Science & Technology Facilities Council
ISIS

Half Integer and High Intensity Limits on the ISIS Ring

C M Warsop,
D J Adams, B Jones, B G Pine, H V Smith, R E Williamson

ISIS, Rutherford Appleton Laboratory, UK

Space Charge Workshop, CERN, April 16-19, 2013

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Science & Technology Facilities Council ISIS

Contents

- Introduction ~ The ISIS Synchrotron
- Review of Half Integer Studies on ISIS ~ Purpose & Plan
  - ISIS 2D Calculations ~ Coherent Theory
  - ISIS 2D ORBIT PIC Simulations ~ Limits, Loss, Halo
- Real Experiments to Measure Halo ~ Simulations and Results
- Interpretation of Results ~ Future Work
- Relevance to ISIS Operations and Upgrades
- Acknowledgements

The ISIS Synchrotron

- Space charge peaks during trapping

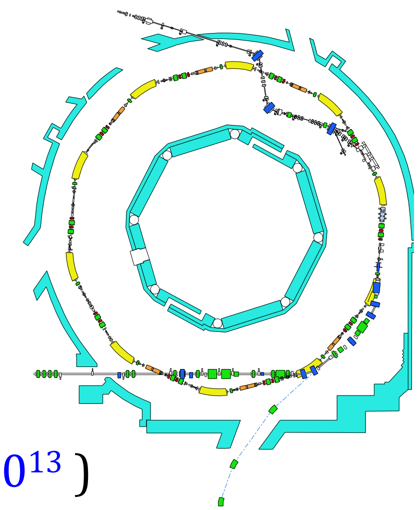
  Low energy & bunching: ΔQ_{incoh}~-0.6

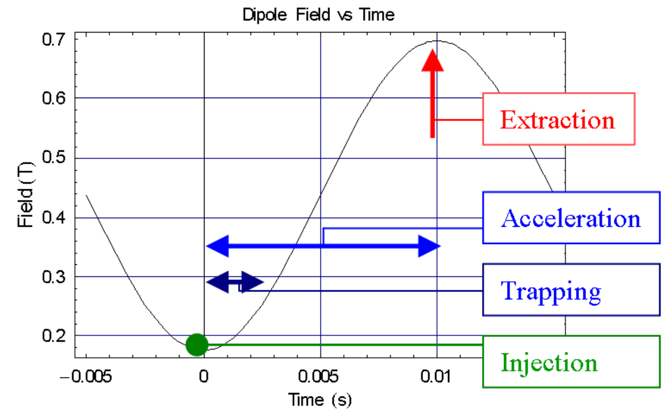
- Losses

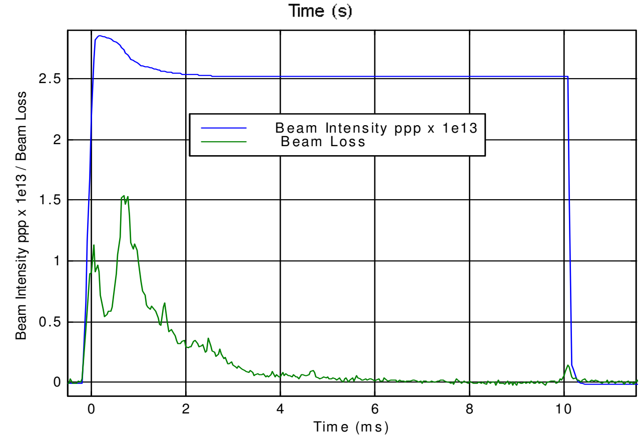
  Fast longitudinal capture

  Transverse space charge, …

  Loss limited machine

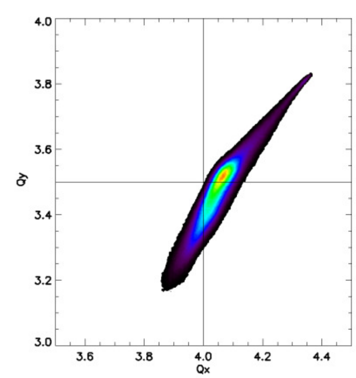






Circumference:	163 m
Energy Range:	70-800 MeV
Rep Rate:	50 Hz
Intensity:	$2.5x10^{13}$ ppp ($3.0x10^{13}$)
Mean Power:	160 kW (200 kW)
Losses:	Inj: 2%, Trap: <5%, Acc/Ext <0.1%
Injection:	130 turn, charge-exchange (not chopped)
Acceptances:	collimated ~300 π mm mr
RF System:	h=2, f_2=1.3-3.1 MHz, V_2 ~160kV/turn
	h=4, f_4=2.6-6.2 MHz, V_4 ~80 kV/turn
Extraction:	Single Turn, Vertical
Tunes:	(Q_x, Q_y)=(4.31,3.83) (*variable*)

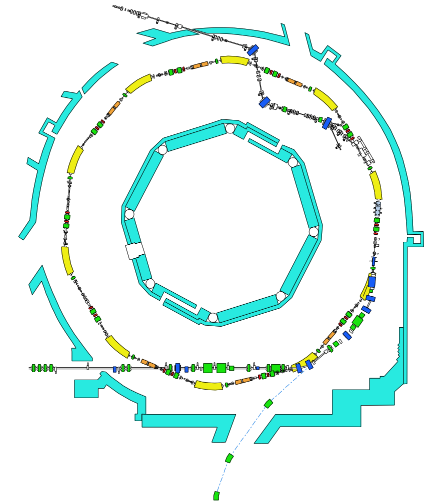
ISIS Tune Shifts



ORBIT, *0.5 ms*
2.8E13 ppp,
RCS mode

ISIS Half Integer Studies

Science & Technology Facilities Council ISIS



- What are we trying achieve?

  Understand the high intensity limits of ISIS

  minimise and control loss during operations

  better understanding for upgrades

  We want to understand what causes loss!

- Normal ISIS operations: 3D (6D) process with rapid ramp (RCS)

  Being studied: benchmarking 3D ORBIT models of machine

  Half Integer: main focus on simpler 2D coasting beam (**S**torage **R**ing **M**ode)

  Long term plan: SRM coasting → SRM bunched → RCS

- Half integer study so far: 2D (4D (x,x',y,y')) coasting beams SRM

  Analytical models, Simulation models → Experimental verification

  Confirm our models with a detailed experimental study of simpler process

  Work our way towards the more challenging RCS case

Calculations of Envelope Modes for ISIS

Science & Technology Facilities Council ISIS

- Calculate coherent mode frequencies from envelope equation

General formula: non-equal beam size (a, b) and tune (Q_x,Q_y) [Sacherer]

$$w^2 = 2\left(Q_{xo}^{\ 2} + Q_{yo}^{\ 2}\right) - \frac{\left(3a^2 + 4ab + 3b^2\right)}{2(a+b)^2} w_p^{\ 2} \pm \sqrt{4\left(Q_{xo}^{\ 2} - Q_{yo}^{\ 2}\right)^2 + 6\frac{(a-b)}{(a+b)}\left(Q_{xo} - Q_{yo}\right)\left(Q_{xo} + Q_{yo}\right) w_p^{\ 2} + \frac{\left(9a^4 - 14a^2b^2 + 9b^4\right)}{4(a+b)^4} w_p^{\ 4}}$$

ISIS: Q=(4.31, 3.83), calculate for nominal (a, b), intensities

Coherent modes w for various approximations: large tune split

Equal (a, b) reasonable approximation (no dispersion)

$$w_p^{\ 2} = \frac{2N \cdot r_0 \cdot R}{\pi \cdot B \cdot a \cdot b} \frac{1}{\beta^2 \gamma^3}$$

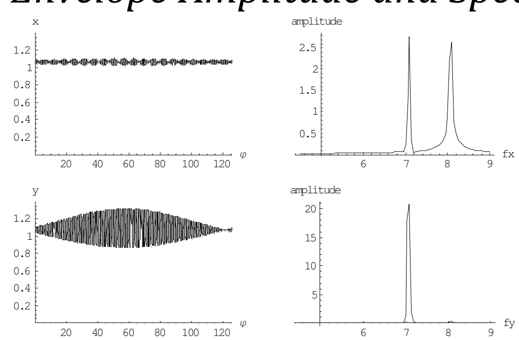
$$w_p^{\ 2} \equiv 2Q_{x0} \Delta Q_{xsc} \frac{(a+b)}{b}$$

