HIGH INTENSITY HADRON BEAMS

JAI Advisory Board meeting

7 March 2019

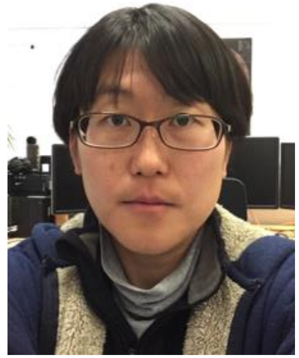
Dr. Suzie Sheehy

Outline

- Last JAI-AB update was 2017, updates since then:
  - IBEX Paul Trap experiment
  - Fixed field accelerators and ISIS-II studies
  - Addition of GCRF/medical LINAC project
  - (+my plans during next 2 years)

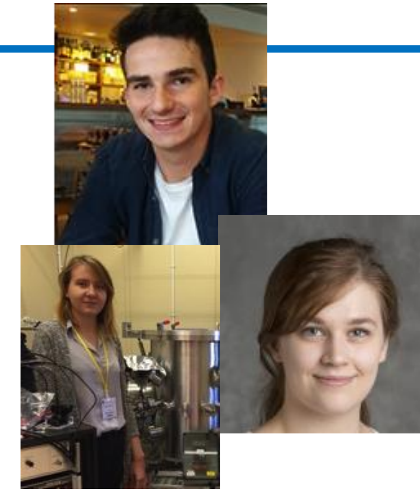
Who are we?

Dr. Suzie Sheehy
Royal Society URF



Dr. Emi Yamakawa
Joint PDRA JAI/STFC

Lucy Martin
(3rd year, Dphil)



Former students on IBEX:
Laurence Wroe, MPhys 2018
Elizabeth Carr - MPhys 2017
Kasia Budzik- Summer 2017

+ RS funded PhD student starting Oct 2019
+ ISIS/STFC funded PhD student starting Oct 2019

Professional staff:
Adam Baird
Electronics (Oxford Physics)

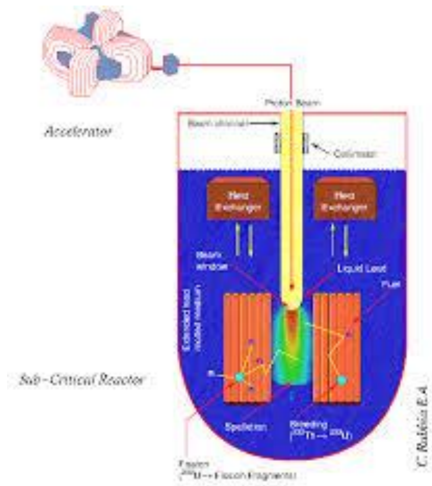
Dr. David Kelliher + Dr. Shinji Machida, STFC/ISIS/RAL

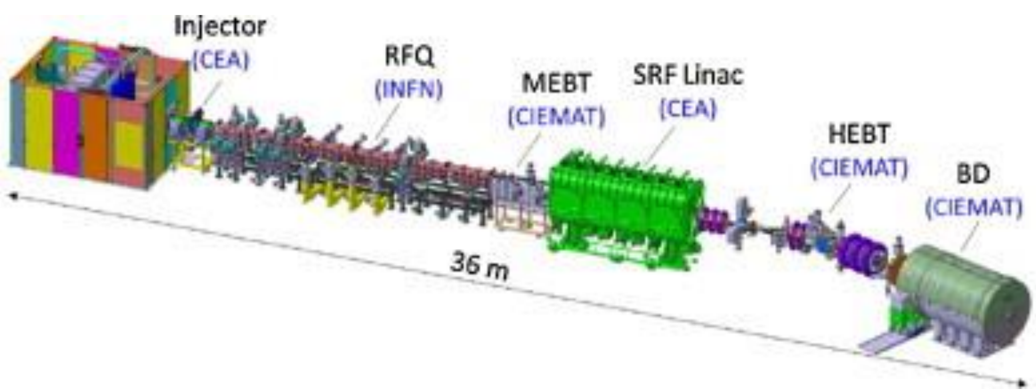
The IBEX lab in R8, RAL

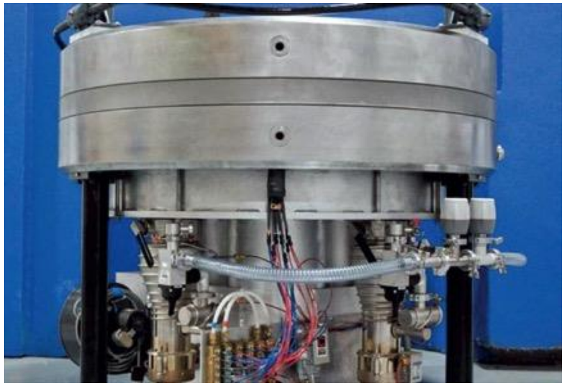
- Peter Griffin Hicks –placement from ISIS/STFC (Controls)
- Vacuum, Engineering & Diagnostics support from Sunil Patel, Richard Hale and Alex Pertica

Uses of intense hadron beams

- Neutron spallation sources - (ie. ISIS, ESS)
- Next generation particle physics experiments (FCC, HL-LHC), neutrinos, etc
- Accelerator driven systems
- Fusion materials irradiation
- Geological activation & security
- Radio-isotope production





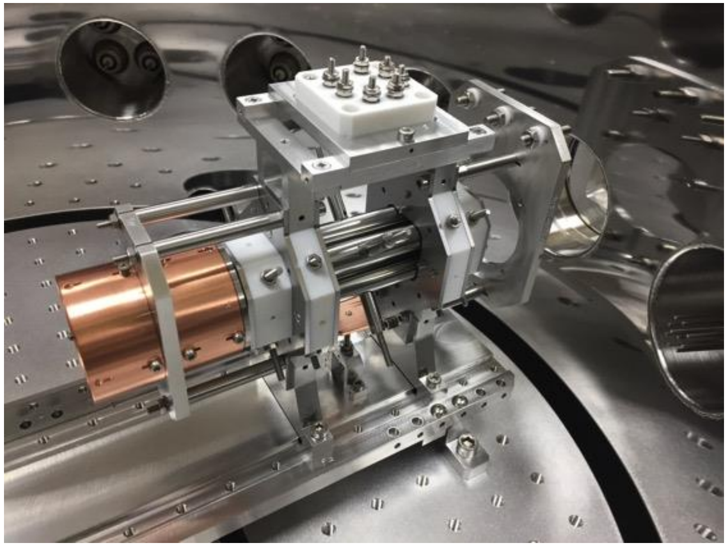


IBEX – Intense Beam Experiment

A linear Paul trap can simulate a linear focusing channel in an accelerator (including space charge), in a compact, inexpensive and flexible system

$$H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K(s)(x^2 - y^2) + \frac{q}{p_0 \beta_0 c \gamma_0^2}\phi$$

Hamiltonian for transverse beam motion



$$H_{\text{S-POD}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K_{\text{p}}(\tau)(x^2 - y^2) + \frac{q}{mc^2}\phi_{\text{sc}}$$

Hamiltonian for Paul trap

HIROSHIMA UNIVERSITY

What is it for?

- **In accelerators:**

  Full dynamical behavior in an accelerator with intense beams is *non-linear* and *not analytically solvable*.

  – Experiments on accelerators = time consuming, complex and expensive. Limited due to radiation from beam loss.

  – Simulations = difficult, computationally intensive.

- **Questions:**

  – **What are the ultimate limitations of intensity in hadron accelerators?**

  – **What are the impacts of *coherent* and *incoherent* resonances on intense beams?**

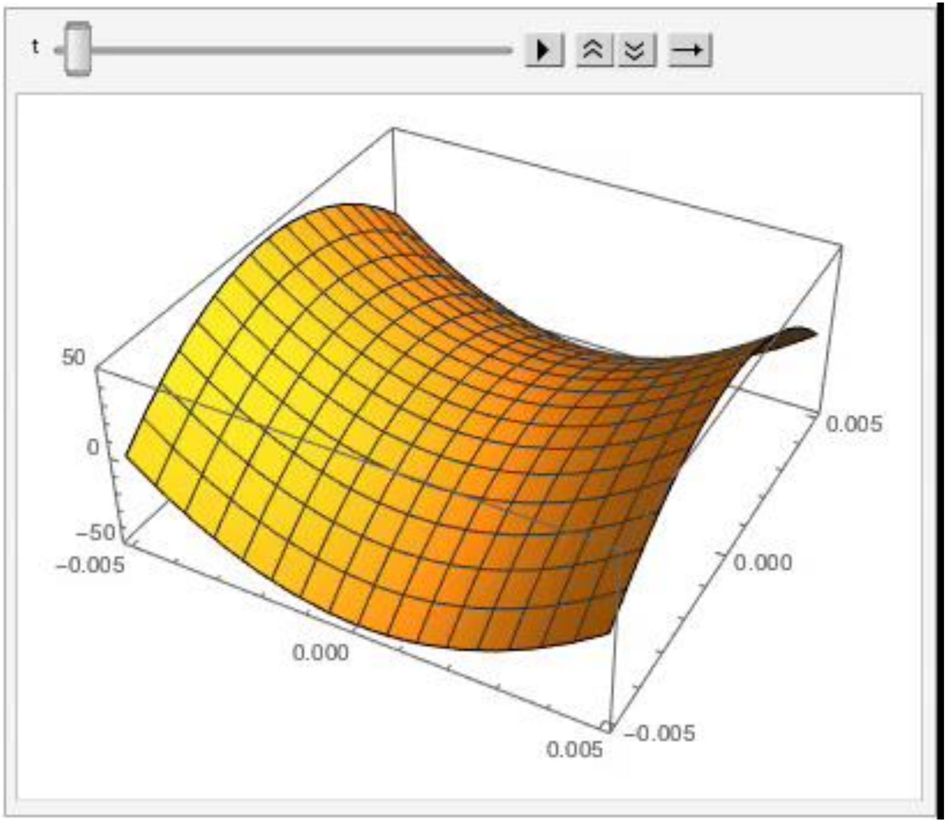
  – **Are some beam effects due to *simulation* errors?**

