Imperial College London

John Adams Institute for Accelerator Science

Science and Technology Facilities Council

Intense Hadron Beams

J. Pasternak

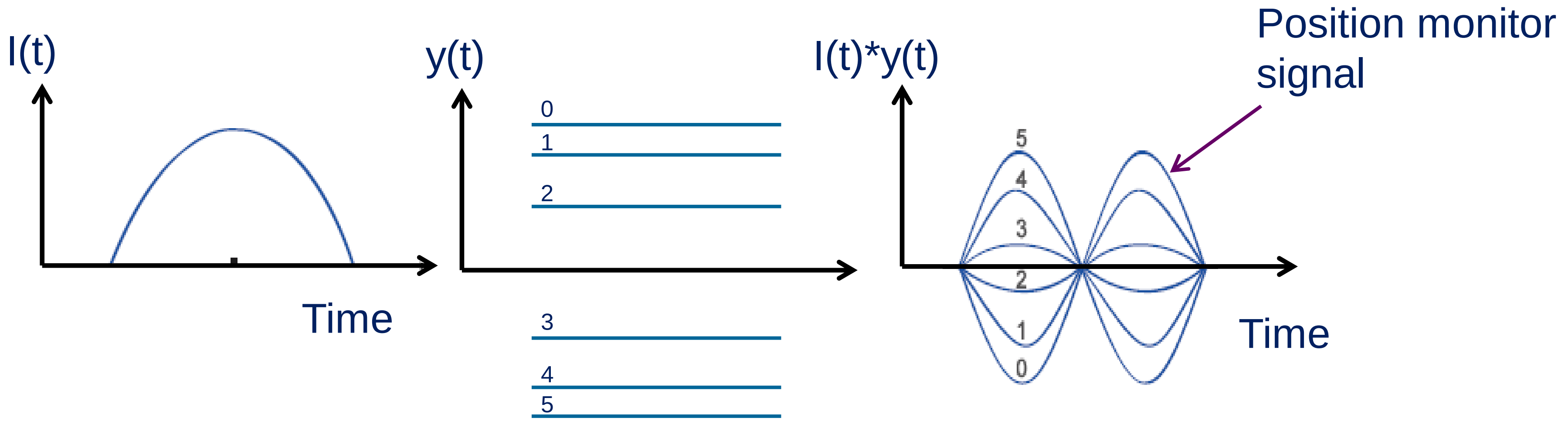
19/04/2021, JAI Advisory Board

Outline

- Studies of Beam Instabilities and Associated Beam Loss on a High Intensity Proton Synchrotron (Rob Williamson)
- Tune Plane Studies in the ISIS Synchrotron (Peter Griffin-Hicks)
- Impedance Characterisation at ISIS (David Posthuma de Boer)
- H^- laserwire (Stephen Gibson)
- Analytical approaches to beam dynamics in VFFA (Max Topp-Mugglestone)
- Collimator Study in VFFA (Emi Yamakawa)
- Beam diagnostics for FETS-FFA (Emi Yamakawa)
- Testing Nonlinear Integrable Optics with IBEX (Jake Flowerdew)
- Creating Exact Multipolar Fields with Azimuthally Modulated RF Cavities (Laurence Wroe)

Head-tail Instability

- Governed by impedance
- Characterised by mode structure
  - Dependent on machine parameters e.g. tune and chromaticity
  - Dependent on beam parameters e.g. bunch length and distribution

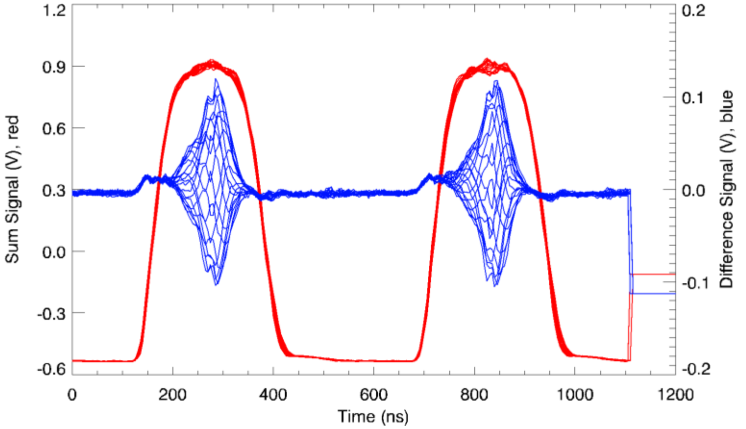


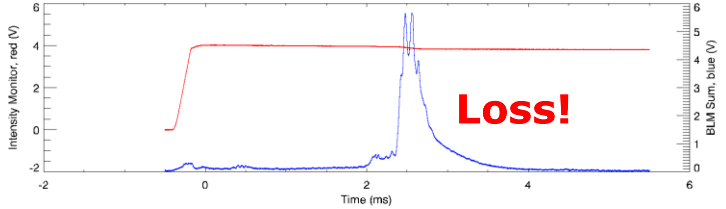
Head-Tail in User Operations

- Intensity limit due to associated loss
- Current instability mitigation
  - Fast vertical tune ramp
  - Injection painting
- Dual harmonic operation
  - Symmetric bunches unstable
  - Asymmetry helps, but not a cure
- Driven by impedances
  - Low frequency narrowband present
  - Resistive wall (?)

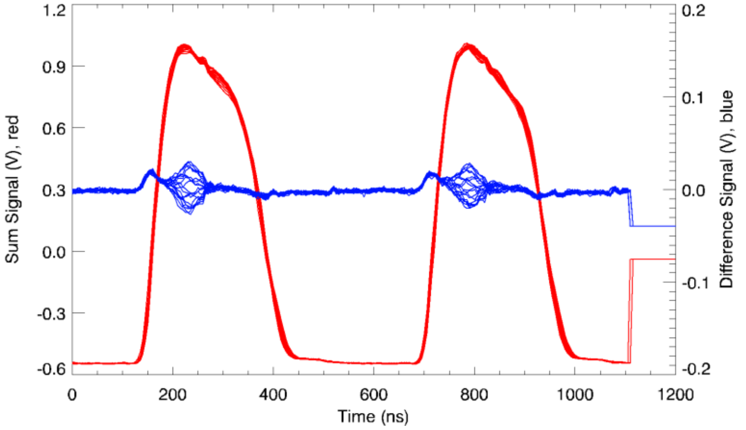
ISIS Beam Bunches at ~ 2 ms

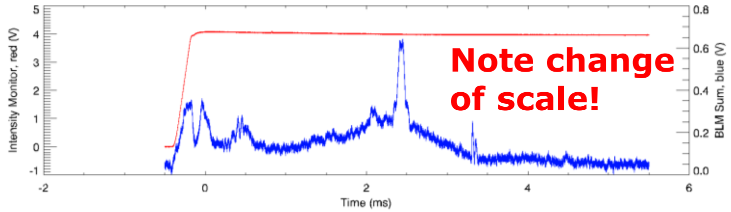
Normal beam + flat bunch
Large loss!





Normal beam + asymmetric bunch
Low loss





- Damper system in development
- R&D progressing – **DPhil**

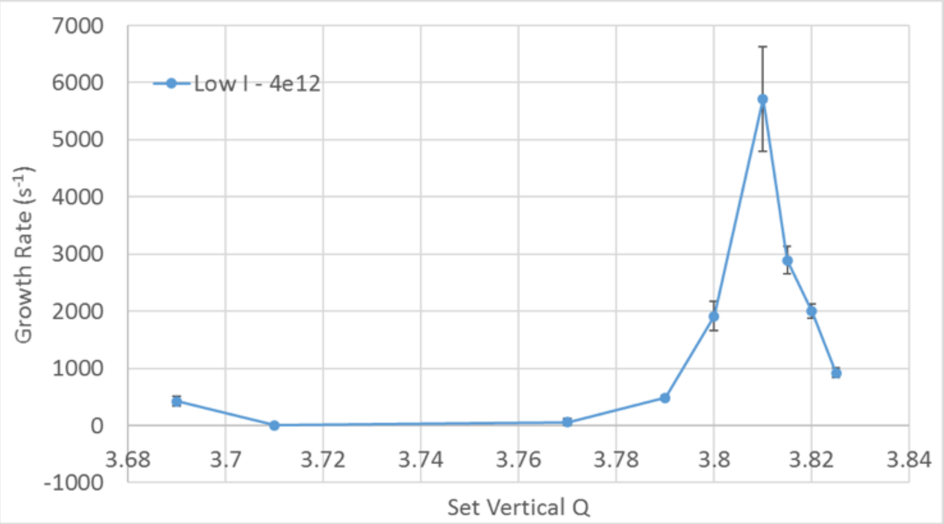
Rob Williamson

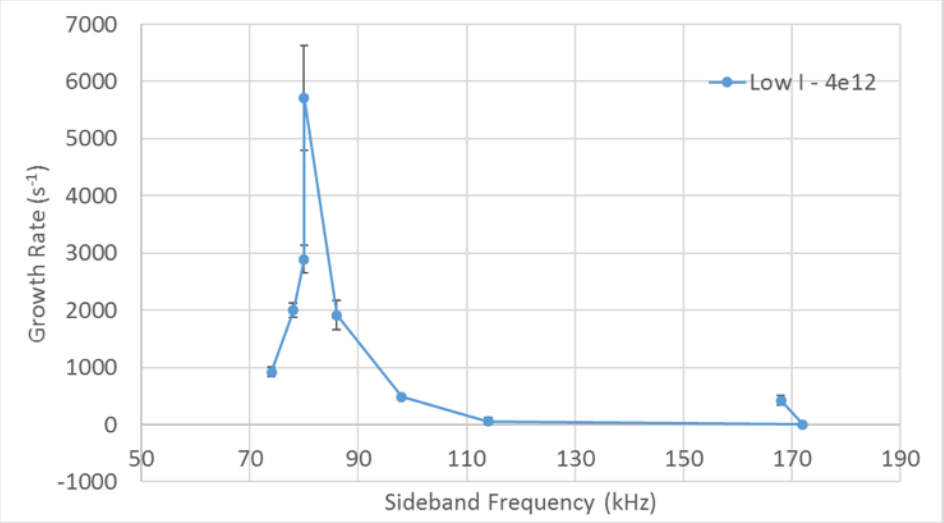
Experimental Campaign

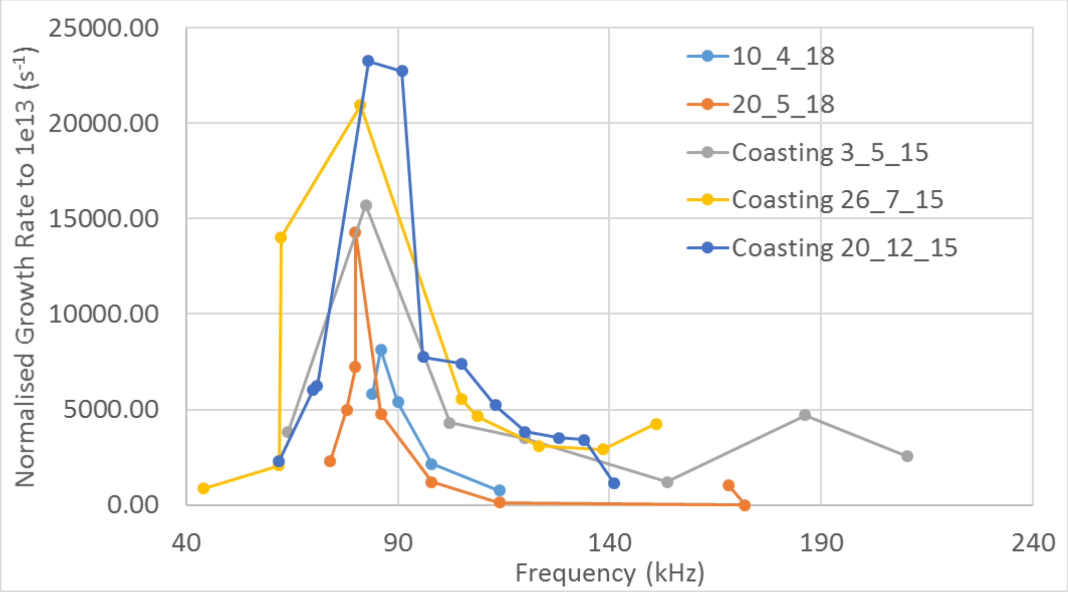
- Rapid Cycling mode
  - Observed in operation for many years
  - Mitigated by tune ramp away from Qv = 4, injection painting and longitudinal bunch asymmetry
  - Observed head-tail mode (m=1) lower than predicted from Sacherer (m=2)
- Storage ring mode (70 MeV)
  - Remove complexity of ramping frequencies, rapid bunch changes
  - Beam based impedance measurements
  - Measurements made with single harmonic RF (h = 2, 4) and dual

Bunched Storage Ring: Low Intensity, Qv Scan

- Growth rate peaks at set Qv = 3.81
- Baseband frequency of 80 kHz
- Growth also seen at other sidebands around RF frequency harmonics
- Matches data from other experiments



