Electron Lenses : New Versatile Accelerator "Swiss Knife"

Vladimir SHILTSEV (Fermilab)

2019 International Particle Accelerator Conference

23 May 2019 – Melbourne, Australia

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

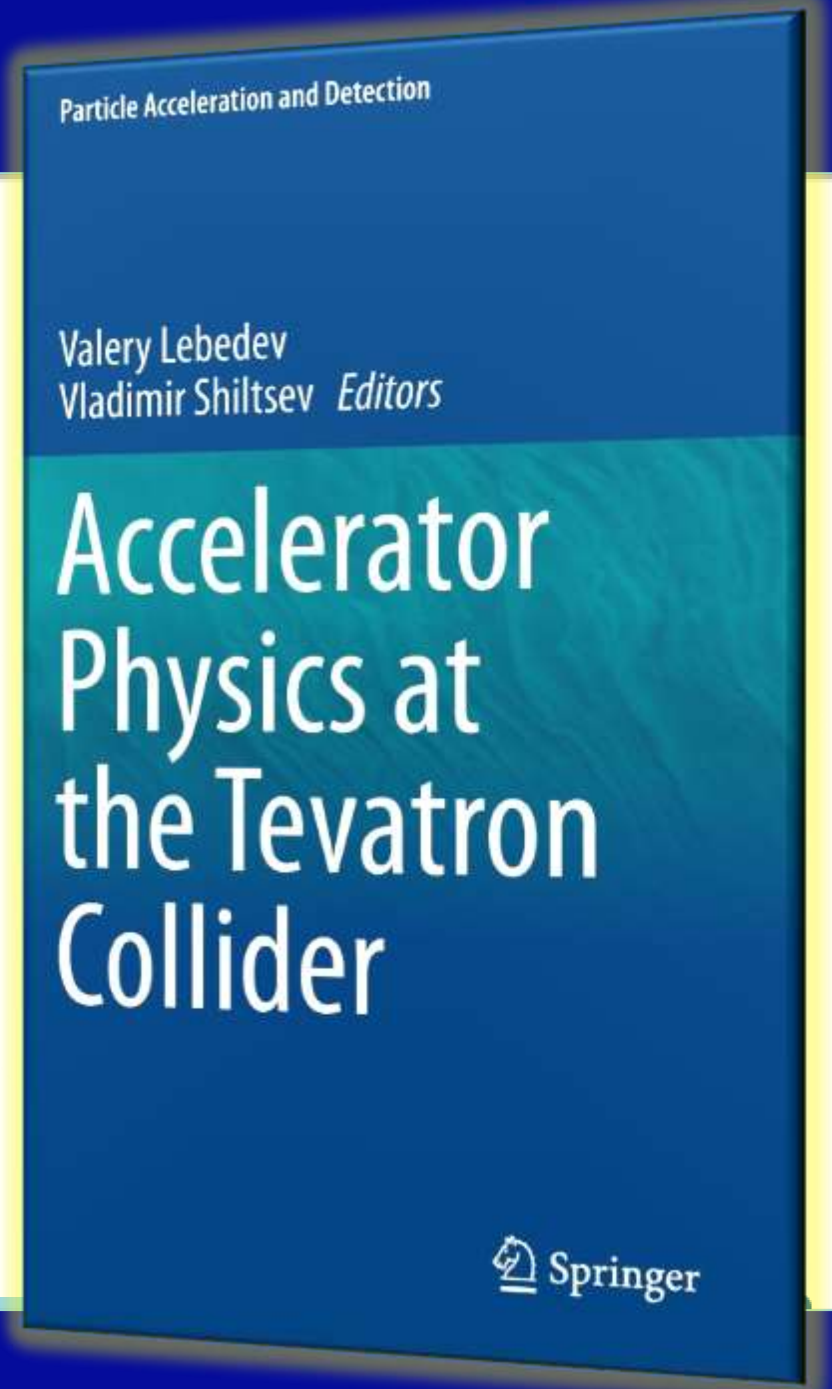

William Wallenmeyer
James Leiss
Kohei Shinozawa
Tetsuji Nishikawa
THE FIRST MEETING OF THE US-JAPAN COMMITTEE ON
HIGH ENERGY PHYSICS
SLAC - 1979


