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Codes Development and Simulations Studies for High Power Machines

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ASTeC/STFC/RAL

high power proton accelerators WG: simulation

Thanks to Chris Prior, Dean Adams, Ben Pine, Ciprian Plostinar, Chris Warsop

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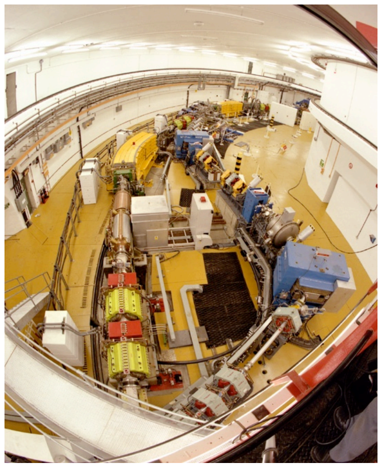
Understand beam power limit

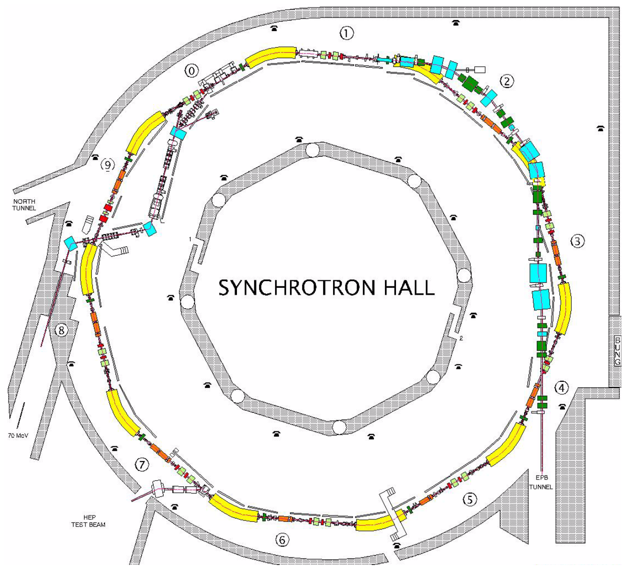
- Mechanism of particle loss?
- Any improvements to push up beam power limit?
- Charge distribution as we expected?

  Dual harmonic rf helps (longitudinal) ?

  Painting works (transverse) ?



ISIS at RAL



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- Code development at RAL
- Code benchmarking and beam study
- Future plans

Code development at RAL

- TrackXD (X=1,2,3): Chris Prior
- Set: Ben Pine, Rob Williamson, Hayley Smith
- Simpsons: Shinji Machida

Code	Space Charge Solver	Boundaries/Images	Impedances	Field Maps	Integration order
IMPACT	spectral	open/periodic/ rectangular/circular	no	yes	2nd order in z
ML-IMPACT	spectral	elliptical/ polygon/lossy	yes	no	2nd in z 5th Runge-Kutta
PARMILA					
GPT	3D multigrid	open conductive rect. pipe, cathode	no	2D,3D	5th Runge-Kutta
BEST	spectral, FD	circular conducting wall	automatic/ external	no	user specified
VADOR	FFT	conductive wall any shape	no	no	2nd
SPUNCH	exact for disc-shaped particles	circular conducting wall	n/	n/a	1st
PATH	Schell, pt-to-pt	open	no	yes	?
TRACEWIN	Scheff/PICNIC/Gaussup	open	no	no	?
DYNAC	Scheff/Scherm/Hersc	open	no	yes	3rd analytical
Synergia	spectral (IMPACT)	open/periodic/ rectangular/circular	no	yes	2nd order in z
WARP	FFT, Cap matrix, multigrid, adaptive mesh, refined MG	square/round pipe, internal conductors, bent pipe, general	*ad hoc*	no	2nd order

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Set (1)

- 1D longitudinal tracker developed by Rob Williamson

  PIC space charge solver using FFT or Difference Algorithm.

  Injection painting including RF steering and variable injection energy.

  Dual harmonic acceleration and manipulation.

  Numerical checks for stability.

  Benchmarked against theory and ORBIT and also against published JPARC results.

