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Studies of High Intensity Proton FFAGs at RAL

Chris Prior
ASTeC Intense Beams Group

Contents

- ISIS Upgrades
- FFAGs
  - advantages
  - options
- Injection
- Experimental aspects

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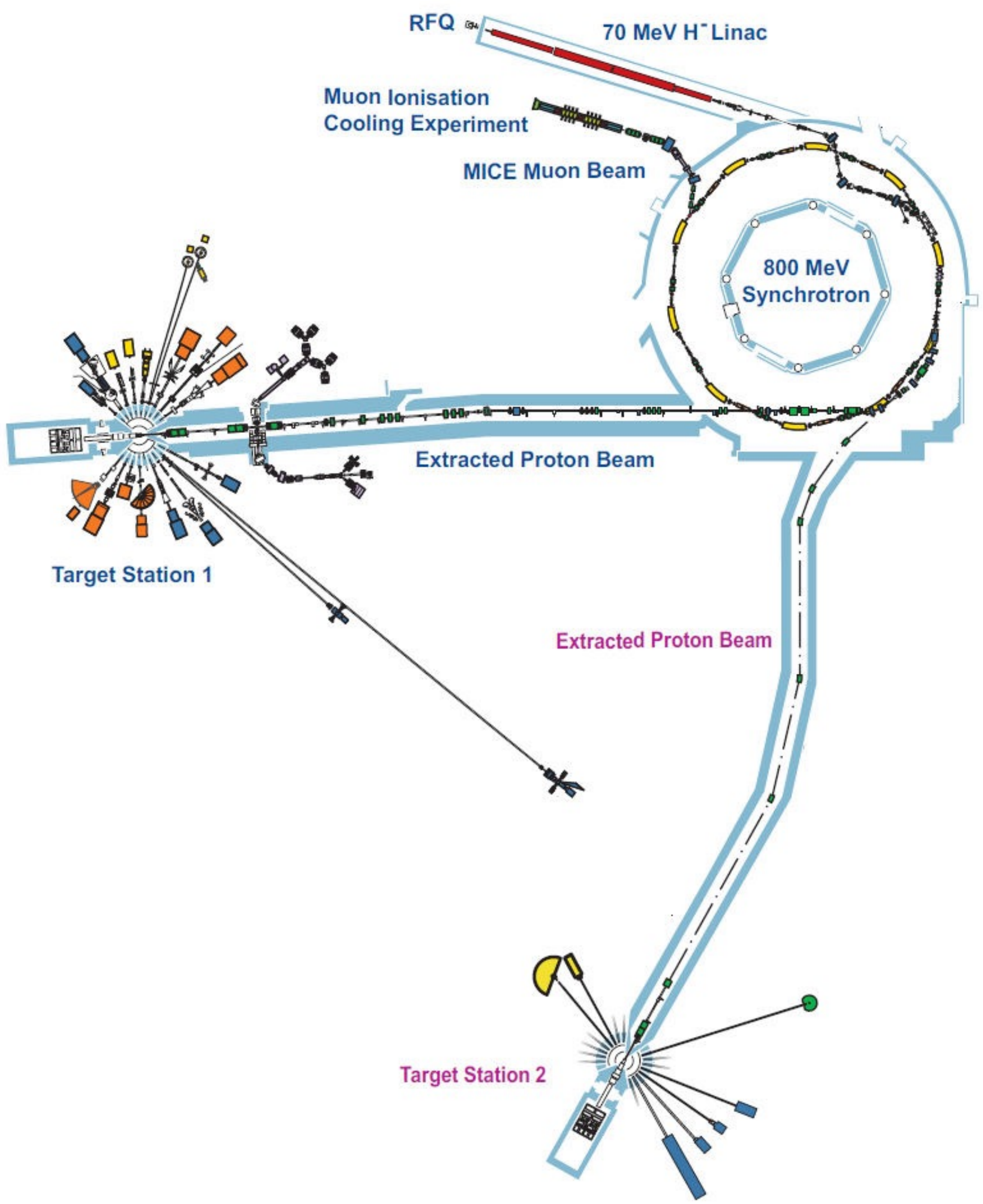
ISIS Spallation Neutron Source

- Long-serving neutron and muon facility, world-leading science
- Operates at 160-180 kW, with two target stations
- Continuous programme of upgrade, maintenance and replacement
- Studies to upgrade to MW level of beam power
- How far can we go and maintain reliability?



Ref: D.J. Adams, Operational experience and Future Plans at ISIS

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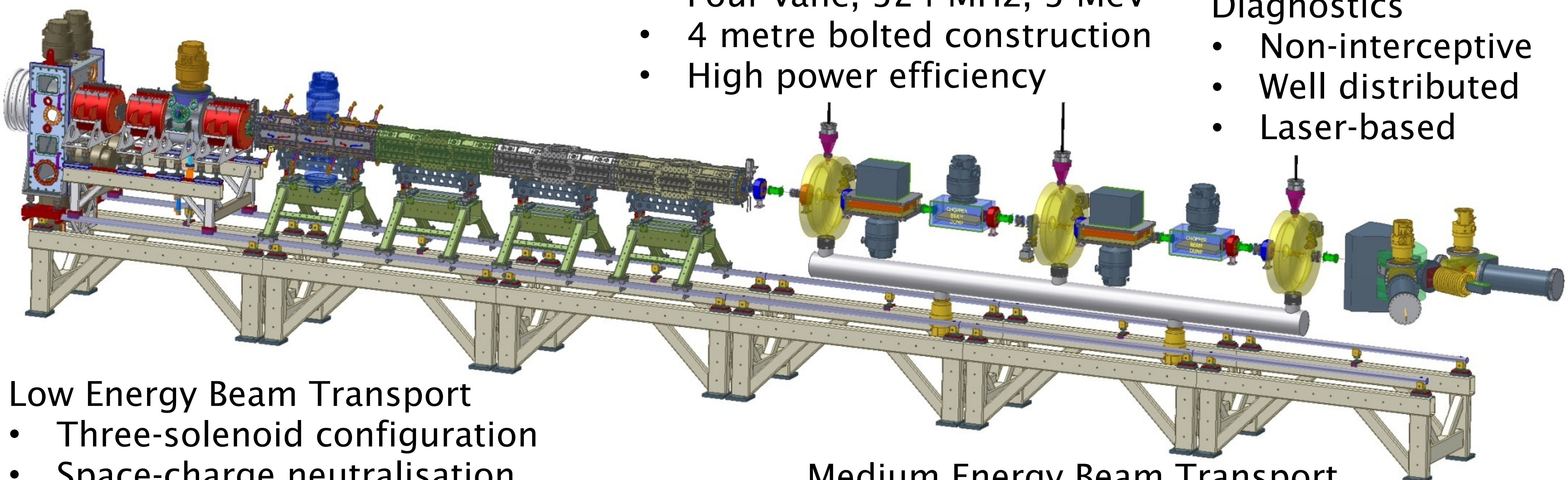
Front End Test Stand (FETS)

High brightness H⁻ ion source
- 4 kW peak-power arc discharge
- 60 mA, 0.25 π mm mrad beam
- 2 ms, 50 Hz pulsed operation

Radio Frequency Quadrupole
- Four-vane, 324 MHz, 3 MeV
- 4 metre bolted construction
- High power efficiency

Diagnostics
- Non-interceptive
- Well distributed
- Laser-based



Low Energy Beam Transport
- Three-solenoid configuration
- Space-charge neutralisation
- 5600 Ls^{-1} total pumping speed

Medium Energy Beam Transport
- Re-buncher cavities and EM quads
- Novel ‘fast-slow’ perfect chopping
- Low emittance growth

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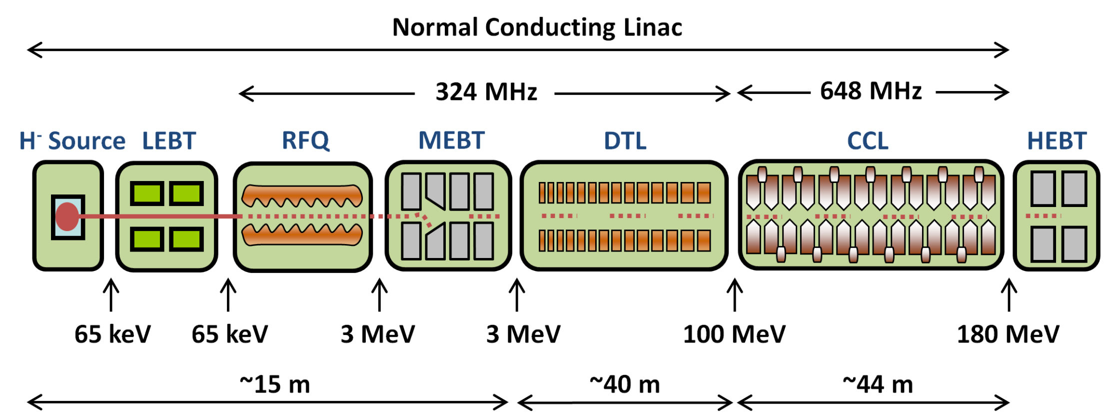
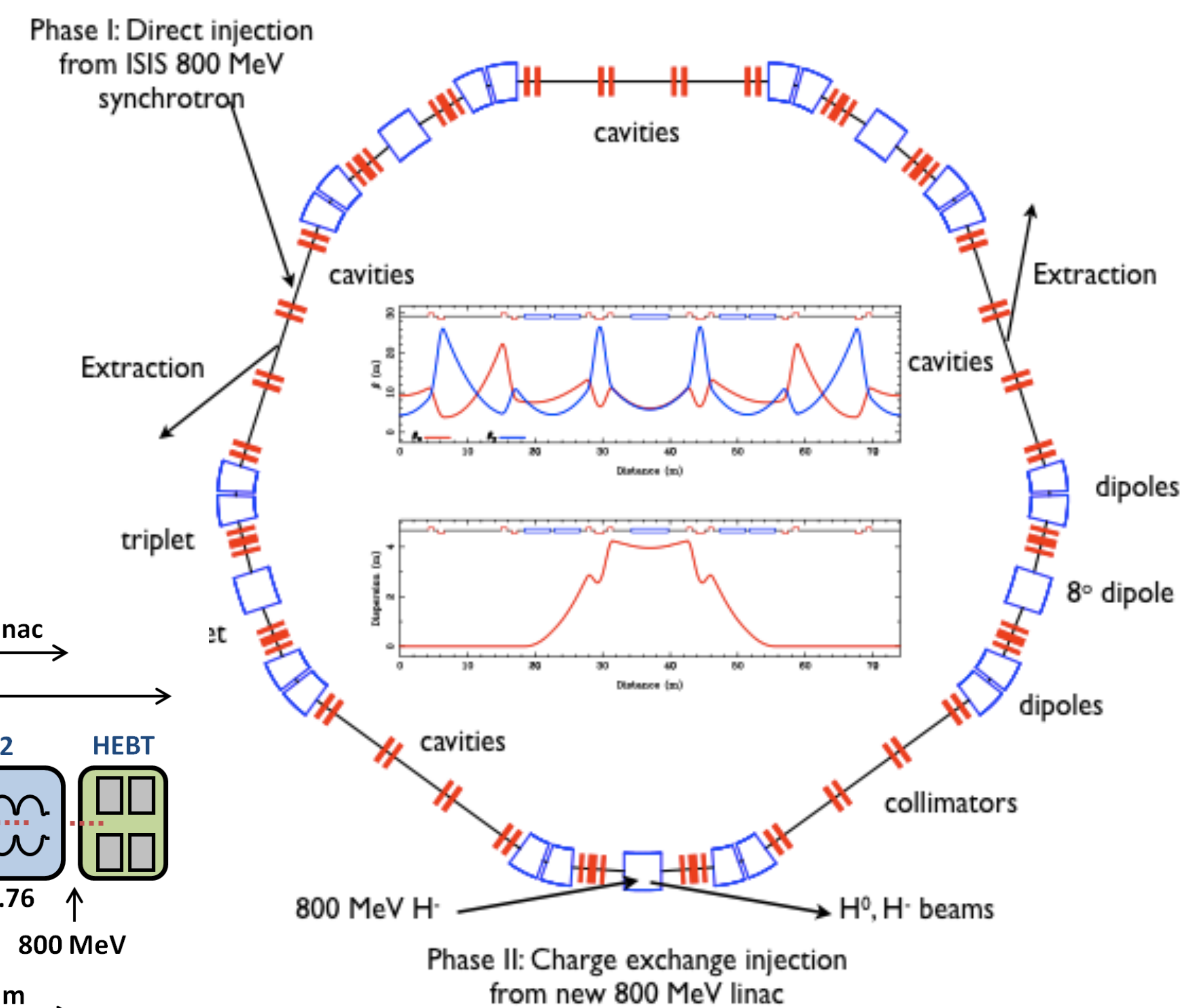
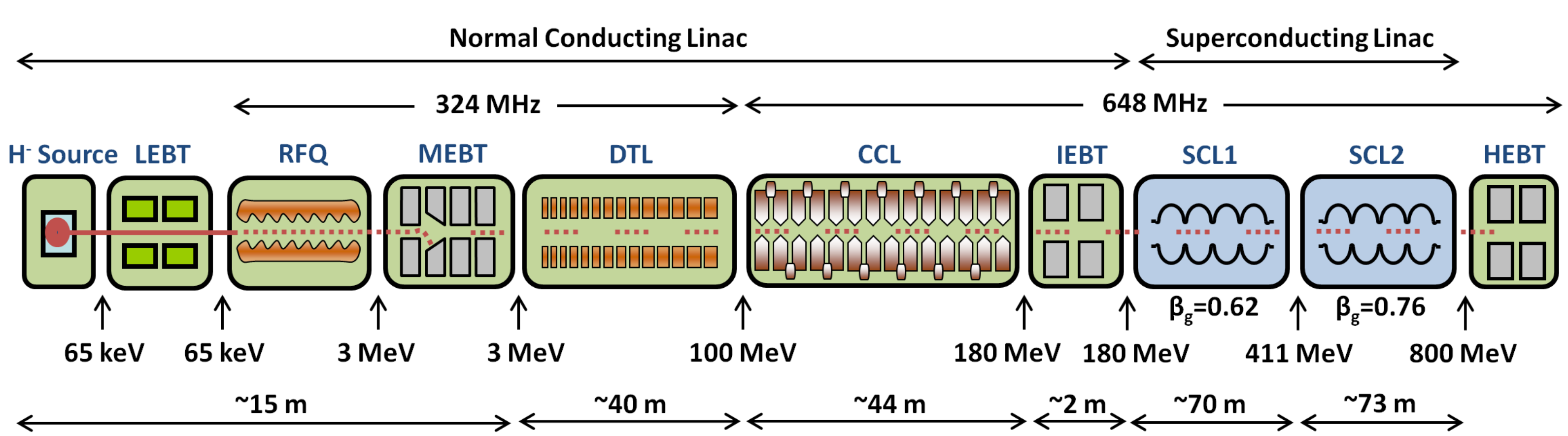
ISIS
ASTeC
JAi John Adams Institute for Accelerator Science
CERN
Imperial College London
ROYAL HOLLOWAY UNIVERSITY OF LONDON
THE UNIVERSITY OF WARWICK
University of HUDDERSFIELD
UCL
ESS bilbao