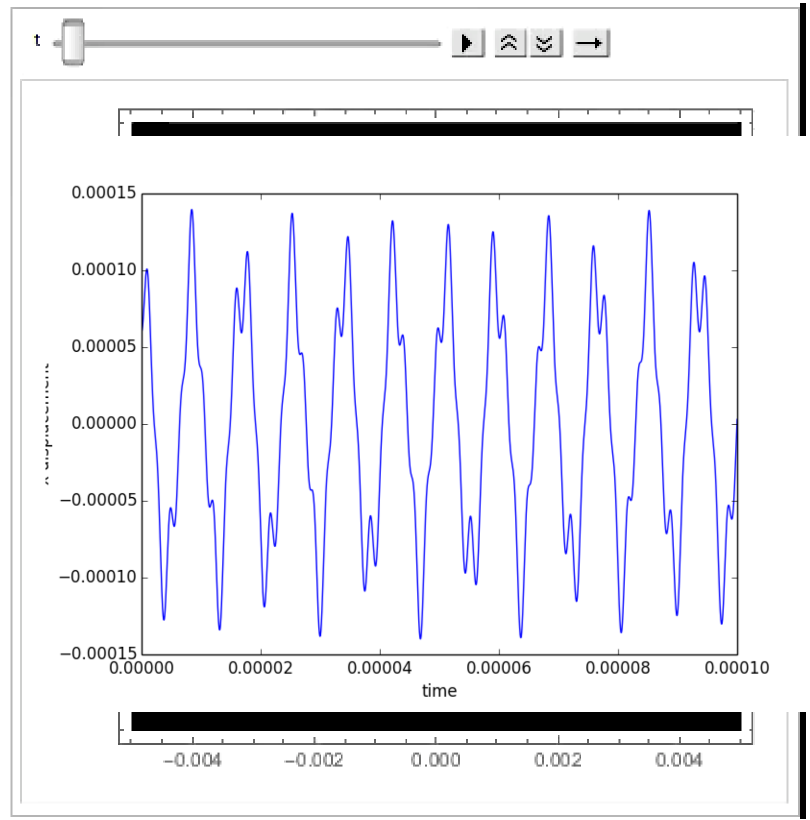
  – **How can we model *novel* accelerators that haven't been built before?**

Particle Trapping

$$F_0 = U + V \cos wt$$

L. Martin

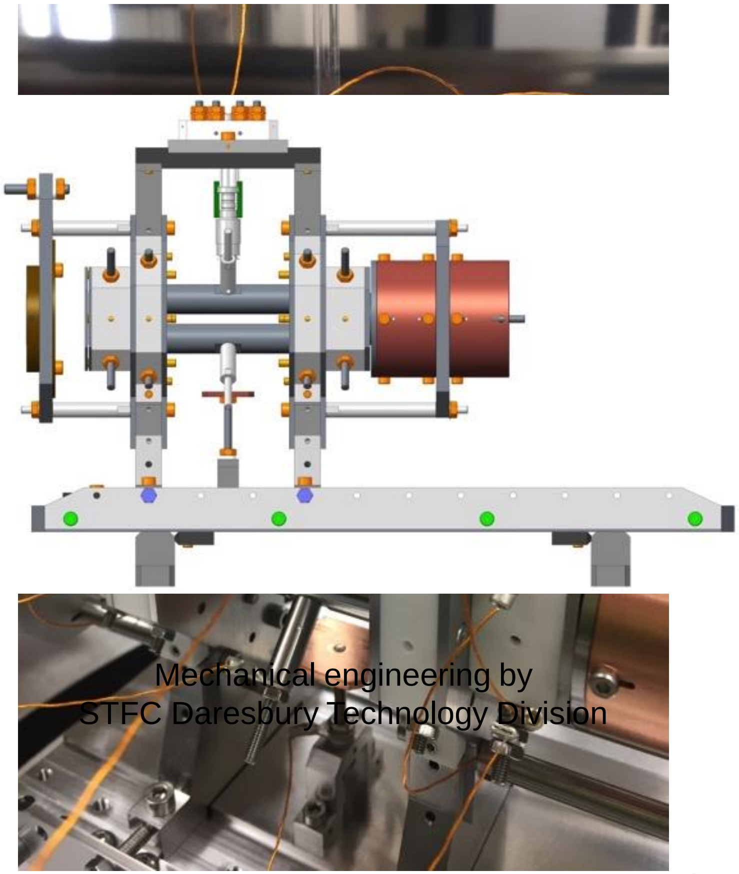




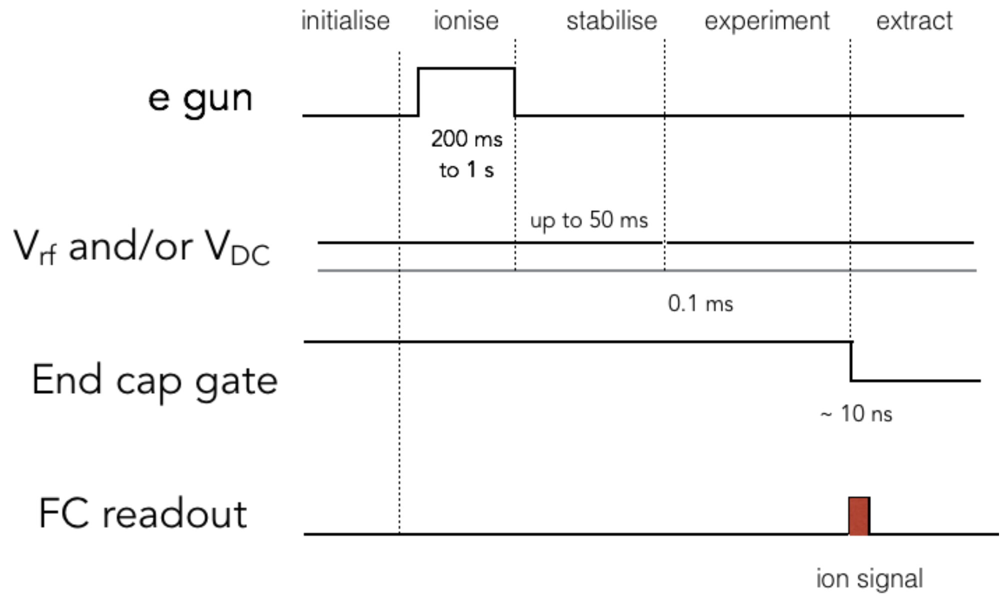
Quadrupole potential varies with time

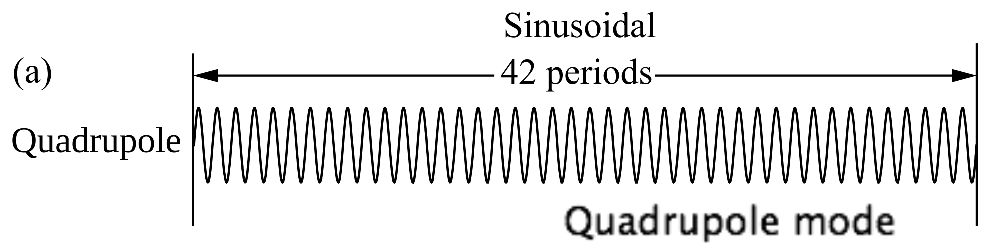
… and traps particles…

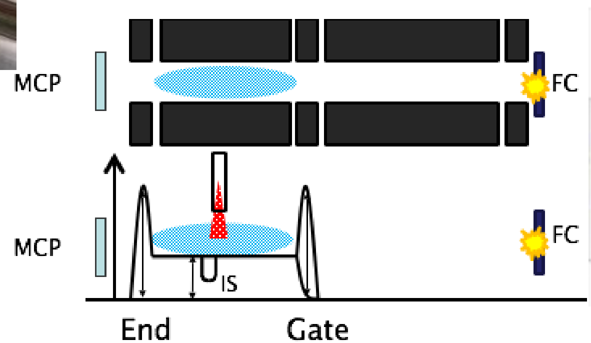
In IBEX

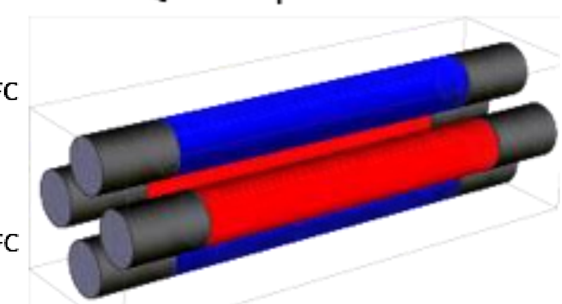


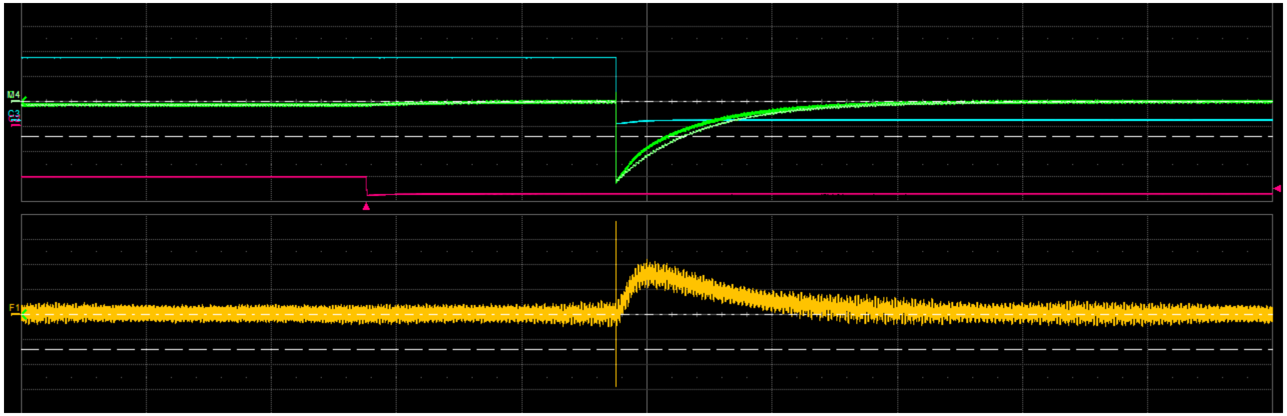
Mechanical engineering by STFC Daresbury Technology Division