Set (2)

- 2D transverse tracker developed by Ben Pine
  - FFT based Poisson solver with rectangular boundaries, can follow ISIS profiled vacuum vessel.
  - Matrix magnet elements / MAD input.
  - FEA Poisson solver in development.
- Foil scattering code developed by Hayley Smith
  - Multiple coulomb scattering.
  - Nuclear inelastic collisions.
  - Lifetime of partially stripped states.
  - Aluminium and carbon foils.
  - Module for foil temperature.

Set (3)

- Features
  - Set is a C++ particle tracker.
  - Developed by small team using common structures.
  - Combined code is 2.5D running in parallel using MPI on the SCARF cluster at RAL.
  - Multi-turn injection is being developed, including painting in both planes.
  - In-house code both increases flexibility of simulations and fosters practical computing skills.

Simpsons (1)

- 2.5-D space charge model

  Transverse space charge force is calculated individually in each longitudinal disk (slice).

- Poisson solver in cylindrical coordinate system

  Mode expansion in azimuthal direction

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\phi\right)+\frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}\phi=-\frac{\rho}{\varepsilon_0}$$

$$\phi=\sum_{m=-\infty}^{m=\infty}\phi_m\exp(im\varphi)$$

$$-\frac{\rho}{\varepsilon_0}(\equiv n)=\sum_{m=-\infty}^{m=\infty}n_m\exp(im\varphi)$$

$$E_r=\frac{\partial\phi}{\partial r}=\sum_{m=-\infty}^{m=\infty}\frac{\partial}{\partial r}\phi_m\exp(im\varphi)=\sum_{m=0}\frac{\partial}{\partial r}(\phi_{m,c}+i\cdot\phi_{m,s})(\cos(m\varphi)+i\cdot\sin(m\varphi))$$

$$=\sum_{m=0}\left(\frac{\partial}{\partial r}\phi_{m,c}\cos(m\varphi)-\frac{\partial}{\partial r}\phi_{m,s}\sin(m\varphi)\right)$$

Simpsons (2)

- Features

  "time" as an independent variable.

  Acceleration with parameters (B(t), rf(t), bump(t), errors(t)) given by table.

  Multi-turn injection.

  Circular beam pipe with no resistivity.

  rms matching routine before start multi-particle tracking.

  Separation of macro particle and test particle.

Status

- Set

  Still under development, but interesting results start coming out.

  Production runs are expected in a year time.

- Simpsons

  Improvements in field solver.

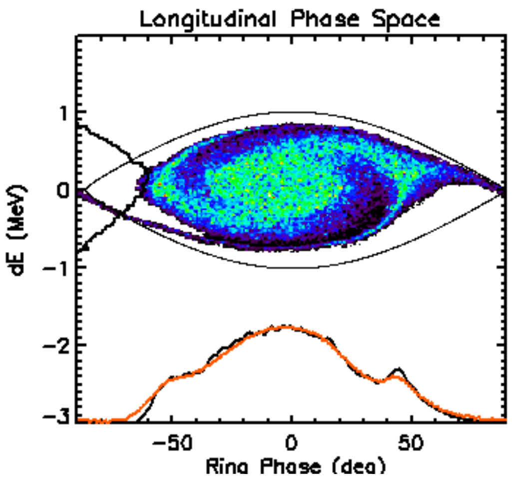
  Toward simulation of a high power FFAG.

Code benchmarking and beam study

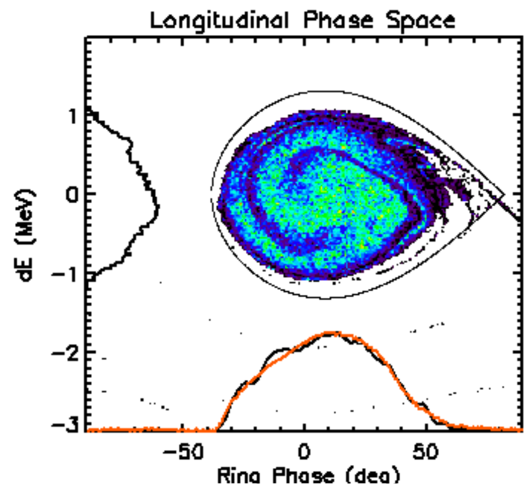
- Longitudinal bunch shape (Orbit, Set)
- Transverse charge distribution (Track2D, Orbit)
- Threshold current (Orbit, Set)
- Beam loss (Orbit, Simpsons)
- Beam loss in linac (TraceWin, Impact)

