Space Charge Modeling for The PIP-II Era Fermilab Booster

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A Partnership of:

US/DOE

India/DAE

Italy/INFN

UK/STFC-UKRI

France/CEA, CNRS/IN2P3

Poland/WUST

Outline

- The PIP-II project
- Required Modifications to the Booster
- Injection painting
- Transition
- Full Booster cycle
- Parting Remarks

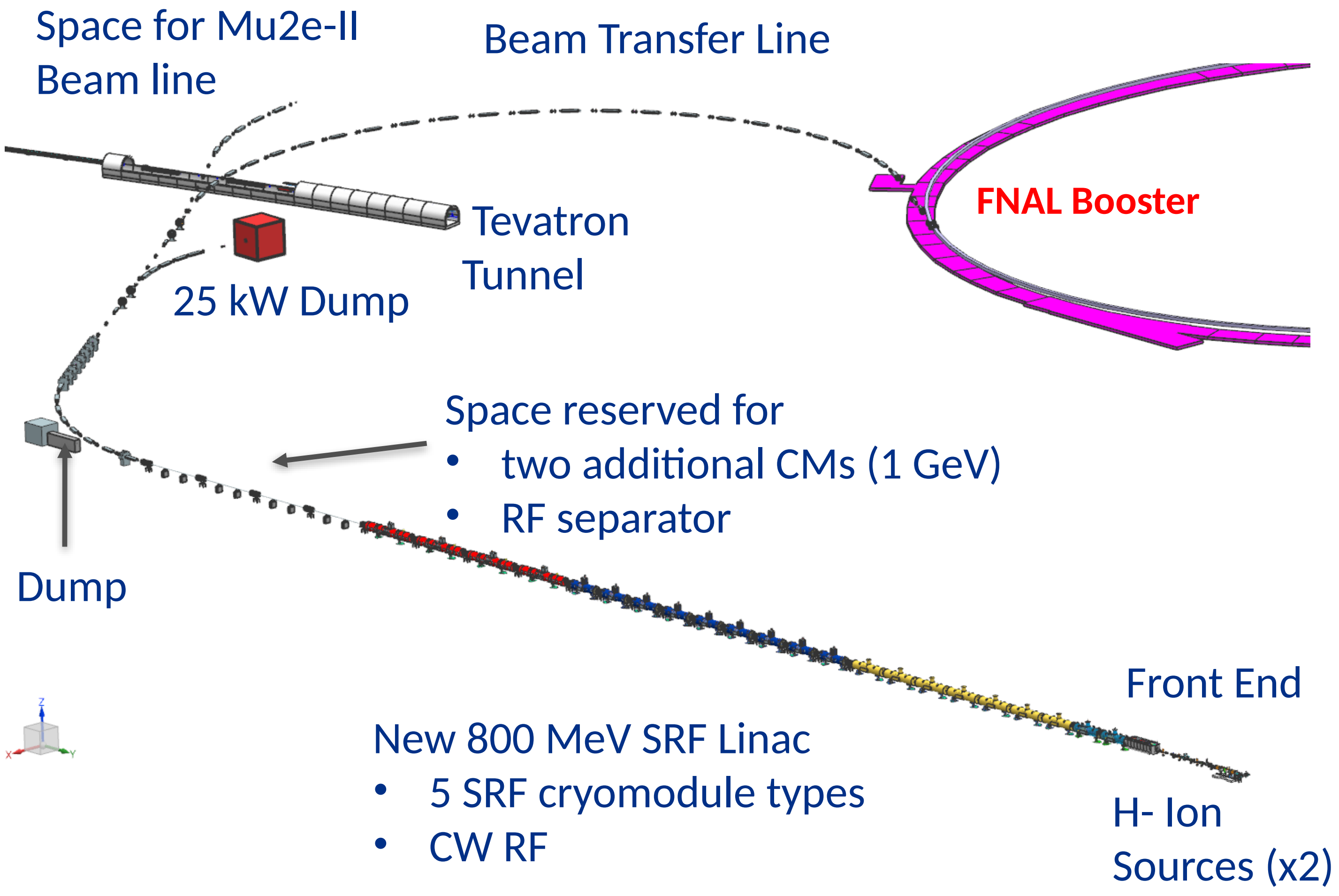
Acknowledgment:

Eduard Pozdeyev, PIP-II Project scientist provided input and assistance in assembling this presentation.

Proton Improvement Plan Phase II (PIP-II)

- Reduce the time required for LBNF/DUNE to achieve goals
  - Deliver 1.2 MW of beam power on LBNF/DUNE target at 120 GeV
  - Provide path for future multi-MW upgrade
- Sustain high-reliability, multi-user operations of the Fermilab complex

PIP-II Project Scope



- 800 MeV H– CW-compatible linac
- Linac-to-Booster transfer line
- Accelerator Complex Upgrades
  - **Booster**
  - Recycler Ring
  - Main injector
- Conventional Facilities

Changes to The Booster to Achieve Performance Requirements

- Increase intensity per pulse by 45%
- Increase Booster cycle frequency from 15 to 20 Hz (33%)
- Injection energy is increased by factor 2 to reduce space charge at injection
- Injection time is increased from 30 µs to 550 µs due to lower linac current
- Current adiabatic capture scheme is replaced by new injection painting scheme. Uniform painted distributions reduce transverse tune spread and peak line density.

Parameter	Current Operations	PIP-II (LBNF mode)
Injection Energy	400 MeV	800 MeV
Particles per Pulse	4.7×10^{12}	6.7×10^{12}
Linac Beam Current	25 mA	2 mA
Linac Pulse Length	30 µs	550 µs
Booster Cycle Frequency	15 Hz	20 Hz
Uncontrolled Beam losses	**475 W**	**475 W**

Beam power increases by a factor 4.
Uncontrolled beam losses do not increase.
Better control of particle loss is nedeed.

Motivation for 6D Tracking Simulations

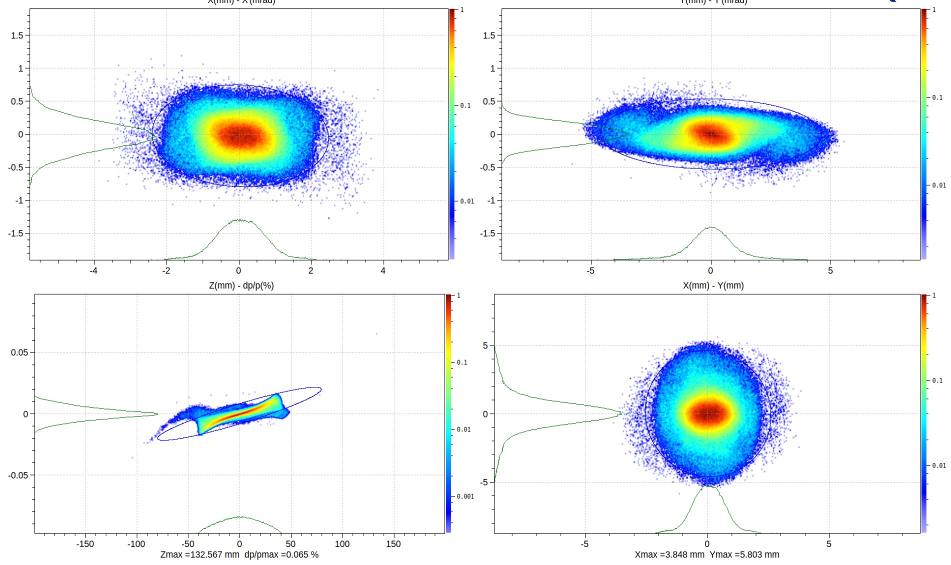
6D tracking is cumbersome and time –consuming; however, it can provide insight to help answer questions such as:

- How significant of a perturbation is space charge during the painting process ?
- To what extent does the final painted distribution have the required emittances and expected uniformity ?
- Are the tune shift/spread associated with the painted distribution consistent with expectations ?
- Will space charge induced tune spread lead to meaningful particle loss in a machine with realistic magnet imperfections or misaligments?
- Can transition be crossed without excessive losses and emittance blowup ?
- Which mitigating measures, if any are effective to reduce loss and emittance blowup through transition ?
- Does beam quality at the end of the acceleration cycle meet requirements for injection in downstream machine ?
- Could we operate beyond 6.7E12 ppp ? What is the limit ? Excessive losses ? Stability ?