Numerical Solution of Envelope Equation

Envelope Amplitude and Spectra

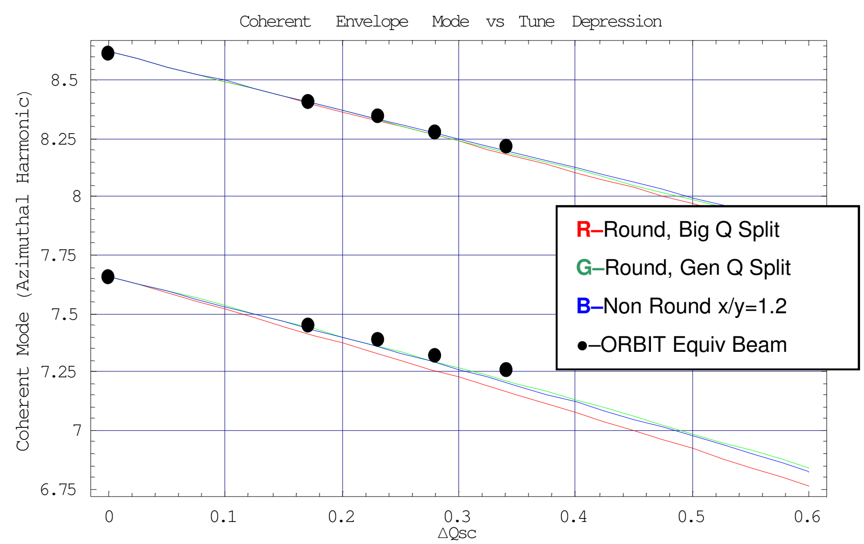
x - plane

y - plane



Independent resonance in driven plane

Summary of Calculations for ISIS



- So expect "coherent advantage"

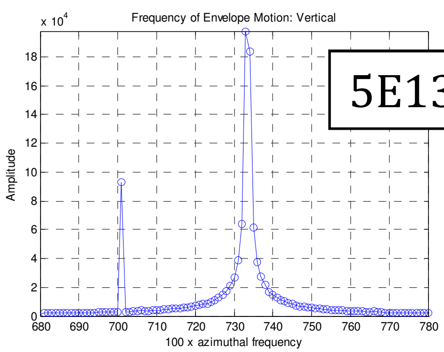
$$Q_0 - C \cdot \Delta Q_{sc} = \frac{n}{2}; \qquad C = \frac{5}{8}$$

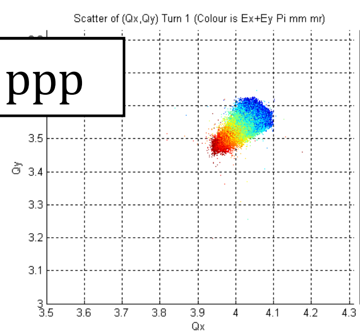
2D ORBIT Simulations: Near Resonance

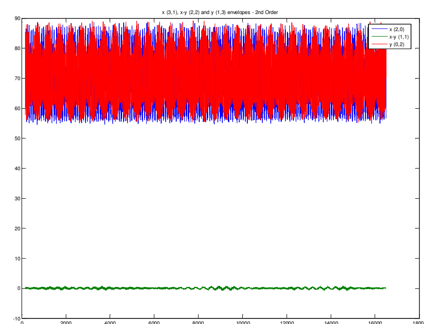
- PIC Simulations: Track RMS matched waterbag beam 100 turns
  $2Q_y$=7 driving term, nominal Q, $\varepsilon_{x,y,rms}$=65 π mm mr, ISIS AG lattice, 70 MeV
- Increase intensity: push toward coherent resonance
  Get: (1) "stable beating" then (2) envelop growth, ε_{rms} increase

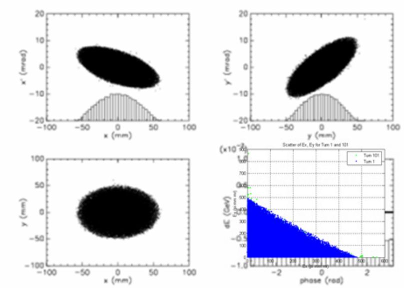
Envelope Frequencies | *Incoherent Tunes* | *Envelope Evolution* | *Turn 100:* (x,x') (y,y') (x,y) $(\varepsilon_x,\varepsilon_y)$

5E13 ppp

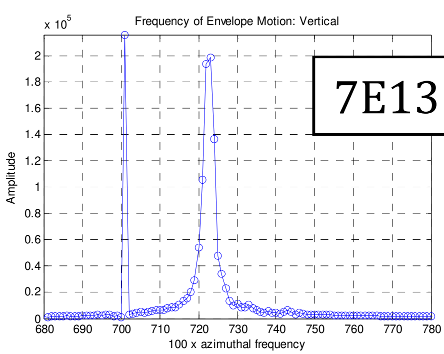


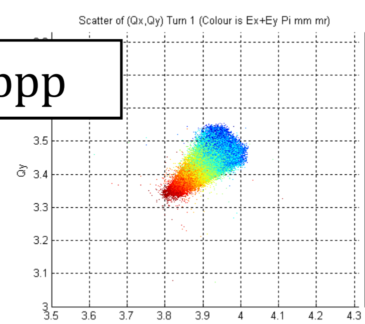


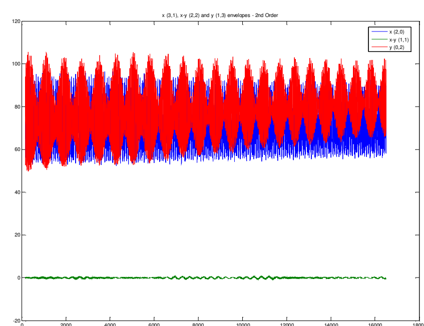


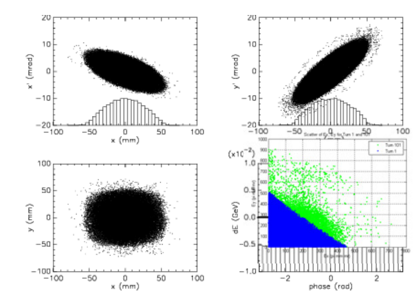


7E13 ppp









2D ORBIT Simulations: Near Resonance

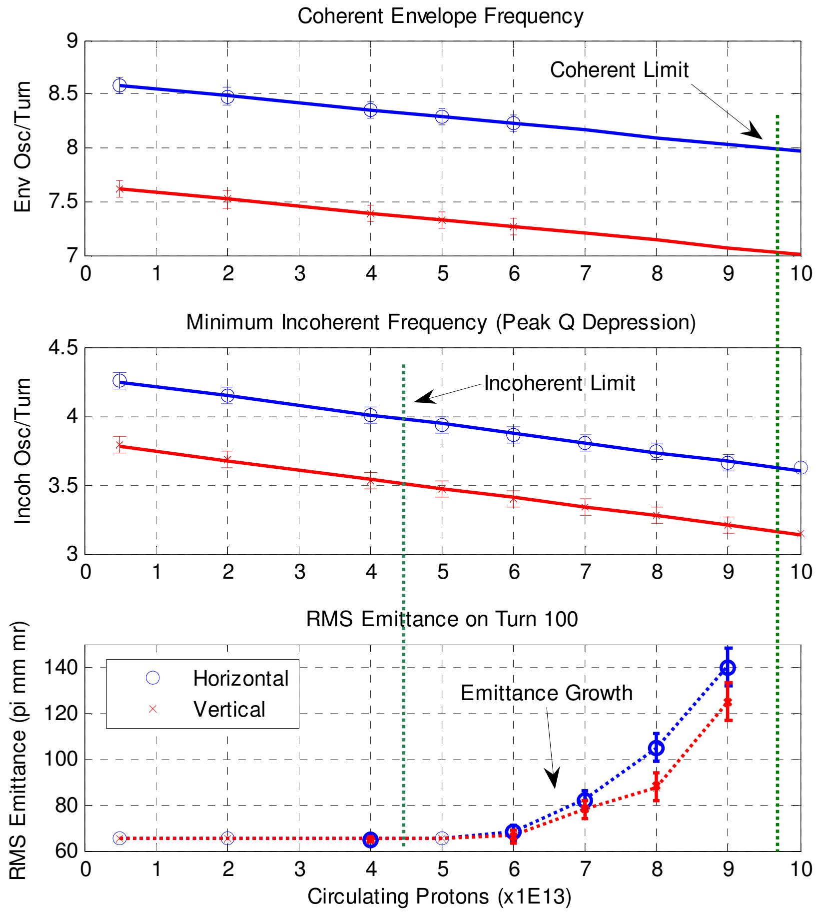
- Repeat simulations: scan ε_{rms} vs intensity

- Approximate 2D model of ISIS
  drive $2Q_x$=8, $2Q_y$=7,strength δQ_{sb}~0.02

- As ramp intensity:
  as expect exceed *incoherent limit*
  ε_{rms} growth before *coherent limit*

- So ε_{rms} grows *between* the limits
  How relevant are they?

