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ISIS Neutron and Muon Source

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ISIS Neutron and
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ISIS-II Update

Peter Griffin-Hicks
With thanks to John Thomason,
Dean Adams, Shinji Machida, et al.
07 April 2022

Agenda

0 ISIS Introduction

1 ISIS-II

2 Conventional Rings

3 Fixed Field Accelerator

4 IBEX

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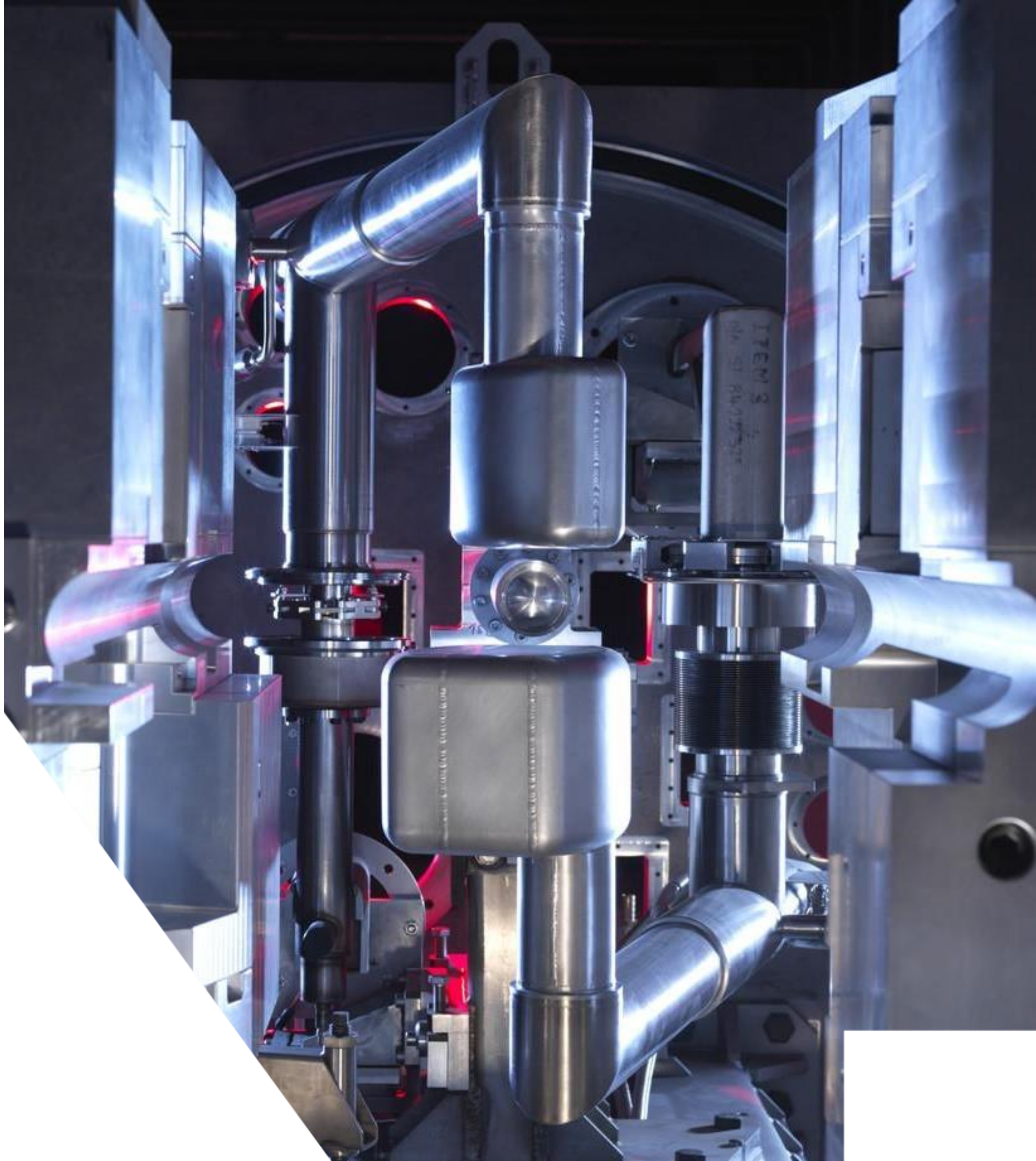

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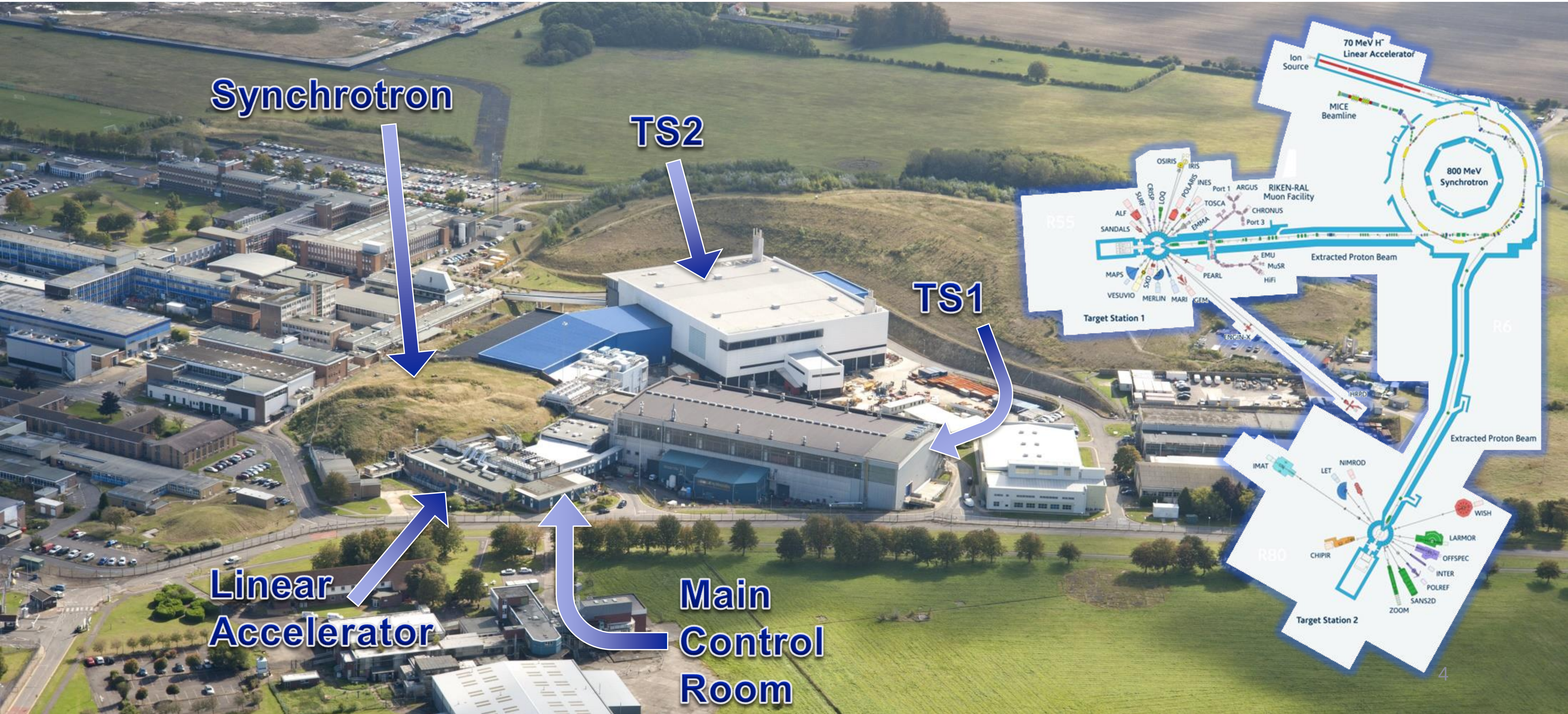

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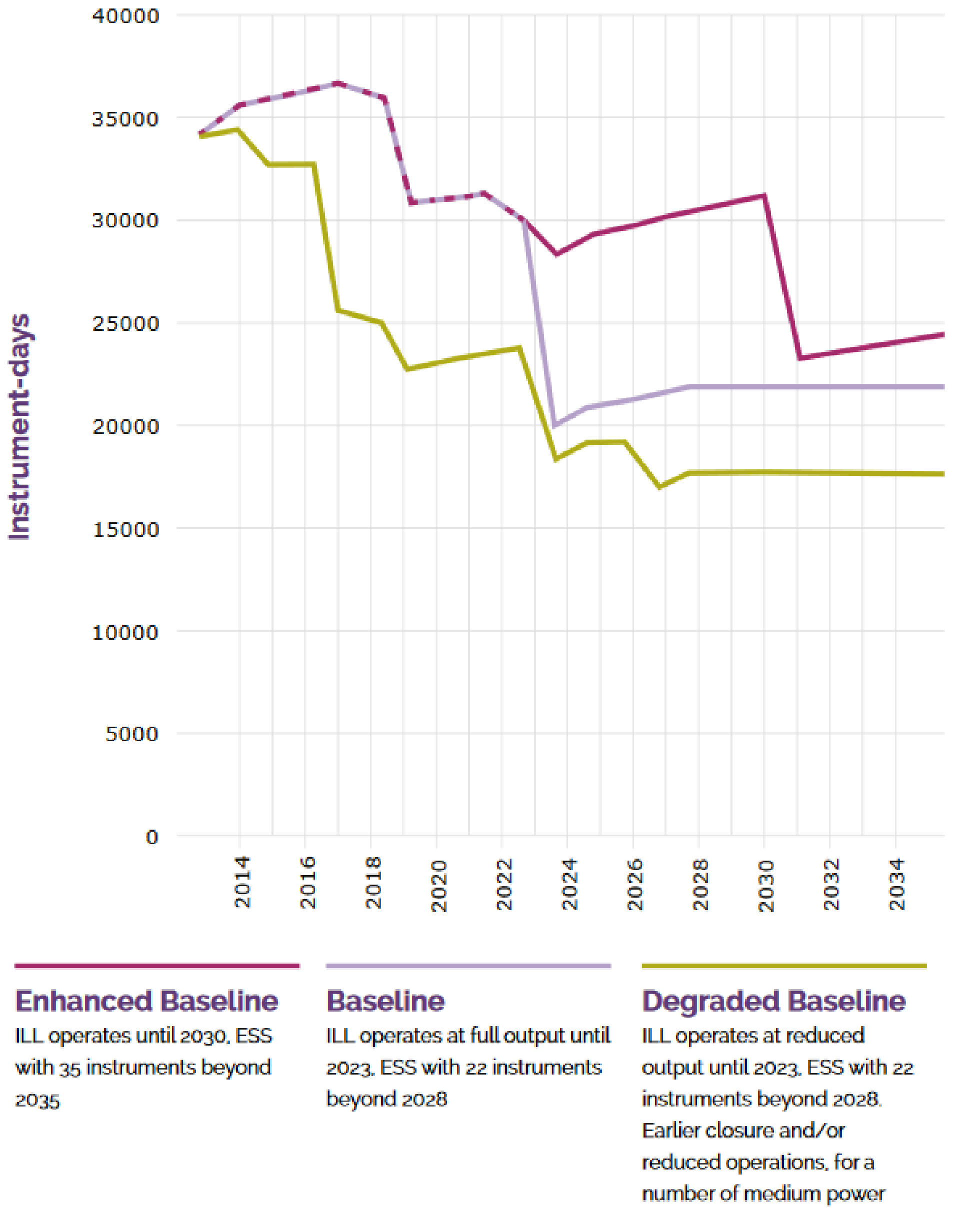
ISIS-II

John Thomason et al.

