Booster Beam Simulations

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Fermilab Workshop on Megawatt Rings

7-8 May 2018

Issues & Goals

stage	E_inj (MeV)	Np/batch (e12)	ΔQx/ΔQy
PIP-I	400	4.5	0.25/0.31
PIP-I+	400	5.6	0.31/0.38
PIP-II	800	6.5	(0.36/0.44)*

*) would be with 400MeV injection

Losses at nominal (PIP-I) intensity are ~8%, will increase at high intensity operation (especially with 20Hz reprate)

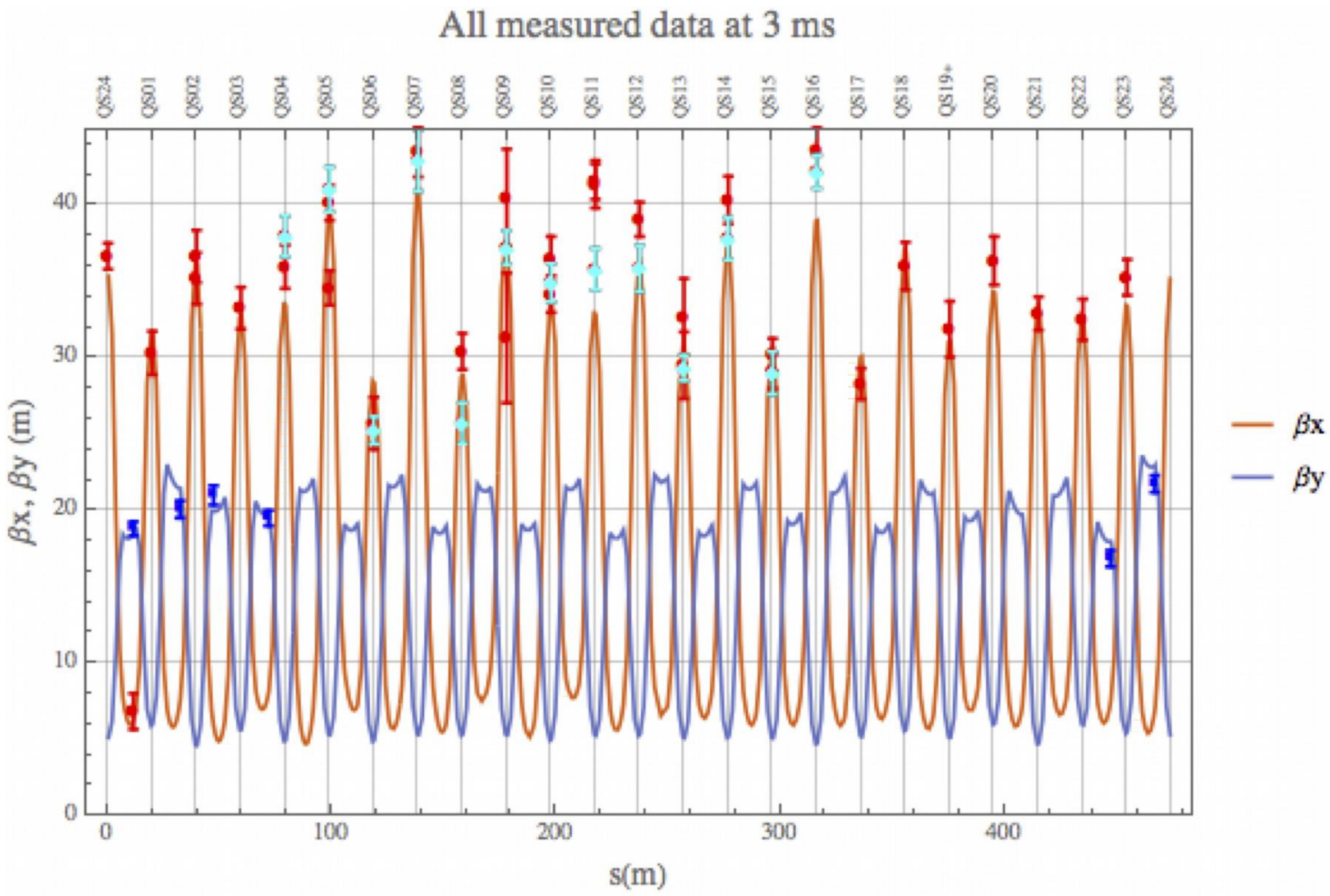
Simulations goals:

- understand experimental observations
- offer ways of improvement

Tools used:

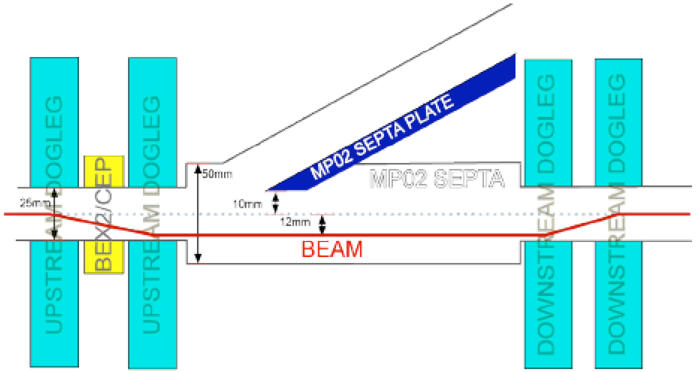
- Synergia (A. Macridin, E. Stern)
- MADX-SC (Y.A., A. Valishev with a lot of help from F. Schmidt)

HEP Optics Measurements



Measurements performed by K-modulation definitely confirm HEP Optics model (MADX)

Optics Perturbation



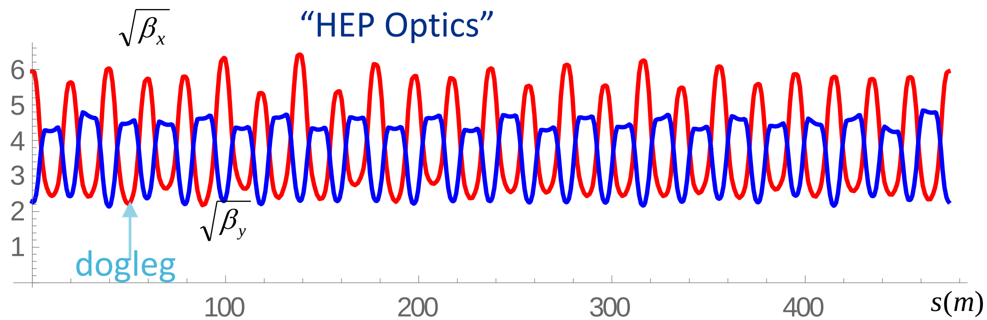
The source of the optics perturbation is well-known: the extraction dogleg created by DC magnets – the strongest effect @ injection.

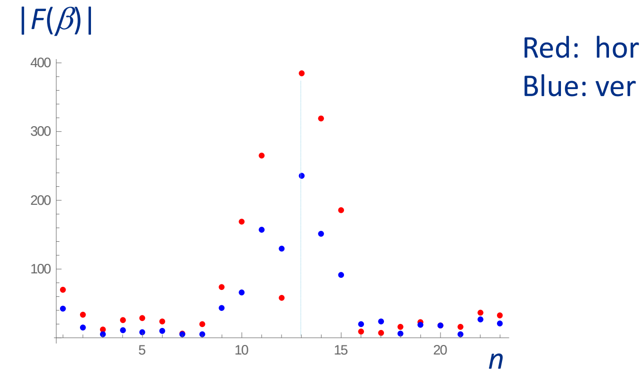
A number of solutions considered:

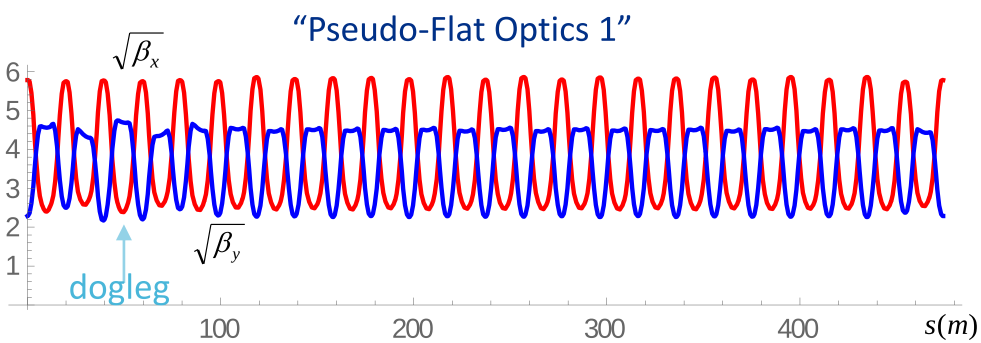
- modify the extraction dogleg using pulsed magnets (expensive)
- half-integer resonance correction using quadrupole harmonic circuits
- "flat" optics (Tan)

