Simulation of Space-Charge Effects in the Proposed CERN PS2

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Outline

• S0: Introduction
• S1: Computational models
• S2: Initial benchmark with 0 current
• S3: Space-charge simulations of PS2 with effects:
  • Synchro-betatron coupling
  • Initial painting schemes
  • RF ramping schemes
• S4: Summary
S0: Introduction

- PS2 was proposed for LHC upgrade with higher injection energy (4 GeV) to mitigate the space-charge effects to reach higher number of protons per bunch ($4 \times 10^{11}$).

Figure 1: Overview on the CERN injector complex upgrade programme: stage 1 (green), stage 2 (orange).

Figure 2: Integration of PS2 within the existing and future CERN accelerator complex.

M. Benedikt, et al., PAC09, WE1GRI03
S1: Computational Models
MaryLie/IMPACT (ML/I)

- Combines capabilities of MaryLie code (A. Dragt, U Md) with IMPACT code (J. Qiang, R. Ryne, LBNL) + new features
- Multiple capabilities in a single unified environment:
  - Map generation
  - Map analysis
  - Particle tracking w/ 3D space charge
  - Envelope tracking
  - Fitting and optimization
- Recent applications: ERL for e-cooling @ RHIC; CERN PS2

- Parallel
- 5th order optics
- 3D space charge
- 5th order rf cavity model
- 3D integrated Green func
- Photoinjector modeling
- “Automatic” commands
- MAD-style input
- Test suite
- Contributions from LBNL, U Md, Tech-X, LANL,…

Map computation from surface data

Error in E-field computed w/ different algorithms applied to a 2D Gaussian elliptical distribution w/ 500:1 aspect ratio

Integrated Green Function on 64x64 grid is more accurate than Hockney on 64x2048, 64x4096, 64x8192.
IMPACT code suite

• IMPACT-Z: parallel PIC code (z-code)
• IMPACT-T: parallel PIC code (t-code)
• Envelope code, pre- and post-processors,…
• Optimized for parallel processing
• Applied to many projects: SNS, JPARC, RIA, FRIB, PS2, future light sources, advanced streak cameras,…
• Has been used to study photoinjectors for BNL e-cooling project, Cornell ERL, FNAL/A0, LBNL/APEX, ANL, JLAB, SLAC/LCLS

One Billion Macroparticle Simulation of an FEL Linac (~2 hrs on 512 processors)
IMPACT-Z

- Parallel PIC code using coordinate “z” as the independent variable

- Key Features
  - Detailed RF accelerating and focusing model
  - Multiple 3D Poisson solvers
    - Variety of boundary conditions
    - 3D Integrated Green Function
  - Multi-charge state
  - Machine error studies and steering
  - Wakes
  - CSR (1D)
  - Run on both serial and multiple processor computers
Particle-in-cell simulation with split-operator method

- Particle-in-cell approach:
  - Charge deposition on a grid
  - Field solution via spectral-finite difference method with transverse rectangular conducting pipe and longitudinal open
  - Field interpolation from grid to particles

- Split-operator method with $H = H_{\text{external}} + H_{\text{space charge}}$
- Thin lens kicks for nonlinear elements
- Lumped space-charge at a number locations
Poisson Solver Used in Space-Charge Calculation

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = -\frac{\rho}{\varepsilon_0}
\]

with boundary conditions

\[
\phi(x = 0, y, z) = 0, \\
\phi(x = a, y, z) = 0, \\
\phi(x, y = 0, z) = 0, \\
\phi(x, y = b, z) = 0, \\
\phi(x, y, z = \pm \infty) = 0,
\]

\[
\rho(x, y, z) = \sum_{l=1}^{N_l} \sum_{m=1}^{N_m} \rho^{lm}(z) \sin(\alpha_l x) \sin(\beta_m y),
\]

\[
\phi(x, y, z) = \sum_{l=1}^{N_l} \sum_{m=1}^{N_m} \phi^{lm}(z) \sin(\alpha_l x) \sin(\beta_m y),
\]