6D Tracking Simulations

- Simulations codes: pyORBIT (ORNL/SNS) and Synergia (FNAL)
- Linac (input) Beam
  - Realistic beam distribution tracked from the RFQ to the Booster injection point
- Booster PIP-II MADX lattice
  - New Booster 800 MeV optics (scaled from 400 MeV)
    - Tunes 6.779, 6.814
    - Most apertures limitations included
    - Nominal chromaticities set to (-8,-8)
  - Includes modifications for PIP-II injection:
    - Longer injection area achieved by introducing new shorter combined function bends upstream and downstream.
  - Foil scattering incorporated (into PyOrbit) simulations

Linac distribution tracked from RFQ



pyORBIT

- Direct descendant of the ORBIT code originally developed to model the SNS storage ring.
- Mix of C++ and python
- Support for lattices in MAD-X format
- A variety of space charge solvers available, different levels of approximation – we have been using transverse 2 1/2 D FFT solver + 1D longitudinal solver
- Main pros for our application:
  - multiple users, different facilities (SNS, CERN, KEK etc..)
  - 2 ½ D SC requires less resources, computing time
  - support for a ring with acceleration
  - Apertures, foil, time-dependent magnet excitation

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The Particle Accelerator Simulation Code PyORBIT

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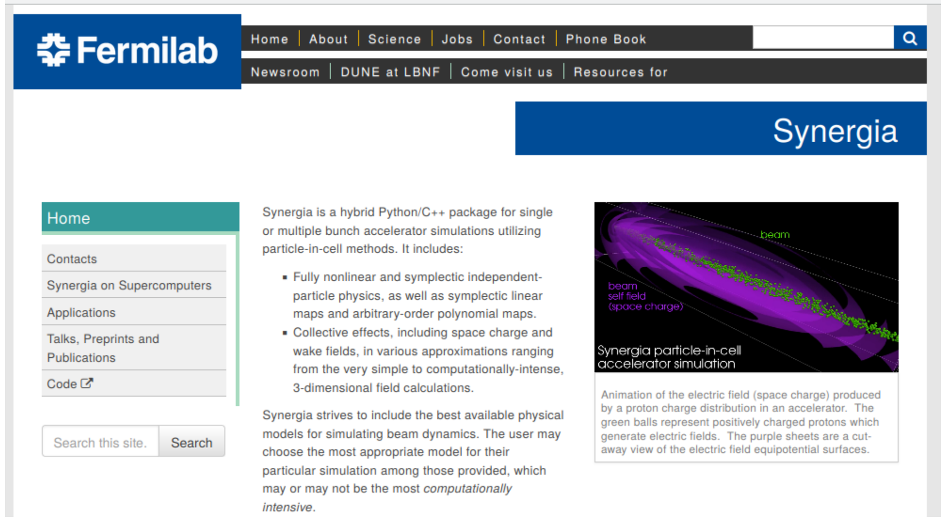
Abstract
The particle accelerator simulation code PyORBIT is presented. The structure, implementation, history, parallel and simulation capabilities, and future development of the code are discussed. The PyORBIT code is a new implementation and extension of algorithms of the original ORBIT code that was developed for the Spallation Neutron Source accelerator at the Oak Ridge National Laboratory. The PyORBIT code has a two level structure. The upper level uses the Python programming language to control the flow of intensive calculations performed by the lower level code implemented in the C++ language. The parallel capabilities are based on MPI communications. The PyORBIT is an open source code accessible to the public through the Google Open Source Projects Hosting Service.

Keywords: Open Source, Python, C++, MPI, Accelerator Simulation, Particles-in-Cell, Space Charge, PyORBIT

Synergia



- developed at Fermilab to model rings (booster provides early motivation).
- C++ and python
- Support for lattices in MAD-X format
- A variety of space charge solvers available
  – have been mostly using full 3D FFT solver (most
- Main pros for our application:
  - local code expertise and support
  - 3D FFT SC solver benchmarked with other codes
  - 3D solver requires significant computational resources but developers have access to additional facilities.
  - Some past experience and success with simulation of transition in the MI ring
  - Apertures, time-dependent magnets and acceleration possible but some features not as well-developed as for pyORBIT.
  - On going interest in cross-checking and validation

Baseline Painting Injection Scheme

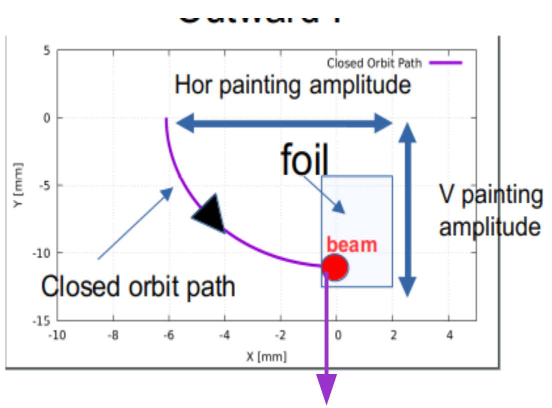
- Transverse: anti-correlated injection, painting scheme approximates a 4-D KV distribution
- Longitudinal: Off-momentum, limited phase window used to paint a hollow distribution (akin to a 2-D KV.) The hollow region reduces the peak line density.

Transverse painting

- Beam spot fixed on the foil
- Closed orbit moves on an elliptical trajectory

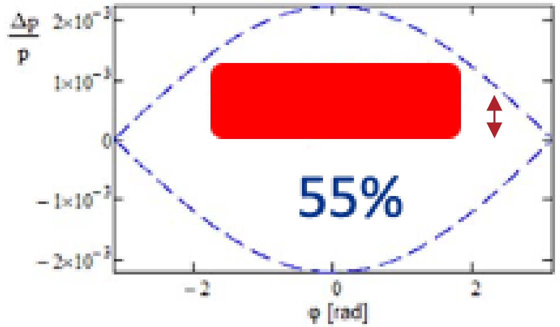
$$\boxed{\begin{aligned} X(\tau) &= X_m \cos\left(\frac{\pi}{2}(1-2\xi)\tau + \frac{\pi}{2}\xi\right) \\ Y(\tau) &= Y_m \left\{1 - \sin\left(\frac{\pi}{2}(1-2\xi)\tau + \frac{\pi}{2}\xi\right)\right\} \\ \xi &= 0.08 \qquad T_{\text{inj}} = 550\ \mu s \\ \tau &= \frac{t}{T_{\text{inj}}} = \frac{n}{N_{\text{inj}}} \qquad N_{\text{inj}} = 294 \text{ turns} \end{aligned}}$$

$$\boxed{X_m = 5.3 \text{ mm} \quad Y_m = 9.6 \text{ mm}}$$

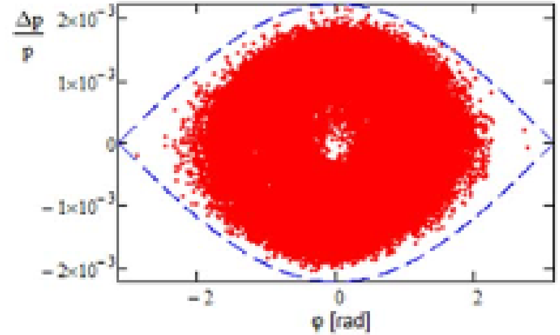


Longitudinal painting

- Bucket-to-bucket injection from linac to Booster
- Phase window and energy offset optimized to reduce longitudinal charge density but avoid losses
- Linac bunches outside the window removed by the MEBT chopper



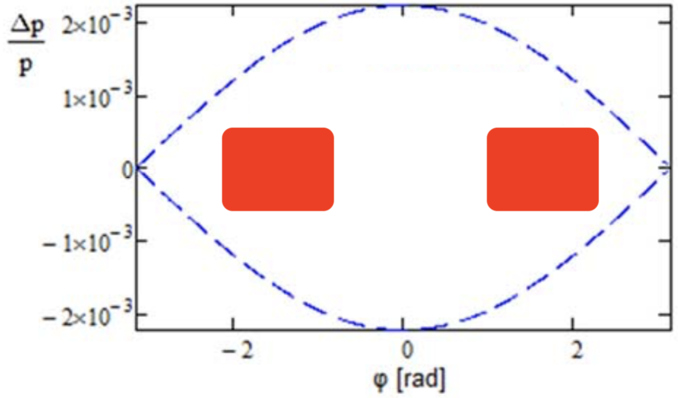
dp/p offset



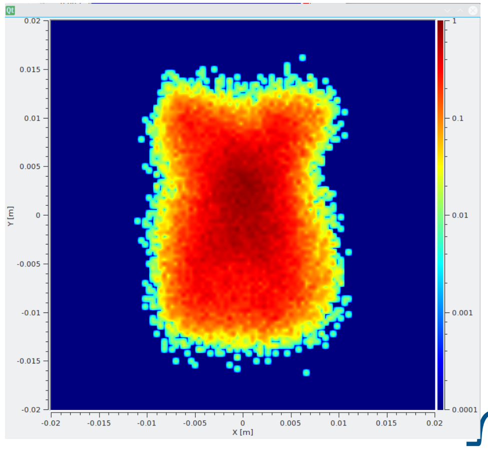
Injection Scheme Is Flexible

- Transverse painted emittances can be tuned using painting functions amplitudes
- Injection energy offset and/or phase range can be changed to optimize injected distribution
  - On-momentum injection with two phase windows was studied. No significant difference from the baseline solution. Lower losses in case of a large linac beam energy spread.
- Correlated painting can be implemented
  - Reduces number of parasitic foil hits (30% reduction), yielding reduced losses caused by scattering on the foil
  - Plan to continue exploring this as an option

