Ring Simulation and Beam Dynamics Studies for ISIS Upgrades 0.5 to 10 MW

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HB 2014, Michigan State University, USA, November 2014

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Contents

- 180 MeV injection upgrade to ISIS (0.5 MW)
  - Overview of ISIS RCS
  - Injection system
  - Transverse and longitudinal painting / Acceleration
  - Study results

- 2-10 MW Facility
  - Overview of Ring
  - Initial 1D and 3D Results.

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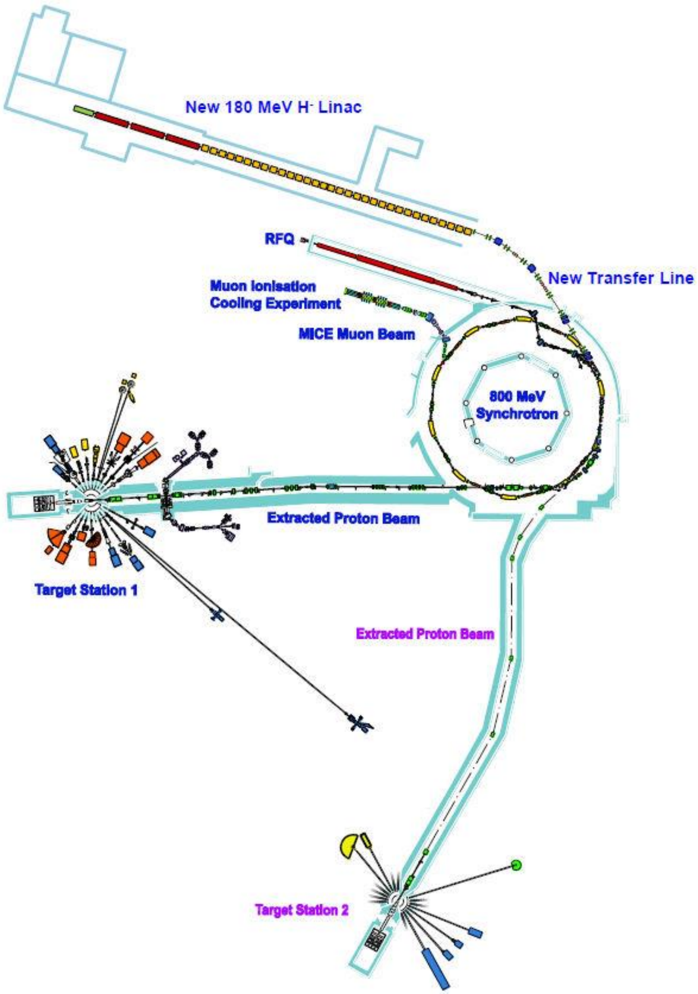
180 MeV Injection upgrade to ISIS



- Increasing the injection energy from 70 to 180 MEV
- Operation $3x10^{13}$ ppp (0.2MW) increases to $8×10^{13}$ ppp (0.5 MW.)
- Improve transverse and longitudinal painting flexibility.
- Address some sustainability issues by replacing existing linac.

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Transverse Space Charge and Stability

$$\Delta Q_{inc} = -\frac{N r_0}{2\pi\beta^2\gamma^3 \varepsilon B_F} \sim -0.5$$

- Peaks at 80 MeV and 180 MeV
- Energy scaling $\beta^2\gamma^3$ and increased bunching factor scale x 3.7 gain
- Current operation 3×10^{13} ppp increases to ~ 11.1×10^{13} ppp for same incoherent tune spread.
- Choose 8×10^{13} (0.5 MW) as a conservative operating level.
- 2D studies with in-house code SET (WB distribution, Space charge, images, half integer driving terms, 100 turns) suggest low loss is achievable.

- Head tail resistive wall instability – damping system in development.

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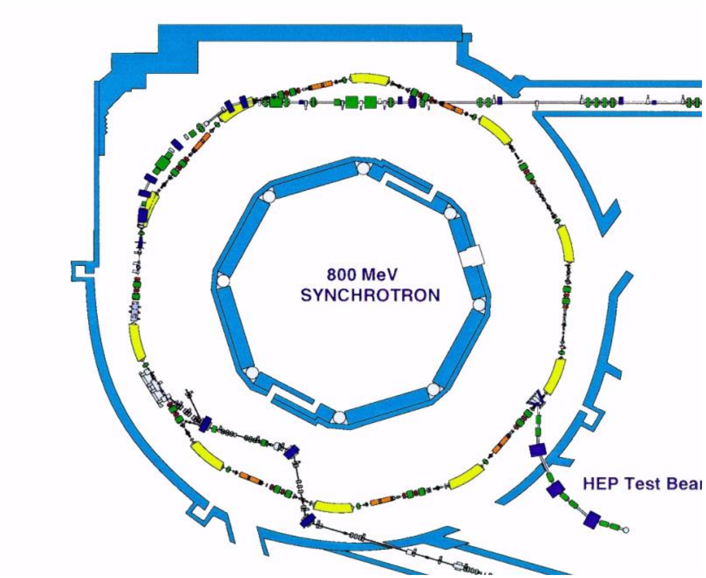
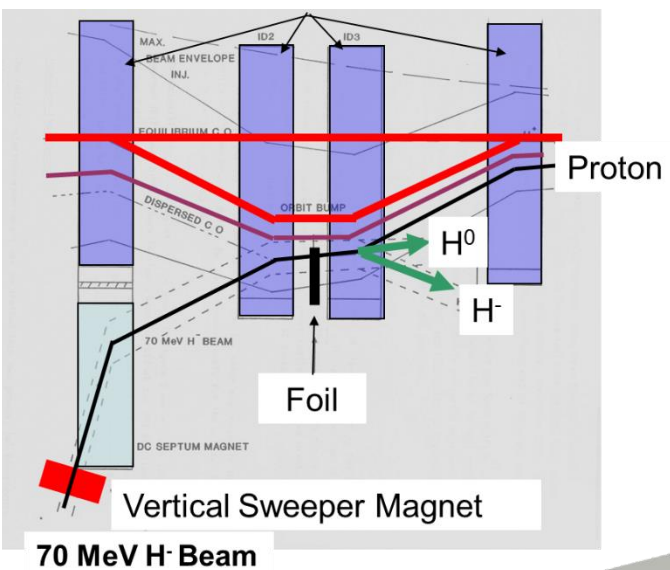
Current ISIS Ring Operation