- What causes ε_{rms} growth?
  Can we understand and minimise it?

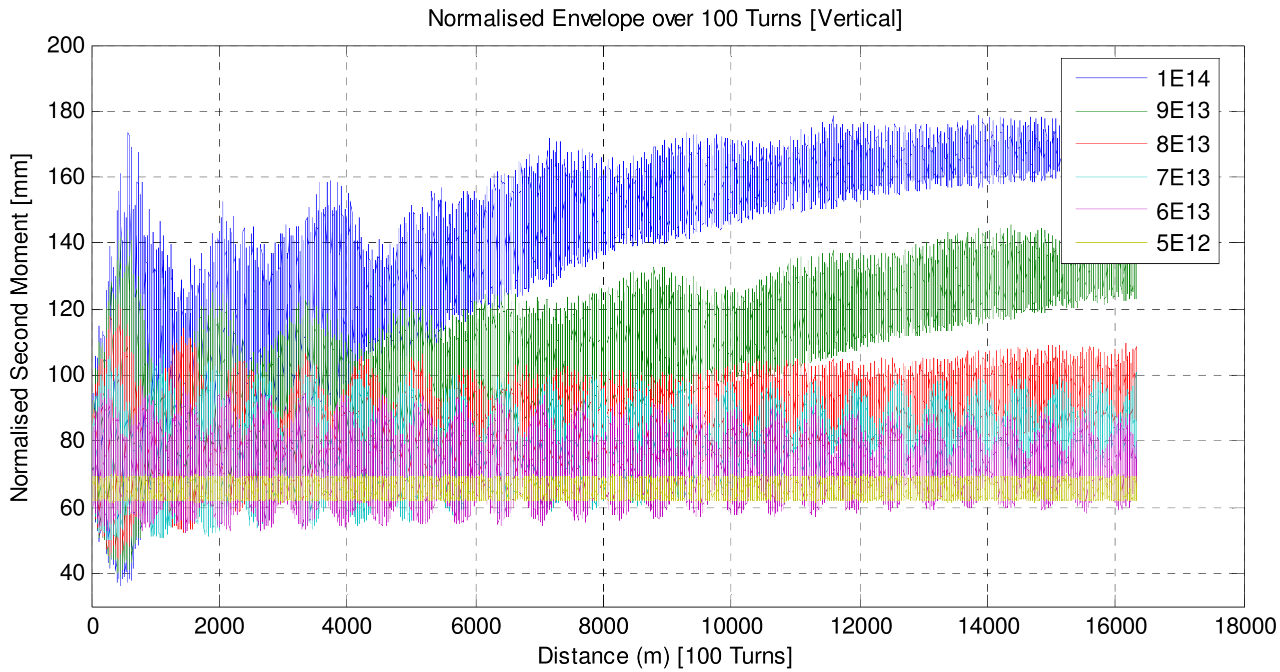


2D ORBIT Simulations: Envelopes

- Look at envelope evolution vs intensity as approach resonance

  As before, approximate 2D model of ISIS: drive $2Q_x$=8, $2Q_y$=7, δQ_{sb}~0.02

Envelope evolution over 100 turns

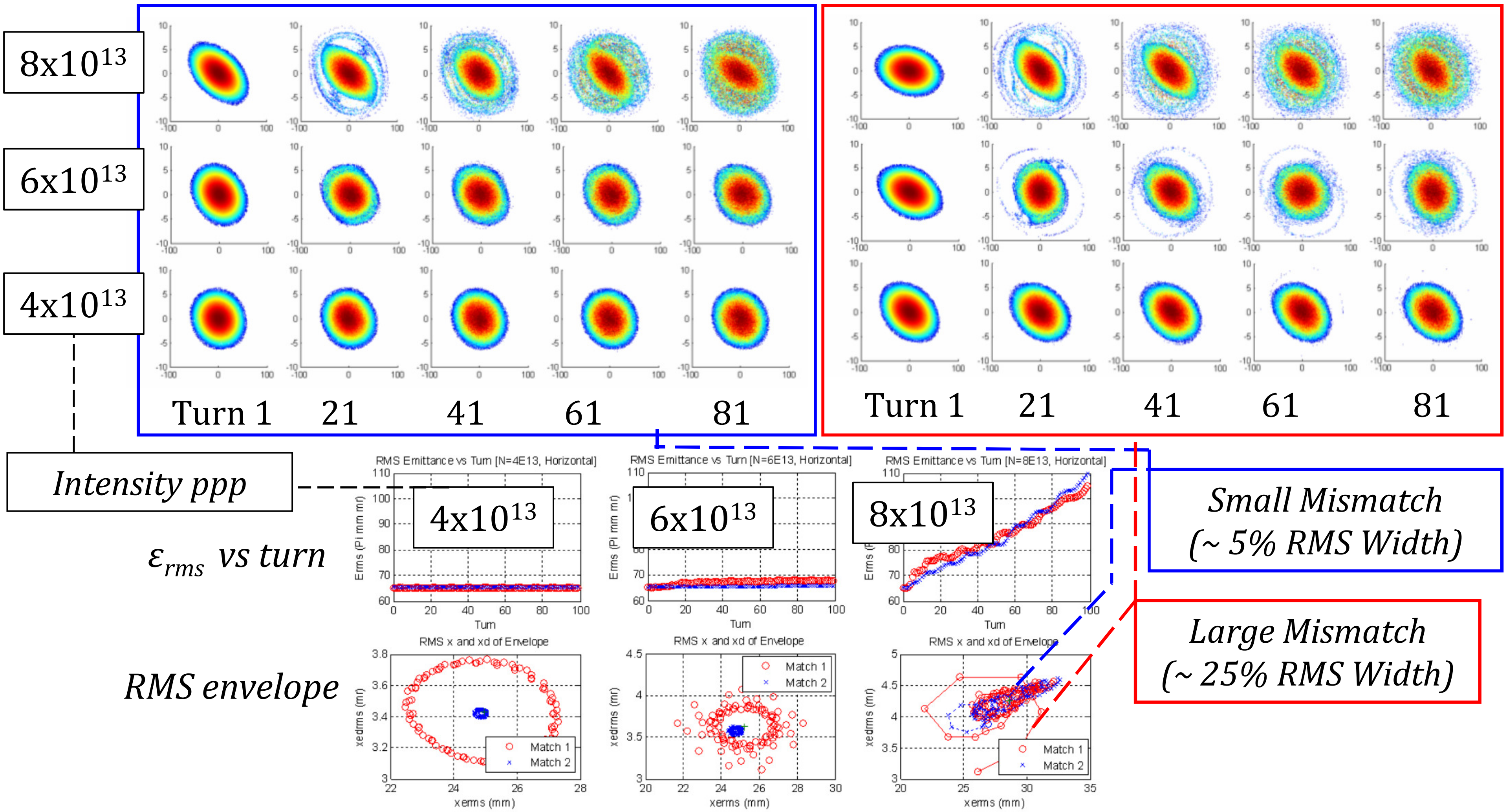


- Apparently transition from "beating" to growth

  Mechanism: Single particle process ~ Envelope Instability?

2D ORBIT Simulations: Halo

- Look at halo as a function of mismatch and intensity
  As before, approximate 2D model of ISIS. Normalised (Y,Y') phase space
  Particles coloured by initial emittance to indicate source of halo



Science & Technology Facilities Council ISIS

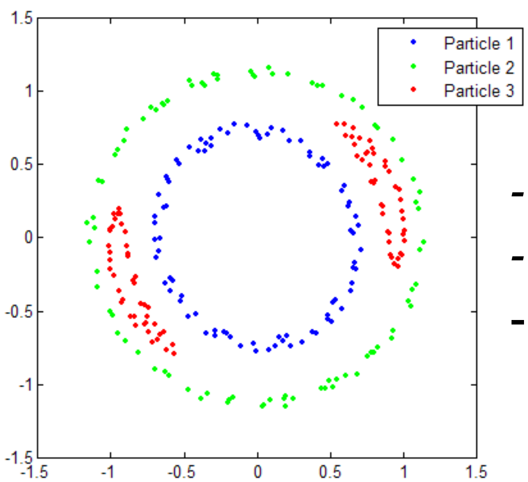
How do these ideas relate to beam loss?

