Science and Technology Facilities Council

ISIS upgrade and feasibility study

Shinji Machida
Rutherford Appleton Laboratory

FFA Workshop at PSI, 19 November 2019

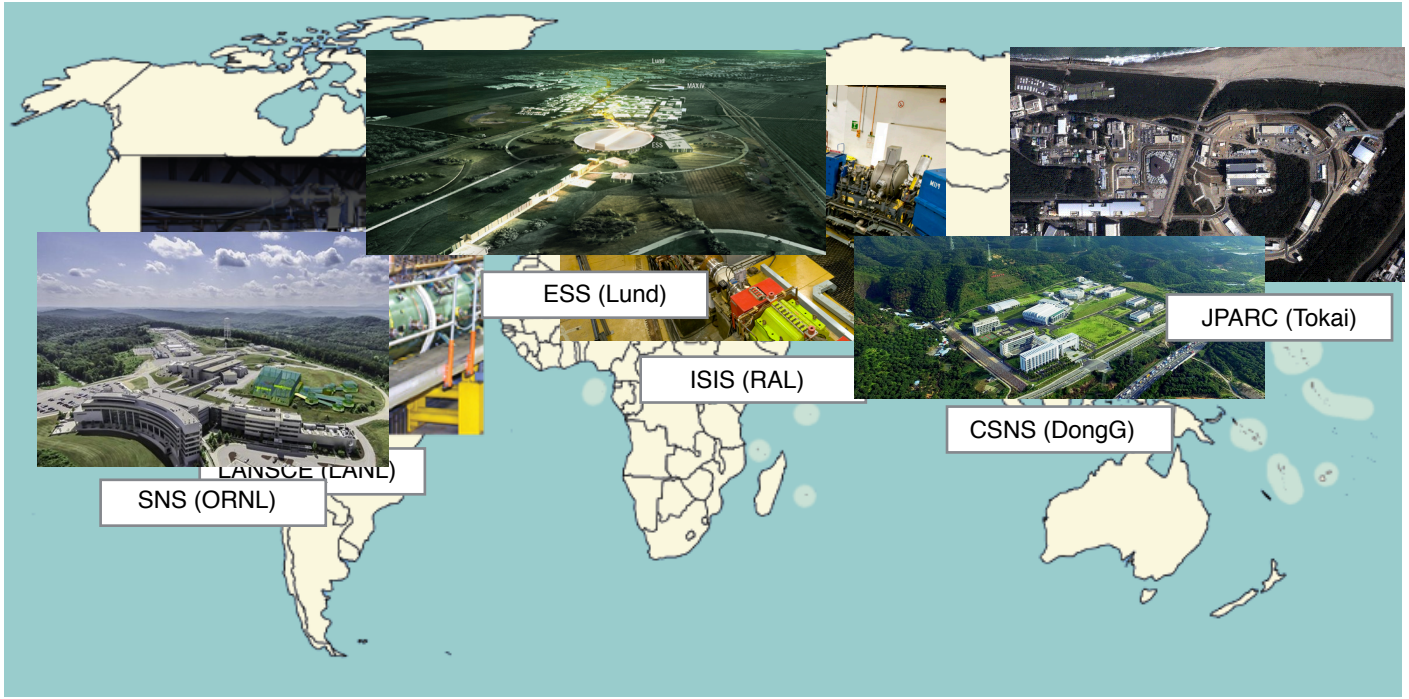
Outline

- ISIS-II: Upgrade of ISIS
  - Demands of short pulse neutron
  - Main parameters
  - Accelerator choice
- FFA and vertical excursion FFA
  - How it works
  - FFA vs vFFA
- Feasibility study
  - Choice of parameters for ISIS-II and FETS-FFA
  - Operational knobs, dynamic aperture
  - FETS and FETS ring
  - Time table
  - Hardware R&D
- vFFA lattice for muon acceleration
- Summary

Science and Technology Facilities Council

ISIS-II: upgrade of ISIS

ISIS-II
landscape



Science and Technology Facilities Council

- Number of neutron sources is declining in Europe.
- Start of European Spallation Source (ESS) in Lund is not enough to keep the whole neutron science community.

ISIS-II

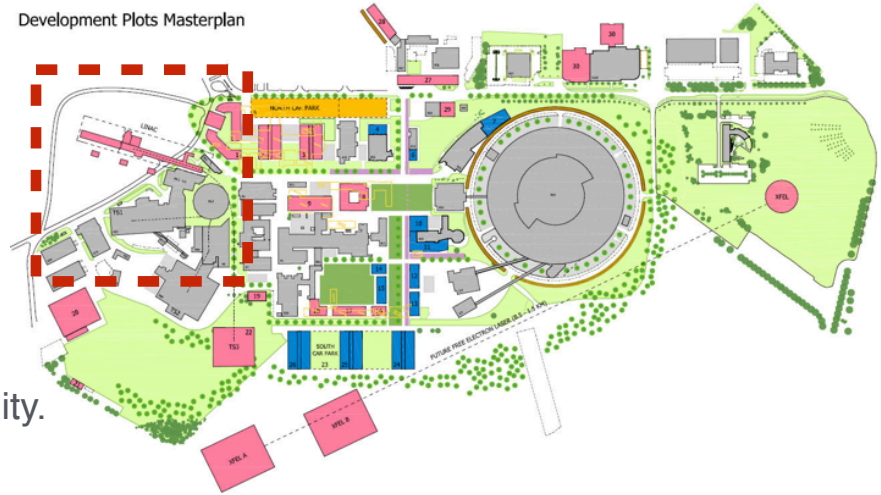
aim

ISIS will/should continue producing **useful neutrons**.

Beam power does not have to be greater than the present standard, **~1 MW**.

- Availability, flexibility, sustainability, low cost to operate.
- Robert McGreevy (Director of ISIS) summarised
  - **Capacity:** number of experiment and size of community
  - **Capability:** particular experiment
- Fit in the present ISIS tunnel or build a stand alone facility.

RutherfordAppletonLaboratory



Science and Technology Facilities Council

ISIS-II

minimum requirements

output energy	**1.2 GeV**
injection energy	**< 0.5 GeV**
beam power	**1.25 MW**
mean radius at injection	**~25 m**
repetition	**~100 Hz**

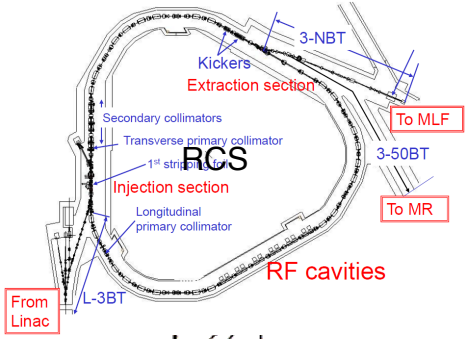
Note: Specifications here is for an option of using ISIS infrastructure. “Stand Alone Facility” option is not much difference in terms of specifications.

