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Suppression of Half-Integer Resonance in FNAL Booster and Space Charge Losses at Injection

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- F.Schmidt, D.Shatilov

Selected References

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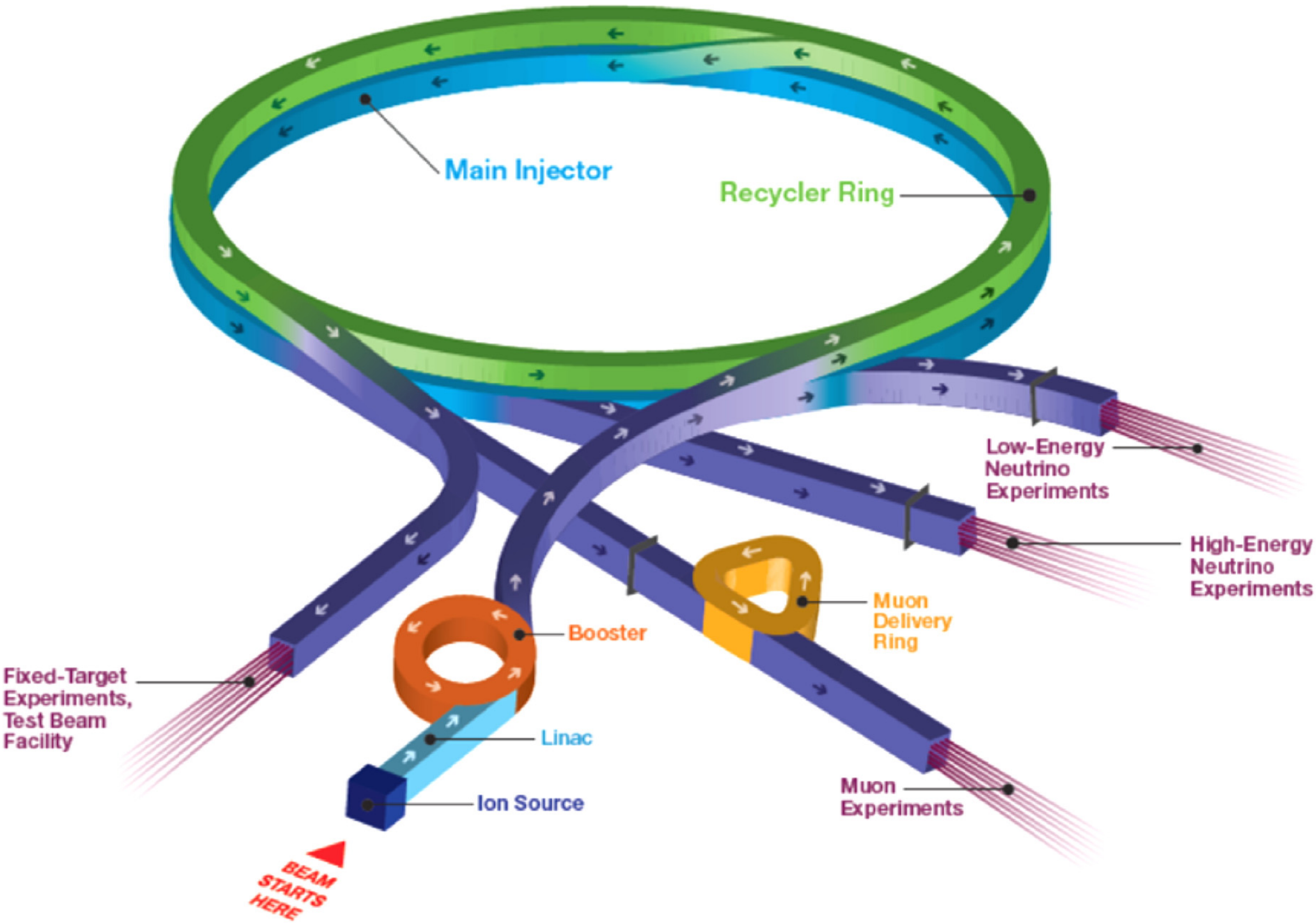
Fermilab Accelerator Complex

