Space Charge and High Intensity Studies on ISIS

C M Warsop

Reporting the work of

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

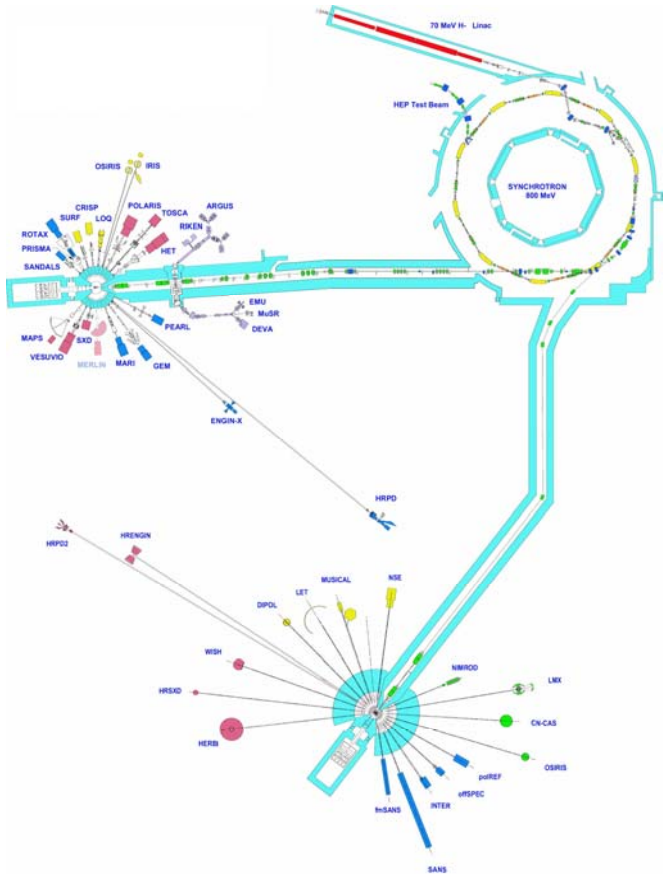
ISIS Synchrotron Accelerator Physics

and: S J Payne, J W G Thomason,
ISIS Accelerator Diagnostics, ISIS Operations, ASTeC/IB.

Science & Technology Facilities Council
ISIS

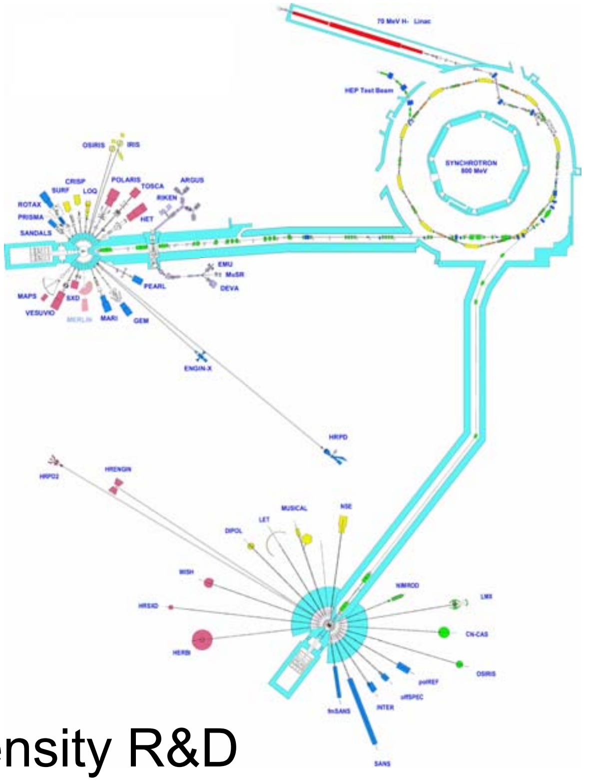
Contents

- Introduction
- Main Topics
    - 1 - Profile Monitor Modelling
    - 2 - Injection Painting
    - 3 - Full Machine Simulations
    - 4 - Half Integer Losses
    - 5 - Image Effects & Set Code
- Summary



Science & Technology Facilities Council
Rutherford Appleton Laboratory

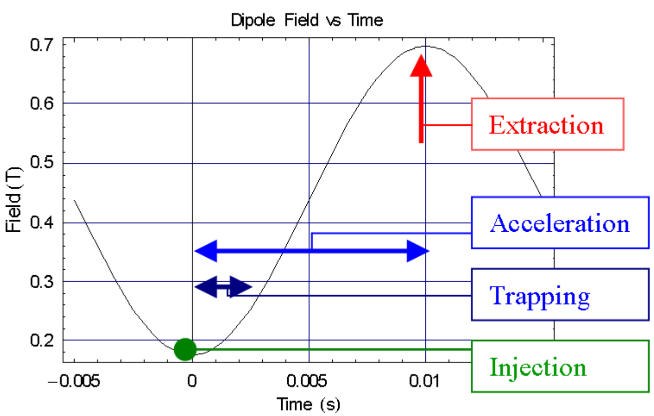
Introduction

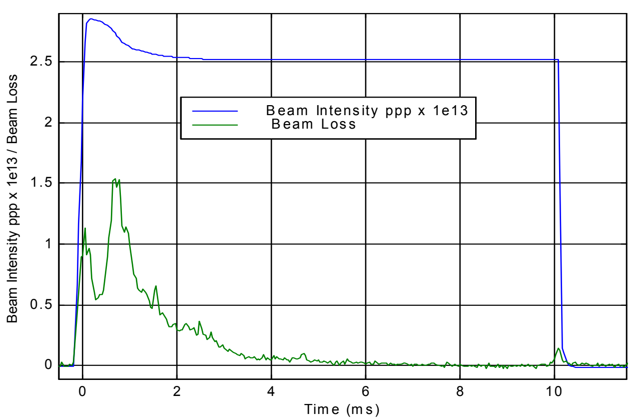


- ISIS Spallation Neutron Source ~0.2 MW
  - Commissioning Second Target Station
  - Now ramping up operational intensity
  - ISIS Megawatt Upgrade Studies started

- Will summarise our programme of Ring High Intensity R&D
  - Underpins the work above (& has wider applications)
  - Aim to understand intensity limits of present and upgraded machines
  - Experimentally verify simulation and theory on ISIS where possible
  - Broad: covers diagnostics, experiments, simulation, theory

The ISIS Synchrotron





Circumference	163 m
Energy Range	70-800 MeV
Rep. Rate	50 Hz
Intensity	$2.5\times10^{13} \rightarrow \sim 3.0\times10^{13}$ protons per pulse
Mean Power	160 → ~ 200 kW
Losses	Mean Lost Power ~ 1.6 kW (≤100 MeV) Inj: 2% (70 MeV) Trap: 5% (<100 MeV) Acceleration/Extraction: 0.1 – 0.01%
Injection	130 turn, charge-exchange paint injected beam of ~ 25 π mm mr
Acceptances	horizontal: 540 π mm mr with dp/p ± 0.6% vertical: 430 π mm mr
RF System	h=2, f_{rf} =1.3-3.1 MHz, peak V_{rf}=140 kV/turn h=4, f_{rf} =2.6-6.2 MHz, peak V_{rf}=80 kV/turn
Extraction	Single Turn, Vertical
Tunes	Q_x=4.31, Q_y=3.83 (*variable with trim quads*)

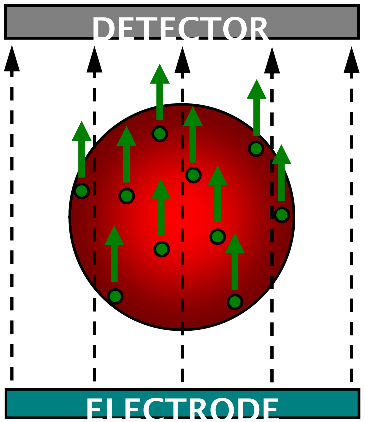
Science & Technology Facilities Council
ISIS

1. Profile Monitor Studies ~ 1

Introduction

Rob Williamson, Ben Pine, Steve Payne

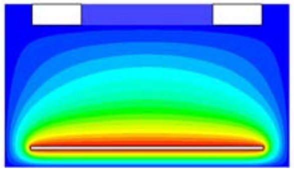
- Profile measurements essential for space charge study
  - **This work**: *Modelling & experiments to determine accuracy*
  - Overlaps with diagnostics R&D work - S J Payne et al
- Residual gas ionisation monitors
  - Detect positive ions in 30-60 kV drift field



