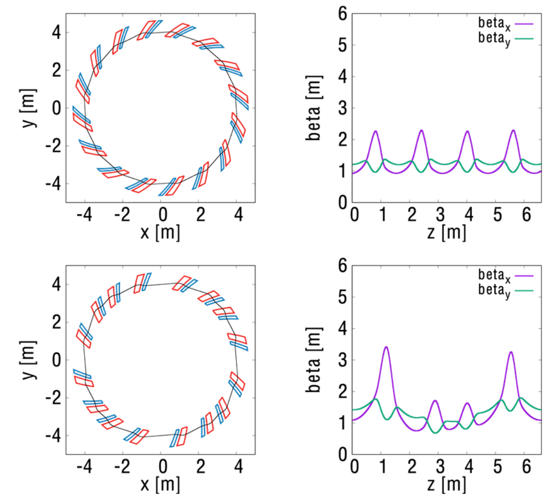

Figure 3: Top view and lattice functions of 16-fold symmetric lattice(top) and of 4-fold symmetric lattice (bottom).

Table 2: Location of systematic resonances for different symmetry lattice. $nQ = pk$, where n is the order of resonance, Q is tune, p is periodicity (p-fold symmetry), k is arbitrary positive integer.

	15-fold symmetry	5 (SP) x 3 (FD)	16-fold symmetry	8 (sp) x 2 (FD)	4 (sp) x 4 (FD)
Q range	3.0 - 3.75	3.0 - 3.75	3.2 - 4.0	3.2 - 4.0	3.2 - 4.0
n=2	7.5 k	2.5 k	8 k	4 k 4.0	2 k 4.0
3	5 k	1.67 k **3.33**	5.33 k	2.67 k	1.33 k 4.0
4	3.75 k 3.75	1.25 k 3.75	4 k 4.0	2 k 4.0	1 k 4.0
5	3 k 3.0	1 k 3.0	3.2 k 3.2	1.6 k 3.2	0.8 k 3.2, 4.0

Dynamic Aperture

One of the methods to mitigate against space charge effects is to enlarge the beam emittance. In SNS and J-PARC, the geometrical emittance is about 500 π mm mrad, which is created by injection painting. It is desirable to have a similar emittance and enough aperture in an FFA as well to reduce space charge effects. However, the FFA optics are highly nonlinear and dynamic aperture is a concern. Scanning dynamic aperture in tune space shows some resonance lines excited by nonlinearities as shown in Fig. 4.

Previous study shows dynamic aperture is mainly determined by amplitude dependent tune shift due to octupole components [6]. Tune approaches a nearby systematic resonance and a particle is lost. The primary location of octupole terms is in the fringe field region.

To see how the shape of fringe field extent affects dynamic aperture, two lattices are compared with different fringe field length. At the same time, multipole contents along the beam orbit are calculated. We found that reduction of octupole by increasing fringe field length more than doubles the dynamic aperture. A more systematic study using a map and normal form analysis is in progress [7].

In terms of dynamic aperture, we found that a strong dependence on the spiral angle, that is directly connected to

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRAI01

the fringe field extent. An interesting finding is that the FD double spiral lattice has the largest dynamic aperture compared with radial and spiral sector FFAs as shown in Fig. 5.

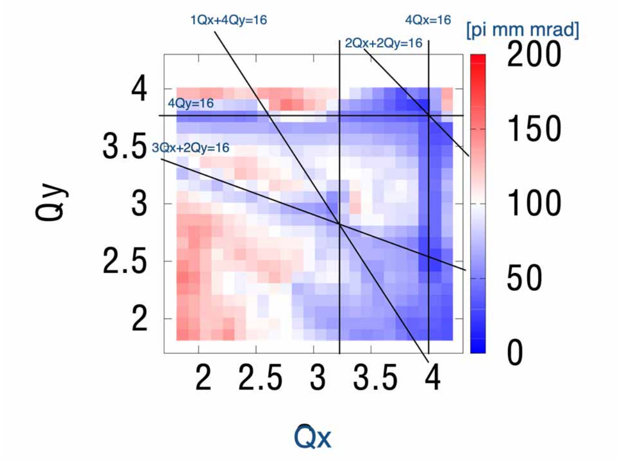

Figure 4: Dynamic aperture scan in tune space. Colour scale shows normalised dynamic apertures Qx and Qy in units of π mm mrad.