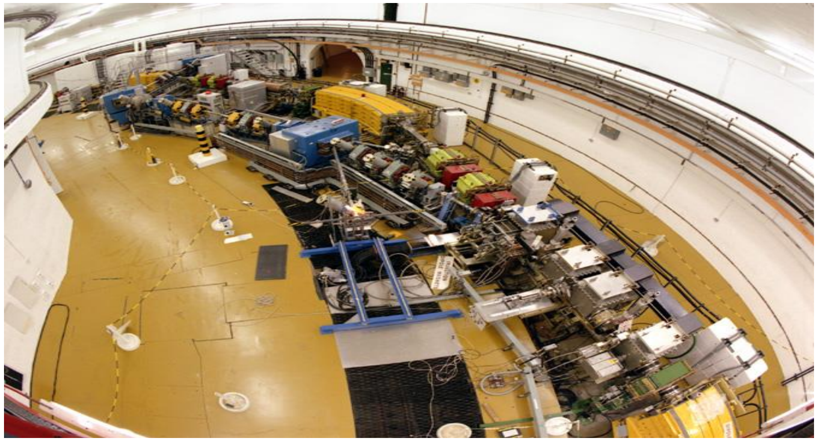


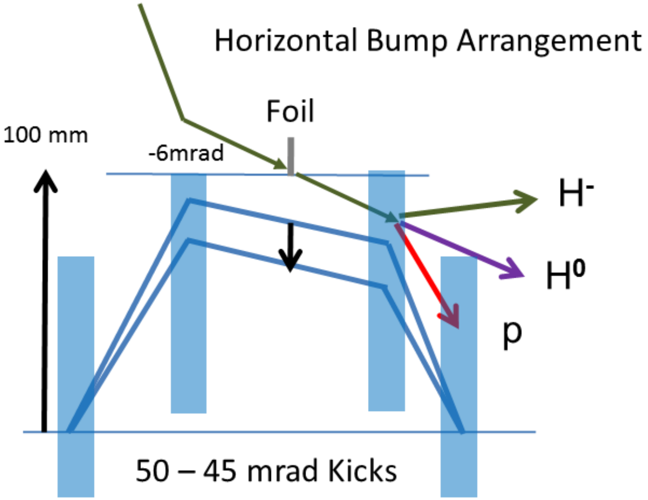


- 70-800 MeV, 50 Hz, RCS
- 70 MeV Injection, charge exchange H-, over 200 µs pulses, ~3.0×10^{13} ppp
- RF Cavities: 6 (h=2) RF cavities Vpeak 160 KV, 4 (h=4) Vpeak 80 KV
- Dispersive horizontal paint, vertical paint via sweeper. No longitudinal paint
- Fast single turn extraction
- Beam Losses ~ 5 % in Super period 0-3

Injection Scheme

- Injection point moved to outside of ring reflecting existing geometries.
- 43 mA injection current, 500 µs (500 turn) H- charge exchange injection 8×10^{13} ppp
- Falling rising or symmetric point of main magnet field.
- Transverse Painting: 60-200 π mm mr to accumulate max emittance 300 π mm mr
- Longitudinal paint ±0-1.3 MeV using injection energy ramp and Ring RF bucket frequency errors.
- Chopped at ± 110° wrt Ring RF phase.
- Use existing RF peak parameters
- Losses ~ 0.1 % to maintain existing activation levels.





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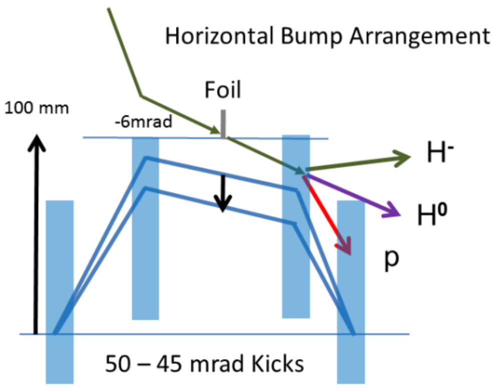
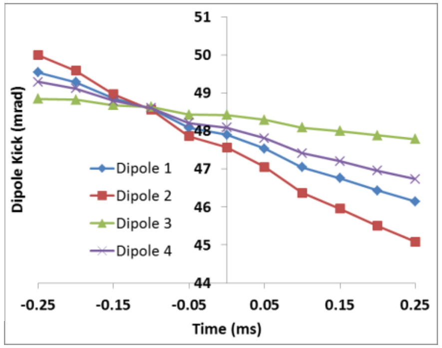
Transverse Injection Painting

Provide flexible painting scheme
60-200 π mm mrad.

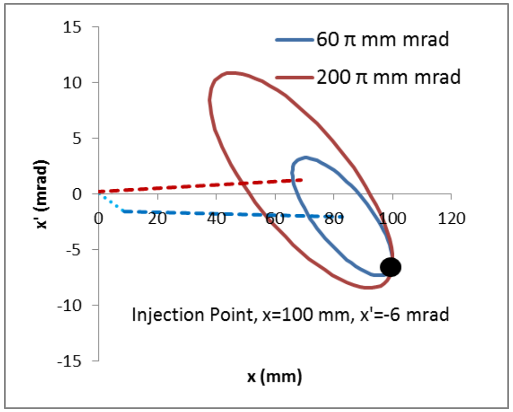
Horizontal Paint: Dispersive (± 1 MeV), dynamic bumps 45-50 mr

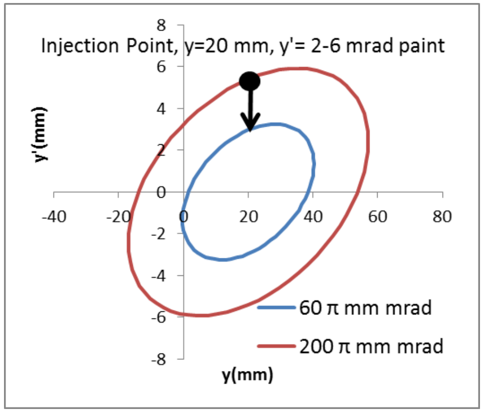
Vertical Paint, 20 mm, 2-6 mrad

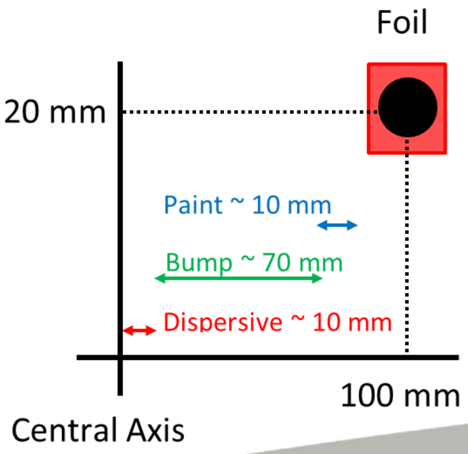




Two corrections per plane control beam on foil.