“Neutron Drought”

- ILL will continue operations, next period starting in 2024.
- Decommissioning 2030/33 [tbd]



Enhanced Baseline
ILL operates until 2030, ESS with 35 instruments beyond 2035

Baseline
ILL operates at full output until 2023, ESS with 22 instruments beyond 2028

Degraded Baseline
ILL operates at reduced output until 2023, ESS with 22 instruments beyond 2028. Earlier closure and/or reduced operations, for a number of medium power

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“Neutron Drought”

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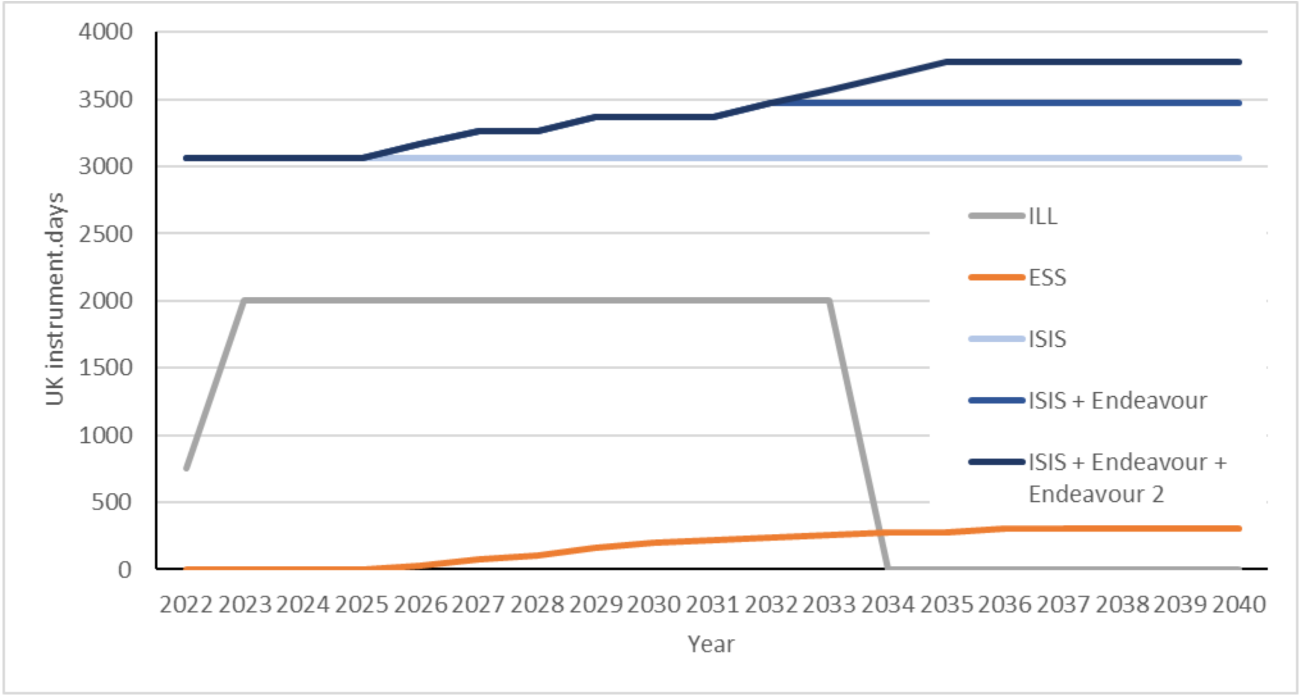
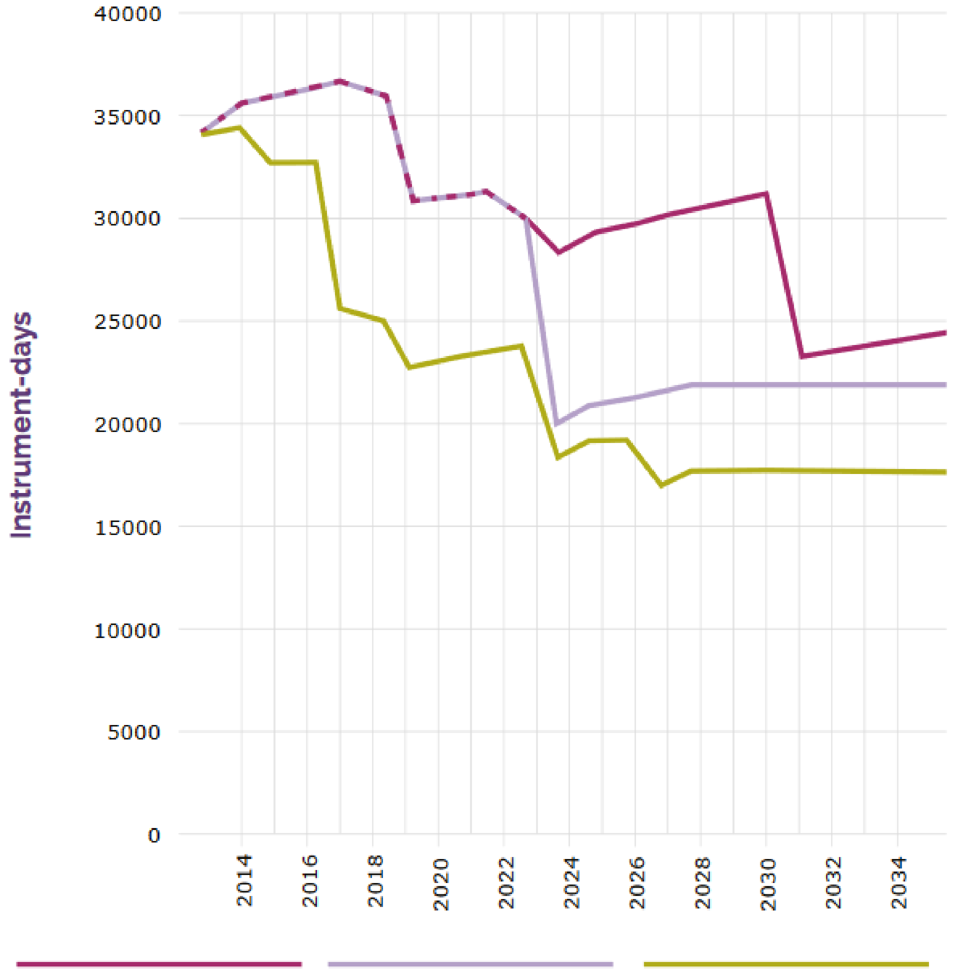
- Decommissioning 2030/33 [tbd]





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Business Case

ESFRI Neutron Scattering Facilities in Europe Report

> *…by far the most cost effective solution would therefore be to build a MW-class short pulse facility at ISIS, reusing existing infrastructure and facilities as well as drawing upon on-site competences. The current facility could operate until the new facility is operational with its initial suite of instruments.*

STFC Accelerator Strategy Review

- *Investment in high power proton beams and targets is recommended to support … neutron facilities research and development.*
- *Collaboration with international partners on facility development and accelerator research activities is recommended, where appropriate.*
- *The UK national laboratories should be charged with the co-ordination of research and development activities across stakeholders in development of future neutron sources.*

STFC Neutron Science and Facilities – An Update to the 2017 Strategic Review

> *The concept of an ISIS-II short pulse facility is exciting, and it has the potential to be very complementary to other sources. Continued exploration is strongly encouraged as a long-term option.*
>
> *…the concept demonstrates visionary forward thinking and could create an exciting technical challenge to engage the whole UK community in.*

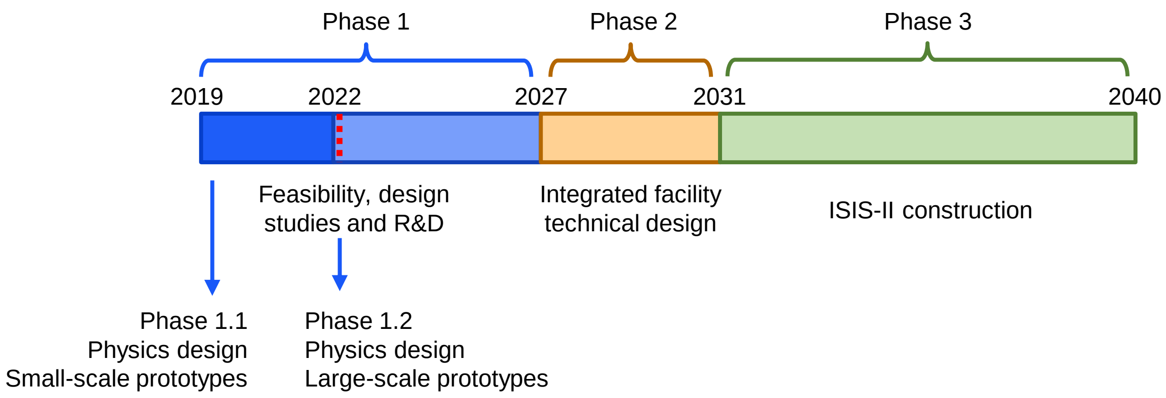
ISIS-II Project

Announcement of £1.5m UKRI infrastructure funding for ISIS-II Feasibility, Design Studies and R&D – ‘Phase 1.2a’ to cover FY21/22, with the promise of more to follow for FY22/23 and FY23/24. This funding will cover staff resources of ~20 FTE and some prototyping

Headline Specification:

- 1.25 MW proton beam
    - TS1: 1 MW 40 pps
    - TS2: 0.25 MW 10 pps
- 1.2 GeV beam on target energy
- 0.1 % beam loss

Exact specification to be determined.