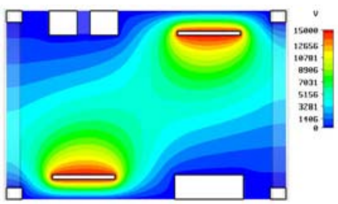
- Two main sources of error:
  - (1) - Drift Field Non-Linearities
  - (2) - Beam Space Charge
- Modelled dynamics of ions with
  - CST Studio™ for fields
  - "In house" particle trackers

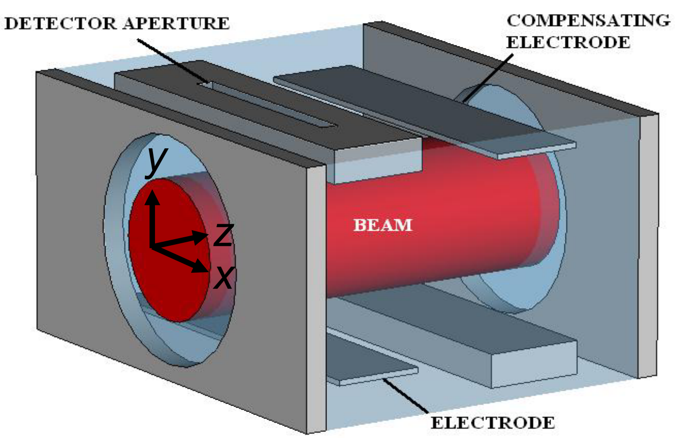
Potential from CST

Φ(x,y)



Φ(y,z)





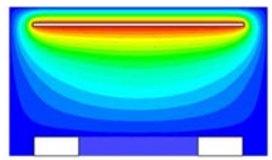
1. Profile Monitor Studies ~ 2

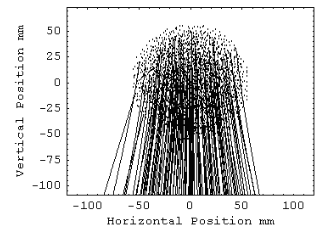
Drift Field Error

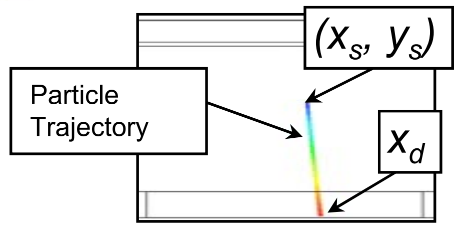
Rob Williamson, Ben Pine

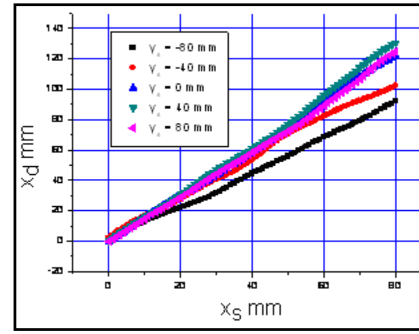
2D Tracking Study

Φ(x,y)









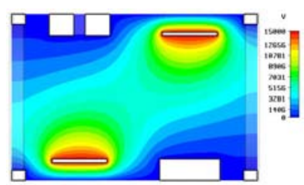
- Field error distorts trajectories
- Measured position x_d=F(x_s,y_s)

For given geometry find:

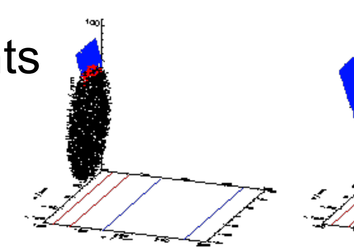
- Averaged scaling correction

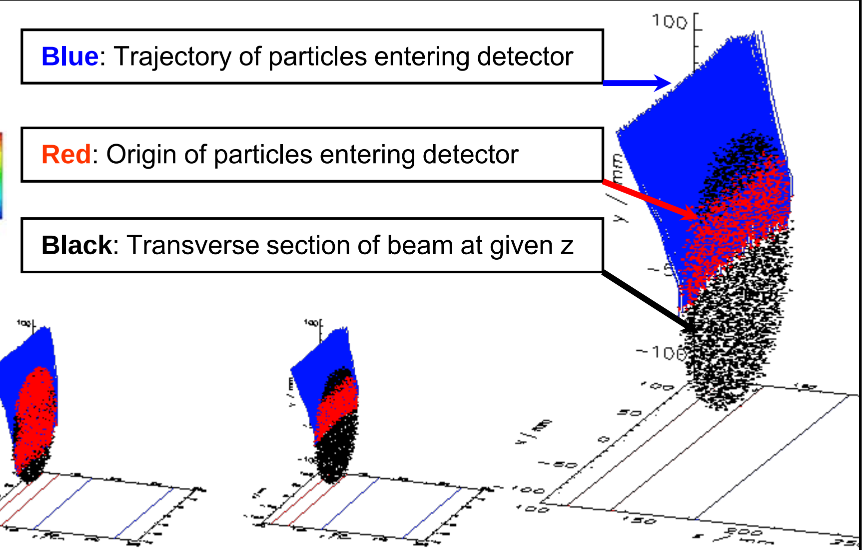
3D Tracking Study

Φ(y,z)



- More complicated in 3D case
- Longitudinal fields – new effects
- Detected ions from many points
- Scaling corrections still work
- Ideas for modifications





Trajectories as a function of z along beam

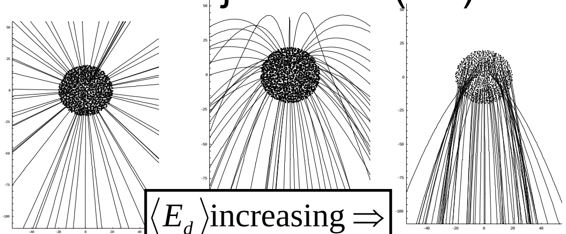
1. Profile Monitor Studies ~ 3

Space Charge Error

Rob Williamson, Ben Pine, Steve Payne

Space charge field distorts trajectories

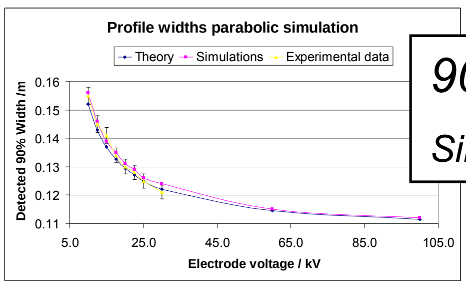
Ion Trajectories (2D)



$\langle E_d \rangle$ increasing $\Rightarrow$

Simple calculation: trajectory deflection

$$\Delta x \propto \frac{\langle E_{sc} \rangle}{\langle E_d \rangle} \propto \frac{1}{V_d}$$



90% Width vs V_d

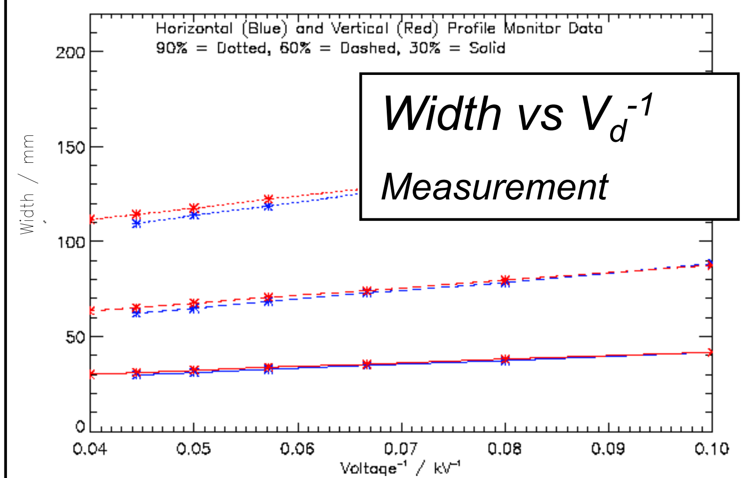
Sim & Meas & Theory

S J Payne

- Increase in given percentage width $\propto V_d^{-1}$

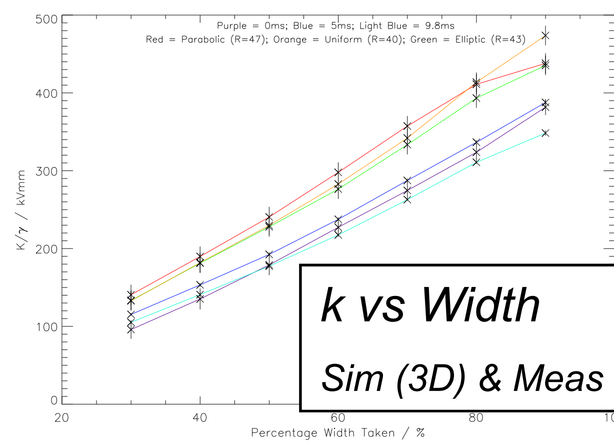
$$\Delta W_{x\%} = k_{x\%} \cdot V_d^{-1}$$

