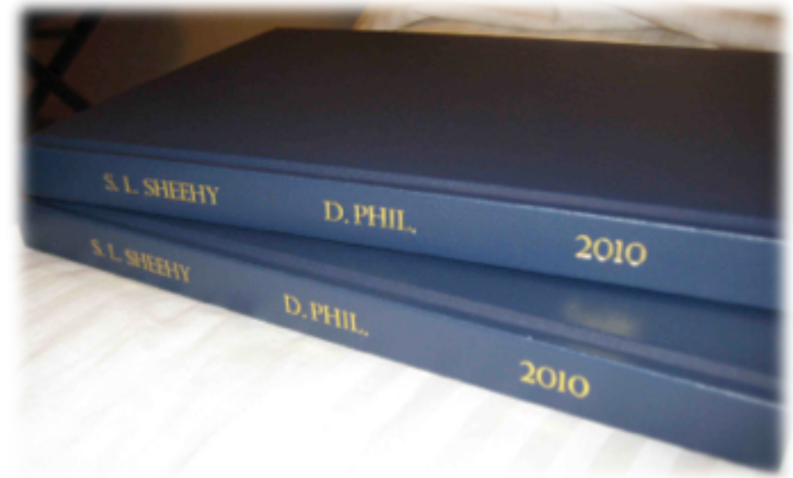
The IBEX Paul Trap:
Studying accelerator physics without the accelerator

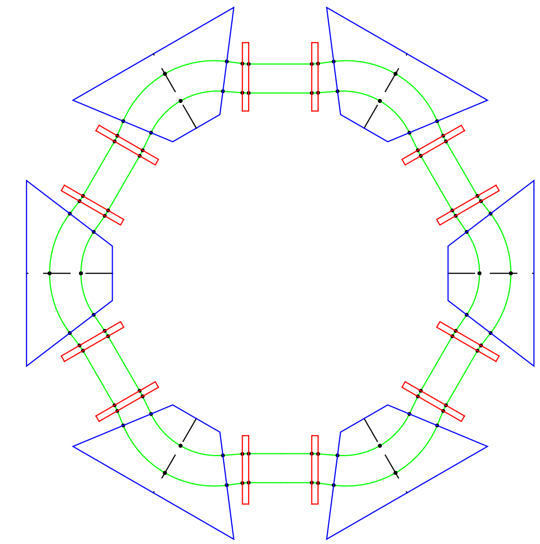
JAI Introducing Seminar
21/5/2015

Dr. Suzie Sheehy
John Adams Institute for Accelerator Science
& STFC/ASTeC Intense Beams Group

Oct 2007 - Oct 2010
DPhil, Oxford
Design of a non-scaling fixed field alternating gradient accelerator for charged particle therapy



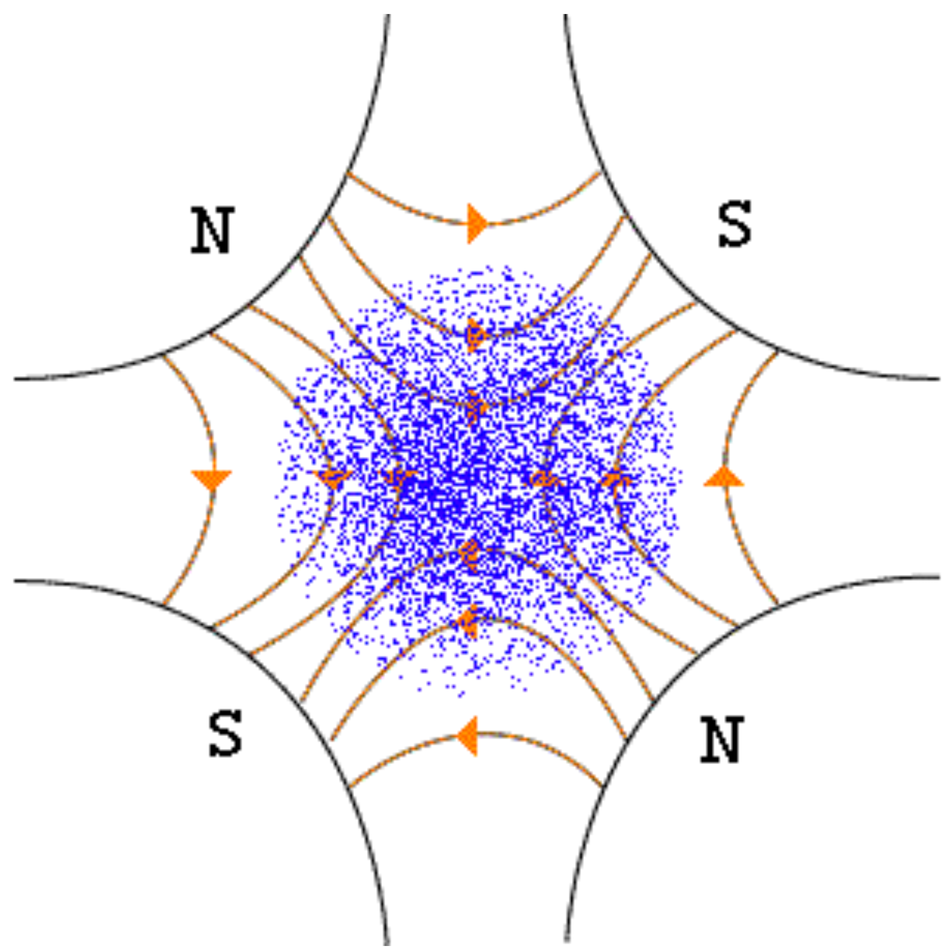
Nov 2010 – Nov 2013:
Research Fellowship (Brunel Fellow)
"Novel high power proton accelerators" based at RAL
Focus on simulations of novel high power accelerators
http://www.royalcommission1851.org.uk/
Collaborating with FNAL, PSI + others



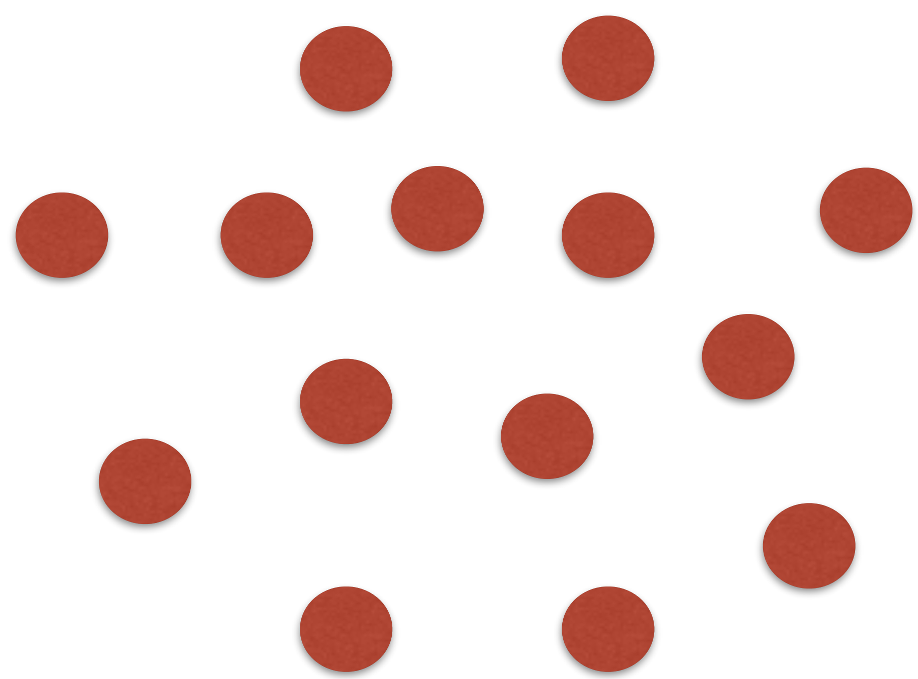
Nov 2013 – March 2015:
Senior Accelerator Physicist, ASTeC Intense Beams Group, RAL
Collaborating with Kyoto University, University of Hiroshima, CERN

April 2015 - present
Researcher, Joint Appointment
JAI/University of Oxford and STFC/RAL/ASTeC Intense Beams Group
Topic: High intensity hadron beams

Challenges in accelerator simulation

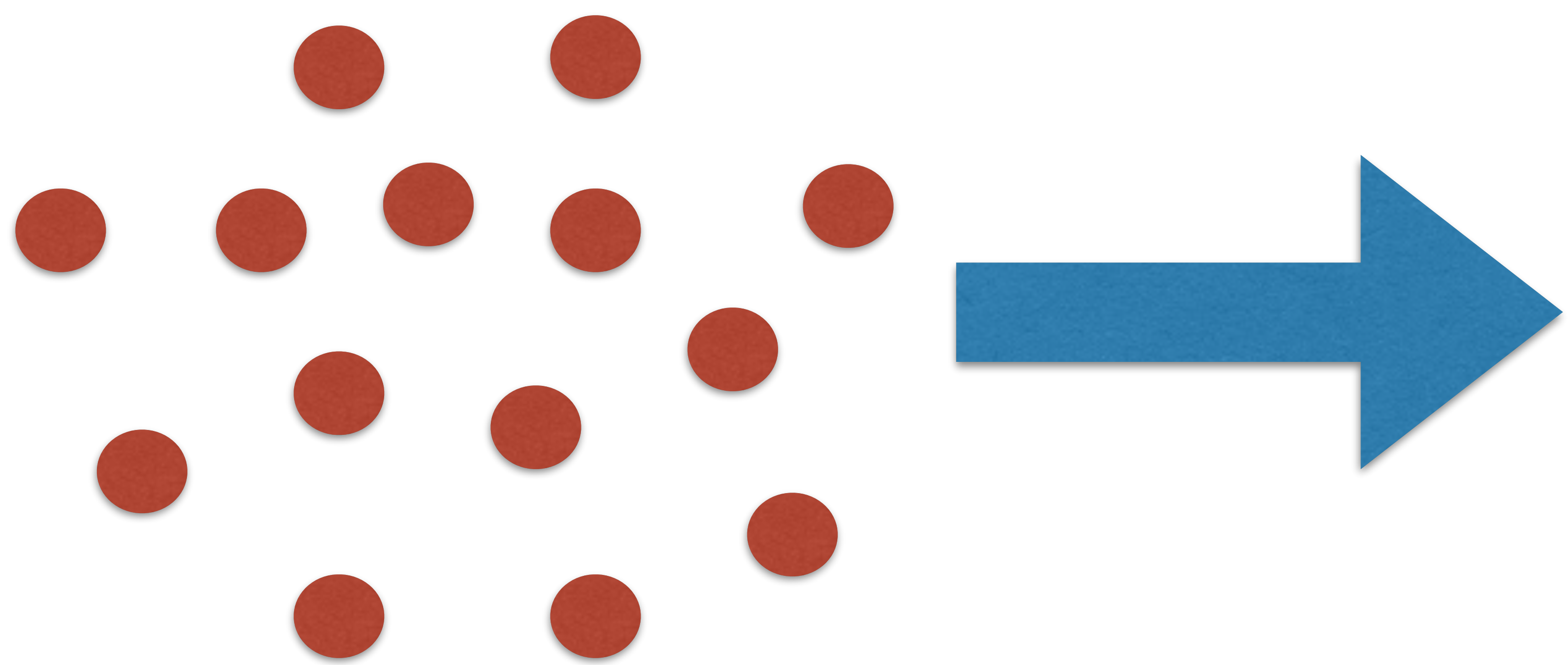


Challenges in accelerator simulation



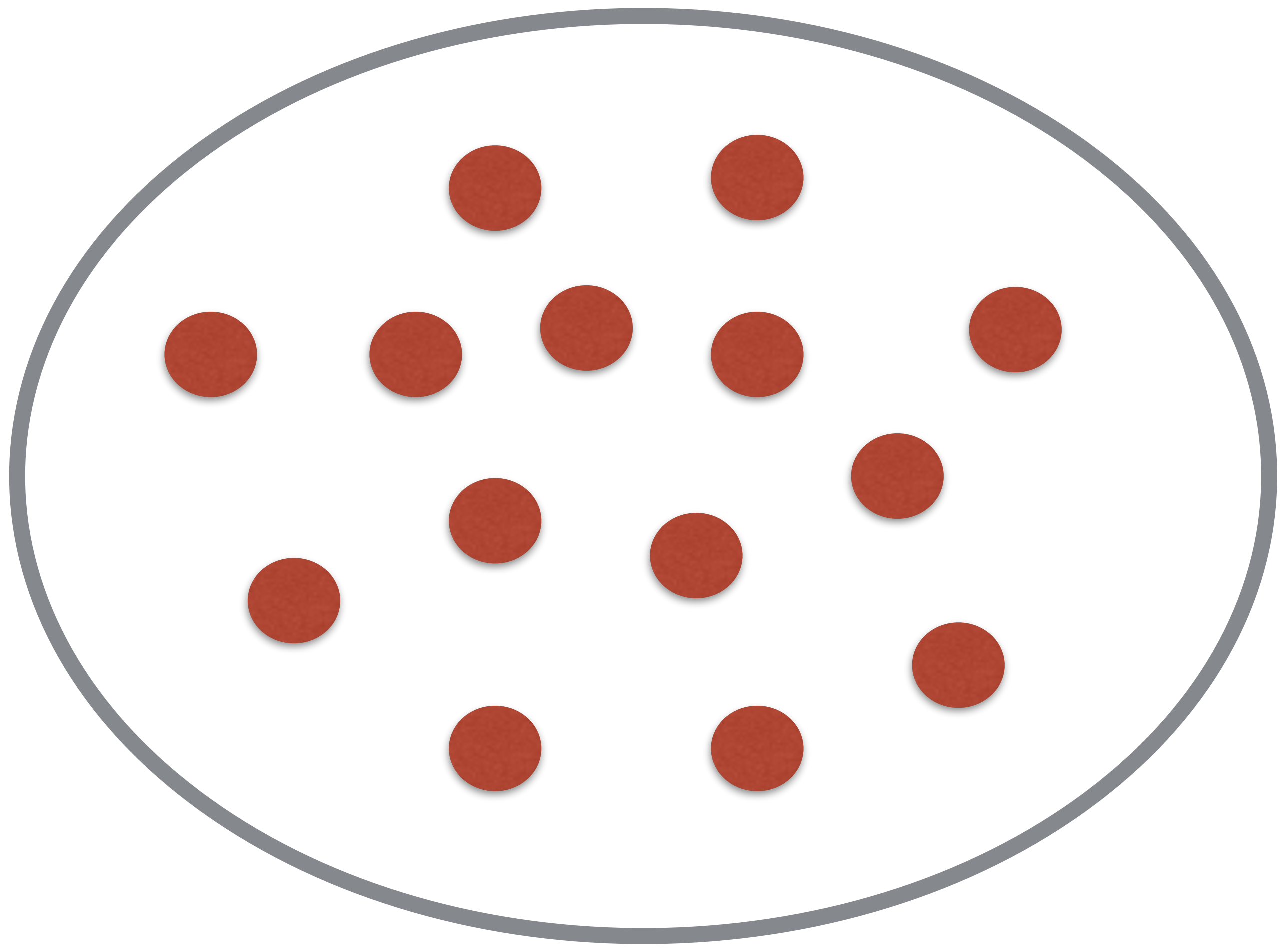
Every particle feels coulomb force…
… from every other particle

