Benchmarking and application of space charge codes in (proton) rings

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IPAC'15

Before start

- This is an overview talk on benchmarking of codes on space charge in proton (hadron) rings.
- I do not talk about individual codes.
- I will focus on benchmarking against measurement.
- I apologise that I just pick up a few cases although many other efforts exist.

Acknowledgement first

This talk was made possible as a result of many people's help.
In particular,

S. Cousineau, R. Potts, J. Holmes (ORNL)

H. Hotchi, H. Harada, K. Okabe (JAEA)

E. Benedetto, V. Forte, S. Gilardoni, R. Wasef, A. Huschauer, H. Bartosik, A. Oeftiger, F. Schmidt (CERN)

G. Franchetti, I. Hofmann (GSI)

C. Warsop, C. Prior (STFC)

and many other colleagues working together on space charge modelling, experiment and benchmarking.

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Motivation

Contents

What is benchmarking?

"Code benchmarking" means comparing code results with

Measurement	Theory	Other codes
See if codes can replicate observations.	In some simplified cases, comparison (often qualitative) should be possible.	New ways of modelling and algorithms can be checked with existing codes.

What is benchmarking?

"Code benchmarking" means comparing code results with

Measurement

See if codes can replicate observations.

This has to be done ultimately.

Theory

In some simplified cases, comparison (often qualitative) should be possible.

Other codes

New ways of modelling and algorithms can be checked with existing codes.

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Why is benchmarking important in space charge codes? (1)

Space charge codes have two parts.

Macro particle tracking with external guiding fields in small time steps.

Calculate space charge potential and macro particle coordinates are updated accordingly.

(Diagnostics)

This has to be repeated more than 100 times per turn because

- Space charge force acts continuously
- Potential is modulated by beam envelope and it is important to include its harmonic components.

Why is benchmarking important in space charge codes? (2)

Space charge codes have two parts.

Macro particle tracking with external guiding fields in a small time step.

Calculate space charge potential and macro particle coordinates are updated accordingly.

(Diagnostics)

Particle tracking with external guiding field is no problem. It can be done with a symplectic integrator.

This has to be done more than 100 times per turn because

- Space charge force acts continuously
- Potential is modulated by beam envelope and it is important to include its harmonics.

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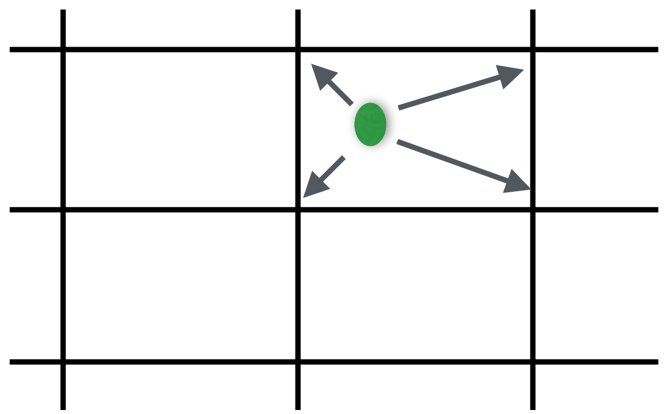
Calculate space charge potential

Particle in Cell and frozen model

Particle in Cell (PIC)

Assign fractional charge of macro particles to the neighbouring spacial grids and solve Poisson eq. to obtain electric field.



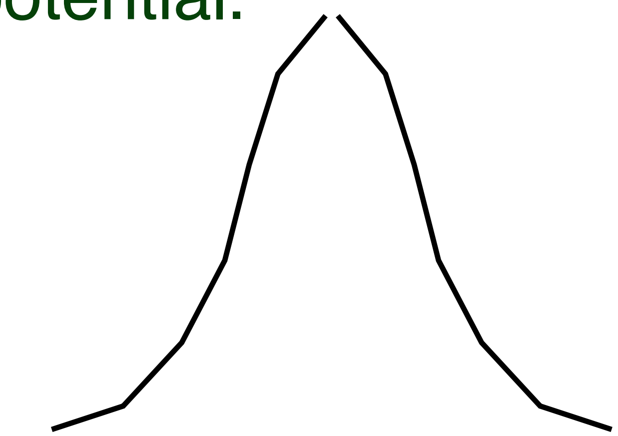
$$\frac{\phi_{j-1,k} - 2\phi_{j,k} + \phi_{j+1,k}}{\Delta x^2} + \frac{\phi_{j,k-1} - 2\phi_{j,k} + \phi_{j,k+1}}{\Delta y^2} = -\rho_{j,k}$$

Pro: Evolution of charge distribution can be maintained in a self-consistent way.

Con: Discontinuity of the electric field around the grid point breaks symplectic condition.

Frozen model

Fix charge distribution at the beginning and update macro particle coordinates by this fixed potential.



$$E_r = \frac{\lambda}{2\pi\epsilon_0} \frac{1 - \exp(-r^2/2\sigma_r^2)}{r}$$

Pro: Smooth space charge potential is included as an external element and symplectic condition is satisfied.

Con: Give up self-consistency and ignore evolution of charge distribution assuming the change is small.

Why is benchmarking important in space charge codes? (3)

Space charge codes have two parts.

Macro particle tracking with external guiding fields in a small time step.

Calculate space charge potential and macro particle coordinates are updated accordingly.

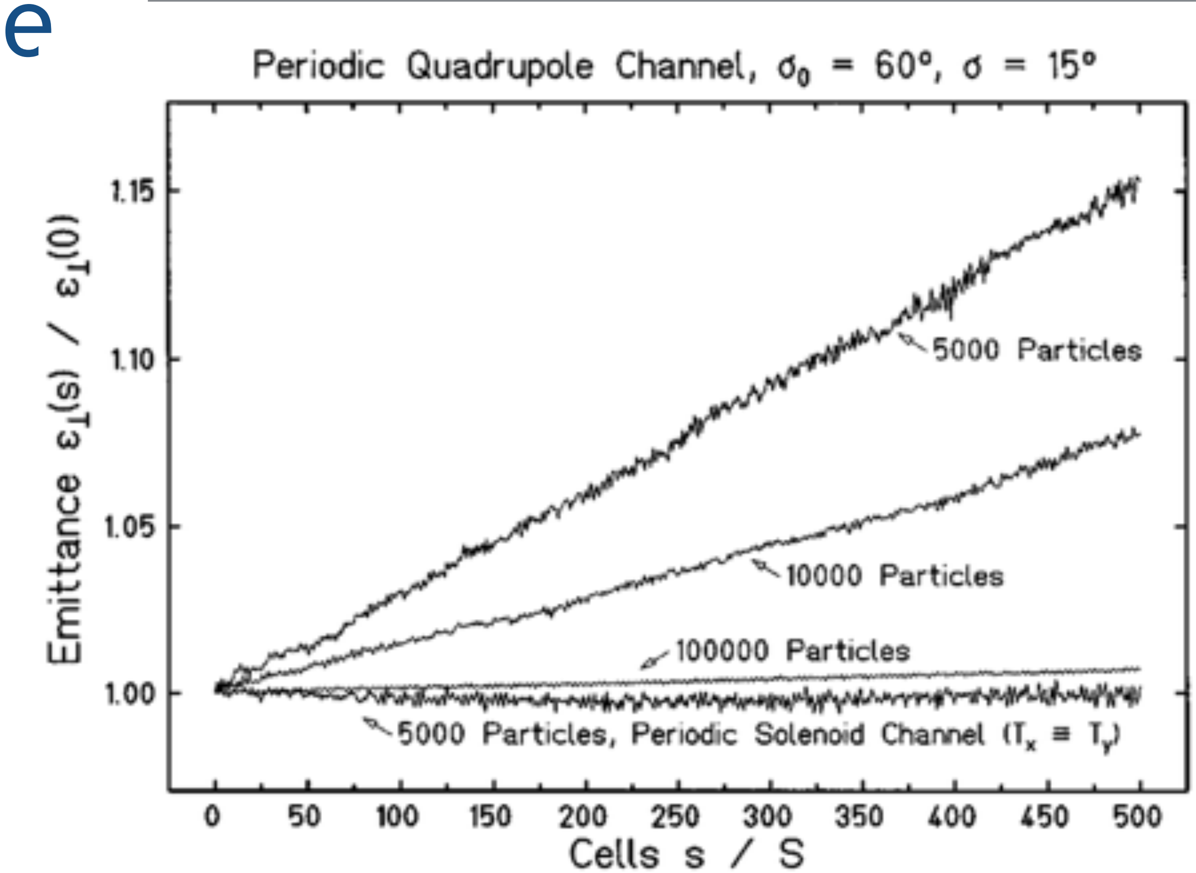
Part of calculating space charge potential could be problematic.

PIC

- Representing ~10^{12} real particles by ~10^{6} macro particles.
- Susceptible to ”noise”.
- Breaking symplectic condition.

Frozen model

- Giving up self-consistency.



Struckmeier, Phys. Rev. E 54 (1996) 830

Bottom line is

Validity and limitation of codes have to be benchmarked (against measurement).

Benefit of having a good code and accelerator model is

- We can see more details of beam dynamics which cannot be measured.
- It gives us confidence in understanding high intensity/brightness beam physics.
- It provides firm ground for a future accelerator design.
- It helps troubleshoot hardware problems and find new physics.

A bit of history

Contents

1. Motivation
2. A bit of history
3. Benchmarking now
4. Summary and future challenges

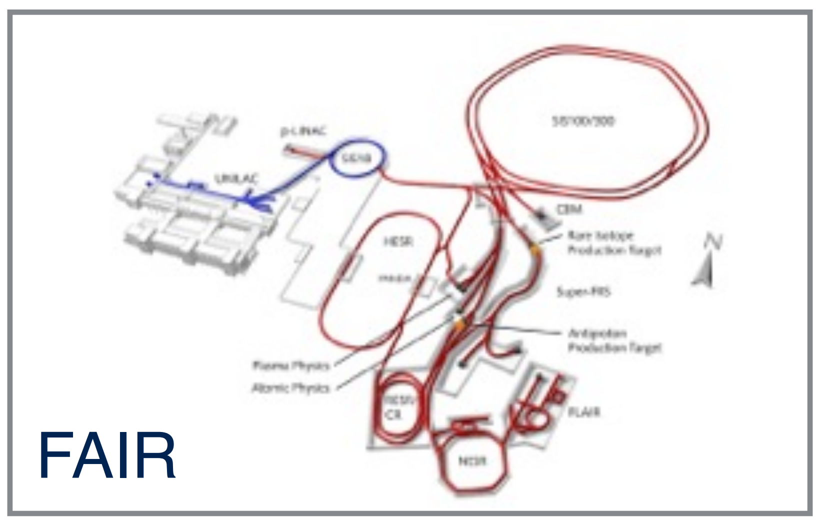
Beam loss and emittance preservation

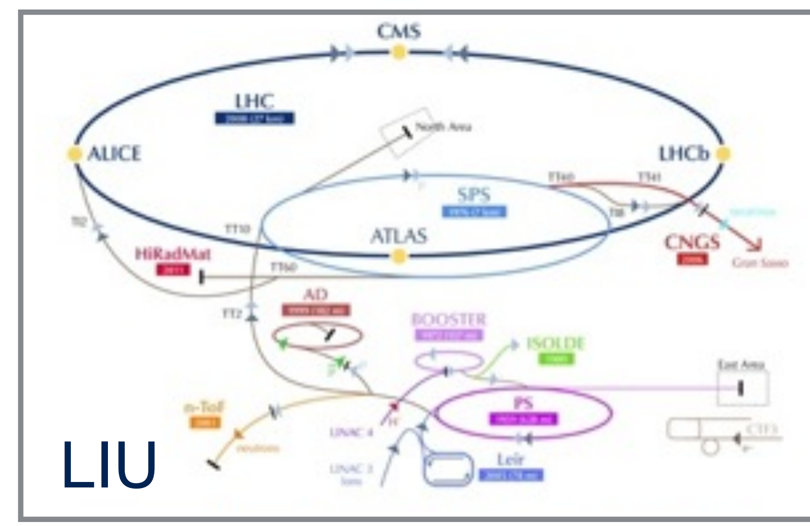
for proposed fast and slow cycling accelerators

Design and construction of SNS, J-Parc, FAIR, LIU (LHC Inj. Upgrade).

- Beam loss of a few per cent or less was/is crucial in proposed accelerators.

- Beam emittance and profile are other important parameters.





Incoherent/coherent resonance model may not tell us these subtle effects.

Understand beam loss mechanism and predict it with simulation.