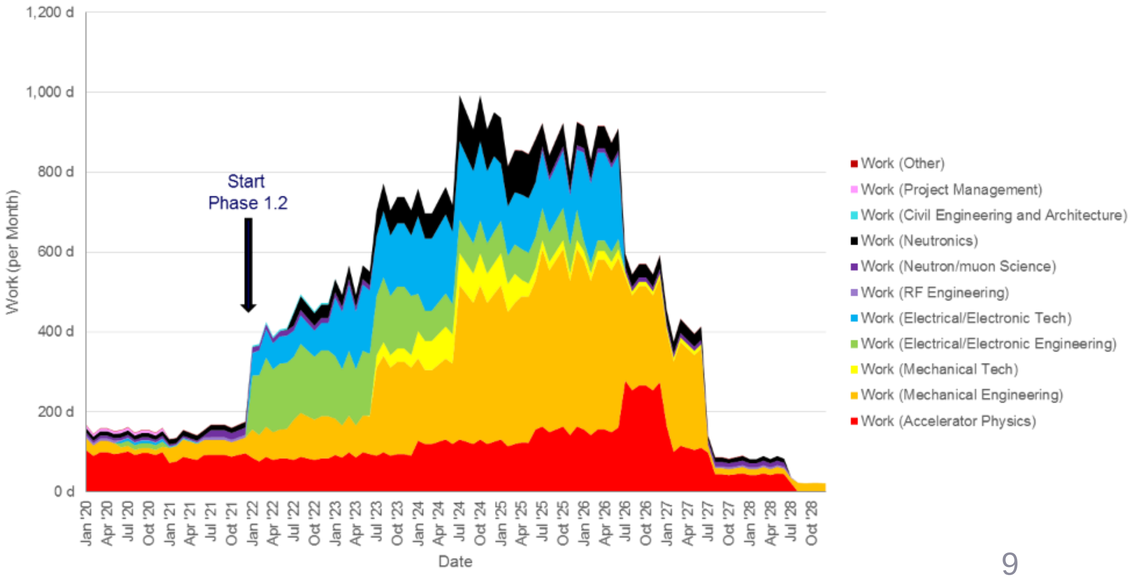
Feasibility, design studies and R&D

Integrated facility technical design

ISIS-II construction

Phase 1.1
Physics design
Small-scale prototypes

Phase 1.2
Physics design
Large-scale prototypes



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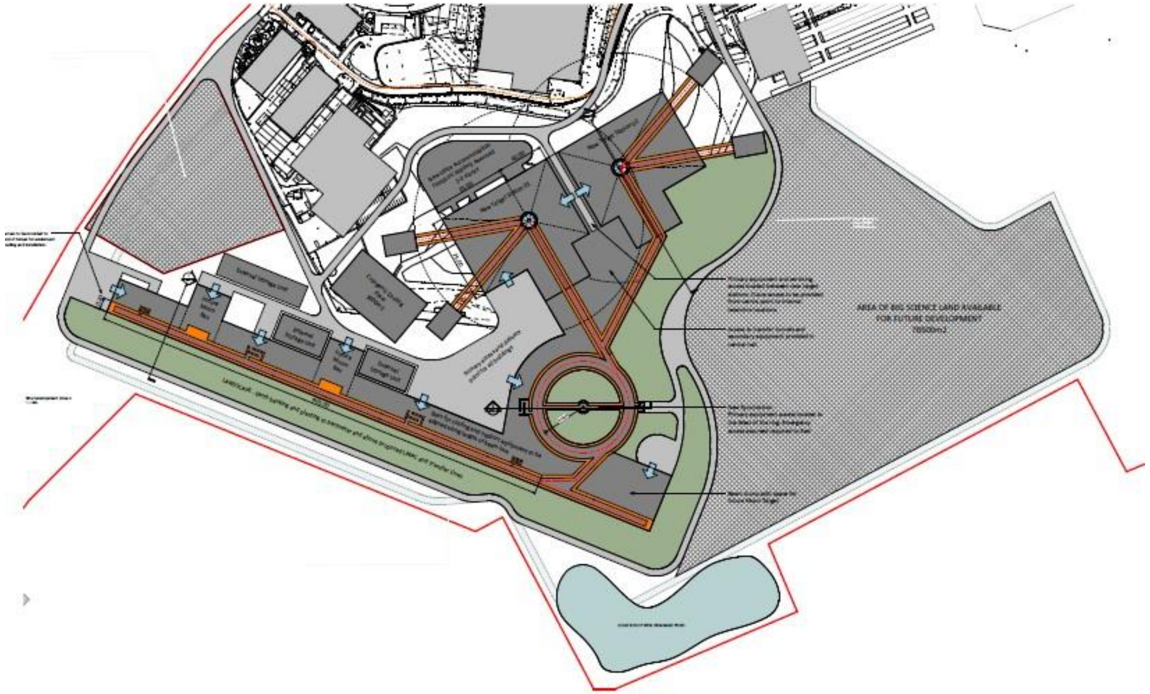
Options

Locations:

- Reuse existing ISIS infrastructure
  - Upgrade existing accelerators
- Standalone development

Design:

- Conventional technology
  - Synchrotron (e.g. J-PARC)
  - Accumulator Ring (e.g. SNS)
- Fixed Field Accelerators



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UKRI Science and Technology Facilities Council

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Conventional Rings

Dean Adams et al.

Overview

Machines:

- ISIS Upgrade
- Standalone
  - RCS
  - AR

For each

1. Lattice Design (DJA)
2. Longitudinal Dynamics (**REW – JAI student**)
3. Transverse Dynamics (*CMW – supervisor of JAI students,* et al)
4. 3D Beam Dynamics Design (DJA et al)
5. Injection Straight Design and Foils (HVC, BK, et al)
6. Correction Systems (**PTH – JAI student**, HR)
7. Collimation, Extraction (HVC, HR et al)
8. Instabilities (**REW, DPdB – JAI student**)

Comparison

Machine	SA RCS	SA AR
Energy Range (GeV)	0.4 - 1.2	1.2
Intensity (ppp)	1.3×10^{14}	1.3×10^{14}
Repetition Rate (Hz)	50	50
Mean Power (MW)	1.25	1.25
Circumference, (mean R) (m)	282 (45)	282 (45)
No Super Periods	4	4
Magnet Excitation	Sinusoidal	DC
Dipole Fields (T)	0.42-0.84	0.84
Betatron Tunes (Q_x, Q_y) (±~0.2)	(6.40, 6.32)	(6.40, 6.32)
Gamma Transition	5.2	5.2
Peak RF Volts h=(2,4) (kV/turn)	(300, 150)	(50, 28)
RF Frequency (h=2) (MHz)	1.52-1.91	1.91
Number of Bunches	2	2
Acceptances: painted, collimation, aperture (*π mm mr) ($\Delta p/p$ ±0.01)	400, 600, 750	300, 350, 500

*un-normalised

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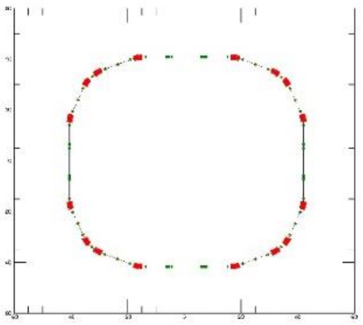
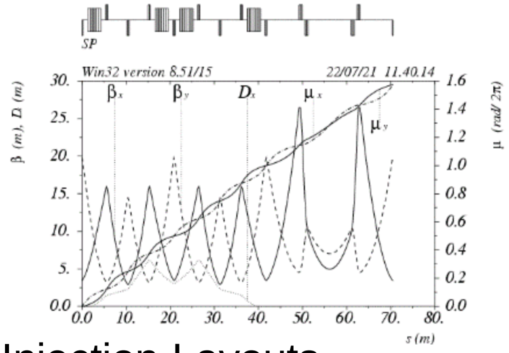
Design Tasks:

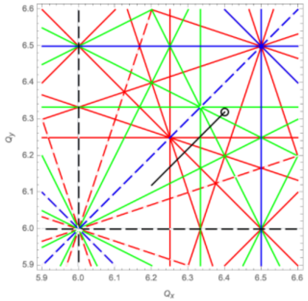
Lattice



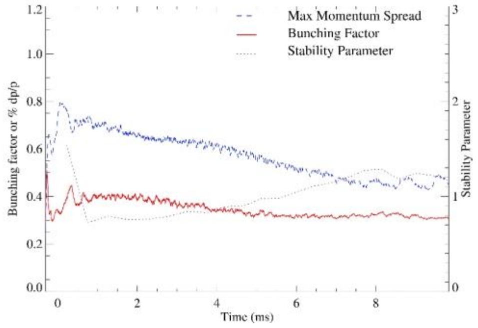
Optics



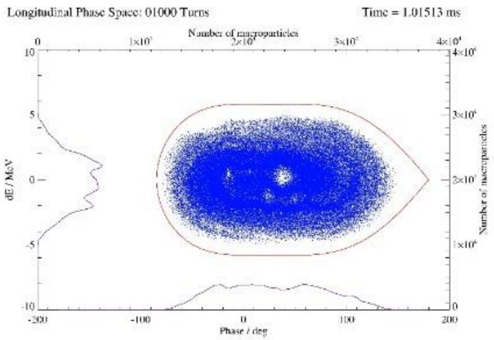
Working Point



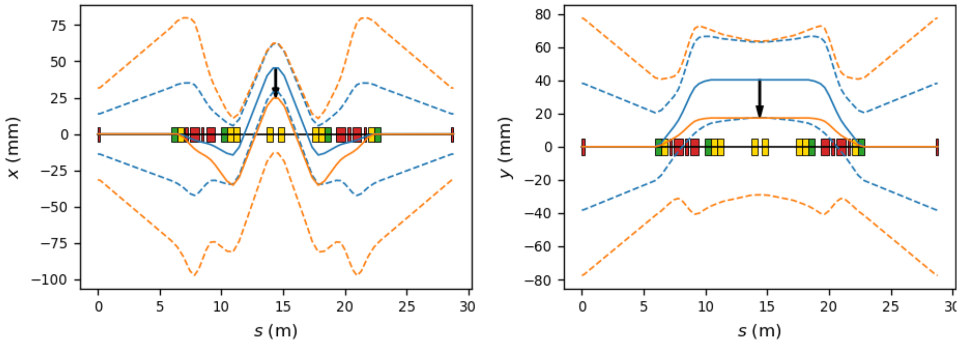
1D Metrics



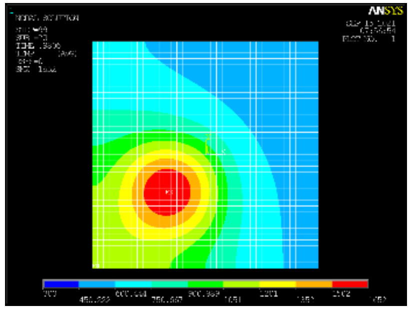
1D Simulations



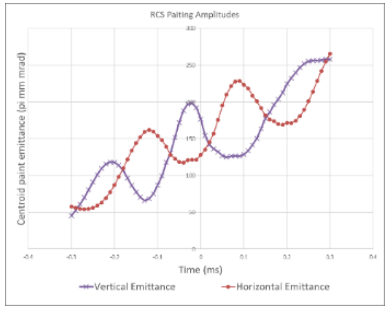
Injection Layouts



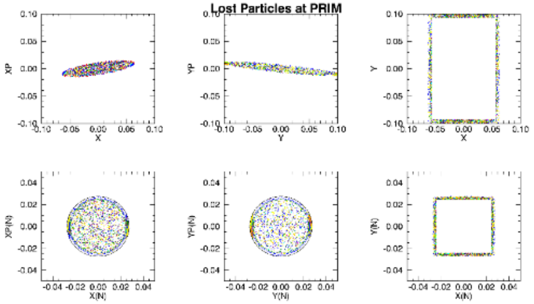
Foil Temperatures



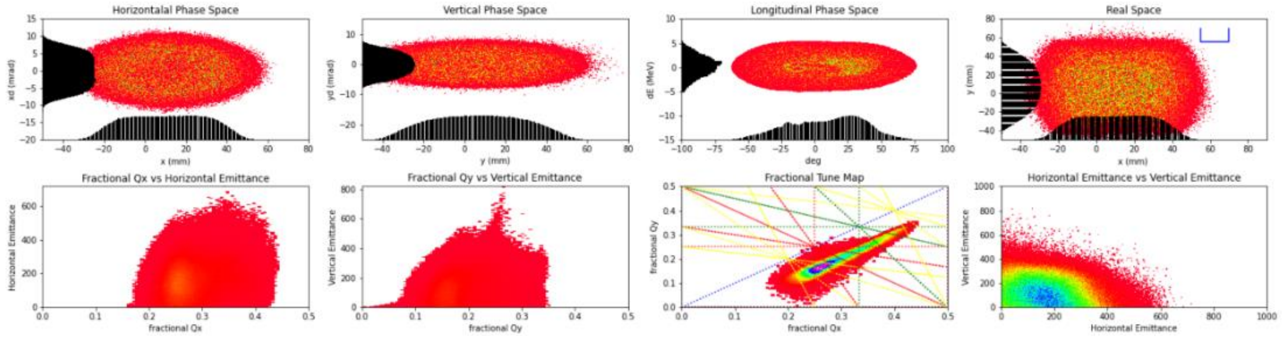
Injection Painting



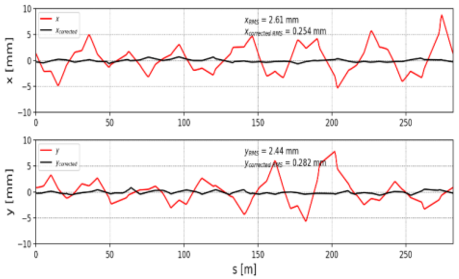
Collimation Simulations



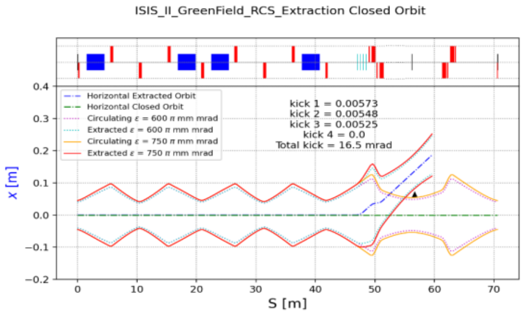
3D Simulations



Closed Orbit Correction

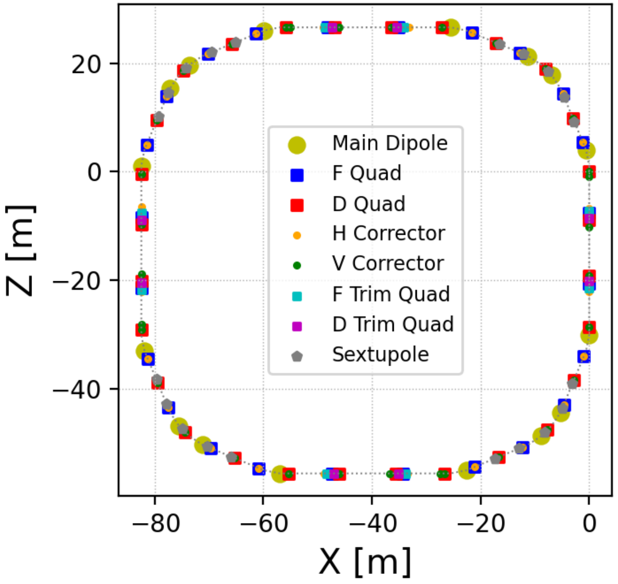


Extraction



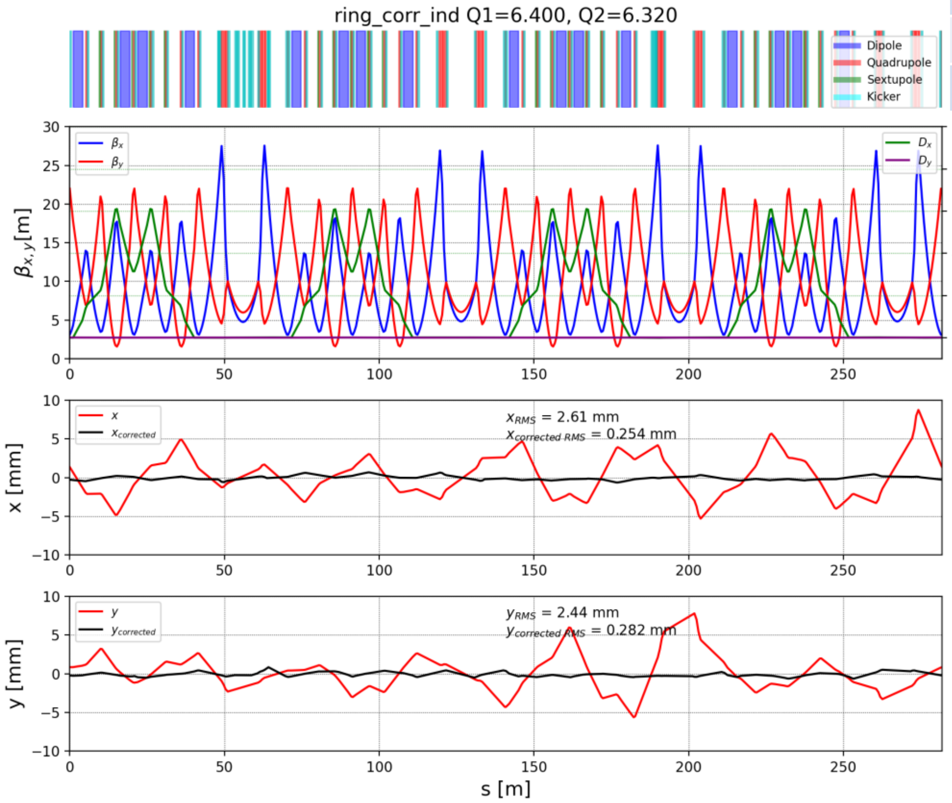
Closed Orbit Correction
– Peter Griffin-Hicks, Haroon Rafique

0.5 m long Corrector/Monitor pairs adjacent to all main quadrupoles
6 Horizontal, 8 Vertical per super-period
24 Horizontal, 32 Vertical = 56 total
1000 cpymad (MAD-X) simulations analysed



Error type	Normal distribution widths
Quad misalignment	0.25 mm
Dipole rotations	0.5 mrad
Relative field errors	1e-4
BPM misalignment	0.25 mm
BPM resolution	0.2 mm

Widths based on Accelerator Technical Design Report for J-PARC, 2003



COD	Uncorrected (mm)	Corrected (mm)	Corrector Strength (mrad)
X_{max}	**7.16 ± 2.26**	**0.45 ± 0.39**	**α = 0.21 ± 0.12**
X_{RMS}	2.45 ± 0.8	0.10 ± 0.06	α = 0.05 ± 0.02
Y_{max}	**9.46 ± 3.52**	**0.60 ± 0.48**	**α = 0.26± 0.09**
Y_{RMS}	3.86 ± 1.83	0.12 ± 0.10	α = 0.06 ± 0.01
	With monitor errors		
X_{max}	**7.16 ± 2.26**	**1.11 ± 0.39**	**α = 0.24 ± 0.13**
X_{RMS}	2.45 ± 0.8	0.32 ± 0.06	α = 0.06 ± 0.02
Y_{max}	**9.46 ± 3.52**	**1.09 ± 0.38**	**α = 0.35± 0.14**
Y_{RMS}	3.86 ± 1.83	0.34 ± 0.06	α = 0.08 ± 0.02

Conclusion: Best **COD Correction Implemented**
Lattice offers space for maximum number of correctors

