Fermilab

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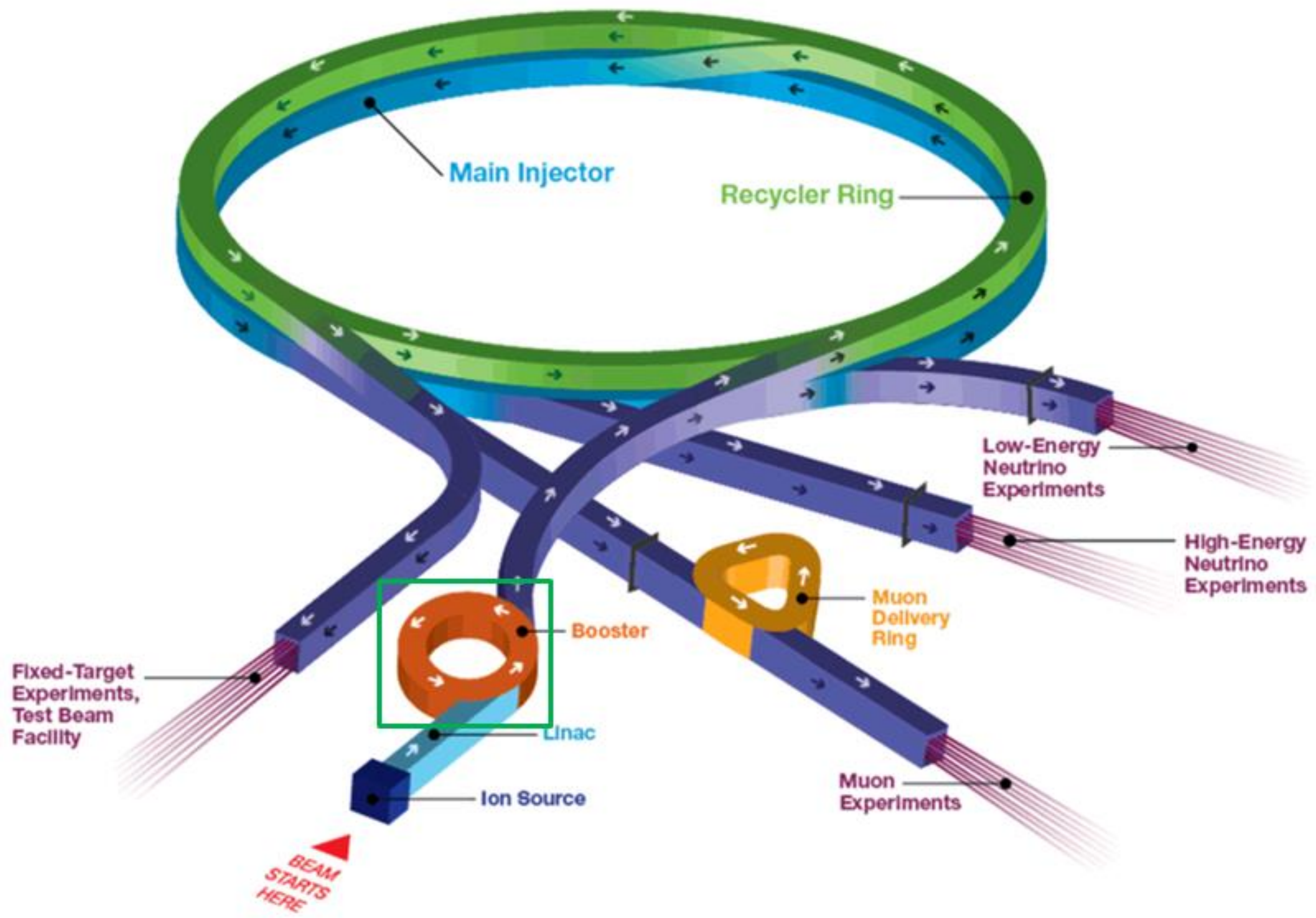
RCS for Multi-MW Facility at Fermilab

Jeffrey Eldred

MW Rings Workshop at Fermilab

May 2018

Fermilab Proton Accelerator Facility



Booster Performance

Booster improvement is an **ongoing effort**

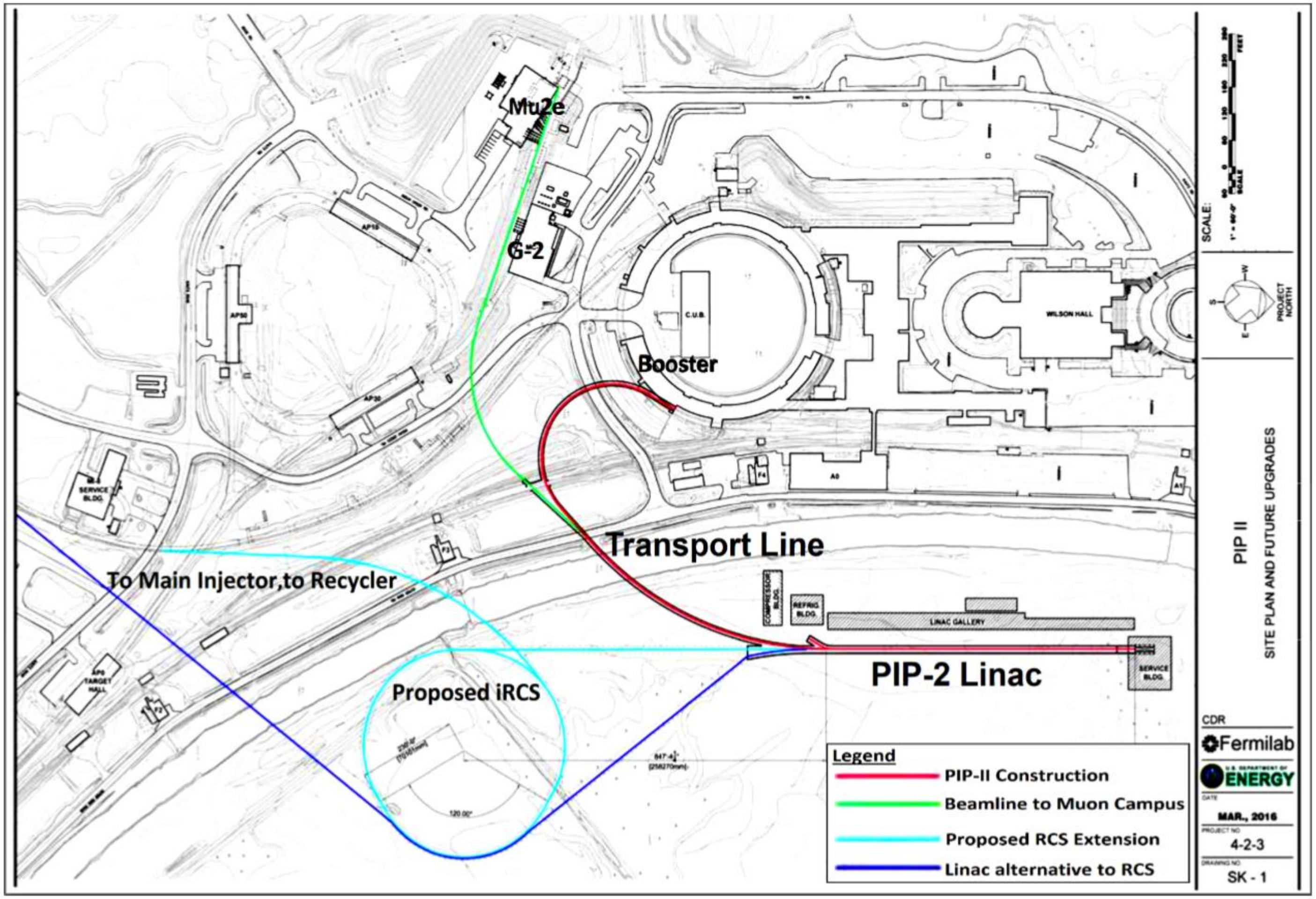
Yesterday's talks provide a good overview.

Known challenges include:

1. Transition crossing.
2. Impedance effects from dipole laminations.
3. Space-charge forces at injection.
4. Lattice optics correction.

New RCS for Multi-MW Facility

(Proposed) RCS Intensity Upgrade



Benefits of Modern RCS Design

Eliminate Transition Crossing

Lattice Improvements for Injection Intensity

- Higher periodicity, for suppression of harmonic resonances.
- Lower maximum beta functions, for greater beam acceptance.
- Well-characterized separate-function magnets, for better optics.

Other Improvements

- Reduce sources of impedance.
- Dispersion-free RF acceleration.
- Perpendicular-bias RF cavities.
- Low-SEY coating for mitigation of electron cloud.

Basic Scenario – Intense Boxcar Stacking

PIP-II for **1.2 MW** at 120 GeV:

- Booster intensity of **6.5e12** with 20Hz ramp-rate.
- Slip-stacking in Recycler.
- **12** batches in Main Injector with **1.2 sec** ramp.

RCS for **2.4 MW** at 120 GeV:

- RCS intensity of **36e12** with 20Hz ramp-rate.
- Boxcar stacking in Recycler (**no slip-stacking**)
- **5** batches in Main Injector with **1.4 sec** ramp.

To achieve 2.4 MW, we need to quadruple the linear charge density.

If we can do that, an RCS opens options for even higher power.

