The Intense Beam Experiment (IBEX):

a scaled experiment to model intense hadron accelerators

MIT Tabletop Workshop, August 2017

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John Adams Institute for Accelerator Science

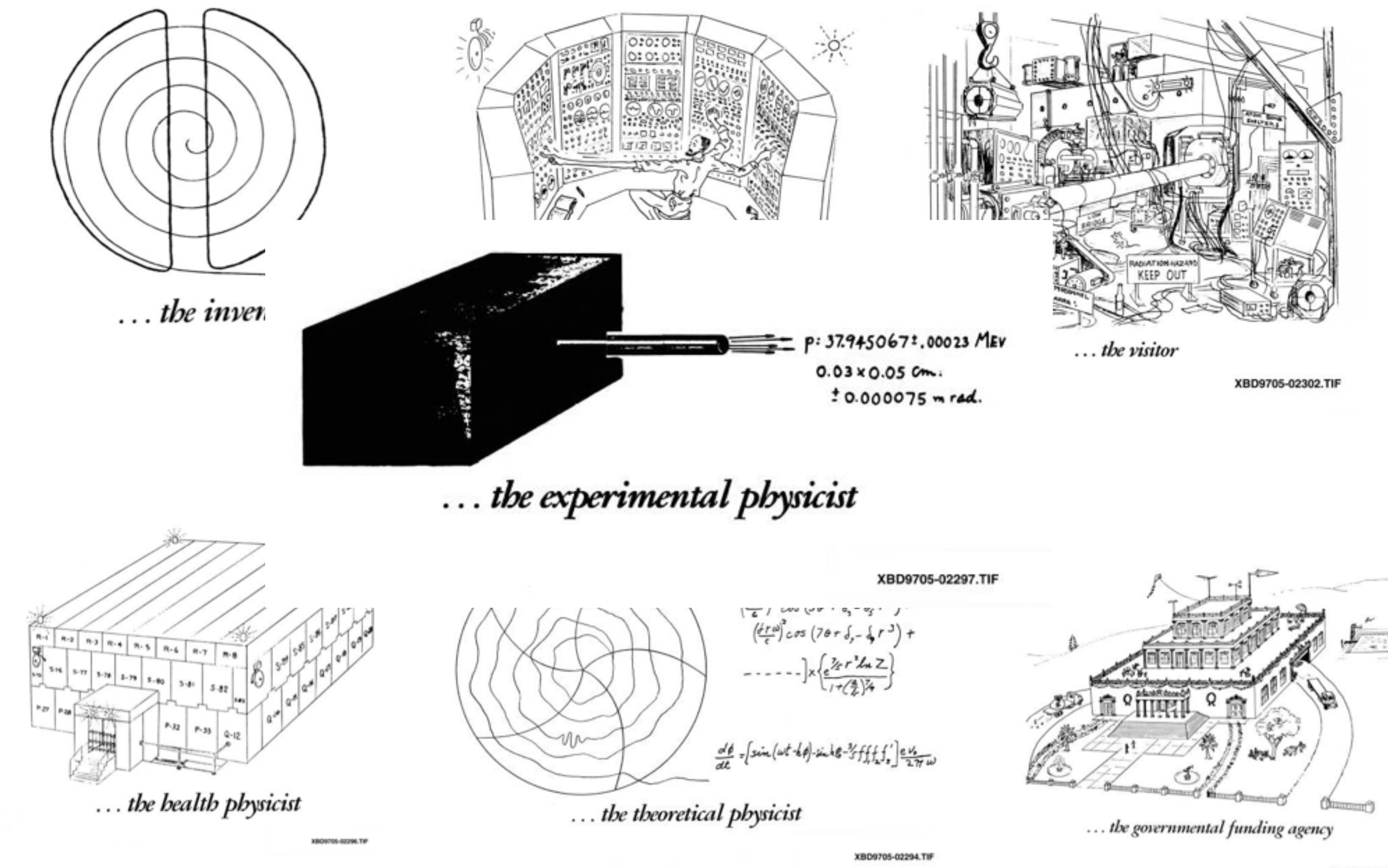
UNIVERSITY OF OXFORD

Science & Technology Facilities Council

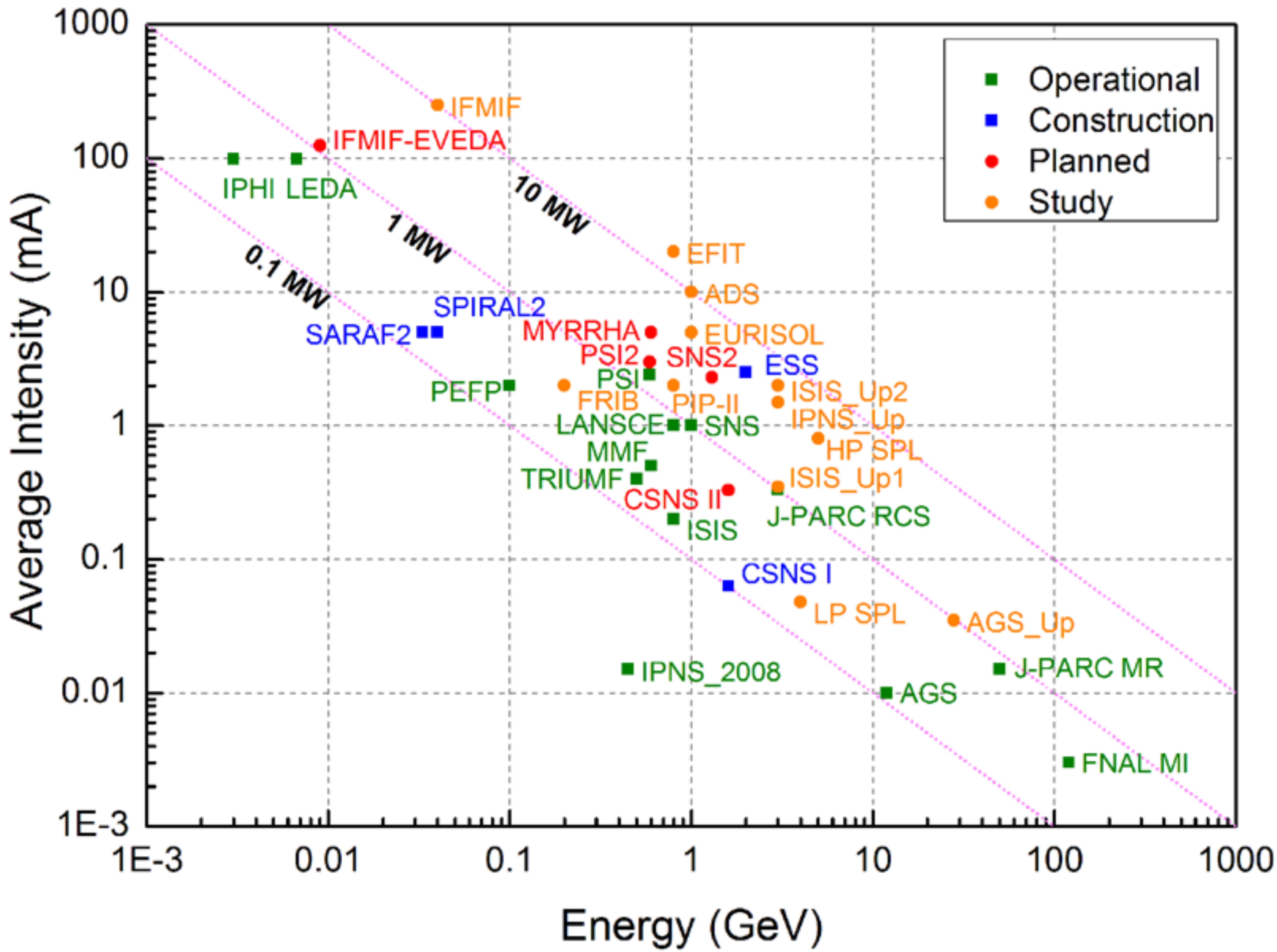
Outline

- Why accelerator physics?
- Challenges in high intensity accelerators
- A new technique to study beam dynamics
- Progress and status
- Future perspective

The accelerator, as seen by…

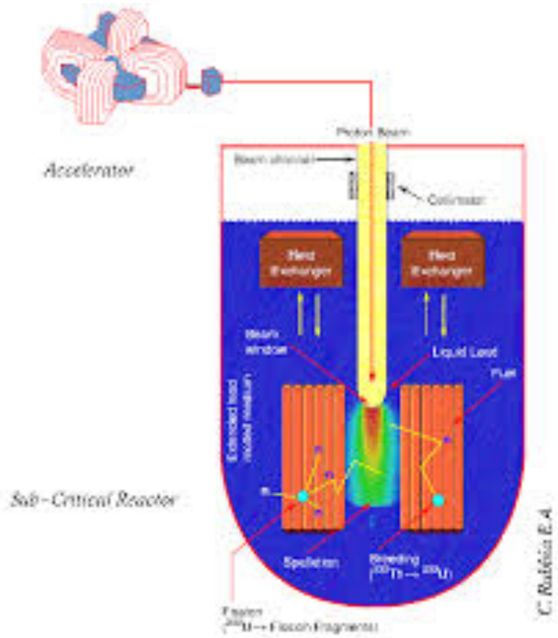


Cartoons by by Dave Judd and Ronn MacKenzie, taken from the Berkeley Lab On-line Photo Archive

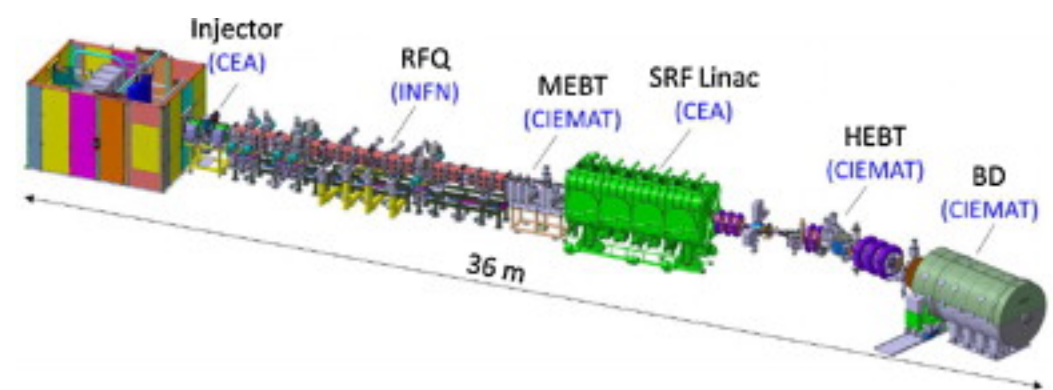


C. Plostinar, AccApp'17

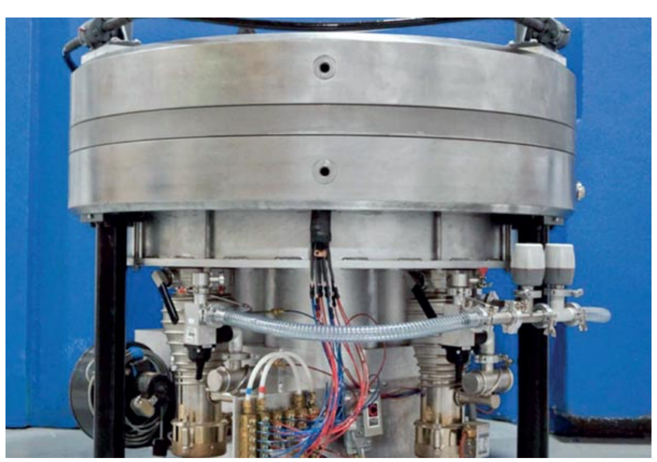
High intensity hadron beams in society & industry



Accelerator Driven Systems

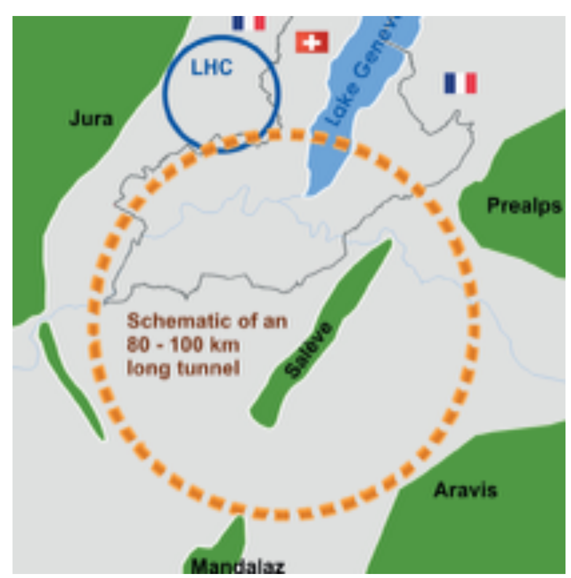


Fusion Material Irradiation Facilities



Radio-isotope production

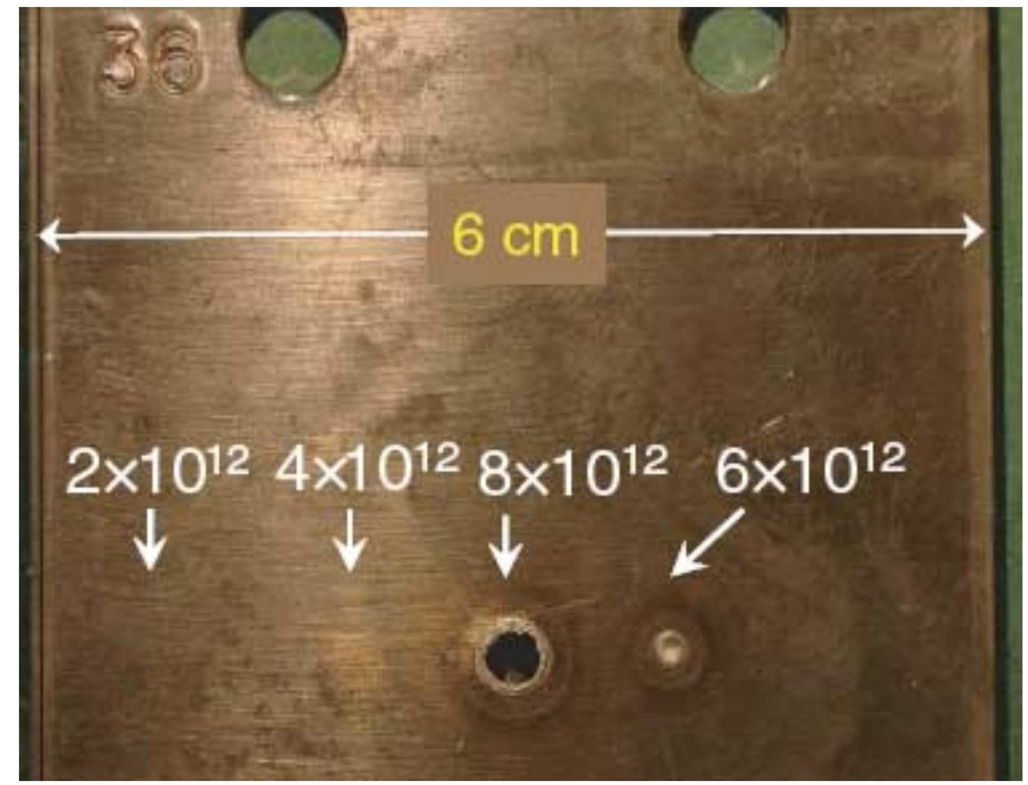
Next generation PP experiments
(FCC, HL-LHC), neutrinos, etc…



Neutron spallation sources
(ie. SNS, JPARC, ISIS, ESS)

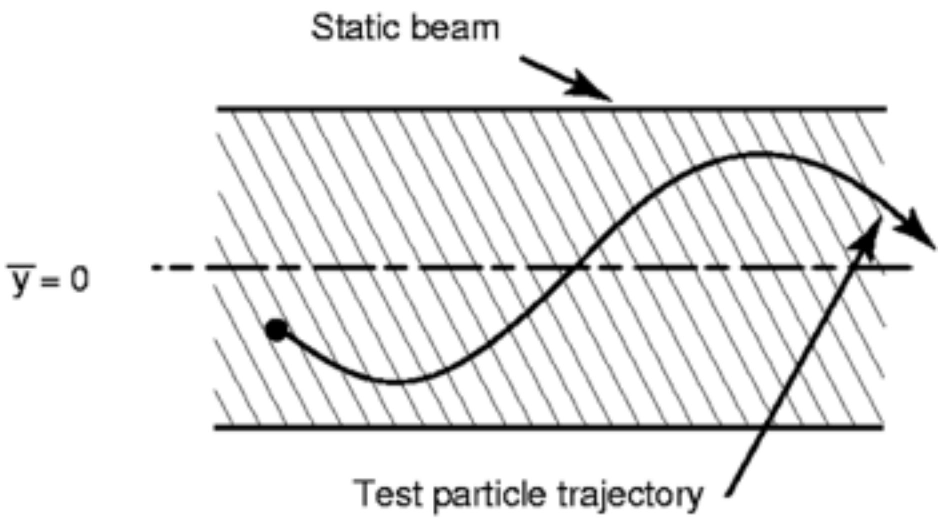
Challenges of High Intensity

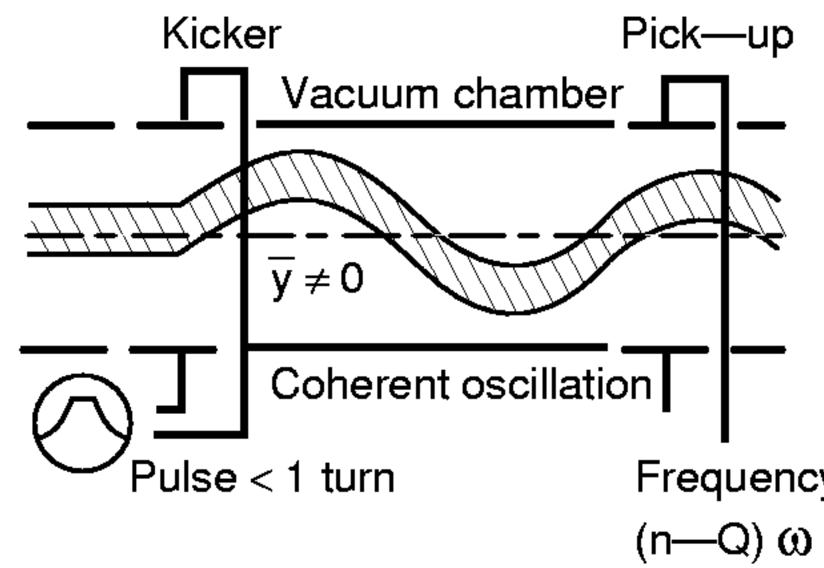
- Keep activation to 'hands-on' levels
- Challenging target technology
- Thermal and power management
- Space charge and instabilities
- Injection and extraction issues

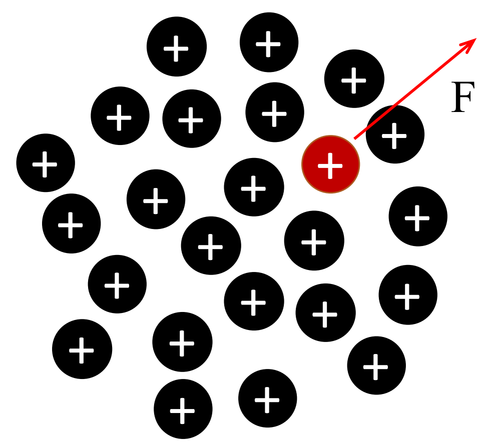


450 GeV proton beam on metal target
R. Schimdt et al, New J. Phys. 8 (2006) 290

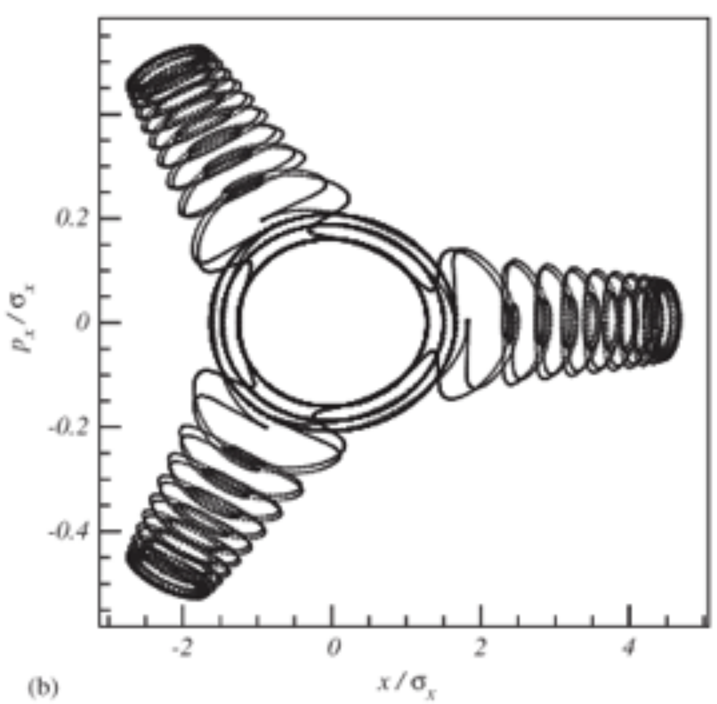
Coherent vs Incoherent



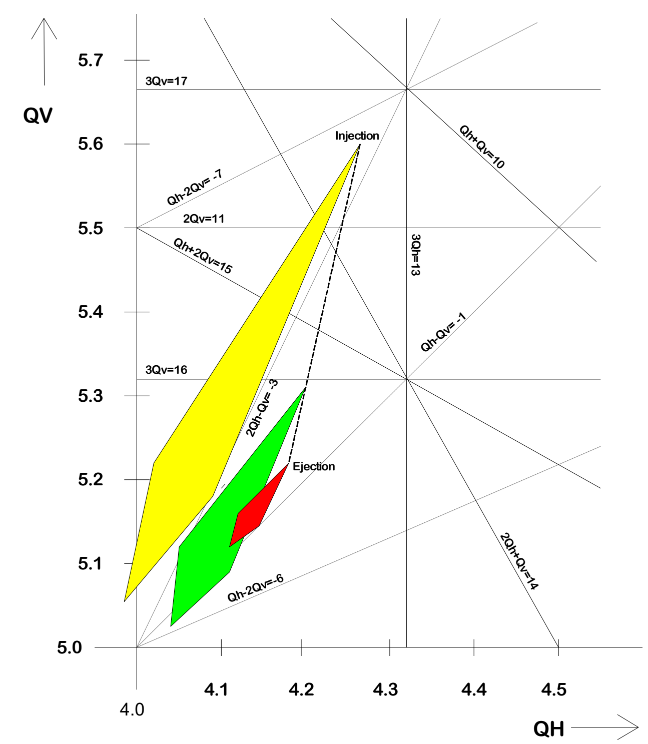




Beam Halo formation



Resonances, coupling and tune spreads



Why we want a new technique:

Study mechanisms of beam loss

As many particles as we like with all interactions

Vary over a wide parameter space

Detailed and systematic studies of resonances (at high intensity)