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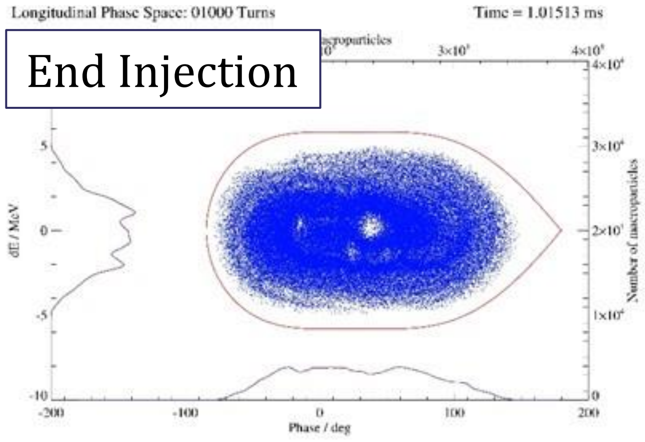
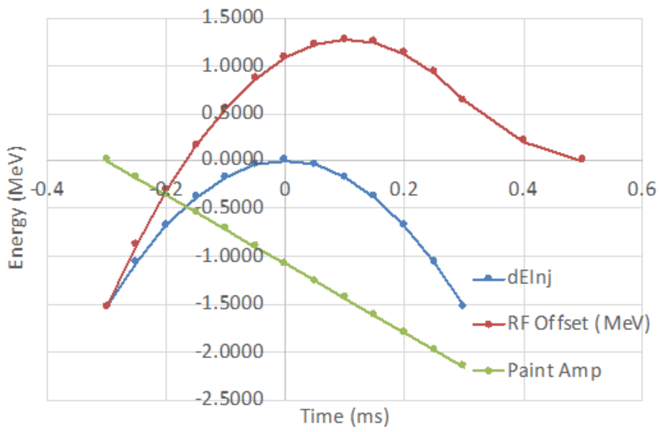
Longitudinal Dynamics and Instabilities – Rob Williamson

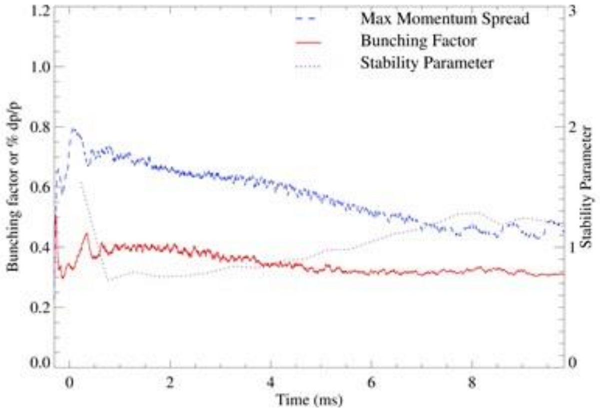
E.g. Standalone RCS:

- Symmetric injection
- Good bunching factor
- Stability parameter peaks above one
- Extraction gap 274 ns



End Injection





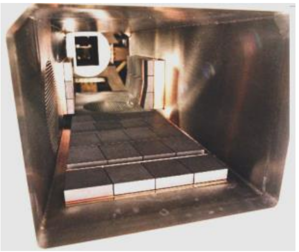
- Persistent hole in distribution
- Scope for improvement with theta sweep, variable injection energy

- Primary impedances
  - Space charge (-333 $i\Omega$, -3.53 $iM\Omega$/m)
  - Resistive wall (0.482 Ω, 7.23 kΩ/m)
  - Narrowband and broadband contributions
- Instabilities (Basic Calculations)
  - Longitudinal microwave – STABLE
  - Transverse coasting – Possible unstable modes up to n=76
  - Head-tail – STABLE up to m=7
  - *Coupled bunch*
  - *E-P*

Cures/Mitigations

- Impedance budget
- Beampipe geometry
- RF shields
- Inductive inserts
- HOMs damping
- Trim elements
- Injection Painting
- Active damping systems
- Clearing electrodes, low SEY coating

Investigating Instabilities – David Posthuma de Boer

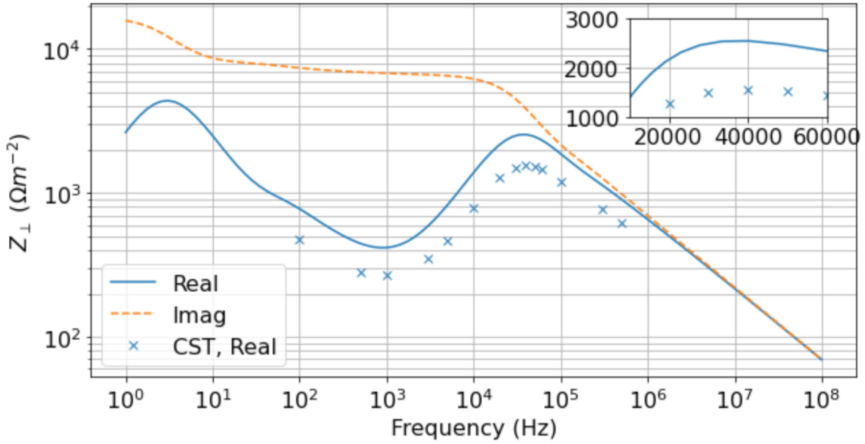


Impedances on ISIS obtained using finite element software, a new field matching code for multi-layer beam pipe structures and bench measurements.

- One related publication https://www.nature.com/articles/s41598-020-76447-x

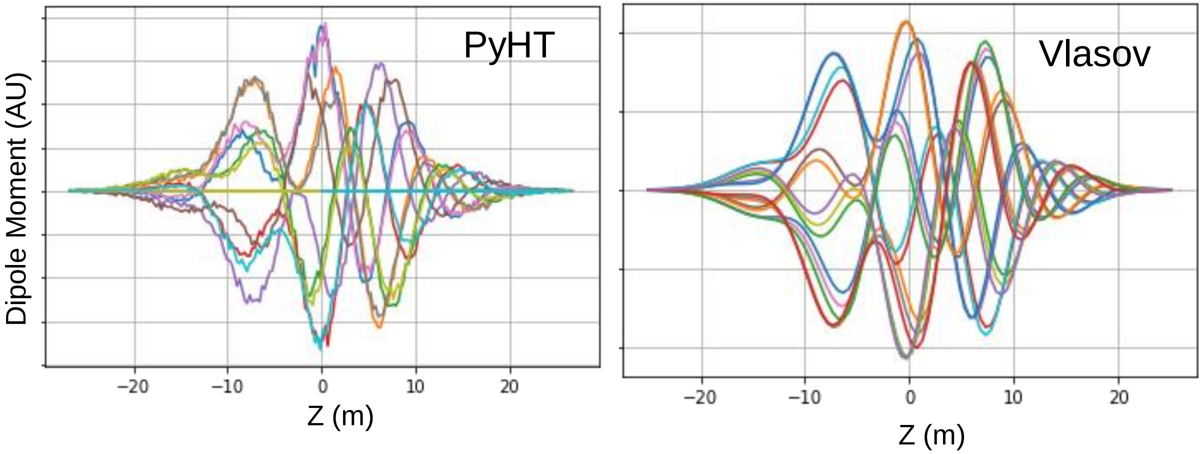
Equipment investigated so far

- Wire wages inside dipole magnets Resistive wall in RF cavities
- Resistive wall in collectors (example shown)
- Injection dipoles
- Extract kicker magnets



A new code to solve the Vlasov equation for head-tail modes and TMCI has been developed.

- Take beam coupling impedance as an input, and predicts instability growth rates.
- Code works for arbitrary longitudinal distributions by utilising the properties of Laguerre polynomials.
- Code is also being extended to include transverse distribution.



1.3 MHz Resonator, R=1MOhm/m, Q=3

Chromaticity = -1.4, Qy=3.83, 3E13 PPB

6.7 m Gaussian, beta=0.37, Circ = 163.3 m

PyHT: 260 us Vlasov: 245 us

Results show good agreement with PyHEADTAIL

- Example shows agreement for both growth time and perturbed longitudinal distribution.

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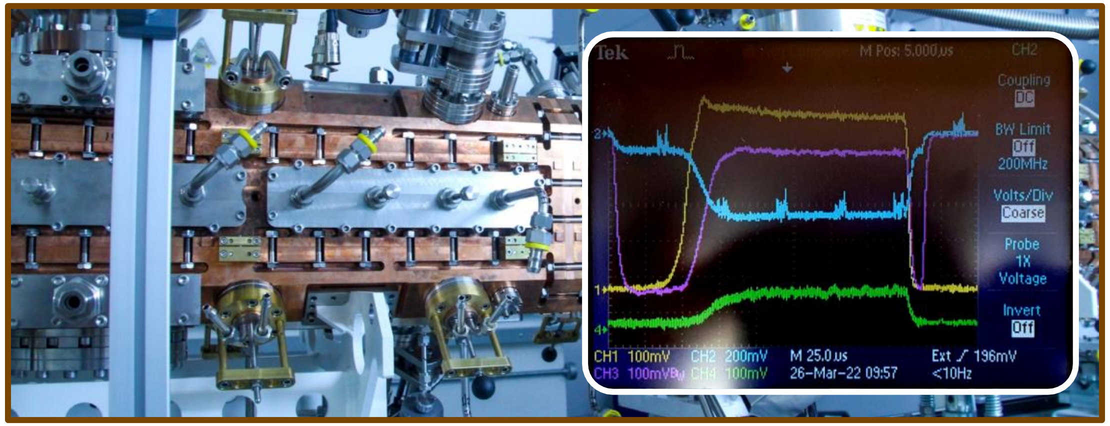
FFA

Shinji Machida et al.

