PIP-III Options and Overview

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Objectives

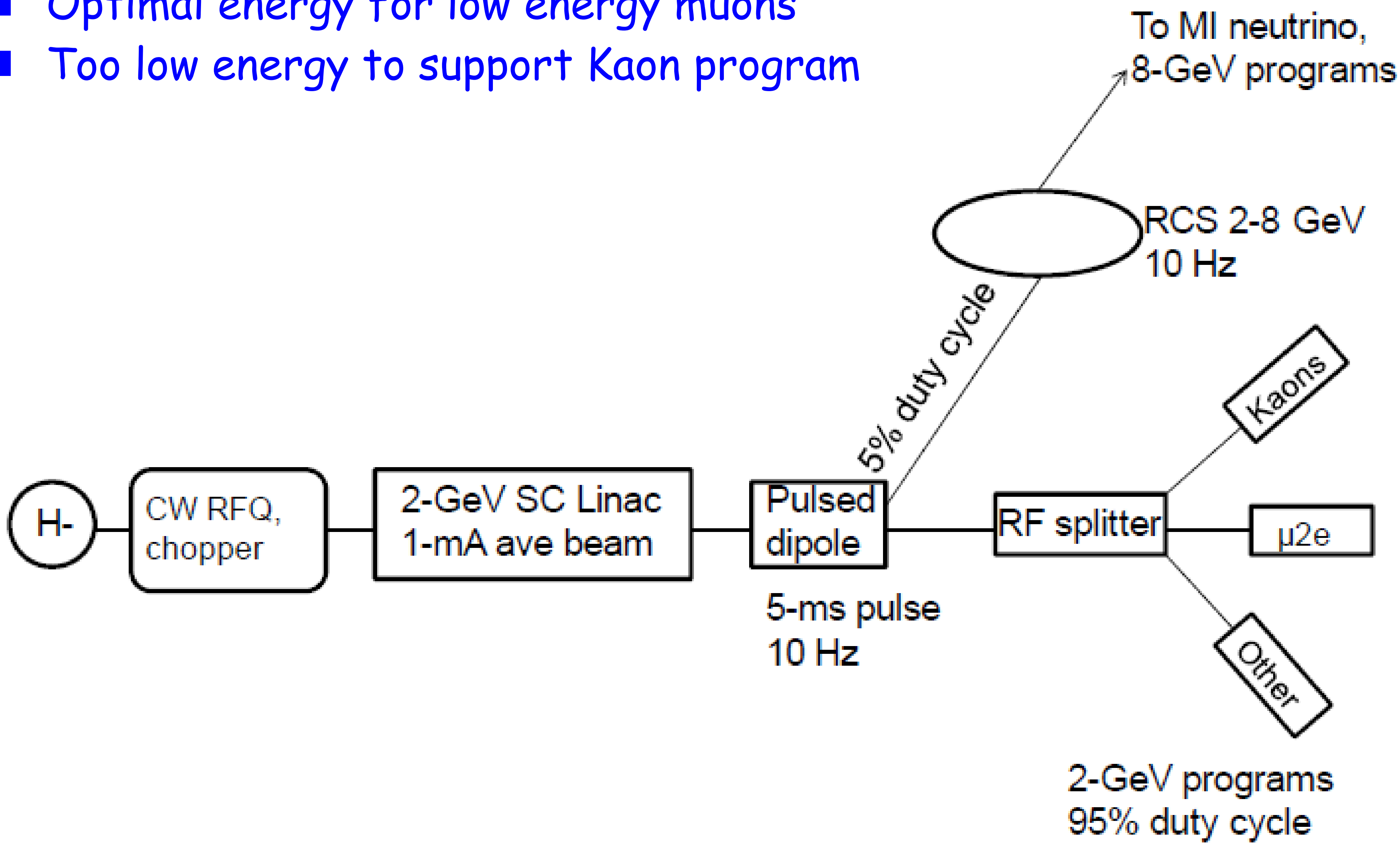
- The only definition of PIP-III we know: PIP-III will follow PIP-II
- Choice of parameters and technology will be determined by requirements of HEP experiments
- Following experiments were discussed/proposed as part of Project X
  - Neutrino program. Pulsed beam (duty factor ~10^{-5}, S/N ratio)
    - Support of neutrino program in MI at P>2 MW
    - Support of neutrino program at 8 GeV at P~100 kW ???
  - Experiments with slow μ's (CW beam, energy range 0.8 – 3 GeV)
    - Mu2e-II (P~100 kW); $\mu \to 3e$, … (P~?)
  - Experiments with kaons (CW beam, energy range 3-5 GeV)
  - Transmutation, Nuclear physics etc. (~1 MW, ~1 GeV)
- Physics part of Project X proposal presents our vision in 2013
  - "Project X - Part 2"
    - Physics Opportunities" Proj.X.doc.db 1199, June 2013
  - "Project X Part 3"
    - Broader Impacts" Proj.X.doc.db 1200, June 2013
- To formulate PIP-III goals we must know better a future Fermilab Physics program

Project-X History

- Initial proposal (2010)
  - "Project X Initial Configuration Document-2"
    Proj.X.doc.db Doc-230 in https://projectx-docdb.fnal.gov, March 2010
  - Based at 2 GeV SC CW linac and 2-8 GeV RCS with strip injection
- Final Project X proposal (2013)
  - "Project X Reference Design Report, Part 1"
    (Proj.X.doc.db Doc-776 in https://projectx-docdb.fnal.gov, June 2013))
  - Major difference – support of kaon program. Based at 3 SC linacs:
    - CW: 0-1 GeV (2 mA), 1-3 GeV (1 mA)
    - Pulsed 3-8 GeV
  - Transition from RCS to SC linac was done to support a Muon Collider proposal requiring multi-MW beams
  - Costs of RCS and 8 GeV SC linac are close
- PIP-II presents a low energy part of Project X (0 – 0.8 GeV)
  - Significant cost reduction
  - Reuse of Booster instead of RCS additionally reduces the cost
  - Linac energy is chosen so that it would support a reduction of the space charge effects at Booster injection & Mu2e upgrade (800 MeV min.)