- Also $k_{x\%} \propto W_{x\%}$ - for “normal” distributions
- So can correct a profile for space charge
- Confirmed experimentally & in 2D/3D simulations



Width vs V_d^{-1}

Measurement



k vs Width

Sim (3D) & Meas

1. Profile Monitor Studies ~ 4

Rob Williamson, Ben Pine

Summary

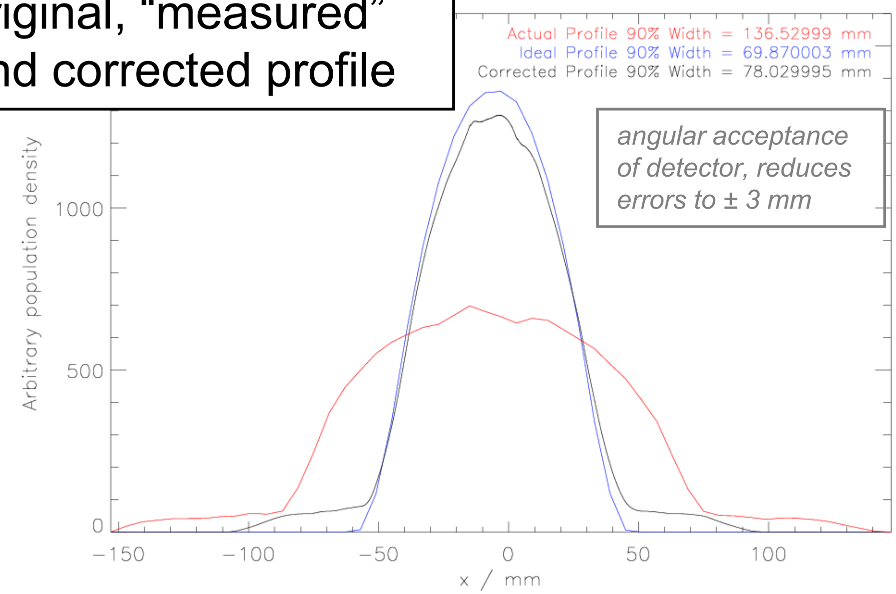
- Good understanding of monitors
  - Correction scheme: good to ±3 mm
- Experimental verification
  - Many checks and agrees well
  - Final checks needed: EPB monitor
- Monitor Developments (S J Payne)
  - Multi-channel, calibration, etc
  - Drift field increase and optimisation
- Seems to work well
  - See next section …

Basic correction scheme

- drift field and space charge
- for near-centred, "normal" beams

$$w_{m,\,p} = K_D w_{t,\,p} + \frac{K_{SC}\, p\gamma}{V_D}$$

3D simulation:
original, "measured" and corrected profile

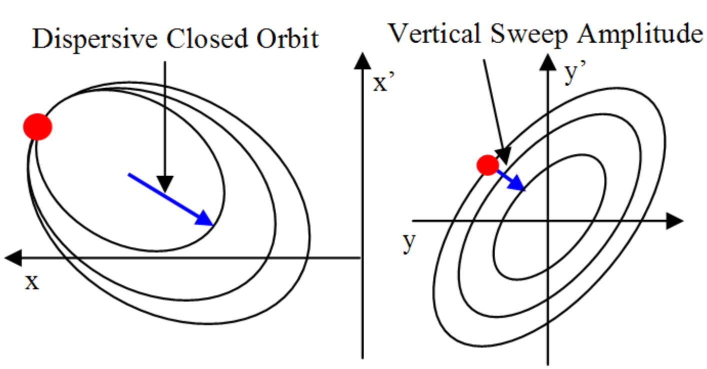


2. Injection Painting ~ 1

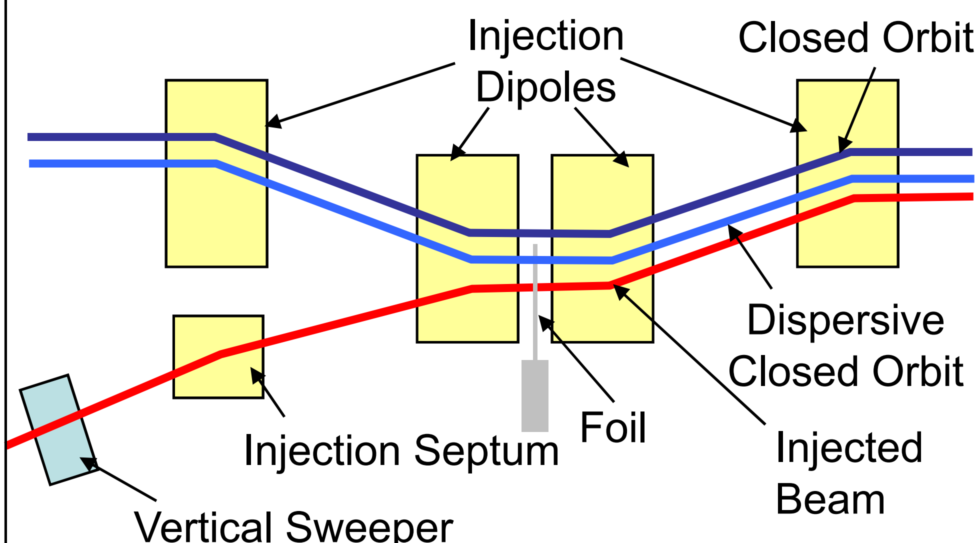
Bryan Jones, Dean Adams

Injection Studies: Aims and Background

- Studies of injection important for:
  - ISIS operations and optimisation
  - ISIS Megawatt Upgrade Studies
  - Space charge studies
- Want optimal painting
  - Minimal loss from space charge, foil
- Start is Modelling-Measuring ISIS



- ISIS Injection
  - 70 MeV H^- injected beam: 130 turns
  - 0.25 μm Al_2O_3 stripping foil
  - Four-dipole horizontal injection bump
  - Horizontal: falling *B[t]* moves orbit
  - Vertical: steering magnet

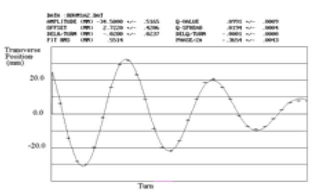


2. Injection Painting ~ 2

Bryan Jones, Dean Adams

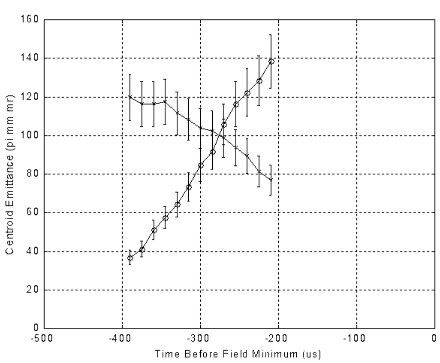
Injection Painting Measurements

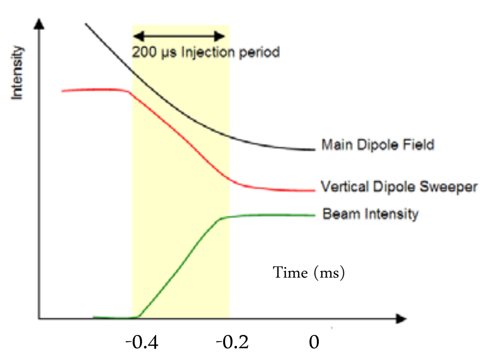
- Direct measurement of painting
  - Use “chopped” beams
  - Low intensity (1E11 ppp); less than 1 turn
  - Inject chopped pulse at different times
  - Least squares fit to turn by turn positions



$$\bar{z}_n = A\exp\left[-\frac{(\delta Q n\pi)^2}{2}\right]\cos[\phi + 2\pi n(Q_0 + n\Delta Q)] + n\Delta\bar{z}_{co} + \bar{z}_{co0}$$

  - Extract initial centroid betatron amplitude





- Profiles measured on RGI monitors
  - Corrections as described above
- Plus other data …
  - Injected beam, sweeper currents, …

