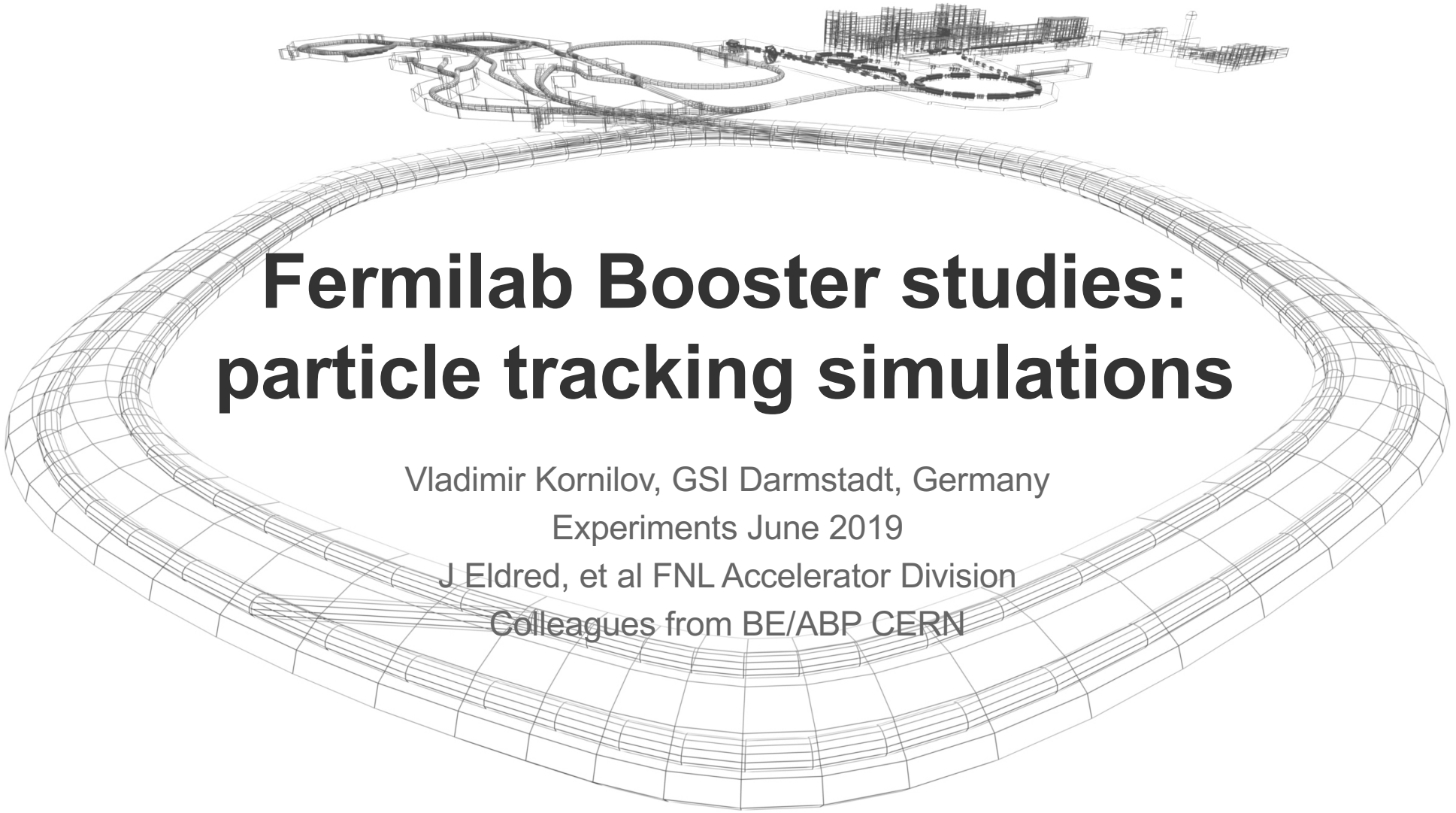


Fermilab Booster studies: particle tracking simulations

Vladimir Kornilov, GSI Darmstadt, Germany

Experiments June 2019

J Eldred, et al FNL Accelerator Division

Colleagues from BE/ABP CERN

Booster bunches

Assumptions for the booster bunches after capture

Kinetic Energy		400 MeV
Revolution		$f_0 = 0.451\ MHz$ $T_0 = 2.216\ \mu s$
Relativistic		$\beta = 0.713$ $\gamma = 1.426$
Bunch length	Total, 4σ	17.4 ns, 3.72 m
Energy spread	rms	1.15 MeV
Momentum spread	rms δp	1.69e-3
Transverse emittance $\varepsilon_x = \varepsilon_y$	Normalized, ε_{95}	11 mm mrad (π mm mrad)
Transverse emittance	Unnormalized, rms	1.88 mm mrad (π mm mrad)
RF Voltage	Stationary bucket	0.7 MV

Transverse emittance

Convention as agreed at Fermilab

Normalized rms and 95% emittance $\varepsilon_{\mathrm{rms}} = \frac{\varepsilon_{95}}{6}$

Not normalized $\hat{\varepsilon} = \frac{\varepsilon}{\beta\gamma}$

Transverse rms beam size
No π appears here $\sigma_y = \sqrt{\hat{\varepsilon}_{\mathrm{rms}}\hat{\beta}_y}$

Effect of the dispersion $\sigma_x = \sqrt{\hat{\varepsilon}_{\mathrm{rms}}\hat{\beta}_x + D_x^2\delta_p^2}$

Transverse emittance dimensions can be given (mm mrad) or (π mm mrad)

Booster bunches

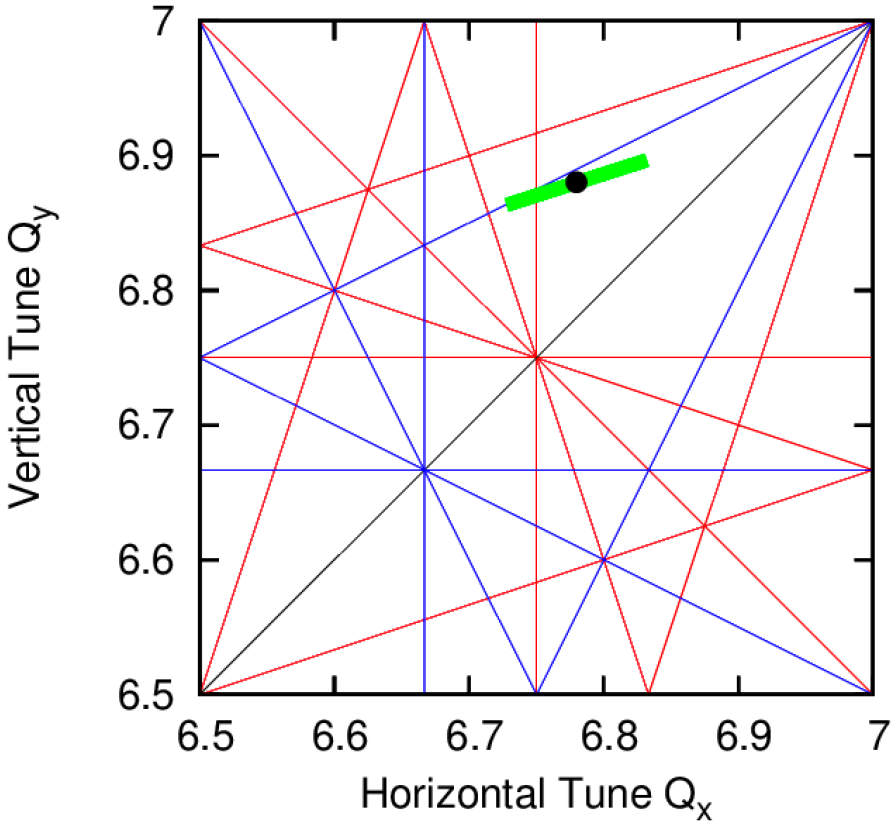
Nominal high-intensity tunes
Q_x=6.78, Q_y=6.88