- How do particles get lost – what is mechanism or model?
  Loss = particles hitting aperture limit or collimator!
- Coherent Model
  ε_{rms} conserved: envelope beating pushes particles to aperture
- Incoherent Model
  ε_{rms} grows: single particle growth to aperture (envelope motion?)
- Real Beam: perhaps both
  If ε_{rms} conserved coherent model is good
  Otherwise behaviour is more complicated
- Here we assume enough aperture for envelope motion
  Study ε_{rms} growth: Can we understand, control and minimise it?
  Results indicate onset of ε_{rms} growth is 1D process - so we study this
  Drive in one plane: 1D (y,y') particle-core, parametric resonance effect?
  Look at details of simulations then try and measure experimentally

2D ORBIT Simulations: Halo Structure

Investigate behaviour of halo

- Check single particle trajectories



- *As before, 2D ISIS model*
- *Drive in one plane* $2Q_y=7$
- Look at (Y, Y') for $\varepsilon_x \approx 0$

(Y, Y') = normalised (y, y')

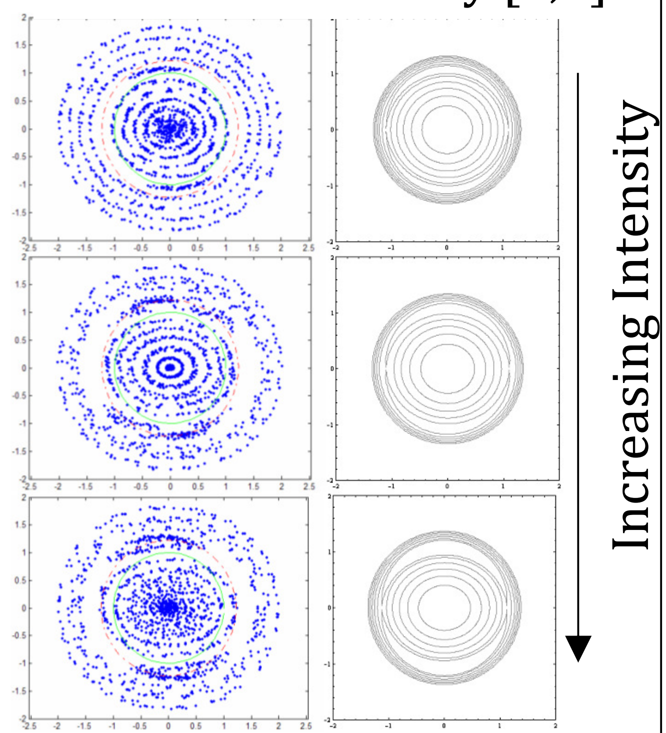
- Halo Structure Study (1D, $\varepsilon_x=0$)

  ORBIT with diagnostic "testHerd": just "*feels*"
  Locks to envelope motion: Poincaré plot
  Similar behaviour to analytical model [1]
  (KV, self consistent, driven, equal tunes, 1D)

[1] M. Venturini, Resonance Analysis for a Space Charge Dominated Beam in a Circular Lattice, PRST-AB, V3, 034203, 2000.
[2] C M Warsop et al., Space Charge Loss Mechanisms Associated with Half Integer Resonance on the ISIS Synchrotron, Proc. EPAC08, p373.

Vertical (Y, Y')

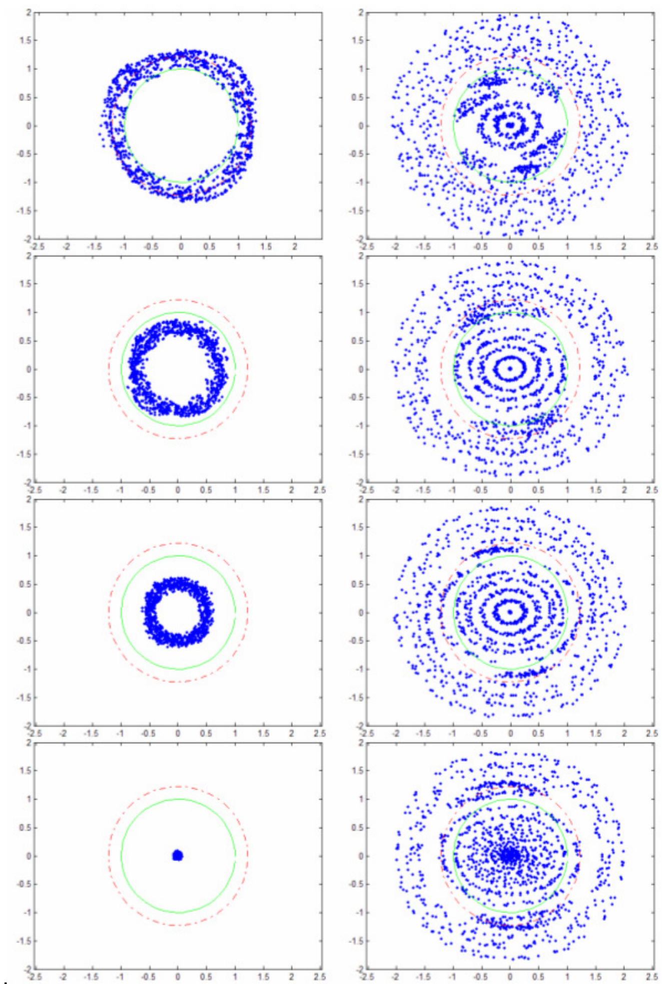
Simulation Theory [2,1]



7.00 $\times 10^{13}$ ppp	7.25 $\times 10^{13}$ ppp
8.00 $\times 10^{13}$ ppp	7.50 $\times 10^{13}$ ppp
8.50 $\times 10^{13}$ ppp	7.75 $\times 10^{13}$ ppp

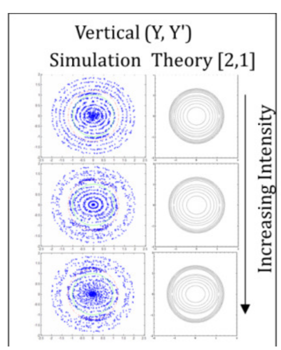
2D ORBIT Simulations: Halo Structure

- What about halo for $\varepsilon_x \neq 0$
  IE particle motion in *x* and *y* planes
  Just driven in *y* plane
- Plots show (Y, Y') as function of ε_x
  Similar for most ε_x
- Motion *could* get complicated!
  But is it?
- Looks like 1D parametric halo?
- Can we measure it?



All at 8.5×10^{13} ppp

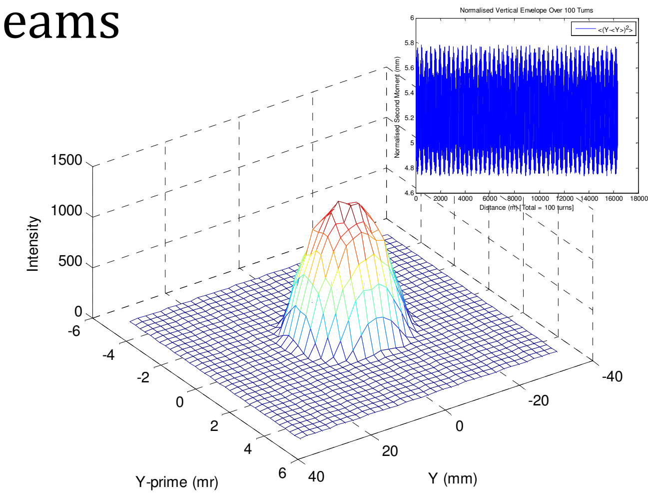
Here ε_x=0, motion in y plane only, as previous page