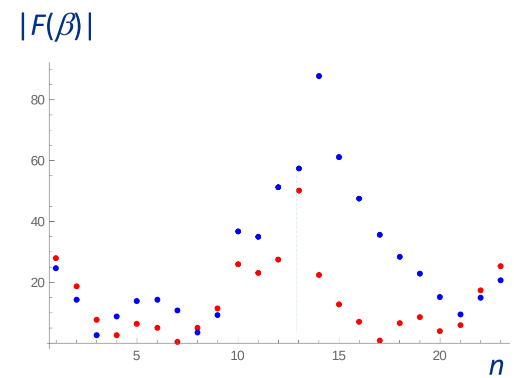
Optics Functions w/o SC

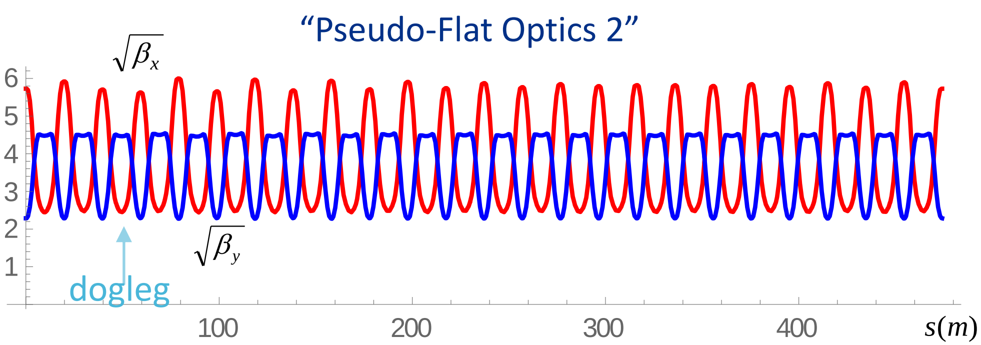
Fourier Sectra of β-functions

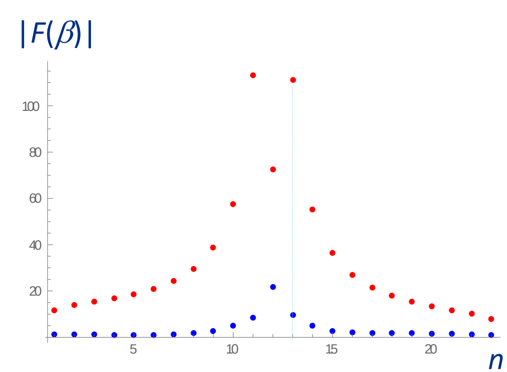












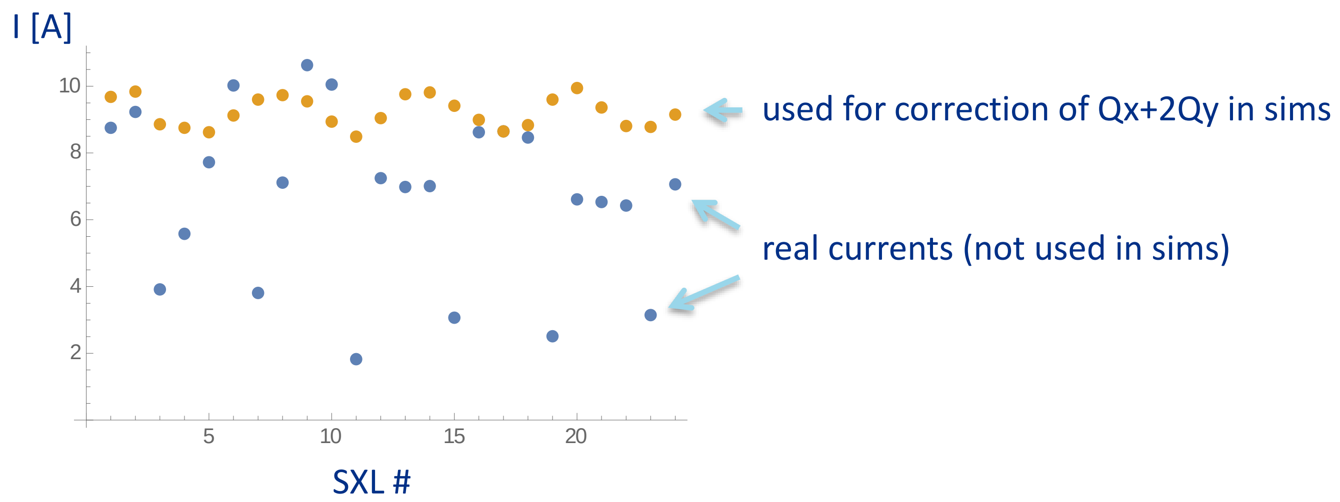
Tracking Simulations

Beam parameters (A. Macridin):