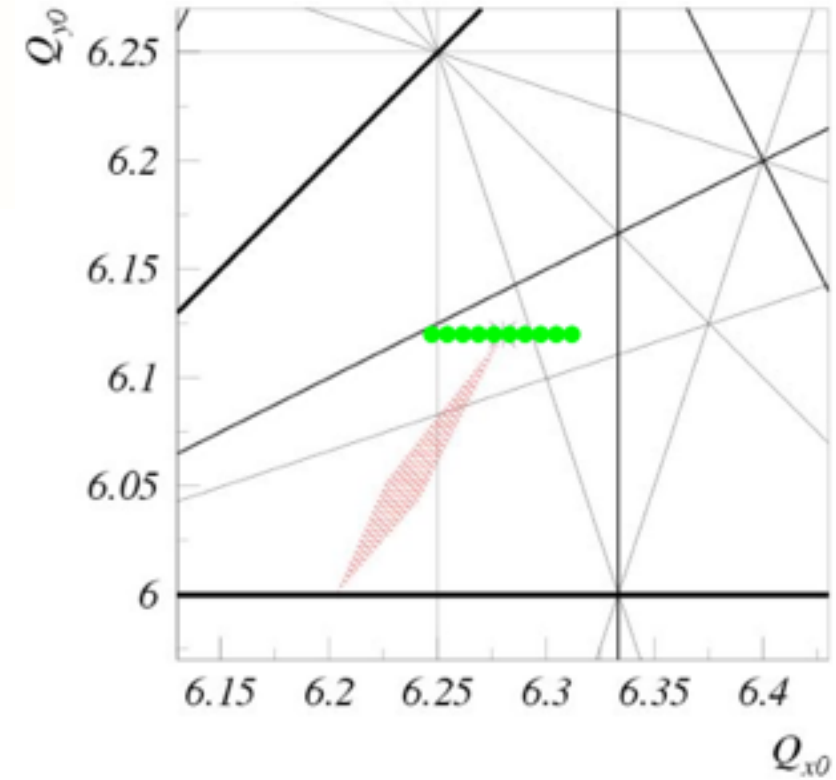
CERN PS experiment in 2002 and 2003

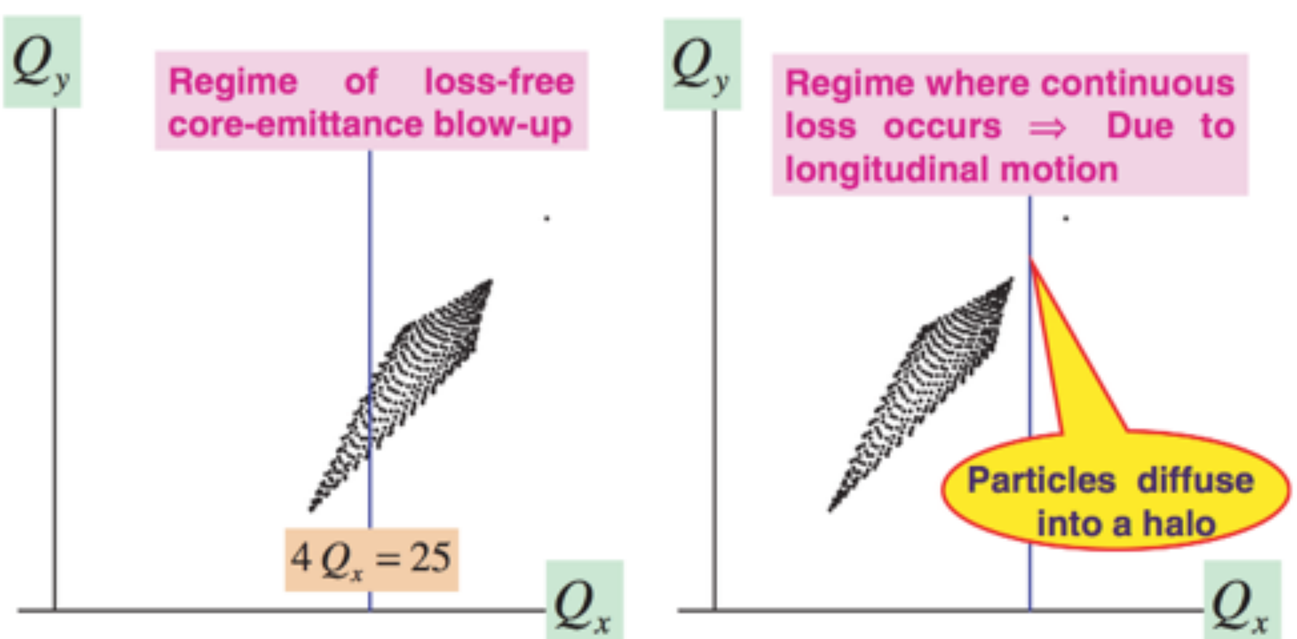
milestone in the community

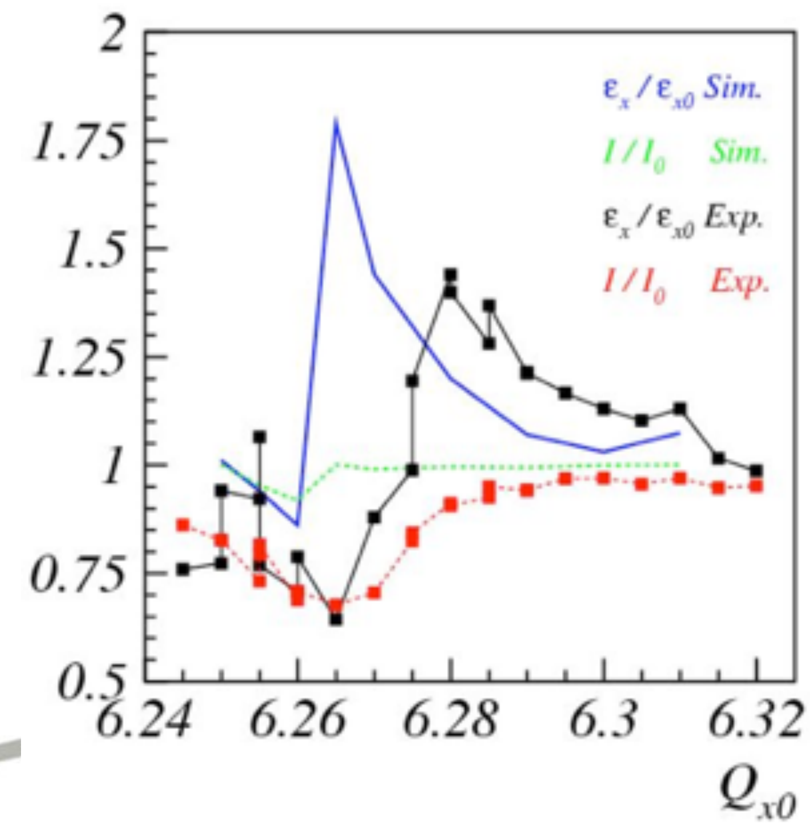
First systematic benchmarking campaign on octupole and Montague resonances.

Core growth regime and beam loss regime were identified experimentally.

Metral, Franchetti, Giovannozzi, Hofmann, Martini, Steerenberg, NIM A561 (2006) 257.



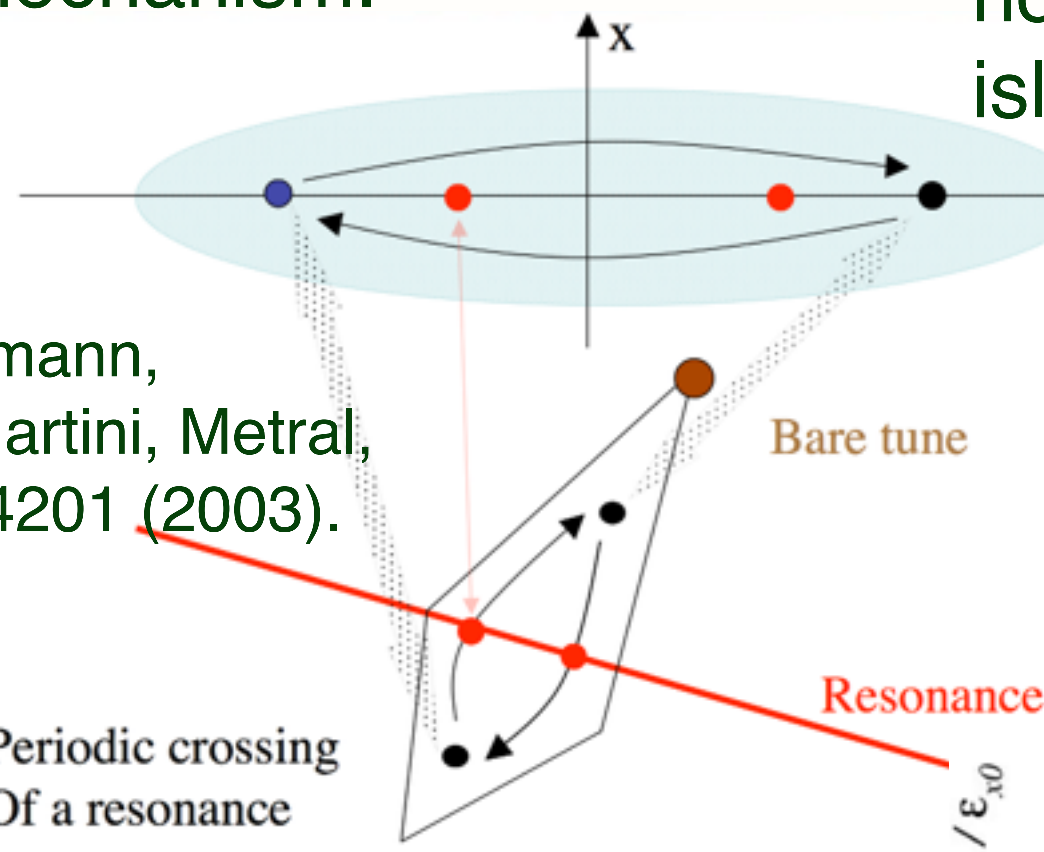




Still qualitative agreement, not quantitative, esp. for beam loss.

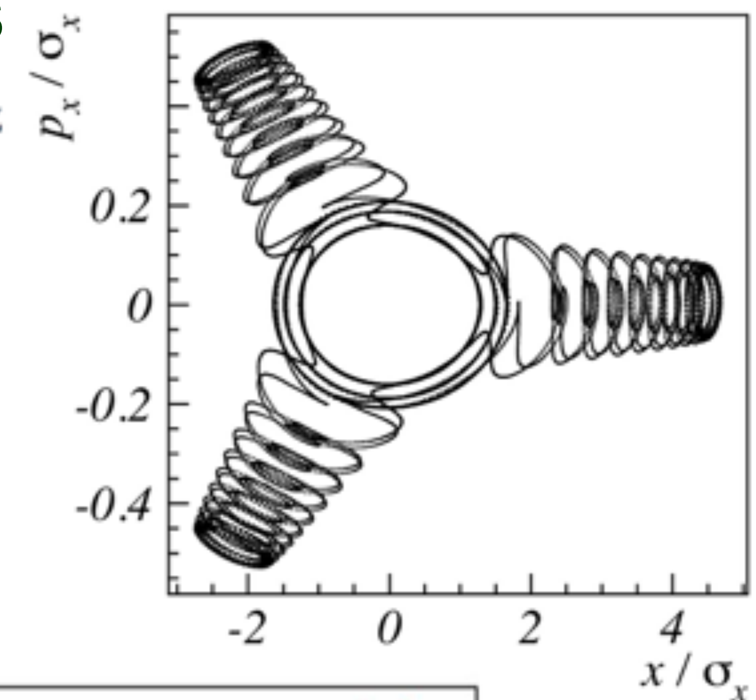
Trapping of particles
benchmarking with theory and codes

Advancement of understanding of beam loss mechanism.

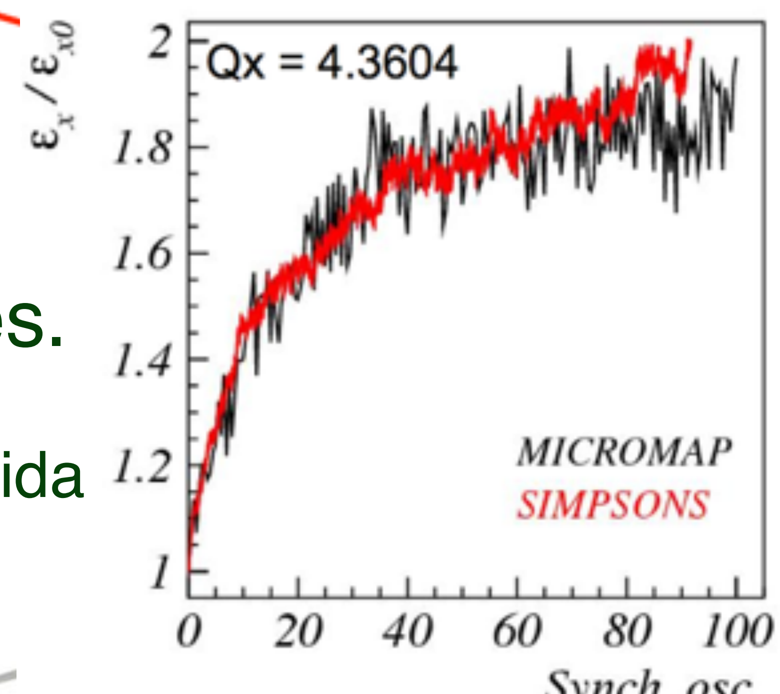


Franchetti, Hofmann, Giovannozzi, Martini, Metral, PRST-AB 6 124201 (2003).

Trapping of particles in nonlinear resonance islands



Benchmarking among codes.



Franchetti, Hofmann, Machida HB2006 (2006) 344.

Summary 10 years ago

PAC 2005 invited talk by Cousineau

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

BENCHMARK OF SPACE CHARGE SIMULATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS FOR HIGH INTENSITY, LOW ENERGY ACCELERATORS

S. Cousineau*, Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

… to routinely produce successful, quantitative space charge benchmarks for a variety of experimentally measurable quantities.

Future challenges

- Simulate beam loss in accelerator by reproducing the distribution to within fraction of a percent (10^{-3} or less).
- Simulate beams during a long storage time, of the order of hundreds of thousands of turns.

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Benchmarking now

Contents

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Benchmarking against measurements
toward quantitative comparison

Progress of code development.

- Good physics and algorithms.
- Parallelisation of codes.
- Database management.
- Friendly user interface.

Accurate accelerator model as an input to codes.

- Lattice errors and alignment.
- Precise shape of input beam.
- Clearly defined operating conditions.

Newly constructed accelerators like SNS and J-Parc have a big advantage of accurate model to codes.

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Progress in the last 10 years

summary first

To what extent do “future challenges” become reality?

- Beam loss in accelerator by reproducing the distribution to within fraction of a percent (10^{-3}).