Laslett Tune Shift

Laslett tune-shift:

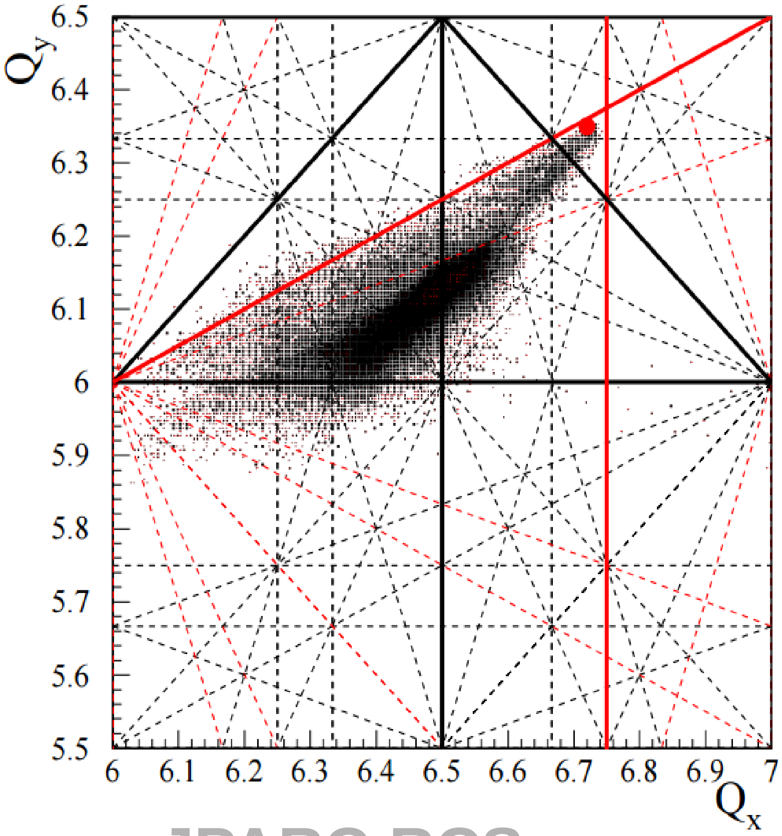
$$\Delta\nu \approx \frac{N r_0}{2\pi\epsilon_N \beta\gamma^2} F B$$

Space-Charge Limit:

$$N \sim \epsilon_N \times \beta\gamma^2 \times \Delta\nu_{\mathrm{max}}$$

↓

v = 6.5 half-integer resonance constrains Booster to 0.3-0.35



JPARC RCS:
Hotchi et. al.

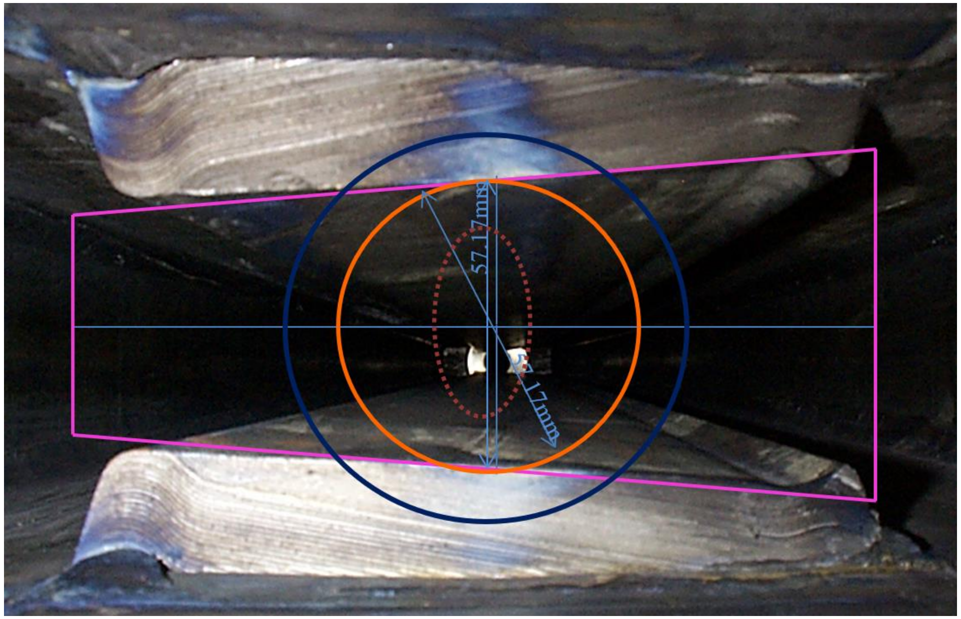
Aperture and Emittance

The vertical gap in the Booster is **5.72 cm (2.25”)** at the location where **β_y = 35 m**.

$$y_{\mathbf{max}} = \sqrt{\left(\frac{\epsilon_{N,\mathbf{max}}}{\beta\gamma}\right)\beta_{y,\mathbf{max}}}$$

This determines the Booster 95% normalized emittance of **15 mm mrad.**

An RCS with smaller betas or higher injection energy can reach a 95% normalized emittance of **30 mm mrad** at the same aperture.



T.K. Kroc

Space-Charge Limit:

$$N \sim \epsilon_N \times \beta\gamma^2 \times \Delta\nu_{\mathbf{max}}$$

Baseline RCS Lattice

Simple FODO Lattice

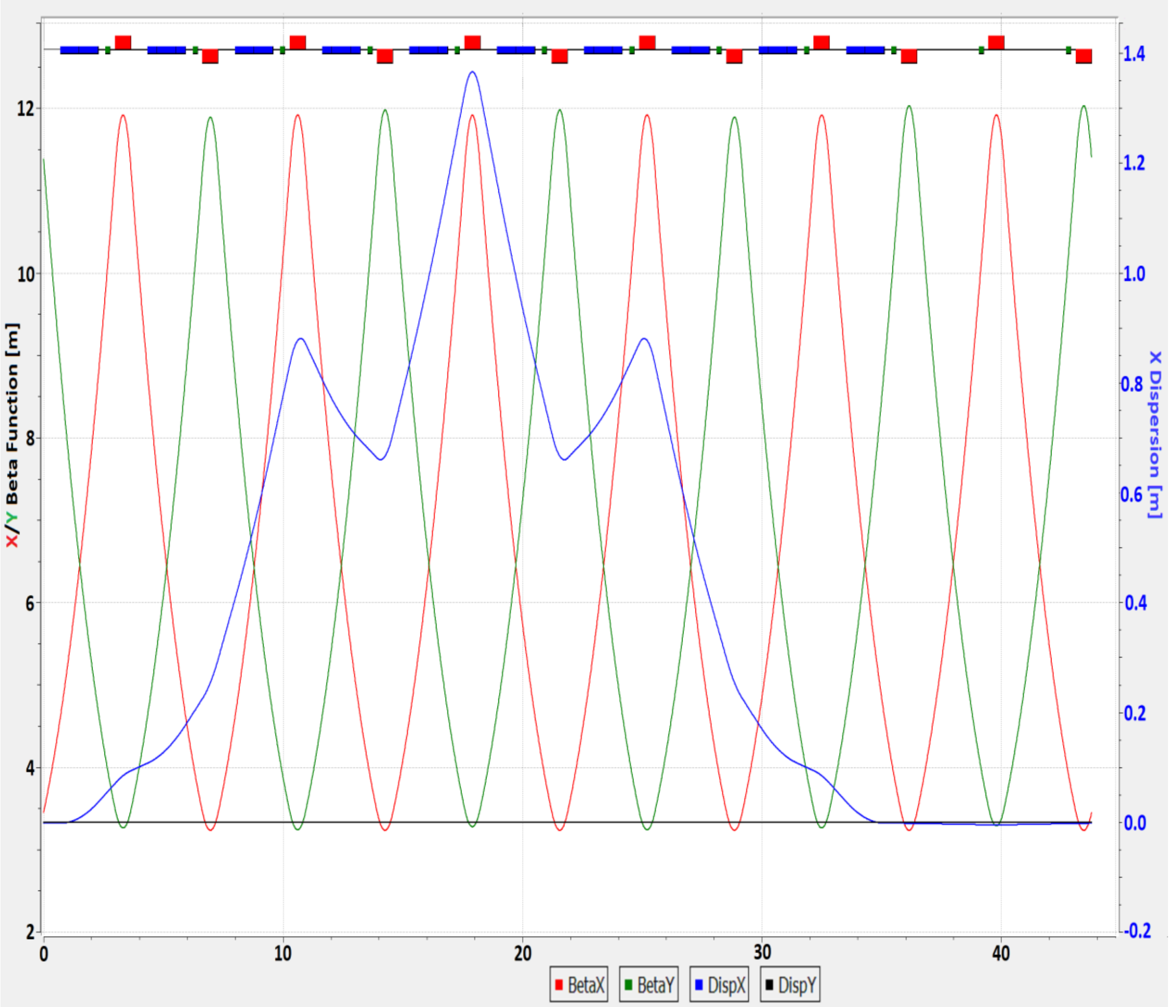
Avoids Transition

Dispersion-free Arcs

Low Max Beta

Circumference 553 m

Backup slides give additional details.



V. Lebedev

J-PARC RCS as Precedent

The J-PARC RCS shows intensity of **83e12** protons, **1 MW** extracted beam power, **0.30 tune-shift**. **Hotchi et al. PRAB 2017.**

This design has a large aperture (x12 Booster) and goes to 3 GeV. Our ring needs higher energy and cannot benefit from that aperture.

Ring Scaling Exercise:

- Scale up injection energy, scale up circumference, scale down aperture, scale down max beta, scale up bunching factor
- Keep the ratios between beampipe acceptance, collimator acceptance, and geometric emittance fixed. Keep maximum space-charge tune-shift fixed.
- Extraction energy **10 GeV**, normalized emittance is **30 mm mrad**, dipole **gap 5.4 cm**, beam intensity **36e12**, tune-shift **0.30** .