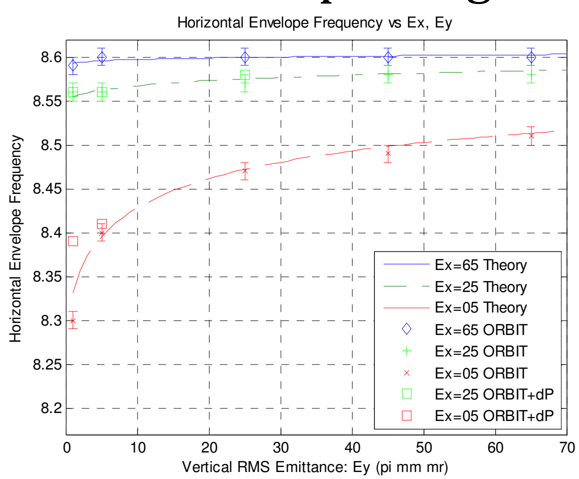


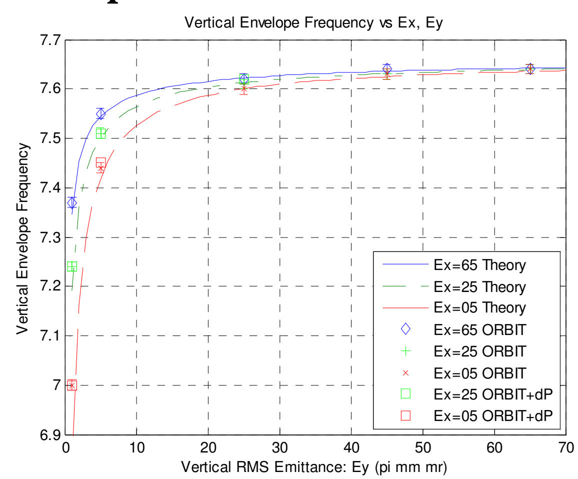
2D ORBIT Simulations: Halo Experiments

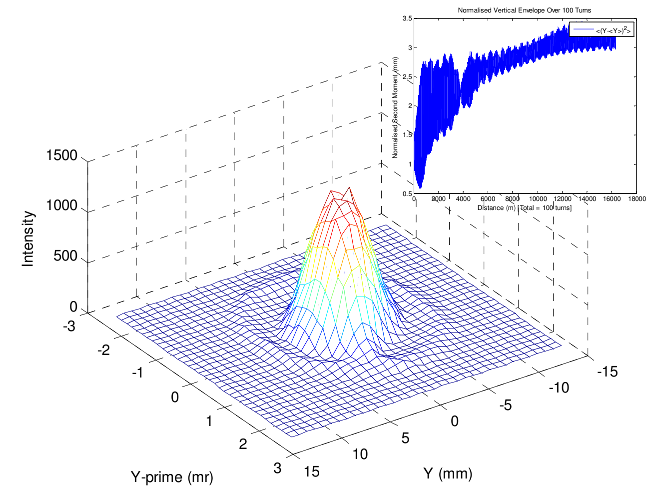
How to generate halo for experiments

- ORBIT simulations – study of test beam 70 MeV, ~ 2.5E12 ppp
  - *Generate halo with small beams, within aperture*
  - Check envelope resonance of small, non-circular beams
- Envelope frequency and halo vs ε_x, ε_y
  - 2D WB, vary ε_{xRMS}, ε_{yRMS} over 5→65 π mm mr
  - Compare mode frequency with theory
  - Push onto resonance and look for halo
- Results
  - Good agreement theory - ORBIT (RMS equiv.)
  - Halo as expect – good for experiments!









Science & Technology Facilities Council
ISIS

2D ORBIT Simulations: Real Experiments

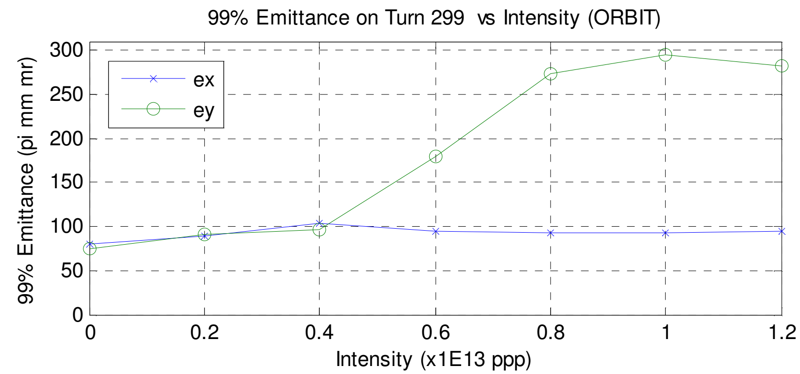
- How to configure a real machine for 2D experiments?
  Storage Ring Mode: coasting beam, RF off, magnets on constant DC
  Realistic painting (not waterbag!)
- Best experiment? How to approach resonance?
  Could ramp intensity, tunes, vary ε, driving terms …
- For these experiments
  Inject constant, small, transverse emittances ($\varepsilon_{rmsx} \approx \varepsilon_{rmsy} \approx 20\ \pi$ mm mr)
  Inject and store 70 MeV beam (0-1.3E13 ppp over ~ 100 turns)
  Set constant lattice $(Q_x, Q_y) \approx (4.30, 3.63)$
  Apply $2Q_y=7$ driving term (amplitude/phase)
  Ramp intensity over injection, push toward $2Q_y=7$
  Look at beam loss and profiles
- Run ORBIT simulation based on detailed 3D RCS model of ISIS
  Will predicts what we should see ~ includes realistic injection

Science & Technology Facilities Council ISIS

ORBIT Simulation of Real Experiment

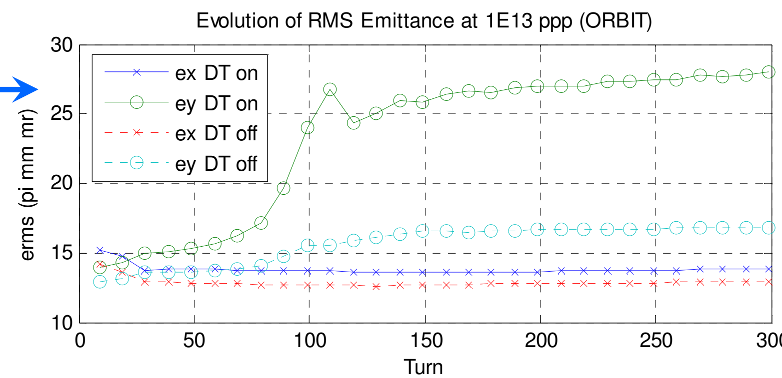
- Multiple runs: vary intensity

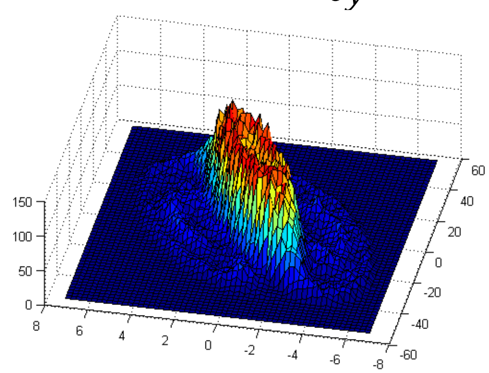
  For ε_{rms}= 15±2 π mm mr, Q_v=3.60
  predict resonance at ~0.5 ±0.1 x10^{13} ppp
  Multiple runs: plot $\varepsilon_{99\%}$ on turn 299
  Clear dependence on driving term



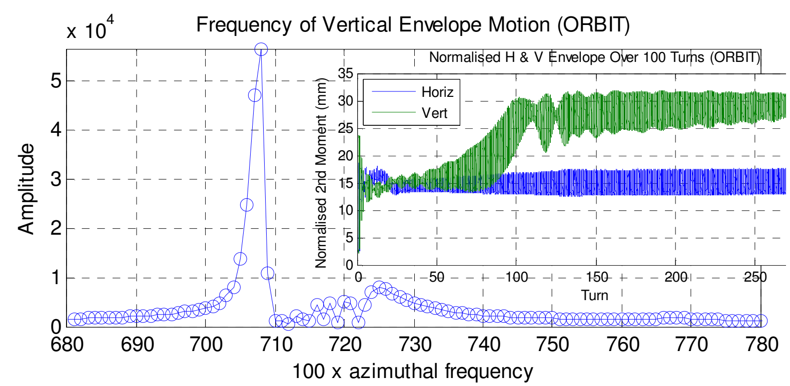
- Single run: evolution over 300 turns

  ε_{rms} increases as expect (vertical only)
  Intensity reaches ~0.5x10^{13} ppp on turn 68
  Strong dependence on driving term
  Clear growth in second moment
  Frequency of 2^{nd} moment near $2Q_y$=7
  Expected "halo"