  Done to 10^{-2}, for fast cycling accelerators by accurate modelling.

- Simulate beams during long ring storage times of the order of hundreds of thousands of turns.

  Great progress, by computational power and reasonable approximation.

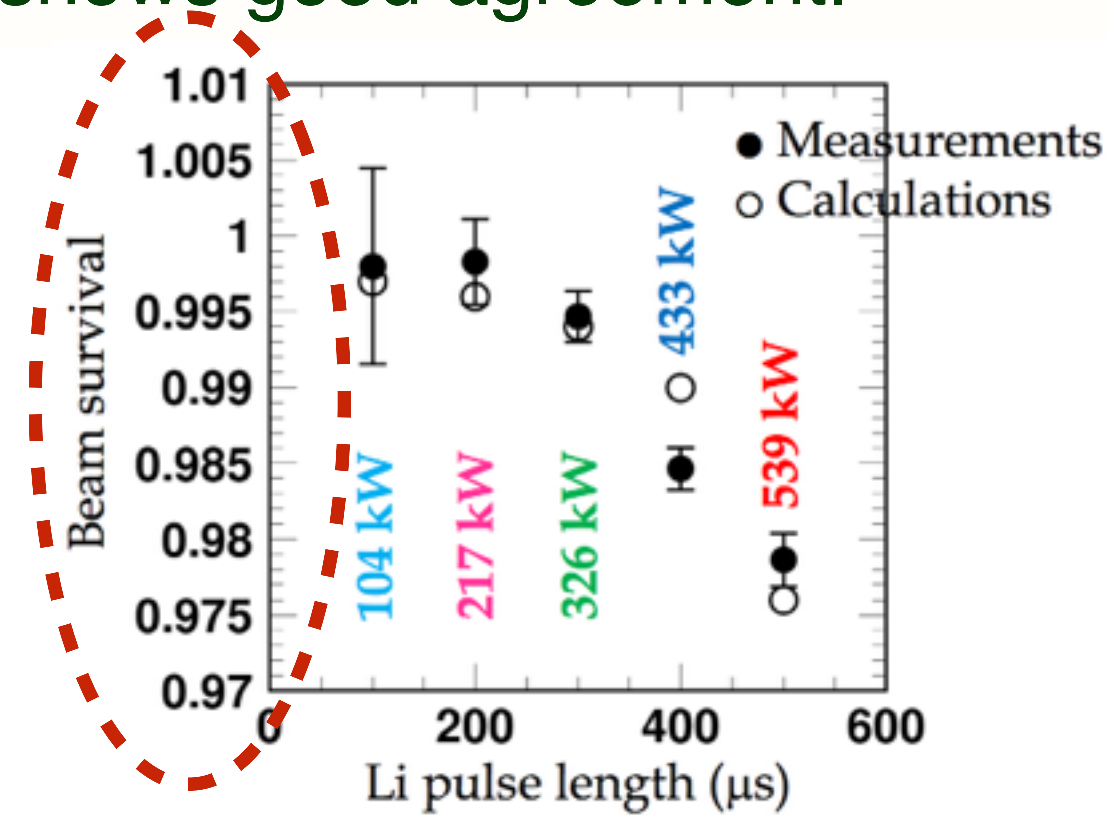
Some evidence follows.

Beam loss in short time scale (1)

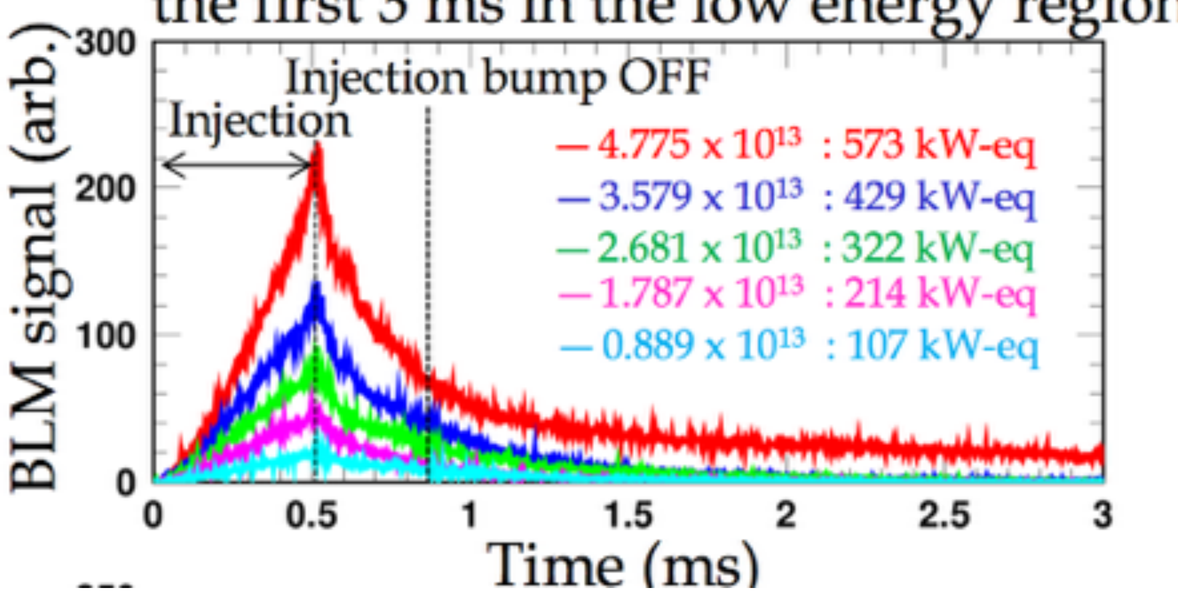
J-Parc RCS

- Beam loss vs beam power is well simulated at a per cent level.
- Time structure of beam loss shows good agreement.

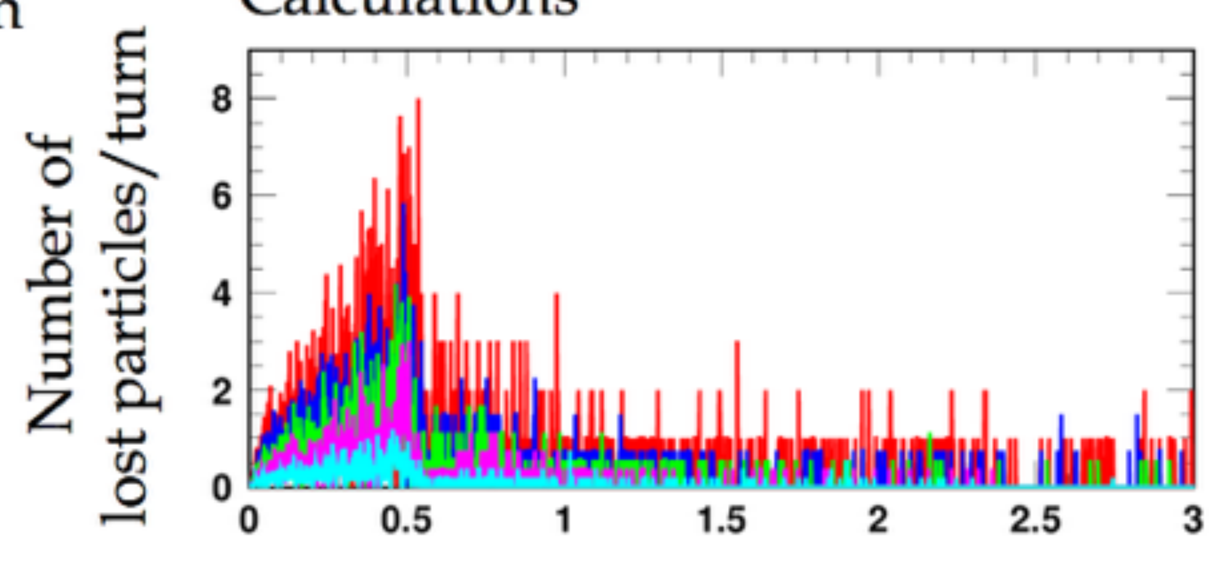
Hotchi, et al, Space charge workshop 2013 at CERN.



BLM signals @ collimator over the first 3 ms in the low energy region



Calculations



Beam loss in short time scale (2)

J-Parc RCS

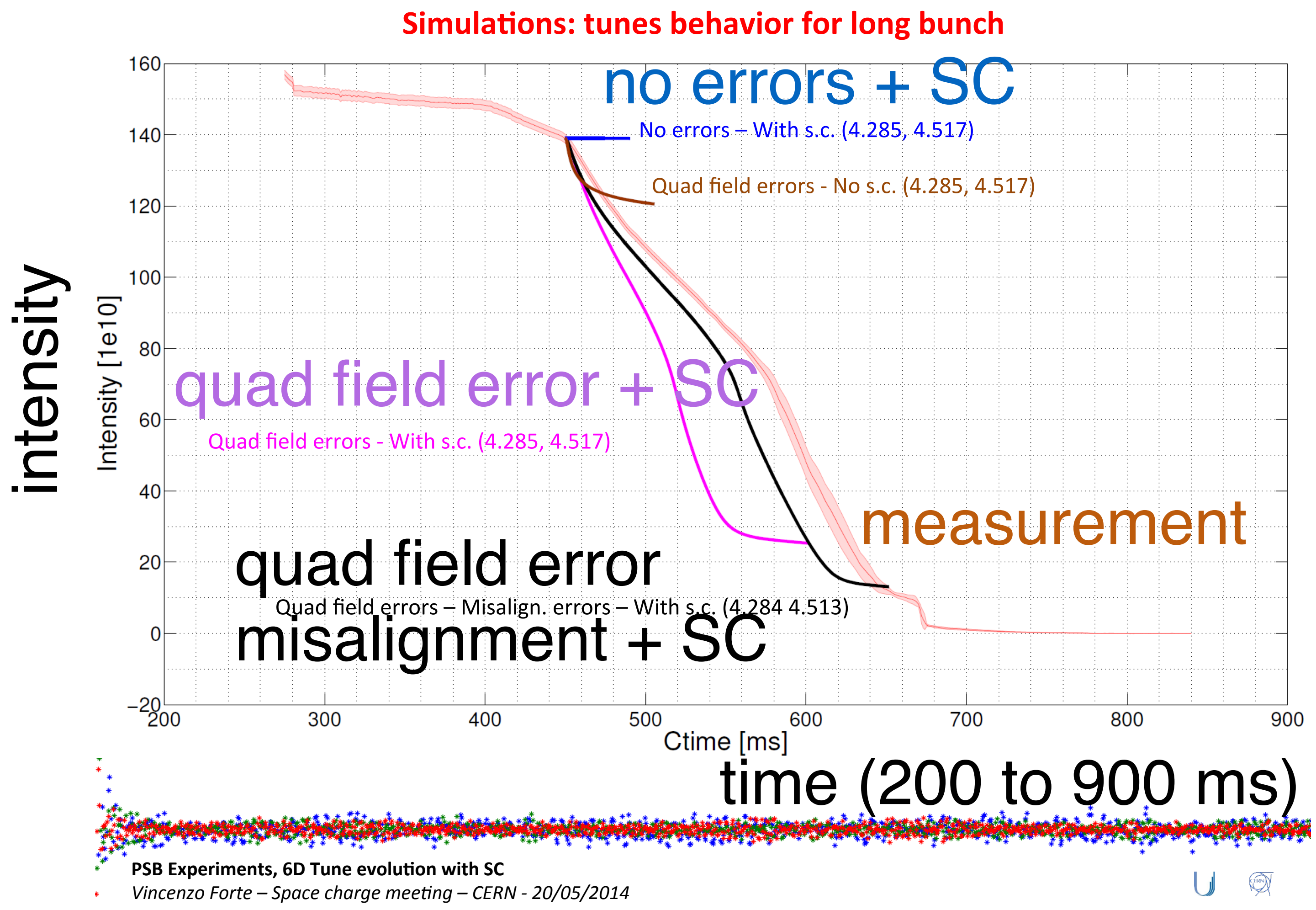
Model of accelerator and beams included in codes.