Longitudinal bunch shape

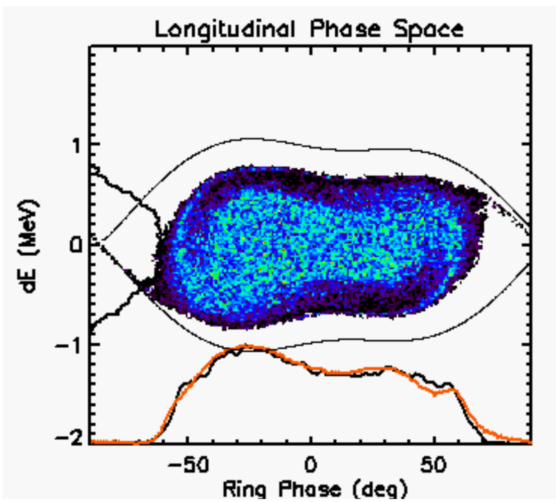
- Comparison between ISIS experiment (R) and Orbit simulation (B).
- W/ and w/o dual harmonic rf.
- Tomographic reconstruction with BPM sum signals.
- Good agreement.



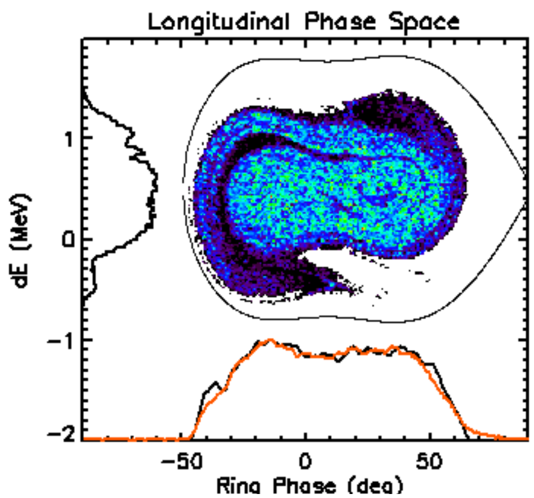
Single harmonic only, 0 ms



