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New Uses of Electron Lenses

Vladimir Shiltsev, Fermilab

Eucard-2 Meeting, Valencia

February 14, 2017

Electron gun and collector from TEL-1
Waiting for installation in the IOTA ring

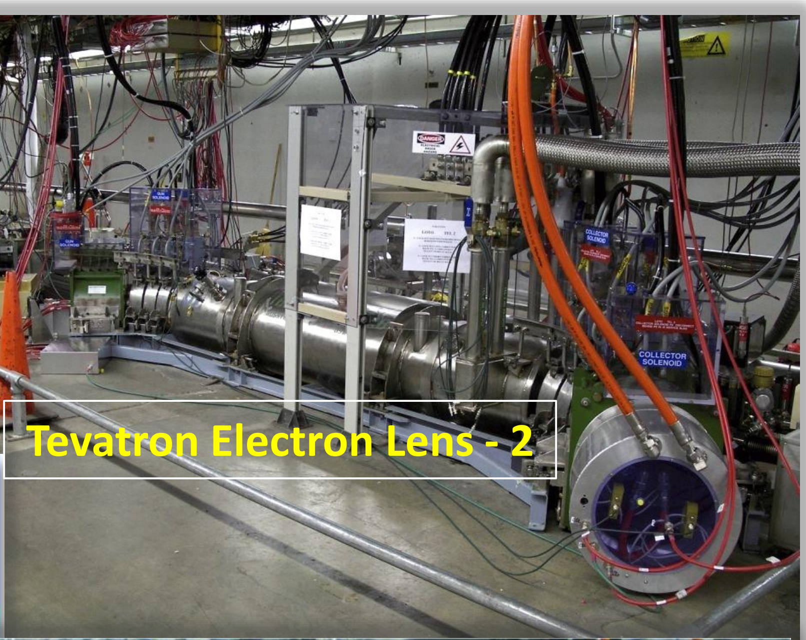
Electron Lenses: Tevatron, RHIC, LHC, FCC

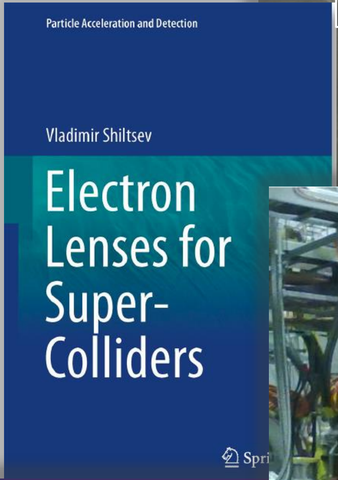
- Proposed HOBBC-1993, LRBBC-97
- TEL-1 and TEL-2 : 2001, 2004
- RHIC electron lenses : 2014
- *Springer* Book : 2016
- LHC electron lenses : ~2021 (?)
- FCC e-lenses: ~2035 (??)

Uniquely effective for:

- Beam-beam compensation
- Halo collimation
- Space-charge compensation

-now in textbooks

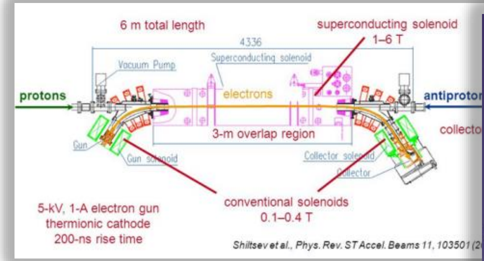

Tevatron Electron Lens - 2


Particle Acceleration and Detection

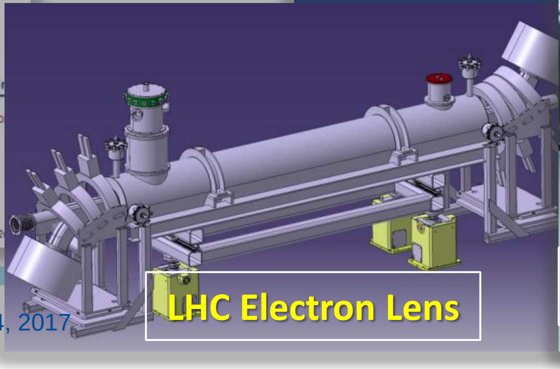
Vladimir Shiltsev

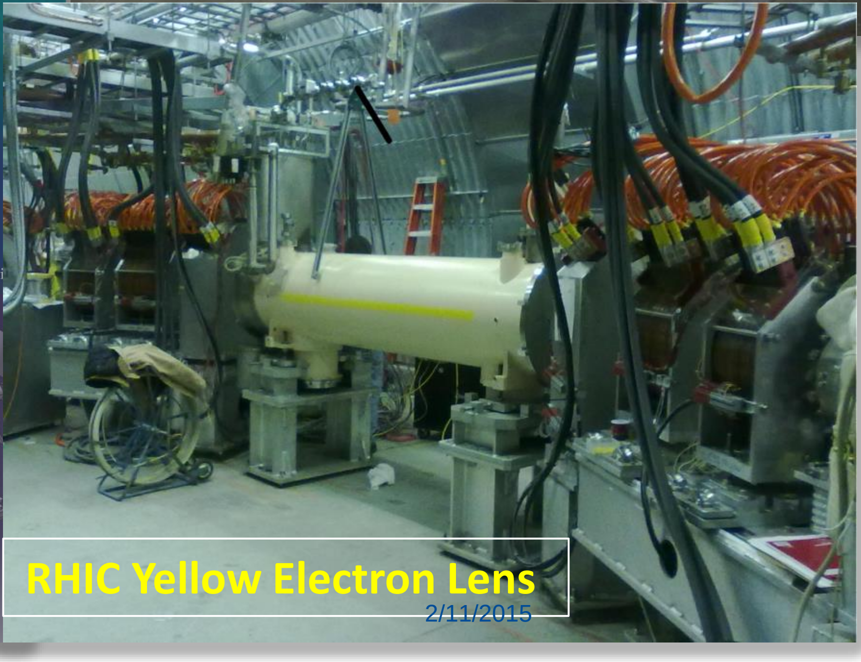
Electron Lenses for Super-Colliders

Spri



Shiltsev et al., Phys. Rev. ST Accel. Beams 11, 103501 (2


LHC Electron Lens

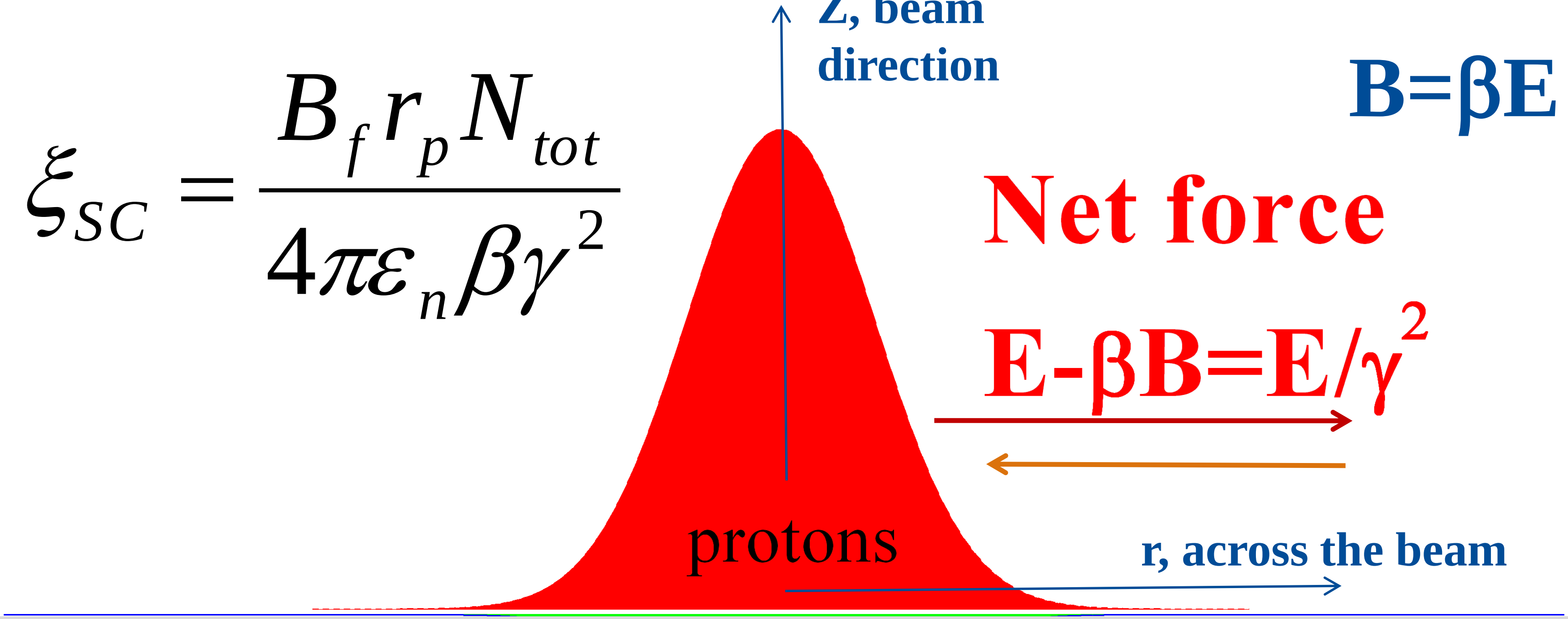

RHIC Yellow Electron Lens

Today: New Uses of Electron Lenses

- Electron lenses for Space-Charge Compensation
- Electron lenses for Integrable Optics
- Electron lenses for Landau damping

Part 1: Space Charge Compensation

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



B=βE

Net force

$E-\beta B=E/\gamma^2$

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

SCC with electron lenses

- Instead of uniformly distributing electrons around the ring with low concentration :

$$\eta = \frac{n_e}{n_p} = \frac{1}{\gamma^2}$$

- Electron columns will generate HIGH concentration of electrons but over a small fraction of ring circumference:

$$f = \frac{N_{EC} L_{EC}}{C} = \frac{\eta}{\gamma^2}$$

First Example: SCC in 8 GeV Booster

Fermilab

2000

FERMILAB-TM-2125 September 2000

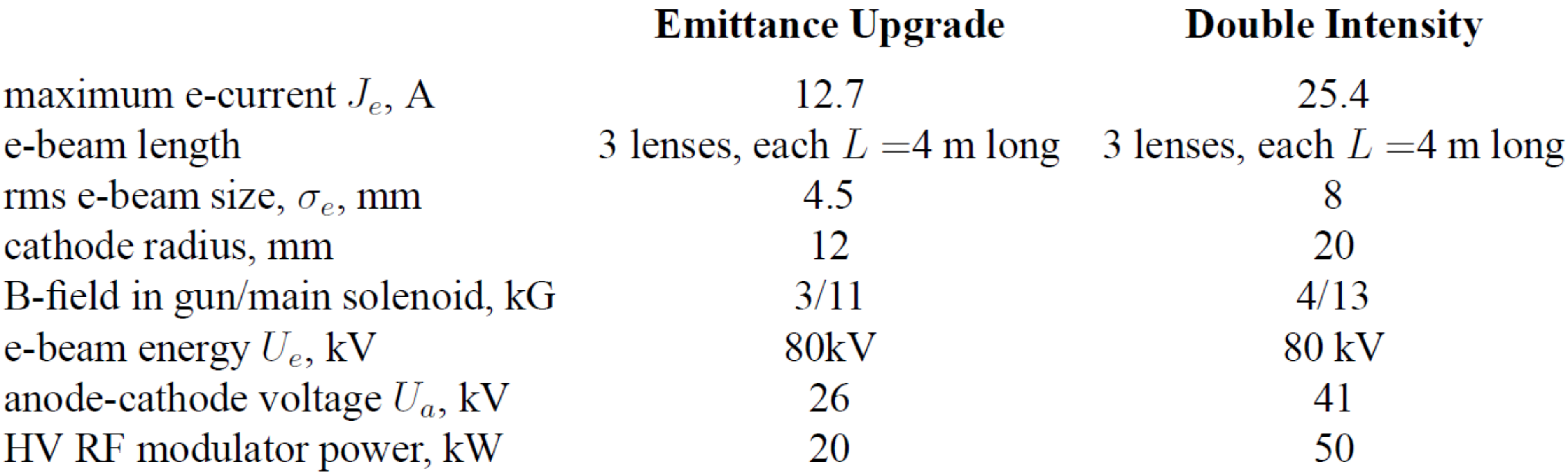
Space-Charge Compensation in High-Intensity Proton Rings

A.V. Burov, G.W. Foster, V.D. Shiltsev

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510

$$J_e = J_p B_f \frac{C}{L} \frac{\beta_e}{\gamma_p^2 \beta_p^2 (1 - \beta_e \beta_p)},$$



	Emittance Upgrade	**Double Intensity**
maximum e-current J_e, A	12.7	25.4
e-beam length	3 lenses, each L =4 m long	3 lenses, each L =4 m long
rms e-beam size, σ_e, mm	4.5	8
cathode radius, mm	12	20
B-field in gun/main solenoid, kG	3/11	4/13
e-beam energy U_e, kV	80kV	80 kV
anode-cathode voltage U_a, kV	26	41
HV RF modulator power, kW	20	50