On-momentum injection with two phase windows



Transverse beam profile after correlated painting with PIP-II intensity

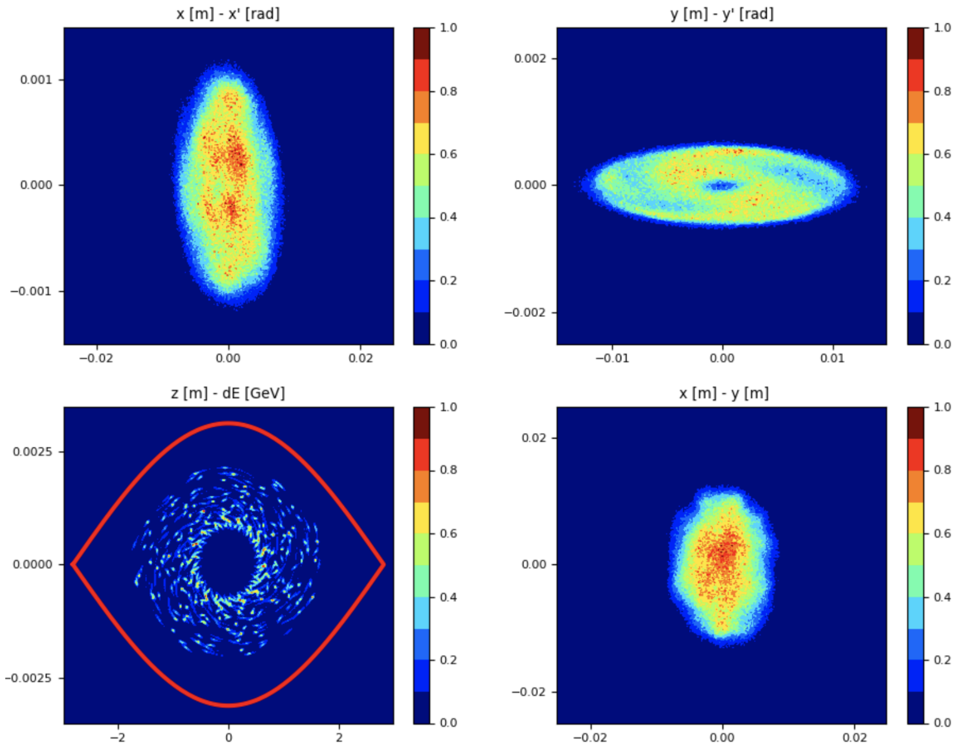


PIP-II

PyOrbit 6D Simulations of Booster Injection Painting

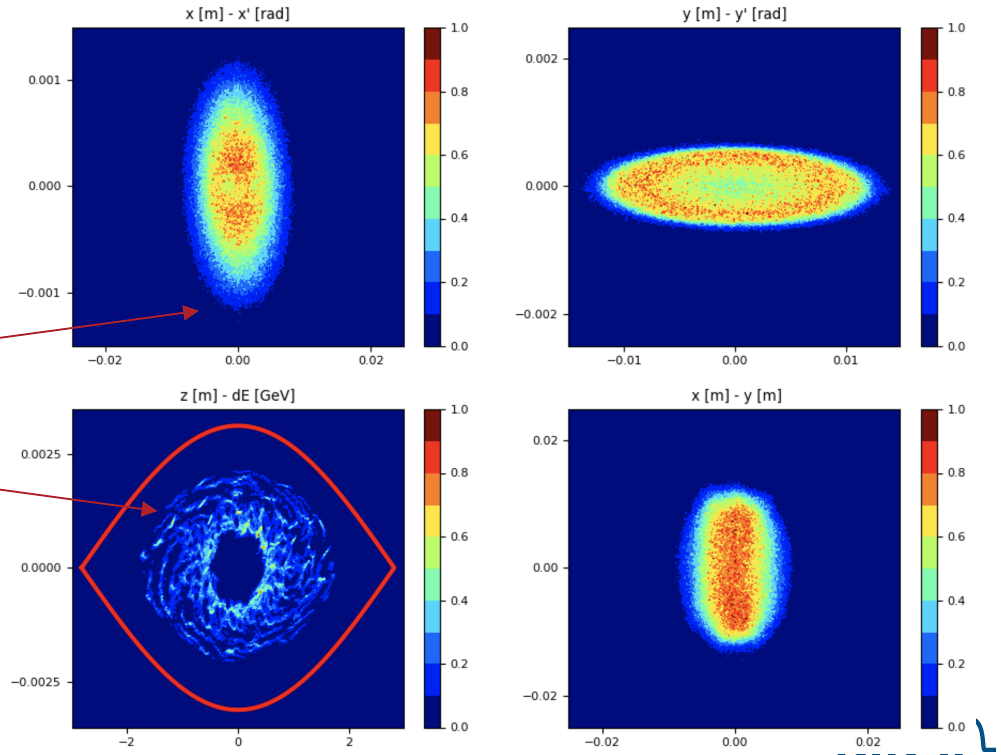
- No observed space charge driven losses at PIP-II intensity
- Modest impact of SC on beam quality
- Results support the validity of the CDR approach

No Space Charge
After Injection



~600k particles

6.7E12 H- per Booster cycle
After Injection



Some halo growth
Smeared distribution

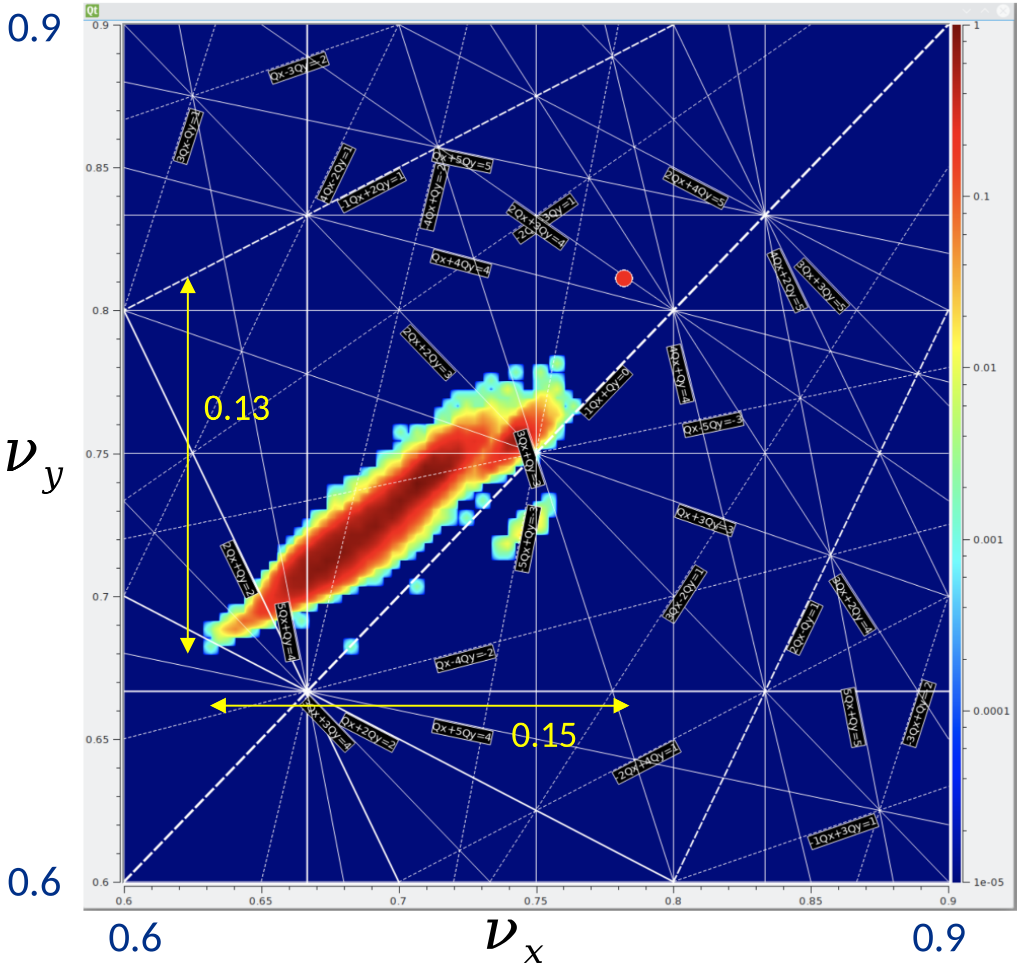
Simulated Tune Shift Is Small and Consistent with CDR Estimate

