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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Versatile Electron Lenses: New Accelerator “Swiss Knife”

Vladimir SHILTSEV (Fermilab)

2019 International Particle Accelerator Conference

23 May 2019 – Melbourne, Australia

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Tetsuji NISHIKAWA (1926-2010)

- 1964-66 BNL linac
- 1969 Japan National Lab for High Energy Physics
  - 12 GeV proton synchrotron
  - Neutron facility (→ J-PARC)
  - 500 MeV cancer treatment synchrotron
  - KEK Photon Factory
  - TRISTAN collider

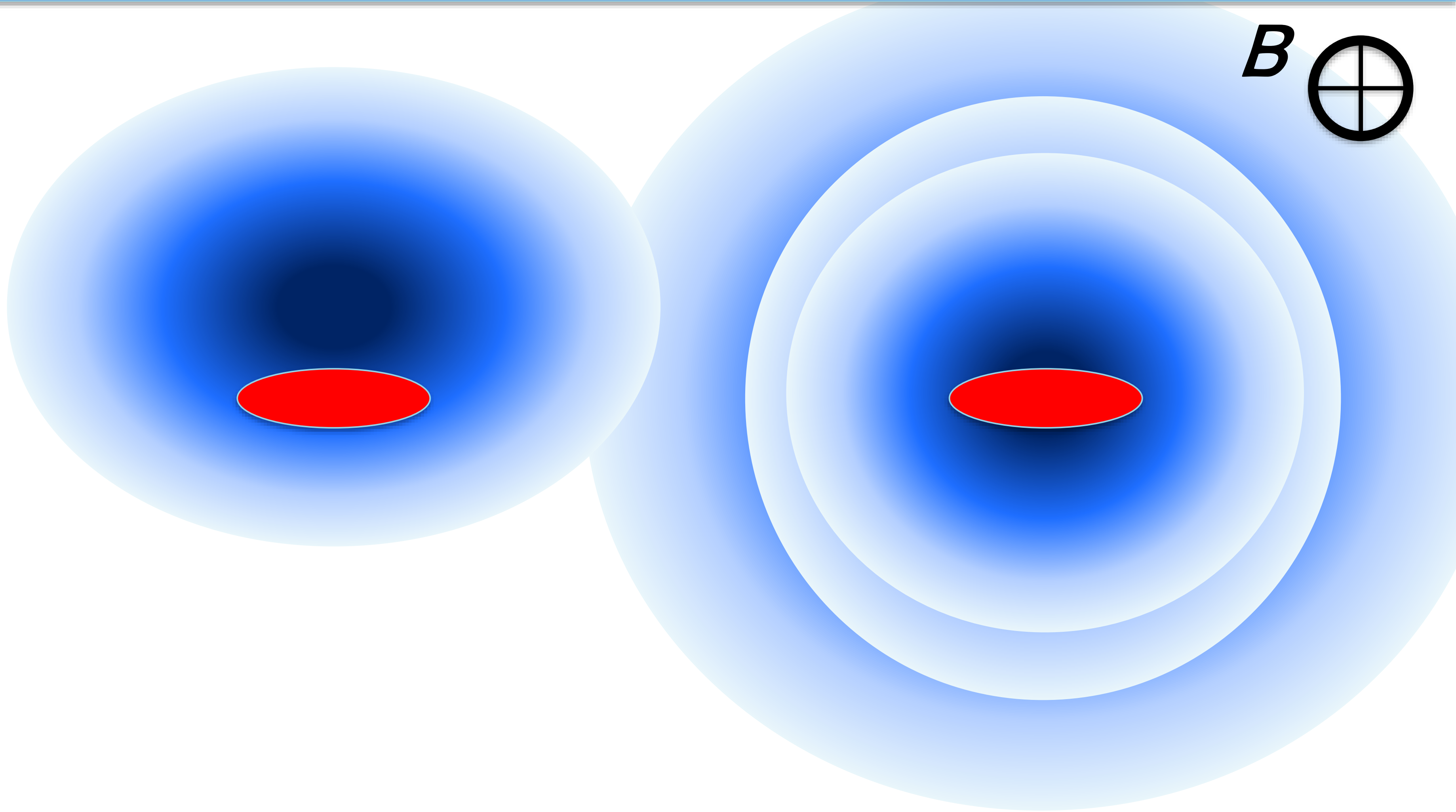

William Wallenmeyer
James Leiss
Kohei Shinozawa
Tetsuji Nishikawa
THE FIRST MEETING OF THE US-JAPAN COMMITTEE ON
HIGH ENERGY PHYSICS
SLAC - 1979


Shun-Ichi KUROKAWA
Chair of IPAC19Prize Committee
2011 IPAC ROLF WIDEROE PRIZE

Fermilab

Many thanks **to those who nominated me and many colleagues I had fortune to work with over many years on the electron lenses, the Tevatron collider and many interesting and important topics from beam-beam effects to bent crystal collimation, ground motion and orbit stabilization, head-tail instability and super-fast HV pulsers, future collider designs and construction of IOTA ring, beam commissioning of the worlds' best ILC CryoModule and very fast cycling HTS magnet.**

What Can Be Done With Electron Space Charge

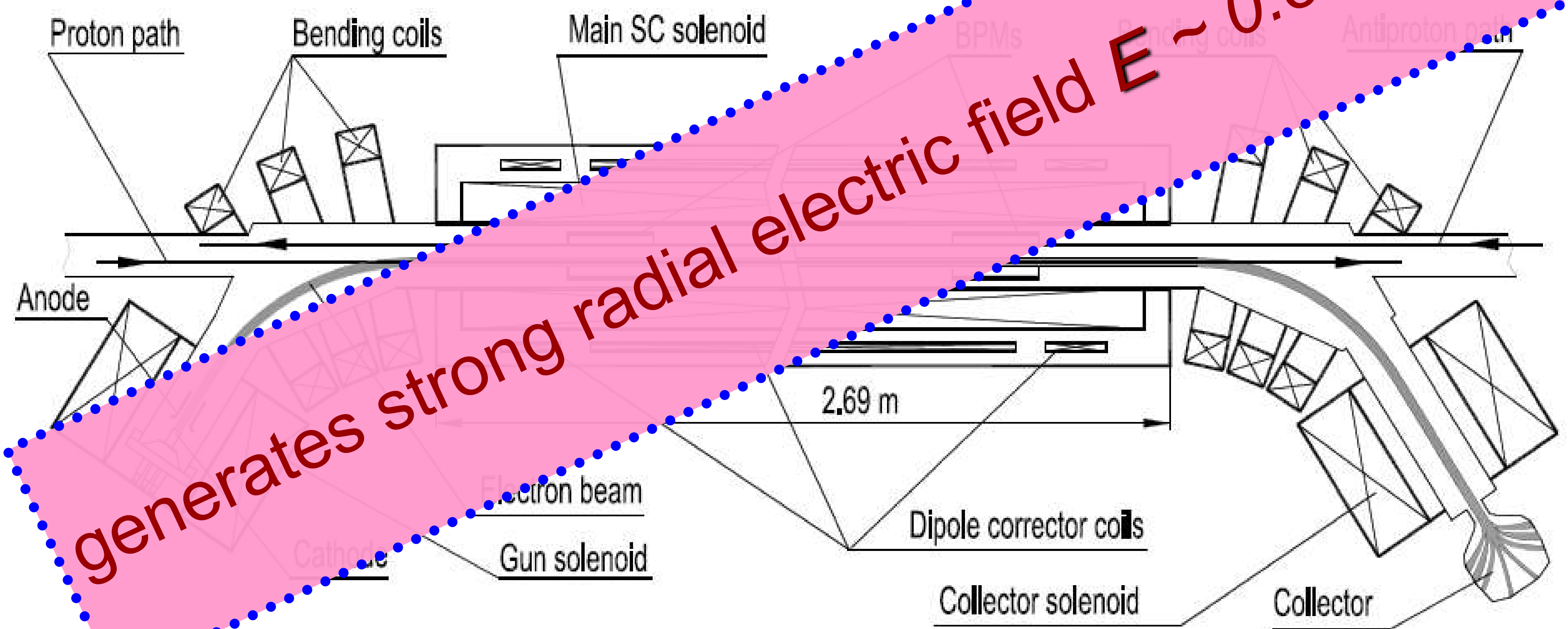


Electron Lens

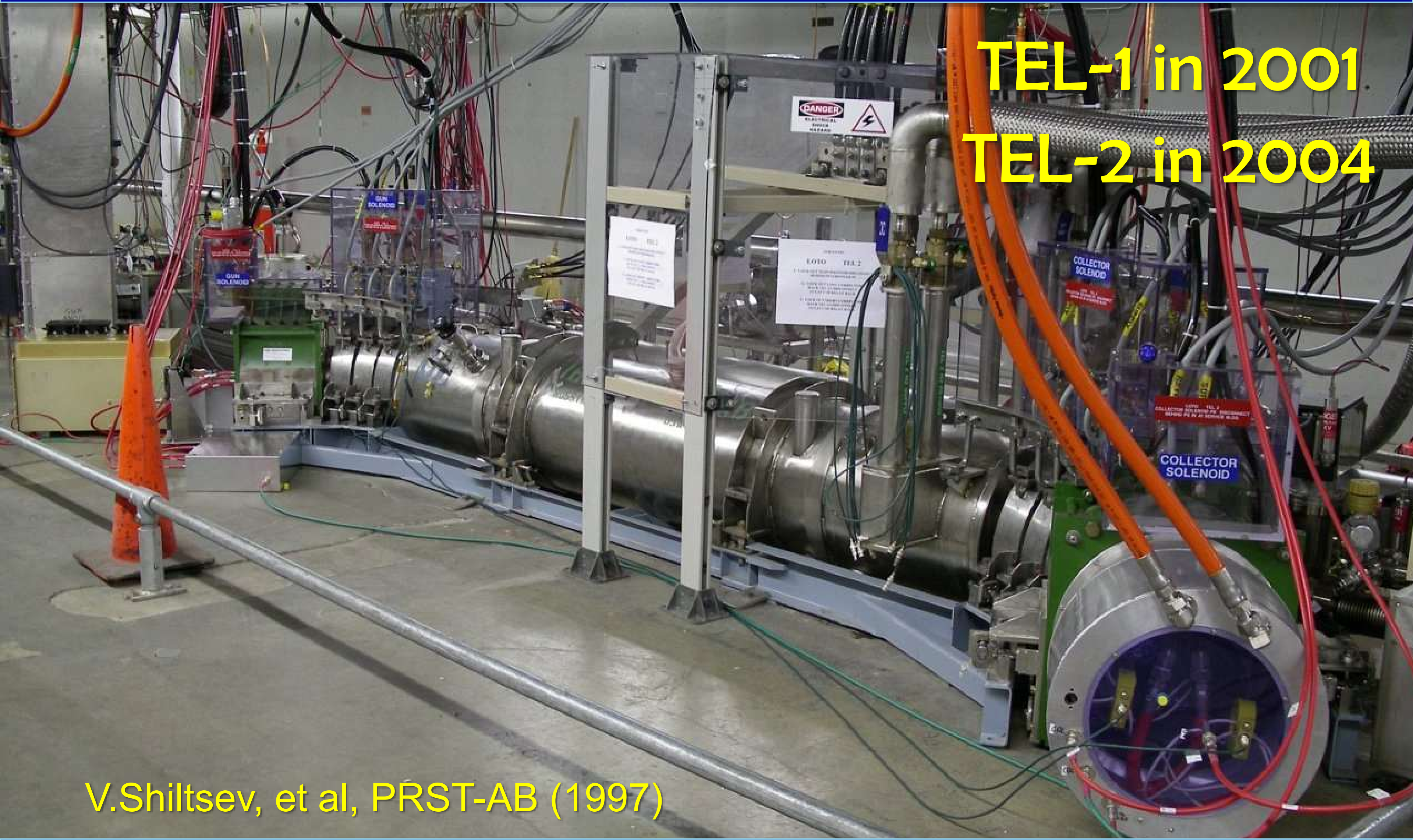
~4 mm dia 2 m long in 3T solenoid beam of ~10kV