↔

Without losing beam (radiation)

In a short time

Without re-building an expensive machine each time

Without the complexities and errors of real machines

Paul trap for beam dynamics

*“It is the skill of the experimentalist to carry out clear experiments in order to get answers to [her] questions undisturbed by undesired effects and it is [her] ingenuity to improve the art of measuring to ever higher precision” **

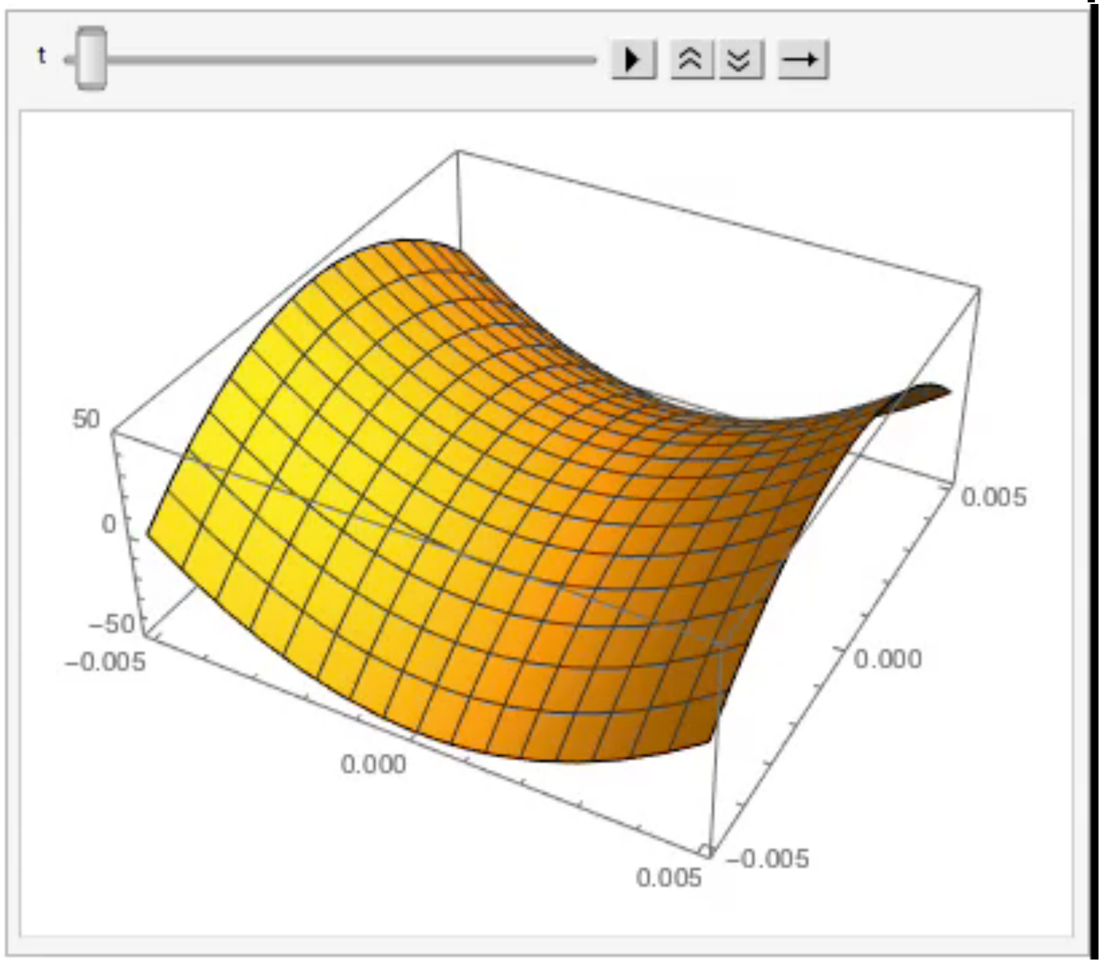
– Wolfgang Paul, Nobel Lecture, December 1989

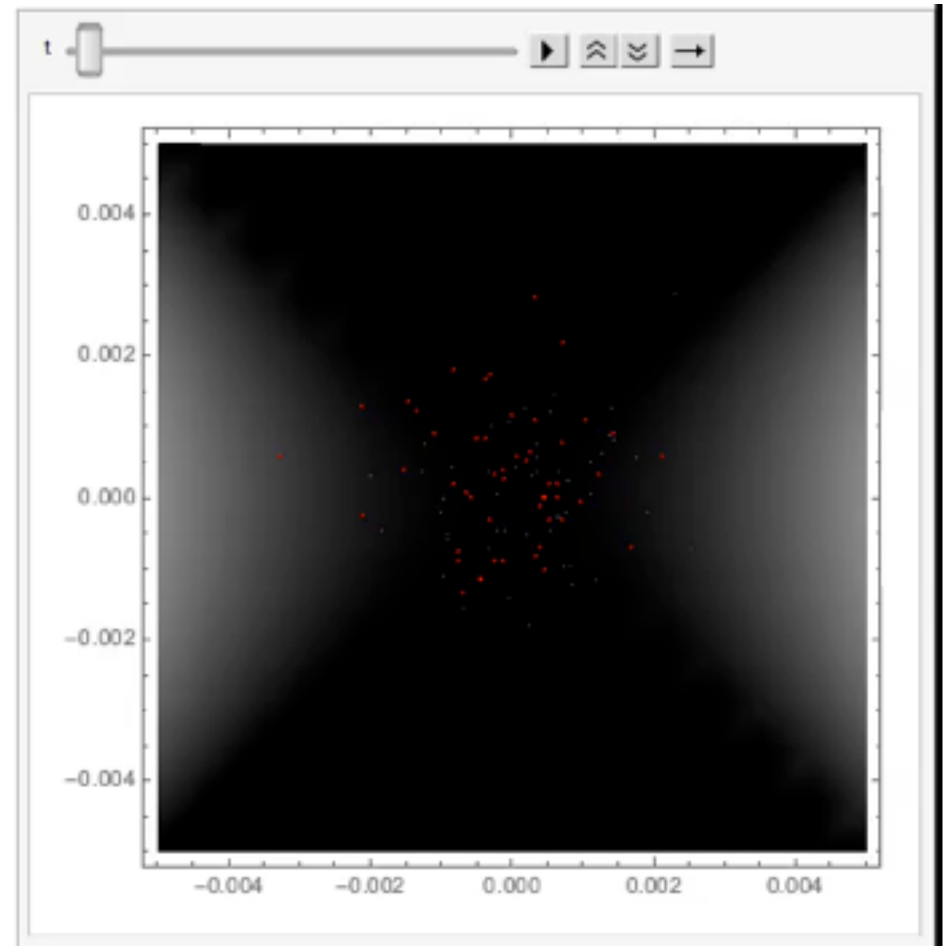
“The idea of building traps grew out of molecular beam physics, mass spectrometry and particle accelerator physics that I was involved in during the first decade of my career”

*Where “her” is understood to refer to any person in the sense that “his” was originally used

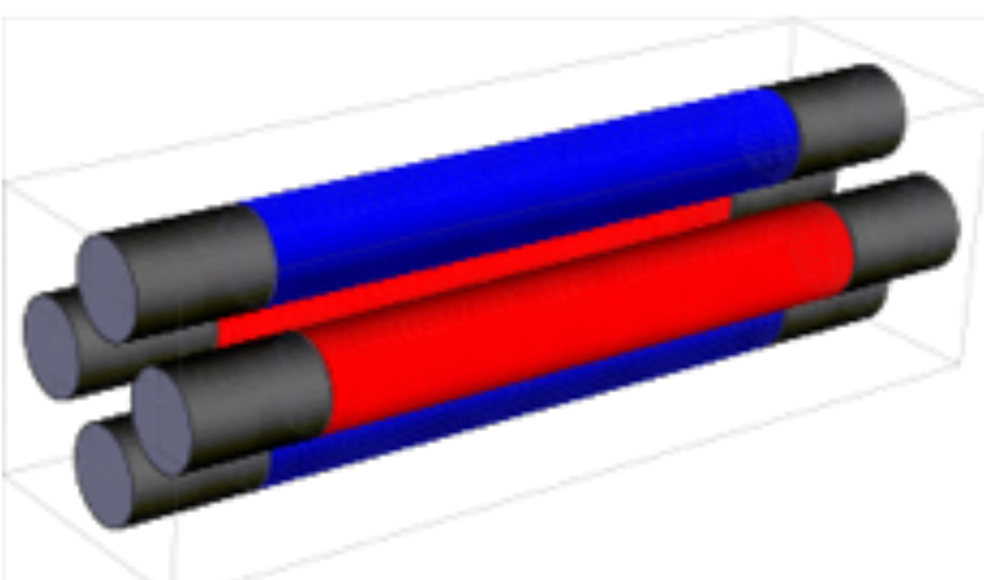
Thanks to L. Martin for simulations

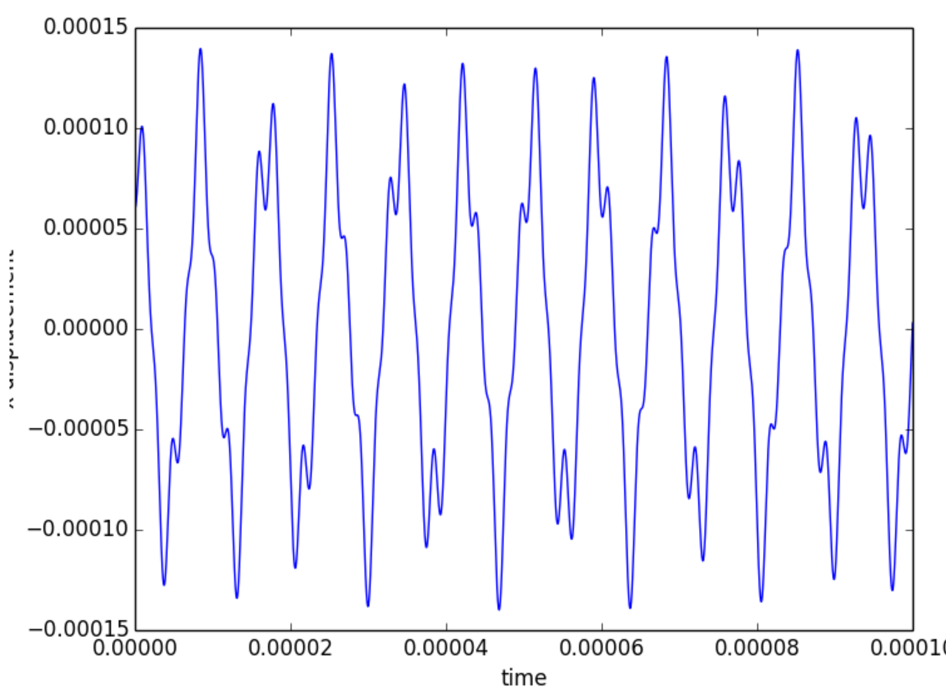
Potentials & particle motion





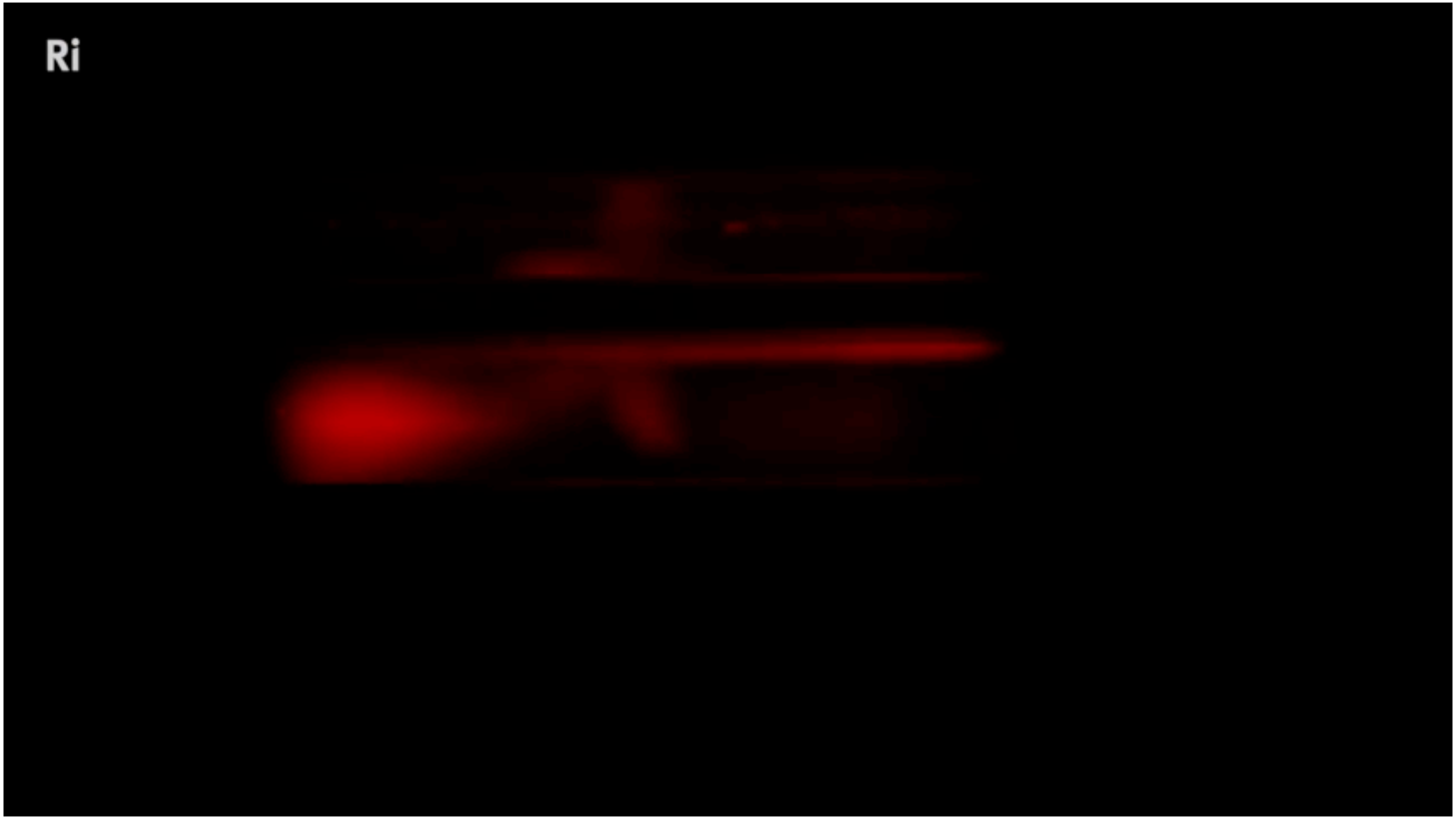
Quadrupole trapping potential varies with time





From “How to trap particles in a particle accelerator” video

(nb. these are pollen grains, not ions!)



http://richannel.org/collections/2016/particle-accelerators-for-humanity

The Royal Institution
Science Lives Here

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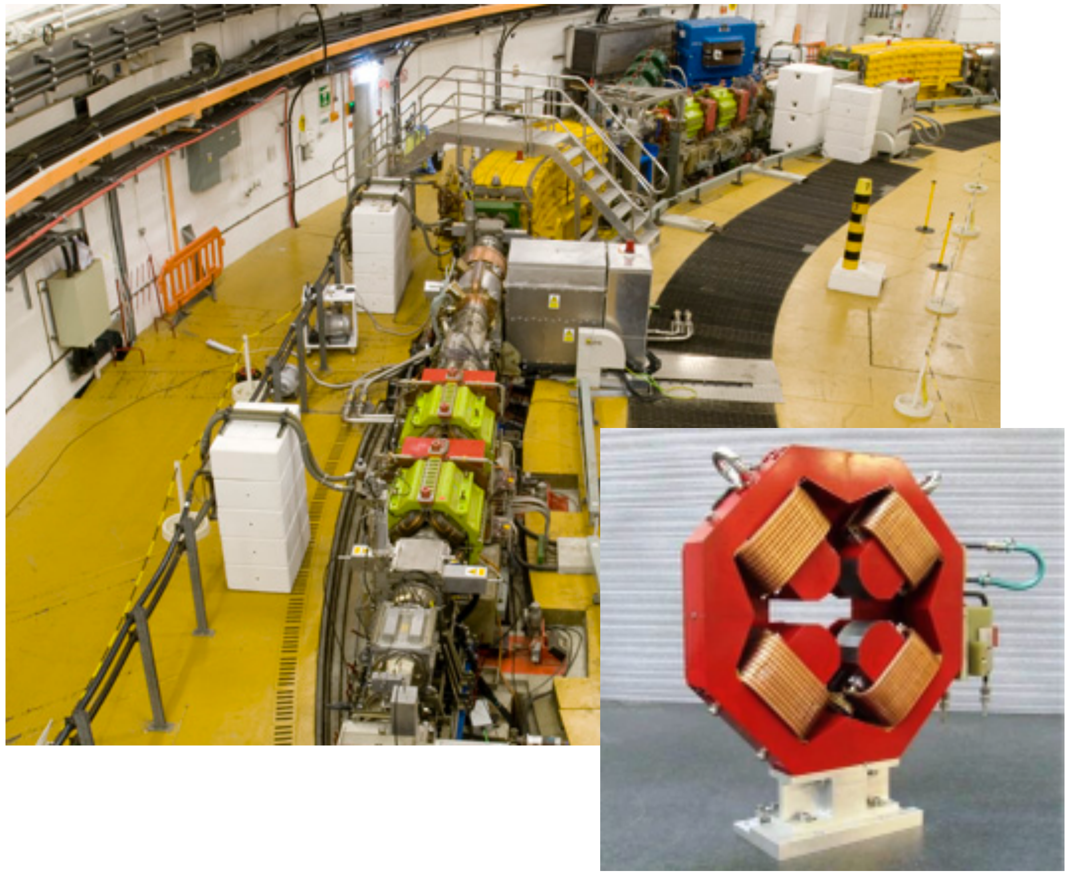
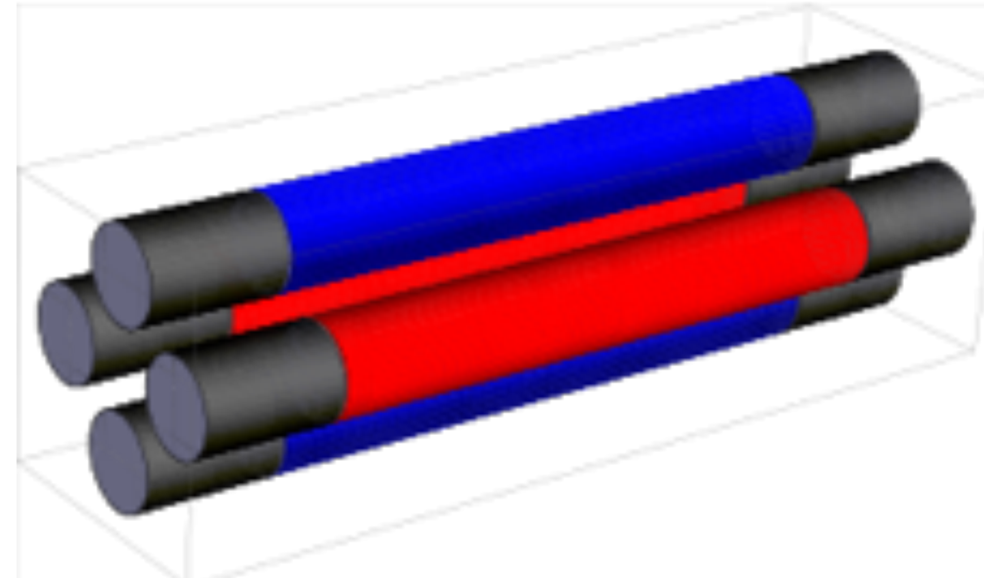




$$H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K(s)(x^2 - y^2) + \frac{q}{p_0\beta_0 c\gamma_0^2}\phi$$

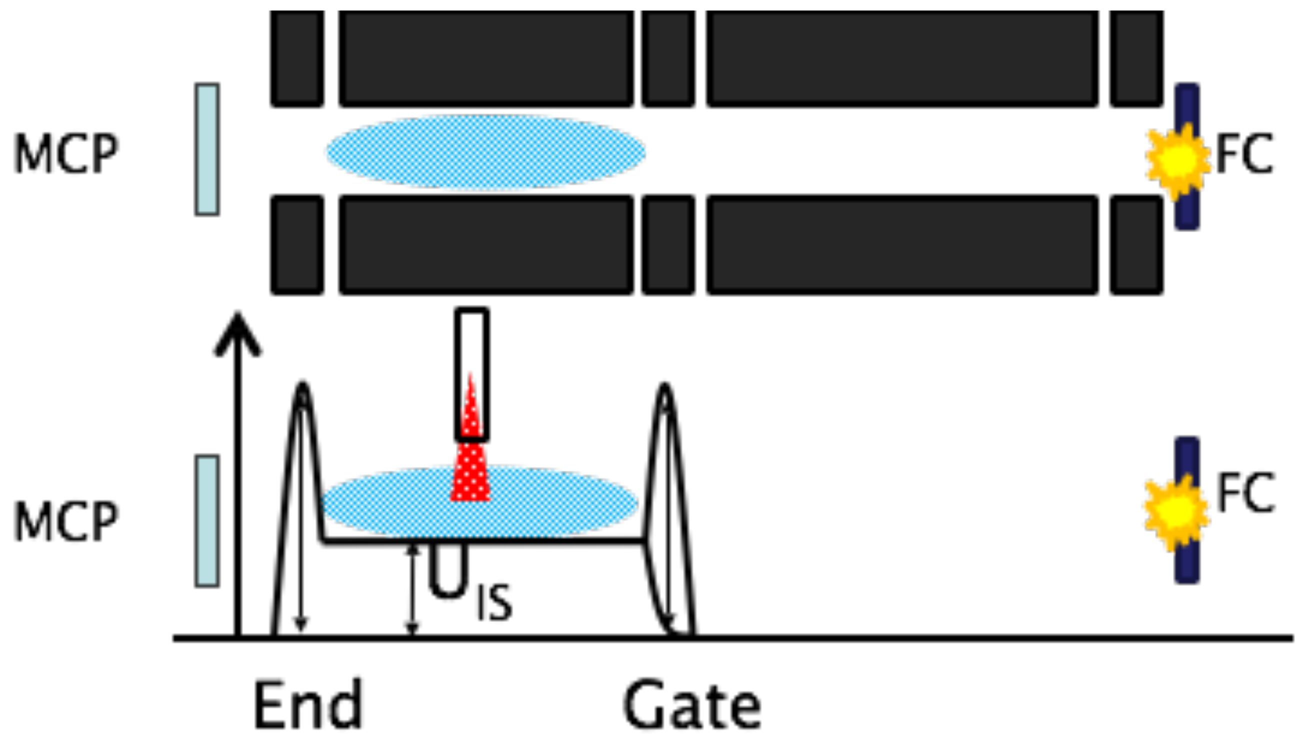
Hamiltonian for transverse beam motion

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

Hamiltonian for Paul trap

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

S-POD: Simulator of Particle Orbit Dynamics at Hiroshima University

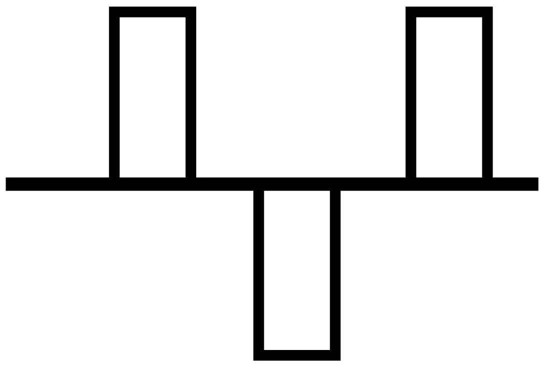


Argon gas ionised by e- gun

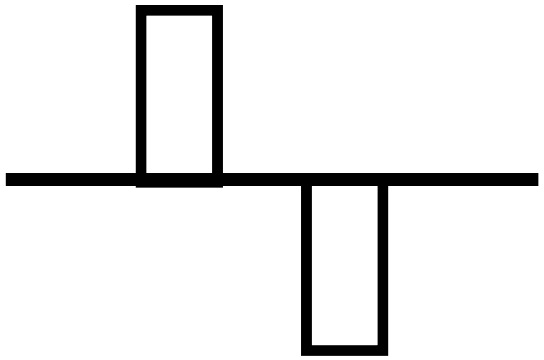
H. Okamoto, Y. Wada, and R. Takai, “Radio-frequency quadrupole trap as a tool for experimental beam physics,” Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 485, no. 3, pp. 244–254, 2002.