Challenges in accelerator simulation



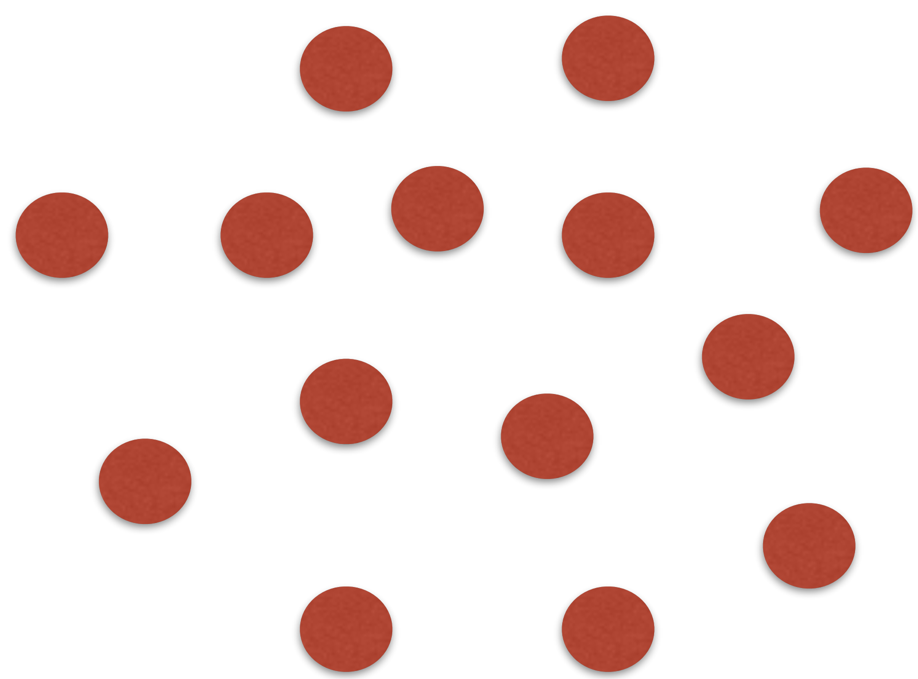
And are moving
…more forces & calculations

Challenges in accelerator simulation



There's a beam pipe as well… which interacts with the beam

Challenges in accelerator simulation

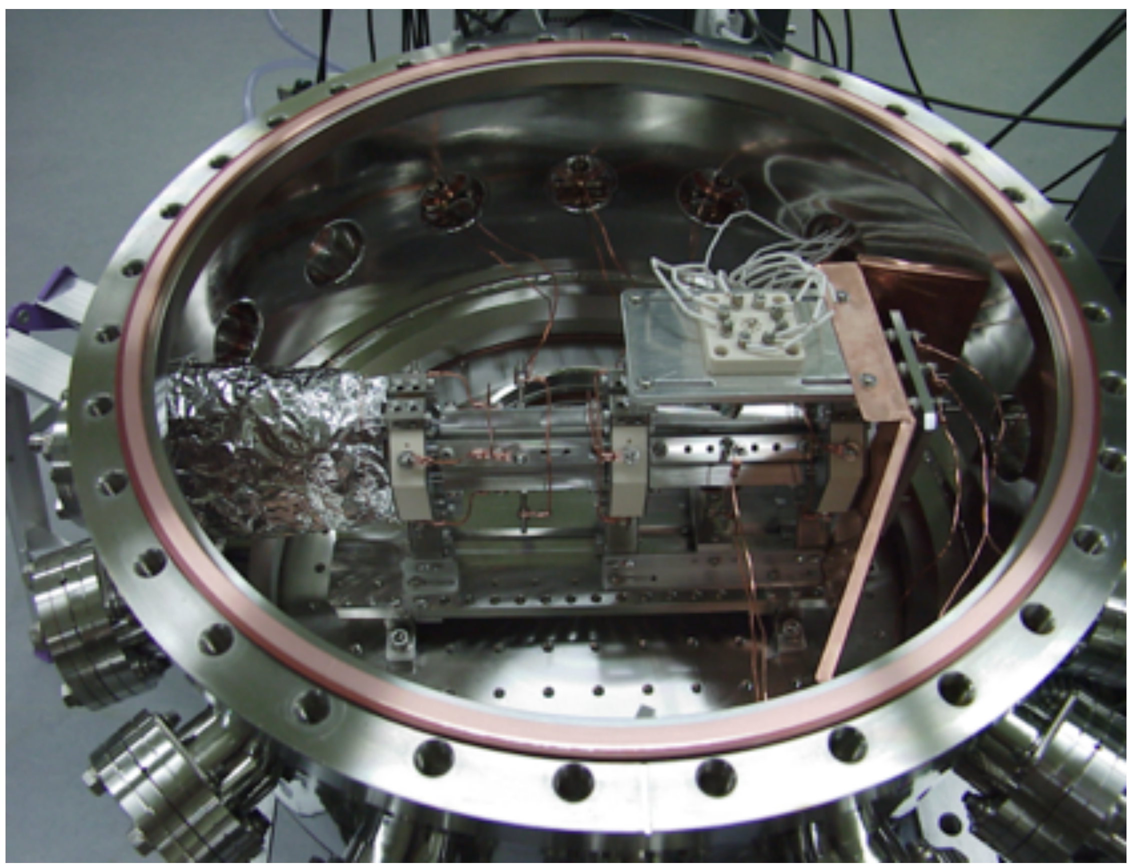


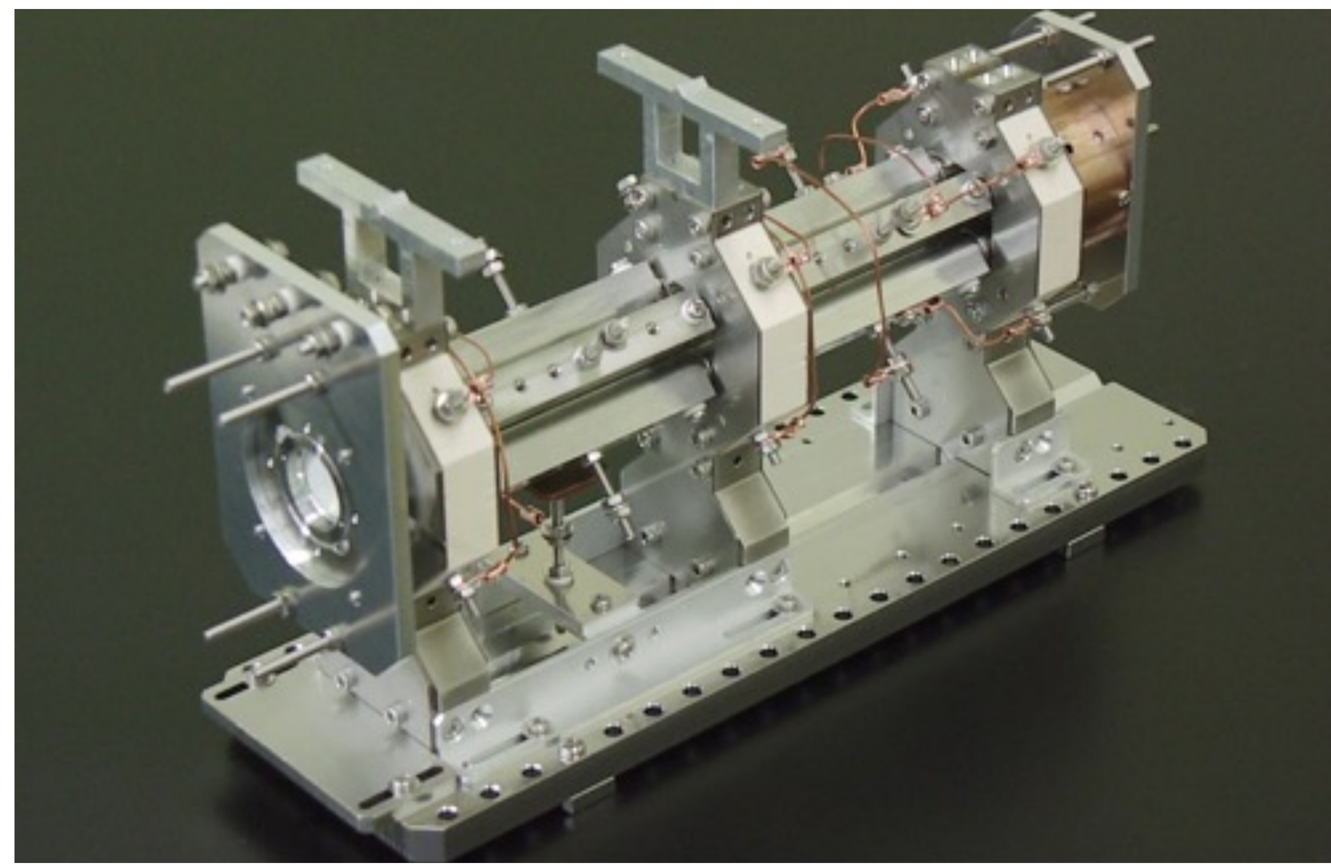
It's not always easy to include imperfections, can't always simplify…

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

Hamiltonian for transverse beam motion

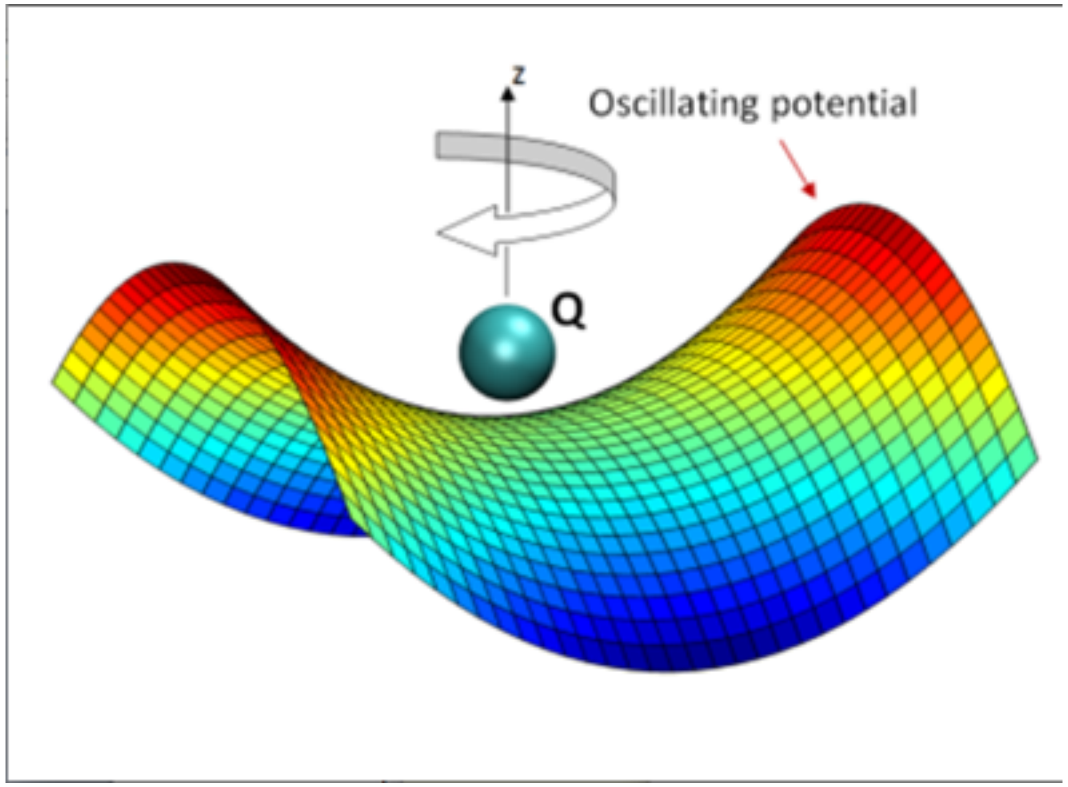
S-POD: Simulator of Particle Orbit Dynamics at Hiroshima University





Paul Trap

Wolfgang Paul
Nobel Prize 1989 (shared)

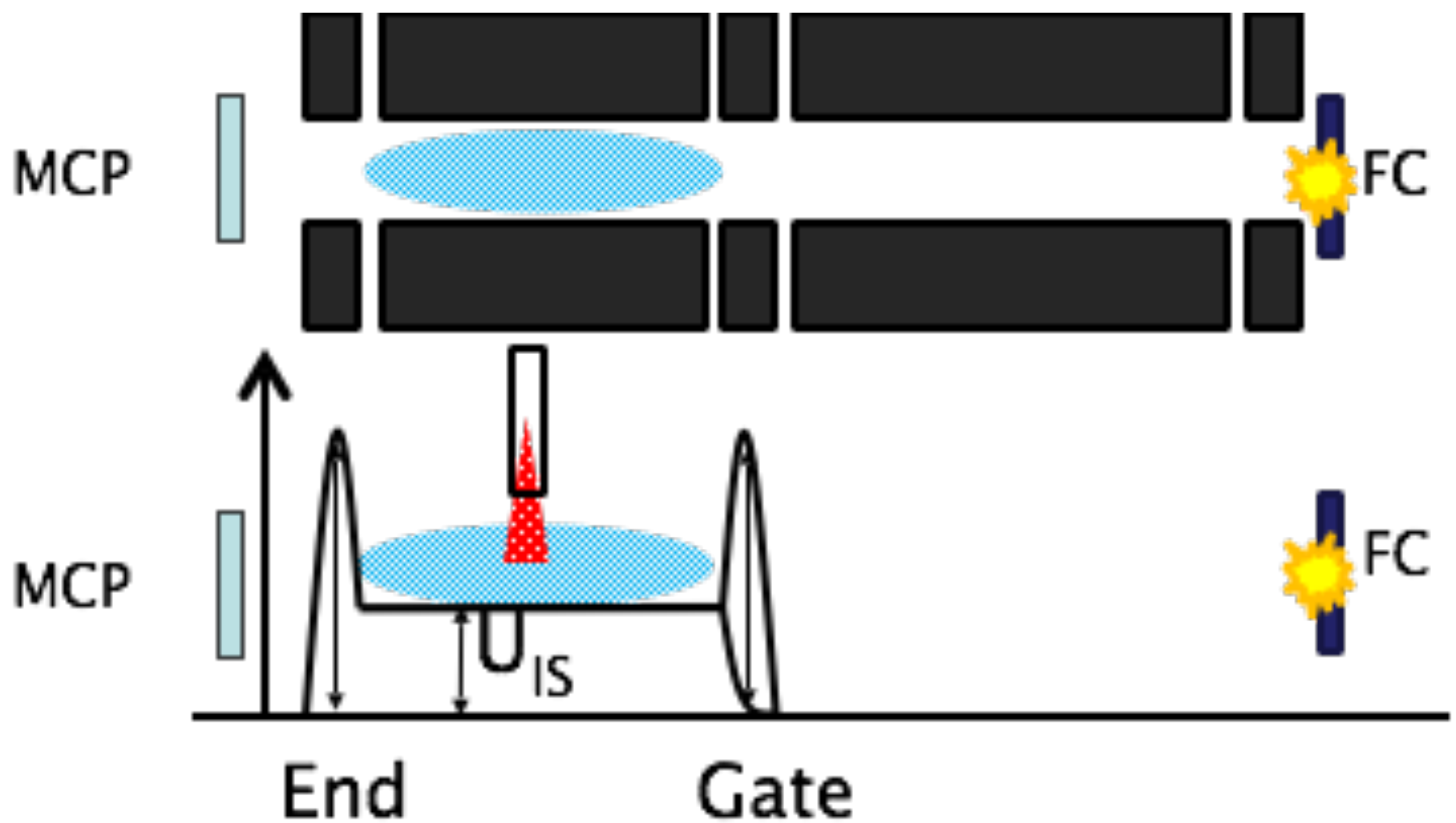


$$H_{\text{beam}} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K(s)(x^2 - y^2) + \frac{q}{p_0\beta_0 c\gamma_0^2}\phi$$