Overview

Machines being designed:

- FETS FFA proof of concept
- Standalone FFA

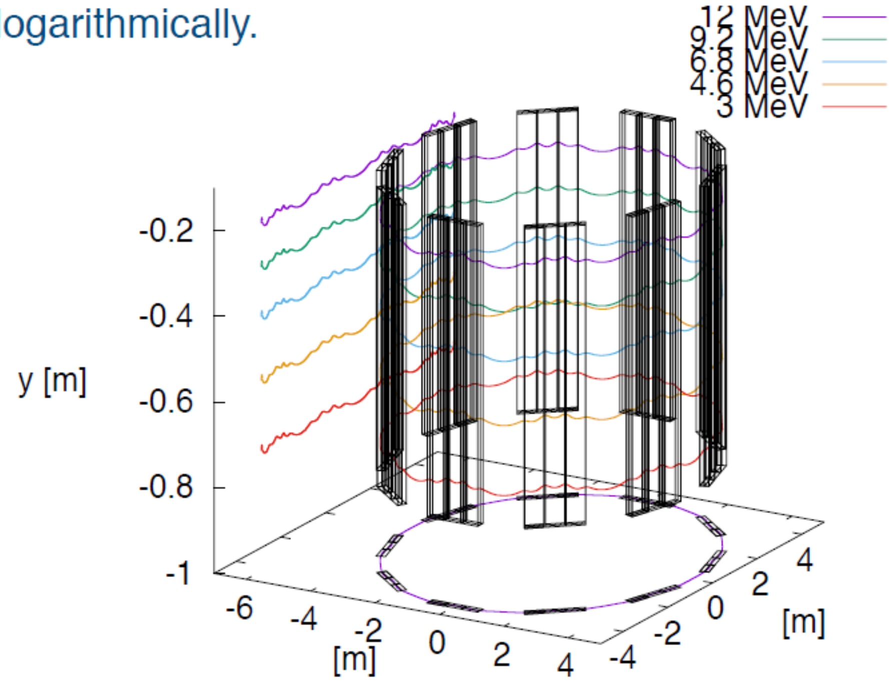


FETS first beam
Limited to 30 mA, 0.78 Hz 0.25 ms pulses for radiation protection testing
Next: test novel beam chopping technique

- Optics and dynamics, *Shinji Machida – ISIS supervisor of JAI student*
- Analytical approach, **Max Topp-Mugglestone – JAI student**
- Collective effects at injection and during beam stacking, *David Kelliher – assisting JAI student*
- Collimation design, **Emi Yamakawa – JAI staff**
- Injection design survey of high intensity machines, Carl Jolly
- Injection and extraction, Chris Rogers/**Jaroslaw Pasternak – JAI staff**
- Magnet physics design, *JB Lagrange – assisting JAI student*
- Magnet engineering design, Kieran Geiger
- SC and NC coil wire calculations, Iker Rodriguez
- Magnet hardware progress, Paul Surtees (Kieran Geiger)
- RF hardware progress, Bradley Kirk/Ian Gardner
- Diagnostics hardware design, Diagnostics group Alex Pertica/**Emi Yamakawa**

Vertical Excursion FFA

Separation of orbits reduces logarithmically.



- **Orbit moves vertically** when the beams are accelerated.
- Path length is constant for all the momenta. **Momentum compaction factor is zero.**

- As a proton driver for spallation source, advantages are
  - Small footprint
  - Rectangular magnet

- 3D magnetic fields increase exponentially in the vertical direction.

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

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

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

x: horizontal, y: vertical, z: longitudinal

$m = (1/B)\,(\partial B/\partial y)$

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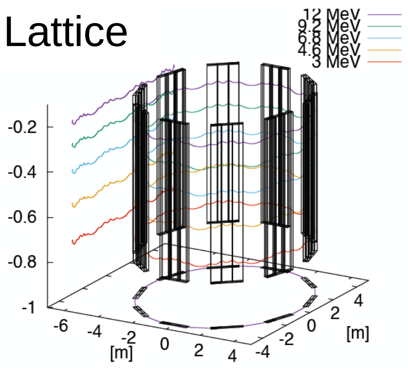
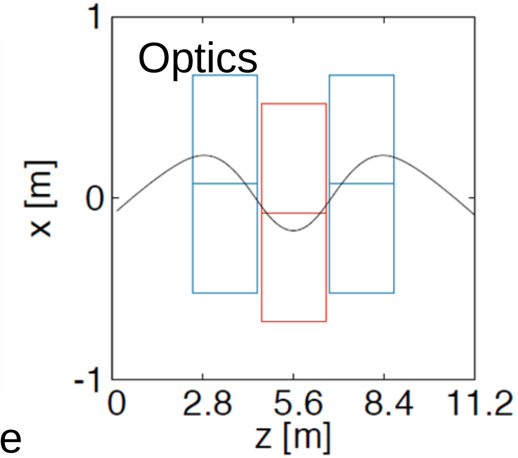
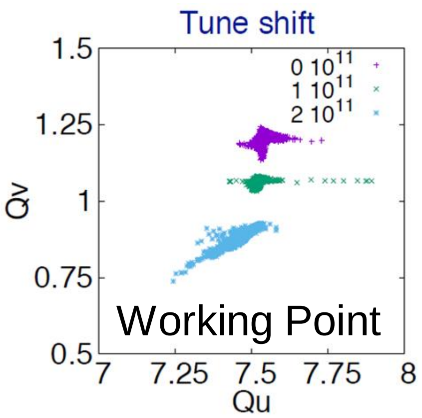
Comparison

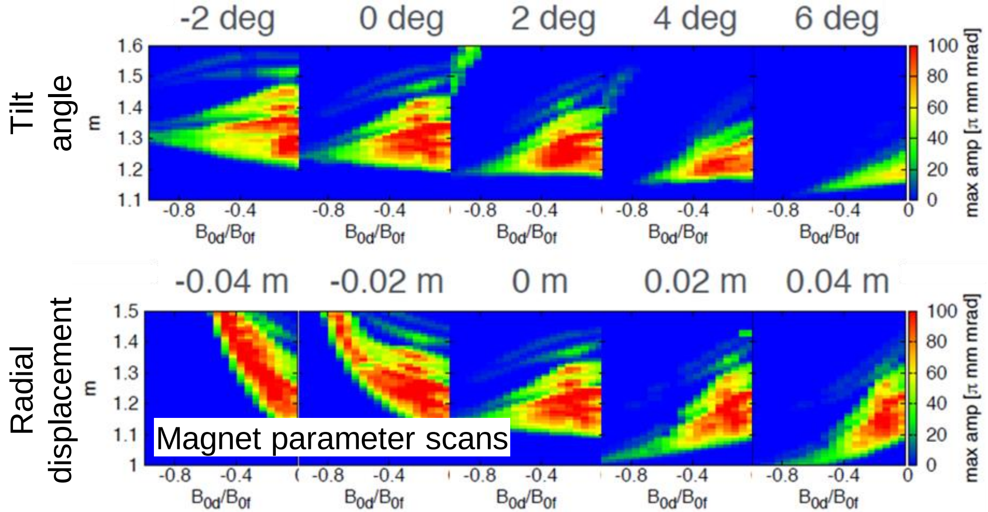
Machine	**FETS FFA**	**SA FFA**
Energy Range	3 - 12 MeV	0.4 – 1.2 GeV
Intensity (ppp)	3.4 x 10^{11}	1.3 x 10^{14}
Repetition Rate (Hz)	100 (50 pps)	90 ~ 120
Focusing	FDF Triplet	FDF Triplet
Circumference (m)	28	224
Number of cells	10	20
Total cell length (m)	2.8	11.2
Bd and Bf core length (M) (m)	0.5	2.0
Straight length (m)	1.24	4.96
Distance between Bd center and Bf centre (m)	0.53	2.12
Horizontal displacement between Bd and Bf (mm)	± 0.0	± 80.0
Fringe field parameter (L) (m)	0.15	0.6
Bd/Bf ratio (nominal)	1.15	1.54
m-value (nominal)	1.31	0.8775
Orbit excursion (m)	0.53	0.79
Tunes (qh, qv, nominal)	0.243, 0.120 (0.757, 0.120)	(0.178, 0.419)
Dynamic aperture (normalised) (*π mm mr)	60, 70	1200, 5700
Nominal 100% emittance (normalised) (*π mm mr)	10	150

Design Tasks (FETS):