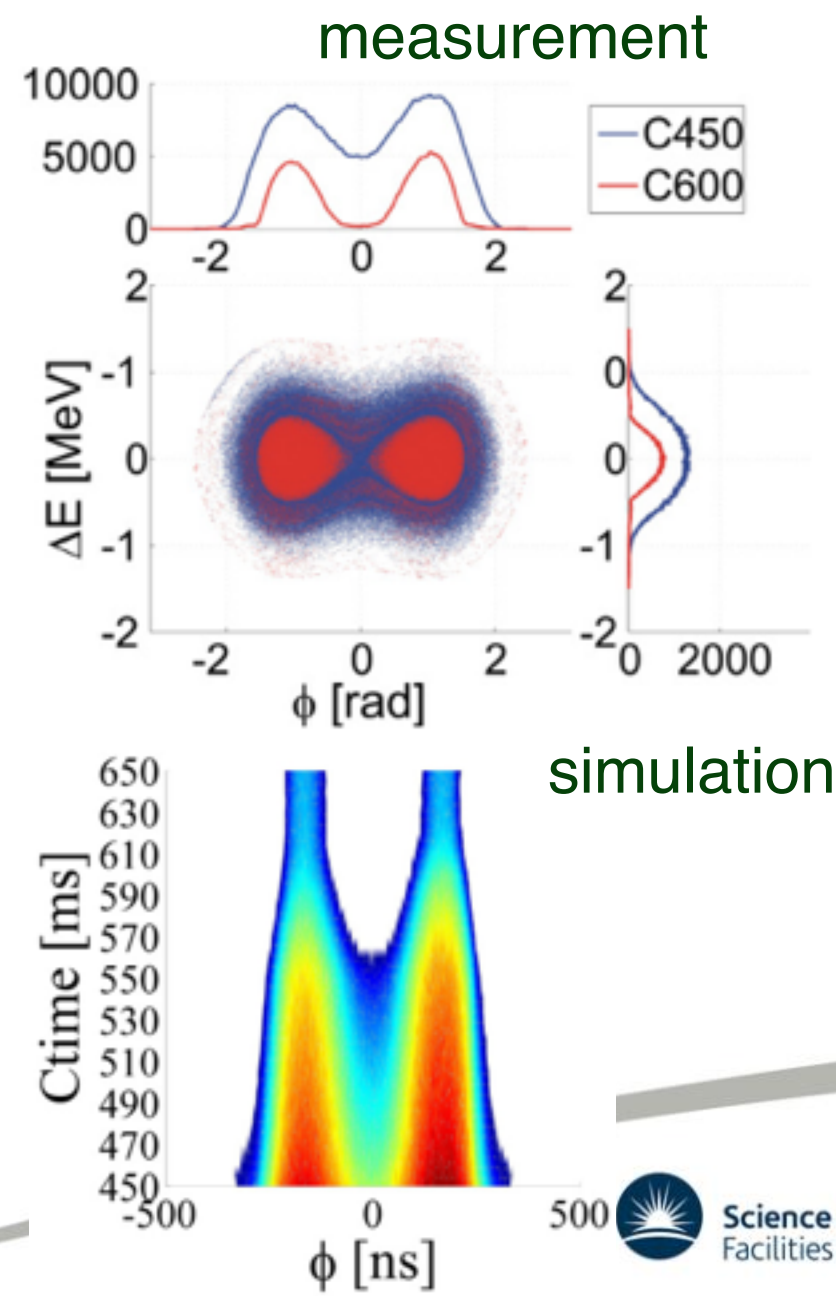
Time scale	20 ms	
Lattice	Time independent imperfections (measured) Time dependent imperfections (measured) Interference with neighbouring magnets Include local aperture	
Beam	Linac beam with tail	
Operation	Multi-turn H- injection with foil	
Diagnostics	Multi-particle Single-particle	
code	Simpsons (PIC)	

Beam loss in medium time scale (1)

CERN PS Booster

- Beam loss simulation over ~200 ms is manageable with PIC.
- Accurate modelling is essential to reproduce measurement: beam loss and bunch shortening..





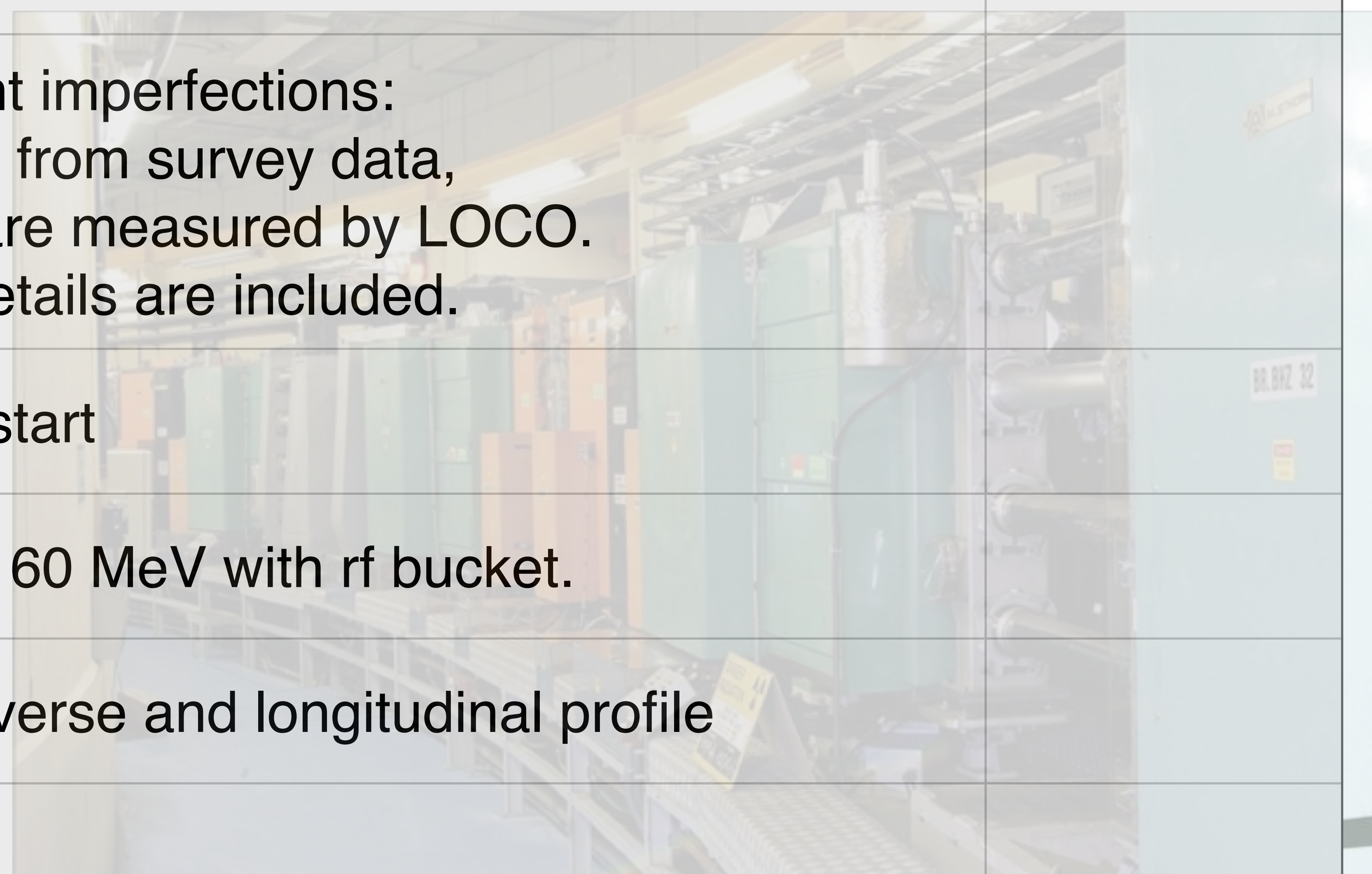
Forte, et al, IPAC 2014.

Beam loss in medium time scale (2)

CERN PS Booster

Model of accelerator and beams included in codes.

Time scale	~ 100 ms	
Lattice	Time independent imperfections: misalignment from survey data, quad errors are measured by LOCO. Aperture: local details are included.	
Beam	Gaussian at the start	
Operation	Fixed energy at 160 MeV with rf bucket.	
Diagnostics	beam loss, transverse and longitudinal profile	
Code	PTC-Orbit (PIC)	

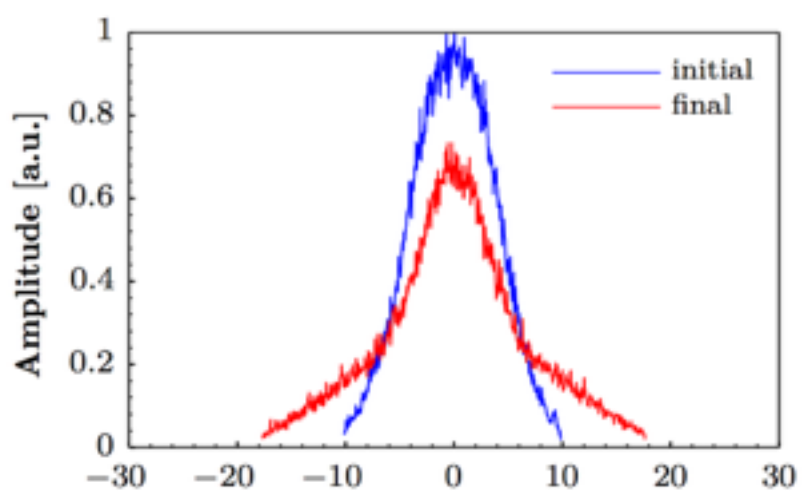


Long term simulation (1)

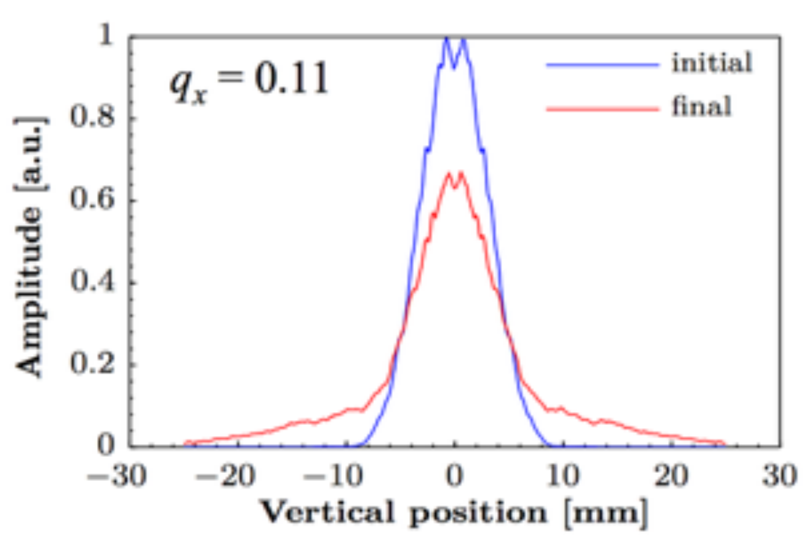
CERN PS

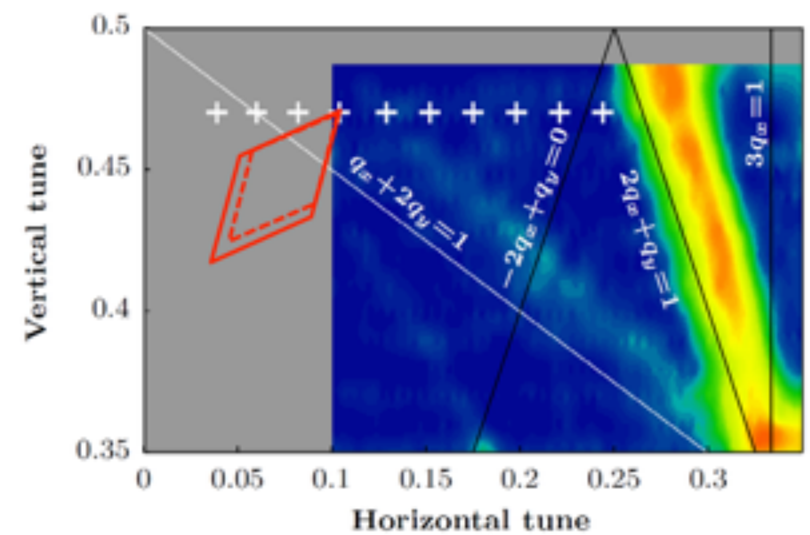
- PIC is not practical for > 1s tracking.
- Frozen space charge model turns out to be reasonable approximation for long term simulation.

Measurement



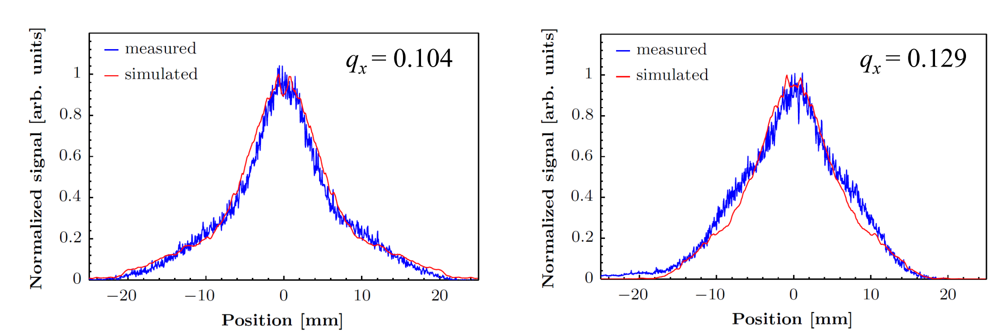
Simulation





Agreement becomes better with slight tune adjustments.

- Reinvestigation of all measured parameters led to observation of slight discrepancy between programmed and measured tunes:
  (0.11, 0.47) → (0.104, 0.476)   (0.13, 0.47) → (0.129, 0.47)
- Tunes in simulations were adjusted accordingly
- Important conclusion: halo development extremely sensitive to working point



Huschauer, et al,
Space charge workshop 2015 at Oxford.

Long term simulation (2)

CERN PS

Model of accelerator and beams included in codes.

Time scale	1.1 s	
Lattice	Time independent imperfections: sextupole to excite resonance + measured multipole (zeroth component)	
Beam	Measured distribution and emittance by 1000 macro particles.	
Operation	Single turn injection and 2 GeV plateau	
Diagnostics	Multi-particle: Beam profile averaged over 1000 turns	
Code	MADX-SC (frozen with update emittance)	

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Agree or not agree

both are equally useful

If codes results agree with measurement, we have more confidence in the code and model.

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If codes results do not agree with measurement, there must be something missing in codes.

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If codes results agree with measurement, we have more confidence in the code and model.

If codes results do not agree with measurement, there must be something missing in codes.

First step to find unknown physical mechanism or simply hardware does not function as expected.

Agree or not agree

both are equally useful

If codes results agree with measurement, we have more confidence in the code and model.

If codes results do not agree with measurement, there must be something missing in codes.

First step to find unknown physical mechanism or simply hardware does not function as expected.