Chromaticity (considered here)

$$\xi_x = -15.4$$
$$\xi_y = -4.93$$

Tune spread (rms) due to chromaticity

$$\delta Q_{\xi x} = 0.026$$
$$\delta Q_{\xi y} = 0.0083$$



Booster bunches

Space Charge
$\Delta Q_x = 0.16,\ \delta Q_y = 0.22$

Horizontal tune shifts are smaller because of the dispersion:

$$\langle D_x \rangle = 2.34\ \mathrm{m}$$

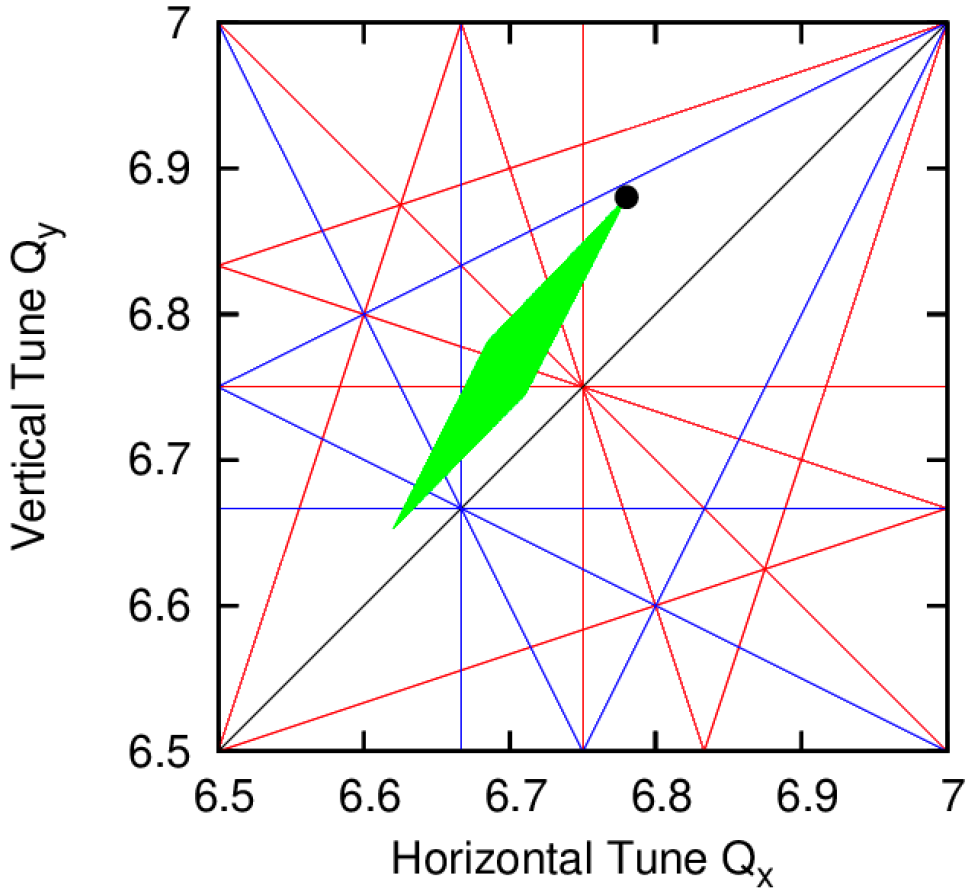
Strong space charge

But, also very strong RF (0.7 MV)