- To study: coherent modes and emittance growth

Simulations : FNAL Booster (Yu.Alexahin & V.Kapin, 2007)

Booster:

400 MeV, 474 m

P=24

N_p~4.5e12

dQ_sc=-0.3

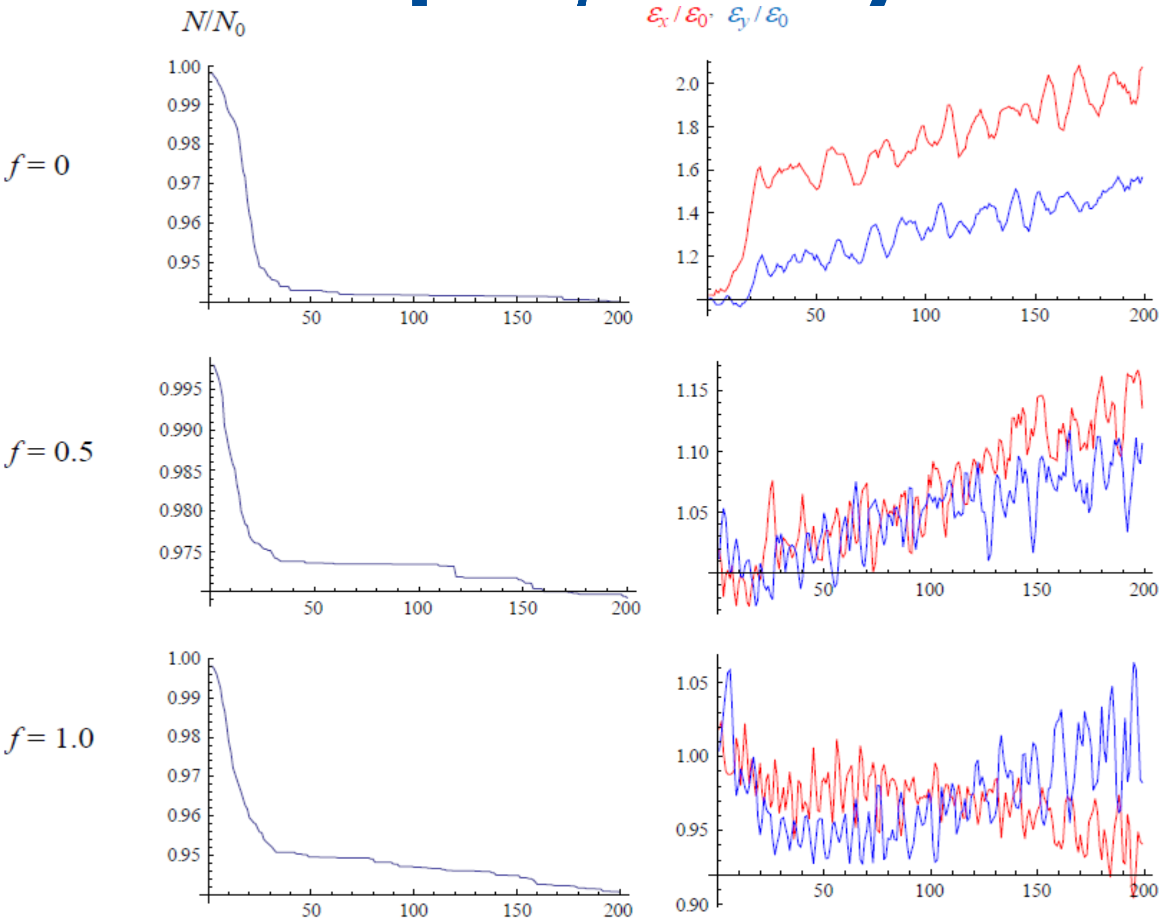


Figure 2. Normalized beam intensity and emittances vs turn number at $N_b = 6\cdot10^{10}$, $n_{columns}$=24 and indicated values of the compensation factor f.

- "space charge compensation with e-lenses works"
- More compensators the better (24→12→3 minimum)

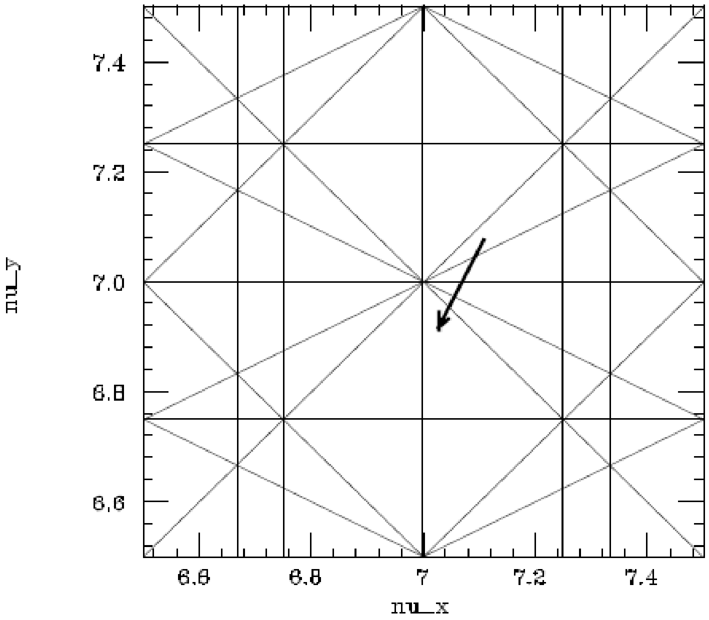
Simulations :KEK PS (S.Machida, 2001)

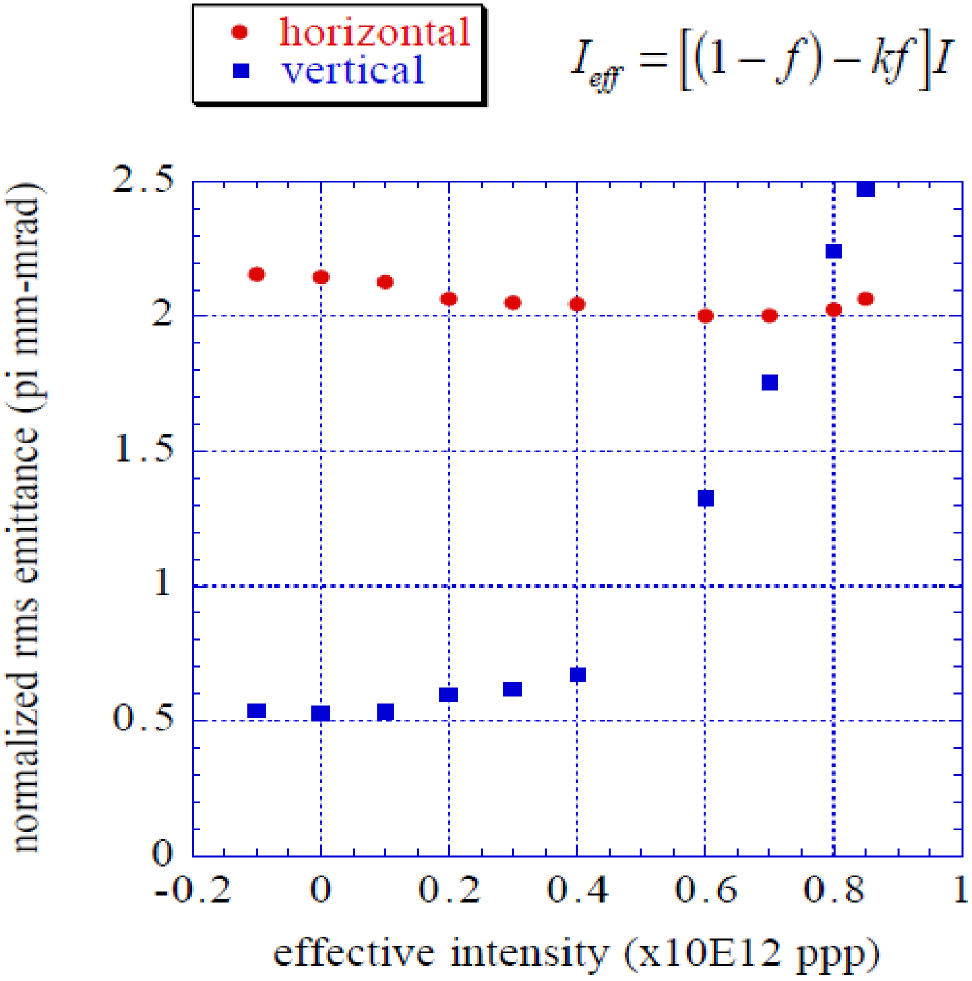
KEK PS:

500 MeV, 340 m

N_p~1e12

dQ_sc=-0.2

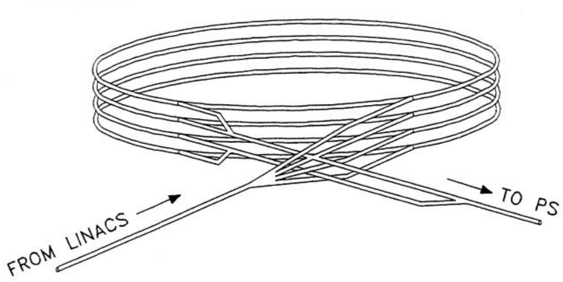




$$I_{eff} = [(1-f) - kf]I$$

- “space charge compensation with e-lenses works”
  - +0.1-0.2 sigma e-p displacement tolerable

Simulations: CERN PS-B (M.Aiba,2007)



PS Booster:

50 MeV, 157 m

P=16

dQ_sc ~ -0.5

Need to increasee for LHC ultimate intensity →

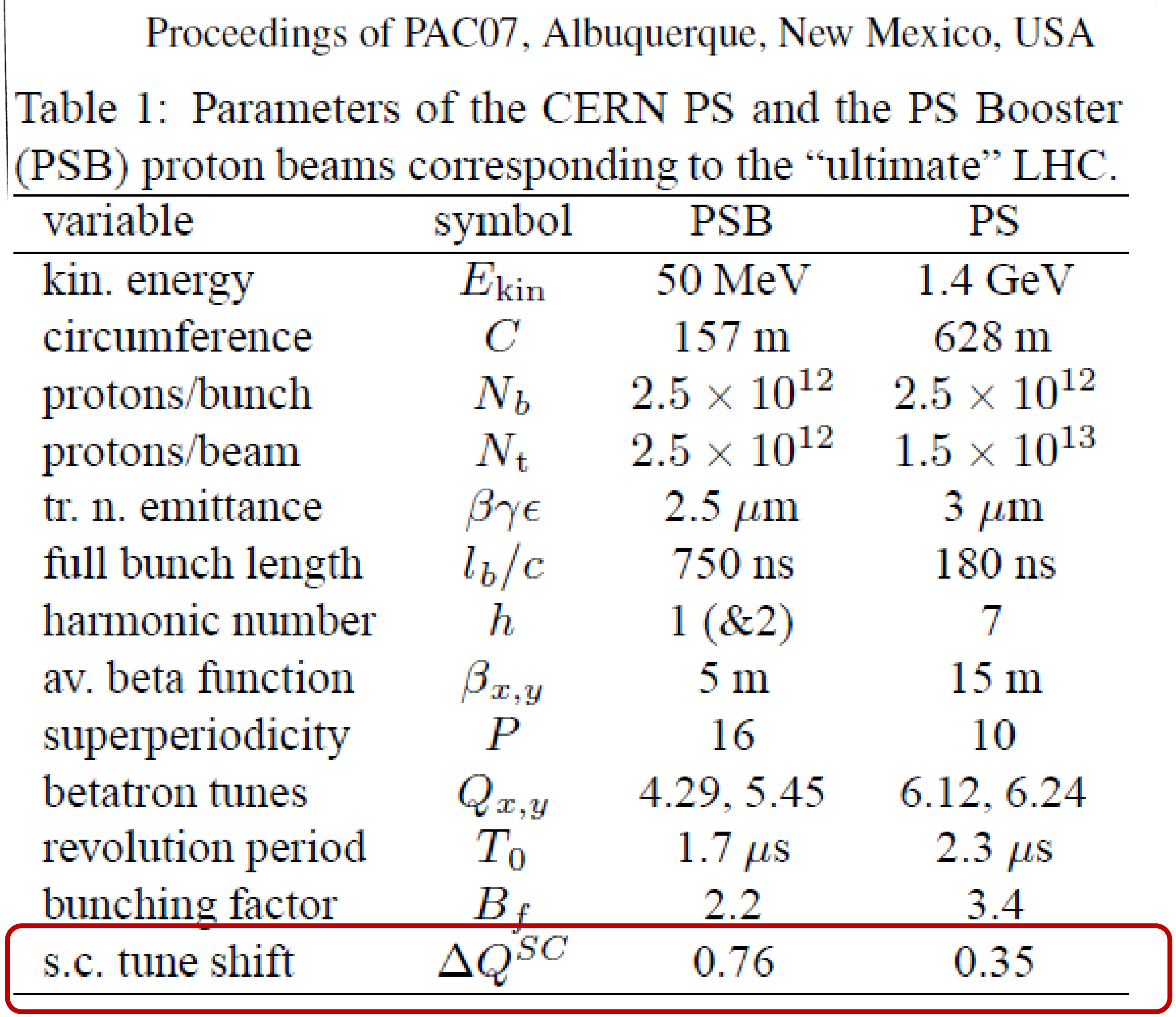
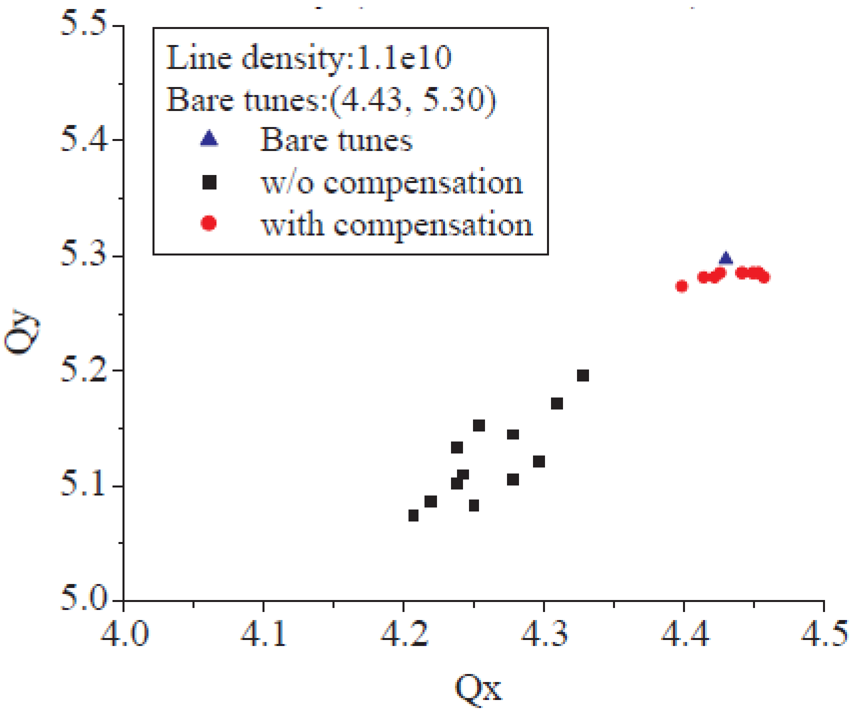

