



---

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

---

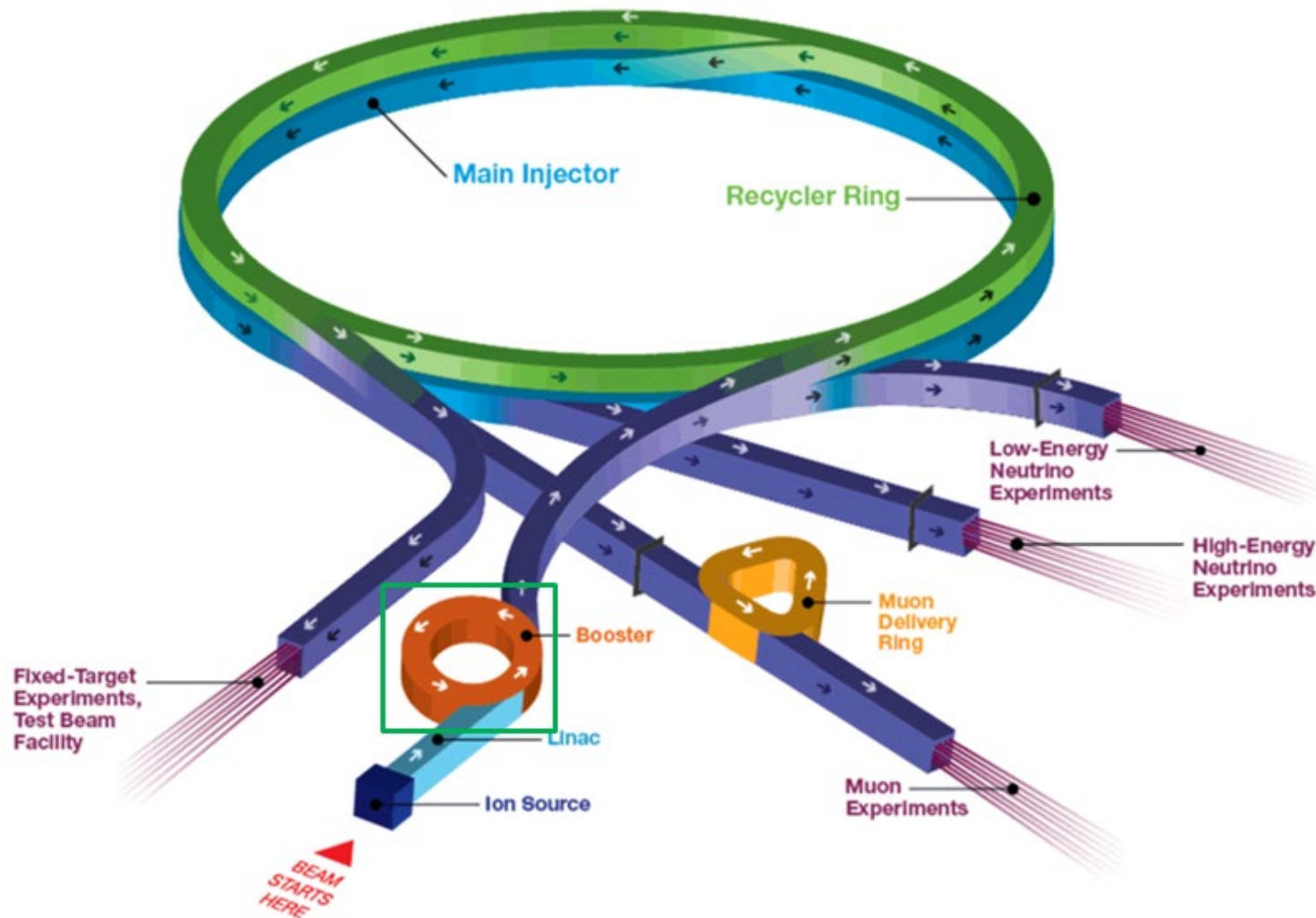
# RCS for Multi-MW Facility at Fermilab

**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.

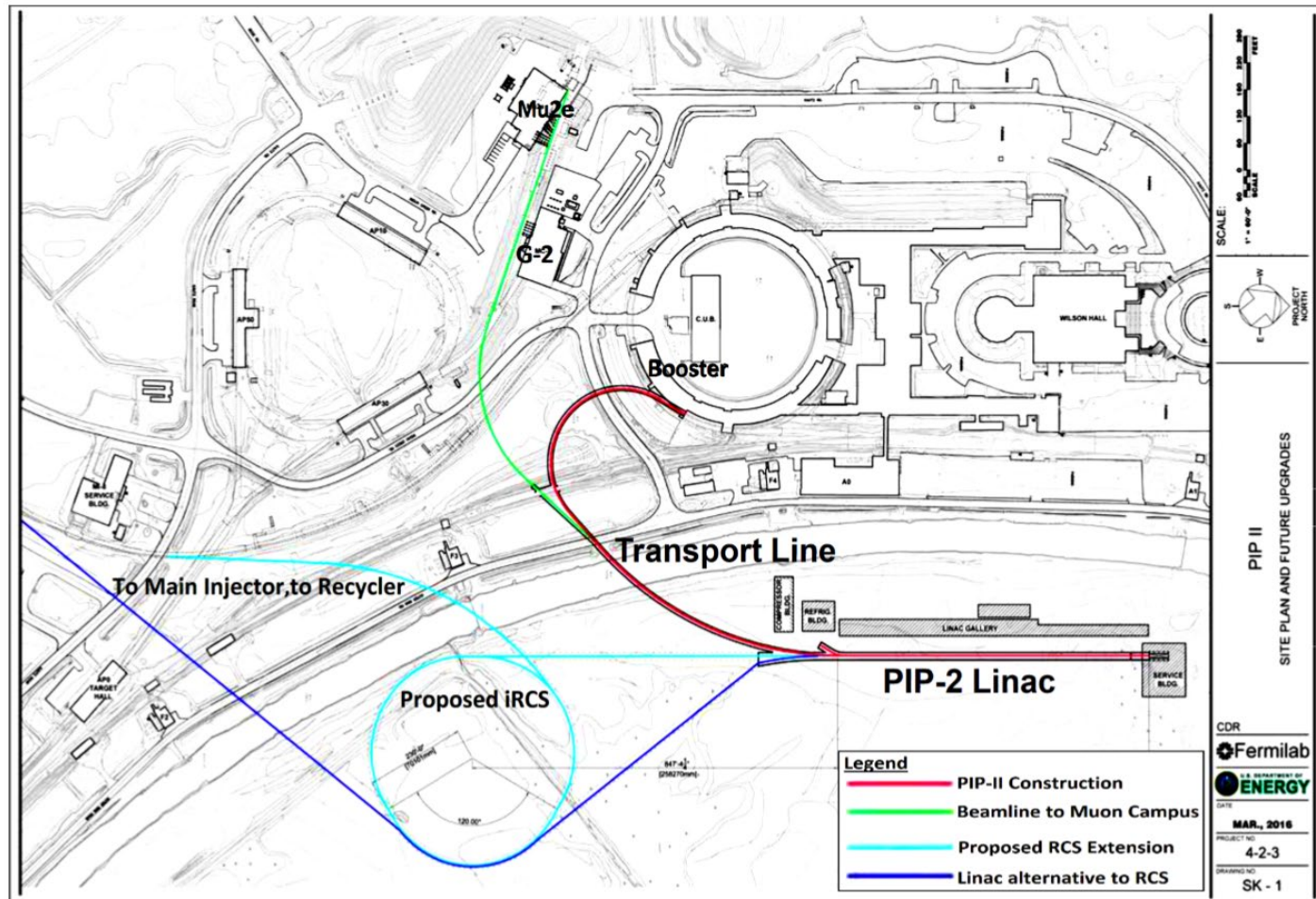
## Known challenges include:

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:

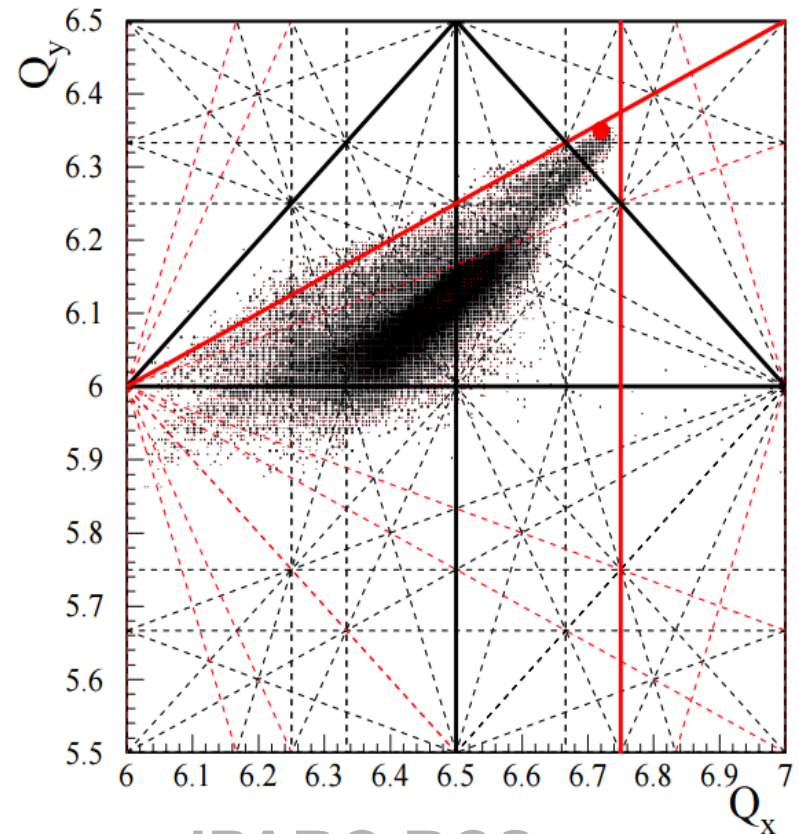
$$\Delta\nu \approx \frac{Nr_0}{2\pi\epsilon_N\beta\gamma^2}FB$$

Space-Charge Limit:

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



$\nu = 6.5$  half-integer  
resonance constrains  
Booster to 0.3-0.35



JPARC RCS:  
Hotchi et. al.

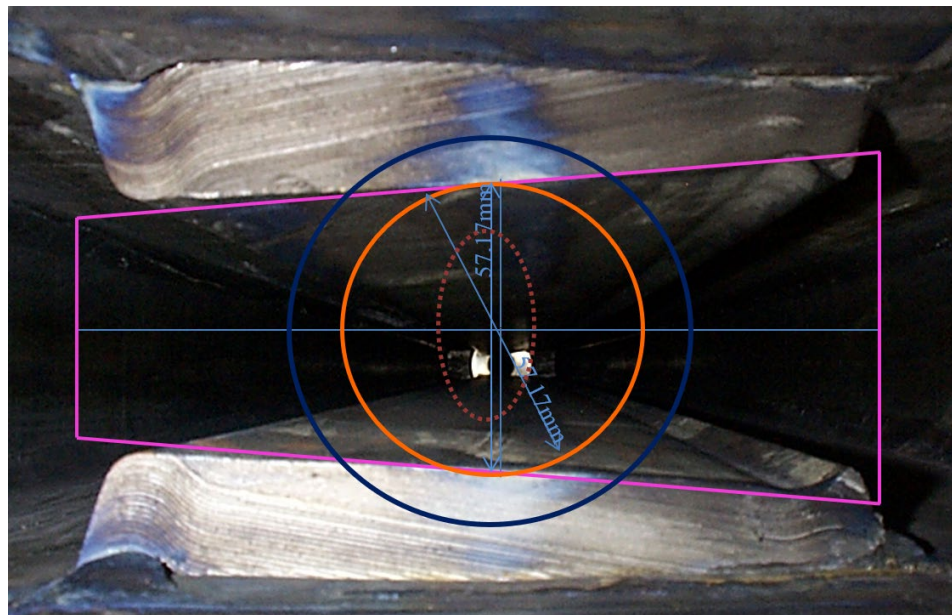
# Aperture and Emittance

The vertical gap in the Booster is **5.72 cm (2.25")** at the location where  $\beta_y = 35 \text{ m}$ .

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

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:

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

# Baseline RCS Lattice

Simple FODO Lattice

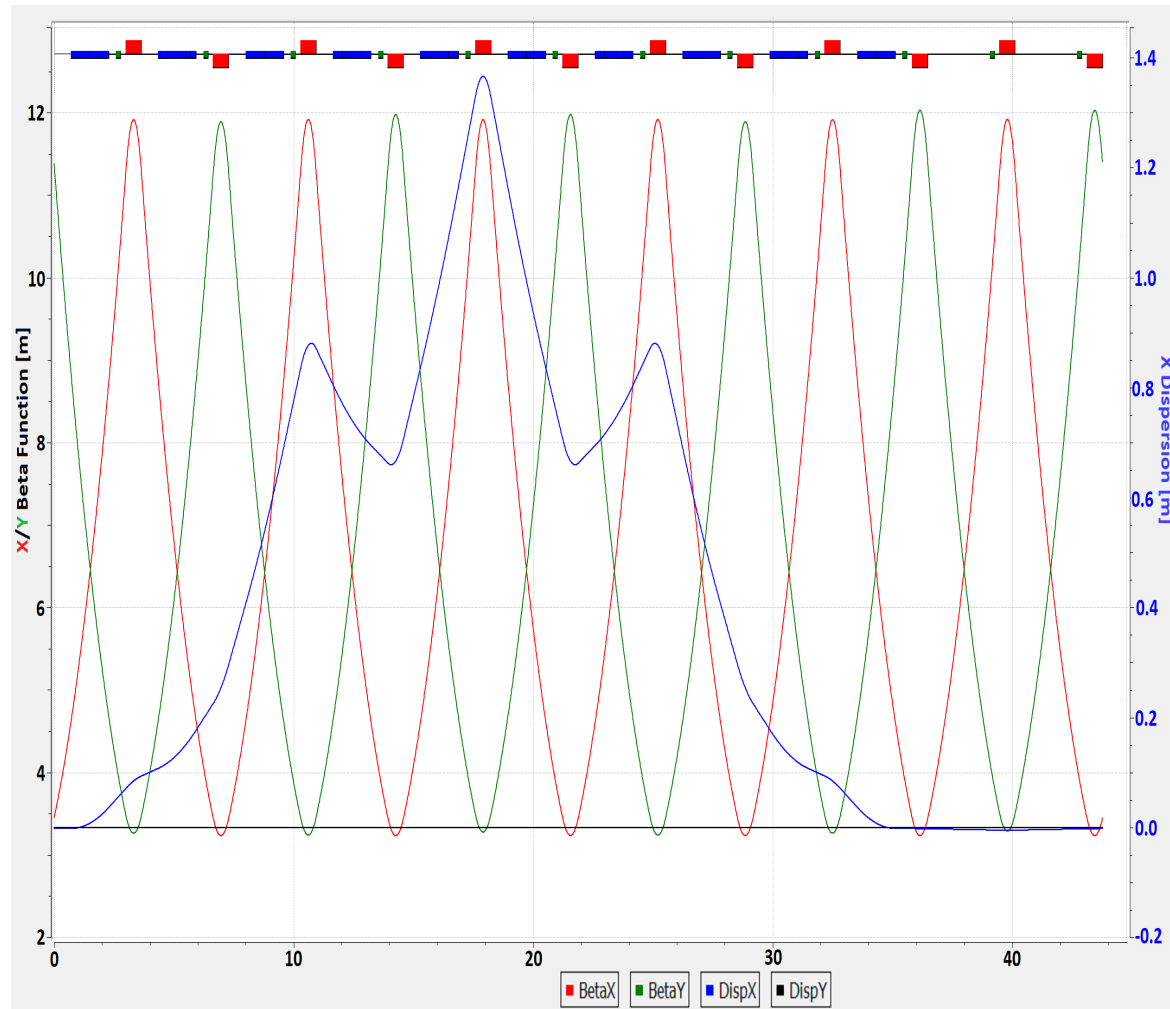
Avoids Transition

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<sup>2</sup>/K

**1.28mm Steel-316:**  $\Delta T = 60$  K

**0.75mm Inconel-625:**  $\Delta T = 20$  K

# Integrable RCS Design

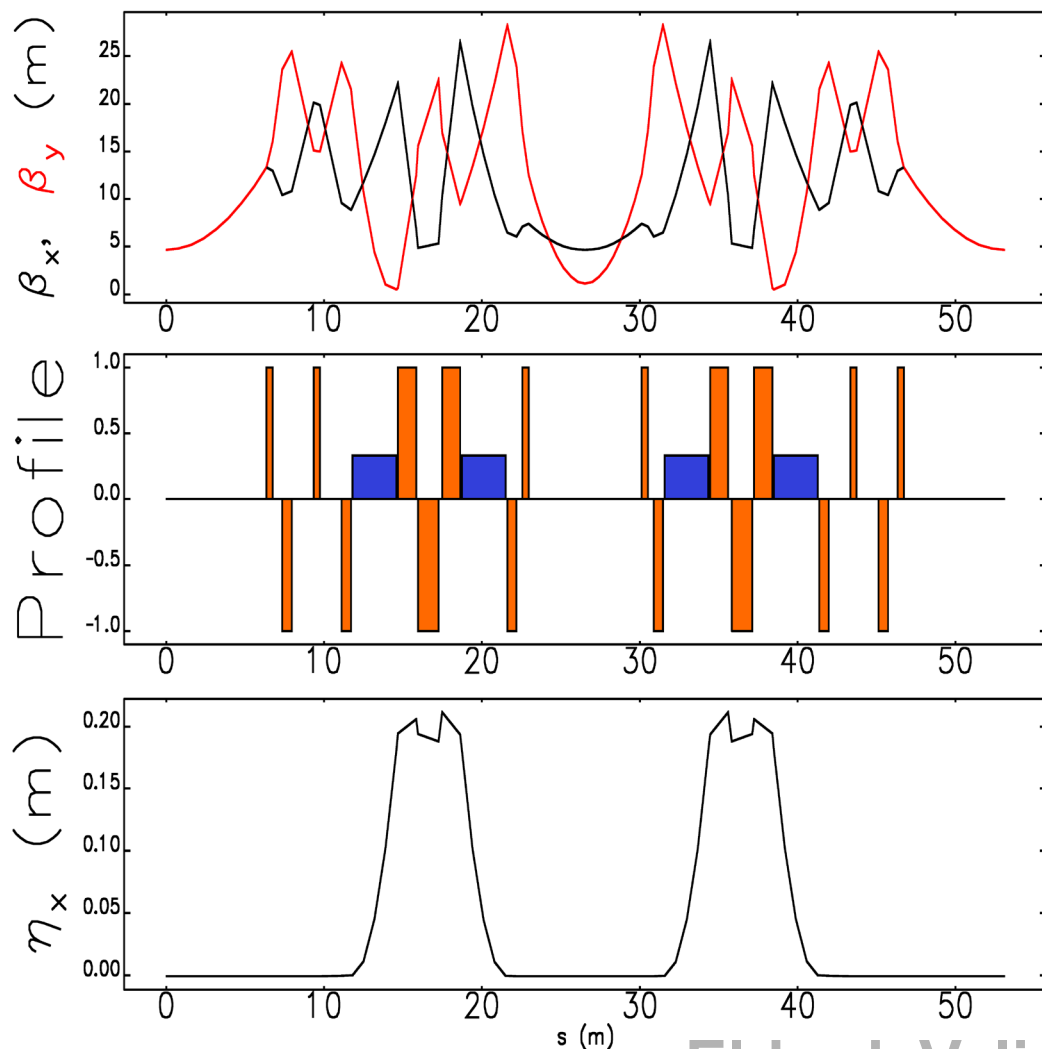
---

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

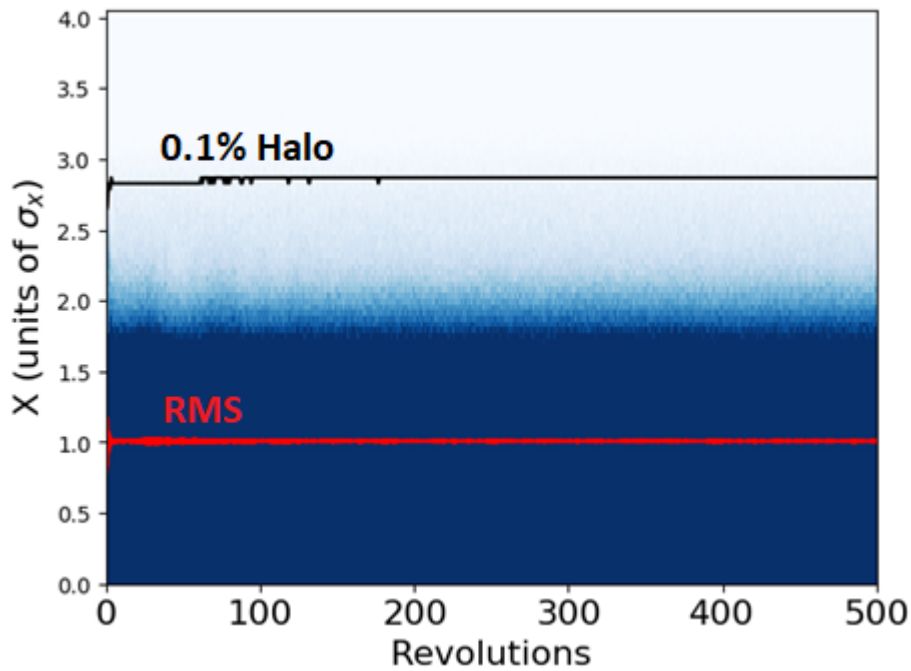
Laslett tune-shift of 0.4, corresponding to  $32 \times 10^{12}$  protons.

Beam stable 5000 revolutions, halo strongly suppressed.

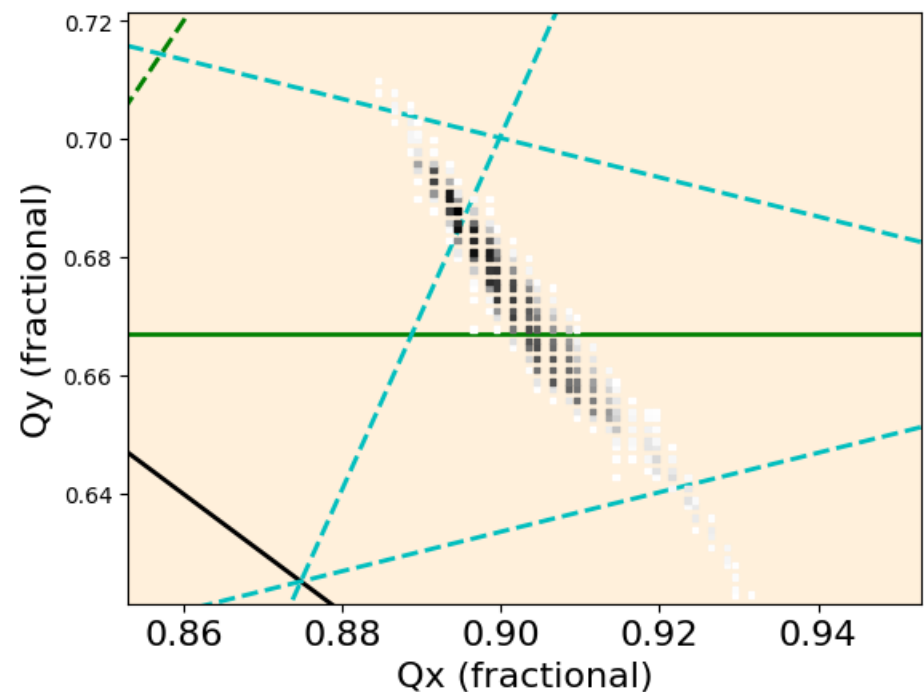
Caveat: Perfect lattice with no errors.

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  $36 \times 10^{12}$  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

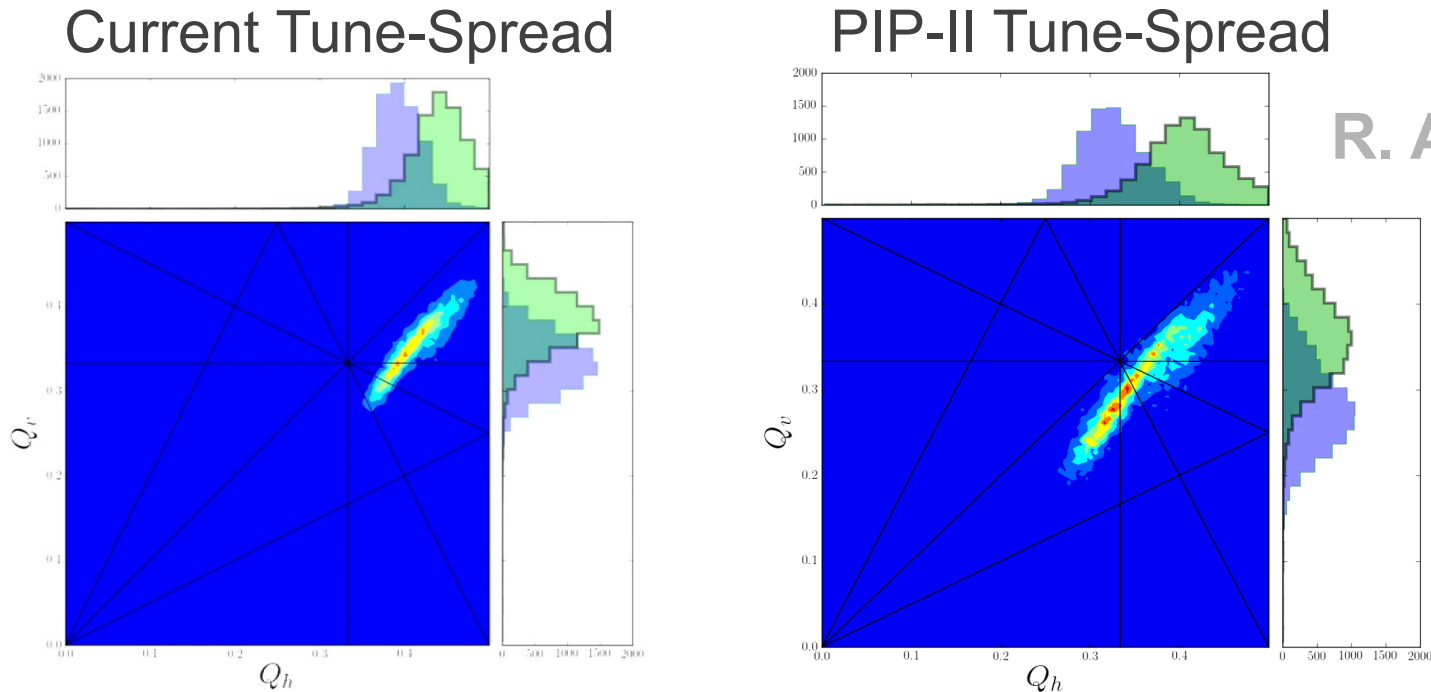
- Laslett tune-spread reduced by factor **1.50** at injection.
- Beam size reduced by factor **1.22** at injection.
- Incompatible with 8-GeV Recycler.