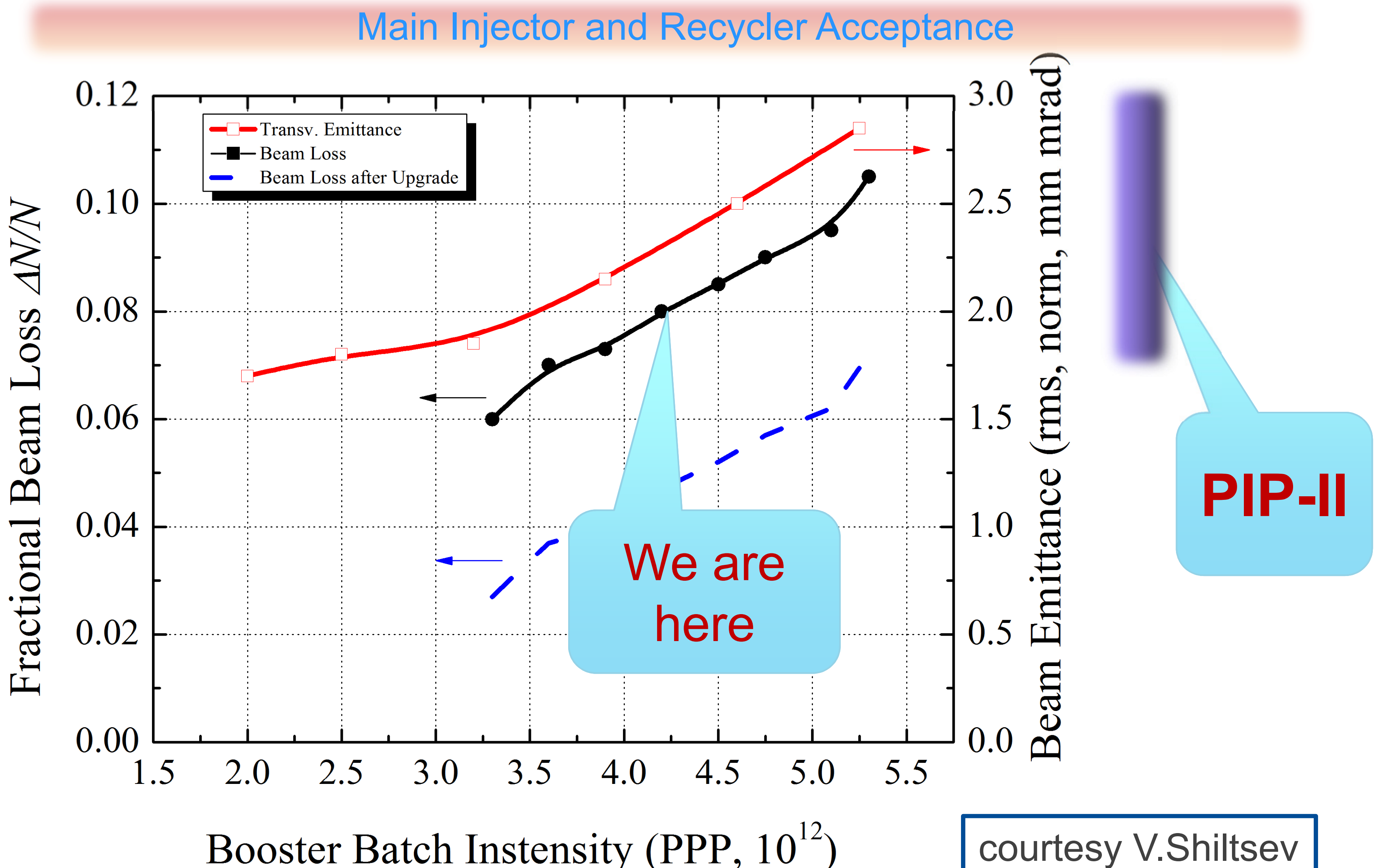


PIP-II Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	**400**	**800**	**MeV**
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.6	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Booster Protons per Pulse	**4.3×10^{12}**	**6.5×10^{12}**	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max; MI @ 120 MeV)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	**0.7***	**1.0-1.2**	**MW**
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*NOvA operations at 120 GeV