Proceedings of PAC07, Albuquerque, New Mexico, USA

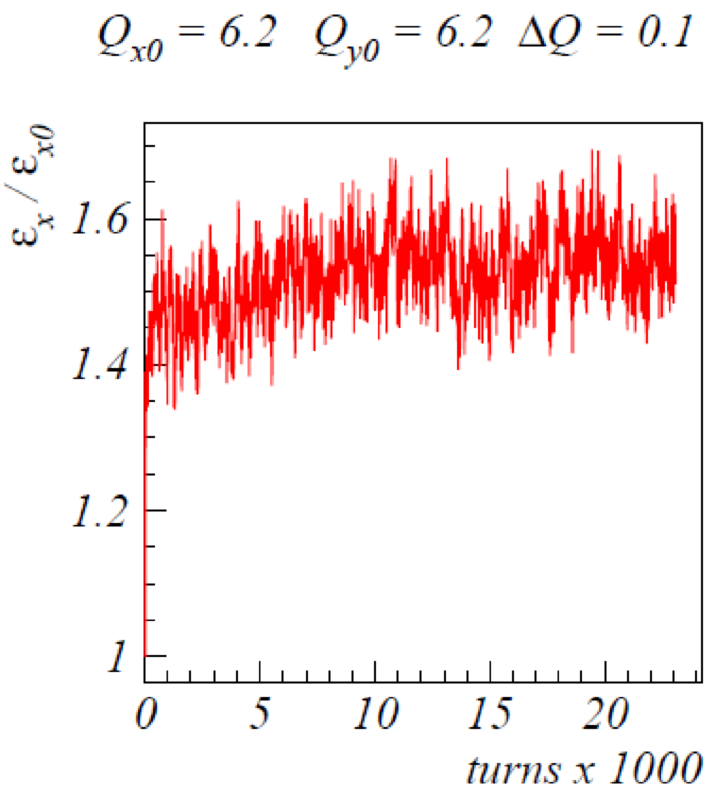
Table 1: Parameters of the CERN PS and the PS Booster (PSB) proton beams corresponding to the "ultimate" LHC.

variable	symbol	PSB	PS
kin. energy	E_{kin}	50 MeV	1.4 GeV
circumference	C	157 m	628 m
protons/bunch	N_b	2.5×10^{12}	2.5×10^{12}
protons/beam	N_t	2.5×10^{12}	1.5×10^{13}
tr. n. emittance	$\beta\gamma\epsilon$	2.5 μm	3 μm
full bunch length	l_b/c	750 ns	180 ns
harmonic number	h	1 (&2)	7
av. beta function	$\beta_{x,y}$	5 m	15 m
superperiodicity	P	16	10
betatron tunes	$Q_{x,y}$	4.29, 5.45	6.12, 6.24
revolution period	T_0	1.7 μs	2.3 μs
bunching factor	B_f	2.2	3.4
s.c. tune shift	ΔQ^{SC}	0.76	0.35

Simulations: CERN PS-B (M.Aiba,2007)

moderate beam intensity (~1/2 the nominal)





- “space charge compensation with e-lenses works in principle… desrves further studies”
  - No evidence for coherent modes limitation in PSB and PS
    - Concern of overcompensation in the head and tail
    - More compensators the better (8 is better than 4)

Issues to Explore in Theory & Experiment

1. Stability of the system (transverse motion)
2. (Dynamic) matching of transverse p-charge distribution
3. Appropriate longitudinal compensation (for not-flat proton bunches)
4. Electron lenses vs electron columns
5. Practical implementation (in existing facilities)

= the Need of Experimental Study at a dedicated facility

→ ***IOTA ring*** (see slides later)

Part 2 : Electron Lenses for Integrable Optics

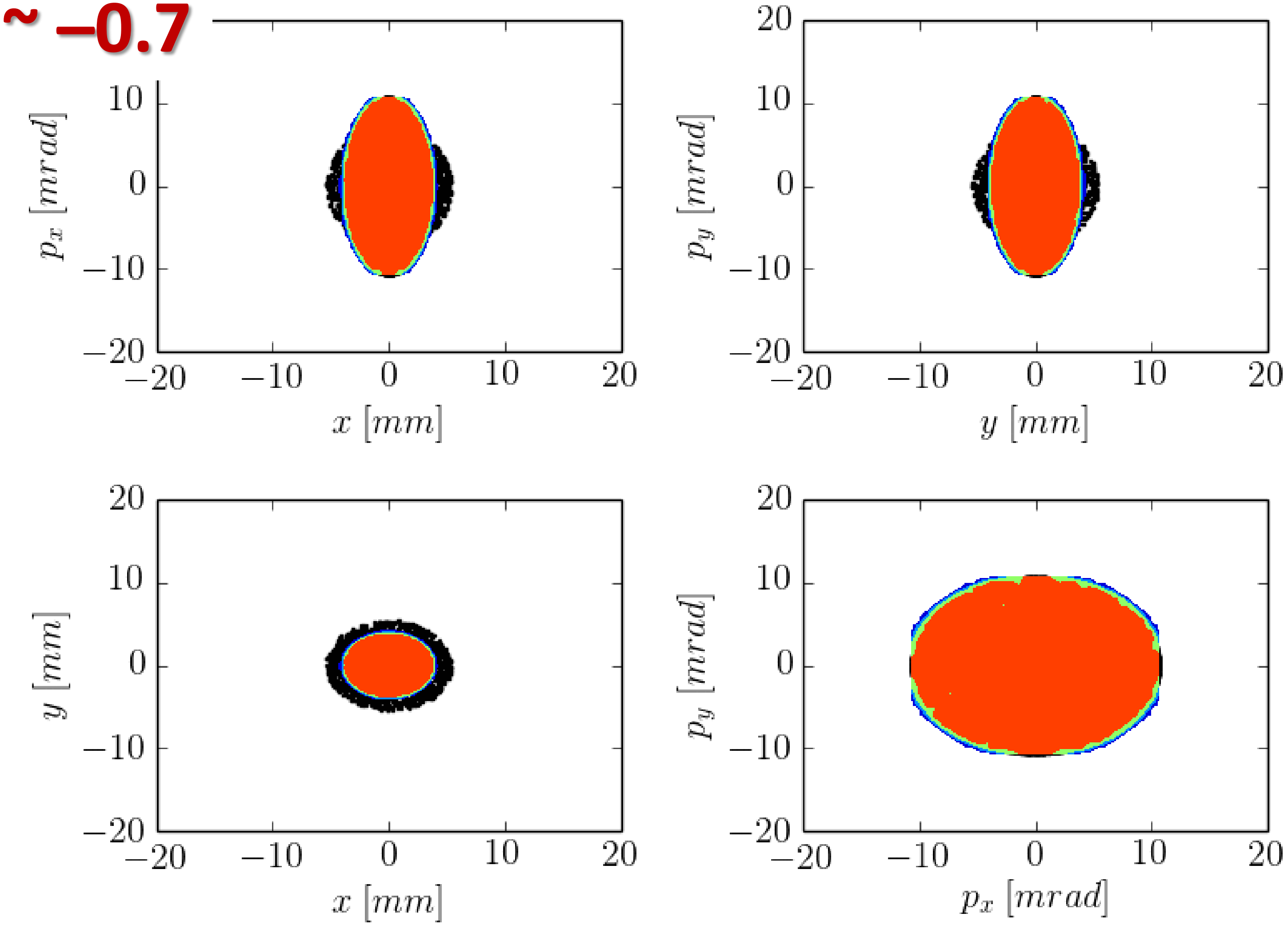
(Danilov, Shiltsev 1997, Danilov,Nagaitsev 2010)

- Employment of special nonlinear fields to stabilize particle’s motion:
  - Make motion limited and long-term stable (usually involves additional “integrals of motion”)
  - Can be Laplacian (with magnets, no extra charge density involved)
  - Or non-Laplacian (with externally created charge – e.g. special electron lens with ***E(r) ~r / (1+r^2)***
  - (That’s what IOTA is for – test with electrons)
  - Should be directly applicable to protons with SC

Space Charge in Linear Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: quickly drives test-particles into the halo

$\Delta Q_{sc} \sim -0.7$

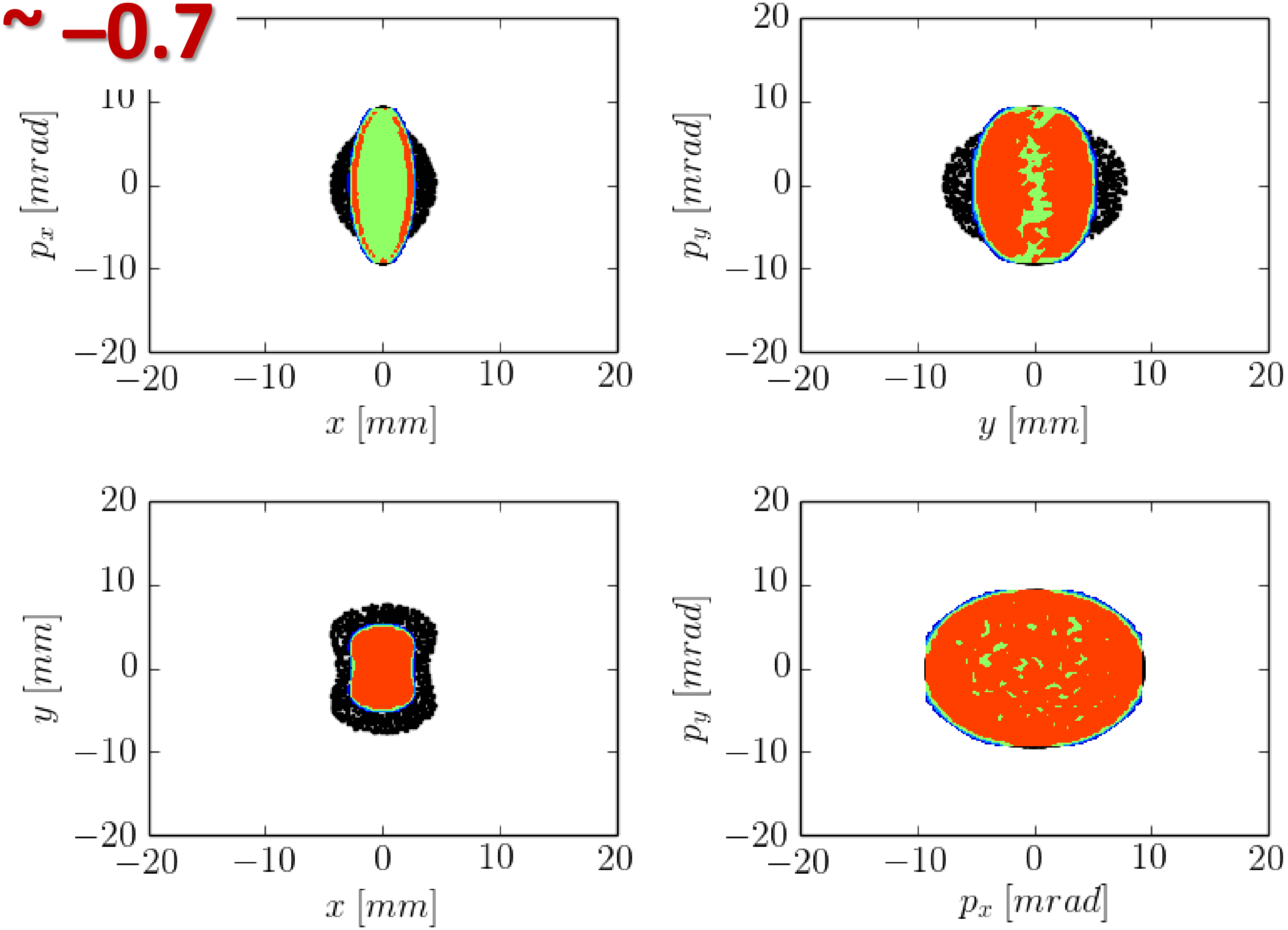


Tech-X, RadiaSoft simulation

Space Charge in NL Integrable Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: nonlinear decoherence suppresses halo