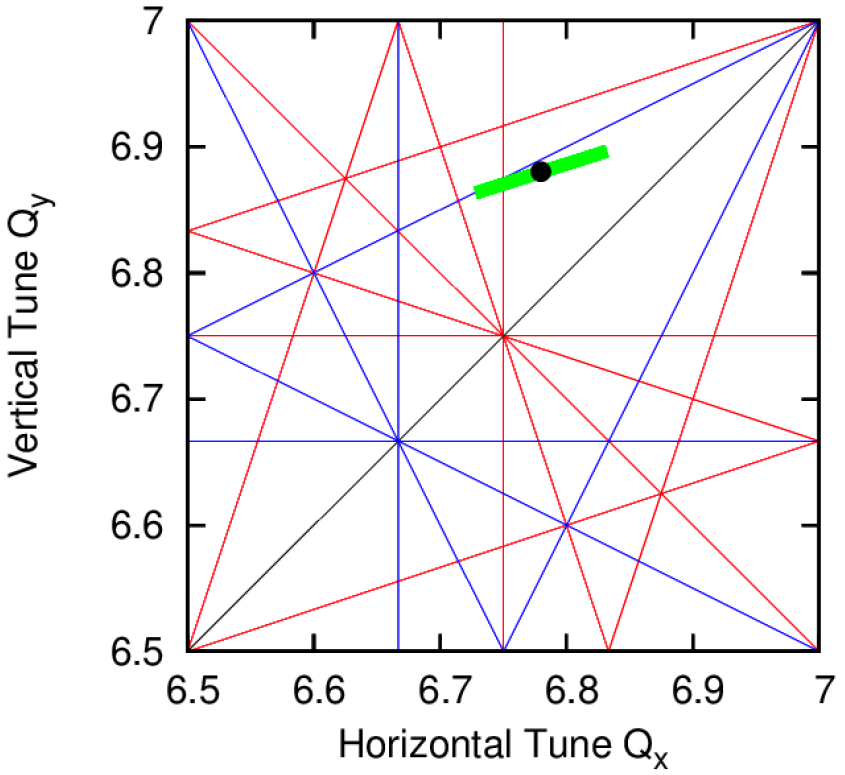
$$Q_s = 0.079$$

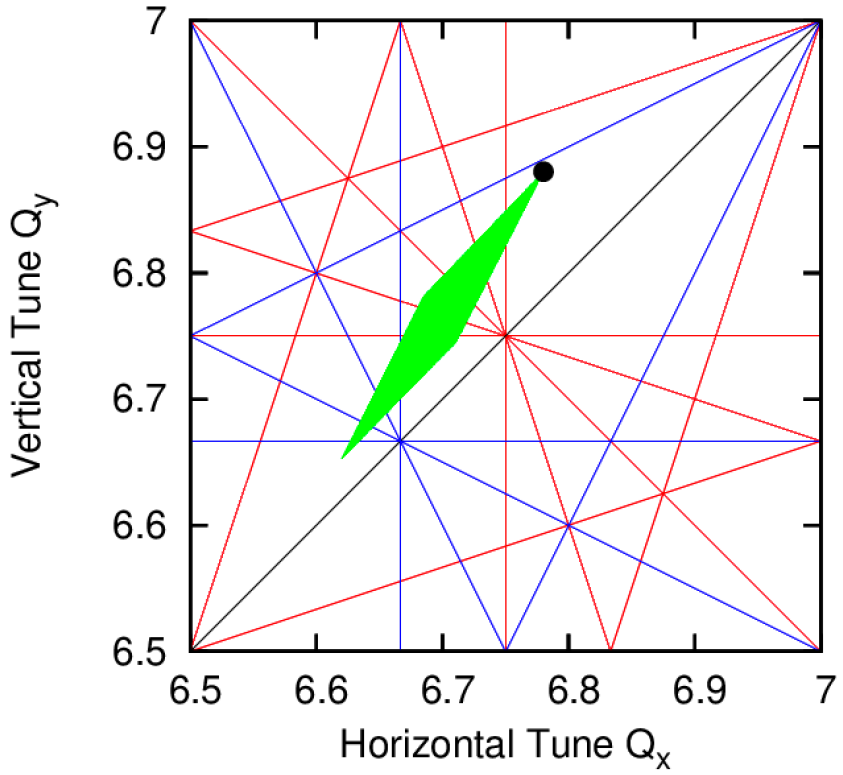
$$q = \frac{\Delta Q_{sc}}{Q_s} = 1.4$$

In this sense, moderate space charge



Booster bunches





Chromaticity and space-charge tunes spreads matter both

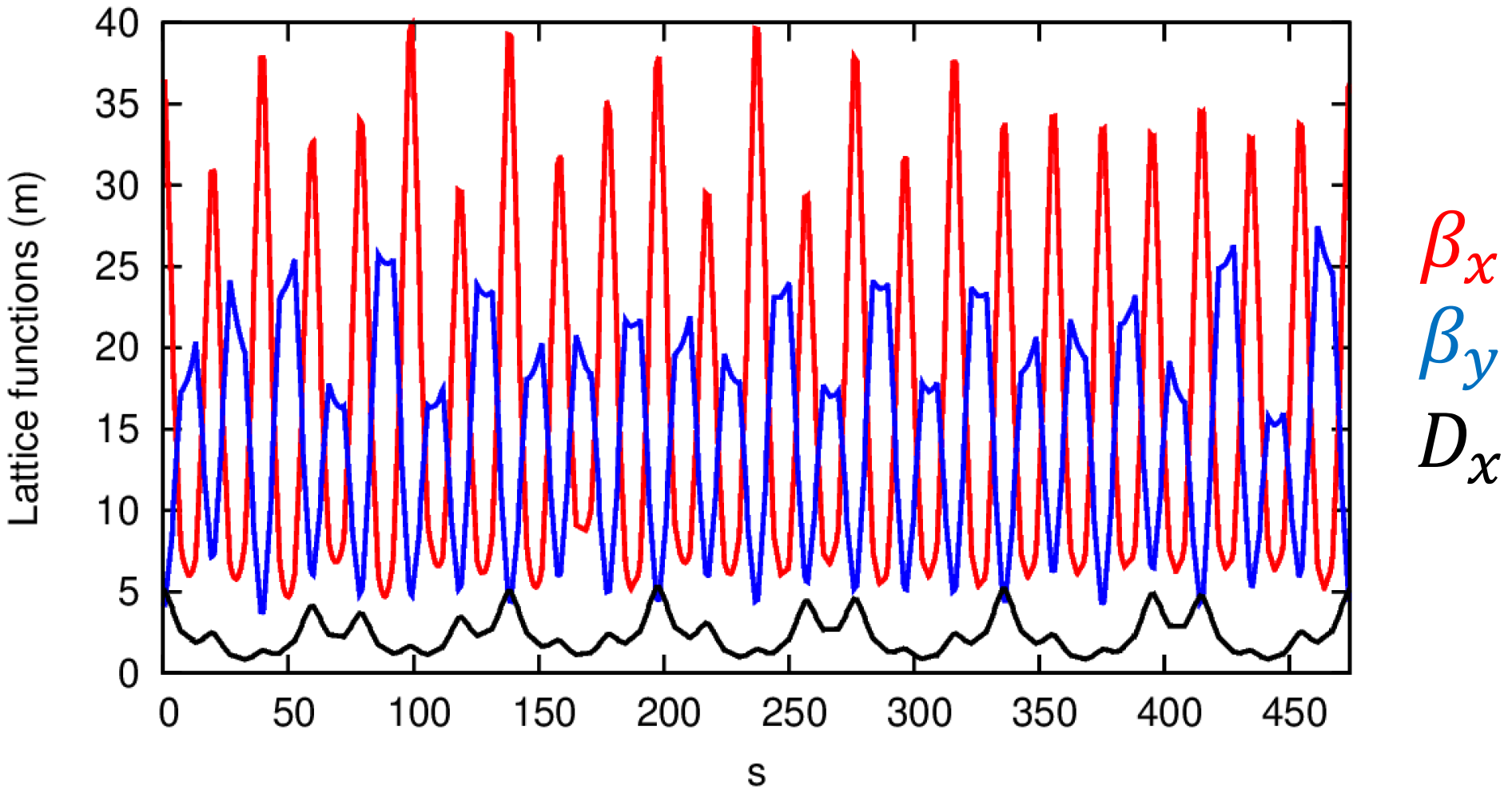
Simulations: Code “elegant”

Particle tracking simulations using the code Elegant

- M. Borland, "*elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation*" Advanced Photon Source LS-287, September 2000.
- Y. Wang and M. Borland, "*Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking*", Proceedings of the 12th Advanced Accelerator Concepts Workshop, AIP Conf. Proc. 877, 241 (2006)

- Proton bunch during the 1 ms tune-shift-time after the beam capture
- 6D particle dynamics in the complete Booster lattice
- Non-periodic lattice, closed-orbit distortions
- 2D tune scan: tune shifts by realistic changes in QL and QS 48 magnets.
- High intensity: frozen nonlinear space-charge model
- Multi-core simulations on the Green IT Cube at GSI