Booster Bottleneck: Emittance, Losses

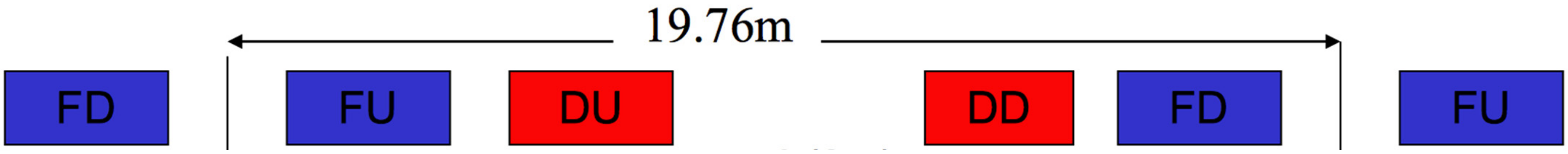


courtesy V.Shiltsev

Limiting Factors

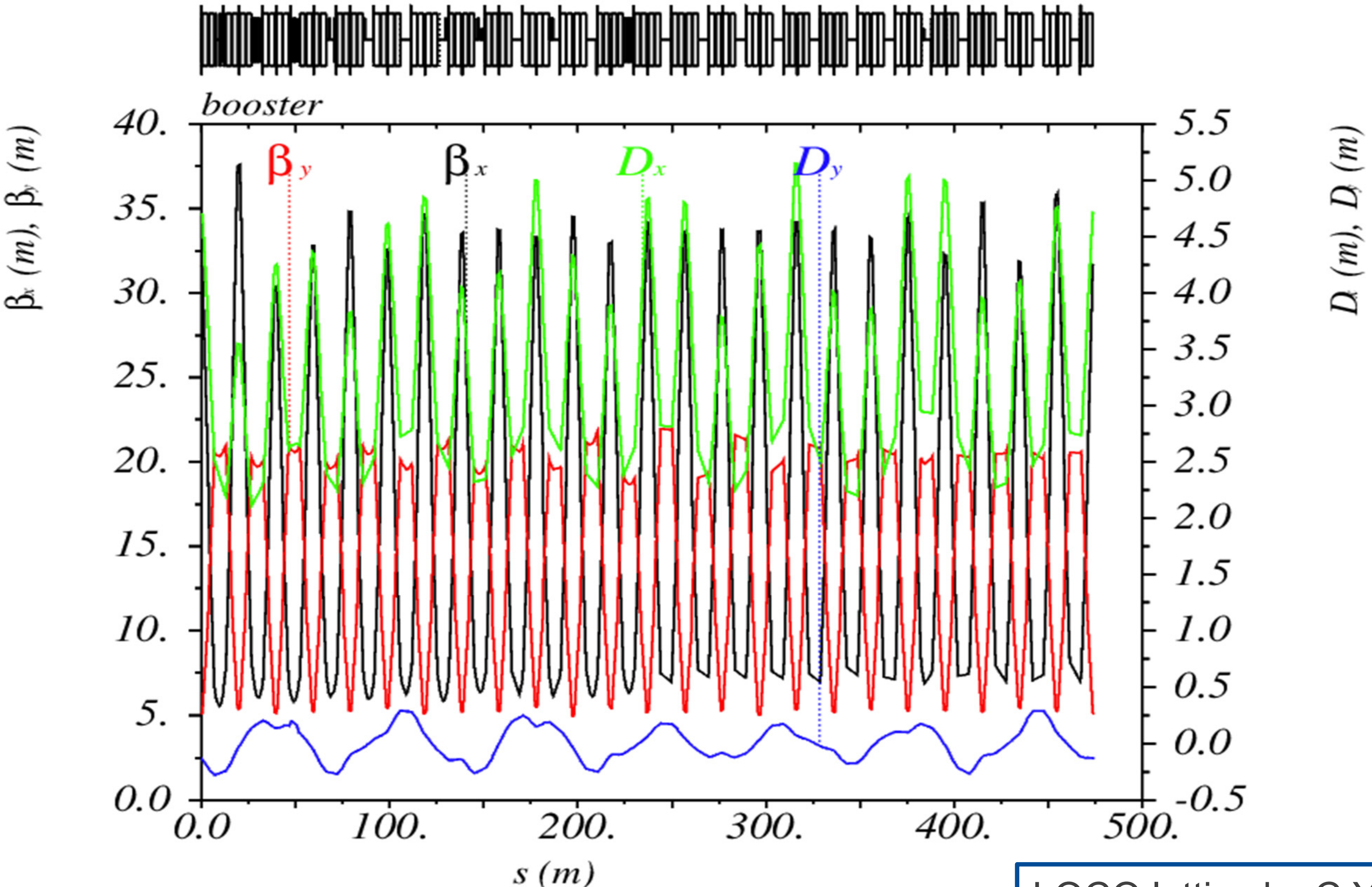
- Coherent instabilities at injection (A.Macridin, Booster workshop, 2015)
- Transition crossing (V.Lebedev, Booster workshop, 2015)
- Beam emittance growth and losses at injection due to incoherent space charge effect – this talk
  - Action of direct space charge on stability of particle motion is through the time modulation of nonlinear transverse field and consequently, betatron and synchrobetatron resonances
  - Goals
    - Understand the current limitations
    - Make projections for PIP-II and make improvements in current operation

Booster Lattice



- 24 lattice periods
- Each lattice period has 4 combined function magnets
- Lattice symmetry is perturbed by DC extraction dogleg
- Betatron tunes $Q_x \approx 6.7$, $Q_y \approx 6.8$
- Aperture at injection $A_x \approx 5\sigma$, $A_y \approx 4\sigma$

