Electron Lenses in the FCC

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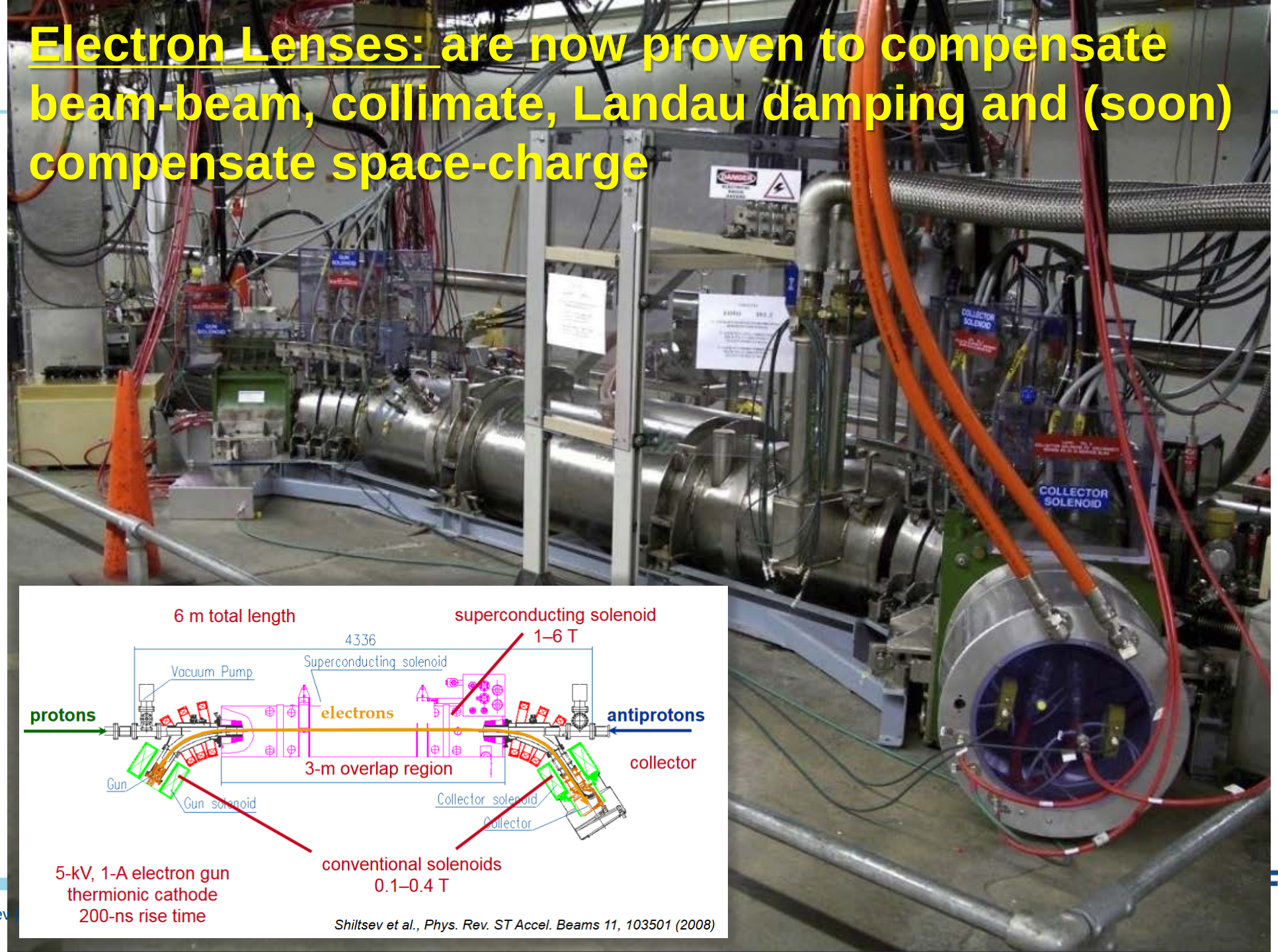
FCC Week, Berlin, May 31, 2017

Electron Lenses: are now proven to compensate beam-beam, collimate, Landau damping and (soon) compensate space-charge



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Major FCC Beam Dynamics Challenges

D. Schulte

FCC-hh, Rome, April 2016

- 10 000 bunches and huge total intensity (2e15)
- 8400 MJ in the beam
- **Serious concerns of :**
  - Collimation of 100 GJ/mm^2 beams
  - Stability of ~0.5A beams in presence of impedance, e-cloud, collimators esp.@0.44π
  - Long-range beam-beam esp under "ultimate scenario" w. ξ=0.03
- These problems are interdependent (eg collimators impedance)

	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

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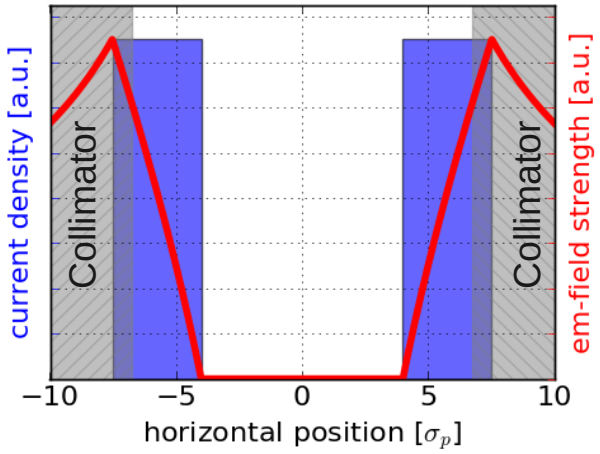
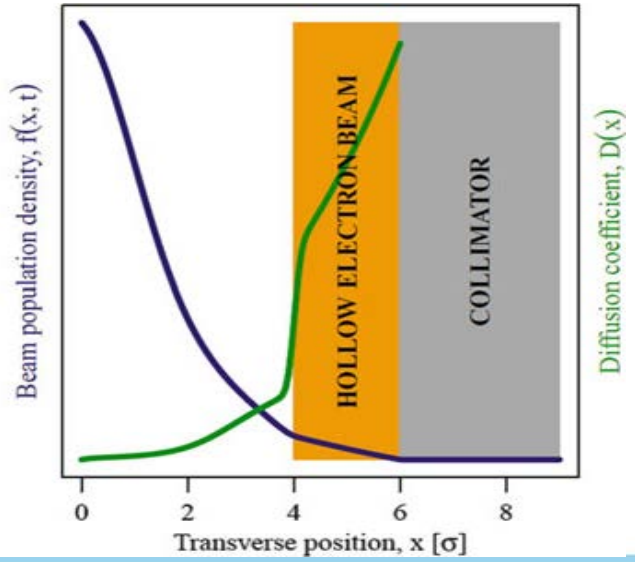
Uses of Electron Lenses in FCC