Eddy Currents in Vacuum Chamber

Vacuum chamber radius a: 2.8 cm.
Ramp rate: 20 Hz

Vacuum chamber heating power by eddy currents

$$\frac{dP}{dz} = \frac{\pi \sigma_r d a^3}{2c^2} \omega^2 B_{AC}^2$$

1.28mm Steel-316: 108 W/m
0.75mm Inconel-625: 36 W/m

Conservative air cooling estimate of convective cooling heat transfer coefficient 10^{-3} W/cm^2/K

1.28mm Steel-316: ΔT = 60 K
0.75mm Inconel-625: ΔT = 20 K

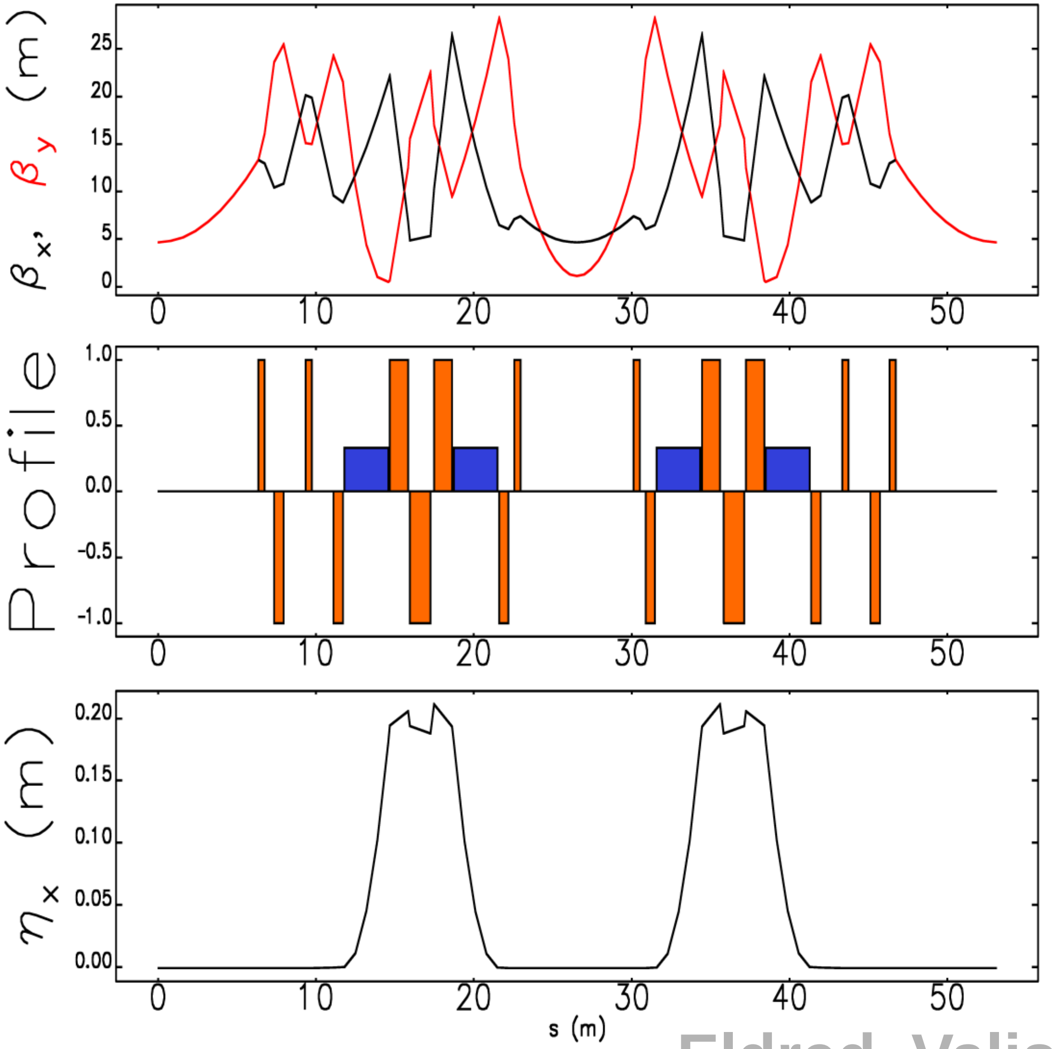
Integrable RCS Design

An RCS based on demonstrated design principles can reach the performance we need based to achieve 2.4 MW at Fermilab.

The RCS upgrade scenario is not contingent on integrable design.

But integrable RCS lattice designs are worth studying. Strong nonlinear focusing offers a way to suppress halo formation and enhance Landau damping.

Integrable RCS Lattice design



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, 4x 1.3m**

NL Insertion length: **12.7 m**

Insert Phase-Advance: **0.4**

Minimum c-value: **3 cm**

Beta at insert center: **5 m**

Betatron Tune: **21.6**

Natural Chromaticity: **-79**

Second-order Chromaticity: **1600**

Synchrotron Tune: **0.08**

Eldred, Valishev IPAC 2018

Space-charge Simulation of iRCS

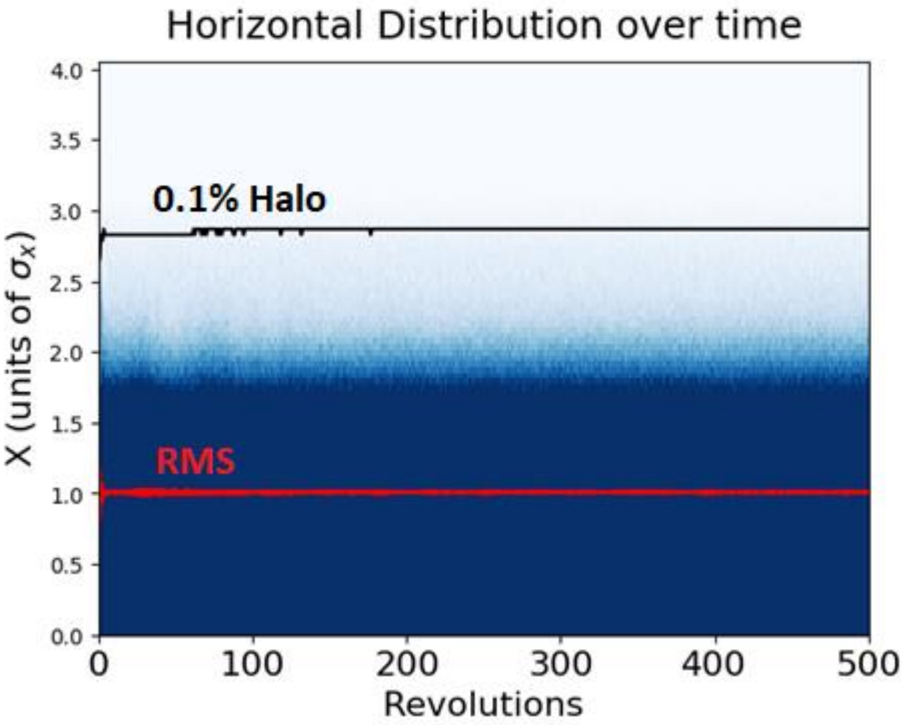
Beam injected with 20% mismatch

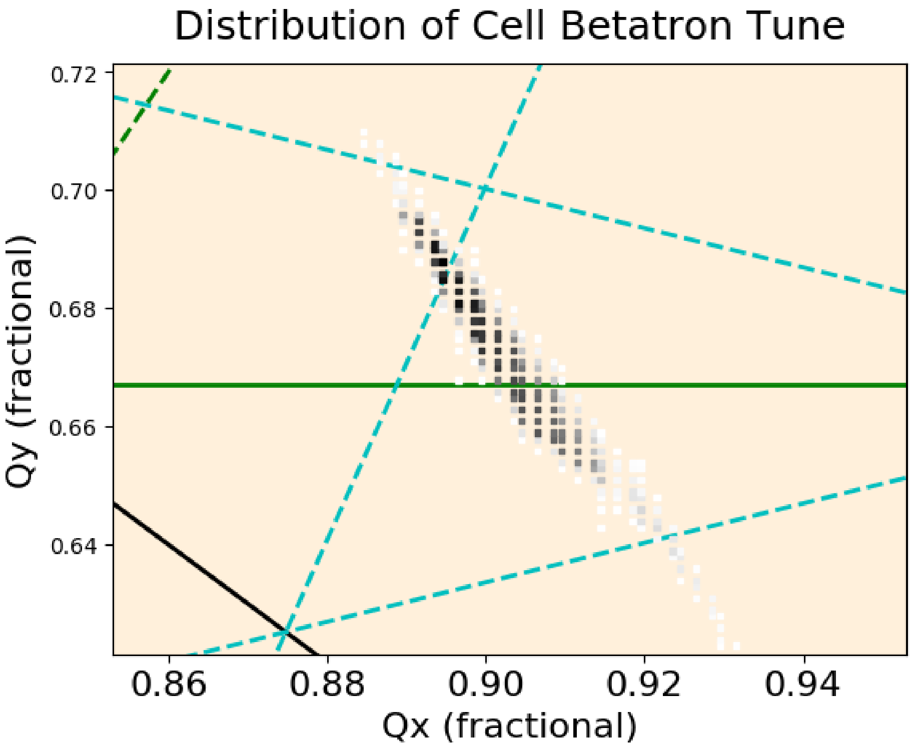
Laslett tune-shift of 0.4, corresponding to 32e12 protons.

Beam stable 5000 revolutions, halo strongly suppressed.

Caveat: Perfect lattice with no errors.

Eldred, Valishev IPAC 2018


Horizontal Distribution over time


Distribution of Cell Betatron Tune

Implications for Linac, Recycler and Main Injector

PIP-II Linac for new RCS

PIP-II Linac

- MEBT chops 5 mA RFQ current to 2 mA,
  - chops two out of five 650MHz bunches.
- Delivers **2 mA** current every **20 Hz** for **0.6 ms**.