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

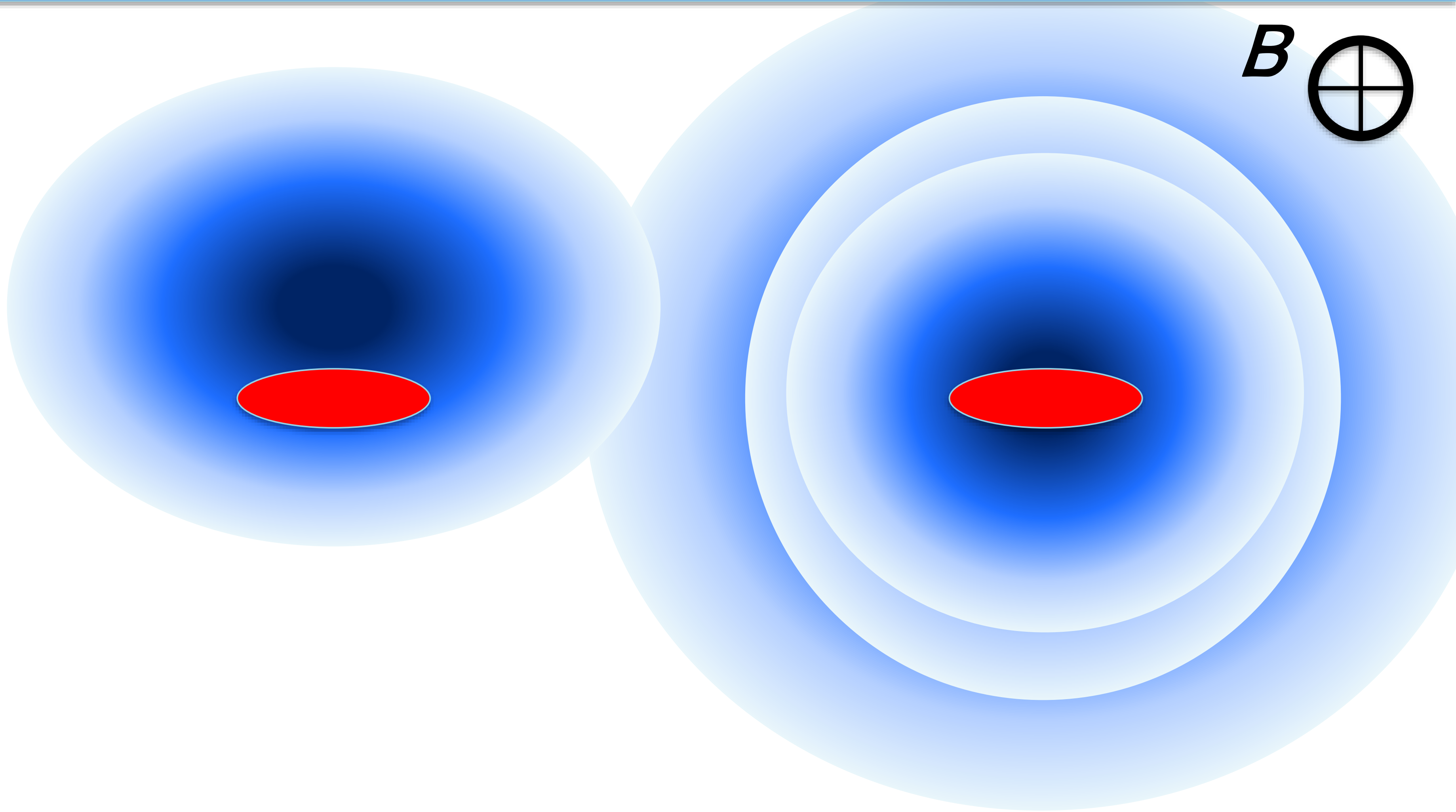
Many thanks to those who nominated me and to many colleagues I had fortune to work with over many years on the electron lenses, the Tevatron collider and many interesting and important topics from beam-beam effects to bent crystal collimation, ground motion and orbit stabilization, head-tail instability 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.

Book (2014)

- A lot of illuminating material on the beam physics of supercolliders can be found in our 2014 book (with Valery Lebedev, eds.)
- Below, I will mostly concentrate on the electron lenses and their applications



