Landau Damping with Electron Lenses in Space-Charge Dominated Beams

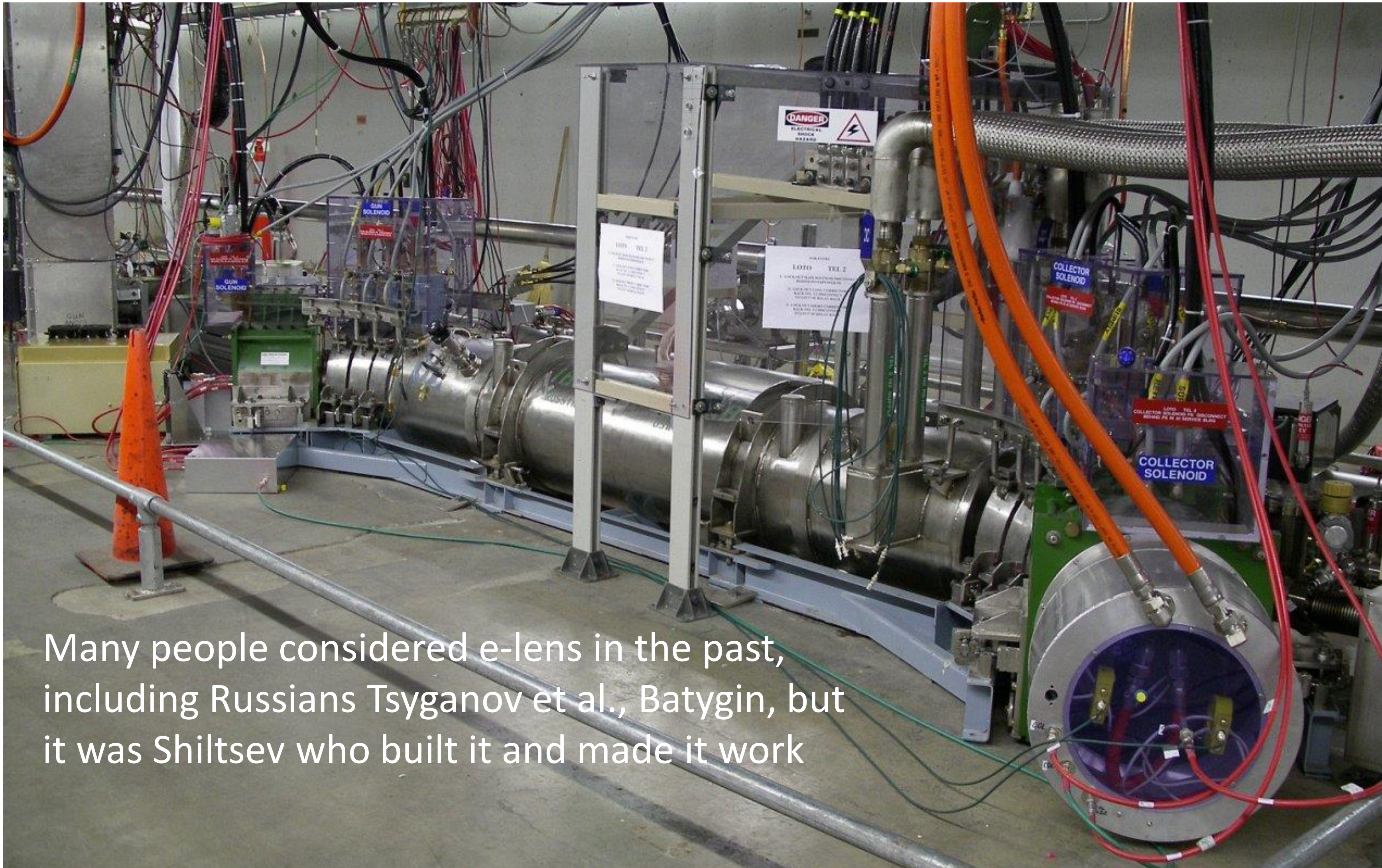
Yuri Alexahin for V. Shiltsev, A. Burov, A. Valishev and Y. A. (FNAL)

ICFA mini-Workshop on Mitigation of Coherent Beam Instabilities in particle accelerators

23-27 September 2019

Zermatt, CH

Tevatron e-Lens 2



Many people considered e-lens in the past, including Russians Tsyganov et al., Batygin, but it was Shiltsev who built it and made it work

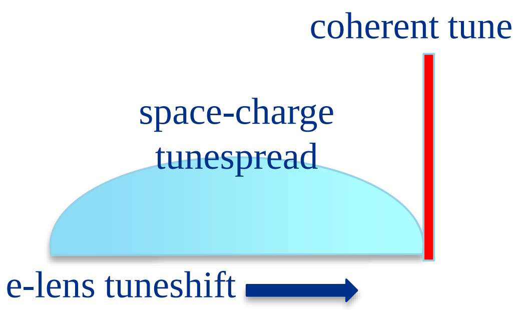
Many Professions of Electron Lenses

- Compensation of the beam-beam tune**shift** (primary objective)
- Abort gap cleaning (first job)
- Reduction of the beam-beam tune**spread** (non-linear BBC)
- Halo collimation
- Reduction of the space charge tunespread in hadron beams (non-linear SCC)
- Restoration of Landau damping
- Introduction of strong integrable non-linearity for the above purpose

In this report:

- Landau damping with hollow e-lens
- Landau damping with Gaussian e-lens
  - for coasting beam with SC (or HO colliding beams)
  - for bunched beam with SC
- e-lens experiment at IOTA

Electron Lenses for Landau Damping



The idea:

shift incoherent tunes back w/o shifting the coherent tune as much

- very similar to situation with Σ-mode in colliding hadron beams

Advantages compared to octupoles:

- Tuneshift with horz. and vert. amplitudes has the same sign,
- e-lens kick falls-off at large amplitudes – lesser effect on the dynamic aperture,
- possibility of the bunch-to-bunch and even intra-bunch profiling

Major questions to answer:

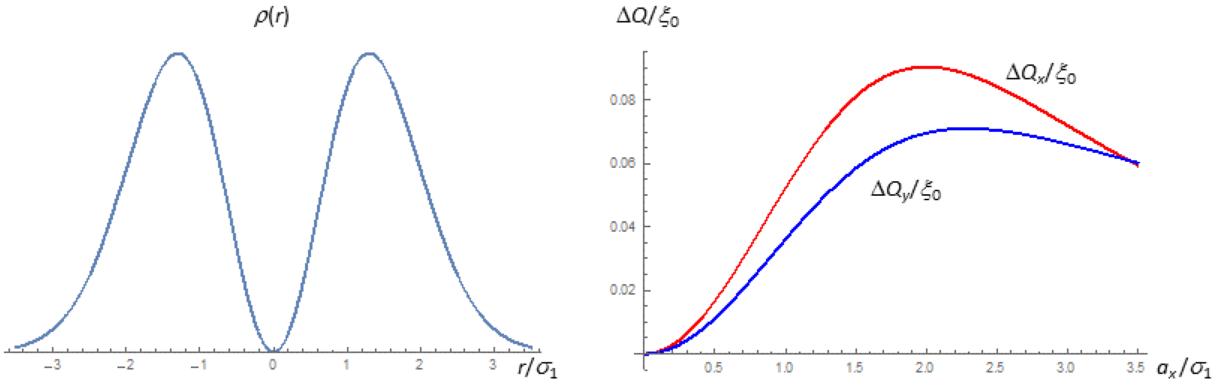
- two-beam instability between e-beam and the accelerator beam?
- can the reduction of the tunespread actually switch-off Landau damping?
- Will the e-lens non-linearity reduce the Dynamic Aperture?
- coherent tuneshift?

Electron Lenses for Landau Damping

- A. Burov answered the 1st question: two-beam instability be suppressed by freezing electrons with strong (axial) magnetic field
- Various tools (MADX-SC, Synergia, Lifetrac) used to answer the other questions.

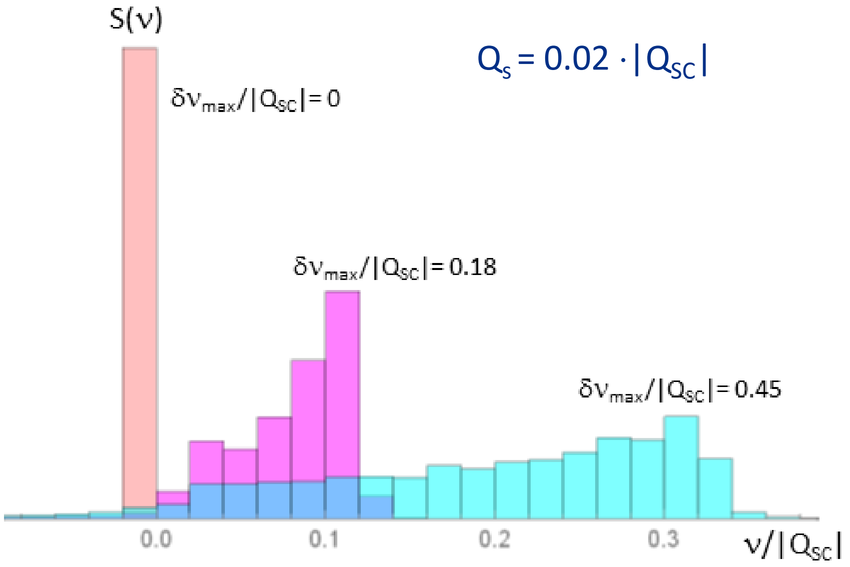
Two versions of the transverse shape considered:

- hollow e-beam – octupole-like effect, no effect at small amplitudes,
- bell-like shape (e.g. Gaussian) – maximum effect at small amplitudes



Electron lens density profile for σ_2/σ_1=0.85 (left) and tuneshifts as functions of a_x/σ_1 at a_y=0 (right).
"Bi-Gaussian" transverse profile: Gaussian hole ($\sigma = \sigma_2$) in a Gaussian beam ($\sigma = \sigma_1$)

Landau Damping with Hollow Electron Lens



Method of eigenmodes of the Vlasov equation

Spectral density of transverse oscillations in a **bunched*** beam after receiving a kick in the presence of a hollow electron lens. With increasing $\delta\nu_{max}$ the spectral peak is shifting (but not as much) and widens thus testifying of increased Landau damping. The higher Q_s is the stronger e-lens is needed.

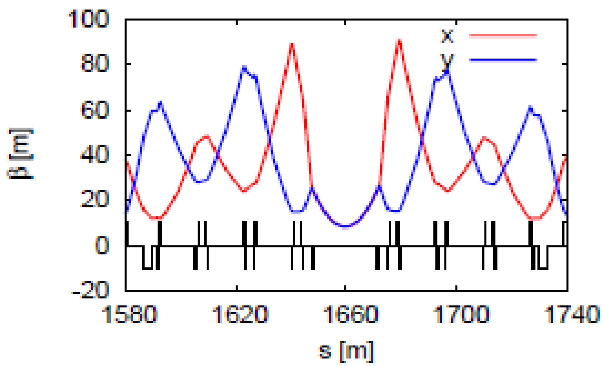
*) in a coasting beam the spectral peak is shifting more precluding the overlap by incoherent tunes (!) – a runaway effect predicted by A. Burov, confirmed by the eigenmode analysis. In a bunched beam the particles in the longitudinal tails can intercept the coherent tune.