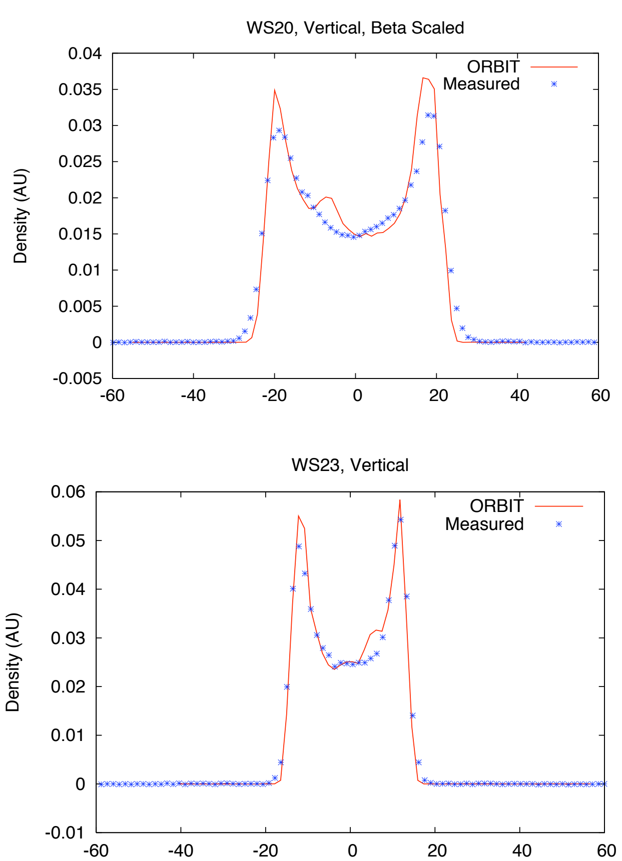
Recent progress in both simulations and measurements gives us a better idea whether agree or not agree.

Agree

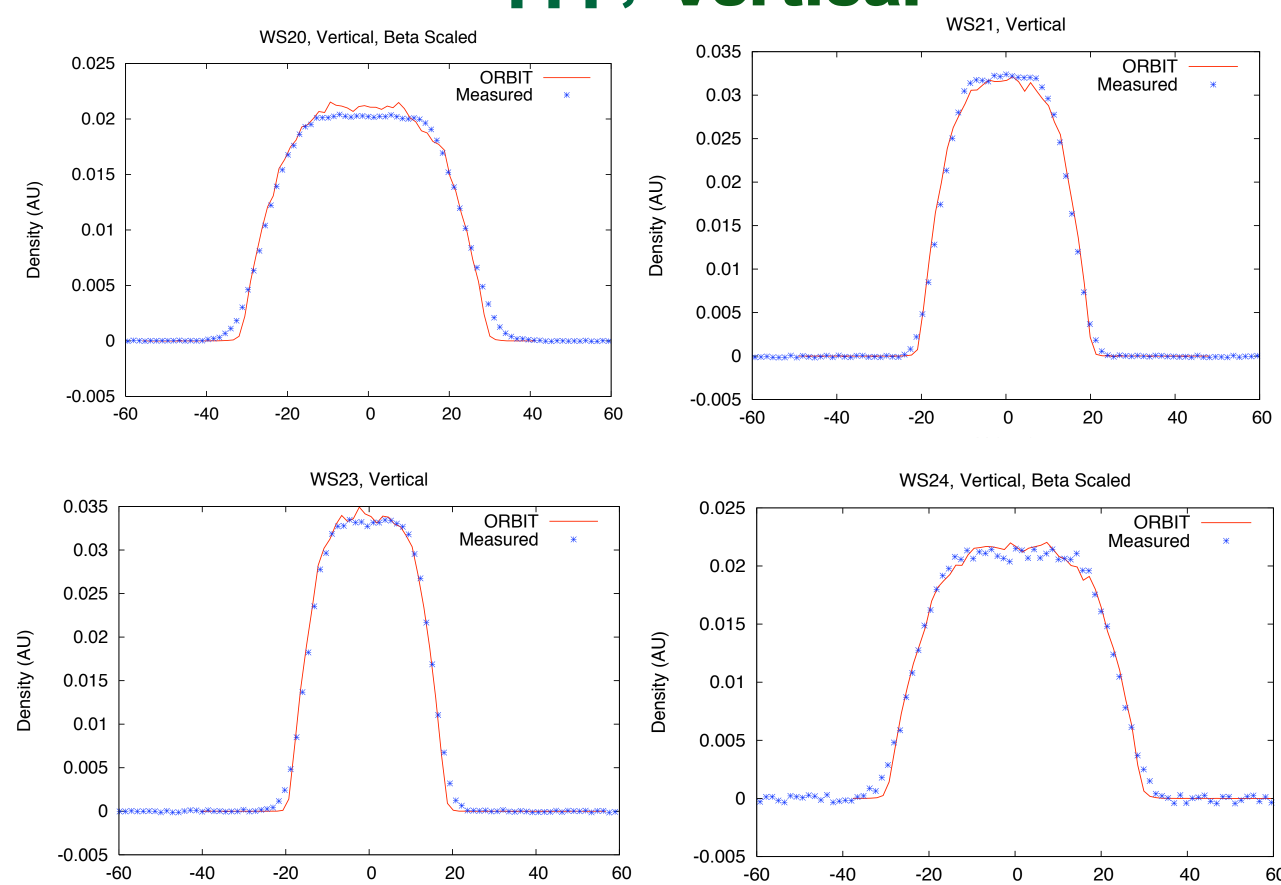
SNS accumulator ring (1)

- Multiturn injection with *no painting.*
- Beam profile vs beam power is well simulated.

Benchmark of Flattop Beam 8e12 ppp, Vertical



Benchmark of Flattop Beam 5e13 ppp, Vertical



Courtesy of Cousineau.

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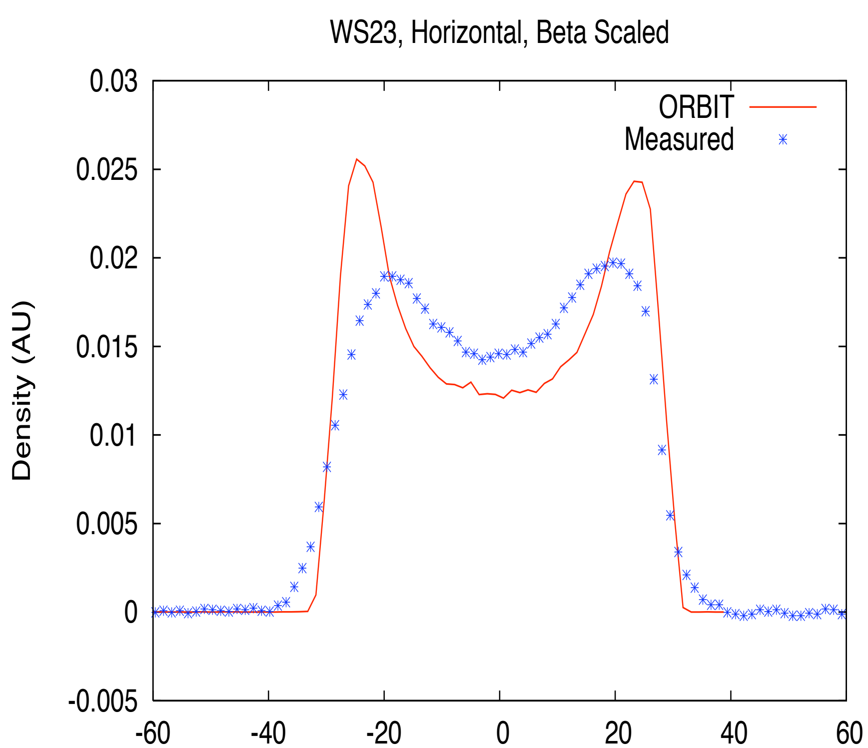
Not agree

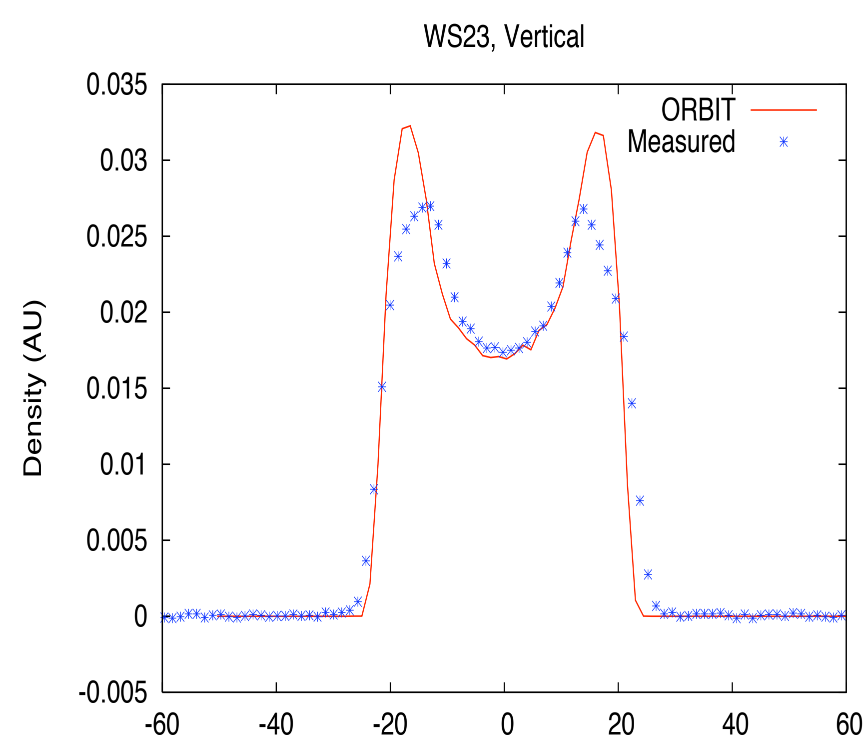
SNS accumulator ring (2)

- Multiturn injection with *painting*.
- Beam profile does not agree even with low intensity.

Sample of Benchmark of Painted Beam
8e12 ppp

We miss the mark on low intensity profile shape, especially in horizontal plane.





Courtesy of Cousineau.

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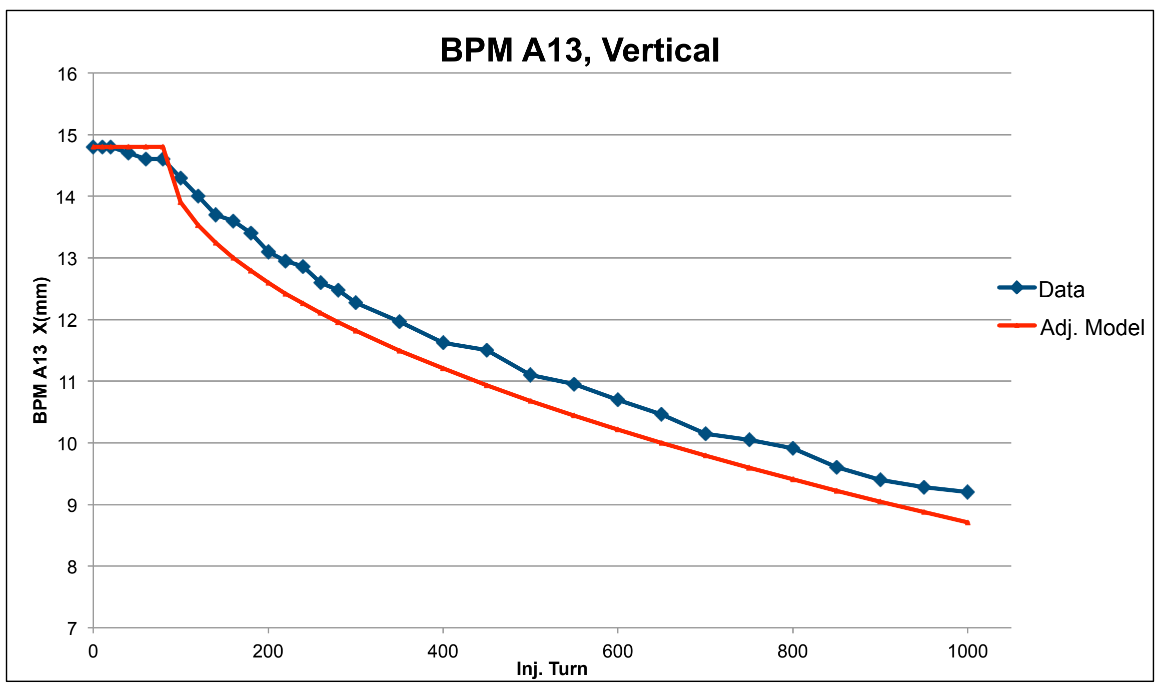
Troubleshoot hardware problem

SNS accumulator ring (3)

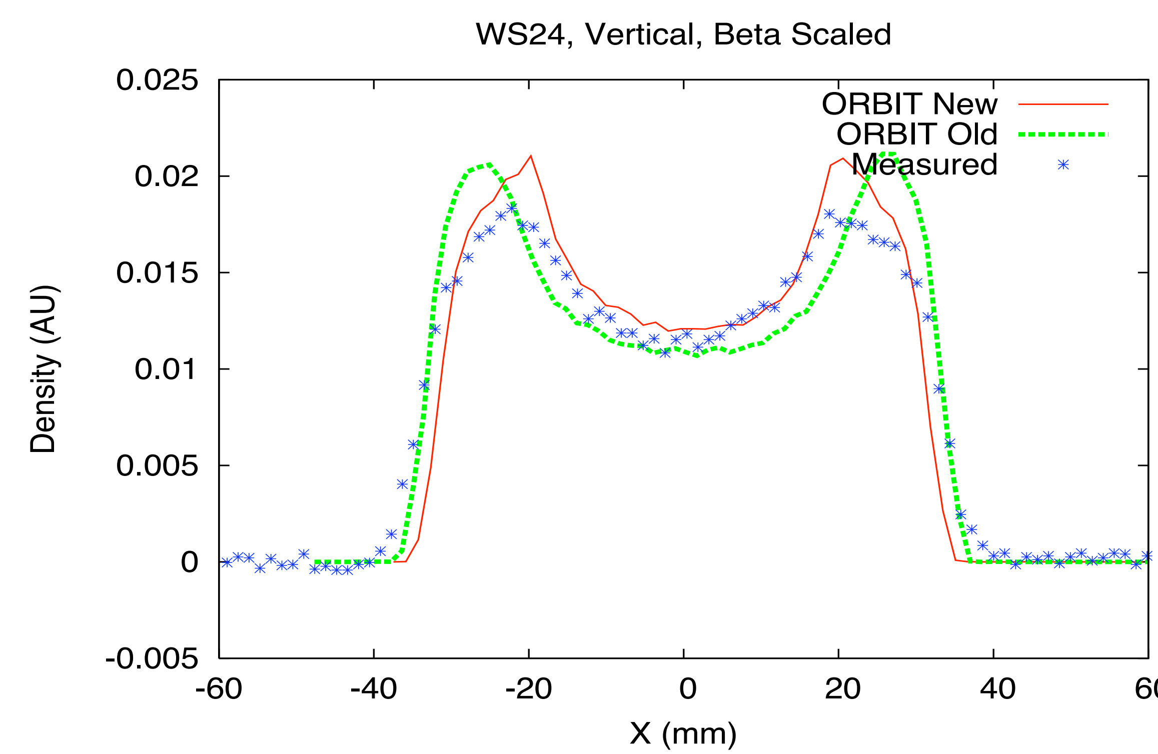
It turned out painting kicker was not functioning as expected.