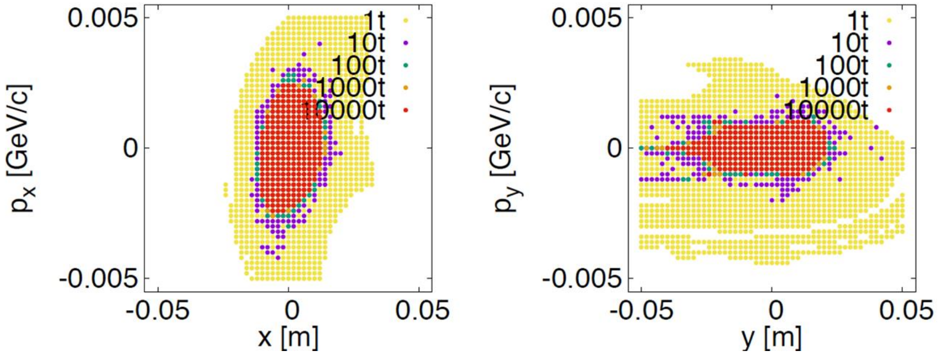




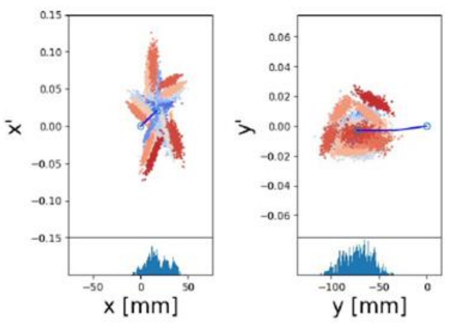


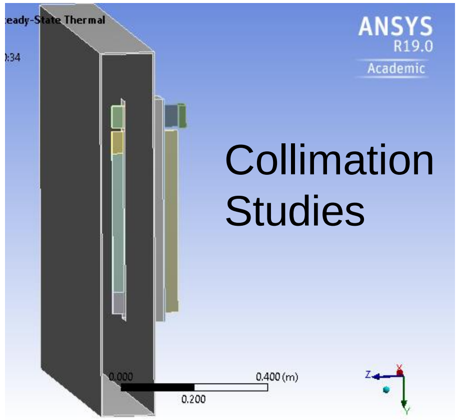


Dynamic Aperture

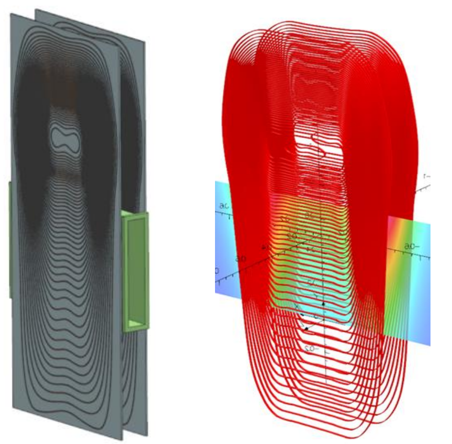


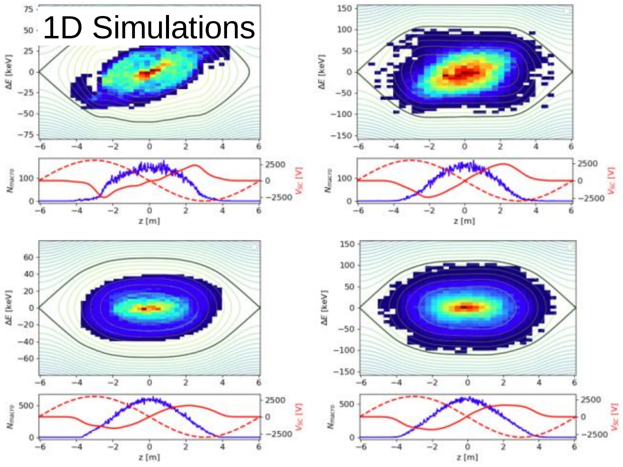
Injection



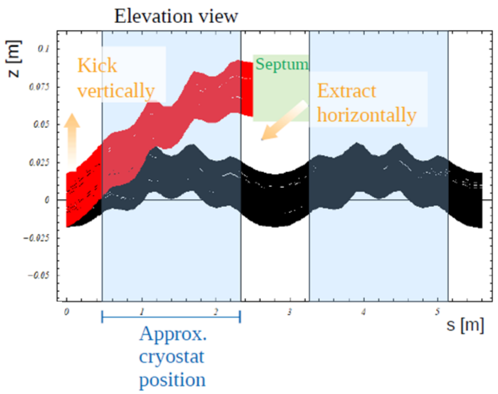


Magnet Design

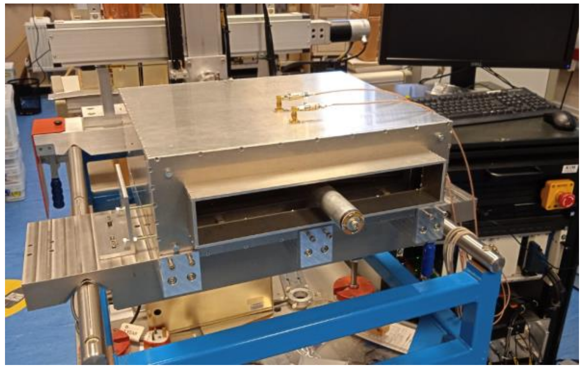




Extraction



Beam Diagnostics



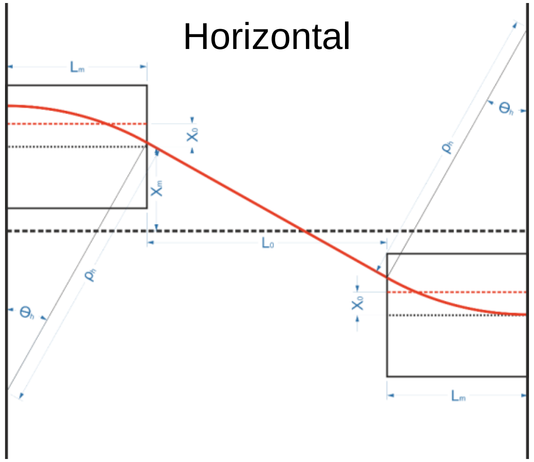
RF Cavity Design

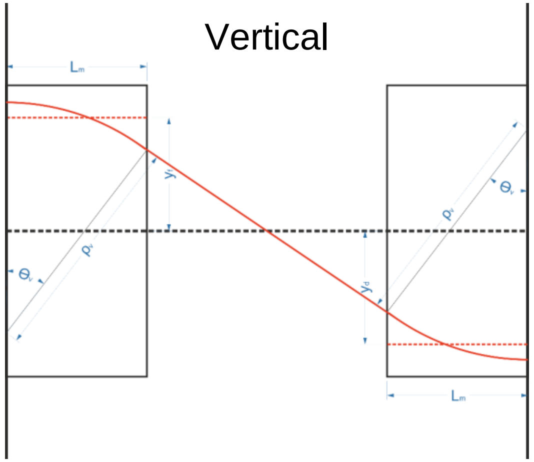
Analytical Approach to Modelling vFFA – Max Topp Mugglestone

Current modelling of vFFA relies on numerical simulation

- Lengthy simulations required
- Slow design and optimisation processes
- Limited understanding of the behaviour and optics
  - How does the coupling work?
  - How do input parameters affect e.g. tune?
  - Why are certain regions of parameter space unstable?
  - Difficult to determine tolerances to field errors etc

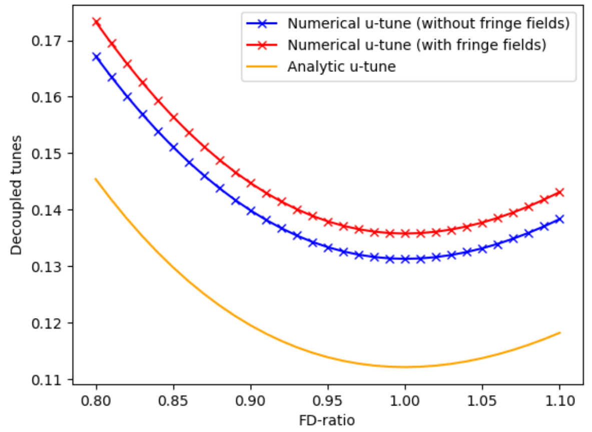
Investigate a simplified analytical model

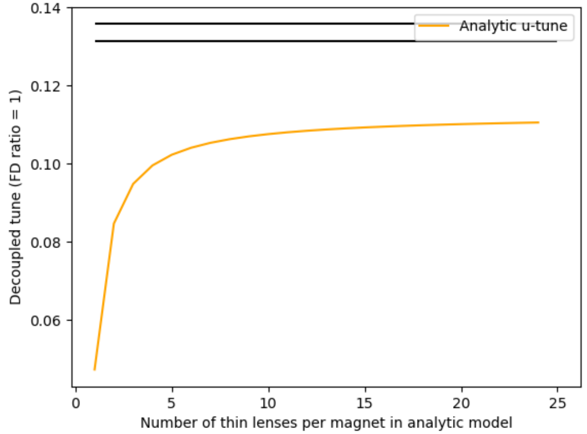




Able to predict dependence of tune on FD ratio.

Analytic tune does not converge precisely on same value as numerical tune.





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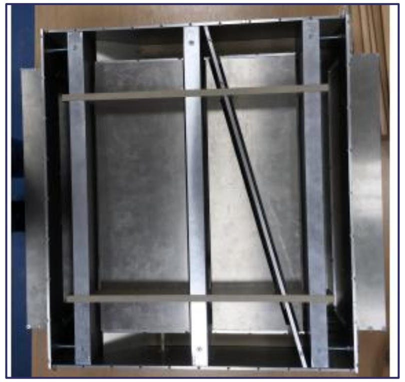
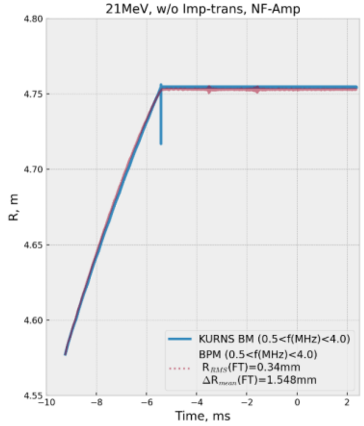
FFA Beam Diagnostics and Collimation – Emi Yamakawa

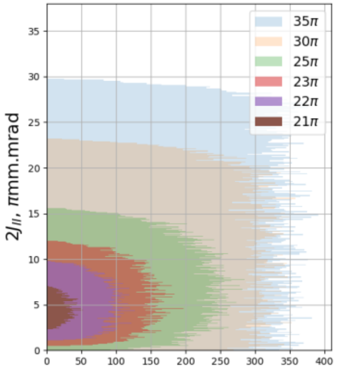


Half-size prototype BPM, tested in the diagnostics lab.

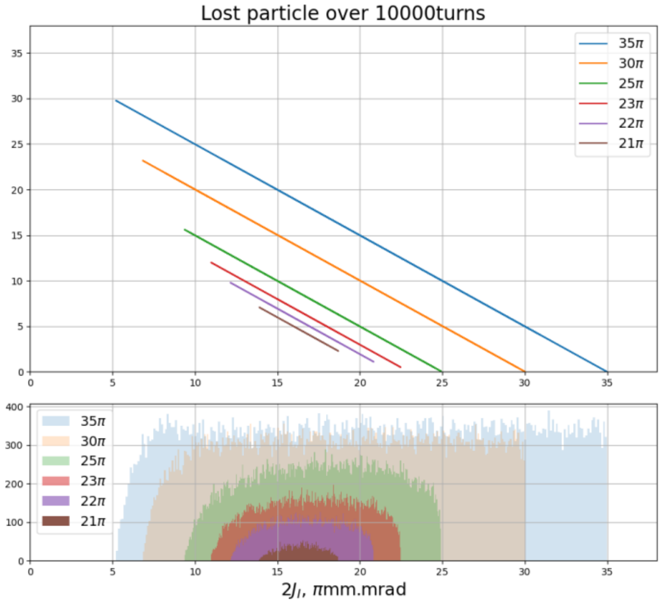


Beam position measurements by BPM and KURNS BM.

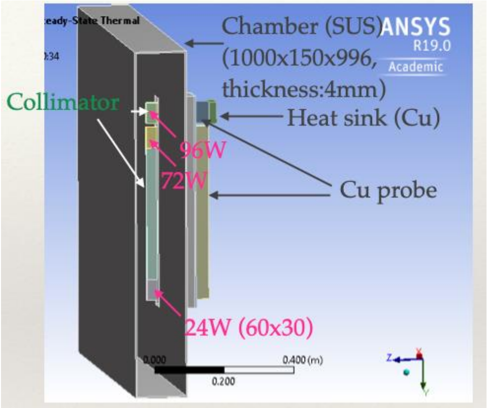
- To demonstrate feasibility and reliability of vertical excursion Fixed Field Alternating gradient accelerator (FFA), the small scale test ring (FETS-FFA) will be built by 2034.
- Preliminary design of Electro-static Beam Position Monitor (BPM) was generated in CST.
- Prototype BPM (half-width) was manufactured and tested in horizontal excursion FFA ring at Kyoto university in Japan in December 2021.
    - Horizontal beam displacement with beam energy was measured by BPM, which is consistent to the existing bunch shape monitor (KURNS BM) at Kyoto.
    - Betatron tunes and position accuracy measurements will be performed in May 2022 at Kyoto.