Lattice Structures

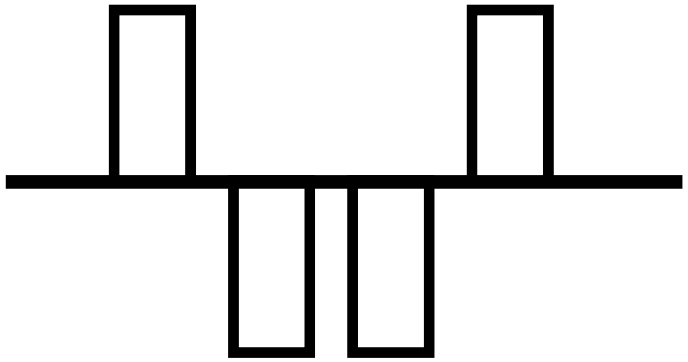
FDF



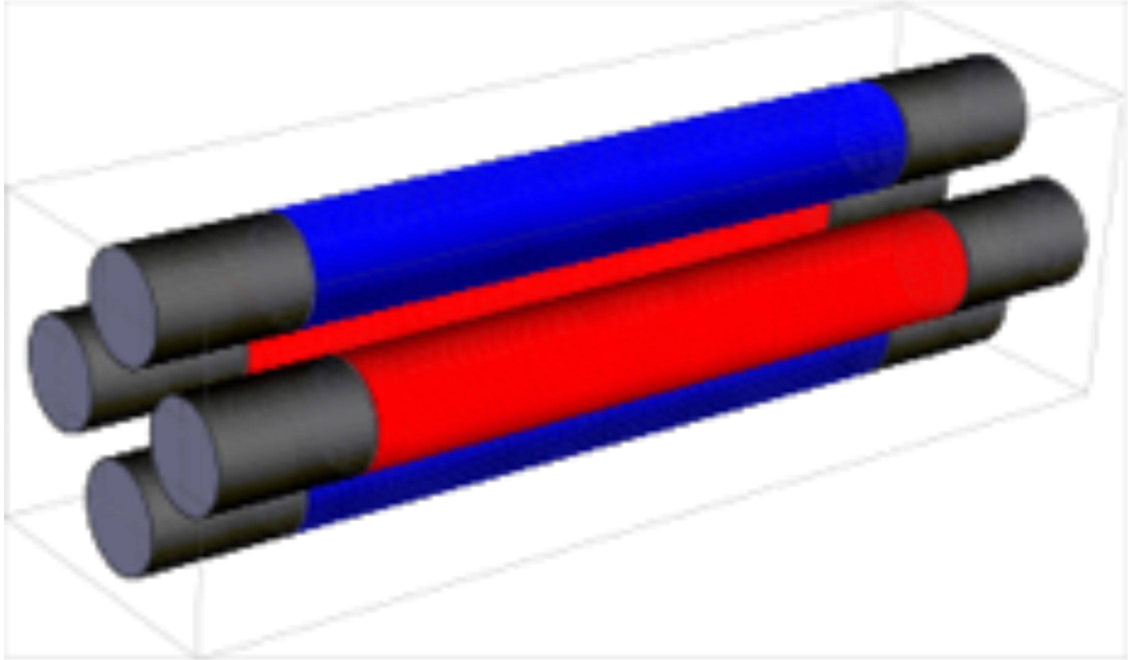
FODO

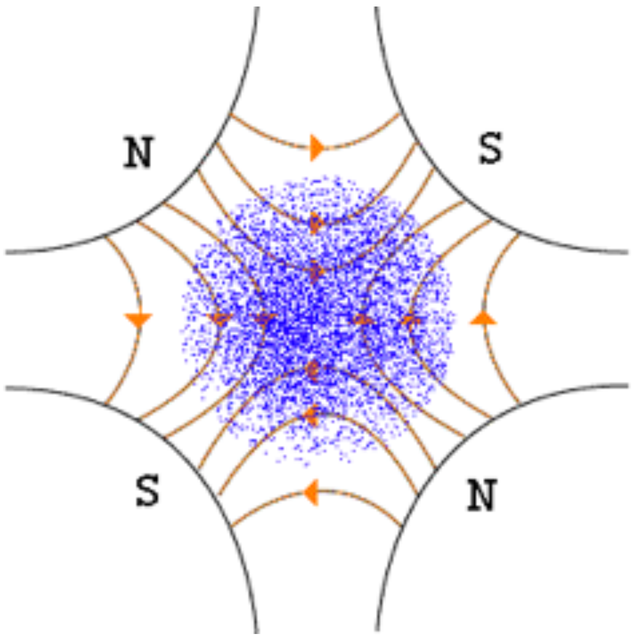


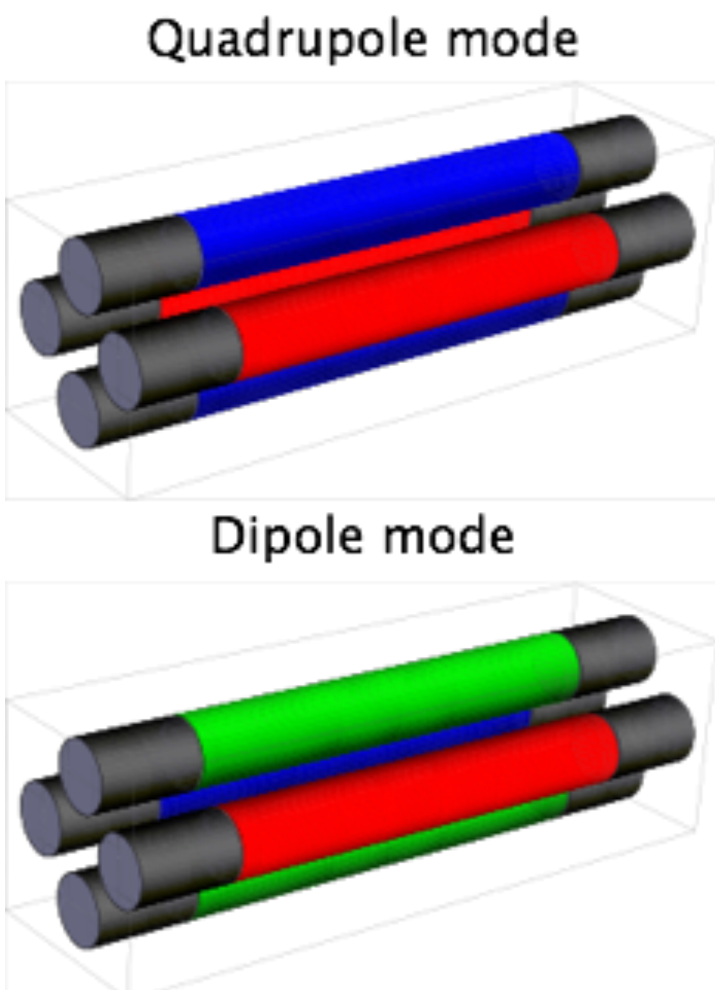
FDDF



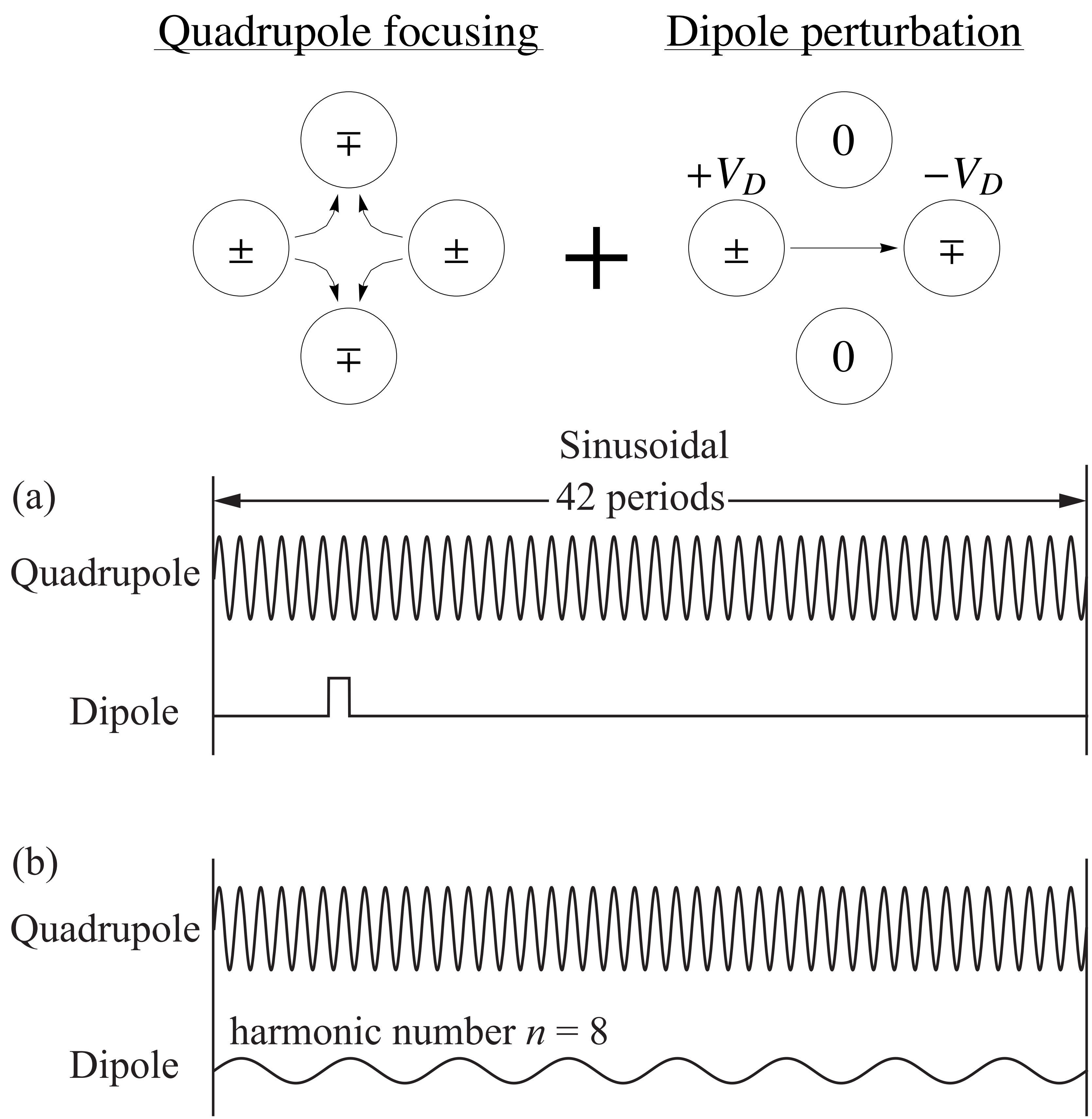
Quadrupole mode





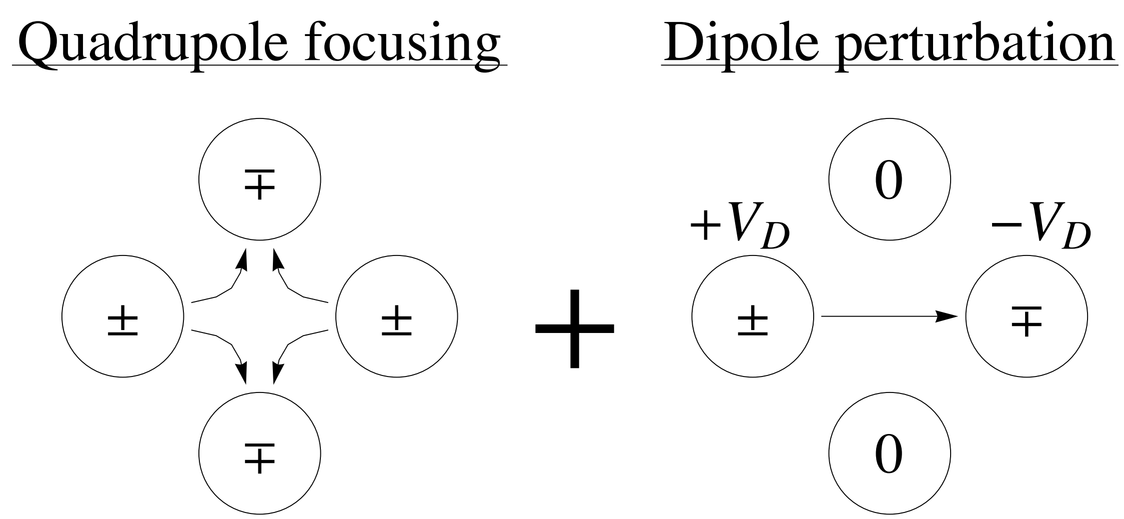


Quadrupole mode
Dipole mode



Quadrupole focusing
Dipole perturbation
∓
±
±
∓
+
0
$+V_D$
$-V_D$
±
∓
0
Sinusoidal
(a)
42 periods
Quadrupole
Dipole
(b)
Quadrupole
harmonic number $n = 8$
Dipole

Motion with dipole perturbation



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

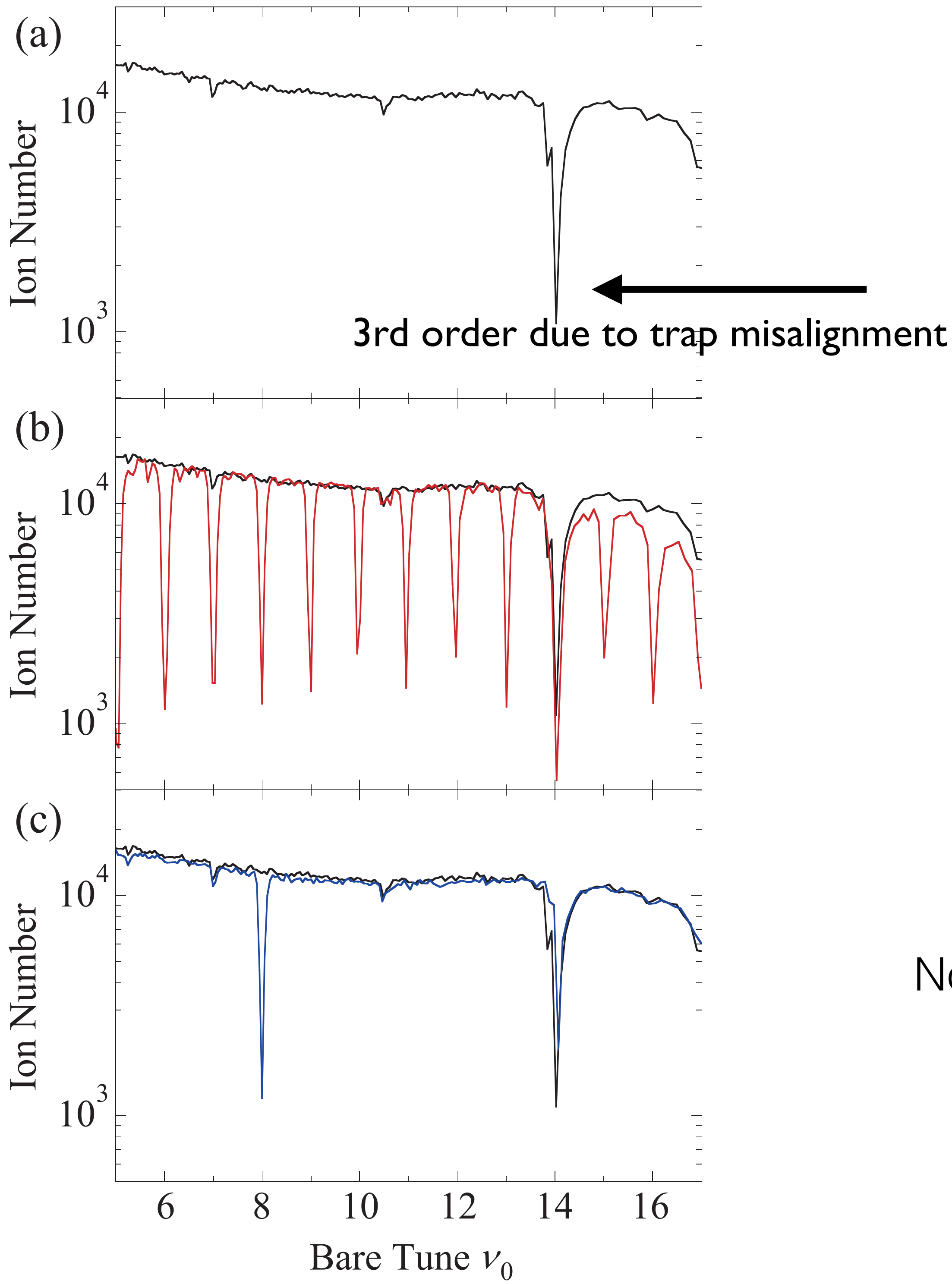
COD equation of motion in circular accelerator

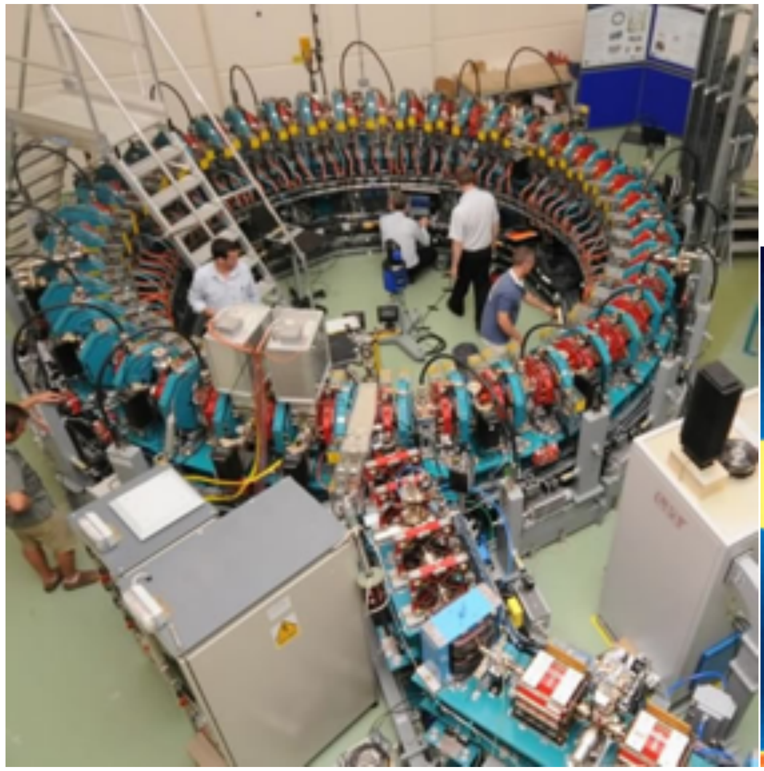
↔

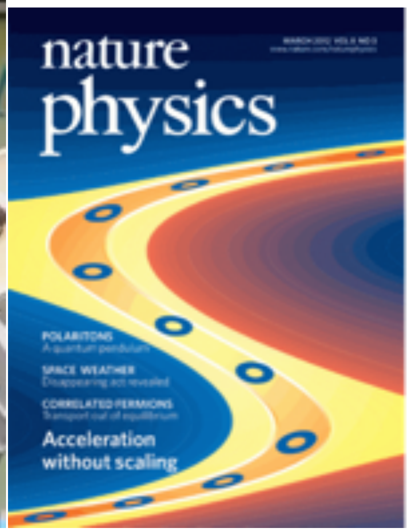
$$\frac{d^2 x}{d\tau^2} + K_{rf}(\tau) x = -\frac{q}{mc^2 r_0} V_D(\tau)$$

Equation of motion in S-POD with dipole perturbation field

Establishing integer stopbands with dipole perturbation







EMMA - world's first non-scaling FFAG
Crosses integer resonances during acceleration

Note that we can excite each integer individually by expanding dipole field into fourier harmonics:

$$\frac{\Delta B}{B\rho} = \sum_n b_n \cos(n\theta + \phi)$$

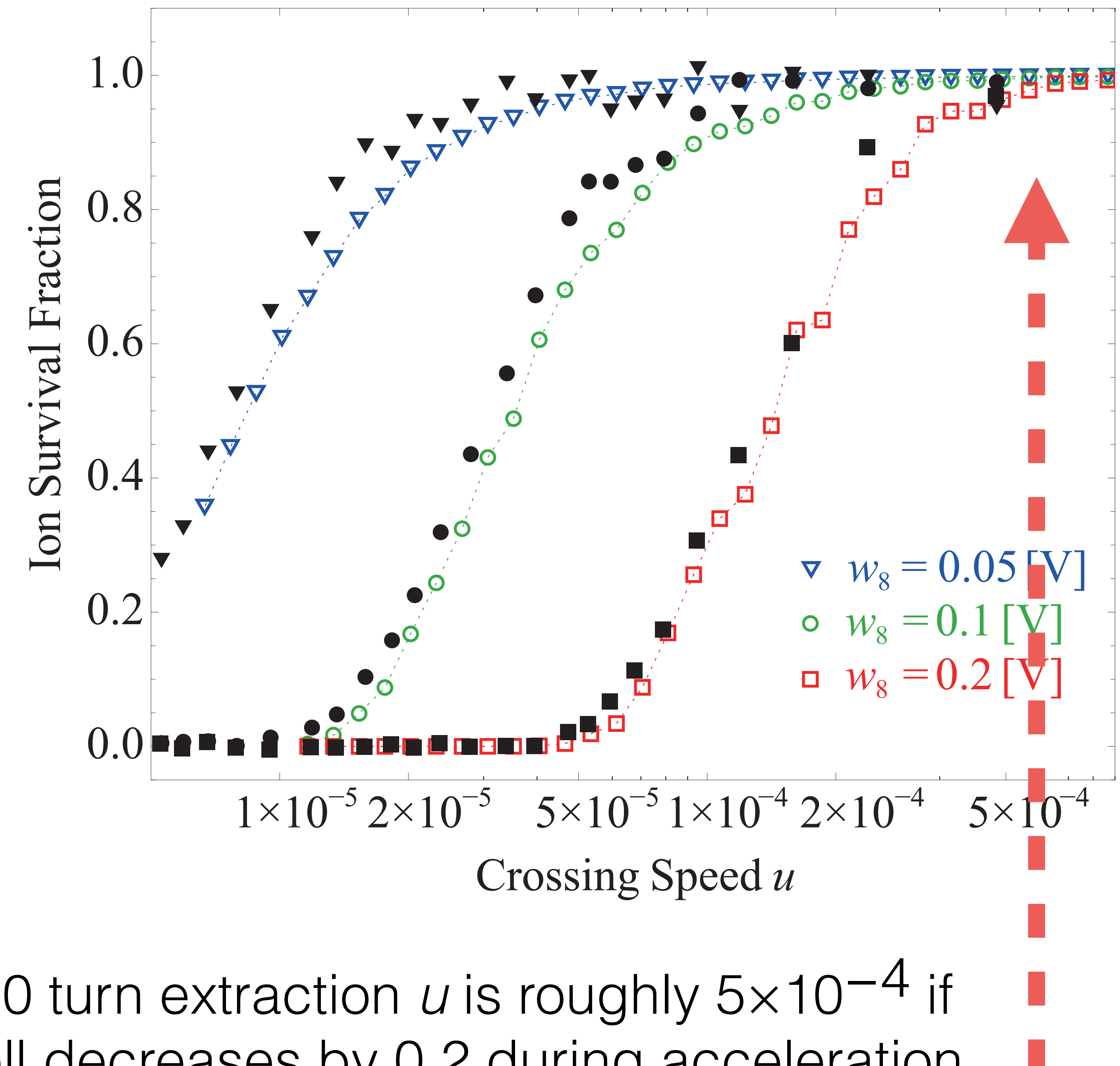
K. Moriya, K. Fukushima, K. Ito, T. Okano, H. Okamoto, S. L. Sheehy, D. J. Kelliher, S. Machida, and C. R. Prior, *Experimental study of integer resonance crossing in a non-scaling fixed field alternating gradient accelerator with a Paul ion trap*, Phys. Rev. ST-AB 18, 034001, March 2015.