“elegant” simulations



“elegant” output from the Booster model provided by Jeff

“elegant” simulations

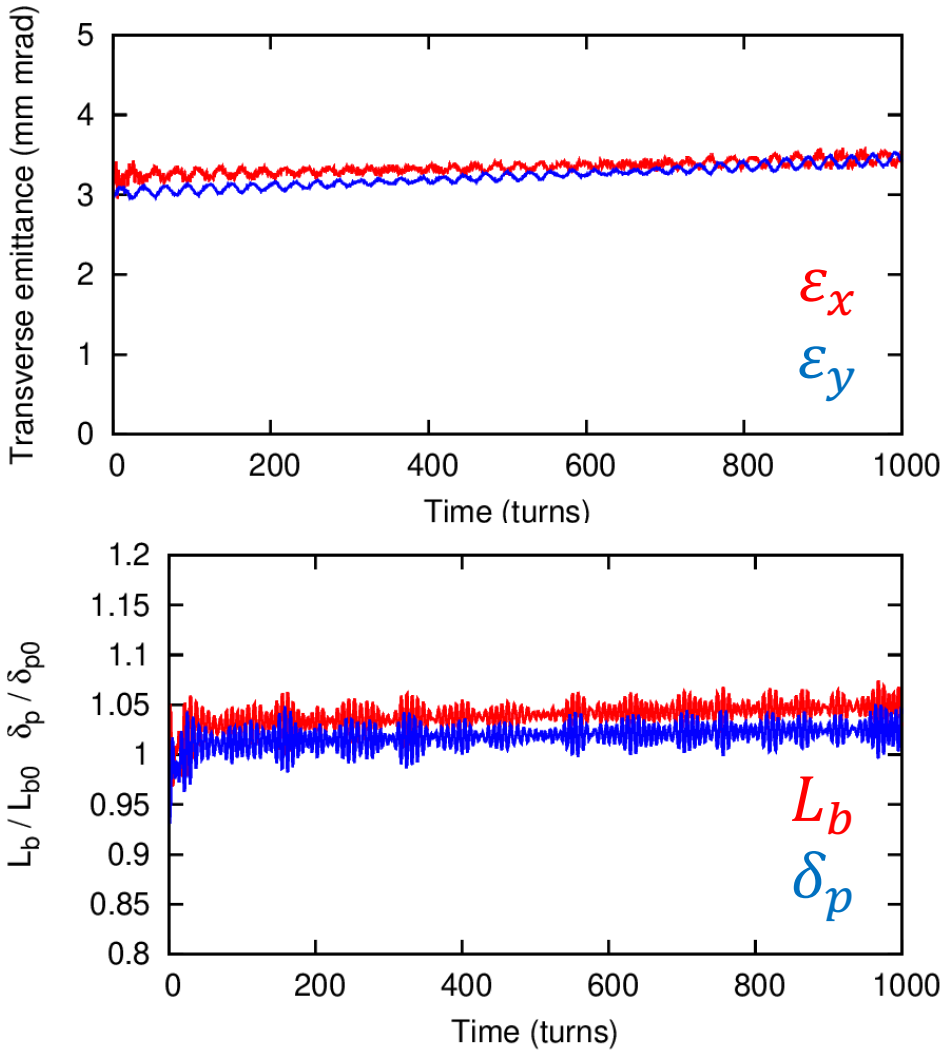
Additional necessary assumptions for tracking:

- Aperture (RF cavity) 80 mm, and not 57 mm. Otherwise, fast losses at start.
- Bunch length 12 ns. Otherwise, RF losses (important for the case with space charge)

The rest of the parameters as in the experiment.