Hamiltonian for
transverse beam motion

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

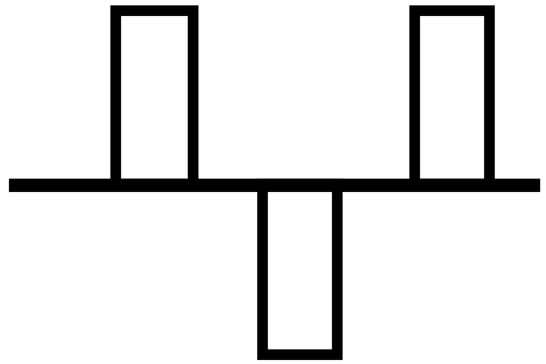
Hamiltonian for Paul trap



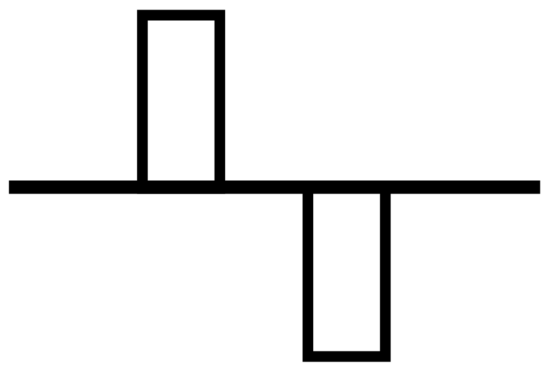
Argon gas ionised by e- gun

Lattice Structures

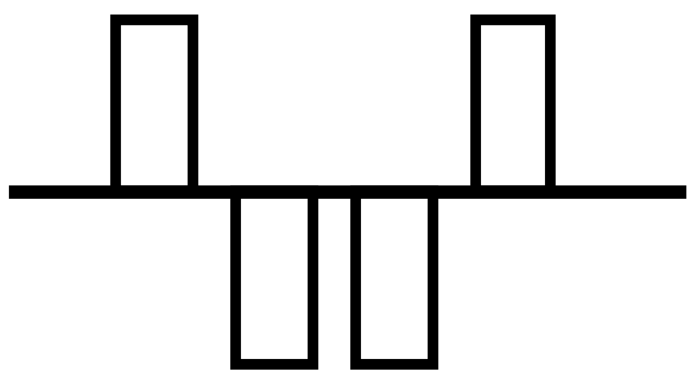
FDF

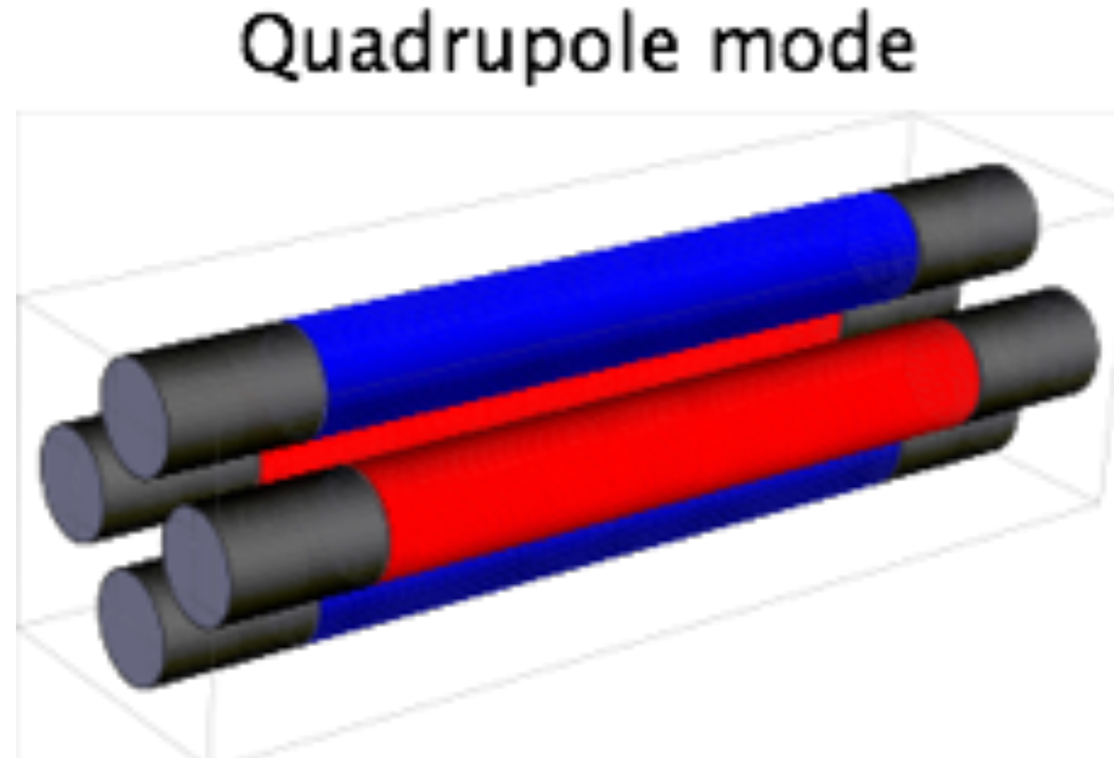


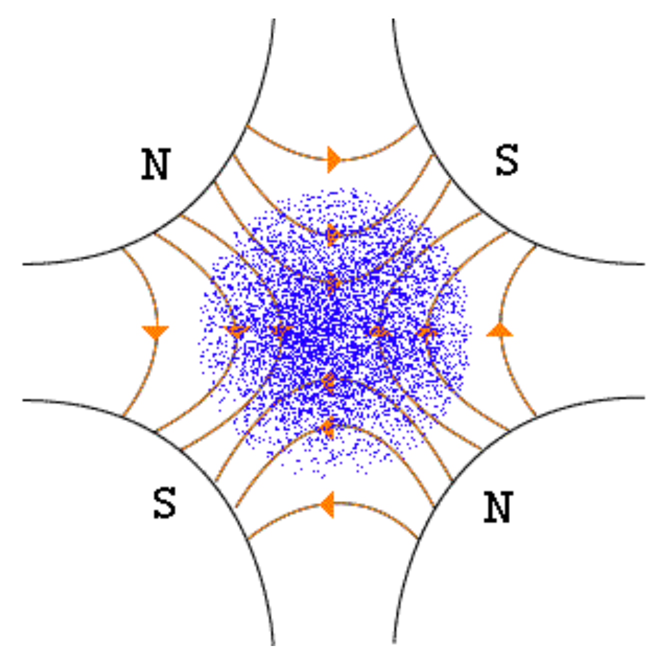
FODO

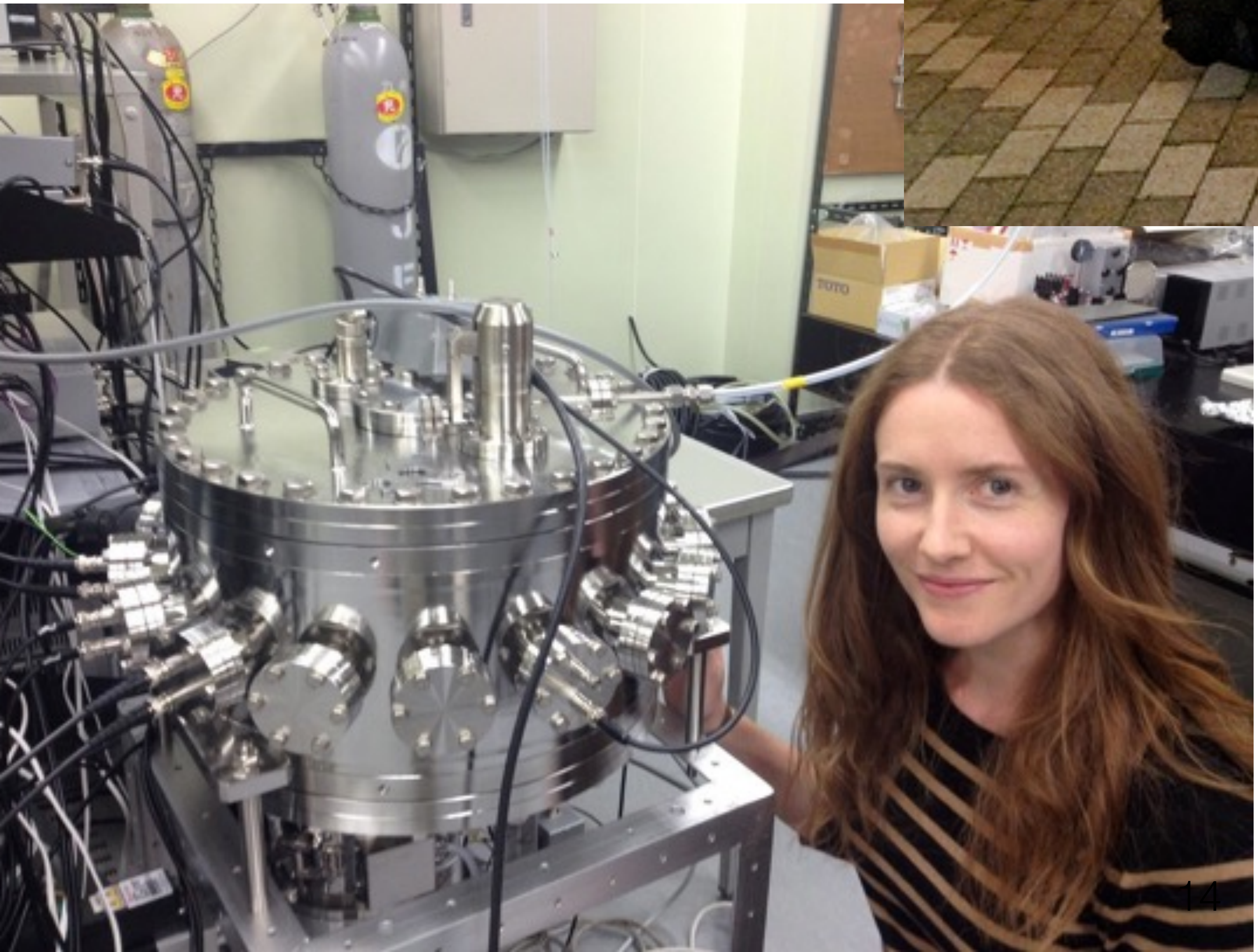


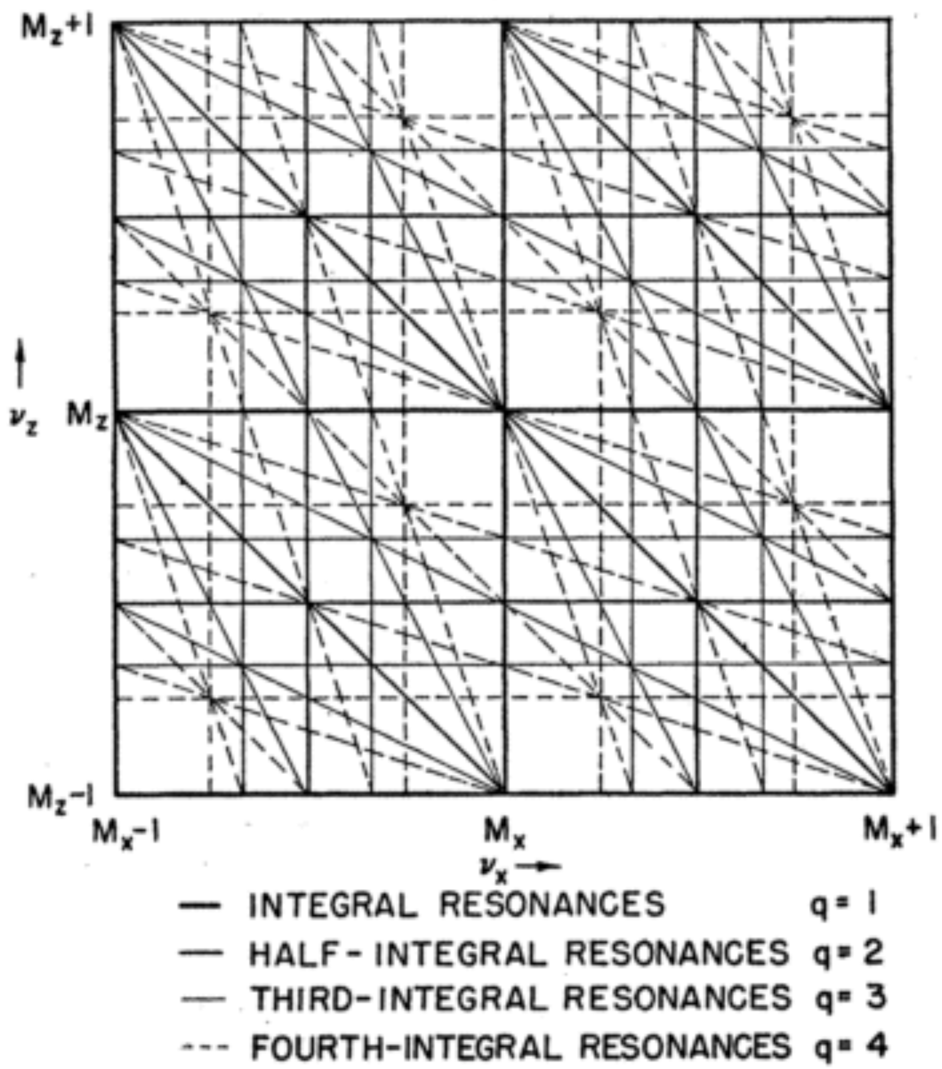
FDDF



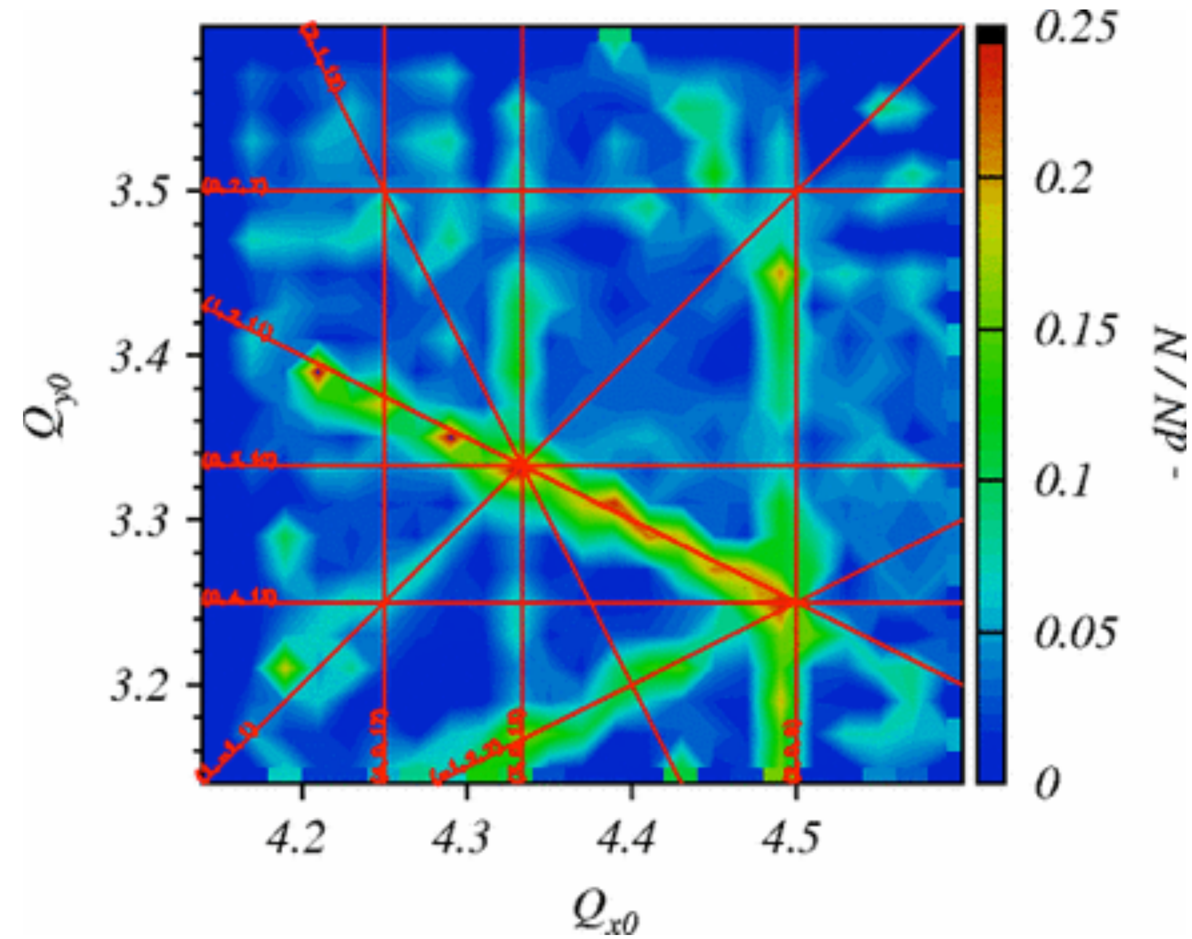






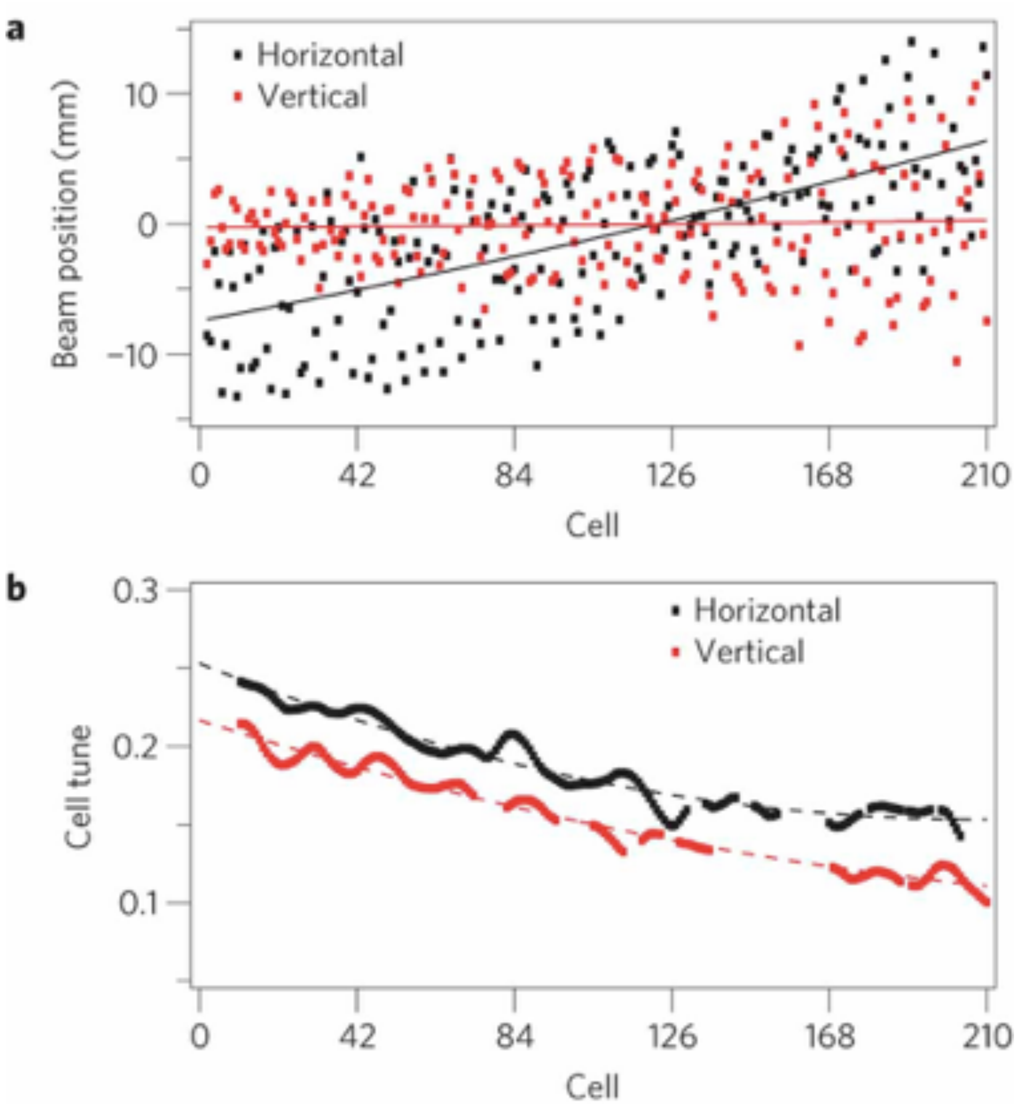


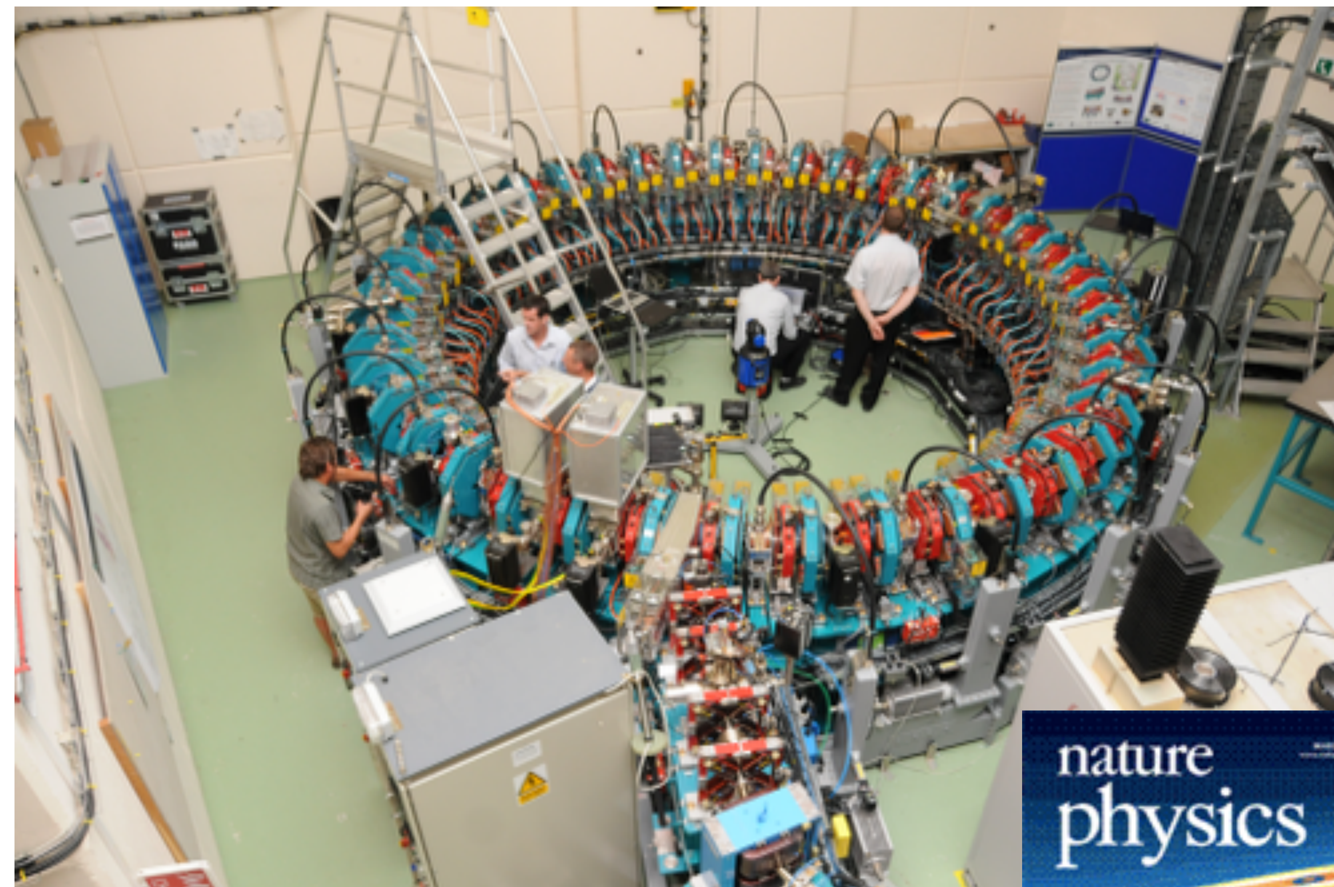
$$n\nu_x + m\nu_y = 0,1,2...$$

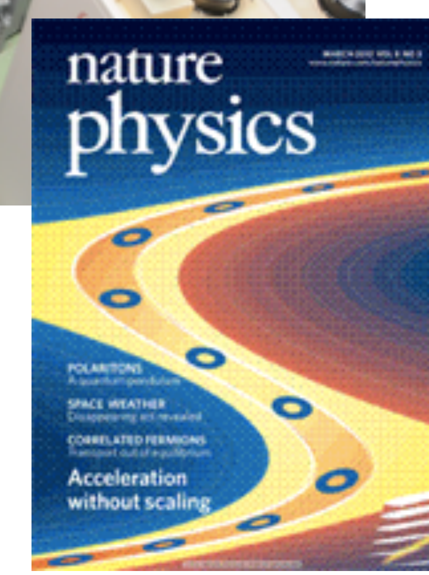


Beam losses in SIS18 from tune scans