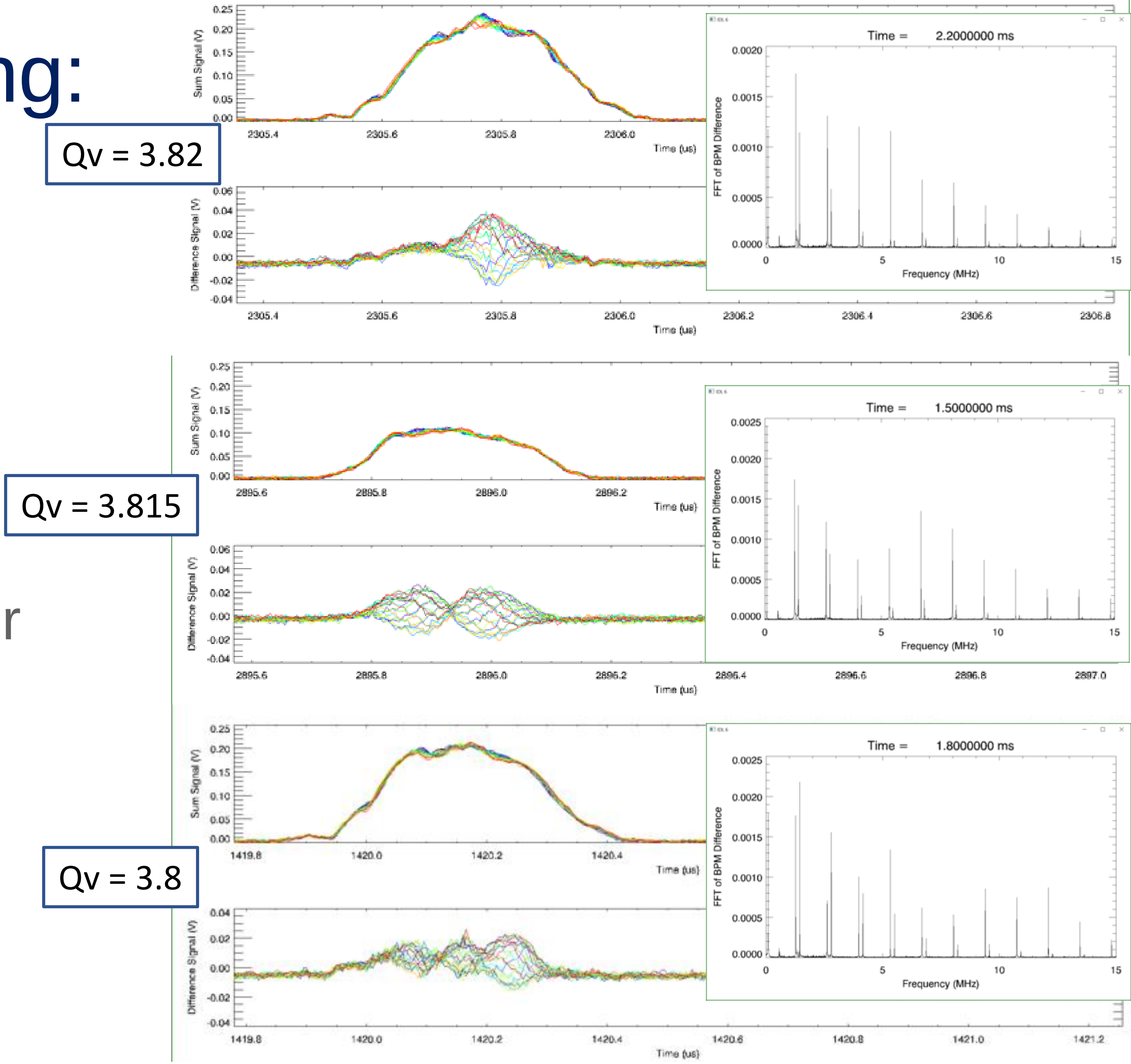




Rob Williamson

Bunched Storage Ring: Mode Structure

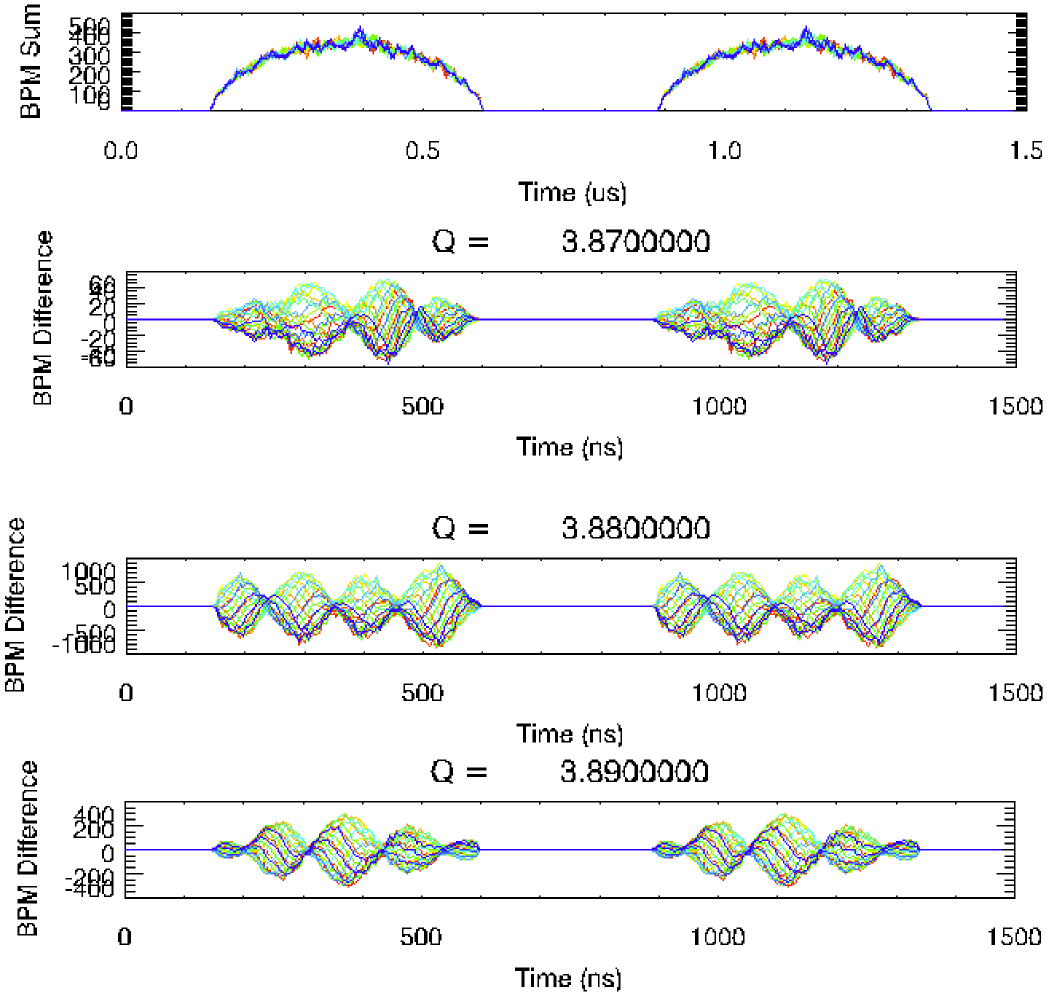
- Not consistent
- Small change of Qv alters mode structure
- Modes 0, 1 and 2 observed (mode 3 or 4 expected)
- Growth rates higher for lower order modes
- Only portion of bunch oscillating



Rob Williamson

PyHEADTAIL simulations

- Bunched storage ring mode
- Idealised distributions
- 80 kHz narrowband to match observed growth rate vs tune
- Mode m=3 and 4 observed as predicted from theory
- Entire bunch length oscillates as expected
- More physics required to match experimental observations



Rob Williamson

Summary

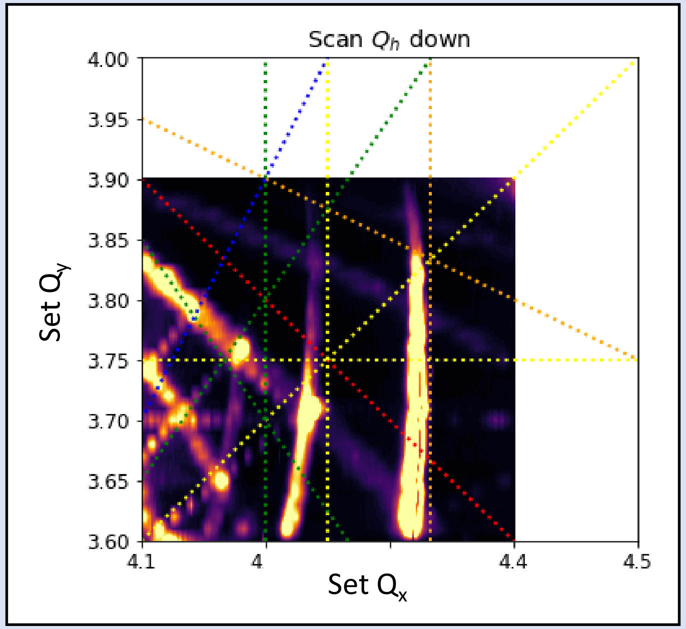
- Vertical head-tail observed in ISIS operation
- Mode unexpected and less than the full bunch oscillating
- Lower intensity, single harmonic data in bunched storage ring mode (70 MeV) shows:
  - Mode number change with small change in Q
  - Instability only over a fraction of the bunch
- Simulations with low frequency narrowband and idealised distributions match theory not observations

Future Work

- Simulations using in-house code and PyHEADTAIL
  - Narrowband + resistive wall
  - Effect of space charge (frozen, PIC)
  - Effect of injection dynamics
- Impedance measurements (beam-based and bench) and simulations
- Further comparison of simulation with theory/experiment
- Collaborative work with GSI and CERN on various aspects

Tune Plane Studies in the ISIS Synchrotron

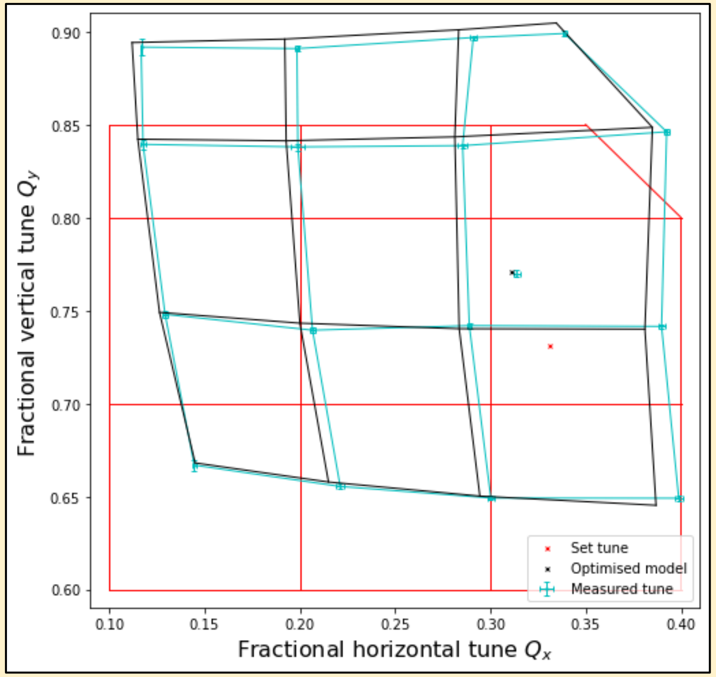
Understanding the importance of resonances for losses on a high intensity machine.

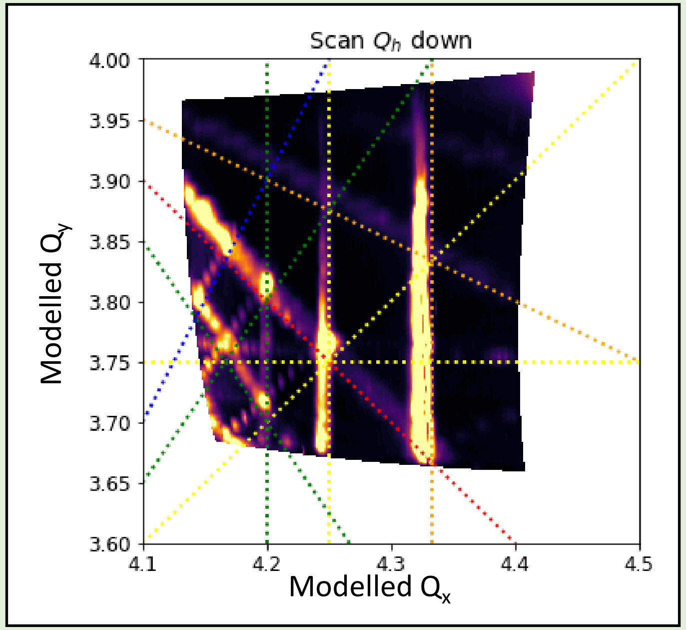


Tune scan experiments at ISIS measured beam loss in the ISIS synchrotron against transverse tune for a low intensity coasting beam.

Losses are associated with resonance lines, but they are curved and offset from predicted locations.

The tune controls were studied analytically. A new control method was derived from the linearised transfer matrix model of ISIS. The controls were tested by measuring tunes across a grid of settings. The model was optimised to give the best fit of the modelled tunes to the measured tunes.





Plotting the beam loss against the modelled tune transforms the plot to align the resonance lines with those predicted by theory.

Understanding how to control the transverse tunes is an important part of studying the mechanisms of beam loss in the tune plane.

Peter Griffin-Hicks

Resonances Observed

2nd order

$$Q_h + Q_v = 8$$

3rd order

$$3Q_h = 13$$
$$-Q_h + 2Qv = 3$$
$$2Q_h - Q_v = 5$$
$$Q_h + 2Q_v = 12$$
$$2Q_h + Q_v = 12$$

4th order

$$4Q_h = 17$$
$$4Q_v = 15$$
$$3Q_h - Q_v = 9$$
$$2Q_h - 2Q_v = 1$$

5th order

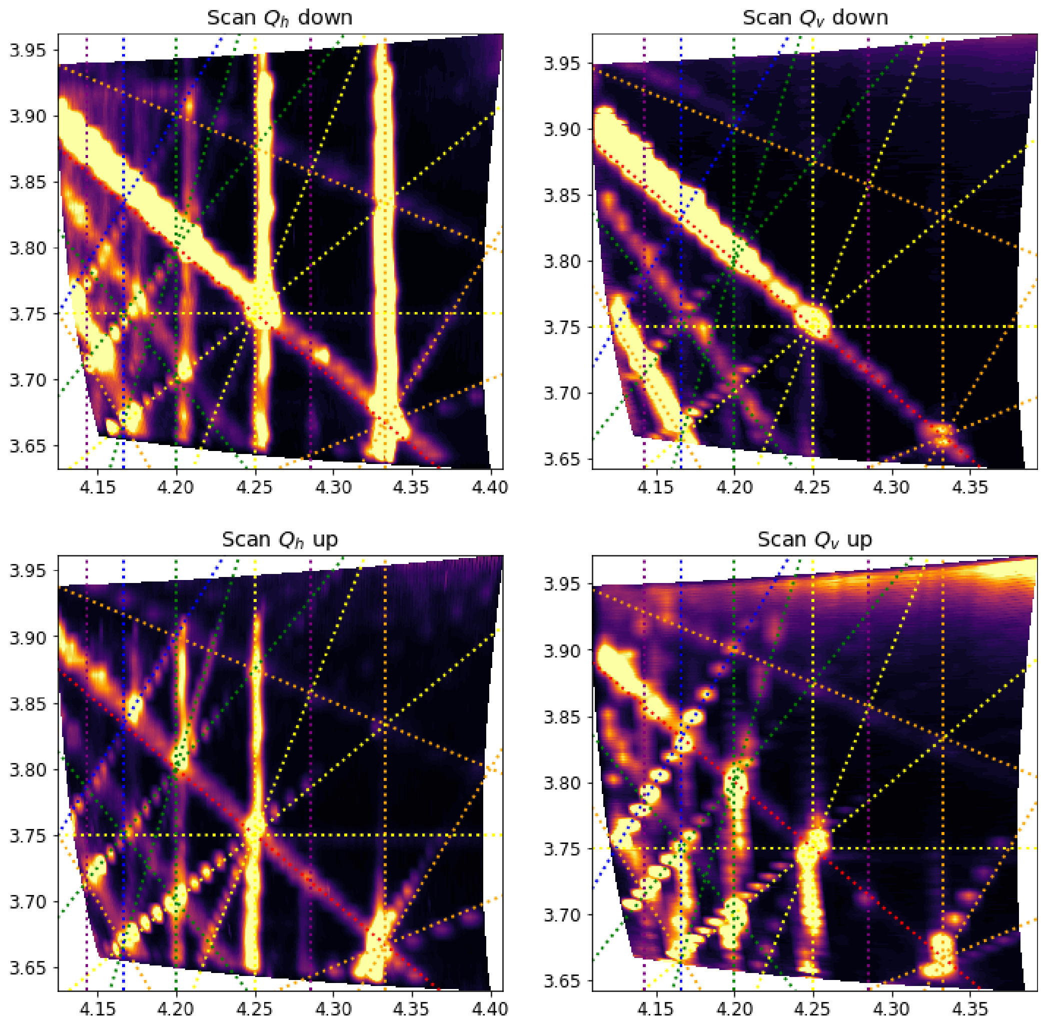
$$5Q_h = 21$$
$$4Q_h - Q_v = 13$$
$$3Q_h - 2Q_v = 5$$
$$3Q_h + 2Q_v = 20$$

6th order

$$6Q_h = 25$$
$$4Q_h - 2Q_v = 9$$

7th order

$$7Q_h = 29$$
$$7Q_h = 30$$



Order:

2nd

3rd

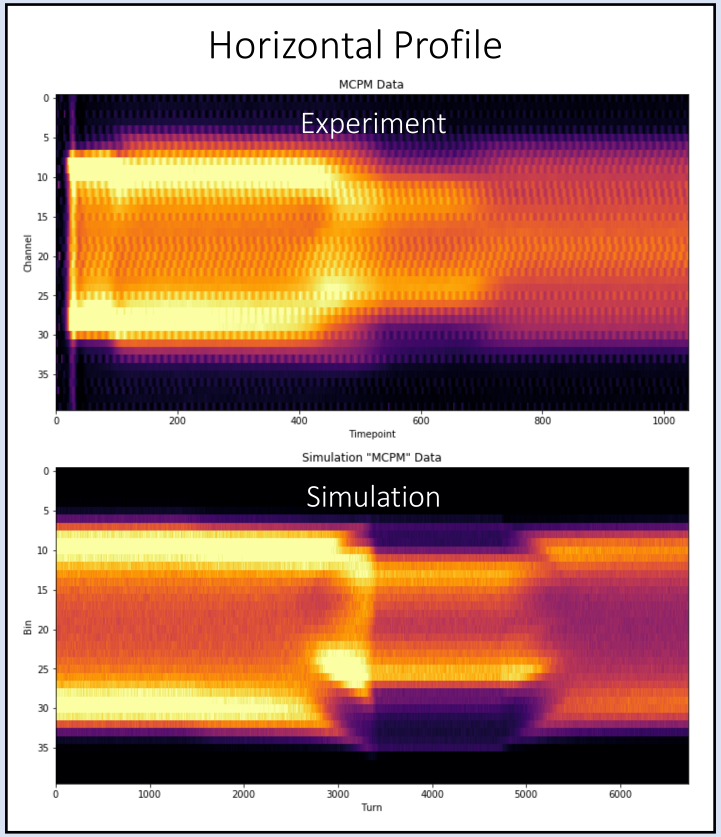
4th

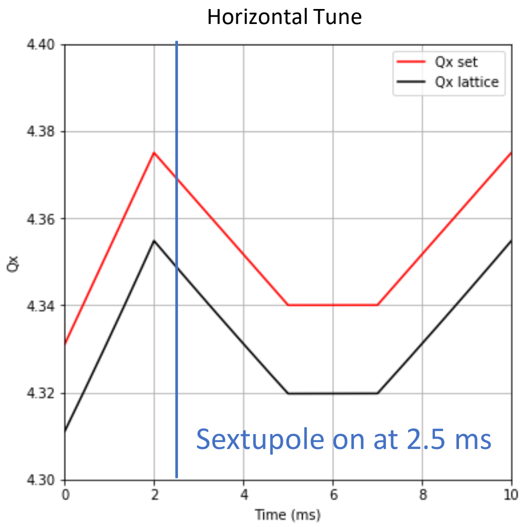
5th

6th

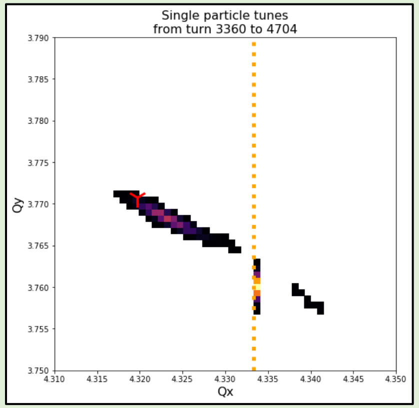
7th

A 2D single-particle tracking program with distributed non-linear kicks was written to study resonances in ISIS. The optimised model was used to simulate an experiment in which a third integer resonance line was driven by a single sextupole.