Timing signals

FC readout

IBEX: First `beam', 24th January 2017

IBEX updates:

- Coherent/incoherent resonance studies
  - S-POD (Japan) and IBEX
- New custom amplifiers for rf waveforms
- Progress toward nonlinear integrable optics
- Science plan – near future

Coherent vs Incoherent Resonances

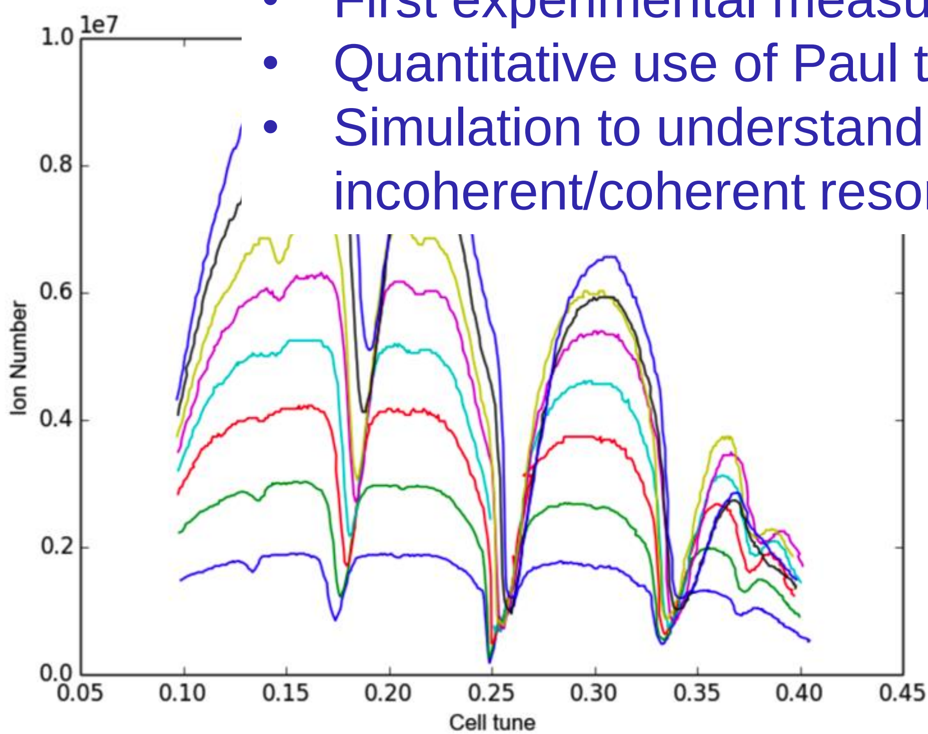
L. Martin

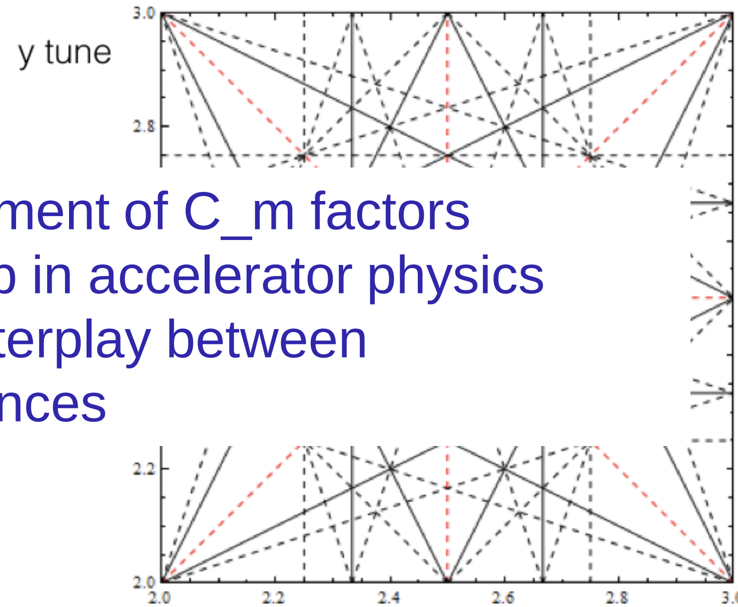
Coherent resonant condition:

$$Q_0 + C_m \Delta Q = \frac{1}{2}\left(\frac{n}{m}\right)$$

This means resonances shift with intensity!

- First experimental measurement of C_m factors
- Quantitative use of Paul trap in accelerator physics
- Simulation to understand interplay between incoherent/coherent resonances





A study of coherent and incoherent resonances in high intensity beams using a linear Paul trap

L K Martin[1], S Machida[2], D J Kelliher[2] and S L Sheehy[1]

[1] Physics Department, University of Oxford, Keble Road, Oxford, OX1 3RH, UK

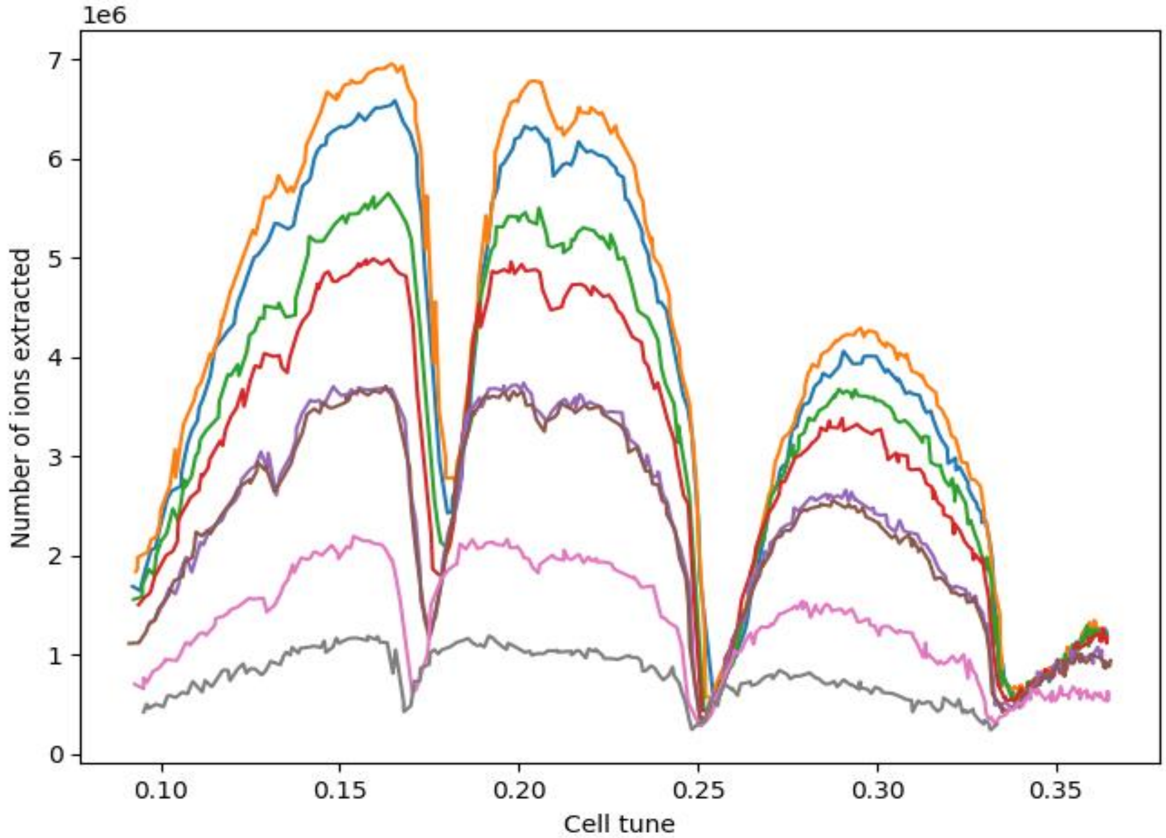
[2] STFC, Rutherford Appleton Laboratory, Harwell Oxford, Didcot, OX11 0QX, UK

E-mail: lucy.martin@physics.ox.ac.uk

SUBMITTED – AUG 18
IN REVIEW

Tune scan with varying intensity

L. Martin



Tune scan data as of 13/11/18 using IBEX.
Ions stored for 100ms, no perturbation applied.