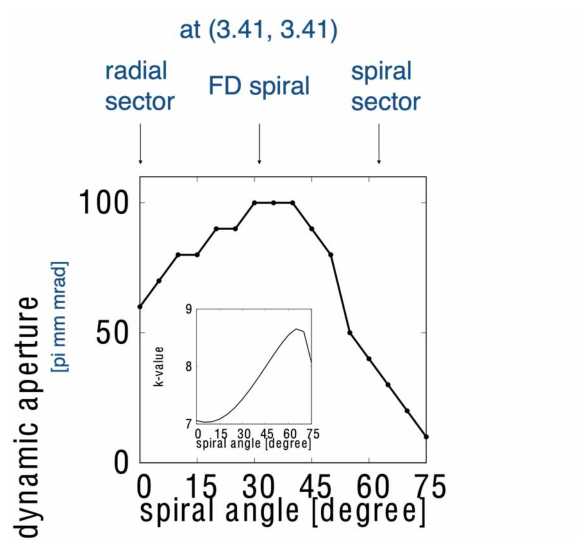

Figure 5: Dynamic aperture as a function of the spiral angle. The inset shows the k adjustment to keep the same tune.

Beam Stacking

From the accelerator point of view, it is always easier to increase repetition rate up to 50 to 100 Hz to obtain high average current. On the other hand, users, particularly neutron users, like to have a low repetition for their experiments, such as 10 to a maximum of about 30 Hz.

Beam stacking is one way to control the rate of the pulses provided to users while maintaining average beam power. It is worth noting that this can only be done by an accelerator with DC magnets like FFAs.

As shown in Fig. 6, a pulse from a linac is injected into an FFA and accelerated to top energy. Instead of extracting the beams every accelerator cycle, we keep the beams at top energy and repeat injection and acceleration N times until we have enough particles or until the number of particles reaches the space charge limit. After N cycles, all the beams are extracted together which gives a high peak intensity. Space charge effects decrease with momentum, hence more accumulation is possible at top energy rather than at injection energy. Figure 7 shows longitudinal phase space at top energy after 4th beam is accelerated and debunched. Since momentum spread increases linearly with the number of the stacked beams, the required RF capture voltage increases quadratically. Figure 7 also shows longitudinal phase space after adiabatically capturing the stacked beams. As an illustration, Fig. 8 shows the acceleration cycle and the beams seen by two targets. In this example, we assume that there are two target stations and the accelerator is running at 120 Hz. The figure shows that the target station 1 accepts the beams by stacking with 30 Hz repetition and the users see it every 33 ms. Target station 2 sees a beam pulse with 15 Hz.

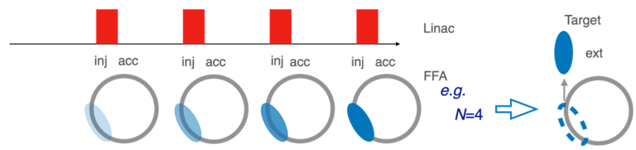

Figure 6: Beam stacking keeps N accelerated pulses at the top energy and extracts them all at once.

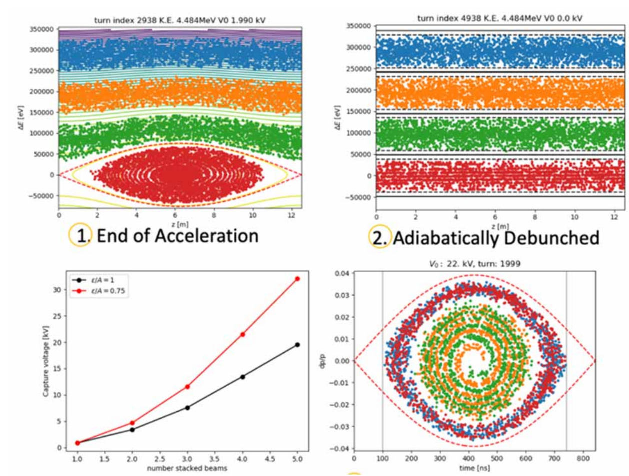

Figure 7: Longitudinal phase space at the end of acceleration of 4th beam (top, left), after debunching of 4th beam (top, right). Required RF voltage to capture the beams vs. the number of stacked beams (bottom, left). Longitudinal phase space after capture (bottom, right).