$\varepsilon_{\perp N}^{(r.m.s.)}$=2.34μm ($\varepsilon_{\perp N}^{(95\%)}$=14π mm·mrad)
σ_z= 0.831532m, σ_p/p= 0.00185,

Longitudinal profile is not Gaussian, corrections were made that reduced space charge tuneshifts to 0.28, 0.38 for Np=7.e10/bunch

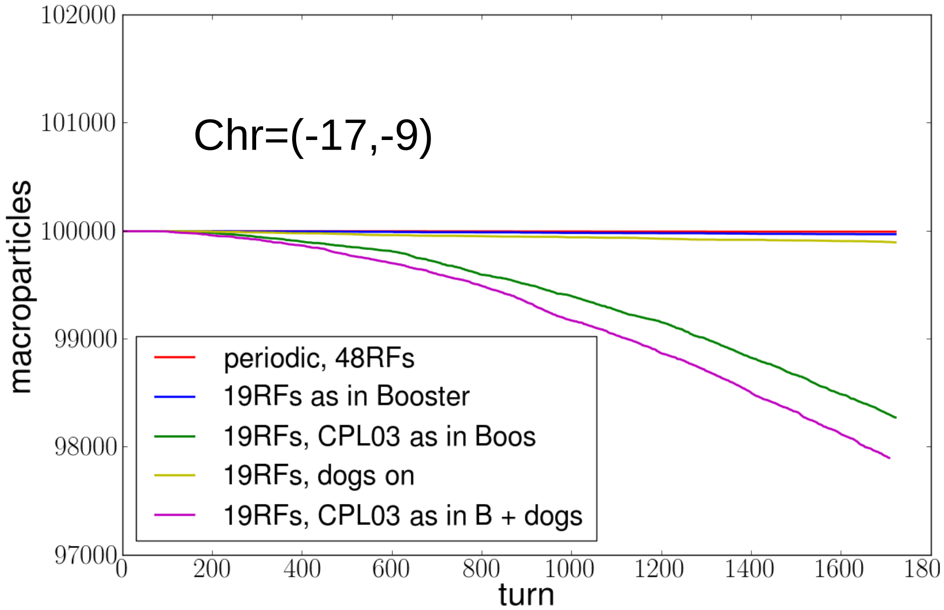
Synergia simulations w/o dogleg bump
⇒ still losses due to longitudinal shift in SXL03 position by 4.75m
⇒ excitation of Qx+2Qy=20
⇒ can be compensated by tuning other sextupoles