'Split' tunes

L. Martin

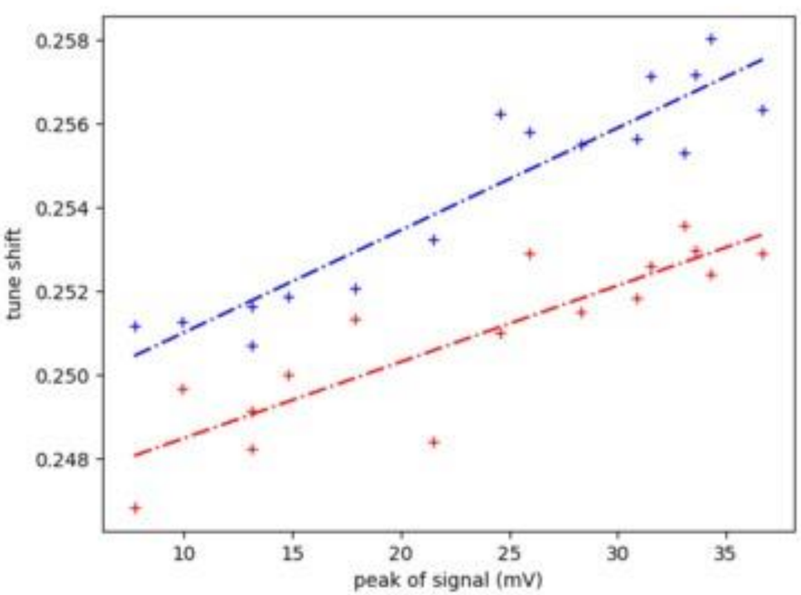
- **Usually operate in Qx=Qy, however, now able to 'split' tunes to cross the tune diagram.**

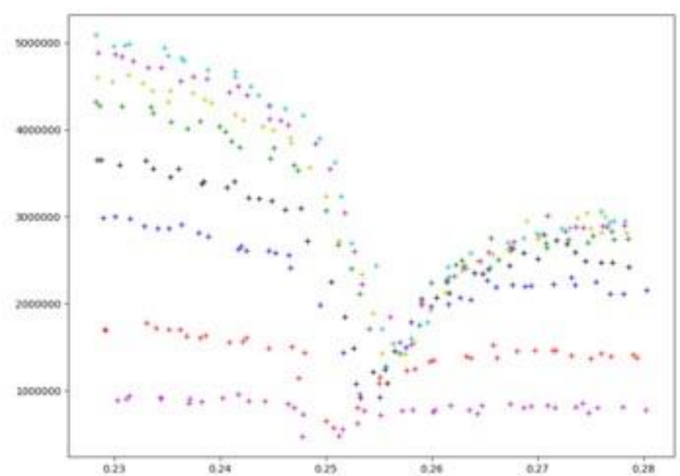
LabView controls: Peter Griffin-Hicks

C_m with split tunes

L. Martin

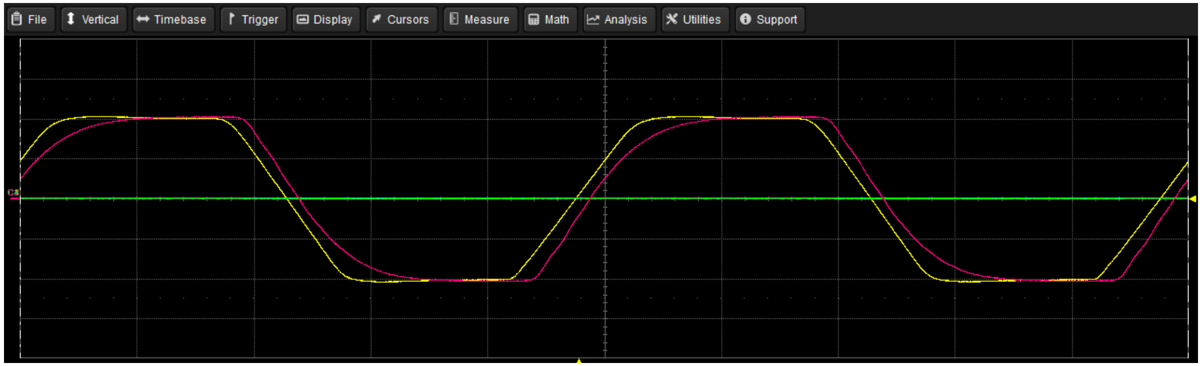
- The C_m value should be different when the tunes are ‘split’.
- New experimental results from IBEX show this experimentally (for the first time).
  - *We are now in proper science mode with IBEX*

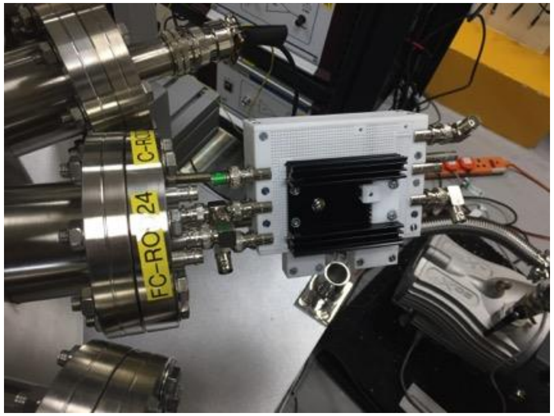




New custom amplifier

- **Can mix AC (usually 1MHz) & DC components. Low noise & up to 225V output. Driven by AWG & TTL.**
- **Developed by A. Baird (Ox Central Electronics)**
- **Recently commissioned: excellent performance.**





Custom 3D printed enclosure, mounted directly to vacuum feedthrough for performance.

Testing shows:

- ✓ Lower noise than commercial WMA300
- ✓ More accurate gain at high voltages
- ✓ Better bandwidth for square pulses (despite these not being specified - will be helpful)

Non-linear Integrable Optics (NIO)

L. Martin

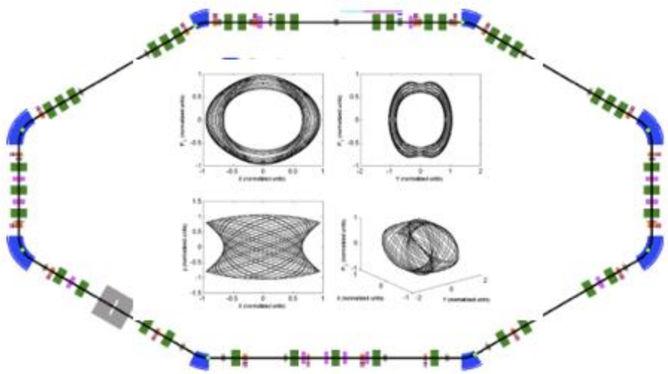


Figure 3. Layout of the Integrable Optics Test Accelerator (IOTA) ring.

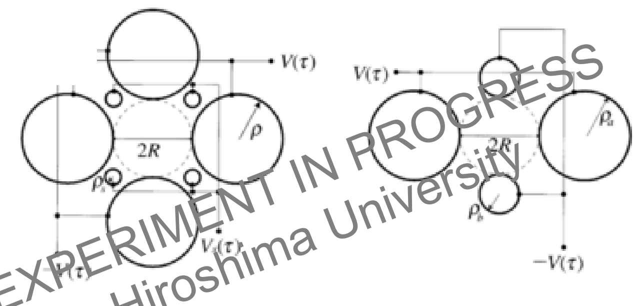


Fig. 6. Cross-sectional view of modified Paul traps.

H. Okamoto, Y. Wada, and R. Takai

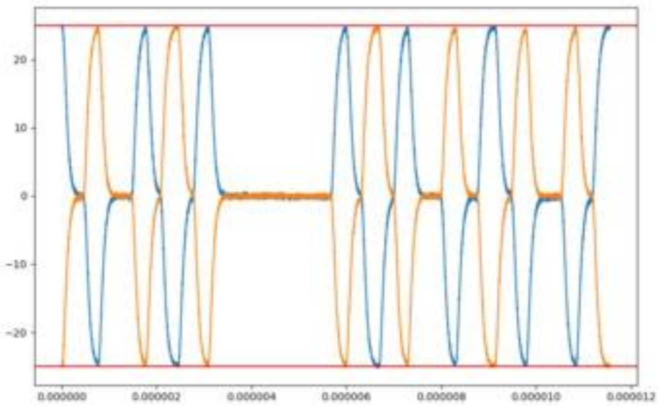
- **Requirements:**
  - 'T-insert' linear optics (next slide)
  - Fast ramping non-linear fields in 'drift'
  - Equal beta functions in drift section
  - Ability to verify optics

"Paul traps with adaptable electric focusing might prove amenable to economically explore long path length transport aspects of Non-linear Integrable Optics. We advocate exploring this more fully. Given funding issues with IOTA, trap experiments might provide a more rapid and economical partial step to explore concept viability."[3]

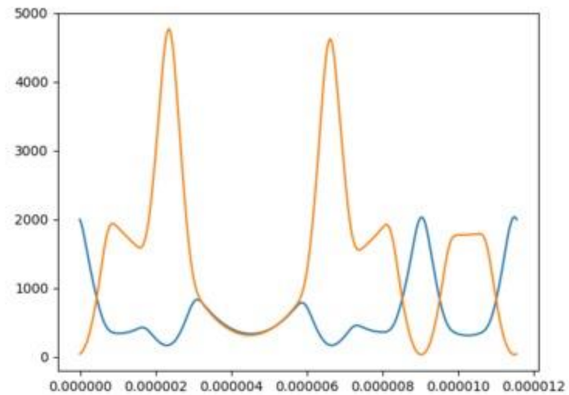
-From summary of HB2014 workshop

Linear T-insert testing

L. Martin

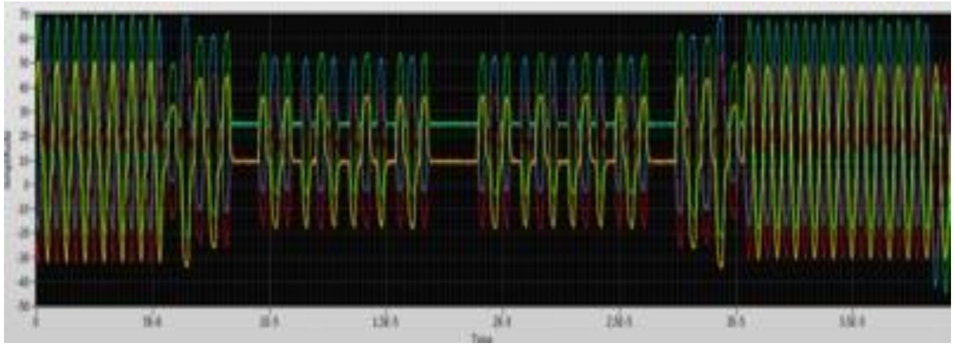


Test of t-insert – voltage on oscilloscope
(improve ‘flat top’ with new amplifiers)