- Compare Measurement-Simulation
  - Normal anti-correlated case
  - Trial correlated case
- Change vertical sweeper to switch
  - Reverse current vs time function

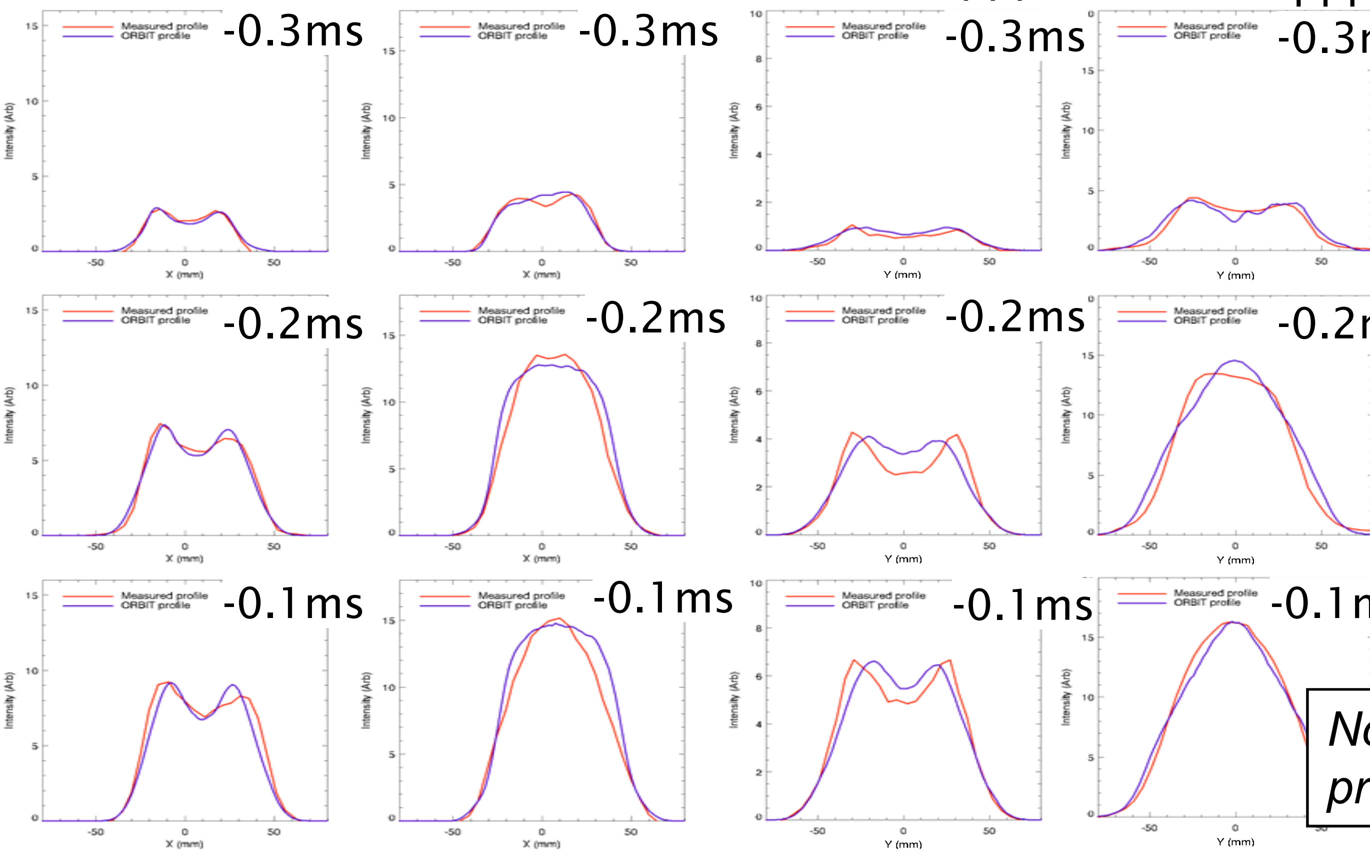
2. Injection Painting ~ 3

Bryan Jones, Dean Adams

Simulation and Measurement: Normal Painting

Horizontal Profile | Vertical Profile

2.5×10^{12} ppp | 2.5×10^{13} ppp | 2.5×10^{12} ppp | 2.5×10^{13} ppp

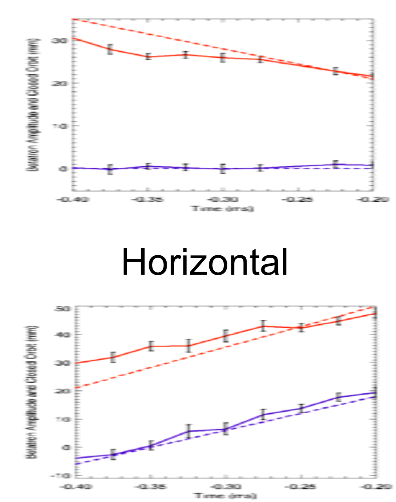


Key - Measured (corrected) - Simulation (ORBIT)