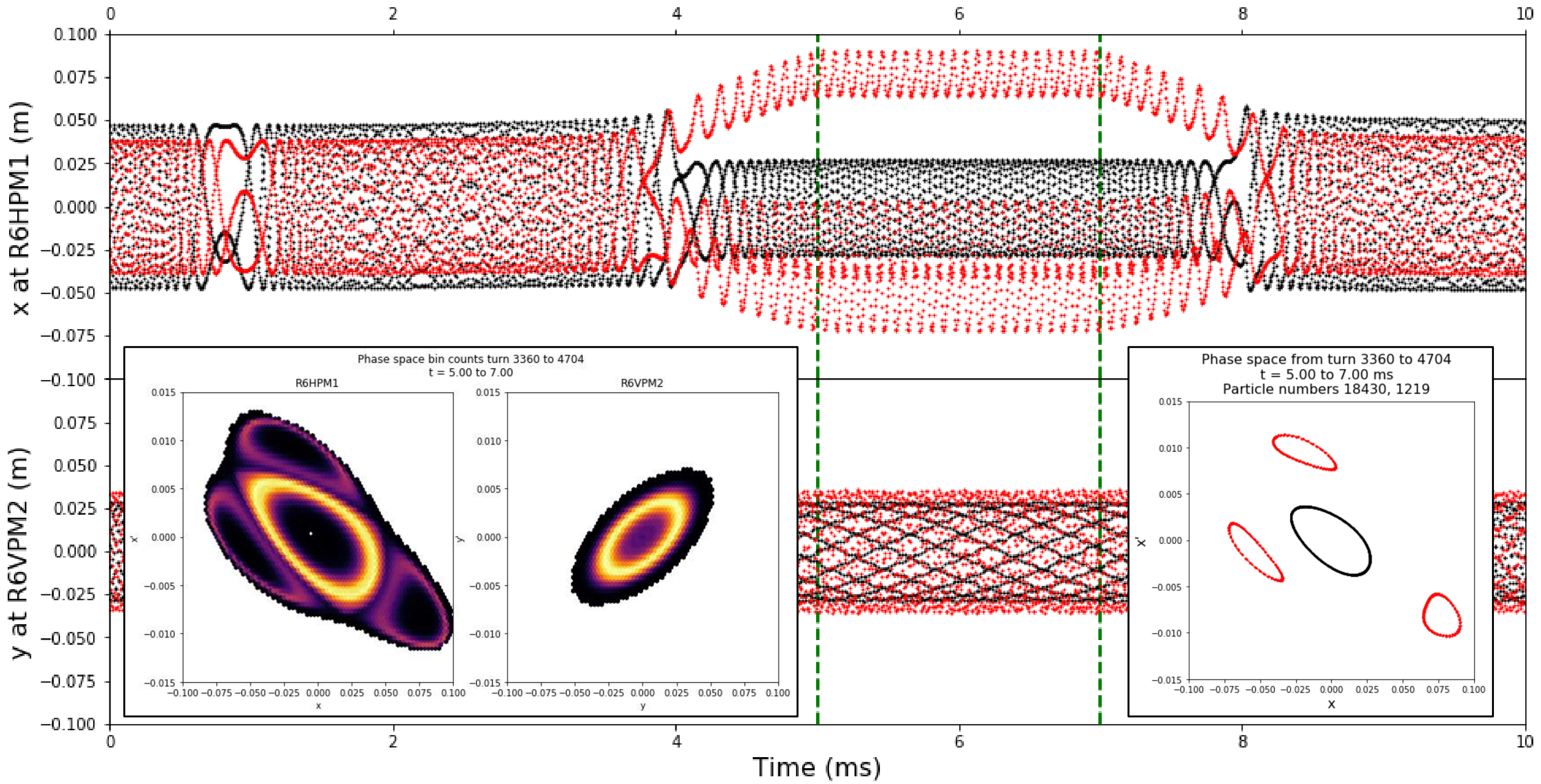




Analysis of the motion of particles in the simulation shows the formation of stable islands in phase space, associated with the third integer resonance.



Non-linear single particle simulation
Particle numbers 18430, 1219

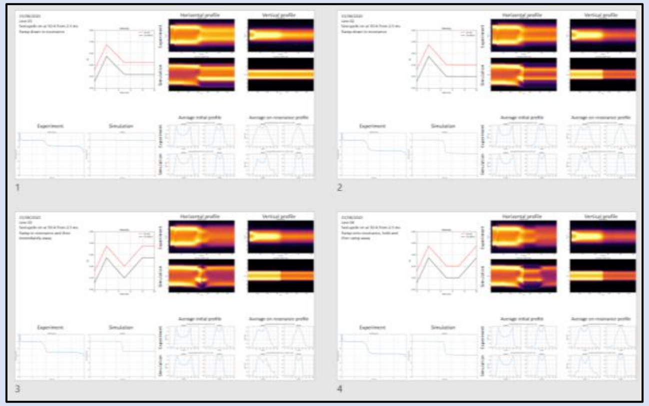


Peter Griffin-Hicks

Future Work

Low intensity

- Carry out improved tune control experiments.
- Develop single particle tracking program, check key parameters. Check against other experiments.



- Conduct detailed experiments to assess the third integer resonance.
- Investigate potential for third order non-linear correction schemes.

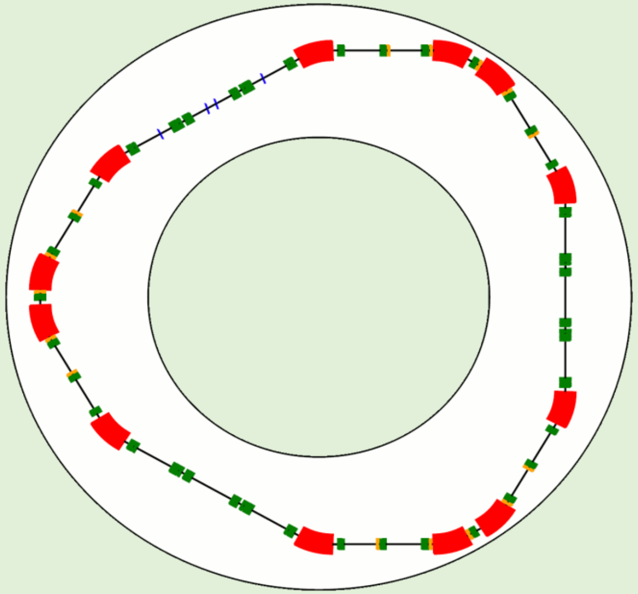
High intensity

- Increase intensity to observe space charge effects.
- Use simulation tools to model space charge in ISIS.
- Study bunched beams where synchrotron motion varies the incoherent space charge tune shift of particles in the longitudinal tails.
- Study efficacy of single-particle non-linear correction systems for high-intensity beams.

[e.g. F. Asvesta et. al., "*Identification and characterization of high order incoherent space charge driven structure resonances in the CERN Proton Synchrotron*", PHYS. REV. ACCEL. BEAMS 23, 091001 (2020)]

ISIS-II

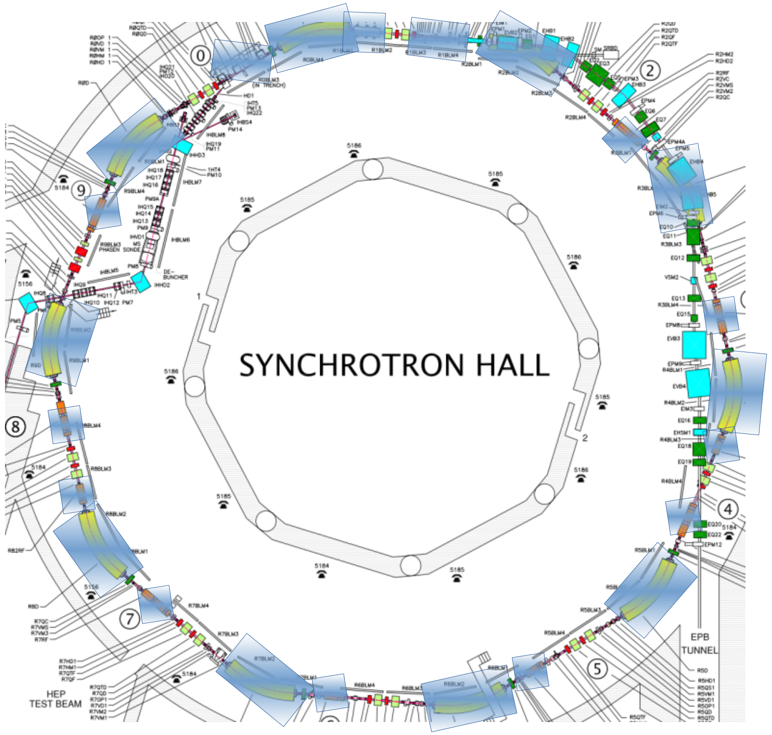
- Study resonances for single particle and high intensity dynamics in ISIS-II designs.
- Develop non-linear error corrections schemes.



Impedance Characterisation at ISIS

David Posthuma de Boer

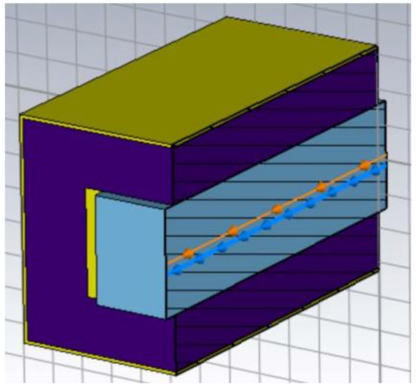
- ISIS suffers from a vertical head-tail instability whose primary cause is a transverse dipolar impedance.
- My aim is to characterise the transverse dipolar impedance of ISIS, identify the source of this impedance and ideally resolve it whilst also investigating associated instability.
- Previous measurements suggest there is a significant low frequency, narrow band impedance. The focus is thus low frequency.
- Estimates for a number of pieces of equipment highlighted on image have been obtained from theory, numerical methods and experiment (highlighted).
  - For theoretical estimates I have developed a field matching code for obtaining the transverse impedance of multi-layer cylindrical structures

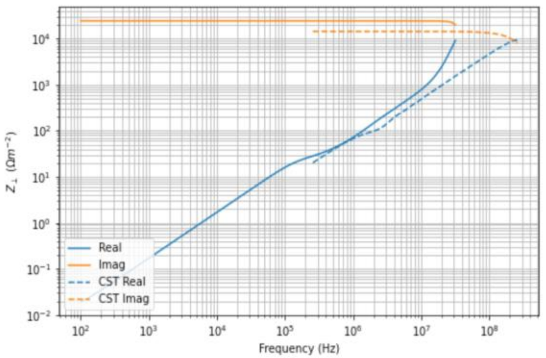


David Posthuma de Boer

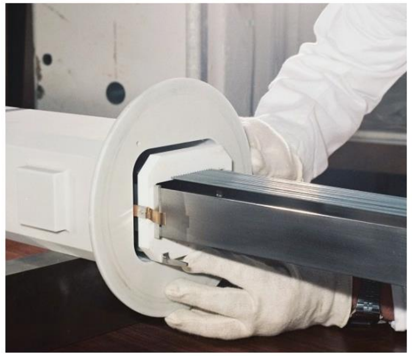
Estimates so far (1/2)

- Horizontal injection kicker magnet with thick ferrite.

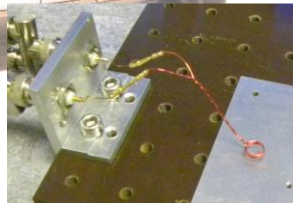


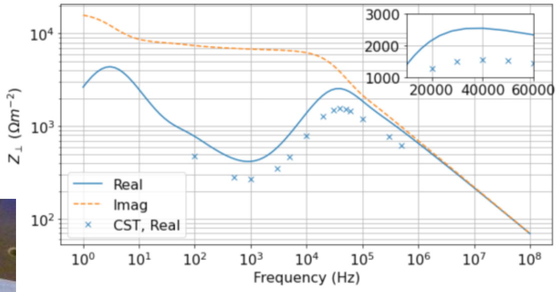


- RF Shields in ISIS dipole magnets.
  - Low frequency transverse impedance derived for cylindrical geometry.



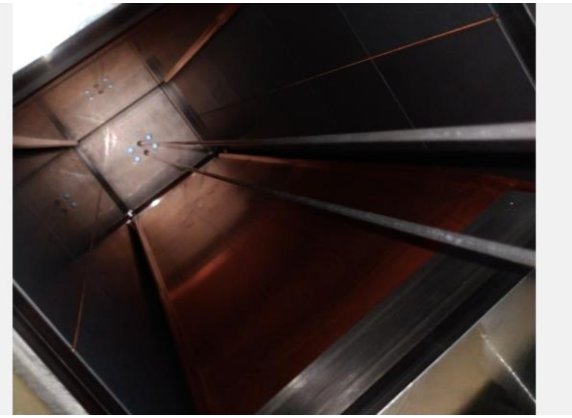
- Collectors
  - Eddy current probes for conductivity measurement.
  - Eddy current probes also used to investigate metamaterials: https://www.nature.com/articles/s41598-020-76447-x

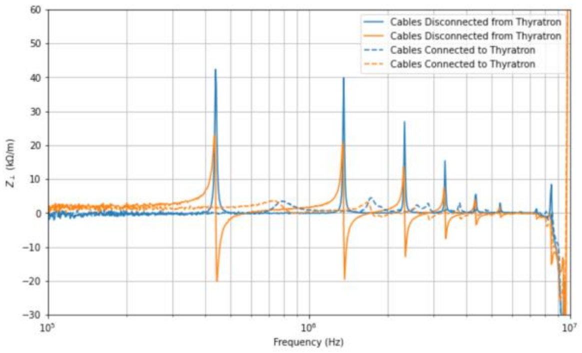




Estimates so far (2/2)

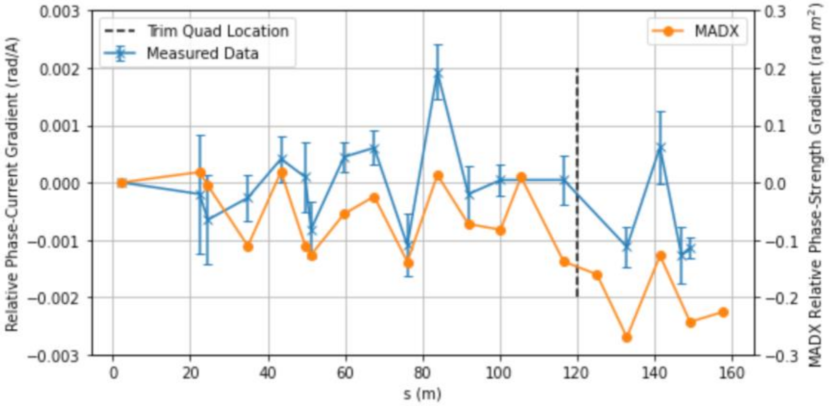
- Vertical extract kickers.
  - Only measurement so far.
  - Investigated impact of termination resistors at power supply.





Other Work

- Early attempts at impedance localisation measurements using the beam and a kicker.
  - Try to identify local changes to betatron phase shifts with intensity.
  - Tests carried out using quadrupole magnets.