- Collimation by Hollow Electron Beam
- Electron lenses for Landau damping
- (may be) long-range compensation by “electron wires” or head-on BBC
- (possibly) Electron Lenses for Space-Charge Compensation

FCC Hollow E-Beam Collimators

V.Shiltsev, 2006





Principle of hollow e-lens:

- increase of diffusion for halo particles
- no effect on core as HEL acts in amplitude space

⇒ *active halo control, no material, no impedance*

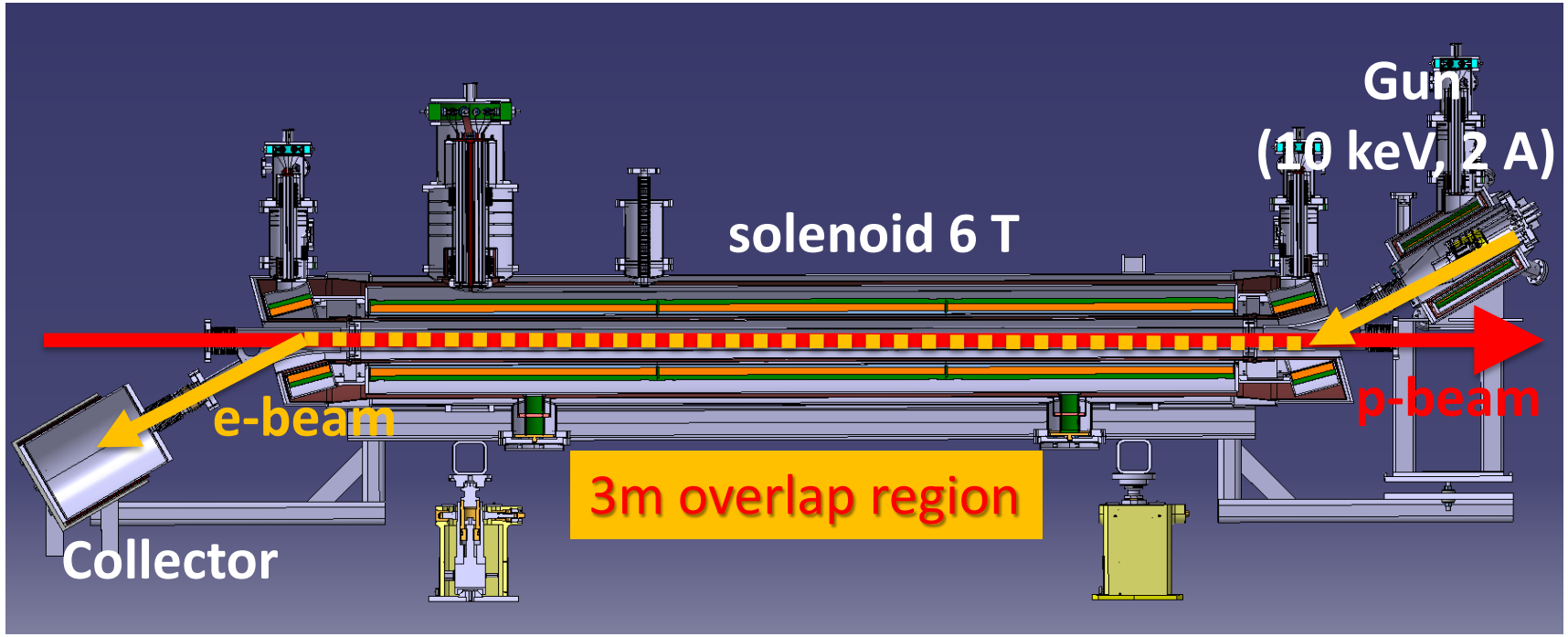
Modes of operation:

- DC as ***standard operation*** mode

⇒ *negligible effect on the beam core – demo'd in Tevatron, see* **Stancari, Shiltsev,PRL 107(2011)**

- pulsed operation to ***further increase diffusion*** (x 10-100 at the same current)
  - random current modulation
  - switch e-lens on/off every *n*-th turn (drives n^{th} order resonances)