where

\[
\rho^{lm}(z) = \frac{4}{ab} \int_0^a \int_0^b \rho(x, y, z) \sin(\alpha_l x) \sin(\beta_m y),
\]

\[
\phi^{lm}(z) = \frac{4}{ab} \int_0^a \int_0^b \phi(x, y, z) \sin(\alpha_l x) \sin(\beta_m y),
\]

\[
\frac{\partial^2 \phi^{lm}(z)}{\partial z^2} - \gamma_{lm} \phi^{lm}(z) = -\frac{\rho^{lm}(z)}{\varepsilon_0},
\]

\[
\phi^{lm}_{n+1} - 2\phi^{lm}_n + \phi^{lm}_{n-1} - \gamma_{lm} \phi^{lm}_n = -\frac{\rho^{lm}_n}{\varepsilon_0},
\]

\[
\phi^{lm}_{n=0} = \exp(-\gamma_{lm} h_z) \phi^{lm}_0, \\
\phi^{lm}_{n=N} = \exp(-\gamma_{lm} h_z) \phi^{lm}_N,
\]
Parallel Implementation: Domain-Decomposition vs. Particle Field Decomposition

- In the application where the number of macroparticles is not dominant, the domain-decomposition has a better scalability than the particle-field decomposition.
S2: Initial Benchmark with 0 Current
Parameters of Simulations for 2010 PS2 Lattice

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Physical Parameters:
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Vrf = ramping with f = 39.3 MHz
Ek = 4 GeV
Emit_x = Emit_y = 3 mm-mrad
Emit_z = .098 eV-sec

Half Aperture = 6.3cm x 3.25 cm
I = 4.0x10^{11}

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Numerical Parameters:
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70 SC per turn
65x65x128 grid points
939,000 macroparticles
IMPACT and ML/I agreed on single-particle trajectories.
Power Spectrum of 0 mom. Dev and off mom. Particle Trajectories

- Single particle calculation to reproduce the machine lattice bare tunes
- Off-momentum particle shows the same tune as the 0 momentum particle due to 0 chromaticity
S3.1: Effects of Synchro-Betatron Coupling
Betatron Tune Footprint with 0 Current and with SC but no Synchroton Motion
Betatron Tune Footprint with 0 Current and with SC and Synchrotron Motion
Transverse Emittance Growth with/without Synchrotron Motion
S3.2: Effects of Initial Painted Distribution
Initial Longitudinal Distribution from Painting

Hallow Current Profile

Parabola Current Profile
Transverse Emittances vs. Turns

- A few percentage emittance growth after 6k turns using an initial hallow painted distribution
- A few percentage emittance growth after 21k turns using parabolic painted distribution
• About 0.24% particle loss after 6k turns using an initial hallow painted distribution

• Only 1 particle out of a million lost in 21,000 turns using the parabolic painted distribution.
S3.3: Effects of RF Ramping
RF Voltage Ramping and Beam Kinetic Energy Evolution
100 ms vs. 50 ms RF Ramping
Fractional Particle Loss and Maximum Phase Amplitude
100 ms vs. 50 ms RF Ramping

- Faster RF ramping causes more particles lost out of RF bucket
Evolution of Longitudinal Centroid and RMS Size with 100 ms and 50 ms RF Ramping
Transverse Emittances with 100 ms and 50 ms RF Ramping

- Slightly larger emittance growth with faster RF ramping
Nominal and New RF Voltage Ramping

RF voltage ramping

kinetic energy evolution with nominal and new RF ramping
Transverse Emittance Growth with Nominal and New RF Ramping

Transverse emittance evolution with nominal and new RF ramping

- X - New
- Y - New
- X - Nominal
- Y - Nominal

emittance growth (%)

turn

21912.5, 7.77569
Longitudinal RMS Size Evolution with Nominal and New RF Ramping
S4: Summary

- Space-charge effects can cause significant beam emittance growth and particle losses at PS2
- Synchro-betatron coupling with 3D space-charge forces causes extra tune spread and emittance growth
- Better painted longitudinal distribution help reduce emittance growth and particle losses
- Optimizing RF voltage and phase ramping help reduce emittance growth and particle losses