Painting

anti-correlated

Vertical



Horizontal

Not the final iteration, but pretty good agreement

2. Injection Painting ~ 4

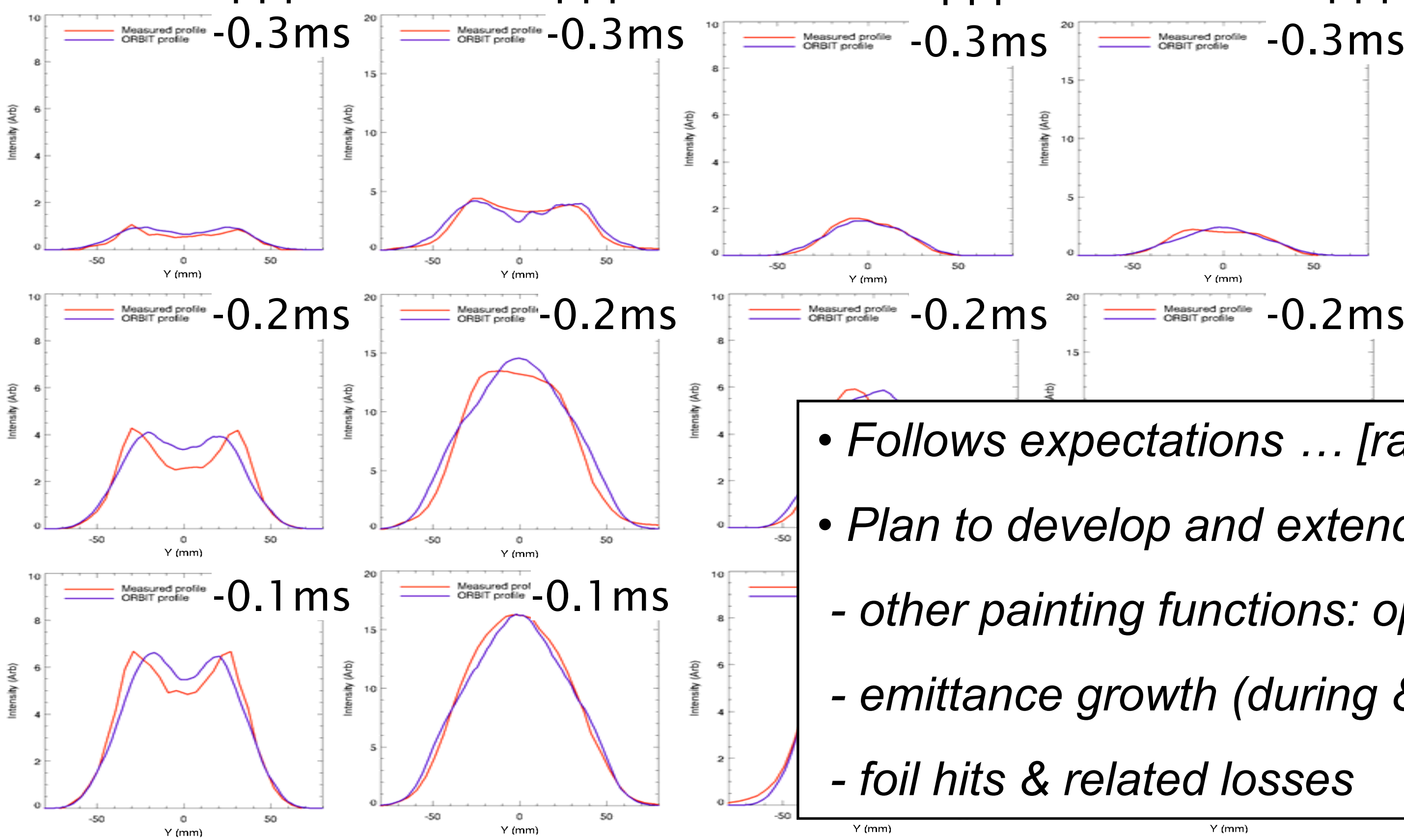
Bryan Jones, Dean Adams

Simulation and Measurement: Painting Experiment

Anti-correlated Vertical Profile

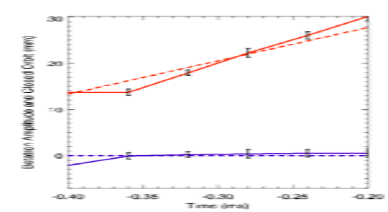
Correlated Vertical Profile

2.5×10^{12} ppp 2.5×10^{13} ppp 2.5×10^{12} ppp 2.5×10^{13} ppp

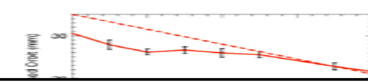


Painting

Vertical - *correlated*



Vertical - *anti-correlated*



- *Follows expectations … [ran at 50 Hz OK!]*
- *Plan to develop and extend to study*
  - *other painting functions: optimal distributions*
  - *emittance growth (during & after injection)*
  - *foil hits & related losses*

Key - Measured (corrected) - Simulation (ORBIT)

3. Machine Modelling ~ 1

Dean Adams, Bryan Jones

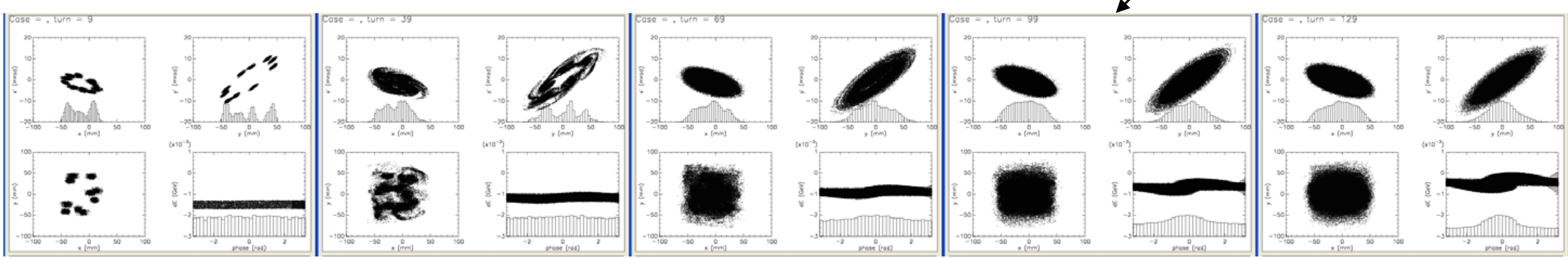
Injection Simulation Details

- ORBIT multi-turn injection model
- Painting: H - Dispersive orbit movement; V - Sweeper Magnet
- Injection bump, momentum spread and initial bunching
- 2D transverse (with space charge)
- 1D longitudinal (no space charge yet)

(x,x')   (y,y')

(x,y)   (dE, phi)

Example: Normal anti-correlated case 2.5E13 ppp



Turn 9   *Turn 39*   *Turn 69*   *Turn 99*   *Turn 129*

ORBIT

3. Machine Modelling ~ 2

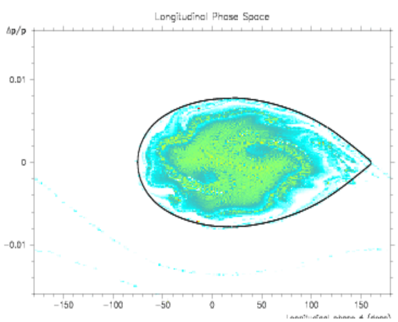
Dean Adams

Longitudinal Studies ~ work in progress

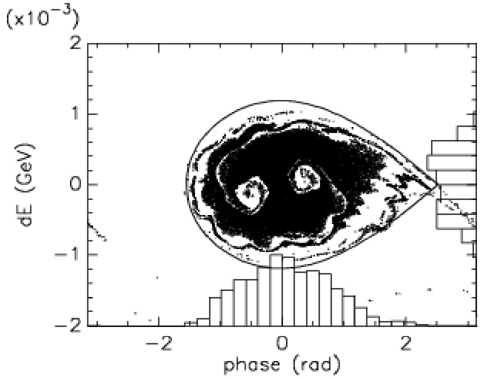
- TRACK1D - works well - basis of DHRF upgrade (C R Prior)
- Now working to model in detail in ORBIT (1D then 2.5D)
- Collaborating on tomography (S Hancock, M Lindroos, CERN)

Comparisons and trials at 0.5 ms after field minimum on ISIS for ~ 2.5x10^{13} ppp

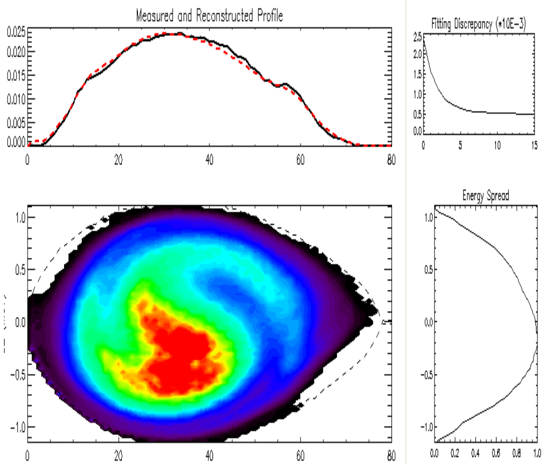
TRACK1D



ORBIT 1D



Tomography trials



(real data!)