FCC Hollow Electron Lens

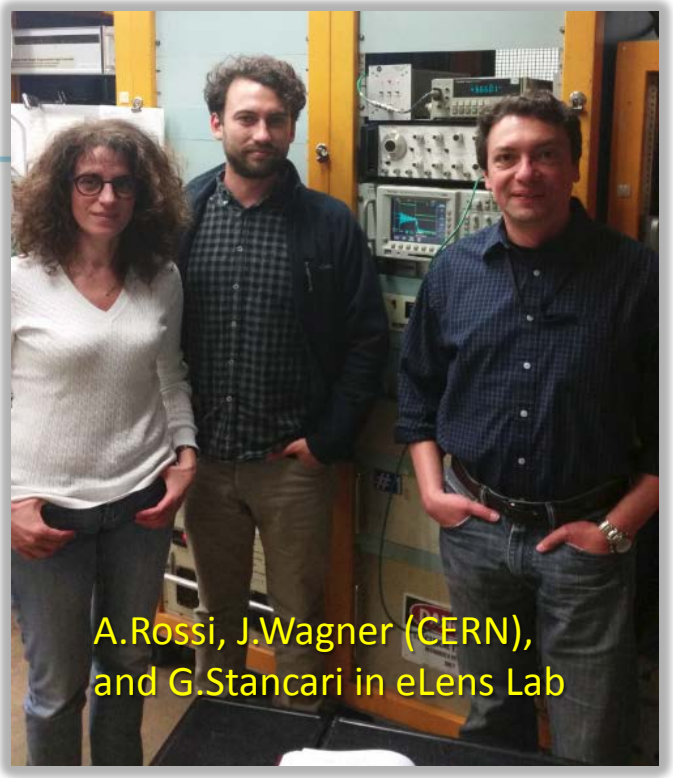


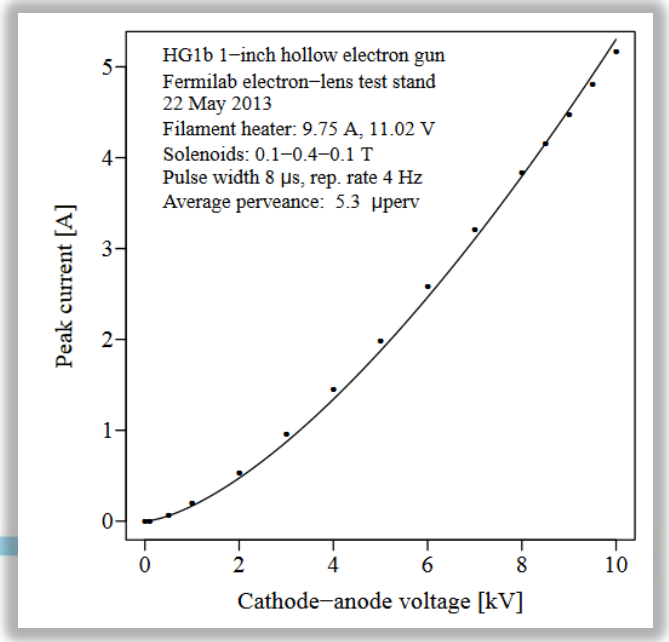
Electron energy	10 kV	Length	3m
Electron current	2-5 A	B_s/B_g	6/0.2-0.4T
E-radius (inner/outer)	1.2/2.4 mm	Cathode radius	12 mm
p-sigma (β=2000m)	0.3 mm	Current dens.	1A/cm^2

Hollow e-beam R&D for HL-LHC

Collaboration: CERN, FNAL, Frankfurt, GSI, Riga, Liverpool

- Strong effort on hollow e-gun development (5A achieved)
- Simulations and LHC beam studies (noise effects)
- Elens test stand at CERN (H.Schmickler, FCC Wk 2016)
- Same team can design/simulate the hollow e-beam collimator for the FCC-hh





Need of Landau damping in FCC

- Challenge even for "ideal" FCC:
  - see FCC Week 2016 talks
- Additional risks:
  - Accuracy of calc's
  - Z_T due to collimators unless hollow e-beam
  - Electron cloud
- Significant uncertainty ~3-10
  - Probably *beyond capabilities of octupoles*
  - esp. taking into account DA

→ **Employment of Landau damping e-lenses**

"FCC octupole power NI should be x20 of LHC"

Vladimir Kornilov, FCC Week 2016,

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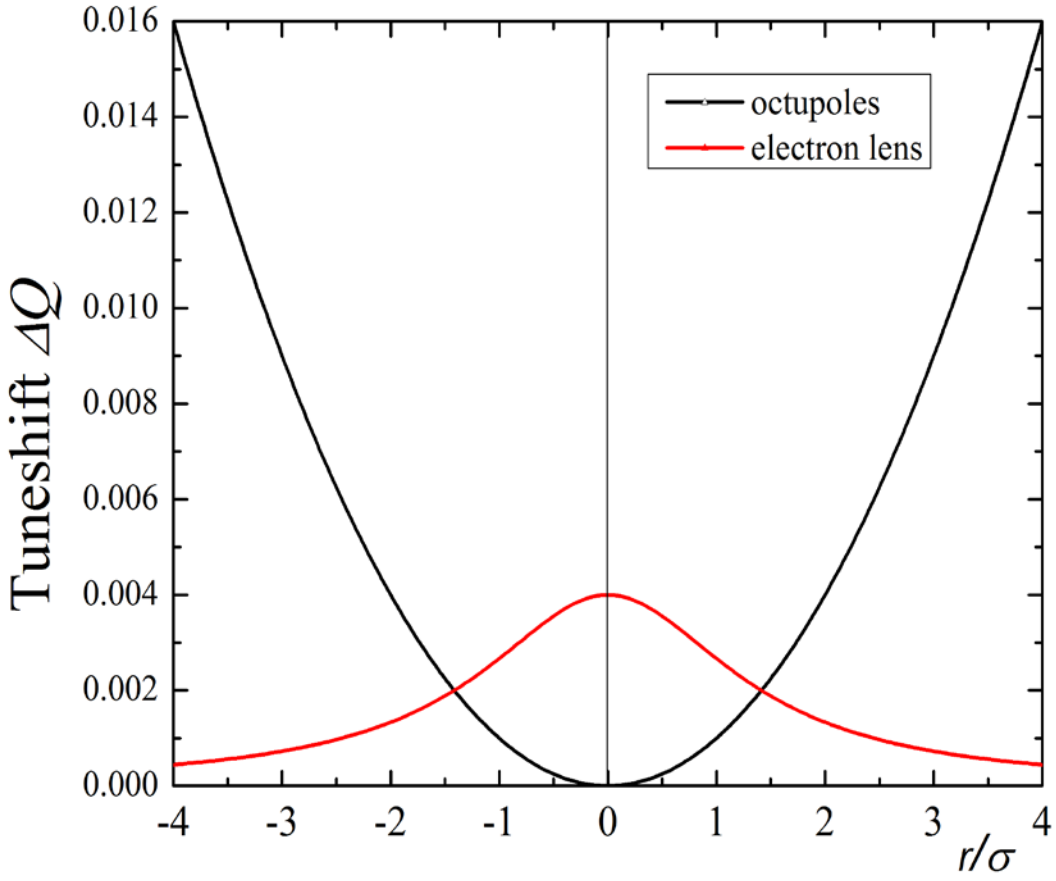
Issues with Octupoles for Landau Damping

$$\Delta Q_{\rm oct} \propto (NI)_{\rm oct}\, \hat{\beta}^2 \frac{\epsilon_\perp}{\gamma^2}$$

dQ ~(few) 0.0001

- **Tevatron 1 TeV :**
  - 35 magnets, 1 m each, 50A
- **LHC 7 TeV :**
  - 168, 0.32 m, 500 A
- **FCC-hh 50 TeV :**
  - 814/1828 LHC-type oct.