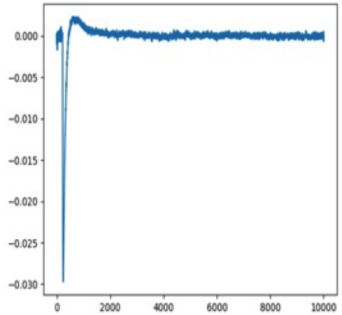


Calculated Beta functions
(able to control to achieve equal betas)

Challenge: matching from FODO to t-insert



Trap, ramp, t-insert, ramp, extract



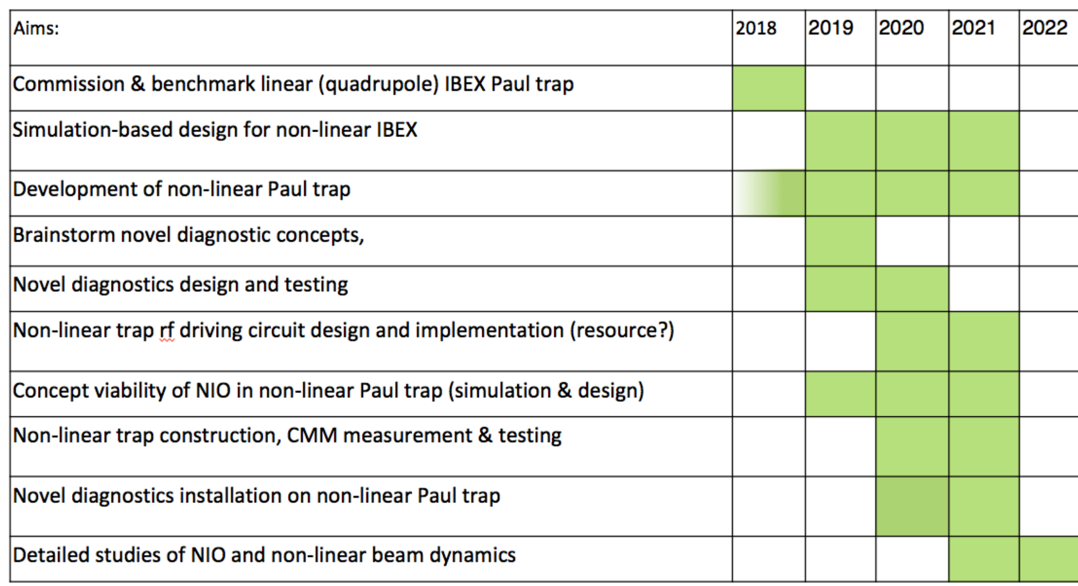
Currently very small ion signal! Work in progress…

Next steps…

- Installing & commissioning MCP (E. Yamakawa) – better signal/noise ratio and distribution information.
- Starting to develop non-linear trap ideas (L. Martin)
- Investigation into required diagnostics for NIO
- Recent science prioritisation exercise – future research plans/scoping

Ideas

- Best working point for high intensity beams
- Higher stability regions of Hills Equation
- Fast Phosphor diagnostics
- 0.25 resonance development in time
- Particle trapping due to tune modulation
- Transverse/Longitudinal Coupling
- Scaling FFA Optics
- SUMMARY DOC
- ISIS half integer studies
- New...

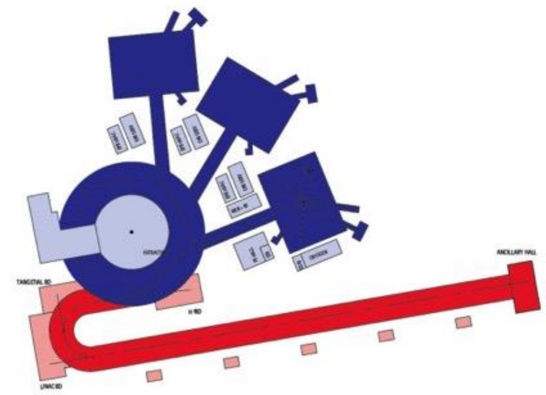


FFAs & ISIS-II Studies

- **Next generation neutron spallation source, "ISIS-II"**

ISIS-II `facility upgrade, not just accelerator upgrade' - J. Thomason, PASI 2015

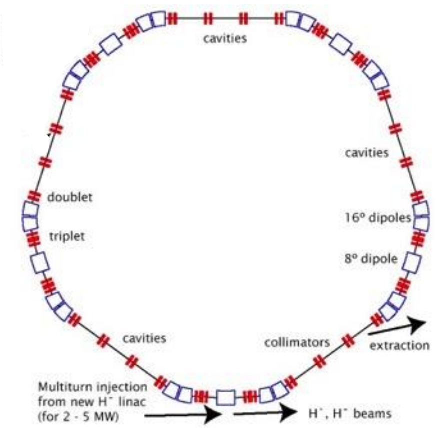
- can we design upgradeable facilities without making them much more expensive?
- can we save power, reduce costs?



Compact test ring

- Prototype relevant components (FFA)

0.8 – 3.2 GeV RCS



0.4 – 3.2 GeV FFA

New DPhil student (funded by STFC/ISIS) to start Oct 2019 - TBC

Can we do better than existing?

Fixed Field Alternating Gradient Accelerators

Beam power is a combination of:

[intensity]

x

[rep rate]

x

[beam energy]

Large horizontal acceptance
Lower SC tune shift

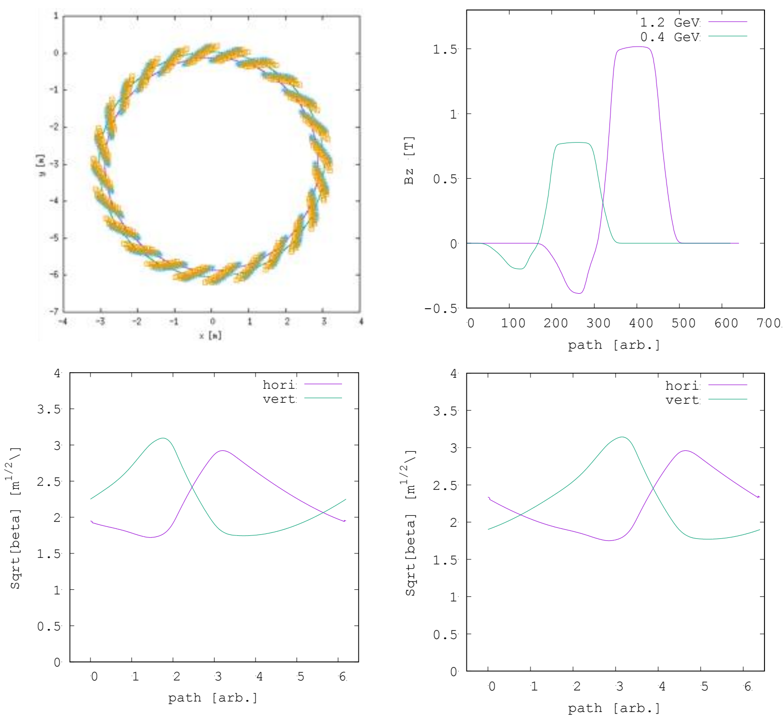
Higher repetition rate
Can accelerate as quickly as RF allows

Strong focusing to high E
Compared to cyclotron

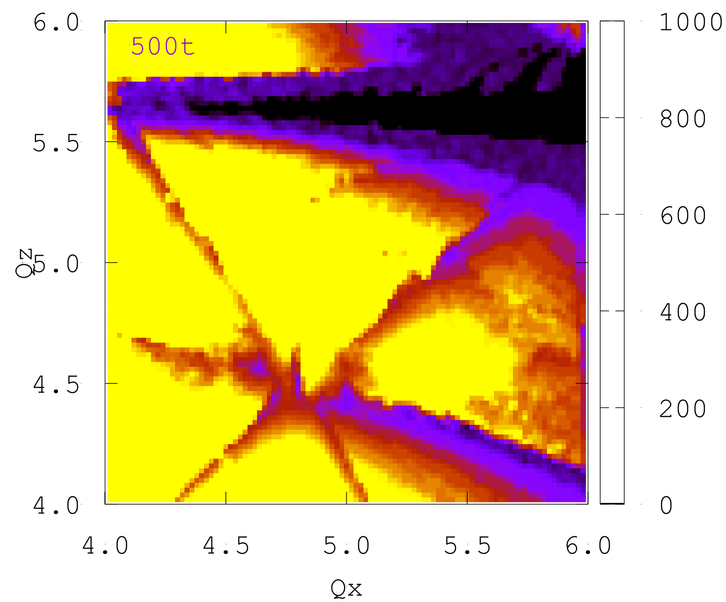
IB Group Studies of FFA for ISIS-II

S. Machida

- FFA accelerator designed to fit in ISIS tunnel
- Dynamic aperture is scanned in tune space.



TL: Foot print, TR: Magnetic field along the orbit,
BL: Beam envelop at 0.4 GeV, BR: at 1.2 GeV.