ISIS Upgrade options

- Upgrade 70 MeV linac with new tank
- Replace injector with 180 MeV linac
- Phased upgrades:
  - add 3.2 GeV RCS
  - add new 800 MeV H⁻ linac
  - 2.5-5 MW







Motivation

A future multi-megawatt proton driver aimed specifically at a spallation neutron source (short pulse), including a small test ring that might also have a practical application. Time scale: 15-20 years?

- Long-term study - can be imaginative
- FFAGs may be a good choice for a high intensity machine; good flexibility
  - no ramping, stable dc power supplies
  - high repetition rate (100 Hz and up), flexible, restricted only by rf programme
    - increased beam power
    - ability to match users' requirements
  - horizontal beam extraction easier

- Large momentum acceptance
  - particles with injection and extraction energy can circulate at the same time; beam stacking
  - horizontal emittance can be enlarged
- Superconducting or permanent magnets can be used
  - high energy efficiency, high availability, low operational costs

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Motivation

$$\Delta Q_v = -\frac{N r_p}{\pi \epsilon_v \left(1 + \sqrt{\epsilon_h/\epsilon_v}\right) \beta^2 \gamma^3} \frac{1}{B_f}$$

RCS

FFAG

Repetition rate	25 Hz	50 Hz	100 Hz
sqrt{$\varepsilon_h/\varepsilon_v$}=1	**1 MW**	2	4
sqrt{$\varepsilon_h/\varepsilon_v$}=2	1.5	3	6
sqrt{$\varepsilon_h/\varepsilon_v$}=3	2	4	**8 MW**

With an FFAG we might be able to push the power up to ~10 MW

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Motivation

$$\Delta Q_v = -\frac{N r_p}{\pi \epsilon_v \left(1 + \sqrt{\epsilon_h / \epsilon_v}\right) \beta^2 \gamma^3} \frac{1}{B_f}$$

Gain an extra factor 3 by increasing the injection energy from 400 MeV to 800 MeV

Repetition rate	25 Hz	50 Hz	100 Hz
sqrt{$\varepsilon_h/\varepsilon_v$}=1	**3 MW**	6	12
sqrt{$\varepsilon_h/\varepsilon_v$}=2	4.5	9	18
sqrt{$\varepsilon_h/\varepsilon_v$}=3	6	12	**24 MW**

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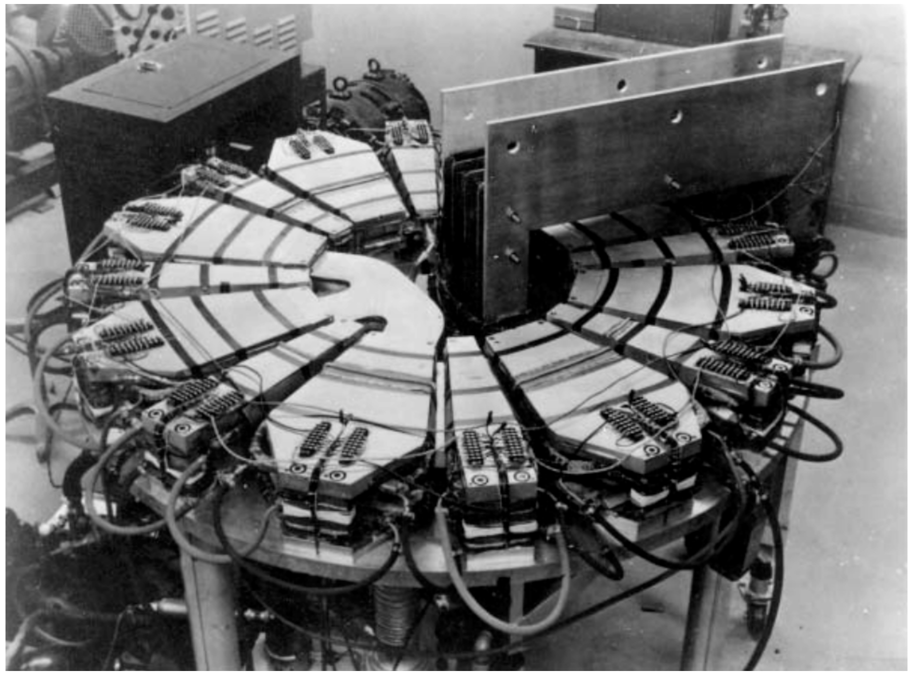
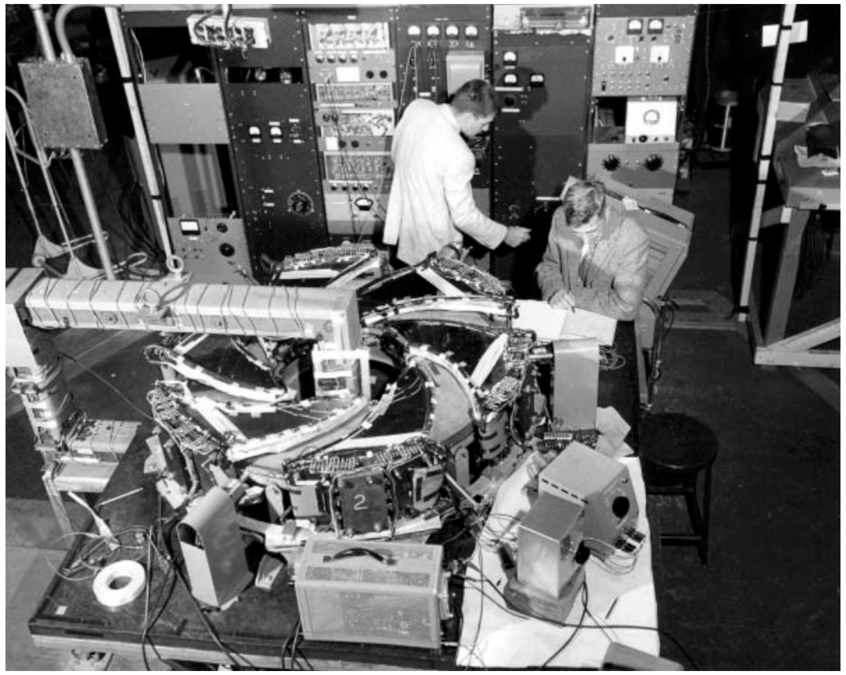
Fixed Field Alternating Gradient (FFAG)