## The RCS should be capable of 10-GeV

- We can keep both options open

# Recycler Intensity Limits

## Space-charge Tune-spread Losses:



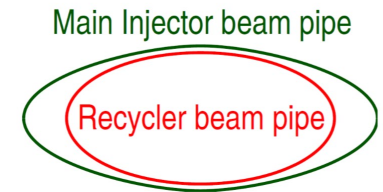
If we go to higher than PIP-II intensity, but without a momentum separation between the beams, we will cross the same res. lines.

How well can we compensate the resonances lines?

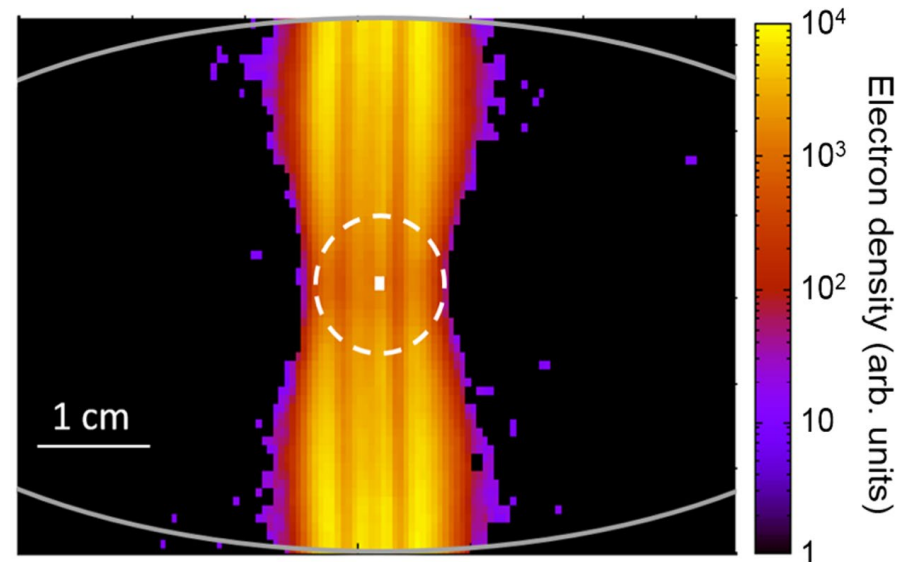
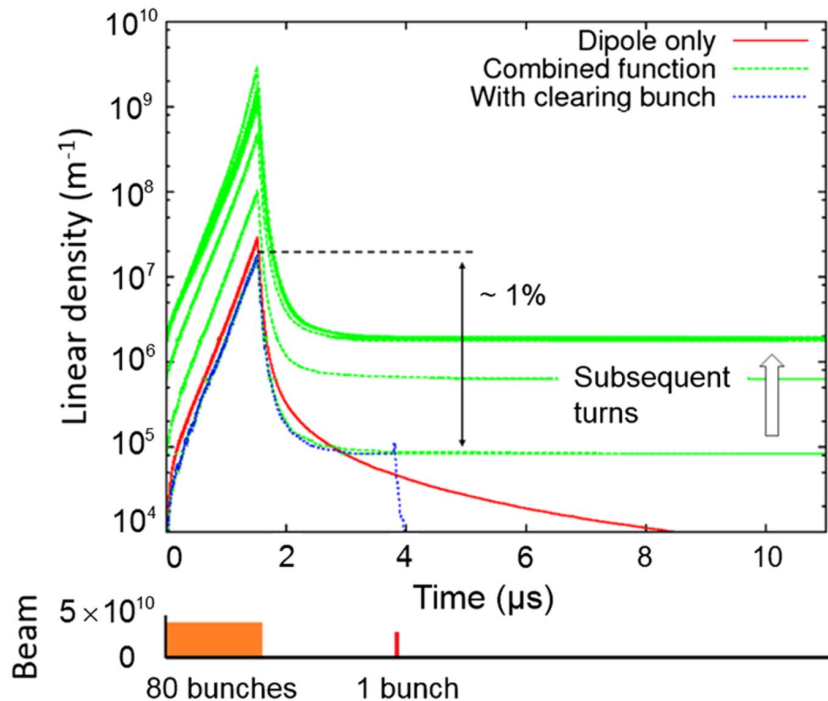
# Recycler Intensity Limits

## 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**.

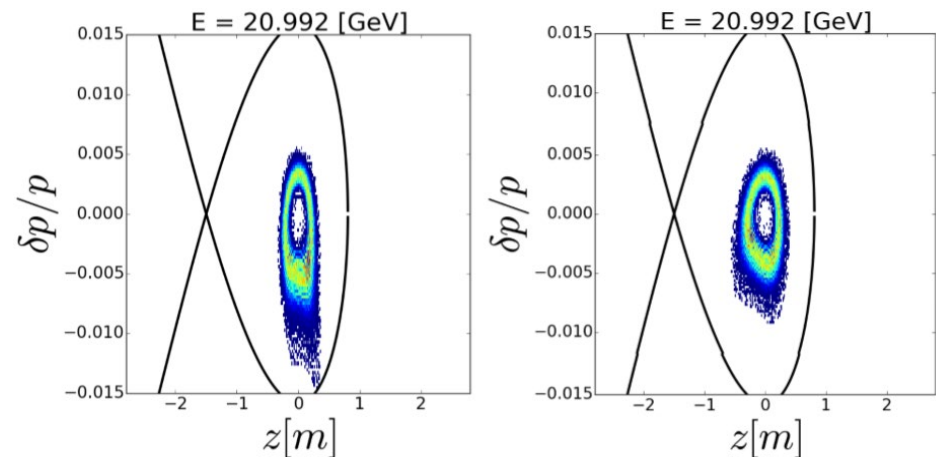
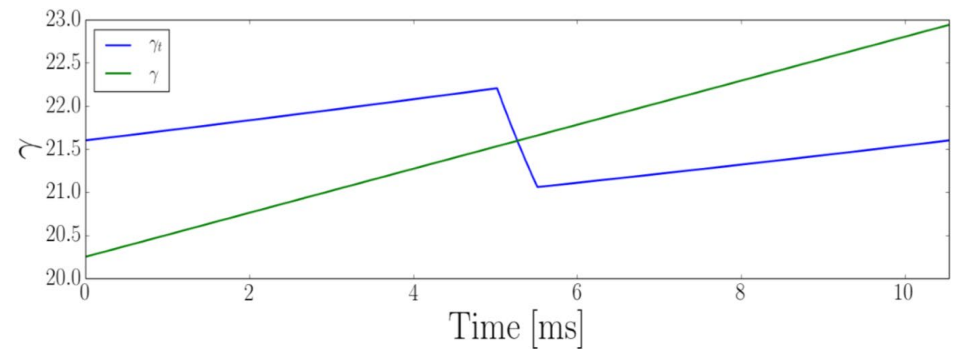
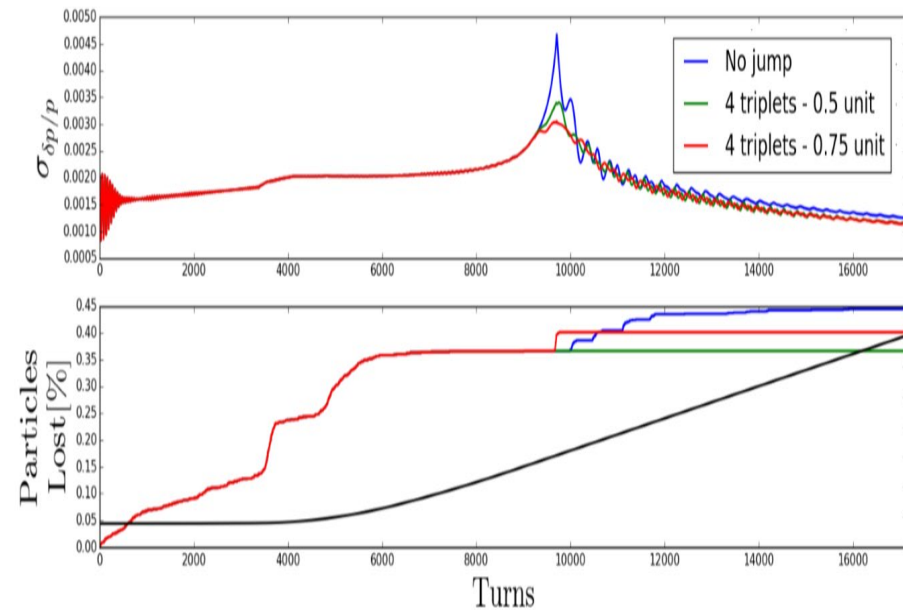
## $\gamma_T$ -Jump for MI Transition Crossing