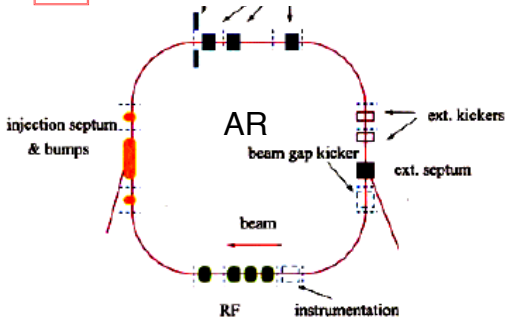
Science and Technology Facilities Council

ISIS-II

accelerator options

RCS: Rapid Cycling Synchrotron
AR: Accumulator Ring
FFA: Fixed Field Alternating Gradient Accelerator





- Could have high repetition rate (100 Hz) from the start or at later stage.
- Good match with **multiple target stations** with flexible operation patterns.
- Simple DC power supply with stable and reliable operation.
- Use of superconducting (permanent) magnets for operational cost saving.

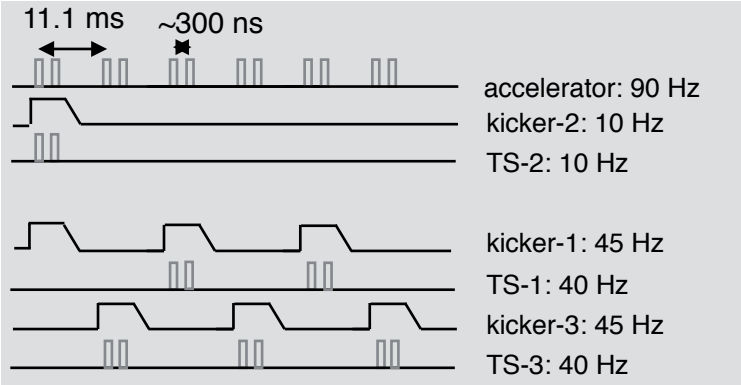
Well established
vs
Something novel

- If ISIS-II starts construction tomorrow, it should be RCS or AR.
- Fortunately we have time to develop alternative option.

ISIS-II

pulse structure for users

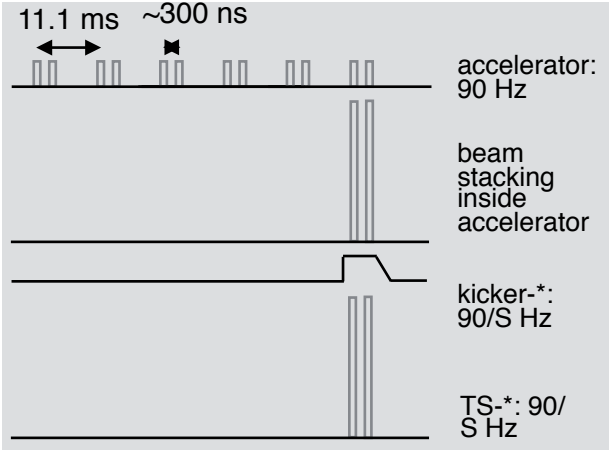
Pattern example 1 Assume 2 bunch per cycle



- TS-2: 10 Hz, (10/90): 0.138 MW
- TS-1: 40 Hz, (40/90): 0.556 MW
- TS-3: 40 Hz, (40/90): 0.556 MW

Total: 1.25 MW

Pattern example 2 Assume 2 bunch per cycle



- TS-*: 90/S Hz
  where S is the number of stacking.

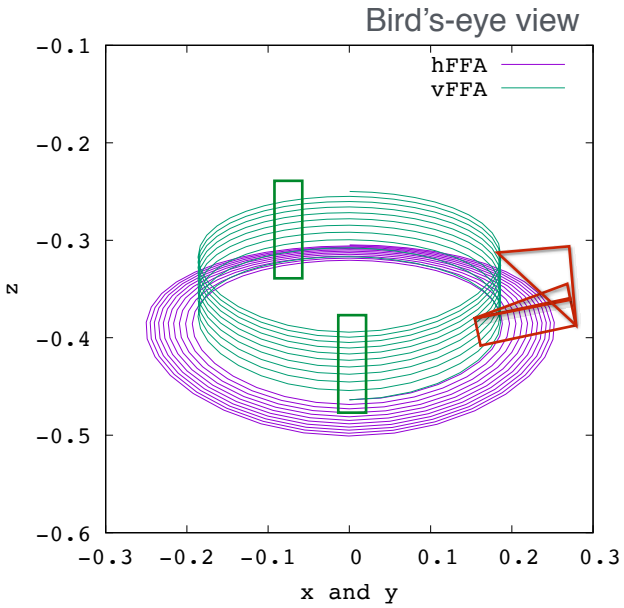
Science and Technology Facilities Council

FFA and vertical excursion FFA

FFA
how it works?

- **Equilibrium orbit** should exist for the range of momenta.
- **Focusing action** should exist to make the beam stay around the equilibrium orbit.

- FFA has alternating gradient focusing. This could be normal or skew.
- Equilibrium orbit is determined by the centrifugal force and the Lorentz force by vertical magnetic field.

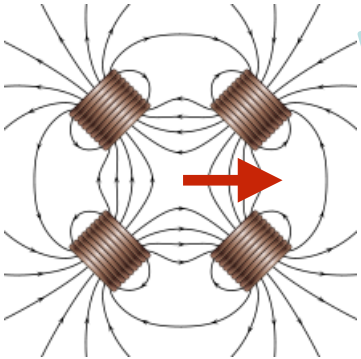


Science and Technology Facilities Council

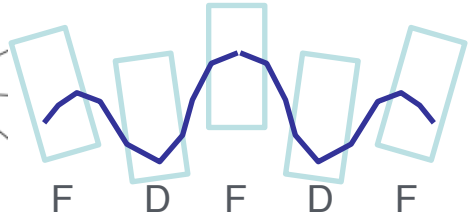
FFA with lowest order focusing (quadrupole)

Normal quadrupole

- Stronger F (normal bend) than D (reverse bend) make the orbit circle.
- Vertical field get stronger **along radial direction**
- **Equilibrium orbit moves horizontally.**



Top view



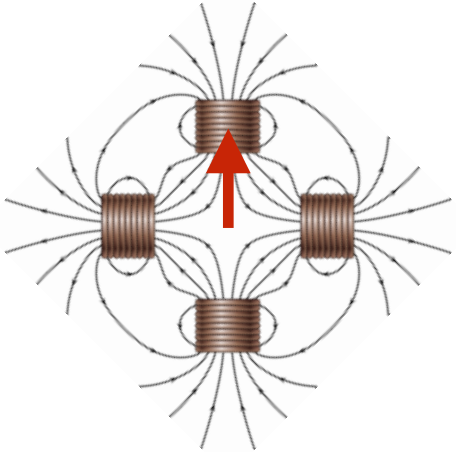
Side view

Science and Technology Facilities Council

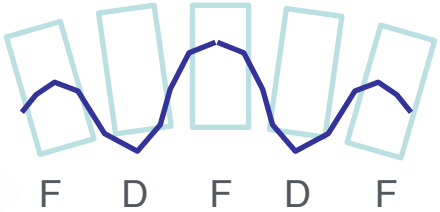
Non-scaling FFA

Skew quadrupole

- Stronger F (normal bend) than D (reverse bend) make the orbit circle.
- Vertical field get stronger **along vertical direction**
- **Equilibrium orbit moves vertically.**