- **While just 1 electron lens**
  - ***+ dQ ~ξ_{EL} ~ 0.007-0.010***
  - ***+ Factor 10-20 over octupoles***



+ no effect on DA

+ stable over beam-beam footprint changes in squeeze

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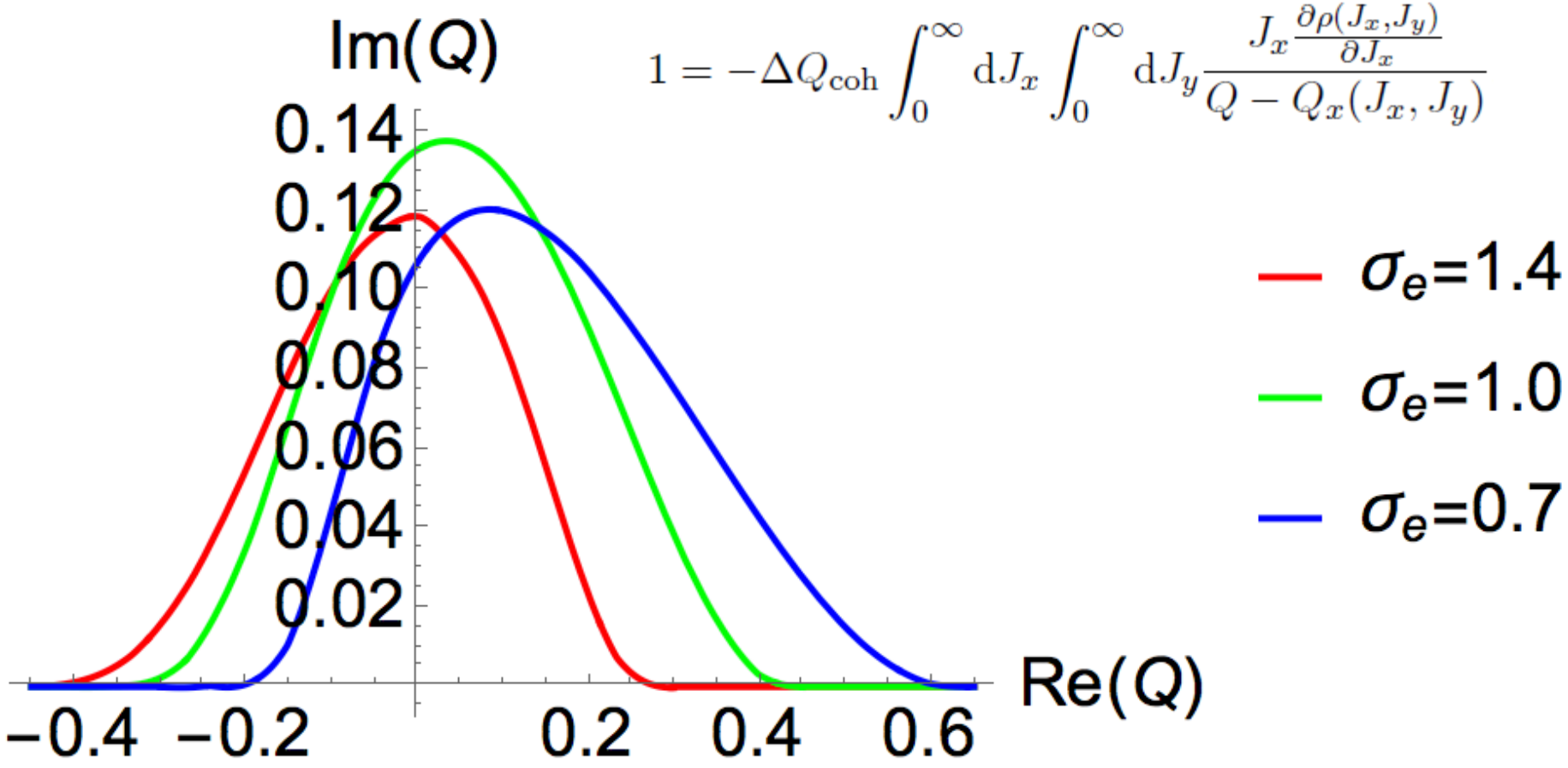
Gaussian e-Lens Stability Diagram

$$1 = -\Delta Q_{\mathrm{coh}} \int_0^\infty \mathrm{d}J_x \int_0^\infty \mathrm{d}J_y \frac{J_x \frac{\partial \rho(J_x, J_y)}{\partial J_x}}{Q - Q_x(J_x, J_y)}$$



Gaussian E-Lens with various sigma_e/sigma_p,
SD in units of the maximal tune shift, dQ_e identical for all the 3 cases.

E-Lens for LD in 50TeV FCC

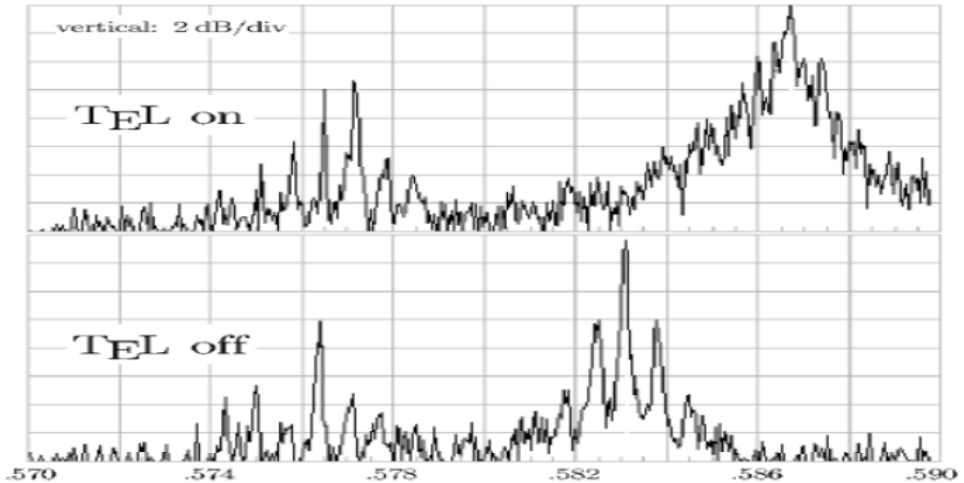
$$\xi_e = +\frac{r_p}{4\pi}\frac{\beta_{x,y}}{(\beta_p\gamma_p)}\frac{(I_e L_e)}{\sigma_e^2}\frac{1+\beta_e}{ec\beta_e}$$