Linac Intensity Upgrade

- RCS intensity of 36e12 with 20Hz ramp-rate.
- Fill time with **5 mA** current every **20 Hz** for **1.3 ms**.
  - Preferable to 2 mA current for 3 ms.
- This fill rate requires a **power-amplifier upgrade** to PIP-II Linac.

Boxcar Stacking from Booster and Future RCS

- Booster Circumference **474 m**, **84** buckets.
- MI/RR Circumference **3318 m**, **7x84** buckets.
- MI extraction kicker gap, **24** buckets

Assume the same integrated dipole field per length as the Booster, but consider a larger circumference:

Circumference	N Batches	Max Energy
474 – 530 m	**6**	**8.0 – 9.0 GeV**
569 – 656 m	**5**	**9.6 – 10.7 GeV**
711 – 796 m	**4**	**12.0 – 13.4 GeV**

Should we use the Recycler?

8-GeV stacking with Recycler

- 5 batches injected at 20-Hz requires 0.2 seconds.
- Using the Recycler for accumulation, MI cycle time goes from 1.4 s. to 1.2 s, for a **1.17** factor improvement in beam power.

10-GeV MI Injection

- Laslett tune-spread reduced by factor **1.50** at injection.
- Beam size reduced by factor **1.22** at injection.
- Incompatible with 8-GeV Recycler.

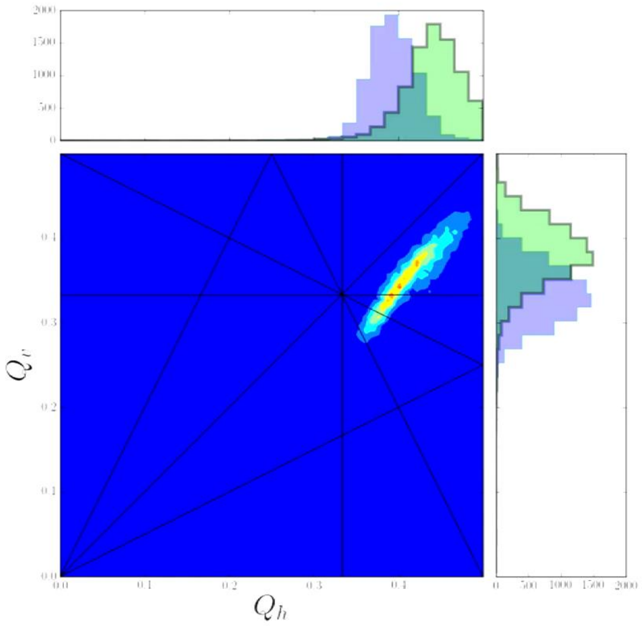
The RCS should be capable of 10-GeV

- We can keep both options open

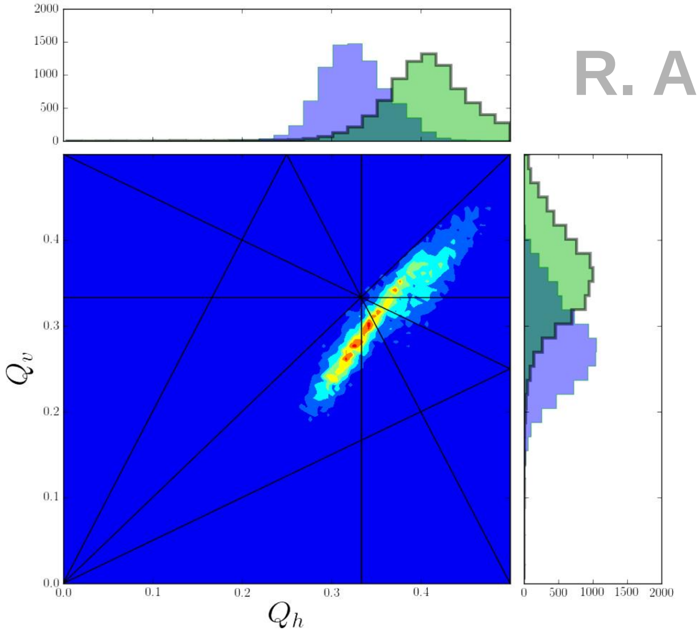
Recycler Intensity Limits

Space-charge Tune-spread Losses:

Current Tune-Spread



PIP-II Tune-Spread



R. Ainsworth

If we go to higher than PIP-II intensity, but without a momentum separation between the beams, we will cross the same res. lines.

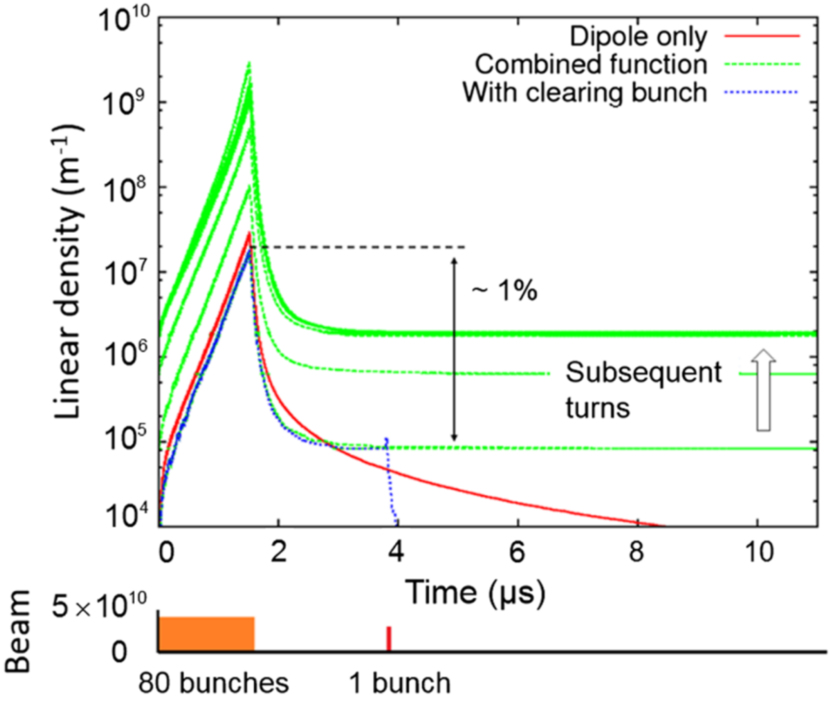
How well can we compensate the resonances lines?

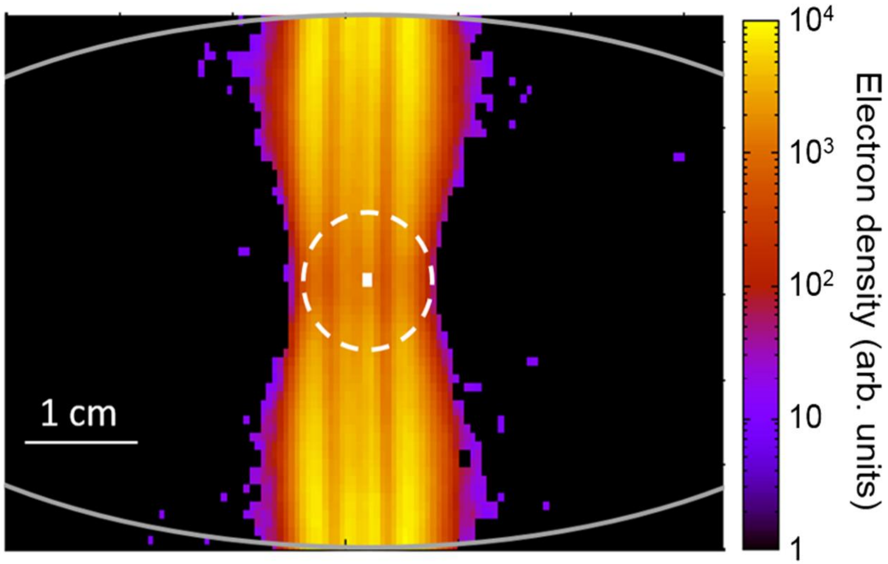
Recycler Intensity Limits

Tight Aperture Losses:

- For PIP-II era, smaller cleaner beam.
- For RCS, limited by RR/MI apertures.

Electron Cloud Instability:





S. Antipov et al. PRSTAB 2017

Main Injector Intensity Upgrade

Aperture and Space-charge Tune-spread

- **4.3 mm mrad aperture restriction** for MI
  - **40 mm mrad** normalized admittance at **8 Gev** or **50 mm mrad at 10 GeV.**
- Alleviated by injecting into MI at higher energy.
- Lattice correction of harmonic betatron resonances.

