Science & Technology Facilities Council
ISIS

High Intensity Studies on the ISIS Synchrotron, Including Key Factors for Upgrades and the Effects of the Half Integer Resonance.

C M Warsop

On behalf of

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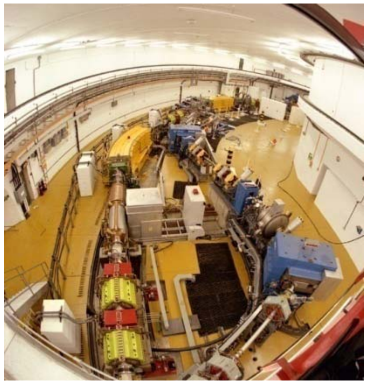
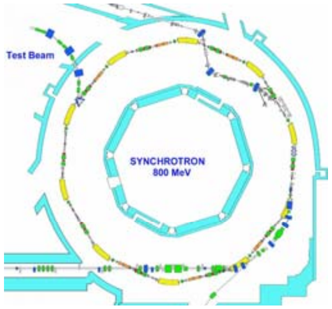
ISIS and *ASTeC, Rutherford Appleton Laboratory, UK



30 September 2010

ICFA, HB2010



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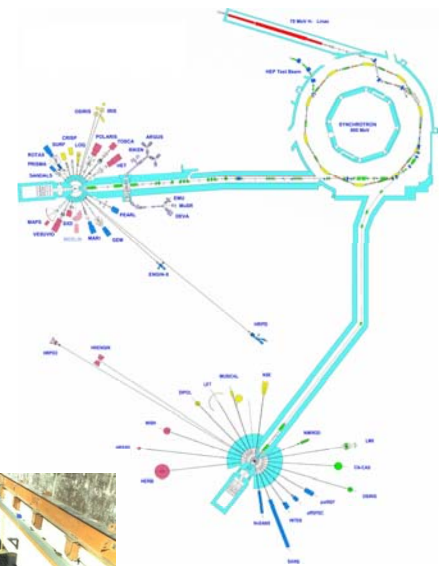
1 High Intensity Rings Work at ISIS



- Present operations for two target stations
  - Operational Intensities: 220-230 μA (185 kW)
  - Experimental Intensities of 3E13 ppp (equiv. 240 μA)
  - DHRF operating well: High Intensity & Low Loss
  - Now looking at overall high intensity optimisation

- Study upgrade with new injector
  - Parts of ISIS 70 MeV linac need replacing
  - Could combine with injector upgrade?
  - More power in the present ring?

- Study megawatt upgrades with a new ring
  - Add a 3.2 GeV Ring → 1MW
  - Add a 3.2 GeV Ring + 800 MeV Linac → 2-5 MW

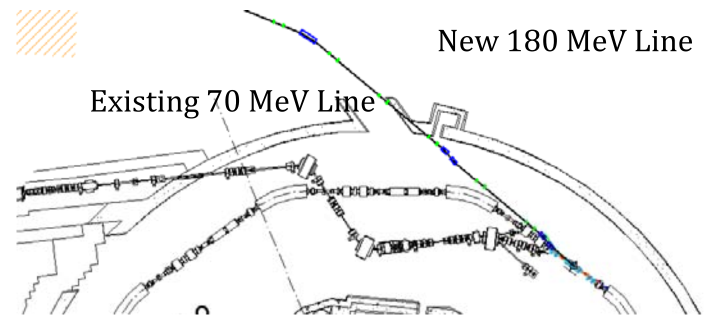
2.1 Overview: Injection Upgrade Study

- Assume a set of working parameters
  The study will show if optimal or possible
  180 MeV Linac design established (G H Rees)
  Intensity of 8E13 ppp i.e. 0.5 MW

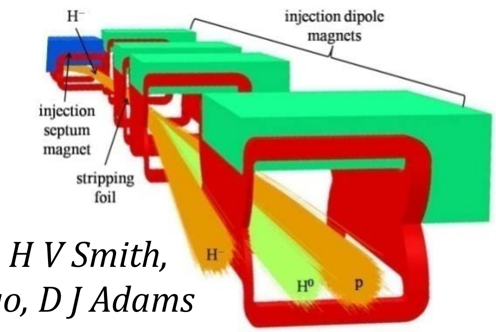
- Many practical aspects to check
  New 180 MeV injection straight
  Increased activation, Loss control
  Foil loss, Extraction loss, ...
  RF system, Main Magnet, Diagnostics, ...

- Many beam dynamics aspect to check
  Space charge, Stability ... Injection

Initial Layout for New Injection



Model of existing 70 MeV Injection

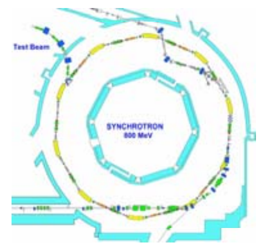


B Jones, H V Smith, S J S Jago, D J Adams

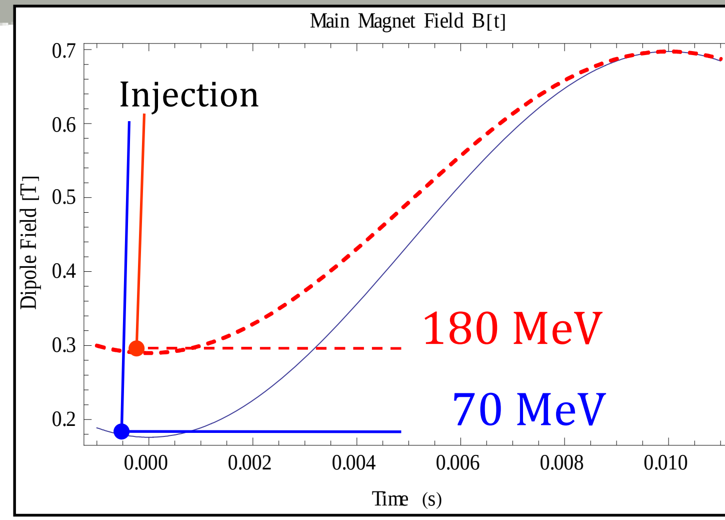
Use to benchmark 180 MeV Design

- Study is addressing all key aspects of upgrade
- Here we just concentrate on selected high intensity issues

2.2 Parameters



- Gains
  - Space Charge, Optimised Injection
- Possible problems
  - Instabilities, Dynamics Changes, Activation
  - 180 MeV Injection, RF Systems, Foils, Loss, …



Basic Ring Parameters	
Circumference	163 m
Superperiods	10
Rep. Rate	50 Hz
No. of Bunches	2
Chromaticity	-1.4, natural
Gamma-t	5.034
Extraction	Fast, Vertical
Acceptances	~300 π μ m r

	Present ISIS	Upgrade Idea
Magnet Field	Sinusoidal	Sinusoidal
Energy Range	70-800 MeV	180-800 MeV
Intensity	2.5-3.0x10^{13} ppp	~ 8.0x10^{13} ppp (?)
Mean Power	160-200 kW	~ 500 kW (?)
Injection	H^-, inside	H^-, outside
Longtl Trapping	"adiabatic capture"	chopped beam
RF System DHRF: h=2, 4	f_2=1.3-3.1 MHz V_{pk} =80, 160 kV	f_2=2.0-3.1 MHz V_{pk}=80, 160 kV
Tunes (variable)	3.83, 4.31	3.83, 4.31 (?)