Booster Lattice



LOCO lattice by C.Y.Tan

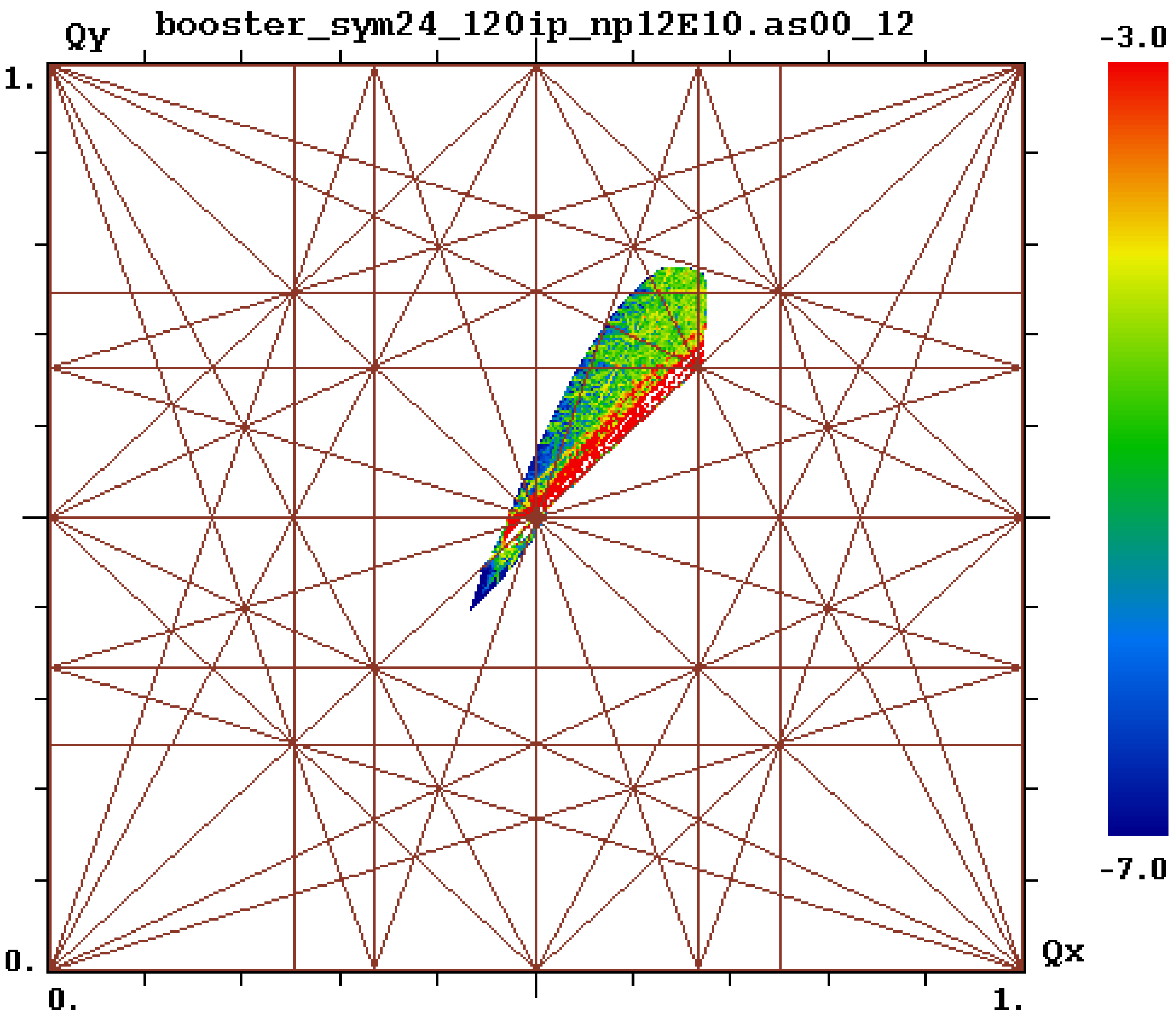
Nominal Booster Injection Parameters

Injection Energy	400 MeV (β=0.713, γ=1.426)
U_{RF}	0→0.7 MV adiabatic capture
Q_s	0.08 (ω_s=35 kHz)
Bucket size	4.2×10^{-3}
Momentum spread	2.1×10^{-3} (σ_z=1.26 m) – fully bunched beam
Transverse emittance	10÷15 mm×mrad (95% normalized)
N_p	0.42×10^{13} in 84 bunches
Bunching factor	2.5
SC tuneshift	ΔQ_x=-0.2, ΔQ_y=-0.27
Betatron tunes	$Q_x\approx6.7$, $Q_y\approx6.8$
Chromaticity	C_x=-20, C_y=-14

Booster Parameters for “PIP-II mode”

Energy	400 MeV (β=0.713, γ=1.426)
U_{RF}	0→0.7 MV
Q_s	0.08 (ω_s=35 kHz)
Bucket size	4.2×10^{-3}
Energy spread	2.1×10^{-3} (σ_z=1.26 m) – fully bunched beam
Transverse emittance	10÷15 mm×mrad (95% normalized)
N_p	0.65×10^{13} in 84 bunches
Bunching factor	2.5
SC tuneshift	ΔQ_x=-0.33, ΔQ_y=-0.46
Betatron tunes	$Q_x \approx 6.70$, $Q_y \approx 6.80$
Chromaticity	C_x=-20, C_y=-14