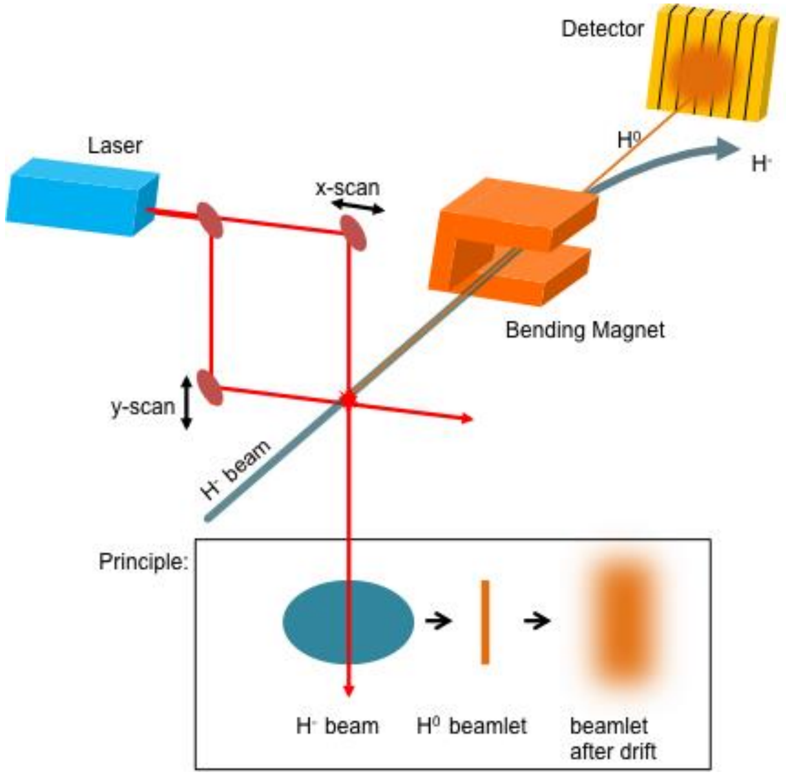
Future Work

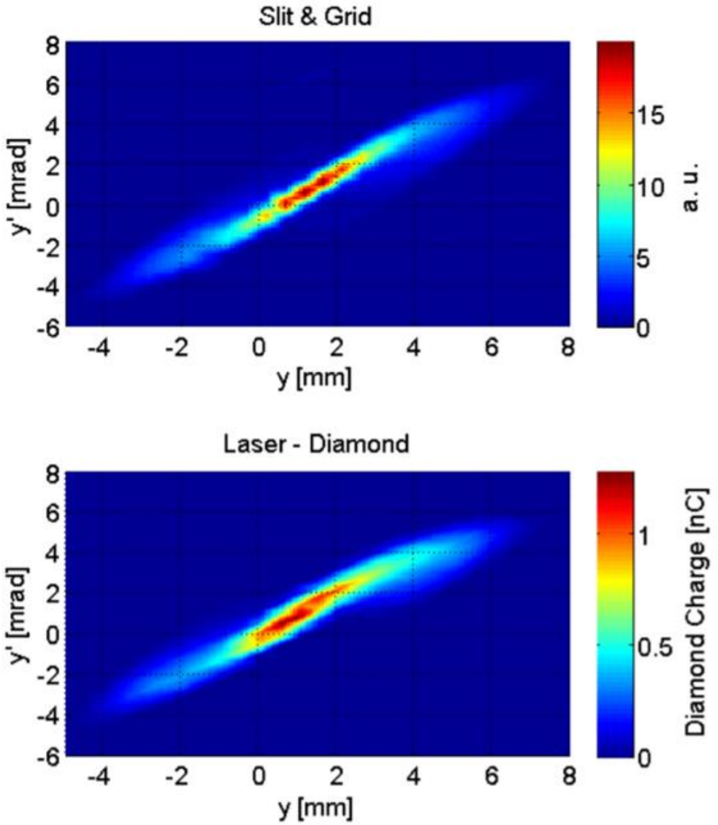
- Find remaining resistive type impedances for elements around the ring and make refinements where possible.
  - RF shields in quadrupoles
  - Bypass capacitors in all RF shields.
  - Collector asymmetry
  - Possible measurements for RF Cavities
- CST simulations or alternative predictions for other structures
  - BPMs
  - Kicker simulations
- Beam Based measurements
  - Continue attempts for impedance localisation measurements, and perform simulations.
  - More sophisticated method of finding location of impedances.

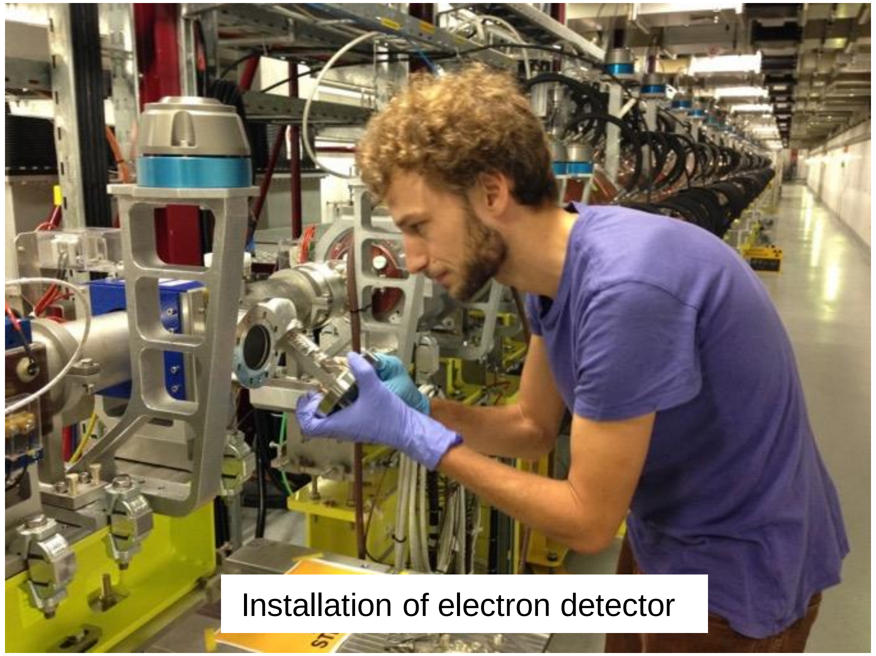
H^- laserwire prototype

T. Hofmann et al

- ***New instrument to measure the transverse emittance has been demonstrated with RHUL-CERN built prototypes in recent years:***
  - Thomas Hofmann's thesis, July 2017: https://cds.cern.ch/record/2282569/







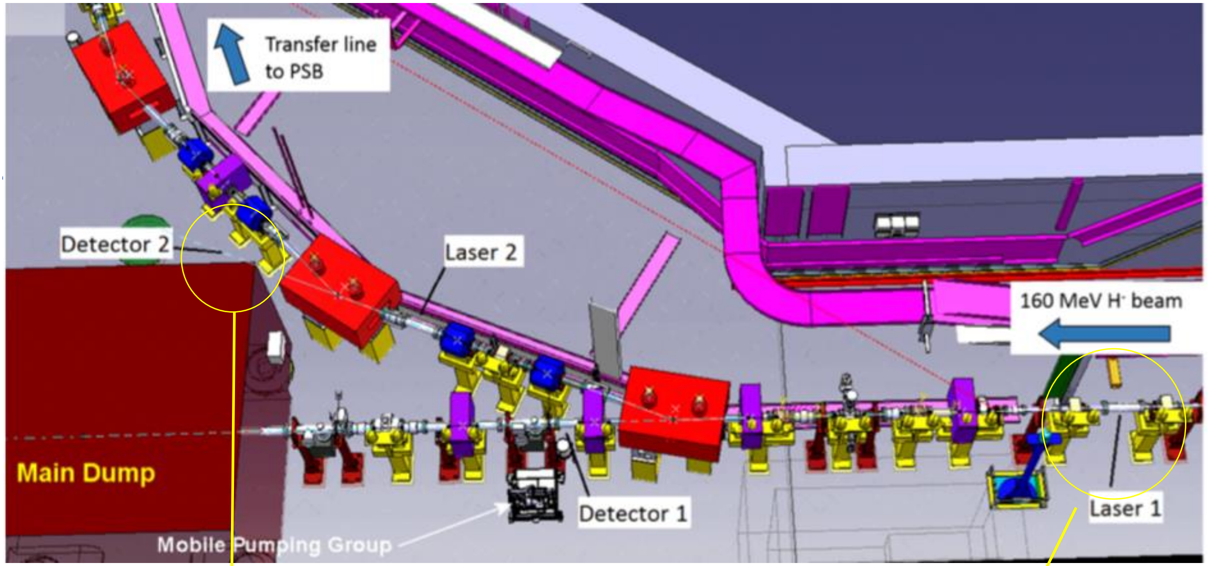
Installation of electron detector

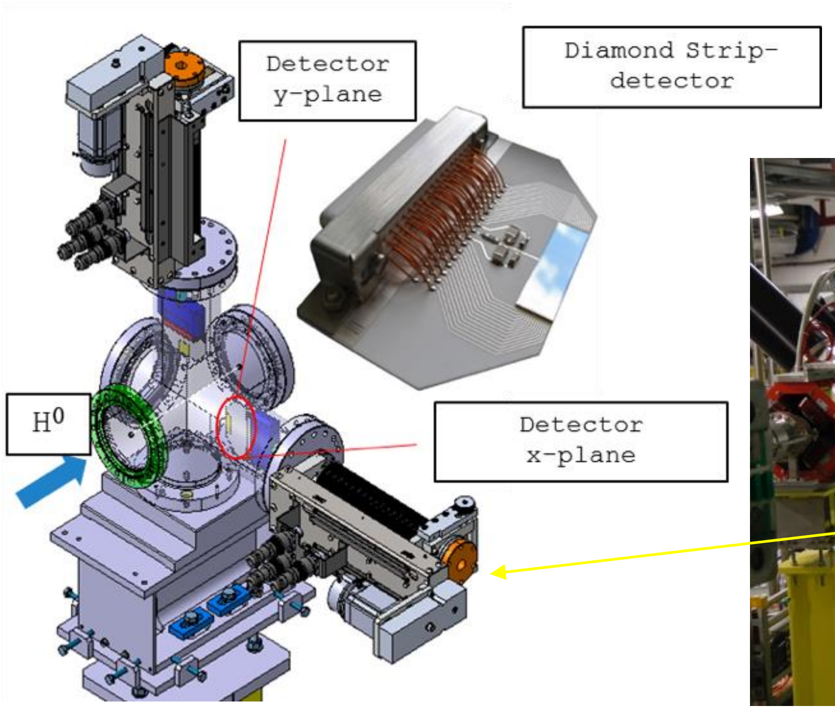
S. Gibson

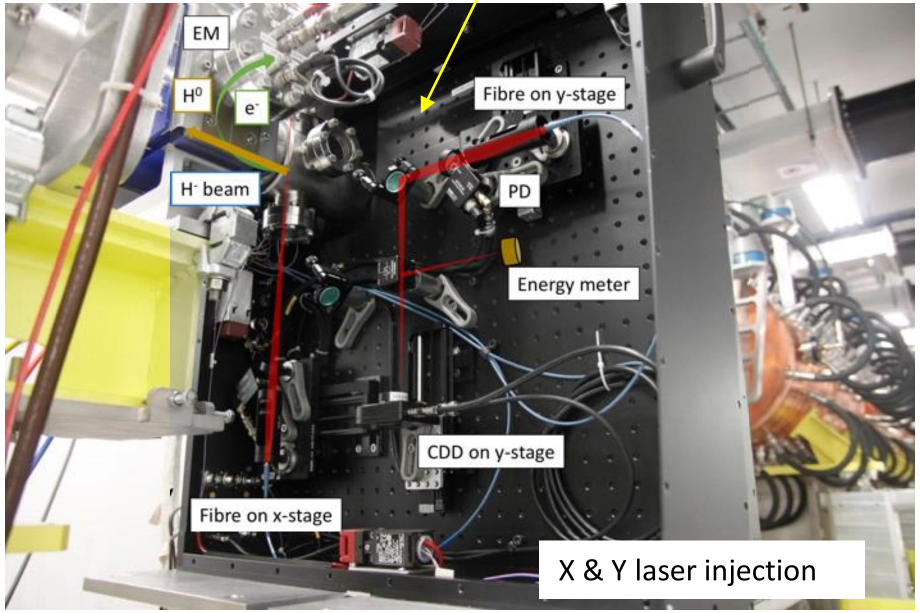
Dual laserwire installed at Linac4

T. Hofmann et al

- ***Non-interceptive emittance monitor***
  - *4 laserwires: in X and Y at two locations*
  - *Commissioned in 2018 at 160 MeV*
  - *Multi-channel diamond strip-detector*







S. Gibson

Dual laserwire commissioning results

T. Hofmann, G.E. Boorman, A. Bosco, S.M. Gibson, A. Goldblatt, F. Roncarolo

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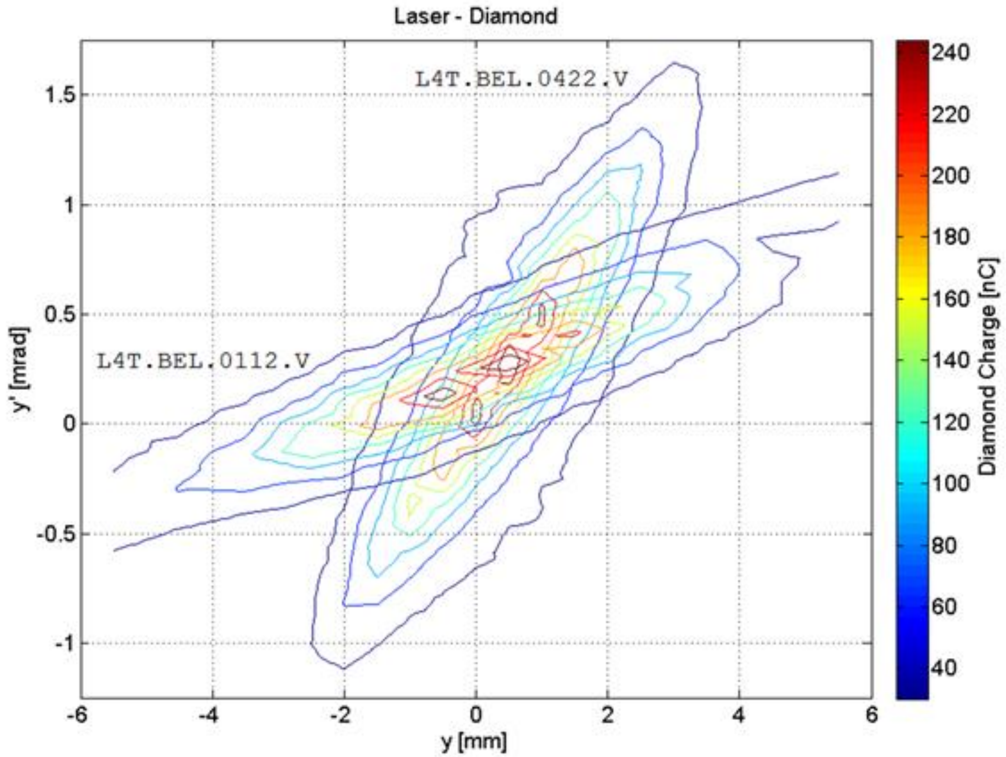
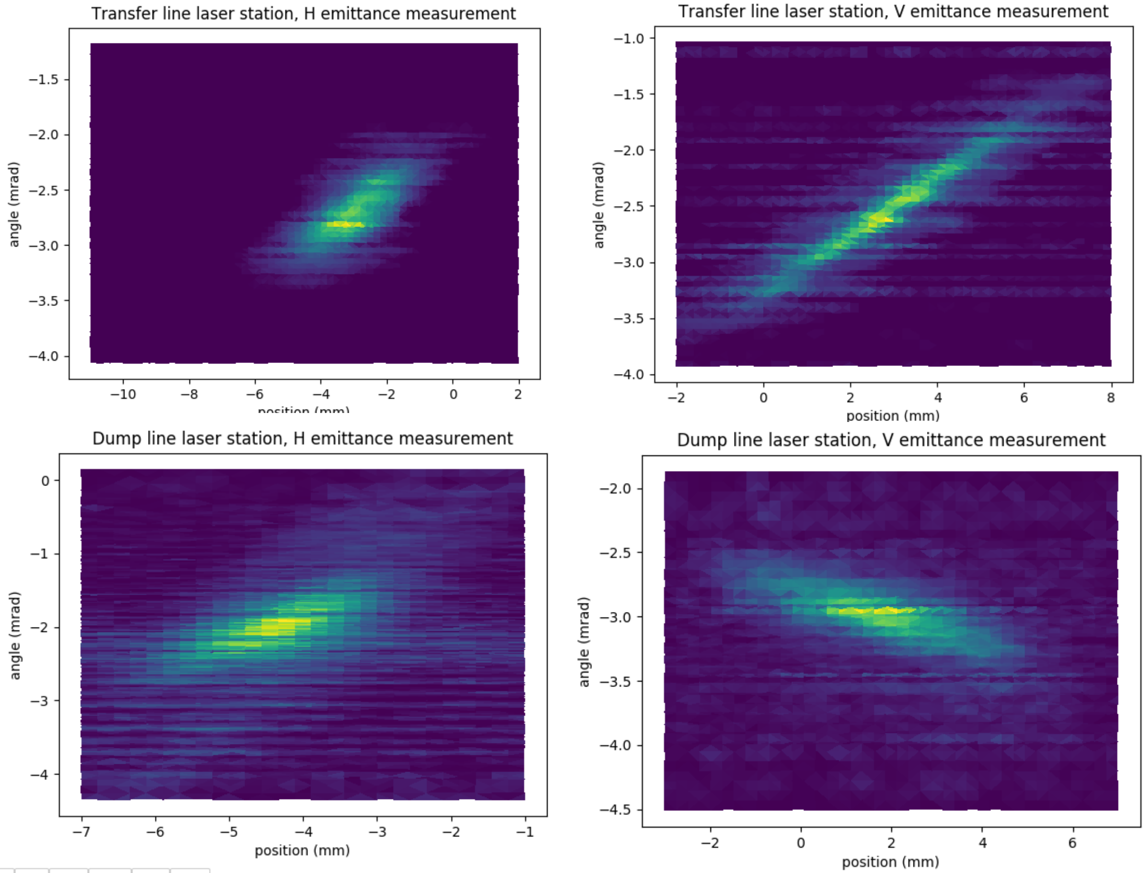
- ***Laserwire Emittance Monitor***
  - *First results showing vertical emittance for two different settings of the line.*