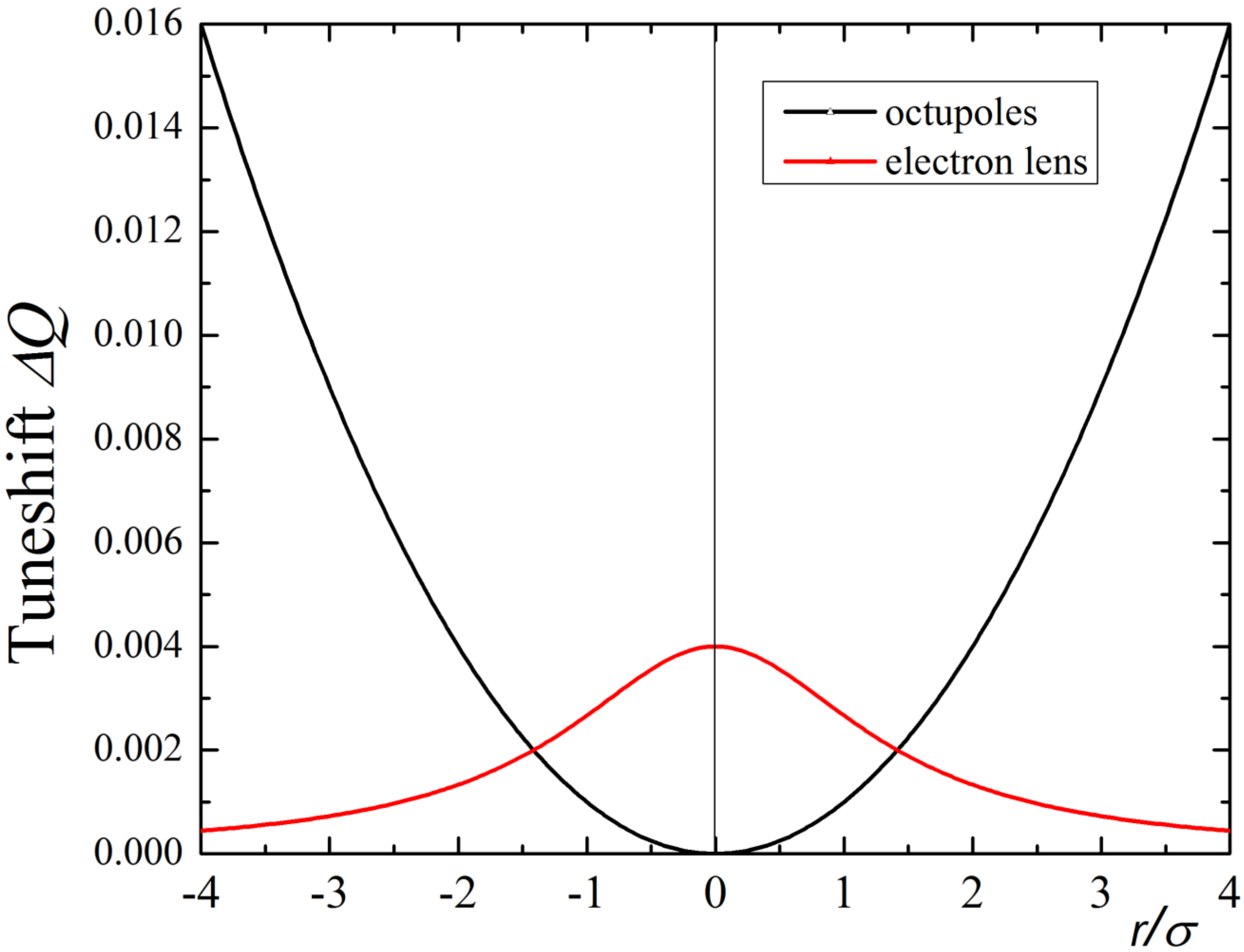
$\Delta Q_{sc} \sim -0.7$



Tech-X, RadiaSoft simulation

Part 3: Landau damping by e-lens

- E-lens effectively generates the tunespread needed for Landau damping of coherent beam instabilities
- Contrary to octupoles, e-lens does that without affecting the dynamic aperture (no impact on large *A* particles)



Analysis of the Stability Diagram with e-lens

Stability diagram (SD) is defined as a map of real axes n on the complex plane D :

$$\mathrm{D} = \left(-\int \frac{J_x \partial F / \partial J_x}{n - lQ_s - \mathrm{D}Q_x(J_x, J_y) + io} d\mathrm{G} \right)^{-1}$$

$$\mathrm{D} = \Omega_c - l\bar{\omega}_s$$

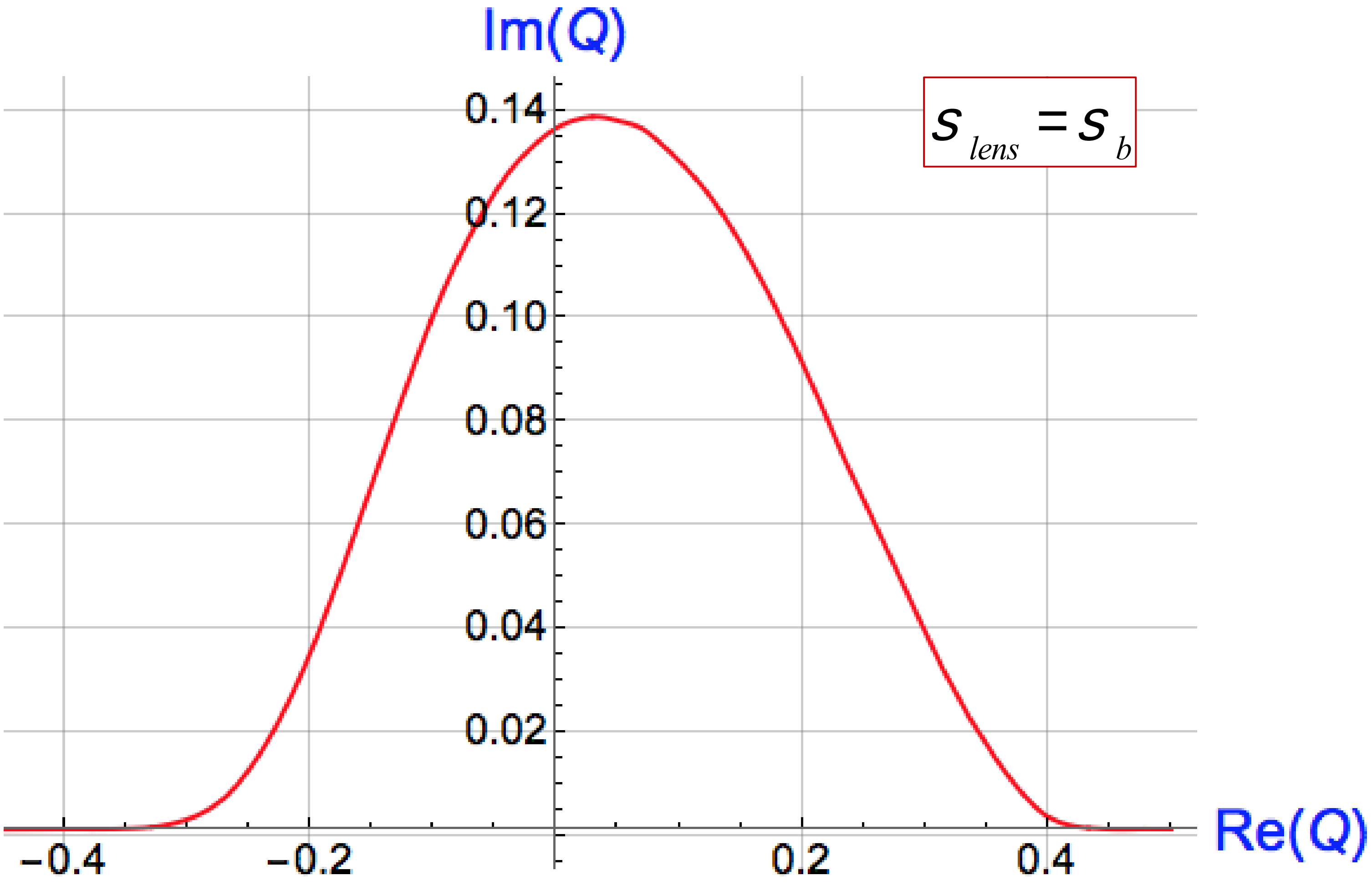
To be stable, the coherent tune shift has to be below the SD.

For Gaussian E-Lens, the tune shifts (G. Lopez, 1993)

$$\Delta Q_x(J_x, J_y) = \Delta Q_{\mathrm{sc}}(0) \int_0^1 \frac{[I_0(\frac{J_x z}{2}) - I_1(\frac{J_x z}{2})] I_0(\frac{J_y z}{2})}{\exp[z(J_x + J_y)/2]} dz.$$