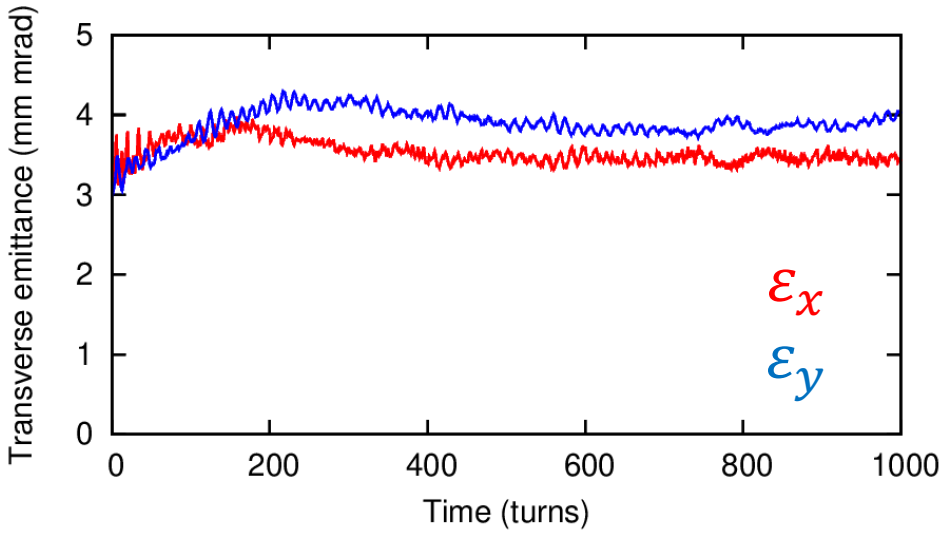
<u>Our interest is: 500 turns</u>

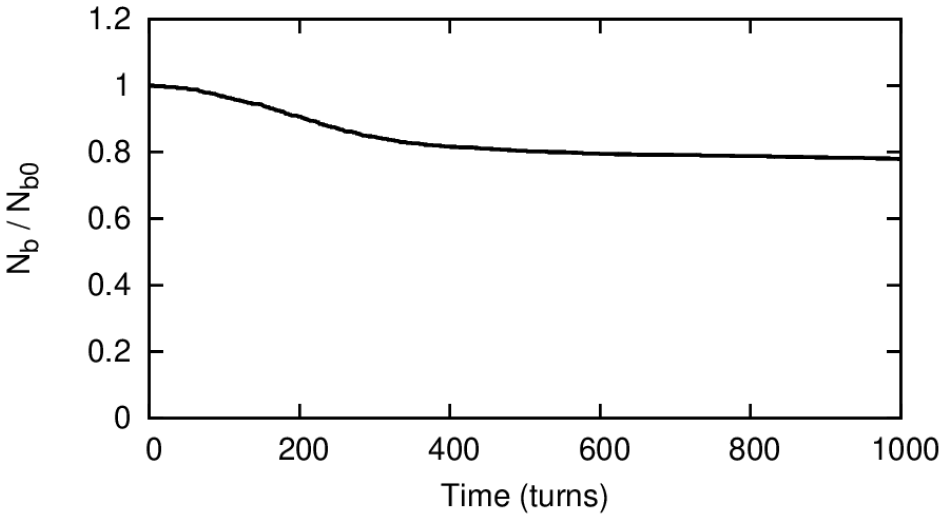
Q_x=6.73, Q_y=6.73



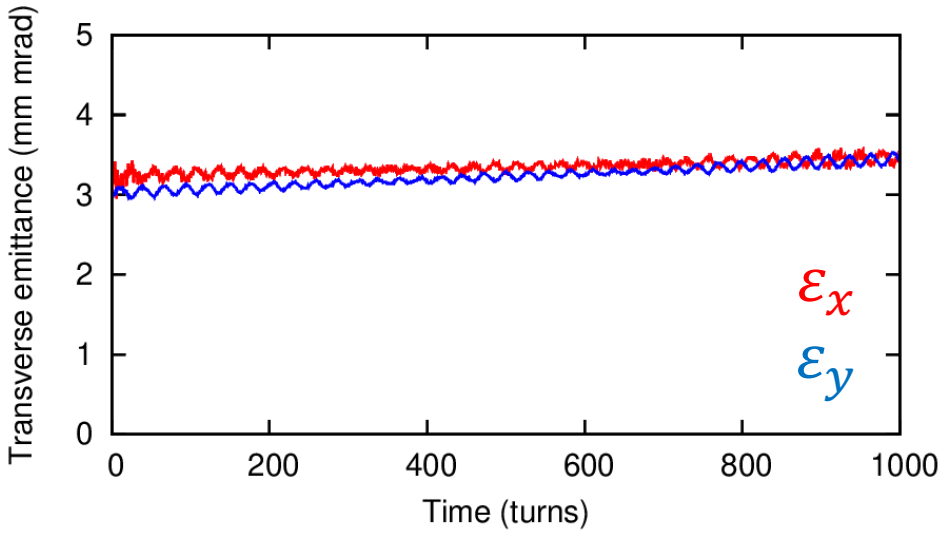
“elegant” simulations

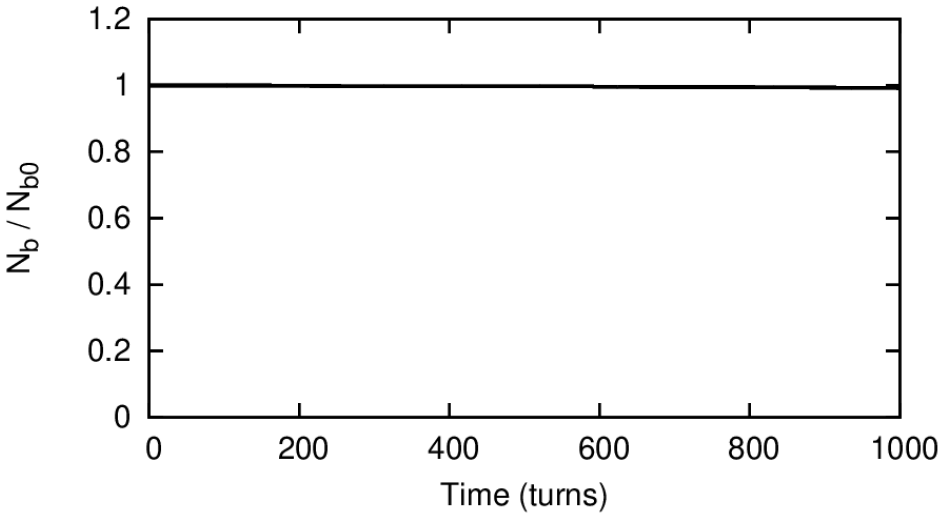
Q_x=6.81, Q_y=6.84





Q_x=6.73, Q_y=6.73





“elegant” simulations

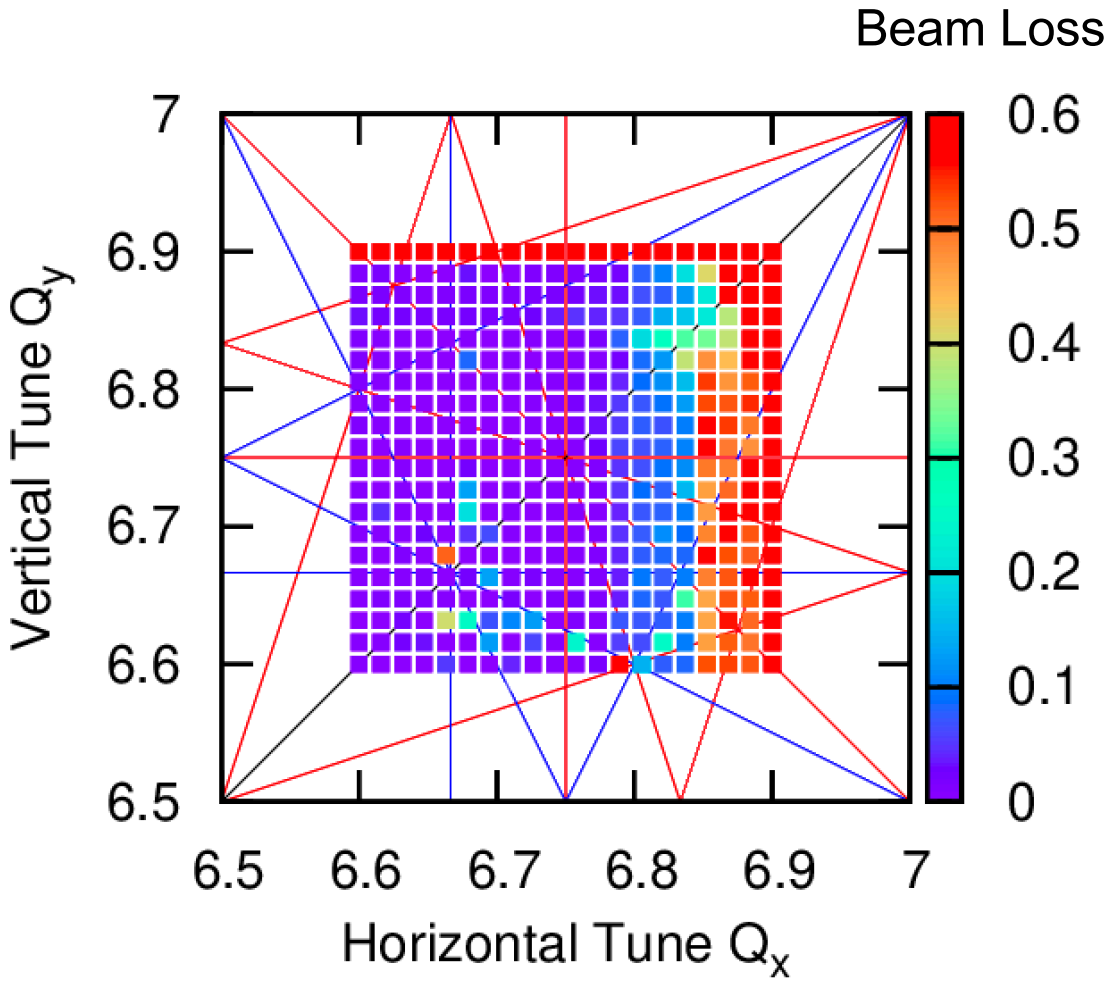
Beam Loss (1 is 100%)
after 500 turns

No space charge

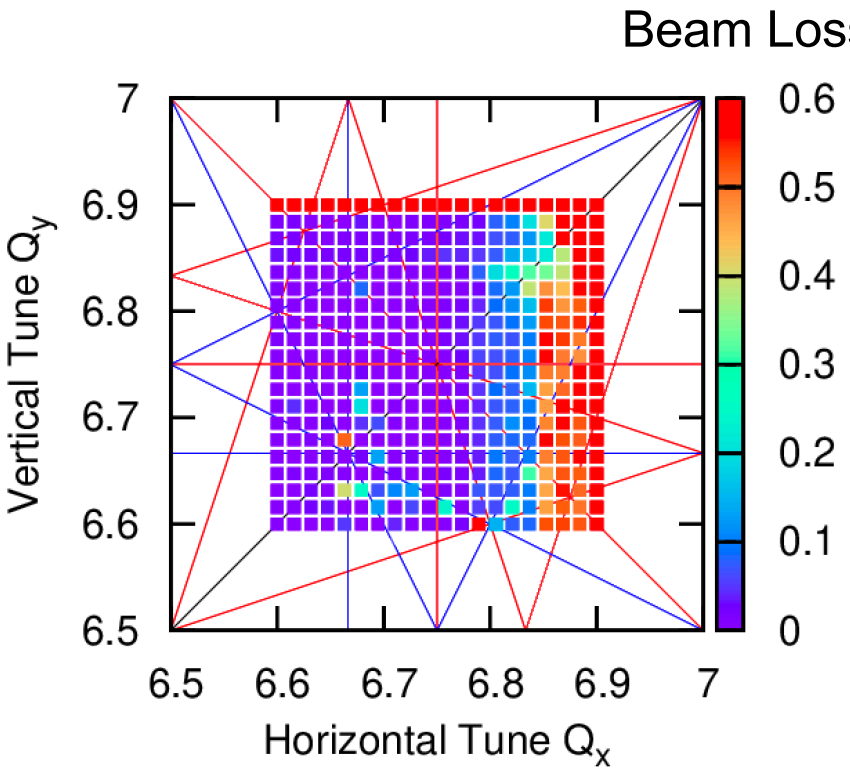
$\xi_x = -15.4$
$\xi_y = -4.93$

No high-order (nonlinear)
field error components

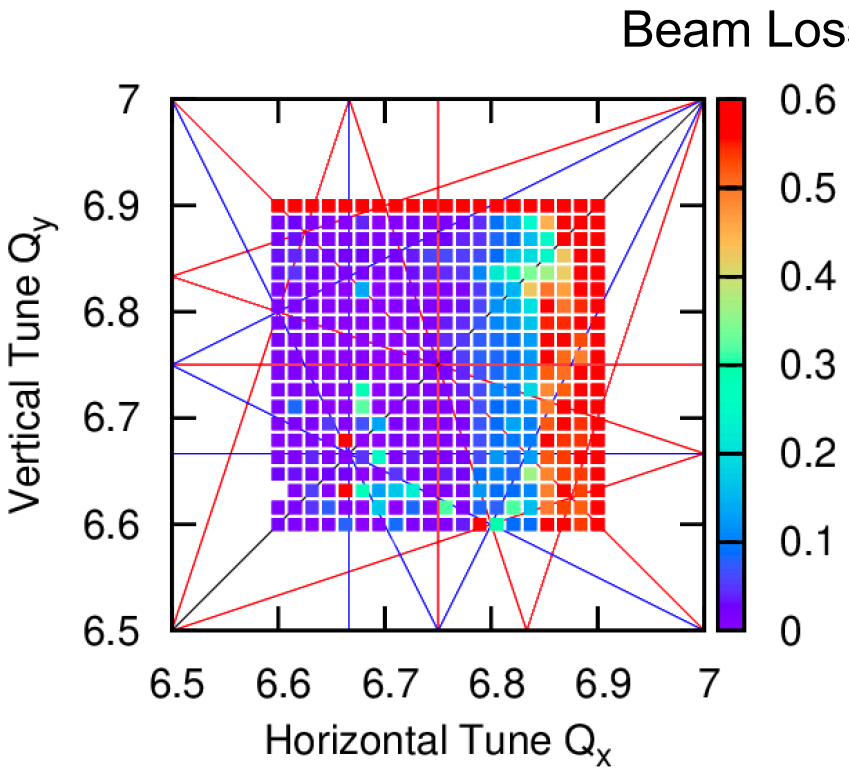
Beam beating,
closed-orbit distortions



“elegant” simulations