Single harmonic only , 0.5 ms



Dual harmonic , 0 ms



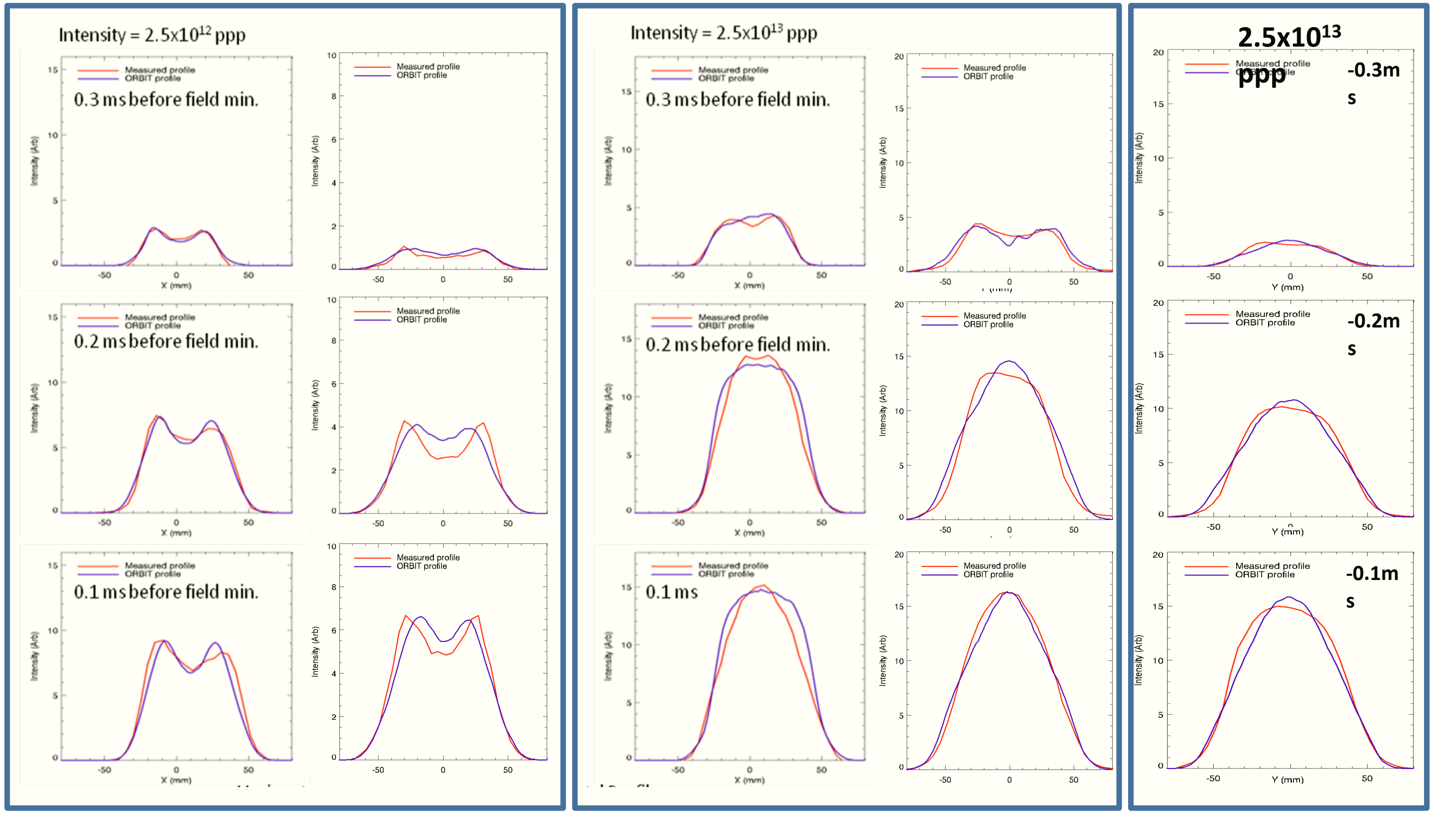
Dual harmonic , 0.5 ms

D. Adams

Transverse charge distribution (1)

- During and after multi-turn injection with space charge.

Low intensity anti-correlated	High intensity anti-correlated	High intensity correlated