Example: Single resonance crossing

8th harmonic excited
Tune varied 9.5 -> 7.5

crossing speed, $u = \dfrac{\delta\nu_{\text{cell}}}{n_{\text{rf}}}$

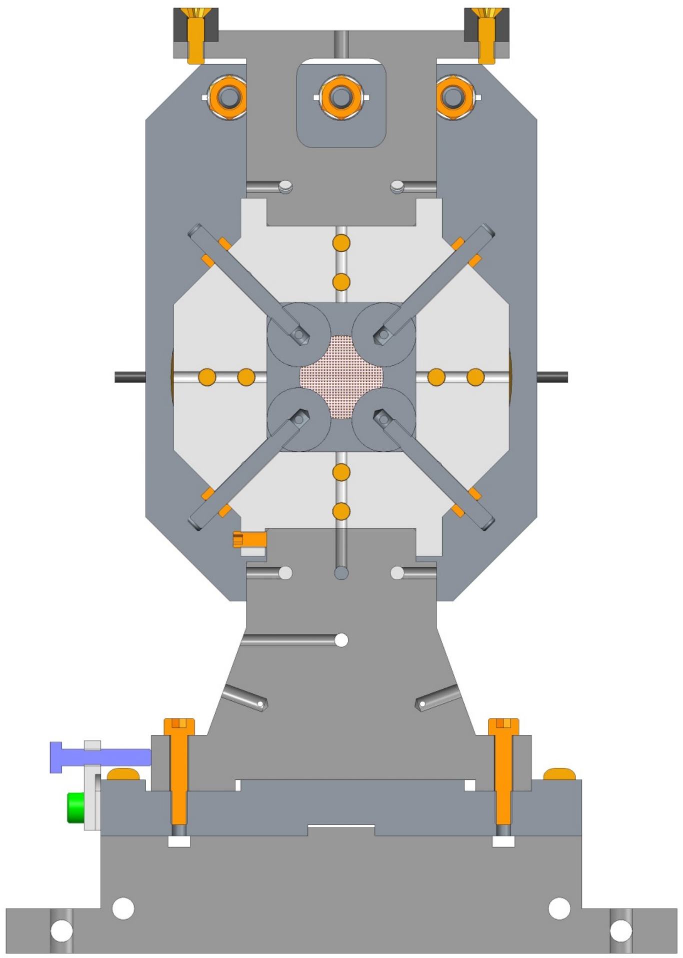
"We can cross integer resonances if acceleration is fast enough"

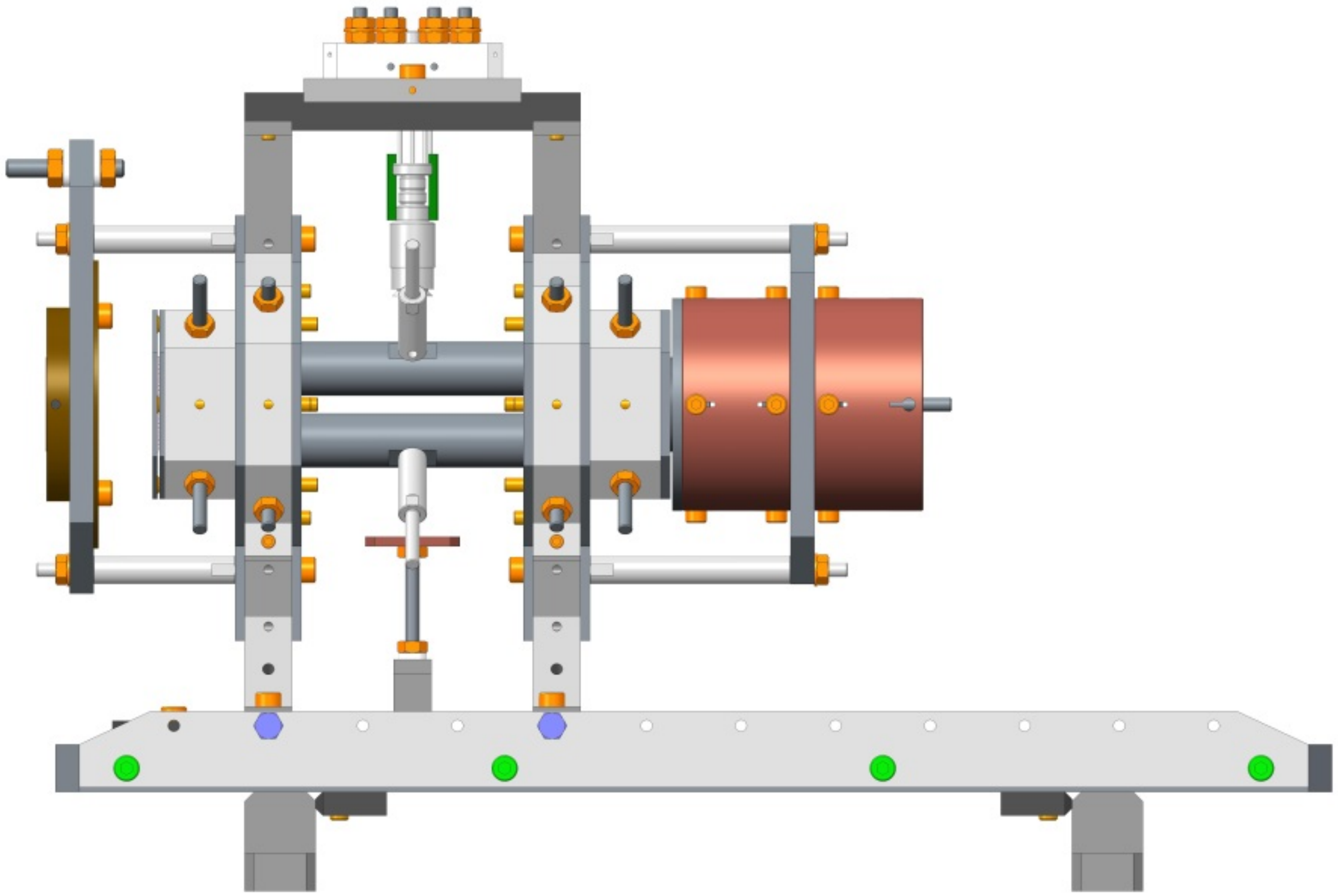


In EMMA, for 10 turn extraction u is roughly $5{\times}10^{-4}$ if the tune per cell decreases by 0.2 during acceleration

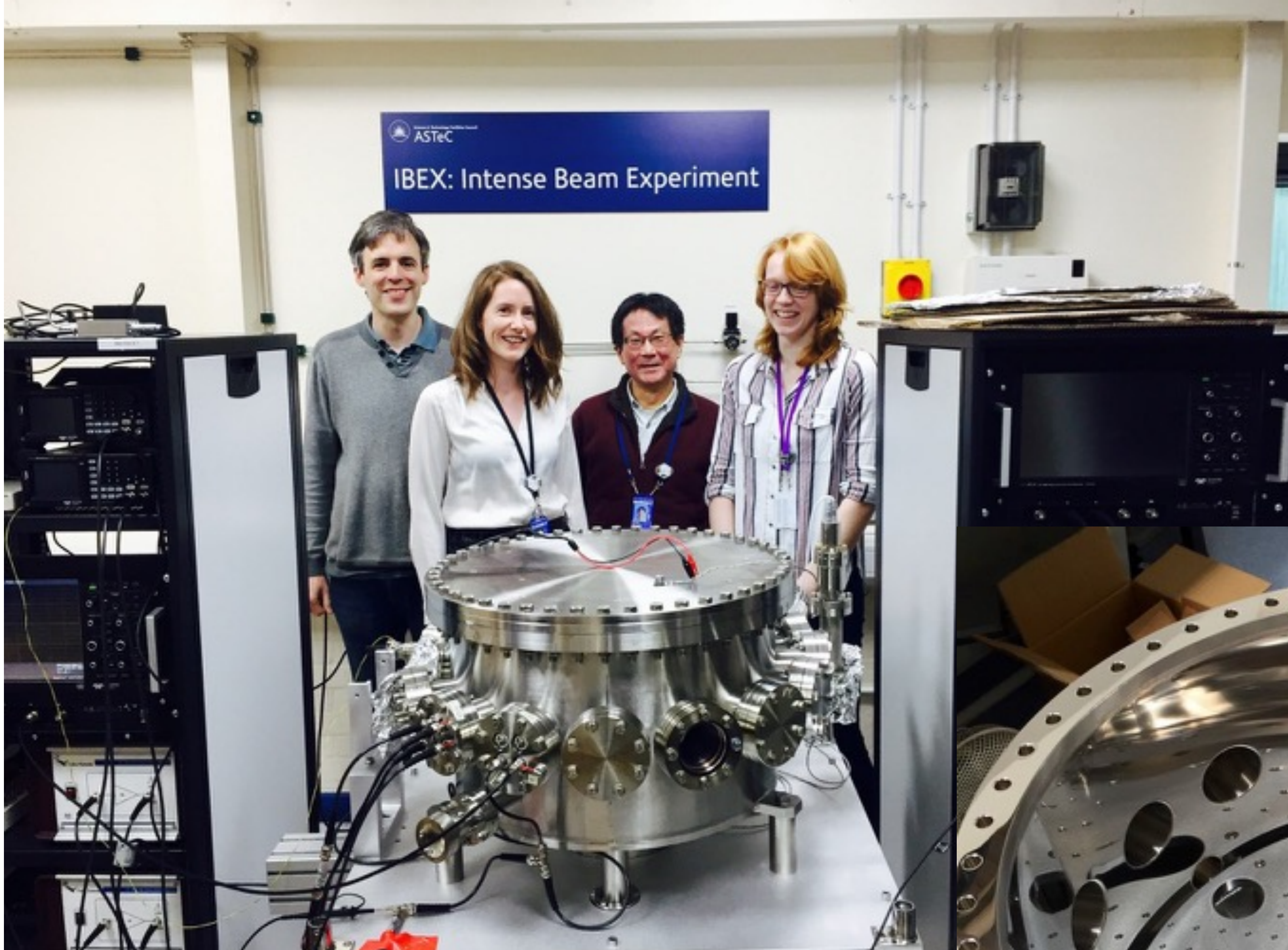
IBEX: Intense Beam Experiment

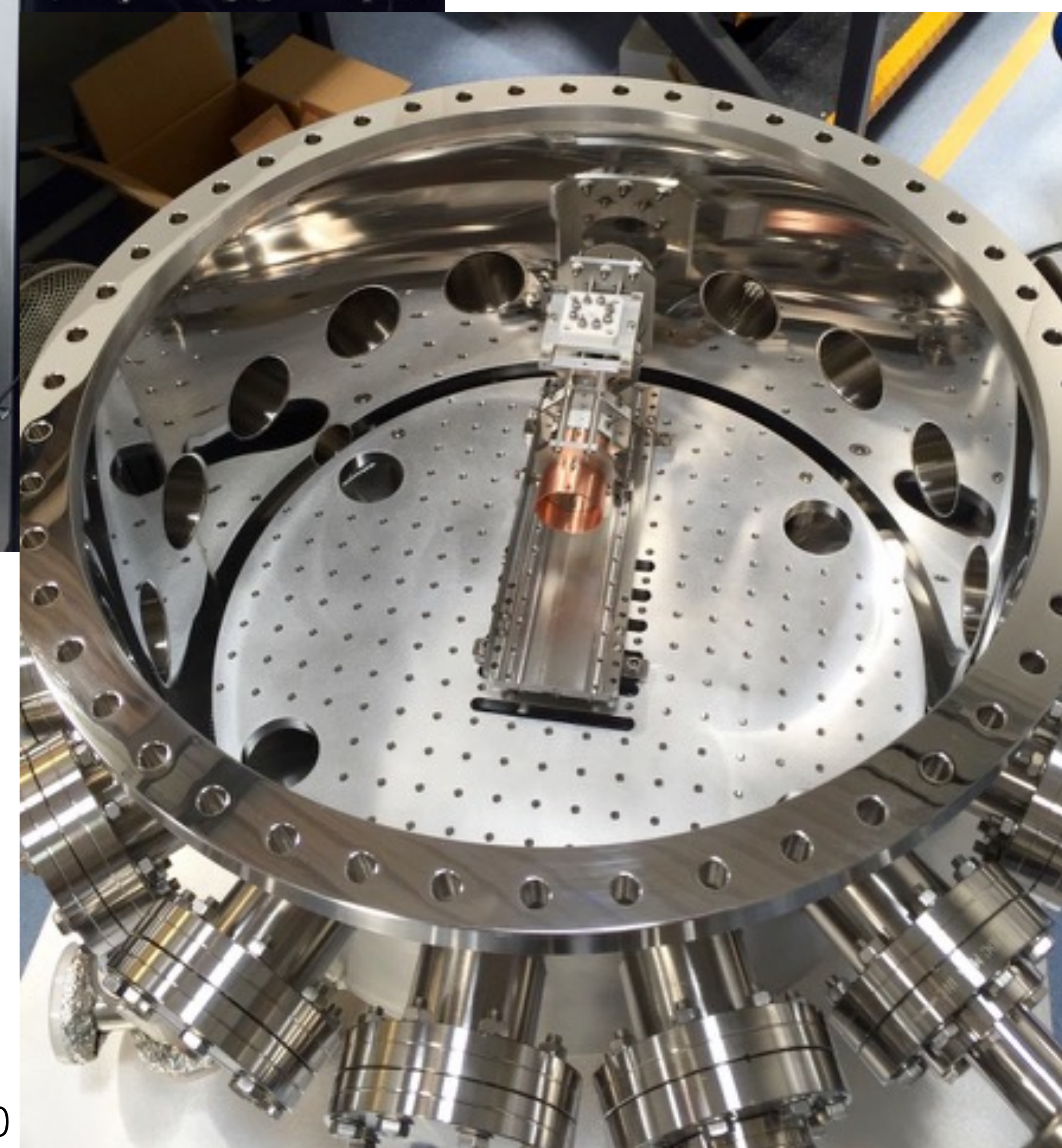
at STFC/RAL/UK





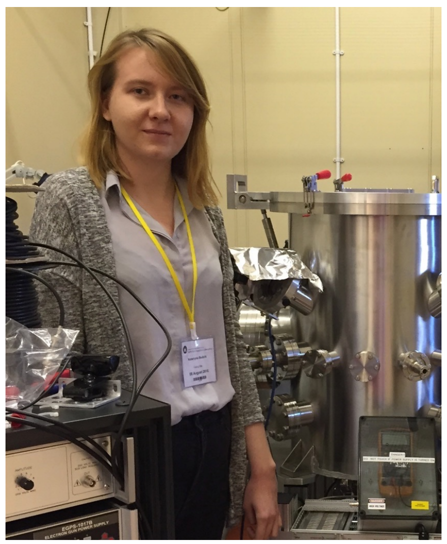
Images courtesy Technology at STFC Daresbury Laboratory


ASTeC
IBEX: Intense Beam Experiment

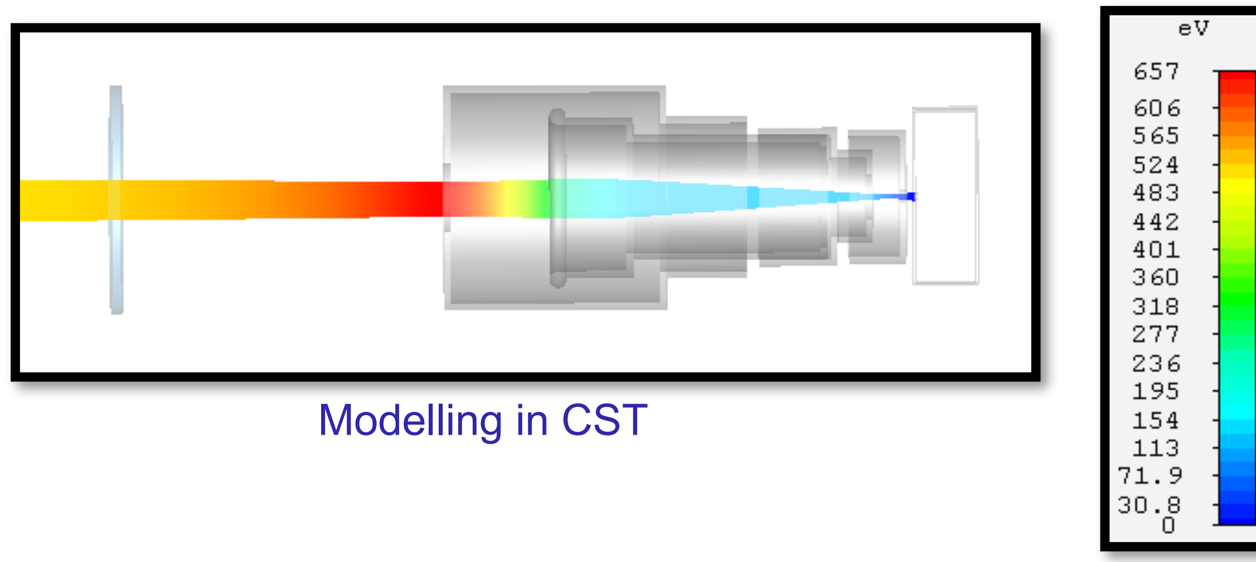


Commissioning

- Characterize electron gun (K. Budzik, summer student 2016)

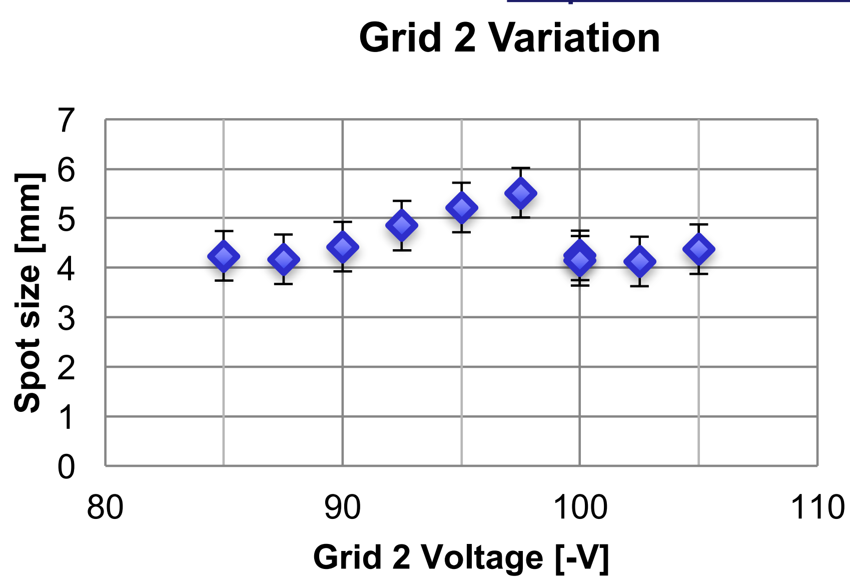


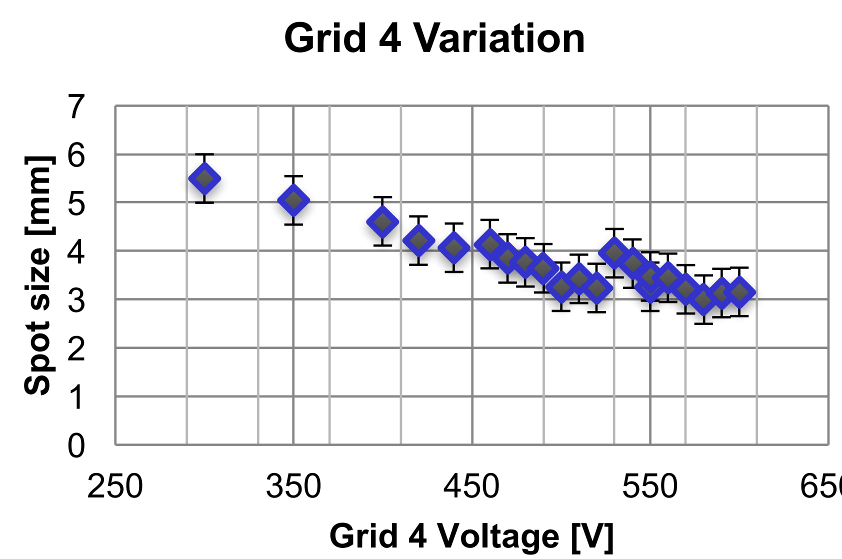
Kasia working with ISIS diagnostic group vessel on electron gun tests