2018 measurements at 160 MeV

- ***Latest data with 4 diamond detectors fully operational:*** *horizontal and vertical emittance reconstruction from both stations:*



T. Hofmann et al ,'Commissioning of the operational laser emittance monitors for Linac4 at CERN', WEPAL074, IPAC 2018.

Front End Test Stand: overview

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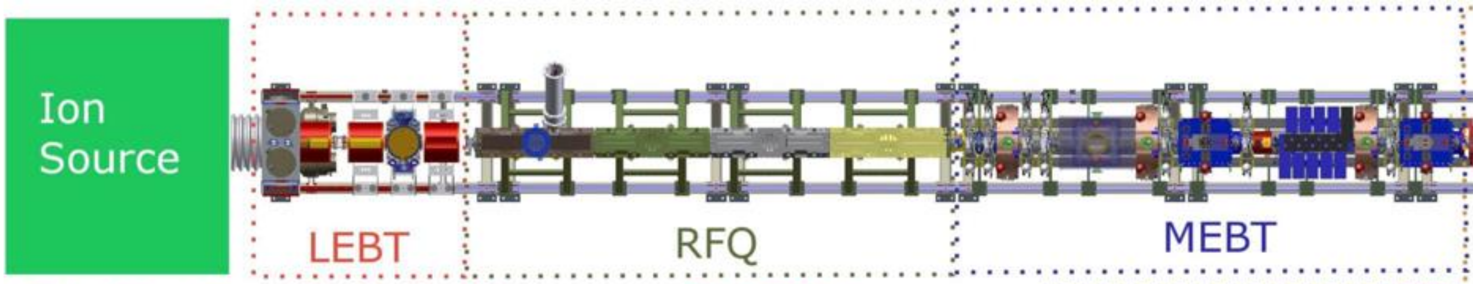
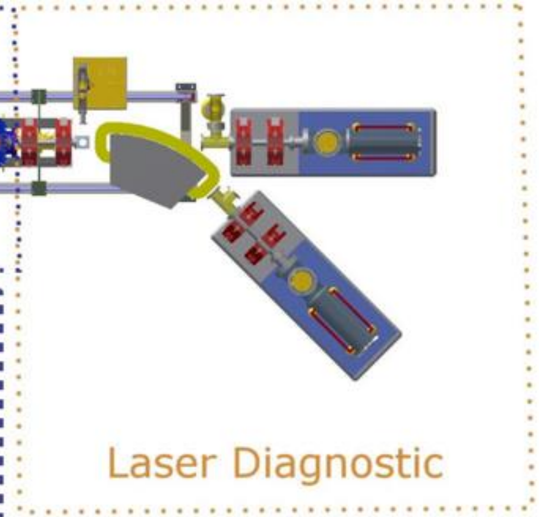
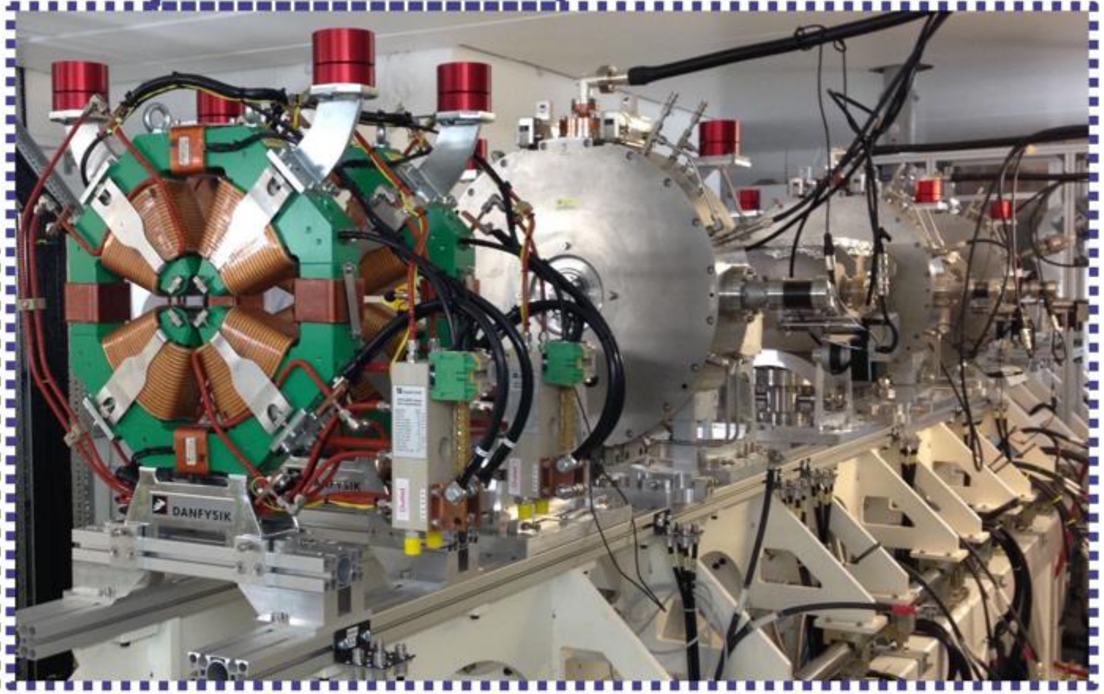




65 keV, 60 mA, 2ms H⁻ source & LEBT

MEBT: 3 rebunching cavities, choppers & small bore quads

324 MHz 4-vane bolted RFQ: 3 MeV



S. Gibson

Front End Test Stand: manufacture at RHUL & RAL

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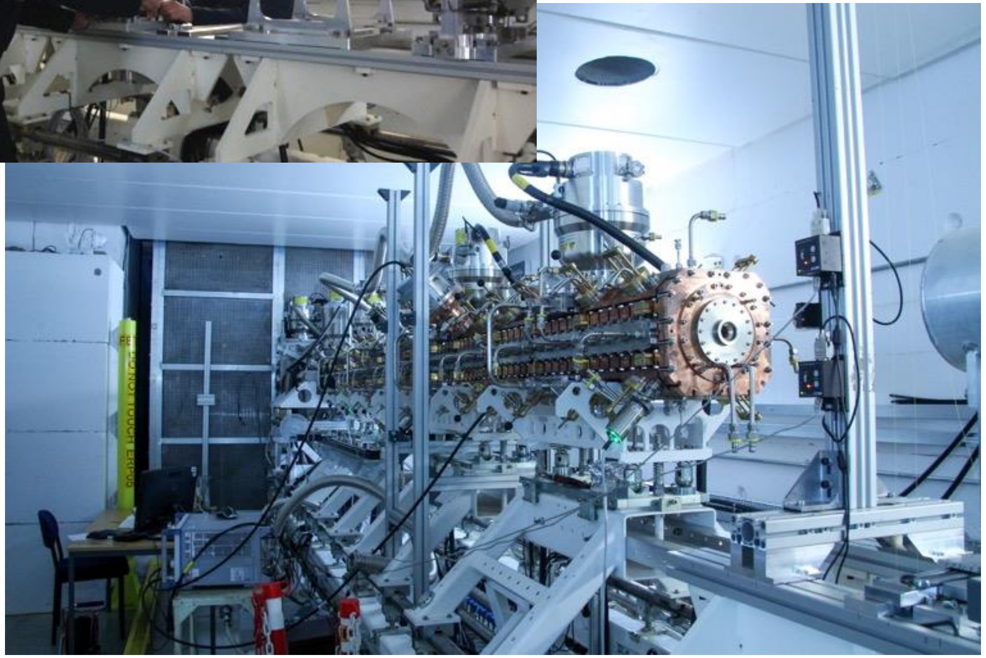
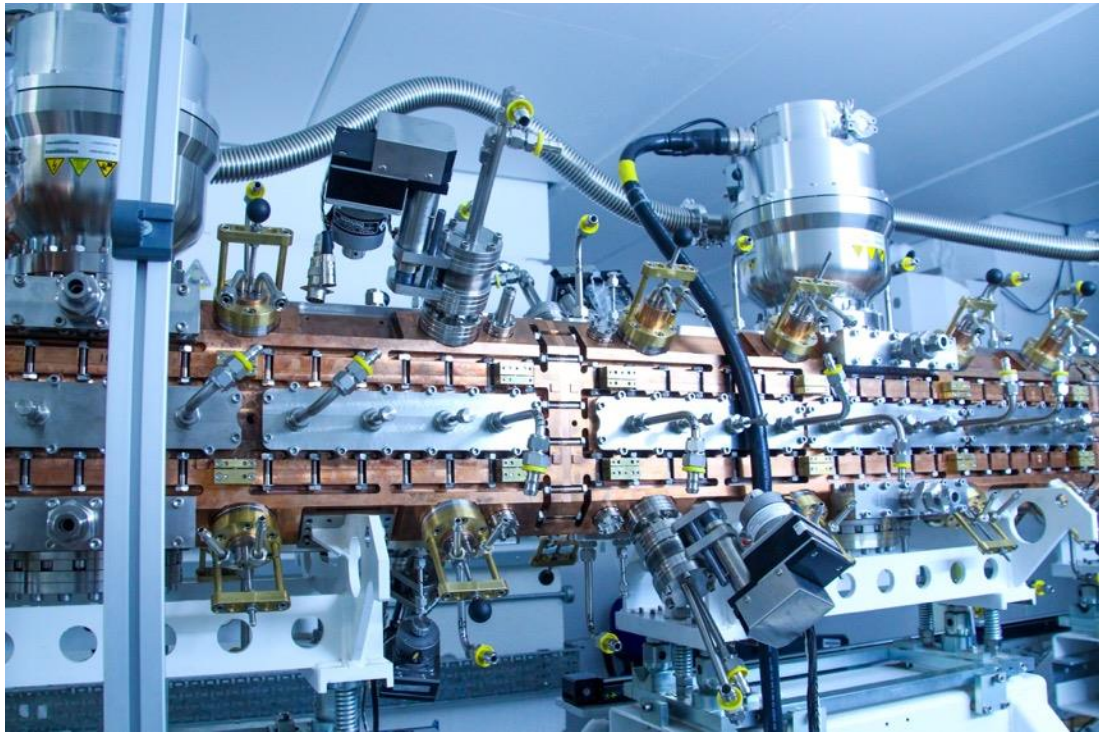
- *FETS is a 3MeV H- front end test stand for the ISIS-2 upgrade.*
- *Many RFQ and chopper components manufactured at RHUL, and assembly at RAL supported by JAI-RHUL technical staff.*
- *Successful RFQ bead-pull and field flattening:*
- *4-vane bolted RFQ assembly now complete, ready for beam.*



S. Gibson

Front End Test Stand: laserwire

S. Alden, A. Bosco, S. Gibson et al

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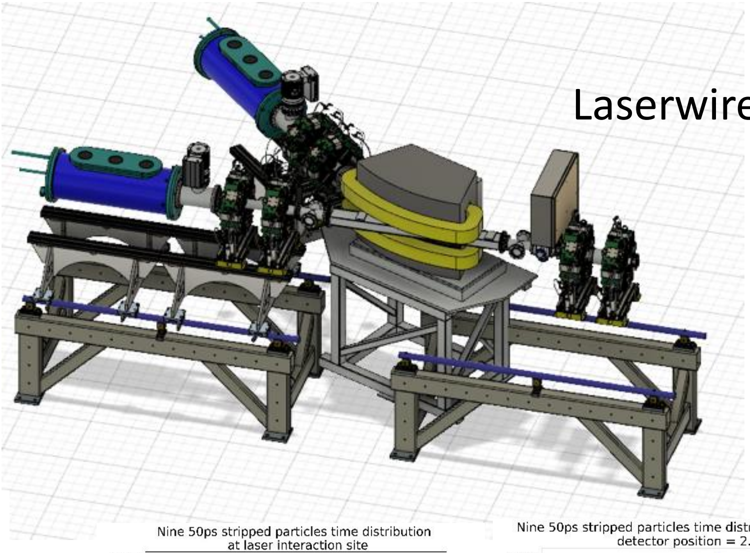
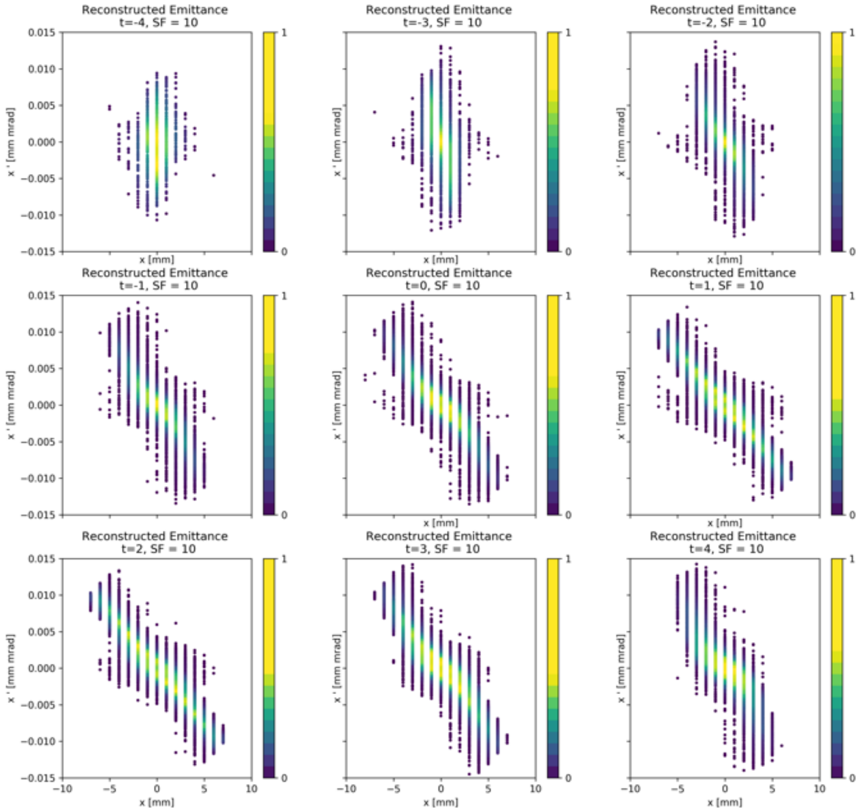
- ***Laserwire diagnostic simulations developed to inform layout of interaction region and detector placement:***
  - ***Transverse laserwire for beam profile emittance***
  - ***Longitudinal laserwire for 6D parameter space:***

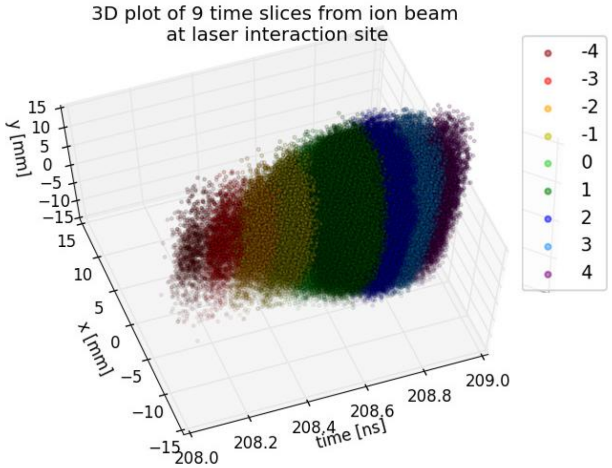


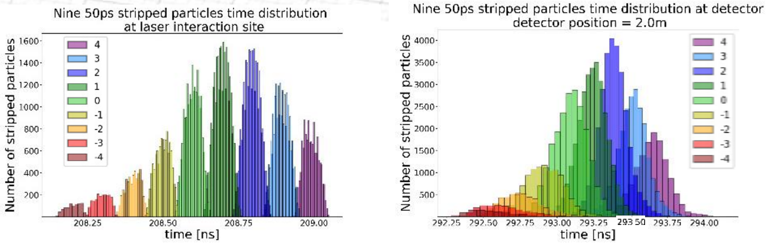
Laserwire at FETS

Time-sliced transverse emittance

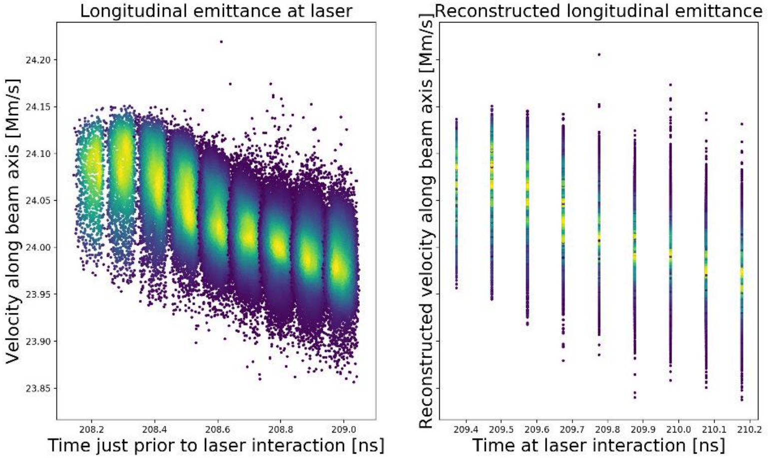


Time-sliced FETS bunch using fast pulsed laser





Longitudinal emittance:



S. Gibson et al, "A novel longitudinal laserwire to non-invasively measure 6D bunch parameters at high current hydrogen ion accelerators" IPAC18

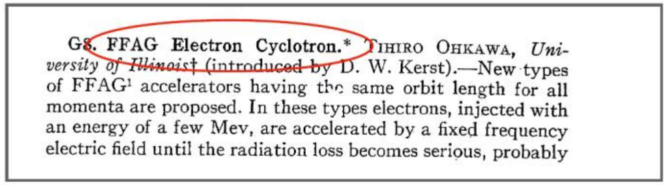
VFFA

From S. Machida at FFA2020

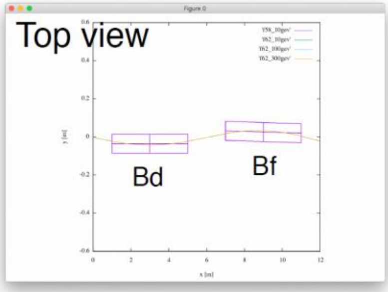
Vertical excursion FFA (vFFA)

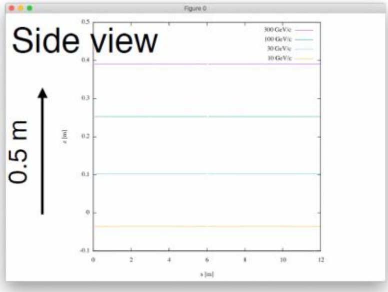
- Invented in 1955 by Tihiro Ohkawa.
- Re-invented in 2013 by Stephen Brooks.
- Orbit moves vertically when the beams are accelerated.
- Path length is constant for all the momenta. Momentum compaction factor is zero.
- It was called electron cyclotron
  - Ultra-relativistic particles can be accelerated continuously with fixed field magnets.