~1A electrons (~10^{12}) can turn on/off in 0.5 usec

generates strong radial electric field E ~ 0.3MV/m



Two Electron Lenses Were Installed in Tevatron



TEL-1 in 2001

TEL-2 in 2004

V.Shiltsev, et al, PRST-AB (1997)

What Electron Lenses Are Good For (1)

In the Fermilab Tevatron Collider:

PAST

- **long-range beam-beam** compensation (varied tune shift of individual 1 TeV bunches by 0.003-0.01);

  *Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)*
- **abort gap collimation** (for years in regular operation);

  *Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)*
- studies of **head-on beam-beam** compensation;

  Shiltsev et al, NJP (2008); Stancari et al., PRL 107, 084802 (2011)
- demonstration of **halo scraping with hollow electron beams**;

  Shiltsev (2006); Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)

What Electron Lenses Are Good For (2)

Presently used in RHIC at BNL for **head-on beam-beam compensation** with significant luminosity gain ~x2

Fischer et al., Phys. Rev. Lett. 115, 264801 (2015)

PRESENT

Current areas of research:

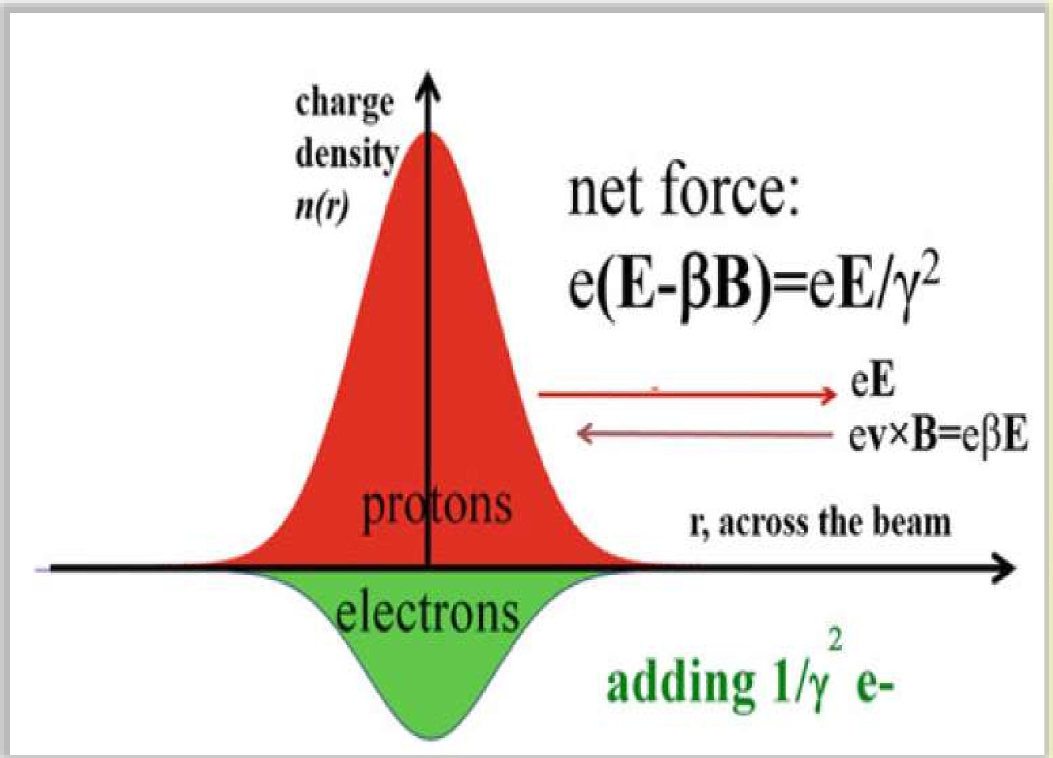
- **hollow electron beam collimation** of protons in the HL-LHC;
  Conceptional Design Report, CERN-ACC-2014-0248 (2014)
- **long-range beam-beam compensation** as current-bearing "wires" in the HL-LHC
  Valishev,Stancari, arXiv:1312.5006; Fartoukh et al., PRSTAB ***18****, 121001 (2015)*
- generation of **nonlinear integrable lattices,** eg in IOTA
  Shiltsev et al, PRSTAB(1997), Nagaitsev, et al., IPAC'12; Stancari et al., IPA
- to generate tune spread for **Landau damping** of instabilities before collisions in the LHC, FCC-hh (>10,000 octupoles), FNAL Recycler
  Shiltsev (2006), Shiltsev, Alexahin, Burov, Valishev PRL (2018)
- to **compensate space-charge effects** in modern RCSs
  Burov, Foster, Shiltsev (2000), Stern et al, IPAC'18

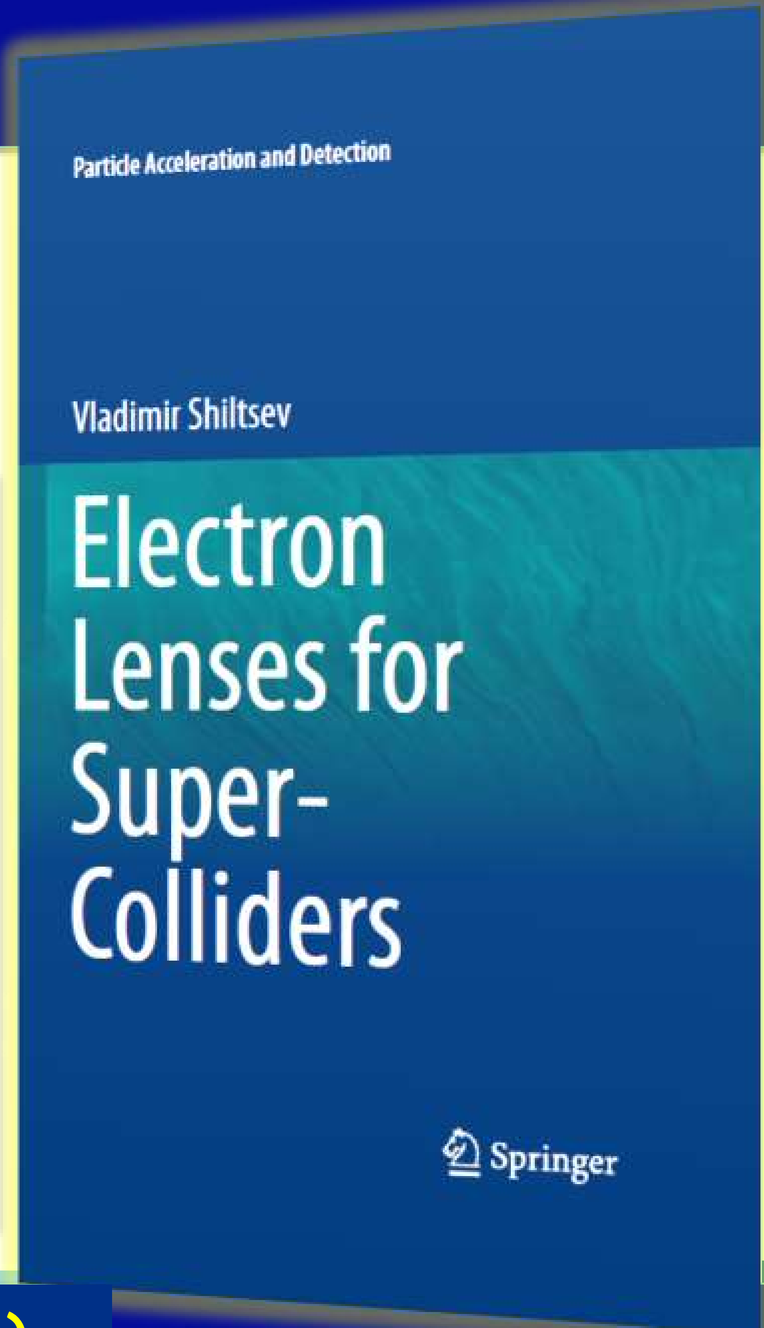
FUTURE

versatile applications depending on e-beam profile + pulsing

Book

Below I present just one example of compensation of space-charge effects by electron lenses

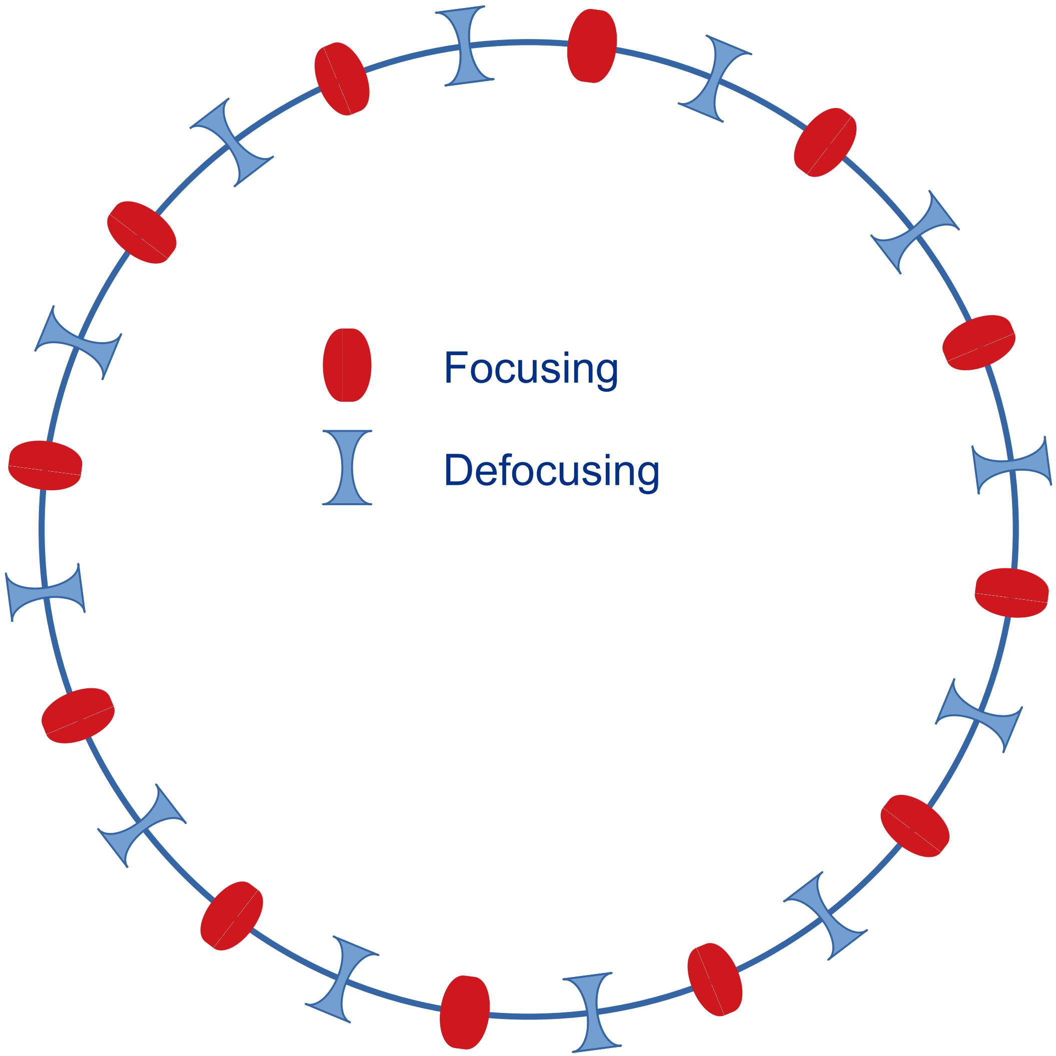




PIC simulations by E.Stern, et al (FNAL)