Modelling in CST

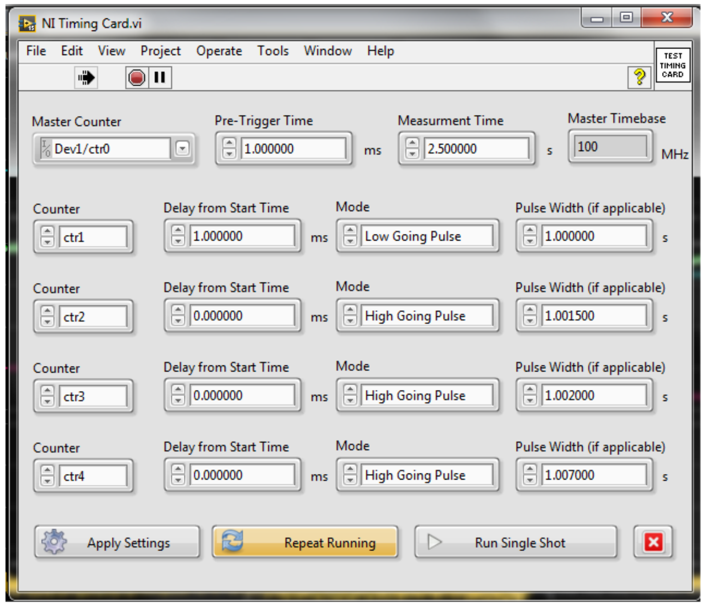
Experimental result: beam spot size tests

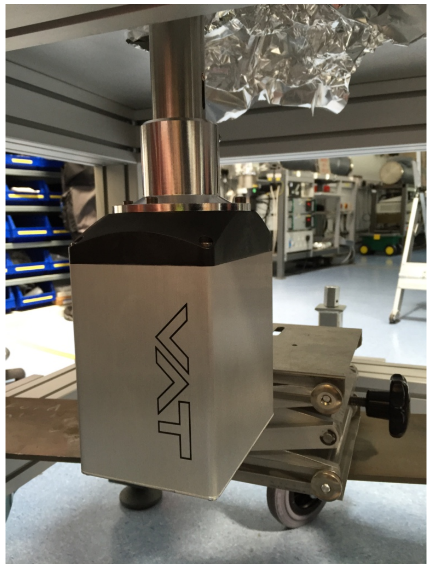


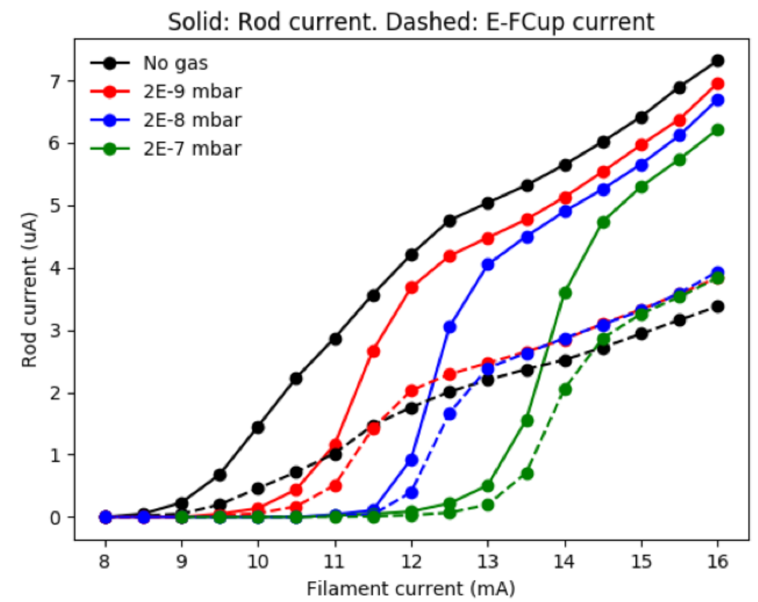


Commissioning

- ✓ Timing: PCIe card for trigger
- ✓ E-gun: sufficient current
- ✓ Argon gas: VAT leak valve
- ✓ Vrf & Vdc: AWG & amplifiers
- ✓ End cap: fast switch
- ✓ FC readout: to oscilloscope

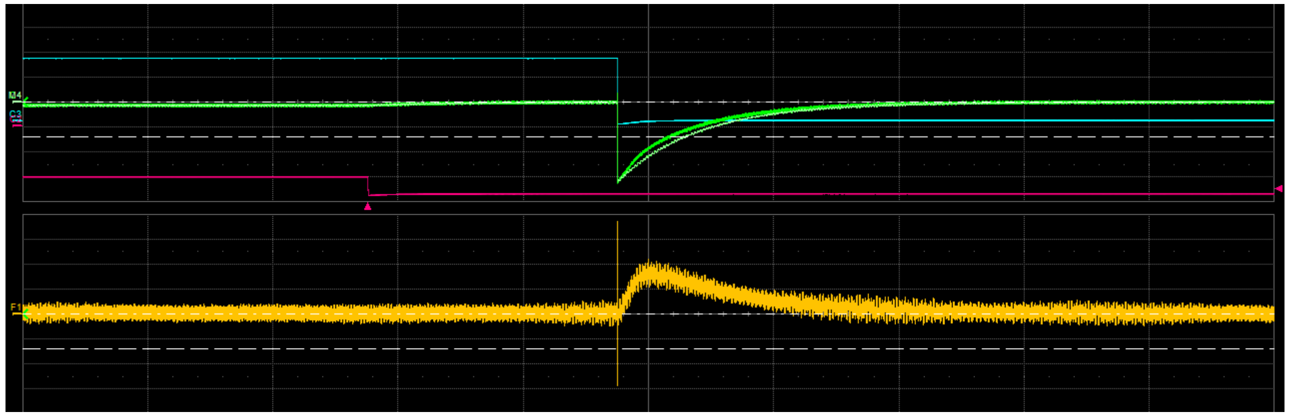






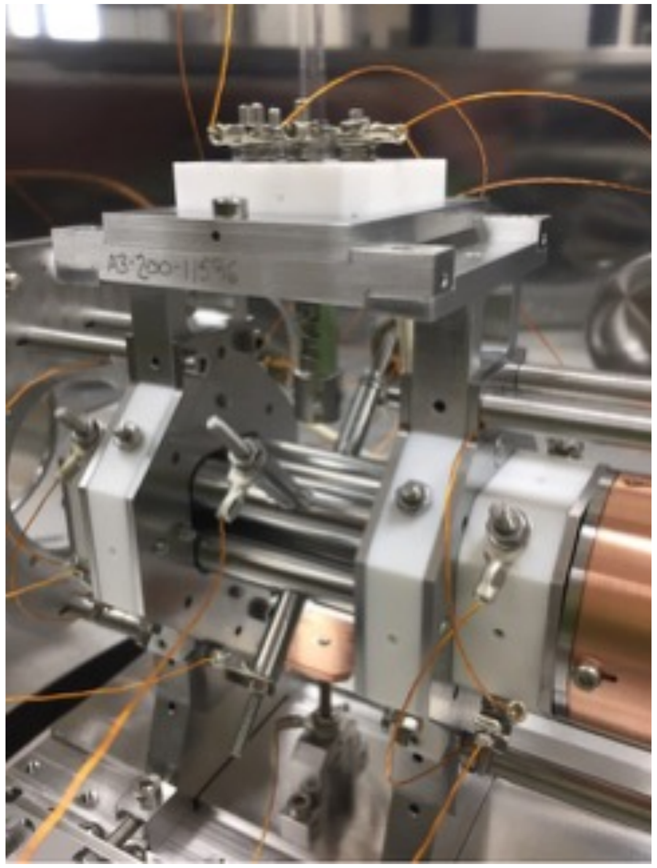
eGun conditioned just once at base pressure, then study undertaken.

First ‘beam’ January 2017

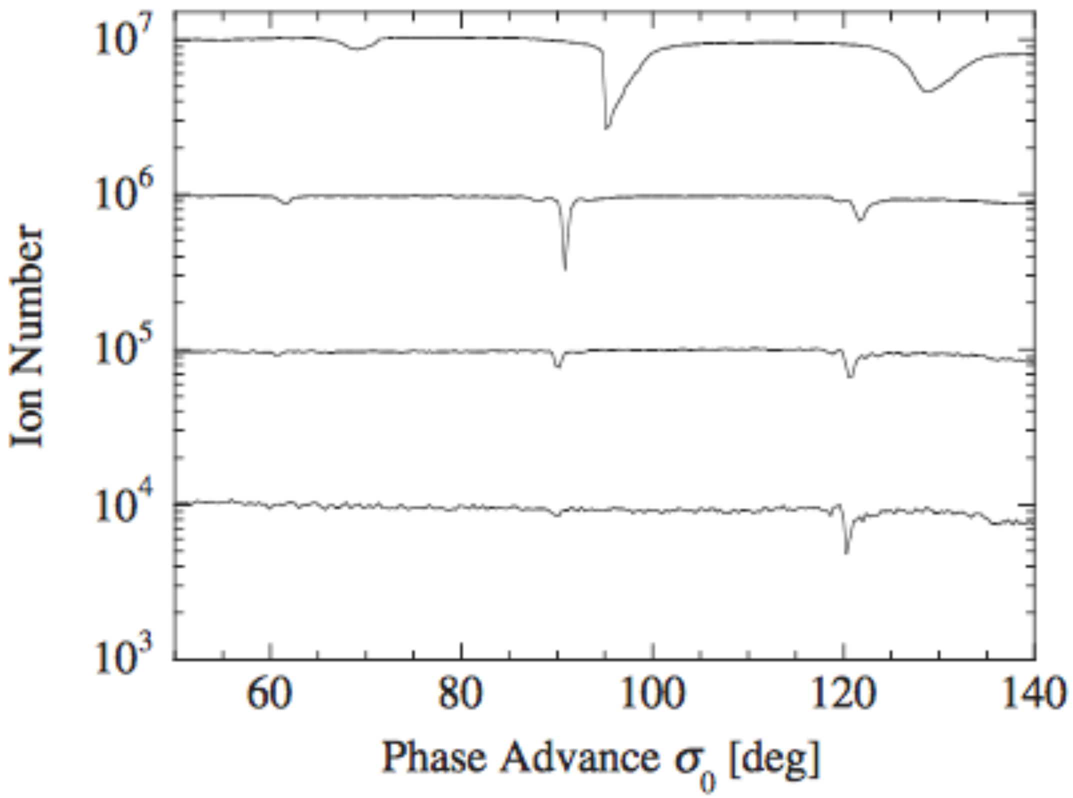


Timing signals

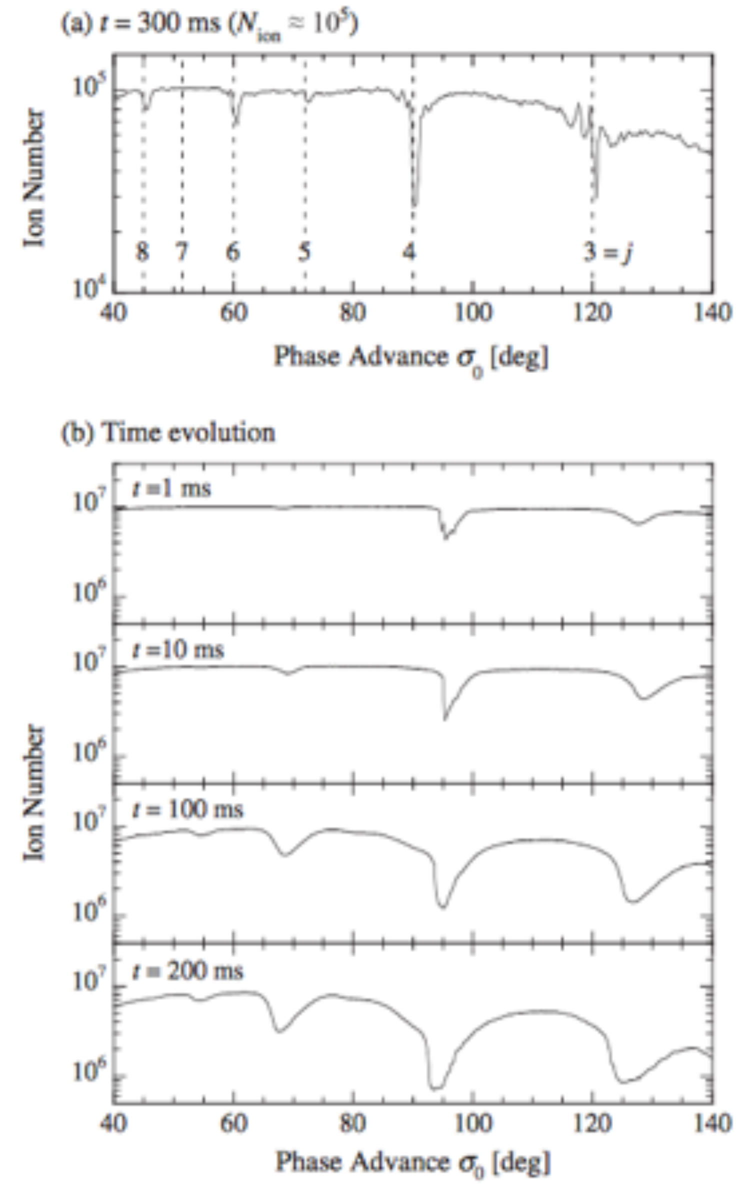
Faraday cup signal (ions!)



Next studies: systematic study of coherent vs incoherent resonances



Ion-loss distributions measured in S-POD with the symmetric FODO potential, 10ms wait. (Fig 7 from paper below)



Long term ion loss stop bands in S-POD Fig. 14 from paper below

K. Ito, H. Okamoto, Y. Tokashiki, and K. Fukushima, “Coherent resonance stop bands in alternating gradient beam transport,” Phys. Rev. Accel. Beams, vol. 20, no. 6, p. 64201, Jun. 2017.

The growing list of research topics…

This technique has wide-ranging applications and will allow us to establish understanding in beam dynamics topics which are vital for the design of future high power proton or ion accelerators.

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

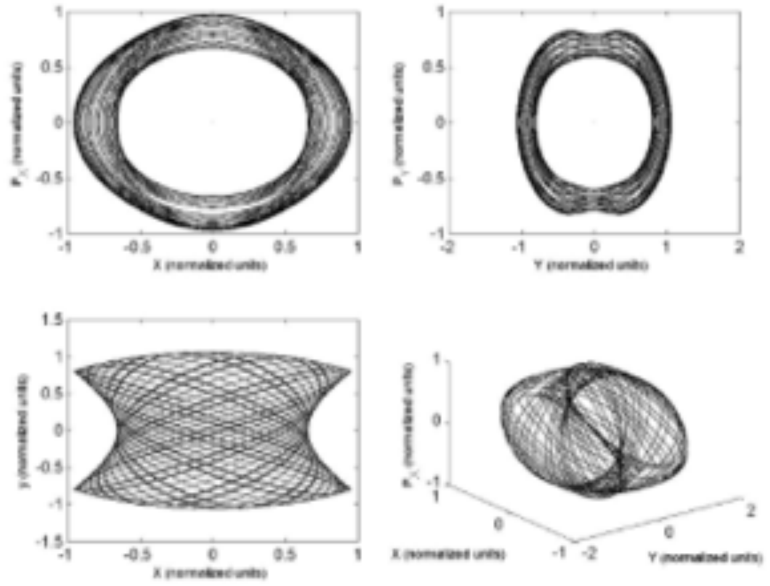
More info D. Kelliher, in Proceedings of IPAC 2015.

Toward future (high intensity) accelerators…
Non-linear Integrable Optics (NIO)

- Hamiltonian in conventional accelerator 'linear' is integrable

$$H(J_1,J_2)=\nu_x J_1+\nu_y J_2$$

- BUT introducing sextupoles, octupoles etc breaks this.
- Danilov & Ngaitsev have proposed a way to include non-linear elements while maintaining integrability.
  - Results in a time-independent Hamiltonian
  - Realisable B and E fields
  - Results in chaotic (but bounded) motion
  - Mitigates instabilities, space charge effects etc…



- Test facility being built at FNAL - IOTA

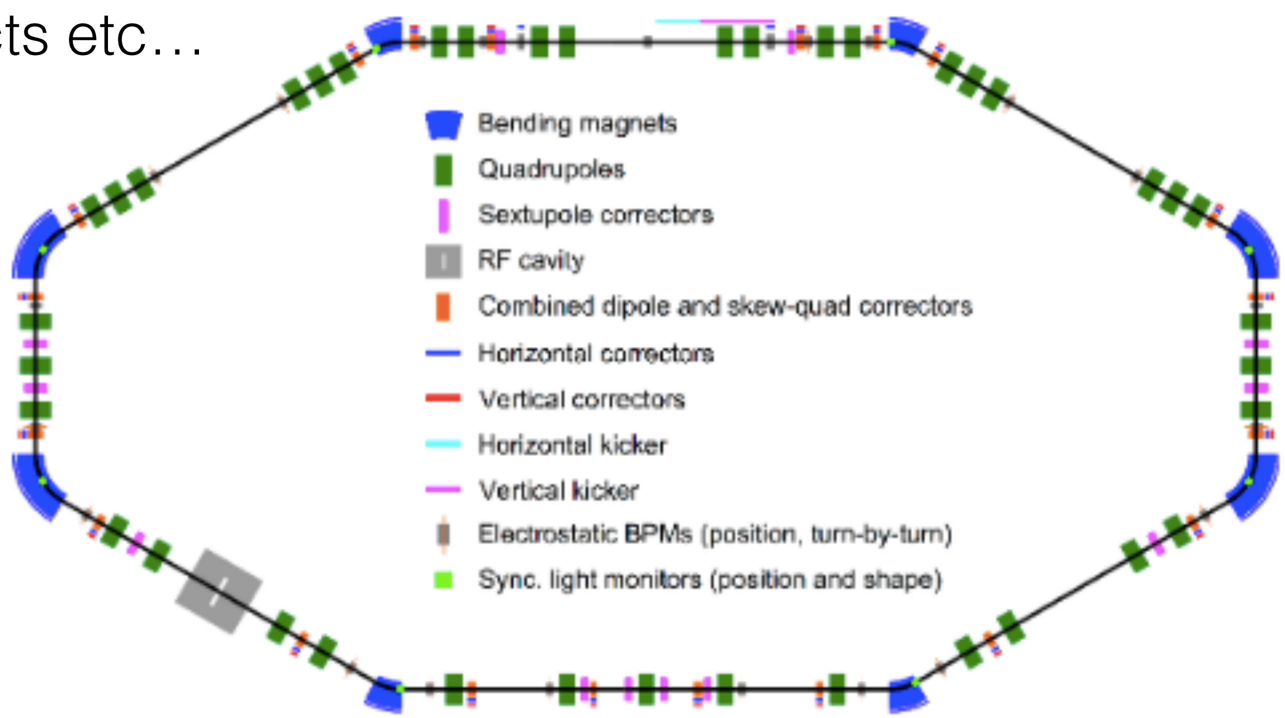


Figure 3. Layout of the Integrable Optics Test Accelerator (IOTA) ring.

https://arxiv.org/pdf/1207.3813.pdf

Non-linear Paul trap

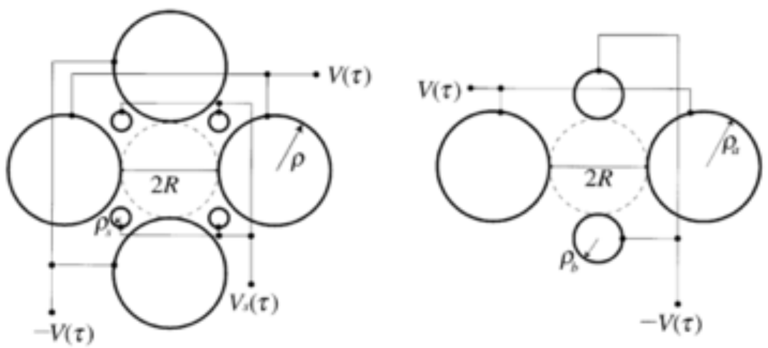
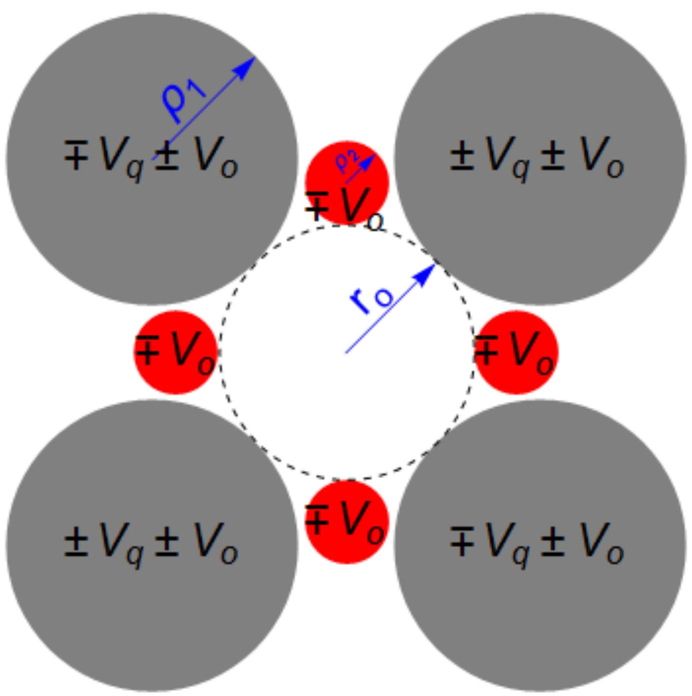
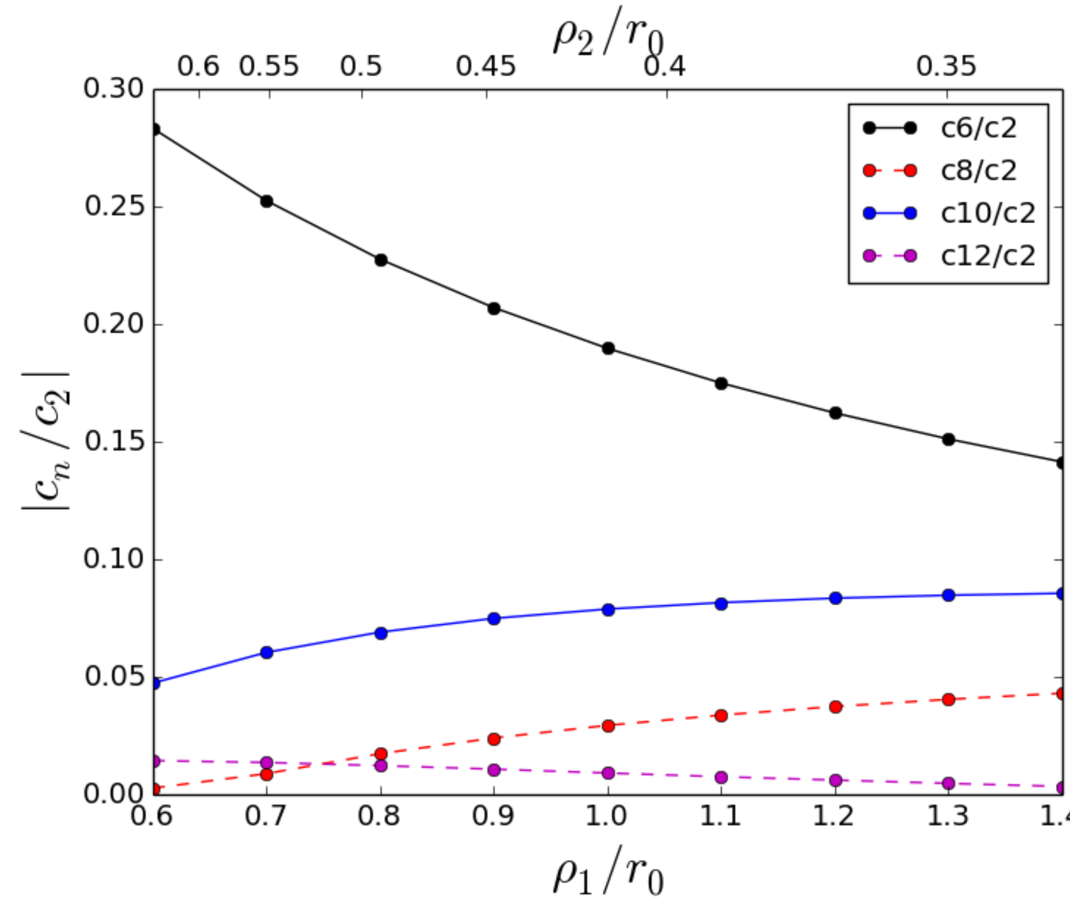


Fig. 6. Cross-sectional view of modified Paul traps.