FMA Footprint for Np=0.45×10^{13}



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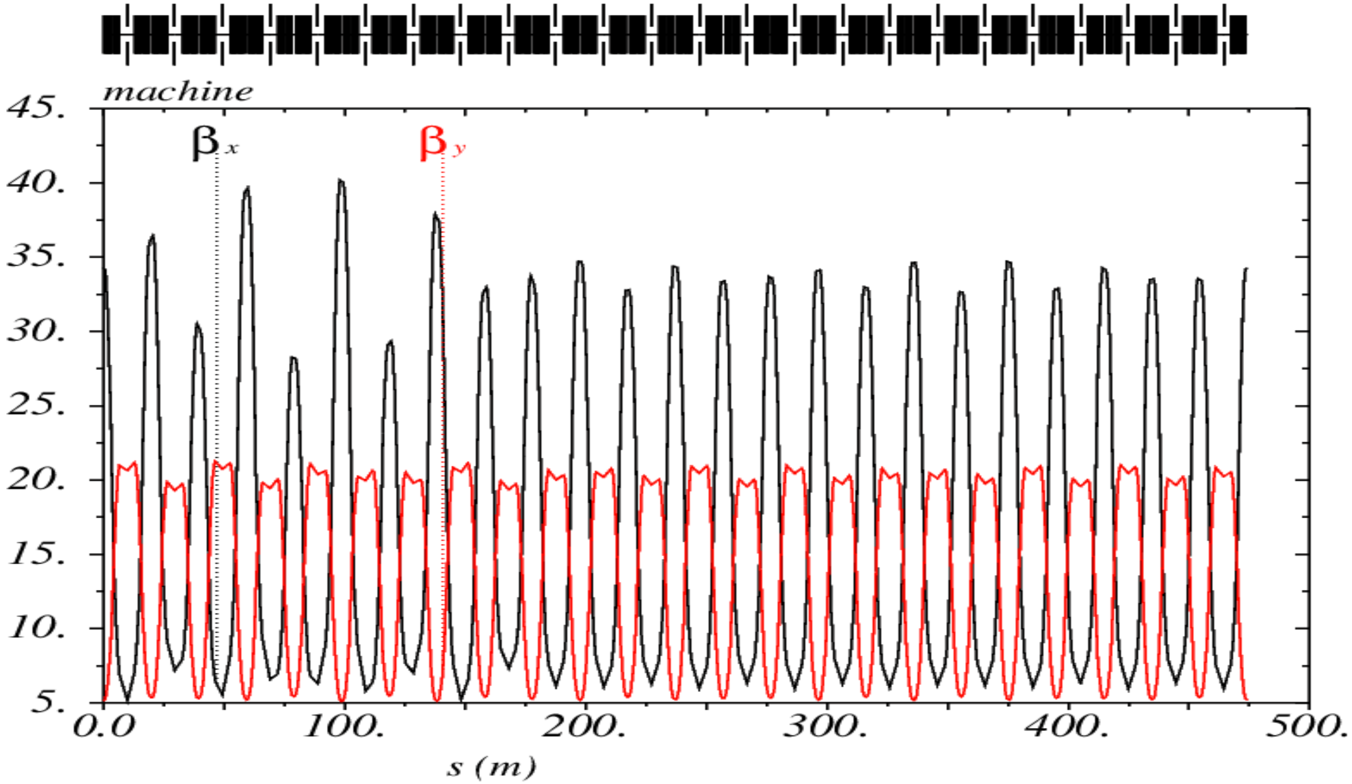
Approach to Modeling

- Numerical simulations of macro-particle bunch dynamics is done with simplifying approximations (MAD-X with *adaptive space charge*):
  a) No full self-consistency: Gaussian beam profile assumed.
  b) Particles tracked through many (>100 per betatron period) thin space charge kicks per turn instead of smooth action.
  c) Beam emittances evaluated once per turn and entered to change the properties of space charge elements.
  d) Transverse kick modulated by longitudinal position (non-symplectic integration).
- This approach offers quick turnaround time with decent physics
  – To be followed by true self consistent modeling.

Lattices Used in Simulation

a) 24-cell ideal fully symetrical FODO (V.Kapin)
b) 24-cell with induced beta-beat, no coupling
c) Actual LOCO-restored (C.Y.Tan)