G. Franchetti et al, Phys. Rev. ST Accel. Beams 13, 114203, 2010





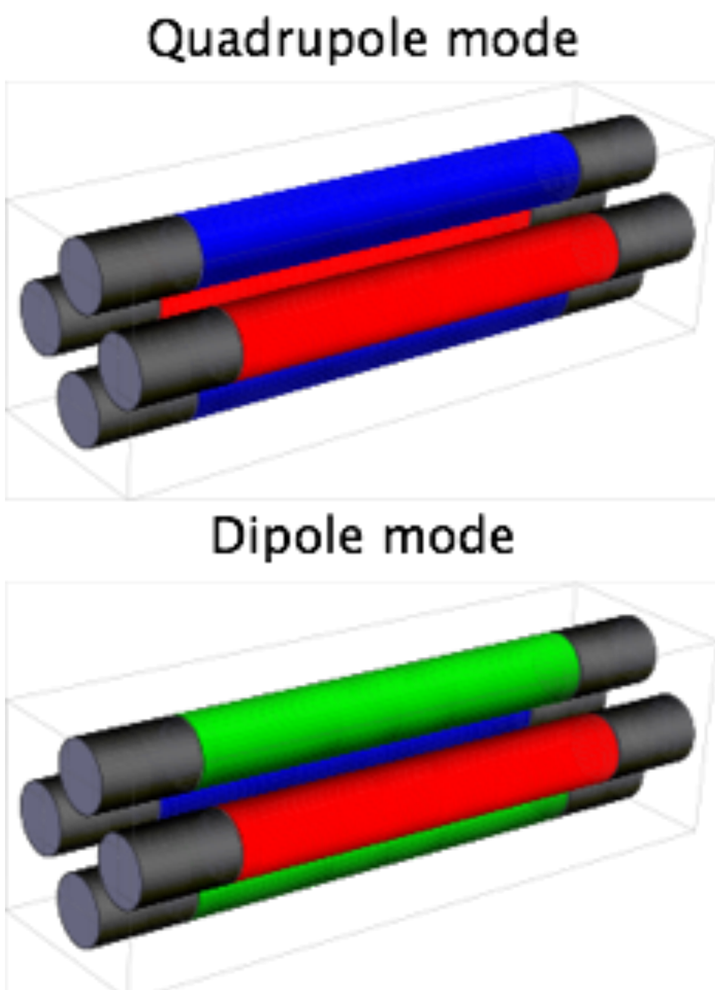


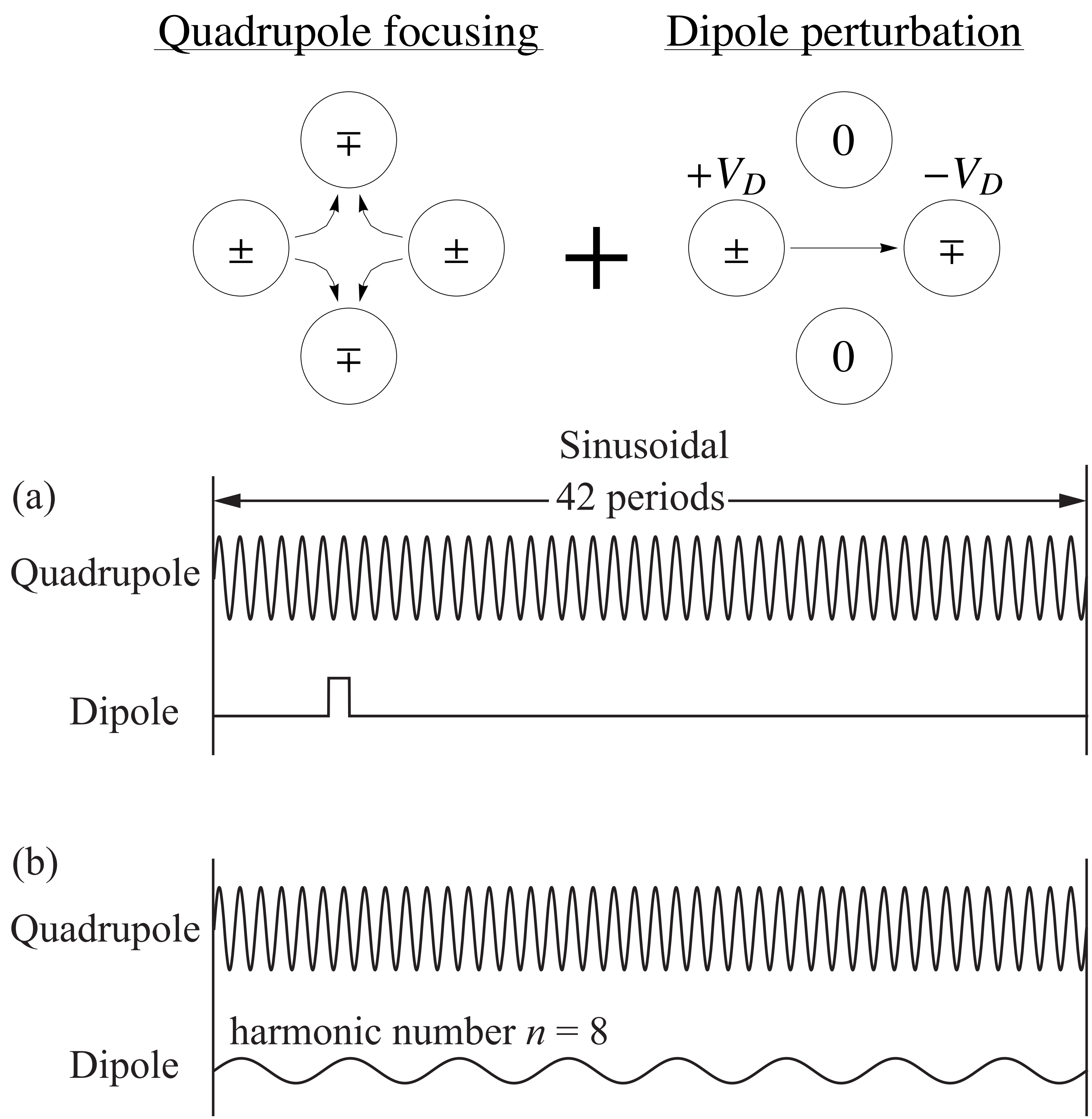
S. Machida et. al., Nature Physics 8, 243–247 (2012)

Resonance crossing, particularly of integers is a *key concern* in the FFAG community, particularly with the development of non-scaling FFAGs.

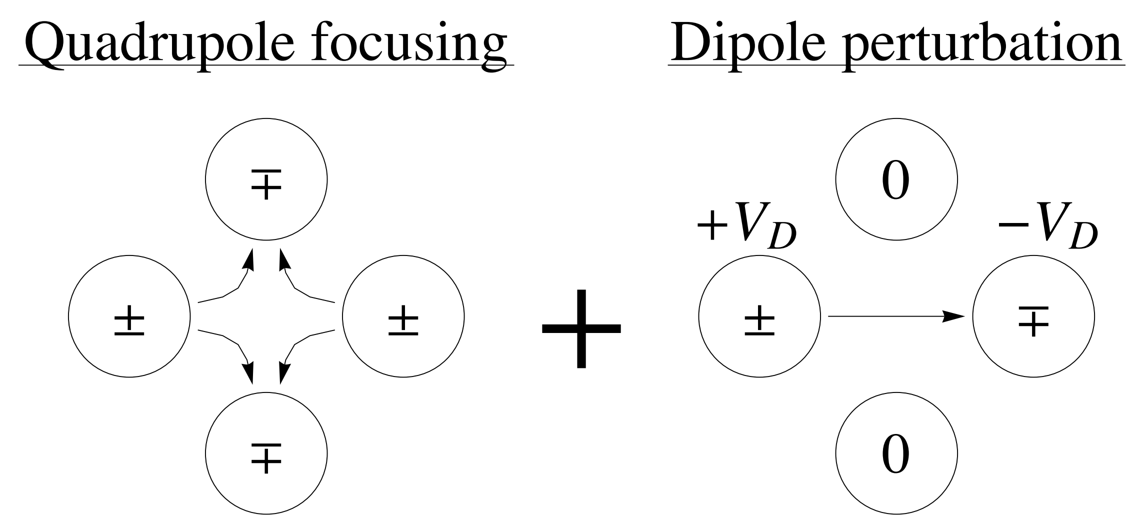
In EMMA and other accelerators, it can be difficult to do slow resonance crossing studies due to:

- Limited parameter range (RF)
- Coupling to longitudinal plane
- Lack of range of control for driving terms
- Time consuming experiments


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