2.3 Transverse Dynamics: Space Charge Effects

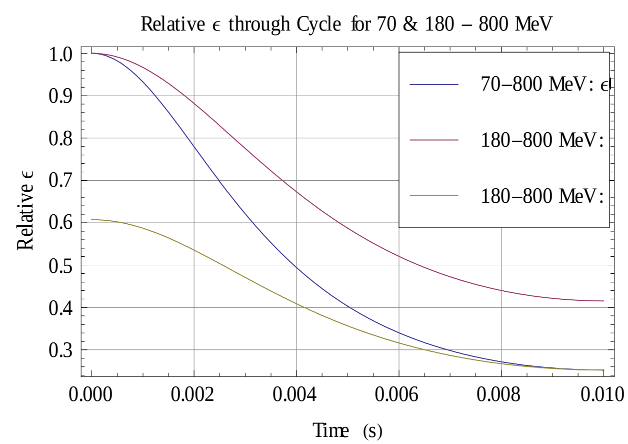
- Space Charge Scaling : $\Delta Q_{inc} = \dfrac{r_p N}{2\pi\beta^2\gamma^3\varepsilon}\dfrac{1}{B}$ Space Charge Limit Scales: $\dfrac{\beta_2^2\gamma_2^3}{\beta_1^2\gamma_1^3}$

Peak space charge moves from 80 to 180 MeV ~ a factor of 2.60 (i.e. ~0.5 MW)

- Ring Acceptances at Injection: As now about 300 π mm mr
- Emittance Damping Change: Conserved as $\varepsilon^* = \varepsilon_1\beta_1\gamma_1 = \varepsilon_2\beta_2\gamma_2$

For upgrade accelerate 180-800 MeV (not 70-800 MeV)
Damping reduced by factor 0.6: *extraction bottleneck?*

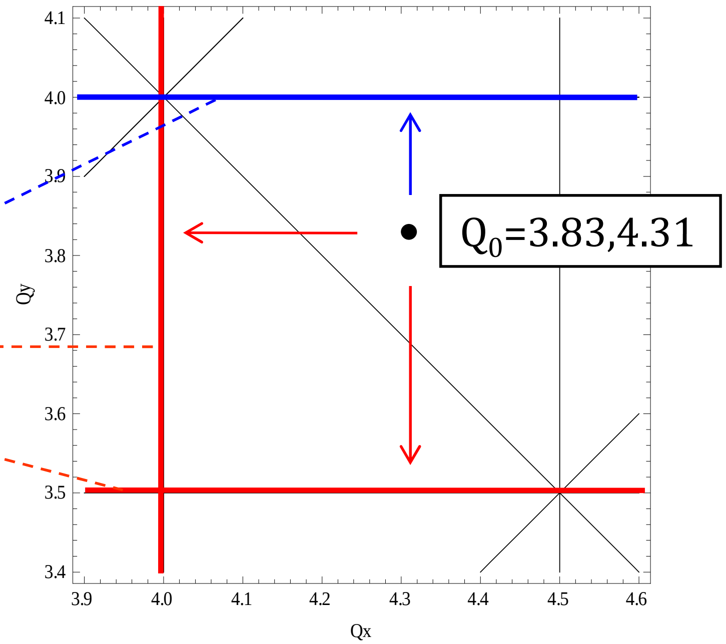
Assume can upgrade extraction acceptance ~300 π mm mr
Details of ring and extraction aperture being studied



- Bunching Factor: Aim for ~0.4, Key aim for longitudinal dynamics – see below

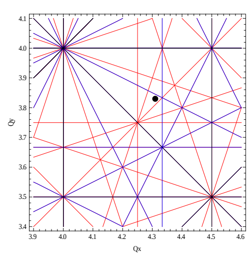
2.4 Transverse Dynamics: Working Point

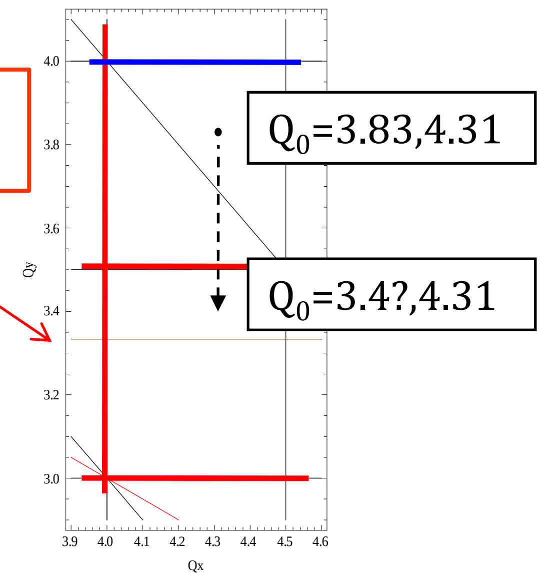
- Main loss mechanisms
  - Head-Tail Resistive-Wall Instability: Q_v=4
  - Half Integer: $2Q_h$=8, $2Q_v$=7
  - Space charge scales down with energy
  - RW Instability: growth rate α intensity



- HTRW could be intensity limit: solutions?
  - Damping System ~ possibility
  - Move Q_v<3.5?

Structure $3Q_v$=10
Excited by images?





- Also need to check:
  - Non-linear terms, e.g. at extraction ...
  - Other instabilities ,..., e-p, etc.

- Transverse dynamics challenging!

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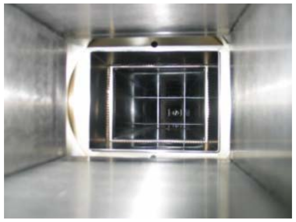
2.5 Transverse Dynamics: Simulation Studies of Space Charge Limit

- Simulation studies of space charge limits using the Set code
  - 2D PIC Simulations: half integer, images, closed orbit errors
  - 180 MeV coasting beam
  - ISIS AG lattice, Q=(3.83, 4.31)
  - Half integer driving terms: $2Q_h$=8, $2Q_v$=7
  - ISIS varying aperture, rectangular vacuum vessels
  - Waterbag beam: $\varepsilon_{rmsh}=\varepsilon_{rmsy}=50\ \pi\ mm\ mr$

ISIS Vacuum Vessel



- Track 100 turns with and without collimation
  - Scan intensities 0→2E14 ppp

- Look for Coherent Modes, Mode Resonance, Emittance growth, Loss

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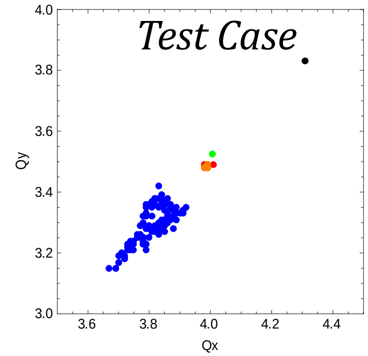
2.6 Transverse Dynamics: Simulation Studies for Space Charge Limit

Incoherent Tune Shifts

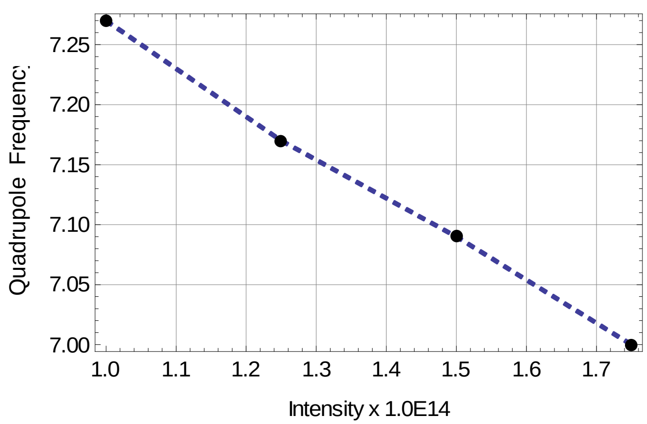


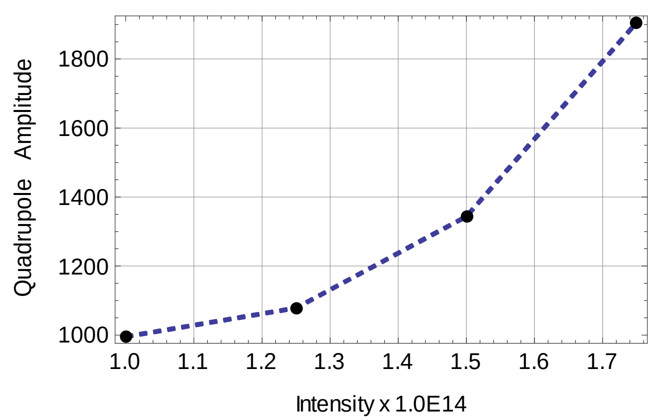
- Half Integer - first limit in vertical plane

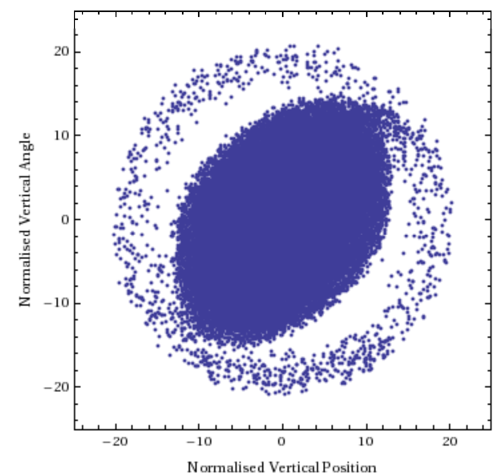
  Limit $2Q_v$=7 is 1.4E14 ppp (6E13ppp for BF=0.4)