Scaling FFAGs with magnetic fields $B \propto r^k$

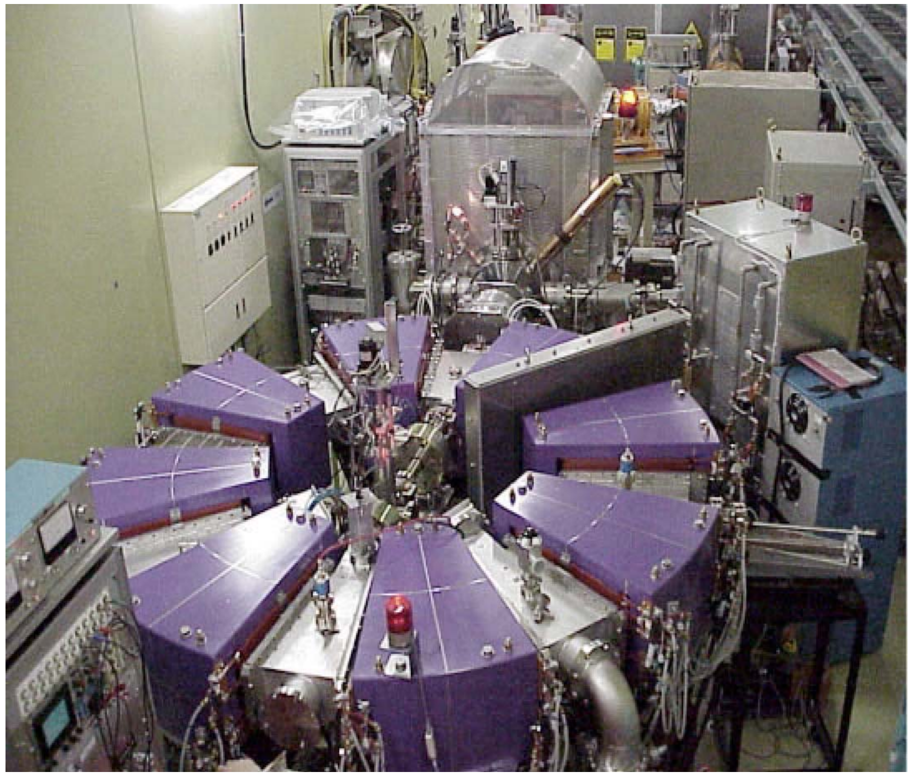
MURA radial sector



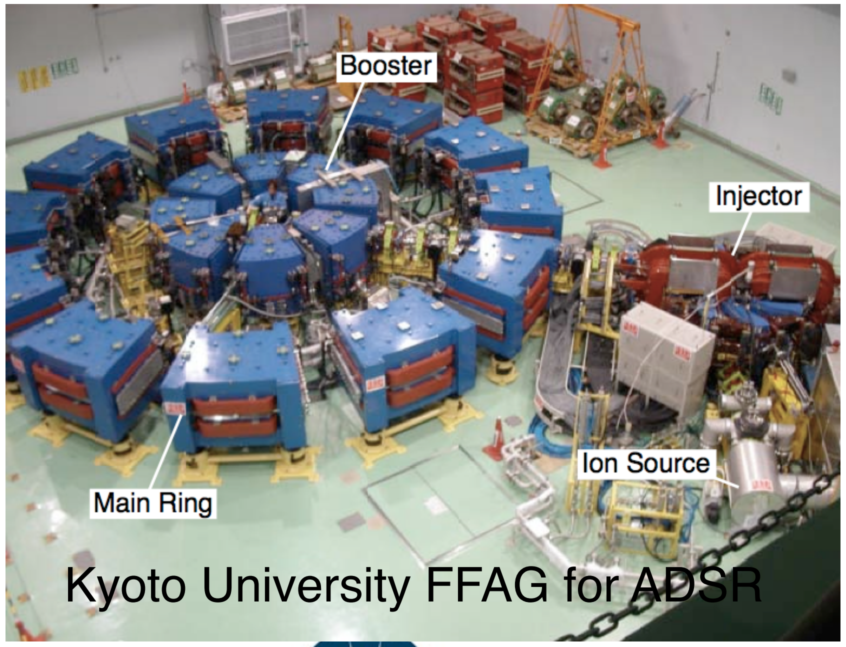
MURA spiral sector



KEK radial sector

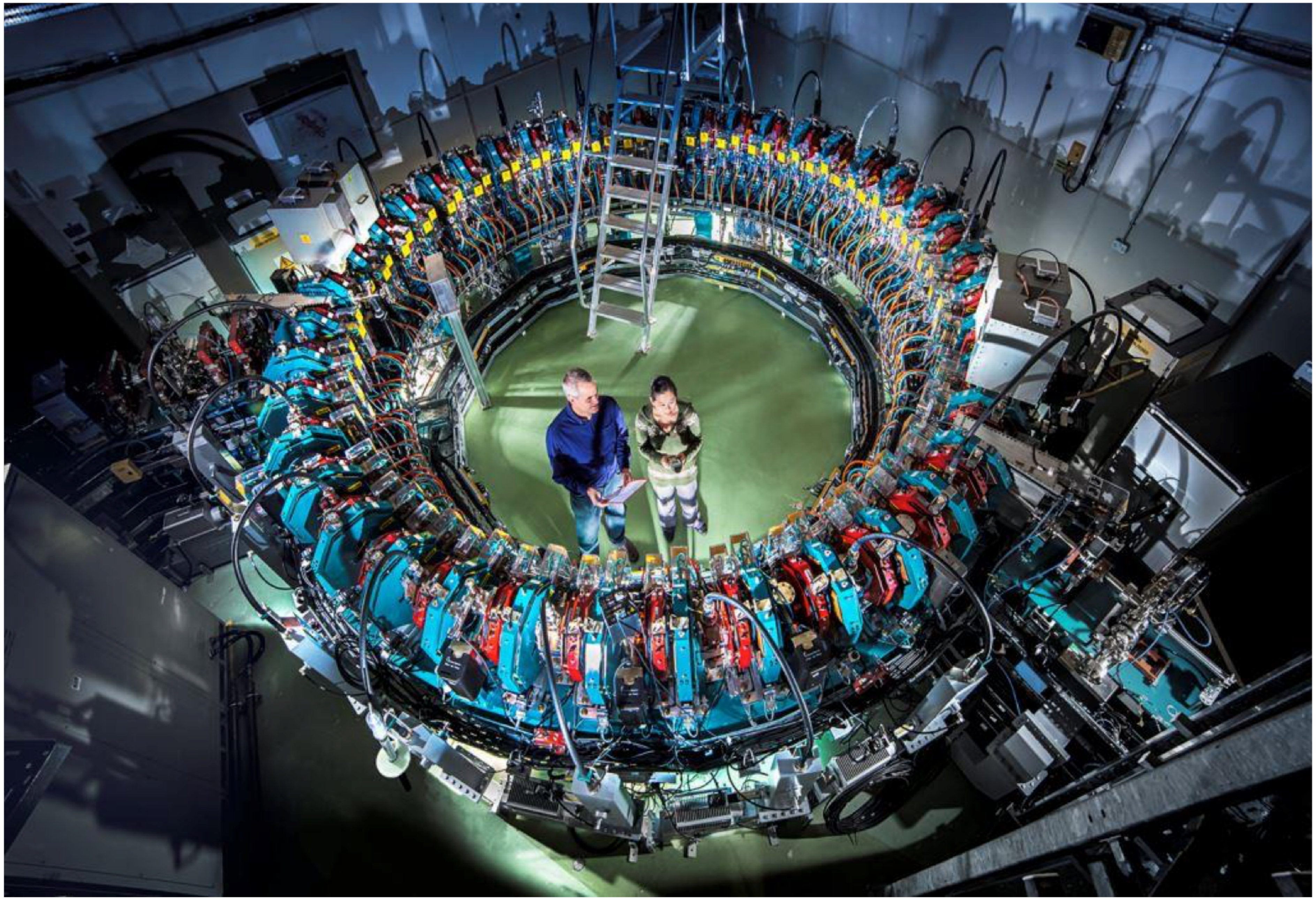


KURRI radial sector



Fixed Field Alternating Gradient (FFAG)

EMMA at Daresbury



Non-scaling FFAG with displaced quadrupole magnets

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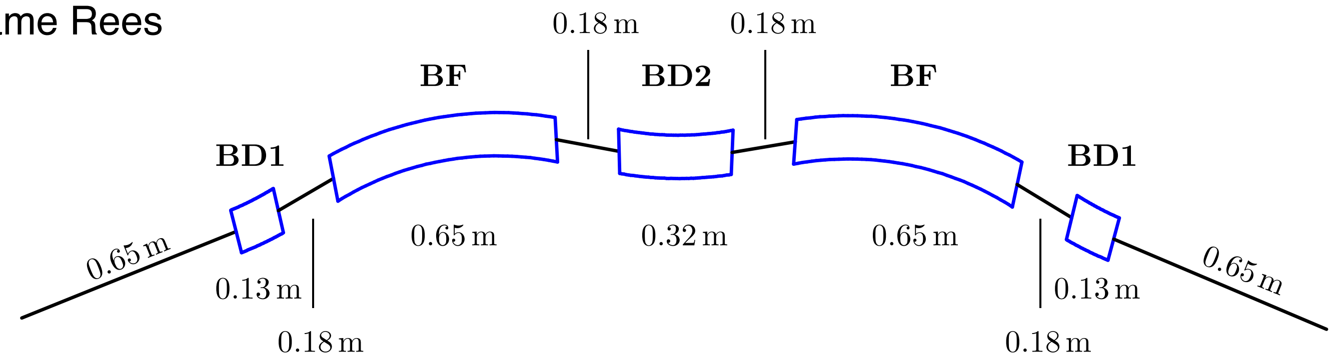
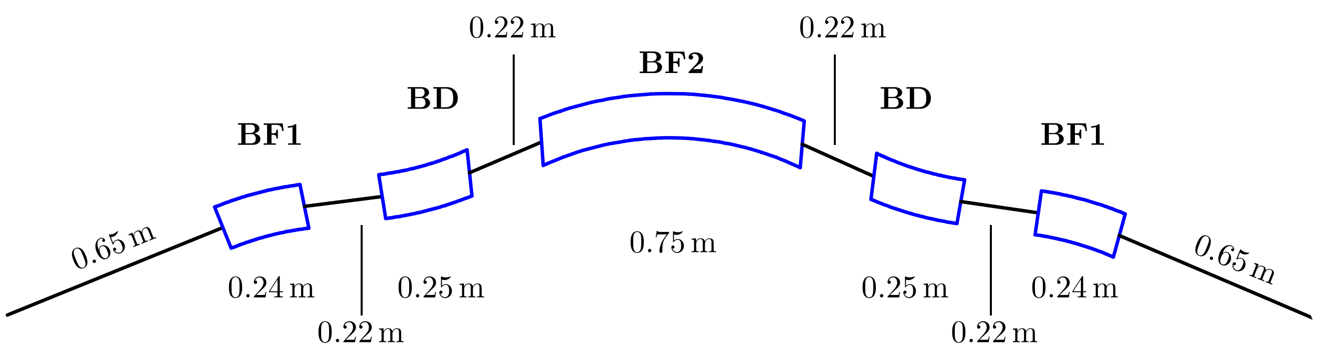
Pumplet FFAGs: test ring

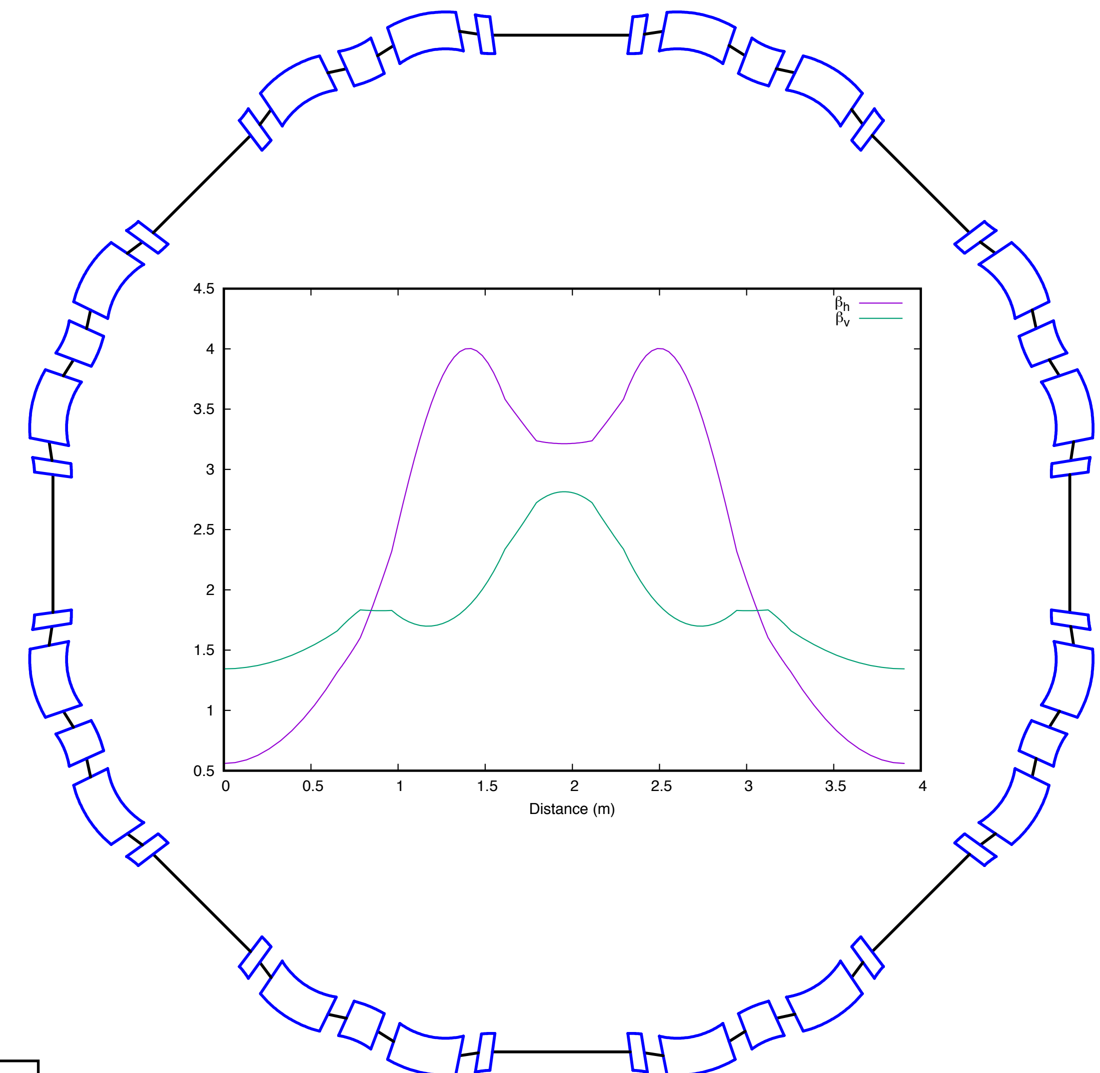
Grahame Rees



Od(-)oF(+)oD(-)oF(+)od(-)O



Of(+)oD(-)oF(+)oD(-)of(+)O



3-10 MeV

Scaling FFAGs

- edges aligned to a common machine centre
- orbits at different energies are similar
- all magnets have same bending radius and gradient
- k ~ 6.2
- Dispersion $0.625<D_h<0.672$ m