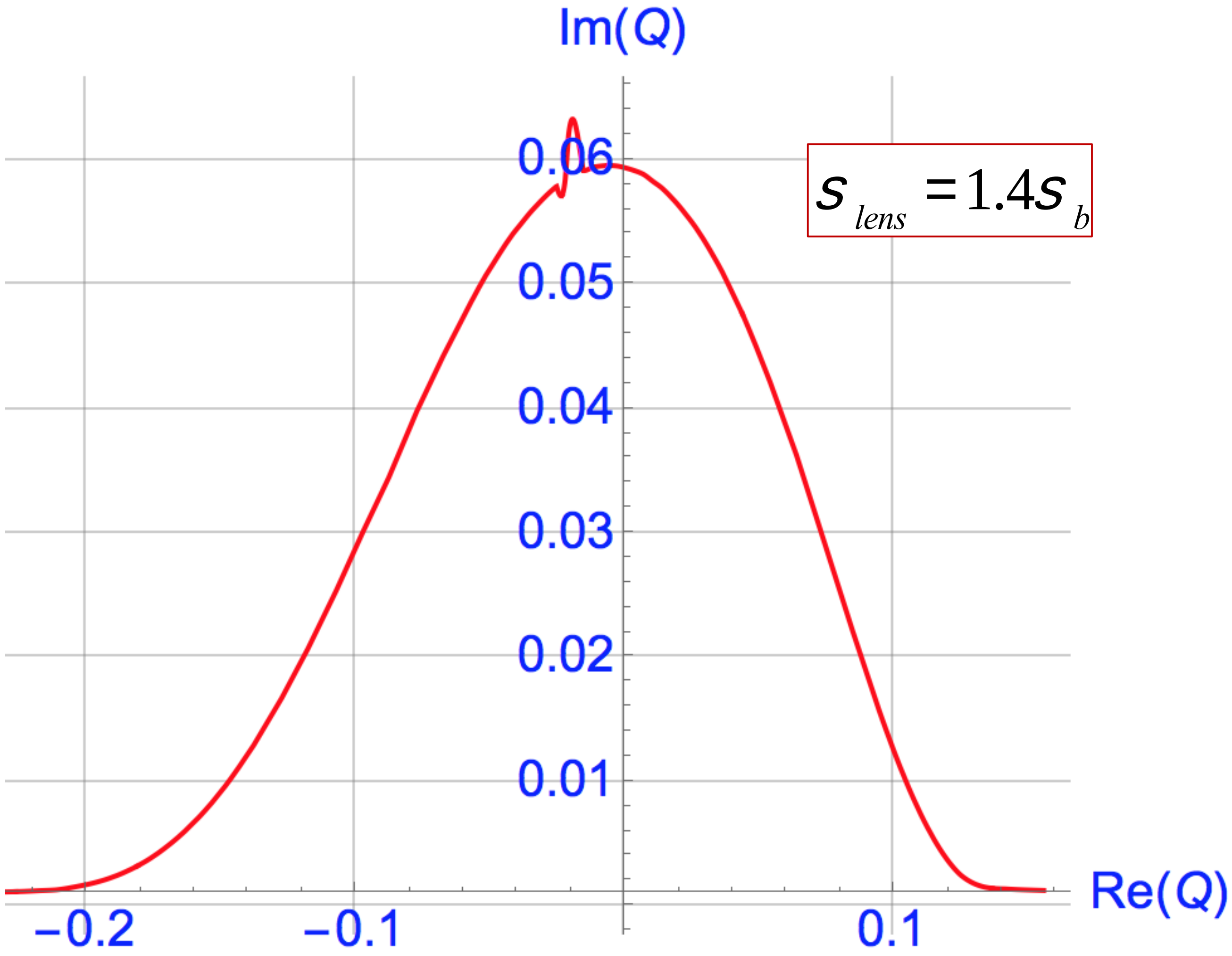
$$J_{x,y} = a_{x,y}^2 / (2s^2)$$

Both beams are round Gaussian, same rms sizes



Stability diagram in the units of the maximal tune shift

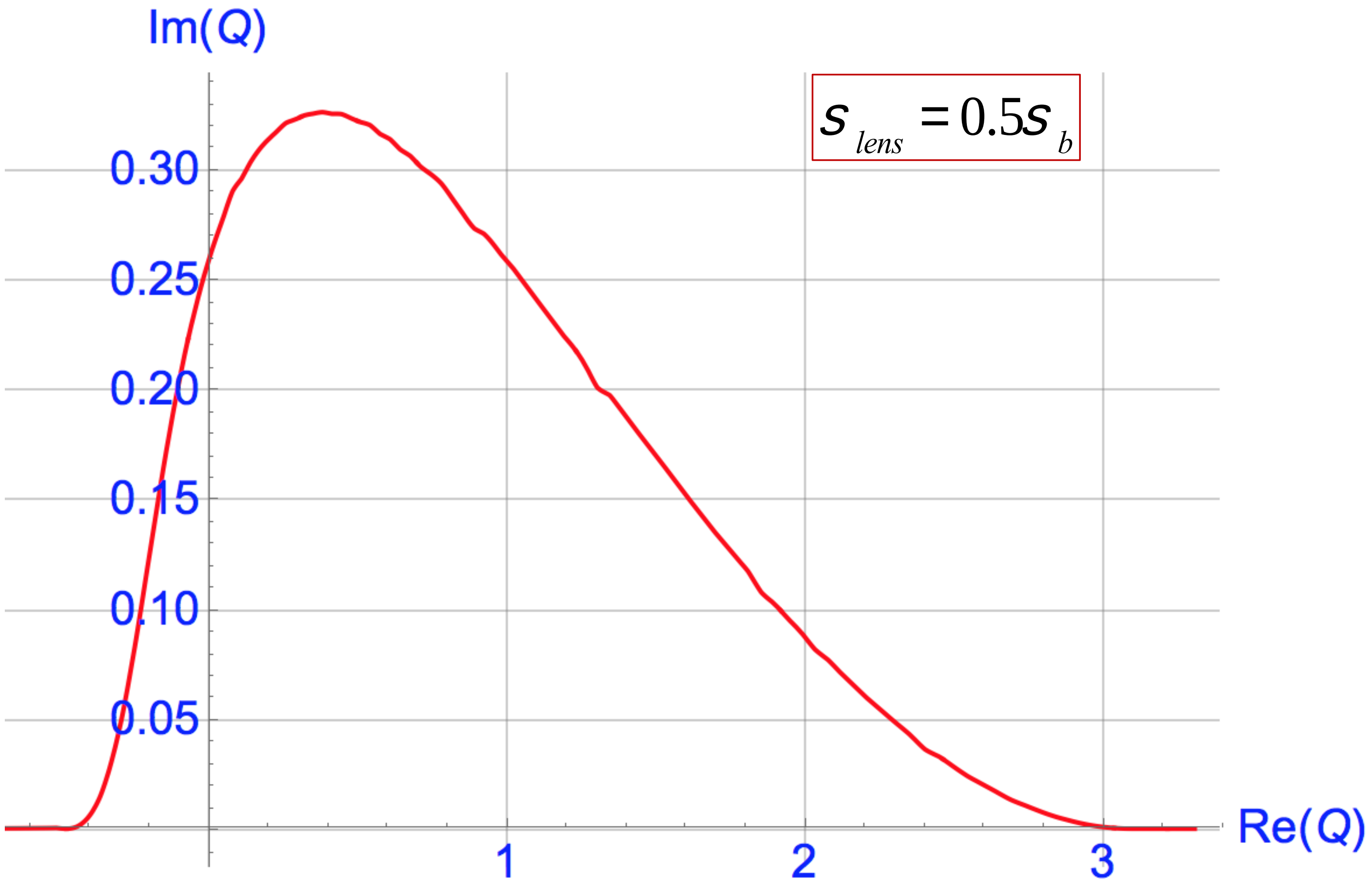
Both beams are round Gaussian, unequal sizes



$s_{lens} = 1.4 s_b$

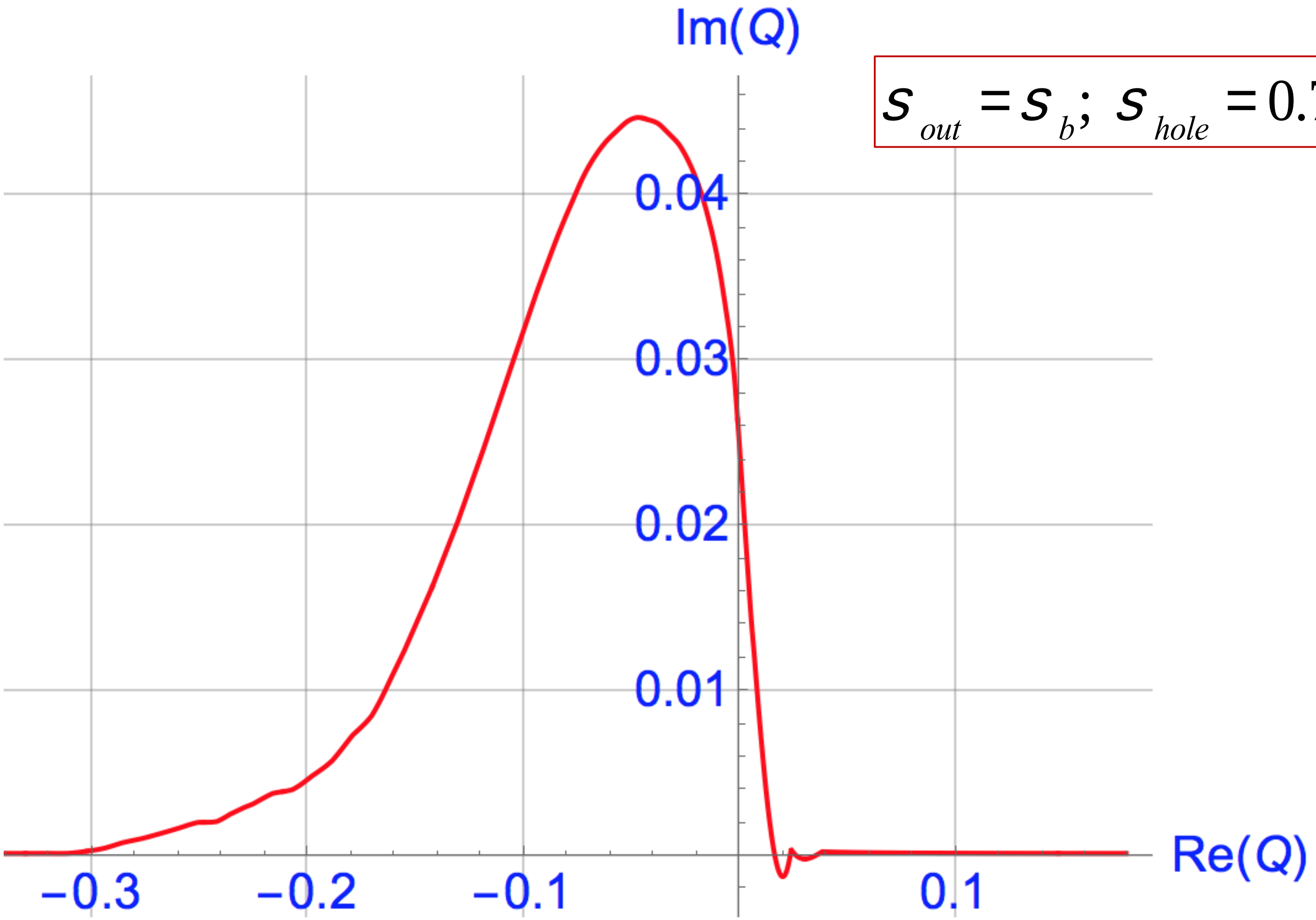
Stability diagram in the units of the maximal tune shift

Both beams are round Gaussian, unequal sizes



Same total current as before,

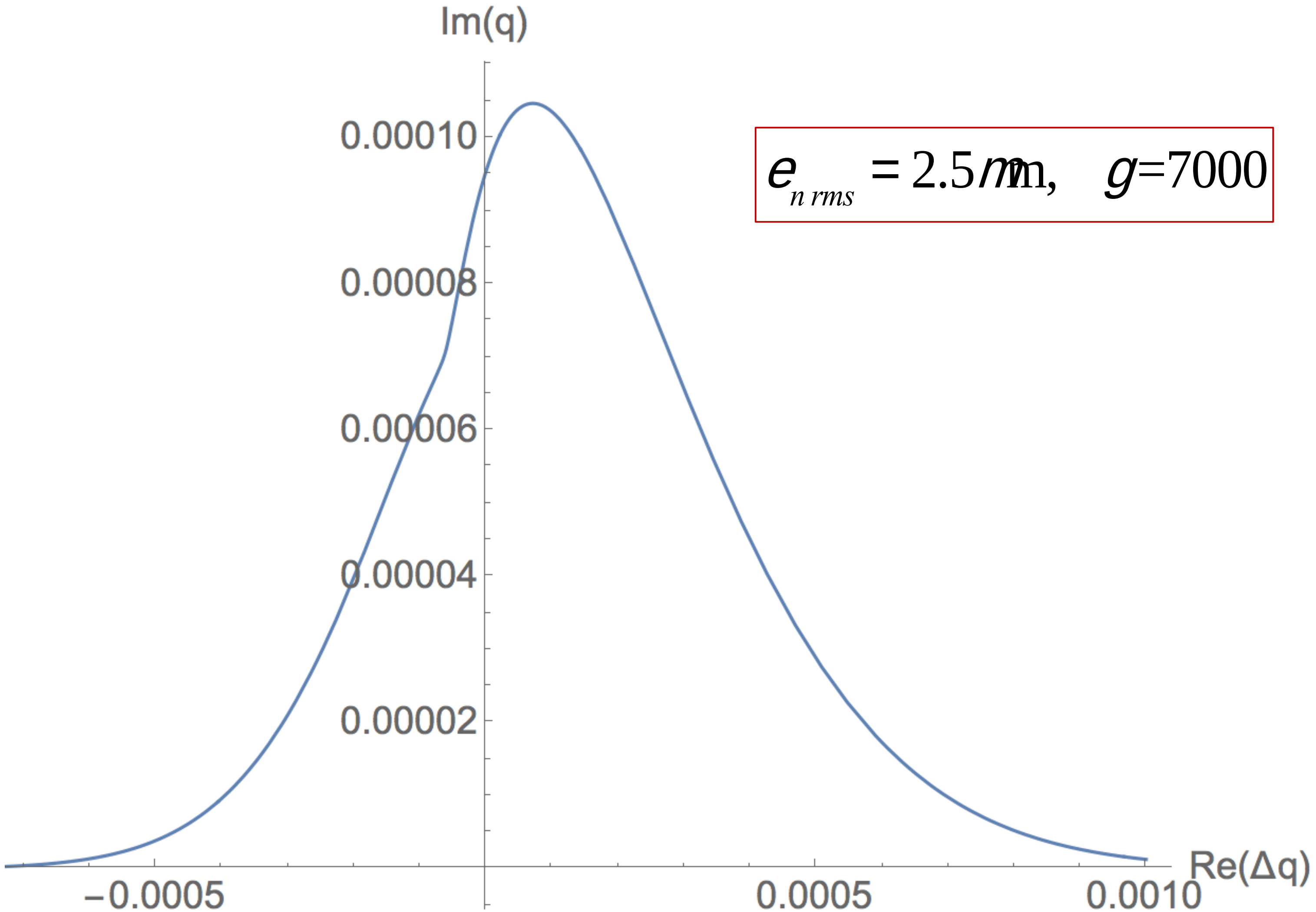
Another degree of flexibility: hollow e-lens



$s_{out} = s_b; \; s_{hole} = 0.7 s_b$

Hollow e-lens, same total current,

Compare SD for LHC octupoles, +500A



$e_{n\,rms} = 2.5\,m\mathrm{m}, \quad g=7000$

AB

What e-lens could do for, e.g., LHC?

Let us assume the following e-lens parameters (very modest):

Beta_x,y	**1 km**
sigma_e/sigma_p	1
sigma_e	0.6 mm
sigma_cath	3 mm
j_max	2 A/cm^2
I_e	1.1 A
L_e	3 m
E_e	20 KeV

This rather moderate set of parameters corresponds to dQ_max=0.015, yielding 10-20 times larger SD than the Landau octupoles at 500 A.

AB

That brings us to….