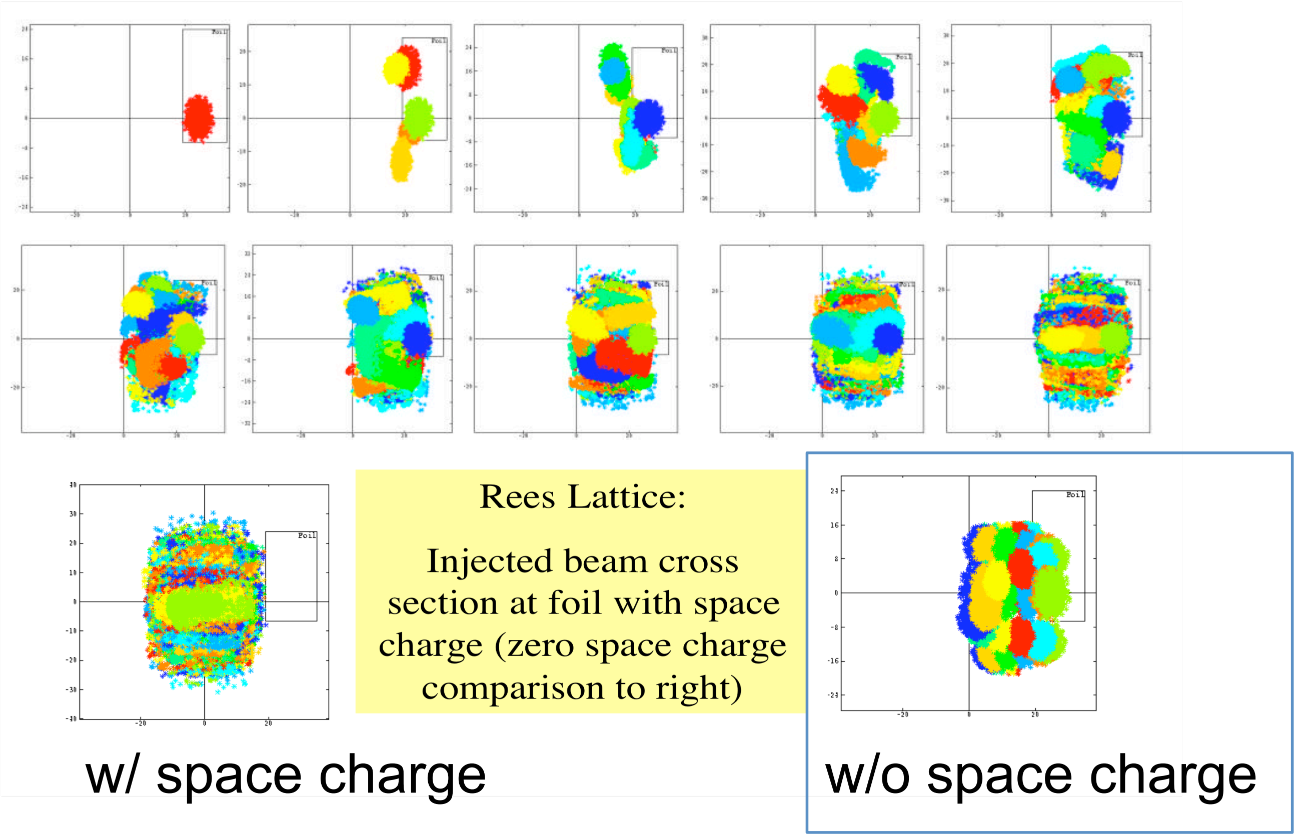


H, V   H, V   V

D. Adams, B. Jones

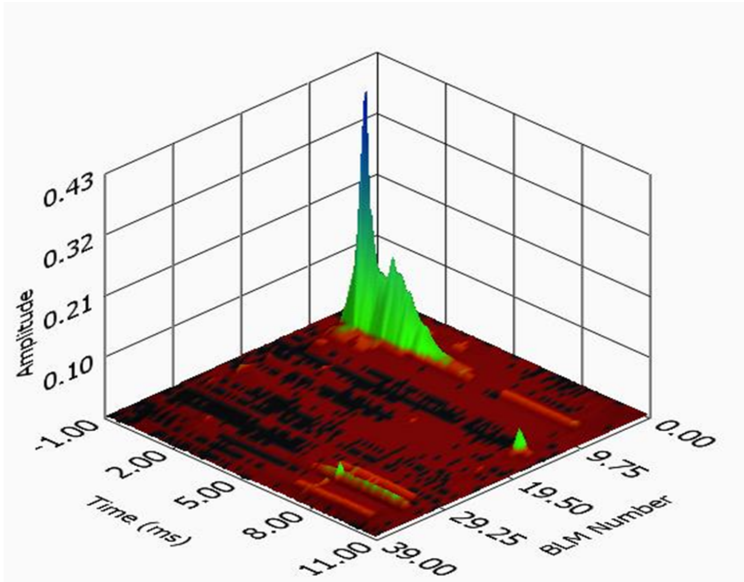
Transverse charge distribution (2)