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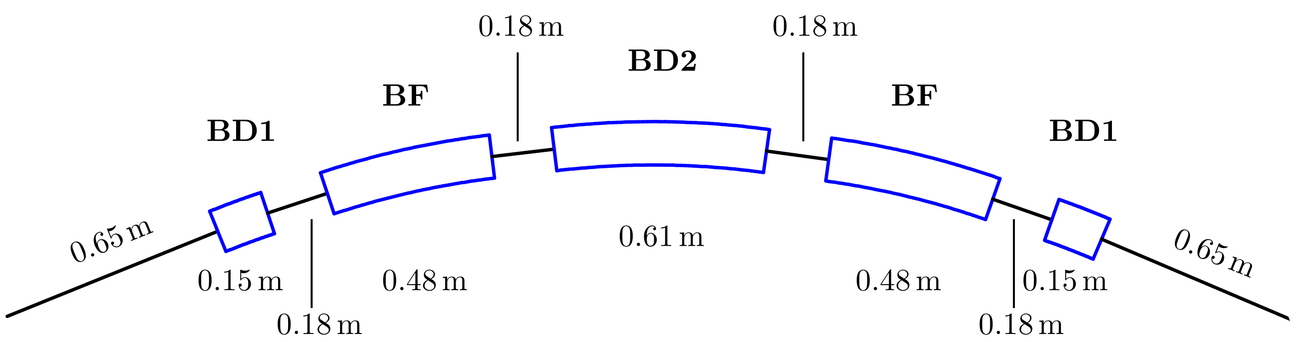
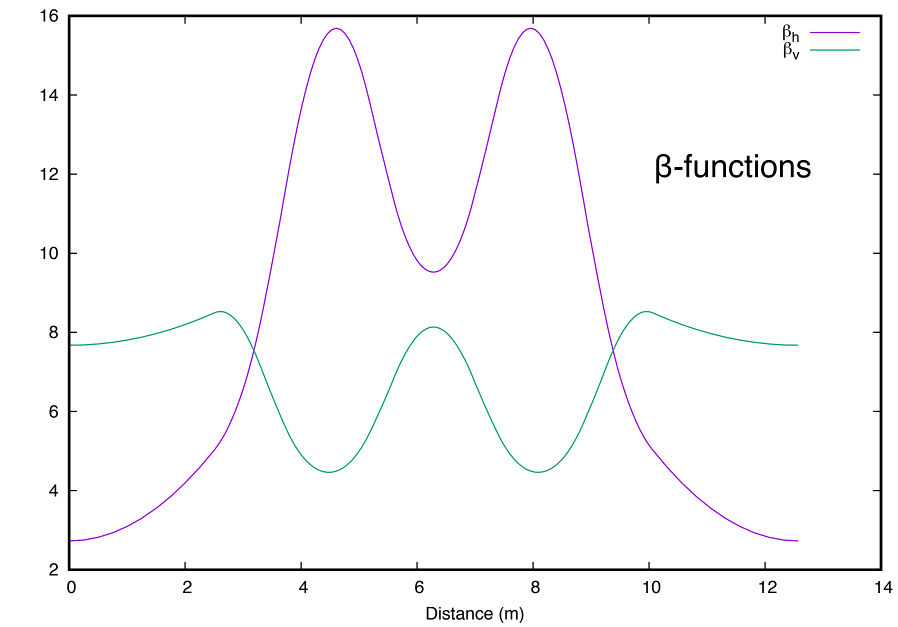
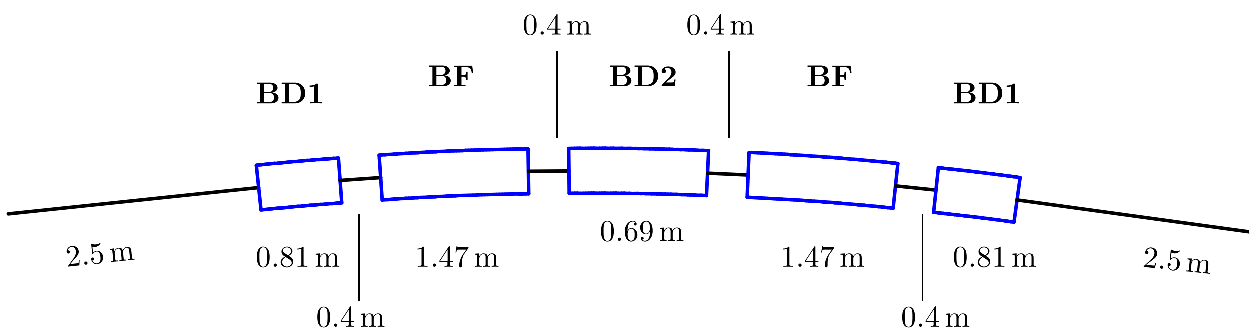
RCS Pumplet Option

Combined function magnets, all bends positive

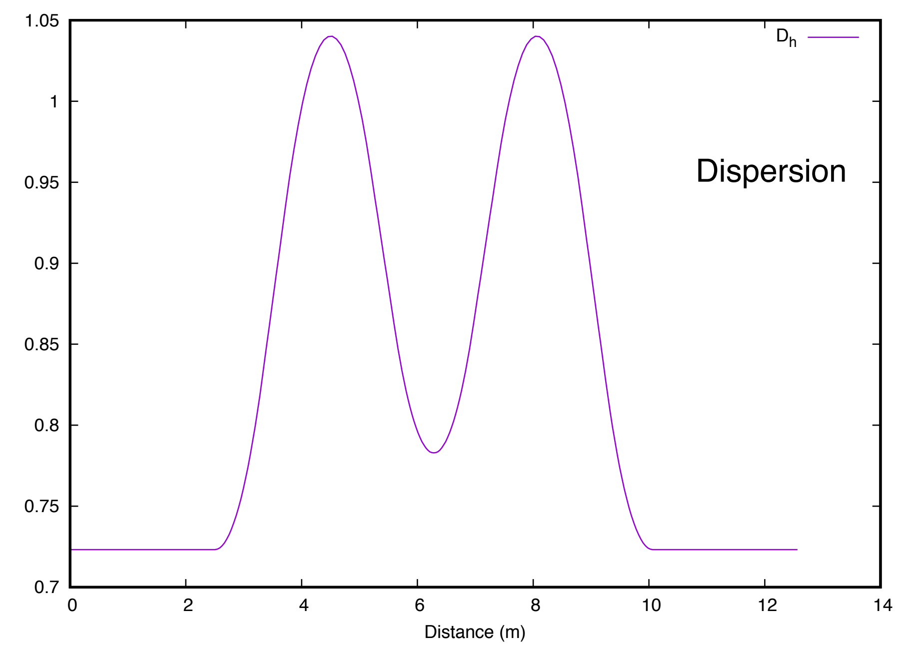


Lattice for small FETS ring: dFDfD, 8 cell structure, R=4.974 m, ρ=2.4 m
3-10 MeV





Lattice for main RCS: dFDFd, 26 cell structure, R=52 m, ρ=24.6 m
0.8-3.2 GeV



Comparison between Models

Model	Structure	Energy (MeV)	R_{inj}(m)	ρ_{inj}(m)	$\hat{\beta}_h$	$\hat{\beta}_v$	$\hat{D}_h$	Q_h	Q_v
Pumplet-1	fDFDf	3-10	4.974	0.91	4.68	2.72	0.71	3.20	2.72
Pumplet-2	dFDFd	3-10	4.974	0.91	4.00	2.81	0.67	3.40	2.82
RCS	dFDFd	3-10	4.974	2.40	2.90	7.20	0.65	3.22	2.73
Pumplet-3	fDFDf	800-3200	52.0	7.60	19.80	10.62	1.36	9.21	7.38
Pumplet-4	dFDFd	800-3200	52.0	7.60	14.93	8.72	1.32	9.21	7.38
RCS	dFDFd	800-3200	52.0	24.60	15.69	8.53	1.04	9.24	7.80

- Scaling dFDFd pumplet-2 model (marginally) preferred for Test Ring
- Non-scaling pumplet model preferred over scaling pumplet for Main Ring design

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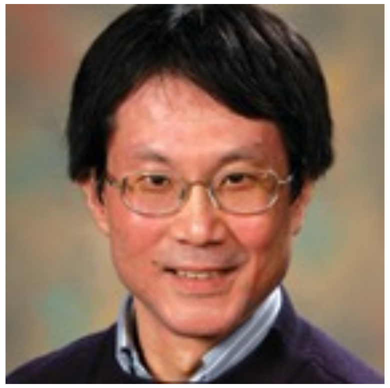


Shinji Machida

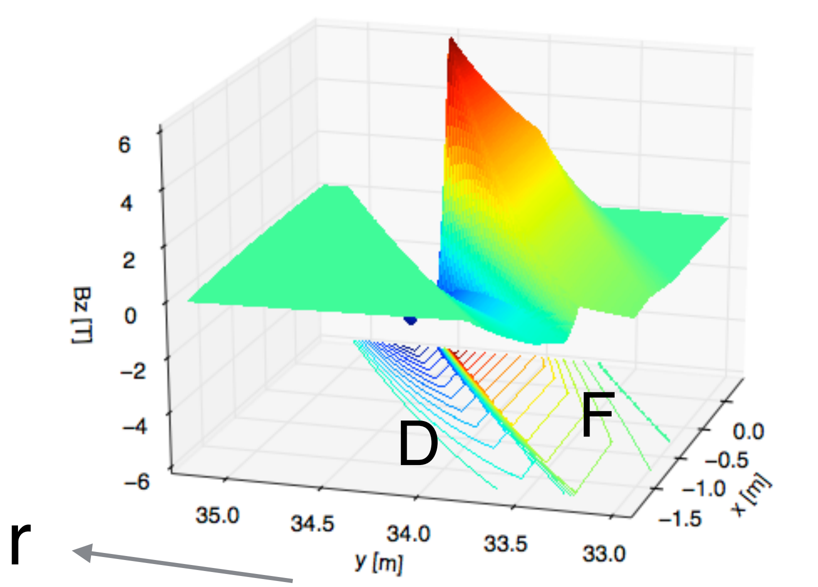
DF-Spiral FFAG

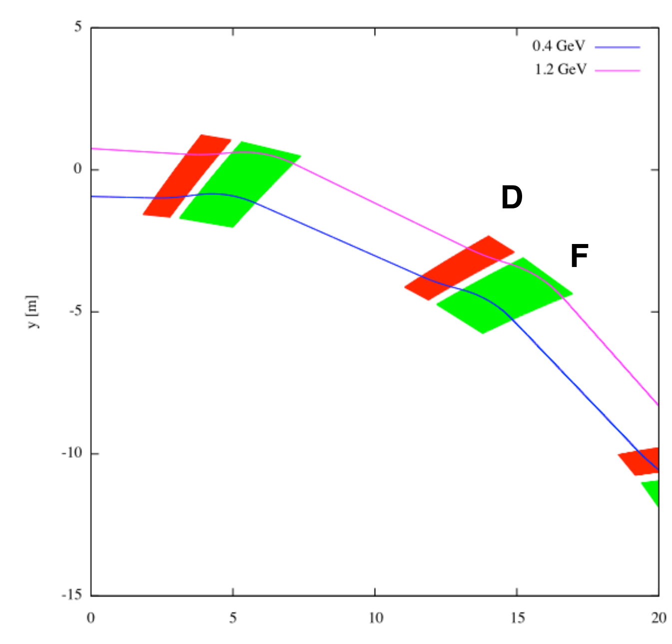
- Combines features of radial and spiral FFAGs to give a compact, versatile design

$$\begin{aligned} Q_h^2 &= k+1 \\ Q_v^2 &= -k + f^2 \tan^2\zeta \end{aligned} \quad \text{where} \quad \begin{aligned} \zeta &= \text{spiral angle} \\ f &= \text{flutter} \end{aligned}$$

$$B = B_0 \left(\frac{r}{r_0}\right)^k \left\{1 + f \cos\left[N_{\text{cell}}\theta - N_{\text{cell}} \tan\zeta \ln(r/r_0)\right]\right\}$$

- Introduce small negative field on one side of main spiral magnet to generate sharp edge between D and F and increase flutter f.