Top view



Side view

Non-scaling vFFA

FFA and vFFA

to make it work for all the momentum range

For a fixed momentum p, linearised eq. of motion,

FFA

$$\frac{d^2y}{d\theta^2} + \frac{\rho_0^2}{\rho^2}y - \frac{\rho_0^2}{\rho^2}ny = 0$$

$$\frac{d^2z}{d\theta^2} + \frac{\rho_0^2}{\rho^2}nz = 0$$

where

$$n = -\frac{\rho}{B_z}\frac{\partial B_z}{\partial y}$$

vFFA

$$\frac{d^2y}{d\theta^2} + \frac{\rho_0^2}{\rho^2}y - \frac{\rho_0^2}{\rho^2}nz = 0$$

$$\frac{d^2z}{d\theta^2} + \frac{\rho_0^2}{\rho^2}ny = 0$$

where

$$n = -\frac{\rho}{B_z}\frac{\partial B_z}{\partial z}$$

Make the orbit and optics independent of p

$$\left(\frac{\partial \rho}{\partial p}\right)_x = 0 \quad \text{: same shape of orbit}$$

$$\left(\frac{\partial n}{\partial p}\right)_x = 0 \quad \text{: invariance of optics}$$

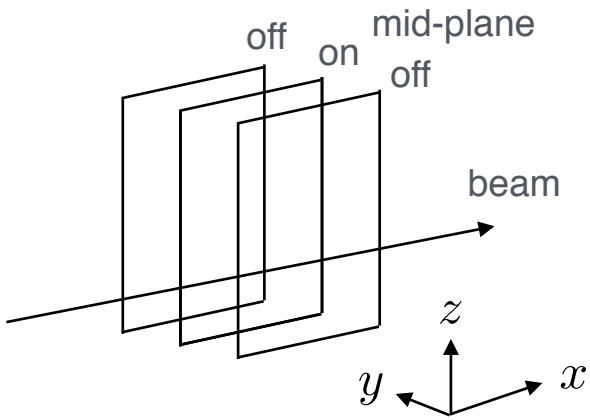
Magnetic field should satisfy with a constant

$$k = \frac{y}{B_z}\frac{\partial B_z}{\partial y}$$

Finally $\boxed{B_z(y) = B_0 y^k}$

$$m = \frac{1}{B_z}\frac{\partial B_z}{\partial z}$$

Finally $\boxed{B_z(z) = B_0 \exp(mz)}$



x Longitudinal

y Horizontal

z Vertical

Science and Technology Facilities Council

vFFA

3D magnetic fields

All 3D magnetic fields have to satisfy the same dependence on the vertical coordinate.

$$B_z(z,x,y) = B_0 \exp(mz) \sum_{i=0}^{\infty} b_{zi}(x)\, y^i$$

$$B_x(z,x,y) = B_0 \exp(mz) \sum_{i=0}^{\infty} b_{xi}(x)\, y^i$$

$$B_y(z,x,y) = B_0 \exp(mz) \sum_{i=0}^{\infty} b_{yi}(x)\, y^i$$

Off mid-plane field is expanded as polynomial with *y*.

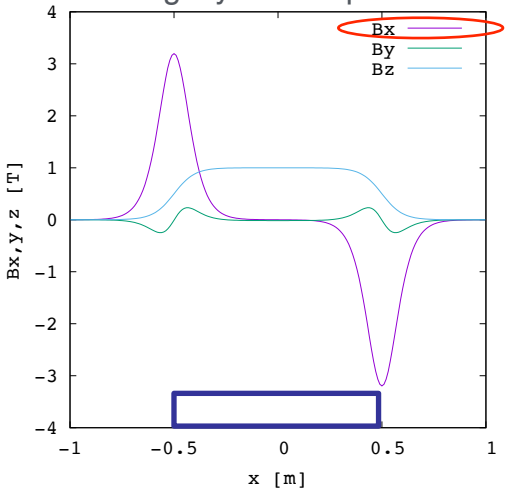
where

$$b_{z0}(x) = g(x)$$

$$\boxed{b_{x0}(x) = \frac{1}{m}\frac{\partial g}{\partial x}}$$

$$b_{y0}(x) = 0$$

Slightly off mid-plane



Non zero longitudinal field on mid-plane is something we did not have in a conventional accelerator.

Skew quadrupole (body) + Solenoidal field (ends)

Science and Technology Facilities Council

vFFA vs FFA

Vertical

Pros

- Magnet is more straightforward (not necessarily simple) with small footprint.
- Coil dominated design is possible. Good for superconducting magnets.
- Separation of scaling law and ring geometry.

Cons

- Magnetic field strength is higher than vFFA.
- Optics is strongly coupled.
- Unexpected things may happen (but it will be the world premiere!)

Horizontal

Pros

- FFA based on similar design has been working: e.g. machines at Kyoto Univ.
- Optics is decoupled, diagnostics is simpler.

Cons

- Magnet design with spiral angle would be more difficult.
- Spiral angle becomes large to squeeze orbit excursion.
- Straight section between spiral magnets could be shorter in reality.
- Magnet footprint is large.

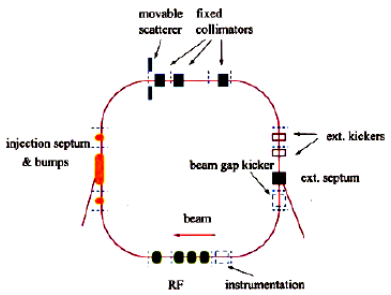
Feasibility study

Feasibility study

outline

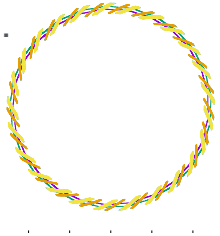
Goal

In the next 7~10 years, provide enough information to decide the right choice of the proton driver for ISIS-II.



How do we proceed?

Work on design of conventional (RCS/AR) and novel idea (FFA) in parallel.



More specific plan

on RCS/AR

- Decide RCS or AR within a few years.
- Determine **the best conventional ring design**.

on FFA

- Construct **a prototype ring** (not funded yet).