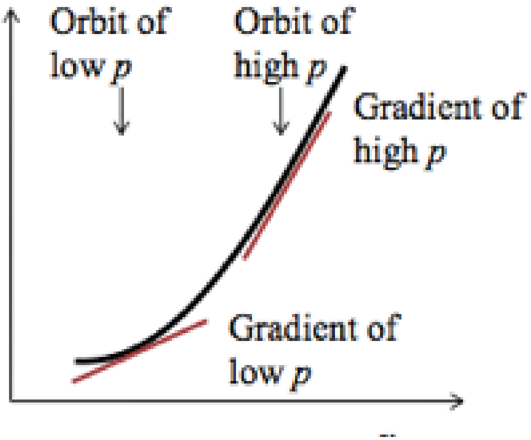


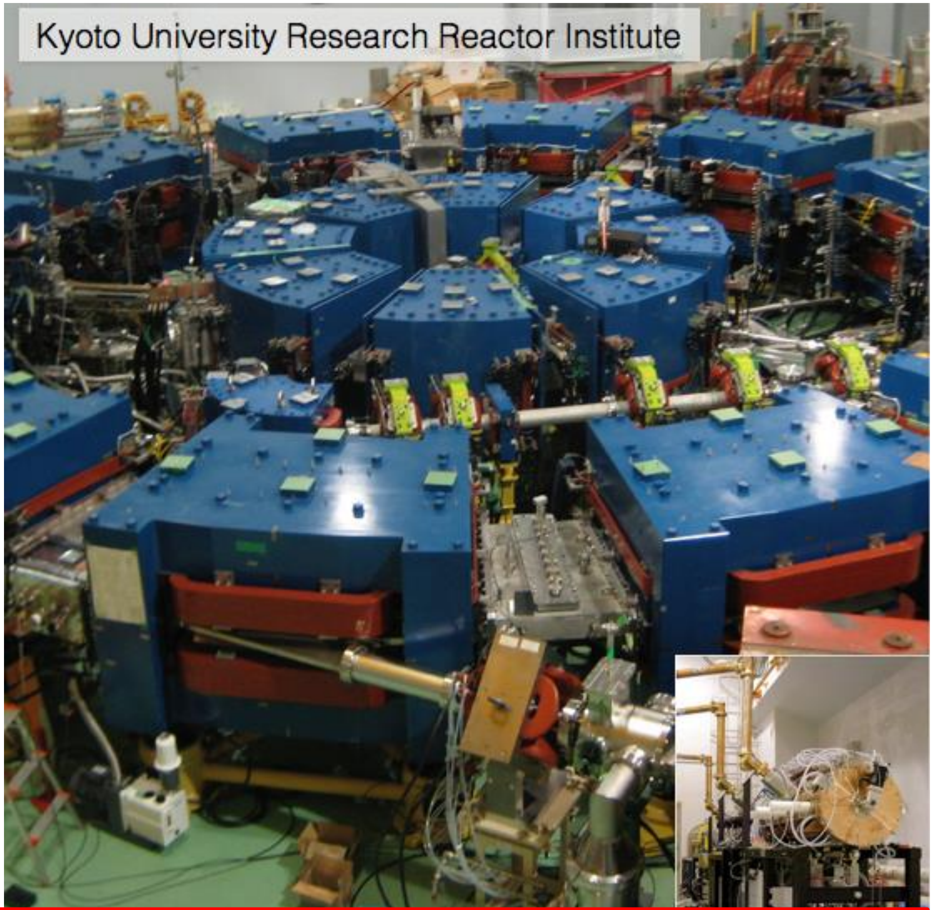
Dynamic aperture in tune space.
Colour scale is pi-mm-mrad
(normalised).

Experimental Collaboration with KURRI

- **Scaling proton FFAG**
- **Injection 11 MeV,**
- **H- charge exchange**
- **up to 100 or 150 MeV**
- **1.6 to 5.2 MHz cavities**

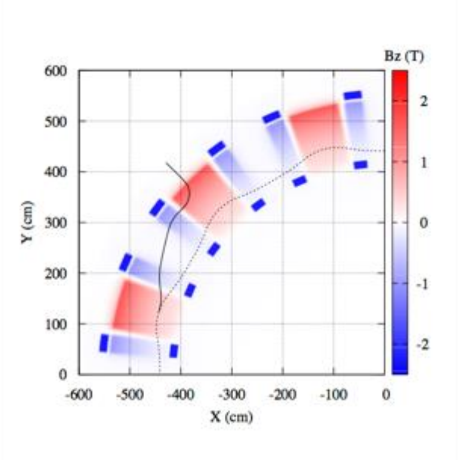
$$B_y = B_0\left(\frac{r}{r_0}\right)^k$$

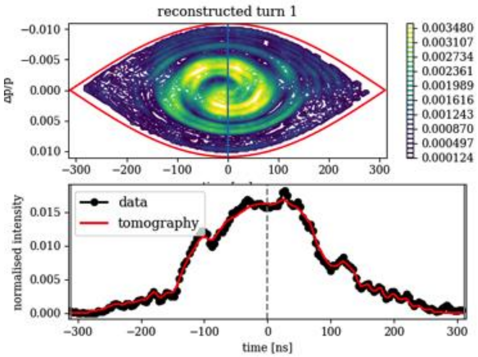


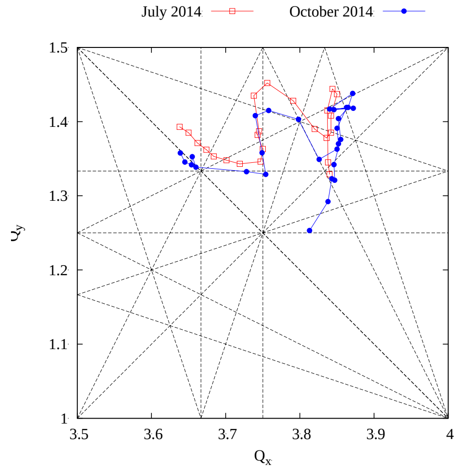


Aim: to demonstrate high bunch charge capability of FFAs

FFA simulation & experimental work







Simulation:

- OPAL code advancements,
- OPAL publication in preparation

Experiments:

- Characterization & methods paper published 2016.
- Machine issues = no experiments 2015 – 2017.
- Beam study experiments re-started 2018.
- Now led by STFC/ISIS Intense Beams Group
  - **Longitudinal tomography**
  - **RF optimisation**

Demonstrating features of FFAs, together with simulations of high intensity effects, means we can be confident we know the principle is suitable for high power.

S. L. Sheehy et al., Prog. Theor. Exp. Phys. 7, 073G01, July 2016

GCRF Medical LINAC project

Visit to Cepto Hospital, Jakarta
(Private hospital with 3 LINACs)

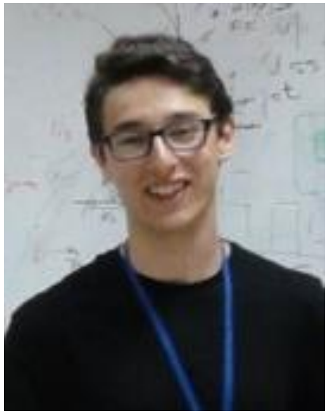
1. Study of Accelerator Technology Options
2. **Robust permanent magnet beam delivery systems**
3. **RF Power Systems and Optimized RF Structures for Electron Beam Acceleration**
4. **Linear Accelerator Simulations for Stable and Sustainable Operation of Developing Country Radiotherapy Linear Accelerators**
5. Cloud-based Electronic Infrastructure in Support of Linac-based Radiotherapy in Challenging Environments

GCRF Medical LINAC project

Dr. Emilia Cruz-Alaniz
2 months on permanent magnet studies & optics

Dr. Muhammad Kasim
Collaboration with Indonesia & automated treatment planning (with S. Vinko)

Laurence Wroe
Laidlaw Scholarship
Downtime/failure mode studies



Adam Steinberg
(3rd year ugrad, optics, simulation and failure mode data analysis)

Comparative analysis of radiotherapy LINAC downtime and failure modes in the UK, Nigeria and Botswana

L. M. Wroe[a], C. S. Chinedu, T. A. Ige[b], S. Grover, R. Makufa[c], S. L. Sheehy[a], on behalf of the CERN-ICEC-STFC Medical LINAC collaboration

[a]*Department of Physics, University of Oxford*
[b]*National Hospital Abuja (NHA), Nigeria*
[c]*Life Gaborone Private Hospital (GPH), Botswana*