Reactive power needed to drive RF cavities

- For PIP-II we can add new power amplifiers to existing RF cavities.
- For 2.4 MW, we need to **replace RF cavities and PAs.**

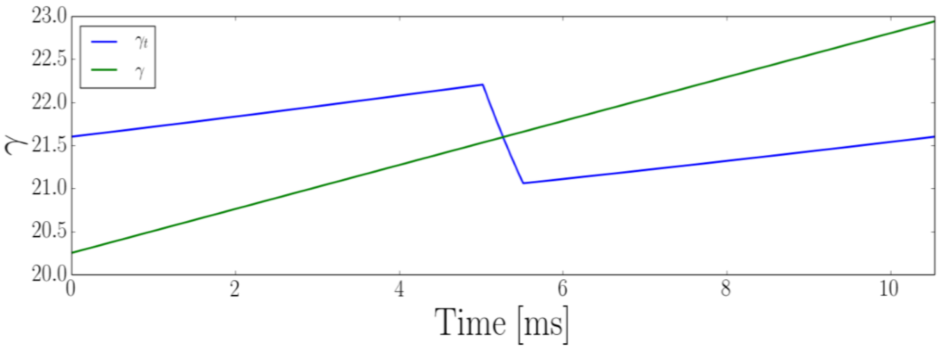
γ_T-Jump for MI Transition Crossing

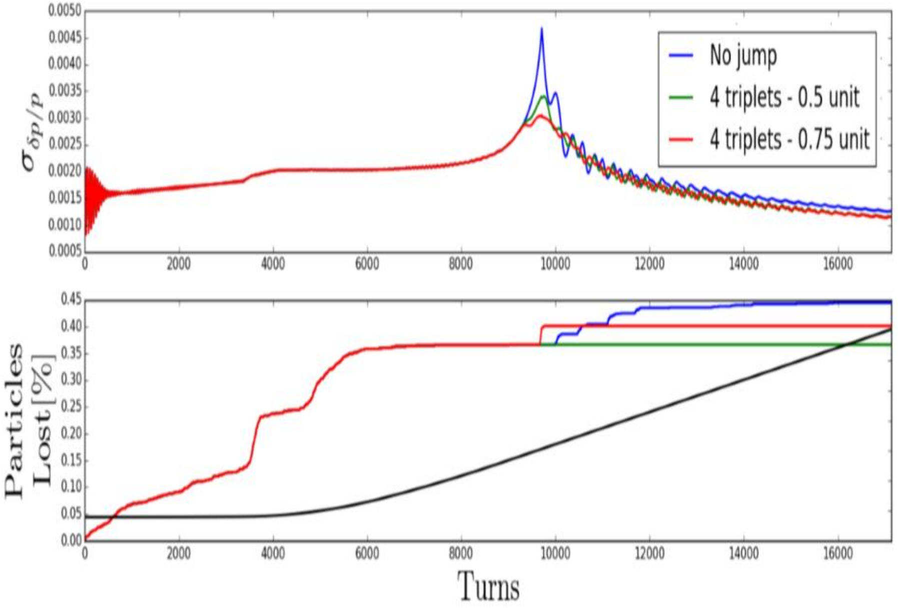
High-Power Neutrino Target

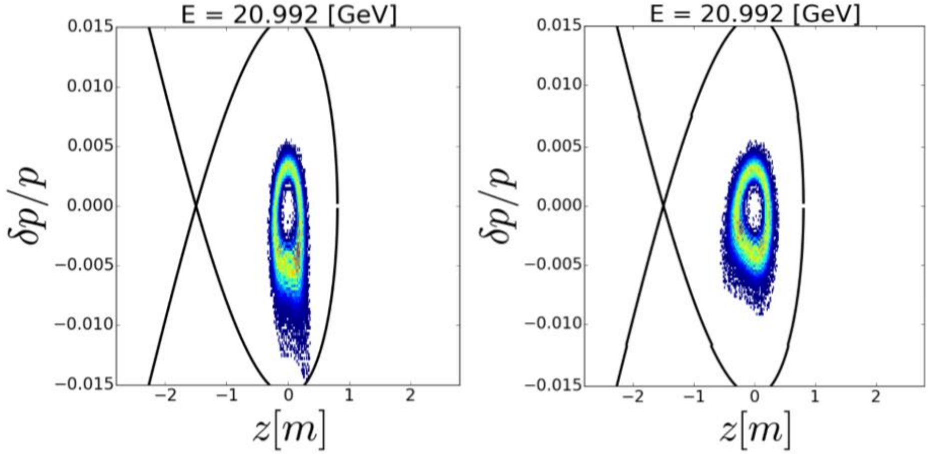
Main Injector Intensity Upgrade

γ_T-Jump for MI Transition Crossing

- Pulsed quads for γ_T-jump to be installed for PIP-II.
- For 2.4 MW, consider going from negative to positive chromaticity at transition crossing.





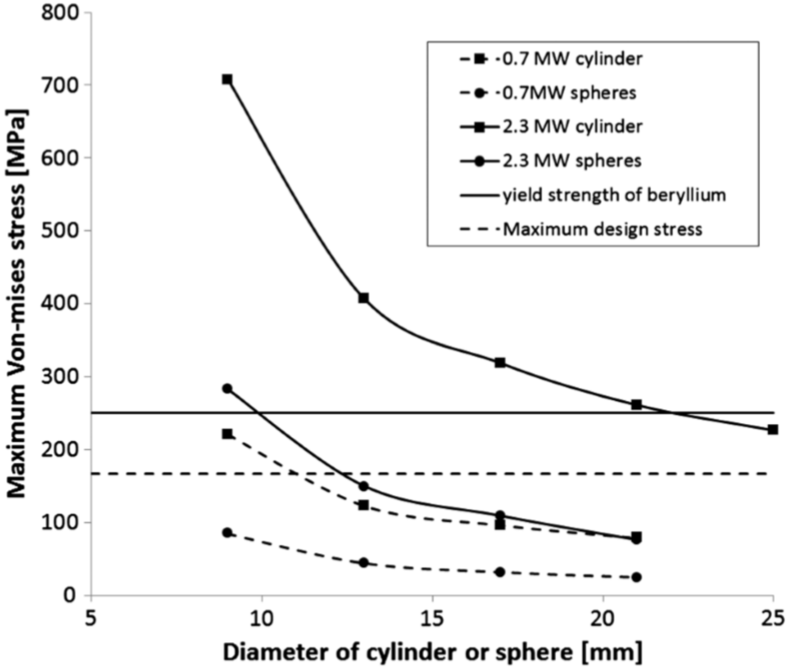


R. Ainsworth et al. IPAC 2017

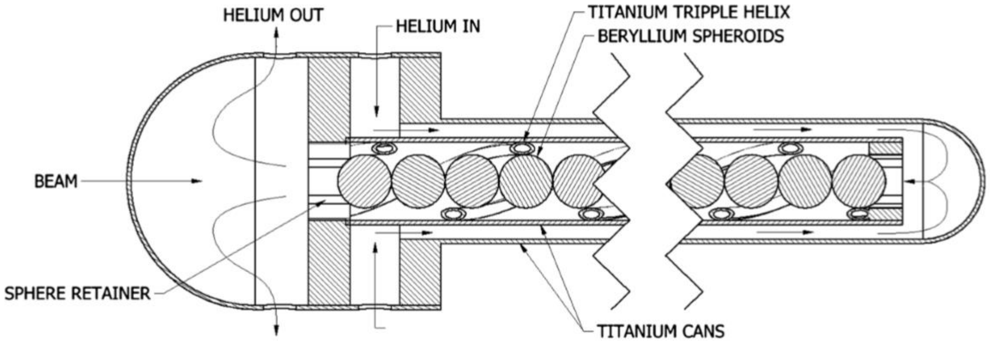
Main Injector Intensity Upgrade

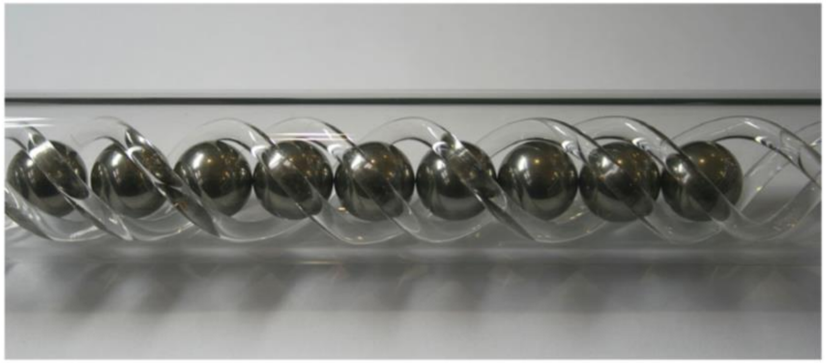
High-Power Neutrino Target

- Detailed design of **2.3 MW Be target** for neutrino beams.
- **Active area of R&D development** – shock test, radiation damage, target design, flux optimization etc.



T. Davenne et al. PRSTAB 2015





Beyond 2.4 MW

Options for Intensity Beyond 2.4 MW

If future physics experiments need even higher power proton beams at 120 GeV, how can that be accomplished?

Options:

1) Better performance from the new RCS
- IOTA technologies such as integrable optics or electron lenses?

2) Extend PIP-II linac to raise RCS injection energy
- An upgrade to a 1.4 GeV Linac could double the RCS intensity.

3) Reduce MI ramp time
- Add magnet power supplies, RF stations, replace RF cavities

4) Use 4+5 Slip-Stacking with a harmonic cavity
- Use harmonic RF to improve stability and bring RF buckets closer.
- Stack in the Main Injector, **+50%** beam power
- Or build a new Recycler, **+80%** beam power.