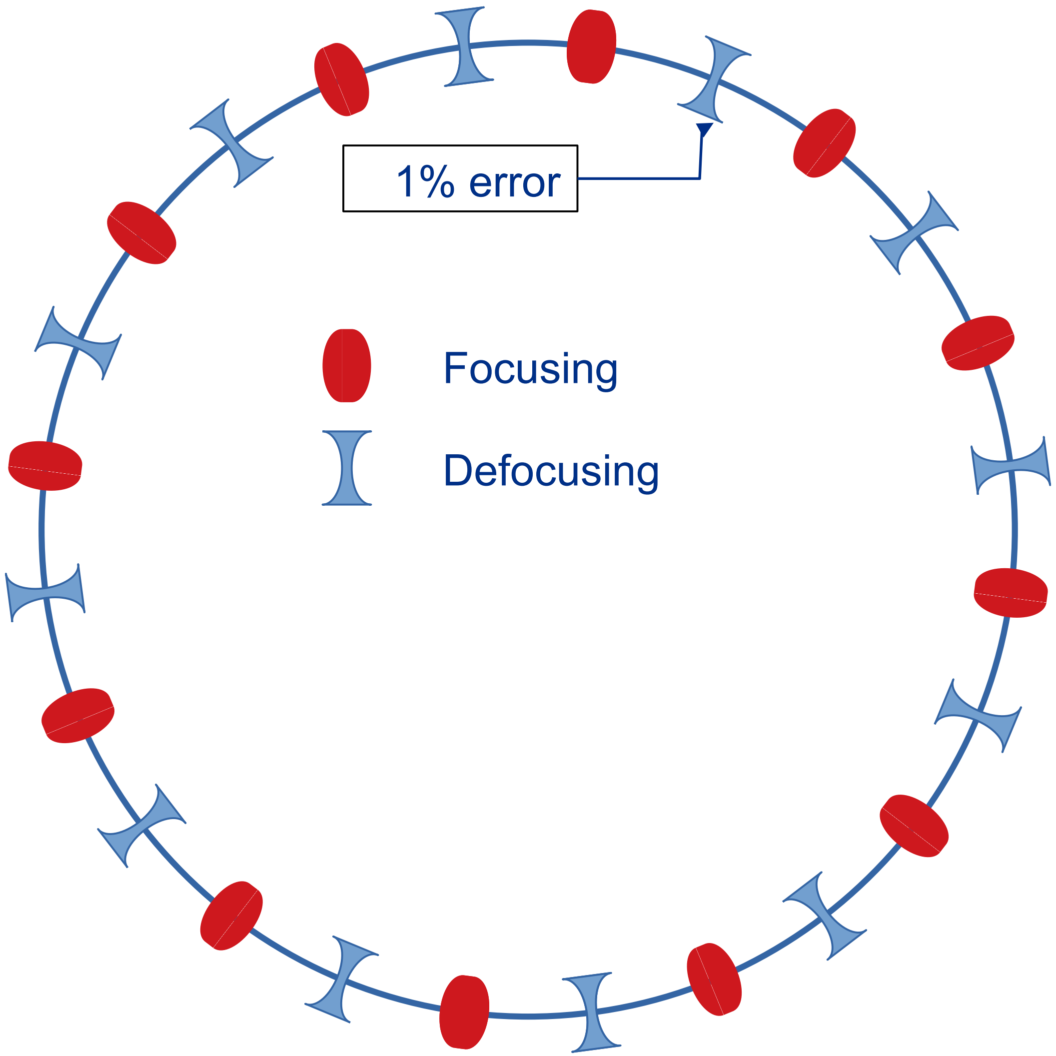
1000 Turns in a Ring with dQ_{SC}=-0.9

Case #1

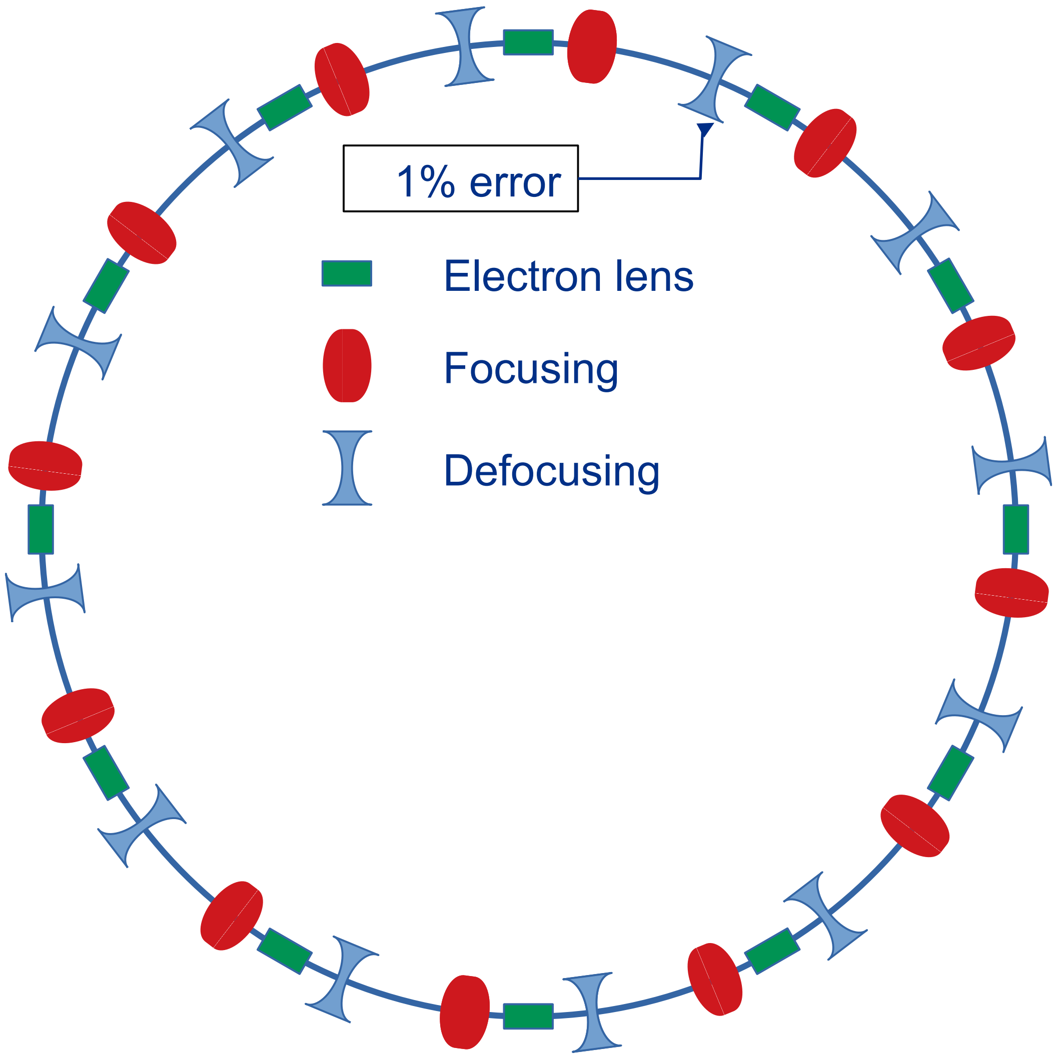


1000 Turns in a Ring with dQ_{SC}=-0.9

Case #2

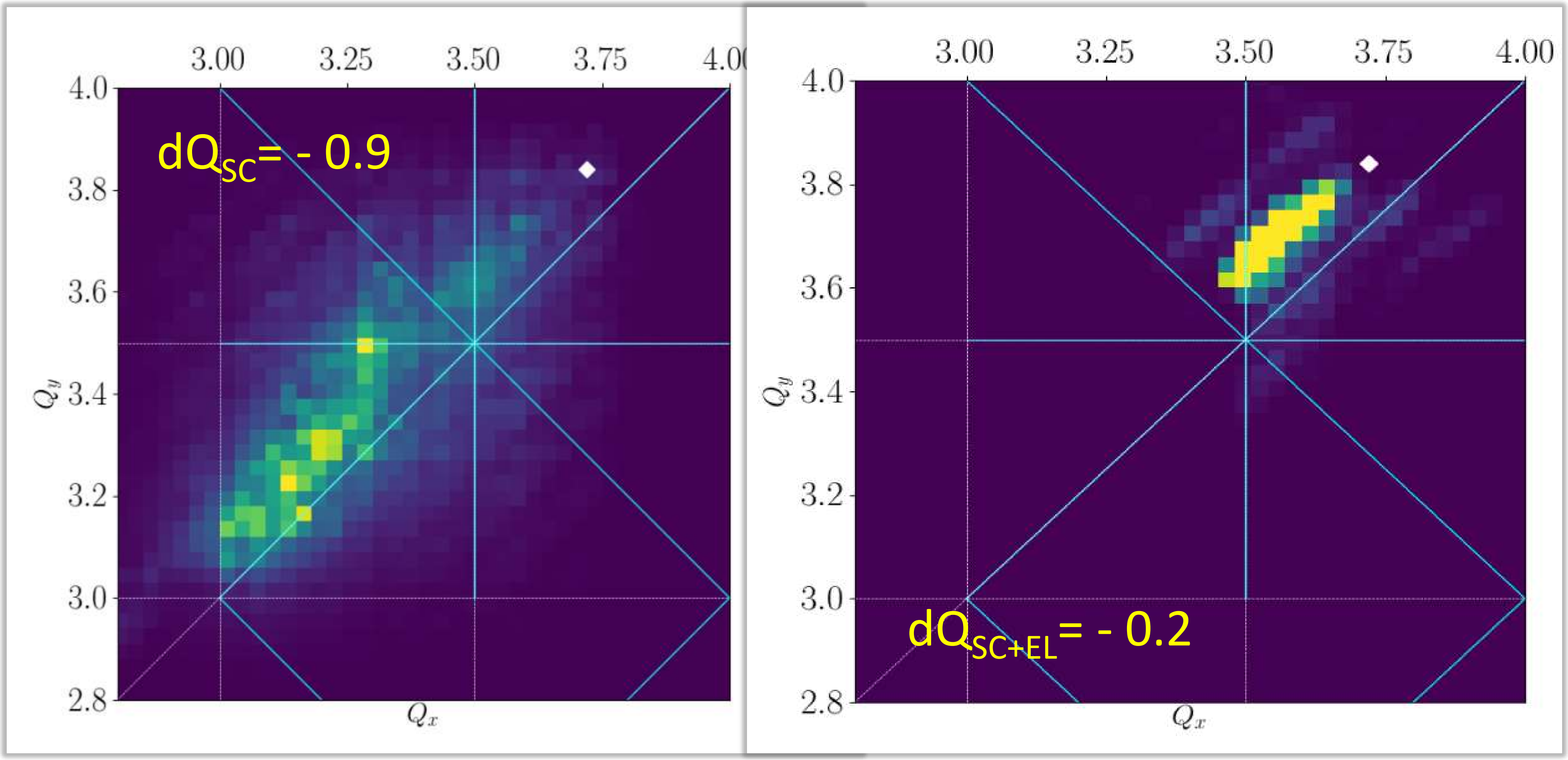


1000 Turns in a Ring with dQ_{SC}=-0.9