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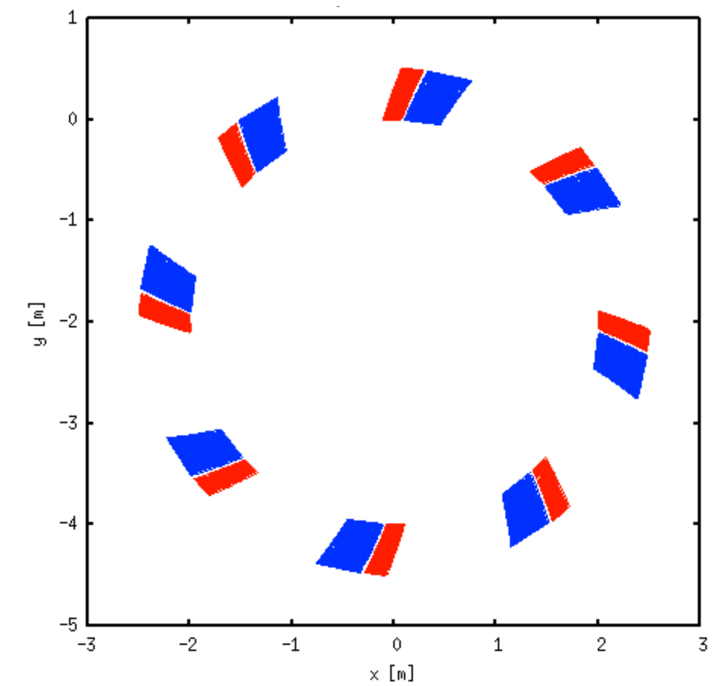
DF-Spiral FFAG: models

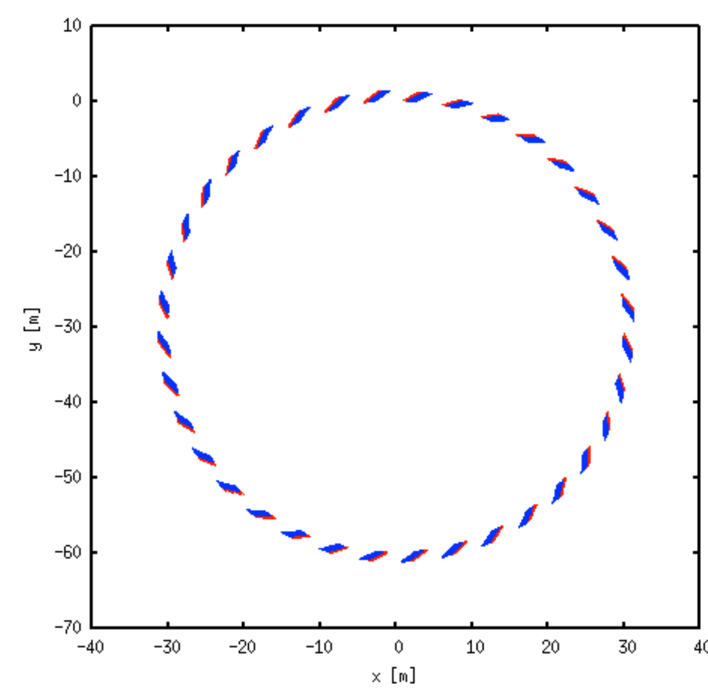
Parameters for test ring

Kinetic energy	3-27 MeV
Momentum ratio	3
Number of cells	8
Spiral angle	20°
Field index	3
Orbit excursion	0.48 m
Radius injection:extraction	2.1 : 2.6 m
Straight	1.1 m



Parameters for main ring

Kinetic energy	0.4-3 GeV
Momentum ratio	4
Number of cells	36
Spiral angle	58°
Field index	50
Orbit excursion	0.82 m
Radius injection:extraction	30.2 : 31.0 m
Straight	3.6 m



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Studies with the Test Ring

- FFAG optics and operation (DF-spiral or pumplet)
- H^- injection and extraction.
- Tunability with additional trim coils.
- Non-uniform painting at injection.
- Operation with asymmetric emittance.
- Stacking at the end and shaping time structure
- Development into small neutron source with energy recovery (*cf* ERIT@KURRI)

Details of DF-spiral magnet with ISIS magnet designers with a view to a prototype

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Injection: Parameter List

Parameter	Main Ring	Test Ring
Kinetic energy at injection (MeV)	800	3
Linac beam current I (mA)	100	1.9
Unnormalised injected emittances (π mm.mrad)	2.70	10.8
Painted horizontal emittance of ring beam (π mm.mrad)	270	270
Painted vertical emittance of ring beam (π mm.mrad)	135	135
Expected tune depression	0.065	0.065
Number of ions N ($\times 10^{11}$)	1950	2.79
Injection interval required, Ne/I (μs)	313.08	23.50
Revolution period at injection, t (μs)	1.29	1.31
Mean radius at injection energy, $\beta ct/2\pi$ (m)	52.00	4.974
Number of injected turns	241	17
Length of injection straight (m)	5.0	1.30

$$\Delta Q_v = -\frac{N r_p}{\pi \epsilon_v \left(1 + \sqrt{\epsilon_h/\epsilon_v}\right) \beta^2 \gamma^3} \frac{1}{B_f}$$

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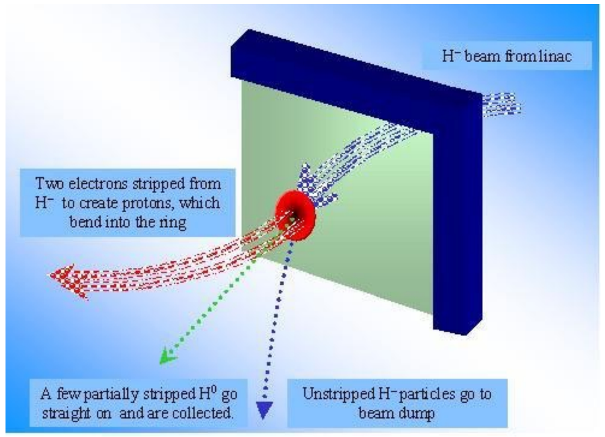
Injection

“The multiturn injection method by proton beam has been almost abandoned for injection from a linac to an RCS, due to its poor injection efficiency. H-minus stripping injection is a must to obtain highly accumulated protons in rings by hundreds of turns.”

Reviews of Accelerator Science and Technology
Volume 6: Accelerators for High Intensity Beams

Downside



- Complicated injection chicane
- Handling of unstripped H^- and H^0 excited states
- Stripped electrons
- Foil heating, lifetime issues, nuclear scattering, multiple scattering, foil traversals
- Lorentz intra-beam stripping in linac and injection line
- These are all causes of beam loss

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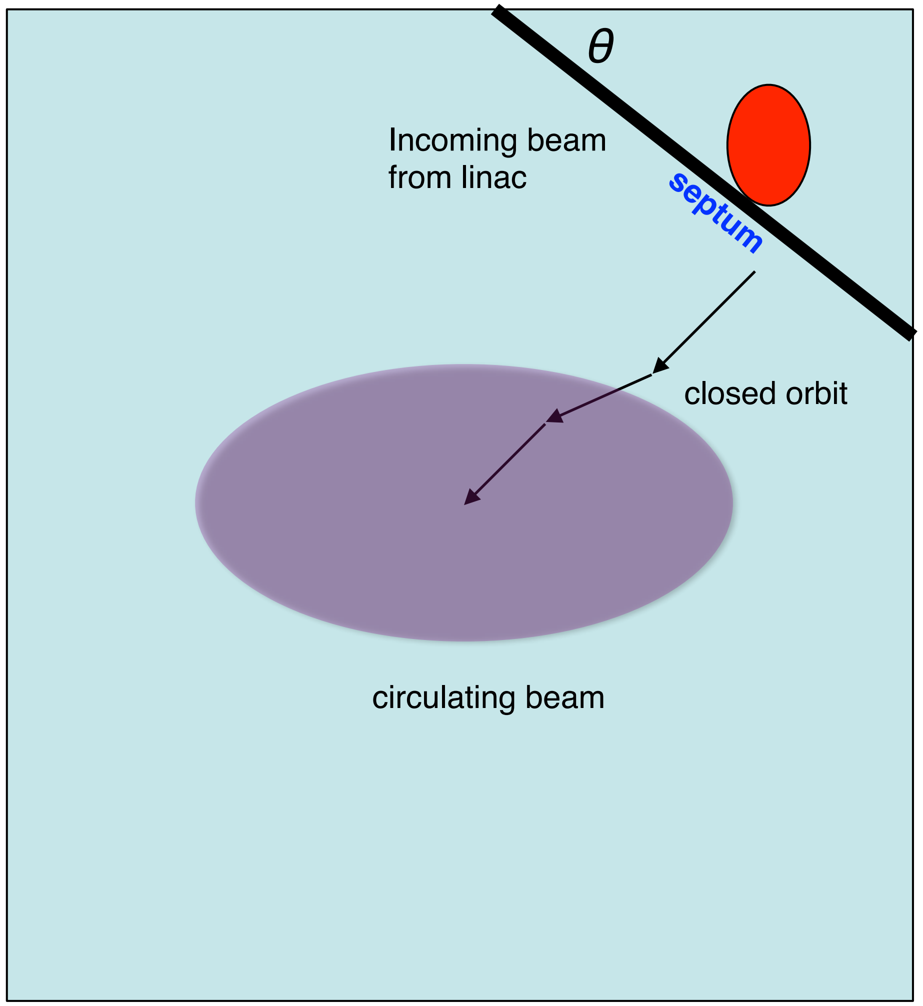
Use Protons, not H^-

- Liouvillean injection using a tilted electrostatic septum
- Simple injection chicane
- Injection simultaneously into 4D transverse phase space
- Optimise h and v closed orbit bumps to minimise beam loss
- Requires careful choice of septum angle θ and ring optics (tunes, β-functions) at injection point.



- Earlier simulations for HIDIF suggest maximum number of turns is

$$N_{\max} \approx \frac{1}{F} \frac{(\epsilon_h \epsilon_v)_{\text{ring}}}{(\epsilon_h \epsilon_v)_{\text{inj}}} \qquad \text{where} \qquad F \approx 20$$

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Optimising Injection

- 'Matching' conditions

$$\frac{\alpha}{\beta} = \frac{\alpha_i}{\beta_i} = -\frac{x'_o - x'_i}{x_o - x_i}$$

$$\frac{\beta}{\beta_i} \leq \left(\frac{\epsilon}{\epsilon_i}\right)^{\frac{1}{3}}$$

Subscript i refers to incoming turn.
(x_i, x'_i) are phase space coordinates of centre of the turn.
(x_o, x'_o) are position and angle of closed orbit.
Parameters without subscript $(\alpha, \beta, \epsilon)$ refer to values in the ring.