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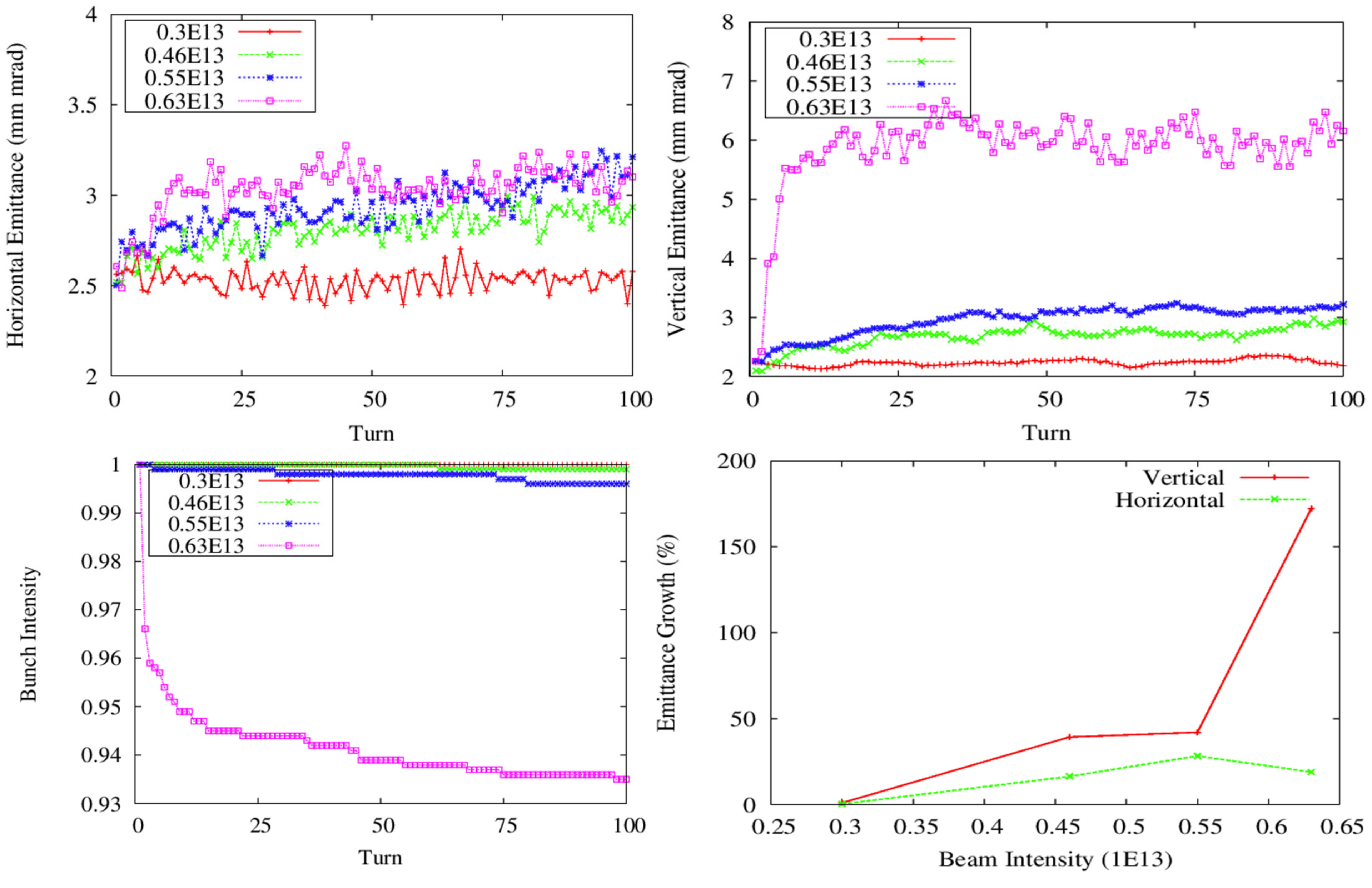
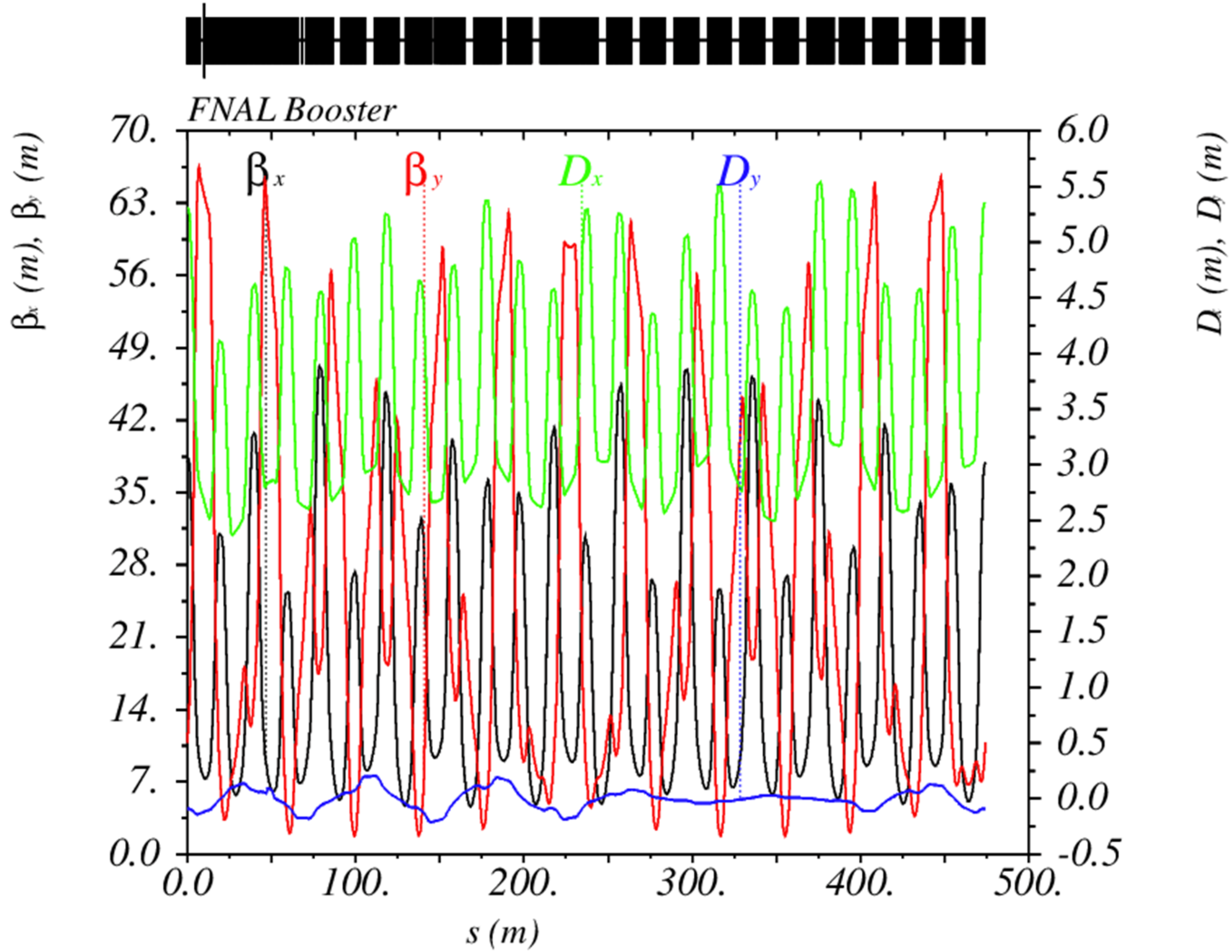
Simulation Results for Current Optics