Particle distribution in (y,y') on turn 109

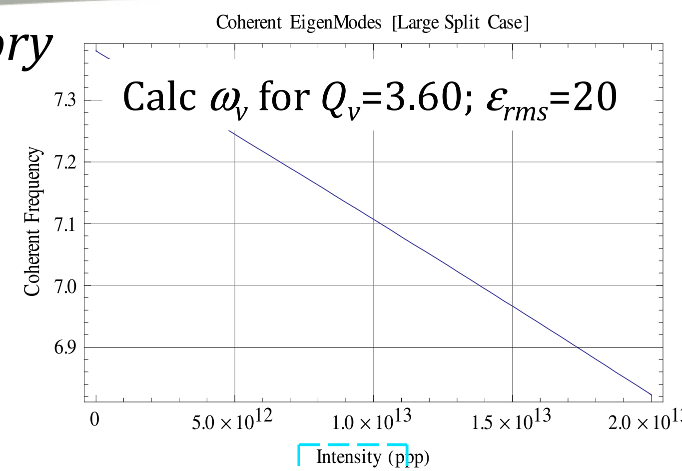


Experiments: Loss Measurements

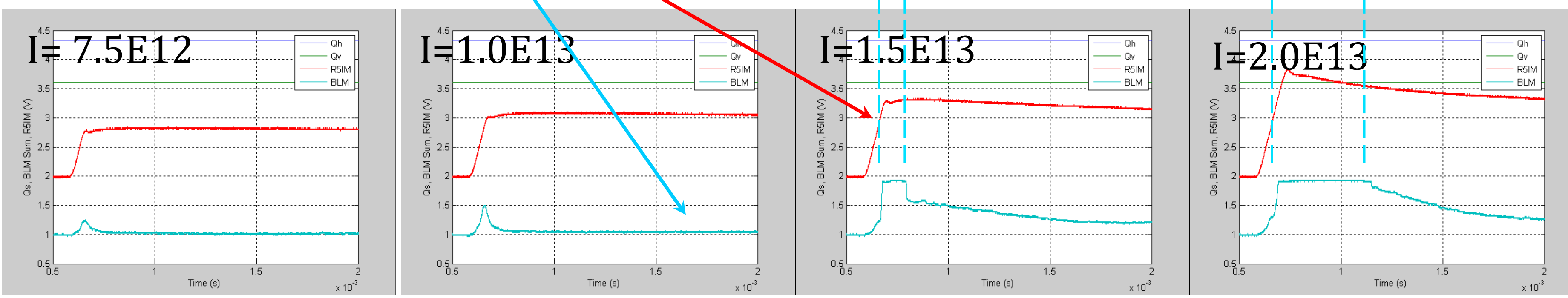
Science & Technology Facilities Council
ISIS

- Beam loss at coherent limit
  - Loss increases as approach
  - See "brick wall" where expect

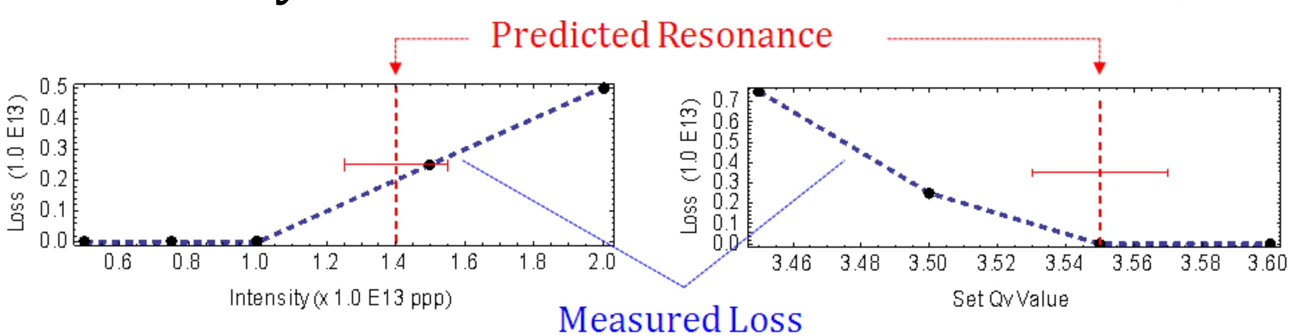
Theory

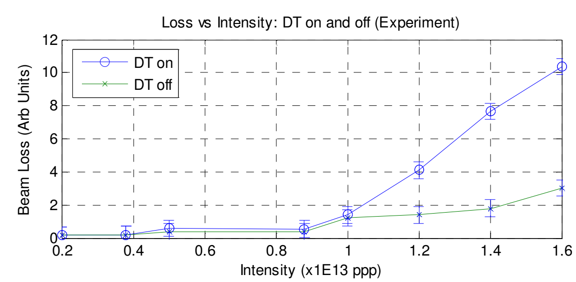


Beam Current (1V=1E13 ppp)
Beam Loss (clipped at > 1V!)



•Summary of loss measurements: Loss vs I, Loss vs Q, Loss vs DT





Experiments: Profile Measurements

- Measure profiles as approach resonance

- Identify as half integer halo?

  Control with driving term

  $\Delta k(\theta)=k\cos(2Q_y\,\theta+\phi)$

  p_0: $k=0$

  p_1: $k=0.02\ m^{-2}$, $\phi=0$

  p_2: $k=0.02\ m^{-2}$, $\phi=\pi$

- For driven resonance

  (y, y') structure locked to θ

  rotates $2Q_y$ times around ring

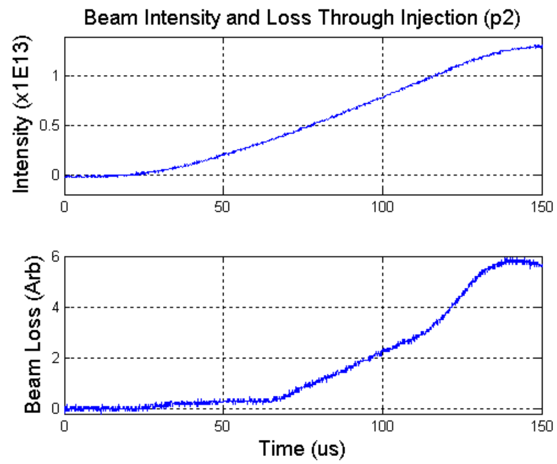
- Effects of these?