Initial Action variables of lost particles at collimator over 10000turns.



- Design concept: owing to transverse coupling optics, a one-sided collimator (I-shape) captures halo particles for both directions at same time/location.
- FETS-FFA test ring: a single I-shape collimator.
    - Capture efficiency can be optimised by *decoupling* matrix in a cell and initial halo distributions. Detail studies will be done with final machine parameters.
    - The first design of localised two collimators has been done by Copper (upper part)/Tungsten (lower part) : easy to change its position by step motor, enabling adjust collimator location at certain beam energy.
- ISIS-II ring: multi-collimator system using I-shape collimators are considered.
    - Detail studies are underway.



First design of two separated collimators.

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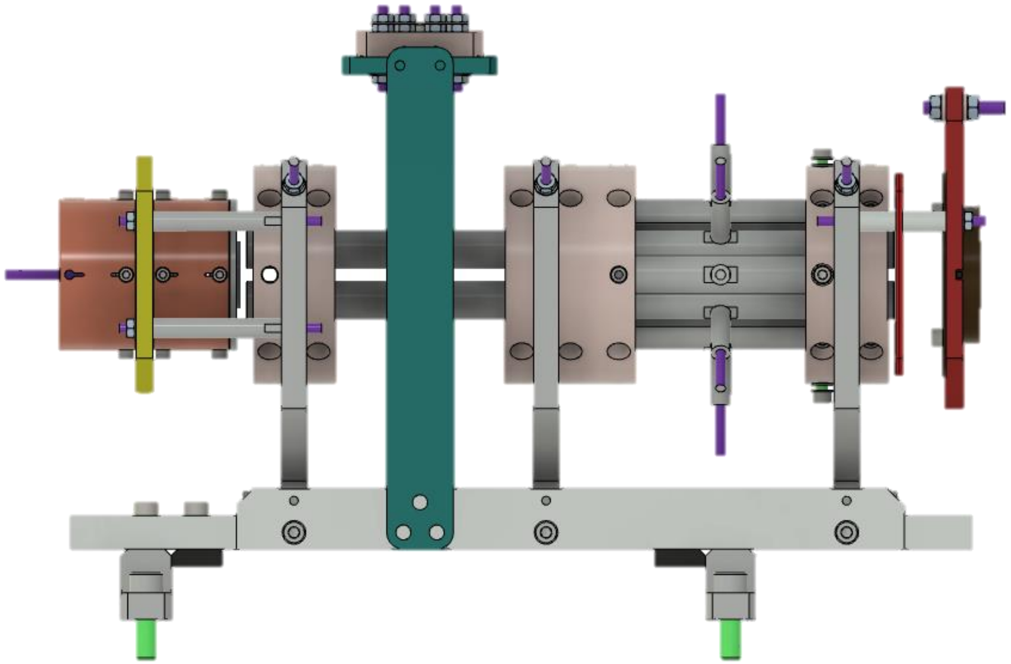
IBEX update

Suzie Sheehy, David Kelliher et al.

Why study accelerator physics in a Paul trap?



- **Fast measurement times** (1s = 1,000,000 FODO cells).
- **Large parameter space:**
  - Can create various different lattice types.
  - Can easily change the number of particles (intensity).
- **Low energy** ions – will not damage components when lost.
- **Dispersion-** and **chromaticity-free** environment.
- **Cost effective** when compared to building an accelerator.

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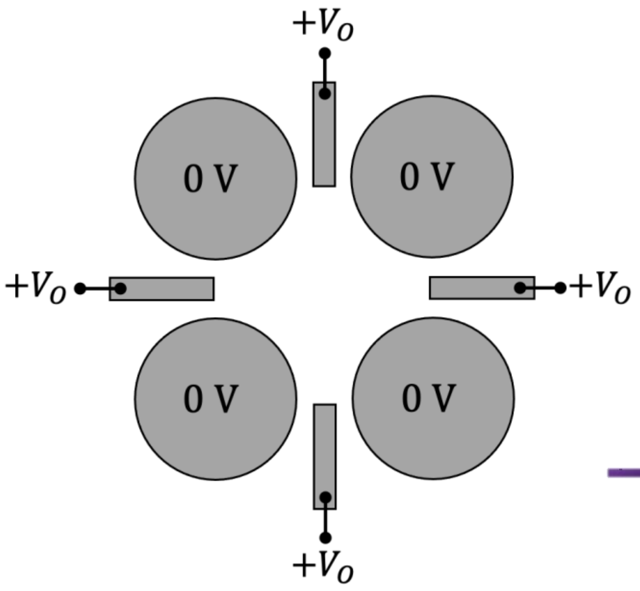
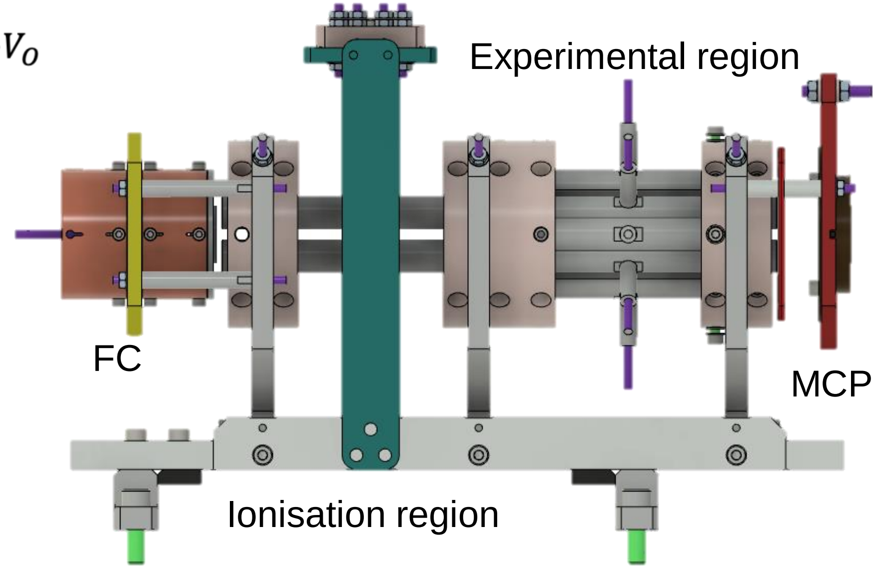
Non-linear upgrade to IBEX – Jake Flowerdew

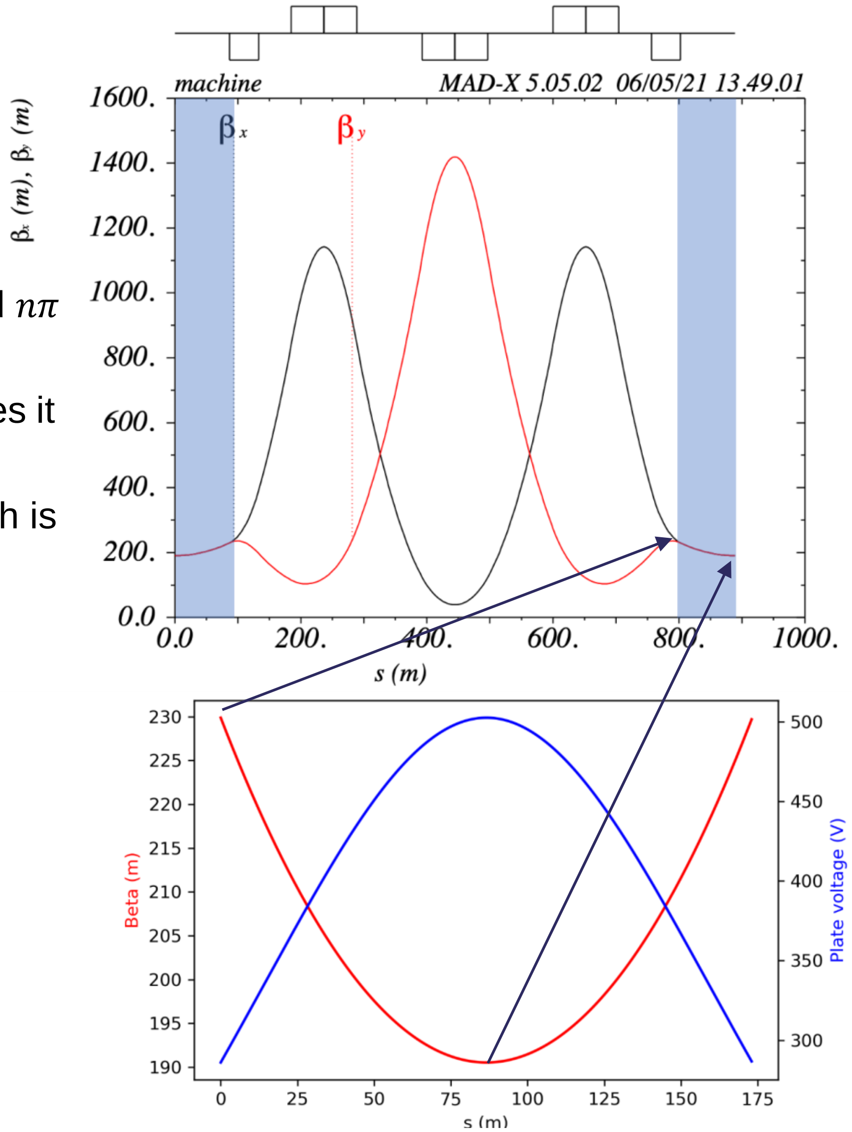
Addition of plate electrodes to allow for the creation of octupole fields



- Requires round beams and $n\pi$ phase advance.
- $1/\beta^3$ octupole scaling makes it time independent.

(Quasi-) Integrable lattice which is robust to small perturbations.





$$V(x,y,s) = \frac{k}{\beta(s)^3}\left(\frac{x^4}{4} + \frac{y^4}{4} - \frac{3x^2y^2}{2}\right)$$

Goal is to test Nonlinear integrable Optics – Using nonlinear elements to dampen instabilities while maintaining a large dynamic aperture.

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Questions?