  Limit $2Q_h$=8, slightly higher

- Envelope tune depression, amplitude growth, resonance







- Take limit at 5% loss, with collimation at realistic limits

  Main effect envelope resonance …(will extend to include dp/p, 3D motion)

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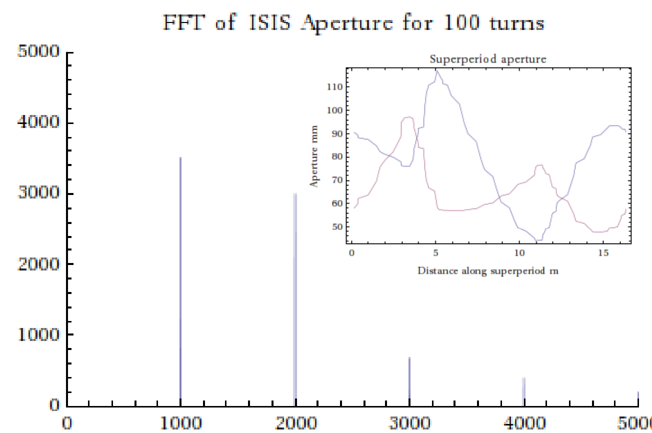
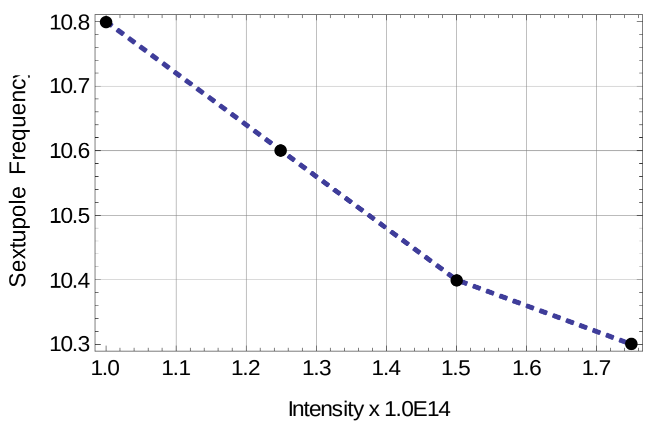
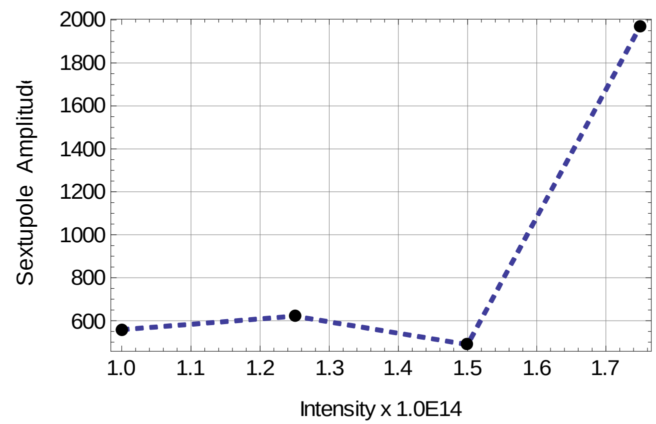
2.7 Transverse Dynamics: Simulation Studies for Space Charge Limit

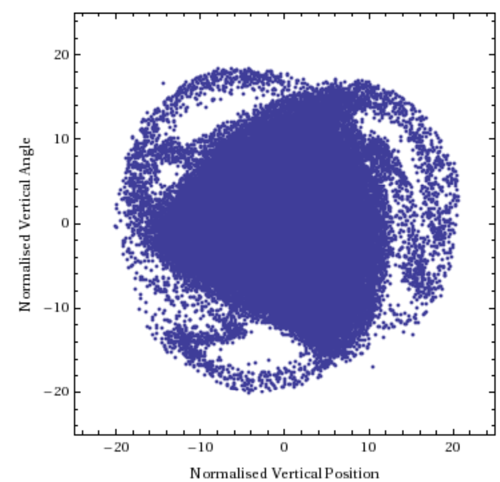
- Image driven 3rd order structure resonance?
  Apparent coherent mode $3Q_v$=10
  At nominal Q's, loss at ~2E14 ppp
  For lower Q_v, (3.8→3.4) ~ a possible problem



- Sextupole mode depression and resonance







- May be an important effect – needs more study

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2.8 Longitudinal Dynamics: Basic Acceleration at 8E13 ppp

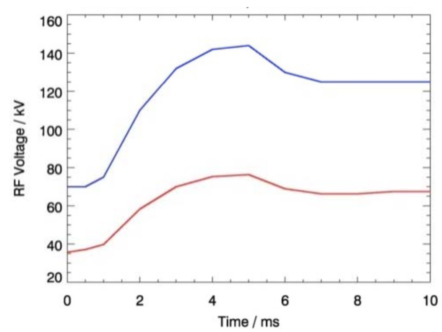
- Ensure acceleration is possible and practical

  Space Charge Effects, Stability, Bunching Factor, dp/p, ε_l damping, extraction …

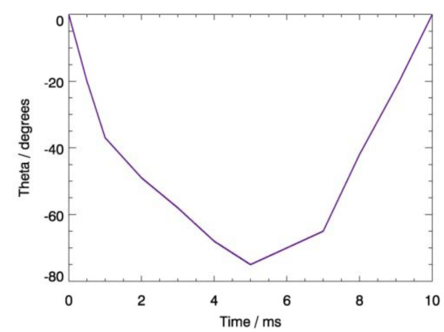
- Calculations & simulations with Hofmann-Pedersen distribution

- Find workable solution with dual harmonic RF $V = V_1 \sin\varphi - V_2 \sin(2\varphi + \theta)$

V_1, V_2 variation

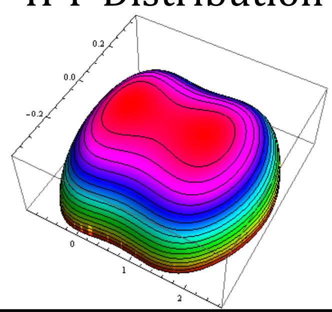


θ variation

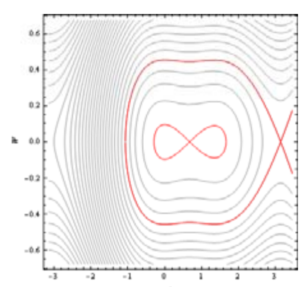


- H-P Disn (not realistic!)
- φ±110°, 180-800 MeV
- n_b=4E13 protons
- Stability OK (k_{sc}<0.4)
- BF OK (~0.4)
- dp/p ~±0.6%
- Extraction OK
- Loss OK
- g=1.45
- Includes space charge