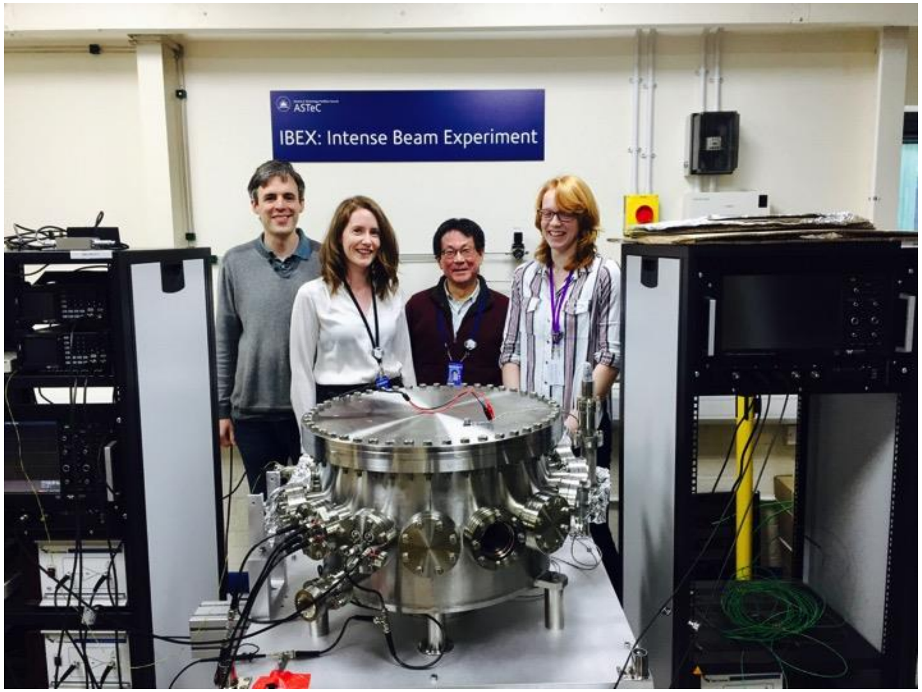
SUBMISSION TO CLINICAL ONCOLOGY

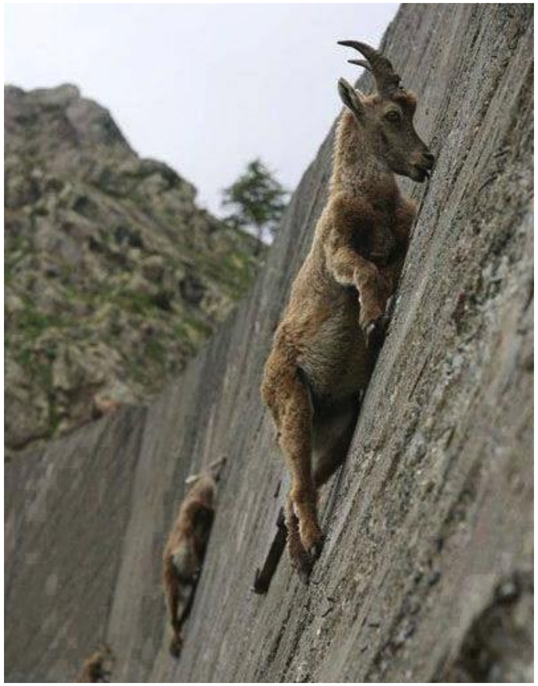
Eve Shalom (summer student 2018) – magnet design and test setup
Dr. Paul Coe (former postdoc) – permanent magnets/RF studies

My plans for next 2 years...

- **Senior Lecturer in Medical Accelerator Physics at University of Melbourne, Australia.**
- **50/50 time split with Oxford (RS URF) for 2 years (periods of 3-4 months in each), moving to permanent in 2021.**
- **Aim to create first Australian academic group in accelerator physics.**
- **Build collaborations, links and training program (Masters level course).**
- **Hope to work closely with JAI (student visitor exchanges). Areas:**
  - **Hadron therapy accelerators and gantry systems**
  - **Radiotherapy LINACs – cf. GCRF project.**
  - **X-band technology (CERN are sending XBOX system to Melbourne)**
  - **Isotope production cyclotrons (high intensity)**
  - **Also Australian Light Source connections (lattice upgrades cf. Diamond)**

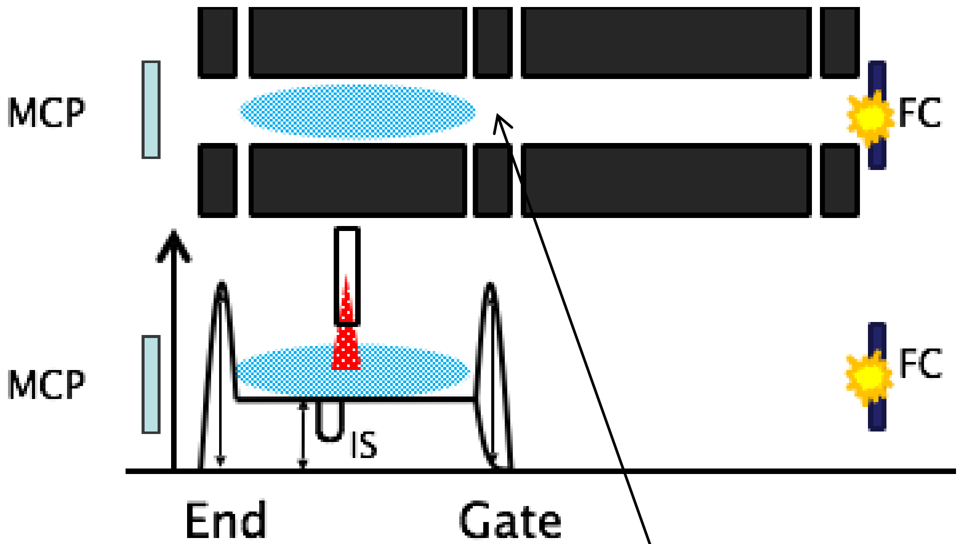
- **NB. All Oxford students will have expert co-supervision (i.e. Oxford, RAL, CERN) and co-supervisors to manage transition.**
- **First PhD student in Melbourne: Greg Peiris, starts June 2019.**
  - **Will work on medical LINAC project, also relevant for Australian rural/regional areas in collaboration with Peter Macallum Cancer Institute.**





