Simulation and Measurement of Half Integer Resonance in Coasting Beams in the ISIS Ring

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Contents

Introduction
The ISIS Synchrotron
Review of ISIS Half Integer Studies Experiments
  Machine Configuration
  Diagnostics
  ORBIT Models
  Loss and Profile Measurements: Halo
Models and Future Work
Conclusions
Acknowledgements
1. Introduction

• ISIS Facility
  Operation centres on 800 MeV proton RCS
  High intensity limits important

• ISIS Developments and Upgrades
  Ongoing operations, improvements (0.2 MW)
  Upgrade 1: New 180 MeV Linac (~0.5 MW)
  Upgrade 2: New 3.5 GeV RCS (~1+ MW)
  Upgrade 3: New 800 MeV Linac (2-5 MW)

• Limiting Factors
  Space Charge, Instabilities, Injection, ...
  Half integer an important factor for all

• Related Papers
  MOP257 (BGP), WEO3C01 (BJ)
  TH01A04 (REW), TH01C02 (DJA)
2. The ISIS Synchrotron

- Circumference: 163 m
- Energy Range: 70-800 MeV
- Rep Rate: 50 Hz
- Intensity: $2.5 \times 10^{13}$ ppp ($3.0 \times 10^{13}$)
- Mean Power: 160 kW (192 kW)
- Losses: Inj: 2%, Trap: <5%, Acc/Ext <0.1%
- Injection: 130 turn, charge-exchange
- Acceptances: collimated $\sim 300 \ \pi \ \text{mm} \ \text{mr}$
- RF System: $h=2, f_2=1.3-3.1 \ \text{MHz}, V_2 \sim 160 \text{kV/turn}$
  $h=4, f_4=2.6-6.2 \ \text{MHz}, V_4 \sim 80 \ \text{kV/turn}$
- Extraction: single-turn, vertical
- Tunes: $(Q_x, Q_y)=(4.31,3.83)$ (variable)
3. ISIS Half Integer Studies

- Want to understand half integer on RCS 3D motion, fast changing parameters
  Staged study: 2D, static 3D, RCS

- Summary of 2D work so far
  Calculated coherent modes (large tune-split)
  ORBIT models: coherent, incoherent limit
  emittance growth, halo ...

Coherent Envelope Mode vs Tune Depression

Minimum Incoherent Frequency (Peak Q Depression)

RMS Emittance on Turn 100

Circulating Protons (x1E13)

RMS Emittance (pi mm mr)

Envelop 100 turns

Tune Footprint ($Q_x, Q_y$)

Beam Stable at Incoherent Limit
4. Experiments: Machine Configuration

- Aim to make experiment as simple as possible
  Straight forward observation of essential behaviour

- ISIS ring in Storage Ring Mode (SRM)
  RF off, main magnets on constant DC
  Inject and store 70 MeV beam (0→1.3E13 ppp)
  Constant painting ($\varepsilon_{rmsx} \approx \varepsilon_{rmsy} \approx 20\pm4\pi$ mm mr)
  Beam occupies a small fraction of acceptance
  Set constant lattice ($Q_x$, $Q_y$)=(4.30,3.63)
  Apply $2Q_y=7$ driving term (amplitude/phase)
  Ramp intensity, push toward $2Q_y=7$

- Look at
  Beam Loss
  Transverse Profiles

Coherent frequencies

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

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

- **Profile Monitors**
  Residual gas ionisation monitors
  Non-destructive, sensitive
  Errors: drift field, space charge
  Detailed study provided corrections
  Now refining: more detail

- **Low Intensity Chopped Beams**
  Less than 1 turn, small emittance
  Measurements of \((Q_x, Q_y)\), painting, ...

- **Intensity Toroids and Loss Monitors**
6. Experiments: Loss Measurements

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

**Beam Current** \((1V=1E13 \ ppp)\)

**Beam Loss** \((\text{clipped at }> 1V!)\)

\[
\begin{align*}
\text{I}= 7.5\times 10^{12} & \quad \text{I}= 7.5\times 10^{12} \\
\text{I}= 1.0\times 10^{13} & \quad \text{I}= 1.5\times 10^{13} \\
\text{I}= 2.0\times 10^{13} & \quad \text{I}= 2.0\times 10^{13}
\end{align*}
\]

- Summary of loss measurements: Loss vs I, vs Q, vs driving term

**Predicted Resonance**

**Measured Loss**
7. ORBIT Model of ISIS

- **3D ORBIT Model of ISIS RCS**
  Detailed AG lattice, injection painting, variable $Q$, apertures, collimation, ...
  Good agreement with observations (D J Adams, IPAC12, THPPP088, p3942)

- **Adapted for ISIS SRM**
  Parameters set as in experiment constant $Q$, constant painting, driving terms, ...
  Track ~300 turns, including injection
  Output distributions, tunes, ...