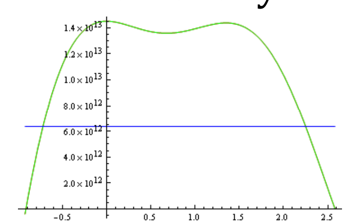
H-P Distribution



DHRF Bucket



Line Density



Plots for 3 ms

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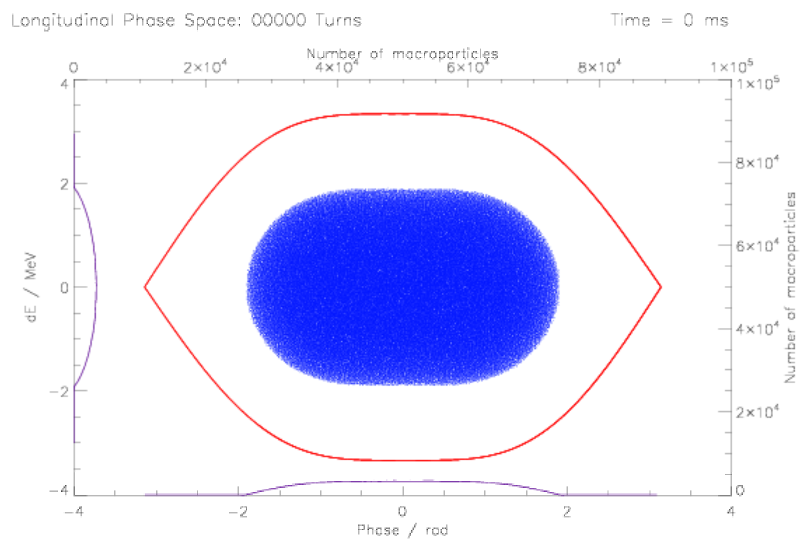
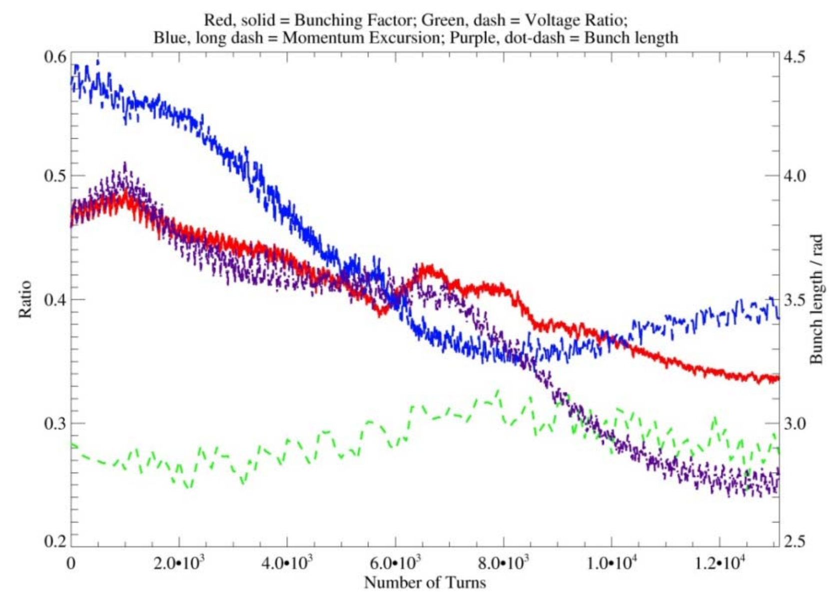
2.9 Longitudinal Dynamics: Simulation

• Acceleration: H-P distribution – Simulations to check calculations ...





• Matched distribution with space charge, parameters as previous slide

• Next need to show is possible with realistic injected/painted distribution

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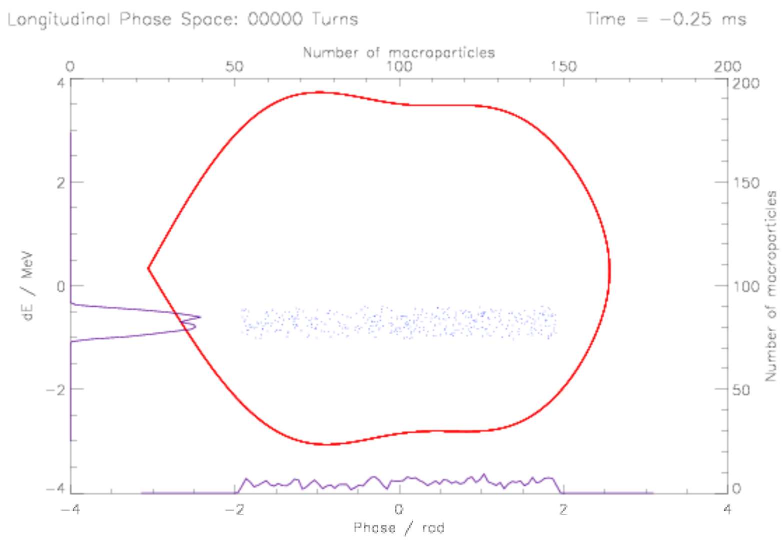
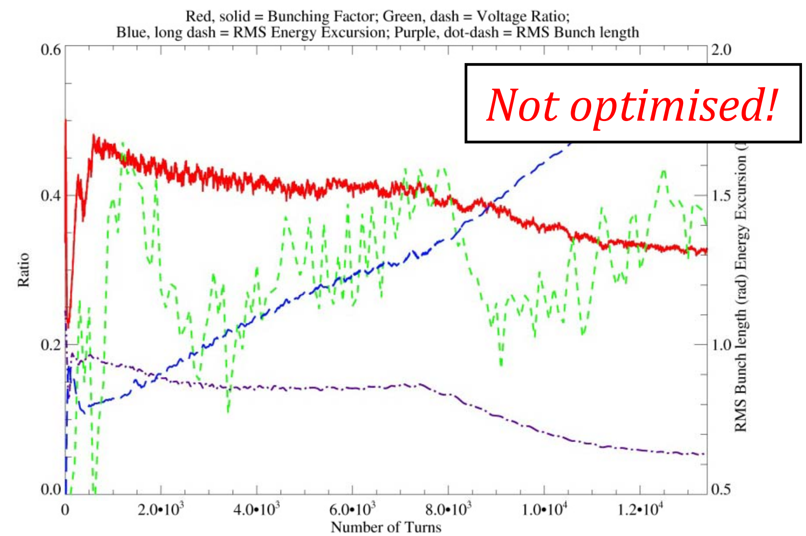
2.10 Longitudinal Dynamics: Injection Painting Trials

- Early injection painting trials and resulting acceleration ... *work in progress*





- Longitudinal painting (JPARC idea)
- Multi-turn, chopped beam
- Vary DHRF and Injected Beam

Promising!

- Painted Injection (includes space charge)
- $\varphi \pm 110°$, 180-800 MeV
- n_b=4E13 protons
- Injected around B_{min}
- dp/p at 0.1% off-set, dp/p ± 0.05%
- Loss 0.7% ~ optimisation ongoing

2.11 Key Topics

- Clearly some challenges in 2D Transverse & 1D Longitudinal

- Next: 3D Injection

    Beam dynamics: Space charge, painting optimal distributions, halo, stability
    Practical designs: Straight design, foil, foil derived loss control
    Presently being modelled (ORBIT & in house codes)…

- Plus

    Activation, collimation and loss control, …

- Many aspects of injection upgrade look plausible, *but key issues to be addressed*

3.1 Measurements on the ISIS Ring: Storage Ring Mode (SRM)

- Studies of coasting beams in SRM help us understand RCS beam
  Simplify dynamics: 2D, "steady state" beam
  Useful for instabilities & space charge

- Storage Ring Mode for the ISIS Ring
  Main Magnet AC Off: DC Only
  RF off: Coasting 70 MeV beam
  Injection painting: Control beam emittances $\varepsilon \approx 60\text{-}300$ π mm mr
  Injection pulse length & diluters: Control intensity 0.1-2.5E13 ppp
  Programmable Trim Quadrupoles: control Q's (~±0.5), add driving terms

  Monitor: Intensity, Loss, Positions, 3D Spectra, Profiles …

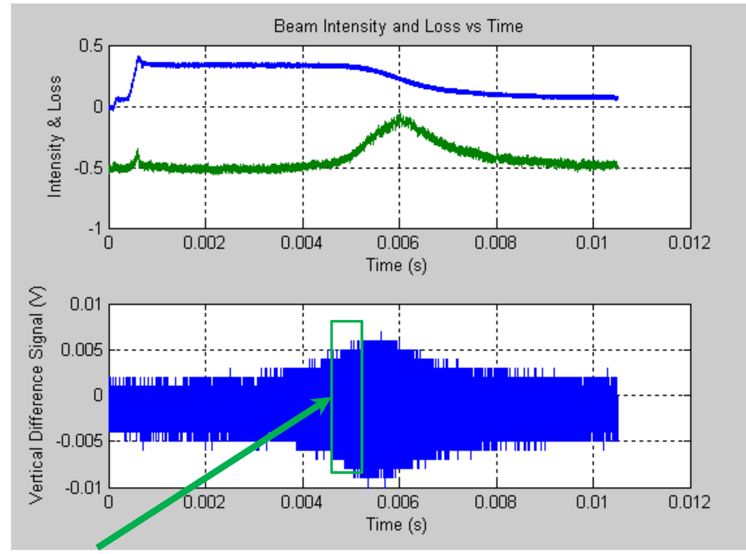
3.2 Storage Ring Mode: Instabilities

- Establish 70 MeV coasting beam ~ 3E12 ppp
  - Nominal tune of Q=(4.31,3.83)
  - Normal painting (~300 π mm mr)

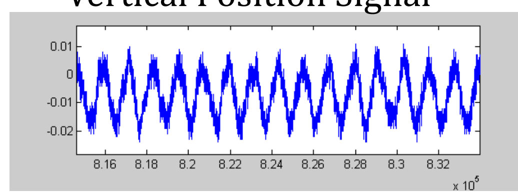
- See Loss and Vertical Coherent Motion
  - Vertical beam profile growth
  - Over time scale of 1-10 ms
  - Vertical resistive-wall instability