3. Machine Modelling ~ 3

Dean Adams

Full Machine Modelling in ORBIT ~ work in progress

• Simulation of full machine cycle 2.5D – some reasonable results

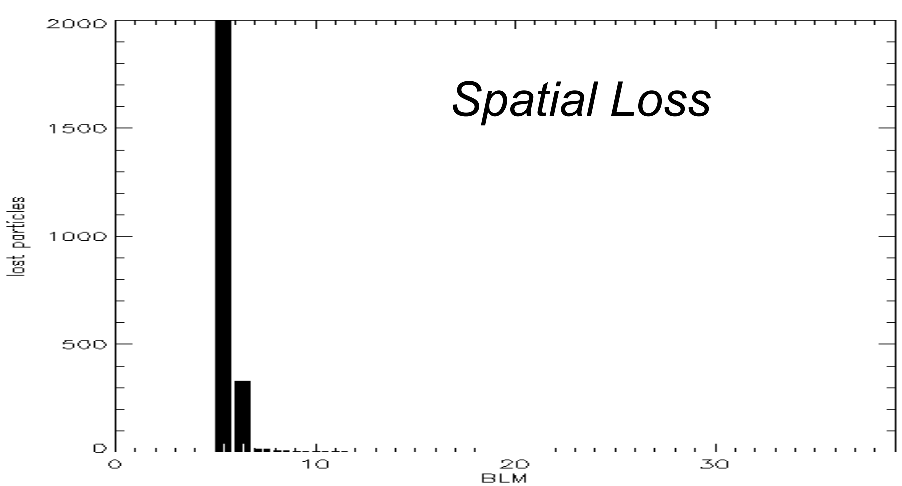
- time variation of loss

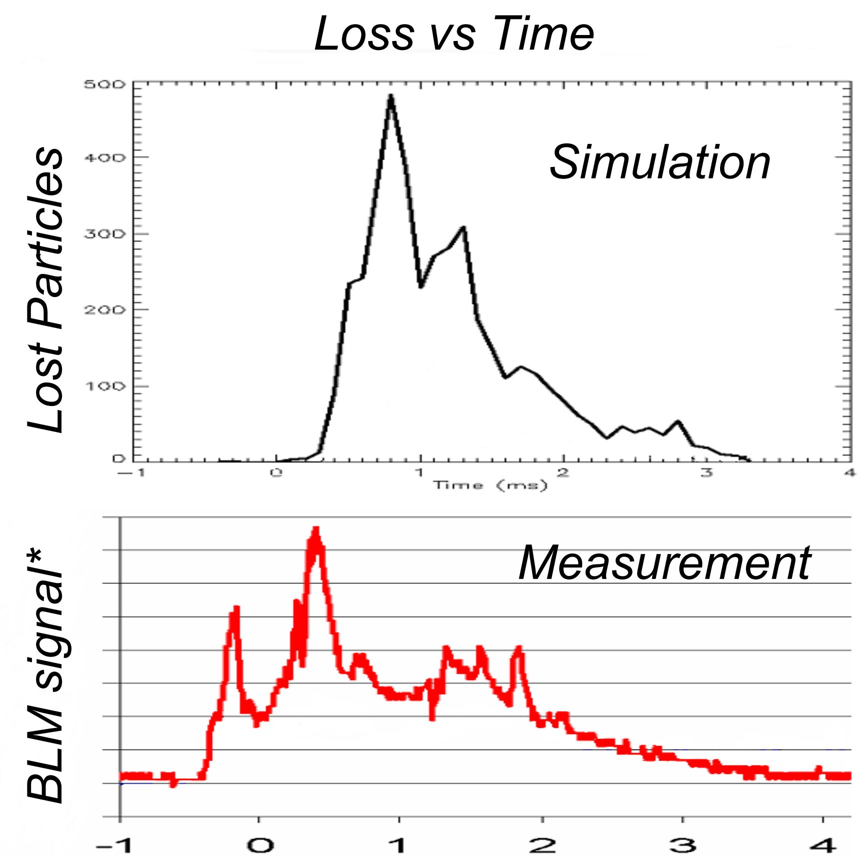
→ reproduces main loss 0 - 3 ms

• Collimators now included

~ space variation of loss

→ good results (normal ops & Mice target)





* some energy dependence

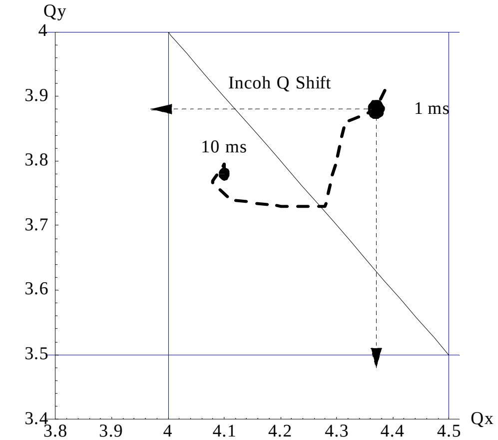
4. Half Integer Losses ~ 1

Chris Warsop

Importance for the ISIS RCS

• Transverse space charge - key loss mechanism

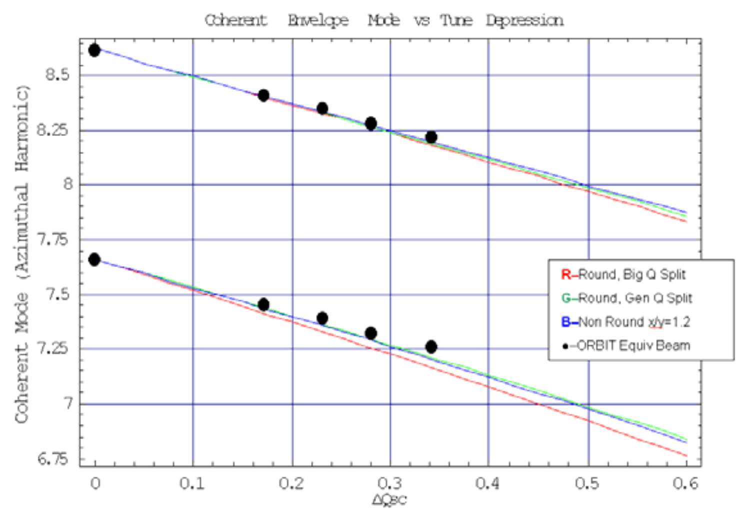
- Peaks at ~0.5 ms during bunching ΔQ_{inc}~-0.4
- In RCS is 3D problem: initially study simpler 2D case



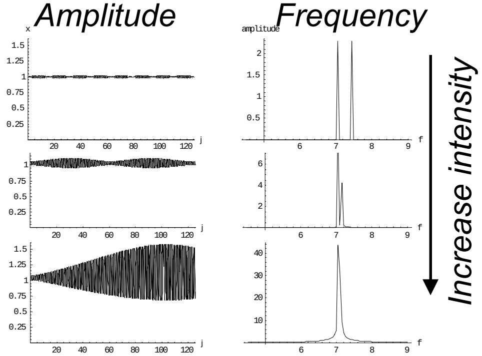
$(Q_h, Q_v)=(4.31, 3.83)$

• First step: envelope equation calculations

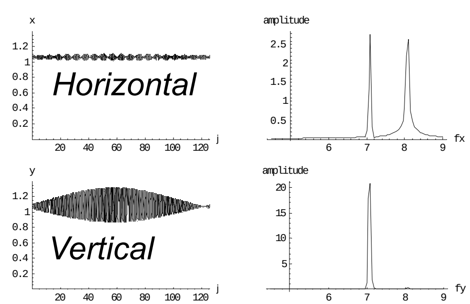
- ISIS large tune split case: independent h and v
- Get 8/5 “coherent advantage” (e.g. Baartman)
- Numerical solutions confirm behaviour



1D



2D



Science & Technology Facilities Council
ISIS

4. Half Integer Losses ~2

Chris Warsop

ORBIT 2D Simulation Results

- 5E4 macro particles; ~RMS matched waterbag beam
- Tracked for 100 turns; driven $2Q_v=7$ term

Turn 100

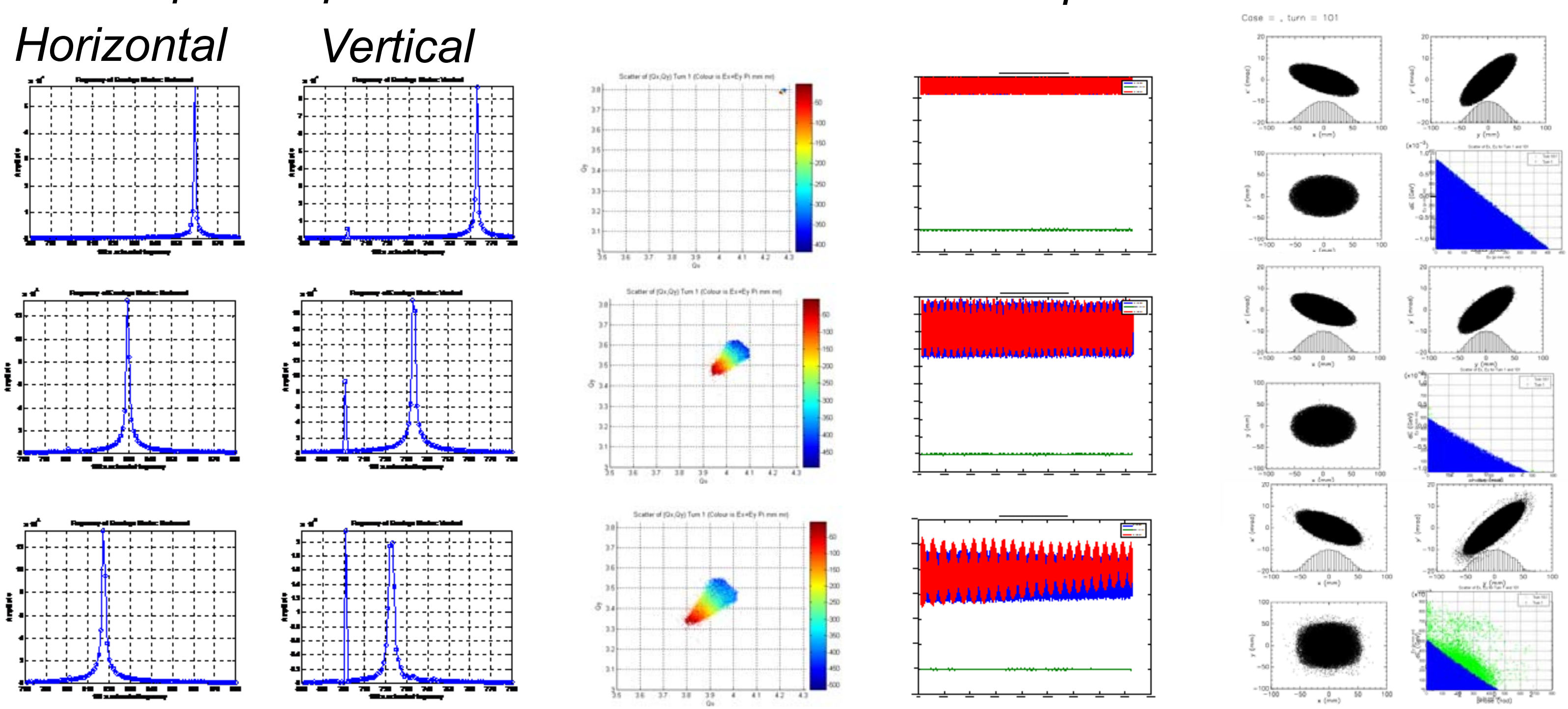
(x,x') (y,y')