## High-Power Neutrino Target

# Main Injector Intensity Upgrade

## $\gamma_T$ -Jump for MI Transition Crossing

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

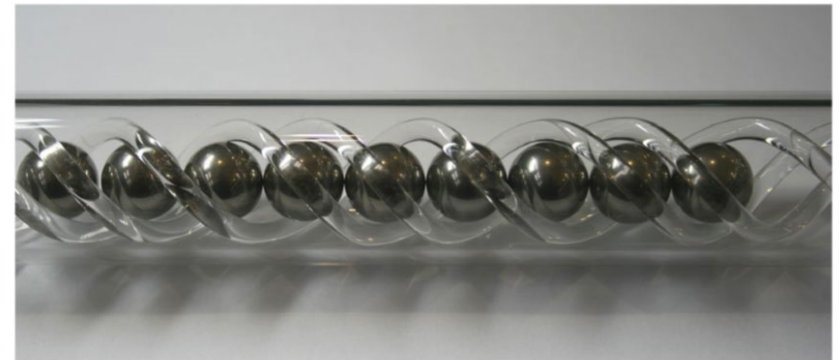
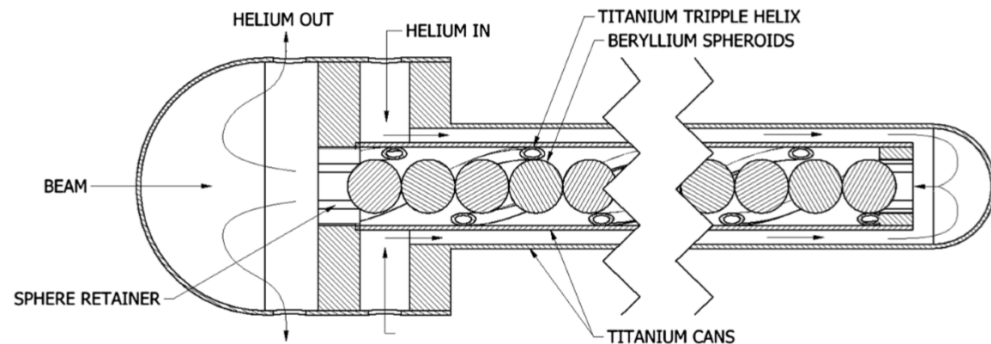
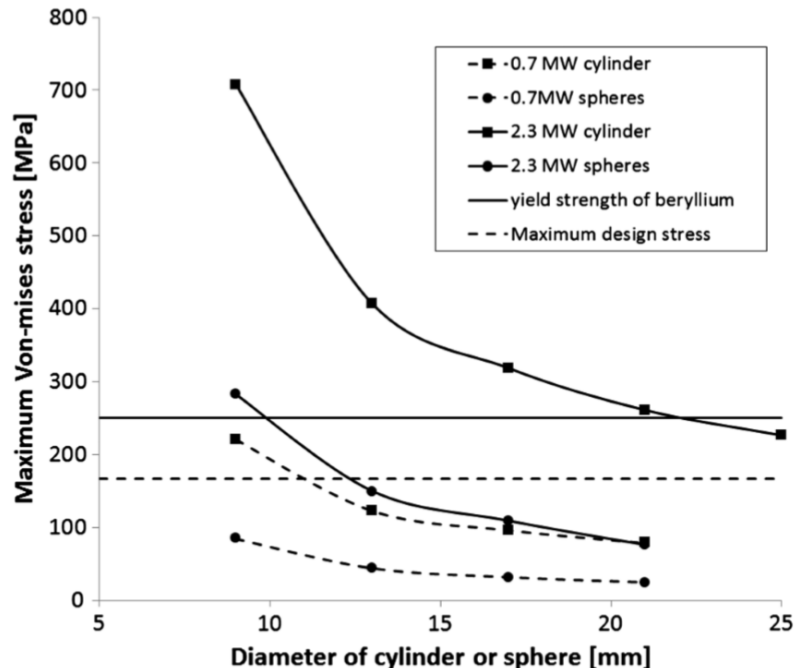