Science and Technology Facilities Council

Feasibility study

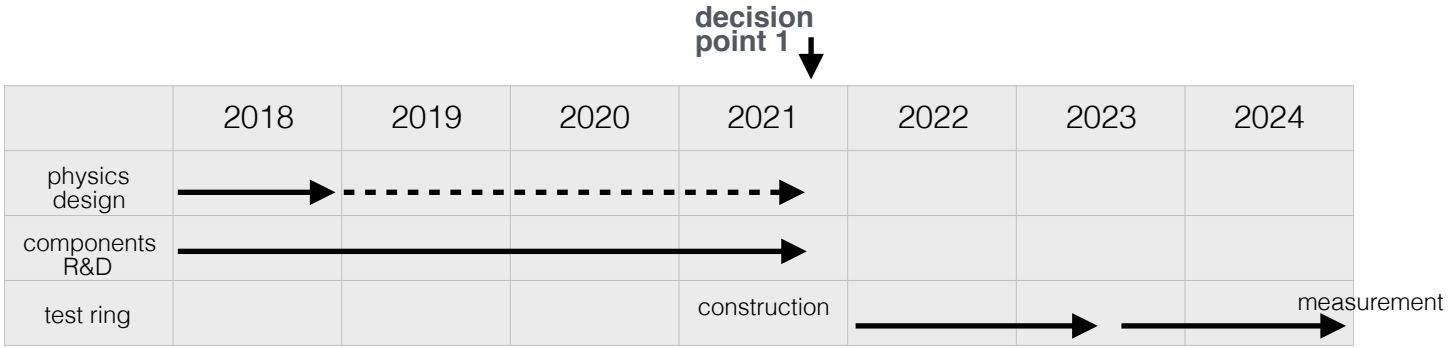
schedule

for physics design

- Show that FFA design works as expected.
- Benchmark simulation code and experimental results.
- Beam dynamics study bench, especially of high intensity beams.

for hardware R&D

- Show engineering feasibility of wide aperture components.
- Choose the best solution to achieve the requirements.
- Develop in-house skills for the whole FFA accelerator system.



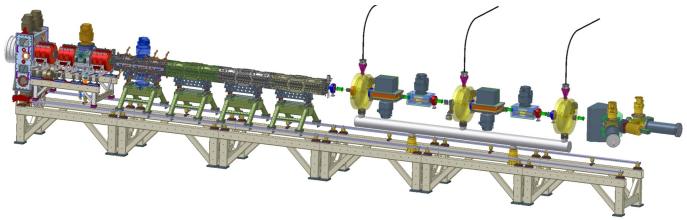
Science and Technology Facilities Council

Feasibility study

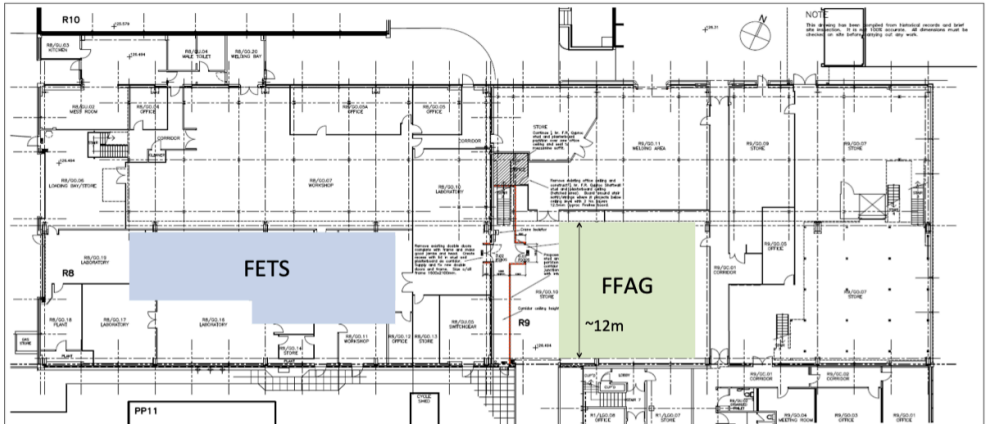
FETS as an injector

- Low enough energy (3 MeV) so that a test ring can fit in the existing building.
- Beam loss can be tolerated at 3 MeV although the ultimate goal is zero loss.

- Physical emittance from FETS is comparable as the ring acceptance.
- Peak current is high so that easily get into space charge limit with one turn injection.



Front End Test Stand (FETS)



Science and Technology Facilities Council

Code benchmarking (1)

No code was available to design vFFA.
Write or modify a code is the first thing.

Potential codes for vFFA design and benchmarking.

- OPAL (PSI and Chris R)
- Zgoubi (BNL and David K)
- FixField (JB)
- Muon1 (Stephen B)
- SCODE+ (Shinji M)

Baseline design has been made by SCODE+ so far

Science and Technology Facilities Council

Code benchmarking (2)