CDR estimated max. SC tune shift at 0.17

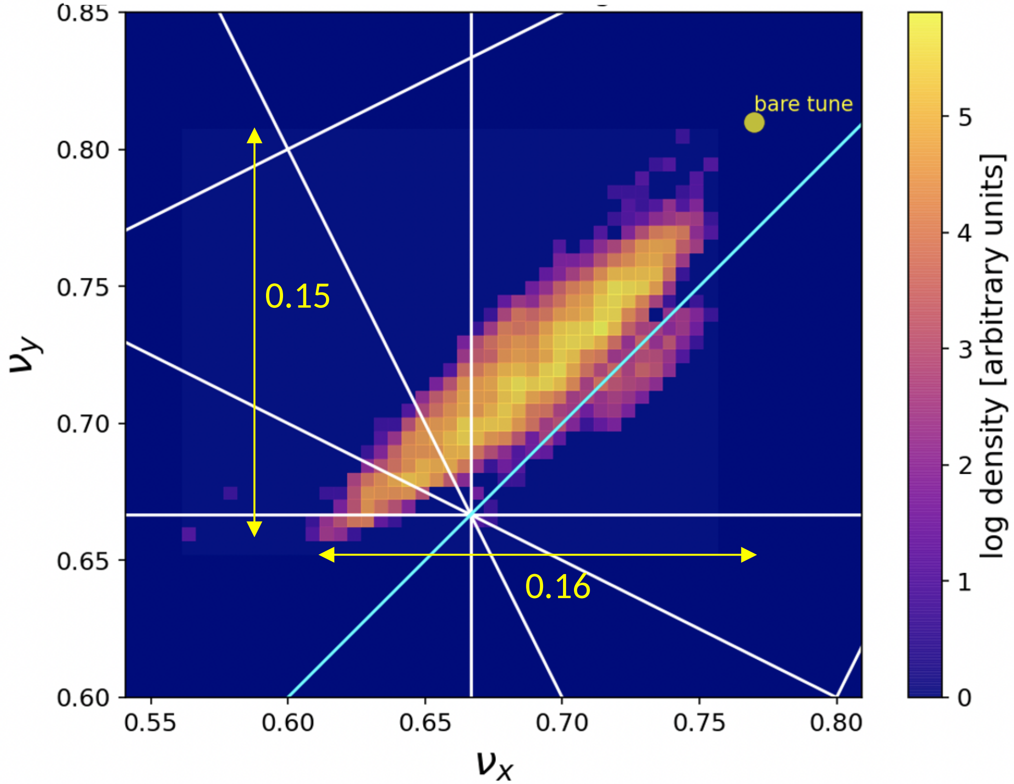
PyOrbit – 0.13, 0.15

Synergia – 0.15, 016

Tune footprint simulated with **PyOrbit**
(at the end of painting injection)

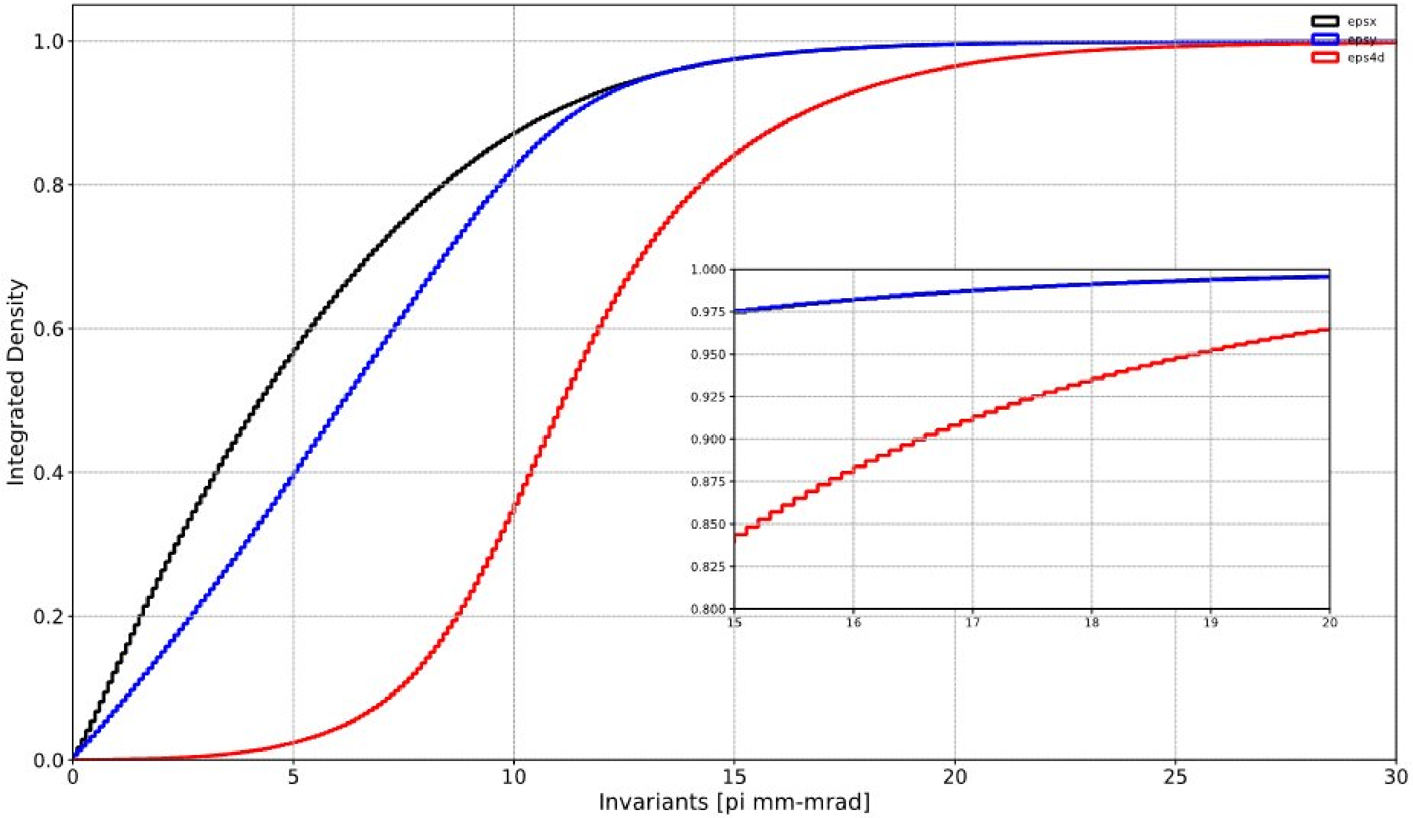


Tune footprint simulated with **Synergia**
(at the end of painting injection)



Emittances Simulated with PyOrbit

Normalized cumulative particle distribution as function of ϵ_x, ϵ_y, and $\epsilon_x + \epsilon_y$



95% emittance of Booster beam transferred to Recycler and acceptance of Recycler

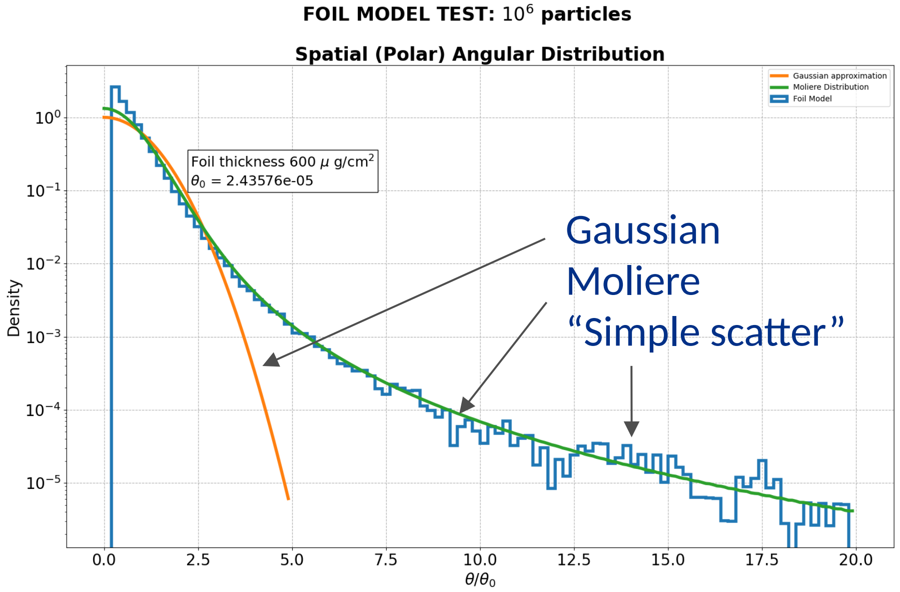
Parameter	Value
$\varepsilon_{x,y_{95\%}}$ of Booster beam transferred to Recycler	16 µm
Recycler acceptance	20 µm