Injection symmetrically about field minimum most flexible correlation painting case

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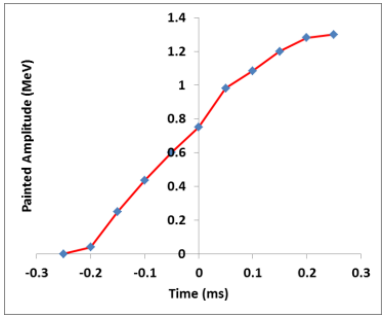
Longitudinal Studies

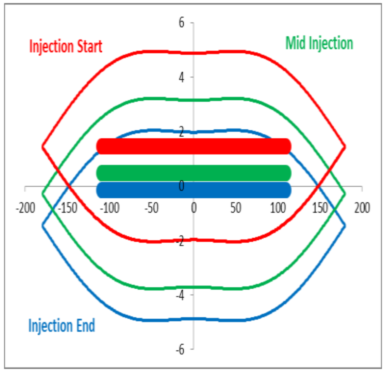
Hofmann-Pedersen (HP) distribution tracked to define upper limit of longitudinal emittance.

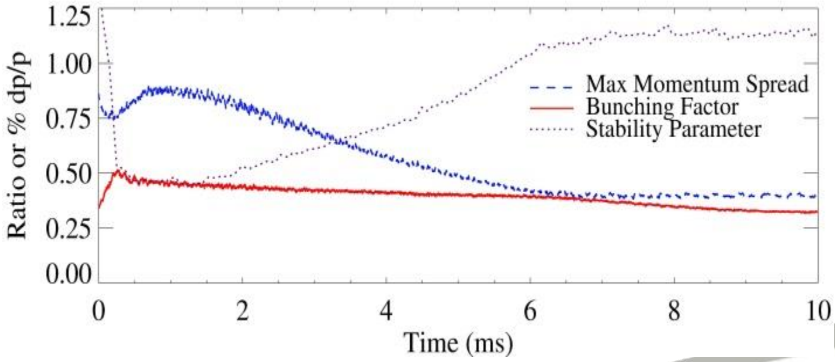
1d in-house code studies define painted beam 0-1.3 MeV (Einj ± 1MeV (transverse constrained), RF bucket offset +/- 2 MeV), Chopping duty factor 61 %

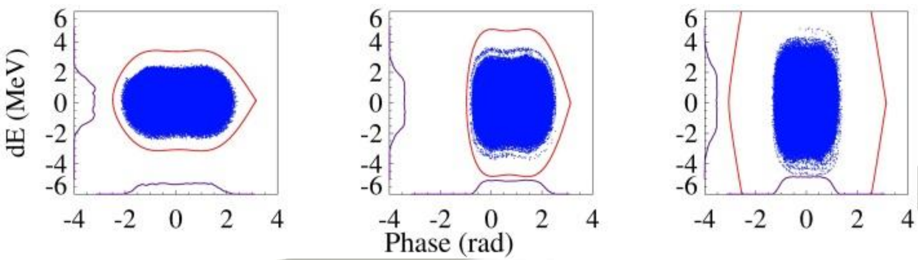
Maximise bunching factors 0.5 at injection >0.4 during acceleration.

Keil-Schnell-Boussard stability criteria used to assess beam stability : ~1. (Normal ISIS operates ~ 6)









0.25 ms 5 ms 10 ms

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ORBIT Model Studies

- Model includes:
  - Linear MAD Model lattice.
  - Multi turn injection.
  - Dynamic bump.
  - RF bucket offset.
  - Foil.
  - Collimators and Machine Apertures.
  - Tune variations and Quadrupole driving errors .
  - 3D space charge routine (128,128,64), ≤ 5 M macro particles.
  - One bunch simulated.

- Convergence Studies.
  - Beam losses @ 0.1 % require 5 M macro particles. (0.1%=5000 particles).
  - 99% emittance ≥ 5 M particles. (2% variation from 2.5 – 5 M.)
  - CPU time limited to 5M particles for simulation runs.

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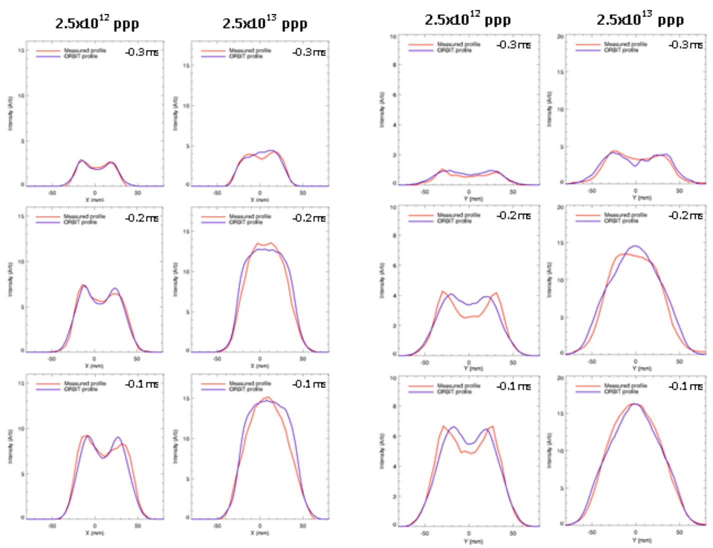
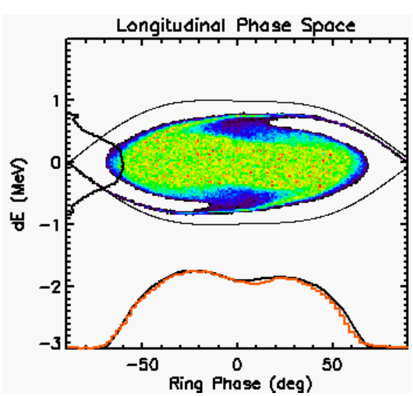
ISIS 70 MeV ORBIT Simulations