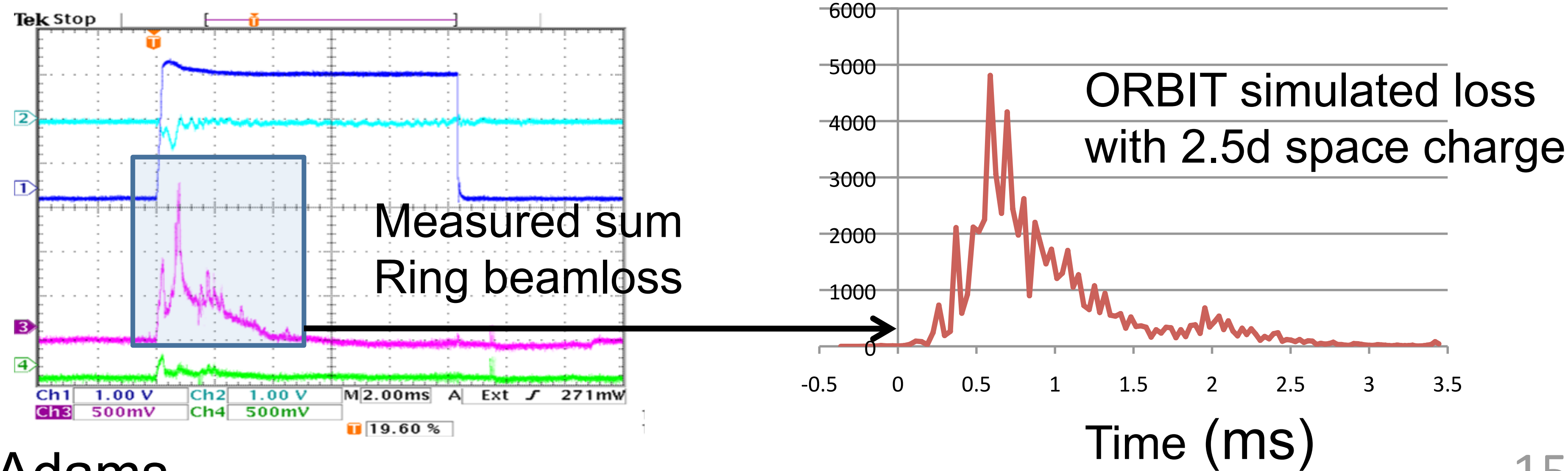
- Evolution in phase space during multi-turn injection.
- From design report of Proton drive II at Fermilab.



Beam loss (1)

- Pattern in time comparing ISIS experiment and Orbit simulation.



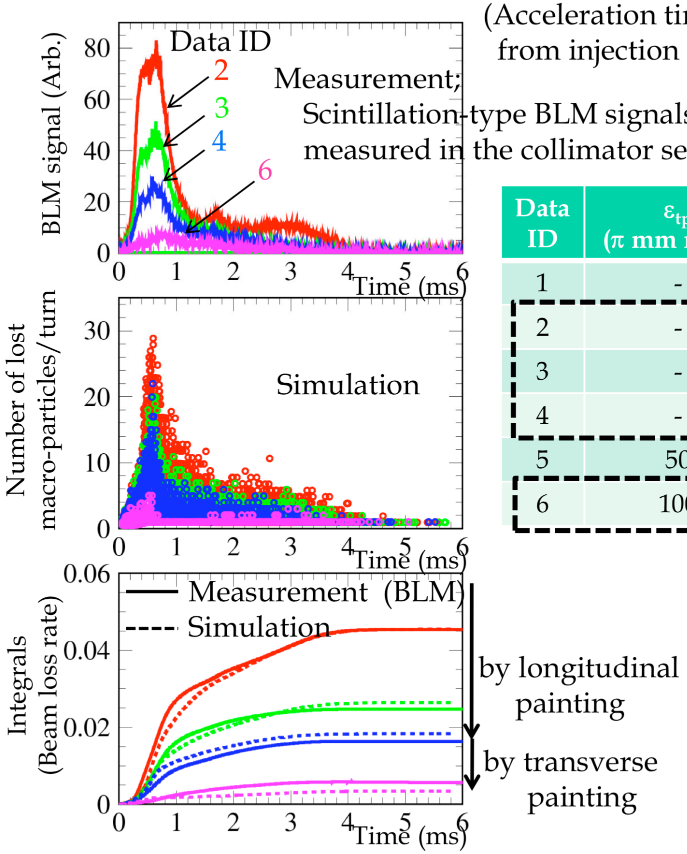


D. Adams

Beam loss (2)

- Overall loss with different injection conditions in J-Parc experiment and Simpsons simulation.

Time structure of the beam loss



(Acceleration time from injection to extraction; 20 ms)

Measurement; Scintillation-type BLM signals for the first 6 ms measured in the collimator section for data ID 2–6.