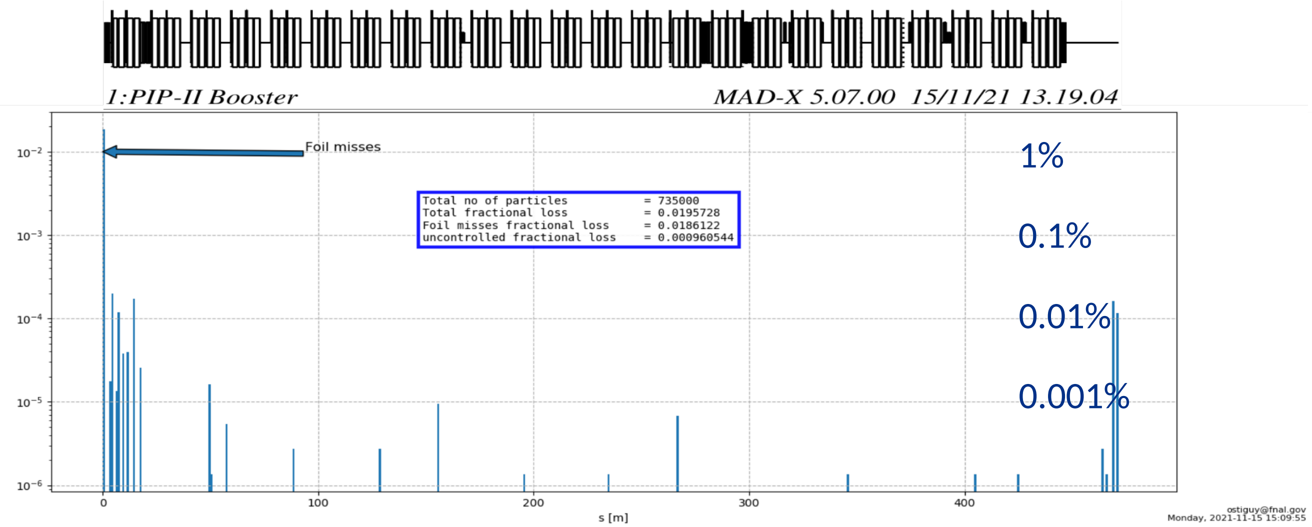
simulated with PyOrbit

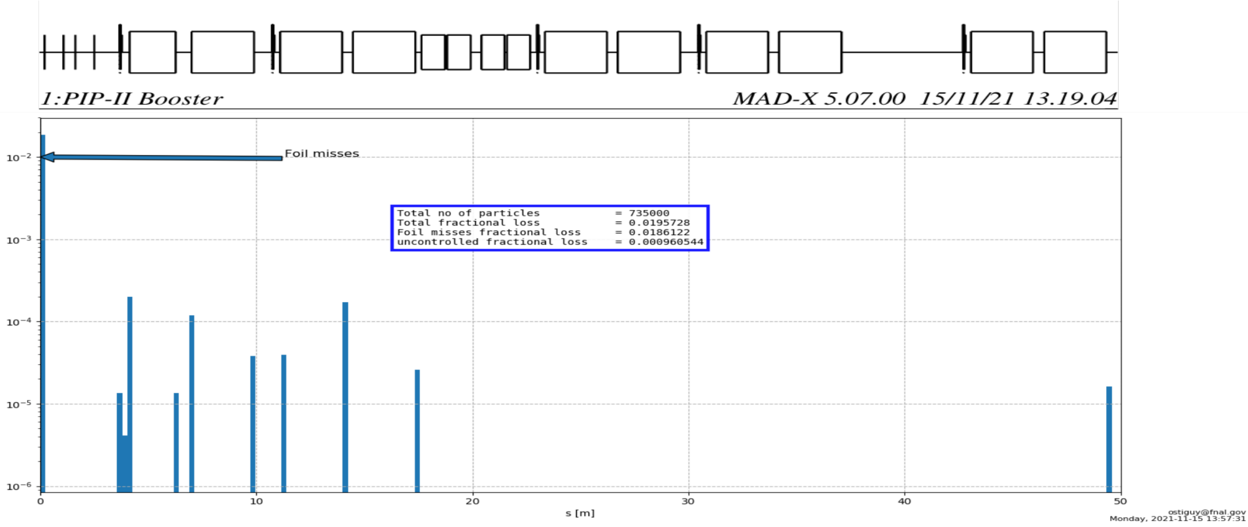
Plane	Value
Horizontal	~13 µm
Vertical	~13µm

Foil Model Integrated in the Simulations

- Simulated losses caused by large angle scattering
- Total loss < 10^{-3} (<17 W)
- Losses in the first few 4 dipoles ~2×10^{-4} (~3.4 W)
- Excited states do not contribute significantly to losses



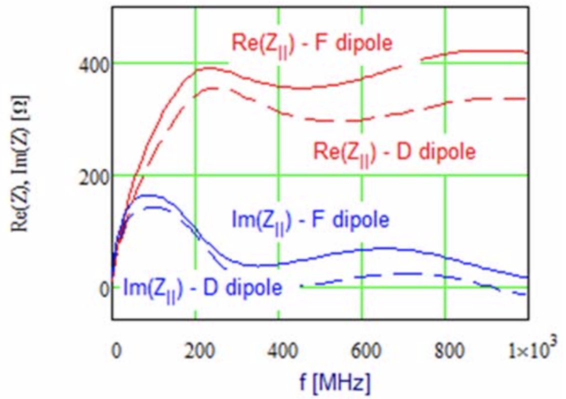




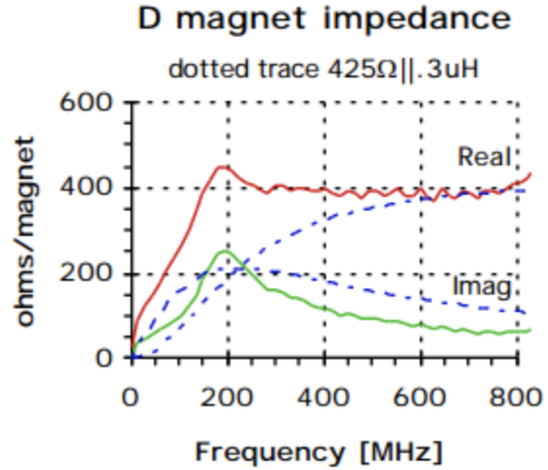
Transition Crossing

- Comprehensive, multi-particle, 1D simulations
  - Longitudinal space charge
  - Realistic longitudinal impedance
  - Dampers
  - Nonlinear chromaticity
  - Q-switch scheme using existing correctors
  - Results documented in CDR
- 1D simulations have been benchmarked against experimental data
- Simulations show Booster beam meets requirements after transition
- Practical realization of a Q-switch (or true gamma_t jump) scheme and the impact of achievable dγt/dt are being further investigated.

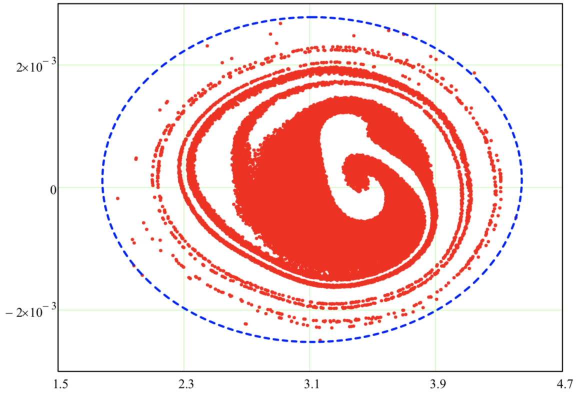
Impedance of Booster F and D magnets predicted by theory



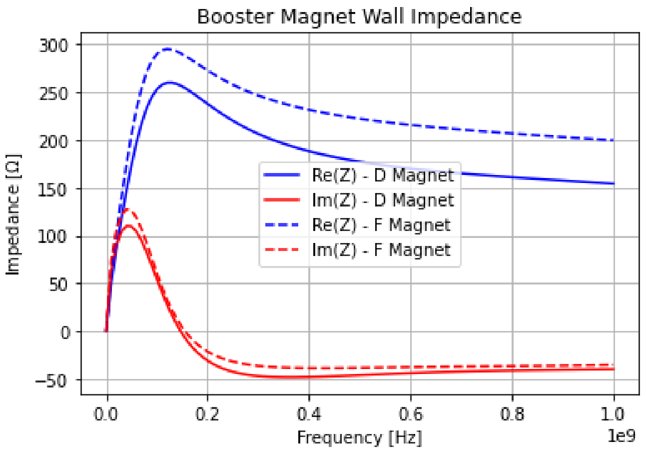
Measured impedance of a D-magnet

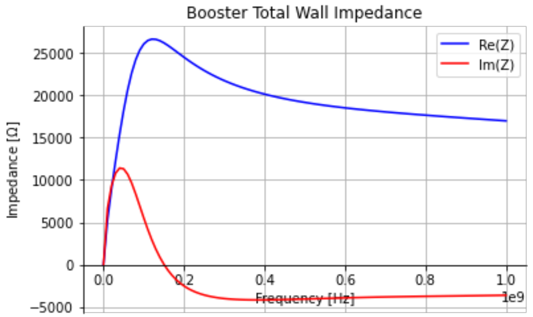


Simulated booster beam distribution at extraction. The blue dashed line shows the 0.1 eVs requirement.