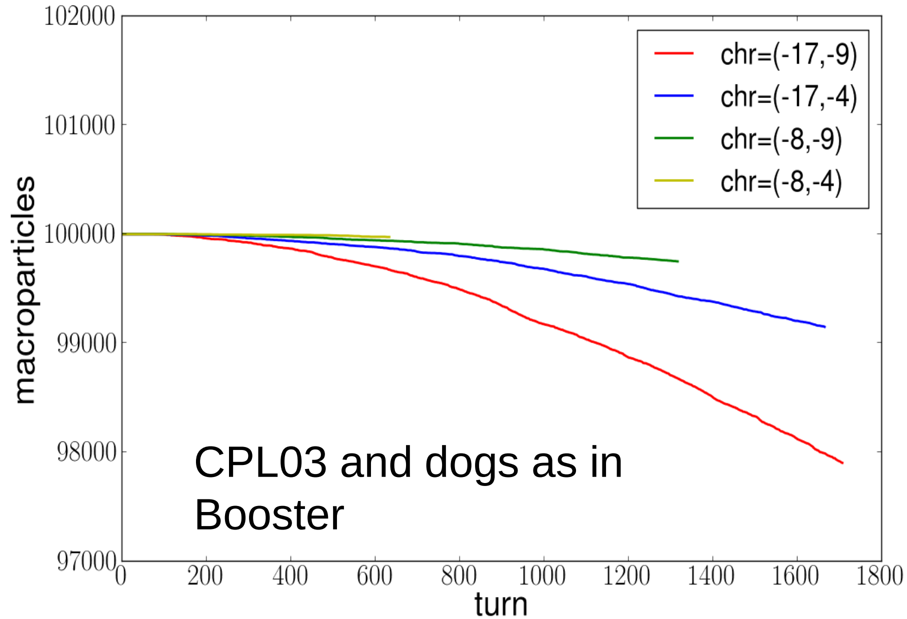


Synergia Simulations

Q_x=0.734 Q_y=0.82

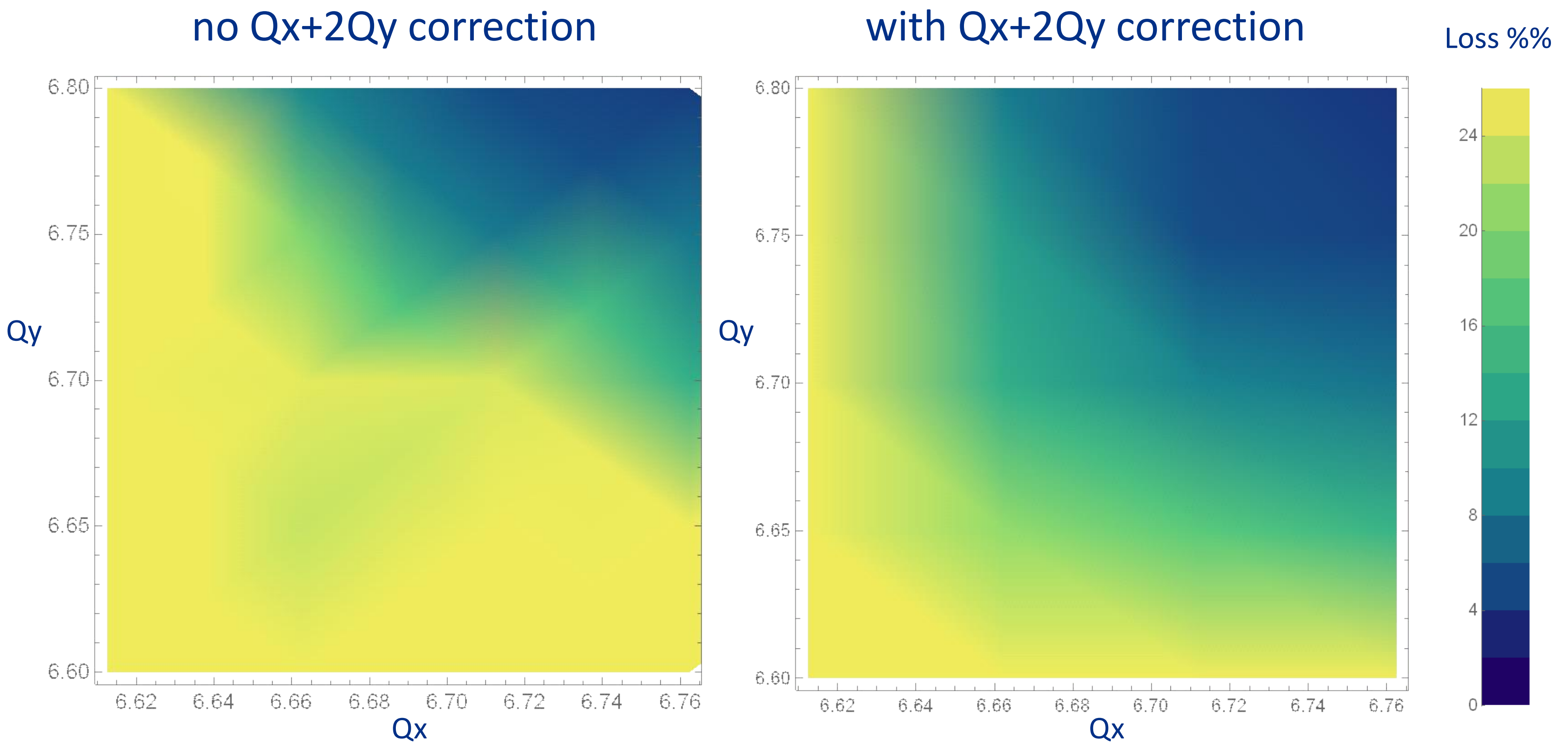
n=7e10 pp bunch





- Position of the CPLO3 corrector package is the main culprit for beam loss
- horizontal chromaticity has a large influence on loss