- Dependences
  - Strongly dependent on how close to Q_v=4
  - Depends on intensity

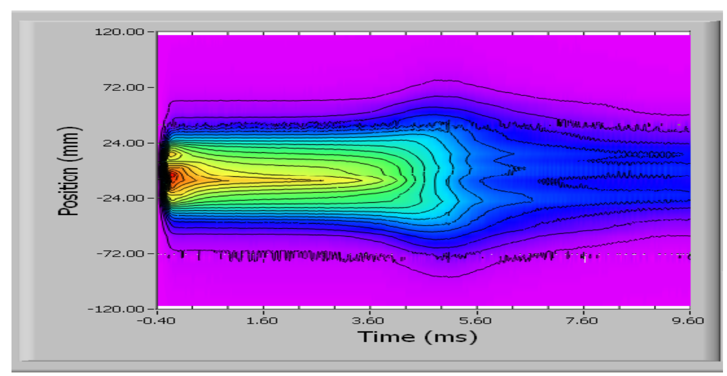
Intensity, Loss, Vertical Position



Vertical Position Signal



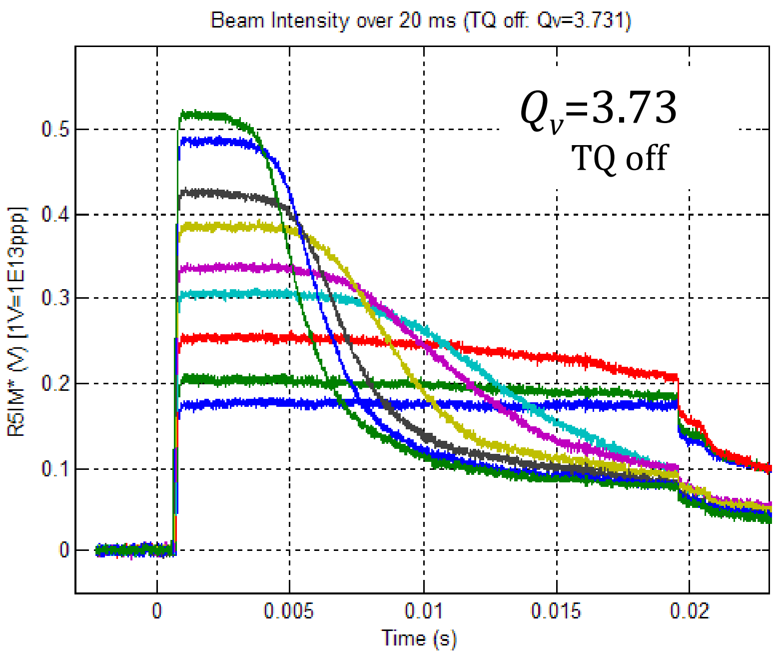
Vertical Beam Profile

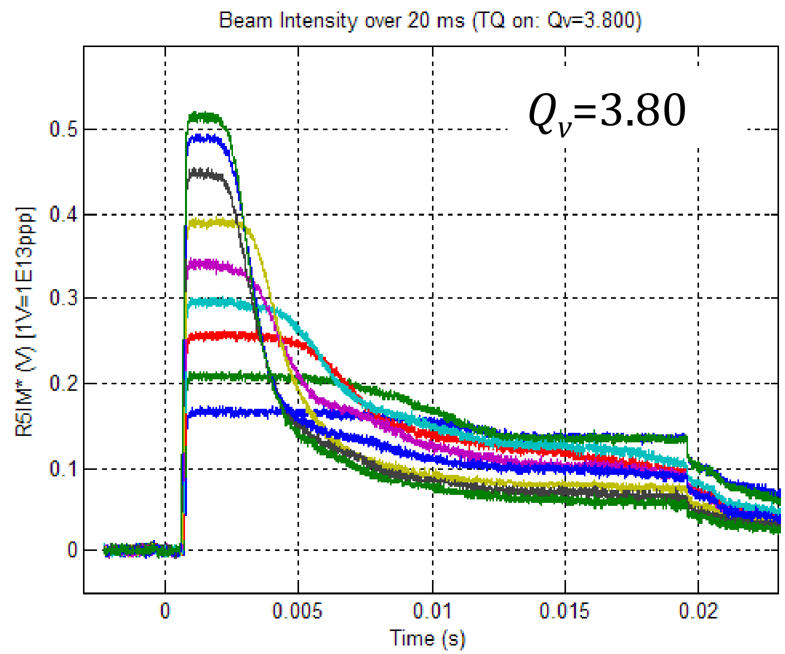


3.3 Storage Ring Mode: Instabilities

Beam Current from R5IM Toroid

- Beam Survival vs Intensity and Q_v



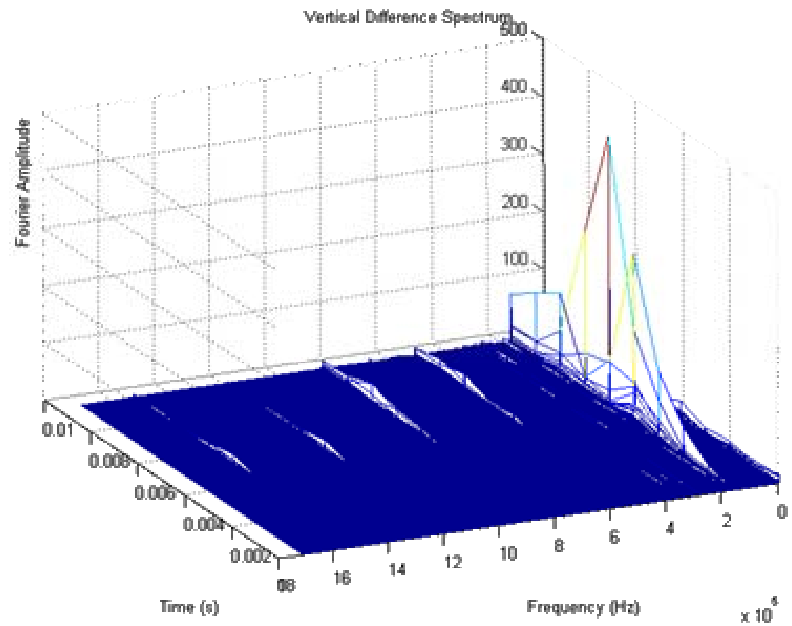


- Lifetime decreases with intensity
- Lifetime decreases as get closer to Q_v=4

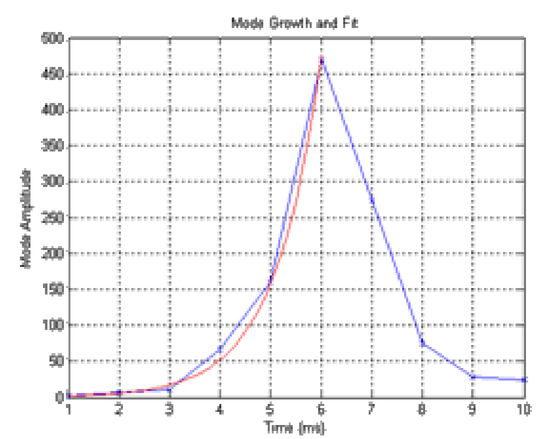
3.4 Storage Ring Mode: Instabilities

- Vertical Difference Spectrum
  as a function of time 0-10 ms
  0-1.8 MHz (f_{rev}=678 kHz)
- Dominant, growing mode $(4\text{-}Q_v)f_{rev}$
  Lowest betatron side-band, as expect
- Higher modes also visible
  After excitation of lowest mode & loss
- Growth of mode fits exponential
  Gives growth times of: $\tau \sim 1$ ms
- Depends on I, Q, beam size

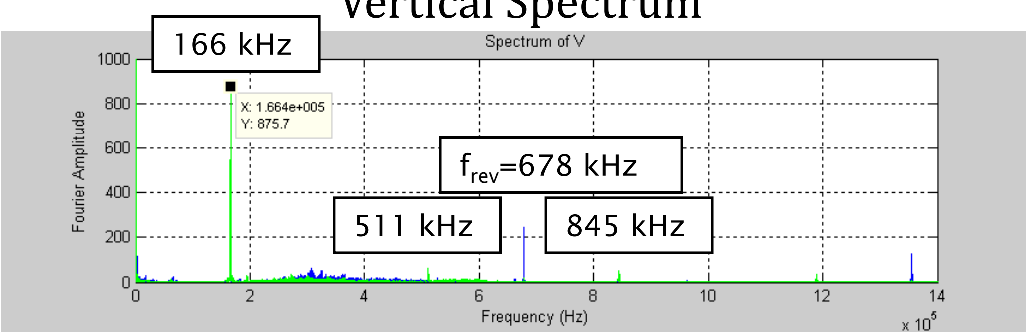
Spectrum: Vertical beam modes



Exponential growth for $(4\text{-}Q_v)$ mode



Vertical Spectrum



3.5 Storage Ring Mode: Instabilities

- Frequency shift and growth rate (no Landau damping)

$$\Delta\omega = i\frac{ec}{4\pi Q\gamma E_0} Z_T I \qquad \frac{1}{\tau} = -\mathrm{Im}[\Delta\omega]$$