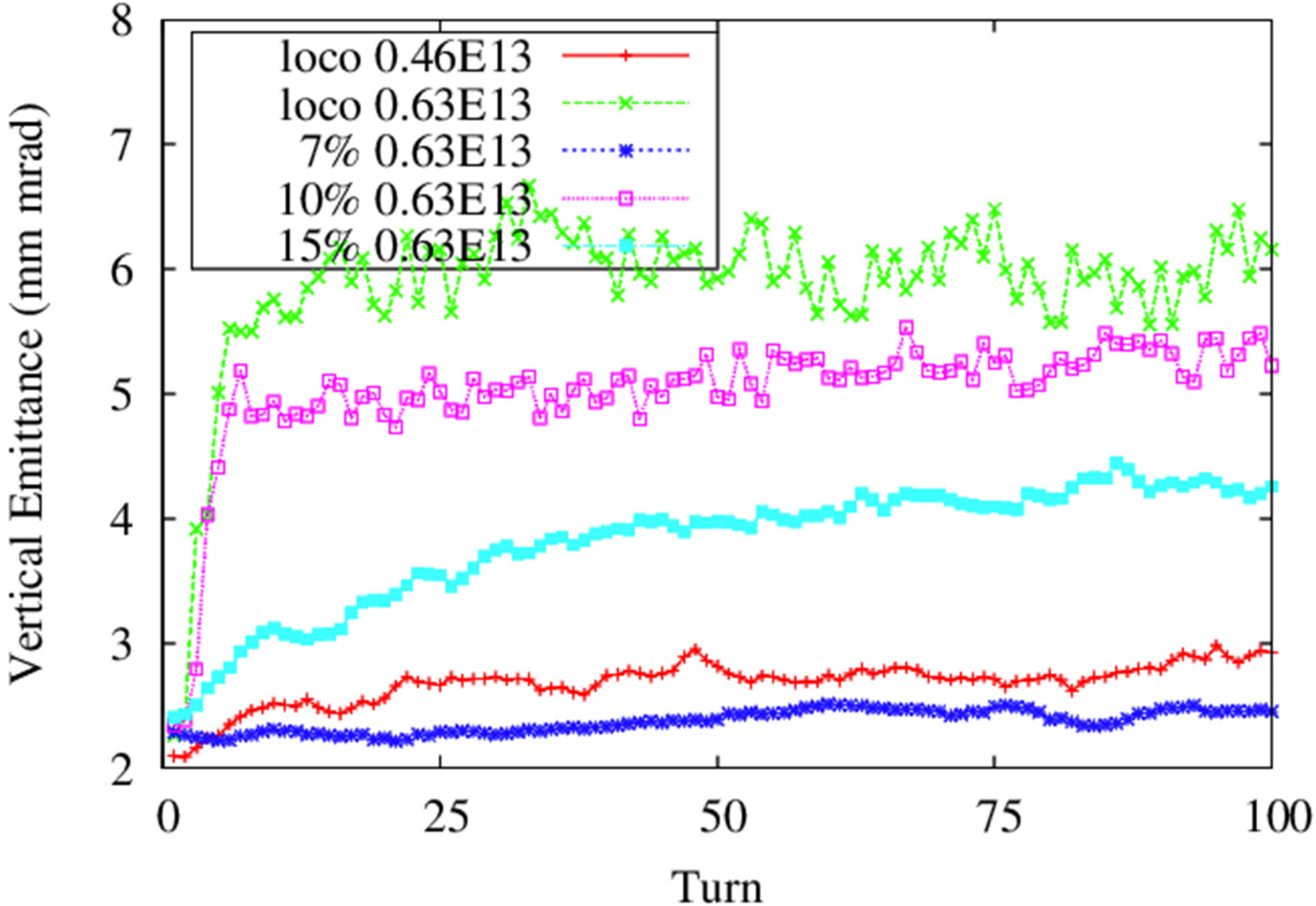


Beta-beat in Current Optics

with SC at Np=0.65×10^{13}



Simulation Results for Corrected Optics



Method of Half-Integer Stop Band Correction

Basic idea

- Close to the resonance 2Q=n (n=13 in Booster) the tune depends on RDT as

$$(Q-n/2)^2=(Q^{(0)}-n/2)^2-|g_{-n}|^2 \quad \Rightarrow \quad Q\approx Q^{(0)}-\frac{|g_{-n}|^2}{2Q^{(0)}-n}$$