Dynamic Aperture with Hollow Electron Lenses

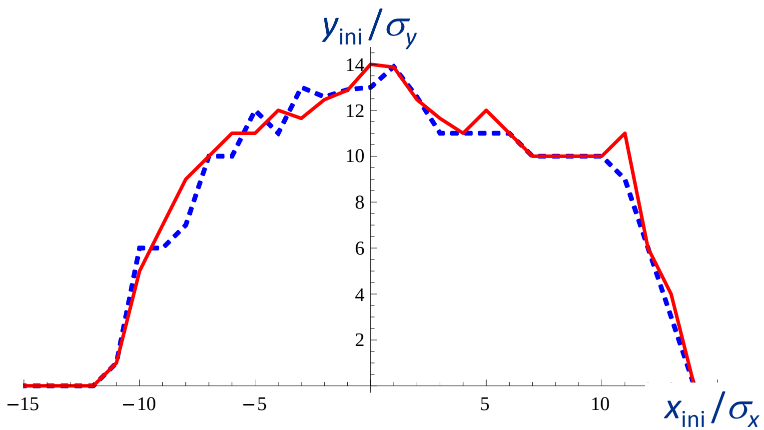
Danilov-Nagaitsev recipe for ~integrable nonlinear optics with octupoles:

- create a low-beta insertion with $\beta_x^* = \beta_y^*$
- vary the octupolar gradient along the length of the lens as $k_3 \sim 1/\beta_x^3$

– this can be achieved with the lens magnetic field profile $B_z \sim 1/\beta_x^{3/2}$



FNAL Recycler RR30 straight can be used to house an e-lens (optics by E. Gianfelice-Wendt), β_x^*= 15.5 m, the lens of length 22m provides $\Delta Q_\perp$ = 0.03 at 1σ amplitude



On-momentum 10^5 turns Dynamic Aperture with SC tuneshift ΔQ_{SC} = - 0.06
blue dashed line – no e-lens,
red solid line – with e-lens described above.
MADX-SC used

Hollow or Bell-Shaped Electron Lens?

Advantages of a hollow electron Lens:

- relaxed tolerances on alignment
- affects mainly particles with intermediate betatron amplitudes $\Rightarrow$

reduces the dynamic aperture only slightly if not at all

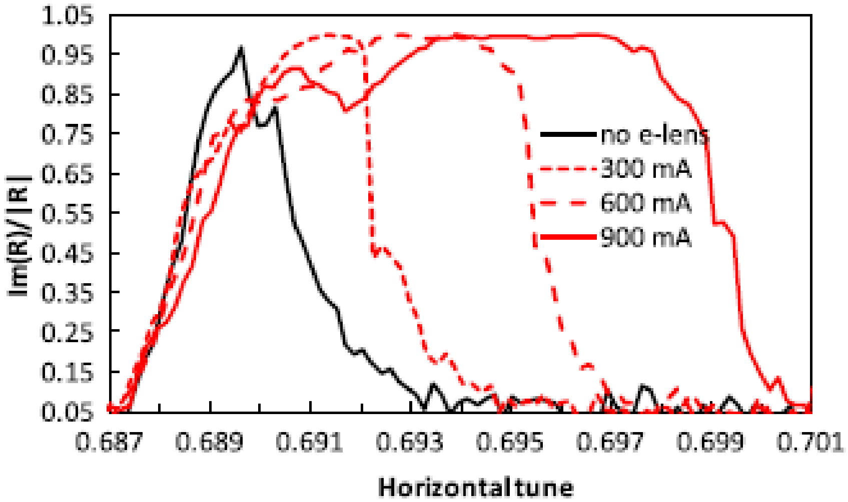
- does not spoil linear optics

Disadvantages due to the runaway effect :

- damping produced by particles in the longitudinal tails (may be absent)
- large e-beam current
- lopsided stability diagram
- does not work in a collider with large HO beam-beam tuneshift

All subsequent results are for bell-shaped e-lenses

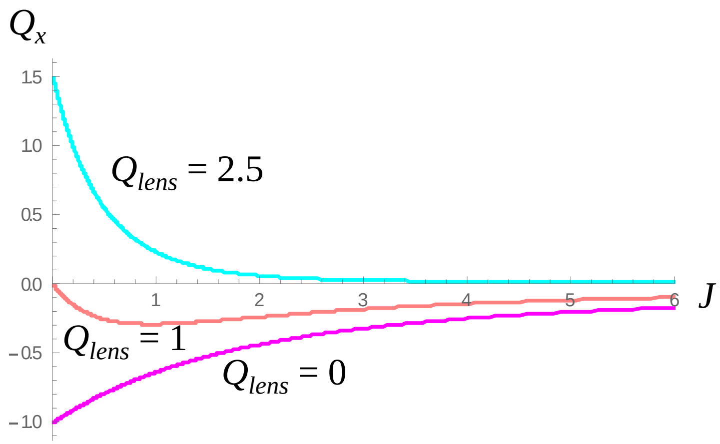
Tunespread by Bell-shaped e-Lens @ RHIC

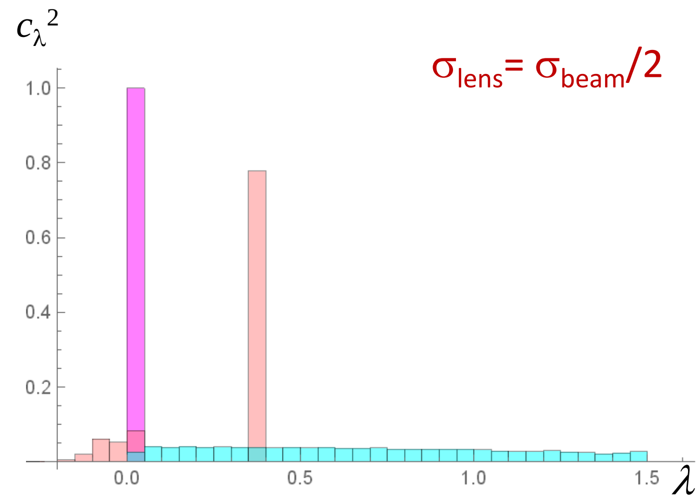


Measured p beam tune distribution width as a function of the electron beam current without beam-beam collisions.
The electron beam size of σ_e = 0.55 mm.
The proton beam size is σ_p = 0.60 mm.
(The curves are aligned at the left for better visibility of the effect)

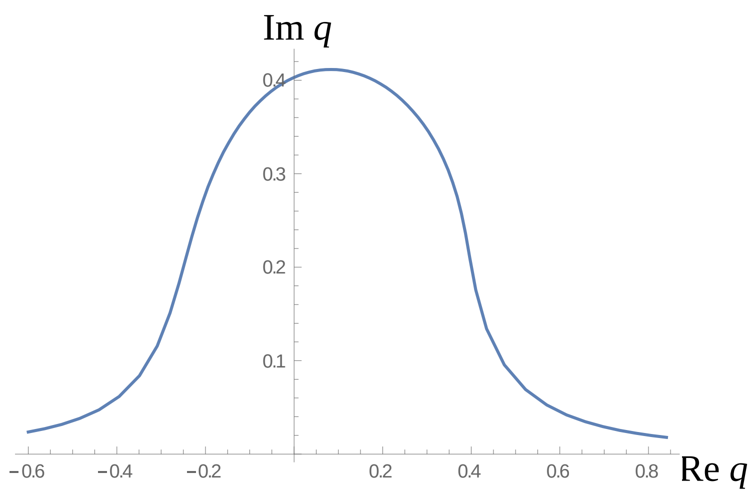
The question is what is happening with coherent tune.
Again, I used the method of eigenmodes of the Vlasov equation

Gaussian e-Lens for Coasting Beam





Left: incoherent tunes in units of | Q_{SC} | at indicated strength of Gaussian e-lens with $\sigma_{lens} = \sigma_{beam}/2$;
Right: spectra of dipole oscillations at the same parameters of e-lens.