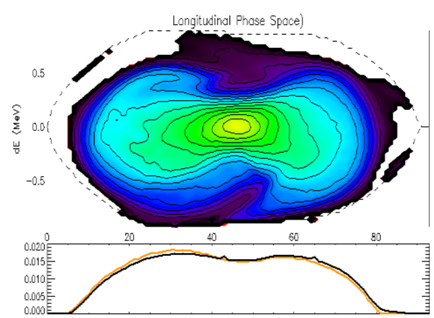
Measured ORBIT injection profiles

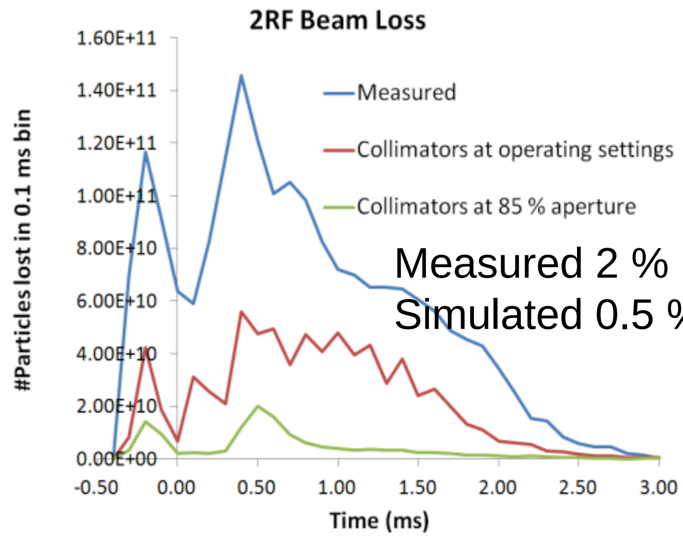


ORBIT@0ms

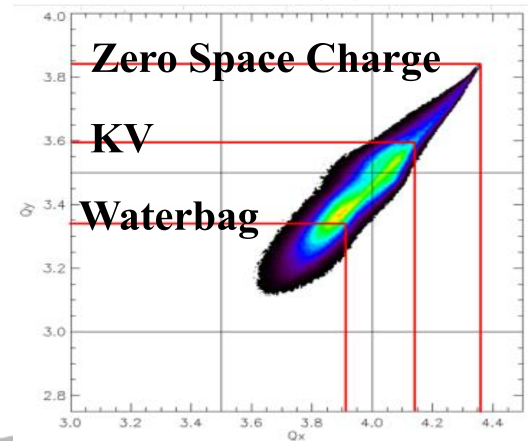


Tomography@0ms





Measured 2 % Loss
Simulated 0.5 % loss



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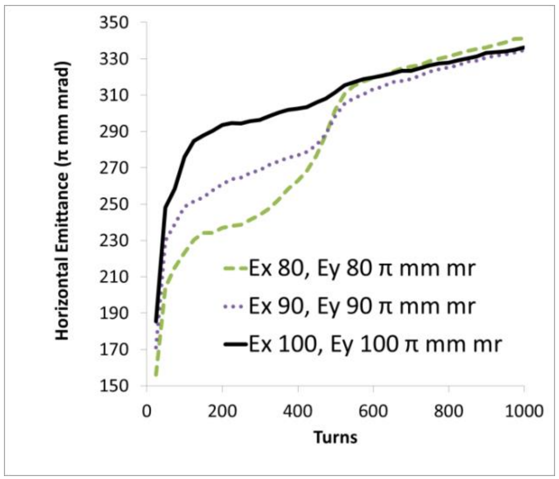
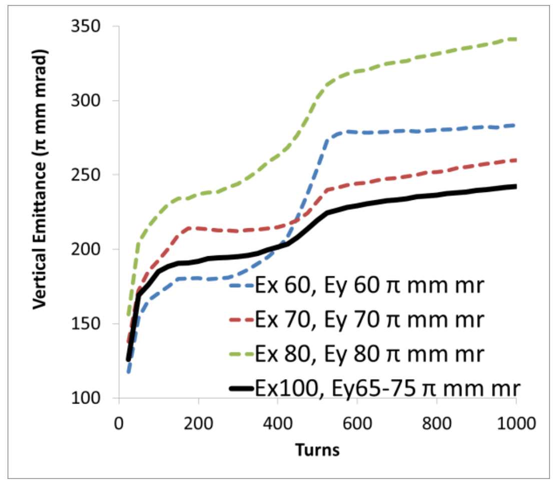
Transverse Injection Painting

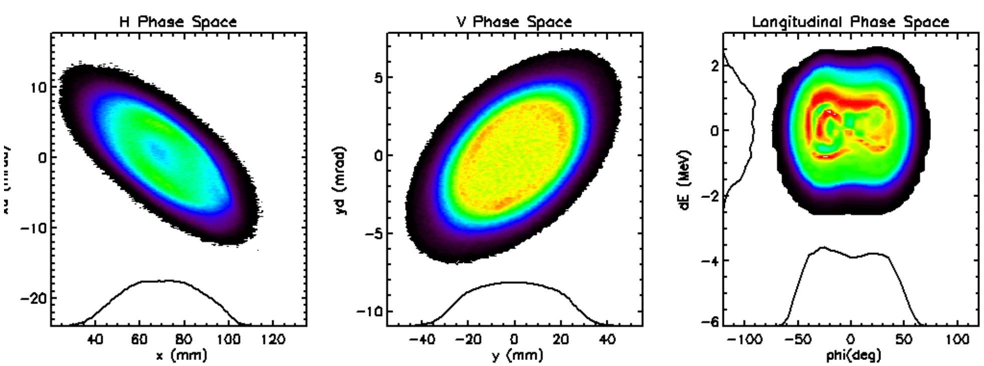
- Aim is to paint a stable beam within 300 π mm mr
- Highly non linear 3D process constrained by hardware
- Scan of constant painting amplitudes to minimise emittance @ turn 1000





- Painting
  εx=100, εy=65-75
- @ turn 1000
  εx=330, εy=230

Studies continue to meet 300 π mm mr specification



Phase space at injection end (turn 500)

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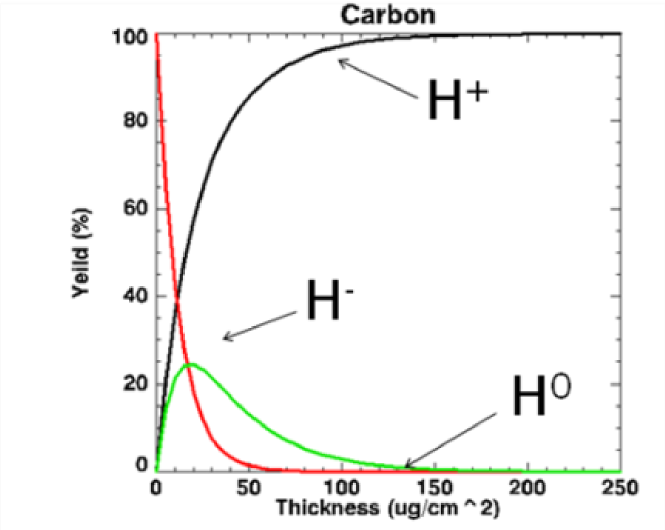
Foil Studies