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

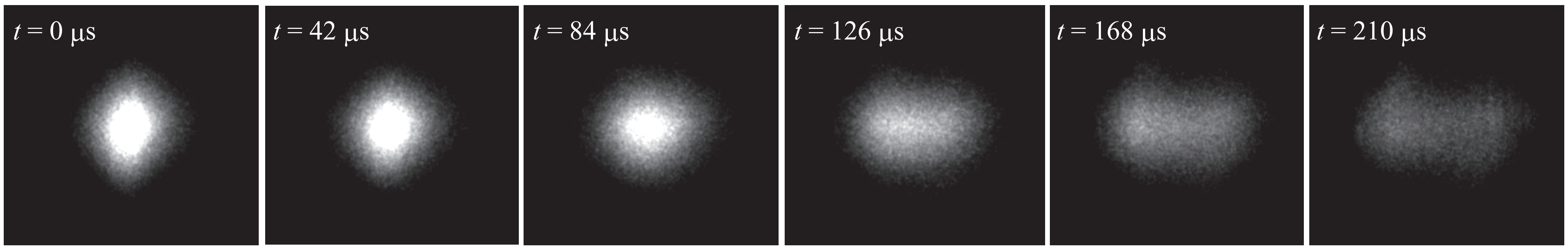
COD equation of motion in circular accelerator

⟷

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

Equation of motion in S-POD with dipole perturbation field

Ion losses on resonance

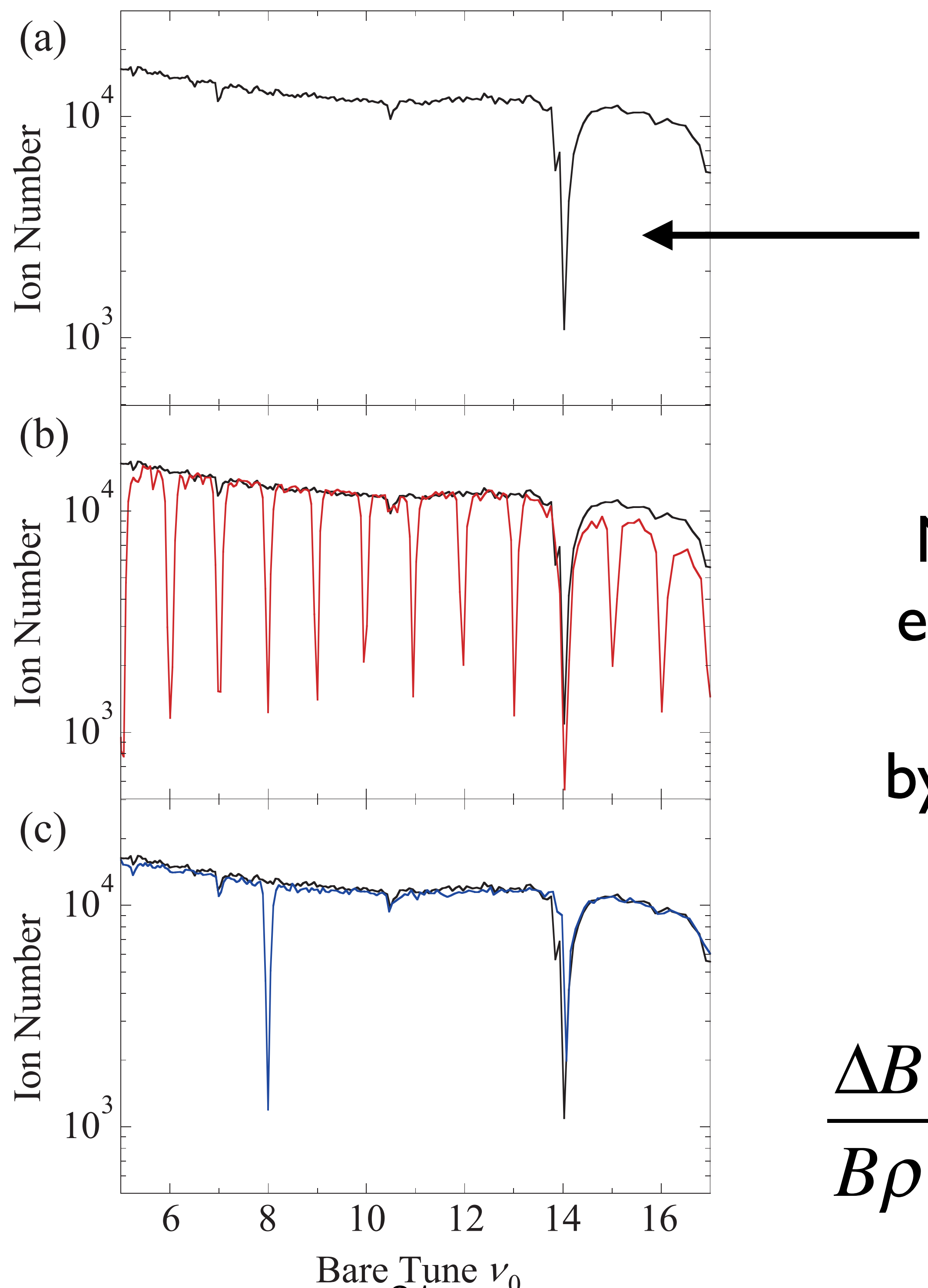


nb: each image is axially integrated distribution

On resonance, we clearly see large ion losses

Can also see a clear widening in the distribution

Establishing integer stopbands with dipole perturbation



3rd order due to trap misalignment

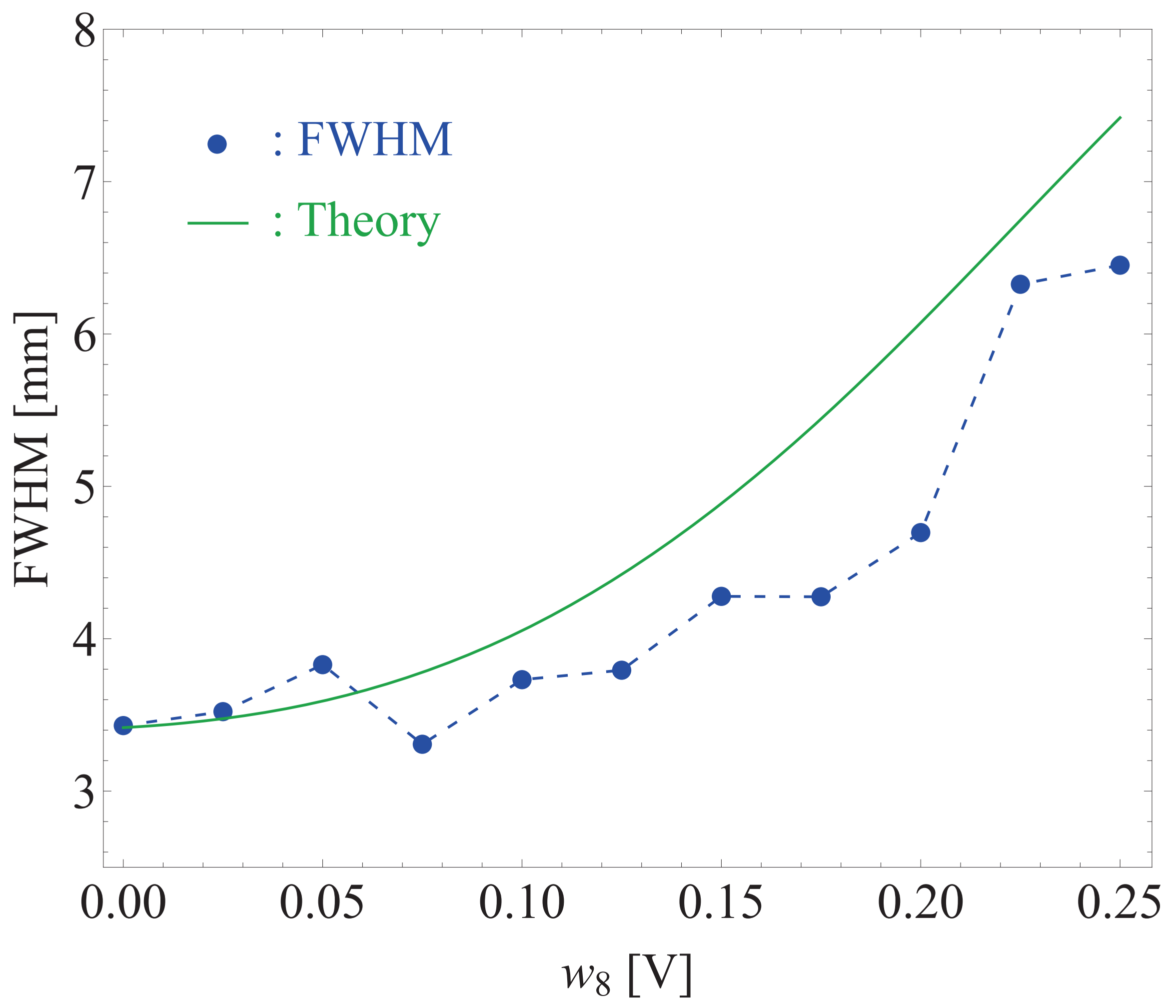
Note that we can excite each integer individually by expanding dipole field into fourier harmonics:

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

Amplitude growth with error

Theory = Gaussian distribution integrated over COD trajectory

tune = 8.1, varying perturbation strength



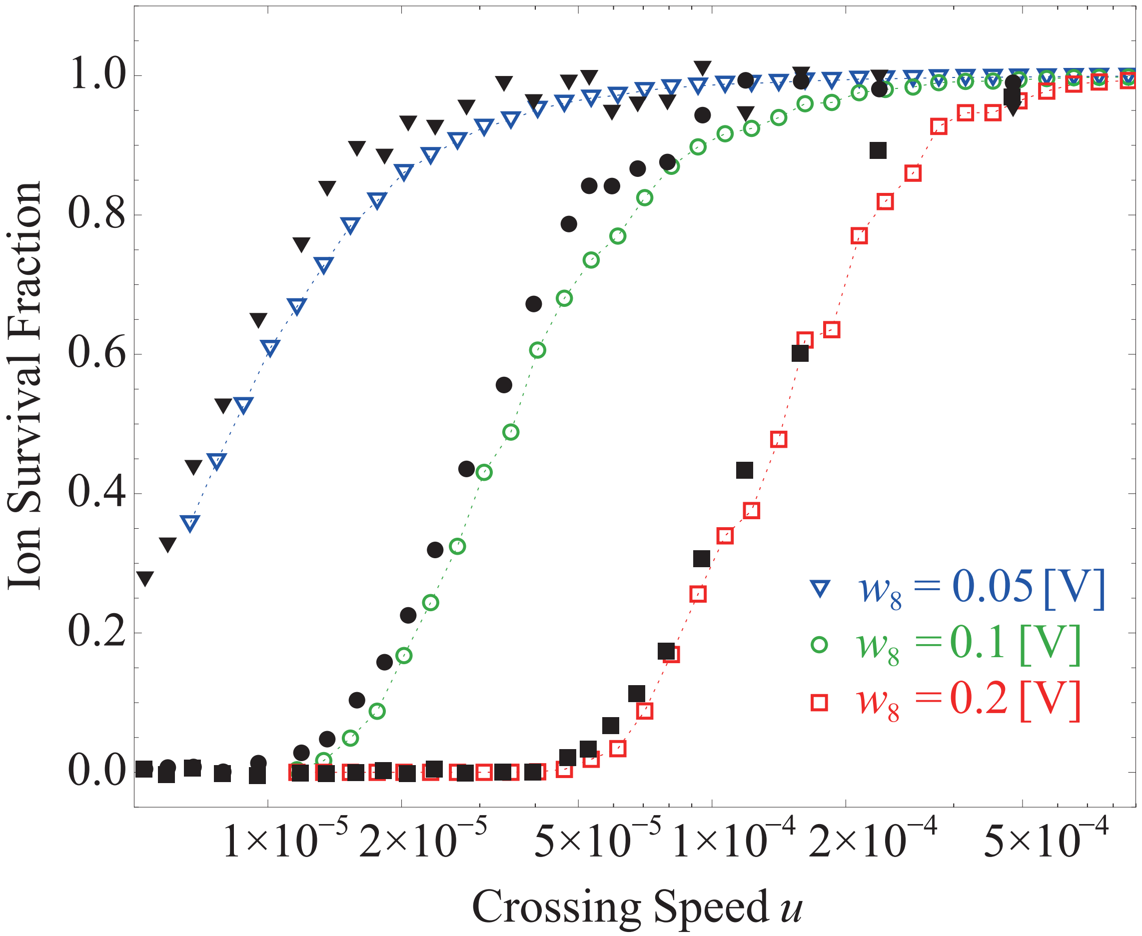
We wanted to confirm amplitude growth when OFF RESONANCE as well

Single resonance crossing

crossing speed, $u = \frac{\delta \nu_{\mathrm{cell}}}{n_{\mathrm{rf}}}$

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

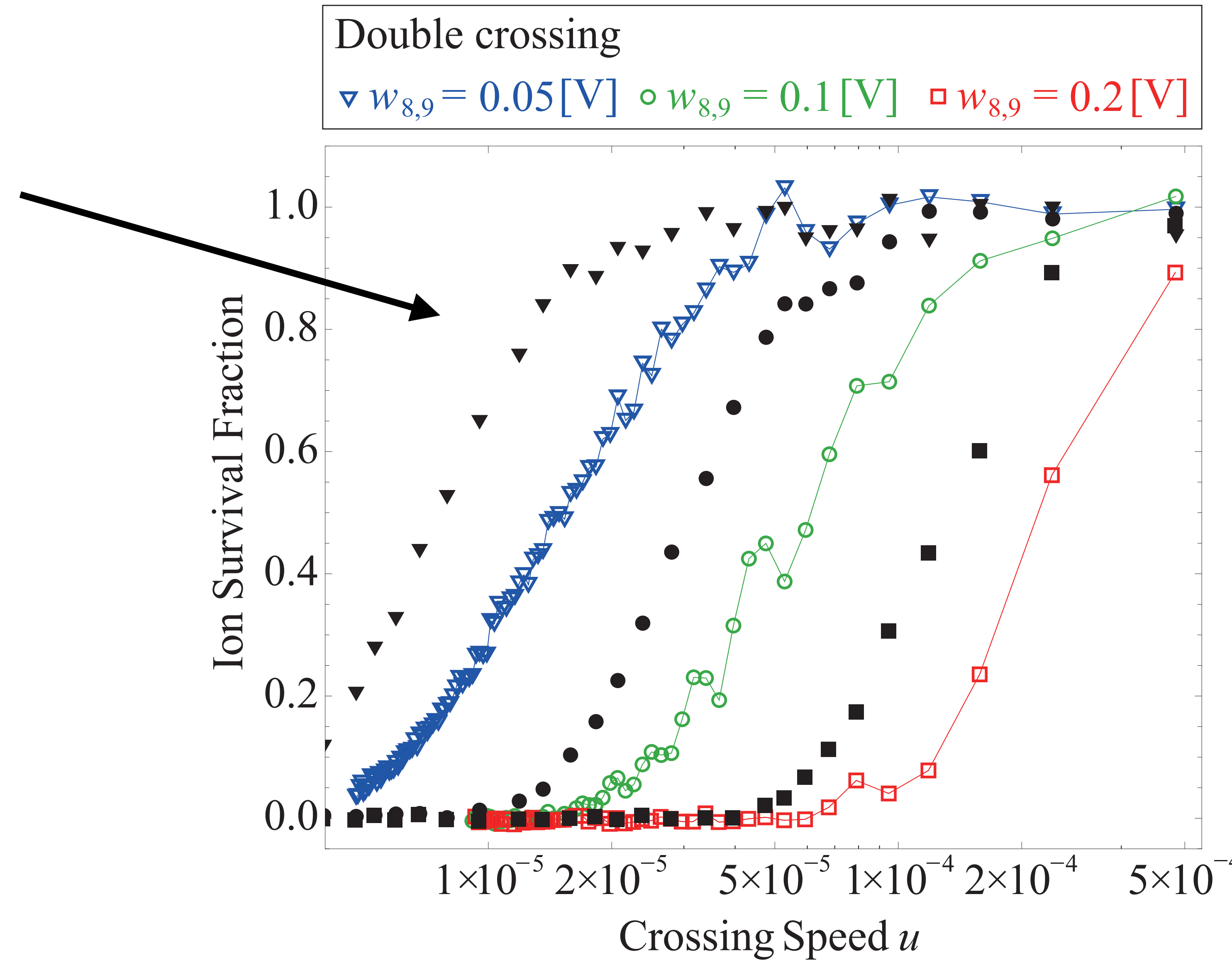
8th harmonic excited
Tune varied 9.5 -> 7.5



Double resonance crossing

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

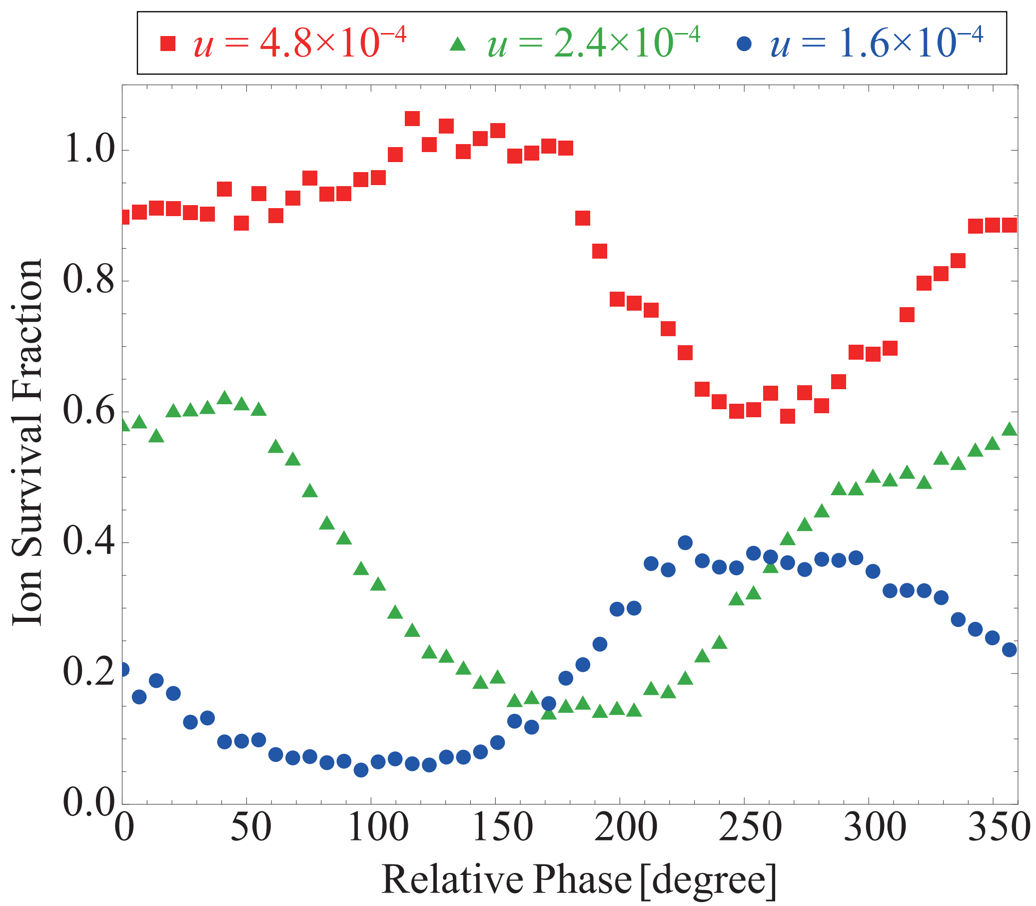
Oscillatory behaviour for high perturbation strength… why?



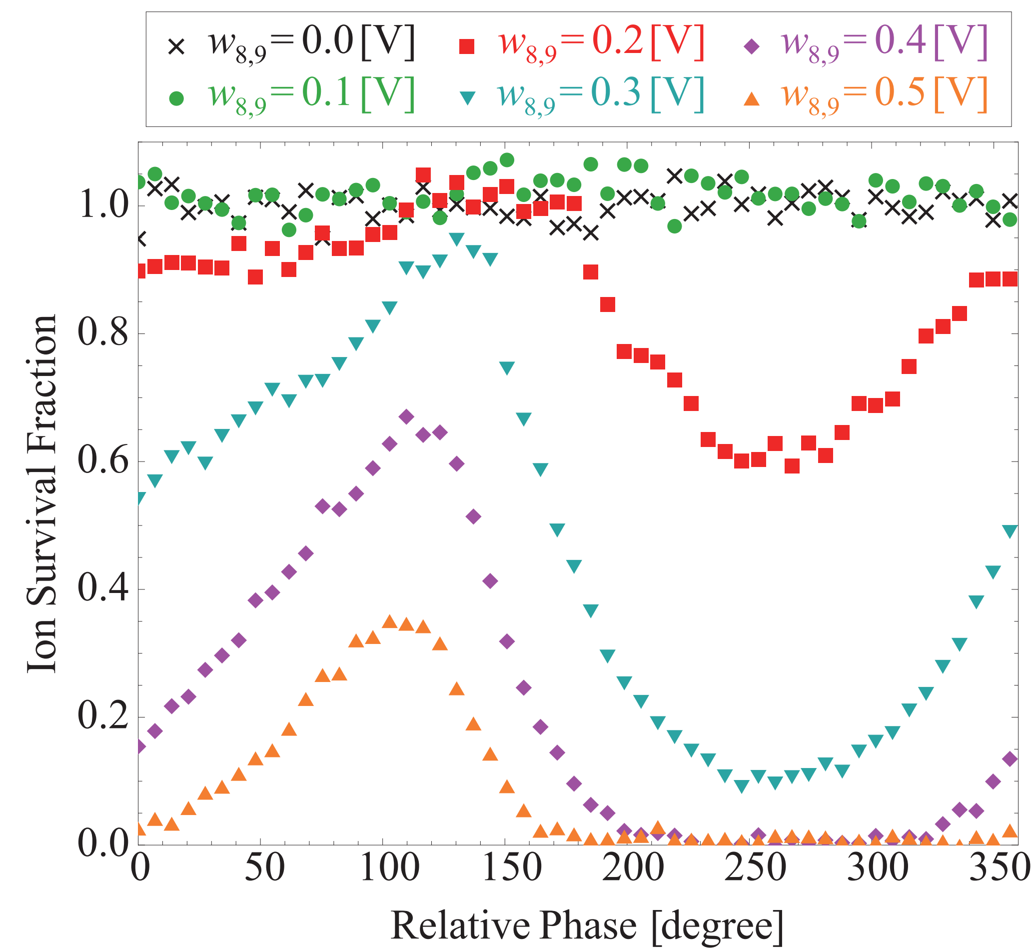
- Single crossing for comparison (black)

Phase dependent effects

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



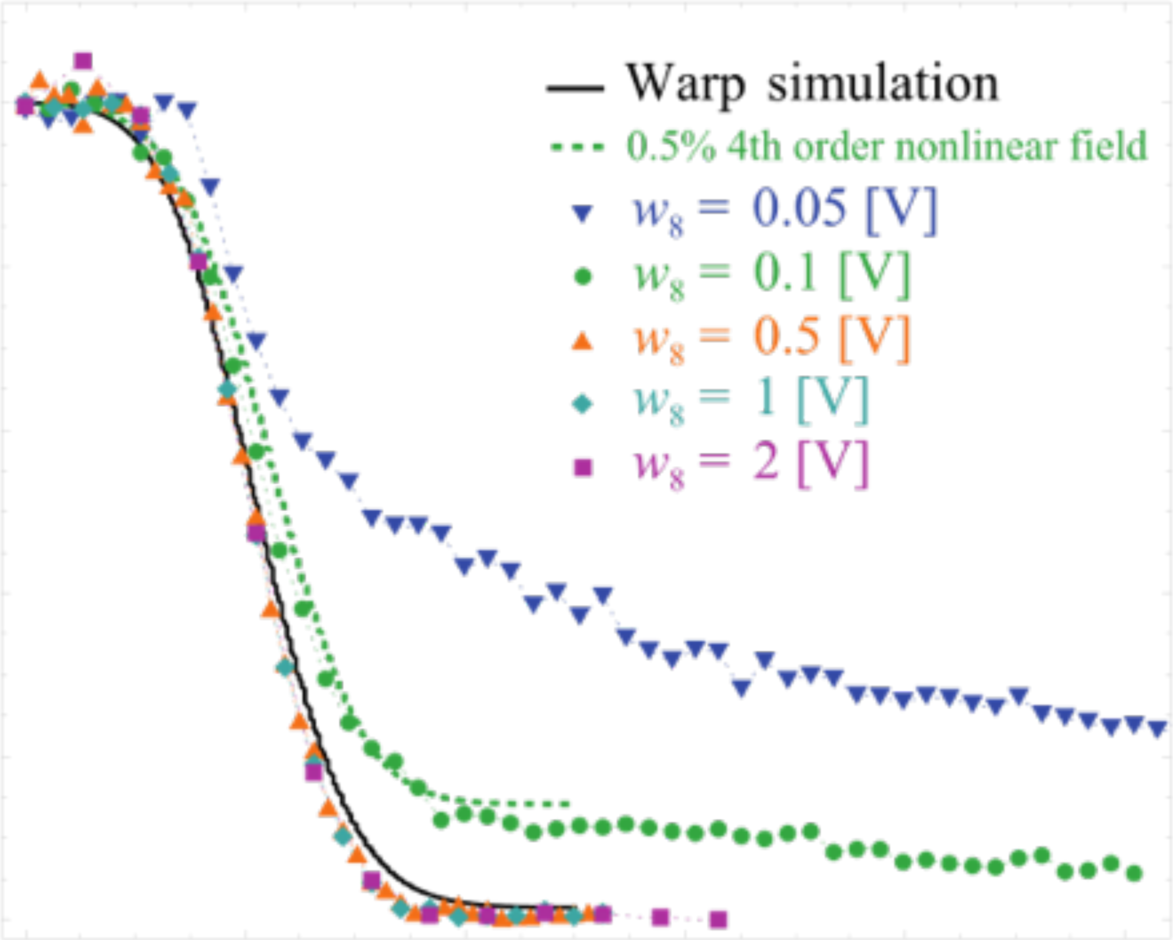
Fixed perturbation
Varying crossing speed



Fixed crossing speed
Varying perturbation

Non-linear fields play a role too…

Many interesting phenomena occur in accelerators which could be studied if the 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).