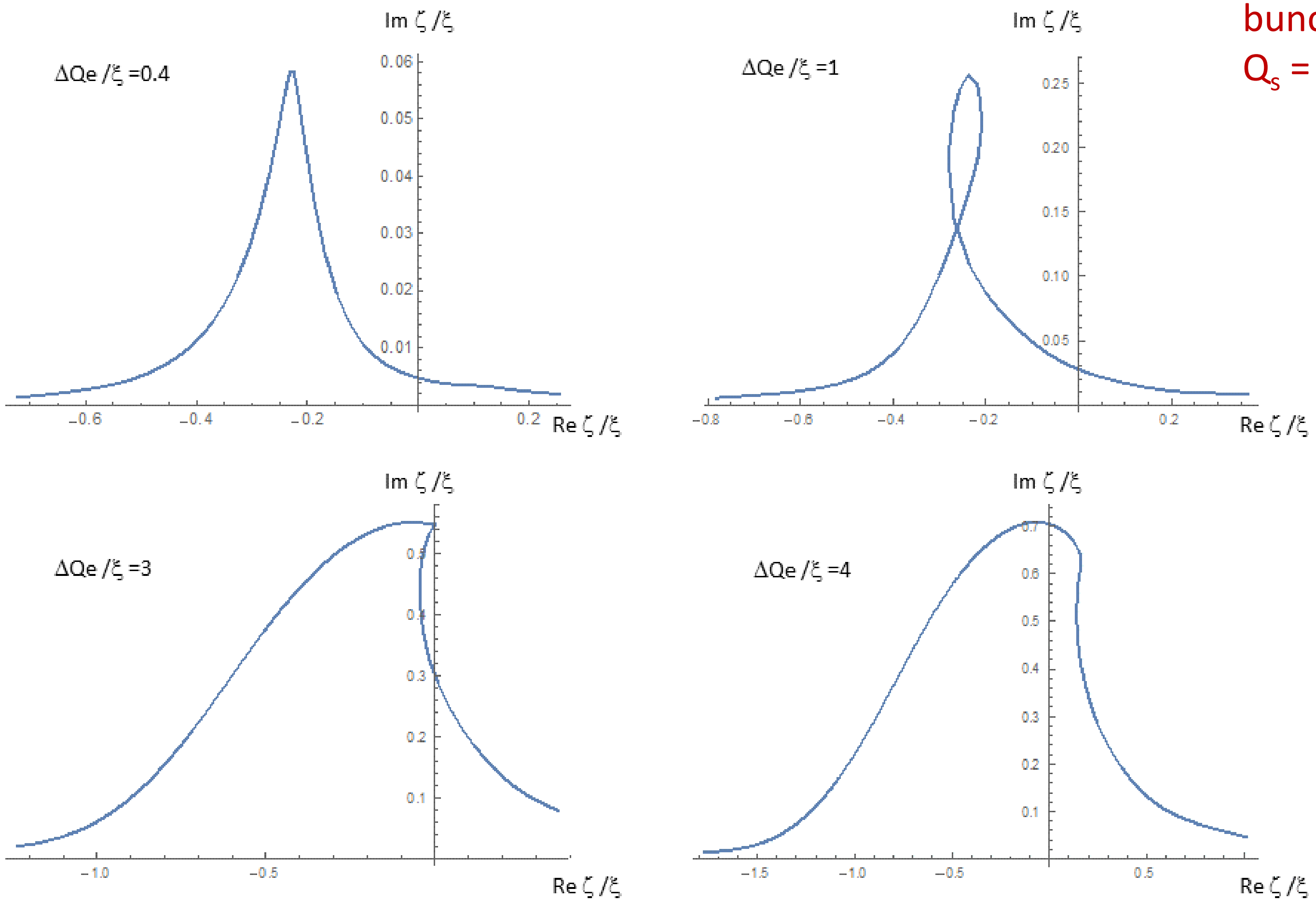
Stability diagram in the case of e-lens normalized strength $Q_{lens} = 2.5$

The maximum stable value of Im q provides Landau damping decrement (~ 0.41 |Q_{SC}|)

Actually we considered HO colliding beams: V. Shiltsev et al., "Landau damping of beam instabilities by electron lenses." Phys.Rev. Letters 119, no. 13 (2017): 134802