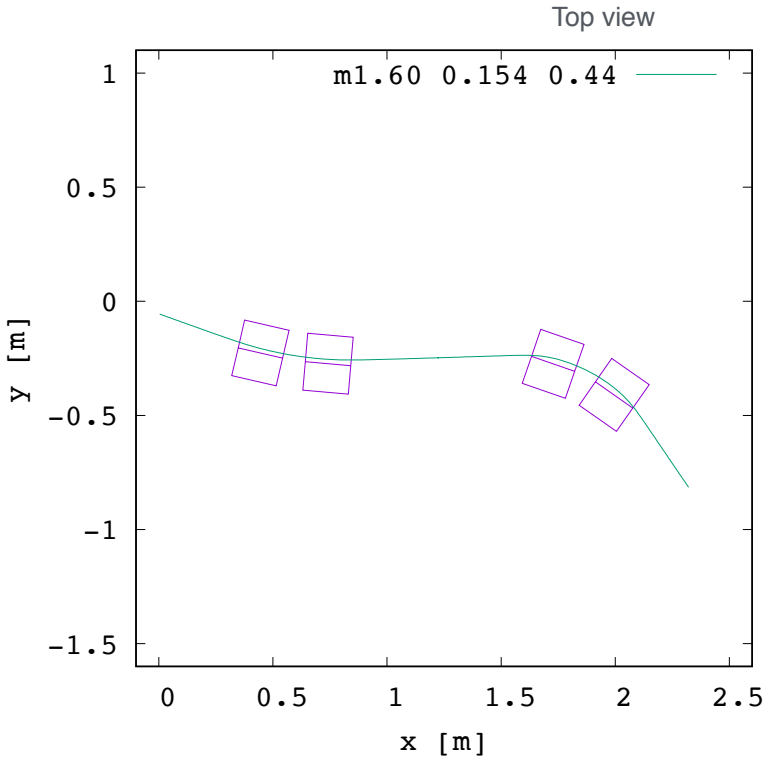
preliminary results

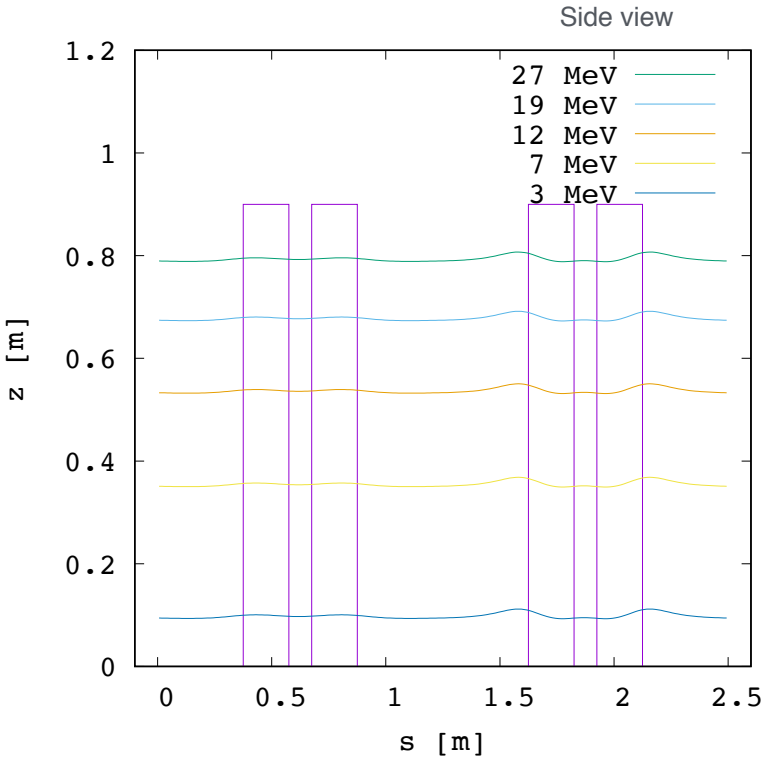
	u tune	v tune	
SCODE+	0.184701	0.231858	0.999960
FIXFIELD	0.183880	0.232180	0.999960
MUON1	0.187858	0.230659	
OPAL (CR)	0.176693	0.239013	1.002388

Chris R will discuss this later.

Science and Technology Facilities Council

Orbits





Science and Technology Facilities Council

- Path length is independent of momentum like linac.
- Orbit moves vertically as the beams are accelerator.

vFFA baseline parameters

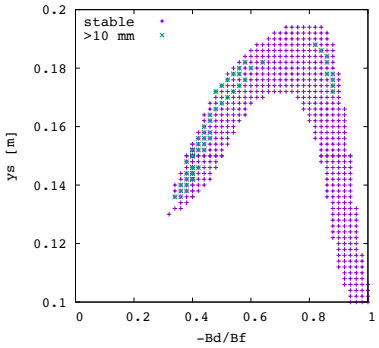
Kinetic energy	**3 - 12 (17) MeV**
Number of cell	**10**
Cell length	**2.5 m** (=1.25 m + 1.25 m)
Num er of Bd segment	2
Length of Bd segment	0.2 m
Space between Bd segment	0.1 m
Angle between Bd segment	-8 deg
Number of Bf segment	2
Length of Bf segment	0.2 m
Space between Bf segment	0.1 m
Angle between Bf segment	+16 deg
Relative displacement btw Bd and Bf	+/- 0.154 m
Length of straight section	**0.75 m**
Fringe length L (Tanh x/L)	0.125 m
-Bd/Bf	0.44
Field index m	**1.58 m^-1**

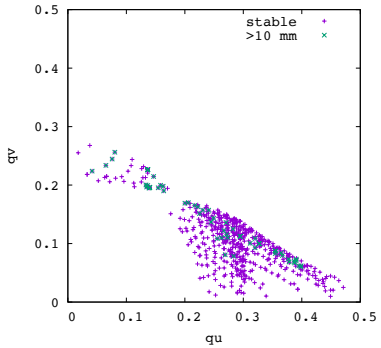
Science and Technology Facilities Council

Tenability

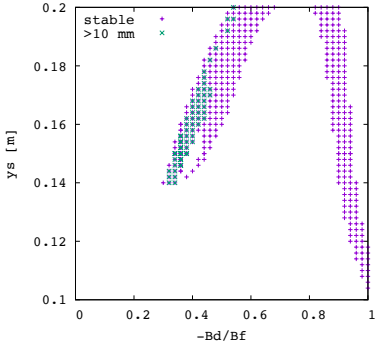
Tuning knobs

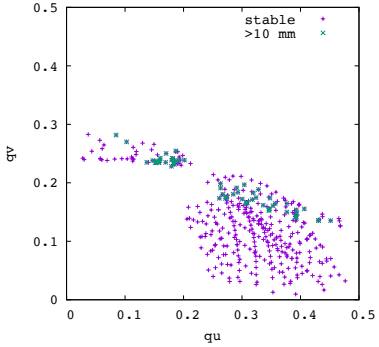
1) field index (gradient) m,
2) ratio of Bd/Bf,
3) radial distance btw Bd and Bf





m=1.60





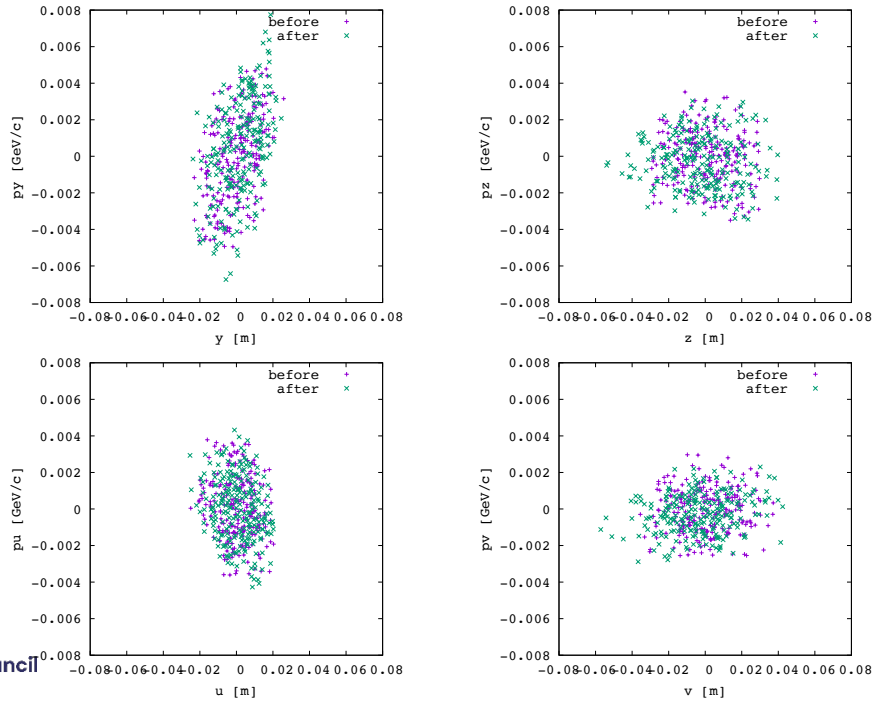
m=2.00

Science and Technology Facilities Council

Dynamic aperture

DA is important figure because of nonlinearity of all orders.

(DA: phase space where a particle survives for 1000 turns)



Coupled space
(y - z)

> 30 pi mm mrad (nor.)