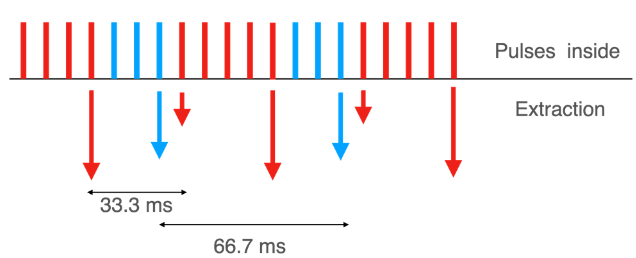

Figure 8: Accelerator runs at 120 Hz. Beam pulses for target station 1 (red) go every 33.3 ms (30 Hz) and beam pulses for target station 2 (blue) go every 66.7 ms (15 Hz).

HARDWARE DEVELOPMENTS

Magnets

Magnets are the most critical elements. The magnets for a high power FFA need to have the right field gradient which imposes high accuracy on the field index *k*. We have looked at several magnet designs to create the field gradient and control the field index over a large range from $k = 6$ to $k = 11$. We initially optimised the magnet with a 2D cross section (Fig. 9) and have now moved to 3D modelling (Fig. 10).

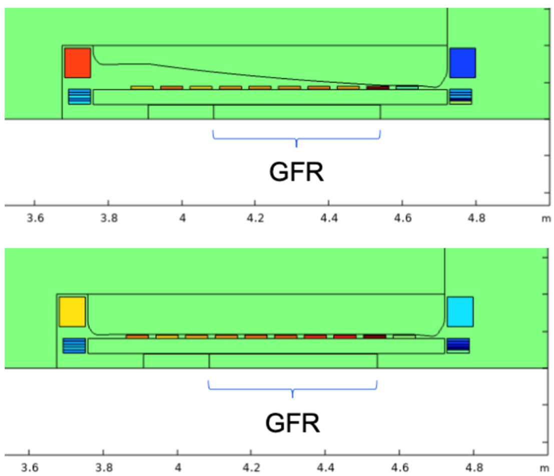

Figure 9: Field gradient is primarily determined by the gap shape. Trim coils along the gap adjust the field index *k*. (top) Field gradient is made by trim coils and the field index *k* is also adjusted by the same trim coils (bottom).

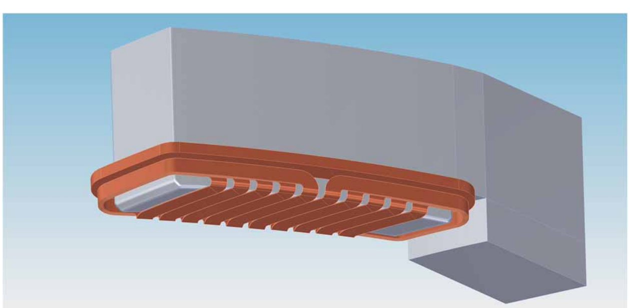

Figure 10: 3D modelling of spiral magnet with field gradient has started.

Diagnostics

Beam diagnostics are another crucial item. Unlike a cyclotron, we want to measure the beam position turn by turn for a wide range of orbits, such as 600 mm non-destructively. We have constructed a half-size Beam Position Monitor and tested it in the FFA at Kyoto University. We saw the beam moving as it is accelerated (Fig. 11). From small oscillations around the closed orbit, we can determine the tune both in horizontal and vertical planes.

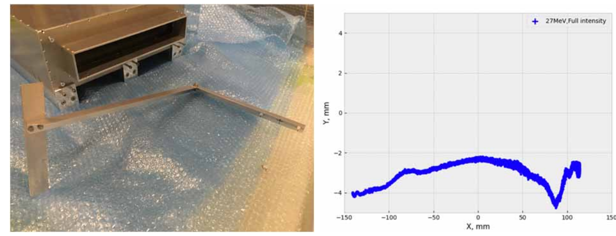

Figure 11: A half size model of Beam Position Monitor installed in the FFA at Kyoto University (left). Measured beam position signal (right).

RF Cavity

Magnetic Alloy is a possible candidate for the RF cavity core. We have started testing a sample core and measured the shunt impedance (Fig. 12).

Figure 12: Magnetic Alloy sample and setup for shunt impedance measurement (Courtesy: Gardner, see [8, 9]).

SUMMARY

Our goal is to demonstrate high power operation of a fixed-field alternating gradient accelerator (FFA). We chose a scaling FFA. From the physics design point of view, this paper discusses three subjects: a proper lattice structure ready for high intensity operation; a superperiodic lattice to give space for beam handling; and dynamic aperture to accommodate a large number of particles. From the operation point of view, we consider beam stacking to produce either high peak current with low repetition rate or low peak current with high repetition rate. We briefly mentioned the hardware design status. Prototyping of critical hardware elements has started.

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