Instability: real negative impedance

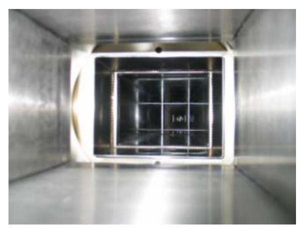
- Use estimate for circular pipe

Low ω High ω

$$\mathrm{Re}[Z_{Trw}] \approx \frac{2cR}{b^3\sigma\omega d} \qquad \mathrm{Re}[Z_{Trw}] = \frac{RZ_0}{b^3}\delta; \quad \delta = \sqrt{\frac{2}{\omega\sigma\mu}}$$

- Calculation gives ~ 50 kΩ/m
- Measurement implies ~200 kΩ/m

(110 kHz ,factor 4 dependency on ε_{rms})



- Calculation is rough

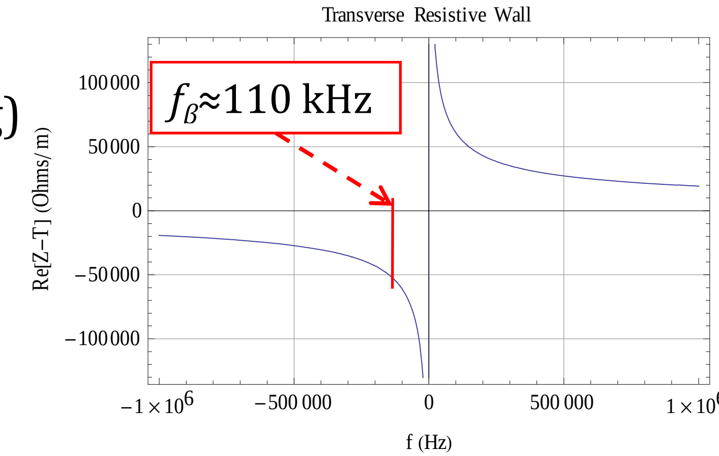
ISIS: rectangular, variable aperture, RF shields

(Steel, d~ 2.8-6 mm, A_v~90-50 mm)

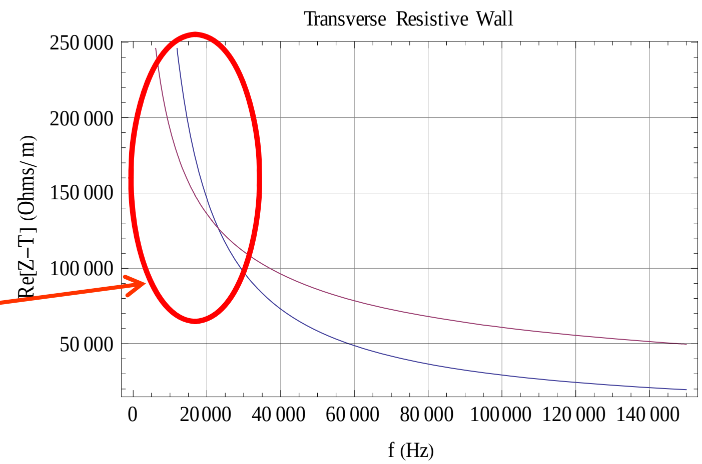
Z_{Trw} uncertain at low frequency

- Estimates OK considering simple model!

Estimated Resistive Wall Z_T



Resistive Wall Z_T: High & Low ω



3.6 Storage Ring Mode: Instabilities

• Measurements now allowing detailed study of Z_T

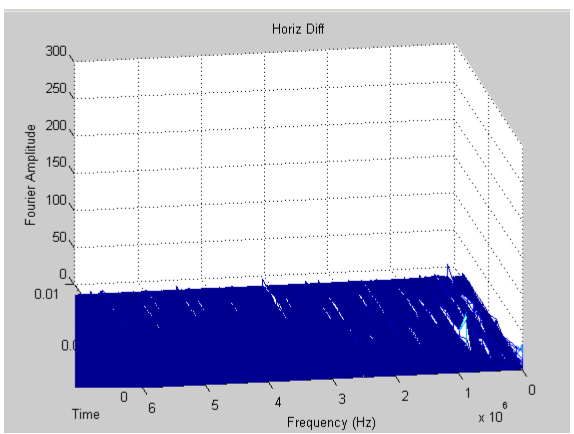
Next: Detailed measurements of frequency shifts and growth rates vs Q, I

Will help us understand and stabilise beam in SRM and RCS

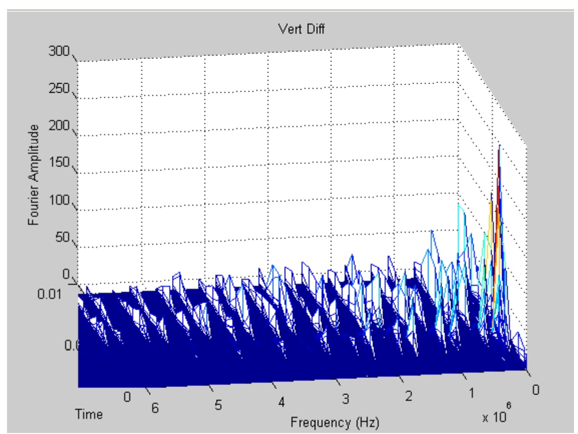
• Will also study longitudinal plane $Z_{//}$

Examples of experimental time dependent spectra in 3 planes

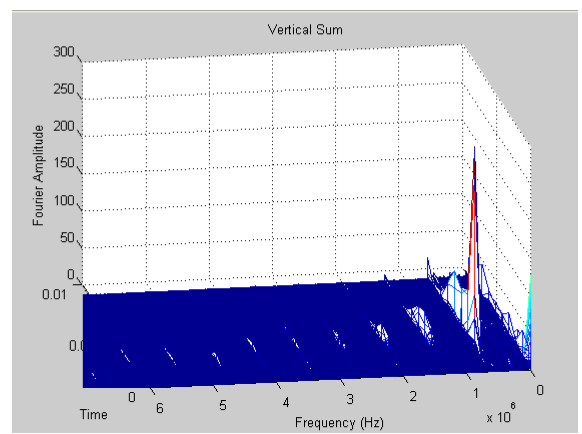
Horizontal Spectrum



Vertical Spectrum



Longitudinal Spectrum



I=1.0E13 ppp

3.7 Storage Ring Mode Experiments: Half Integer

- Aim to learn about half integer loss under "simple" steady state conditions
- Simple experiment: predict beam loss due to envelope resonance (a first step …)
- Experiment

Set up "constant painting" with controlled, minimised emittances

Find emittances from profile measurements, Set $\varepsilon_x = \varepsilon_y$

Calculate envelope tunes for round beam: large tune split case

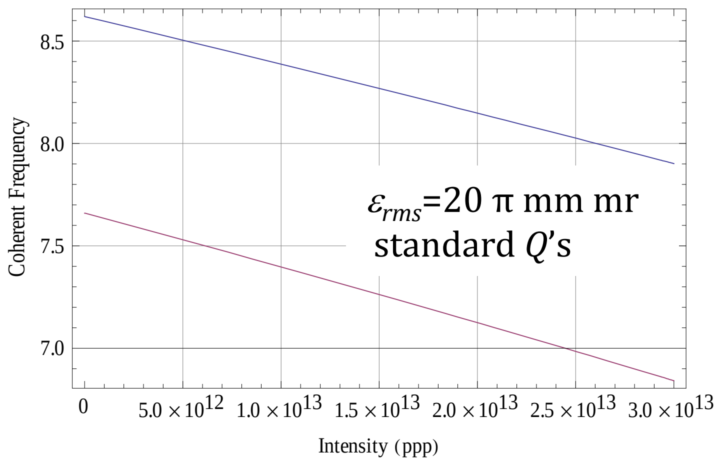
$$\omega_x^2 = 4Q_{0x}^2 - 5Q_{0x}\Delta Q_{inc,x}$$
$$\omega_y^2 = 4Q_{0y}^2 - 5Q_{0x}\Delta Q_{inc,x}$$

$$\Delta Q_{inc} = \frac{r_p N}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B}$$

Apply strong $2Q_v$=7 driving term to Trim Quads

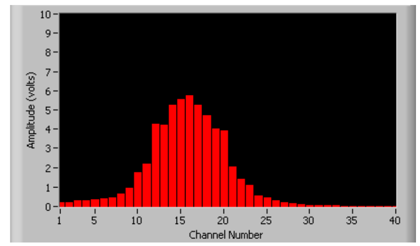
Vary Q, Intensity ~ get loss when expected?