IOTA

Integrable Optics Test Accelerator

(the ring with 70 MeV/c p+ injector)

at FAST

Fermilab Accelerator Science & Technology facility

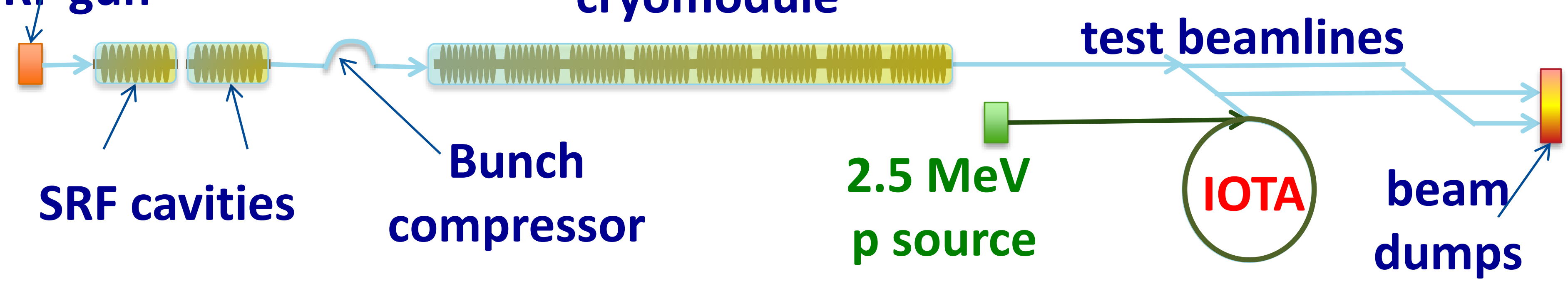
50 MeV e- photoinjector and 250 MeV SRF Cryomodule e-linac

(e- injector to IOTA)

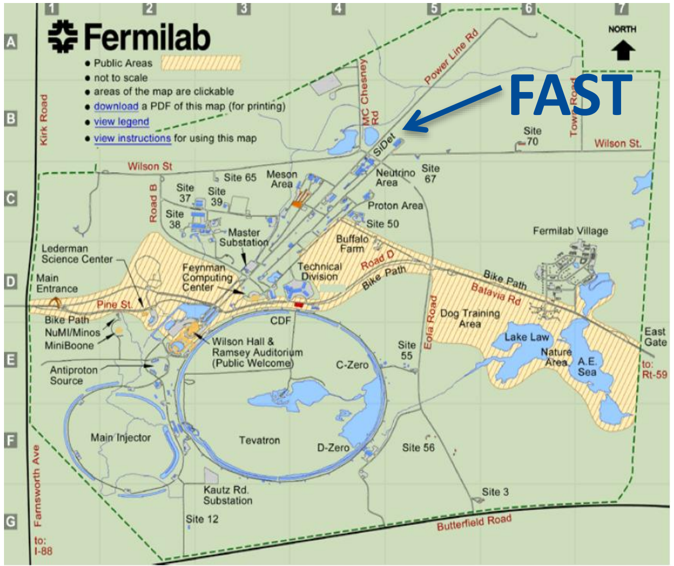
IOTA R&D complex @Fermilab


NML building

~300-MeV e- injector section



- IOTA facility complex includes:
  - IOTA (integrable-optics test accelerator) ring,
  - 150-300 MeV linear accelerator (that nominally serves as an **electron injector** to IOTA),
  - 70 MeV/c **proton source & injector** for IOTA
- Facility is located in the New Muon Lab (NML) building



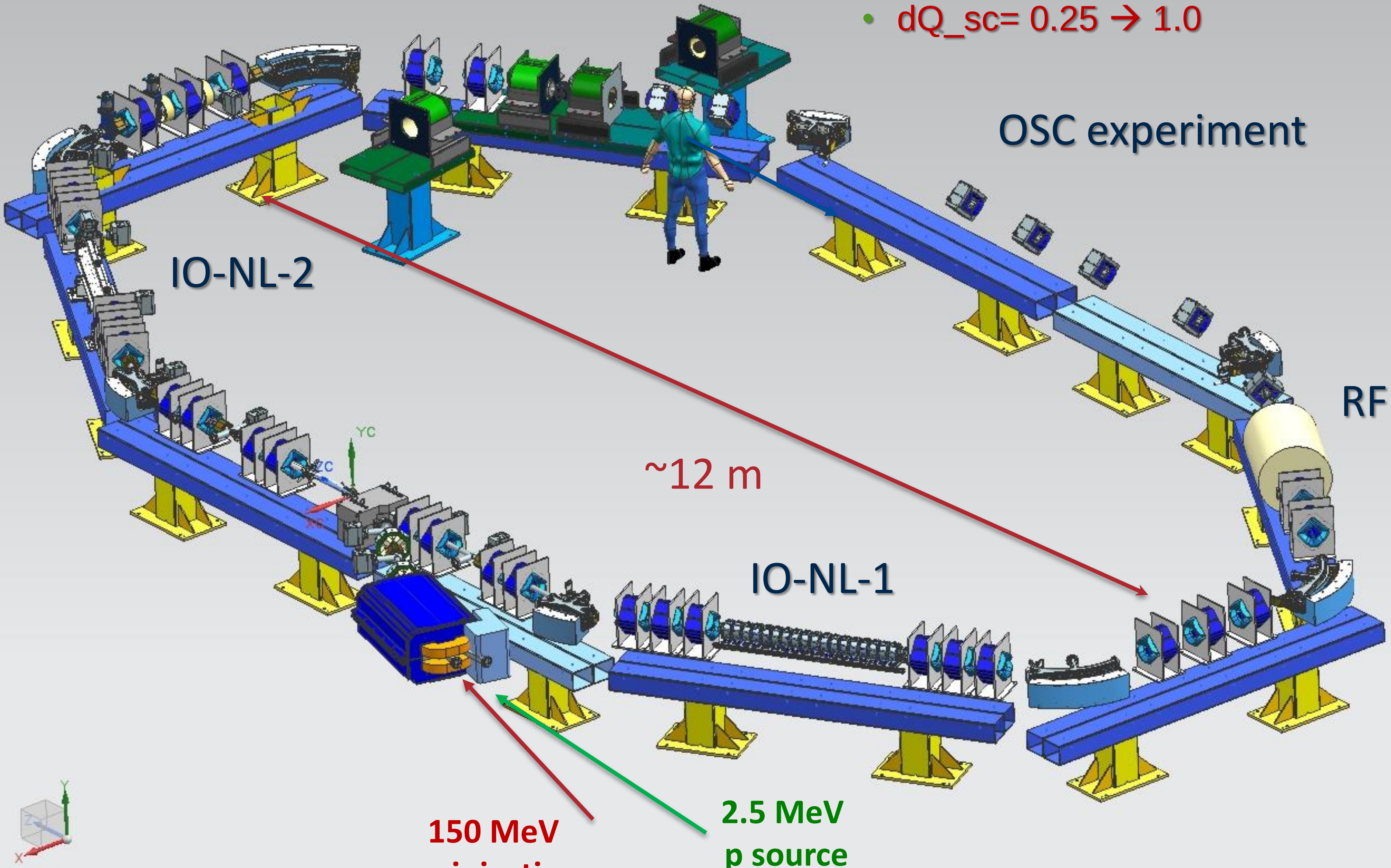
IOTA Ring Parameters

Nominal kinetic energy	e^-: 150 MeV, p+: 2.5 MeV
Nominal intensity	e^-: 1×10^9, p+: 1×10^{11}
Circumference	40 m
Bending dipole field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	0.02 ÷ 0.1
Betatron tune (integer)	3 ÷ 5
Natural chromaticity	-5 ÷ -10
Transverse emittance r.m.s.	e^-: 0.04 μm, p+: 2μm
SR damping time	0.6s (5×10^6 turns)
RF V,f,q	e^-: 1 kV, 30 MHz, 4
Synchrotron tune	e^-: 0.002 ÷ 0.005
Bunch length, momentum spread	e^-: 12 cm, 1.4×10^{-4}

IOTA Layout

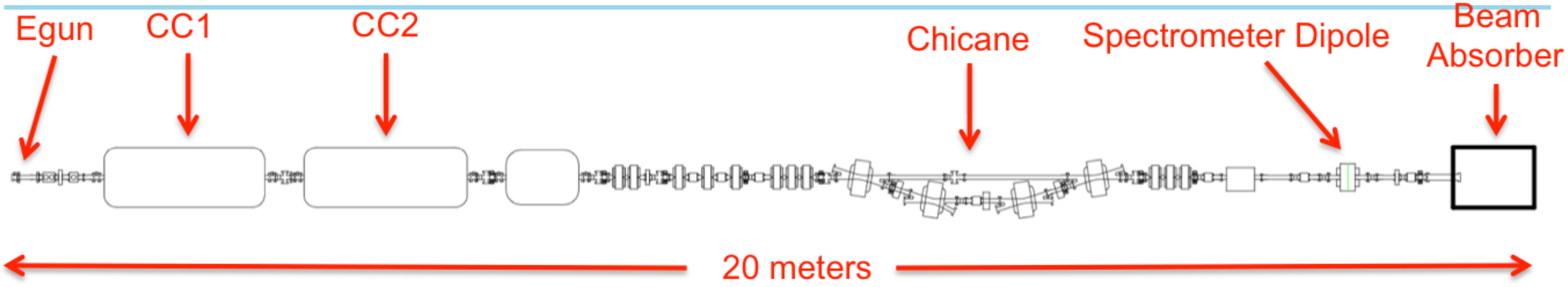
~1m electron lens

- SCC, IO, LD
- Various regimes
- dQ_sc= 0.25 → 1.0



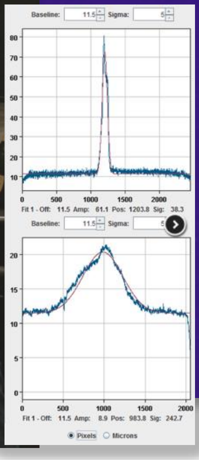
Girders aligned, RF cavity installed, magnets ready, injection magnets and cable trays installed, etc etc

May 2016 : IOTA Electron Injector 50 MeV



52.5 MeV e^- beam through FAST injector !

May 16, 2016: Beam accelerated by both Capture Cavities #1 and #2: 4.5 MeV (gun)+28MeV+20MeV



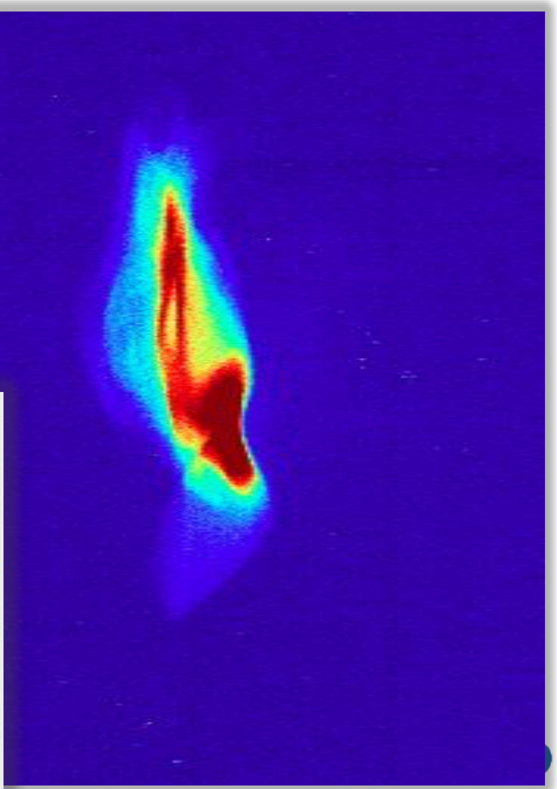
Baseline: 11.5 Sigma: 5

Fit 1 - Off: 11.5 Amp: 61.1 Pos: 1203.8 Sig: 38.3

Baseline: 11.5 Sigma: 5

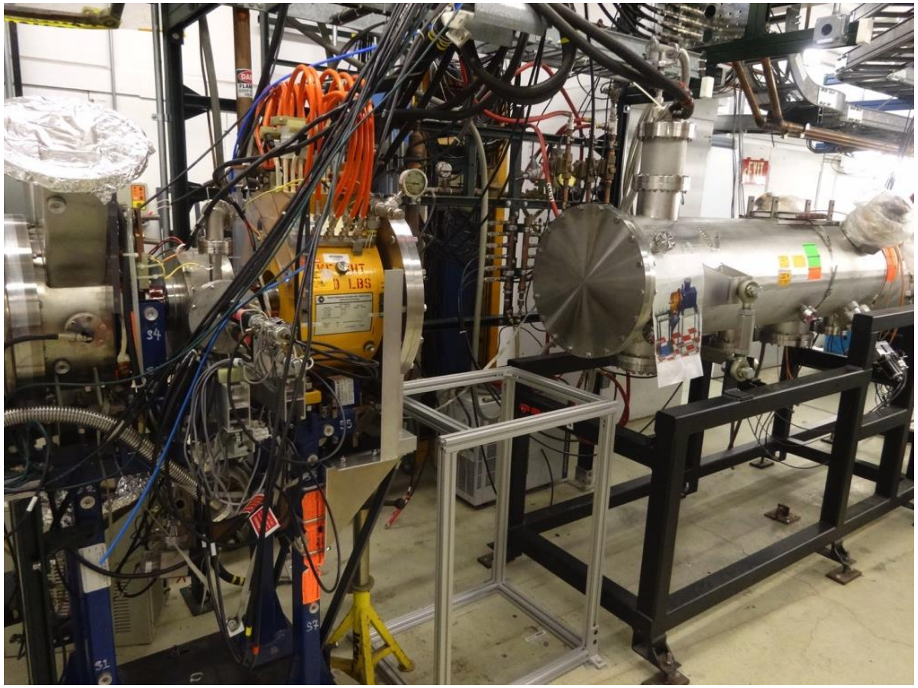
Fit 1 - Off: 11.5 Amp: 8.9 Pos: 983.8 Sig: 242.7

● Pixels ○ Microns



IOTA Proton Injector

2.5 MeV Proton RFQ re-commissioning began:



- Ion source separated from RFQ in preparation for instrumentation.
- All parts requisitioned for refurbishment
- On track to re-commission in Q3 FY2017

- Reconnected 325 MHz klystron to waveguide and coax.
- Continuing reconnection to RFQ
- On track to deliver beam in Q1 of FY2018

Summary

1. **Electron lenses is now a proven, operationally tested technology… very flexible**
2. **New applications of e-lenses** include
   - Electron lenses for space-charge compensation
   - Electron lenses for Integrable Optics
   - Electron lenses for Lanmdau damping
3. **All this concepts need thorough development** theory, modeling, prototyping, experimental beam tests (at IOTA or elsewhere)
4. **It is highly collaborative activity** – we all can participate and benefit – let’s join forces!