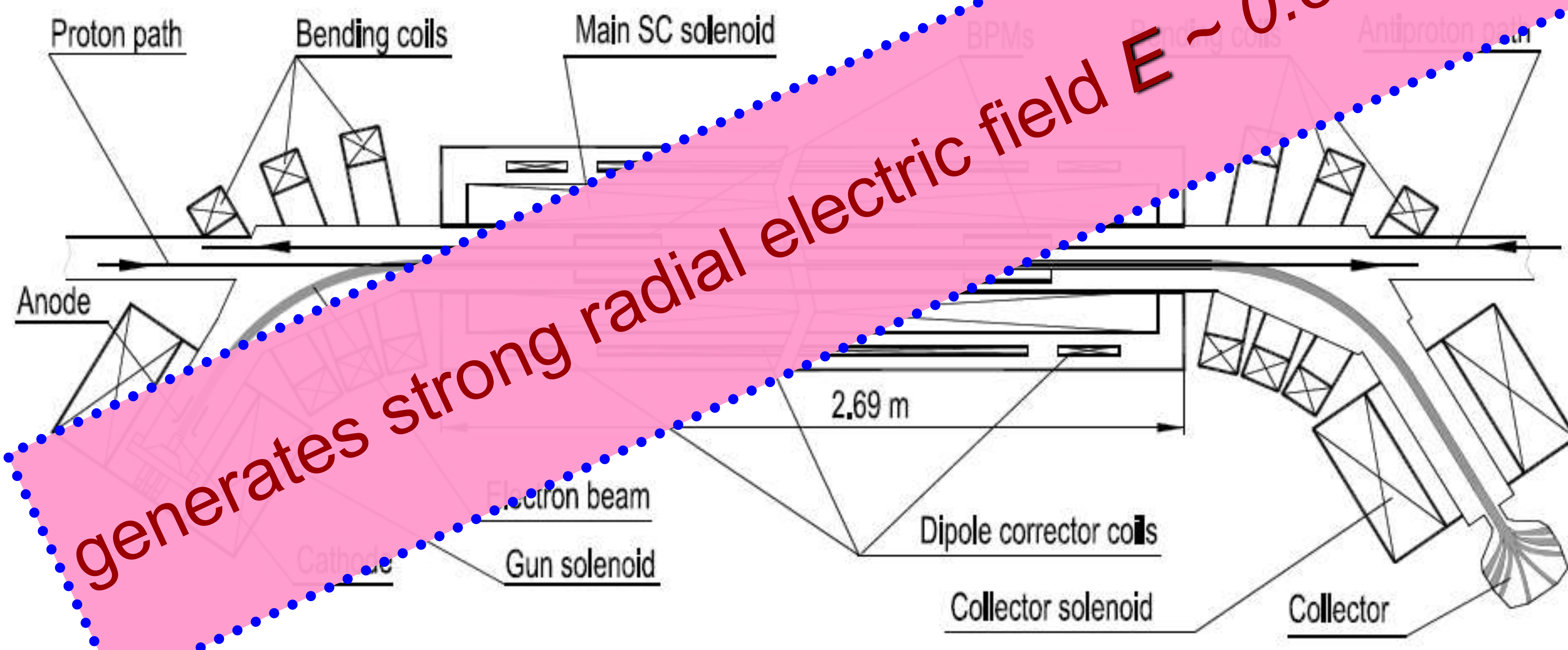
What Can Be Done With Electron Space Charge



Electron Lens

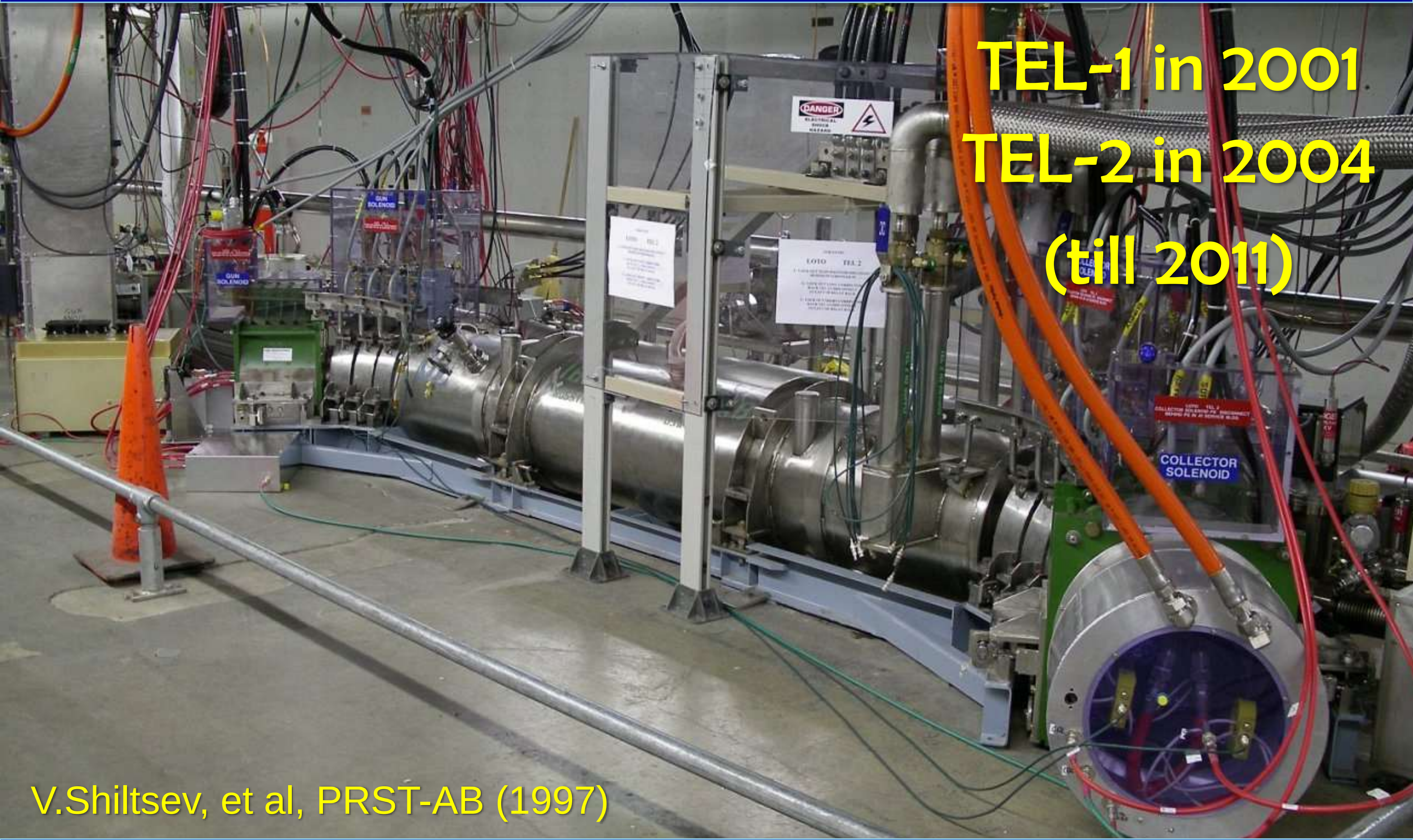
~4 mm dia 2 m long in 3T solenoid beam of ~10kV