Measurement Results - Horizontal



- Delay is again present, and less painting experimentally than in model.

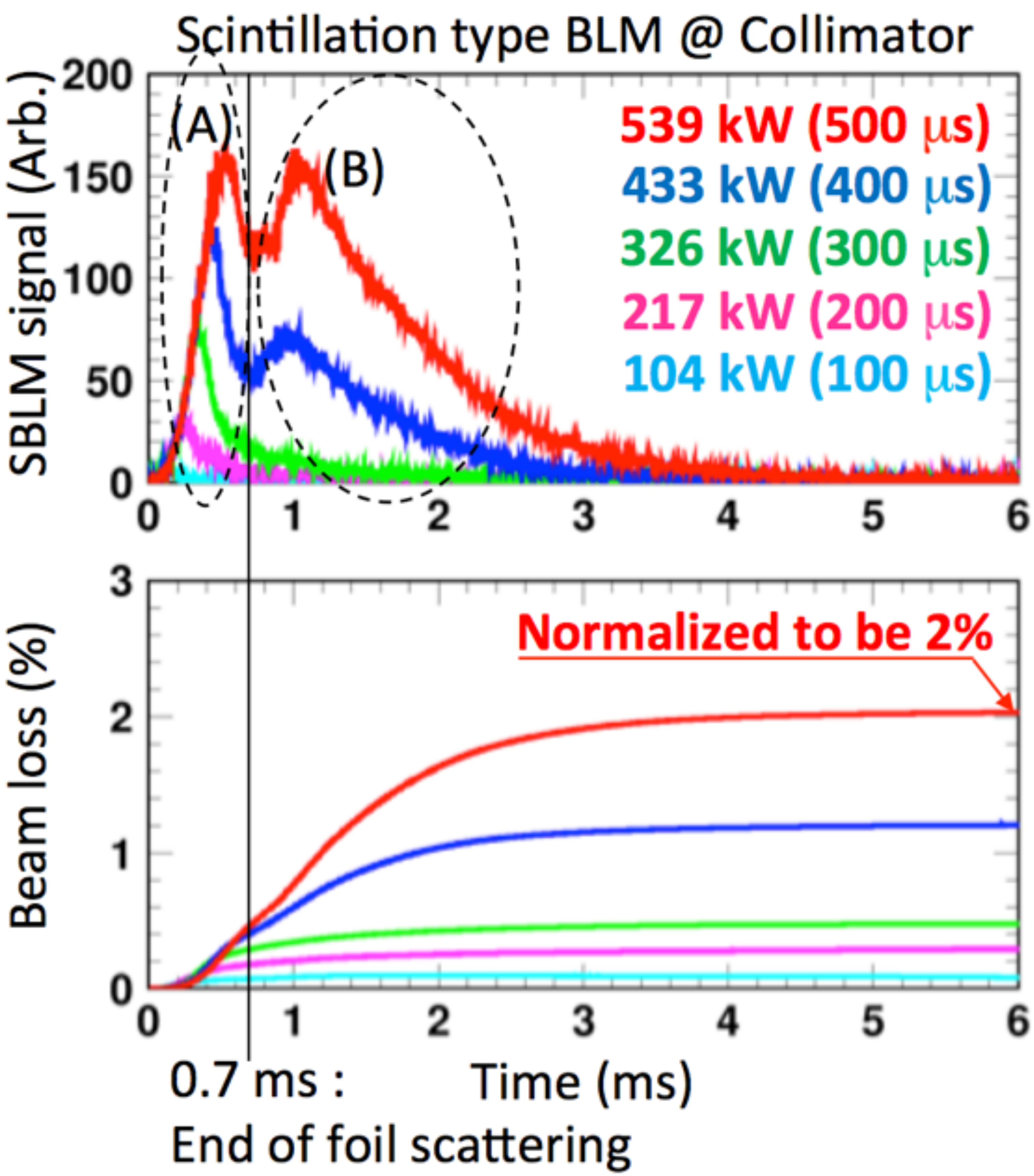
ORBIT Results - Vertical, High Intensity



Courtesy of Cousineau.

Not agree

J-Parc RCS (1)



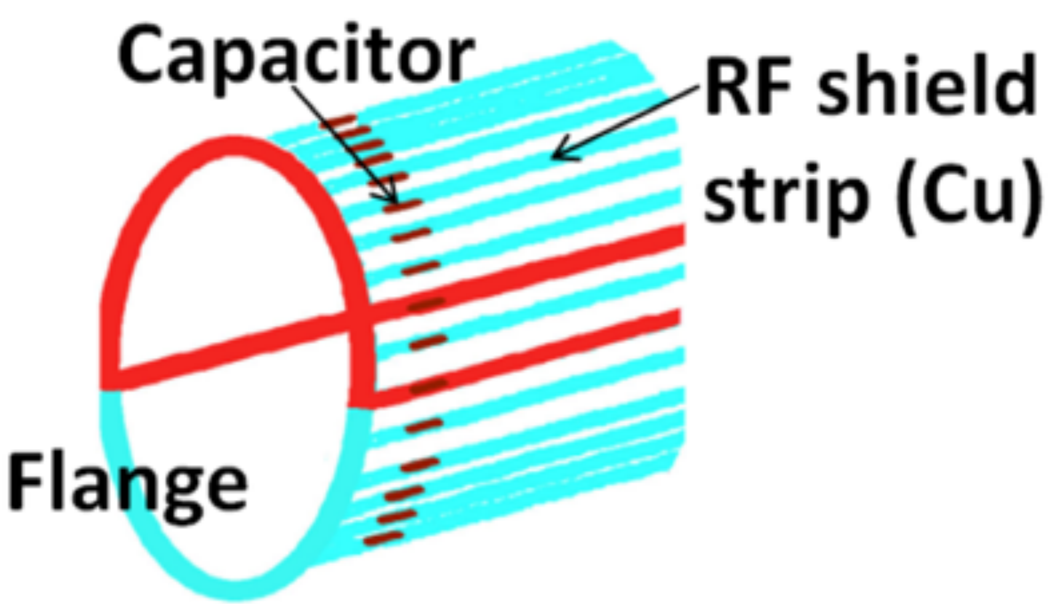
- First peak came from foil scattering.
- Second peak after injection was a mystery.

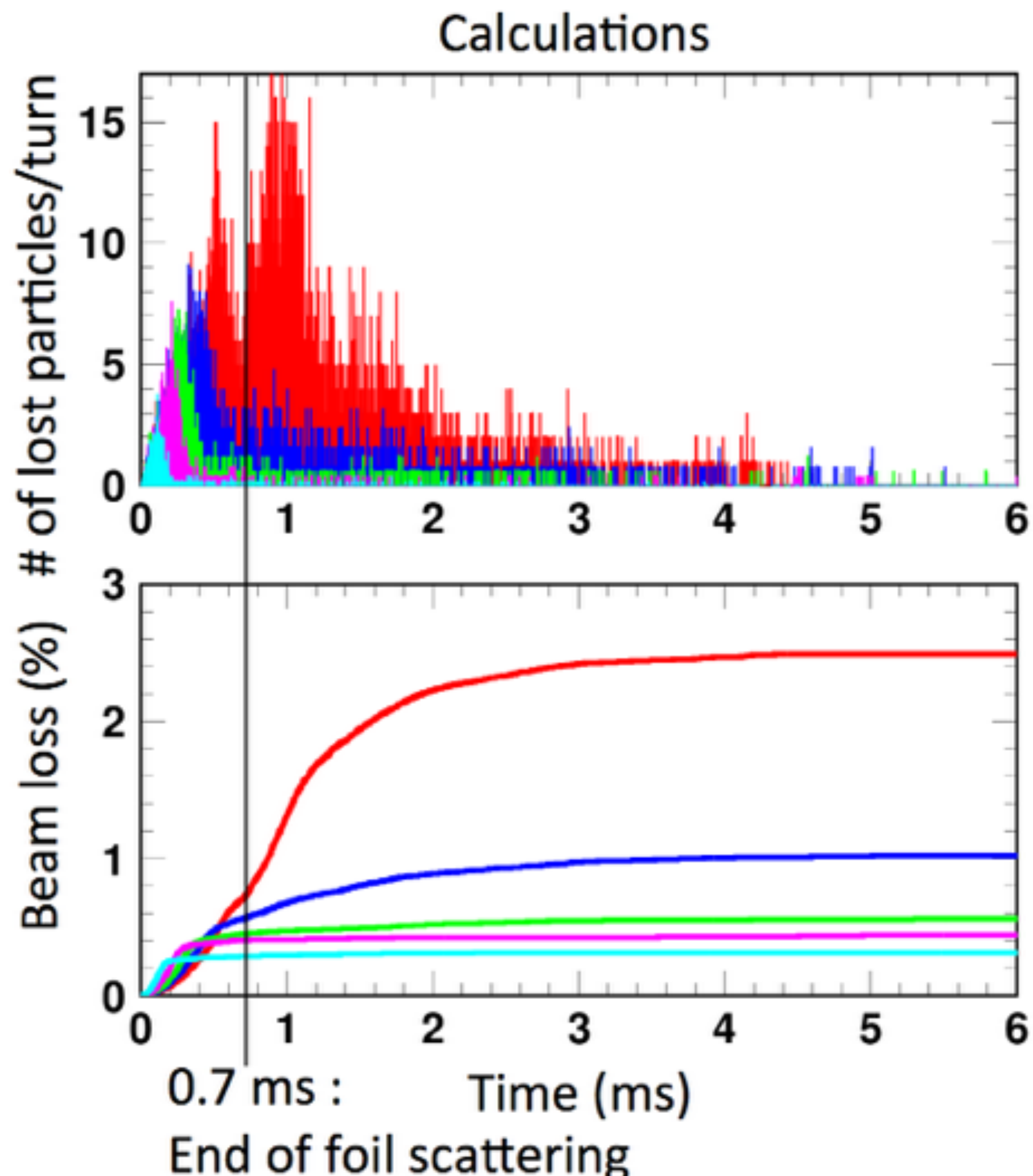
Hotchi, et al, Space charge workshop 2013 at CERN.

Troubleshoot hardware problem

J-Parc RCS (2)

100 kHz ripple was excited by asymmetrical screening of vacuum chamber.





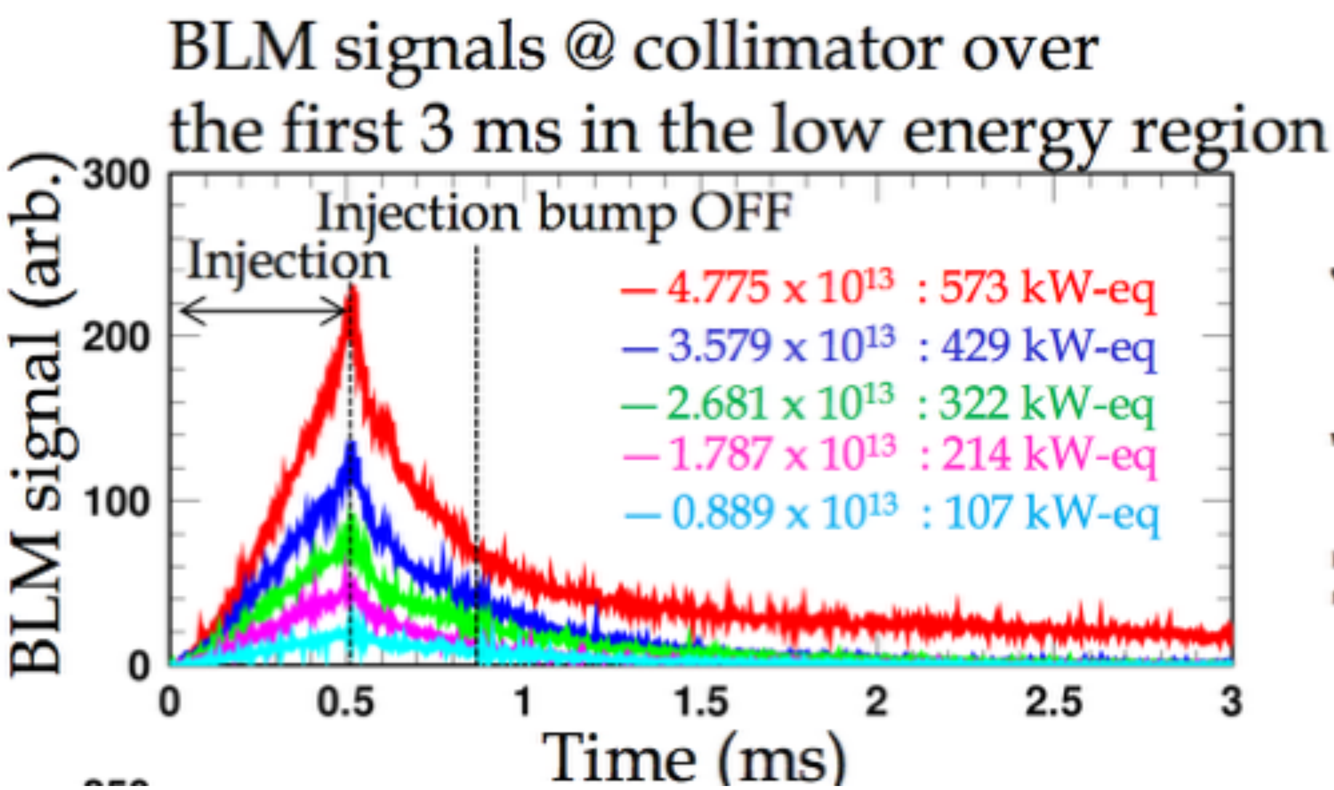
Hotchi, et al, IPAC 2014 (2014) 899.