Bunched Beam SD with Gaussian e-Lens

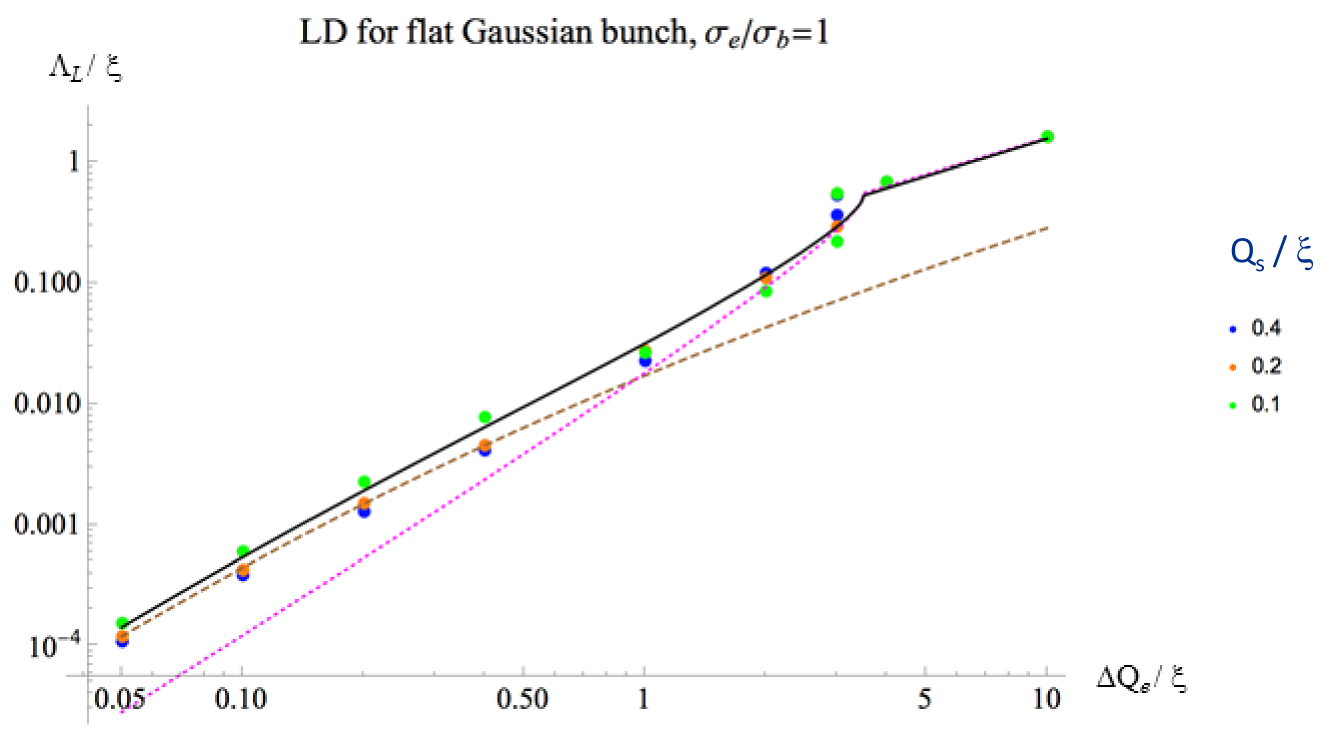
$\sigma_{lens} = \sigma_{beam}$,
bunched beam,
$Q_s = 0.2*|Q_{SC}|$



$Q_s = 0.2 \cdot \xi$, $\xi = | Q_{SC} |$

Y.Alexahin, A.Burov, V.Shiltsev, A.Valishev,
FERMILAB-TM-2655-APC, 2017

Bunched Beam Damping Rate with Gaussian e-Lens



Dots: Vlasov's eigenmode theory for indicated values of Q_s / ξ ,

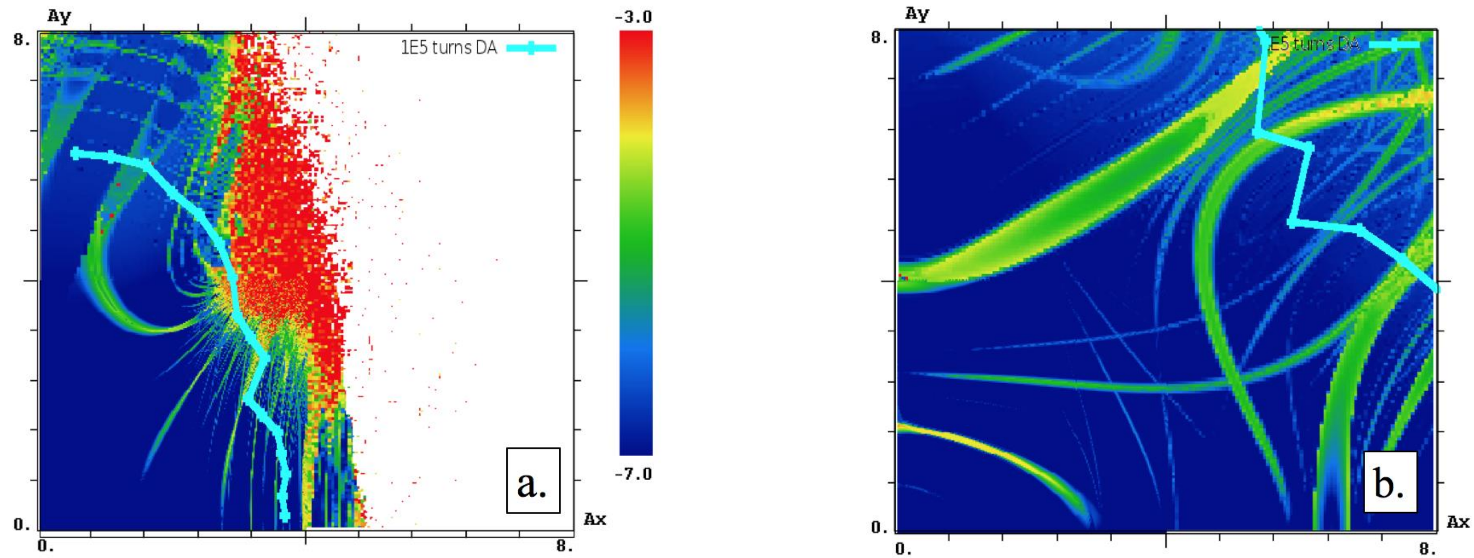
lines: A. Burov's semi-qualitative considerations.