- Optimising code MISHIF (MISOPT, MISPLOT …)
  - based on geometrical properties of beam dynamics
  - able to vary most parameters
  - identify best tunes and ring optics
  - generate orbit bump scheme
  - linear space charge model based on Laslett tune shift
  - output can go straight into particle tracking code

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Results

Ring	Q_h	Q_v	Septum Angle	Turns	loss (%)	Requirement
FETS pumplet-2	3.420	2.887	63.52°	50	0.546	
	3.397	2.921	65.00°	40	0.0	
FETS RCS	3.185	2.708	55.12°	50	0.316	∼20 turns
	3.182	2.708	53.16°	40	0.0	
FETS DF-spiral	2.556	2.603	50.72°	40	0.122	
Main pumplet-4	9.254	7.845	66.43°	350	0.0	
Main RCS	9.230	7.832	65.36°	350	0.0	
Main DF-spiral	2.533	2.789	49.90°	350	0.0	∼250 turns
	2.474	2.692	59.22°	400	0.0	
	2.537	2.790	55.69°	450	0.96	

- Studies for 0.1 mm septum thickness (also for 1 mm)
- Space charge excluded; with space charge, lossless results for main RCS for >200 turns
- No allowance made for non-zero dispersion throughout the rings

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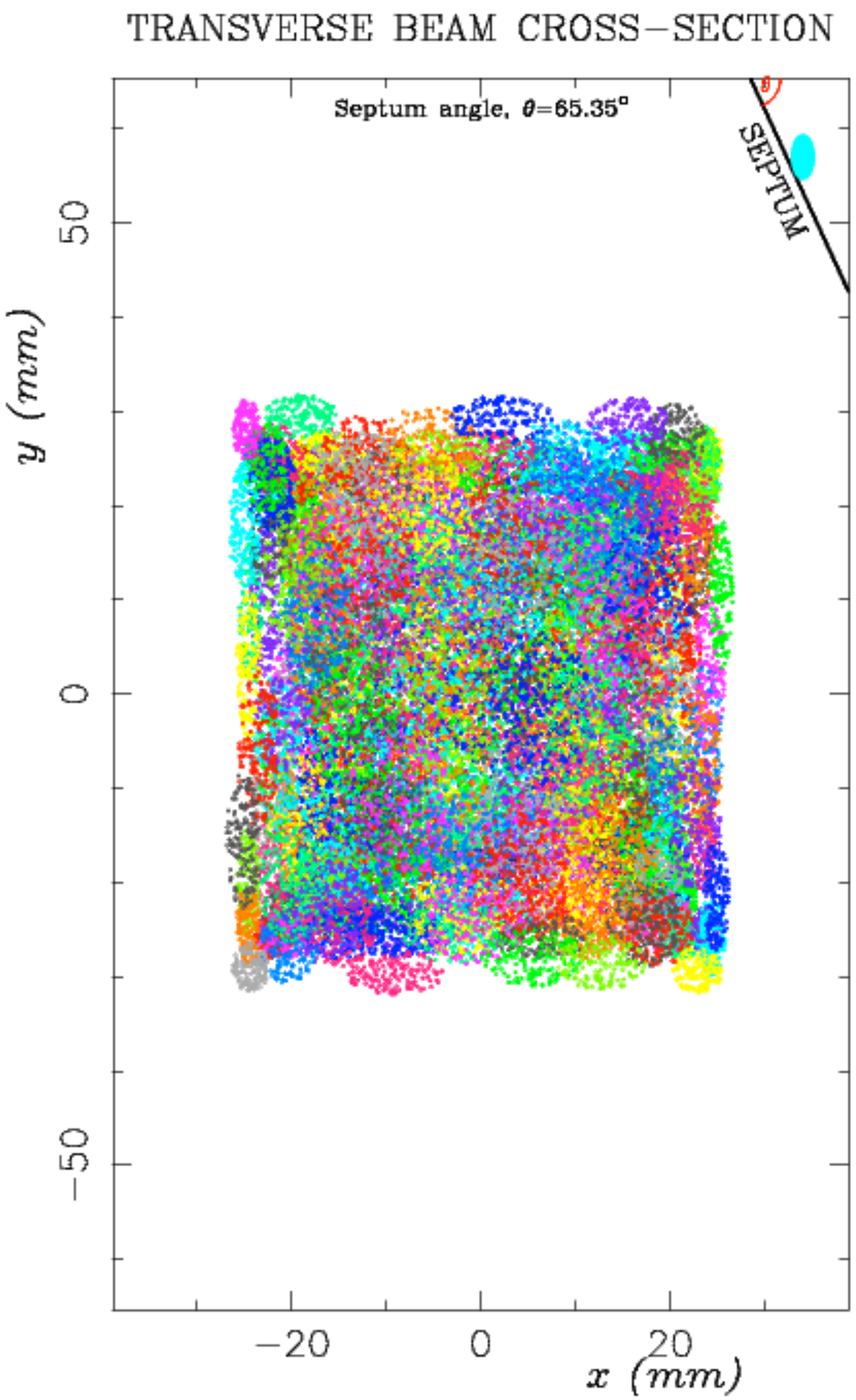
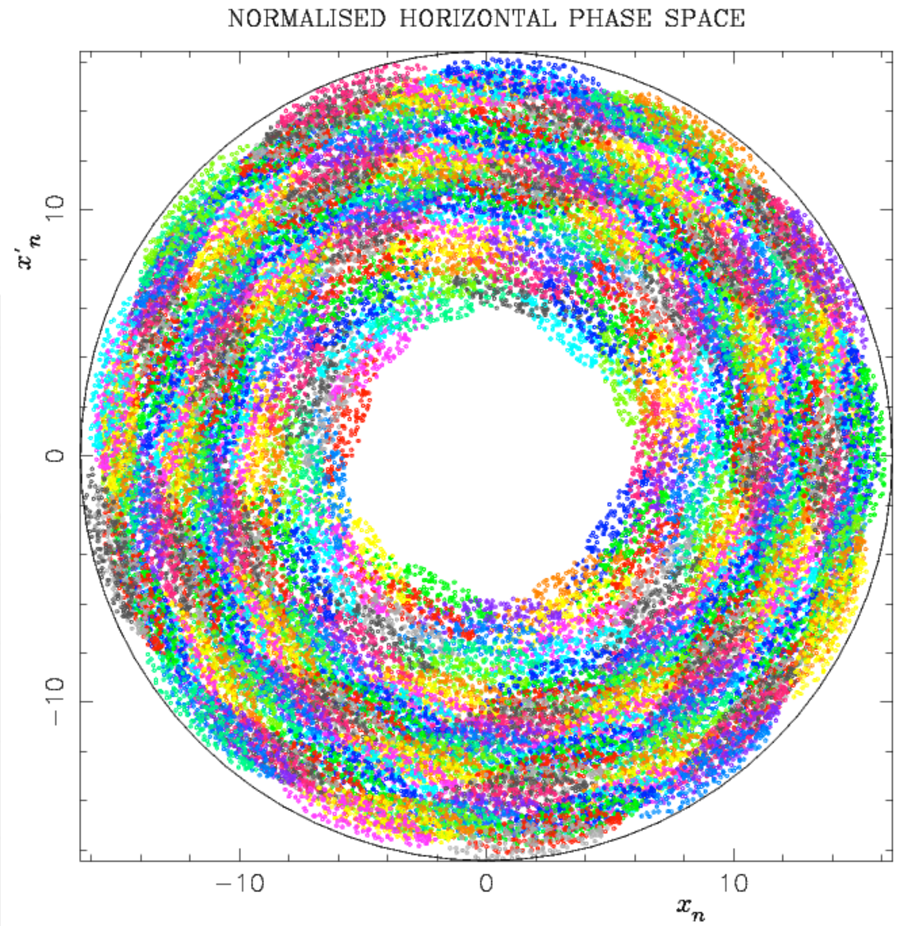
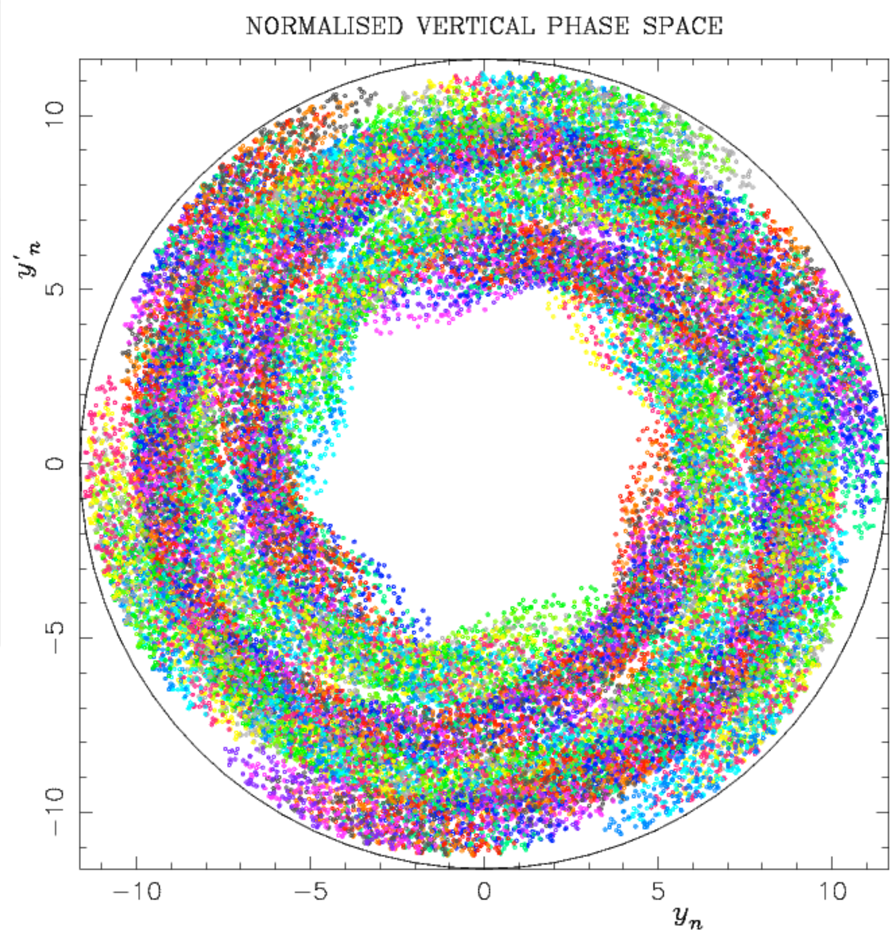
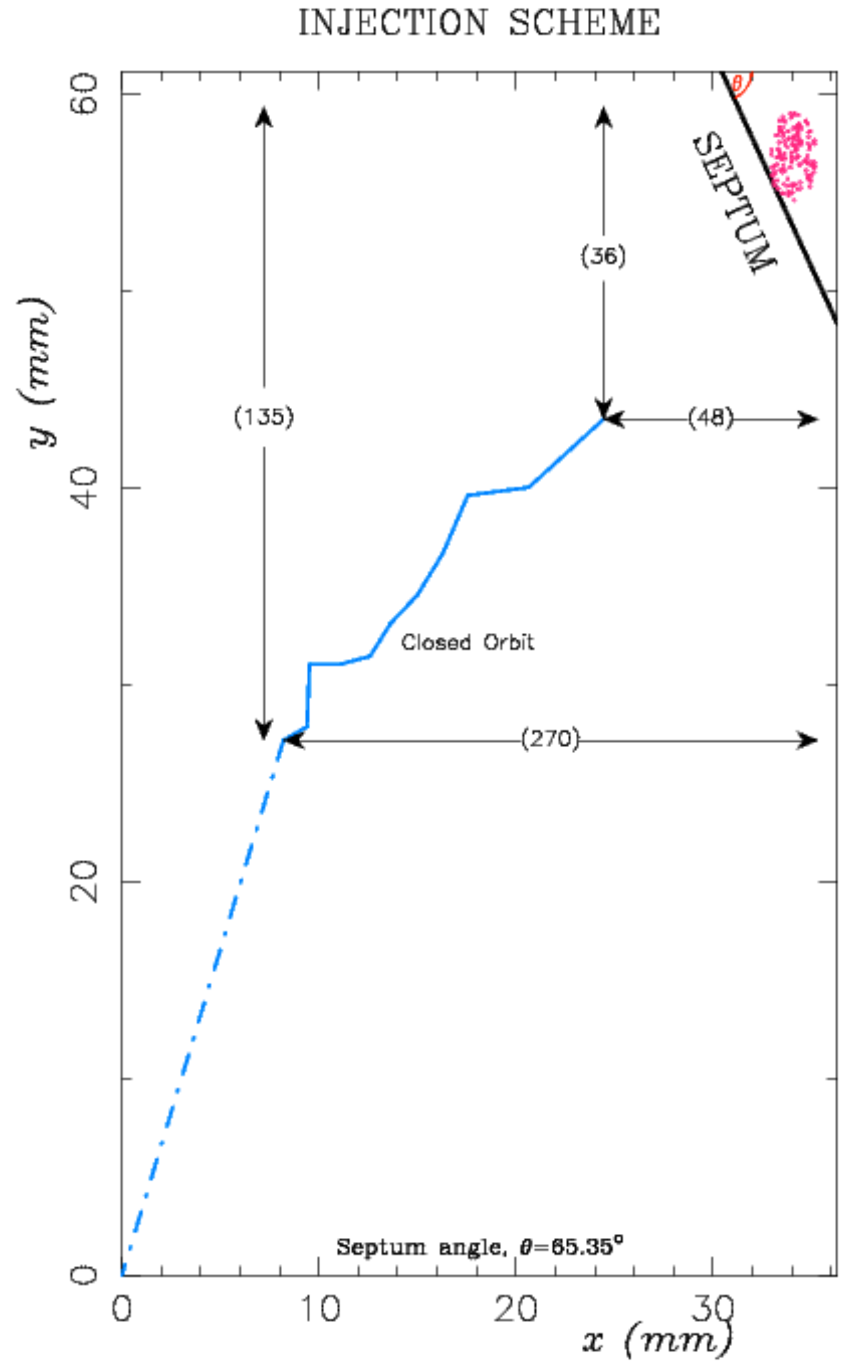