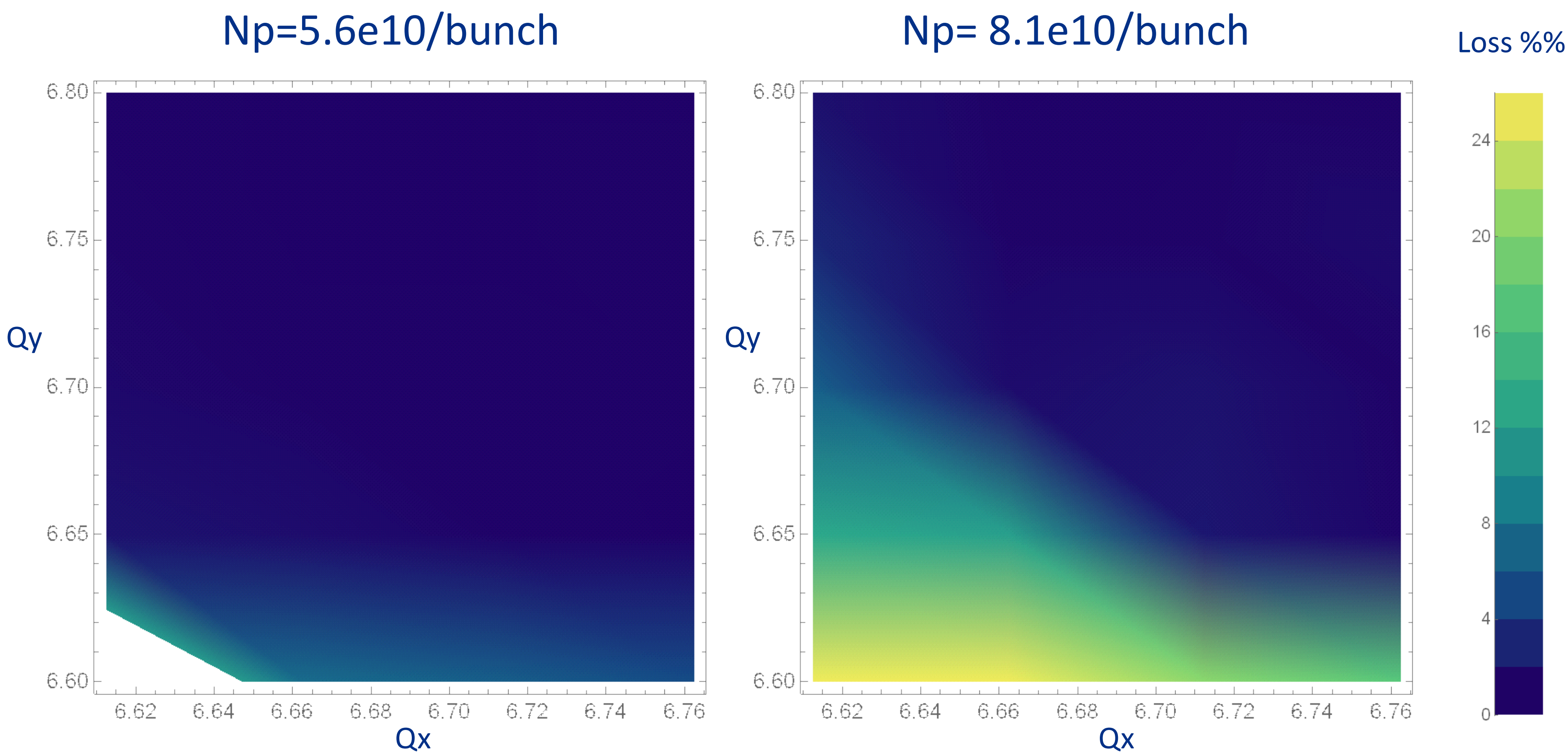
MADX-SC Simulations for HEP Lattice



Losses over 2000 turns as function of bare lattice tunes at nominal Np.

Little improvement at Qx=6.7, Qy=6.8: 4.3% $\rightarrow$ 3.8%

MADX-SC Simulations for Flat Lattice 2

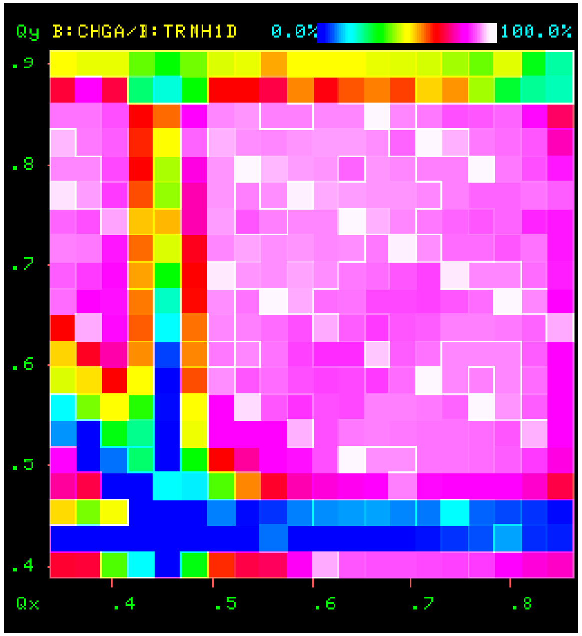


Losses over 2000 turns as function of bare lattice tunes at nominal and PIP-II intensities. Qx+2Qy corrected.