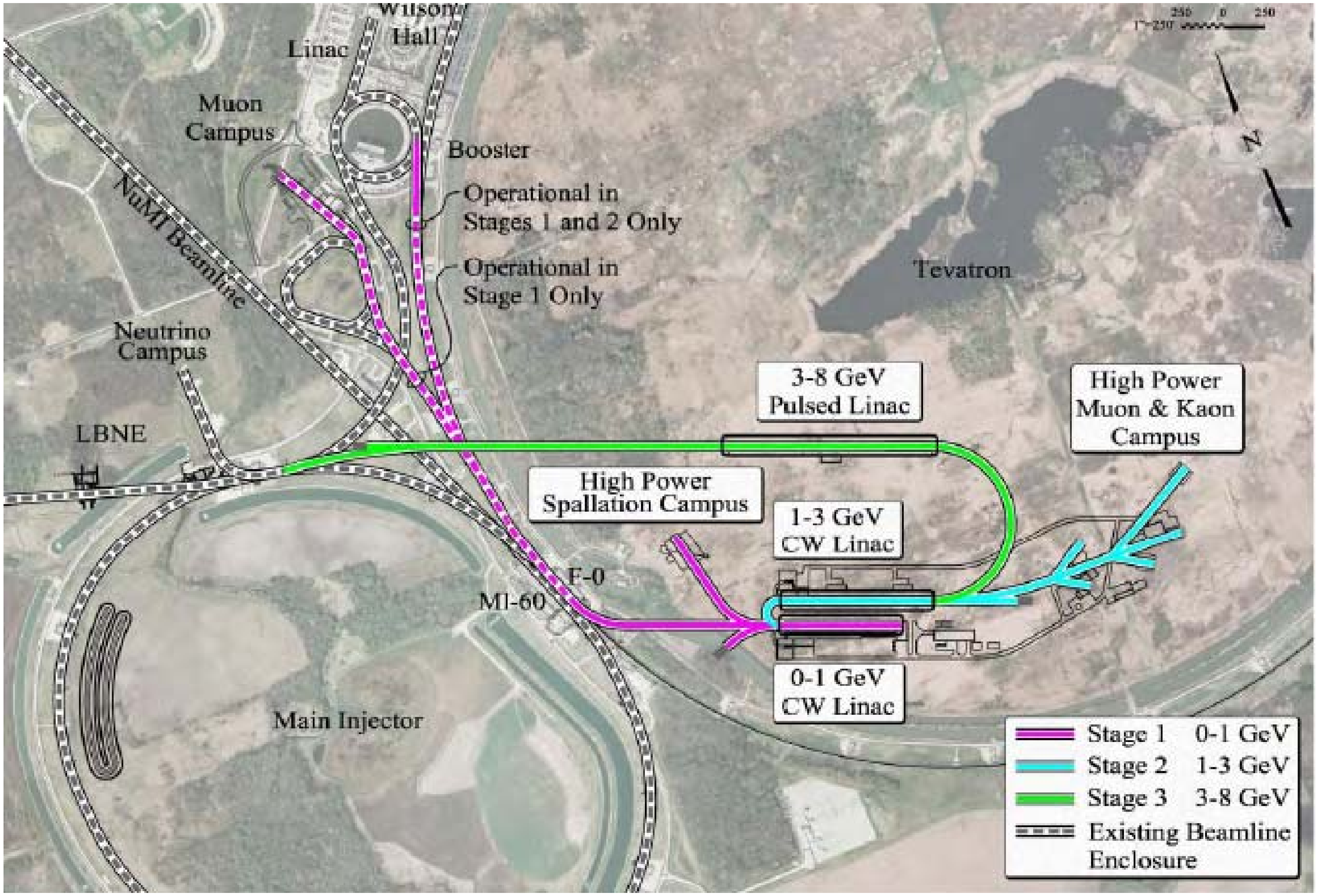
RCS Based Project-X Proposal (ICD-2, 2010)

- Supports neutrino program both at 8 and 120 GeV
- Can simultaneously support multiple experiments
- Optimal energy for low energy muons
- Too low energy to support Kaon program



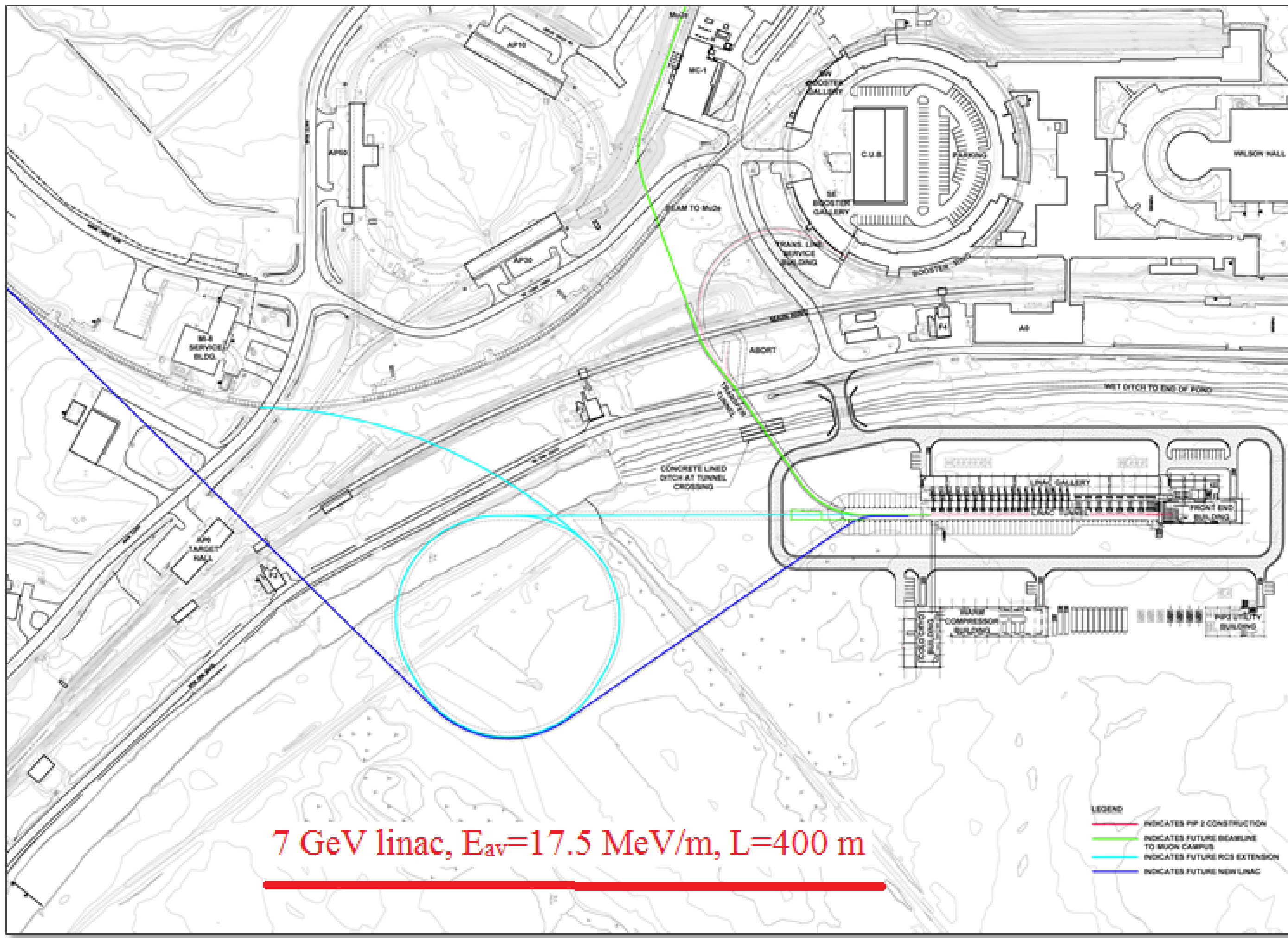
SC Linac Based Project-X Proposal (ICD-2, 2010)

- Staged program
- 8 GeV SC linac supports multi-MW beam delivery for muon collider/ν-factory (It has been the leading reason)
- Construction of SC linac is reasonable only if we expect multi-MW program at 8 GeV



Limitations of PIP-II on PIP-III

- Construction of 8 GeV SC linac for direct injection to MI/Recycler is not compatible with present PIP-II linac location!
  - Large bending radius (~500 m) of transfer line due to H^- stripping by magnetic field (see Project-X layout at the previous slide)
- 8 GeV linac can be built if experimental program supports it
  - But it cannot support ν program unless PIP-II location is changed