TRANSVERSE BEAM CROSS-SECTION
Septum angle, θ=65.35°
SEPTUM
y (mm)
x (mm)
50
0
−50
−20
0
20


NORMALISED HORIZONTAL PHASE SPACE
x'n
xn
10
0
−10


NORMALISED VERTICAL PHASE SPACE
y'n
yn
10
5
0
−5
−10


INJECTION SCHEME
SEPTUM
(36)
(135)
(48)
Closed Orbit
(270)
Septum angle, θ=65.35°
y (mm)
x (mm)
60
40
20
0
10
30

Experimental Programme

- MoU with Kyoto University
  - Exchange scientific materials, publications, information, training etc
  - Provides access to FFAGs at KURRI
- MoU with Hiroshima University
  - Paul trap studies of particle accelerators
    - *opportunities to engage in experiments carried out on traps at Hiroshima*
    - *expert guidance in setting up a new linear Paul Trap at RAL*
    - *provides table-top experiments that work in parallel with simulations*

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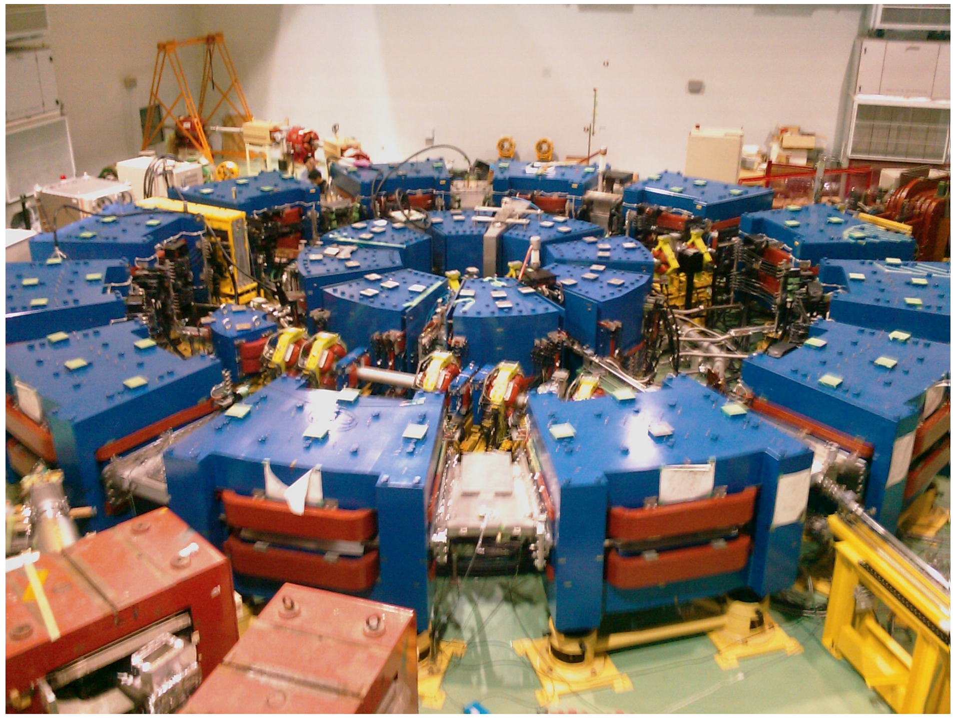
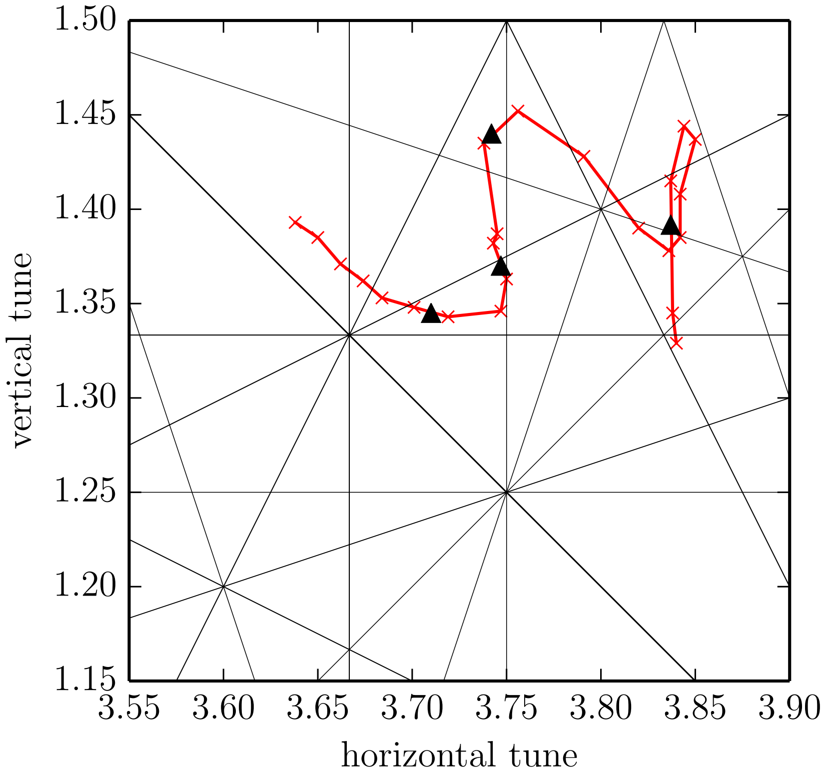
KURRI Collaboration

S. L. Sheehy, D. J. Kelliher, S. Machida, C. Rogers, C. R. Prior, L. Volat, M. Haj Tahar, Y. Ishi, Y. Kuriyama, M. Sakamoto, T. Uesugi and Y. Mori

- Regular success of visits to Japan to investigate experimentally the beam dynamics in the 150 MeV (scaling) proton FFAG.
- Paper arxiv.org/abs/1510.07459 (May 2016) describes the methods developed to characterise the machine and control and improve the quality of the beam.

- Methods to determine the basic lattice and beam parameters, momentum compaction factor, field index *k*, the closed orbit, correction of closed orbit distortion.
- Measurements of dispersion and orbit matching, betatron tunes
- A method to determine the beam energy lost on the thin carbon stripping foil.

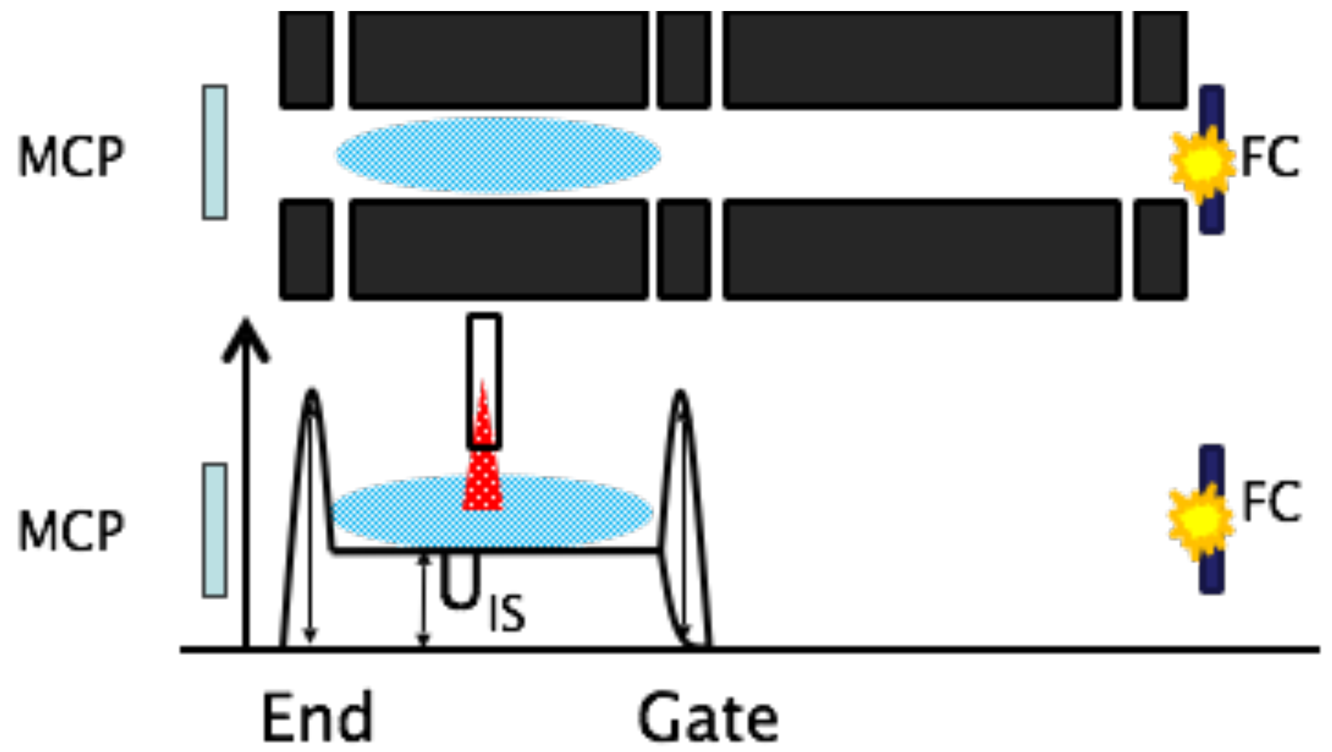




IBEX Paul Trap @RAL

Based on S-POD set-up at Hiroshima University

Argon gas ionised by e- gun



$$\frac{\mathrm{d}^2 x_{\mathrm{COD}}}{\mathrm{d}s^2} + K_x(s) x_{\mathrm{COD}} = -\frac{\Delta B}{B\rho}$$

Equation of motion for closed orbit distortion in a particle accelerator

$\longleftrightarrow$

$$\frac{\mathrm{d}^2 x}{\mathrm{d}\tau^2} + K_{\mathrm{rf}}(\tau) x = -\frac{q}{mc^2 r_0} V_D(\tau)$$

Equation of motion in Paul trap with dipole perturbation field

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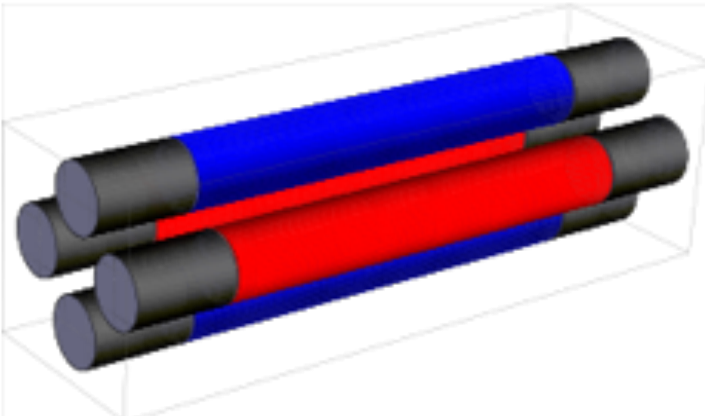
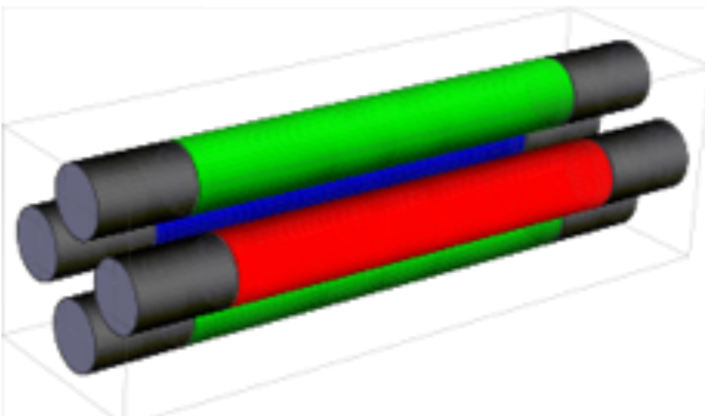
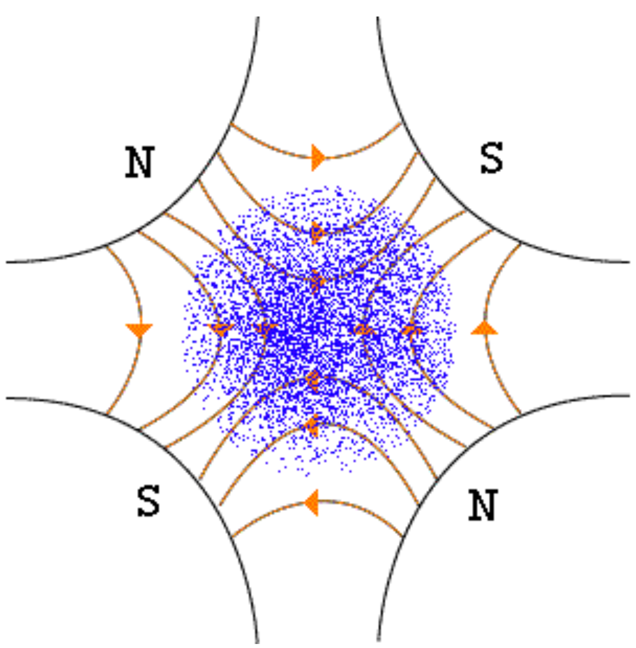
Quadrupole mode