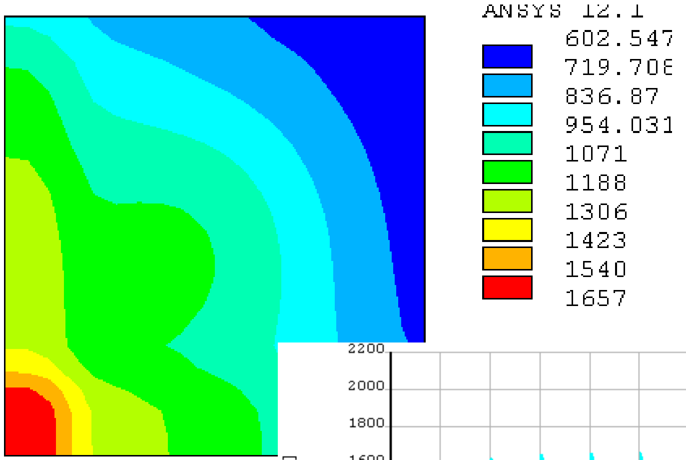


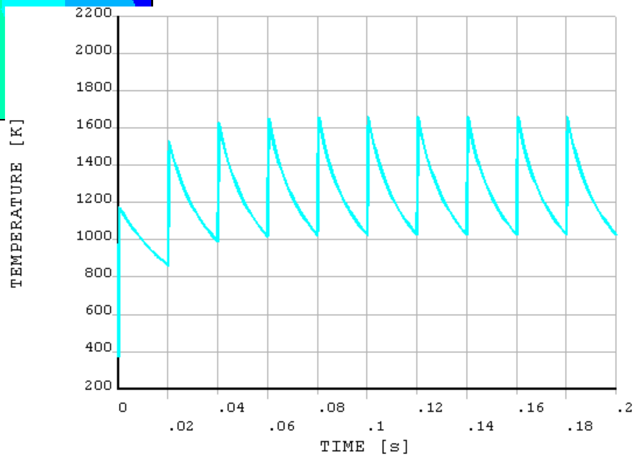
Graphite foil of 200 μg/cm2

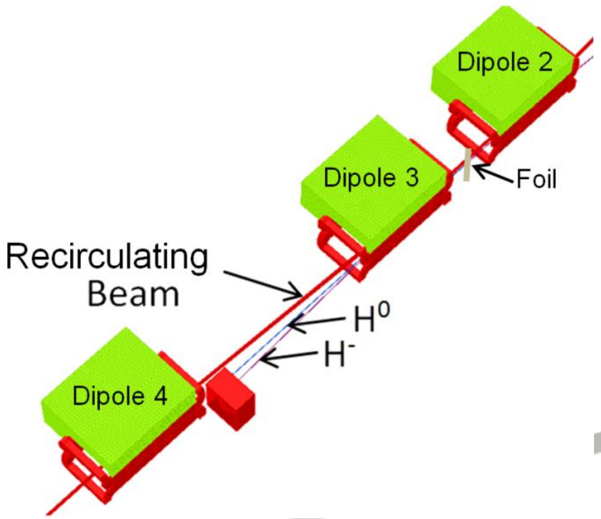
99.75% stripping efficiency

3.7 Foil Re-Circulations

Peak Temperature 1657 K @ 50 Hz (ANSYS)



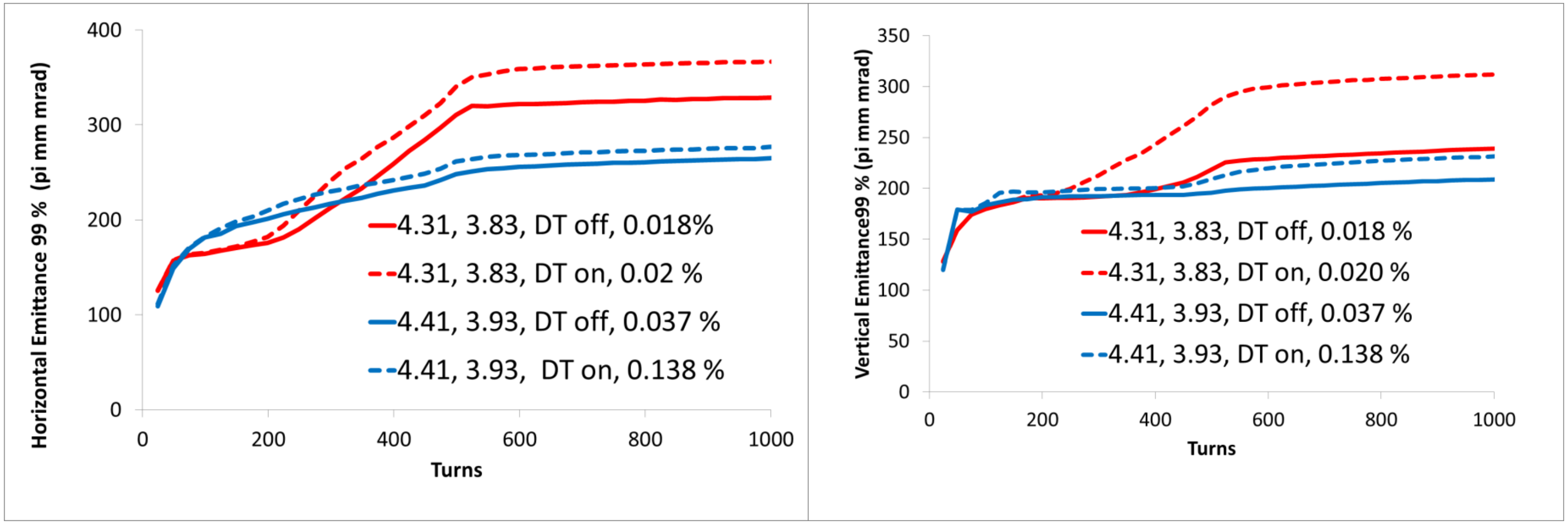




OPERA model of Particle trajectories

Working Point/Quad driving Terms

Half integer resonance driven losses important in design.
Qx=4.31, Qy=3.83, ΔQinc ~ 0.5 at end of injection.
Used ORBIT to assess impact of changing Q and use of Quadrupole driving terms.