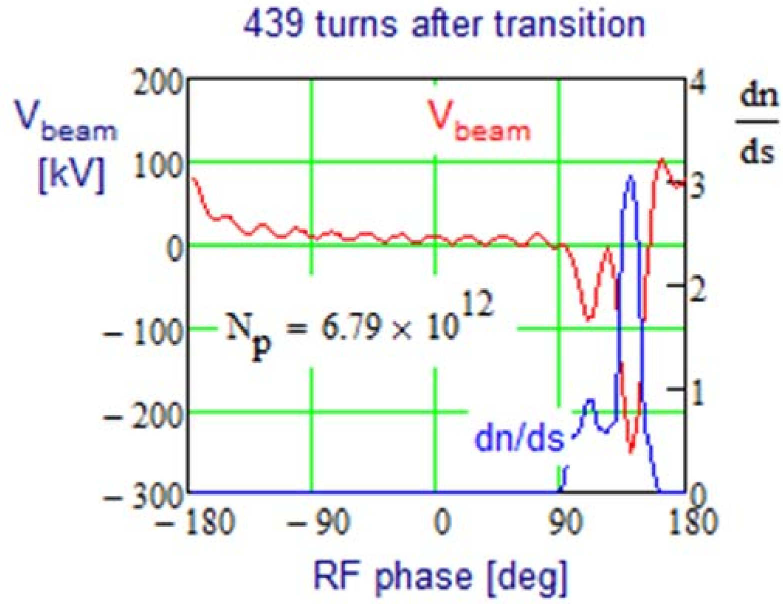


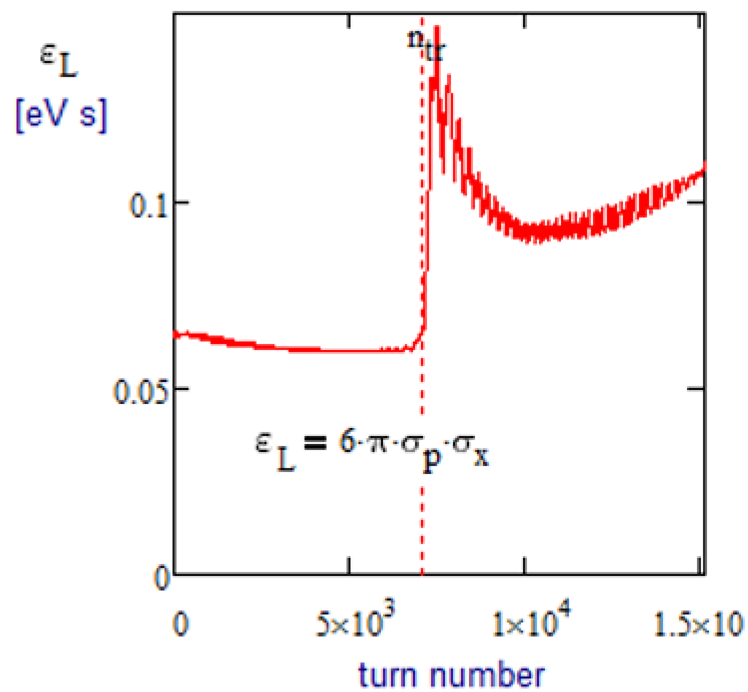
Other Limitations for Usage of 8 GeV SC Linac

- There are other complications with 8 GeV SC linac
  - 8 GeV strip-injection to Recycler/MI will produce more radiation than an injection to the RCS (E_{inj} ~ 0.8 - 3 GeV)
    - Efficiency of strip injection does not depend on energy ($\varepsilon \propto 1/\gamma$, $\Delta p_\perp/p \propto 1/\gamma$)
    - But induced radiation grows somewhat faster than proportionally with beam energy
    - The problem can be addressed but will cost more. More complicated servicing.
  - Strip injection to MI in one pulse with foil is not possible due to foil overheating
    - Laser assistant stripping could resolve this problem
      - However theoretical value of stripping efficiency is worse than for foil stripping (~96% due to spontaneous radiation from excited level)
      - Much more complicated.
      - Untested in an experiment.
  - MI/Recycler injection at energy low than 8 GeV will limit the power below 2 MW

PIP-1+ versus PIP-II

- Beam intensity in Booster is limited by
  - Beam loss at injection due to space charge effects
  - Longitudinal emittance growth at transition crossing
- PIP-II mitigates the injection problem but does not change transition crossing
- Thus, transition crossing is present in both cases
  - It is quite severe limitation which will not allow to use Booster at beam intensity above anticipated in PIP-II
  - The problem arises from the impedance of vacuum chamber set by laminations in dipoles
  - We do not have an experimental proof that we can make transition crossing with PIP-II intensity and long. emittance required for slip-stacking in MI





PIP-1+ versus PIP-II (continue)

- PIP-I+ would allow us to polish the transition crossing well before PIP-II linac will be commissioned
  - but to get to PIP-II intensities in Booster we need to address problems of with space charge effects at injection
  - It could be achieved by making Booster supersymmetric:
    - beta-beating,
    - sextupoles
- If PIP-I+ is successful it addresses the major task of PIP-II – getting 1.2 MW at LBNF target
- PIP-I+ includes the following parts:
  - Booster
    - Addressing beam loss at injection with improvement of Booster super-periodicity
    - Polishing transition crossing
  - MI – Recycler
    - No hardware changes are required to get to 900 kW
    - RF power upgrade is required to get to 1.2 MW
  - Beam power increase has to be supported by development of 1.2 MW target for the LBNF

Why do we need PIP-I+

- This is the only way to get 1 MW+ at the start of LBNE
- PIP-I+ is quite challenging enterprise
    - It will supports qualification and motivation of people involved (Booster, MI and Target departments as well as other involved)

PIP-II

- In a few years we can provide a solid statement about beam power supported by PIP-I+
- If PIP-I+ is successful it makes no sense to recontract Booster for PIP-II beam delivery to Booster
  - Presently, the reconstruction includes
    (1) SC-linac – Booster transfer line and
    (2) Booster injection straight
- Logical outcome of this controversy will be that the initial beam delivery will go to mu2e-II

PIP-II+ or PIP-III

- Next step in the program should be a construction of RCS capable to support >2 MW beam delivery to MI neutrino program
- The cost of RCS can be significantly reduced if some systems of present Booster will be moved to the new RCS
- It would be good to increase energy to ~1.2 GeV
  - Space already allocated in PIP-II tunnel

PIP-III

- In this definitions the PIP-III will be other accelerator complex developments beyond PIP-II+
- If the physics program suggested for Project X still will be considered sufficiently interesting then the following steps look reasonable
  - Increase energy of the PIP-II SC linac to 1.2 GeV.
    - RCS and beam delivery to the muon campus have to be designed to be capable to operate with 1.2 GeV beam
  - Build 3 GeV CW linac to support Kaon program
    - Beam splitters should be anticipated at both 1.2 and 3 GeV points
- If Muon Collider program is expected to follow a construction of SC 8 GeV linac looks reasonable. Then:
  - Increase energy of the PIP-II SC linac to 1.2 GeV.
  - Build 8 GeV SC linac capable to support ν-factory/muon collider operation
    - If possible 12 GeV energy would be a better choice

Conclusions

- PIP-I+ will be capable to support LBNE at 1.2 MW at its start
- PIP-II linac should be CW linac from the very beginning
  - First task is to support mu2e-II at 100 kW
  - There are other experiments which could use 0.8 GeV energy
    - It is time to start thinking about these experiments
- First logical step after PIP-II (PIP-II+)
  - Construct RCS as a replacement for Booster
    - Synchrotron super-symmetry should mitigate SC effects
    - ~2 MW MI power is feasible
  - Construction of 8 GeV linac for injection to MI is not supported by present PIP-II location!!!
- Increase energy of SC linac (PIP-III)
  - There is enough space along the straight line to get to ~2 GeV
  - Increase the RCS injection energy to ~2 GeV
    - It will address possible problems with space charge
  - If kaon program is still attractive increase linac energy to ~3-3.5 MeV
    - Development of SC technology will be very helpful for this step
  - If neutrino factory or muon collider will surface build 8-12 GeV SC linac to support it. This energy increase is not related to MI

Backup Slides

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.)