this factor is 1/emittance_norm if sigma_e = sigma_p, ie energy independent

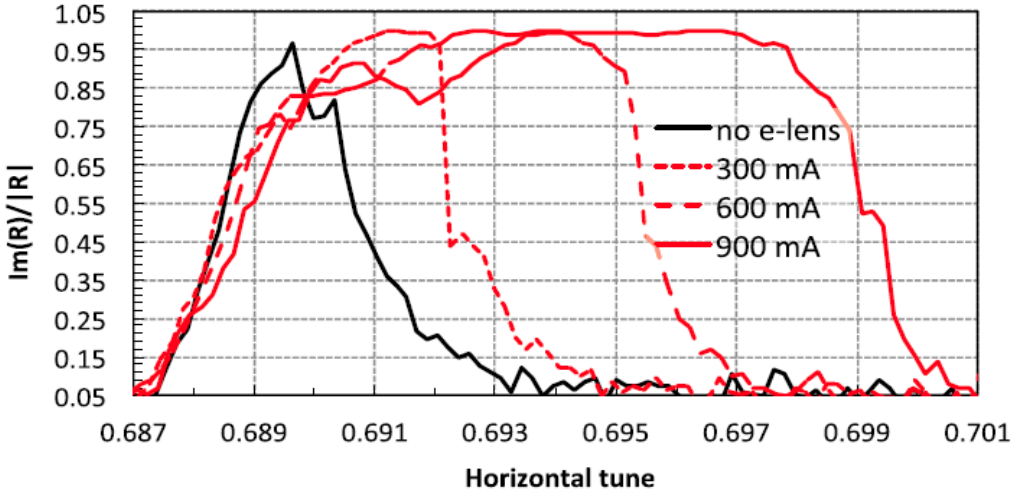
dQ max_x,y	0.010
Beta_x,y	3 km
sigma_e/sigma_p	1
sigma_e	0.36 mm
sigma_cath	2 mm
j_max	3 A/cm^2
I_e	750 mA
L_e	2 m
E_e	10 keV