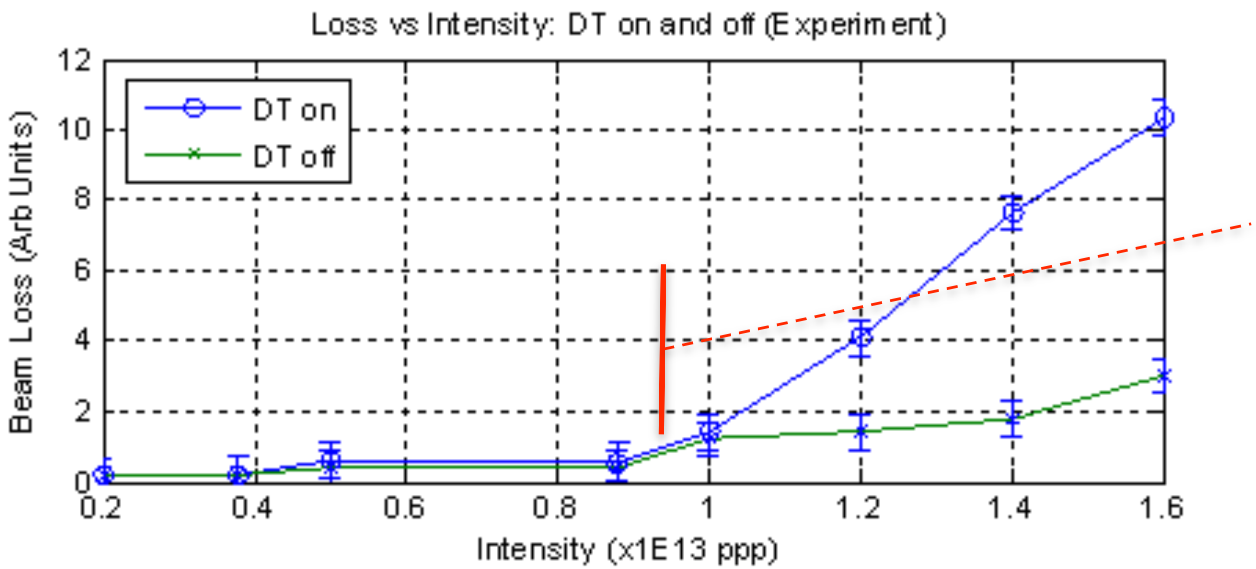
Data ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-			
2	-	80	-100	-0.0
3	-	80	-100	-0.1
4	-	80	-100	-0.2
5	50	80	-100	-0.2
6	100	80	-100	-0.2

It was confirmed in this experiment the present painting injection
- mitigates the space charge effect through charge density control,
- leads to significant beam loss reduction.

H. Hotchi at IPAC11

Threshold current

- Experimental study of half integer loss with space charge.
- ISIS ring in storage ring mode and compare with Orbit simulation.



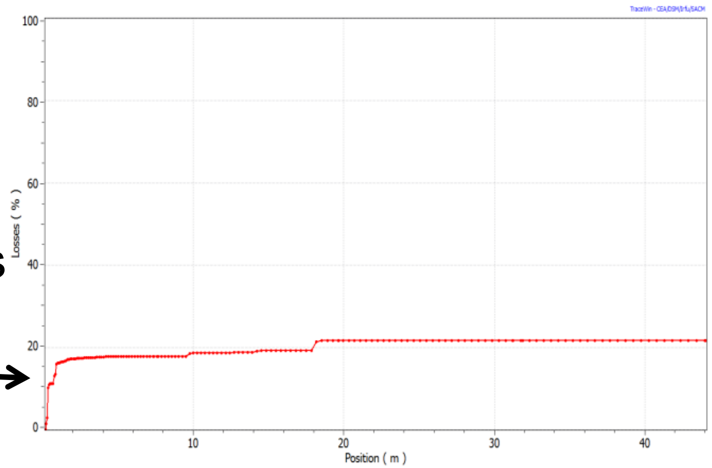
Measurement: loss appears as predicted by coherent theory (appears with expected driving term)