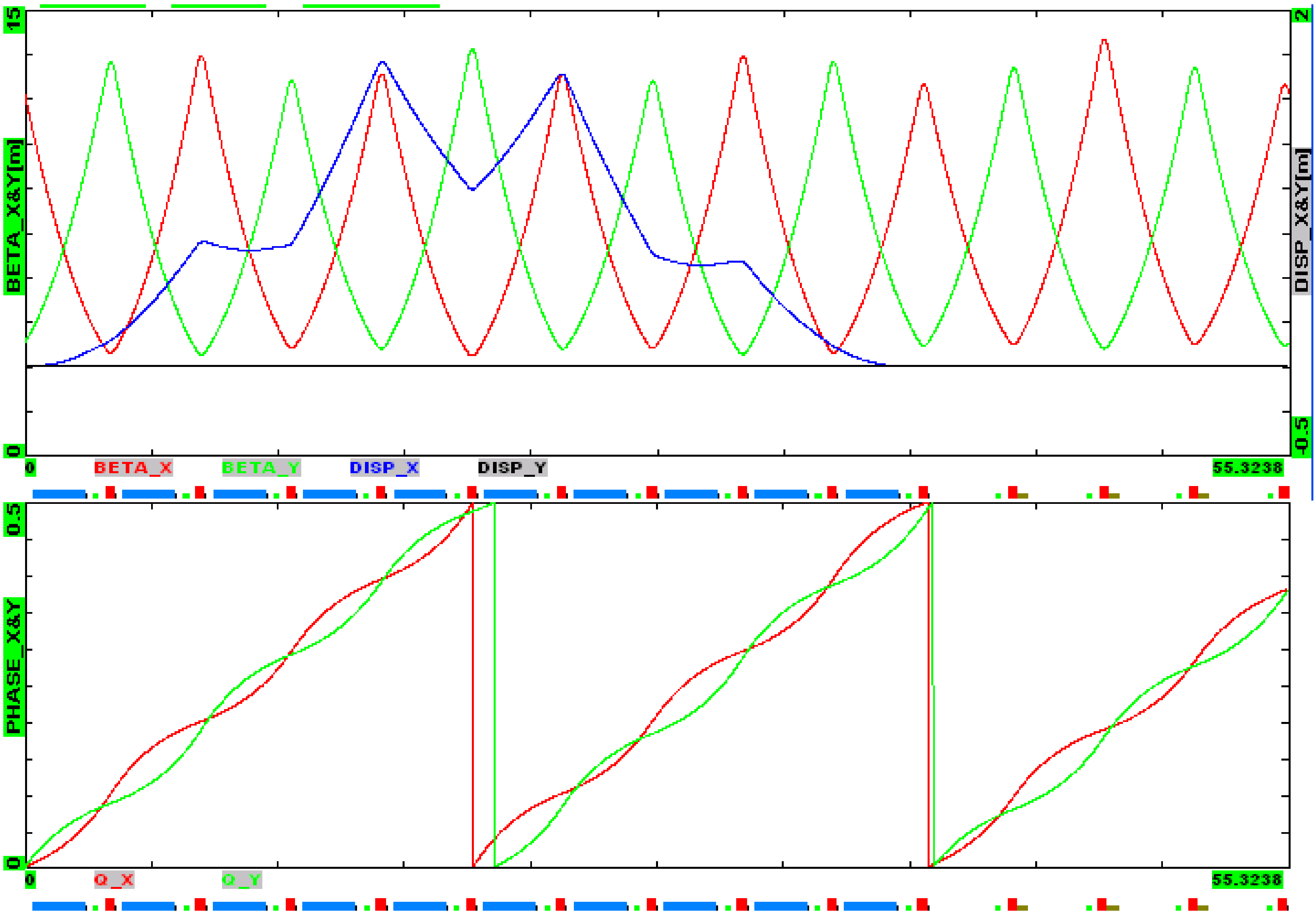
RCS Beam Optics

- 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

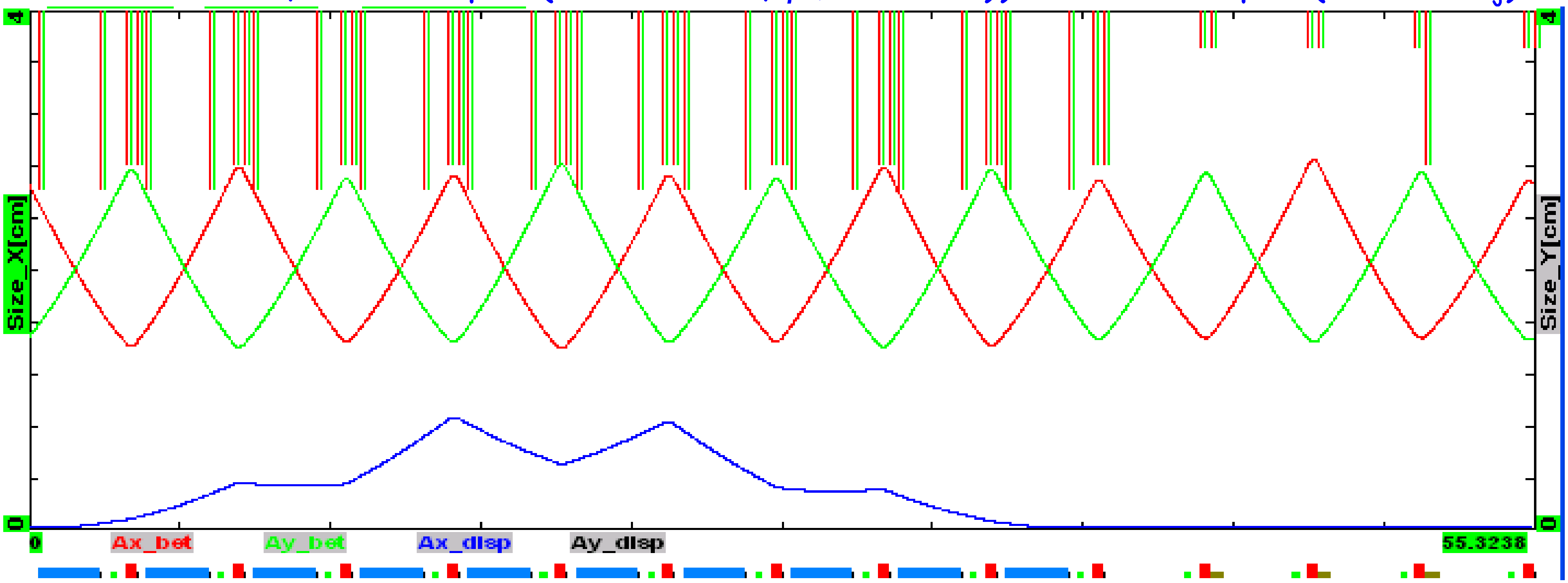
Circumference	553.24 m
Number of super periods	10
Number of cells per super period	7
Betatron tunes, Qx/Qy	13.81/13.80
Phase advances per cell	0.1973/0.1971
Momentum compaction	0.007783
Transition energy (kin.)	9.697 GeV
Natural chromaticities, ξ_x, ξ_y	-15.6/-15.7
Acceptance (geom.)	57 mm mrad

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 Δp/p=5·10^{-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