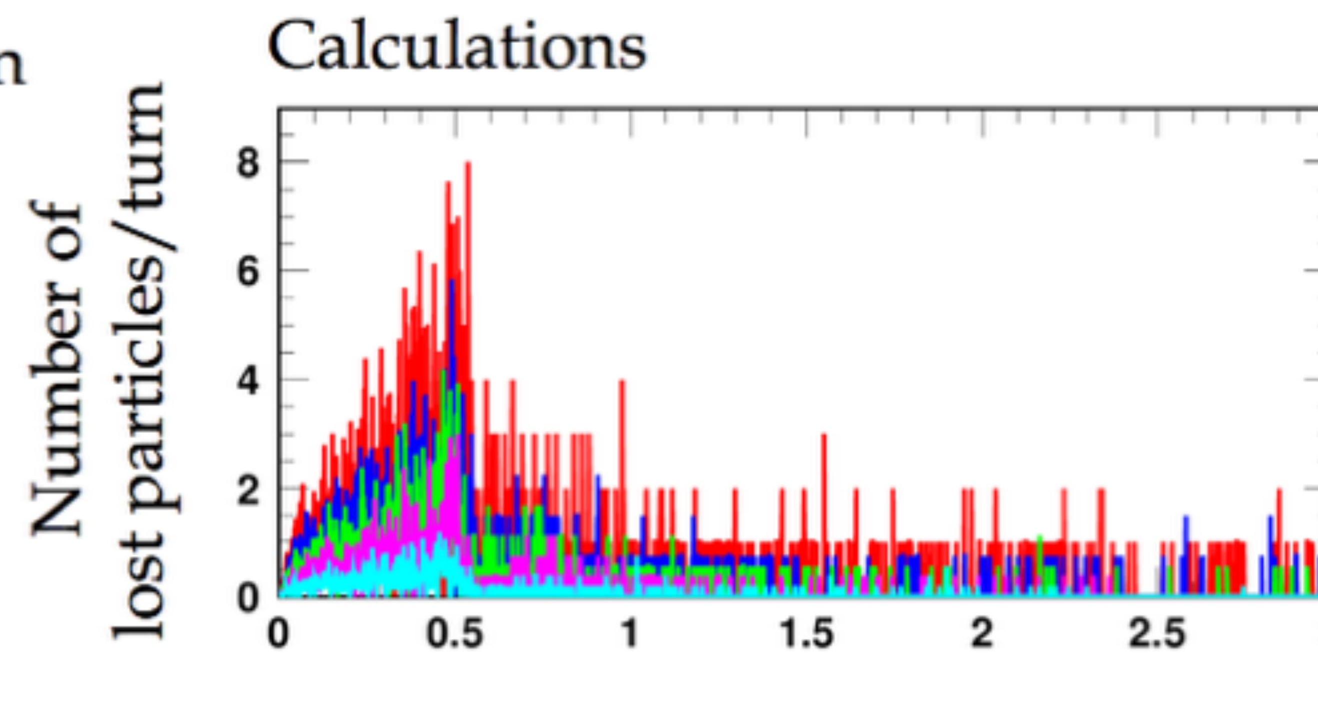
Troubleshoot hardware problem

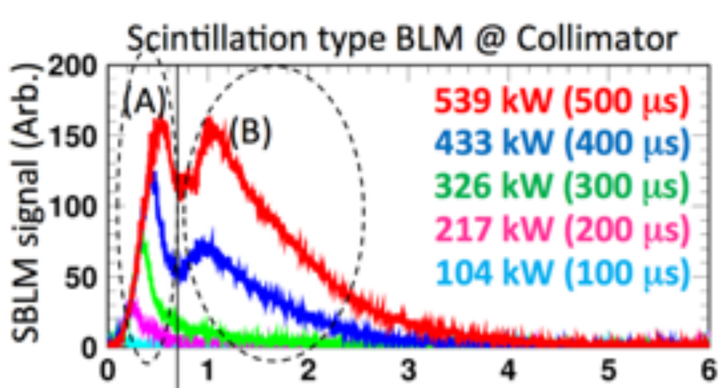
J-Parc RCS (3)

After fixing capacitors, the second peak disappeared.

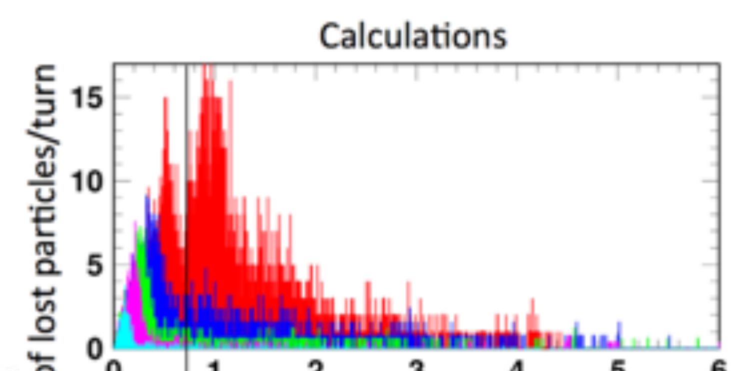
Hotchi, et al, IPAC 2014 (2014) 899.







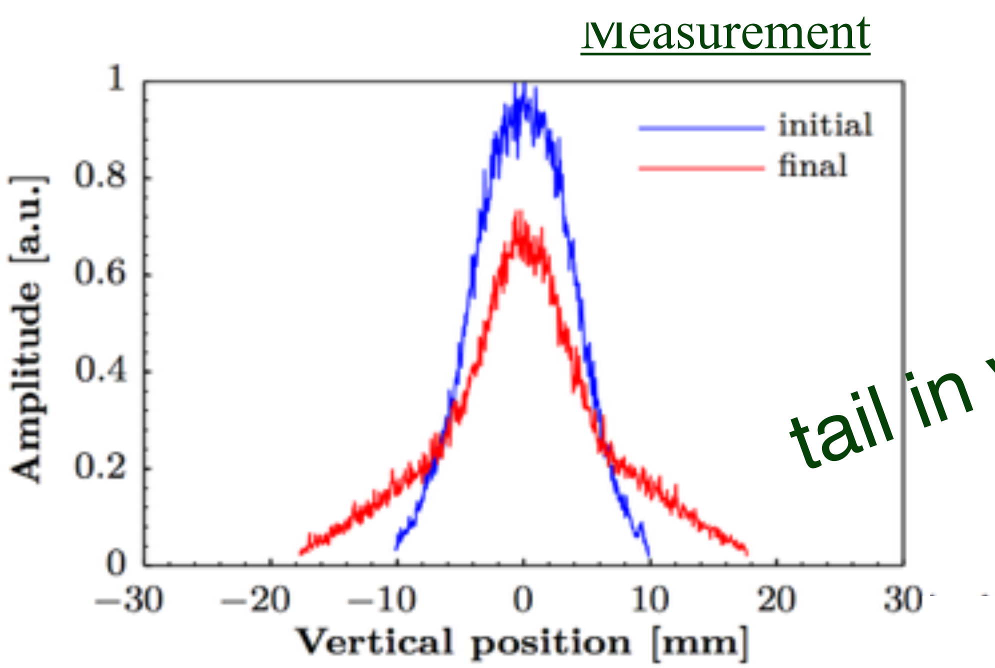
before



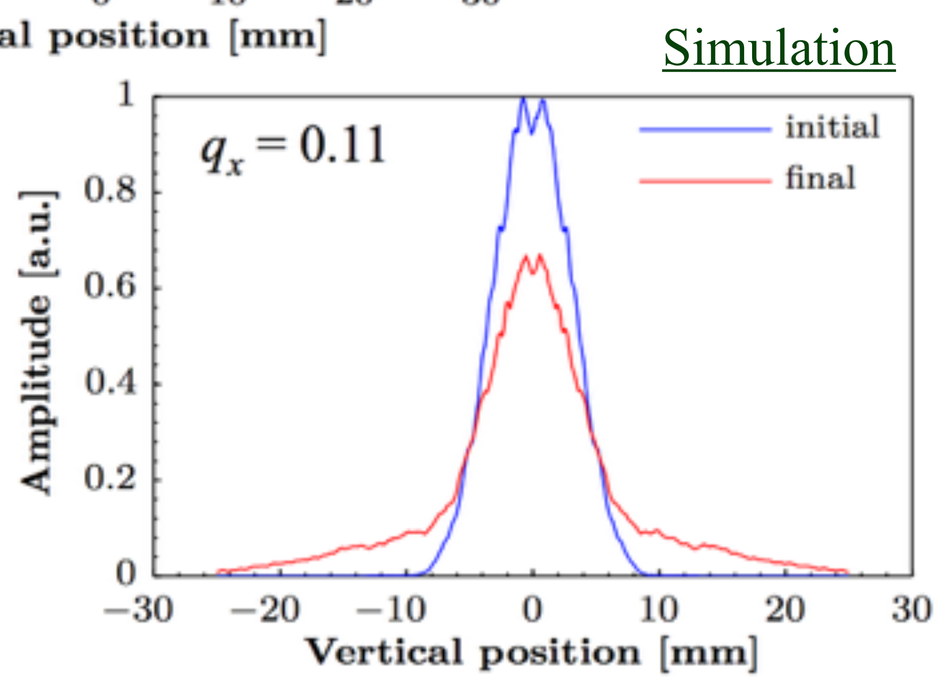
Finding new physics: fixed line

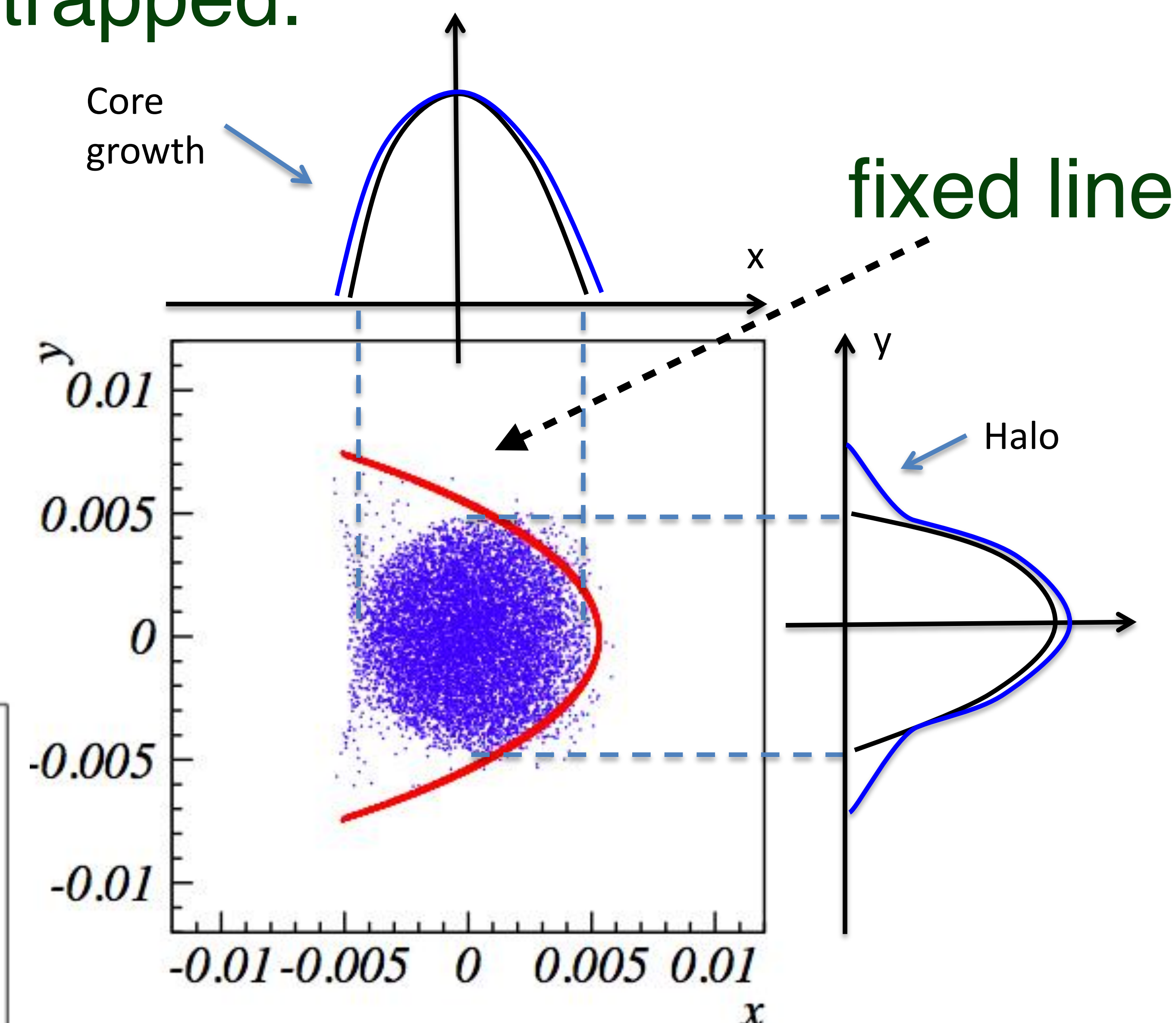
CERN PS

Fixed line (2D equivalent of fixed point) around Qx+2Qy=19 must exist and particles are trapped.