These parameters are easily achievable

Already demonstrated: Tevatron e-Lens max tune shift dQ e ~ 0.01, 1 TeV

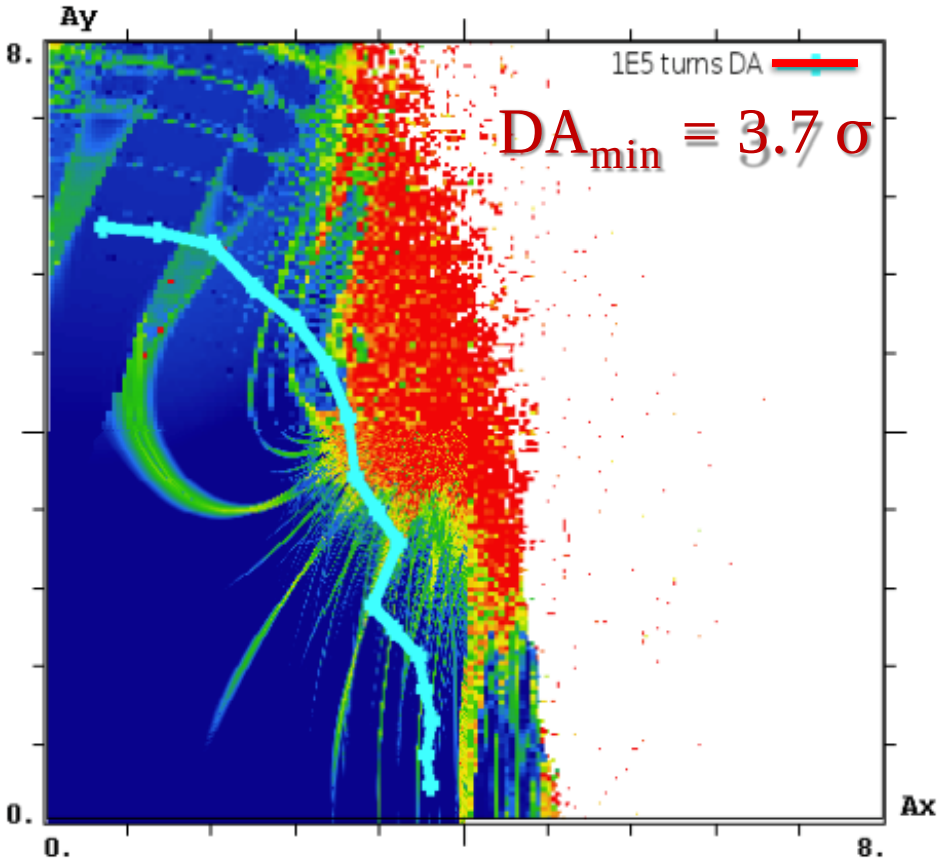


RHIC e-Lens: dQ_e ~ 0.01, 100 GeV

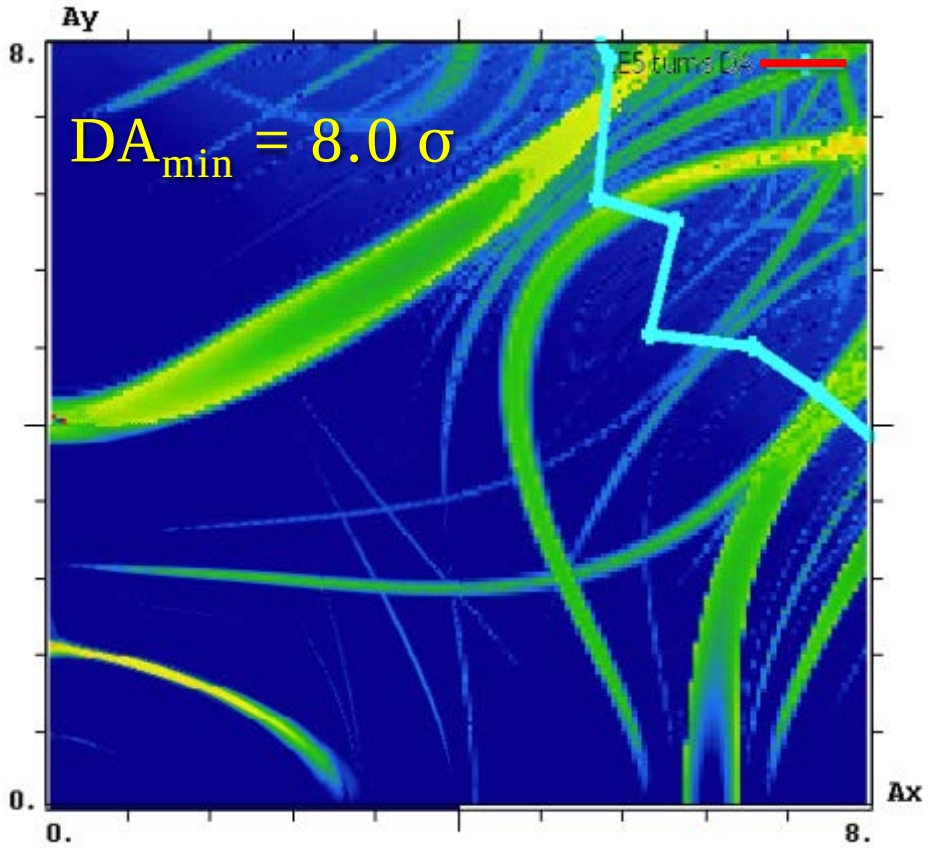


DA with Octupoles and eLens

LHC with octupoles



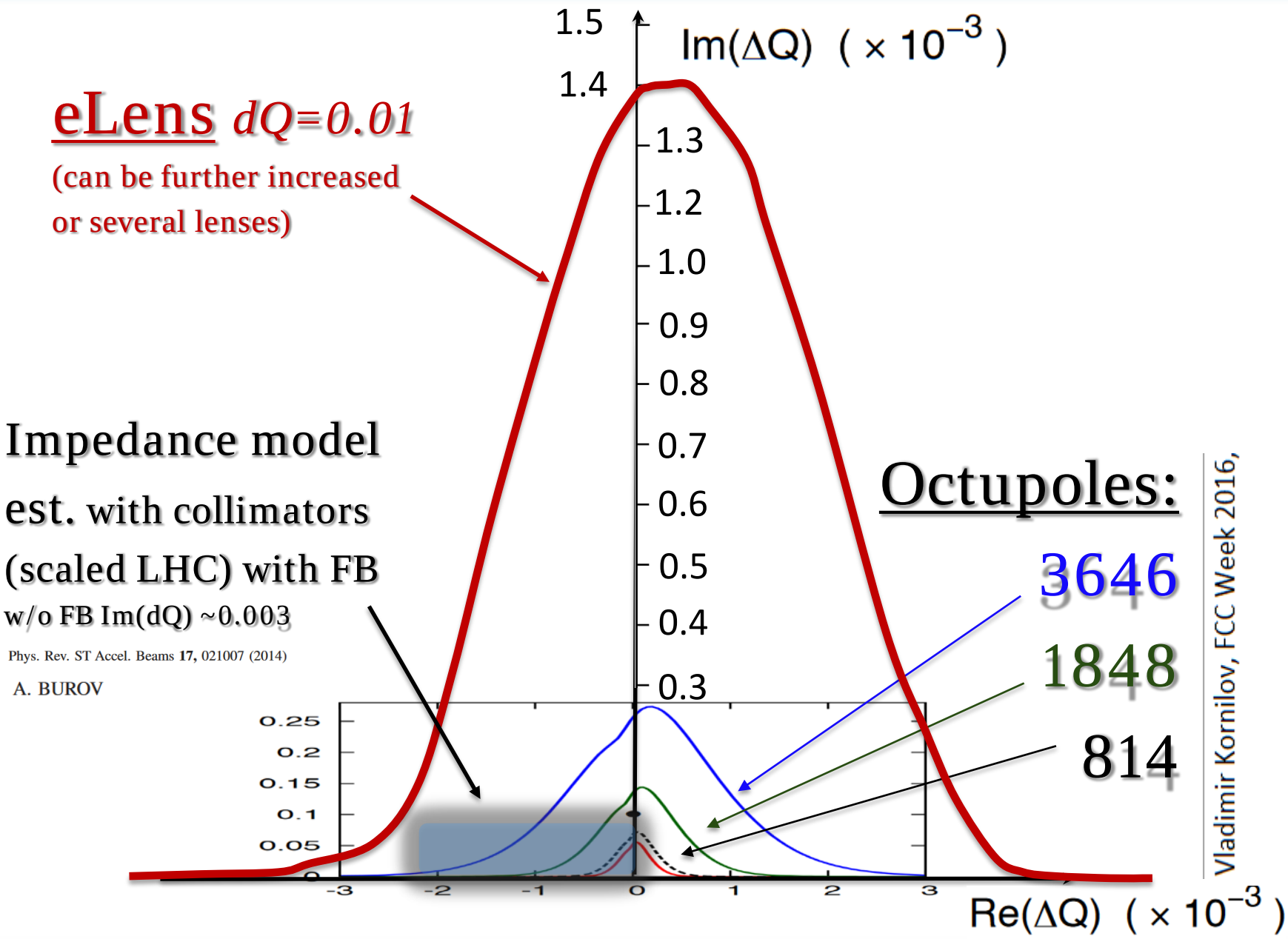
LHC with eLens



Energy 7TeV, no collisions, HL-LHC optics Version 1.0 with multipole errors (1 seed), Chromaticity = 3

- For simulation with octupoles, current increased to -2000A to create tune spread of 0.005 at 2.5 sigma
- Single electron lens at IR4 – the location of Hollow Electron Beam Collimator, Electron beam size matched to size of proton beam (sigma=0.28 mm). Current of EL corresponds to tune spread of 0.005 at 2.5 sigma

Compare Stability Diagrams



Vladimir Kornilov, FCC Week 2016,

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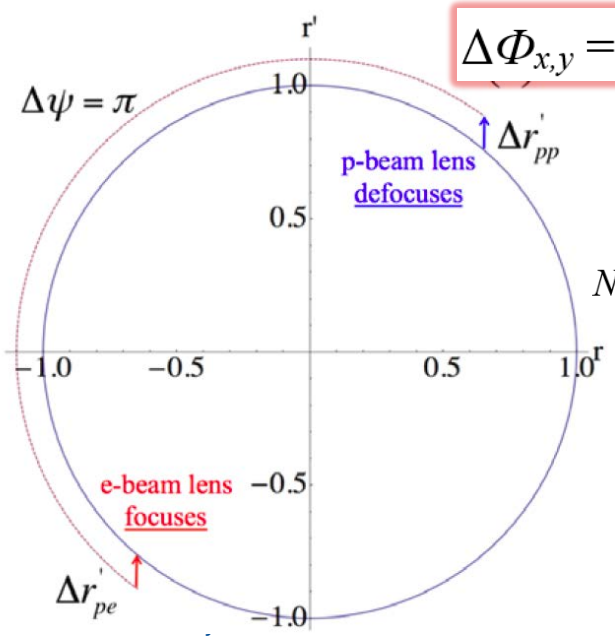
Head-On Beam-Beam Compensation

