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Advanced Proton Booster Design (Integrable Optics for High Intensity Beams)

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Fermilab Proton Accelerator Facility

(Proposed) PIP-III Intensity Upgrade

Rapid-Cycling Synchrotron Design

- Modern RCS design calls for several features:
 - Dispersion-free drifts, for RF
 - Low momentum compaction factor, to avoid transition.
 - Low beta functions, for maximum emittance per aperture.
 - Mitigation of collective instabilities, throughout the ramp.
- Integrable optics design is a promising innovation to provide significant nonlinear focusing with two invariants of motions.
- But first, it is necessary to demonstrate integrable optics is still helpful in the presence of strong space-charge forces.

Danilov-Nagaitsev Integral Design

Time-independent kick:

NL Insert

Achromatic Tins Arc

Nonlinear kick separable in elliptic coordinates:

V. Danilov, S. Nagaitsev "Nonlinear Lattices with One or Two Analytic Invariants" PRST-AB 2010.

Integral Design with Periodicity

Multiple Periodic Cells:

iRCS v2 Lattice Parameters

Lattice functions for

Periodicity: **6**

Circumference: **542 m**

Bend-radius rho: **15.4 m**

Max Beta function: **35 m**

Insertion length: **11.2 m**

Betatron Tune: **16.8**

Insert Phase-Advance: **0.3**

Nonlinear t-value: **0.15**

Minimum c-value: **3 cm**

Beta at insert center: **4 m**

Corrected Chromaticity: **-7.7**

Natural Chromaticity: **-33**

Second-order Chromaticity: **-132**

Synergia Simulation of Halo formed by Beam Mismatched

Simulation Parameters

- Coasting proton beam with 3D PIC space-charge.
- Injection energy of 0.8 GeV.
- Initial normalized emittance 20 mm mrad.
- 2D Waterbag beam initially distributed along equipotential contours except with a 20% mismatch.
- 500 revolutions of iRCS (3000 iterations of periodic cell).
- Phase advance through insert $d\Phi = 0.3$
- Nonlinear strength parameter $t = 0.3$
- 1 Conventional Design, Low Intensity Beam ($dQ = -0.05$)
- 2 Integrable Design, Low Intensity Beam ($dQ = -0.05$)
- 3 Conventional Design, High Intensity Beam ($dQ = -0.20$)
- 4 Integrable Design , High Intensity Beam ($dQ = -0.20$)

RMS Beam Size

1 Conventional, Low Int.

2 Integrable, Low Int.

3 Conventional, High Int.

4 Integrable, High Int.

Transverse Beam Halo

1 Conventional, Low Int.

2 Integrable, Low Int.

3 Conventional, High Int.

4 Integrable, High Int.

Cell Betatron Tune Distribution

1 Conventional, Low Int.

2 Integrable, Low Int.

3 Conventional, High Int.

4 Integrable, High Int.

Ring Betatron Tune Distribution

Description	90% Horizontal Tune Spread	90% Vertical Tune Spread
1 Conventional, Low Int.	0.044	0.044
2 Integrable, Low Int.	0.12	0.18
3 Conventional, High Int.	0.16	0.16
4 Integrable, High Int.	0.15	0.25

Nonlinear Parameters

Space-charge tune shift **$dQ = -0.05, -0.20$**

Phase advance through Insert **$d\Phi = 0.3$**

Nonlinear strength parameter **$t = 0.3$**

Mismatched Waterbag with Chromatic Tune Shift

Simulation Parameters

- Chromaticity doesn't have to be zero, it just has to be matched between horizontal and vertical.
 - Webb, Bruhwiler, Valishev, Nagaitsev, Danilov “Chromatic and Dispersive Effects in Nonlinear Integrable Optics” PR-AB (Submitted).
- Nominal momentum spread based on zero-charge longitudinal simulation of RF capture of injected beam.
- Chromaticity (matched horiz. & vert.): **-33**
- Chromatic tune-shift (nominal): **0.25%**
- **2** Integrable Design, **Low** Intensity, $\sigma_p = 0$ (**Monoenergetic**)
- **5** Integrable Design, **Low** Intensity, $\sigma_p = 0.250\%$ (**Nominal**)

RMS Beam Size

2 Integrable WB, $\sigma_p = 0$

6 Integrable WB, x20 σ_p

Transverse Beam Halo

2 Integrable WB, $\sigma_p = 0$

5 Integrable WB, Nominal σ_p

Cell Betatron Tune Distribution

2 Integrable WB, $\sigma_p = 0$

5 Integrable WB, Nominal σ_p

The chromatic tune-shift occurs diagonally and the amplitude tune-spread occurs off-diagonally.

No evidence particles are bound by the resonance lines.

Higher Periodicity Lattice, Higher charge

iRCS v2 Lattice Parameters

Lattice functions for

Periodicity: **6**

Circumference: **542 m**

Bend-radius rho: **15.4 m**

Max Beta function: **35 m**

Insertion length: **11.2 m**

Betatron Tune: **16.8**

Insert Phase-Advance: **0.3**

Nonlinear t-value: **0.15**

Minimum c-value: **3 cm**

Beta at insert center: **4 m**

Corrected Chromaticity: **-7.7**

Natural Chromaticity: **-33**

Second-order Chromaticity: **-132**

iRCS v3 Lattice Parameters

Periodicity: **12**

Circumference: **636 m**

Bend-radius rho: **15.4 m**

Max Beta x,y function: **25 m**

Max Dispersion function: **0.22 m**

RF Insertion length: **7.2 m, 2x 1.4m**

NL Insertion length: **12 m**

Insert Phase-Advance: **0.3**

Minimum c-value: **3 cm**

Beta at insert center: **2.2 m**

Betatron Tune: **21.6**

Natural Chromaticity: **-74**

Cell Betatron Tune Distribution

4 Periodicity 6, $dQ = 0.2$

6 Periodicity 12, $dQ = 0.4$

RMS Beam Size

4 Periodicity 6, $dQ = 0.2$

6 Periodicity 12, $dQ = 0.4$

Transverse Beam Halo

4 Periodicity 6, $dQ = 0.2$

6 Periodicity 12, $dQ = 0.4$

Summary & Upcoming Work

Summary:

- Integrable optics provide a **large nonlinear tune-spread** without introducing new resonances and can be used to **mitigate the formation of beam halo**.
- Integrable optics is reasonably tolerant to space-charge and chromatic **phase-errors**.
- New lattice will examine advantages of high periodicity.

Upcoming Work:

- Analyze particles trajectories to better understand the physics.
- Use random quad errors to **break periodicity** and investigate effects of integrable optics.
- **Bunched beam** with RF and 3D space-charge forces.