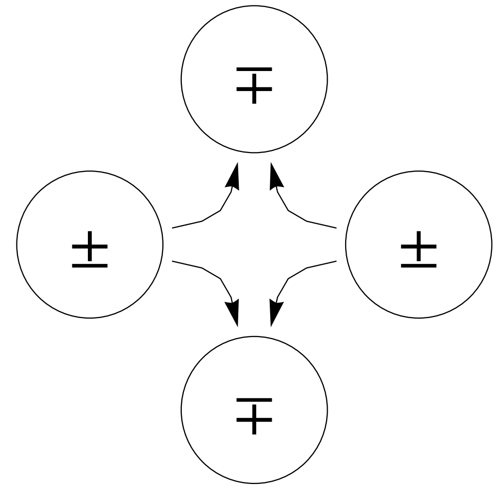


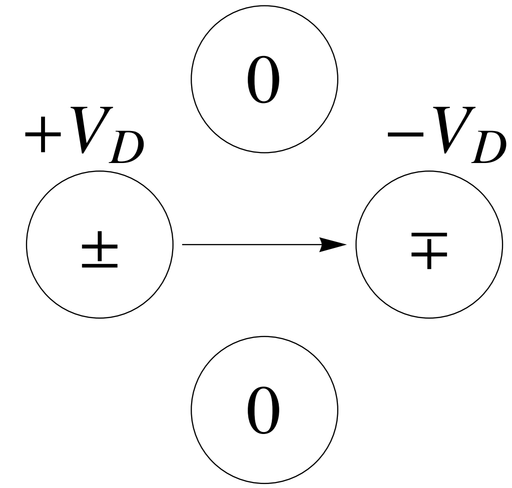
Dipole mode





Quadrupole focusing + Dipole perturbation

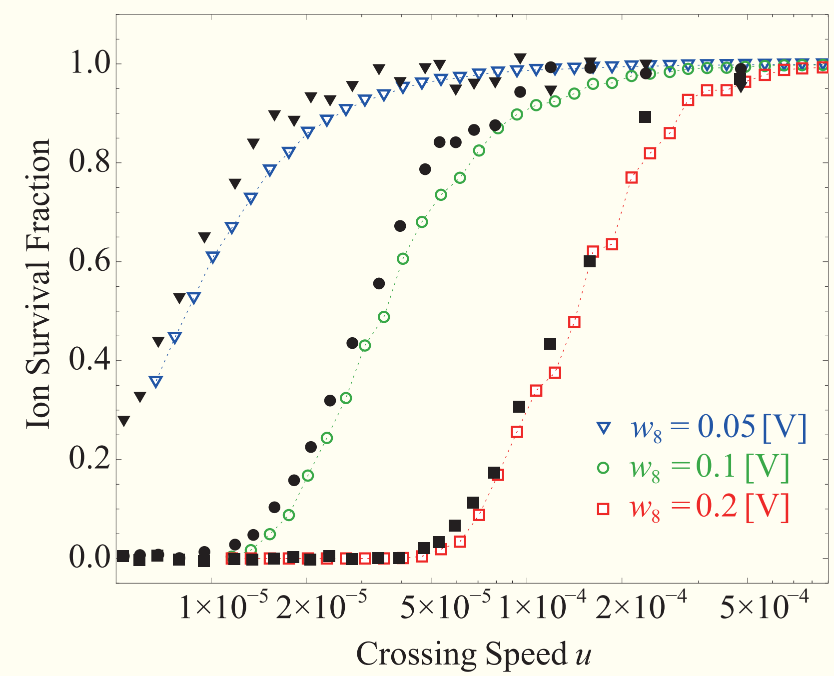




Sample Study: Resonance crossing in EMMA

8th harmonic excited
Tune varied 9.5→ 7.5

In EMMA, for 10 turn extraction crossing speed is roughly 5×10^{-4} if the tune per cell decreases by 0.2 during acceleration



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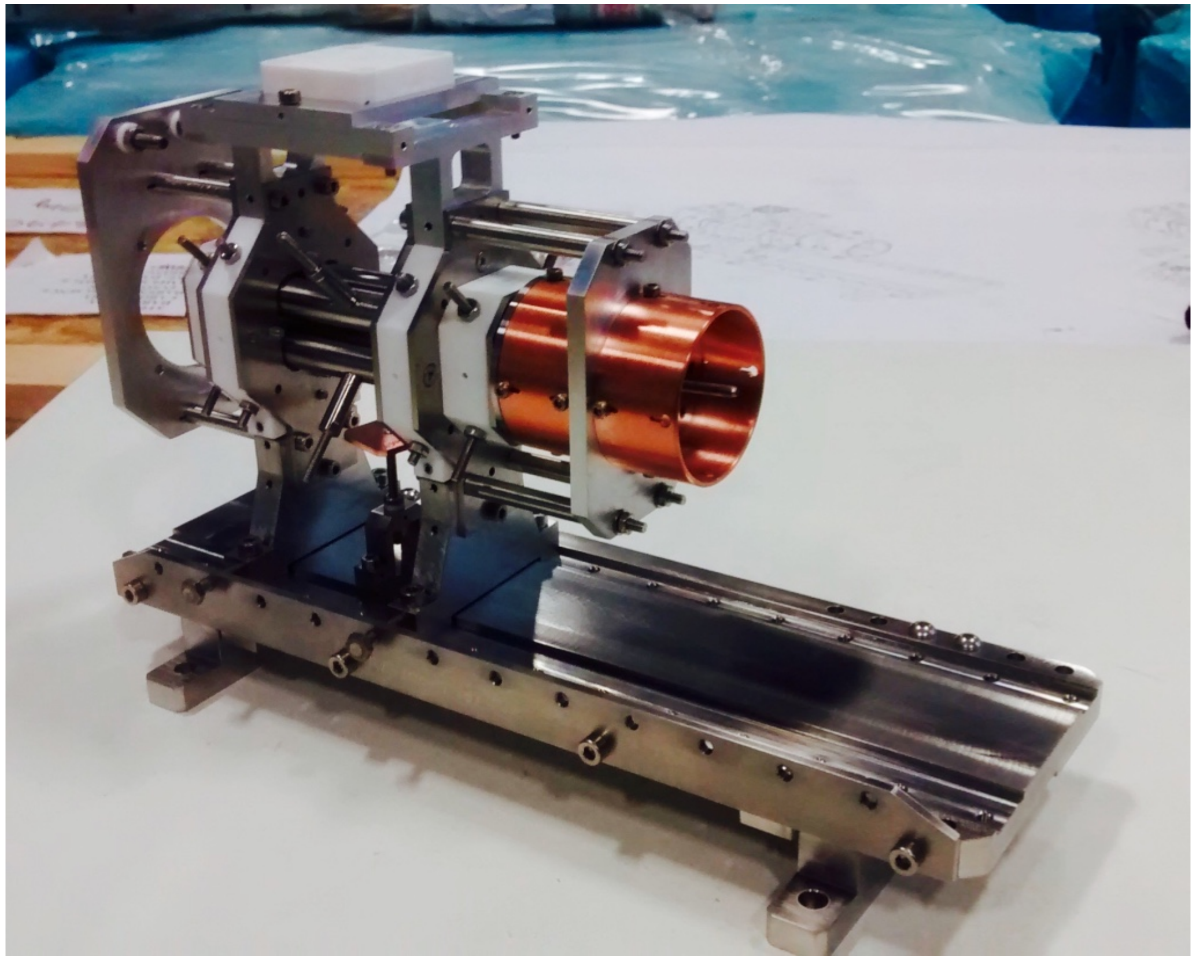
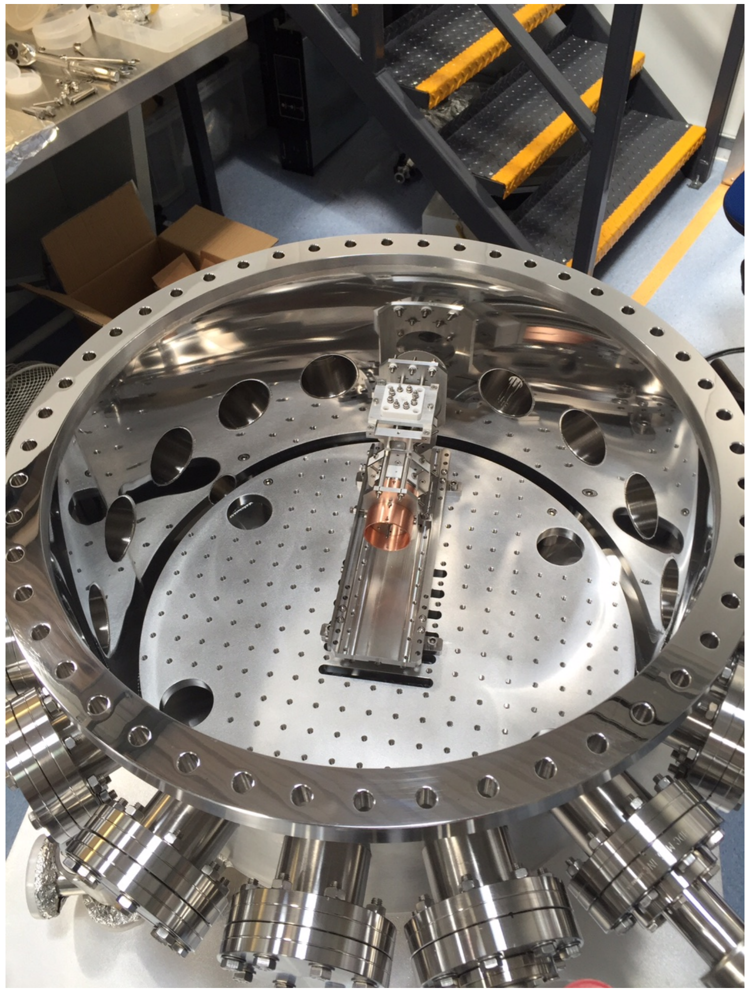


- Lab space set up; air conditioning, gas lines, risk assessed, electrical safety upgrade
- Vacuum vessel - machined, vacuum processed



- Paul trap - machined, aligned, vacuum processed
- Electronics - in progress and testing has begun
- Control system - LabView
- Commissioning - about to start

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RAL Paul Trap Programme

Proposed Experiment	Trap Required
Half-integer studies of ISIS and other rings.	Quadrupole
Long-term stability studies at various intensities.	Quadrupole
Benchmarking codes to simulate high intensity rings.	Quadrupole
Halo production driven by space charge.	Quadrupole
Comparison of different lattice types.	Quadrupole
Resonance crossing studies in the presence of lattice non-linearities.	Quad-Octupole
Quasi-integrable optics.	Quad-Octupole
Space charge effects in scaling FFAGs.	Higher order trap
Integrable optics (IOTA).	Higher order trap

Summary

- An encouraging start to the study of FFAGs as a driver of a next-generation neutron source
  - several different designs created for both main ring and small test ring
- Depending on the results of simulation with space-charge, and with suitable technological advances, the proposal to use H^+ rather than H^- could well be viable.
- Note the implications for ESS
  - neutrino proposals could avoid the need for H^- ions in the linac
- Study assisted through experimental opportunities in Japan and the new Paul Trap set-up at RAL

Annual FFAG workshop,6th-9th September, Imperial College London

https://indico.cern.ch/event/543264/overview

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