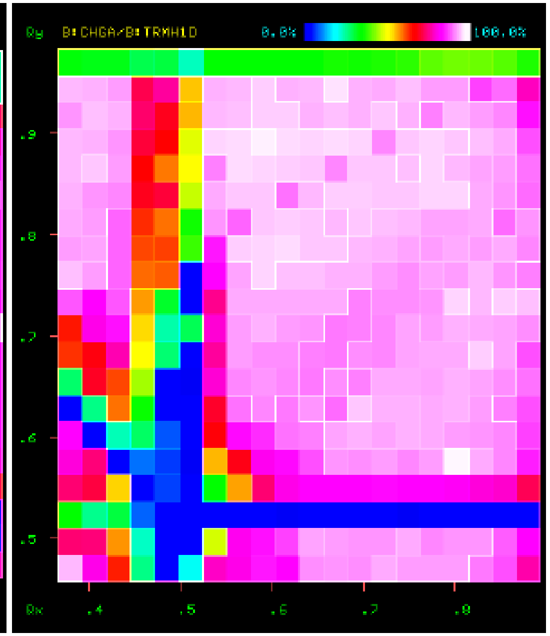
At Qx=6.7, Qy=6.8 losses are negligible: 0% $\rightarrow$ 0.07%

Tune scan

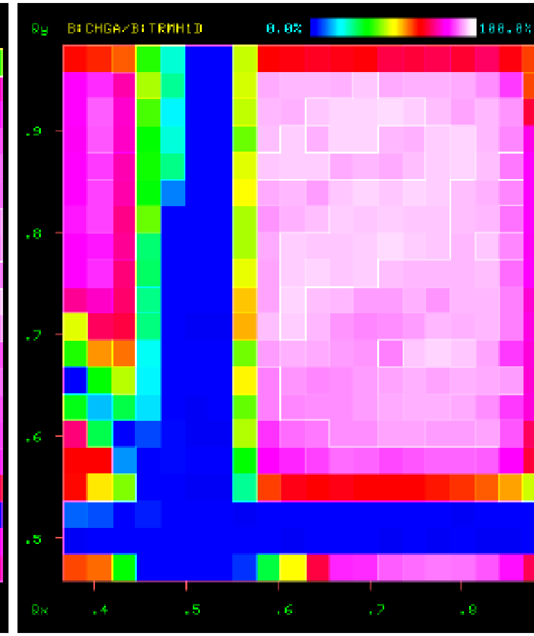
(low intensity)



Pseudo-flat lattice 1



Pseudo-flat lattice 2



HEP

Pseudo-flat lattice 2 has smaller vertical 1/2 integer resonance and slightly larger horizontal 1/2 integer resonance.
Both pseudo-flat lattices are much improved over HEP lattice.

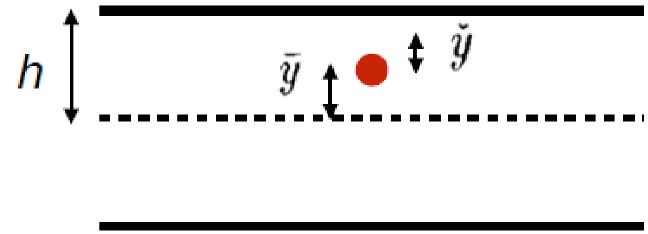
Pseudo-Flat Optics 2 looks like a victory, but there is no better working point than with HEP lattice at high intensity!

Effect of Image Charges*

Start from Baartman's expansion

AIP conference proceedings 448, 56 (1998)

Parallel plates at y = +/- *h*



$$U = -2\lambda \log \left| \frac{\sin\left(\frac{\pi y}{2h}\right) - \sin\left(\frac{\pi \bar{y}}{2h}\right)}{1 + \cos\left(\frac{\pi(y+\bar{y})}{2h}\right)} \right|$$

$$\frac{E_{\mathrm{yimage}}}{4\lambda} \approx \frac{\pi^2}{48}\frac{\check{y}}{h^2} + \frac{\pi^2}{16}\frac{\bar{y}}{h^2} + \frac{\pi^4}{192}\frac{\bar{y}^3}{h^4} + \frac{\pi^4}{128}\frac{\check{y}\bar{y}^2}{h^4} + \frac{\pi^4}{256}\frac{\check{y}^2\bar{y}}{h^4} + \frac{7\pi^4}{11520}\frac{\check{y}^3}{h^4}$$

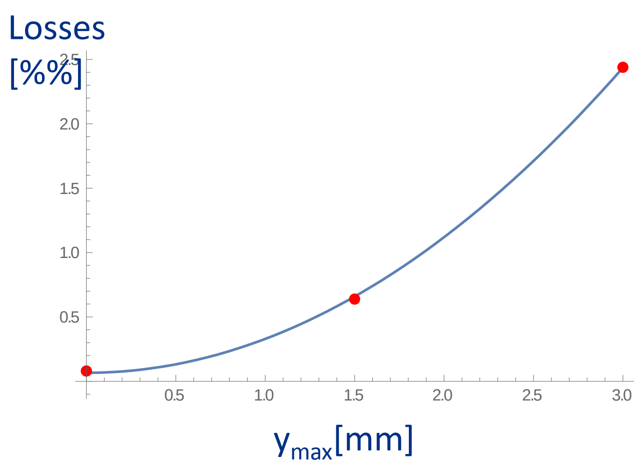
- Electric field by image charge can have all higher order in $\check{y}$.
- The coefficients depends on COD amplitude $\bar{y}$.