$$g_{-n}=g_{-n}^{(lattice)}+g_{-n}^{(corrector)}$$

- the tune reaches extremum (max if Q>n/2, min if Q<n/2) when g=0

Recipe

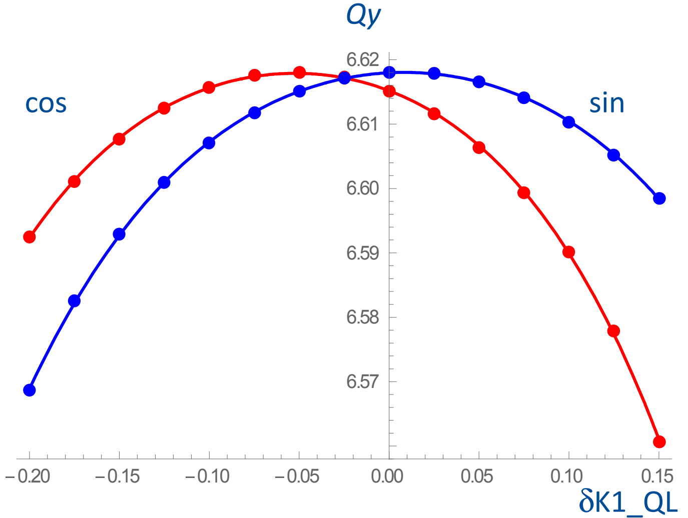
- Introduce harmonic quadrupole (n=13) modulation

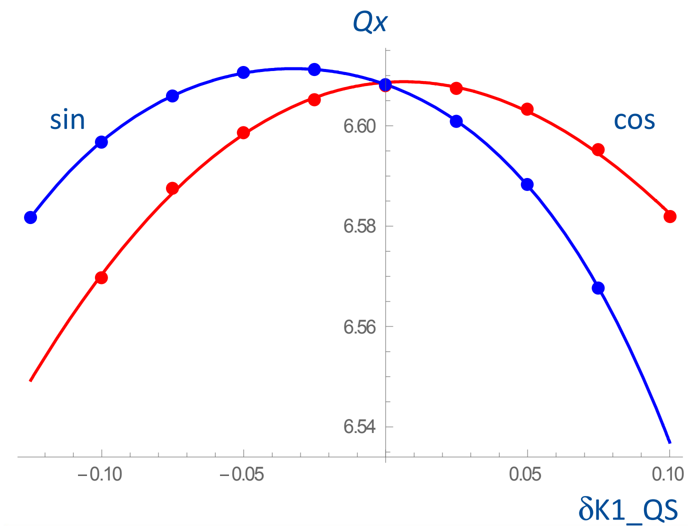
$$I_{QS\_k}=I_{QS\_k}^{(0)}+I^{(1)}\cos 2\pi n\frac{k}{N_{QS}}+I^{(2)}\sin 2\pi n\frac{k}{N_{QS}}, \quad k=1,\dots,N_{QS}$$

- With small intensity beam, measure tunes with different settings for $I^{(1)}$ and $I^{(2)}$
- Interpolate $Q(I^{(1)}, I^{(2)})$ and find extremum

Model of Half-Integer Stop Band Correction

LOCO fitted optics original stop bands are $\Delta Q_x^{(0)} \approx 0.037, \quad \Delta Q_y^{(0)} \approx 0.048$

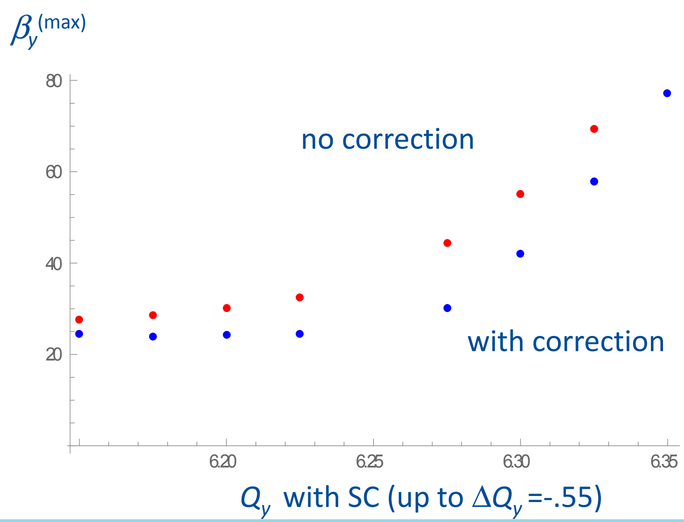




Tunes near half-integer vs. amplitude of sine and cosine modulation of QS and QL (13th harmonic). Calibration:

Resonance correction (first Qy then Qx):
δK1_QL(1)=-0.052, δK1_QL(2)=0.008 ⇒ δI_QL=1.6 A
δK1_QS(1)=0.006, δK1_QS(2)=-0.033 ⇒ δI_QS=1.0 A

After correction: $\Delta Q_x^{(0)} \approx 0.003, \quad \Delta Q_y^{(0)} \approx 0.008$



Summary

- With known limitations, the adaptive space charge method allows for very fast evaluation of options
  - PIC simulations to follow
- The half-integer resonance is a performance limiting factor
  - At intensity of 4×10^{12} simulation results are consistent with observations
  - At Np=6.5×10^{12} emittance growth and losses are prohibitively high
  - 6.5×10^{12} is allowed in the ideal 24-fold symmetry lattice
  - Beta-beat correction to better than 5% may be necessary
- A method of stop-band measurement and correction was evaluated in modeling
  - Strategy for experimental studies was developed