- Will probably be needed at the ultimate FCC-hh with b-b parameter ξ=0.03 / 2 IPs
  - RHIC 0.01 per IP = 0.02 total (no LR)
  - Tevatron: max 0.04 (2IPs), ops.0.028 with LR
  - LHC 2016: 0.013 (2 Ips) with LR

1 IP HO compensation conditions



$$\Delta\Phi_{x,y} = |\Phi_{e\text{-}lens} - \Phi_{IP}| = k\times\pi$$

$$\sigma_e = (\varepsilon\beta_{e\text{-}lens}/\gamma_p)^{1/2} = \sigma_p$$

$$N_e^* = J_e\,(1+\beta_e)\;L_e/(ec\beta_e) = N_p$$

$$D_x\sigma_{dE/E} << \sigma_e$$

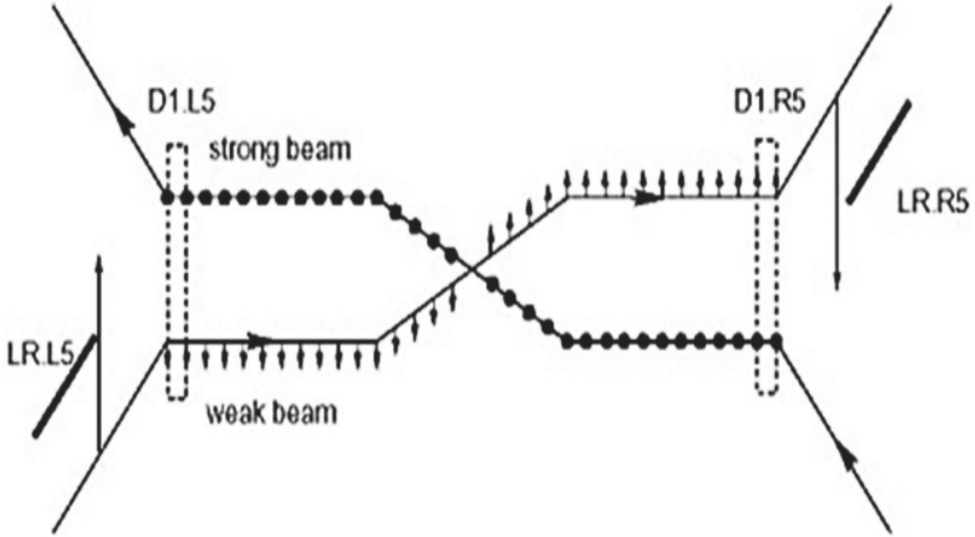
dQ_e	**0.015**
Beta_x,y	3 km
sigma_e=sigma_p	0.35 mm *
sigma_cath	1.9 mm
j_cath_max	4.9 A/cm^2
I_e	1.1 A
L_e	2 m
E_e	10 keV

* w. emittance 2.2 μm; challenging 0.16mm @ 0.44 μm

Long-range Beam-Beam Compensation

- Not clear yet whether LR BB compensation will be needed
  - strongly dependent on the separation

$$N_{\mathrm{LR}} N_p e c \frac{1+\beta_p^2}{2\beta_p} = L_e I_e \frac{1 \pm \beta_e \beta_p}{\beta_e \beta_p}$$



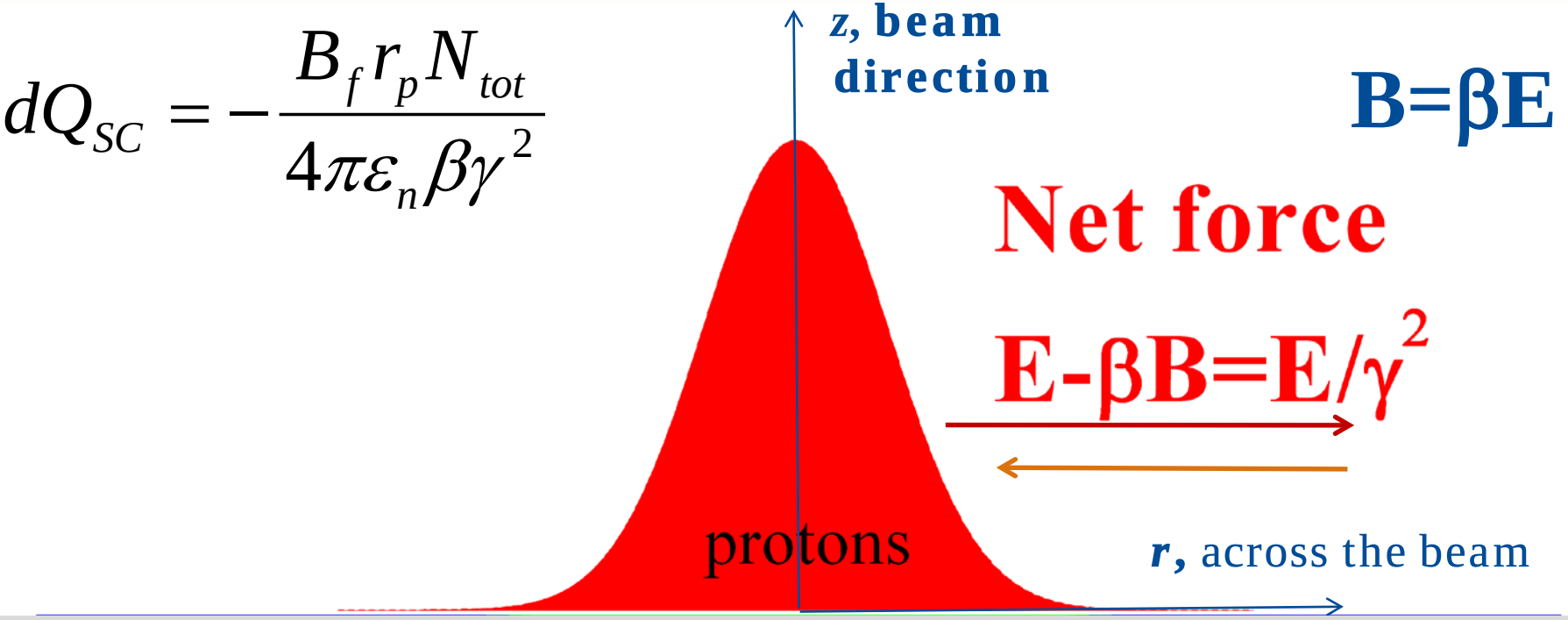
If one takes HL-LHC electron beam wires as an example