Case #3

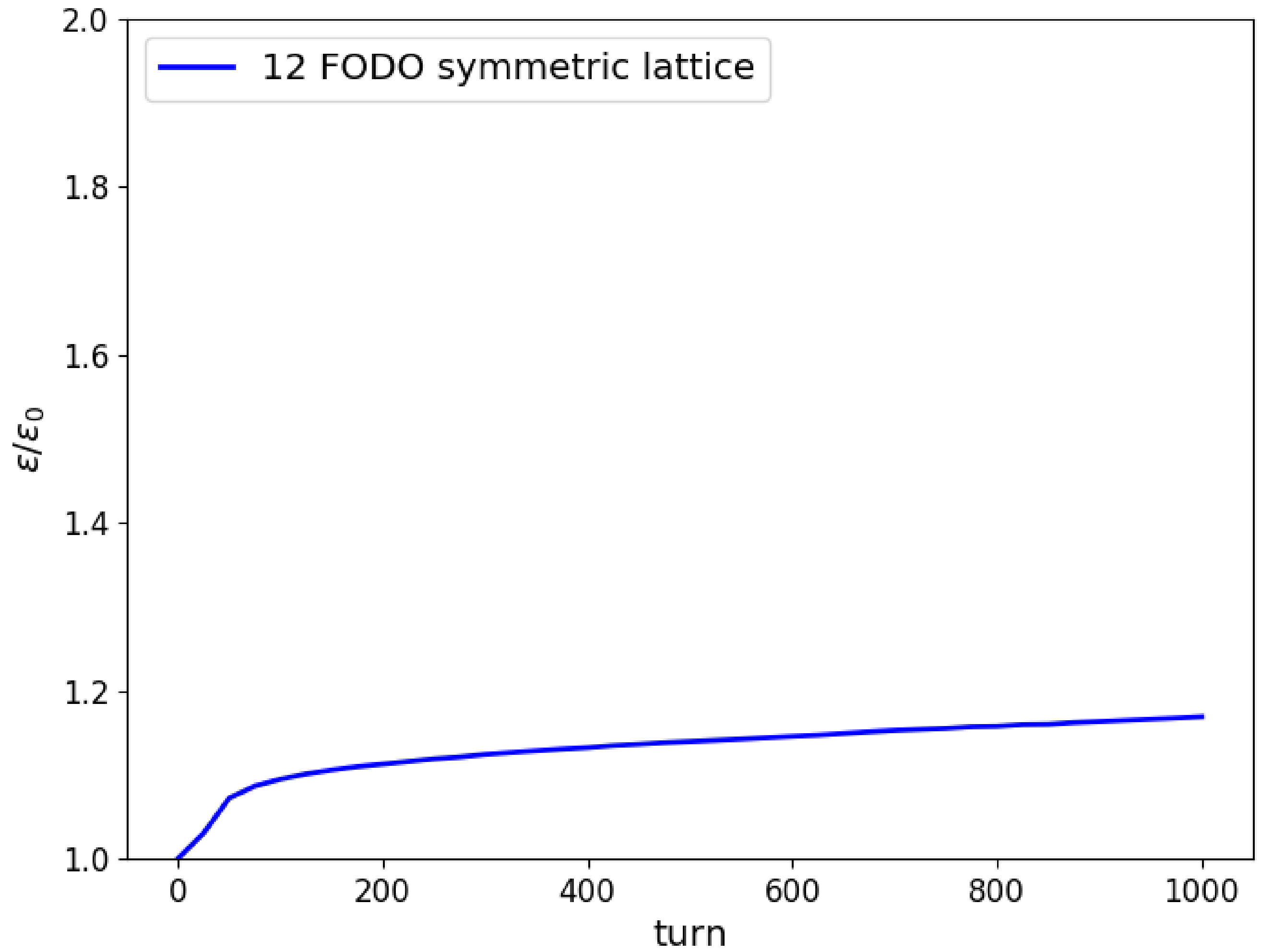
Tune Footprint dQ_{SC}=-0.9



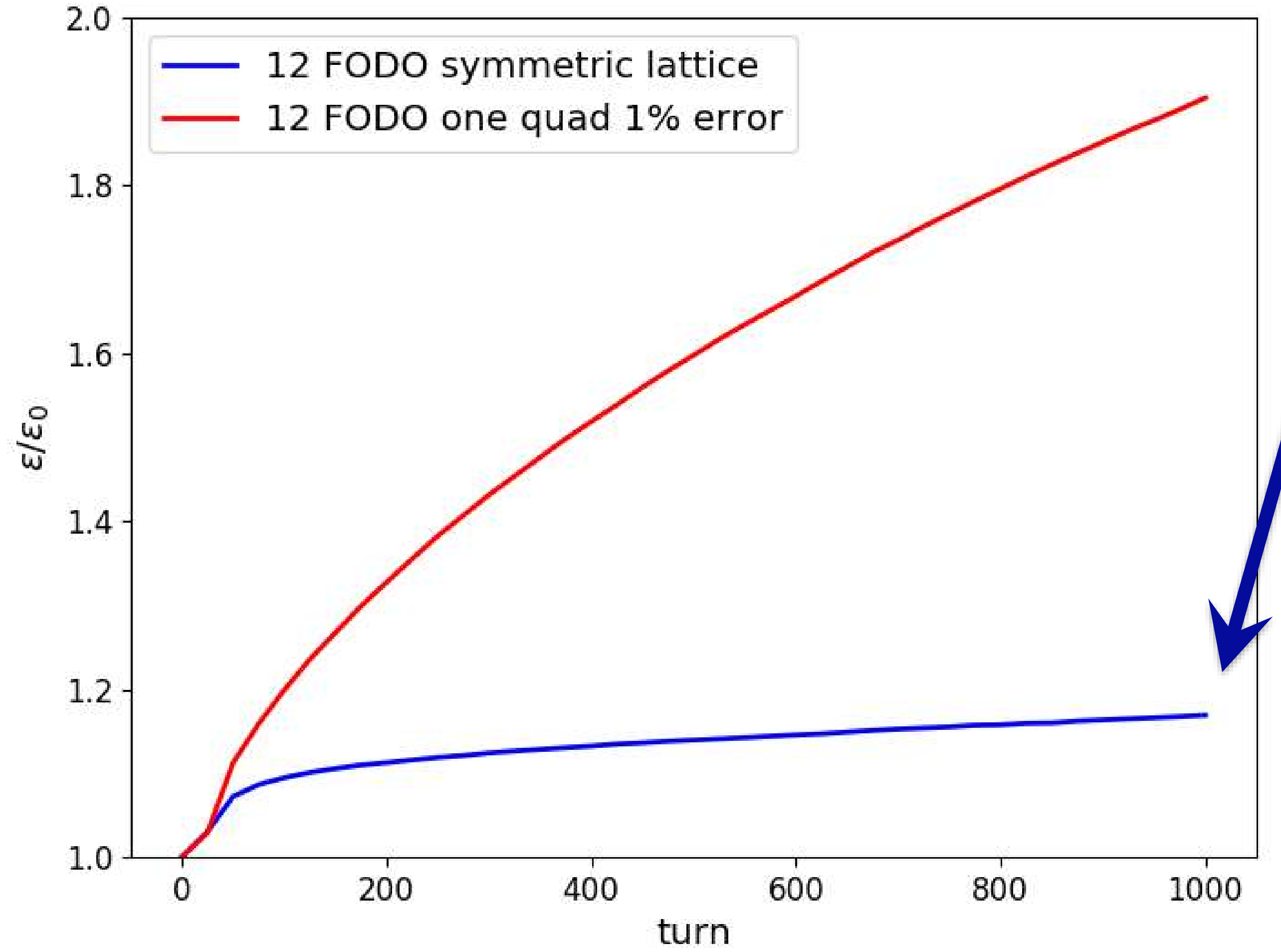
no e-lenses **~75% e-lens compensation**

Stern et al, THPAF075, IPAC18, Beams Document 6790-v1 FNAL (2019)