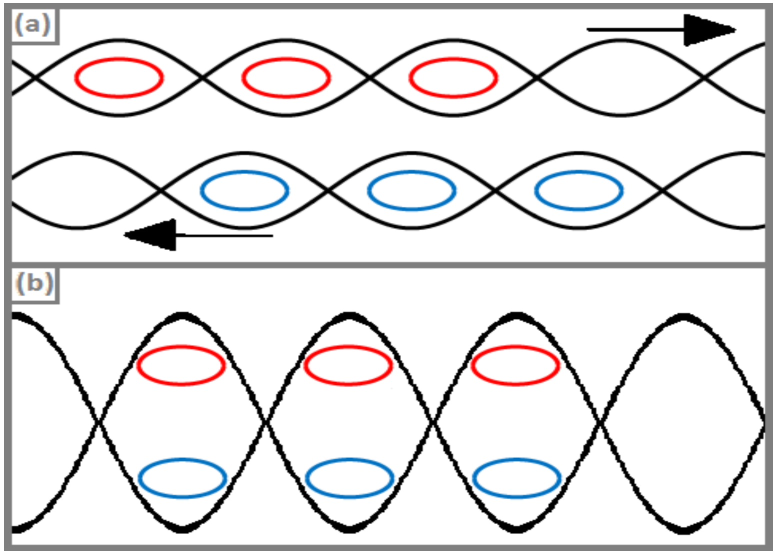
Conclusions

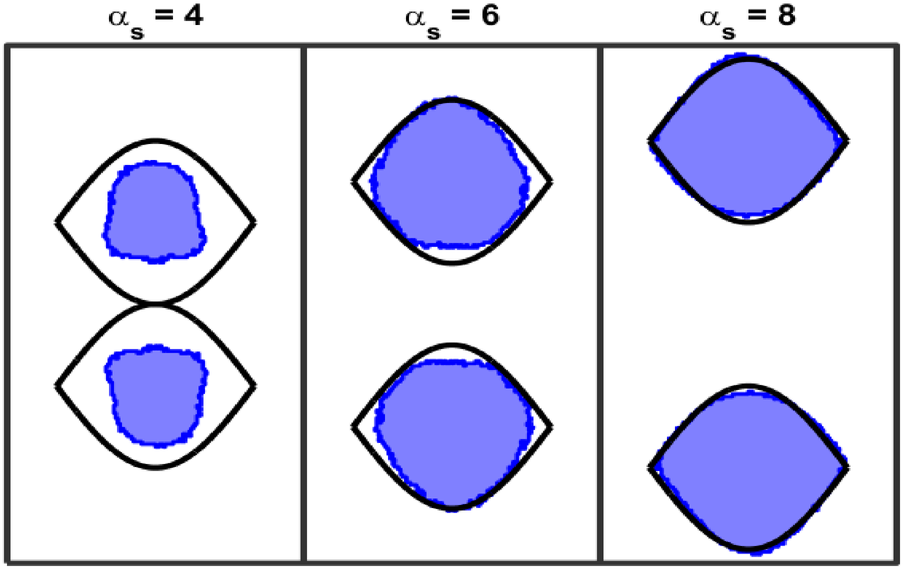
1. A **new RCS can quadruple intensity per unit length** by avoiding transition crossing, reducing betas, increasing periodicity, and improving lattice correction.
2. To fill the RCS at 5 mA, the PIP-II Linac would require a **power amplifier upgrade.**
3. It may be preferable to inject directly into the **MI at 10-GeV** and eliminate the use of the Recycler.
4. At 2.4 MW, the Main Injector would need to **new RF cavities and PAs** to provide the reactive power for the beam loading.
5. An RCS also opens up good options **beyond 2.4 MW.**

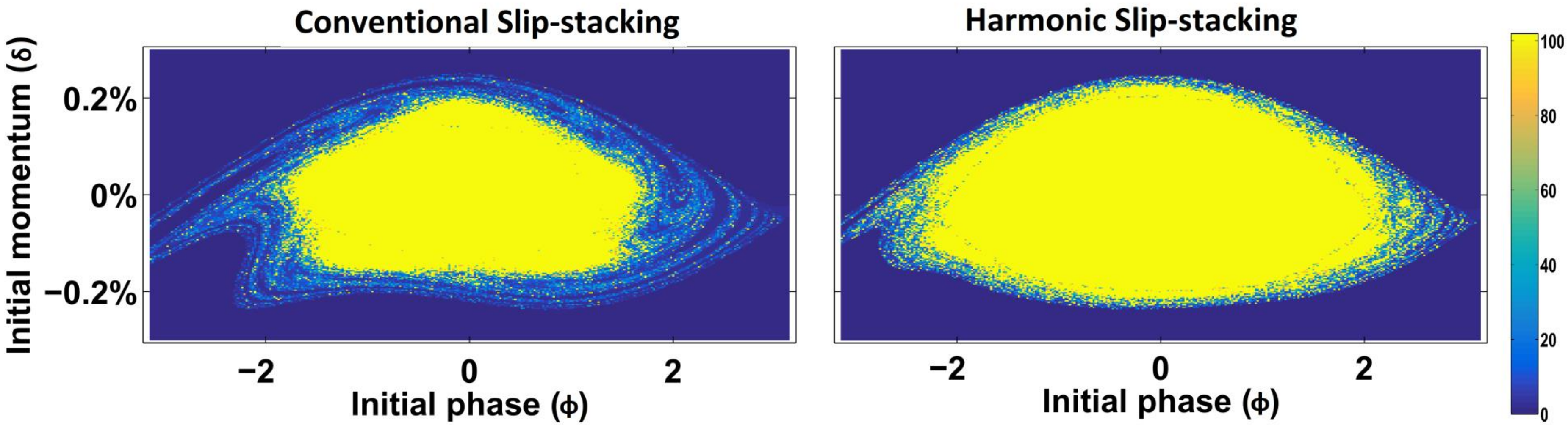
Backup

Harmonic Slip-stacking

Eldred, Zwaska PRAB 2016







Backup
Lebedev RCS Design

Rapid Cycling Synchrotron for PIP-II+

- New RCS is aimed to support 2.4 MW beam power to LBNE
- Its 20 Hz rep. rate corresponds to 760 kW beam power of RCS beam and will be greatly supportive to 8 GeV program
- The ring high periodicity suppresses the resonances driven by beam space charge
- FODO optics is chosen
  - Simple and uniform through the ring
  - Zero dispersion in straights
  - Betatron phase advances per cell are less than 90 deg.
- No transition crossing
- Reduction of B field in dipoles reduces heating of vacuum chamber by eddy currents
  - Circumference of RCS is larger than Booster circumference (1/6 of MI circumference instead of 1/7)
  - Larger betatron tunes increase number of dipoles and quads and reduce percentage of orbit taken by dipoles. It yields that

    Booster: B_{max}=7.26 kG => RCS: B_{max}=8.09 kG (in spite of larger circumf.)

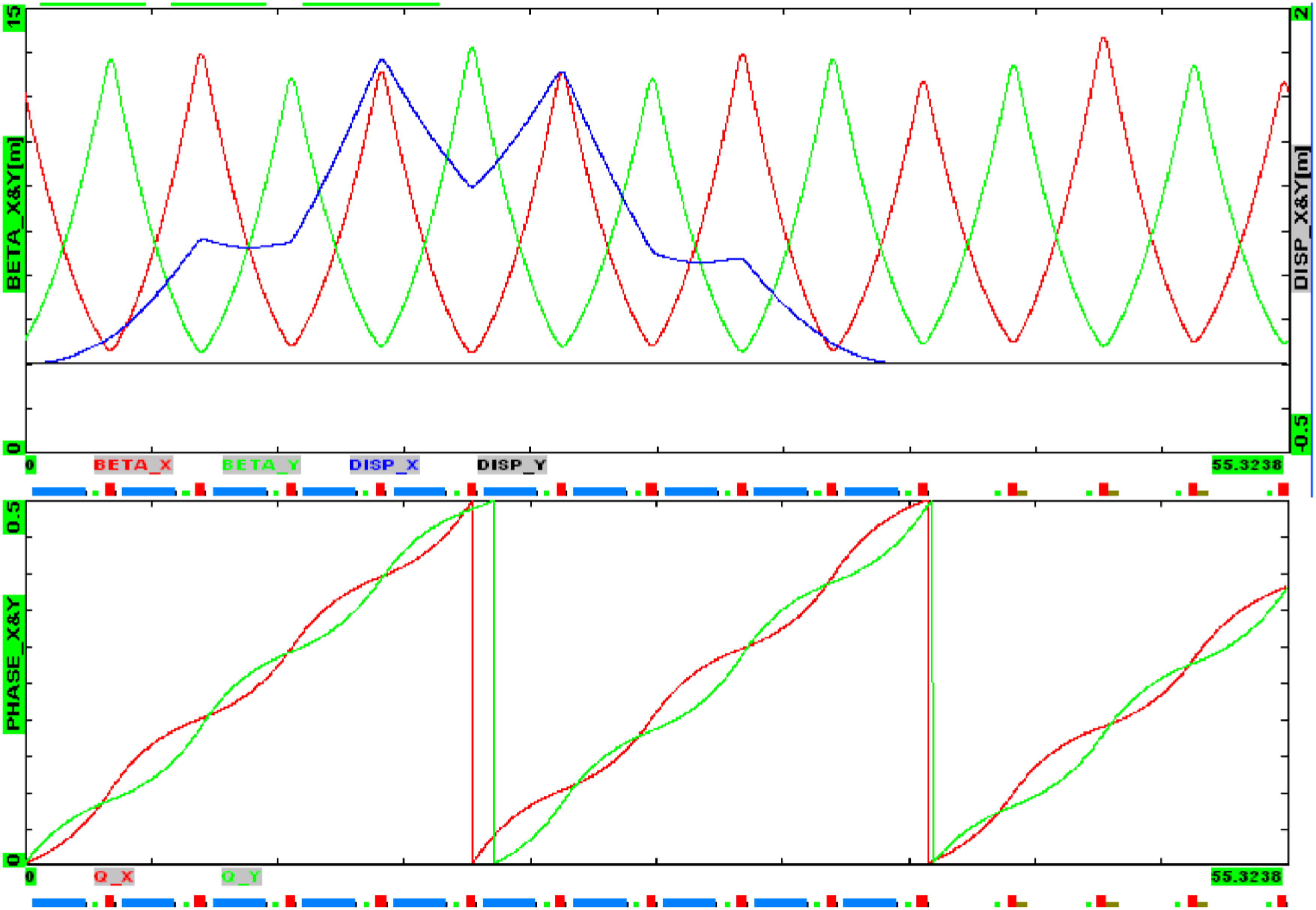
RCS Beam Optics

- All dipoles and Quads are connected serially
  - Trim quadrupoles located in each corrector pack near each quad correct discrepancy between quad and dipole fields and set tunes and optics
  - Resonance circuits tune the ramp frequency to 20 Hz
- Apertures are set by acceptance of MI