R. Ainsworth et al. IPAC 2017

# 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

---

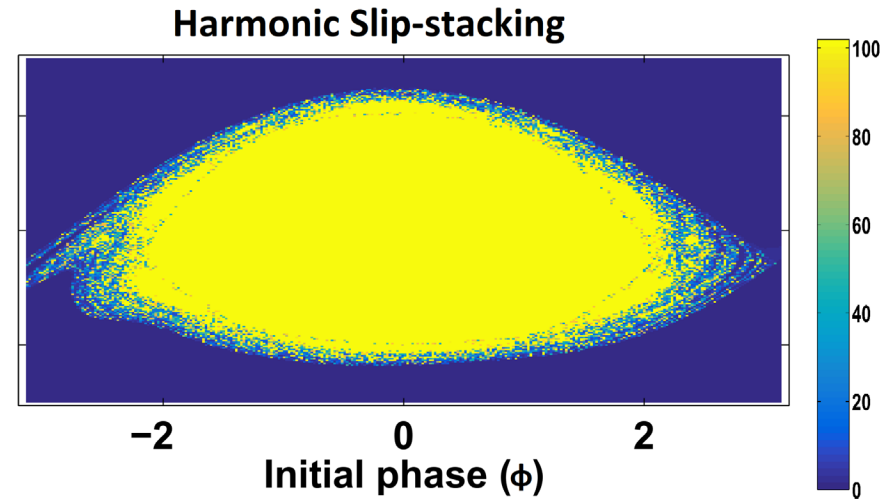
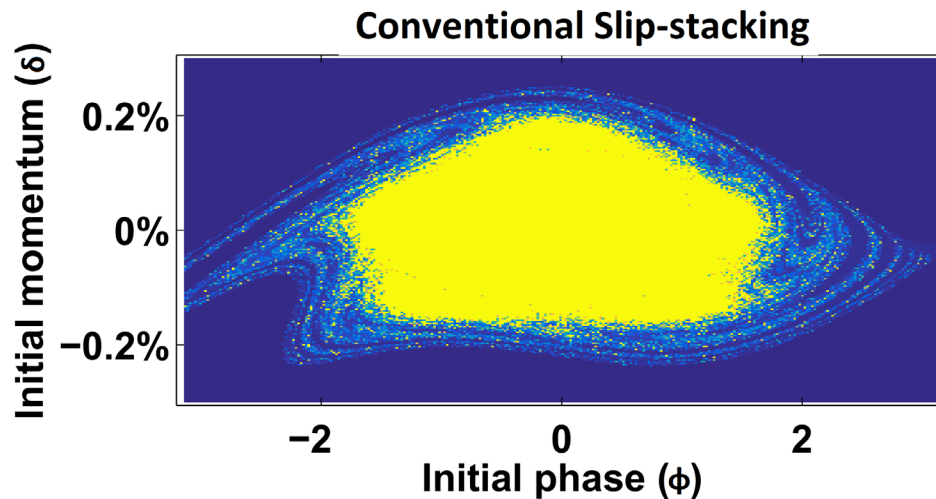
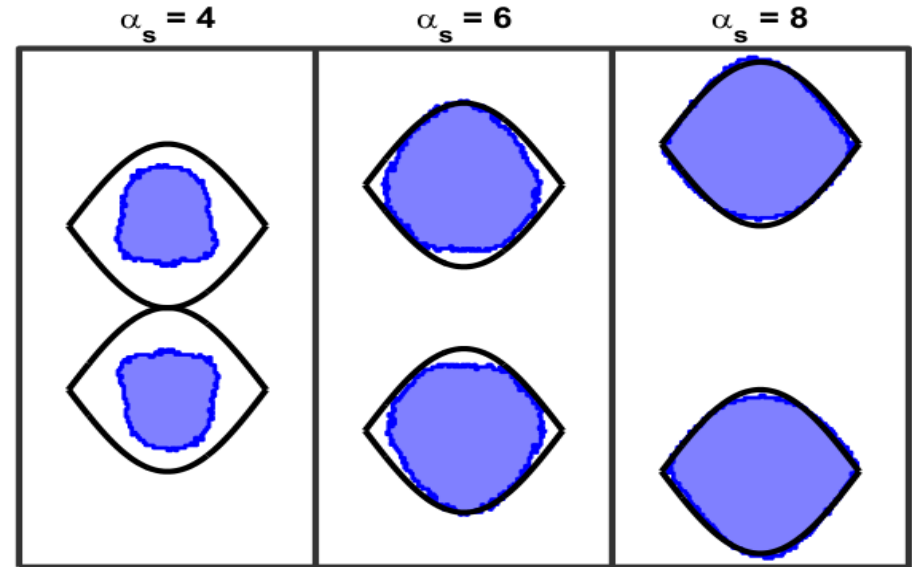
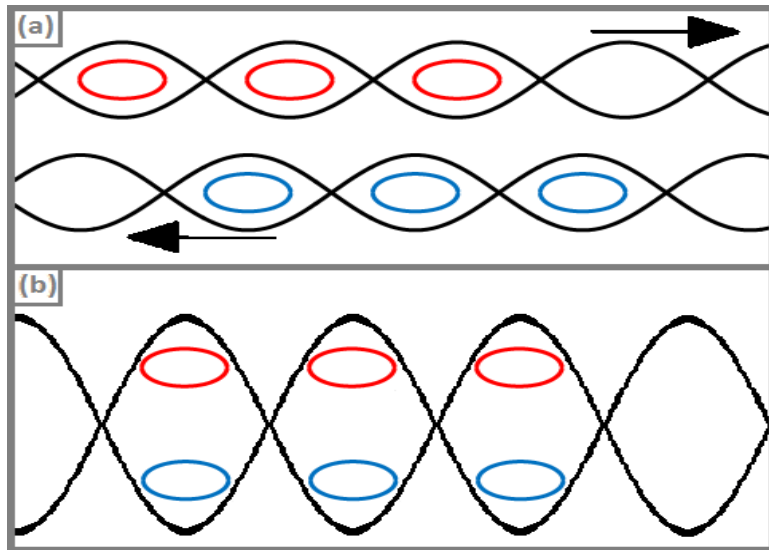
1. A **new RCS can quadruple intensity per unit length** by avoiding transition crossing, reducing betas, increasing periodicity, and improving lattice correction.
2. To fill the RCS at 5 mA, the PIP-II Linac would require a **power amplifier upgrade**.
3. It may be preferable to inject directly into 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  $\Rightarrow$  RCS:  $B_{\max}=8.09$  kG (in spite of larger circumf.)