- As a proton driver for spallation source
  - High rep rate
  - Small footprint
  - Simple rectangular magnet


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

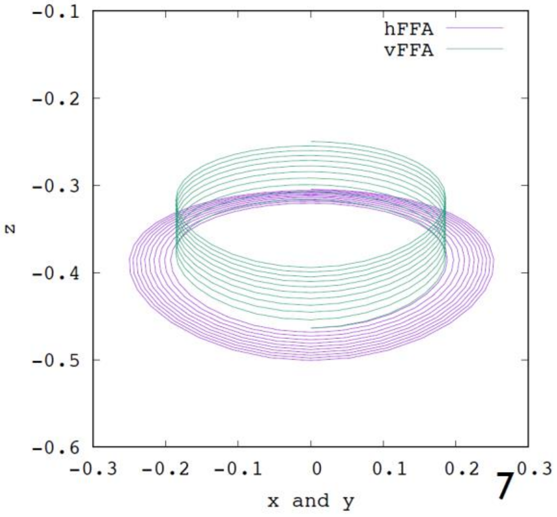
Bull. APS 30, 20 (1955)
by Tihiro Ohkawa





$$B = B_0 \exp(my)$$

m : field index
y : vertical



Science and Technology Facilities Council

Important aspects:

- Coupled optics (difficult to model)
- Vertical orbit excursion (implications for the beam diagnostics)
- Candidate for ISIS-II and technology demonstrator using FETS (FET-FFA)

Analytical Approaches to Beam Dynamics in VFFA

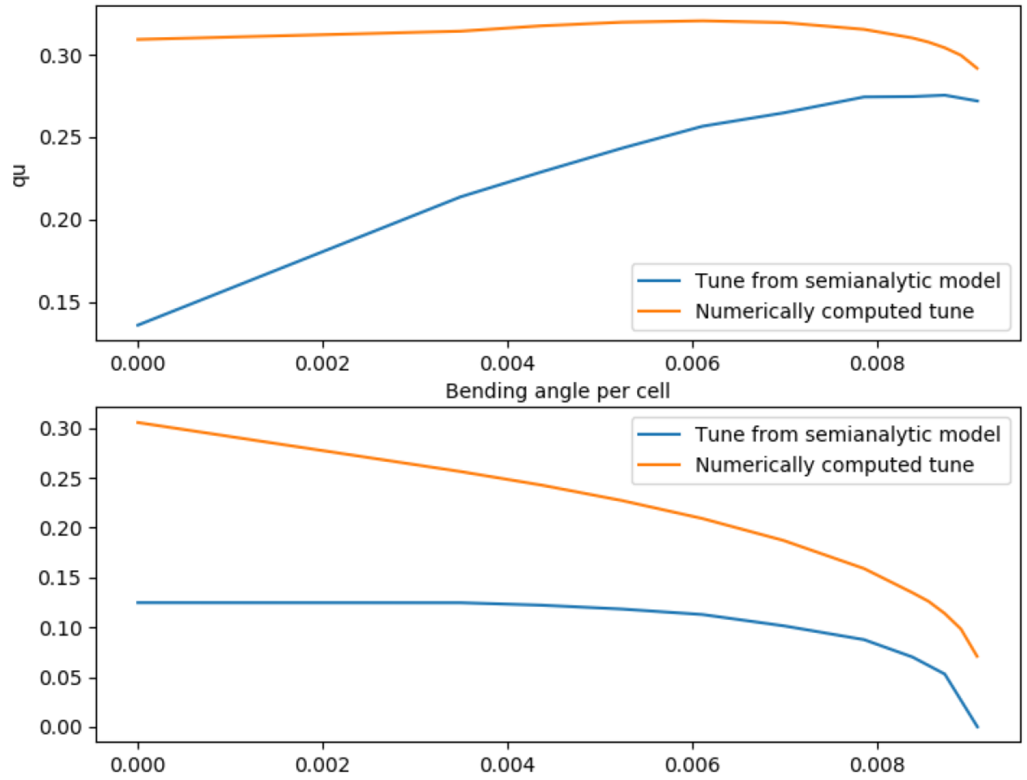
Motivations

- Current models rely on full simulation of machines
- Computationally intensive and time-consuming
- Has to be done for individual lattices
- Limited understanding of how input parameters affect output parameters

Need to develop an analytic approach!

Analytic approach – preliminary results

Max Topp-Mugglestone

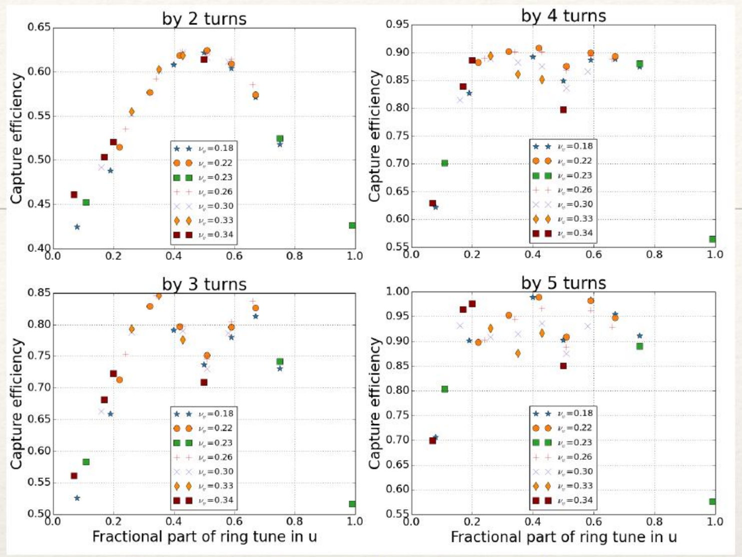


- Test lattice: large VFFA ring (a la muon collider)
  - Small curvature
  - Long magnets relative to fringe
- Model tested via numerical integration of analytic equations of motion

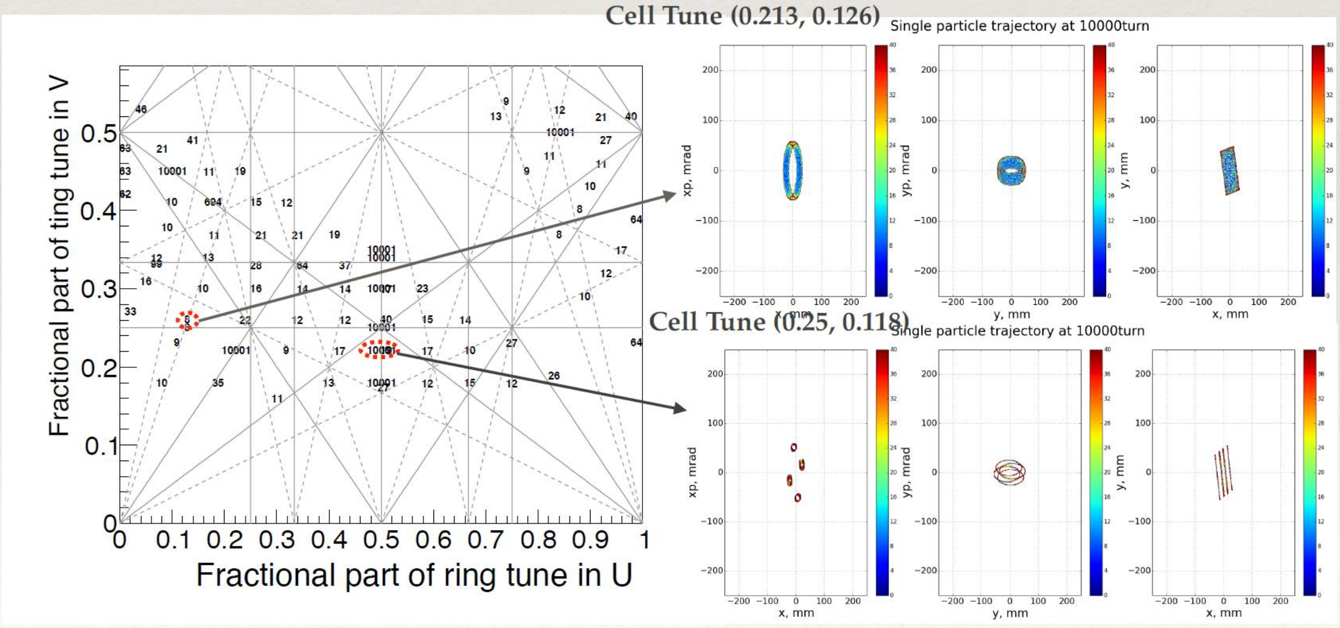
Agreement is currently poor! This shows the need for further work in understanding the nature of the VFFA, and emphasises the need for development of a bespoke model

Collimator Study Updates
understanding capture efficiency

- Focus on capturing Halo particles generated during beam injection scheme in FETS-FFA.
- Owing to transverse coupling between horizontal and vertical planes, a collimator placed in one plane captures halo particles in both planes.
- Capture efficiency was computed by different fractional part of ring tune. In this study, I-shape collimator is located in x plane.
- In short time scale (within 5 turns), the capture efficiency has a strong trend in *u* tune variation as the collimator is located on x plane in this study. Coupling angle does not affect capture speed/strength.
- In long time scale, required turn number to capture all halo particles is also relating to *u* tune. When the fractional part of ring tune in *u* space is fixed on the resonant conditions, the amplitude of particles are limited in between islands. In this case, one place collimator cannot capture particles which amplitude is smaller than the collimator aperture.
- From these studies, the capture efficiency can be optimised by turn control, that is similar approach to design synchrotron collimator. However, in vFFA, advantage of single I-shape collimator is that
    - halo particles are captured in x and y direction simultaneously
    - x sided I-shape collimator can collimate halo particles over the hole range of beam energy by stretching its vertical size.



Capture efficiency in short time scale

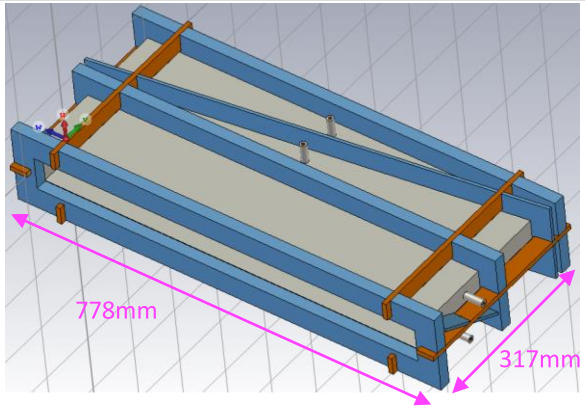


Turn number in long time scale

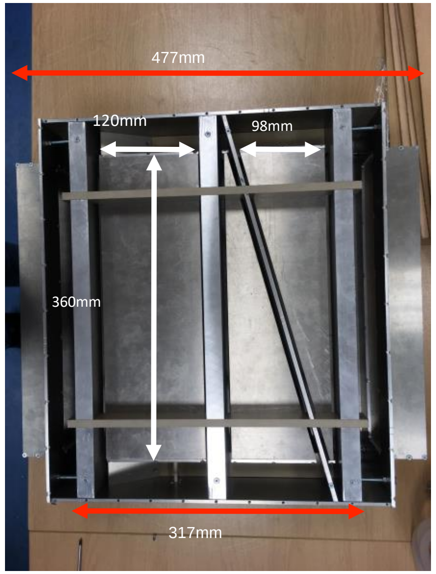
E. Yamakawa

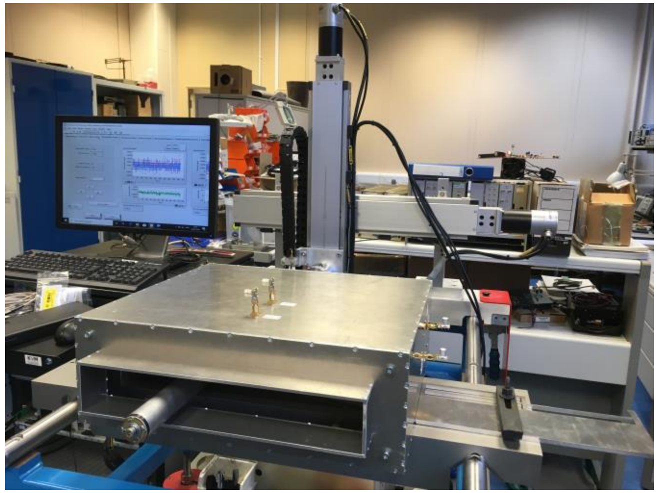
Beam Position Monitor

- High mechanical tolerances over the large electrode & body surface areas are needed to keep errors low over the vertical aperture.
- Prototype BPM, half the width of preliminary design, has been manufactured to verify the design simulations. This will be delivered at Kyoto University FFA ring (KURNS) in Japan for beam test this year.
- Preliminary design of FETS-FFA BPM will be improved by the test results of prototype BPM next year.



Preliminary design of FETS-FFA BPM, modelled in CST



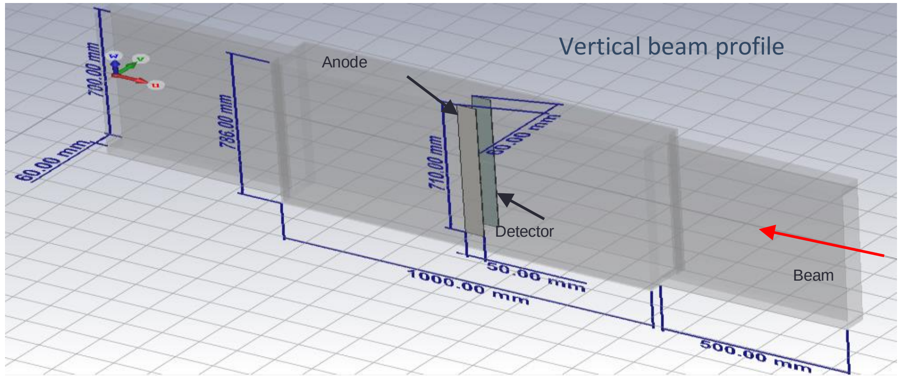


Half-size prototype BPM, tested in the diagnostics lab.