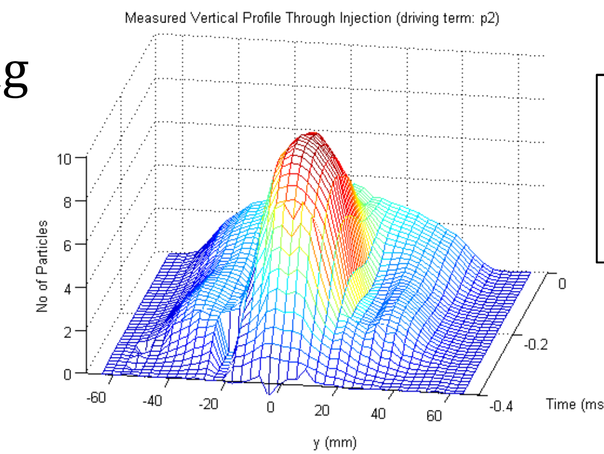
  Strength: loss

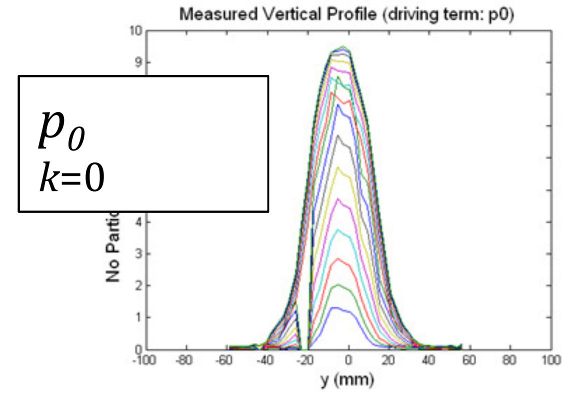
  Phase: (y, y') orientation

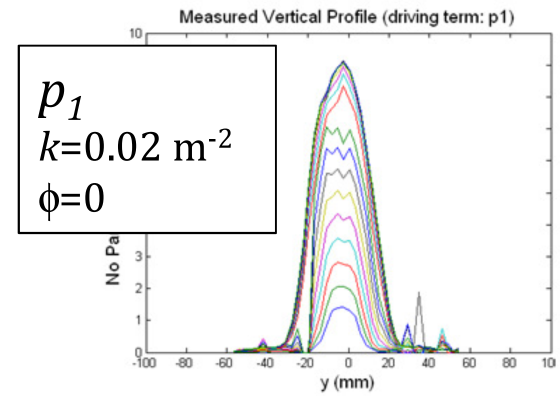
  profile is y projection

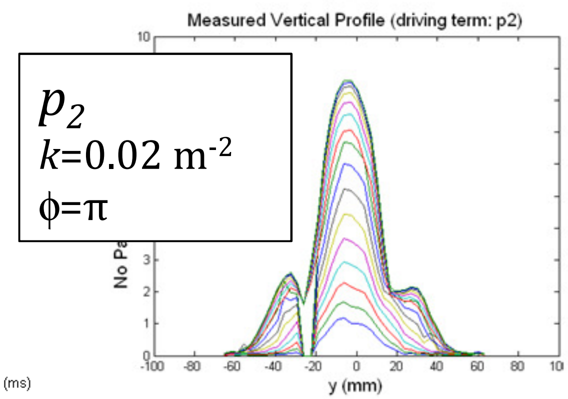
I and Loss vs time









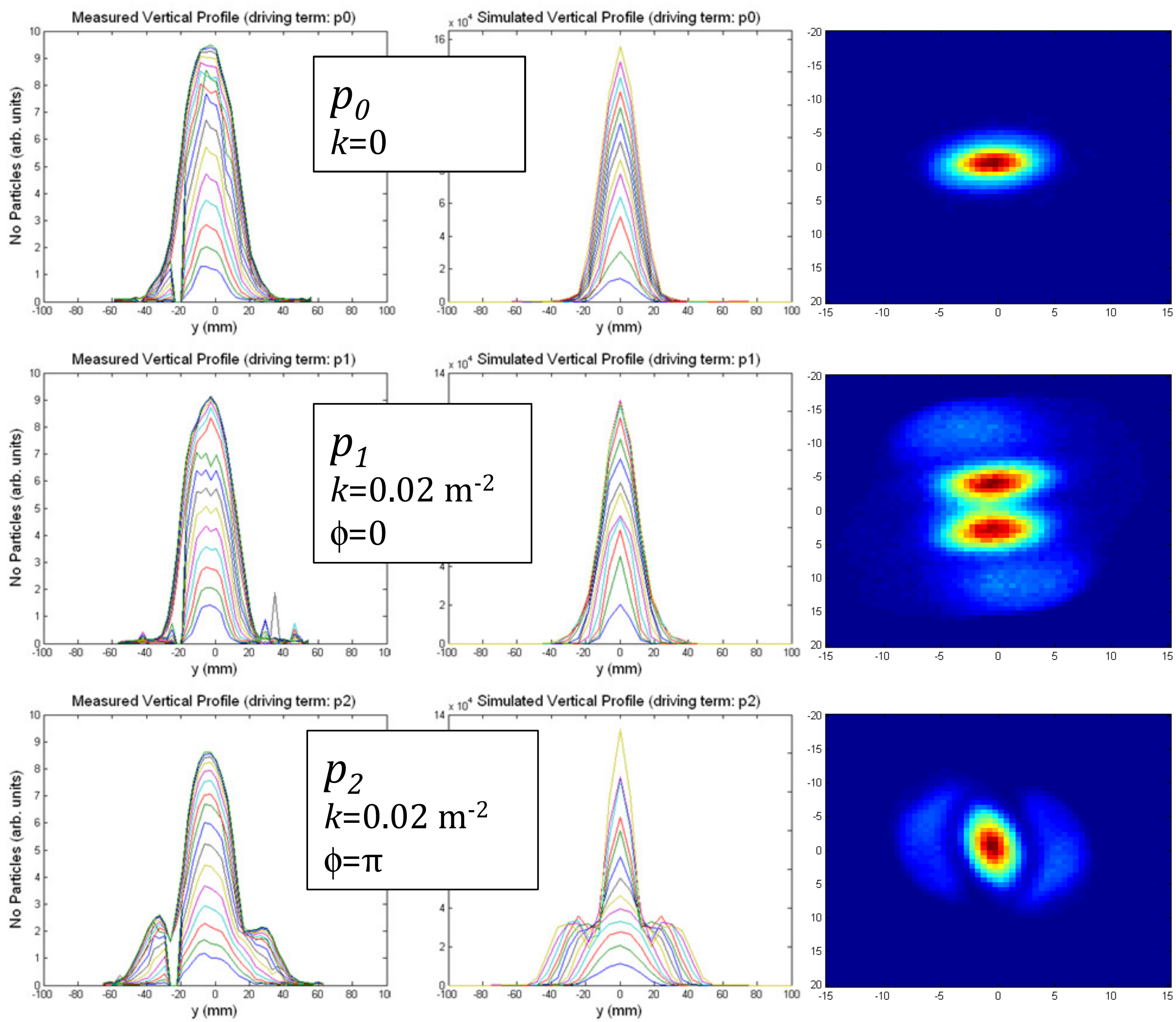


Compare with ORBIT simulation

Science & Technology Facilities Council
ISIS

- Same Features
- See “Hips”
  Phase control
- Complicated!

Measured profile | ORBIT profile | ORBIT (Y,Y')

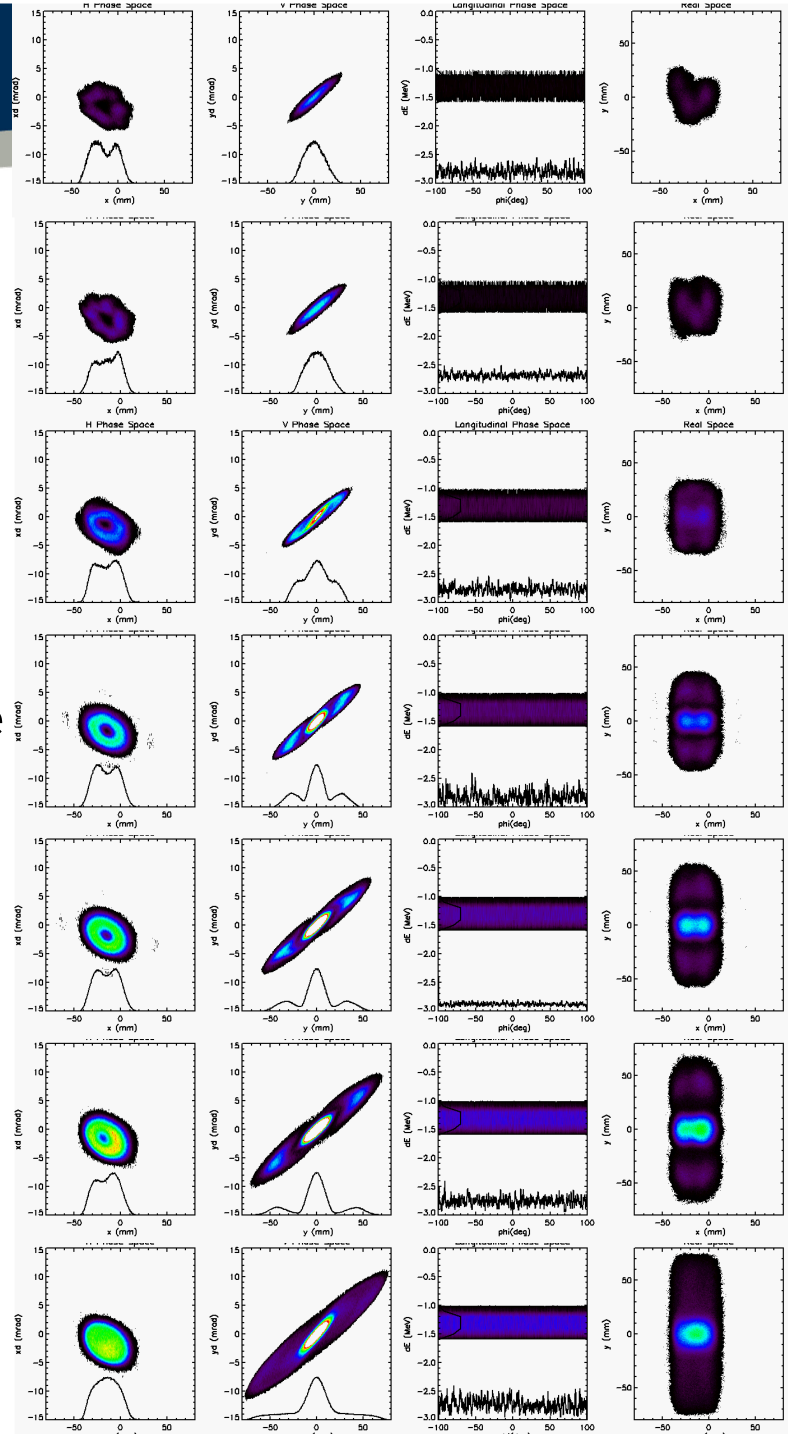


Science & Technology Facilities Council
ISIS

What is the growth process?

- ORBIT Results

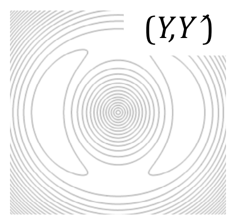
Plots: (x, x') (y, y') $(\varphi, \Delta E)$ (x, y)
Turns: 9, 14, 34, 54, 74, 94, 114



- Main features

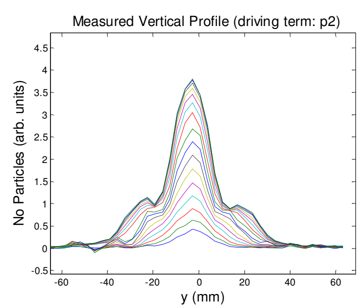
Inject beam of constant amplitude (size)
Intensity increases: pushes onto coherent mode
- Coherent envelope motion increases
- Non-linear space charge forces increase

Conditions for evolving PH
Keep injecting into this structure
(may be more complicated!)