No space charge, 500 turns



No space charge, 1000 turns

Not much happens between 500 and 1000 turns

“elegant” simulations

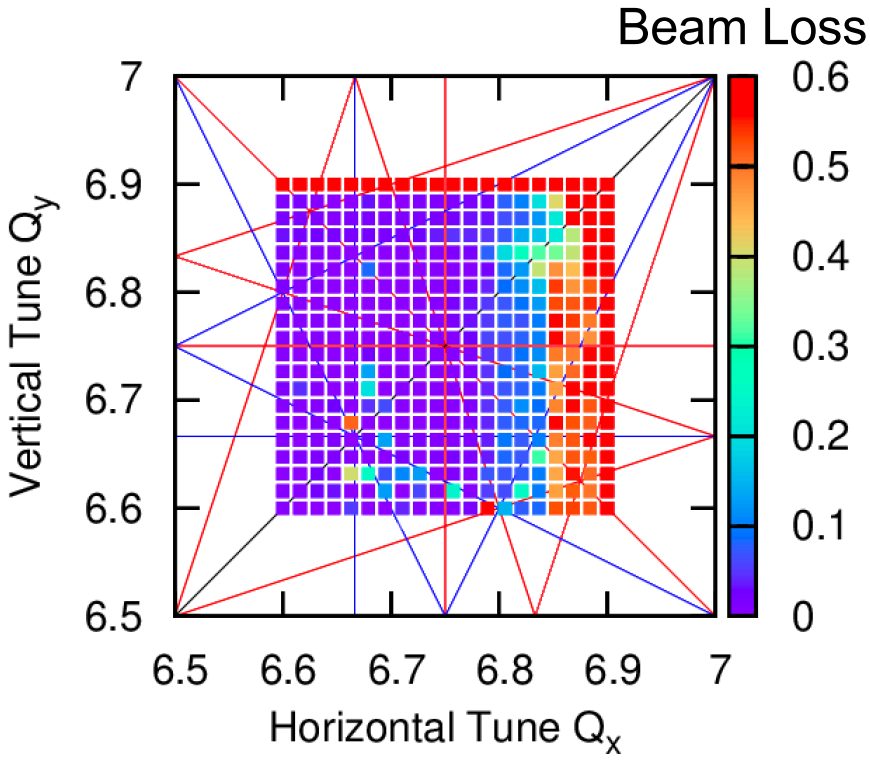
Nonlinear space charge for a Gaussian bunch

$$\Delta x' = \frac{K_{sc} L e^{-z^2/(2\sigma_z^2)}}{2\sigma_z\sqrt{\sigma_x^2-\sigma_y^2}} Im\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}} w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

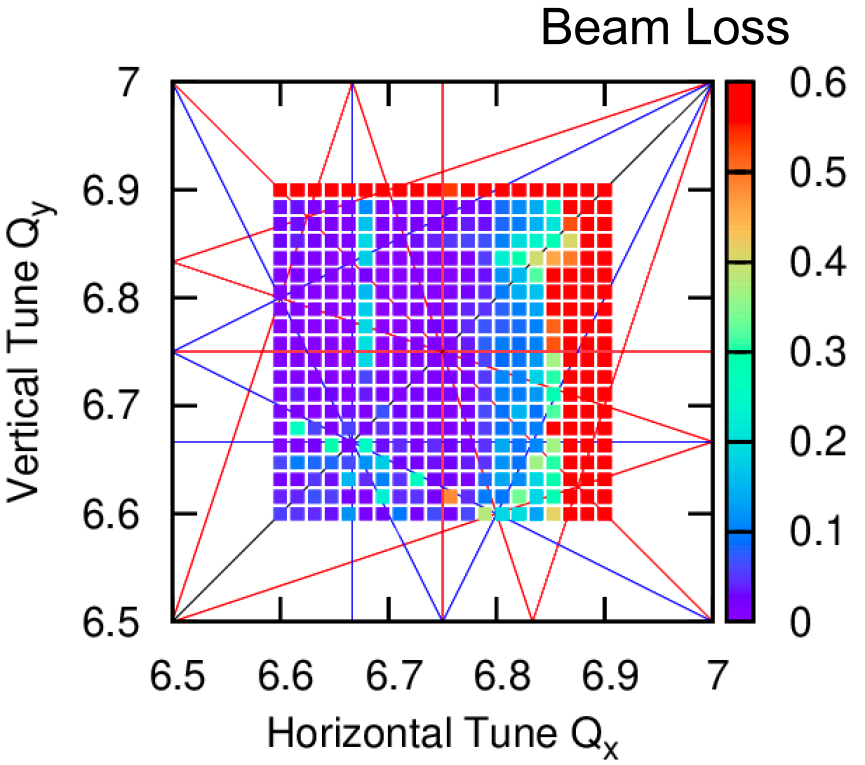
$$\Delta y' = \frac{K_{sc} L e^{-z^2/(2\sigma_z^2)}}{2\sigma_z\sqrt{\sigma_x^2-\sigma_y^2}} Re\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}} w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