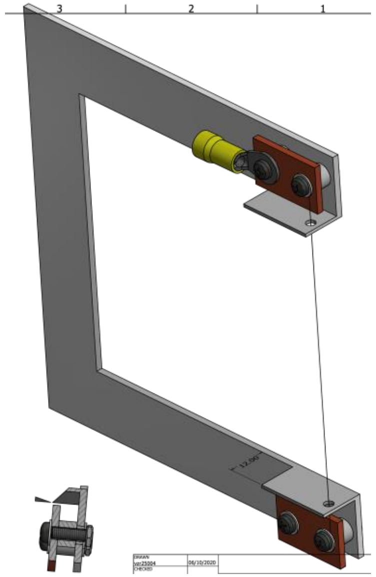
Emi Yamakawa

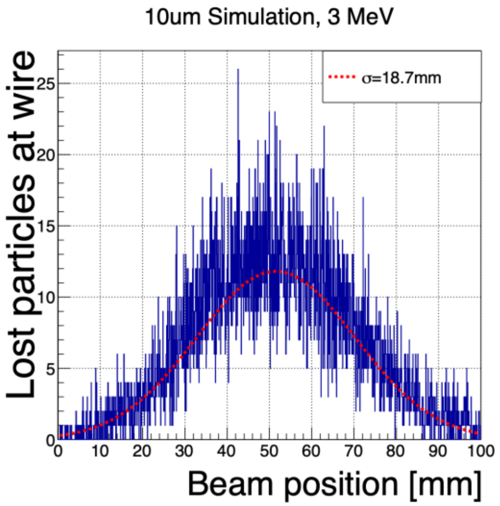
Beam Profile Monitor

- Ionisation Profile Monitor (IPM) has been designed as a non-destructive beam profile monitor.
  - Fundamental design study has been done in CST.
  - Further studies are necessary to verify reliability of the monitor.
- Wire Profile Monitor (WPM) has been also developed as a destructive beam profile monitor.
  - Wire position is fixed in the ring, as the beam will move across the wire in FFA.
  - Very thin wire (ϕ10um) is required to be able to measure a beam profile during acceleration.
  - Prototype WPM will be manufactured and delivered to KURNS for beam test this year.



Preliminary design of FETS-FFA IPM, modelled in CST



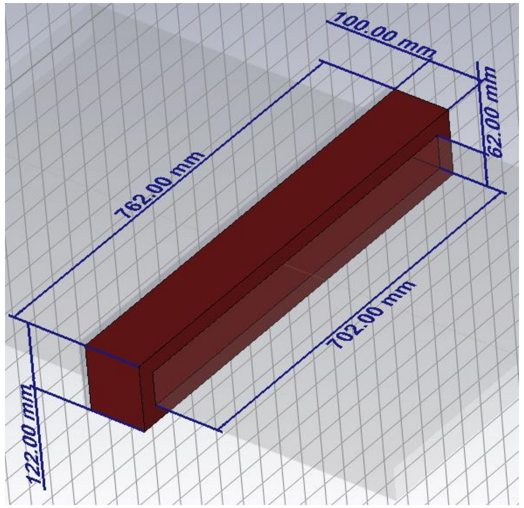


Prototype FFA WPM with ϕ10um CNT wire

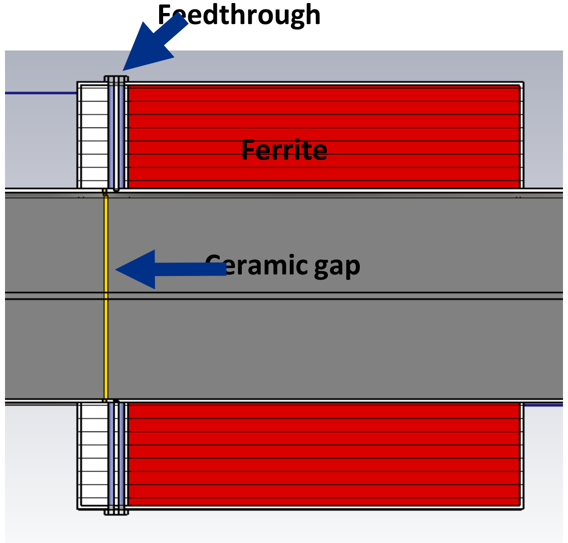
Emi Yamakawa

Beam Current Monitor

- Non-destructive Beam Current Monitor is required to be developed to measure the beam intensity in the ring.
  - Design study of Wall Current Monitor (WCM) has been started. Manufacture of a large permeability Ferrite core could be challenging.
  - Preliminary simulation suggests very weak measured signal strength due to size of beam aperture.
  - Prototype WCM is planed to be designed and manufactured to verify design simulations in a few years.
- DC Current Transformer (DCCT) is also required to be developed to measure a DC component of the beam.
  - Design study will start in a few years.



WCM Ferrite Core Shown in Red



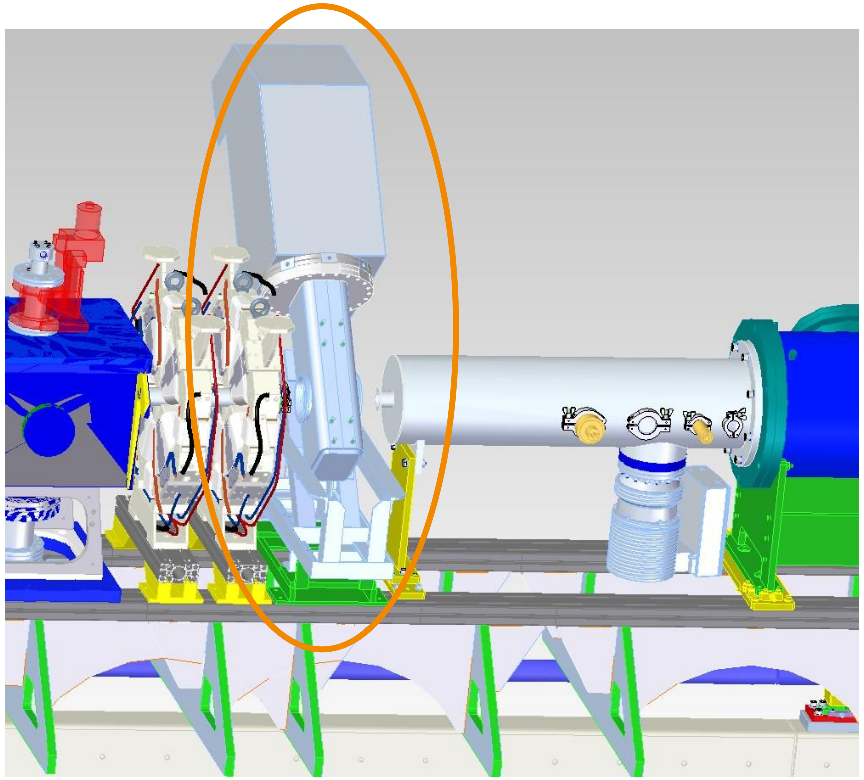
Cross Section View of FFA WCM

Preliminary design of FETS-FFA WCM

Emi Yamakawa

Material tests using FETS beam

- Set of tests are planned in FETS beam line once it is operational.
  - Prototype WPM will be installed in front of the FETS beam dump to test material properties (Thermal damage and Radiation damage) and performance when intercepting 3 MeV beam.
  - Scintillation screen materials (YAG crystal, P46 and quartz) are also tested to identify suitable materials with reasonable lifetimes while interacting with the beam.
- Beam Loss Monitors
  - Is it possible to measure a beam loss generated by a low energy and low current beam outside the beam pipe?
  - A stainless steel block will be installed into the path of the FETS beam to generate beam loss in a controlled way and test an ISIS ionisation BLM to see if the loss can be measured.



Preliminary design of WCM

FETS beam line

Emi Yamakawa

Testing Nonlinear Integrable Optics with IBEX

Jake Flowerdew

Nonlinear Integrable Optics

- Desirable to make an **integrable lattice** which is nonlinear.
  - ➢ **Supress instabilities** without reducing the dynamic aperture.

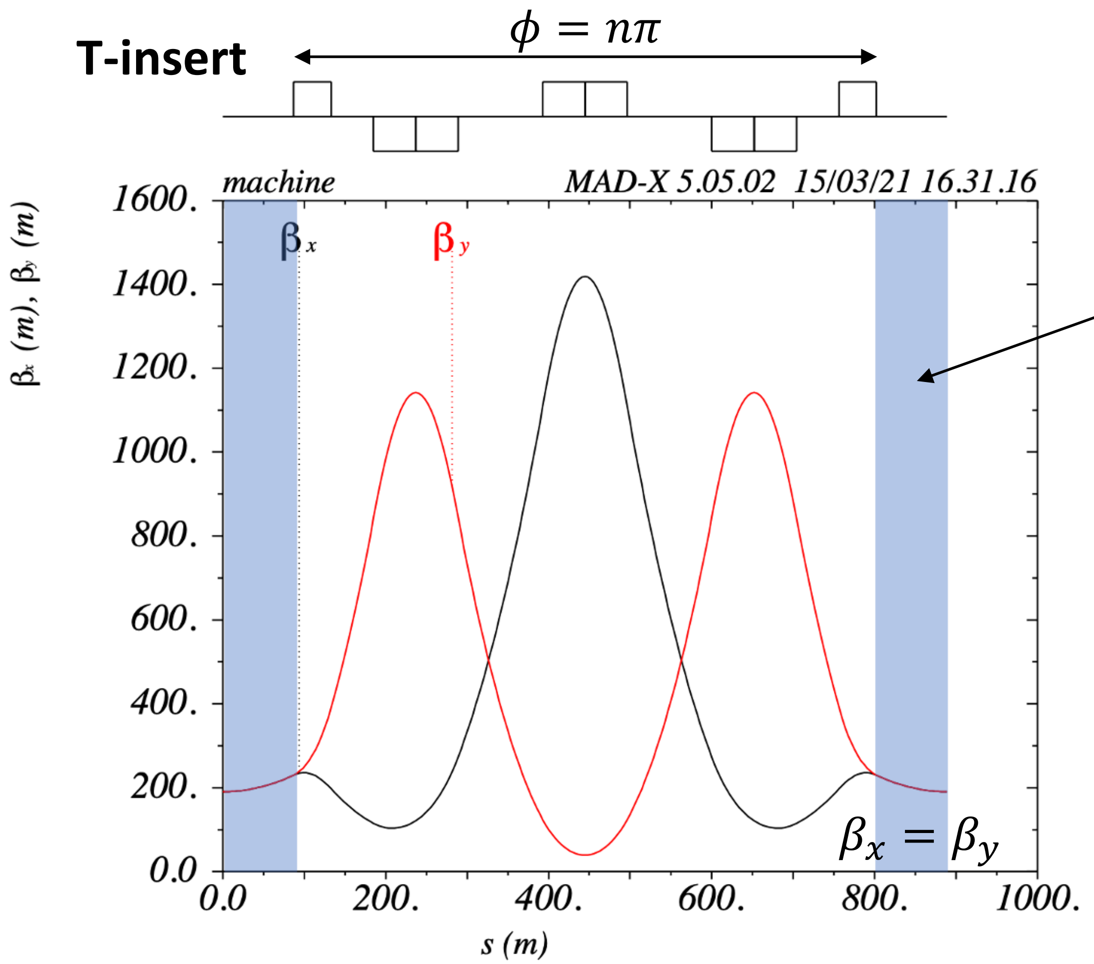
Remove time dependence from the Hamiltonian, making it an integral of the motion.

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N).$$

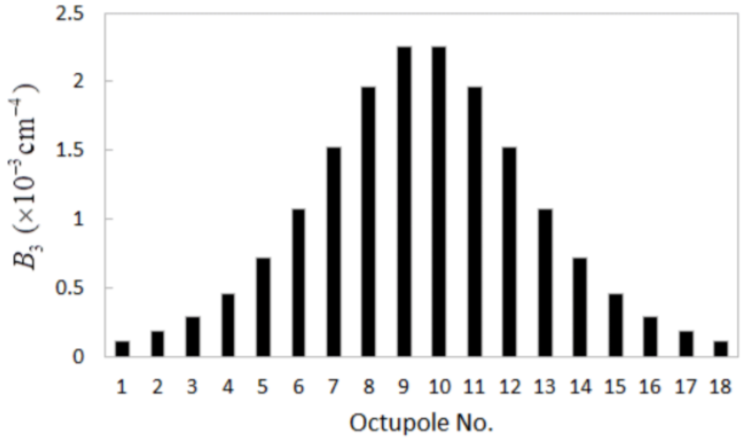
$$U(x,y) \approx \frac{t}{c^2} \operatorname{Im}\left((x+iy)^2 + \frac{2}{3c^2}(x+iy)^4 + \frac{8}{15c^4}(x+iy)^6 + \frac{16}{35c^6}(x+iy)^8 + \ldots \right)$$

- Complicated elliptical potential can be approximated as octupole (Quasi Integrable Optics)

Nonlinear Integrable Optics



Octupole strength scales with $1/\beta^3$



- Requires round beams and $n\pi$ phase advance.
- Octupole scaling with β makes it time independent.
- (Quasi-) Integrable lattice which is robust to small perturbations.

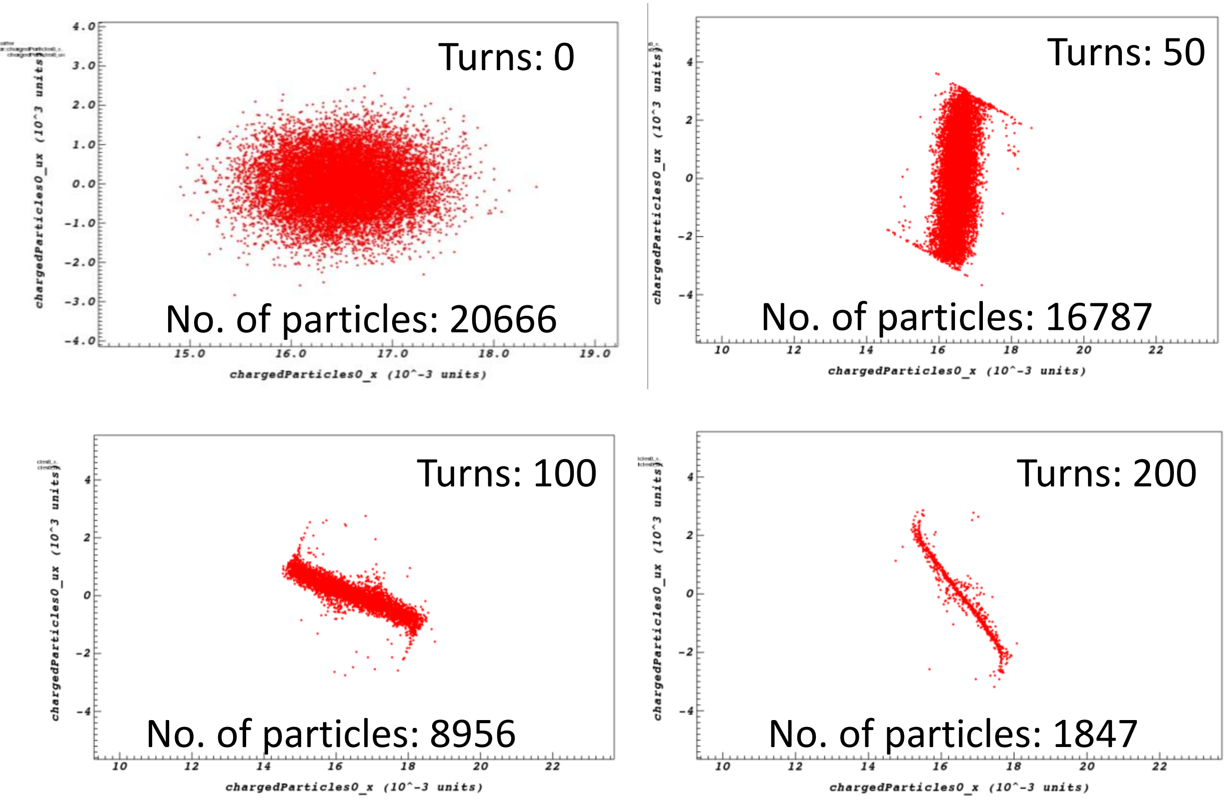
Jake Flowerdew

Why study accelerator physics in a Paul trap?