- Profiles agree

Measurements being refined



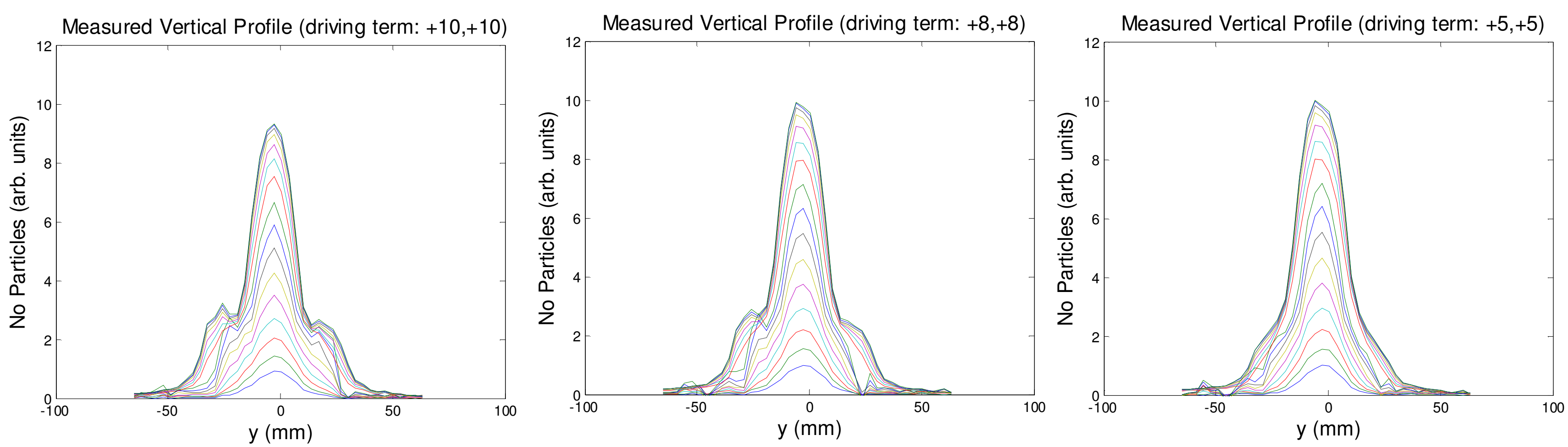
Latest Results

Still being processed … look reasonable

- Vary driving term strength

  "Hips" shrink as expect – not simulated yet

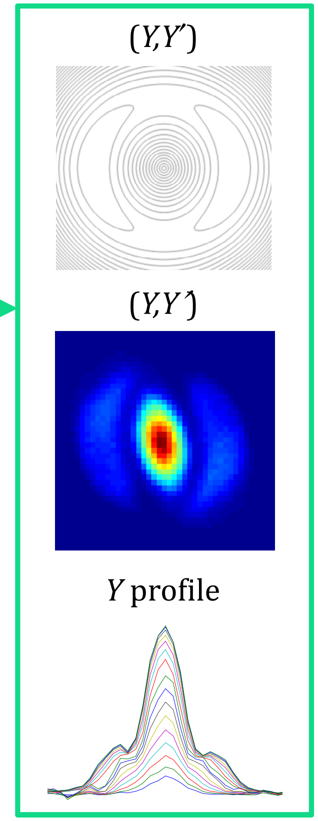
$\Delta k(\theta)=k_n\, cos(2Q_y\,\theta+\phi)$
p_2: $k_1=0.020\ m^{-2}$, $\phi=\pi$
p_2: $k_2=0.016\ m^{-2}$, $\phi=\pi$
p_2: $k_3=0.010\ m^{-2}$, $\phi=\pi$



- Also working on fine rotations of structure …

What next?

- Improve measurements
  - Detailed lattice measurements, driving terms, optics
  - Profile simulation, voltage scans, tests for halo structure
  - Study of halo behaviour
- Develop beam model
  - Look at simple simulation and analytical models (particle-core, with slowly varying waterbag core?)
- Do a better experiment?
  - Inject and form beam above coherent resonance
  - Vary quads to slowly ramp Q onto resonance
  - Try to approach resonance from below?
- 3D Study
  - Experiments with bunched beam in storage ring mode
  - Studies of 3D ORBIT simulations of RCS mode



Summary

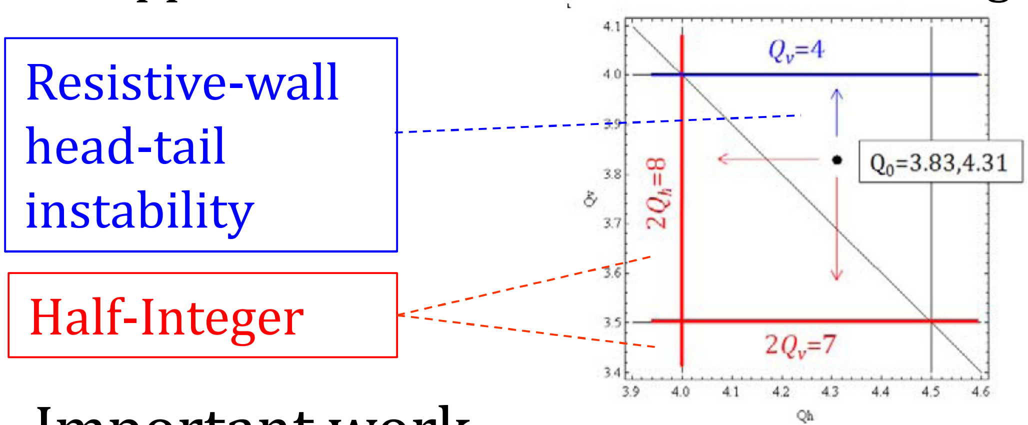
- Have outlined calculations and simulations of 2D half integer on ISIS
- Used these to suggest 2D SRM experiments – so we can study a real process
- Now getting good – detailed – agreement between simulation-experiment
- A basis for detailed code benchmarking, *developing models*, understanding!
- Working on improving accuracy of measurements
- Looking at other experiments: suggestions welcome!
- Will extend to: bunched-storage ring mode and full RCS modes

- So what?

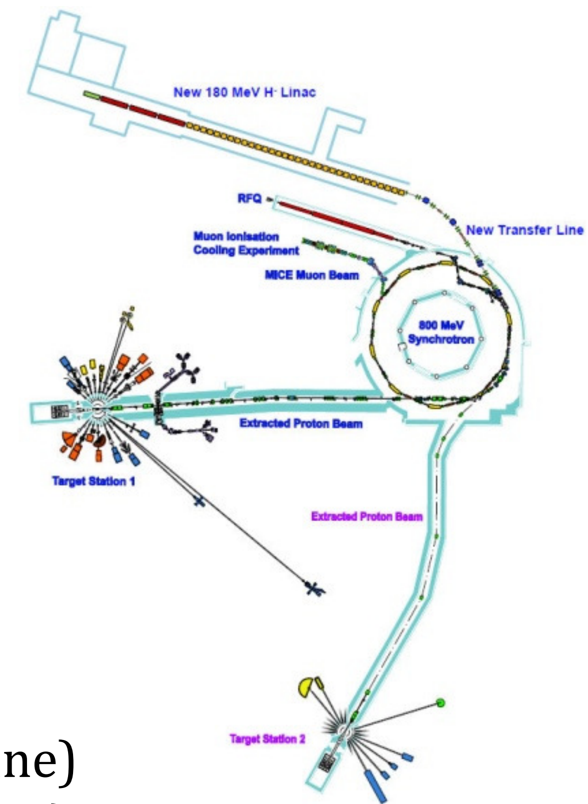
  If we can develop a better understanding of loss, perhaps we can achieve a more detailed optimisation of the beam and reach higher intensity?

High Intensity Limits

- Presently studying 180 MeV Linac Upgrade
  - Powers ~0.5 MW Regime: Main limit transverse
  - Trapped between Head-tail and Half-integer



- Important work
  - Half-integer, Head-tail instability
  - Image effects, working points, ISIS Set code (talk B Pine)
  - Longitudinal dynamics and stability (talk R Williamson)
  - Injection, modelling, …
- Key topics for present operations and ISIS 1-5 MW upgrades



Science & Technology Facilities Council
ISIS

Acknowledgements

- Many thanks to …

  ISIS Diagnostics Section
  ISIS Operations

- Thanks for useful discussions with ASTeC/IB