- **Plots show SRM example ($p_2$ case)**
  Left-right: $\left(x, x', y, y'\right)$ (phi, dE) $\left(x, y\right)$
  Top-bottom: turns 14-114 (step 20)
  See later
8. ORBIT Simulation of Experiments

• Multiple runs: vary intensity
  With $\varepsilon_{rms} = 15\pm2 \ \pi \ mm \ mr$, $Q_v = 3.60$
  Predict resonance at $\sim 0.5 \pm 0.1 \times 10^{13} \ ppp$
  For each run: plot $\varepsilon_{99\%}$ on turn 299
  Clear dependence on driving term

• Single run: evolution over 300 turns
  $\varepsilon_{rms}$ increases as expect (vertical only)
  Intensity reaches $\sim 0.5 \times 10^{13} \ ppp$ on turn 68
  Strong dependence on driving term
  Clear growth in second moment
  Frequency of 2\textsuperscript{nd} moment near $2Q_y = 7$
  Expected “halo”

Particle distribution in $(y,y')$ on turn 109
9. Experiments: Profile Measurements

- Measure profiles as approach resonance

- Identify as half integer halo?
  Control with driving term
  \[ \Delta k(\theta) = k_0 \cos(2Q_y \theta + \phi) \]
  \[ p_0: k_0 = 0 \]
  \[ p_1: k_0 = 0.02 \text{ m}^{-2}, \phi = 0 \]
  \[ p_2: k_0 = 0.02 \text{ m}^{-2}, \phi = \pi \]

- For driven resonance
  \((y, y')\) structure locked to \(\theta\)
  Rotates \(2Q_y\) times around ring

- Effects of these?
  Strength: loss
  Phase: \((y, y')\) orientation
  \(\sim\) profile is \(y\) projection
10. Compare with ORBIT simulation

- Compare ORBIT
- Same Features
- See “Hips” due to phase
- Details?

**Measured profile**

**ORBIT profile**

**ORBIT \((Y,Y')\)**

\[ p_0 \]
\[ k_0 = 0 \]

\[ p_1 \]
\[ k_0 = 0.02 \text{ m}^{-2} \]
\[ \phi = 0 \]

\[ p_2 \]
\[ k_0 = 0.02 \text{ m}^{-2} \]
\[ \phi = \pi \]
11. ORBIT Simulation Details

- More detail of $p_2$ case
  Evolution $(Y,Y')$ in ORBIT
  Turns 29-79 (step 10)
  Intensity ramps 0.2-1.2 E13 ppp
  Pushes onto resonance ≈ single particles at $Q_y=3.5$

![Measured ORBIT (Y,Y')](image)

Typical tune footprint at resonance

![Incoherent Tunes after 39 Injected Turns](image)
• Beam Models
  Experiments presently ahead of beam model!

• Coherent model useful
  Until beam blows up ...

• Very useful model in literature
  Venturini & Gluckstern [1]
  KV, self-consistent, driven, equal tunes ...
  1D halo ~ looked at in [2] – similar behaviour

• Experiments show observable halo
  Next – try a simple non self-consistent model
  e.g. waterbag, particle-core, driven ...
  Will hopefully describe short term structure

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13. Next Steps

• Results are promising, but there is much further to go!

• Reduce errors and optimise use of profile monitors
  Better models of beam and machine (beam parameter measurements)
  More detailed information from profile monitors (more modelling)

• Develop simple models
  Simplified simulation/analytical models (particle-core, WB, driving term)

• Develop experiments and link with closely related work
  Studies of ISIS working point and image effects (MOP257)
  Planning experiments with bunched, non-accelerated beams (TH01A04)
  Study of RCS mode (3D ORBIT simulations and use of ISIS Set 3Di code)
14. Summary

• Detailed observation of half integer resonance
  Measurement and manipulation of halo as predicted by simulation

• Promising results
  Now hope to improve detail and accuracy ...
15. Acknowledgements

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