Parameters of beam optics

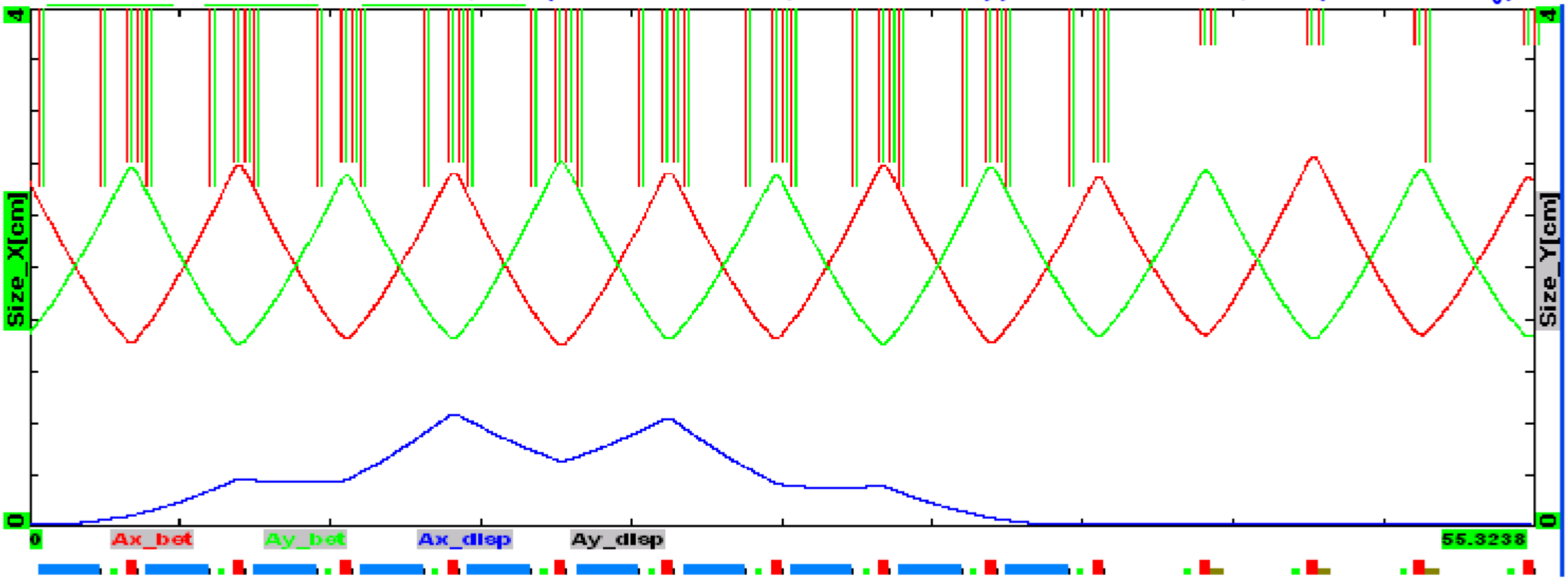
Circumference	553.24 m
Number of super periods	10
Number of cells per super period	7
Betatron tunes, Qx/Qy	13.81/13.80
Phase advances per cell	0.1973/0.1971
Momentum compaction	0.007783
Transition energy (kin.)	9.697 GeV
Natural chromaticities, ξ_x, ξ_y	-15.6/-15.7
Acceptance (geom.)	57 mm mrad

Dispersions, Beta-functions and Betatron Phase Advances



Acceptances and RMS emittances

- Acceptance of RCS is matched to the acceptance of MI determined by the vacuum chamber in dipoles (other aperture limitations in MI are not accounted, ε_{MI}=9.5 μm (h=2.39 cm, β_{max}=60 m)) => ε_{RCS}=58 μm (lower P_{inj})



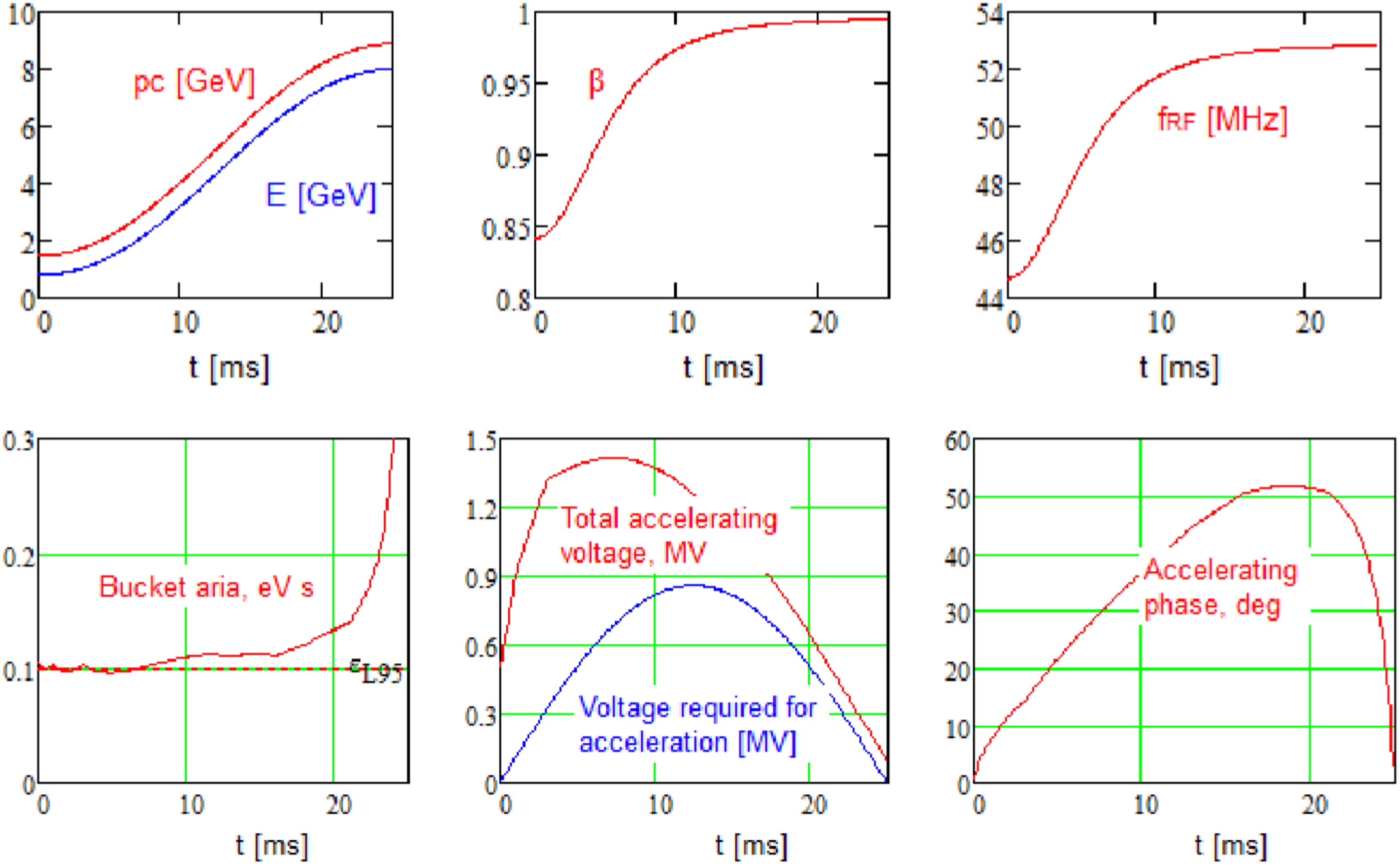
Beam envelopes at the acceptance (ε=58 mm mrad) and maximum $\Delta p/p=5\cdot10^{-3}$

- Accounting allowances for vacuum chamber (2 mm) we obtain apertures: in dipoles r=28 mm and in arc quads r=30 mm
  - Steering errors are already accounted in MI aperture
- Quads in straights have larger aperture to accommodate injection and extraction

Parameters of Magnets

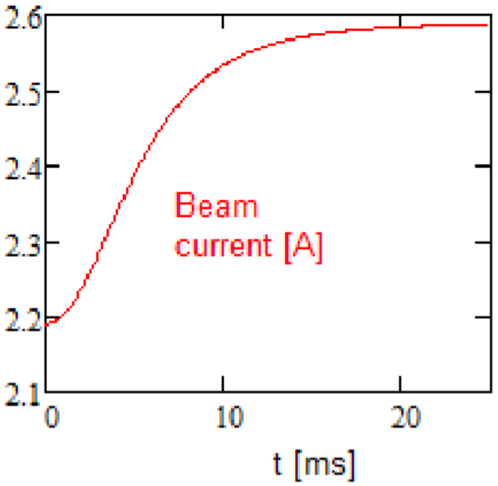
Dipoles	
Number of dipoles	100
Dipole length	2.302 m
Dipole magnetic field at 8 GeV	8.09 kG
Gap	56 mm
Low aperture (located in arcs) quads	
Number of quads	110
Quad length	40 cm
Quad gradient at 8 GeV	2.3 kG/cm
Aperture (Ø)	60 mm
Large aperture (located in straights) quads	
Number of quads	30
Quad length	50 cm
Quad gradient at 8 GeV	1.84 kG/cm
Aperture (Ø)	100 mm
Number of quads	30