Dynamic Aperture with Gaussian Electron Lens

HL-LHC at 7 TeV

octupoles

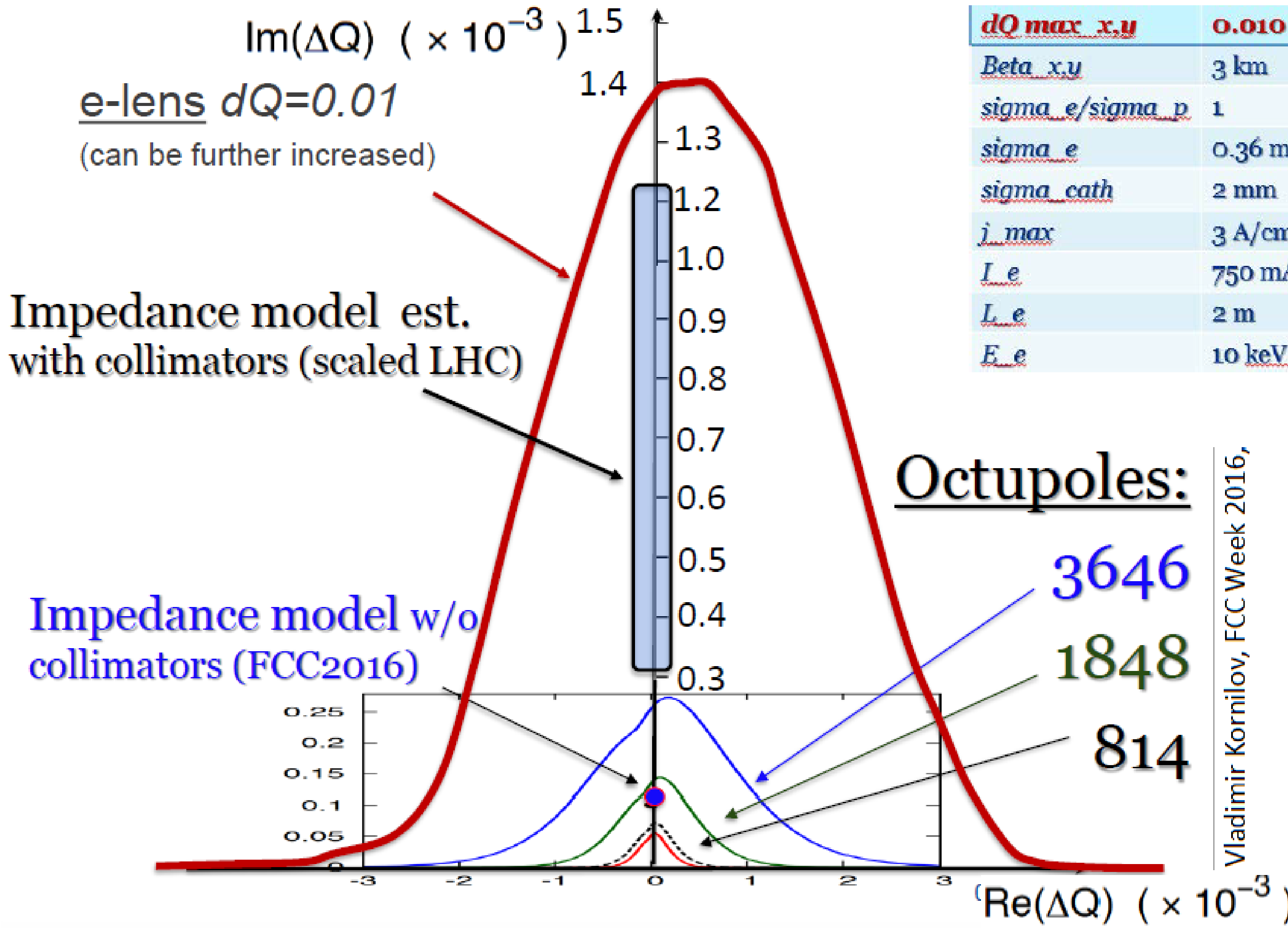
e-lens



Frequency Map Analysis (FMA) and Dynamic Aperture modeling of HL-LHC proton dynamics with comparable strength Landau damping provided by octupole magnets (a) and by the electron lens (b). Horizontal and vertical axes – initial particle amplitudes A_x, A_y in units of the rms beam size varying from 0 σ_p (core) to 8 σ_p (halo). Brighter colors indicate exponentially stronger tune modulation indicating resonances (see color palette). 100,000 turns DA is shown in cyan lines

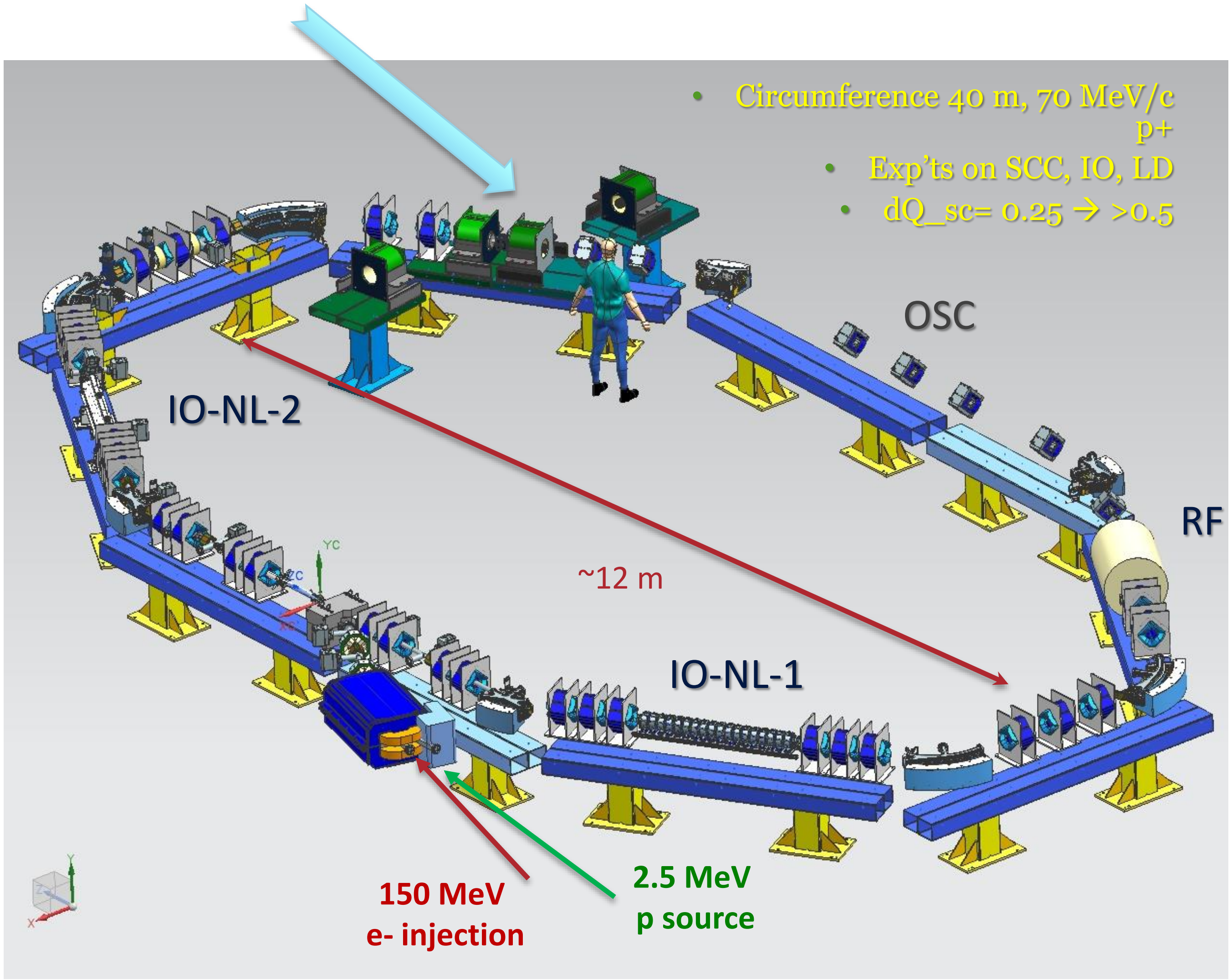
A. Valishev, FERMILAB-TM-2659-AD-APC, 2017