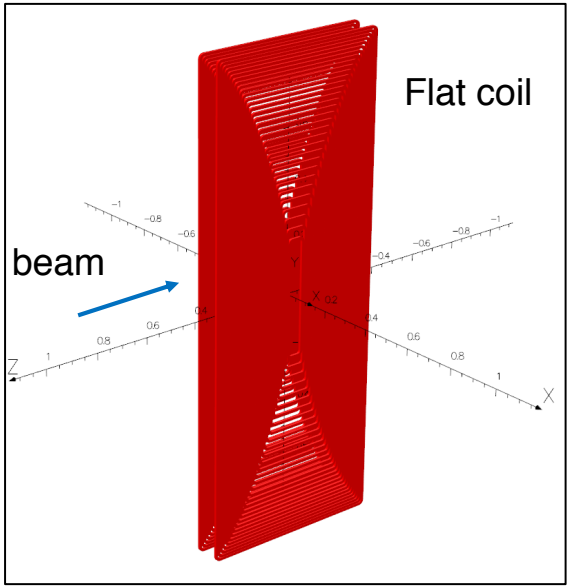
Decoupled space
(u -v)

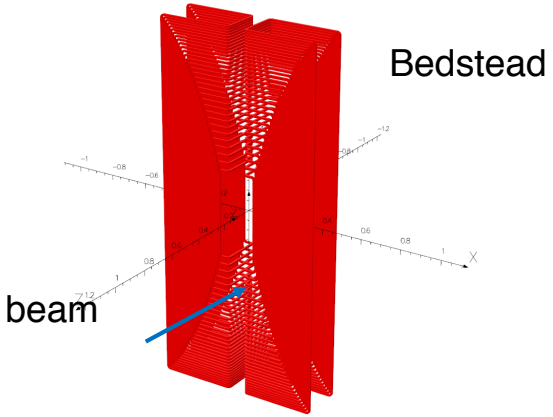
Science and Technology Facilities Council

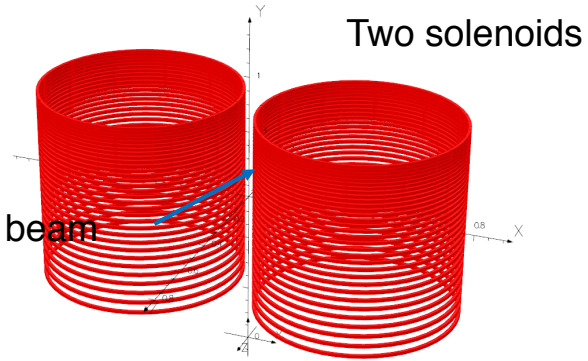
Hardware R&D

superconducting magnets (1)

- Several options to realise the fields.







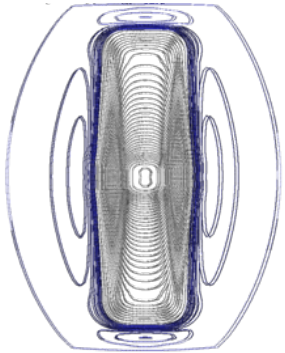
Science and Technology Facilities Council

(I. Rodriguez, et al)

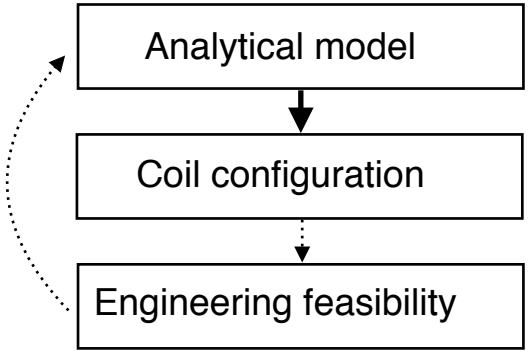
Hardware R&D

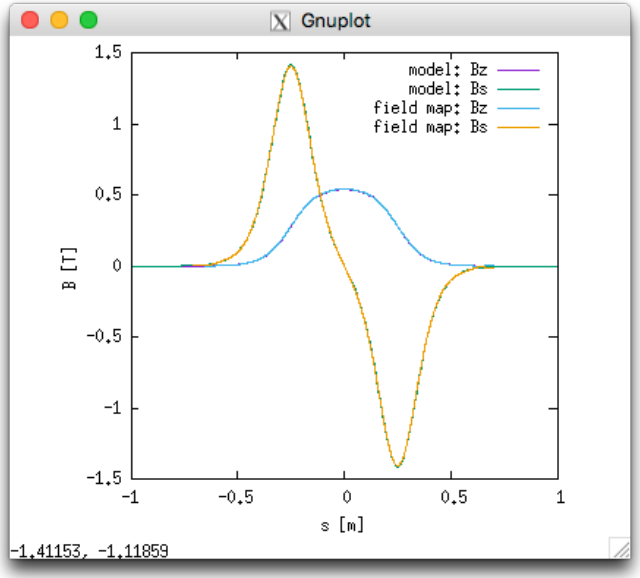
superconducting magnets (2)

- Solve Biot-Savart law inversely to find coil shape (S. Brooks at BNL).
- Fringe field shape and length are free parameters!



Flat coil with complex current density





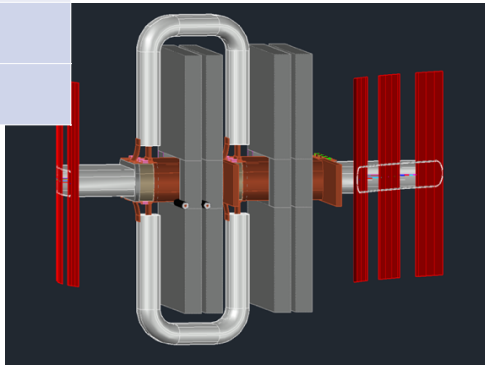
Science and Technology Facilities Council

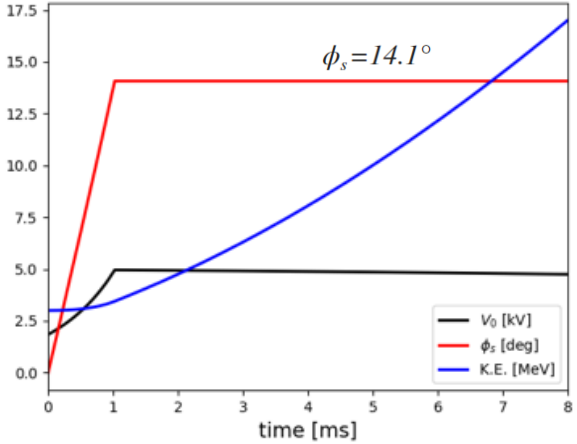
(S. Brooks)

Hardware R&D

RF specifications and prototype

Parameter	Value
Average radius	(25/2*pi) m
Energy range	3 – 12 (17.0) MeV
Harmonic	2
RF frequency range	1.91 – 3.8 (4.5) MHz
Injected bunch dp/p	+/- 0.0075 [0.045
RF voltage	5 kV per turn





Science and Technology Facilities Council

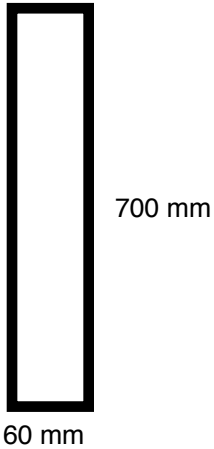
(D. Kelliher and R. Mathieson)