Vacuum Chamber in Dipoles

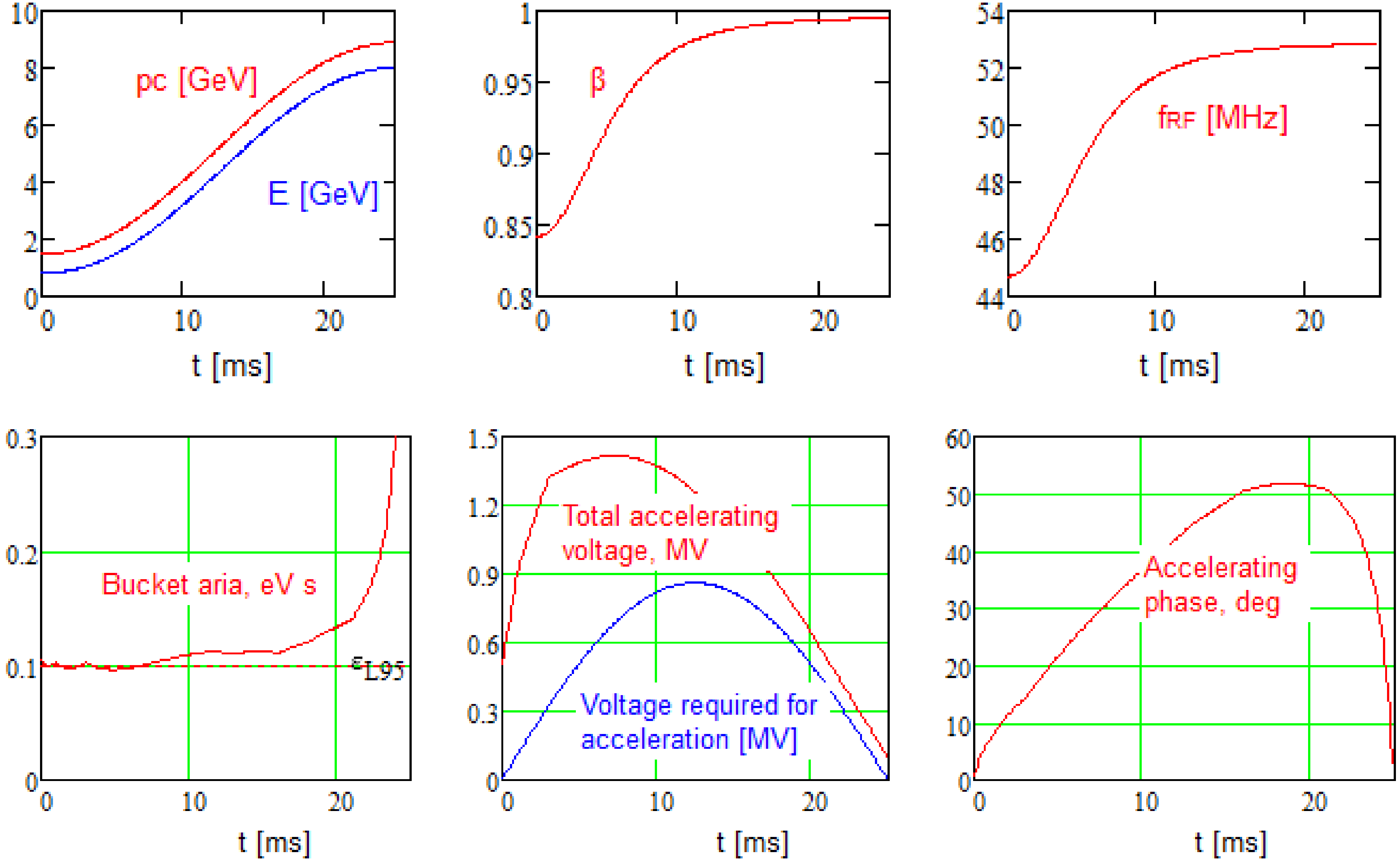
- Vacuum chamber is round for better mechanical stability
  - Internal radius: in dipoles r=28 mm, in quads r=30 mm,
  - The wall thickness - 0.75 mm
    - This thickness is sufficient for mechanical stability against atmospheric pressure
      - Additional ribs can be added to improve rigidity
        - They also improve vacuum chamber cooling but make the chamber more expensive
  - Material is Inconel-625 ($\rho=129\cdot10^{-6}$ Ω/cm)
- Vacuum chamber heating power by eddy currents: 36 W/m @ 20 Hz

$$\frac{dP}{dz}=\frac{\pi\sigma_R d_w a_w^3 \omega_{ramp}^2}{2c^2}B_{AC}^2$$

  - Particle loss of ~1 W/m makes negligible contribution to heating

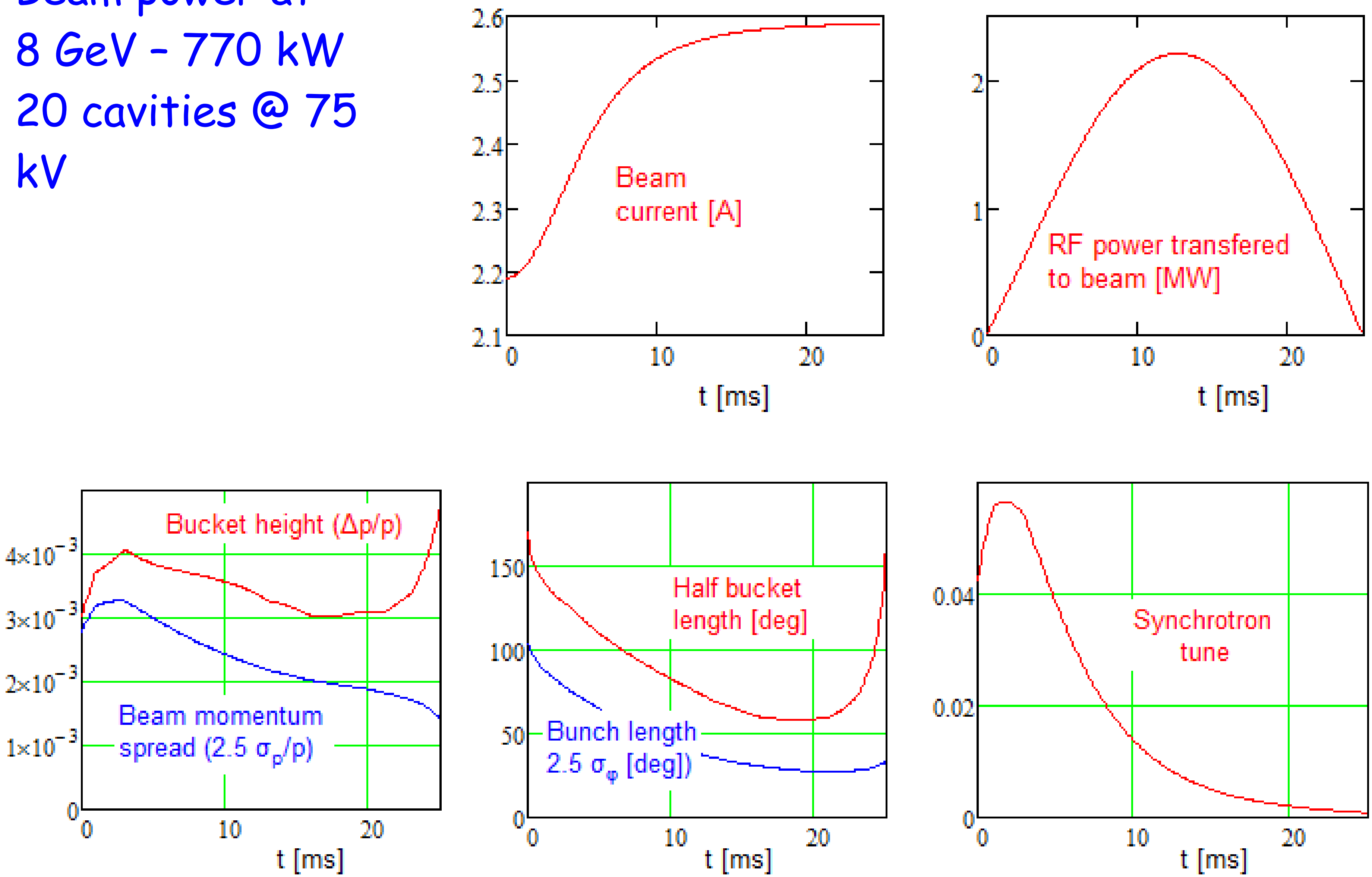
- An estimate of equilibrium temperature of vacuum chamber is based on a conservative air cooling estimates for the case of convective cooling
  - the heat transfer coefficient 10^{-3} W/cm^2/K.
    ⇨ ΔT=20 K