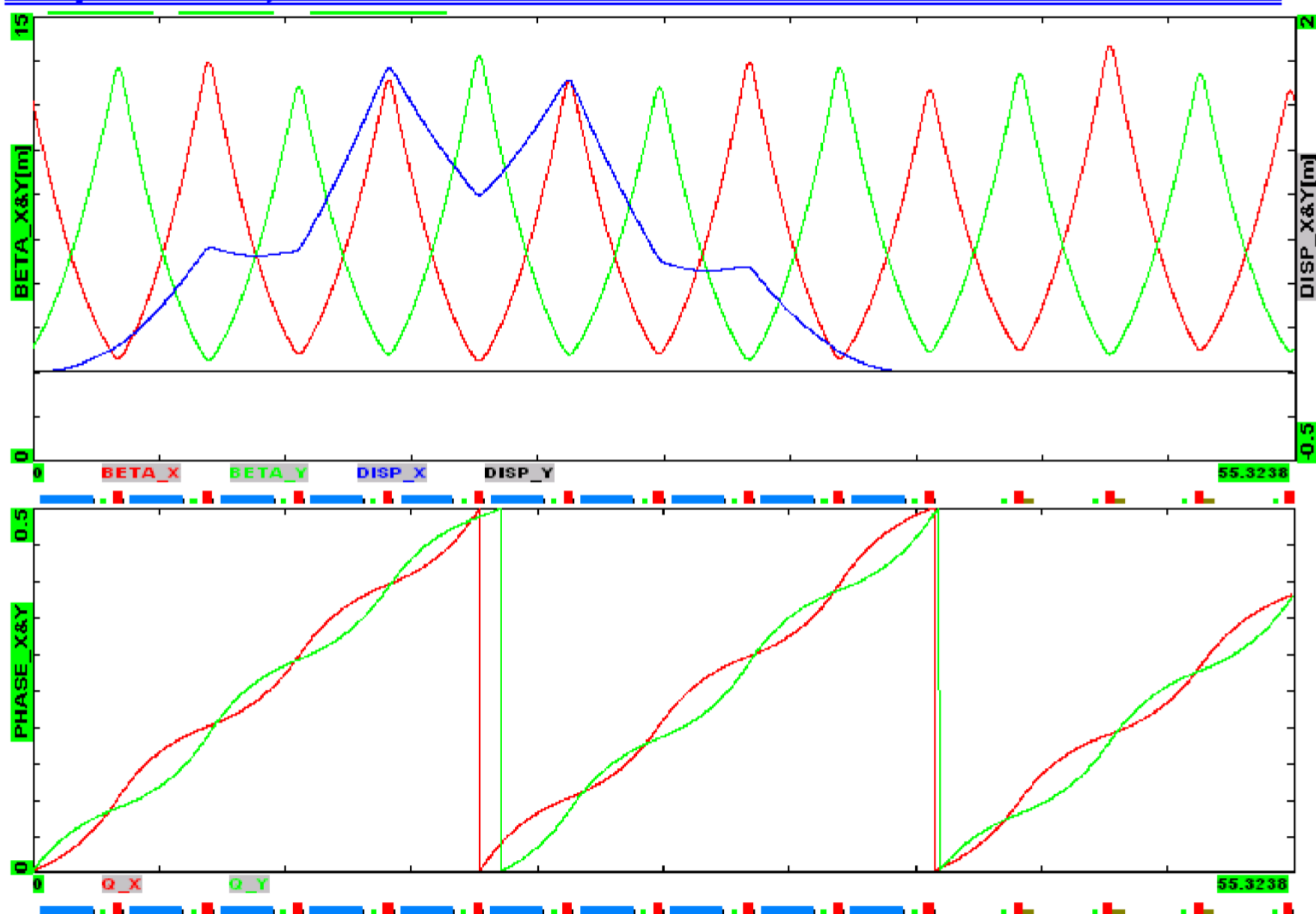
# RCS Beam Optics

- 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

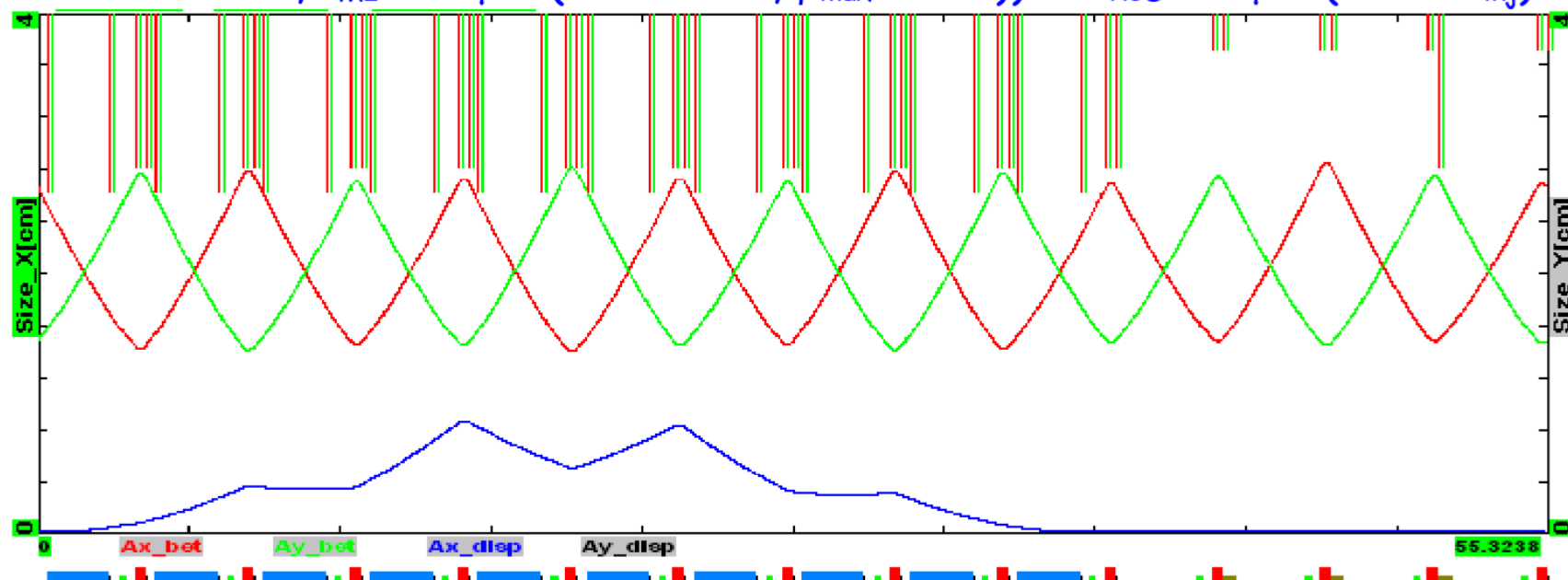
Circumference	553.24 m
Number of super periods	10
Number of cells per super period	7
Betatron tunes, $Q_x/Q_y$	13.81/13.80
Phase advances per cell	0.1973/0.1971
Momentum compaction	0.007783
Transition energy (kin.)	9.697 GeV
Natural chromaticities, $\xi_x, \xi_y$	-15.6/-15.7
Acceptance (geom.)	57 mm 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,  $\varepsilon_{MI}=9.5 \mu\text{m}$  ( $h=2.39 \text{ cm}$ ,  $\beta_{\text{max}}=60 \text{ m}$ )  $\Rightarrow \varepsilon_{RCS}=58 \mu\text{m}$  (lower  $P_{inj}$ )



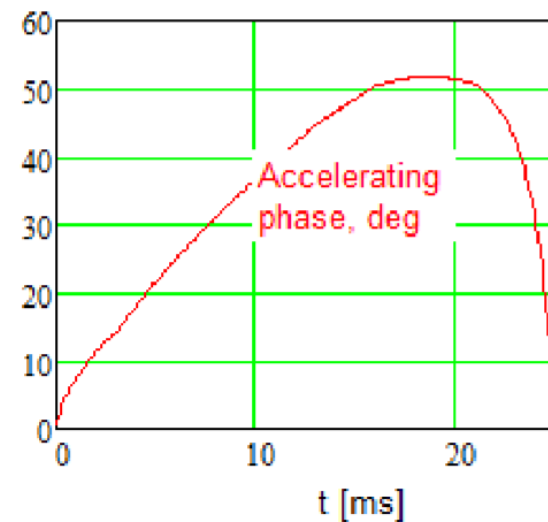
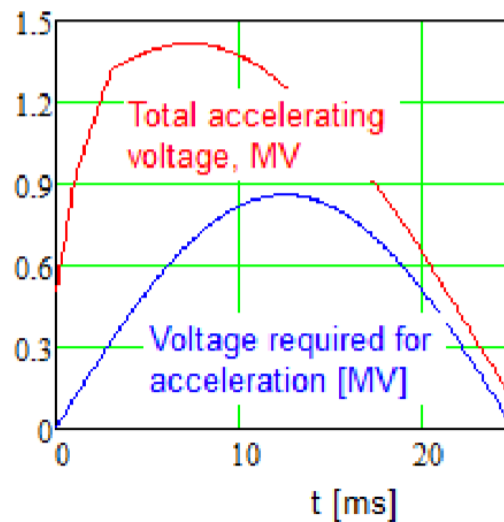
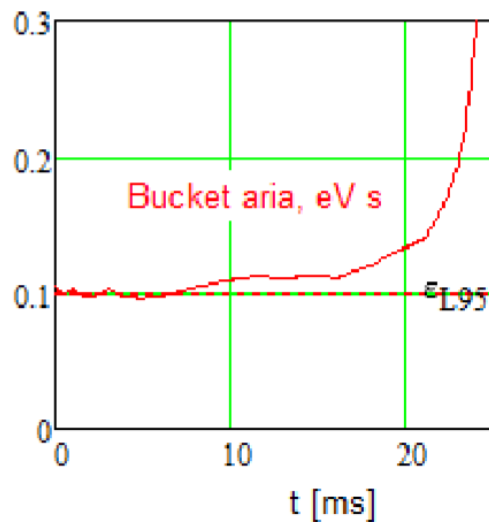
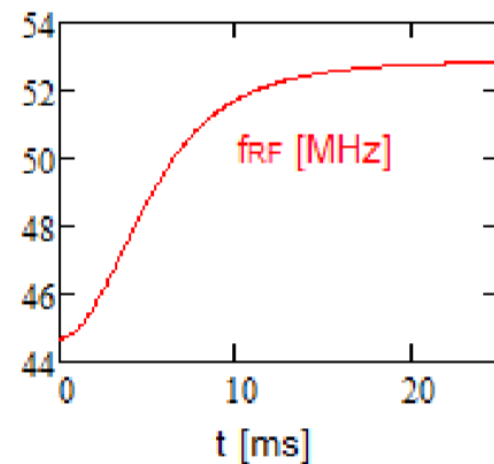
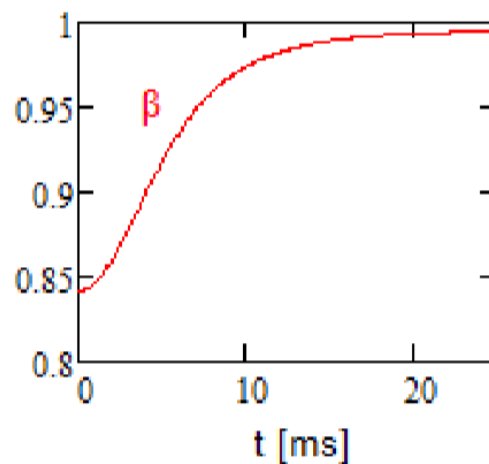
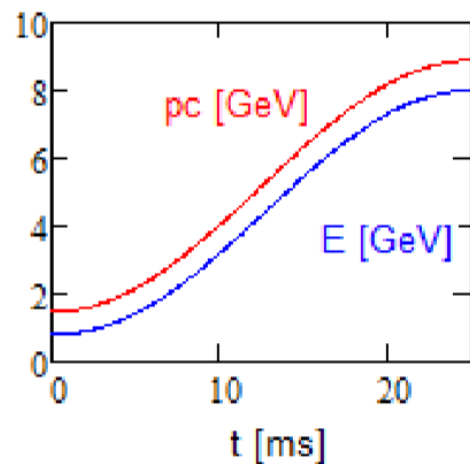
*Beam envelopes at the acceptance ( $\varepsilon=58 \text{ mm mrad}$ ) and maximum  $\Delta p/p=5 \cdot 10^{-3}$*