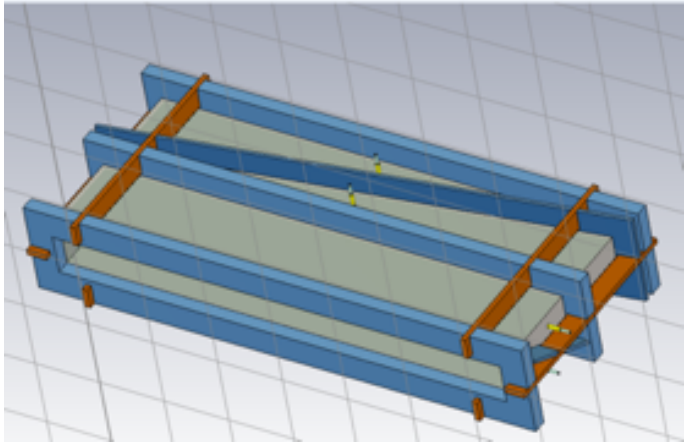
Magnetic Alloy cavity is also being considered.

Hardware R&D

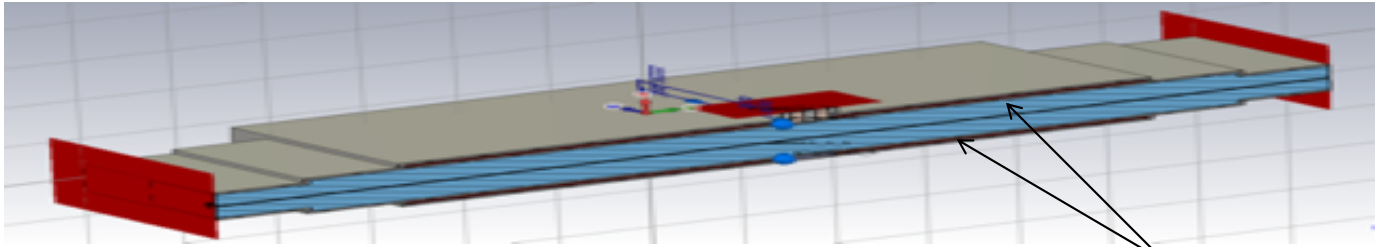
diagnostics

Diagnostics for rectangular aperture.





Preliminary design of the FFA BPM, modelled in CST



Scaled-down CST model of the WCM, to illustrate extreme shaping of the ferrite (these red bits, 1mm thick).

Science and Technology Facilities Council

(C. Wilcox and E. Yamakawa)

vFFA lattice for muon acceleration

Science and Technology Facilities Council

vFFA for muon

Fixed field	**No need to ramp the magnetic field unlike RCS. It has huge momentum acceptance.**
Zero chromaticity	**Wide momentum range of acceleration such as a factor of 30 with fixed field magnets within a reasonable aperture.**
Fixed path length like linac	**For ultra relativistic particles, revolution frequency is constant. High-Q fixed frequency cavity can be used.**
Scaling condition is separate from geometry	**Shape of the ring is independent of scaling condition. Long straight insertion is a possibility.**

Science and Technology Facilities Council

10 to 300 GeV/c

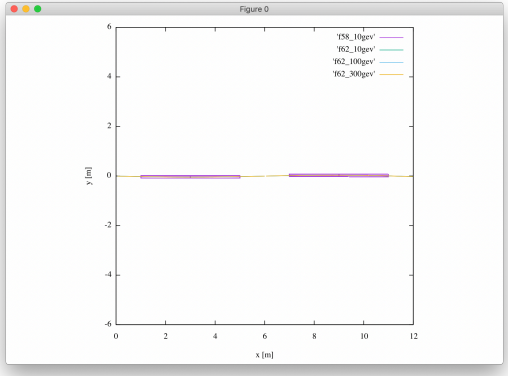
Momentum range	**10 - 300 GeV/c**
Circumference	**12 km***
Maximum field	**12 T***
Number of cell	**1000**
Radius	**1910 m**
FODO cell length	**12 m**
Length of straight section	**2 m**
Length of magnets	**4 m**
Field index m	**8**
Orbit excursion	**0.425 m**
Tune per cell in decoupled space	**(0.3109, 0.2239)**

* this is simply because the design is not optimised.

Science and Technology Facilities Council

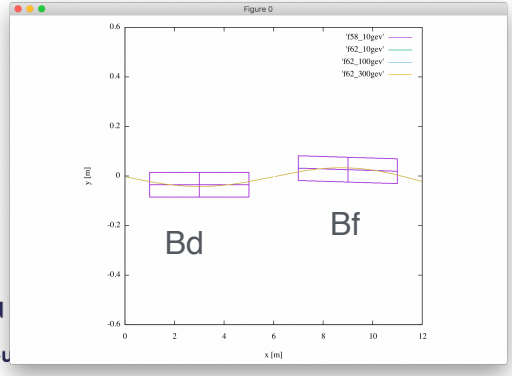
Orbit

Top view

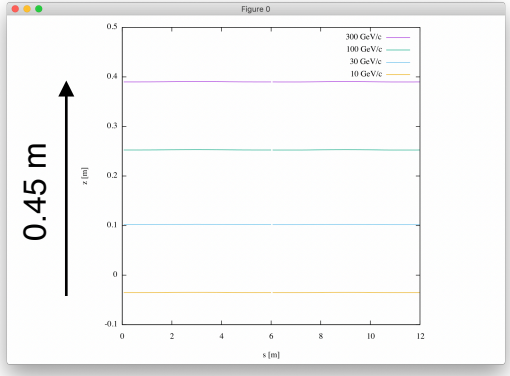


0.36 degree bend per cell

(Expanded)



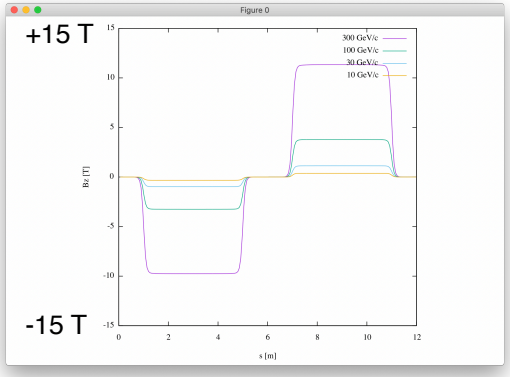
Side view



Science and Technology Facilities Cou

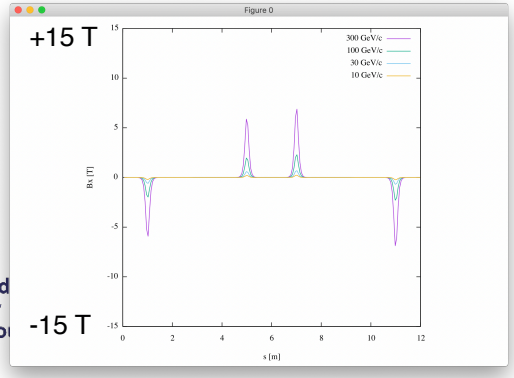
Magnetic fields

Bz: Vertical



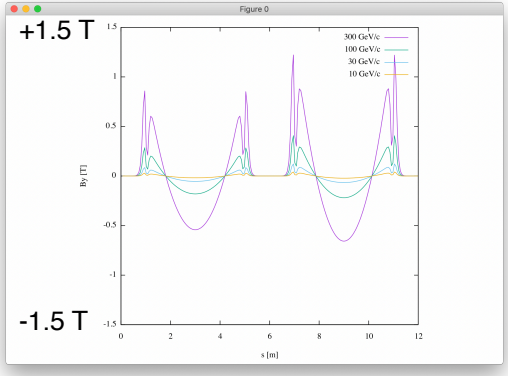
12 m

Bx: Longitudinal



Significant cancellation of the normal bending by reverse bending in this design.