Beam Losses induced by miss-match between beam envelope and conformal ISIS vacuum vessels

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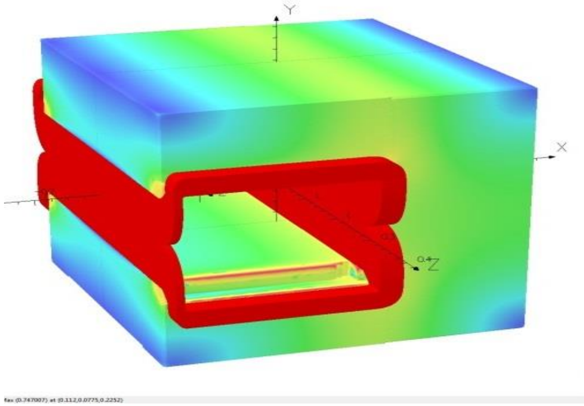
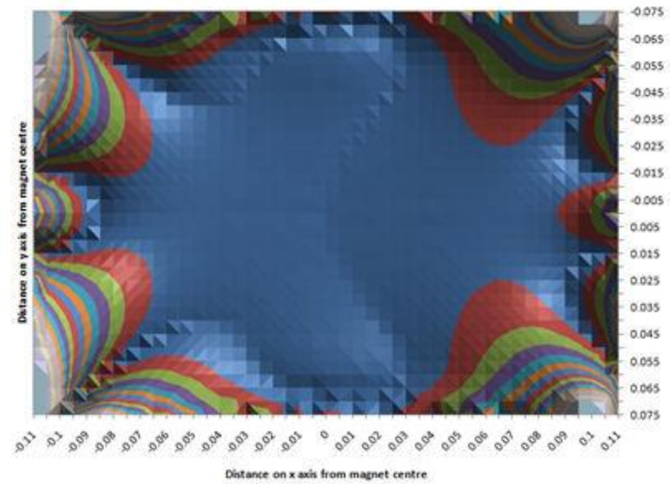
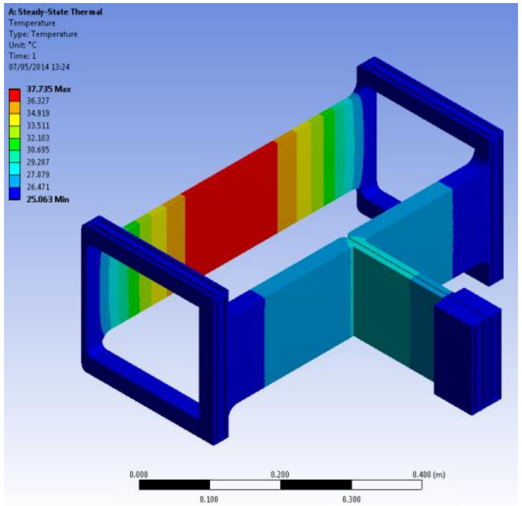
Injection Straight Magnets

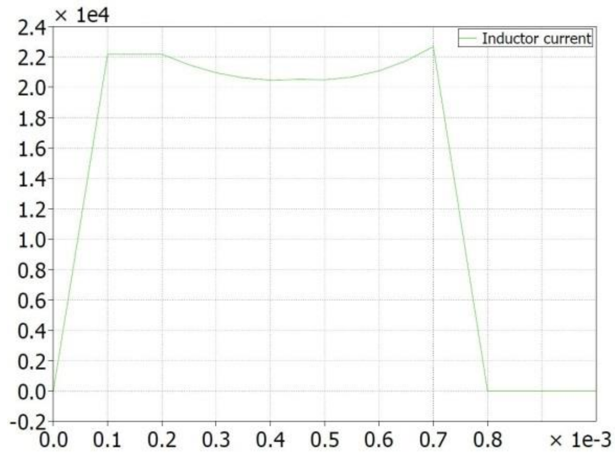


Injection dipole, peak field 0.165 T @ 26000 A (55 mr)

Blue zone 0.125% uniformity







Time mS	Current kA
0	0
100	22.152
200	22.152
250	21.450
300	20.928
350	20.591
400	20.446
450	20.496
500	20.466
550	20.649
600	21.060
650	21.718
700	22.653
800	0

Power supply and cooling calculations look reasonable

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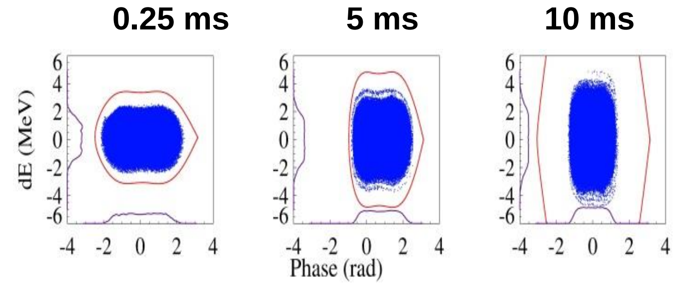
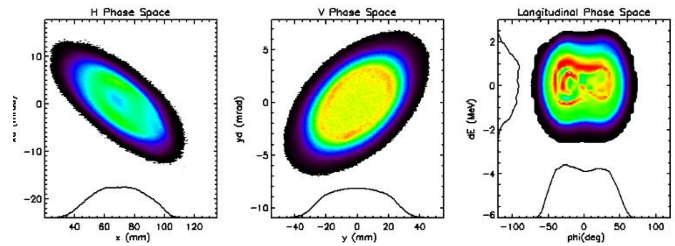
Design Results

1D and 3D studies produce reasonable results with <0.1% loss, (ORBIT 3D Space charge routine, apertures, Foil scattering, 5M particles.



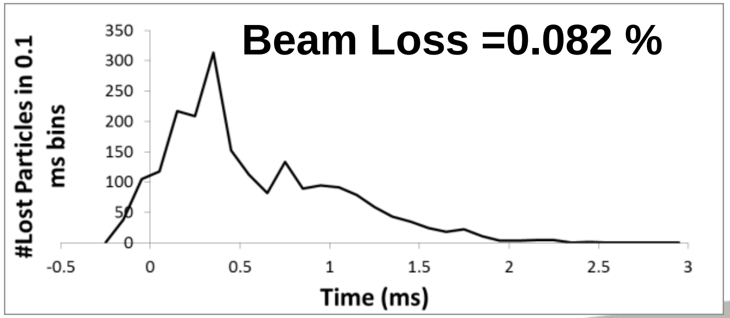
Emittance > 300 π mm mr : Bunch factor good , painting and working point studies continue.



Phase space at injection end (turn 500)

Foil re-circulations ~ 3.7 (peak temp 1657 K)

Beam losses required h=4 RF volts 115KV (Current capability 96KV)



Injection dipole magnets and power supplies look good.

At this stage the result suggests a plausible and workable design. Future studies to refine the design would be inclusion of non linear optics, impedances and magnet errors.