Envelope Tune vs Intensity

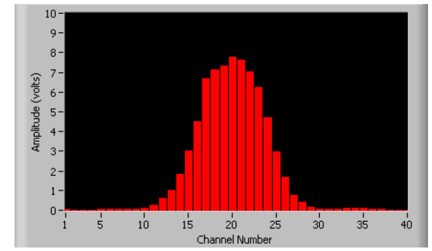


3.8 Storage Ring Mode Expts: half integer

Horizontal Profile

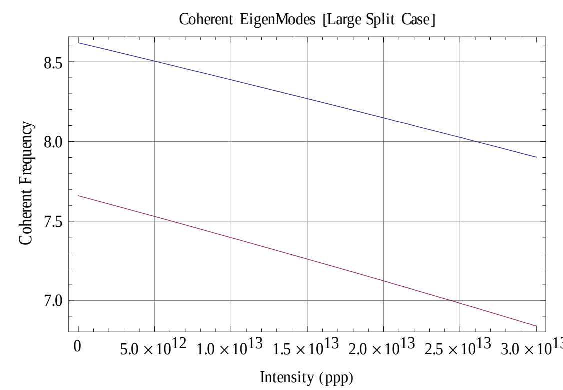


Vertical Profile

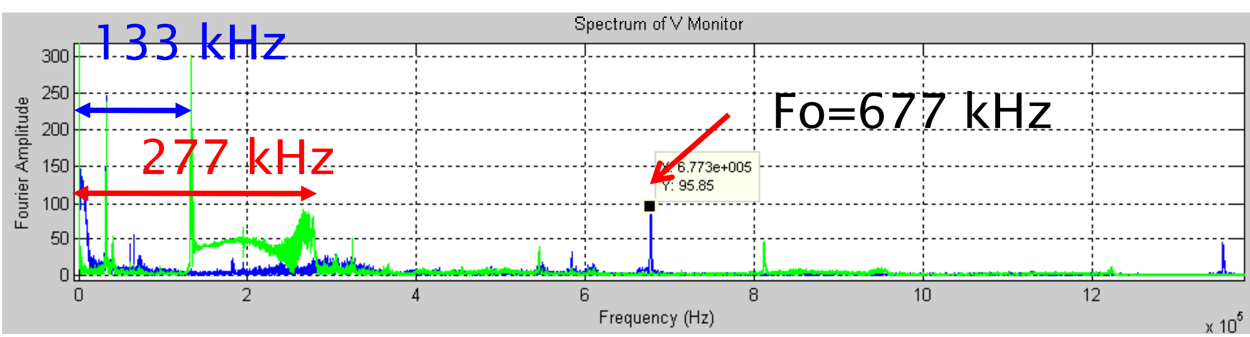


- Transverse Profiles
  - New multi-channel gas-ionisation monitors
  - Apply corrections for drift field errors and space charge (see HB2008 paper)
  - Get $\varepsilon_{rms} \approx 20 \pm 4\ \pi$ mm mr
- *Q* Control & Measurements
  - Control *Q*'s with Trim Quads
  - Measure dipole coherent *Q* value using vertical spectrum
  - Gives value of low intensity envelope frequency

Calculate *Q*, *I* for Resonance



Vertical Spectra: Measured Shift of Q_v (1E13ppp)



Measurement taken during ramp of *Q* over defined range

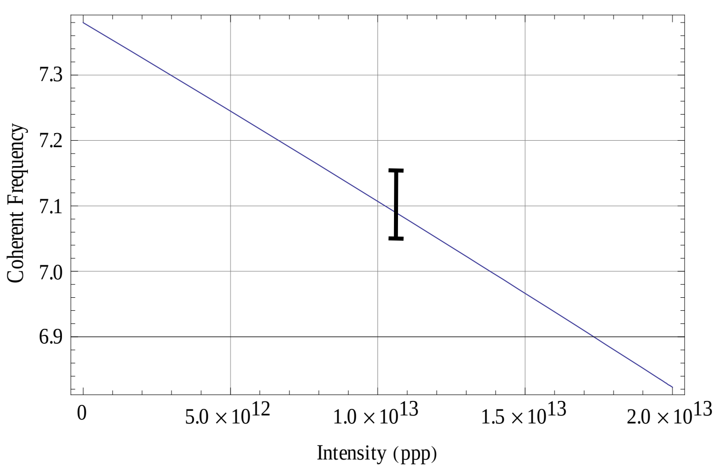
q=0.20, Q=3.80 [set=3.73]
q=0.41, Q=3.59 [set=3.50]