Booster Laminated Wall impedance Model (Burov & Lebedev*)



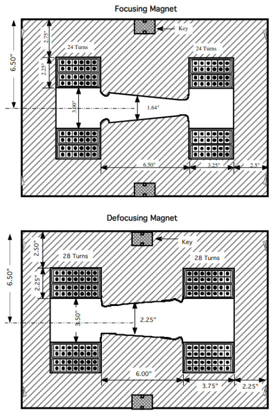


Inter-lamination gap $h = 20\ \mu m$

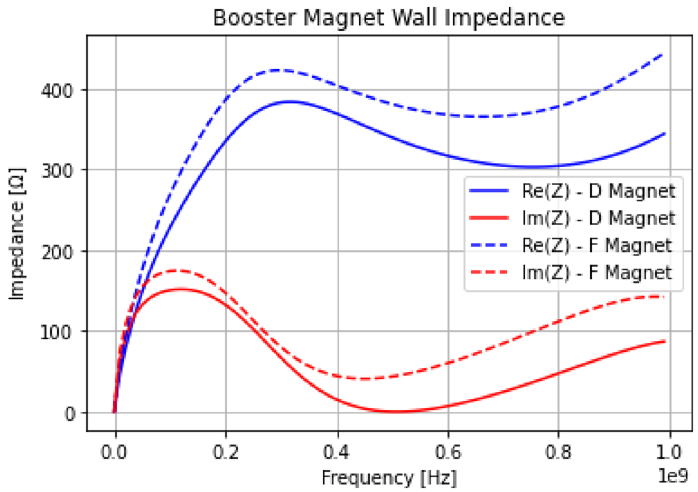
Depending on the size of the interlamination gap, the reactive part of the impedance may either compensate or enhance the space charge defocusing.

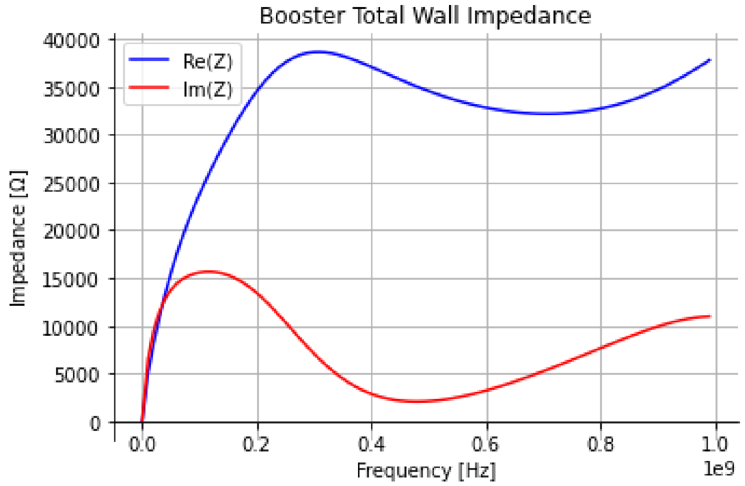
A most important feature of the wall impedance is the large magnitude of its resistive (lossy) part.

As a result of the energy loss, the bunch centroid rf phase is shifted ahead to preserve synchronism.



Beam is directly exposed to the laminations

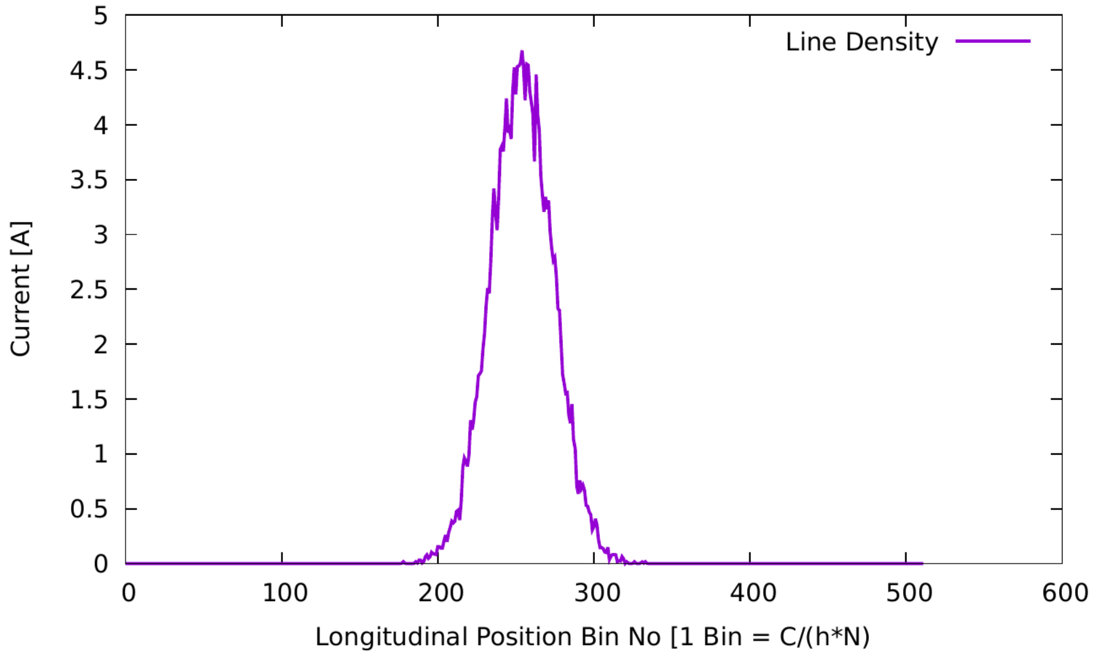




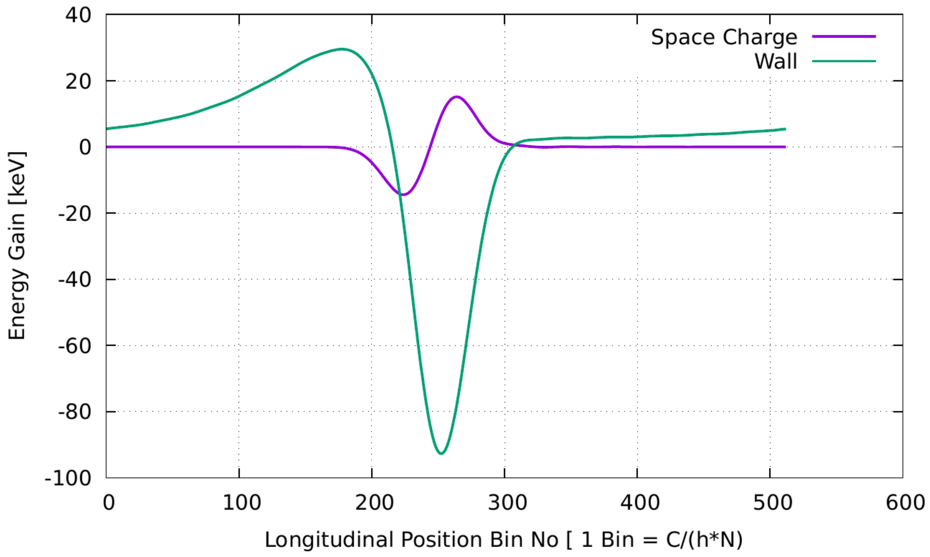
Inter-lamination gap $h = 60\ \mu m$

* Ref: FERMILAB-TM-2492-AD

Longitudinal SC and Impedance Contributions Near Transition



Test gaussian bunch



Energy gain computed by pyORBIT (SC + impedance kick)

Assumptions: Bunch width at transition 0.75 ns, Q = 4.3e12/h, gamma=5.45 (conditions for current 400 MeV Booster)

6D Simulation of a Booster Cycle with pyORBIT

While pyORBIT provides support for modeling acceleration, we encountered a number of practical and technical difficulties e.g.:

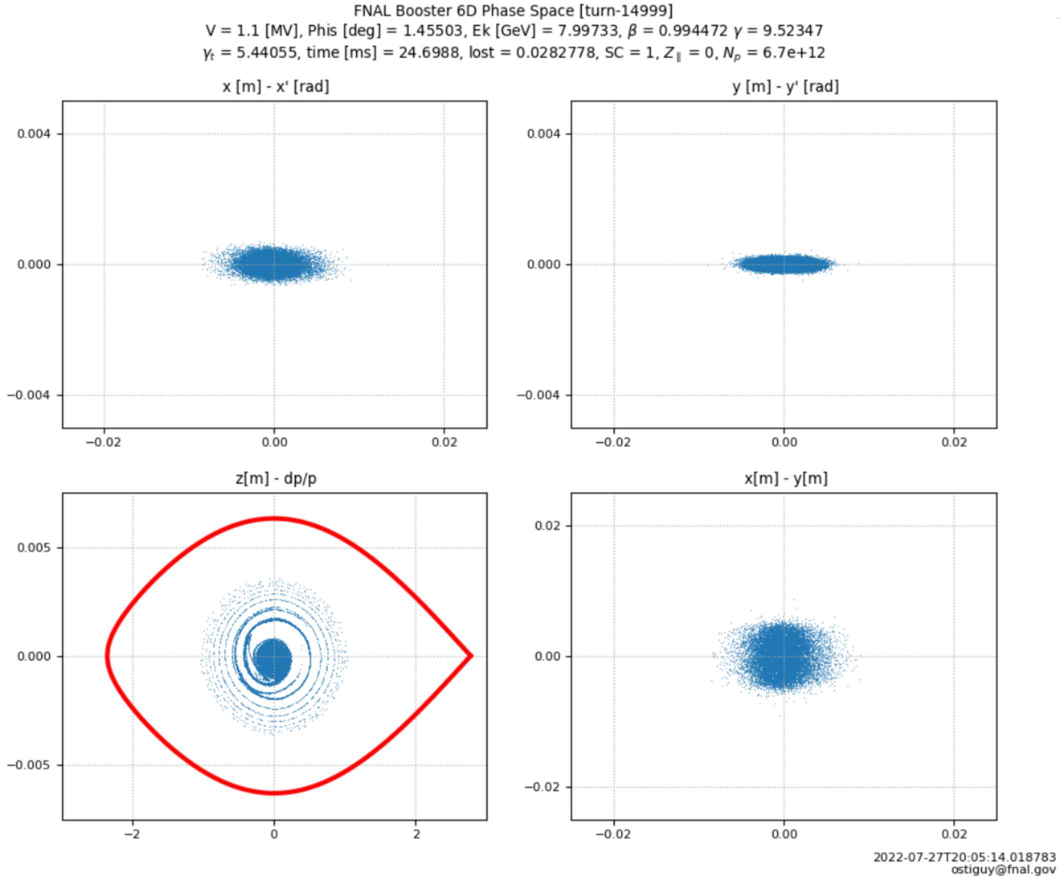
- Unlike in a 1d code, transition energy is not an explicit input; it must be determined directly and accurately from the pyorbit model. Element segmentation has an impact on the exact value for a given lattice therefore gamma_t must be computed by pyorbit.
- Longitudinal space charge not computed properly for a h > 1 machine (we modified the longitudinal SC calculator element to get agreement with a simple test case).
- Some ambiguity and/or inconsistency in the definition/specification of external impedances.
- Adiabatic damping is - as far as we could determine - not accounted for.
- Pyorbit relies on external rf amplitude and phase tables for the energy and phase of the synchronous particle. Although the transition gamma is required as an input parameter for an accelerating harmonic cavity, the parameter has no effect on the rf phase -- the phase curve needs to explicitly include the jump at transition energy. There is no convenient mechanism to adjust the timing or amplitude of the jump – the rf phase amplitudes curve must be externally regenerated. Optimizing the the rf curves is a tedious process.
- There is no readily available built-in support for modeling dampers.
- Pyorbit currently cannot easily compute the momentum compaction beyond first order (known to be important to control emittance blowup).
- …

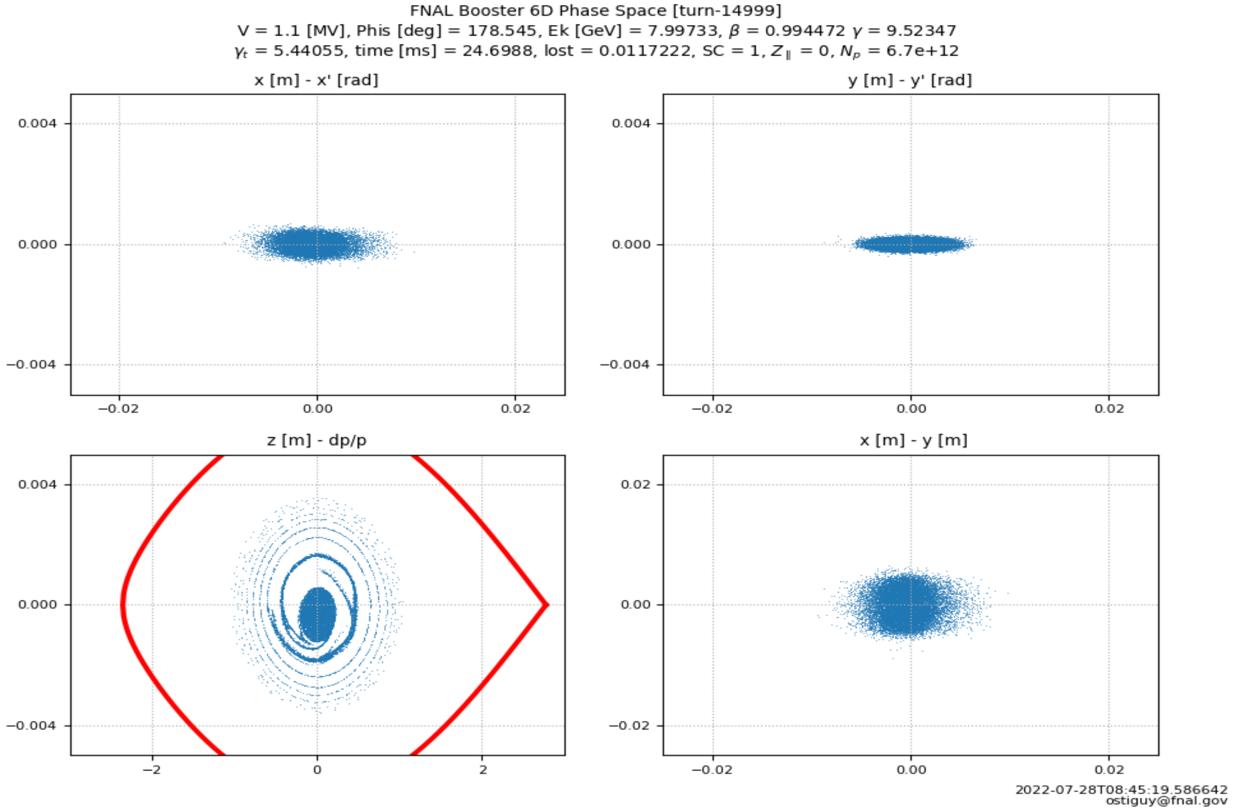
Status of Full Machine Cycle 6D Tracking Simulations

- Full cycle 6D tracking, but longitudinal space charge only for now (transverse sc turned off)*.
- Verified that without (resistive) longitudinal impedance, transition can be crossed with minimal losses by adjusting the transition timing (delay).
- With longitudinal wall impedance, the perturbation due to the resistive voltage near transition is severe, and without mitigation measures, observed losses are significant.
  This is not unexpected; earlier longitudinal only simulations indicate that successful transition crossing requires careful tuning of the gamma_t phase jump timing and amplitude together with active dampers (to limit losses) and some form of a Q-switch (to limit emittance blowup).
- Phase jump amplitude control dampers and Q-switch are currently being implemented/tested.
- Only when conditions resulting in acceptable losses at transition are achieved will tracking runs with full 3D space charge be initiated.

* a full booster cycle is 15000 turns. Even with a 2.5 D approximation, by extrapolating for previous experience with injection simulations (294 turns) , this represents >24 hr turnaround time on a midsize cluster.