C. Warsop

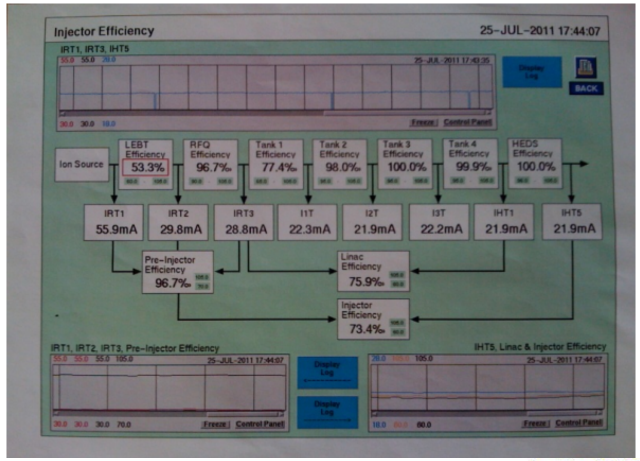
Beam loss in linac

- Beam loss due to initial mismatch.

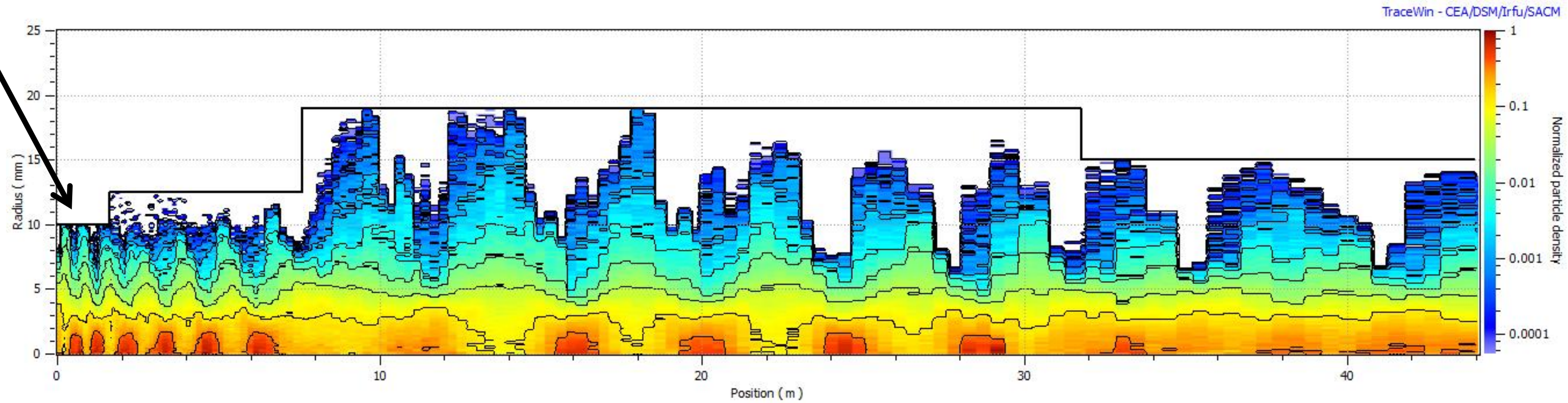
Model



Control Room



Major beam loss in Tank 1 due to mismatch.



Status

- Very good agreement in longitudinal bunch shape with space charge w/ and w/o dual harmonic rf.
- Good agreement in transverse profile. Space charge fills phase space at the centre of a hollow beam.
- Fair agreement of beam loss. The more we know about the lattice, the more quantitative agreement (J-Parc RCS).
- Linac beam loss is dominated by initial beam shape /distribution.

Future plans

- Benchmarking
  - Code vs code
  - Code vs experiment

- Investigate physics behind
  - Single particle behavior
  - eg. identify resonance phenomena

Comment on “code vs experiment”

- Beam experiments in a new accelerator (J-Parc RCS for example) seems to give much cleaner and quantitative comparison because it has all precise information on individual lattice component.

- Although there were some benchmarking efforts before in CERN, GSI, ISIS, Fermilab, etc., simulation could be much more reliable after comparing with J-Parc and/or SNS experiments.

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- Thank you for your attention.