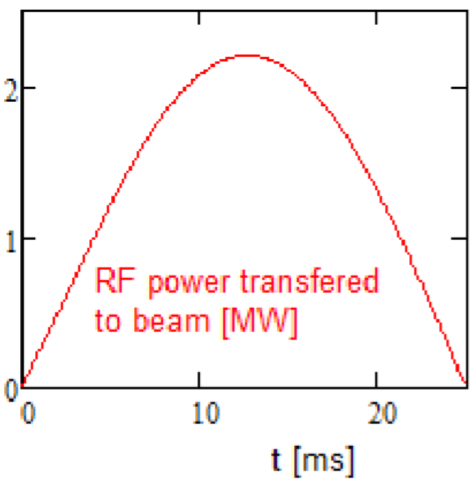
Beam Acceleration in RCS

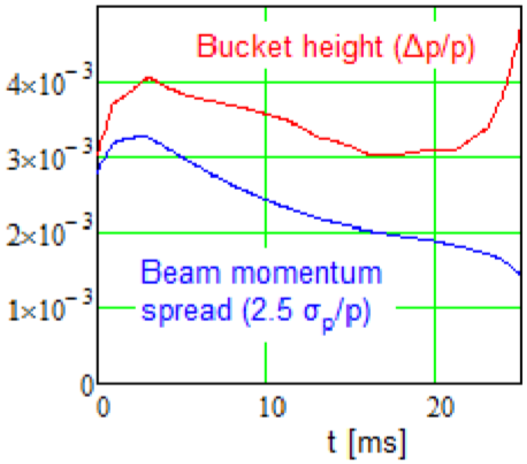


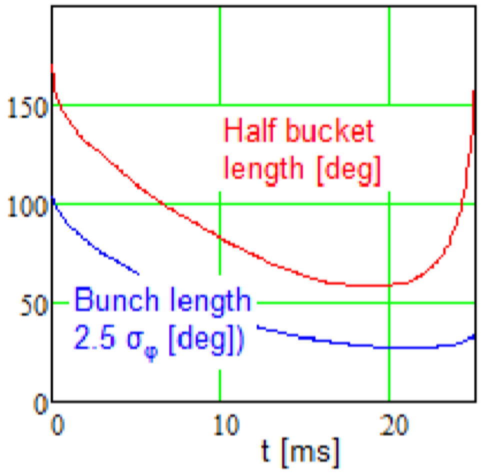
Beam Acceleration in RCS (P_{MI}=2.4 MW)

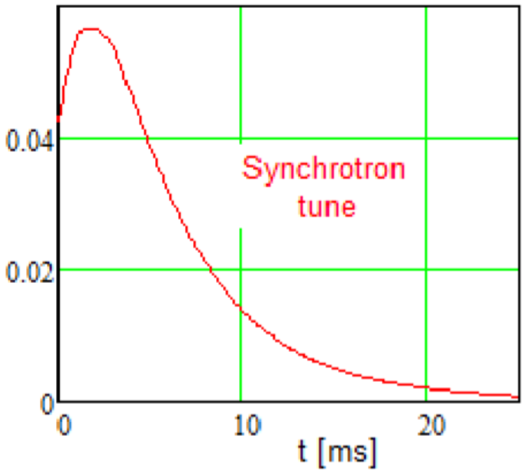
- Beam power at 8 GeV – 770 kW
- 20 cavities @ 75 kV





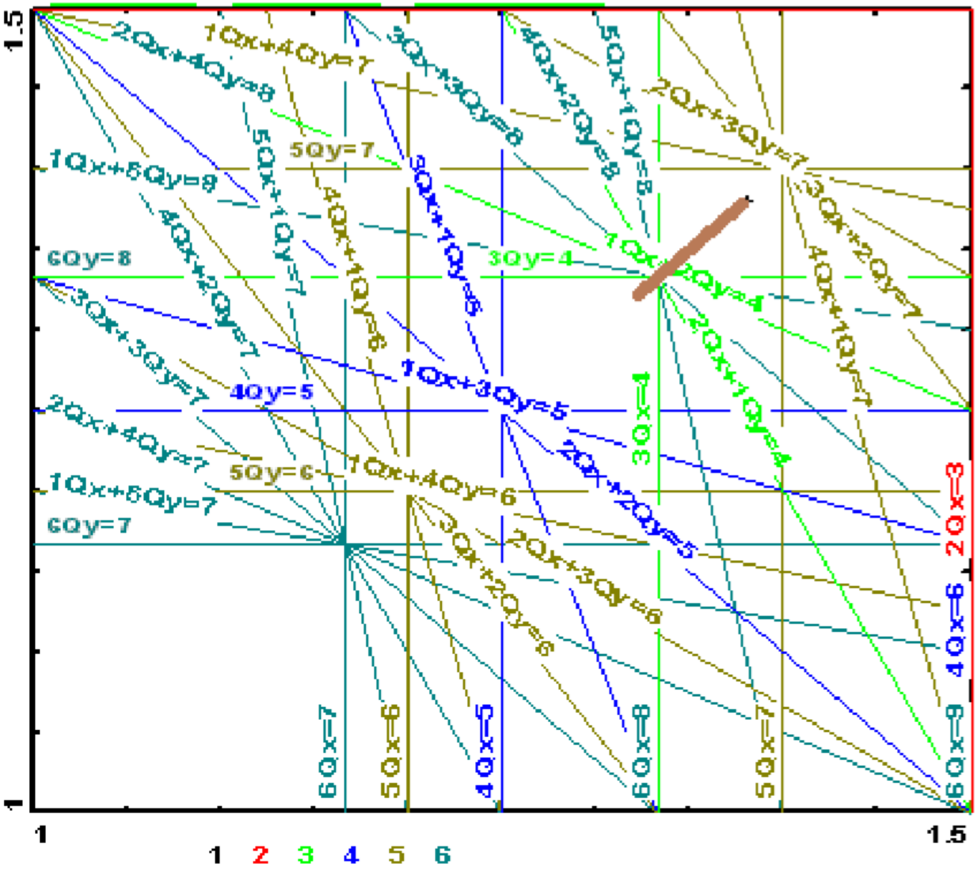






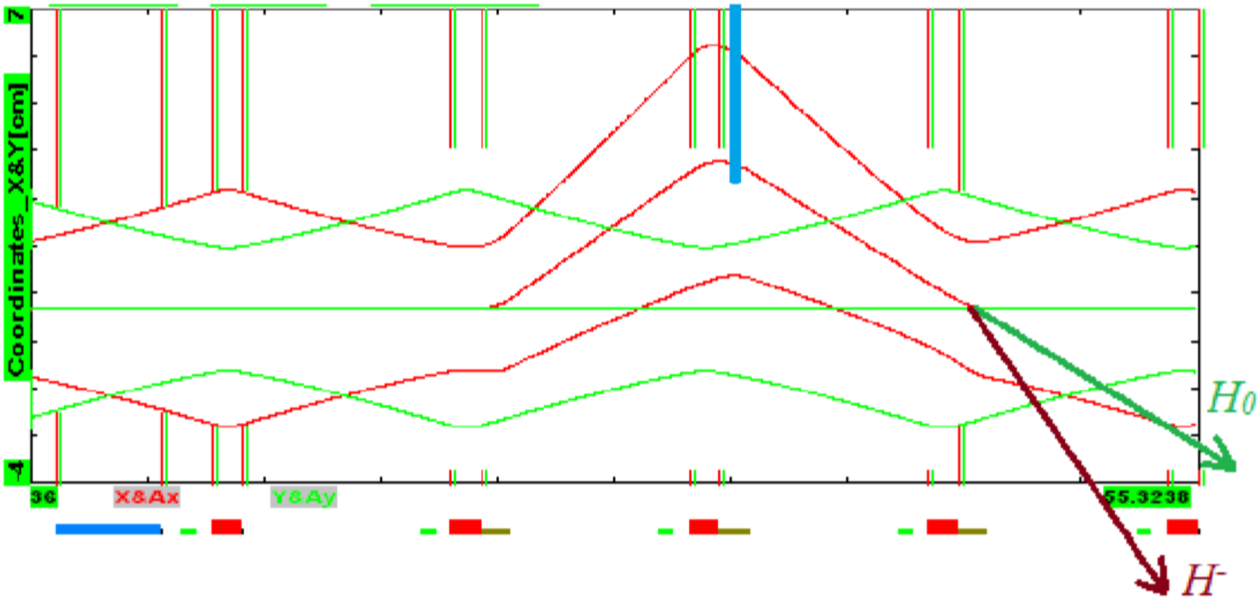
Space Charge Tune Shifts for Supersymmetric RCS

- RCS optics is built from 10 identical periods
- If periodicity is sufficiently accurate ($\Delta\beta/\beta < 5\%$) then the space charge tune shifts have to be accounted for 1 period:
  - ⇨ $\Delta\nu_{x,y} \approx 0.062$
  - ♦ Realistic simulations are required
  - ♦ Experimental prove should come from PIP-I+ and IOTA
- To mitigate SC effects
  - ♦ Phase advance per cell was chosen 71° (<90°)
  - ♦ Phase advance per period (~1.38) is far enough from 4-th resonance
- Additional linac energy increase may require to mitigate the space charge



Injection

- To keep supersymmetry of the ring 3 central quads and nearby corrector packs in each straight will have an increased aperture
    - Sextupoles are not required in the straights
- Strip injection through foil (similar to ICD-2 proposal) will be used
    - KV distribution painting in both transverse planes
    - Peak foil temperature ~ 1300 K°
- During 1100 turns injection the bending field is changed by 2.9%.
    - It can be compensated by correctors. 22 of 40 A is used if Booster like correctors are used



Extraction

- Extraction with vertical kicker (200 cm and 770 G) and Lambertson septum (200 cm and 13 kG)
  - ◆ Orbit distortion at may reduce required kicker strength