Strength I_e L_e	***~30 Am***
Beta_x,y	~1500 m
radius_e	<0.8 mm
j_cath_max	~10 A/cm^2 *
I_e	7 A
L_e	4 m
E_e	~15 keV

* challenging , might require longer electron lens

Space Charge Compensation by eLenses

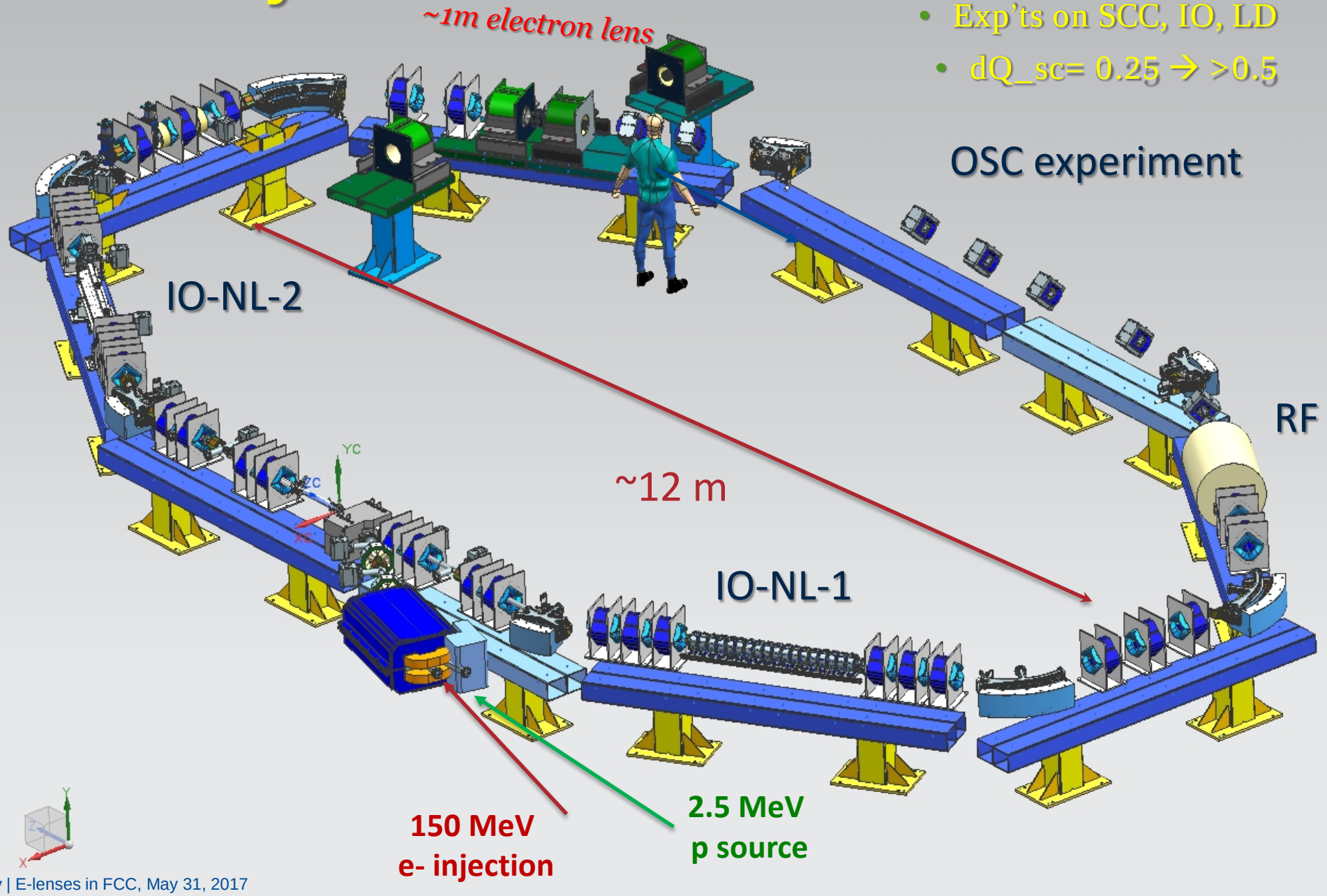
$$dQ_{SC} = -\frac{B_f r_p N_{tot}}{4\pi\varepsilon_n \beta\gamma^2}$$



A. Burov, G. Foster, V. Shiltsev, FNAL-TM-2125 (2000)

IOTA Layout

- Circumference 40 m, 70 MeV/c p+
- Exp'ts on SCC, IO, LD
- dQ_sc= 0.25 → >0.5



IOTA = Integrable Optics Test Accelerator

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Summary

1. **Electron lenses is now a proven, operationally tested technology… very flexible**
2. **Most useful applications of e-lenses in FCC**
   - Hollow electron beams for Collimation
   - Electron lenses for Landau damping
   - eLenses for beam-beam compensation
   - Electron lenses for space-charge compensation
3. **All this concepts need thorough development** theory, modeling/simulations, prototyping, experimental beam tests (at IOTA or elsewhere)
4. **Collaboration needs to be set up** – let's join the forces!

FCC impedance estimate

- **LHC scaling to FCC:**
  - As we know, LHC normally works at 500A in its 160 octupoles, which is a bit above the threshold with a reasonable safety factor (like a factor of 2). Let's assume that for the FCC we want to have the same safety factor, which sounds reasonable. Then, for the same current of 500A, for the FCC we will need 168*3.7*3.5*6.5=14000 octupoles.
  - 3.7=100km/27km;
  - 3.5=(50TeV/7TeV)*(beta_LHC/beta_FCC);
  - **6.5=Impedance_FCC/Impedance_LHC** (the impedance is going to be dominated by the collimators).
    - ~ 1/b^3~(gamma/beta/emittance)^3/2~6.5
  - Now you may look at the FCC2016 (Kornilov's) blue dot, and see that it is ~10 times below.
  - Small emtance 0.44pi makes it worse by another factor sqrt(5)=2.2