FCC Stability Diagram (V. Kornilov, 2016)

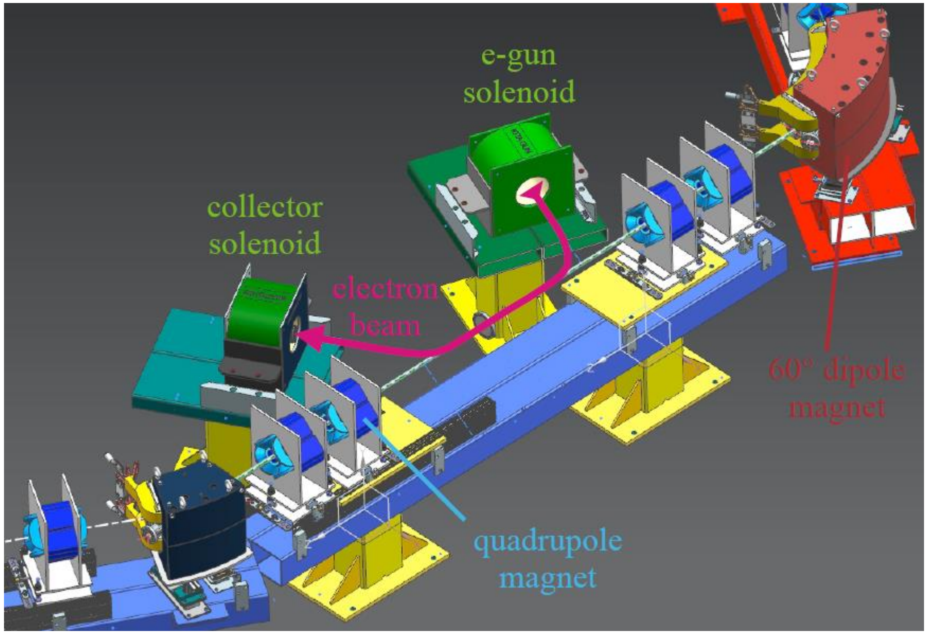


dQ max x,y	0.010
Beta x,y	3 km
sigma_e/sigma_p	1
sigma_e	0.36 mm
sigma_cath	2 mm
j_max	3 A/cm^2
I_e	750 mA
L_e	2 m
E_e	10 keV

Electron Lens in IOTA



Electron Lens in IOTA



The main option considered:

1. Thin McMillan lens ($\beta_\perp$>> L_{lens})

current density $j(r) = \dfrac{j_0 a^4}{(r^2+a^2)^2}$

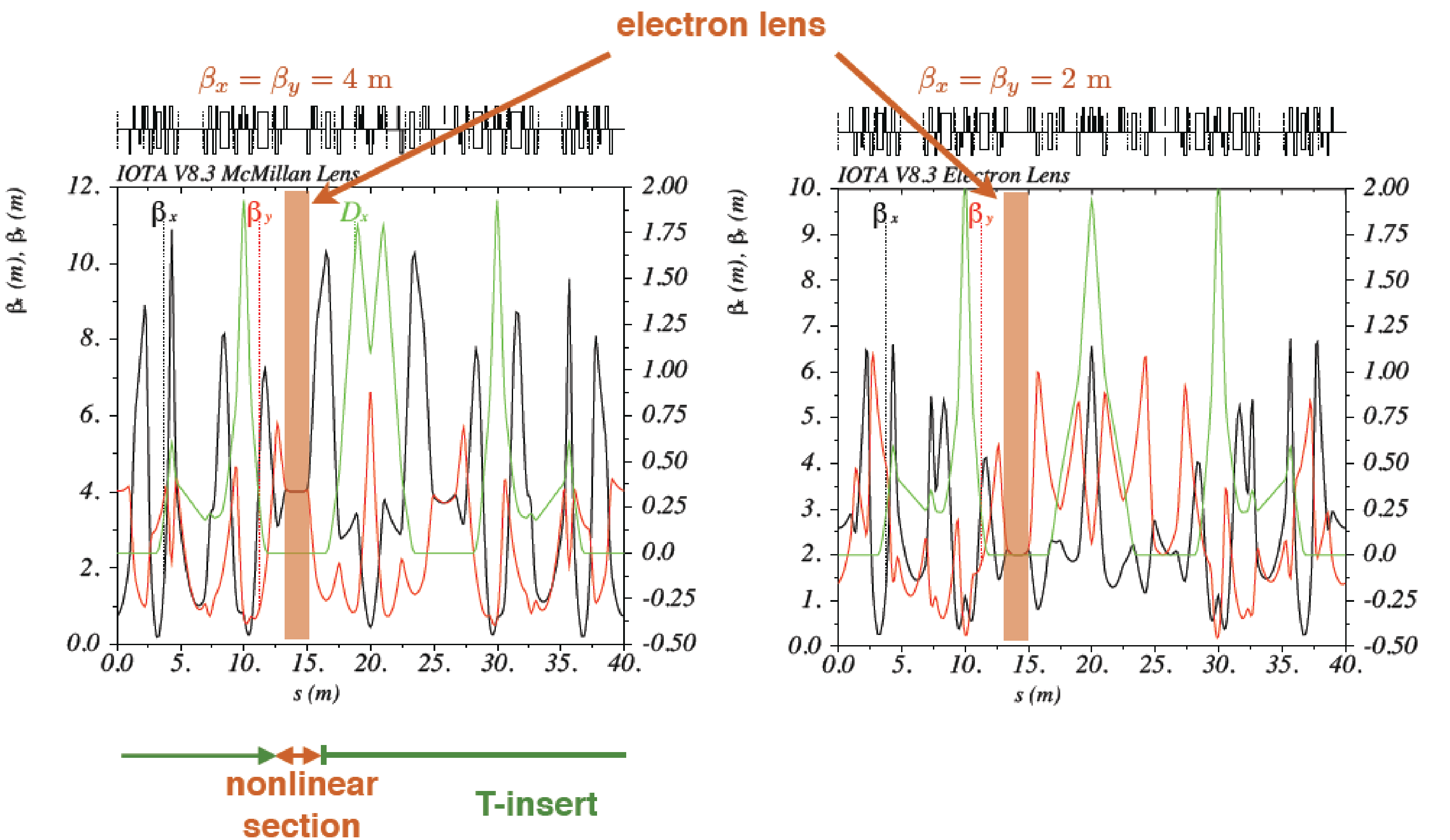
transverse kick $\theta(r) = \dfrac{k_e a^2 r}{r^2+a^2}$