- Dependence of ΔQ_{sc} on the transverse amplitudes
- Effect of the longitudinal profile on ΔQ_{sc} : variation along the synchrotron oscillation
- Effect of the transverse beam size (but not profile)

“elegant” simulations



No space charge
After 500 turns



With space charge
N_{beam}=4e12, N_{bunch}=5e10
ΔQ_{sc}=0.22

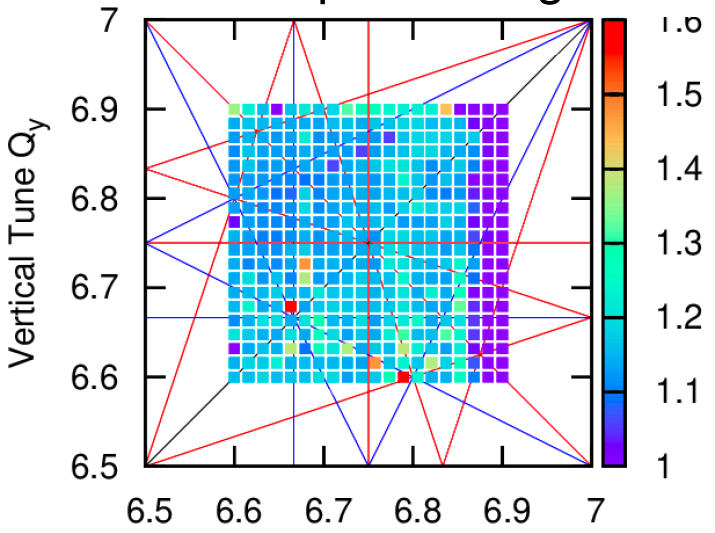
Space charge (large tune shifts) does not change the beam loss structure.
1. Loss mechanism is unrelated 2. Very quick synchrotron oscillations