IBEX
Intense Beam Experiment

- Construction of a linear Paul Trap apparatus at RAL with funding from ASTeC (£77,000)
- Complementary to the existing setup at Hiroshima and built in close collaboration.
- Lots of interest from accelerator community already - FNAL (IOTA, S. Ngaitsev), CERN PS (M. Giovanozzi), ISIS (C. Warsop)

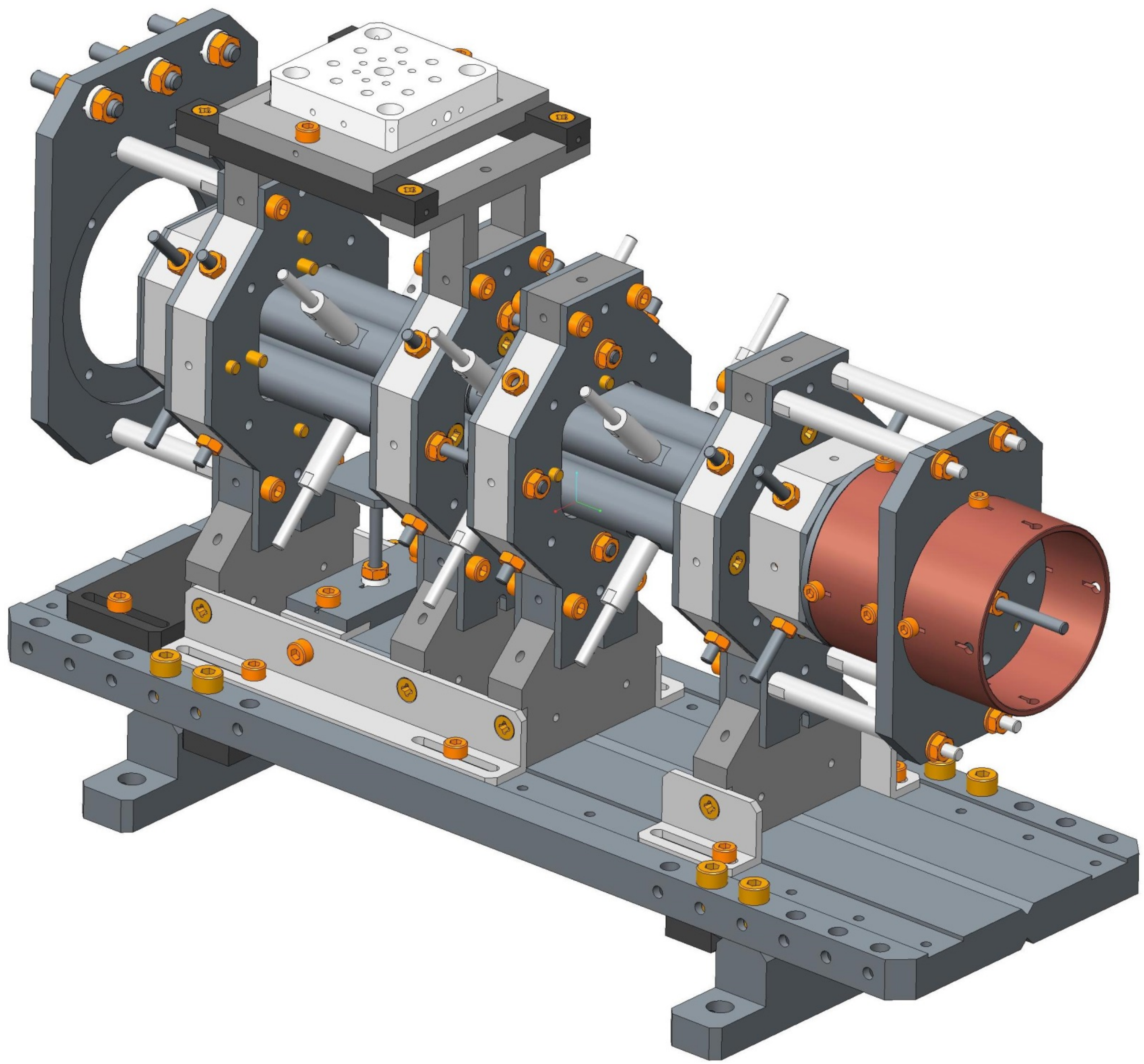
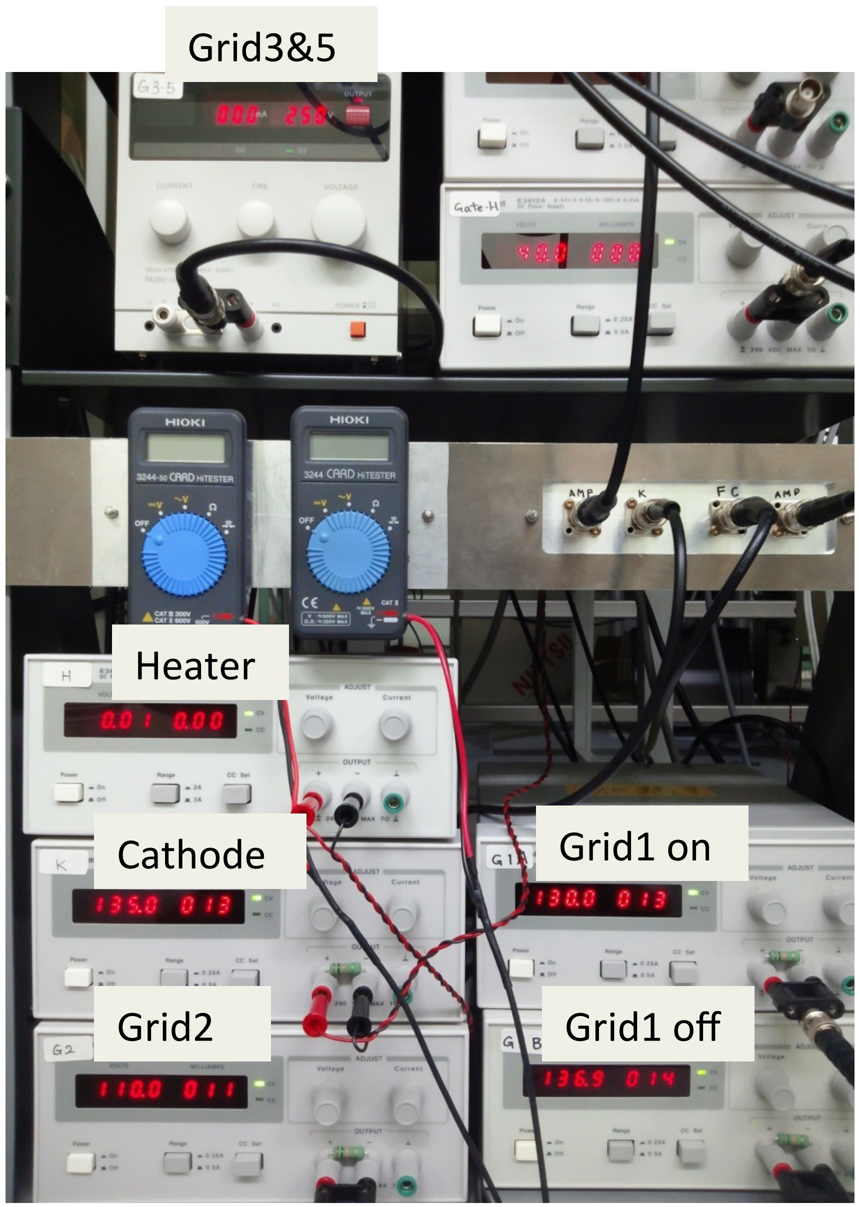
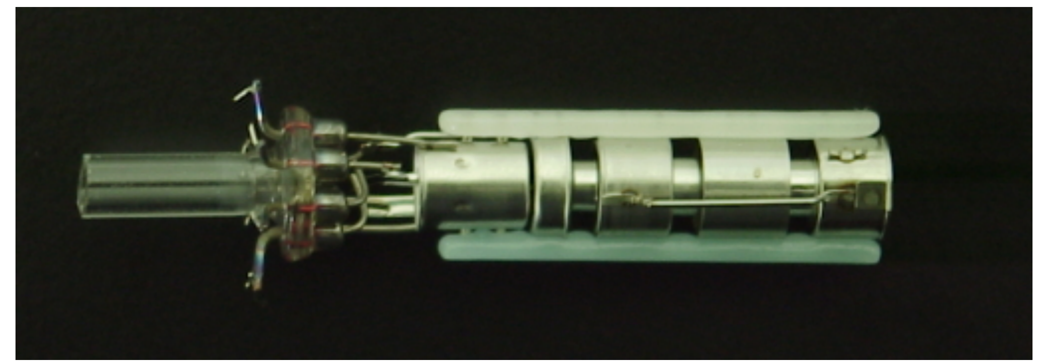


Image courtesy Technology at Daresbury Laboratory

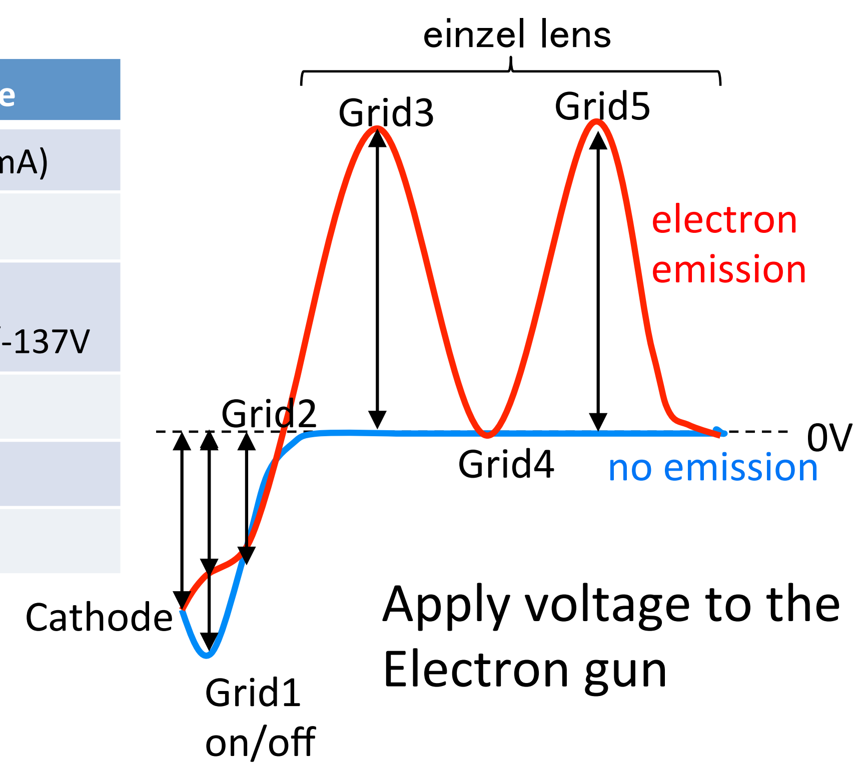
e-gun to ionize Ar



Electron gun



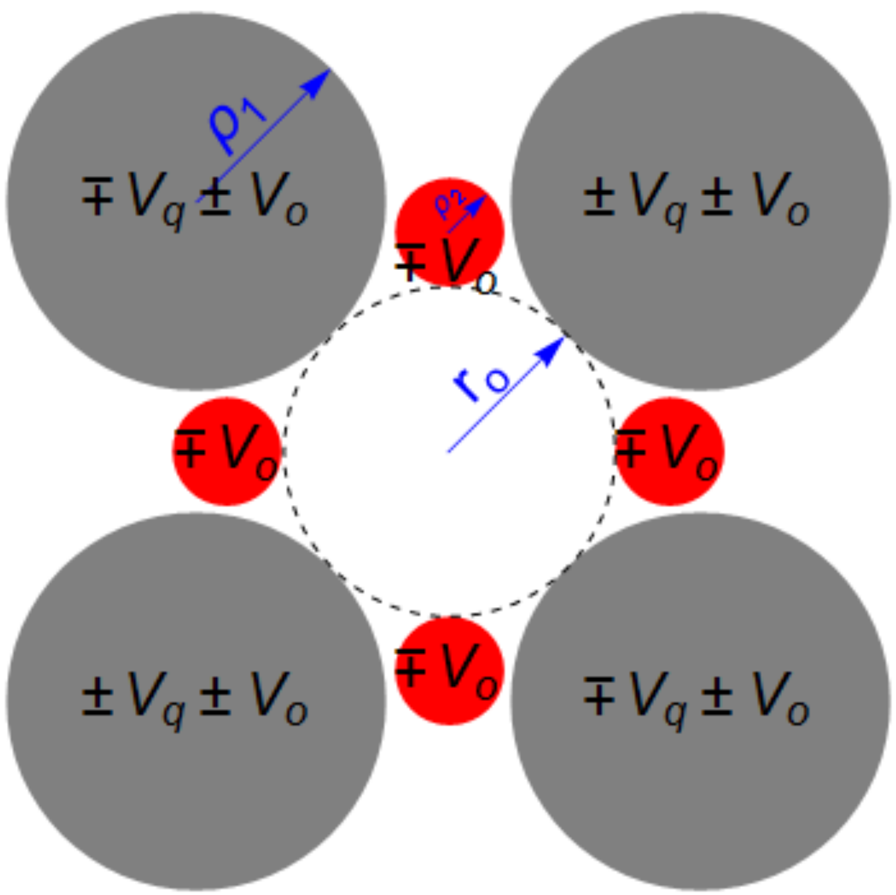
	Voltage
Heater	6V(70mA)
Cathode	-135V
Grid1 on/off	ex) -130V/-137V
Grid2	-110V
Grid3&5	250V
Grid4	0V