By: Horizontal



Science and Technology Facilities Co

10 to 100 GeV/c

Momentum range	**10 - 100 GeV/c**
Circumference	**3.6 km**
Maximum field	**4.7 T**
Number of cell	**300**
Radius	**573 m**
FODO cell length	**12 m**
Length of straight section	**1.2 m**
Length of magnets	**4.8 m**
Field index m	**5.6**
Orbit excursion	**0.41 m**
Tune per cell in decoupled space	**(0.3163, 0.0835)**

Science and Technology Facilities Council

vFFA for muon

observation

- When the total number of cells is large, say more than 300, and the bending angle per cell is small, e.g. less than 1 degree, it is easy to find the lattice with large m.
- Dynamic aperture with large m could be an issue. This is study in the future.

Summary

Summary

- 1.25 MW, 1.2 GeV proton driver is designed as ISIS-II.
- Flexible and energy efficient features of FFA could potentially give the best design as a proton driver for neutron and muon source.
- At RAL, we started feasibility study for the next 7~10 years of FFA development including a test prototype ring as well as conventional ring (RCS/AR) study.
- vFFA shows clear advantage for muon acceleration.

Thank you for your attention.

Science and
Technology
Facilities Council

Proposal of “electron cyclotron”
by Tihiro Ohkawa

“If path length can be kept constant in the fixed field accelerator, ultra relativistic particles like electrons and muons can be accelerated continuously with fixed RF frequency.”

Bull. APS 30, 20 (1955)

S G AND H Phys Rev 100 1247 (1955)

oscillations about these orbits are derived. Two kinds of alternating gradient focusing terms appear, which may be referred to as “edge-type” and “gradient-type” focusing. Approximate formulas for betatron oscillation frequencies are derived relating them to momentum content, magnetic field flutter, and other machine parameters. The character of these relationships depends on whether the focusing is predominantly gradient-type or edge-type. An approximate treatment of nonlinear betatron oscillations can be given for machines whose equilibrium orbits are nearly circles.

* Supported by the National Science Foundation.

G8. FFAG Electron Cyclotron.* TIHIRO OHKAWA, *University of Illinois*† (introduced by D. W. Kerst).—New types of FFAG[1] accelerators having the same orbit length for all momenta are proposed. In these types electrons, injected with an energy of a few Mev, are accelerated by a fixed frequency electric field until the radiation loss becomes serious, probably at a few Bev. The necessary cavity voltage is, for example, 200 Kev with 3 Mev injection energy. Two types of guiding fields, similar to Mark I (alternate field type) and Mark V (spirally ridged type) are used. In both, the magnetic field increases exponentially in the vertical direction so that as the particle energy increases, its orbit rises vertically. The field also depends on the radius and the azimuthal angle in such a way that the focusing properties are very similar, respectively, to Mark I and to Mark V. Other types of FFAG having the orbit surface not on a median plane are also proposed.

* Reported by the present author at the meeting of the Physical Society of Japan in June, 1955.
† On leave from the University of Tokyo.
[1] Reported by the present author at the meeting of the Physical Society of Japan in October, 1953; K. R. Symon Phys. Rev. 98, 1152(A) (1955).

Science and Technology Facilities Council

Stephen Brooks reinvented 50 years later.

	Physical [pi mm mrad]	Normalised [pi mm mrad]	Half size [mm]
Beam core (ISIS-II)	100	100	+/- 32
Collimator acceptance (ISIS-II)	200	200	+/- 45
Vacuum chamber acceptance (ISIS-II)	400 ~ 800	400 ~ 800	+/- (63 ~ 89)
Beam core in Test-R (simple scale of 1/6)	16.7	1.33	+/- 5.33
Collimator acceptance (simple scale of 1/6)	33.3	2.67	+/- 7.5
Vacuum chamber acceptance (1/6)	66.7 ~ 133	5.33 ~ 10.7	+/- (10.5 ~ 14.8)
Beam core in Test-R (enlarged)	33 or 67	2.7 or 5.3	+/- 7.5 or +/- 10.7
Collimator acceptance (enlarged)	67 or 133	5.3 or 10.7	+/- 10.7 or +/- 15.1
Vacuum chamber acceptance (enlarged)	133 ~ 267 or 267 ~ 533	11 ~ 21 or 21 ~ 43	+/-(15 ~ 21) or +/-(21 ~ 30)

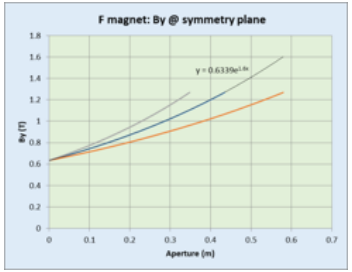
c.f. Norm emittance of linac beam (**rms**) ~ 0.25 pi mm mrad.

Kinetic energy	0.4 to 1.2 GeV
Number of cell	25
Cell length	6 m
Straight length	**2.4 m**
Field index	0.88 m^{-1} +/- ?%
Magnet length	2 x 0.25 m with 0.1 m space
Bd/Bf	**?**
Angle between 2 segments	0 for Bd, 0 for Bf (see figure)
Relative displacement between Bd and Bf	0.350 +/- ? m
Inner aperture	? mm^2
Coupling angle	Depends on tune
Nominal cell tune	(0.2252, 0.1366)
Orbit excursion	0.79 m when m=0.88
Fringe extent of Tanh	0.30 m

Parameter table is updated on the ISIS/Shares holder.
"MainParametersISISIIandFETSring_v.X"

Science and Technology Facilities Council

- To change tune, the field gradient *m* has to change.
- When *m* changes, orbit excursion changes.
- Extraction orbit position depends on tune.



$$\boxed{\frac{p_e}{p_i} = \exp\left(\frac{m}{m_0}\log\left(\frac{p_e}{p_i}\right)_0\right)}$$

m_o Nominal m=1.6

$\left(\frac{p_e}{p_i}\right)_0$ Nominal momentum ratio=2

m	pe/pi	Final energy [MeV]
1.2	1.7	8.5
1.6	2.0	12
2.0	2.4	17

baseline

Prepare magnets and RF for acceleration to 17 MeV.

(David's talk)

Science and Technology Facilities Council