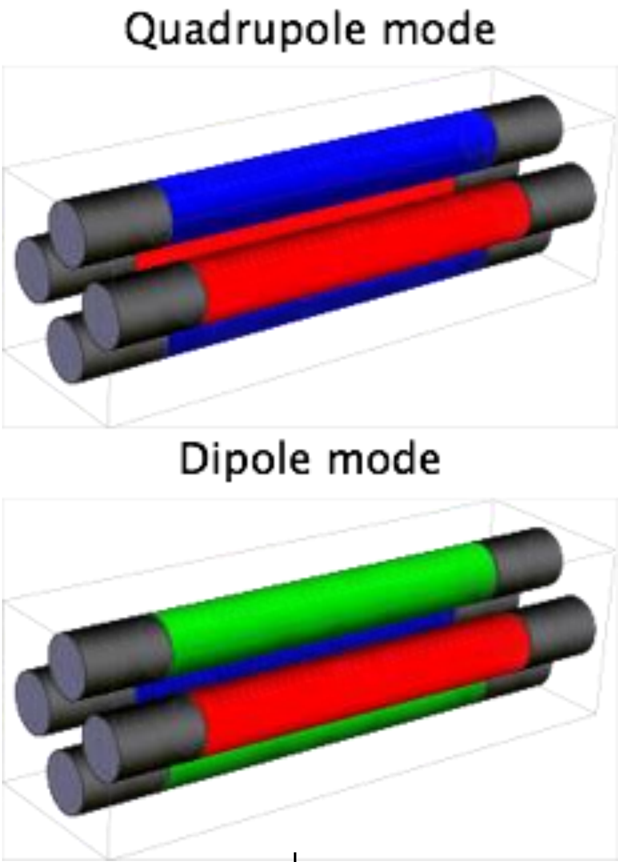
Thanks for your attention

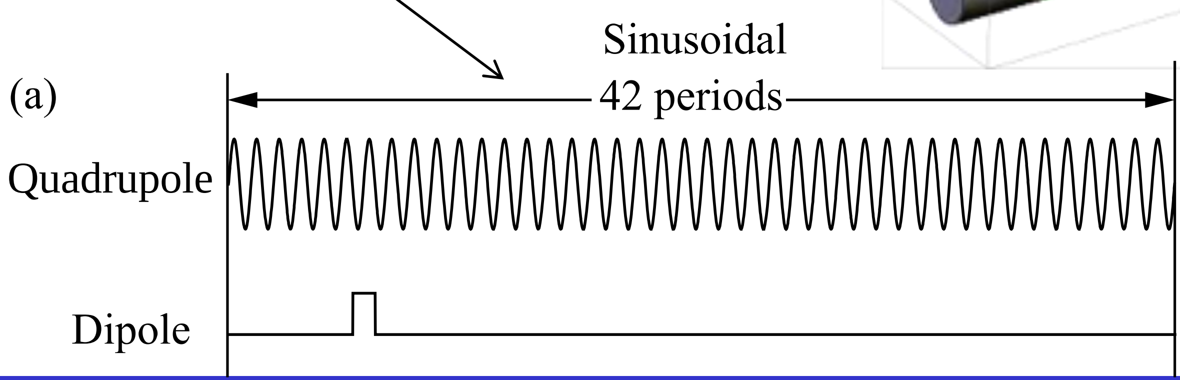
Using S-POD for accelerator studies



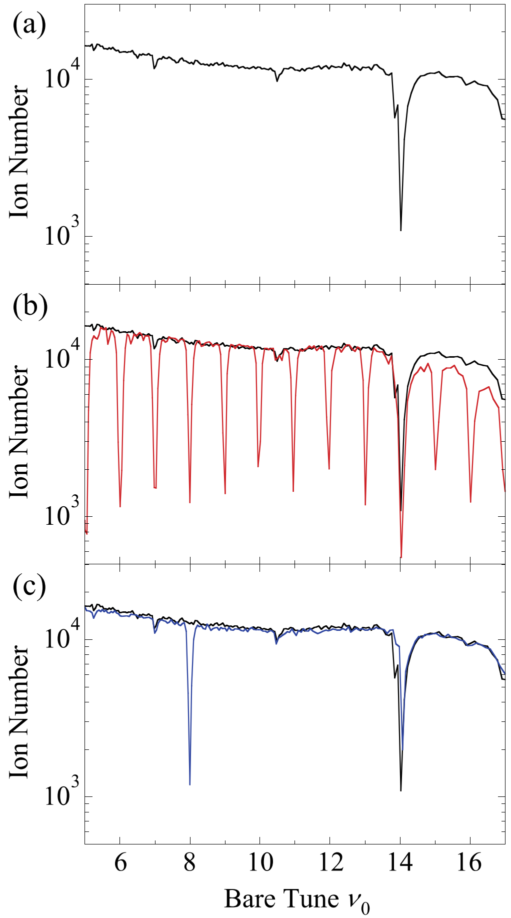
Argon gas ionised by e- gun

1MHz confinement wave



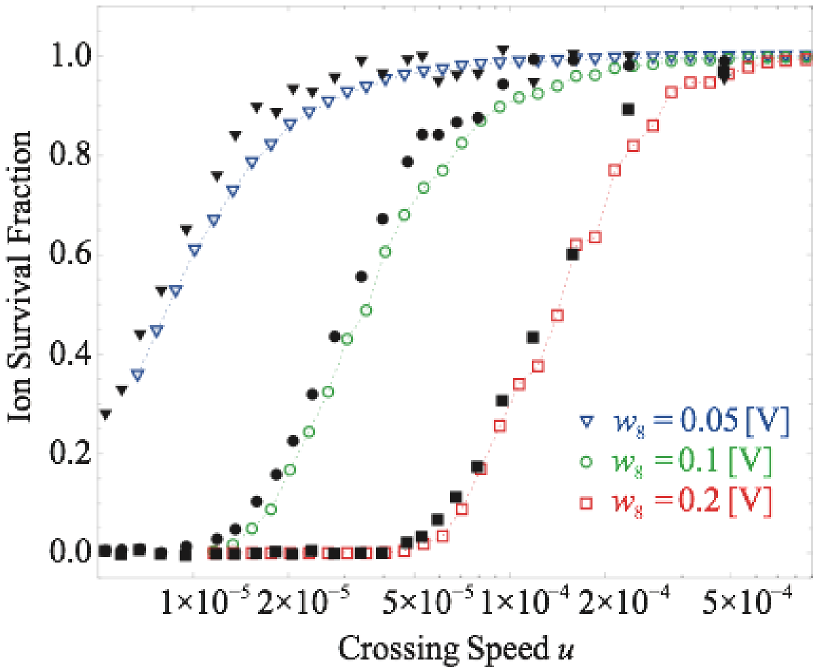


Integer resonances can be excited & crossed



8th harmonic excited

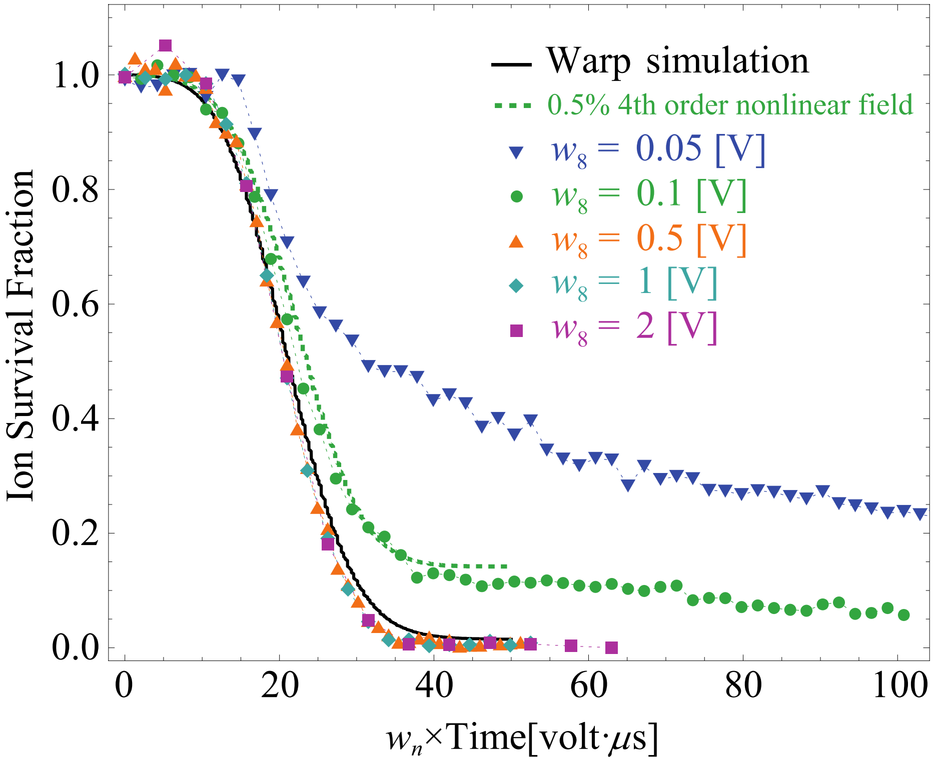
Tune varied 9.5 -> 7.5



S. L. Sheehy, D. J. Kelliher, S. Machida, C. R. Prior et al, *Experimental studies of resonance crossing in linear non-scaling FFAGs with the S-POD plasma trap*, In Proc. International Particle Accelerator Conference 2013, pp.2675, Shanghai, China, 2013.

Non-linear fields play a role too…

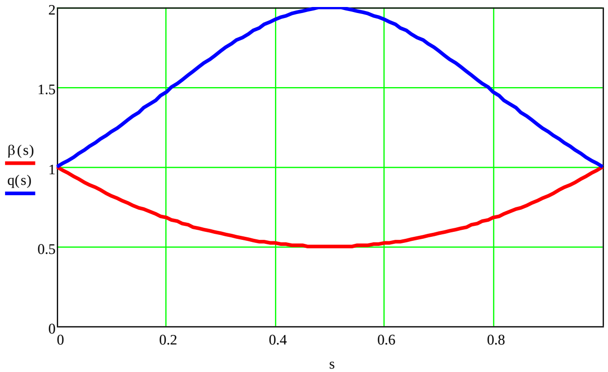
Many interesting phenomena occur in accelerators which could be studied if non-linear components are controlled



- K. Moriya, …, S. L. Sheehy, et al., *Experimental study of integer resonance crossing in a non-scaling fixed field alternating gradient accelerator with a Paul ion trap*, Phys. Rev. ST-AB, **18**, 034001 (2015).

RAL Paul Trap Experiment

- Construction of a linear Paul Trap apparatus at RAL with funding from ASTeC (£77,000)
- C*omplementary* to the existing setup at Hiroshima and built in close collaboration.
- We hope to control non-linear trap components
- Study non-linear phenomena and space charge effects.
- Lots of interest from accelerator community already - FNAL (IOTA, S. Ngaitsev), CERN PS (M. Giovanozzi), ISIS (C. Warsop)



S. Ngaitsev, time dependent quadrupole focusing

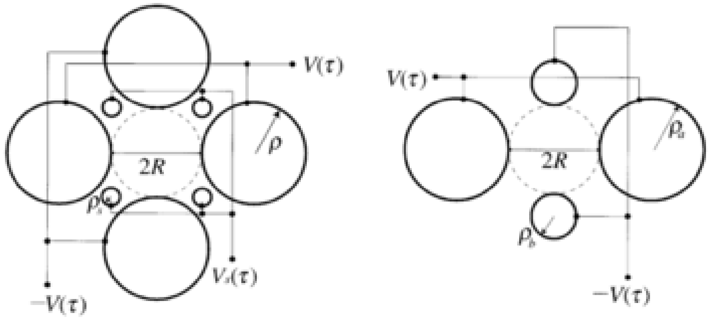


Fig. 6. Cross-sectional view of modified Paul traps.

H. Okamoto, Y. Wada, and R. Takai

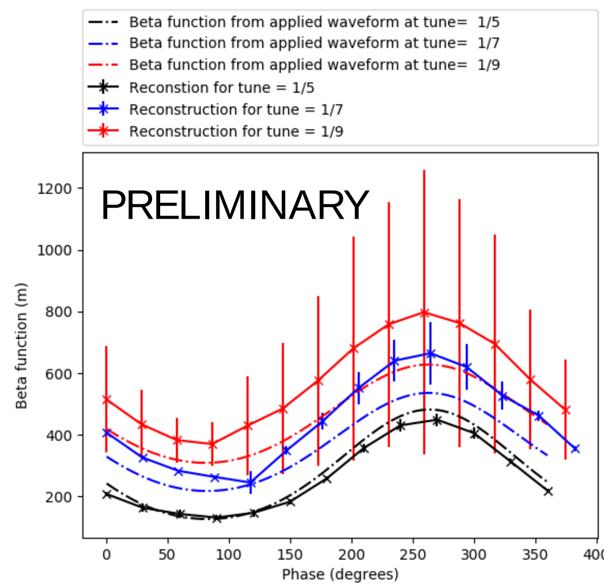
BUT NEED TO VERIFY EQUAL BETA FUNCTIONS…

We have recently developed a method to measure beta functions in Paul traps

Dipole kick gives:

$$x_2 = \theta\sqrt{\beta_1\beta_2}sin(\Psi_{12})$$

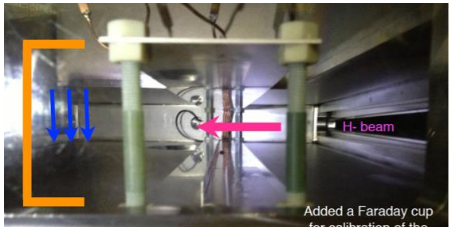
Varying phase & applying kick until ions are lost:



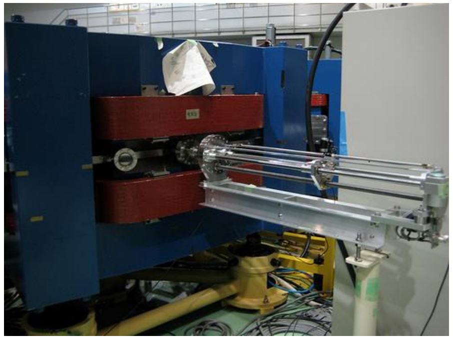
X

KURRI Experimental Campaign

- 2 week pre-experimental visit Nov 2013
  - Improved instrumentation of diagnostics
  - Tools and methods for analysis of experimental data
- 3 week experimental visit March 2014
  - Closed orbit distortion measurement & correction
  - Field index measurement
  - Tune measurement with acceleration
- 3 week experimental run July 2014
  - Dispersion measurement and matching
  - Energy loss on foil measurement
- (3 week experimental run March 2015 - postponed)



Vertical bunch monitor


Radially moving diagnostics

S. L. Sheehy, D. J. Kelliher, S. Machida, C. Rogers, C. R. Prior, *Characterisation of the KURRI 150 MeV FFAG and Plans for High Intensity Experiments,* in Proceedings of HB2014, MOPAB27, Michigan, IL, 2014.