Beam Acceleration in RCS



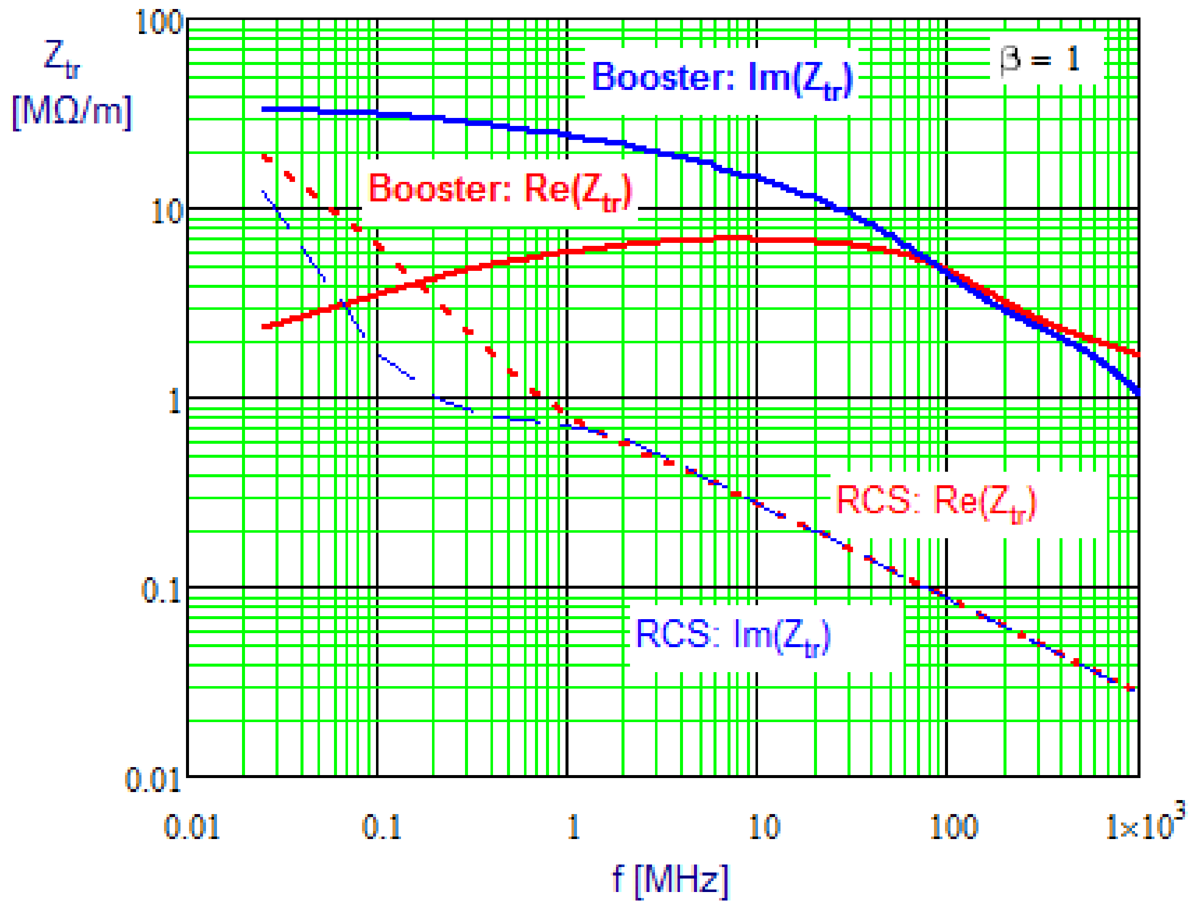
Beam Acceleration in RCS (P_{MI}=2.4 MW)

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



Instabilities

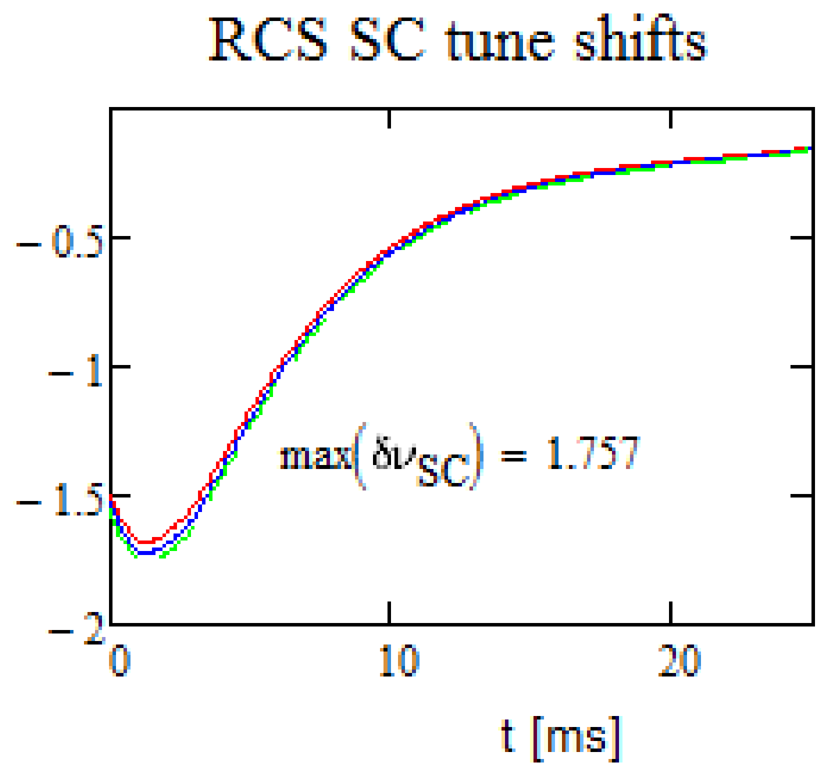
- Transition from Booster "laminated" vacuum chamber to the Inconel vacuum chamber reduces impedances significantly more than an increase of beam current
  - ⇨ Instabilities are not expected to be a problem
- Natural chromaticity of the ring is ≈ -15.6
  - ♦ It has correct sign and is large enough to mitigate instabilities
- Detailed study of beam stability in the presence of strong space charge should follow