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

The next step in this field:
Control multipole components!





More info D. Kelliher, in Proceedings of IPAC 2015.

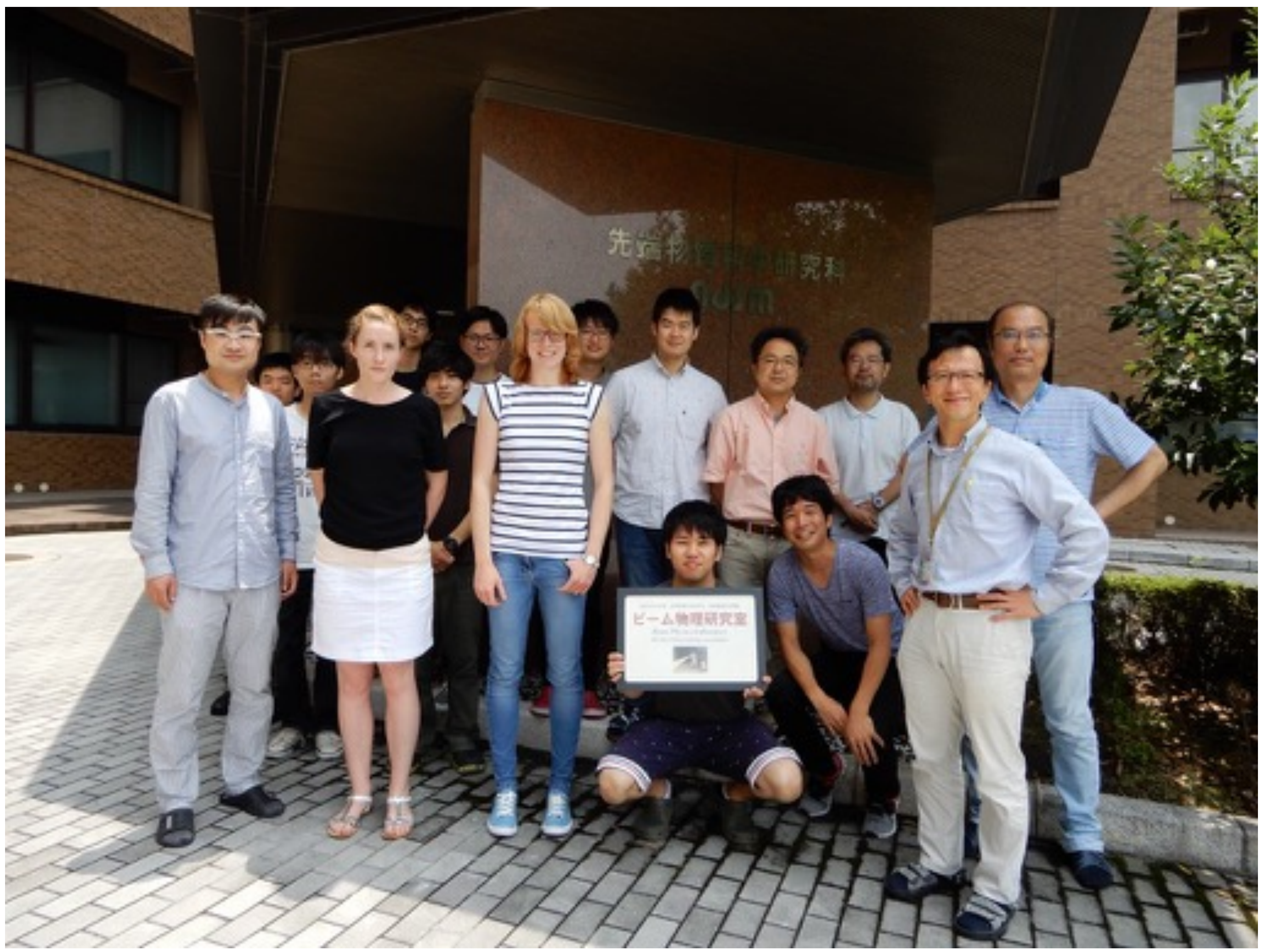
Toward future accelerators…

“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. […] trap experiments might provide a more rapid and economical partial step to explore concept viability.”

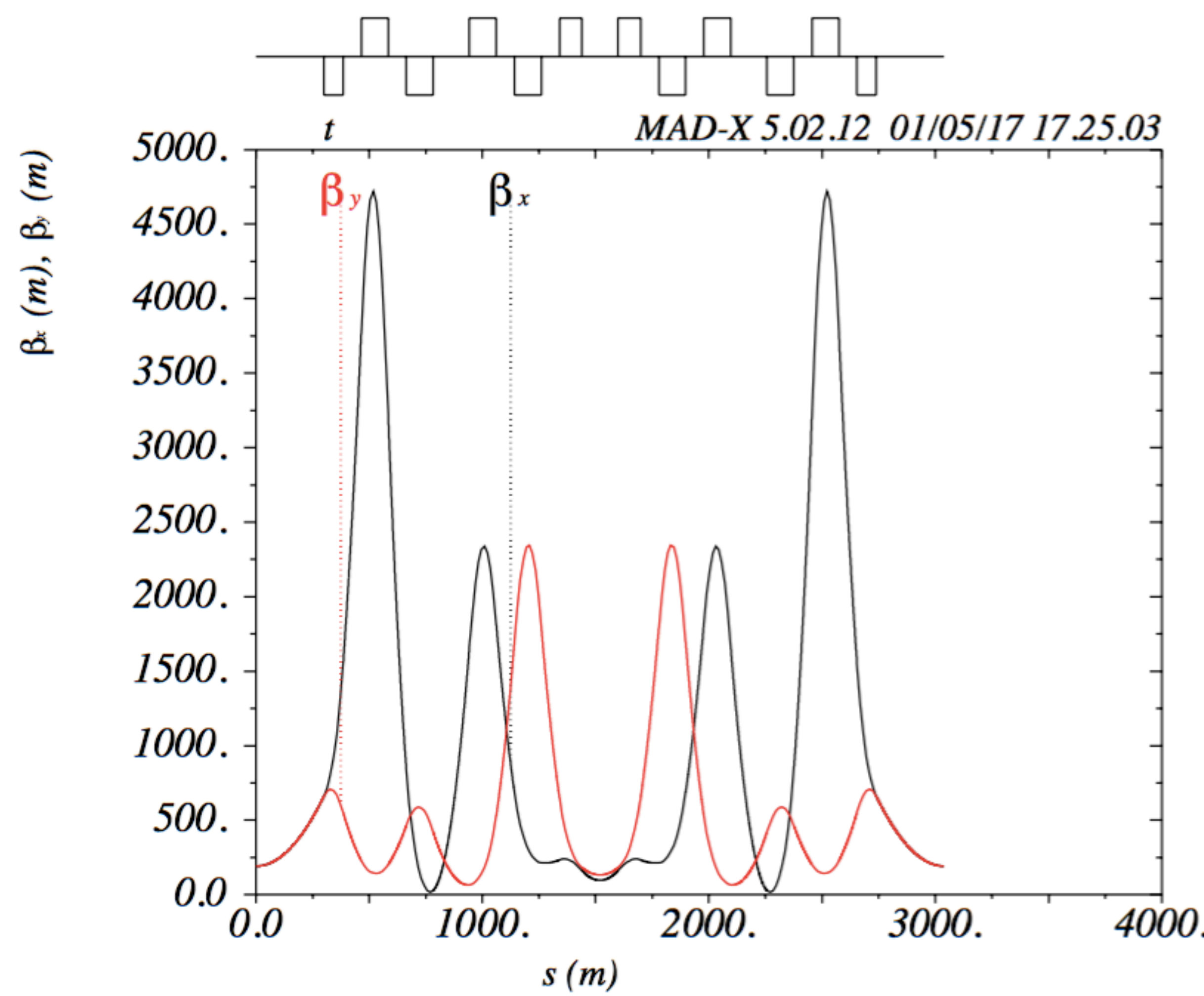
-From summary of HB2014 workshop

Steps towards NIO test on Paul traps:

- Establish underlying lattice (T-insert) & verify equal beta functions
- Non-linear trap development (with Univ. Hiroshima, under construction)
- Generate suitable waveforms to model longitudinal change in B field (electrical engineering)
- Develop new diagnostics for observables (ideas welcome!)



Suzie Sheehy and Lucy Martin (Oxford) with the Hiroshima University Beam Physics Group of Prof. Hiromi Okamoto (far right), July 2017



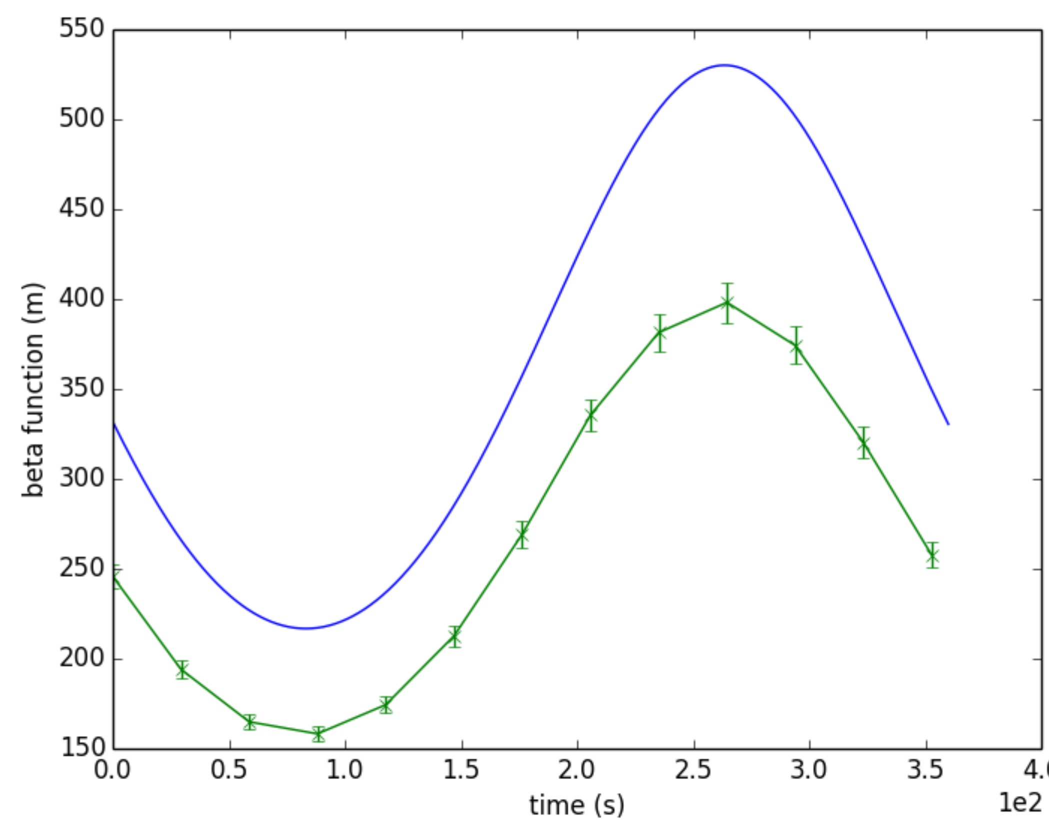
We are developing a method to measure beta functions in Paul traps

… and it seems to work

Dipole kick gives:

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

Varying phase & applying kick until ions are lost:



L. Martin (obviously… very preliminary!)

Summary

- We still have a lot to understand about intense beams in accelerators
- Experiments (on accelerators) and simulations both have limitations
- Paul trap systems provide a low-cost, small, flexible, radiation-free system to address major questions in accelerator physics.
- Tabletop is a great scale for students to use!
- Groundbreaking new accelerator principles may be tested using this technique. Steps toward this are already underway.

John Adams Institute for Accelerator Science

UNIVERSITY OF OXFORD

Science & Technology Facilities Council

Thankyou!

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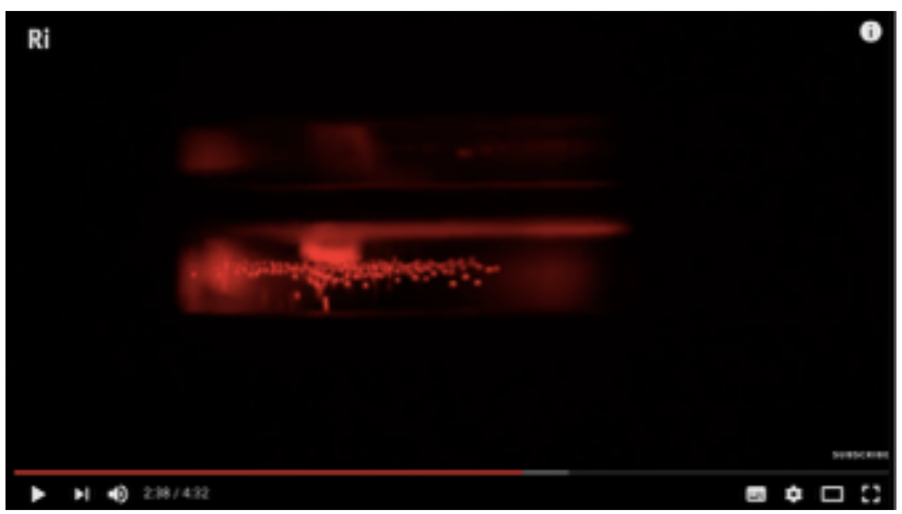
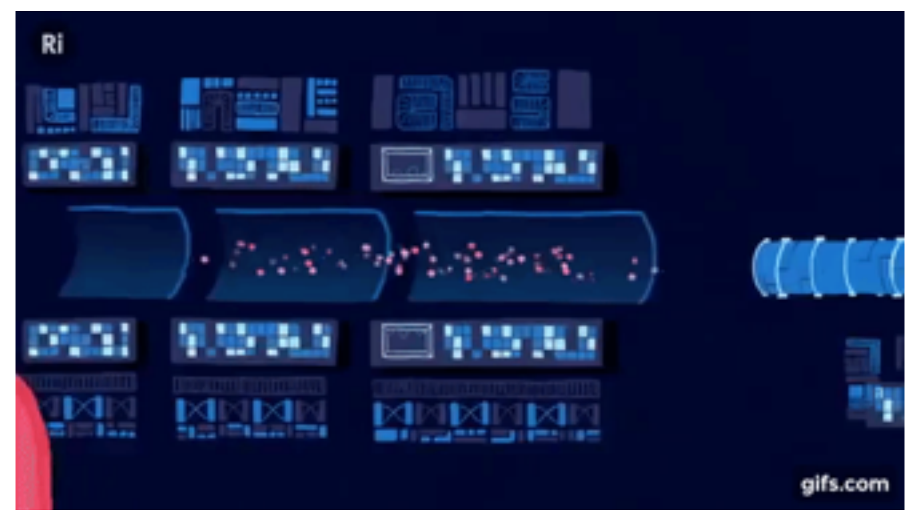
Extra slides

Particle Accelerators for Humanity

http://richannel.org/collections/2016/particle-accelerators-for-humanity


A high quality video series about accelerators and their applications.

Full evaluation report available

Creative commons licensed (you can use them!)

+ on YouTube

The Royal Institution
Science Lives Here

Science & Technology
Facilities Council

Oxford
Physics

'Particle Accelerators for Humanity'

NB. Full evaluation report available, contact S. Sheehy

I found it fascinating. Great video and I love the channel. Keep going on :) – Survey comment

the explanation and visuals were really good – Survey comment

I think I wanted more and more. the fluid story telling was something hooked me and when you have cracked it, you can increase the information in video – Survey comment

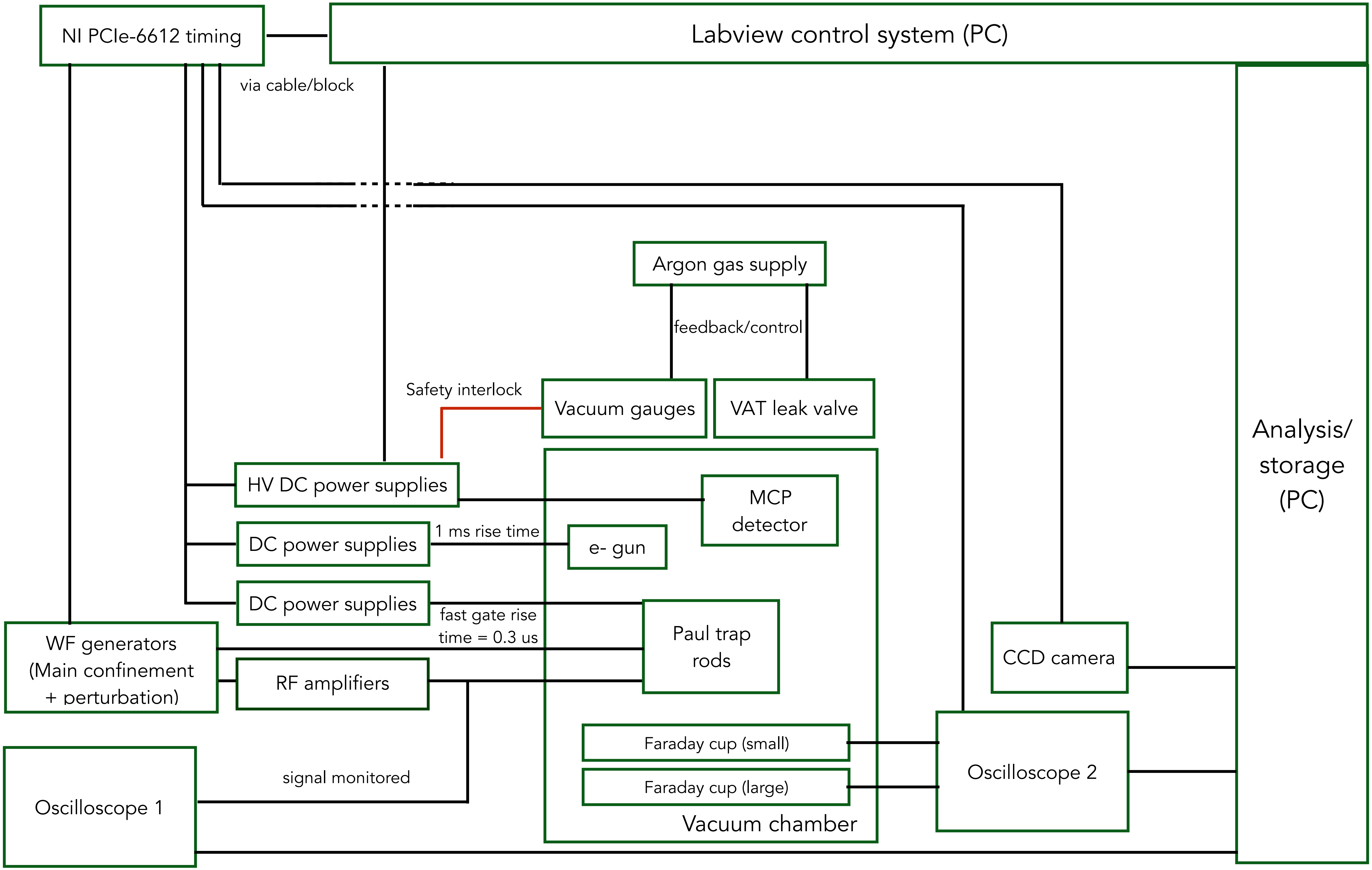
It was perfect – Survey comment

This was amazing, thank you so much! A big thank you to Suzie for taking the time to participate and teach us plebs something very interesting :) – YouTube comment

I think the video hit the correct level of technical detail while trying to keep the message simple to understand. The video production and length was good too, so I can't think of a fault in the video – Survey comment

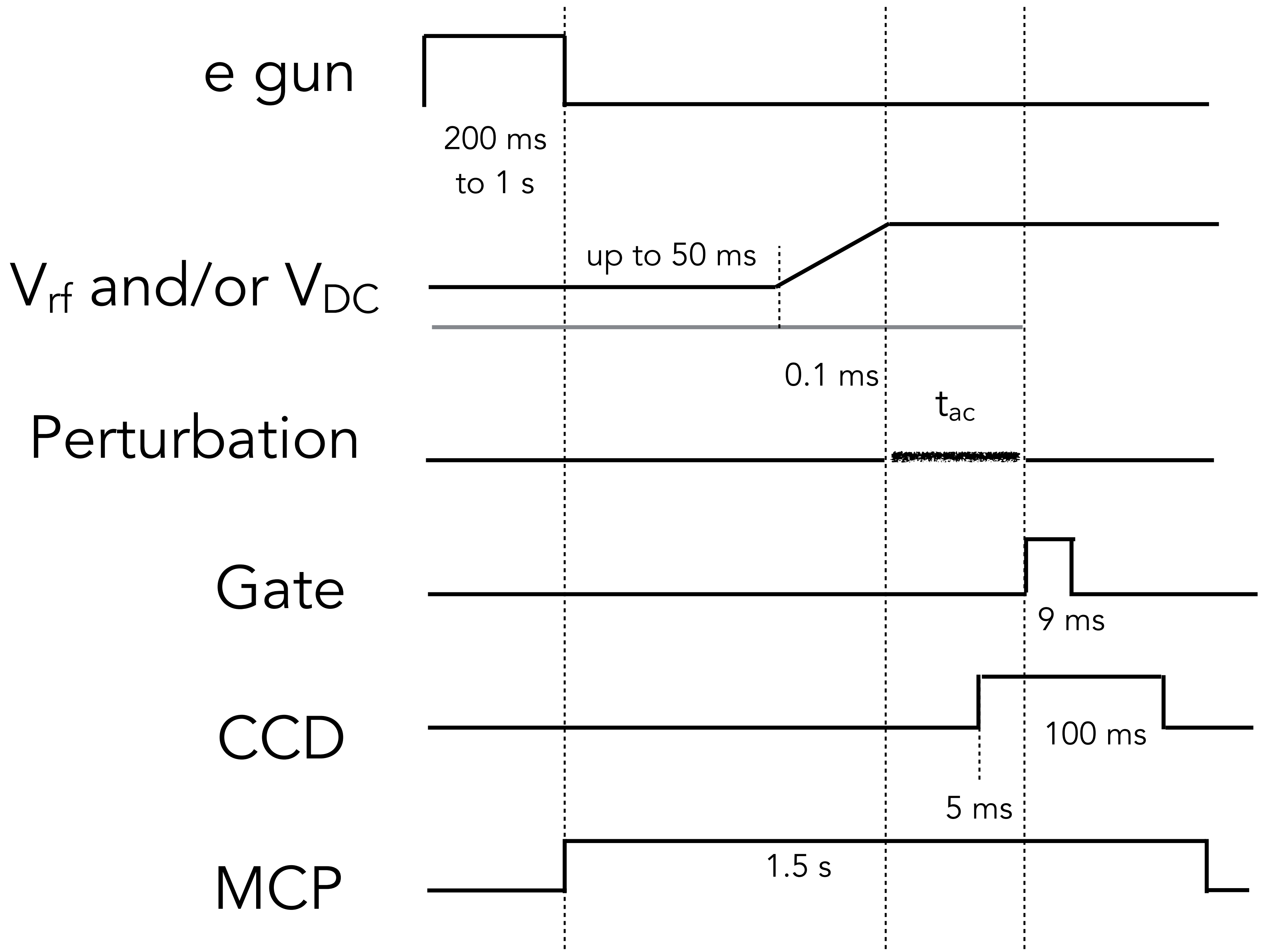
The subject was explained well and the music and visuals were spot on - Survey comment