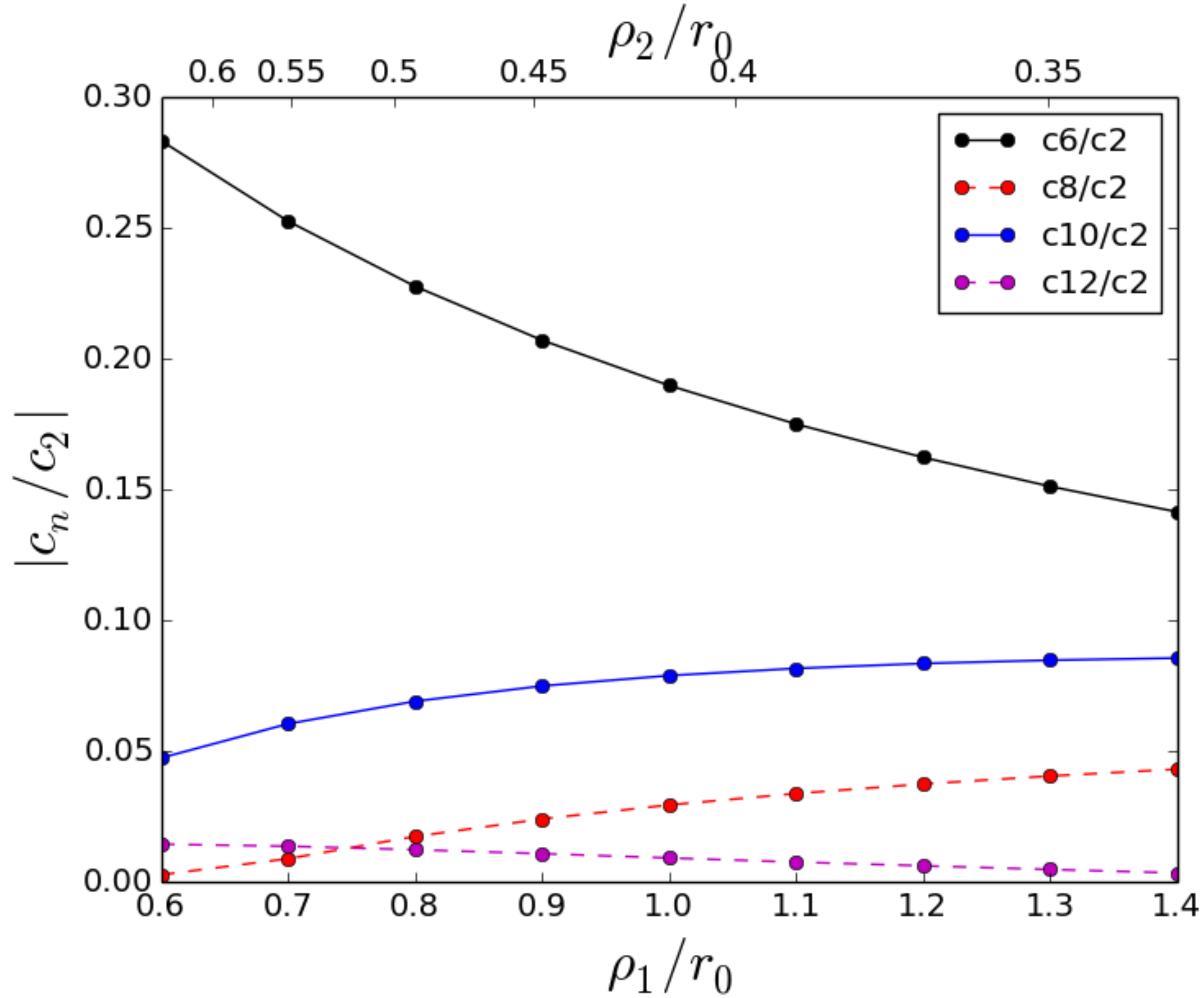


Apply voltage to the Electron gun

slide courtesy H. Okamoto's group, University of Hiroshima

Non-linear Paul trap





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

Future 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."

- Combination of resonance crossing with intense beams is a natural extension
- Lattice variants and higher order stability regions
- Systematic study and control of non-linear effects (possible CERN PS topics)
- **Integrable optics idea with FNAL**
- More general non-linear beam dynamics (with ISIS & CERN)

"Integrable Optics"

S. NGAITSEV

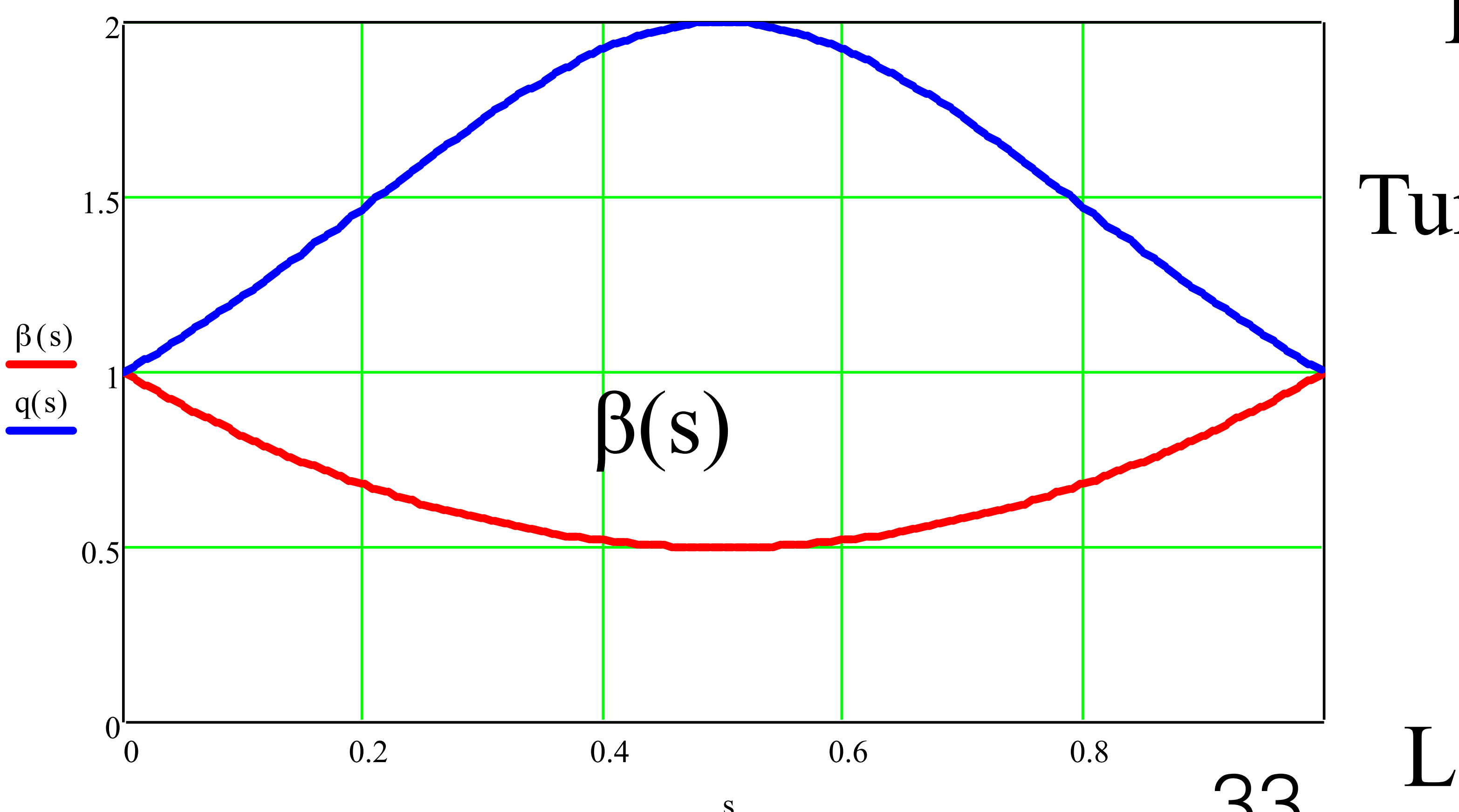
How to make the Hamiltonian time-independent?

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + \beta(\psi) V\left(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi)\right)$$

$$V(x,y,s) = \frac{q}{\beta(s)^2}\left(x^2 - y^2\right) \qquad U(x_N, y_N) = q\left(x_N^2 - y_N^2\right)$$

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + q\left(x_N^2 - y_N^2\right)$$

quadrupole amplitude

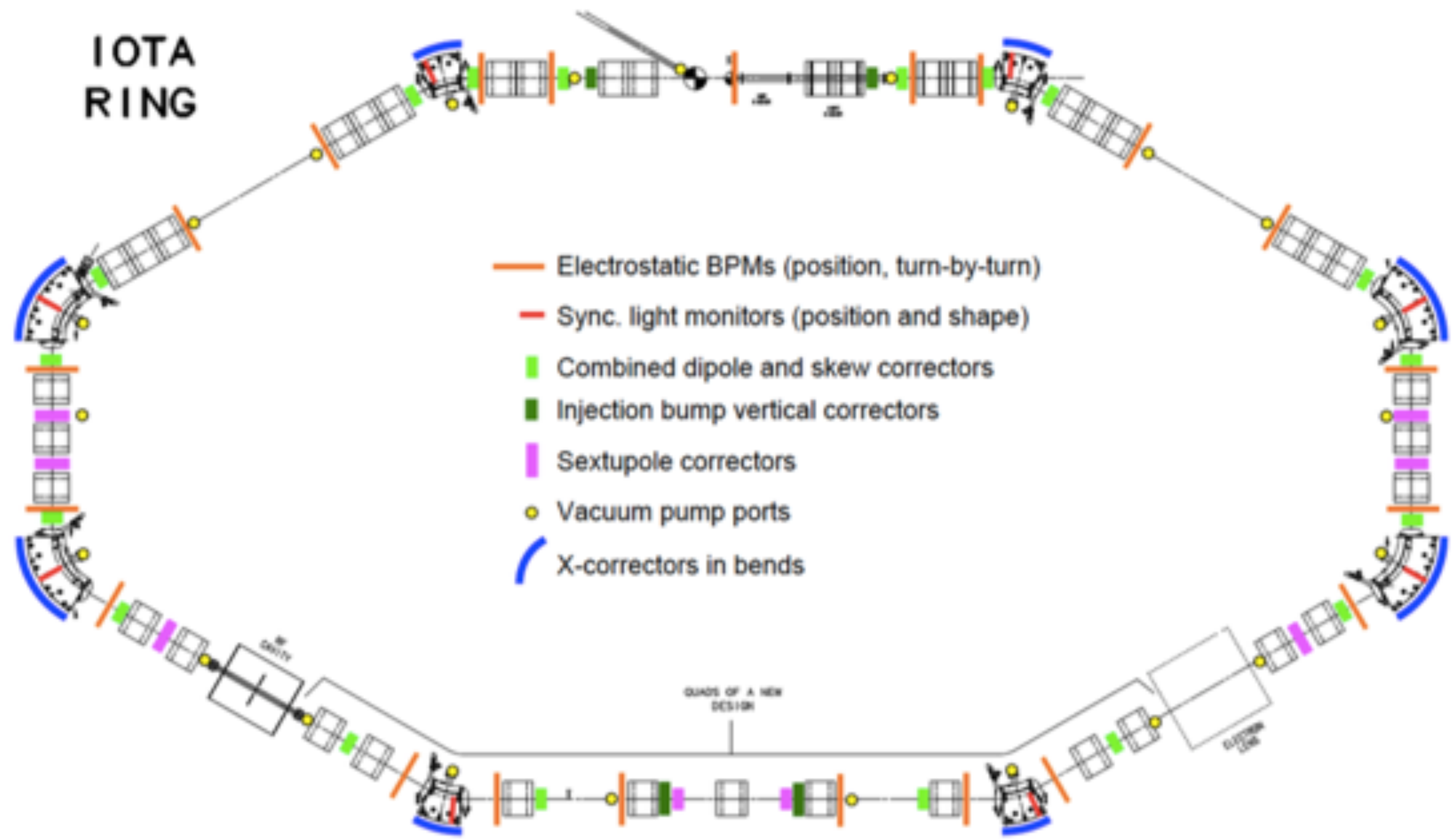


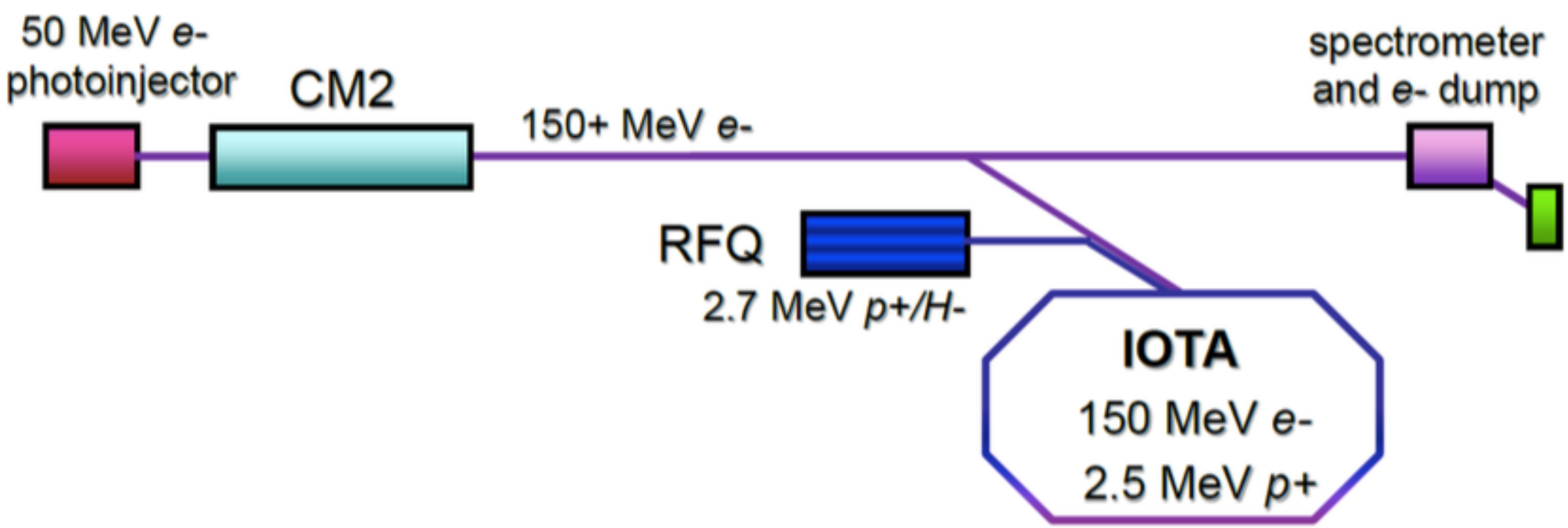
Integrable but still linear…

Tunes:

$$\nu_x^2 = \nu_0^2(1+2q)$$
$$\nu_y^2 = \nu_0^2(1-2q)$$

Tune spread: zero





From IOTA Profile, A. Valishev, April 1, 2015

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.

Interested in getting involved? Please get in touch!

Opportunities:
2 MPhys projects offered for 2015/2016:

1. A new electron gun for the Intense Beam Experiment (IBEX)

2. Design and simulation of a new multipole plasma trap for the Intense Beam Experiment (IBEX)