tail in vertical



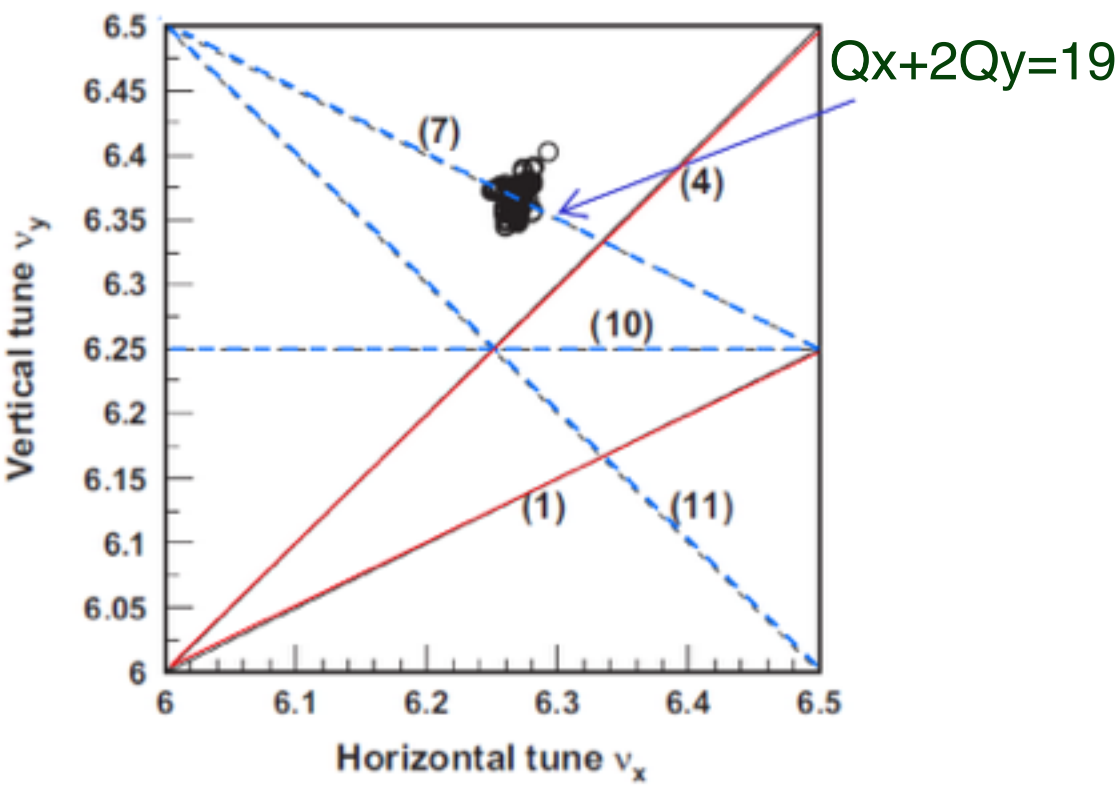


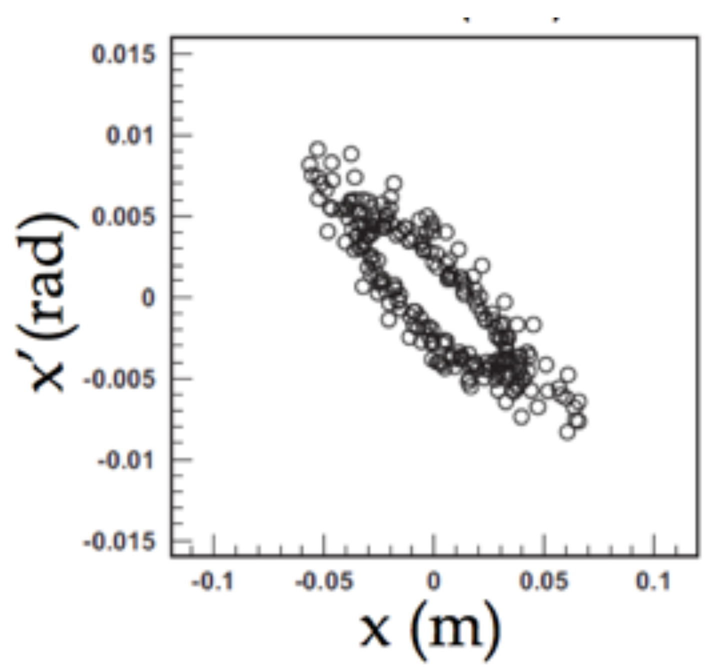
Schmidt and Franchetti, to be published.

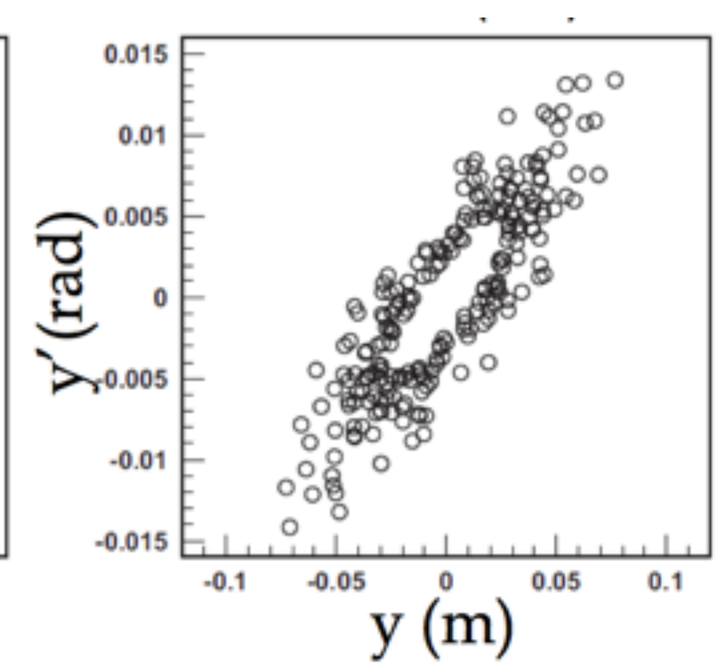
Finding new physics: fixed line

J-Parc RCS

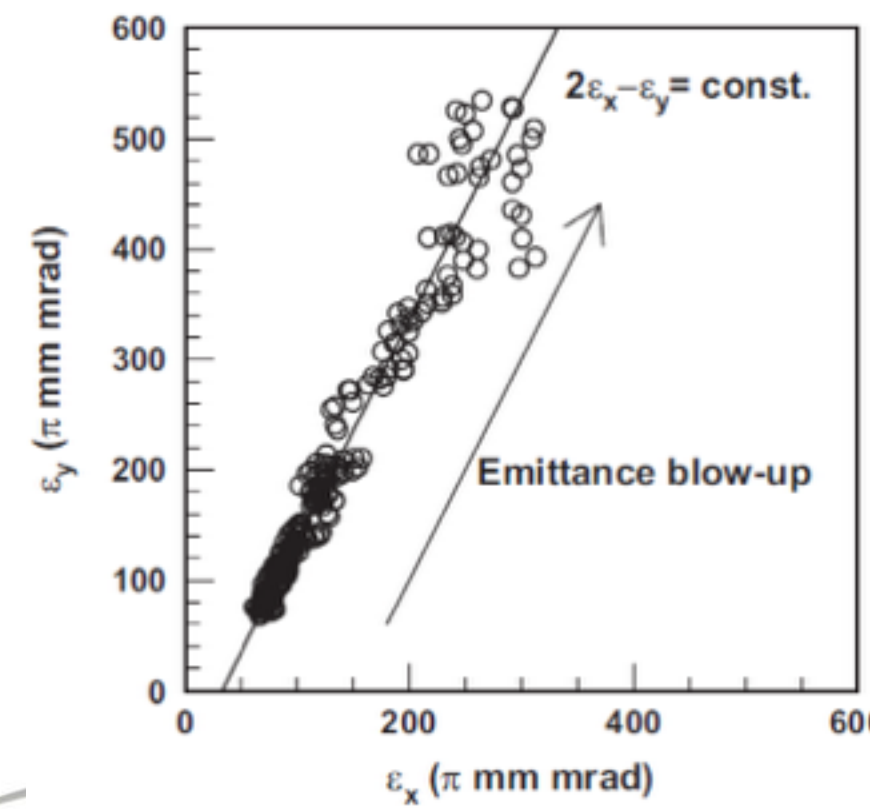
One of macro particle trajectory in J-Parc RCS simulation supports the same idea.







Hotchi, et al, Space charge workshop 2015 at Oxford.



Summary and future challenges

Contents

Summary and future challenges (1)
beam loss

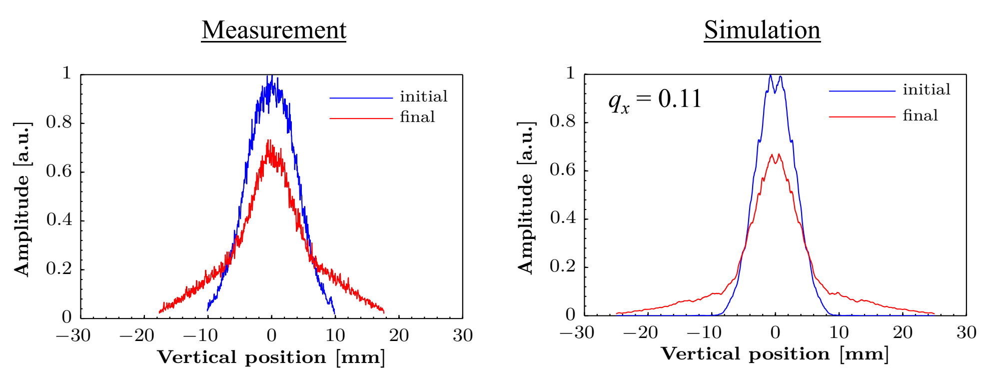
- Simulation of beam loss of a percent level becomes possible (10^{-3} yet), at least for fast cycling accelerators.
- Detail information of lattice, beam and operational conditions are essential toward quantitative simulations.
  - Newly constructed accelerators like SNS and J-Parc have a big advantage in that respect.
- Simulations are capable of troubleshooting hardware problems and finding new physics.
- Simulation of beam loss of 10^{-3} is still challenge.

Summary and future challenges (2)

long term tracking with frozen model

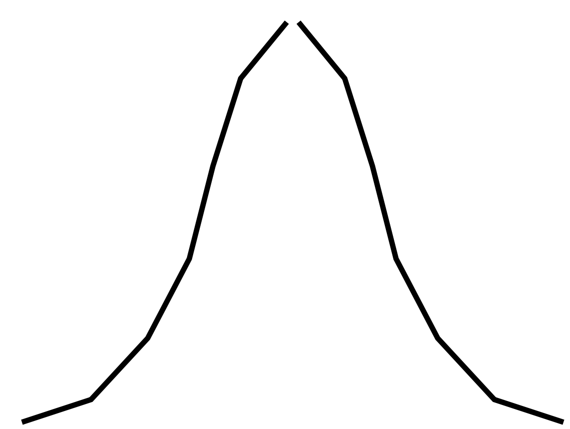
- Frozen space charge model and its variants are useful technique for long term tracking.
- It is not clearly understood why frozen space charge model works well.
  - Can we identify which part of frozen model is essential for long term tracking, rms emittance, higher moment, peak density?

Profile comparison



- Simulated profiles obtained by summing the 1000 macro-particles over 1000 turns
- Assumed to be an equivalent approach to the measurement with the wire scanner (duration approx. 1000 turns)
- Less tail development predicted by the simulations

14



$$E_r = \frac{\lambda}{2\pi\epsilon_0}\frac{1-\exp(-r^2/2\sigma_r^2)}{r}$$

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Summary and future challenges (3)

long term tracking with PIC

- Can we use PIC for long term tracking simply with the help of computational power?
  - Both number of macro particles and number of turns are being significantly increased.
  - However, noise and non-symplectic nature of PIC tracking is a concern.

Symplectic matrix M is defined as $M = -S(M^T)^{-1}S$

where $M_{jk} = \dfrac{\partial X_{1j}}{\partial X_{0k}}$ is the Jacobian for the transformation $X_1 = T(X_0)$

When space charge potential is not a smoothed function, M_{jk} has a singularity.

  - Can we assure symplectic tracking by constructing a smooth function out of the PIC potential?

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Summary and future challenges (4)
hybrid method

- Hybrid method of PIC and frozen model is under development.
    - Semi-frozen: distribution is fixed, but update a few characterising parameters like rms emittance.
    - Semi-PIC: calculate potential by PIC method only once a while and introduce smoothing.
- Self-consistent, noise-free, symplectic and fast codes.

2025

Looking forward to a talk on "benchmarking of space charge codes" at IPAC 2025 !

2015

2005

Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

BENCHMARK OF SPACE CHARGE SIMULATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS FOR HIGH INTENSITY, LOW ENERGY ACCELERATORS

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