(x,y) (ε_x,ε_y)

Envelope Frequencies — *Horizontal* | *Vertical*

Incoherent Q's

Envelopes



5×10^{13} ppp

6×10^{13} ppp

7×10^{13}ppp

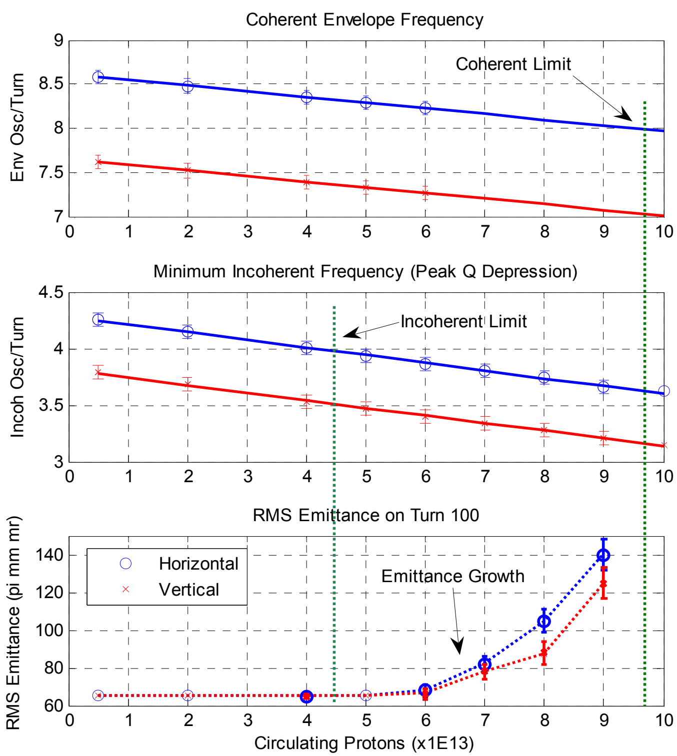
4. Half Integer Losses ~3

Chris Warsop

ORBIT 2D Simulation Results

- Repeat similar simulations, but driven by representative $2Q_h$=8 & $2Q_v$=7 terms

- If allow for BF and energy is compatible with loss observation on ISIS



Driven both planes
$2Q_h$=8 & $2Q_v$=7

Questions important for real machines …

- What causes ε_{rms} growth?

  Mis-match, non stationary distributions,

  driving terms from lattice, … ?

- Can we minimise it?

- Do codes give good predictions?

- can they predict emittance growth & loss?

Have compared ORBIT with theory

- to see if behaviour follows models

4. Half Integer Losses ~ 4

Chris Warsop

Study of Halo & Future Work

- Comparison of halo structure with theory →

- ORBIT: Poincare routines: AG ISIS Lattice; RMS Matched WB; quad driving term; large tune split;

- Theoretical model: Smooth, RMS equivalent KV, quad driving term; "small tune split" (equal)
[*Venturini & Gluckstern PRST-AB V3 p034203,2000]

- Main features agree …

- Next

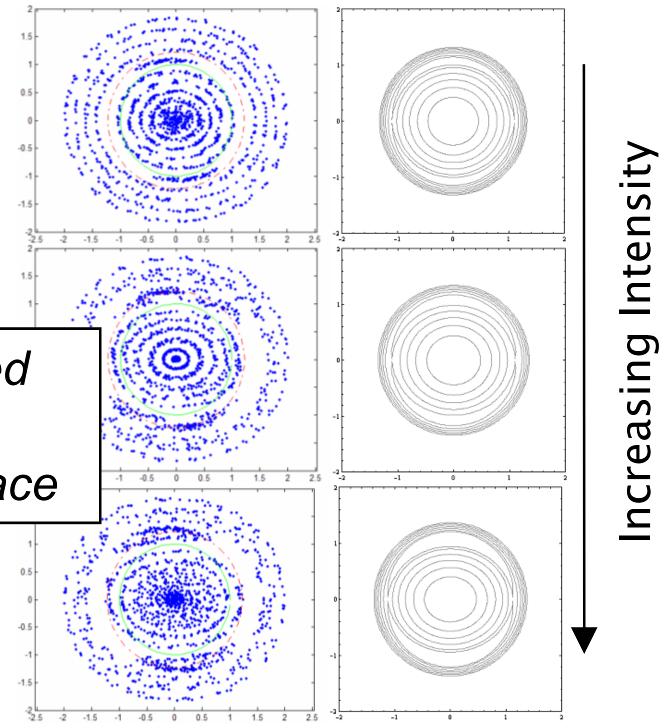
- Check number of particles migrating into halo …?

- Introduce momentum spread (then extend to 3D)

- Comparison with ISIS in Storage ring mode
  ~ trials now underway

Vertical (Y_N, Y_N')

Simulation Theory [*]



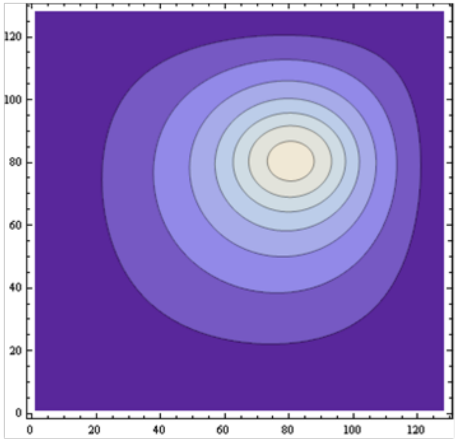
Normalised vertical phase space

7.00 x10^{13} ppp	7.25 x10^{13} ppp
8.00 x10^{13} ppp	7.50 x10^{13} ppp
8.50 x10^{13} ppp	7.75 x10^{13} ppp

5. Images and Set Code ~ 1

Ben Pine

Developing a space charge code “Set"

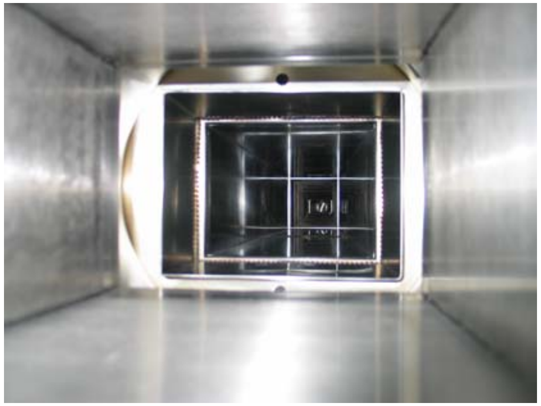


(1) Model and Study Rectangular Vacuum Vessels in ISIS

- implement the appropriate field solvers
- study image effects: rectangular vs elliptical geometry

(2) Develop our own code

- allow us to understand operation and limitations
- develop and enhance areas of particular interest
- presently 2D: will extend …
- plus use of ORBIT, SIMBAD, TRACK*n*D, etc



View inside ISIS vacuum vessels

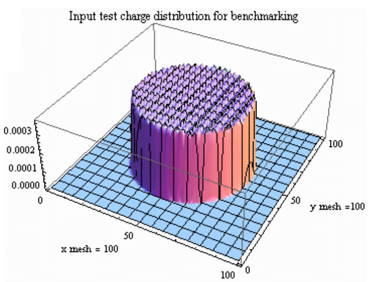
5. Images and Set Code ~ 2

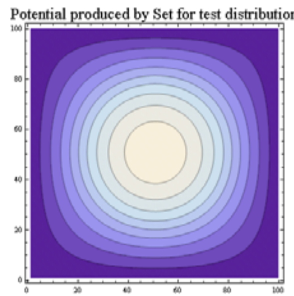
Ben Pine

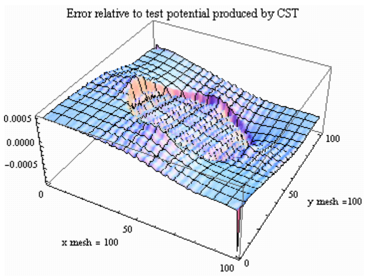
Field Solver Benchmarking: Set solver vs CST Studio