Block Diagram of IBEX system



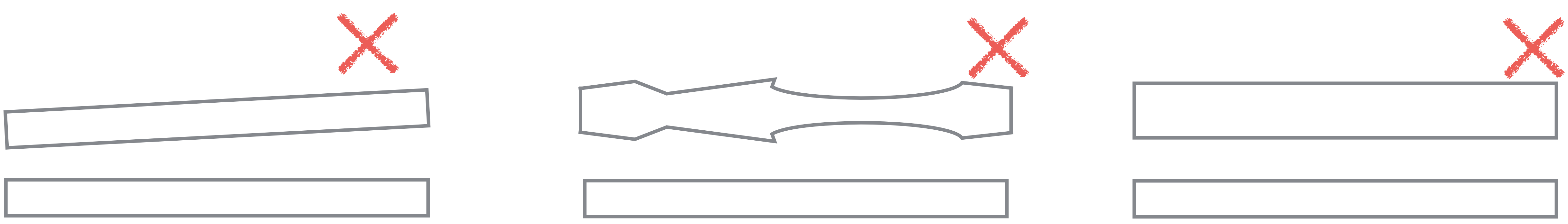
Timing chart

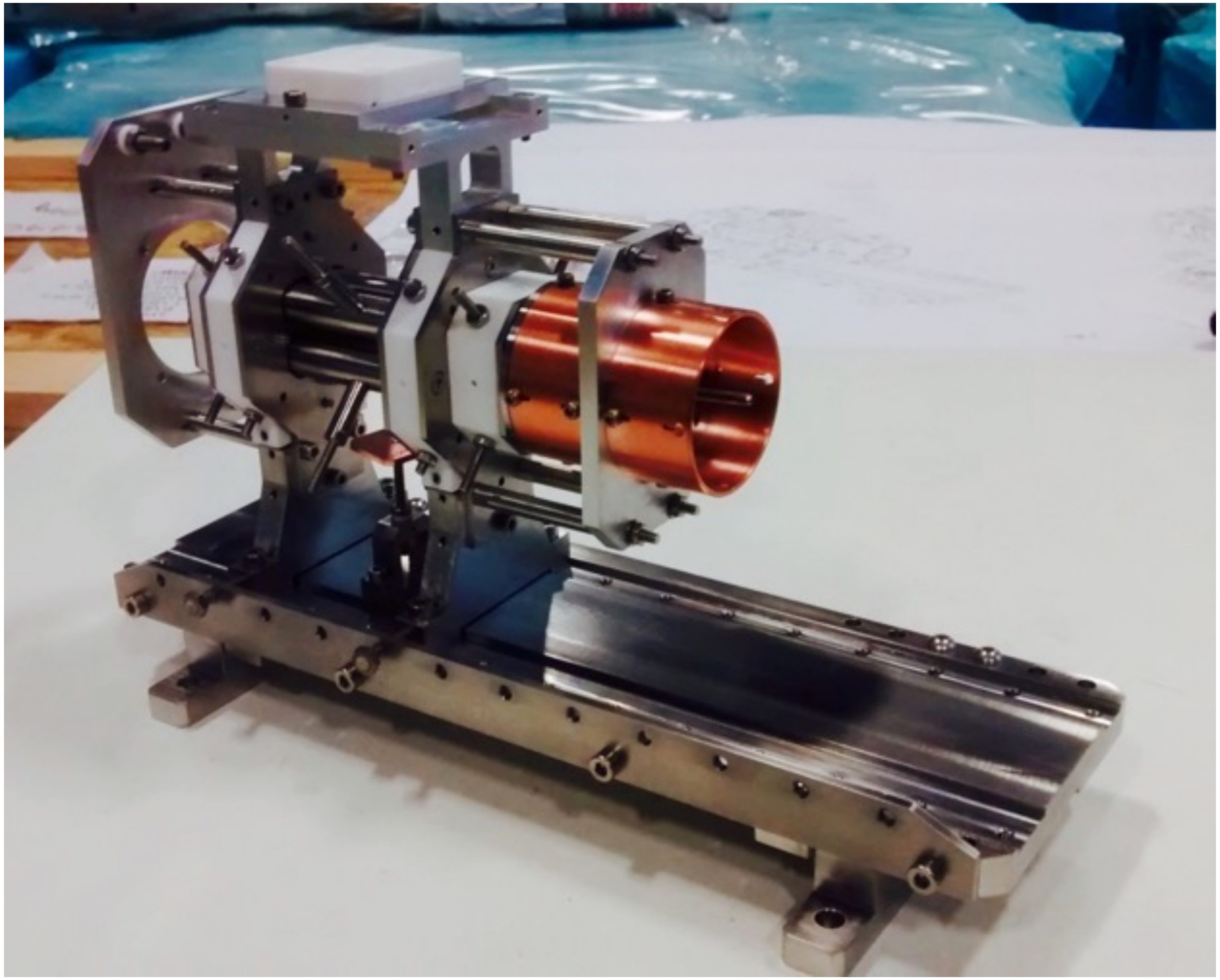
(Based on Ito-san's S-POD timing chart)



Paul Trap rods

The four rods (two seen here) must be well aligned to each other (to micron-level), have a very smooth surface and be identical in diameter.

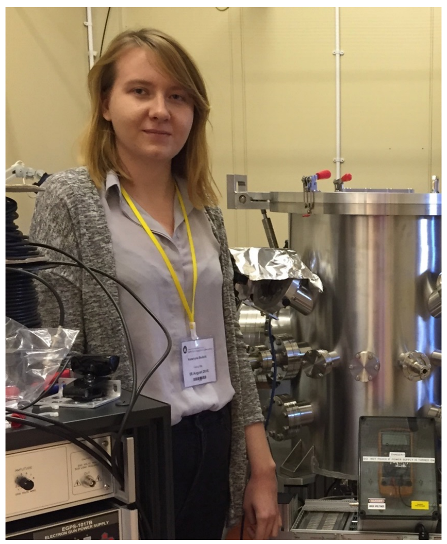




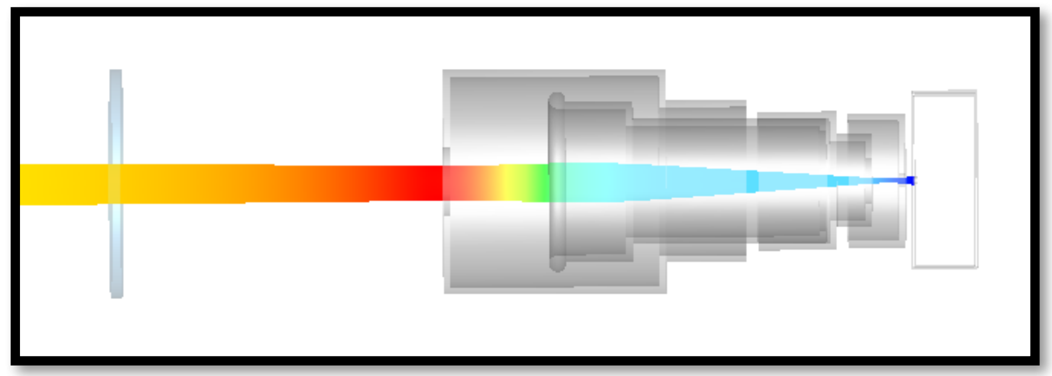
IBEX Paul Trap constructed and ready for alignment measurement…

Commissioning

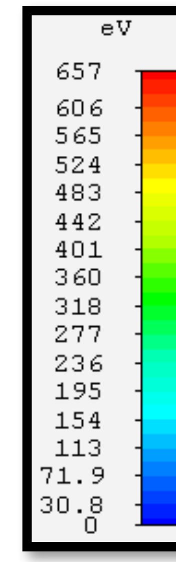
- Characterize electron gun (K. Budzik, summer student 2016)



Kasia working with ISIS diagnostic group vessel on electron gun tests

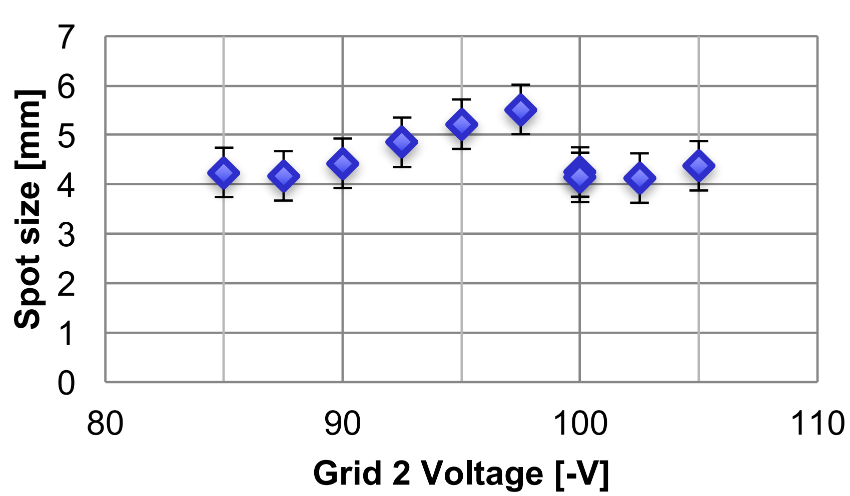


Modelling in CST

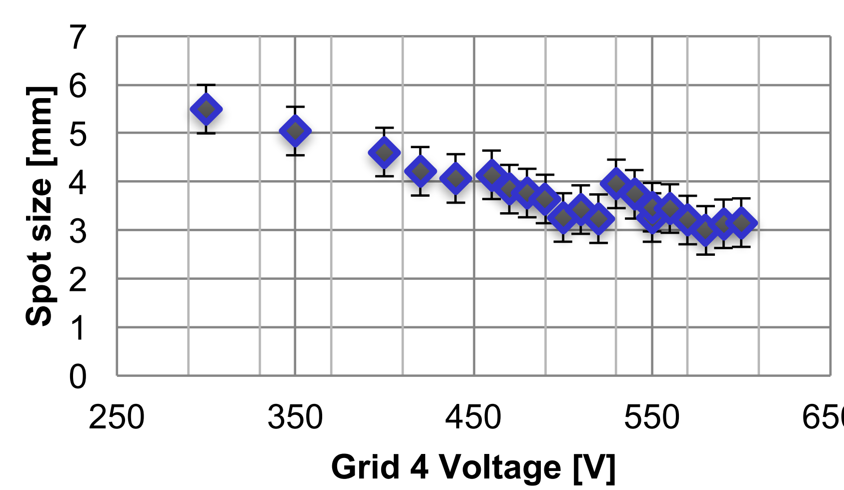


Experimental result: beam spot size tests

Grid 2 Variation



Grid 4 Variation



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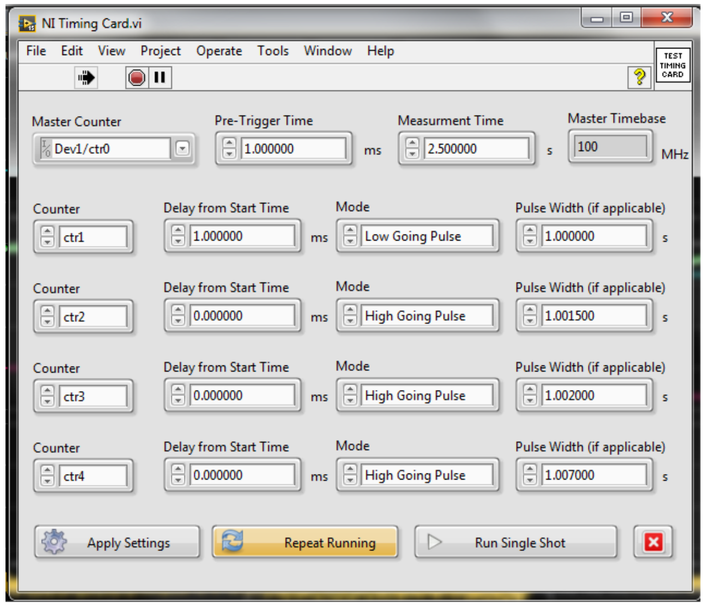
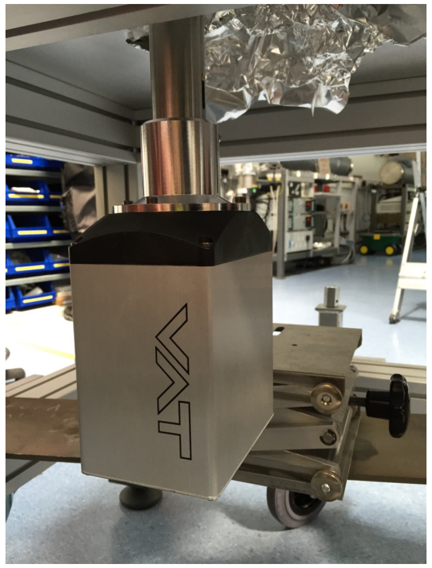
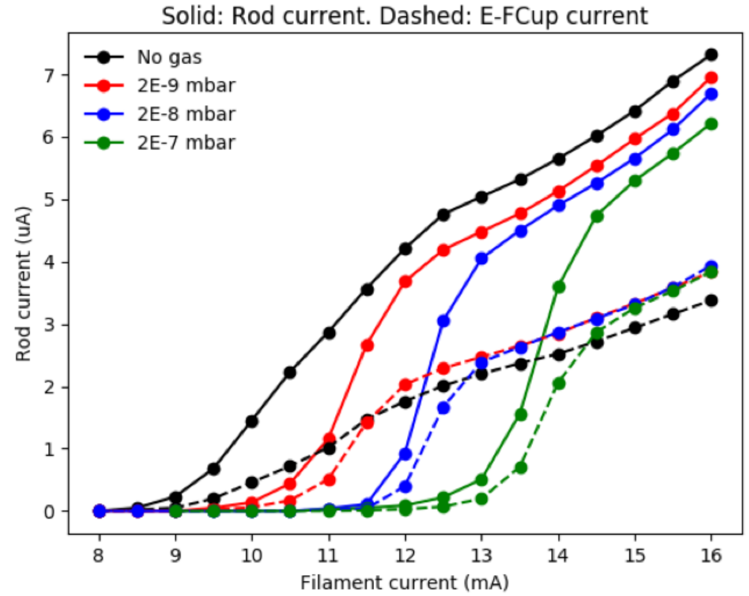
Commissioning

- ✓ Timing: PCIe card for trigger
- ✓ E-gun: sufficient current
- ✓ Argon gas: VAT leak valve
- ✓ Vrf & Vdc: AWG & amplifiers
- ✓ End cap: fast switch
- ✓ FC readout: to oscilloscope

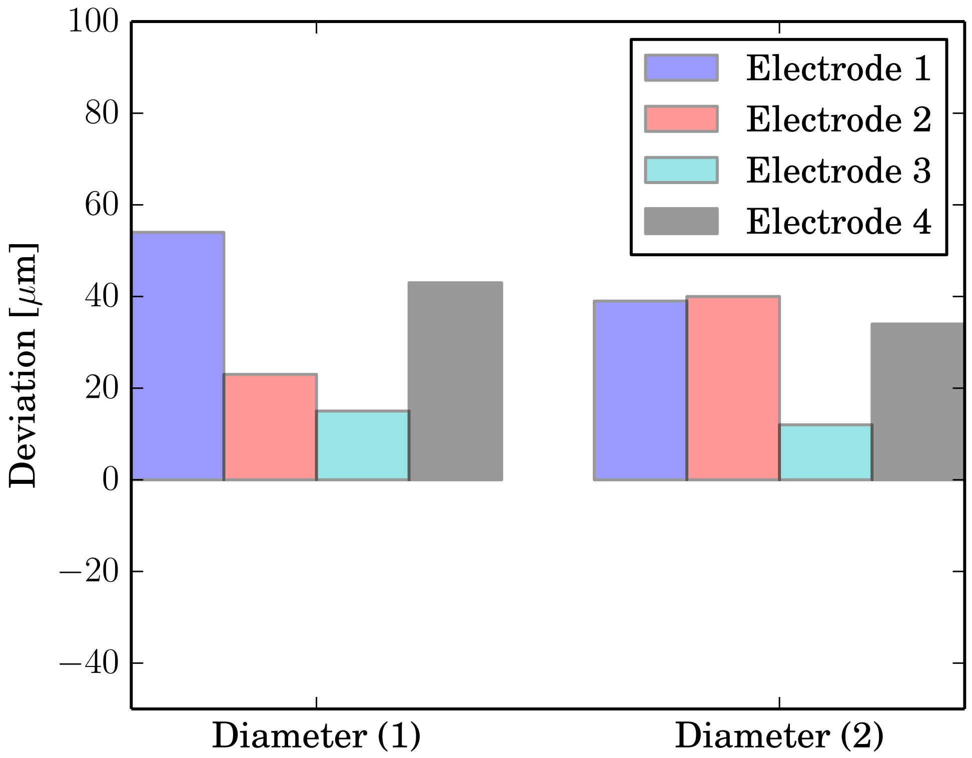


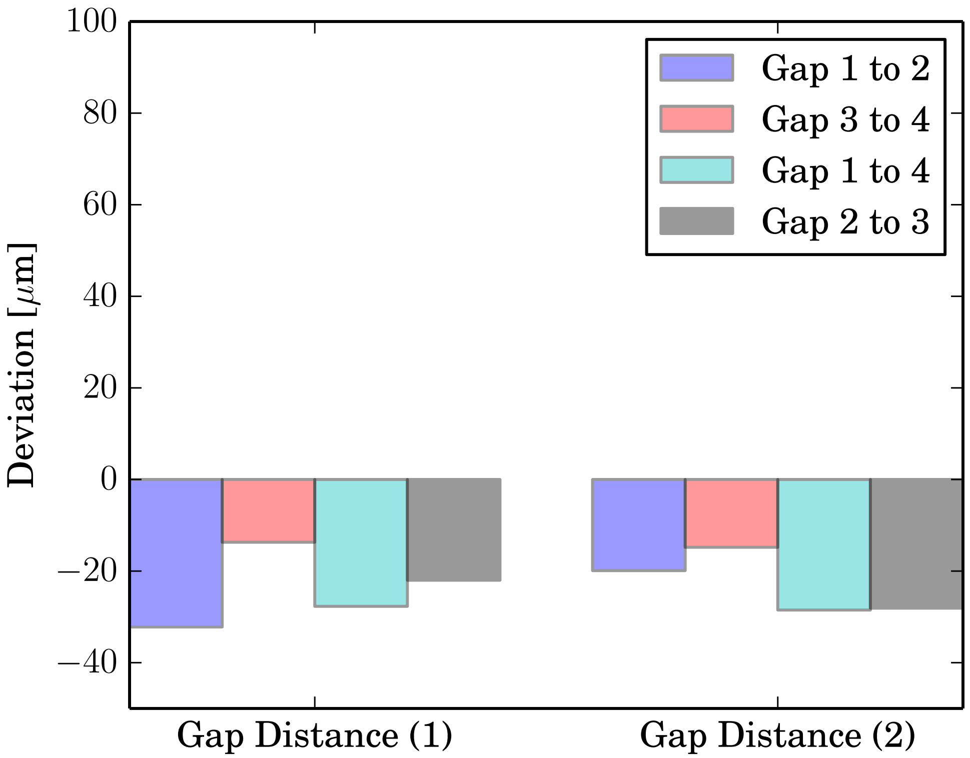




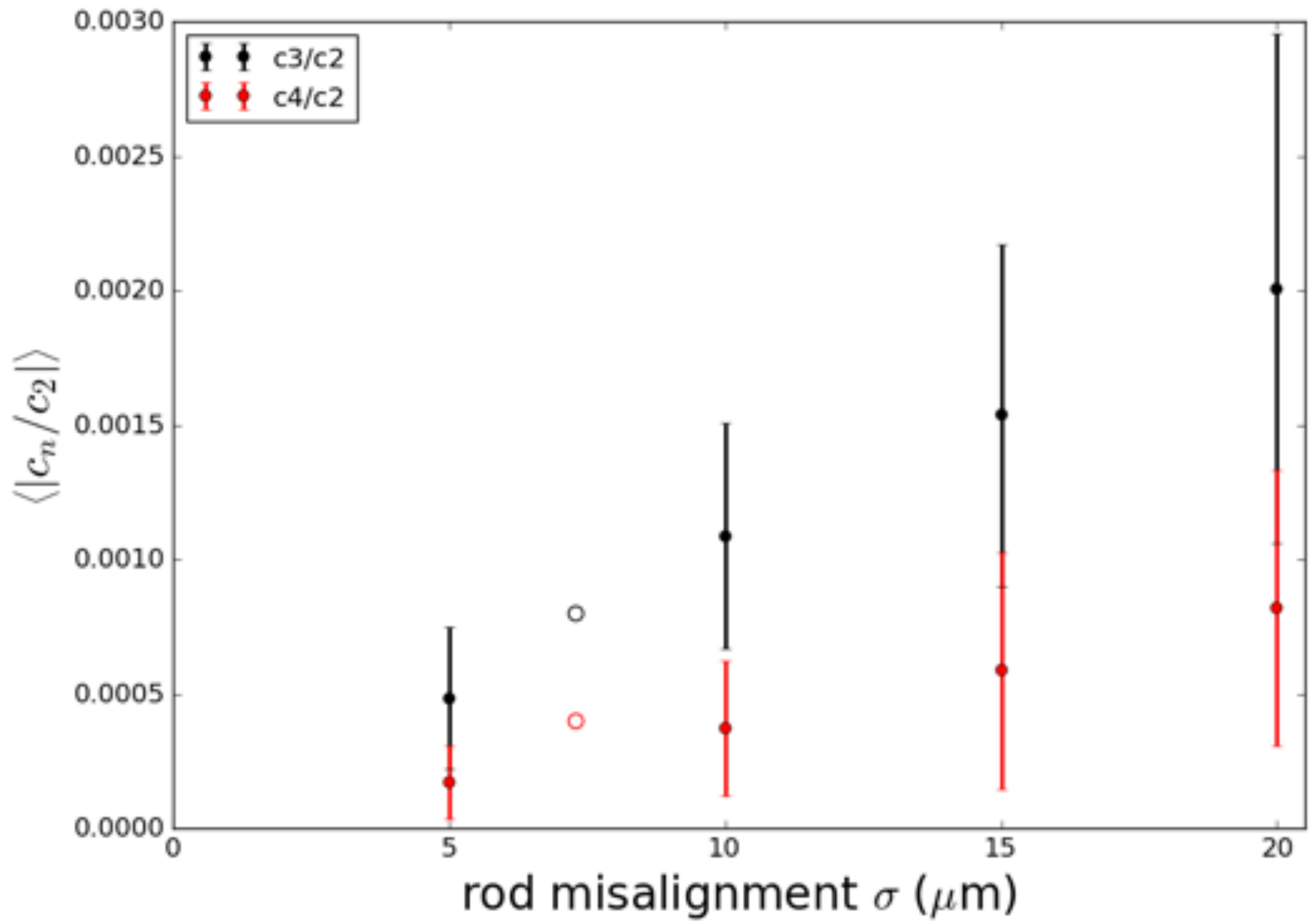
eGun conditioned just once at base pressure, then study undertaken.