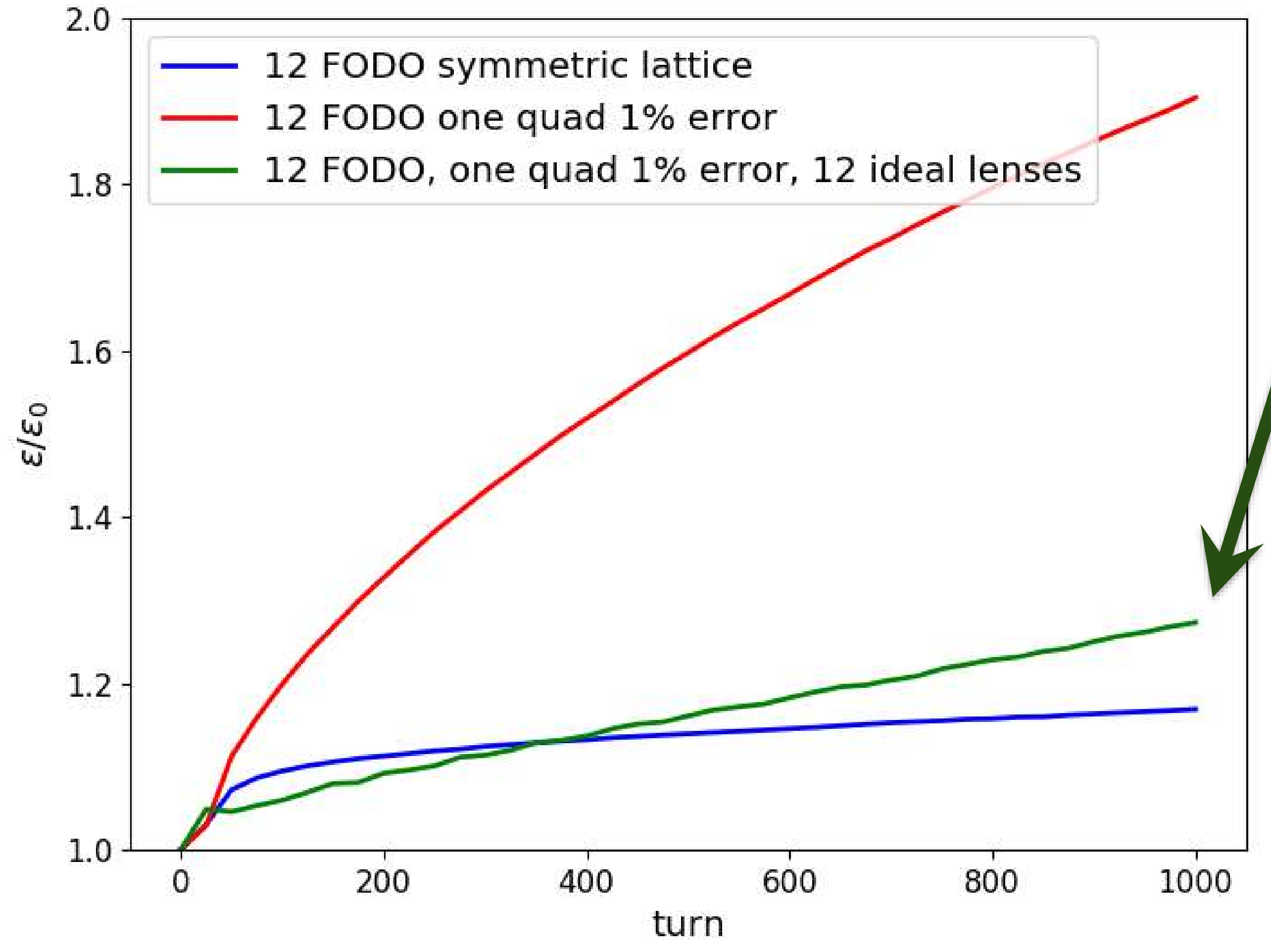
Emittance Growth – Case #1



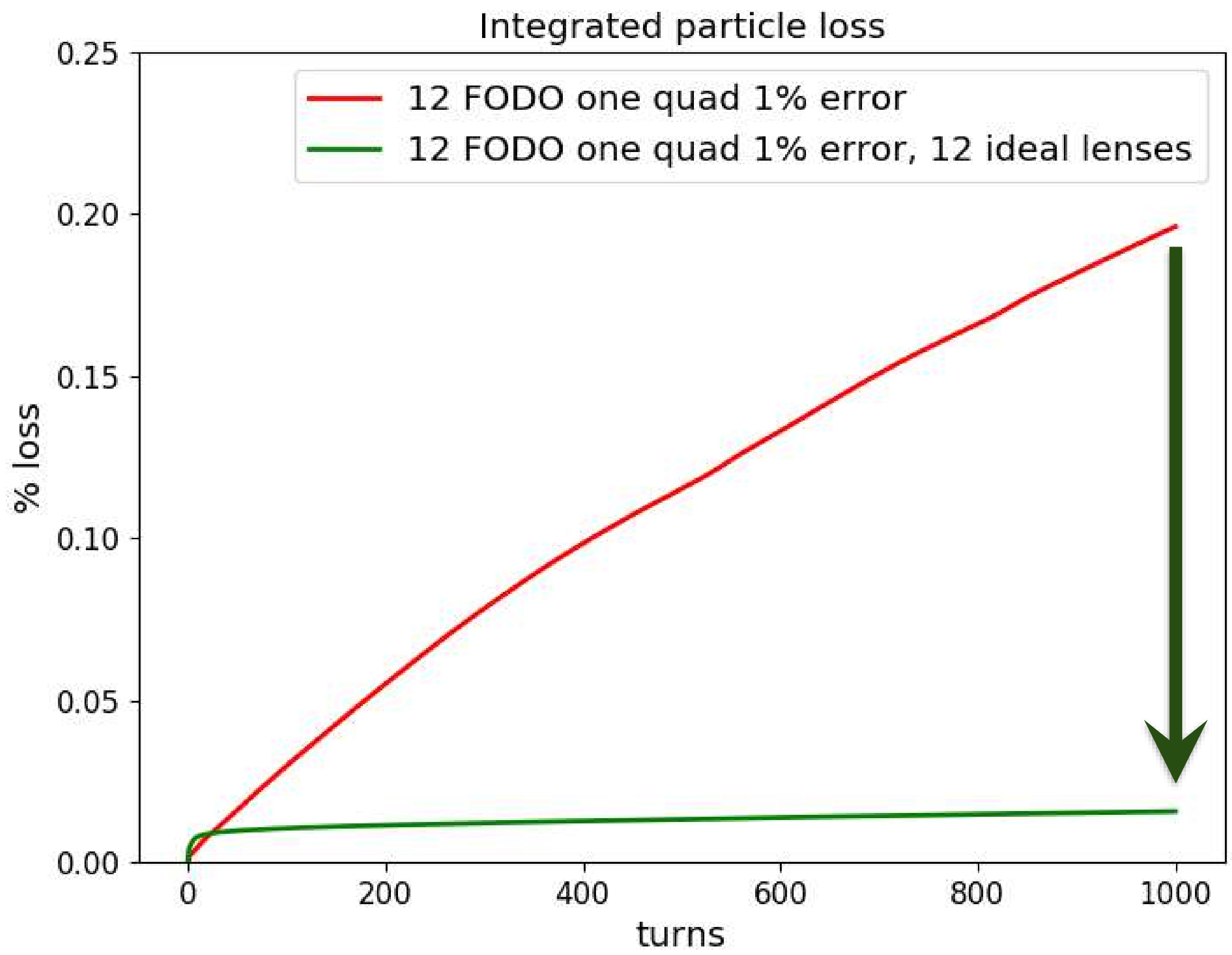
Emittance Growth – Case #2



Emittance Growth – Case #3

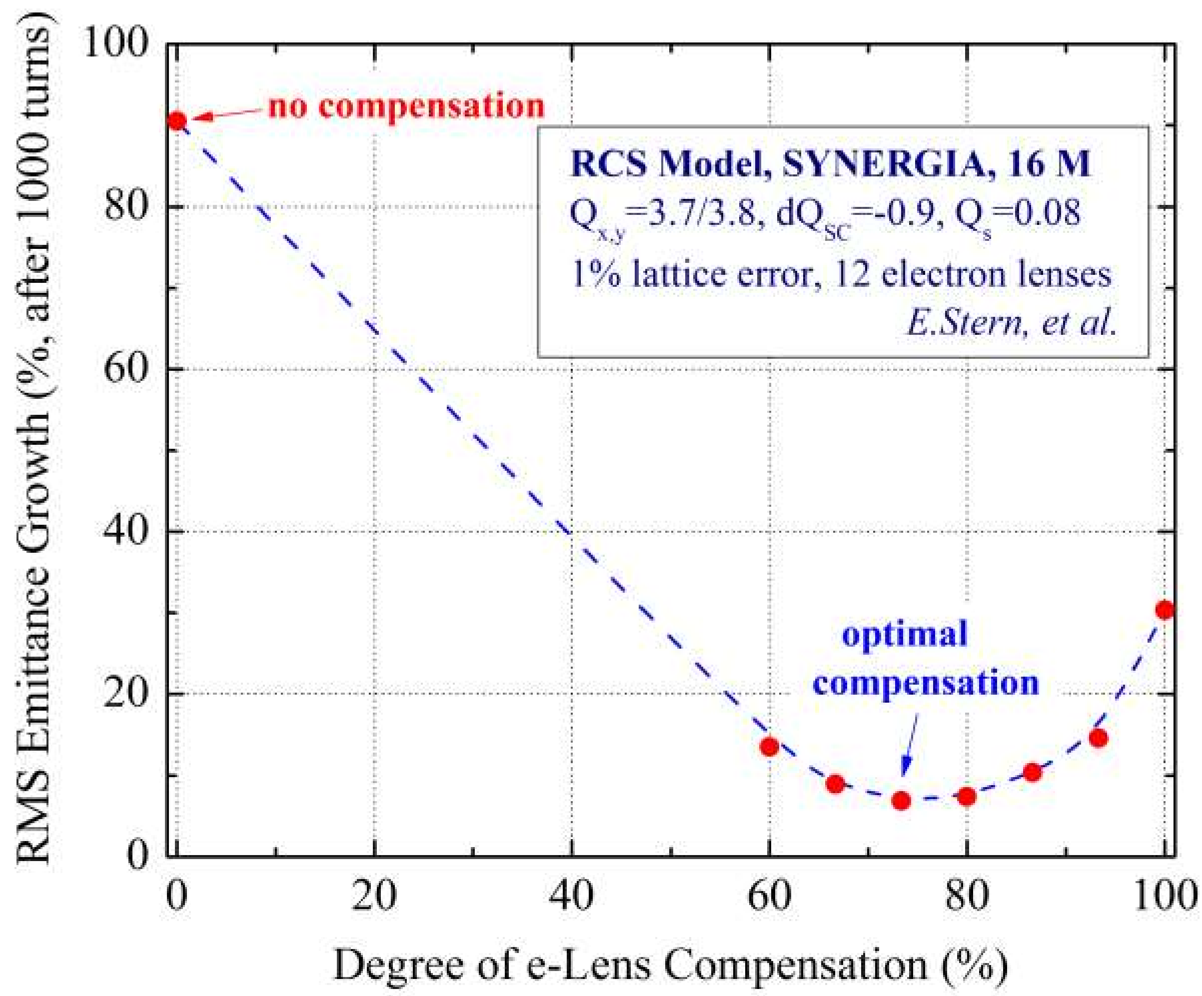


Particle Losses at 4σ – Case #2 and #3

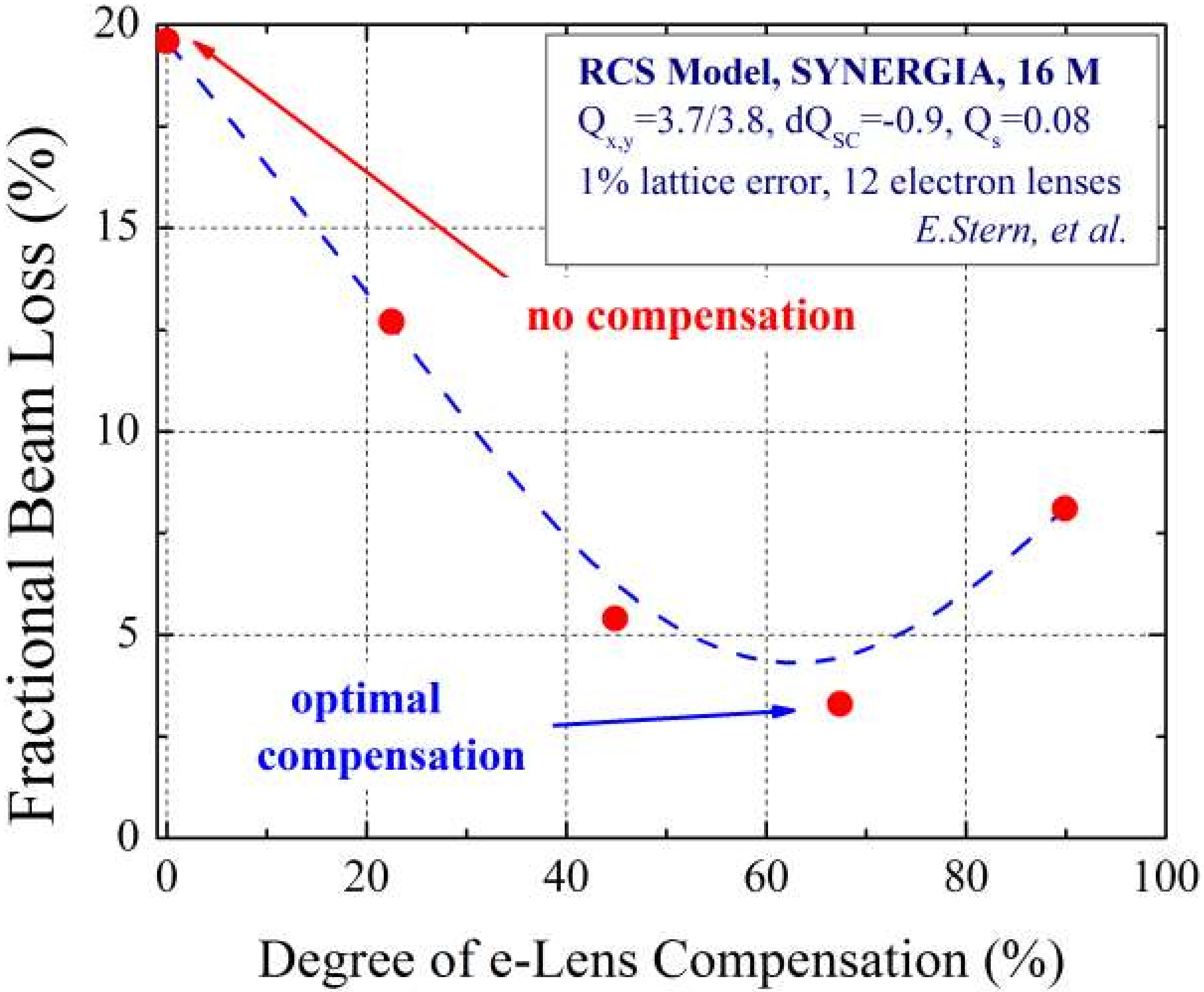


e-lenses reduce losses ~6 fold !

Optimal Compensation ~75% (emitt. growth)



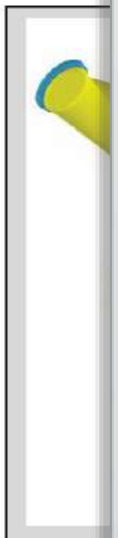
Optimal Compensation ~70% (beam losses)



IOTA: *Integrable Optics Test Accelerator*

Lin… der

V.Shiltsev, Physics-Uspekhi 55 (10), 965 (2012)



Fermilab, June 24-26, 2019

Workshop on Beam Acceleration in Crystals and Nanostructures

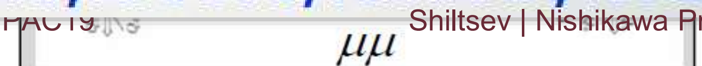
https://indico.fnal.gov/event/19478/

Organized by T. Tajima (UCI) and V. Shiltsev (FNAL)
Proceedings Editors: G. Mourou, V. Shiltsev, T. Tajima

Endorsed by: APS GPAP, APS DPB, ICFA ANA, ICUIL

…0 TeV

n_μ ~1000
n_B ~100
f_{rep} ~10^6
L ~10^{30-32}



Join

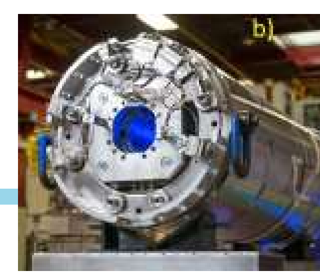
Division of Physics of Beams

APS Division of Physics of Beams (DPB) is the world's largest and oldest (est. 1985) professional association of accelerator physicists and engineers. The DPB is a highly respected, international organization, open to all with interest in the science, technology and applications of accelerators.