Space Charge Tune Shifts

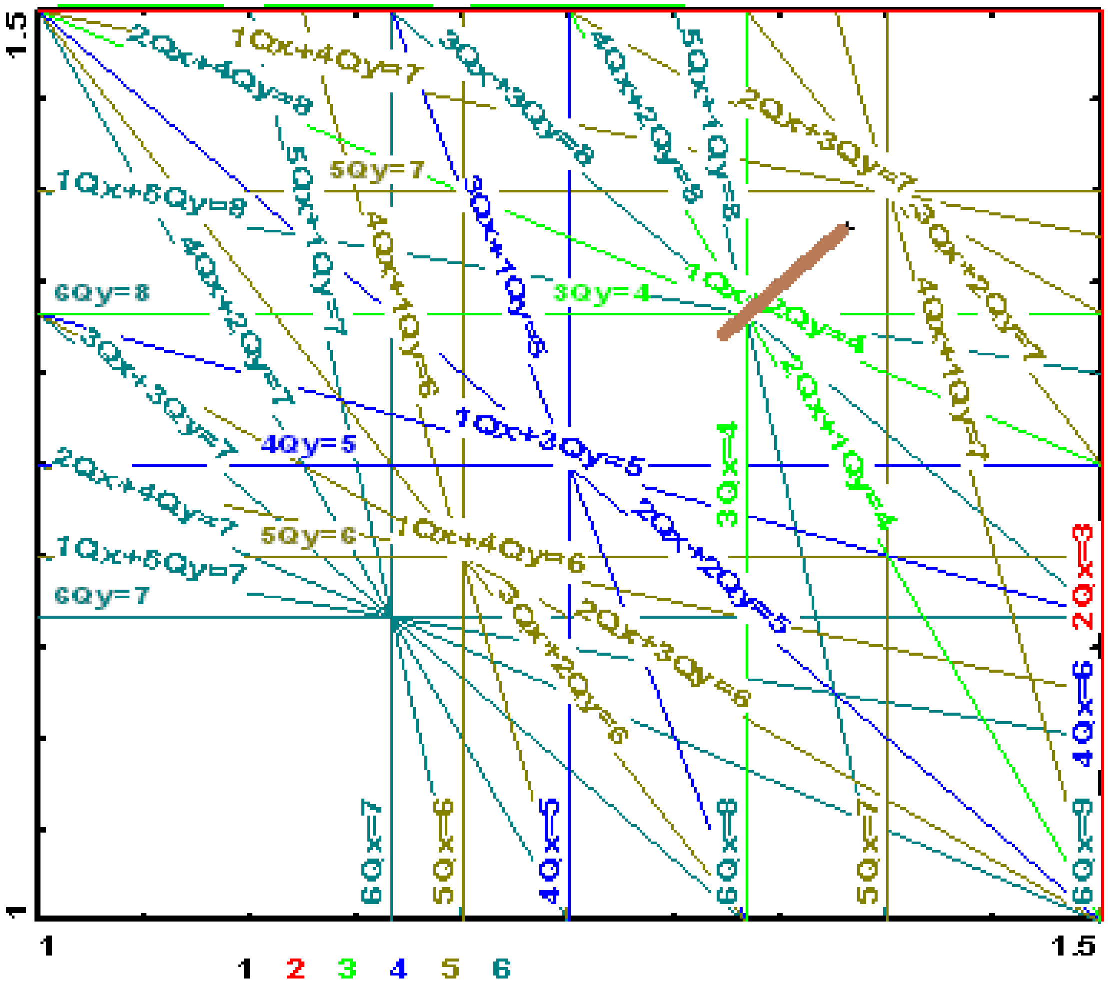
$$\Delta\nu_{x,y} = \frac{r_p N_b q B}{2\pi\beta^2\gamma^3 C}\int_C \frac{\beta_{x,y}\,ds}{\left(\sigma_x+\sigma_y\right)\sigma_{x,y}} \xrightarrow[\varepsilon_n=\beta\gamma\varepsilon_x=\beta\gamma\varepsilon_y]{D=0} \frac{r_p N_b q B}{4\pi\beta\gamma^2\varepsilon_n}$$

- Peak of space charge tune shift for present Booster for $N_p=5\cdot10^{12}$
  - $\Delta\nu\approx0.45$ (B = 3, ε_{95n}=16 μm)
- RCS has much larger beam current but twice larger energy reduces tune shift by ~2 times
  - $\Delta\nu_{x,y}\approx 1.7$
    (Gaussian beam, ε_{n95}=16 μm)
- Painting for KV distribution decreases the tune shift by ~2, and a usage of second harmonic yields additional 35 %
  - ⇨ $\Delta\nu_{x,y}\approx 0.62$



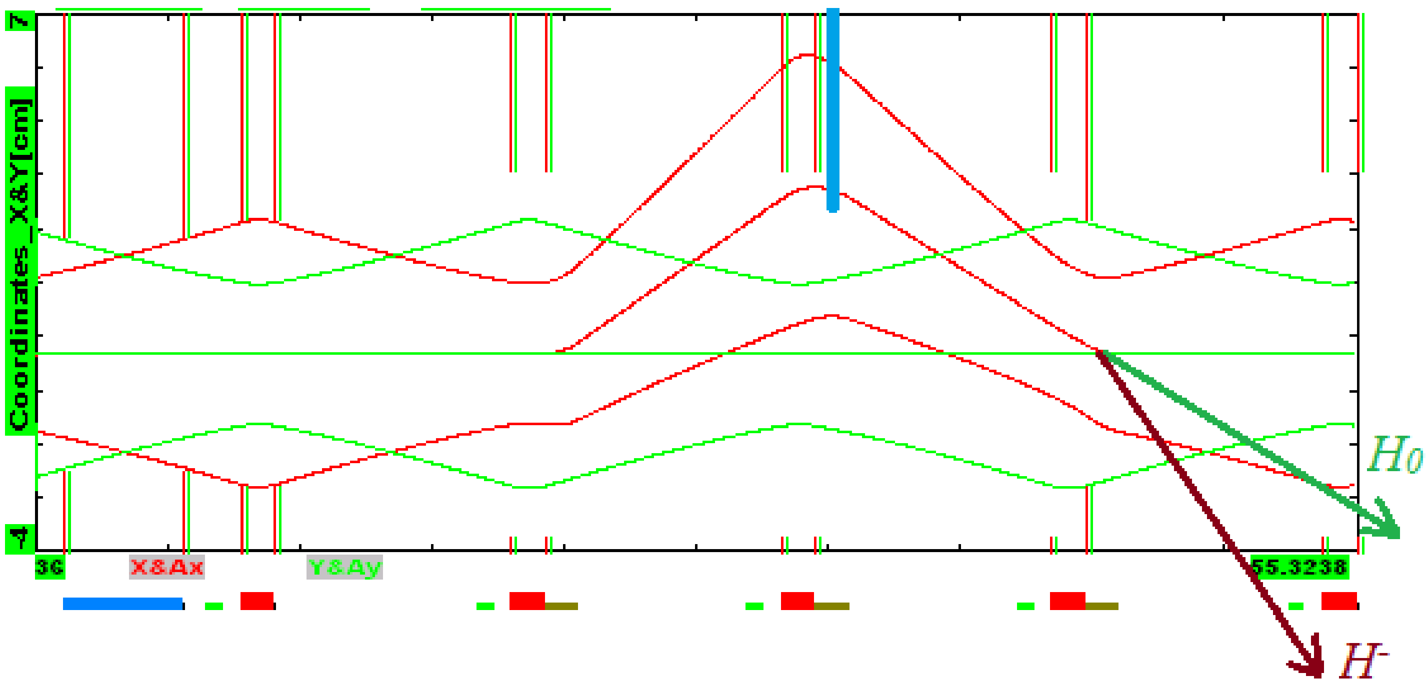
Space Charge Tune Shifts for Supersymmetric RCS