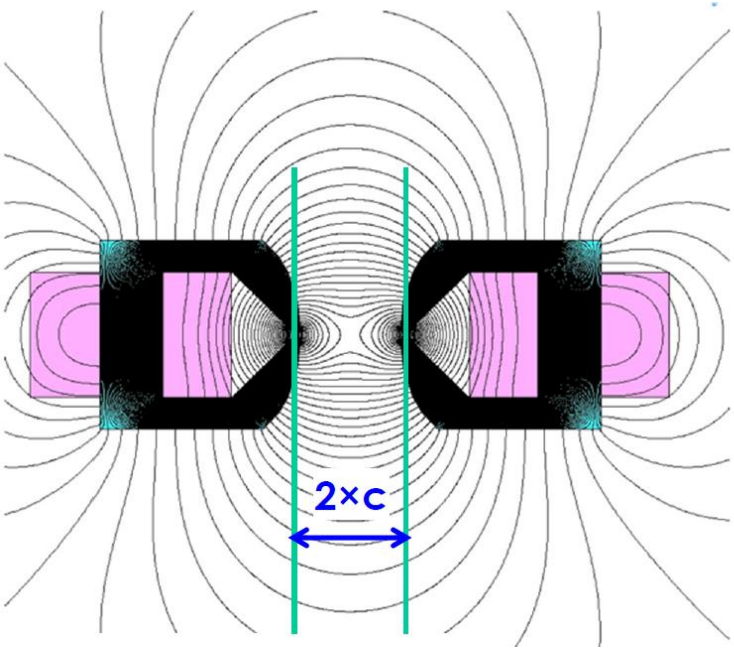
Acknowledgements

- Input from:
  - Yu. Alexahin
  - A. Burov
  - S. Nagaitsev
  - G. Stancari
  - A. Valishev

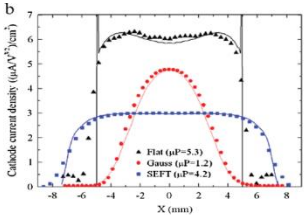
Back-Up Slides

Integrable Optics Concept

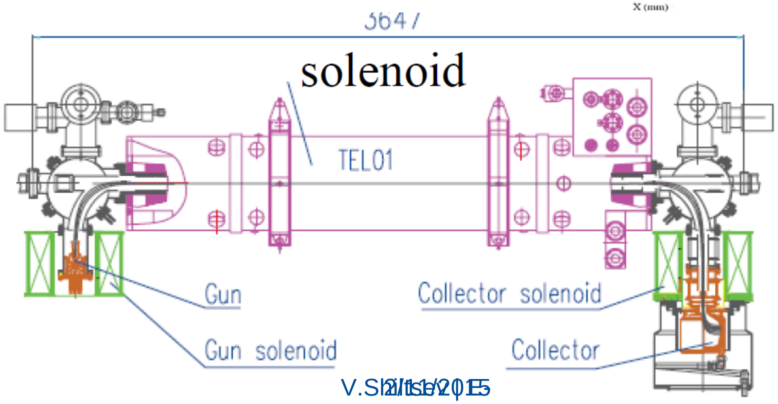
- “Integrable Optics” solutions:
  - Make motion limited and long-term stable (usually involves additional “integrals of motion”)
- Can be Laplacian (with special magnets, no extra charge density involved)



$$n(r) \propto \frac{I}{\left(ar^2+1\right)^2}$$



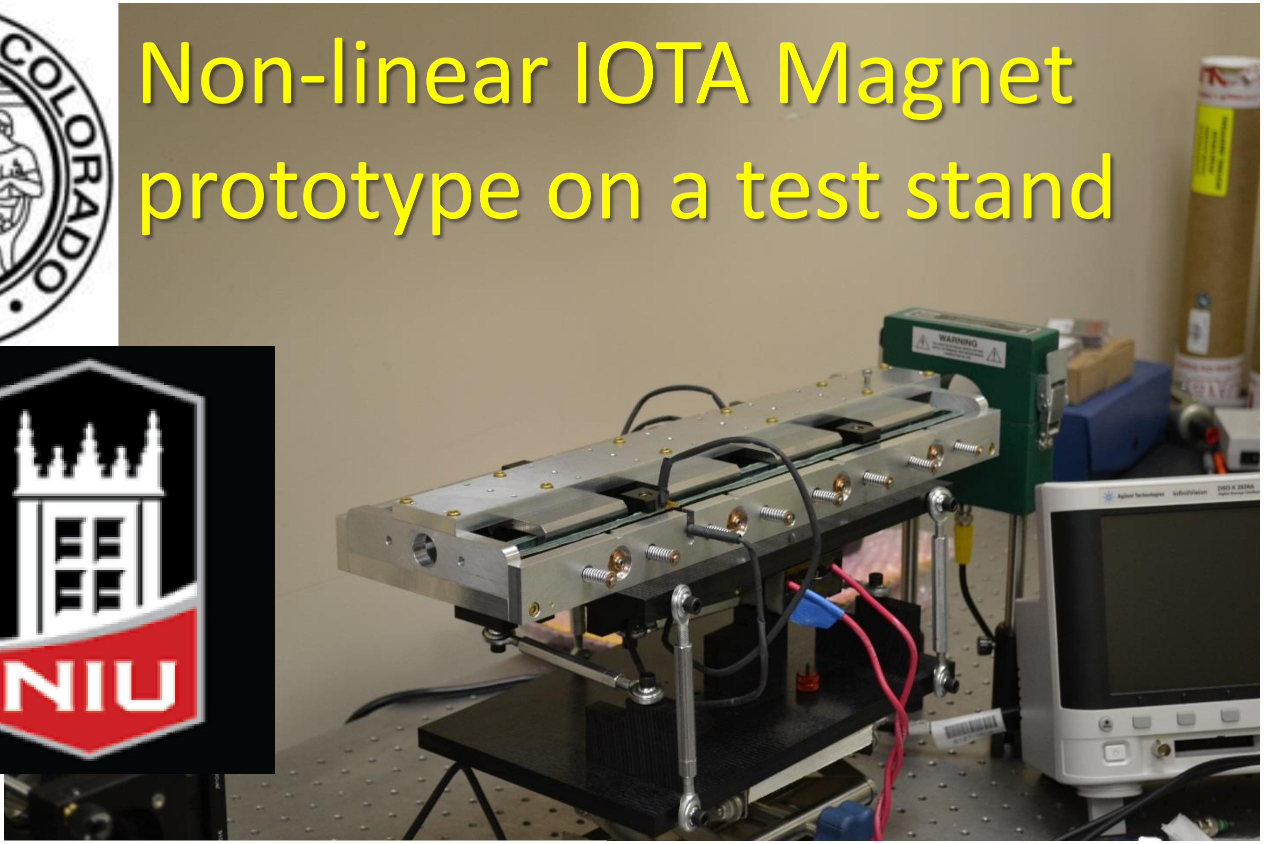
- Or *non-Laplacian* (with externally created charge by special **e-lens** *E(*
~r/(1+r^2)
- *Effect is fascinating*