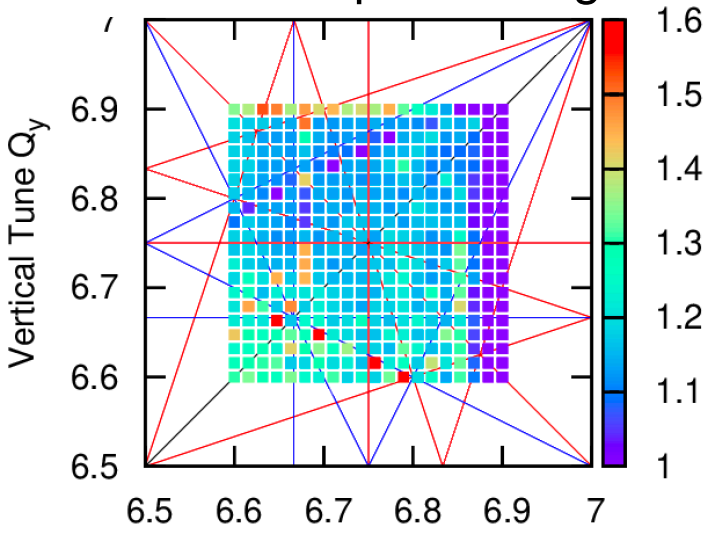
“elegant” simulations: emittance blowup

No space charge

With space charge

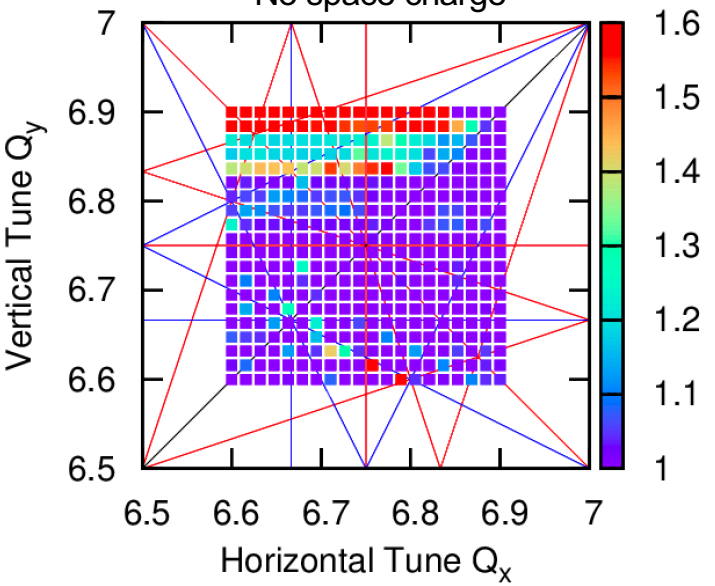
Horizontal

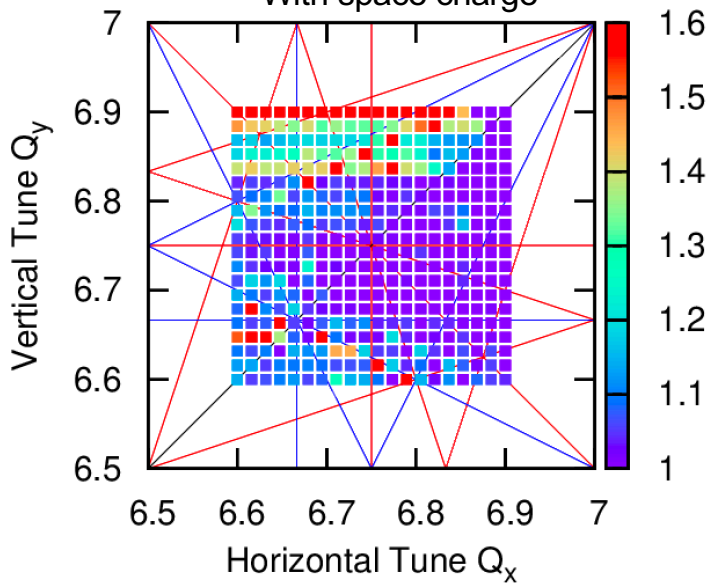




$$\frac{\varepsilon_x}{\varepsilon_{x0}}$$

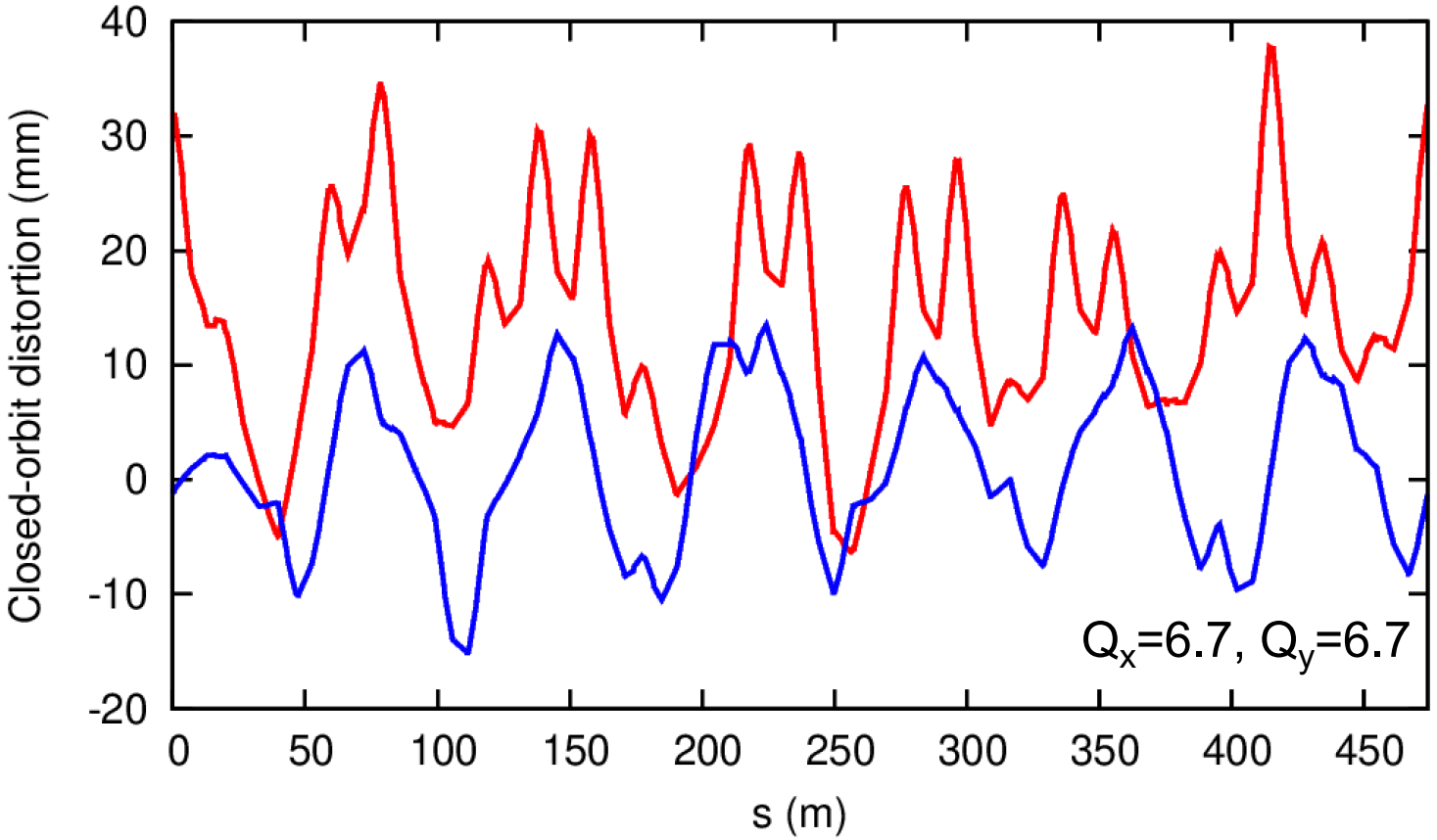
Vertical





$$\frac{\varepsilon_y}{\varepsilon_{y0}}$$

“elegant” simulations

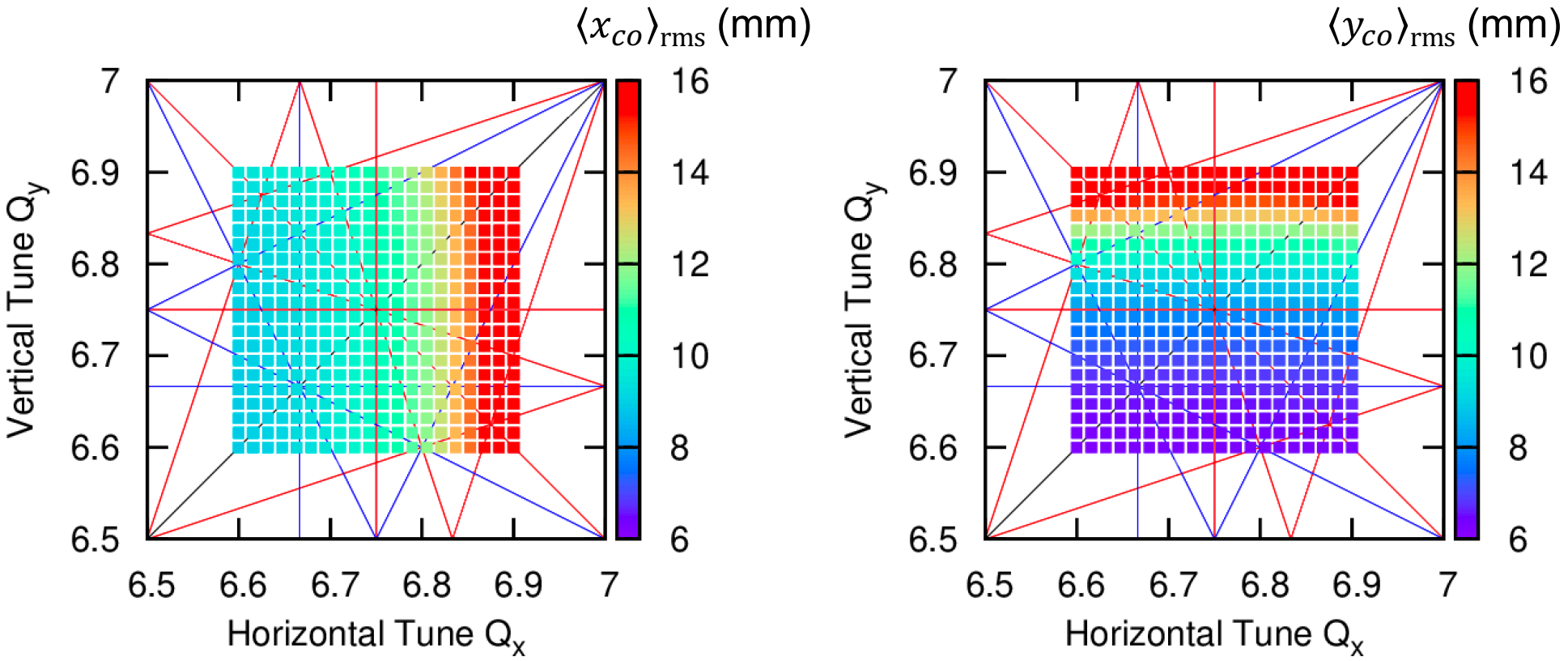


x_{co}

y_{co}

Closed-orbit distortions along the Booster ring, “elegant” output

“elegant” simulations



rms closed-orbit distortions from a 2D tune scan
(color scale is up to 16 mm, max $\langle x_{co} \rangle_{\mathrm{rms}}$ is 22 mm)

Beam losses in these simulations seem to be related to the closed-orbit