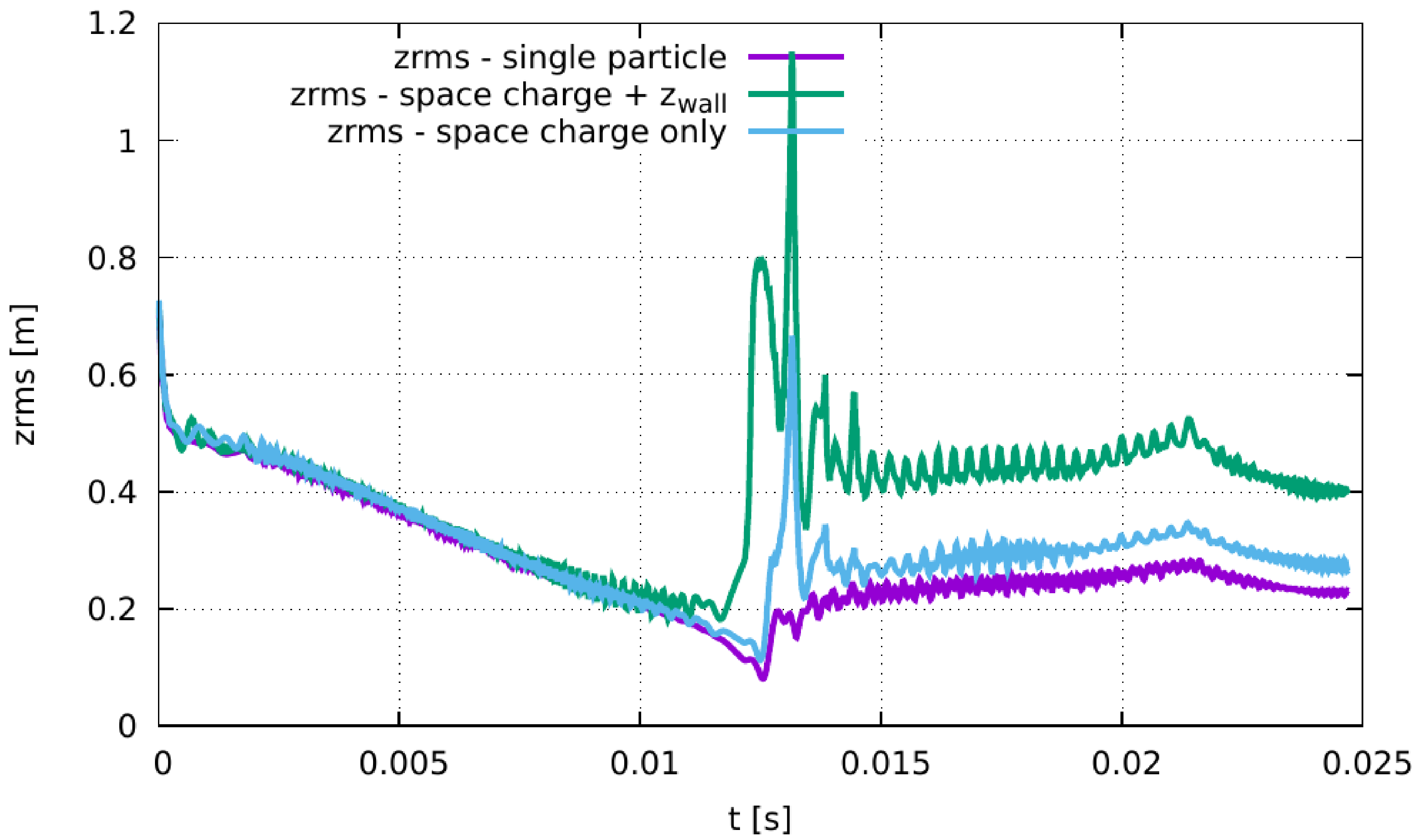
Delayed Gamma-t Jump





6 D with Longitudinal Space Charge only

RMS Bunch Size Evolution Through Transition



Note: Phase jump at gamma = gamma_t.

No transition timing or phase jump amplitude tuning.

Parting Remarks

- Comprehensive numerical simulations have confirmed the choice of parameters made at the conceptual design stage.
- Specifically, 6D simulations confirmed that the painting scheme results in a distribution with uniformity, tune shift/spread and emittances consistent with expectations.
- pyORBIT 6D simulations have provided useful information about the distribution of losses associated with foil scattering.
- No space charge induced losses at injection have been observed in simulation. Additional effort will be required to explore/observe possible impact of various types of lattice imperfections.
- Based on comprehensive, longitudinal only simulations, it is expected that transition losses can be kept at a very low level and longitudinal emittance blowup minimized to meet the requirements of the PIP-II project. This will be further validated experimentally in the coming months.
- We are continuing to pursue full 6D tracking simulations. So far, we have only been partially successful. We encountered a number of practical and technical issues that we hope to have the opportunity to discuss more at length with interested parties at this workshop.

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Summary slide, 5th ICFA mini-workshop on Space Charge
Theme: Bridging the gap in space charge dynamics

In 1-2 sentences, summarize the content of this presentation

Overview of the PIP-II project at Fermilab. Intensity in the existing Boooster rapid synchroton (protons) will be increased by 50%, cycle time reduced by 33% and injection energy doubled from 400 to 800 MeV. Injection painting will be introduced to miminize space charge tune shift (expected: 0.17). Space charge and lossy impedance are expected to be a significant perturbation at transition.

From your perspective, where is the gap regarding space charge effects? (understanding/control/mitigation/prediction/?)

Making useful, reliable numerical predictions remains a challenge. It is reasonable to expect theoretical advances to increasingly hinge more on controlled numerical experiments. Such experiments are an essential tool both to validate and understand the limitations of theoretical models.

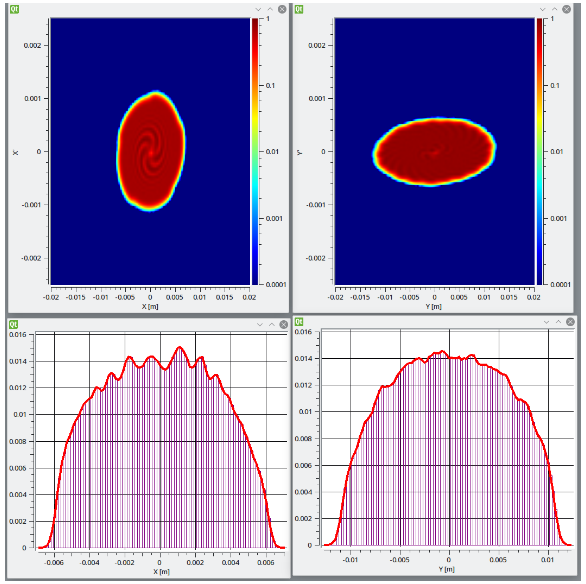
What is needed to bridge this gap?

Order(s) of magnitude scale improvements in performance. Systematic, long term commitment to develop and grow an appropriate software ecosystem. Timely use of available hardware innovations.

Backup

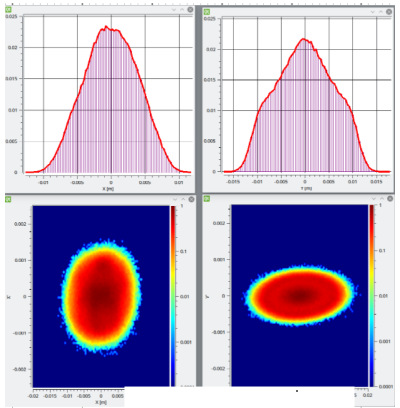
Painting a KV distribution

Anti-correlated ideal Sqrt(t) Painting

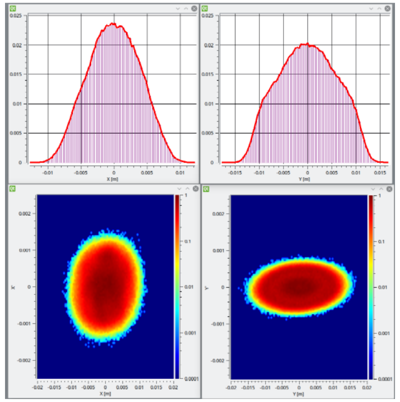


Difficult to realize in practice

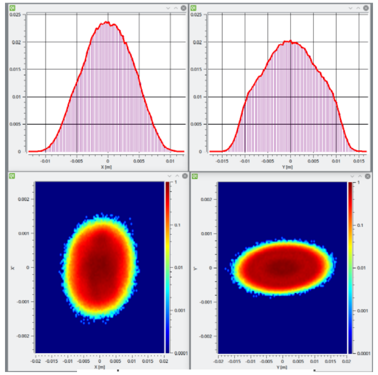
Anti-correlated Sinusoidal Painting



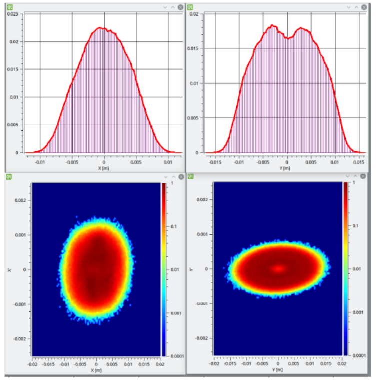
$\xi = 0$



$\xi = 0.08$



$\xi = 0.08$



$\xi = 0.12$