Join us to strengthen the prestige and professional standing of accelerator physics and influence its future development! To learn more and sign up – please, see the American Physical Society (APS) table at this Conference or go to our Web site:

https://www.aps.org/units/dpb/



Celebrate Science! – 2019 is UNESCO

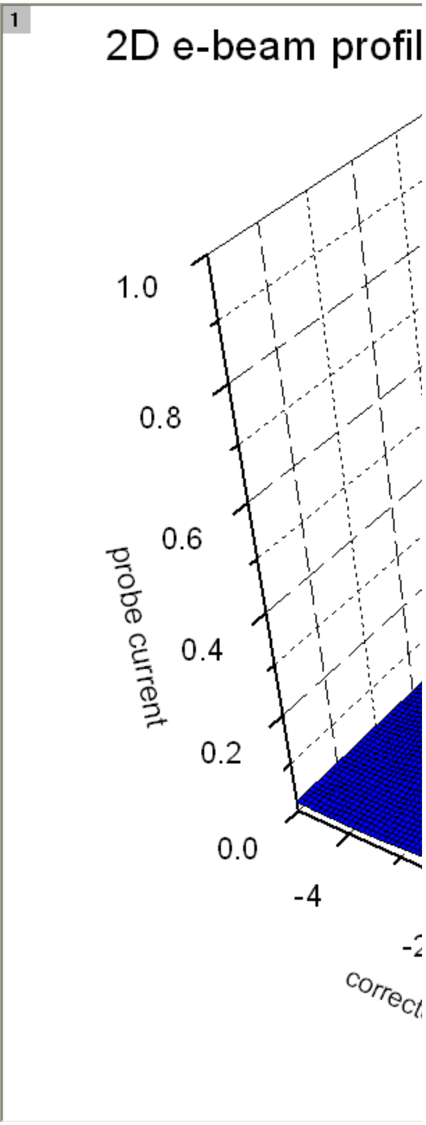
Int'l Year of Periodic Table (150 yrs)

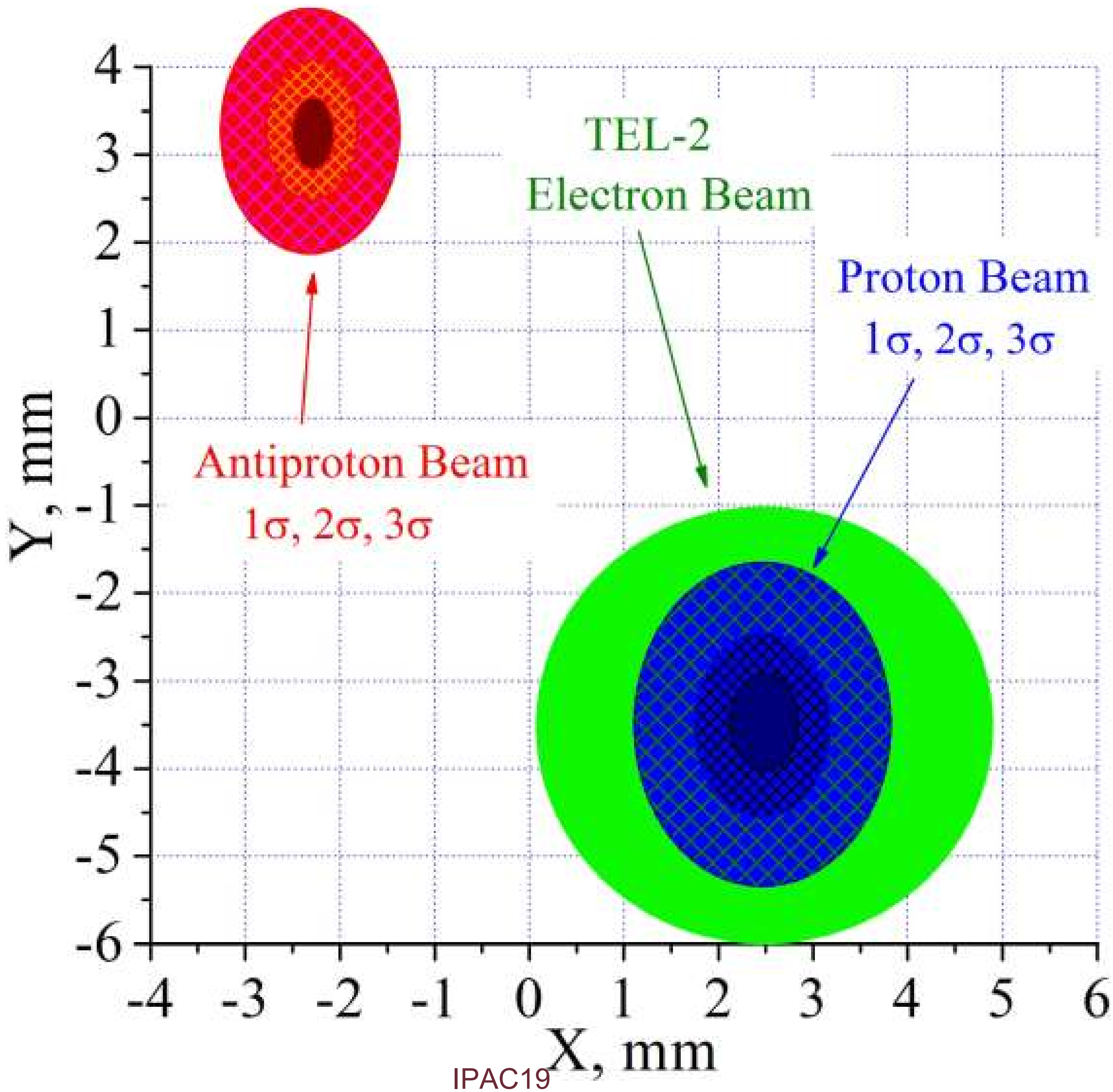
Series	Zero Group	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII	Group VIII
0	x								
1	y	Hydrogen H=1·008							
2	Helium He=4·0	Lithium Li=7·03	Beryllium Be=9·1	Boron B=11·0	Carbon C=12·0	Nitrogen N=14·04	Oxygen O=16·00	Fluorine F=19·0	
3	Neon Ne=19·9	Sodium Na=23·05	Magnesium Mg=24·1	Aluminium Al=27·0	Silicon Si=28·4	Phosphorus P=31·0	Sulphur S=32·06	Chlorine Cl=35·45	
4	Argon Ar=38	Potassium K=39·1	Calcium Ca=40·1	Scandium Sc=44·1	Titanium Ti=48·1	Vanadium V=51·4	Chromium Cr=52·1	Manganese Mn=55·0	Iron Fe=55·9 Cobalt Co=59 Nickel Ni=59 (Cu)
5		Copper Cu=63·6	Zinc Zn=65·4	Gallium Ga=70·0	Germanium Ge=72·3	Arsenic As=75·0	Selenium Se=79	Bromine Br=79·95	
6	Krypton Kr=81·8	Rubidium Rb=85·4	Strontium Sr=87·6	Yttrium Y=89·0	Zirconium Zr=90·6	Niobium Nb=94·0	Molybdenum Mo=96·0	—	Ruthenium Ru=101·7 Rhodium Rh=103·0 Palladium Pd=106·5 (Ag)
7		Silver Ag=107·9	Cadmium Cd=112·4	Indium In=114·0	Tin Sn=119·0	Antimony Sb=120·0	Tellurium Te=127	Iodine I=127	
8	Xenon Xe=128	Cæsium Cs=132·9	Barium Ba=137·4	Lanthanum La=139	Cerium Ce=140	—	—	—	— — — (—)
9		—	—		—	—	—	—	
10	—	—	—	Ytterbium Yb=173	—	Tantalum Ta=183	Tungsten W=184	—	Osmium Os=191 Iridium Ir=193 Platinum Pt=194·9 (Au)
11		Gold Au=197·2	Mercury Hg=200·0	Thallium Tl=204·1	Lead Pb=206·9	Bismuth Bi=208	—	—	
12	—	—	Radium Rd=224	—	Thorium Th=232	—	Uranium U=239		