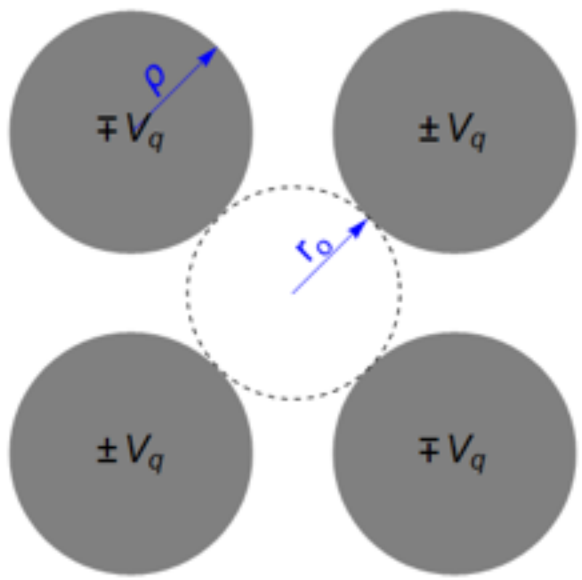
Rod alignment measurement





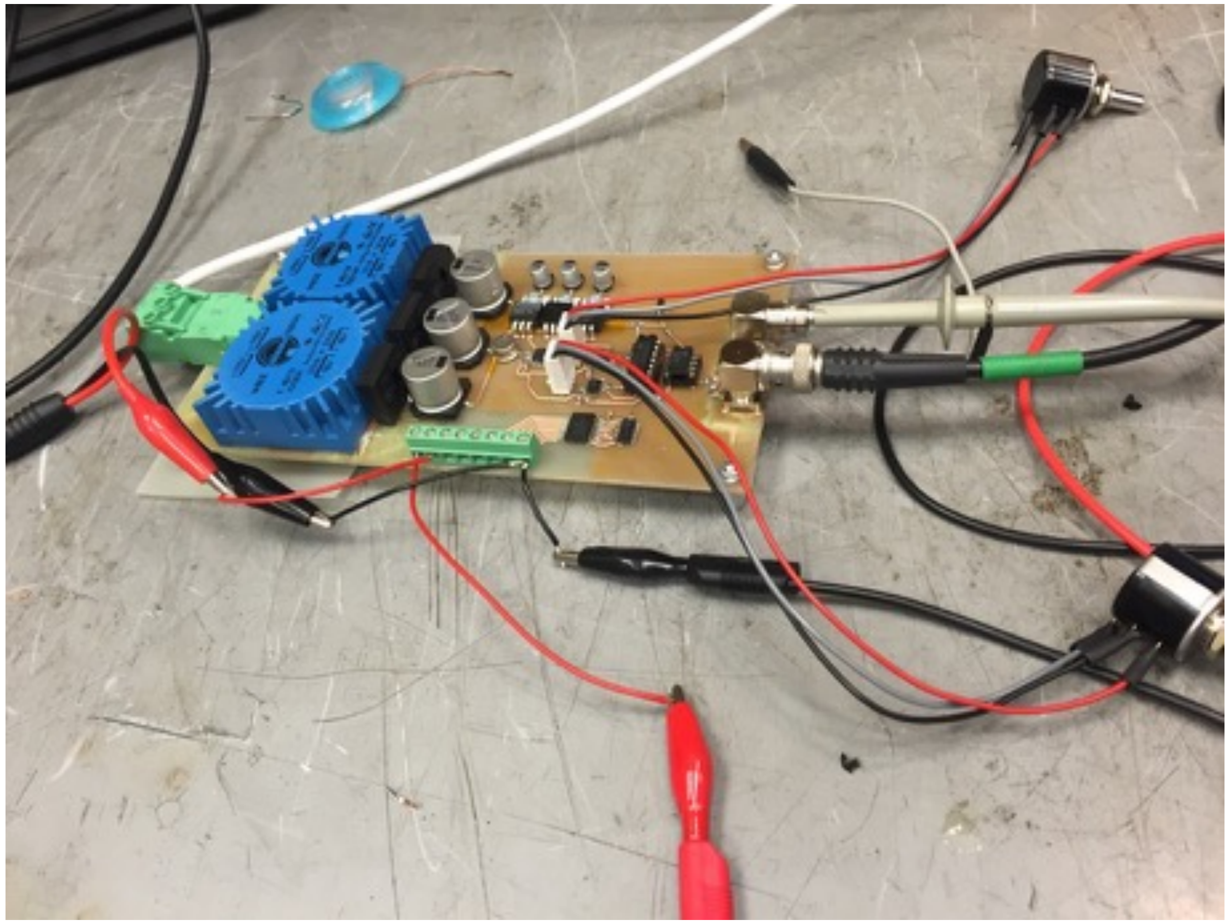
Rod alignment - what effect?





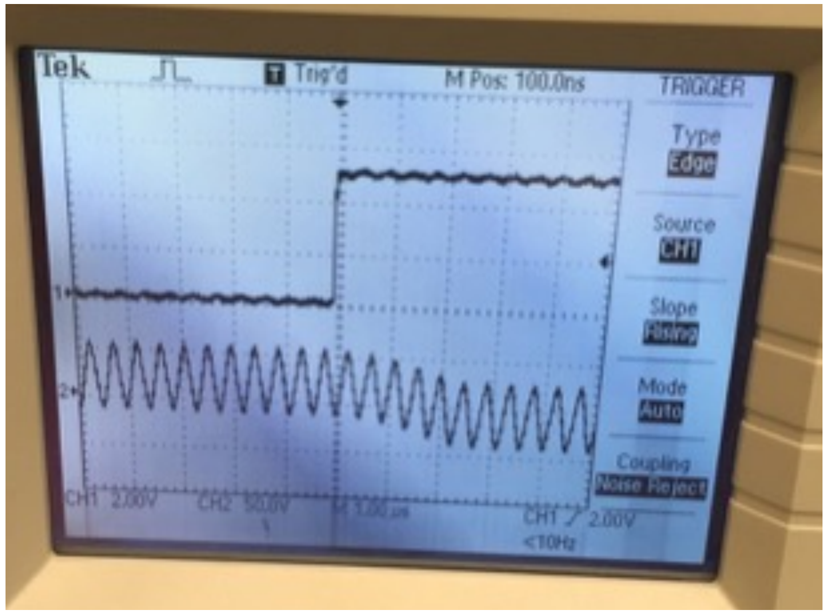
Estimated multipole errors resulting from rod misalignments are shown. (c_3 = sextupole, c_4 = octupole)

RF, DC and electronics



Test circuit - Oxford Central Electronics

DC fast switch off in ~ 1 musec

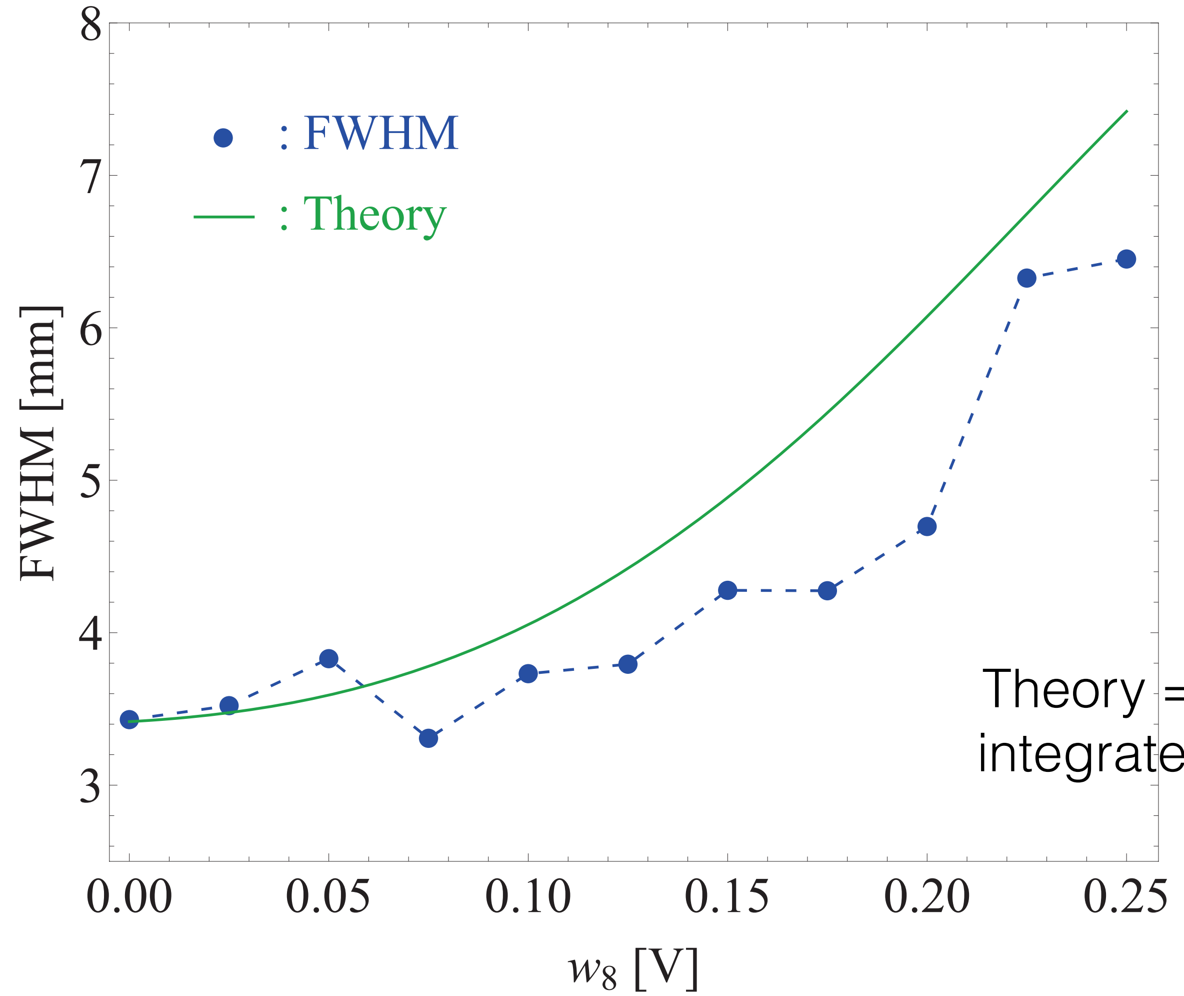


DC fast switch off with 50V RF in ~ 2 musec

Integer resonance crossing work with Hiroshima University S-POD system 2014-2015

Observe amplitude growth with error

Tune = 8.1. Vary perturbation strength.



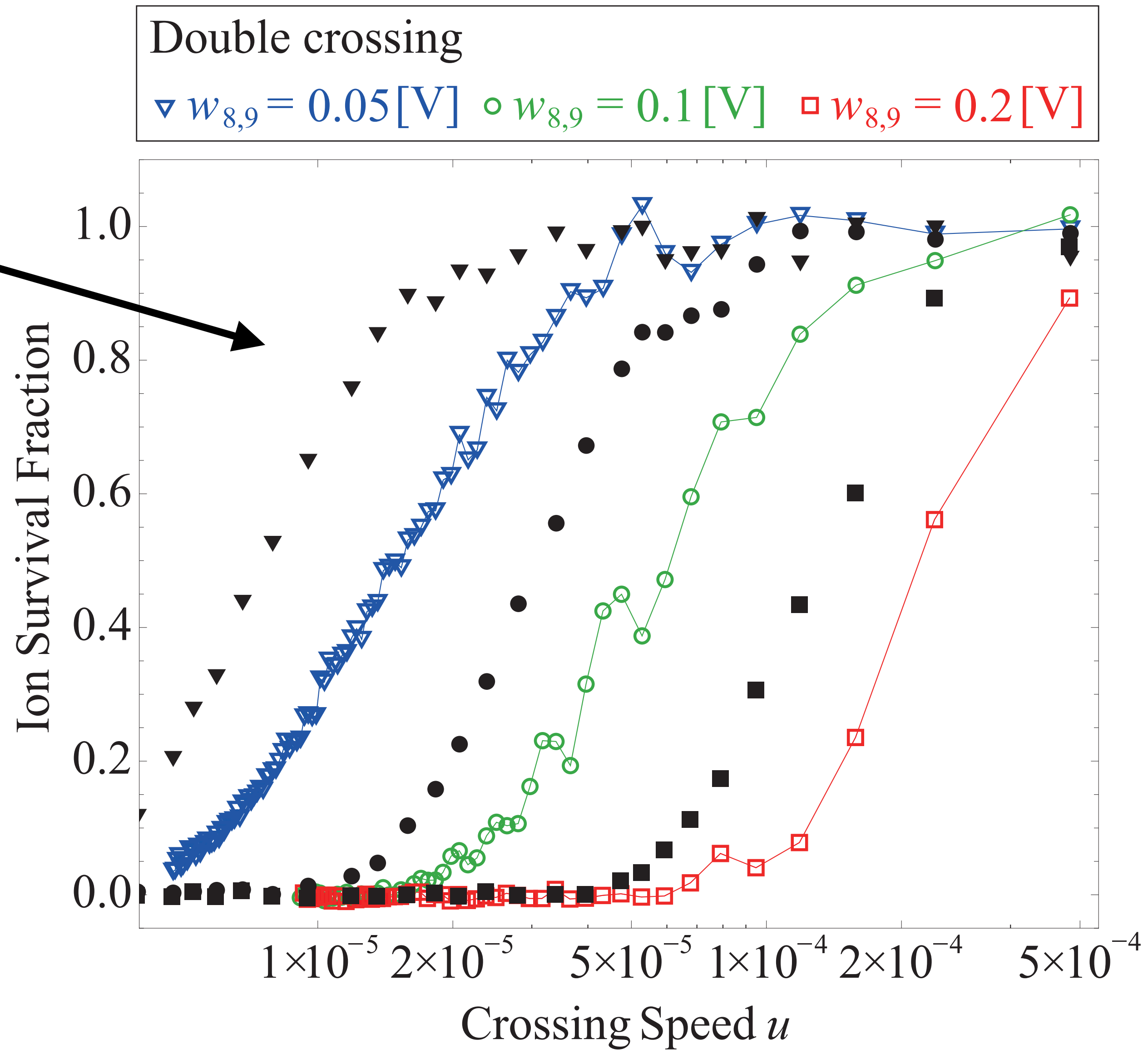
Theory = gaussian distribution integrated over COD trajectory

We wanted to confirm amplitude growth when OFF RESONANCE as well

Double resonance crossing

8th & 9th harmonic excited
Tune varied 9.5 -> 7.5

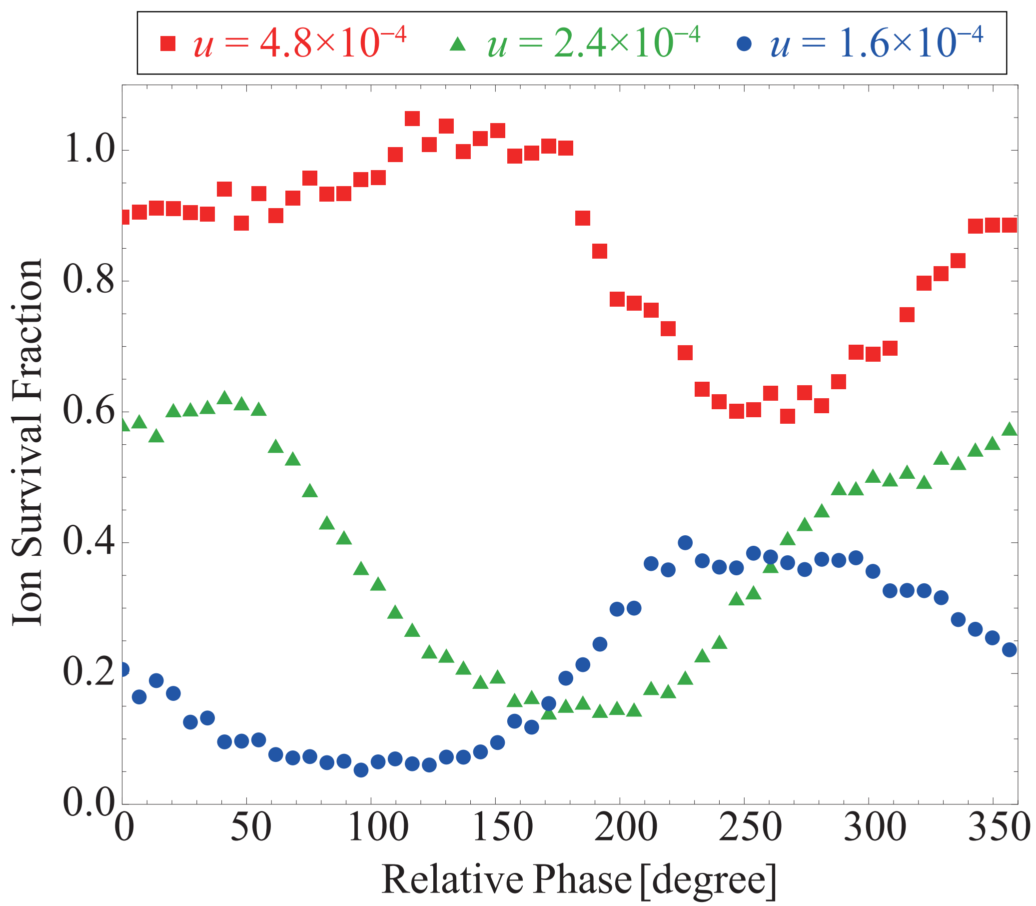
Oscillatory behaviour for high perturbation strength… why?

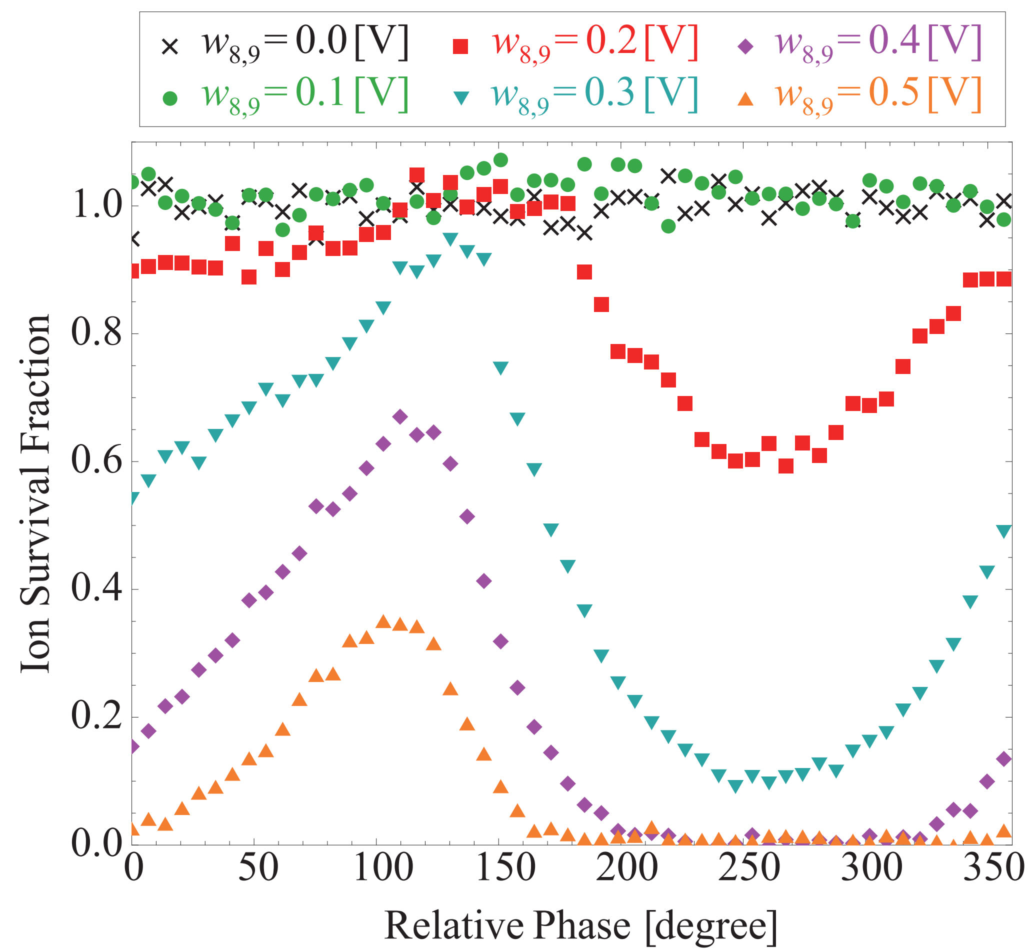


- Single crossing for comparison (black)

Phase dependent effects

Vary phase of 8th harmonic, cross 9th & 8th





Fixed perturbation
Varying crossing speed

Fixed crossing speed
Varying perturbation

What are the issues?

From this workshop: P. Ngheim (Mon afternoon):

High intensity **=** **High power (even tiny losses are harmful)** **+** **Strong space charge (strong non-linear forces)**

Even simulations are limited… we can't always simulate ALL particles and ALL interactions!

C. Plostinar (Mon afternoon):

- "Rules of thumb" are applied in design (i.e. phase advance < 90 degrees)
- Theoretical understanding is emerging but…
- Experimental evidence and impact remain limited.