- 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



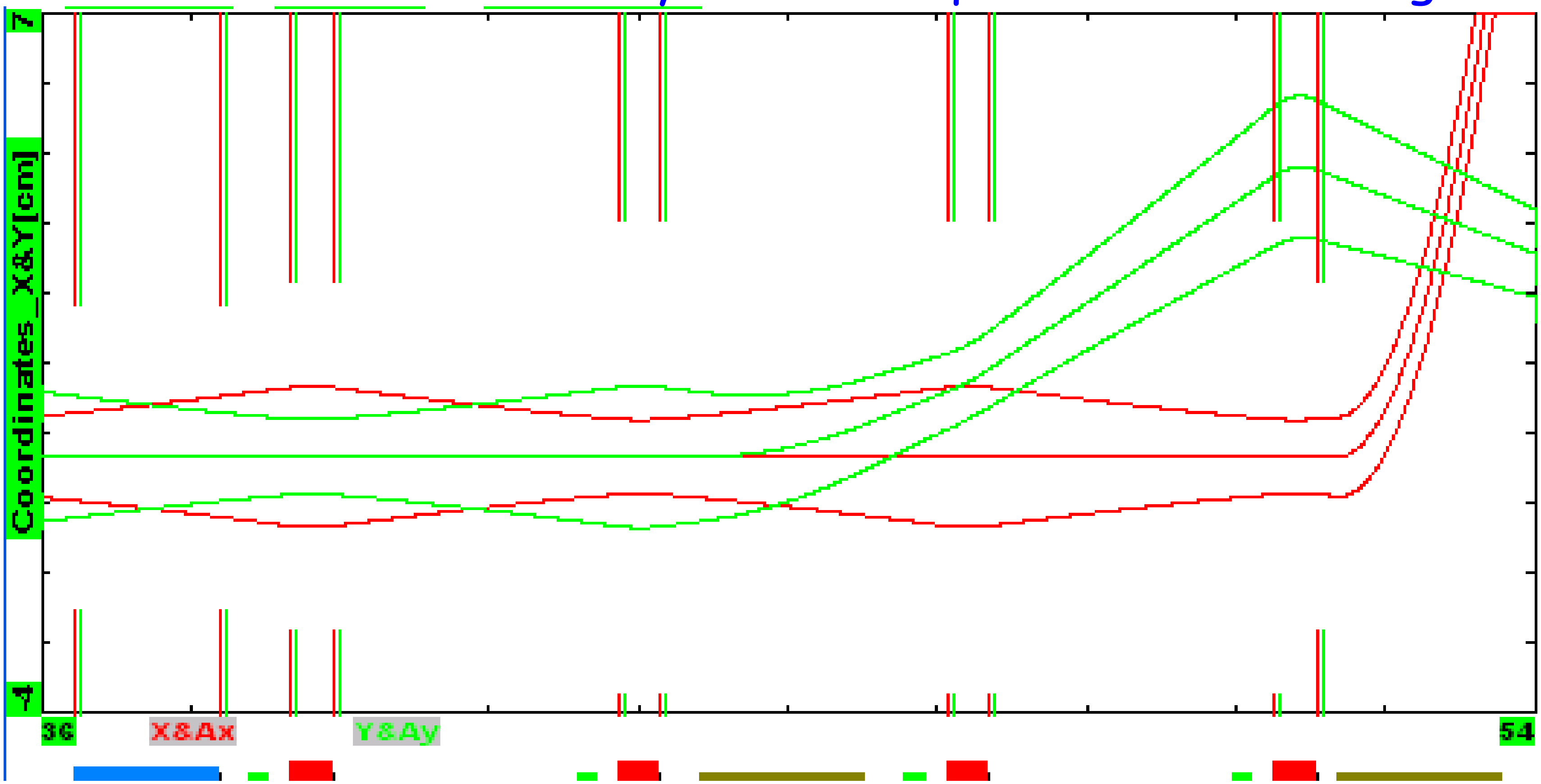
Injection

- 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



Distribution of Accelerator Equipment in the Ring

- There are 40 slots in straights which can be used for accelerator systems (2.8 m)
- Injection and extraction use 3 slots each
- Scraping system – 2 slots
- Dampers – 3 slots
- RF cavities – 20 slots (1.5 MV total, 75 kV per cavity)
  - Present RF cavity length is 2.35 m
- 2nd harmonic RF cavities - 8 slots
- Other – 1 slot

Main Injector Main Parameters

MI cicle time:	$T_{MI} := 1.2$ s	
MI beam power:	$P_{MI} := 2.4\cdot 10^{6}$ W	
Top energy:	$E_{MI} := 120\cdot 10^{9}$ eV	$N_{MI} := \frac{P_{MI}\cdot T_{MI}}{e_{SI}\cdot E_{MI}}$
Total number of particles in the beam:	$N_{MI} = 1.498\times 10^{14}$	
Number of RCS batches coming to MI:	$n_{tr} := 5$	
Harmonic number:	$q_{MI} := 588$	$q_{RCS} := \frac{q_{MI}}{n_{tr}+1}$
Harmonic number in RCS:	$q_{RCS} = 98$	$n_{b\_RCS} := q_{RCS} - 3$
Number of bunches in RCS:	$n_{b\_RCS} = 95$	
Particles per bunch:	$N_b = 3.154\times 10^{11}$	$N_b := \frac{N_{MI}}{n_{tr}\cdot n_{b\_RCS}}$
MI circumference:	$C_{MI} := 3.31942\times 10^{5}$	
MI injection energy:	$E_{MIinj} := 8\cdot 10^{9}$	$\gamma_{MIinj} := \frac{E_{MIinj}}{m_p}$; $\beta_{MIinj} := \sqrt{1-\frac{1}{(\gamma_{MIinj})^2}}$
Relativistic parameters at inj:	$\gamma_{MIinj} = 8.526$	
	$\beta_{MIinj} = 0.993$	$f_{0MI} := \frac{c\cdot\beta_{MIinj}}{C_{MI}}$
Revolution frequency in MI at injection:	$f_{0MI} = 8.969\times 10^{4}$	$I_{MI} := e_{SI}\cdot N_{MI}\cdot f_{0MI}$
MI beam current:	$I_{MI} = 2.153$ A	$C_{RCS} := \frac{C_{MI}}{(n_{tr}+1)}$; $P_{max} := \sqrt{(E_{MIinj}+m_p)^2 - m_p^{\,2}}$
RCS circumference:	$C_{RCS}\cdot 0.01 = 553.237$ m	

Linac and RCS injection

Linac Energy:	$E_{min} := 0.8\cdot 10^{9}$	$\gamma_{inj} := 1 + \frac{E_{min}}{m_p}$
Linac current:	$I_{linac} := 2\cdot 10^{-3}$ A	$P_{min} := \sqrt{(E_{min} + m_p)^2 - m_p^{\;2}}$ $\beta_{inj} := \sqrt{1 - \frac{1}{(\gamma_{inj})^2}}$
Repetition rate:	$f_{rep} := 20$ Hz	
Relativistic parameters at inj:	$\gamma_{inj} = 1.853$ $\beta_{inj} = 0.842$	$f_{inj} := \frac{c\cdot\beta_{inj}}{C_{RCS}}$ $I_{RCS} := f_{inj}\cdot e_{SI}\cdot N_b\cdot n_{b\_RCS}$
MI beam current:	$I_{RCS} = 2.19$ A	$n_{injT} := \frac{I_{RCS}}{I_{linac}}$ $T_{inj} := \frac{n_{injT}}{f_{inj}}$
Number of injection turns:	$n_{injT} = 1.095\times 10^{3}$	
Injection time:	$T_{inj}\cdot 10^{3} = 2.4$ ms	$\Delta p\_p_{inj} := \left(\frac{\gamma_{MIinj}\cdot\beta_{MIinj}}{\gamma_{inj}\cdot\beta_{inj}} - 1\right)\cdot\frac{1}{4}\cdot\left(2\cdot\pi\cdot f_{rep}\cdot\frac{T_{inj}}{2}\right)^2$
Momentum change during injection (uncompensated):	$\Delta p\_p_{inj} = 0.025$	