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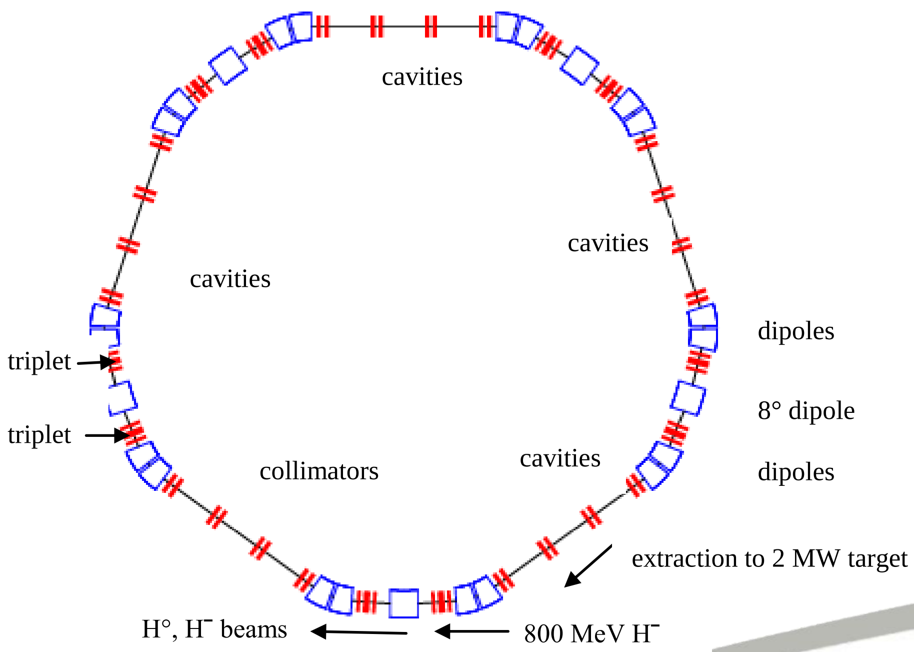
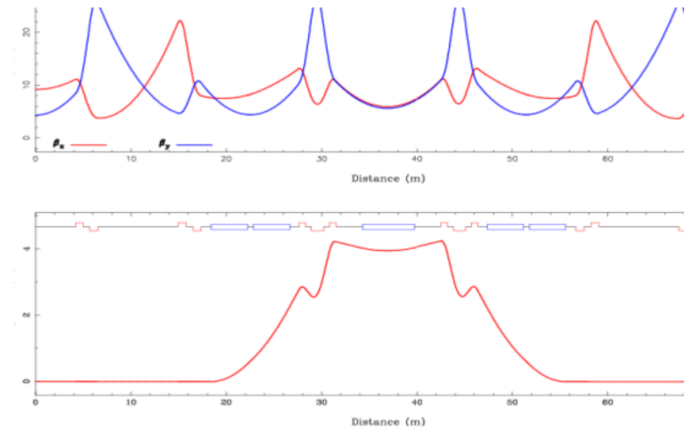
Multi MW Facility Studies

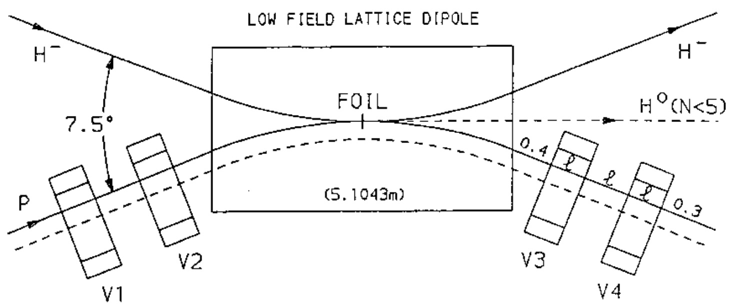
- Want to determine best 1+ MW short pulse facility designs for the future
- Flexible facility:
  - Upgradable (1, 2 …10 MW)
  - Multi target (2, 3, 4 …)
- Baseline design uses an RCS solution
  - 0.8 - 3.2 GeV RCS 2 MW (800 MeV linac)
- Other routes also to be explored
  - FFAG (ASTeC/IB RAL)

2-10 MW RCS Ring Study

0.8 – 3.2 GeV RCS
5 Super Period, 370 m, RF(h=4)
Optimised for low loss multi turn H^- injection
Operation at 30 Hz, 1.3 10^{14} ppp (2MW),
Upgrade to 50 Hz, 2.0 10^{14} (5 MW)
Two stacked rings produce 10 MW.







Ring Parameters

Ring circumference (m)	370.0000	Number of protons per cycle	$1.3\ 10^{14}$
Gamma transition value	7.2044	Beam power at 3.2 GeV (MW)	2.0
Betatron tunes ($Q_{h,}$ Q_v)	7.21, 7.73	Space for rf cavities (m)	56.4
Long straight lengths (m)	15 x 8.40	Freq. for h = n = 4 (MHz)	2.7283-3.1566
F quad lengths (m)	0.77974, 0.8637, 0.693	Bunch area for h = 4 (eV sec)	1.8
D quad lengths (m)	0.8657, 0.8580, 1.2834	kVolts & $\Delta p/p$ @ 0.8 GeV	$69\ \&\ \pm 4.3\ 10^{-3}$
Transv. acceptance (mm mr)	400 (π)	kVolts & $\Delta p/p$ @ 1.96 GeV	$422\ \&\ \pm 4.5\ 10^{-3}$
Transv. un-nor. max ε (mm mr)	135 (π)	kVolts & $\Delta p/p$ @ 3.2 GeV	$218\ \&\ \pm 4.6\ 10^{-3}$
Quadrupole gradients ($T\ m^{-1}$)	2.166-5.965	Quad inscribed radius (mm)	90.0
No of 8.0° rectangular dipoles	5	Number of 16°, sector dipoles	20
Length of 8.0° dipoles (m)	5.4446	Length of main dipoles (m)	3.8
Radius of 8.0° dipoles (m)	38.9941	Bend radius of main dipoles (m)	13.6077
Fields for 8.0° dipoles (T)	0.1252-0.3448	Fields of main dipoles (T)	0.3587-0.9880
Dipole v, h good field (mm)	130.0, 165.0	Dipole v, h good field (mm)	132.0, 145.0