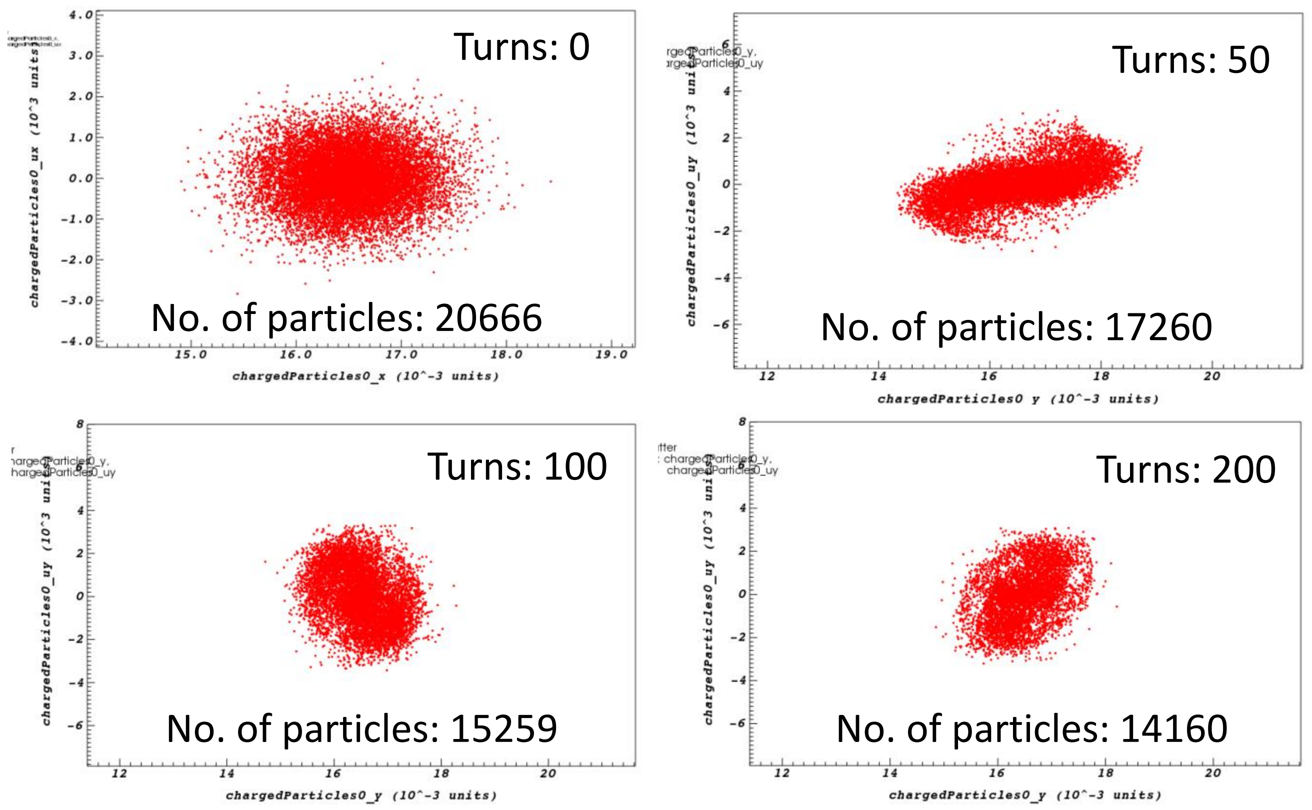
- **Cost effective** when compared to building an accelerator.
- **Dispersion-** and **chromaticity- free** environment.
- **Low energy** ions – will not damage components when lost.
- **Large parameter space:**
  - Can create various different lattice types.
  - Can easily change the number of particles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

Jake Flowerdew

Testing QIO with IBEX

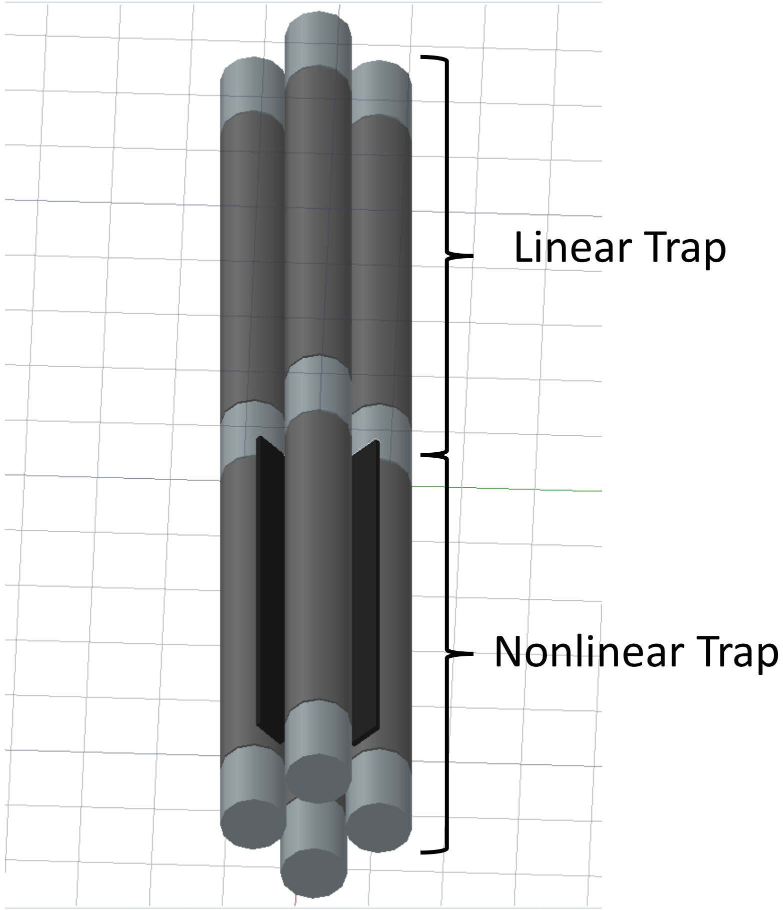


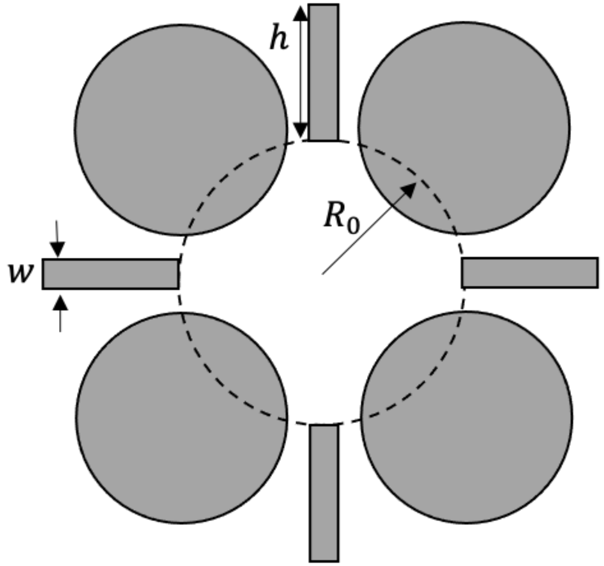
Octupole OFF with 0.2 V perturbation
Particle loss: 91 %



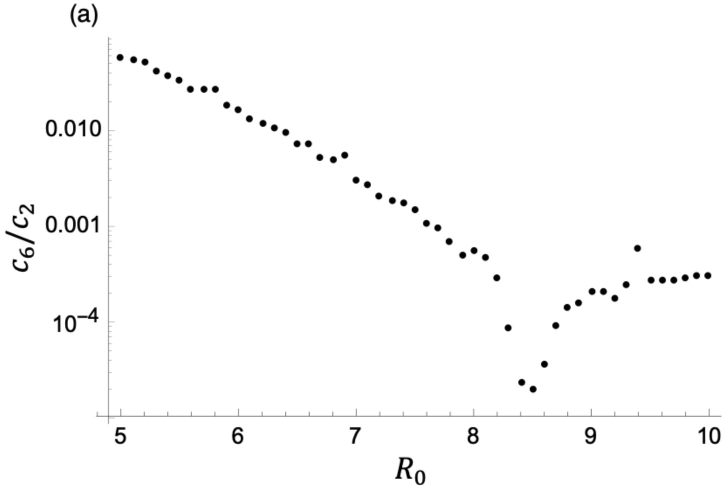
Octupole ON with 0.2 V perturbation
Particle loss: 31 %

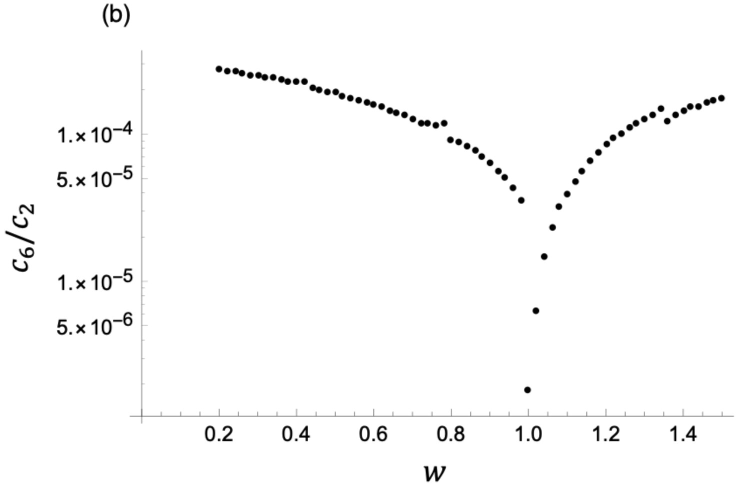
Nonlinear upgrade to IBEX





- Still need good quadrupole field.
- Inscribed radius and width of plates was optimised to minimise c_6 nonlinearity.
- $R_0 = 8.5$ mm, $w = 1$ mm





Jake Flowerdew

Creating Exact Multipolar Fields with Azimuthally Modulated RF Cavities

Laurence Wroe

Aim

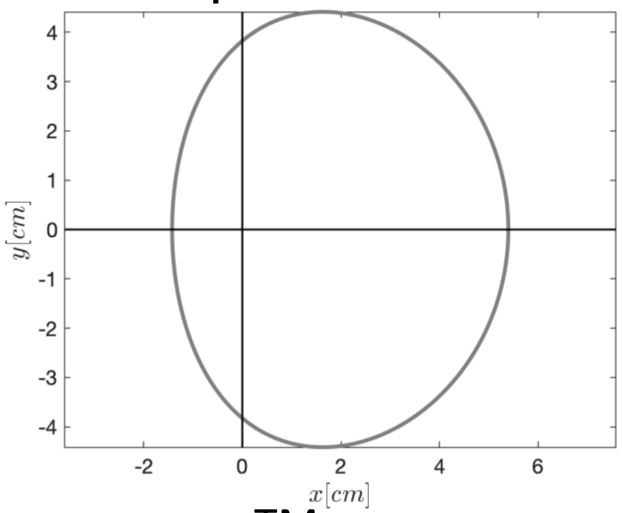
- Currently:
  - Majority of accelerating cavities are azimuthally symmetric and operate in TM_{010}-exact mode. Solely accelerate a beam – no transverse fields
  - Transverse-affecting cavities (e.g. crab cavities) that operate in operate in TM_{m10}-like modes have novel and elaborate designs to:
    - separate the frequencies of the 2-fold degenerate TM_{m10}-like mode
    - damp instabilities caused by the lower order fundamental accelerating TM_{010}-like mode
    - minimise unwanted multipolar components

- Initial question - can we design an RF cavity that simultaneously:
  - Accelerates beam
  - Also has an exact, user-specified transverse multipole components (e.g. quadrupole, sextupole …)
  - Operates in non-degenerate, fundamental mode

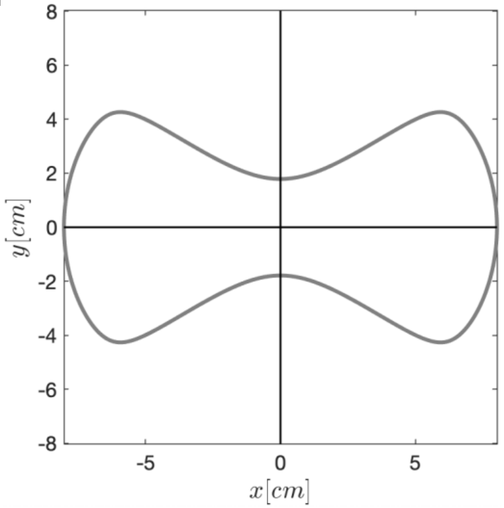
- Uses:
  - Introduce desired multipolar components (e.g. for quadrupole focusing)
  - Remove undesired multipolar components (e.g. remove dipole component introduced by RF power coupler)

How?

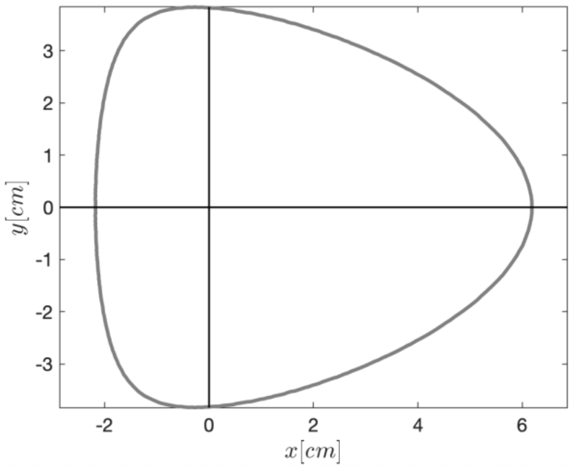
- User expresses desired ratio of accelerating component to multipolar component (how much does cavity longitudinally accelerate compared to transversely focus?)
- Determine the azimuthally varying radius of a 'pillbox-like' RF cavity that solves the boundary conditions of EM field for desired field and multipolar components
- Example 3 GHz RF cavity shapes:



$TM_{\{0,2\}10}$
2x more dipole deflecting than longitudinal acceleration



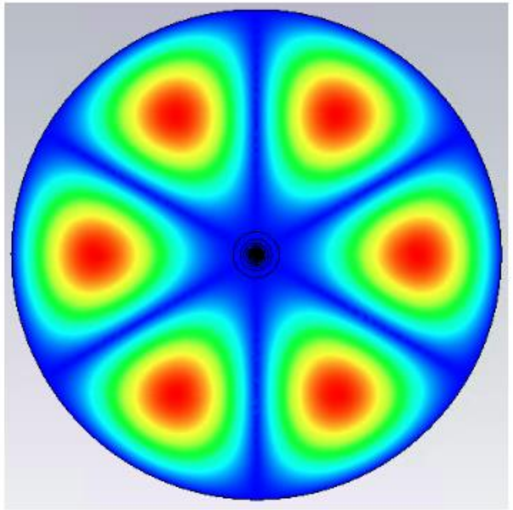
$TM_{\{0,2\}10}$
5x more quadrupole focusing than longitudinal acceleration



$TM_{\{0,1,3\}10}$
Equal ratios of dipole deflecting, sextupole focusing and longitudinal acceleration

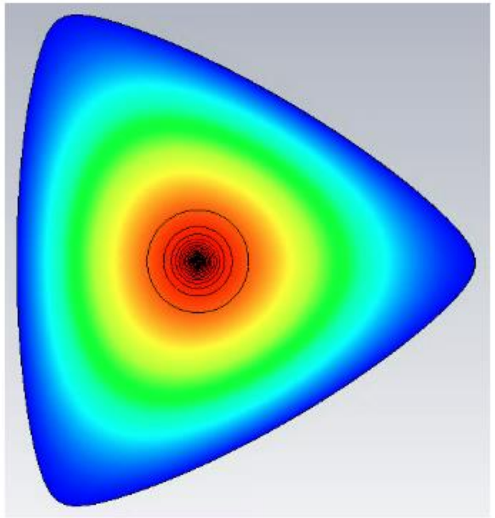
Verification of results

- Theoretical analysis has been verified through simulation by performing field decompositions of cavities using CST
- Theoretical analysis to be verified through experimentation:
  - Workshop tasked with building cavity that operates in the $TM_{\{0,2\}20}$ mode. Quadrupole term 5x greater than acceleration
  - Will use bead pull experiment to experimentally verify results
- Theory and simulation have been written into paper. Will be submitted to journal once experimental results taken and added in



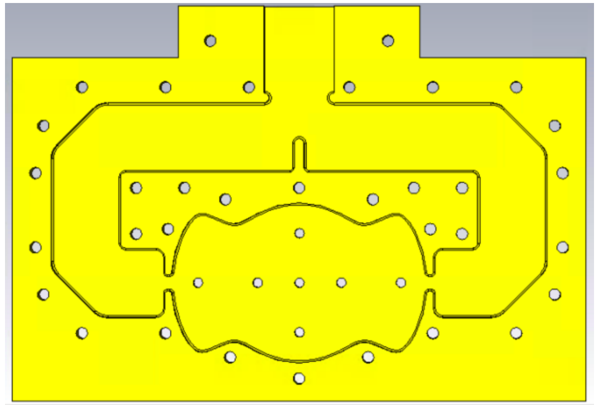
TM_{310}

Pillbox

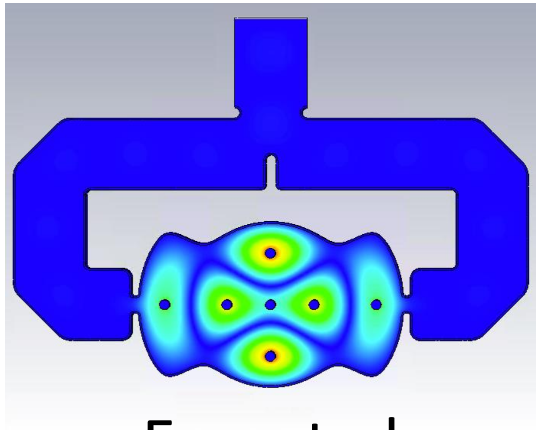


$TM_{\{0,3\}10}$

Ratio of sextupole component to accelerating of 0.95



Mechanical design (Al)



Expected field pattern

Laurence Wroe

Summary

- JAI conducts essential research on intense hadron beams by
  - Improving understanding required to operate high intensity machines, essential for ISIS operations
  - Developing novel beam diagnostic tools
  - Studying novel concepts and potentially revolutionary accelerator systems for next generation applications, etc.
- It performs its mission to educates new scientists in the field
- Institute continues its essential international collaborations with leading accelerator centres worldwide