ρ(x,y) *Φ(x,y)* *Relative Error Φ(x,y)*

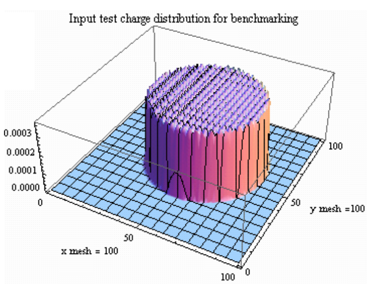
$(x_c,y_c)=(0,0)$

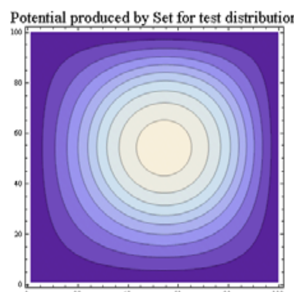


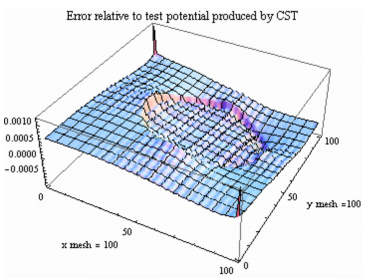




$(x_c,y_c)=(5,5)$

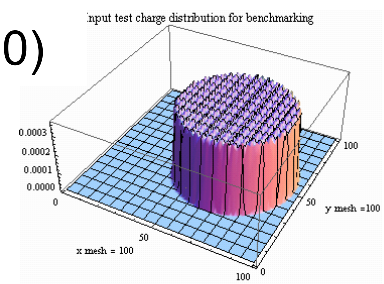


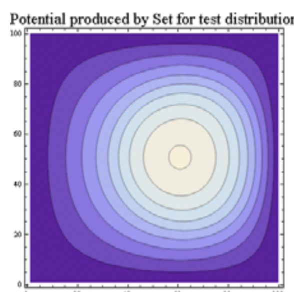


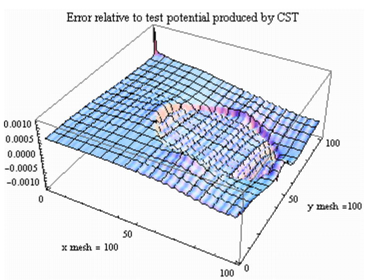


Set solver and CST agree to <0.1%

$(x_c,y_c)=(15,0)$







5. Images and Set Code ~ 3

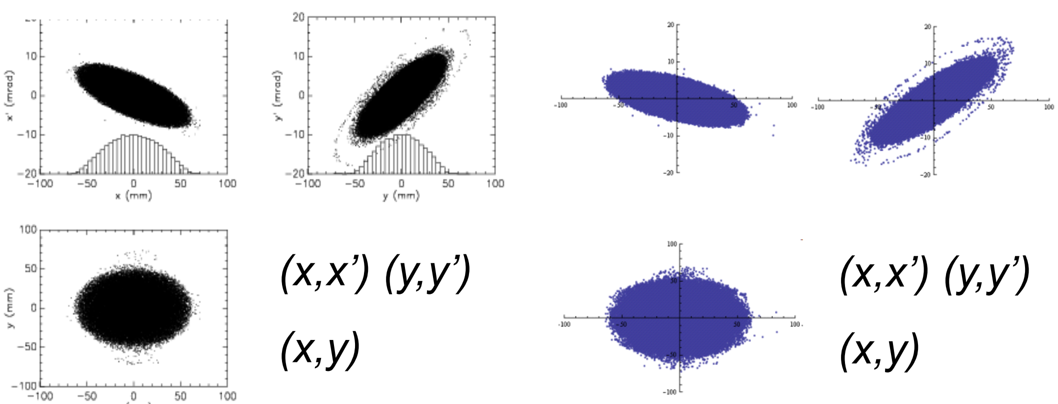
Ben Pine

Comparisons of Set with ORBIT

- ISIS half integer resonance (as above)
  - *~ RMS matched WB beam, $2Q_v$=7 term etc*
  - *Track for 100 turns; vary intensity*
- *Good Agreement - where expected*
  - *Incoherent tunes, envelope frequencies*
  - *evolution of ε_{rms}, beam distributions*

Distributions on turn 100

ORBIT *Set*



(x,x') (y,y')

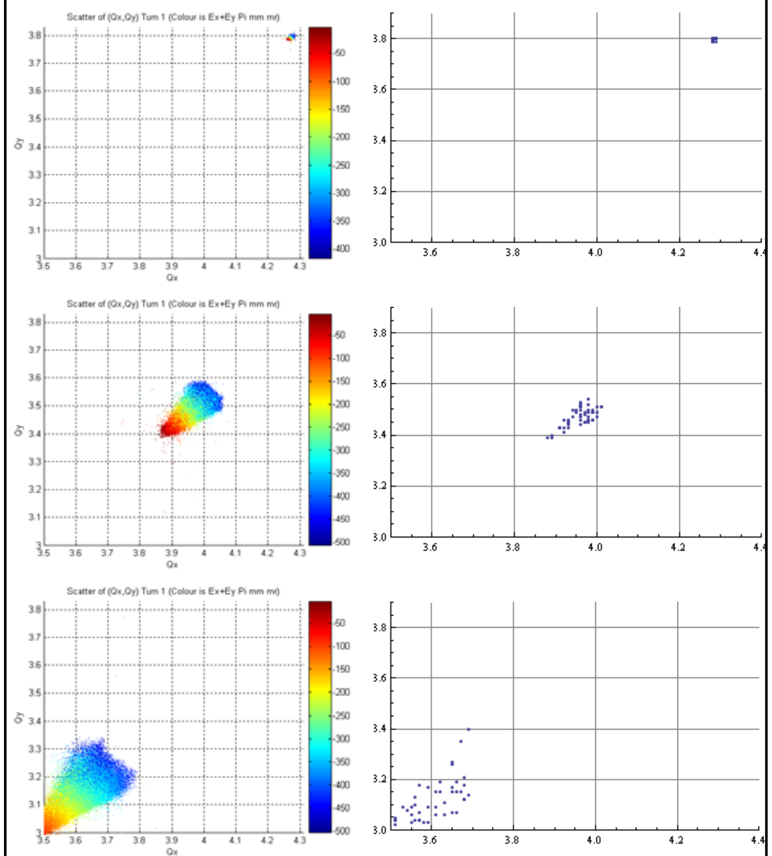
(x,y)

(x,x') (y,y')

(x,y)

Incoherent Tune Shifts

ORBIT *Set*



5. Images and Set Code ~ 4

Ben Pine

Set: Dipole Tune Shift and Next Steps

- Coherent Dipole Tune Shift in Set

 - Expect some differences between ORBIT & Set

 - ORBIT - just direct space charge (as we used it)

 - Set - images give coherent tune shift

- Next Steps

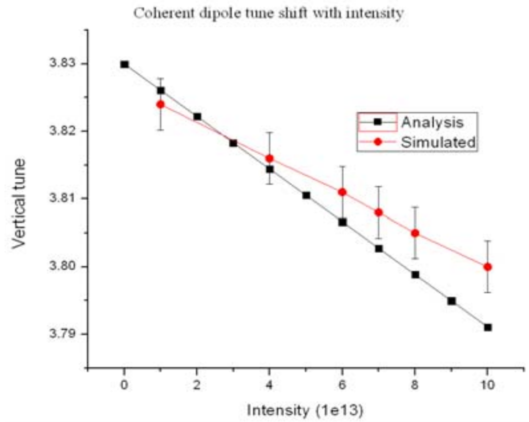
- Are now modelling closed orbits with images

- See expected variations in orbit with intensity

- evidence of non linear driving terms …

- planning experiments to probe images …

Coherent tune shifts from Set



Summary

- Making good progress in key areas
  - experimental study (collaboration on diagnostics)
  - machine modelling and bench marking
  - code development and study of loss mechanisms

- Topics covered
  - Current priorities: Space charge and related loss, injection.
  - Next: Instabilities, e-p, …

- Essential for ISIS upgrades

- Comments and suggestions welcome!

Acknowledgements:

ASTeC/IB - S J Brooks, C R Prior ~ useful discussions

STFC e-Science Group ~ code development

ORNL/SNS ~ for the use of ORBIT