IOTA Collaboration

THE UNIVERSITY OF CHICAGO

UNIVERSITY OF COLORADO 1876



Non-linear IOTA Magnet prototype on a test stand

OAK RIDGE National Laboratory

NIU

radiasoft

Fermilab

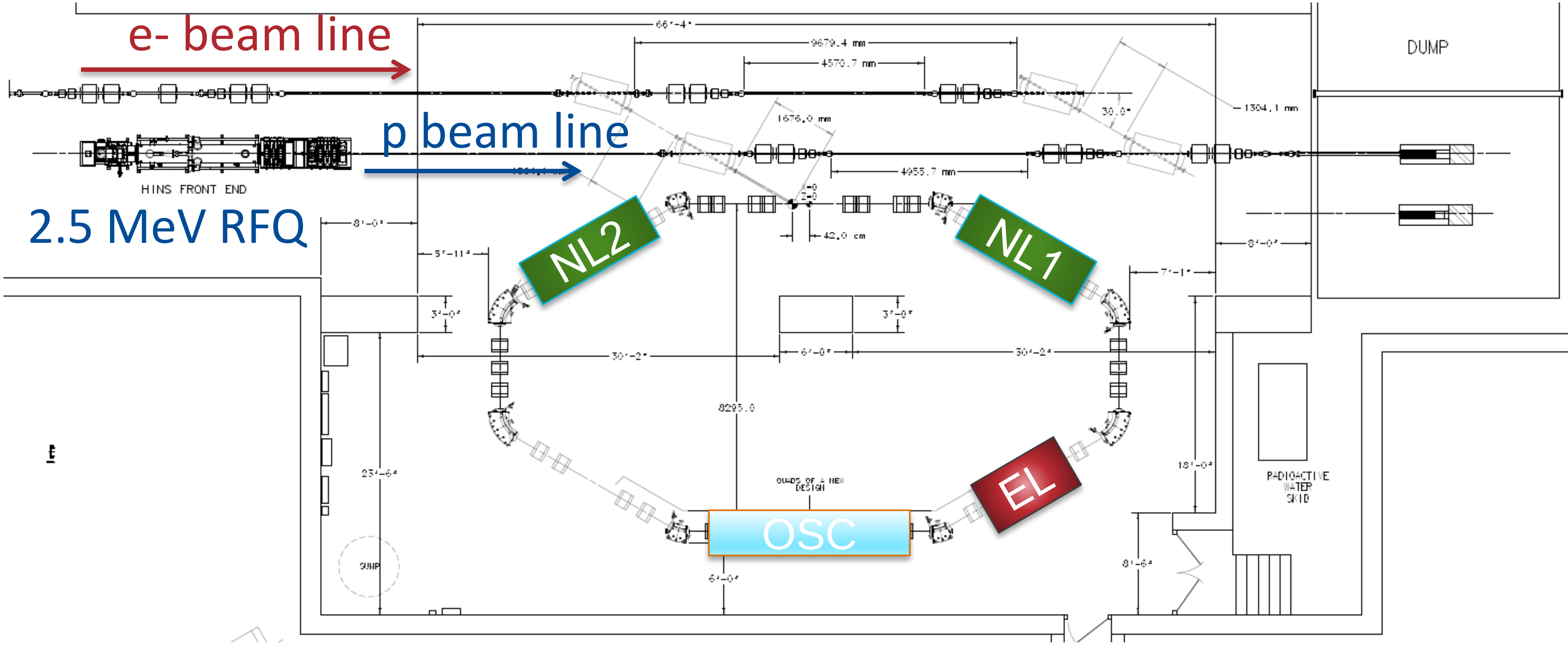
JINR

Massachusetts Institute of Technology

UNIVERSITY OF MARYLAND 1856

TECH-X

IOTA Ring: 40 m ; 2.5 MeV *p*+ or 150 MeV *e*-



Electron Charge Distribution

Similar development for RHIC-ELs

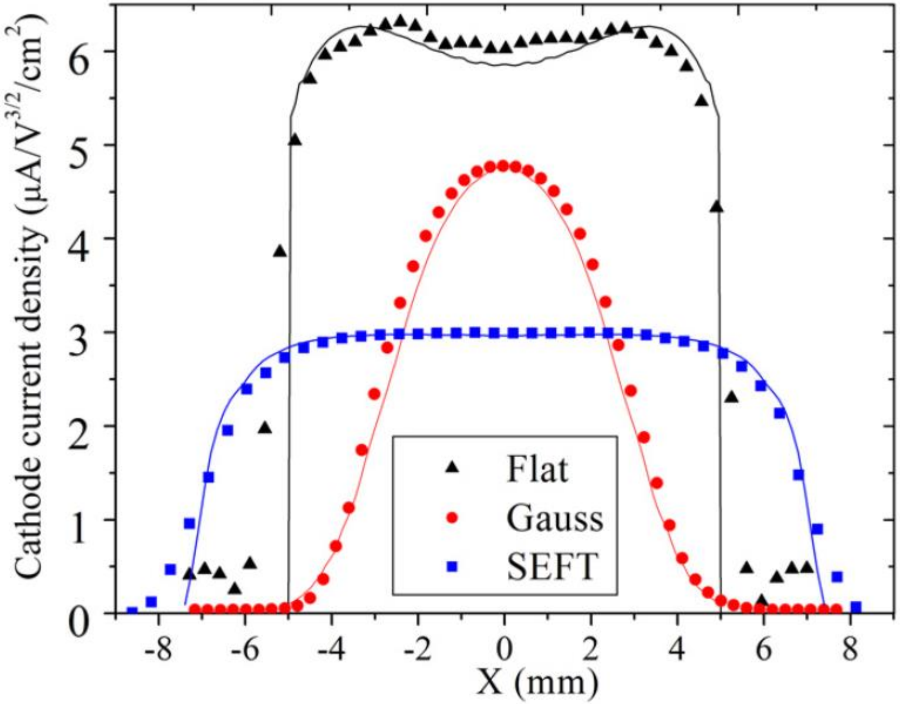
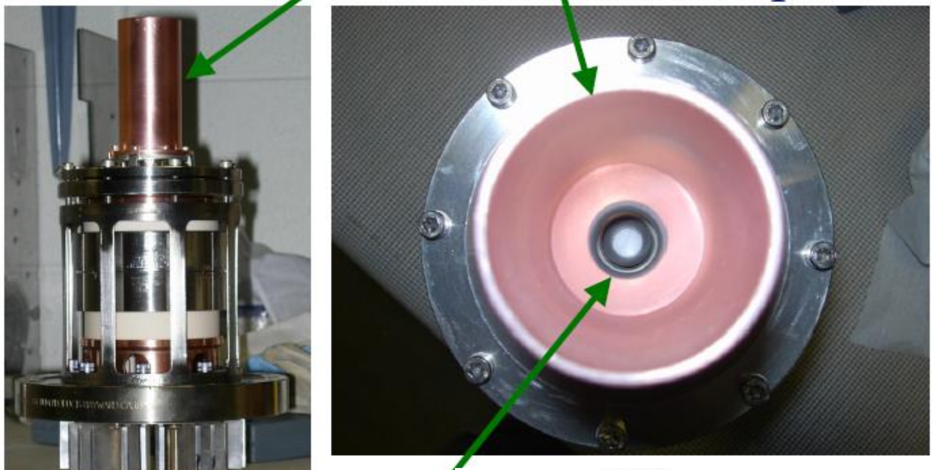


Figure 2. Three profiles of the electron current density at the electron gun cathode: black, flattop profile; red, Gaussian profile; blue, SEFT profile. Symbols represent the measured data and the solid lines are simulation results. All data refer to an anode–cathode voltage of 10 kV.

Shiltsev et al., *PRL* 99, 244801 (2007), *Shiltsev* et al., NJP 10,

Electron gun

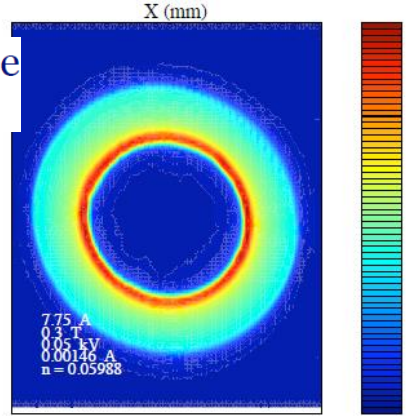


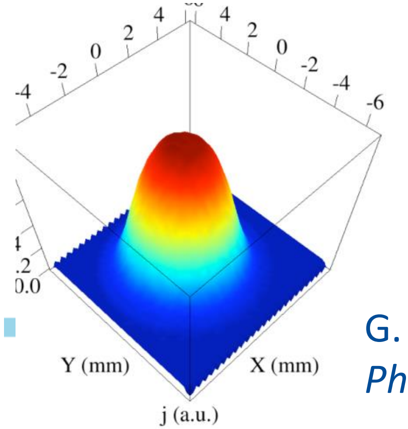
side view

Copper anode

top view

Tungsten dispenser cathode with convex surface



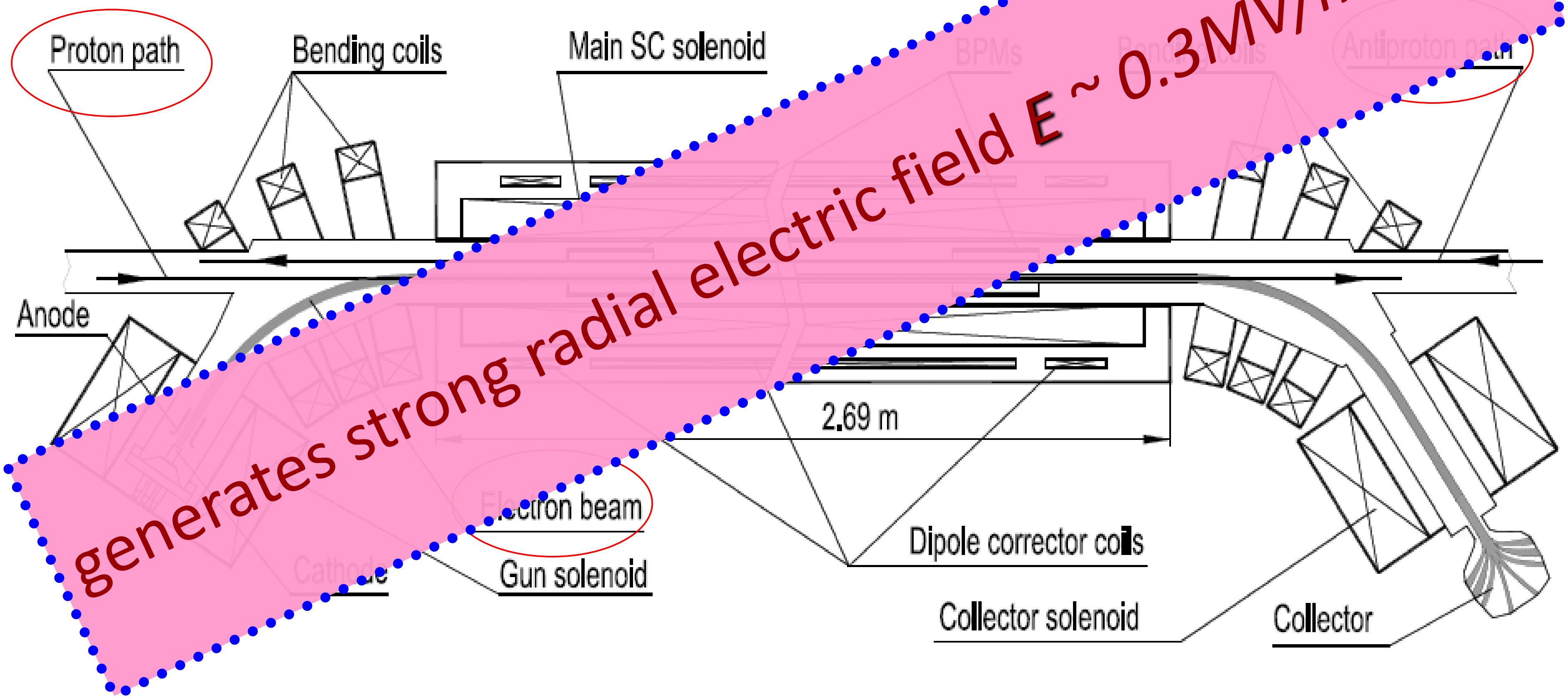


G. *Stancari*, et al. (2011) *Phys. Rev. Lett.* 107, 084802

Some Facts on Electron Lenses

~4 mm dia 2 m long very straight beam of ~10kV

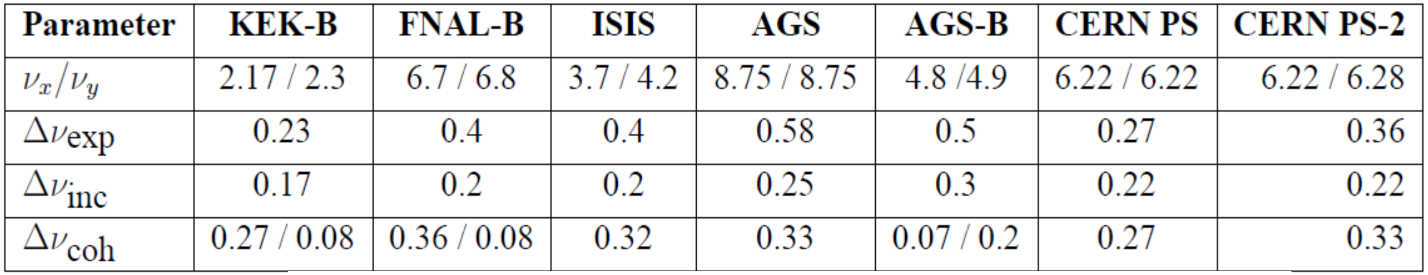
~1A electrons (~10^{12}) immersed in 3T solenoid



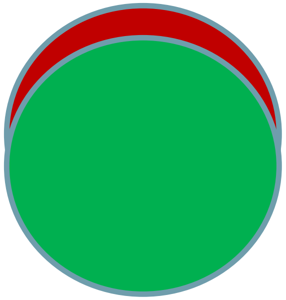
generates strong radial electric field *E* ~ 0.3MV/m

FERMILAB-TM-2125 September 2000

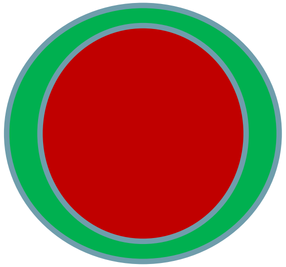
Coherent Modes



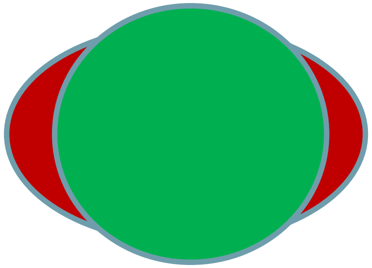
Parameter	KEK-B	FNAL-B	ISIS	AGS	AGS-B	CERN PS	CERN PS-2
ν_x / ν_y	2.17 / 2.3	6.7 / 6.8	3.7 / 4.2	8.75 / 8.75	4.8 /4.9	6.22 / 6.22	6.22 / 6.28
$\Delta\nu_{\mathrm{exp}}$	0.23	0.4	0.4	0.58	0.5	0.27	0.36
$\Delta\nu_{\mathrm{inc}}$	0.17	0.2	0.2	0.25	0.3	0.22	0.22
$\Delta\nu_{\mathrm{coh}}$	0.27 / 0.08	0.36 / 0.08	0.32	0.33	0.07 / 0.2	0.27	0.33



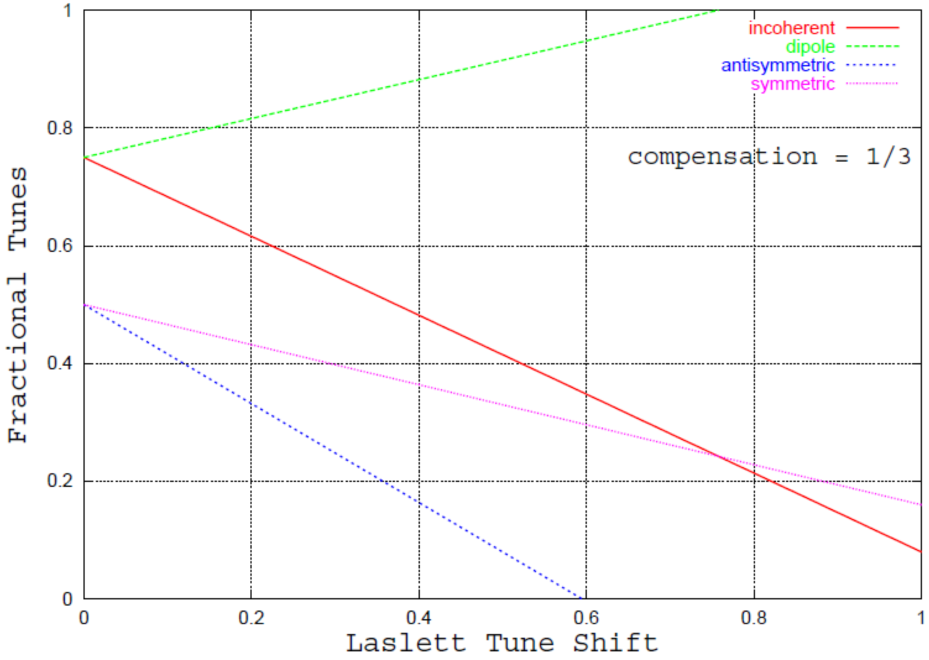
- dipole



- **symmetric**



- **asymmetric**



- **Is that a real concern? – need computer modeling**
- **Even if yes – dipole FB may help**

Space Charge Compensation in IOTA

- *Integrable Optics Test Accelerator*
- For beam physics research
- Under construction now
  - – 40 m
  - – 150 MeV/c *e-*
  - – 70 MeV/c *p+*
- Space-charge dominated
- Electron lens
  - SCC, IO, LD
  - Various regimes
  - dQ_sc= 0.25 → 1.0