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

# **Parameters of Magnets**

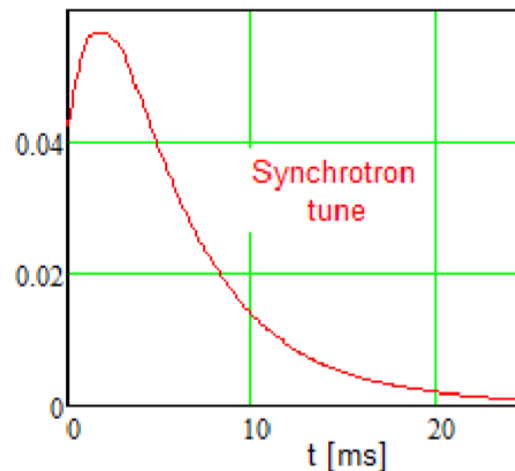
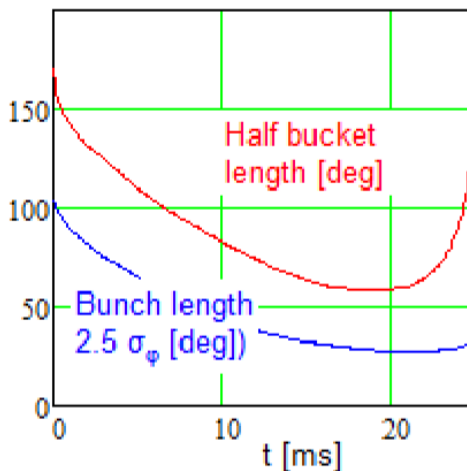
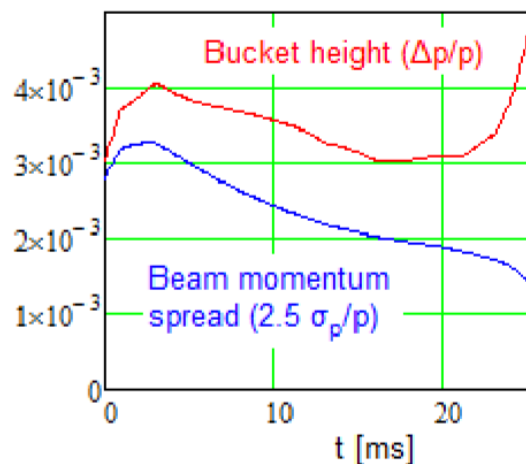
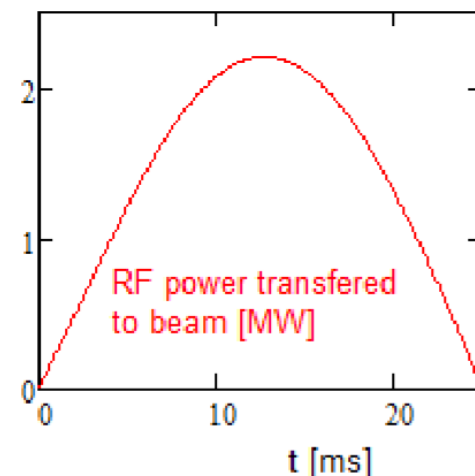
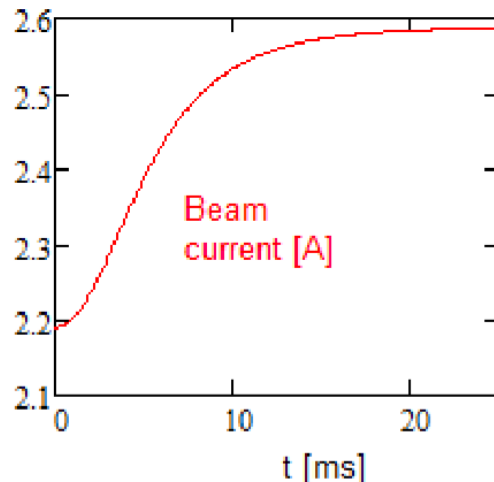
<b>Dipoles</b>	
Number of dipoles	100
Dipole length	2.302 m
Dipole magnetic field at 8 GeV	8.09 kG
Gap	56 mm
<b>Low aperture (located in arcs) quads</b>	
Number of quads	110
Quad length	40 cm
Quad gradient at 8 GeV	2.3 kG/cm
Aperture (Ø)	60 mm
<b>Large aperture (located in straights) quads</b>	
Number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

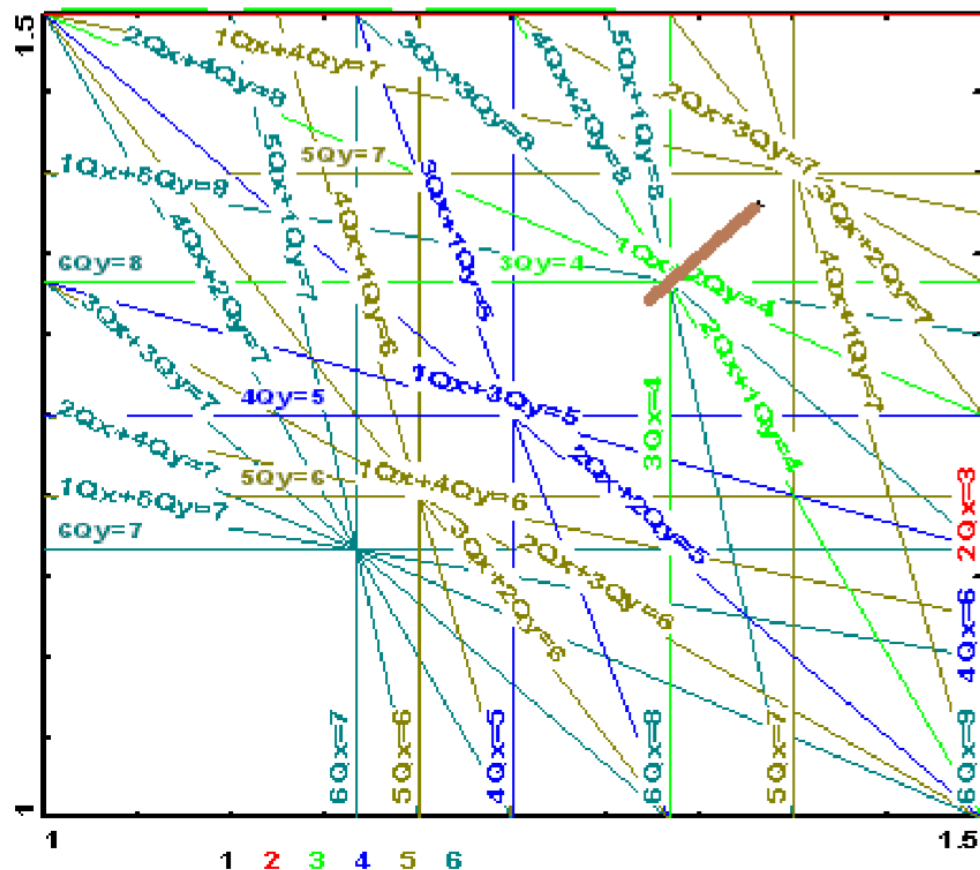


# Space Charge Tune Shifts for Supersymmetric RCS

- 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:

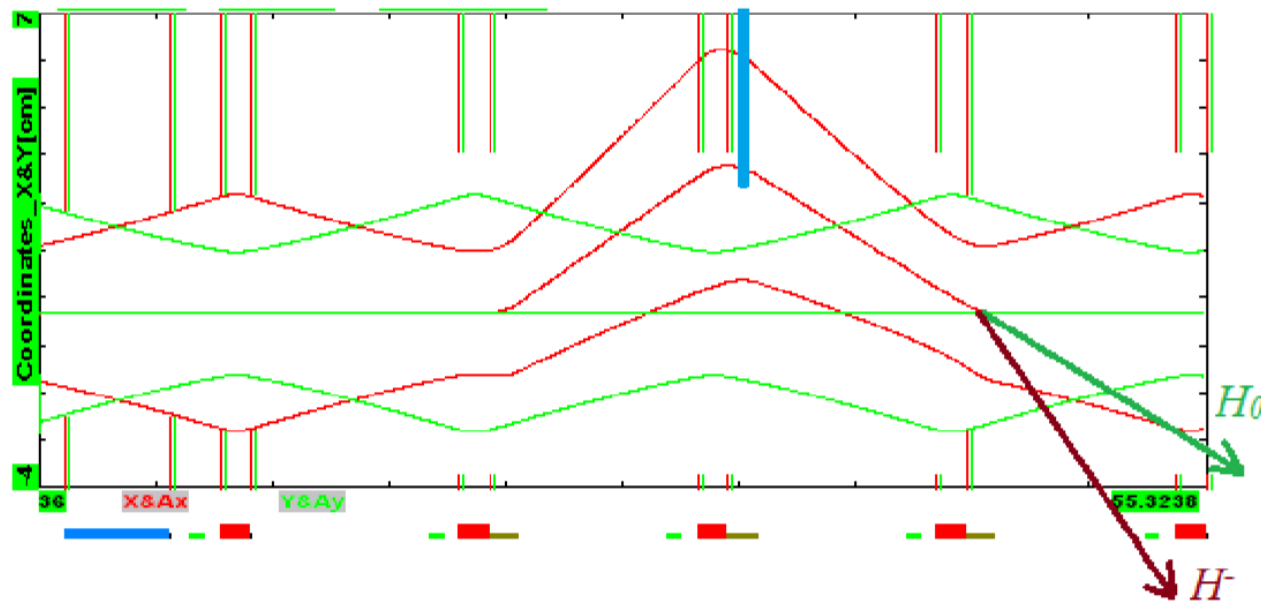
$$\Rightarrow \Delta\nu_{x,y} \approx 0.062$$

- ◆ Realistic simulations are required
- ◆ Experimental prove should come from PIP-I+ and IOTA
- To mitigate SC effects
  - ◆ Phase advance per cell was chosen  $71^\circ$  ( $< 90^\circ$ )
  - ◆ Phase advance per period ( $\sim 1.38$ ) 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  $\sim 1300\text{ K}^\circ$
- 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