achievable tune spread $\sim \dfrac{\beta k_e}{4\pi}$

up to ~0.3 with IOTA e-lens parameters.

2. To obtain larger tunespreads a stronger focusing e-lens is needed which will affect the linear optics ($\beta_\perp$ ~ L_{lens}=0.7m). The optics can be adjusted according to the Danilov-Nagaitsev recipe.

IOTA Optics with e-Lens

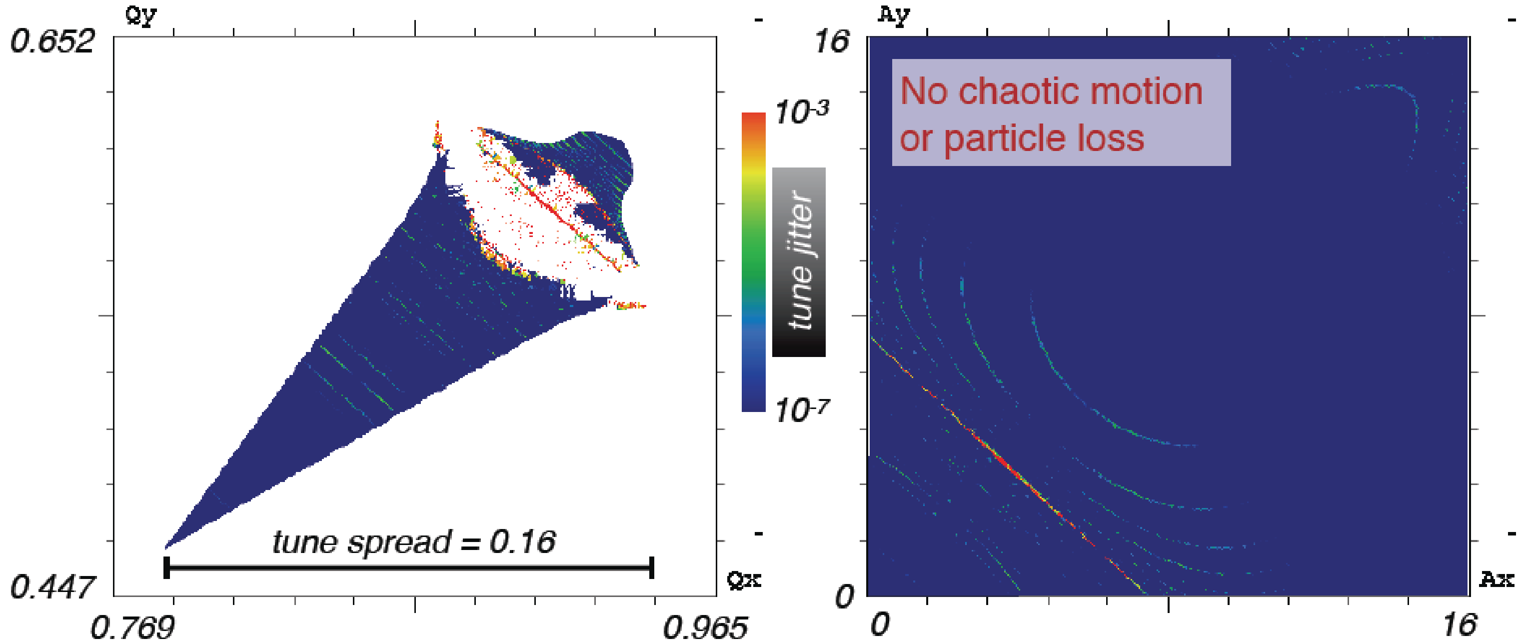


The lattice can be modified for $\beta_\perp = L_{lens}$=0.7m

Tracking Simulations and FMA

IOTA with McMillan lens in 0.7-m solenoid, k_e = 0.6 /m (1 A)
IOTA lattice v6.6, $\beta_x = \beta_y$ = 3 m

$$\frac{\beta k_e}{4\pi} = 0.14$$



Summary & Outlook

- The e-lens can provide sufficient Landau damping in SC dominated beams
- Hollow e-lens can work efficiently for bunched beam, but not so for coasting beam or HO colliding beams
- The e-lens effect on the Dynamic Aperture can be minimized by the optics design in accordance with either McMillan or the Danilov-Nagaitsev recipe.
- The e-lens can replace hundreds if not thousands of octupoles in high-energy colliders providing strong Landau damping w/o compromising the DA
- It is planned to study the effect of strong e-lens with integrable optics in IOTA