Initial results for 30 Hz , $1.3\mathrm{x}10^{14}$ ppp beam presented

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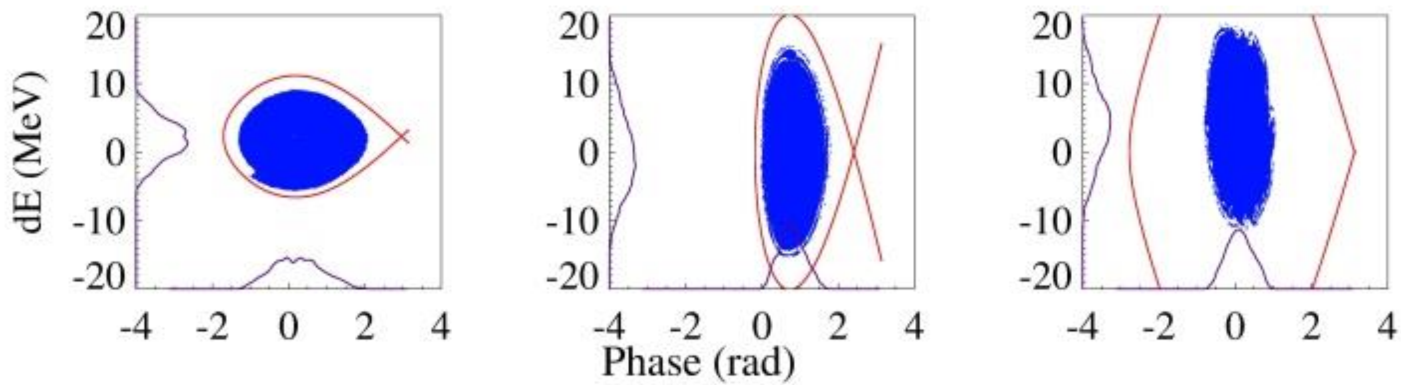
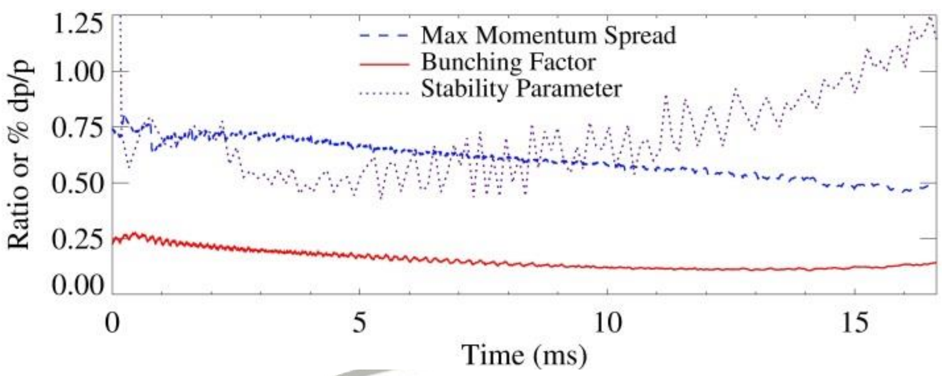
1D Injection/Acceleration Studies

- Studies tracking Hoffman-Pederson distribution determine max emittance
- For intensity 1.3×10^{14}, h=4, 30 Hz option 1d in-house code studies define:
  - Painting 0-2.1 MeV (E_{inj} ± 2.5 MeV, RF bucket offset 0 - 7 MeV)
  - Chopping duty factor 48 % ,
  - RF :100 KV through injection, 450 KV mid cycle.
- Assumes Linac: 800 MeV, 57 mA , 800 µs pulse length (~550 turns)



Phase spaces @ Injection End, Mid cycle, extraction



KSB stability < 1 for most of cycle

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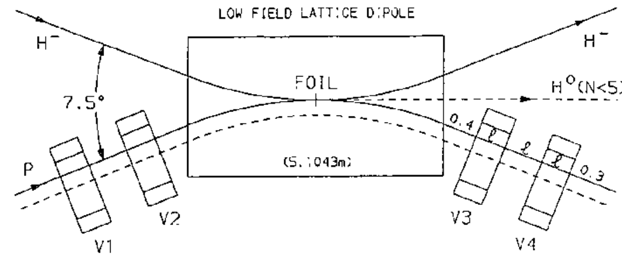
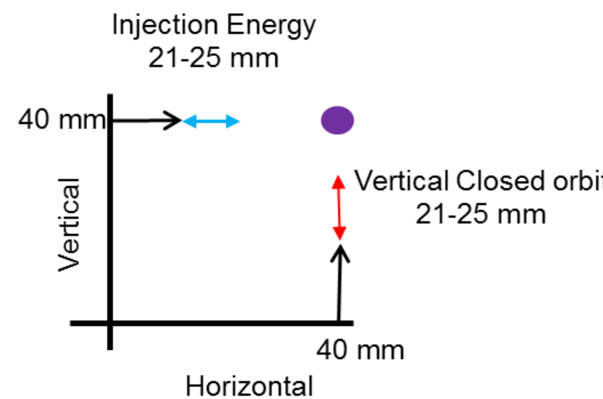
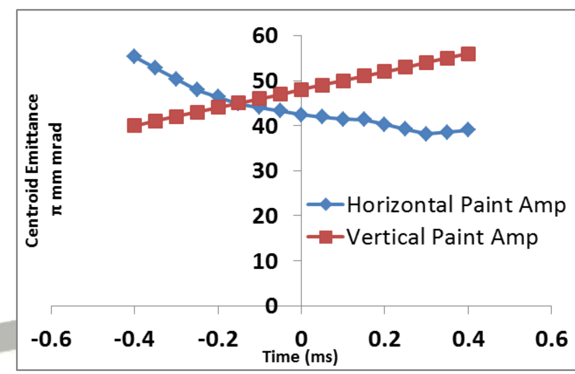
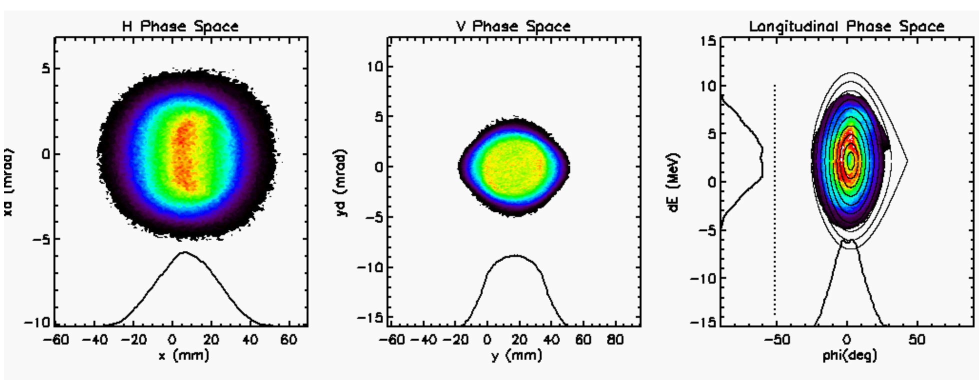
3D Injection Studies

- Injection timed symmetrically about field minimum
- Injection position x=40 y=40 mm (constant)
- Horizontal paint: Dispersive, $E_{inj} \pm$ 2.5 MeV gives centroid paint amplitudes 55-40 mm mr
- Vertical paint: 4 local steering magnets $V_{1\text{-}4}$, deflecting 44-49 mrad gives paint amplitudes 40-56 π mm mr
- ORBIT studies show well controlled accumulated beam with 99 % emittances 147(h),150(v) π mm mr. Design spec 135 π mm mr.
- Many more studies planned…..









Phase space at end of injection

Summary

- Have established workable beam dynamics designs for a 180 MeV injection upgrade to the existing RCS that would allow ~0.5 MW beams (present R&D will refine these!)
- Started studies for MW machines, designs of a 3.2 GeV RCS that could form the core of a flexible, upgradable MW facility look promising …
- Benefit from practical experience of running ISIS, experimental bench marking and R&D