BACK UP SLIDES

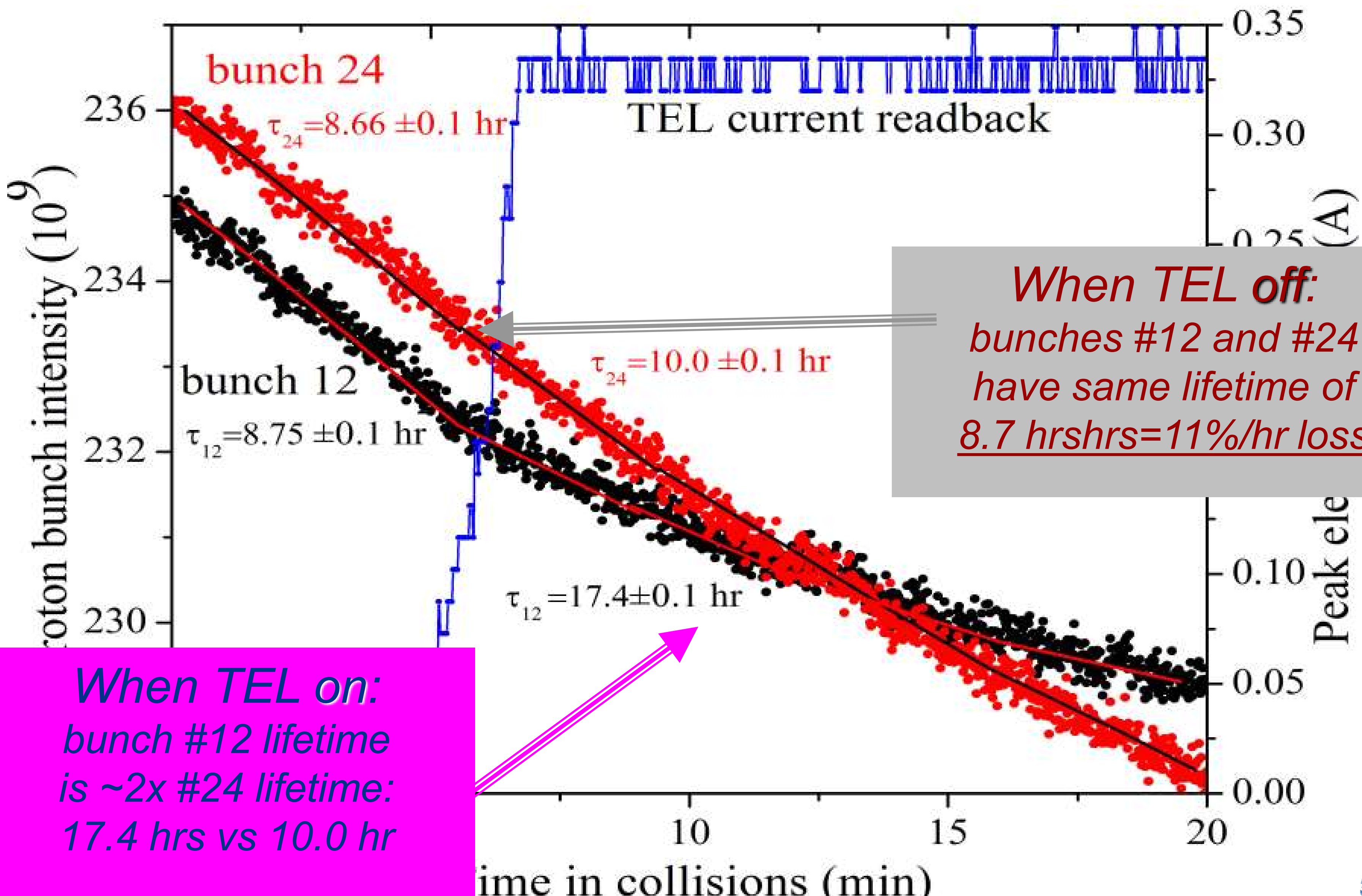
Beam-Beam Compensation

in Tevatron operation - TELs compensated of long range BB effects





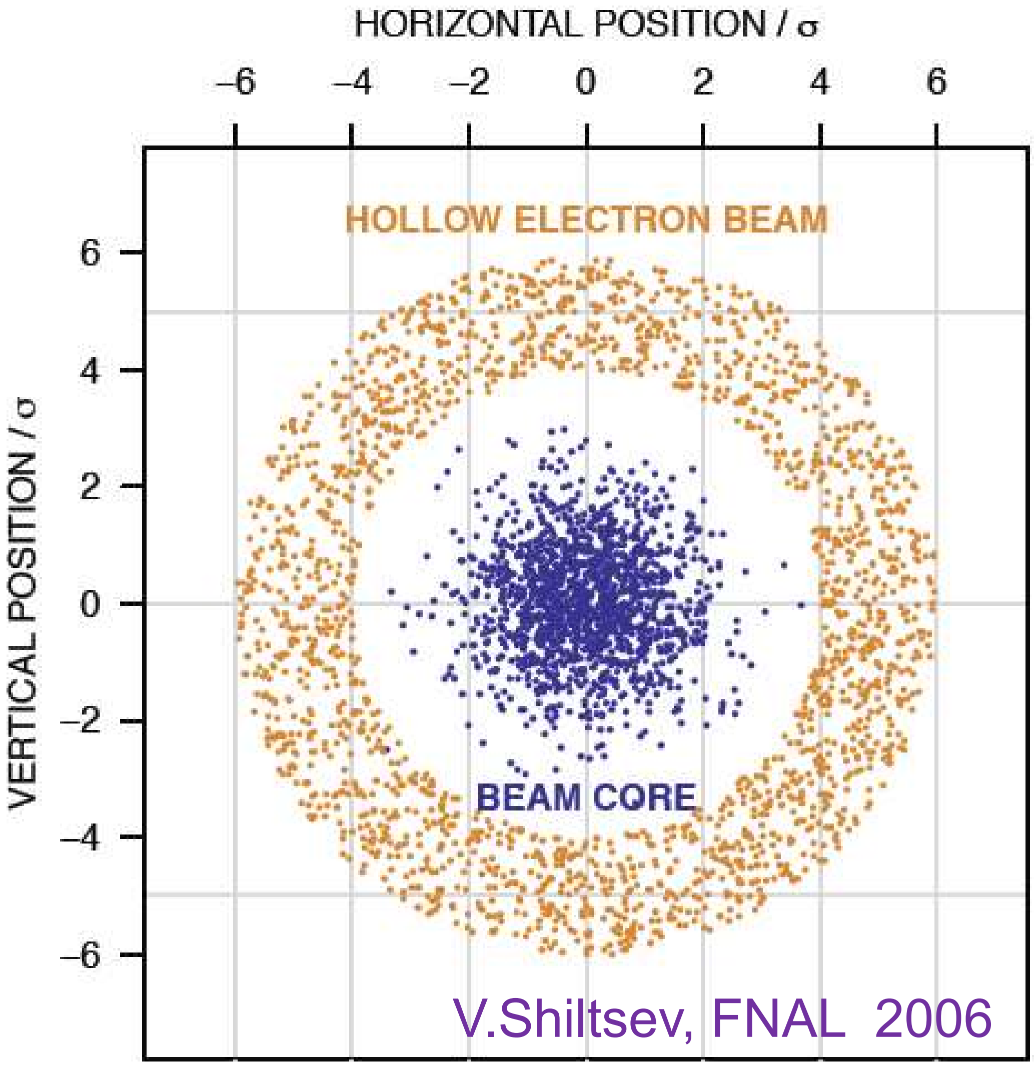
TEL2 on One “Bad” Bunch (P12)



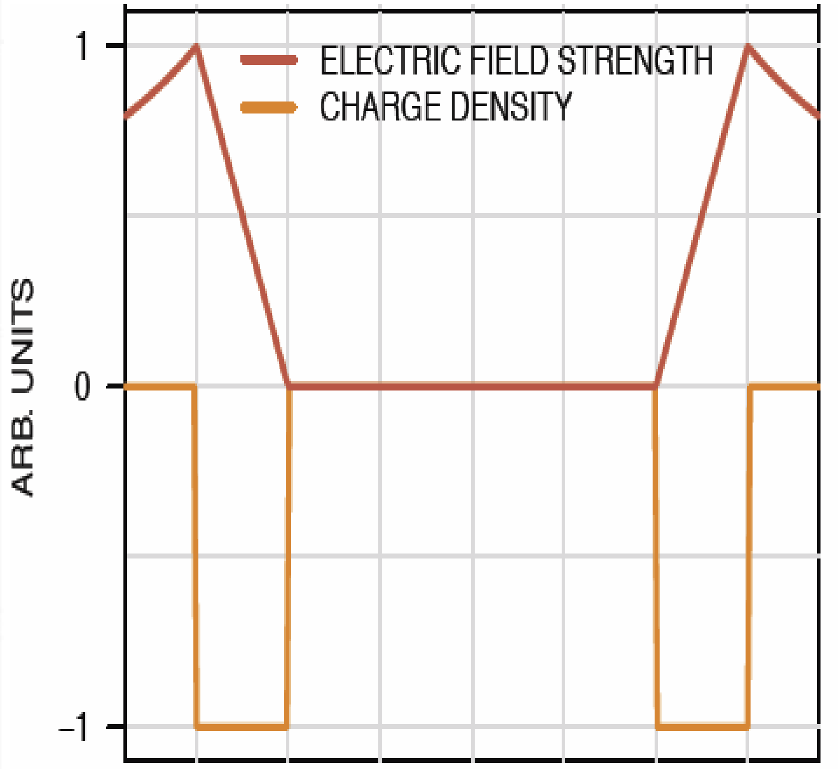
When TEL off:
bunches #12 and #24
have same lifetime of
8.7 hrshrs=11%/hr loss

When TEL on:
bunch #12 lifetime
is ~2x #24 lifetime:
17.4 hrs vs 10.0 hr

Physics: Hollow Electron Beam Collimation

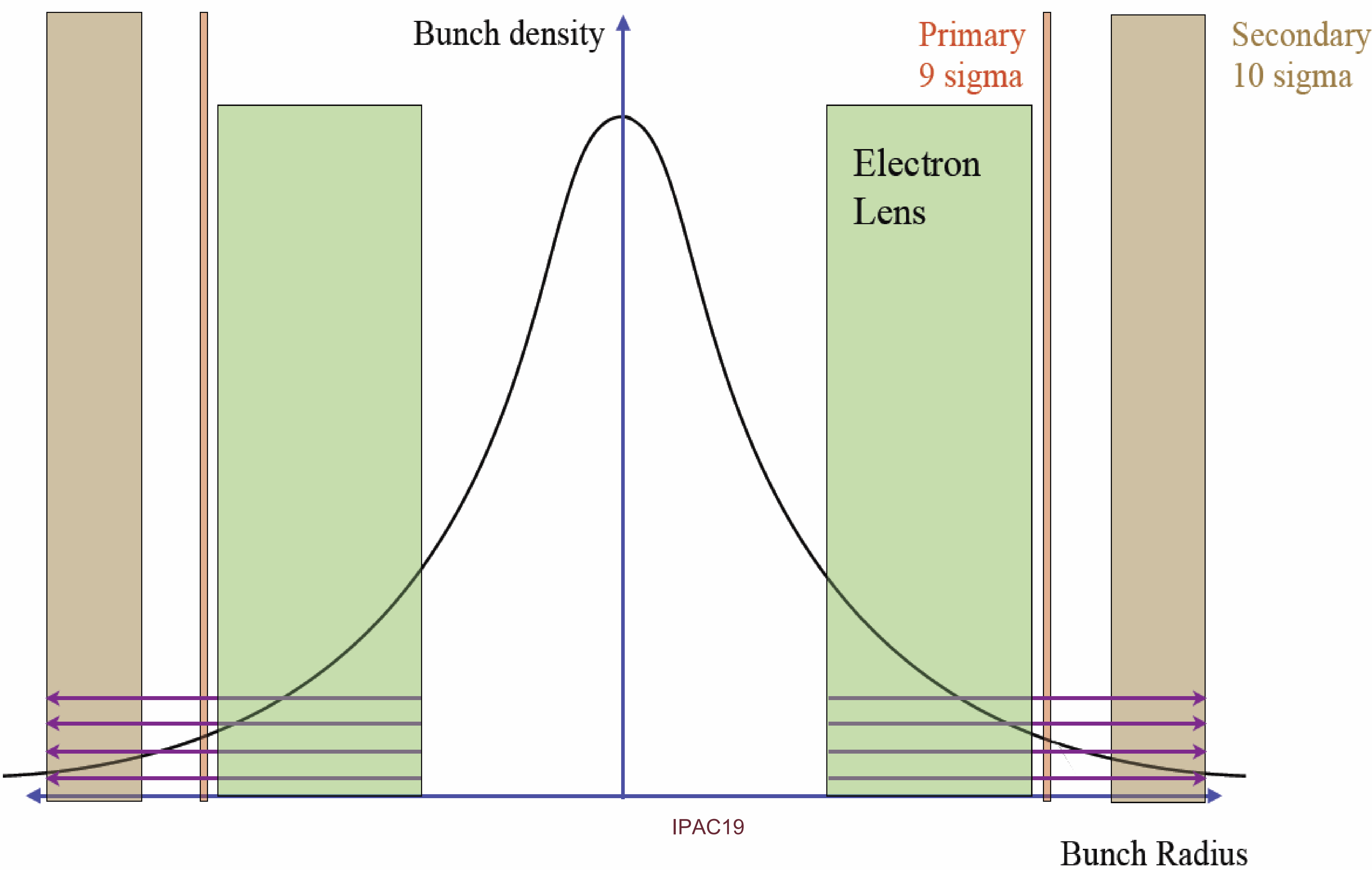


No EM field inside
Strong field outside



Concept Hollow Electron Beam Collimation

Tevatron – 2 MJ beams, LHC – 360 MJ beams

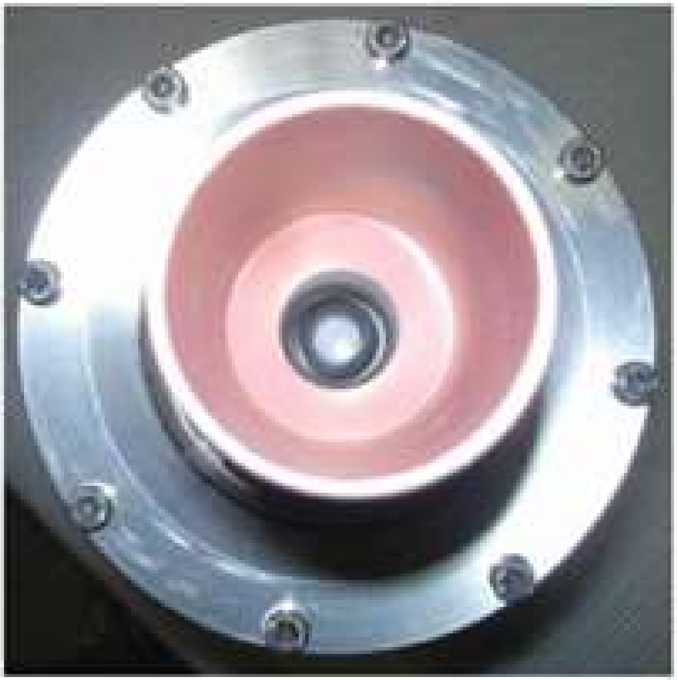


Tevatron Hollow e-Collimator

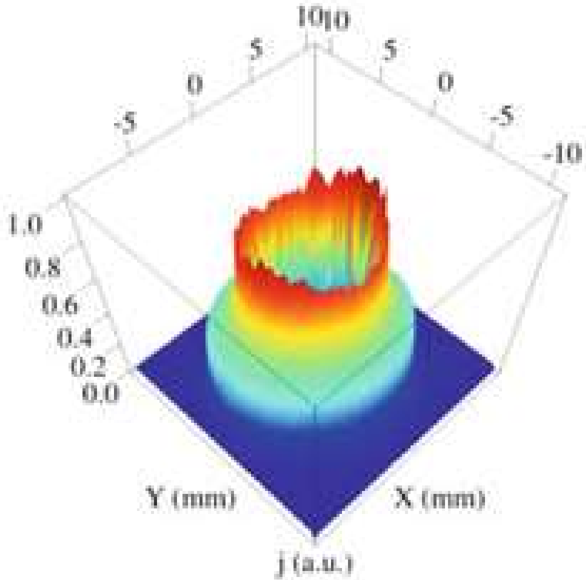
Advantages:

- Kicks are small but not random
- Halo diffusion enhancement ("smooth" scraper)
- Resonant excitation is possible (pulsed e-beam)
- No material damage
- No ion breakup
- Low impedance
- Position control by magnetic field (no motors or bellows)
- Established e-lens technology

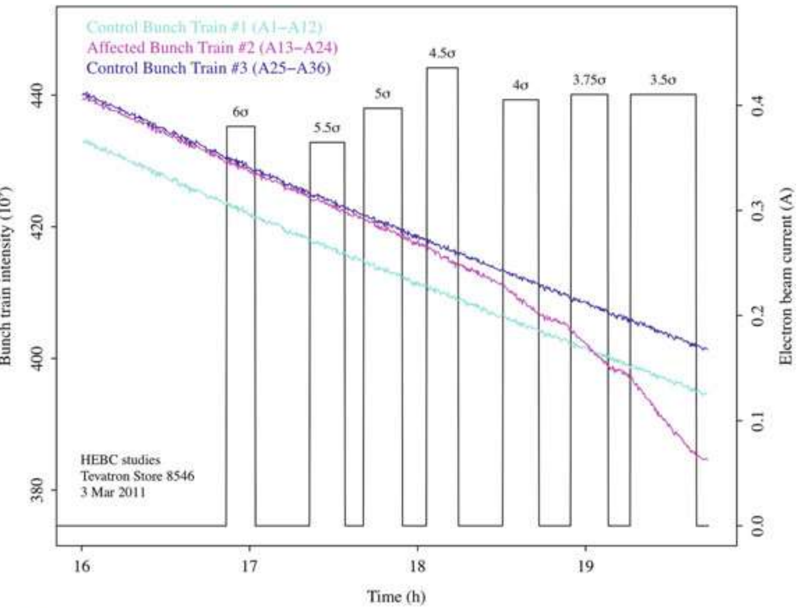
e



c



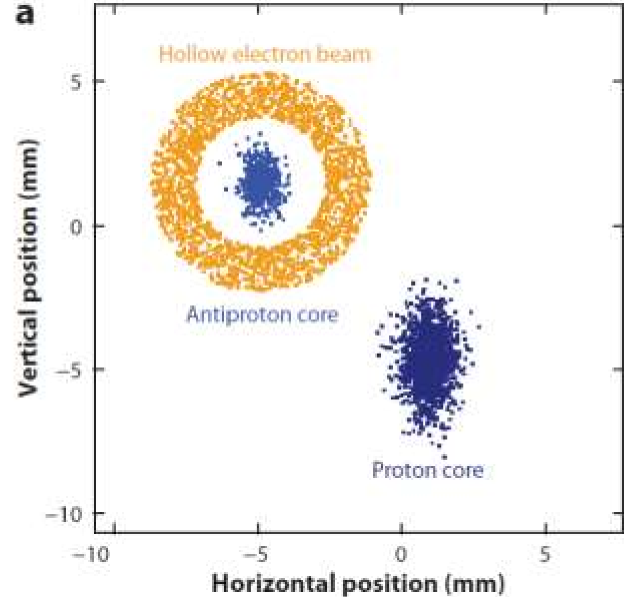
Hollow e-Beam in Tevatron



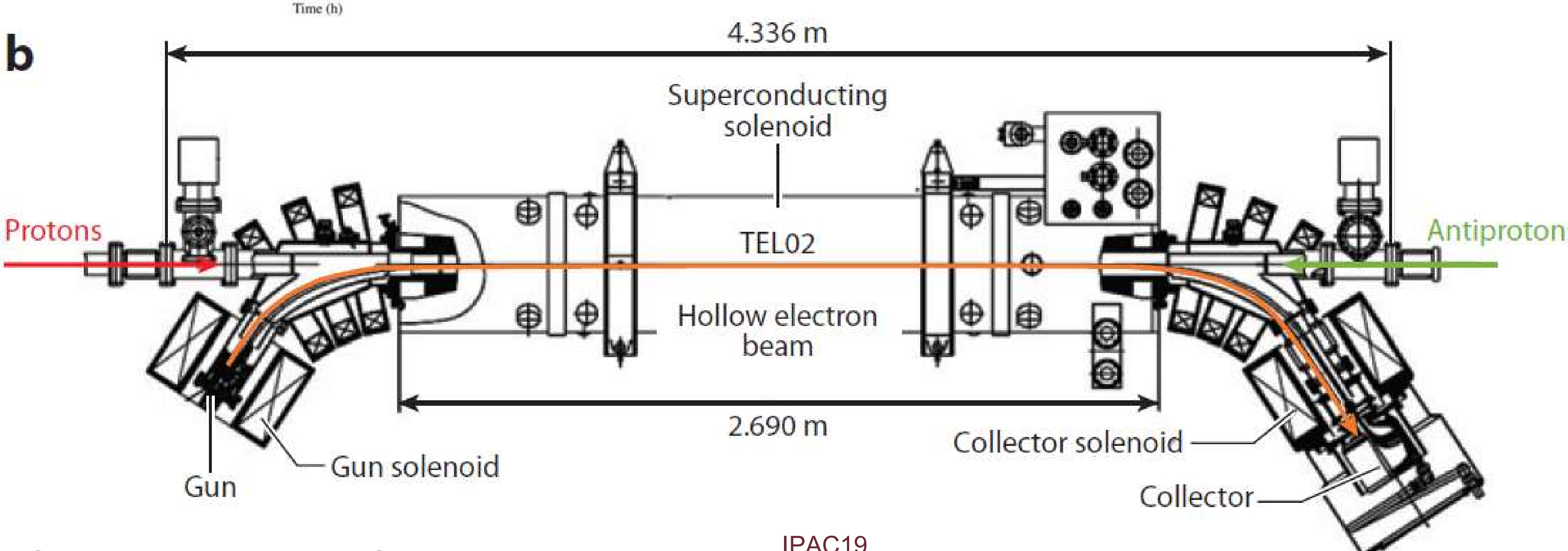
Tevatron Electron Lens:

hollow e-beam removed halo protons (3.5-6 sigma) without affecting luminosity

a



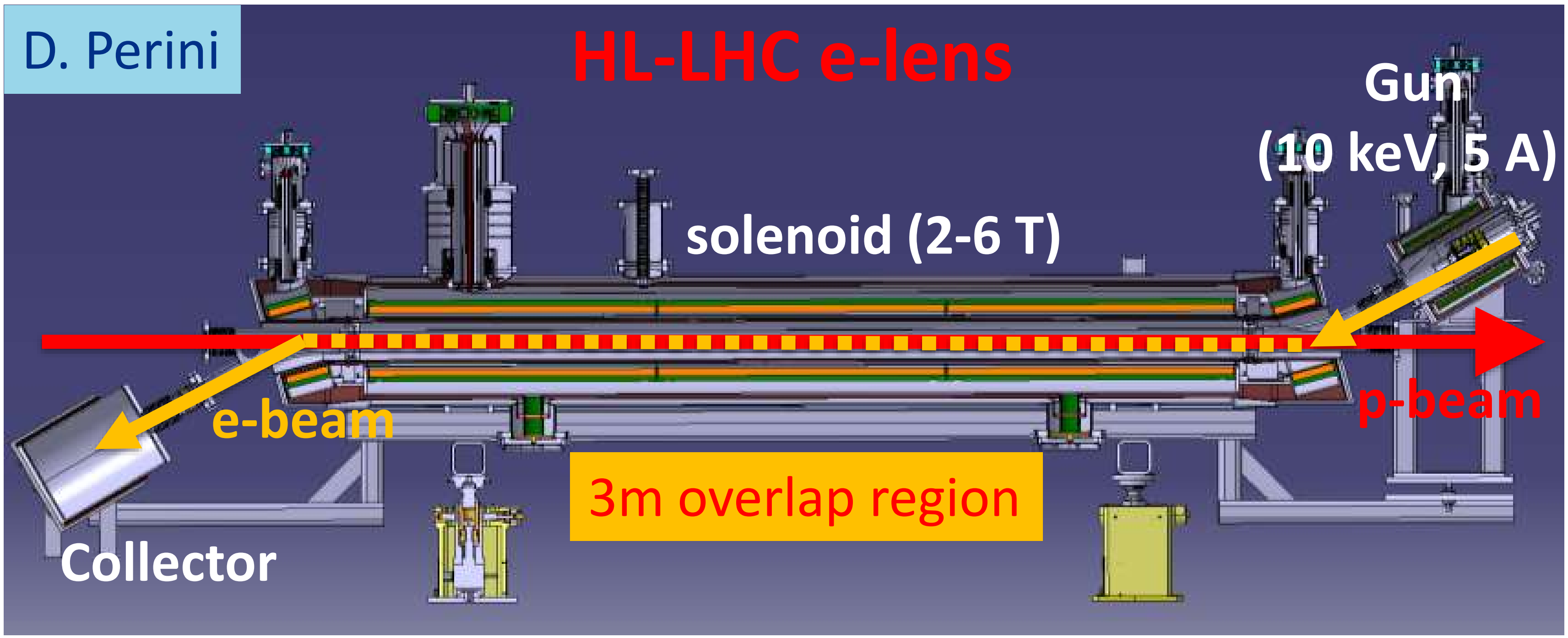
b



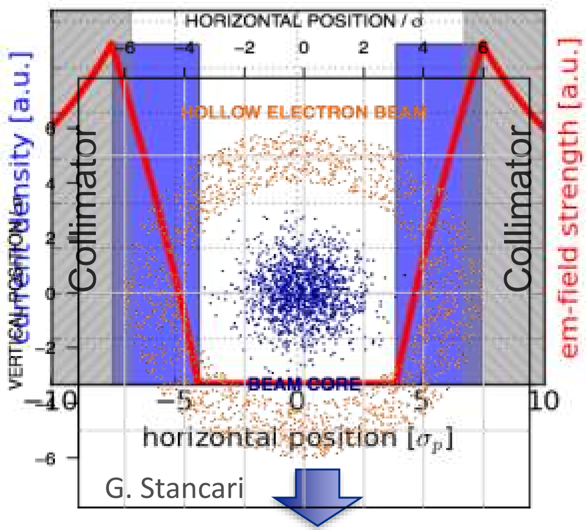
Stancari, Valishev, Shiltsev

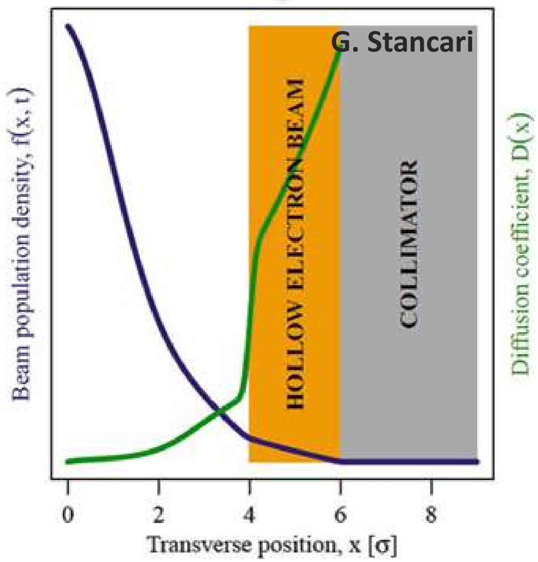
What is an electron lens?

- DC or pulsed low-energy e-beam
- circulating beam affected by electromagnetic field of e-beam
- e-beam confined and guided by strong solenoids



Hollow electron lenses at the LHC





Principle of hollow e-lens:

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

$\Rightarrow$ *active halo control*

Modes of operation:

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

$\Rightarrow$ *negligible effect on the beam core (to be confirmed)*

- pulsed operation to ***further increase diffusion***:
  - random current modulation
  - switch e-lens on/off every nth turn (drives n^{th} order resonances)

$\Rightarrow$ *e-lens could introduce noise on the p-beam core*