*) the interest renewed by S. Machida at 2nd SC collaboration meeting (CERN, March 2018)

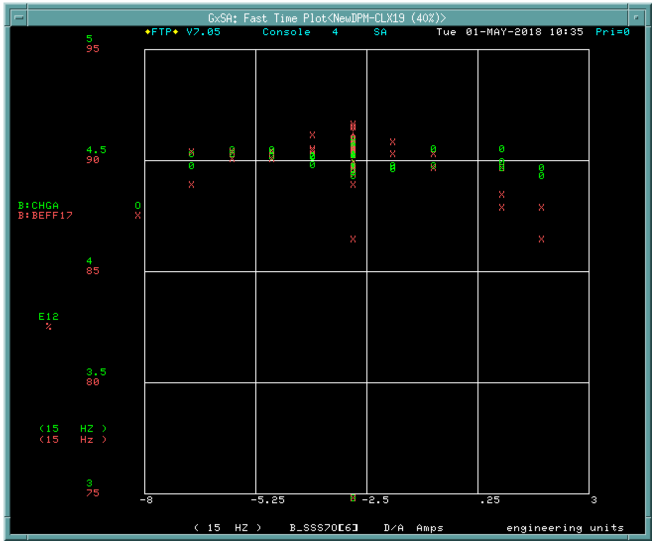
Skew Sextupole Studies

Bending magnets have small (half) apertures:
F-magnets $h=2.1$ cm, $L=2.9$ m x 48, $ks2^{(image)}=0.001m^{-3}$ for y=1mm, Np=7.e10 $\Rightarrow$ can drive 2Qx+Qy
D-magnets h=2.9 cm $\Rightarrow$ can drive 3Qy

The image charges were simulated as skew sextupoles components in F- and D-magnets ~ y ~ $\beta_y^{1/2}\cos(n \cdot s/R)$ with n=20



MADX-SC simulations show that vertical offset should be ~0.3σ_y to produce a noticeable effect in 2000 turns – too large?



Booster measurements show little effect (if any) of SSS located close to F-magnets (K. Seiya)

Summary

- From the standpoint of transverse dynamics with space charge there should be no problem with PIP-II intensity at the present injection energy when using "flat" optics.
- However, we could not reduce losses with these apparently better optics

We tried:

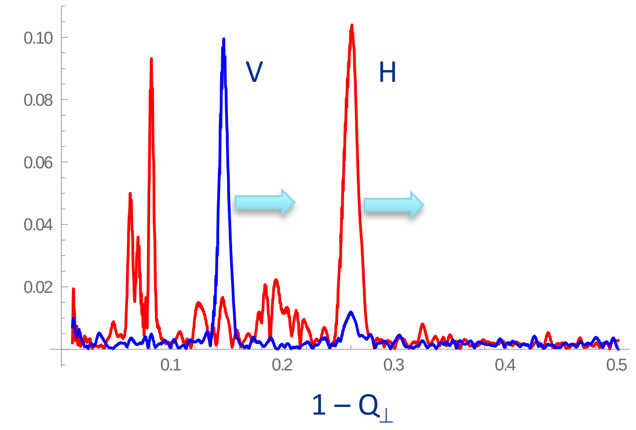
- injection orbit and optics matching
- aperture scans
- decoupling (though Qx+Qy has not been looked at since 2011)
- correction of the 3rd order using upright and skew sextupoles
- reduced chromaticity
- to see head-tail instability
- to detect dipole noise using TBT data

(quad noise seems unlikely)

- all to no or very limited success.

Had we missed anything important?

TBT spectra



Outlook

- Can RF phase errors that C.-Y. Tan and Chandra Bhat are looking at now be the reason for increased losses with improved optics? Even if so, the explanation must be found – studies necessary.
- Simulations studies ongoing or planned:
  - longitudinal dynamics with wakes and SC
  - Effects of RF and quadrupole noise
  - 6D dynamics during RF capture with 3DoF SC
  - coherent (envelope) oscillations with MADX-SC
  - …