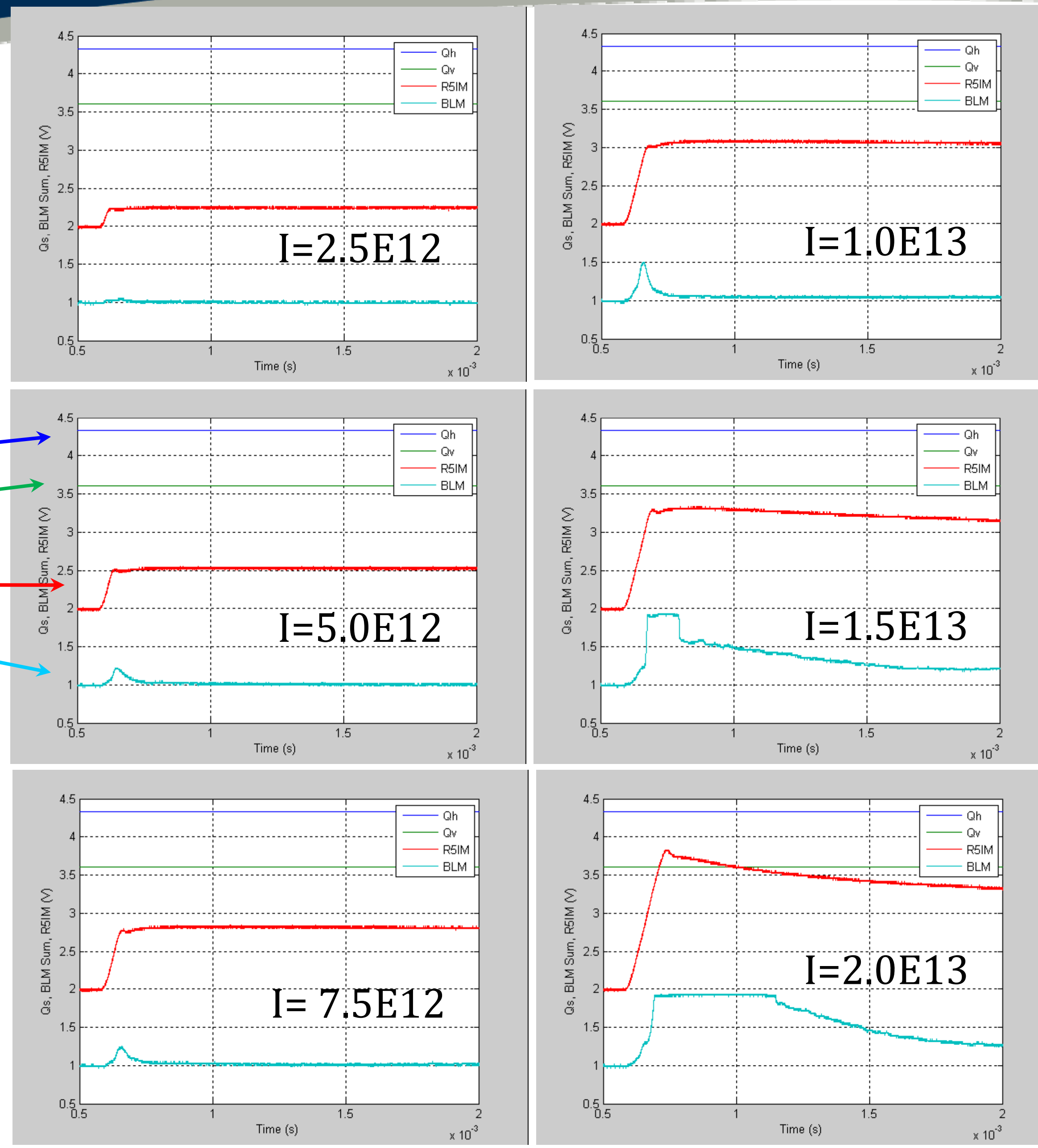
3.9 SRM: half integer

- Experiment 1
  Vary Intensity 0.25-2.0E13 ppp
  Fix Q_v=3.6

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

Calc ω_v for Q_v=3.60; ε_{rms}=20

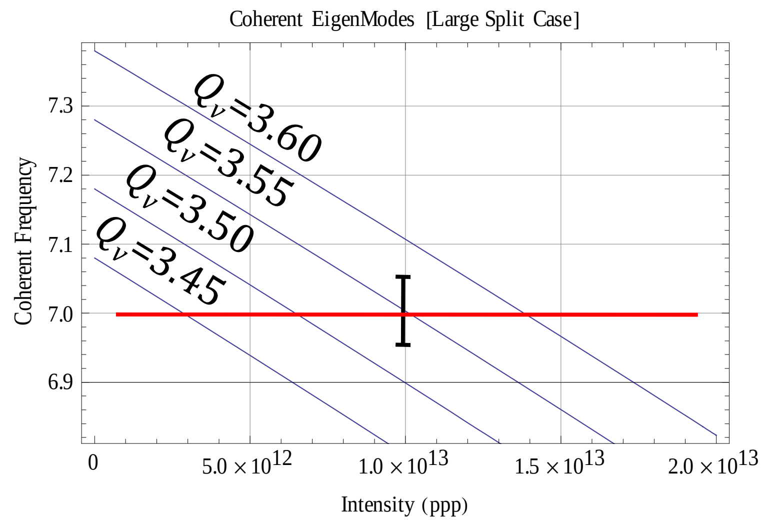




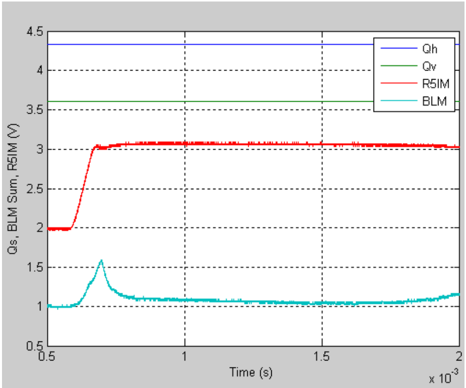
3.10 SRM: half integer

- Experiment 2
  Vary Q_v 3.60-3.45
  Fix Intensity 1E13 ppp

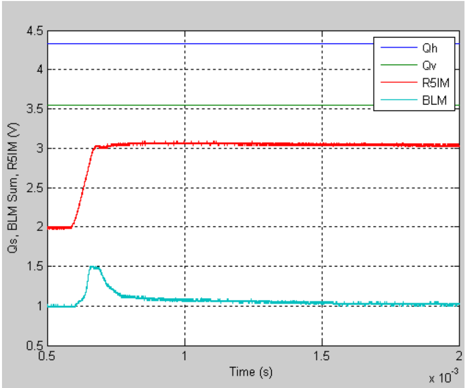
Calc ω_v for ε_{rms}=20,
Q_v=3.60, 3.55, 3.50, 3.45



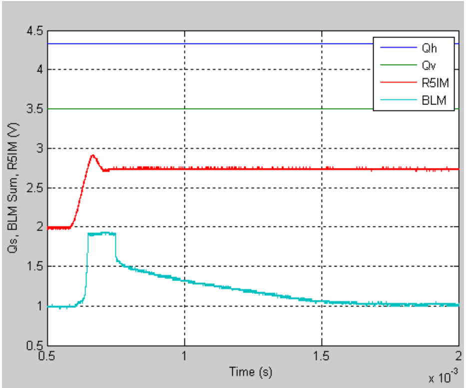
Set Q_v=3.60



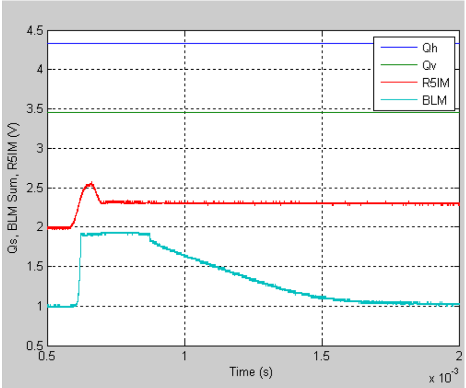
Set Q_v=3.55



Set Q_v=3.50

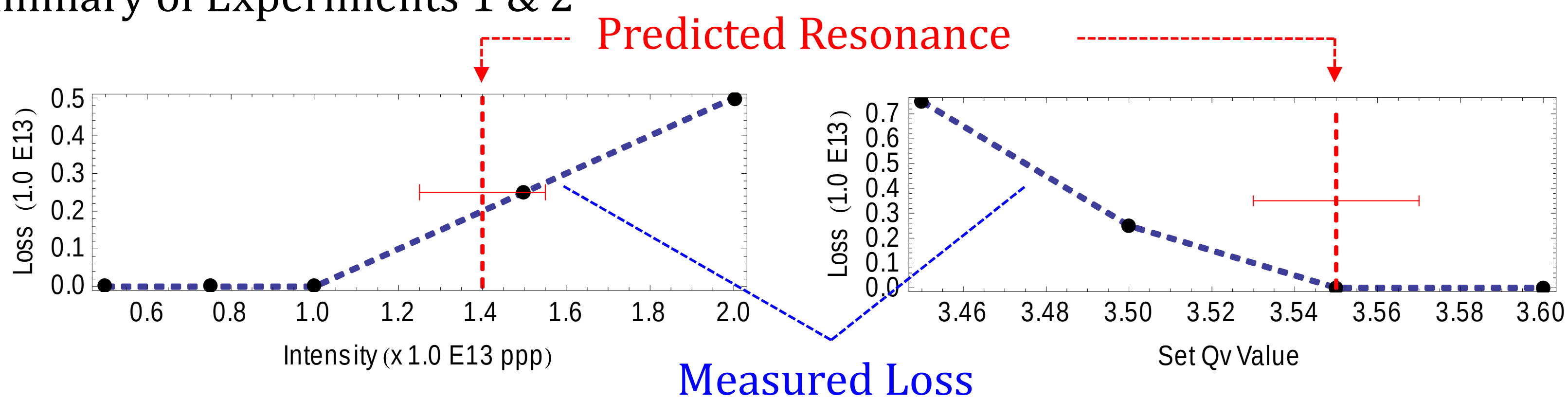


Set Q_v=3.45



3.11 SRM: half integer

- Summary of Experiments 1 & 2



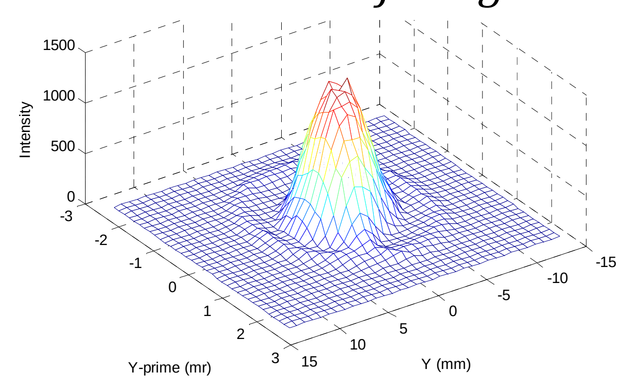
- Basic measurements - but a useful first step
  Will refine profile measurement and beam control

- Hope eventually to measure parametric halo
  Should be possible …

- Plan to install quadrupole monitors and kickers
  Direct observation of envelope oscillation …

ORBIT Simulation

Halo from small emittance beam near half integer



4 Summary

- High Intensity Studies Essential for Present ISIS Operations and for Upgrades
- Complimentary Studies: Beam Dynamics, Codes, Experiments, Diagnostics
- Studying Upgrades: Injection Upgrade (0.5 MW), New Ring (1-5 MW)
- We still have much to learn from the ISIS Synchrotron!