~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
(till 2011)

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 10 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:

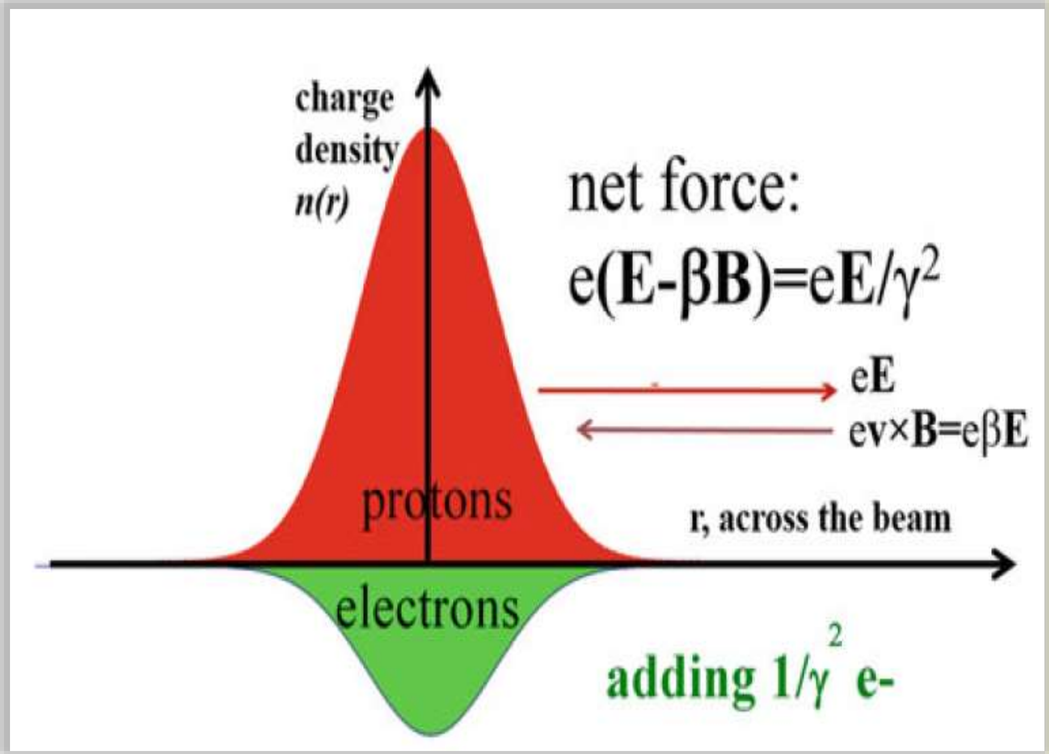
- **hollow electron beam collimation** of protons in the HL-LHC;
  Conceptional Design Report, CERN-ACC-2014-0248 (2014)
- **long-range beam-beam compensation** as current-bearing “wires” in the HL-LHC
  Valishev,Stancari, arXiv:1312.5006; Fartoukh et al., PRSTAB ***18****, 121001 (…15)*
- generation 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 coherent instabilities in the LHC, FCC-hh (better than 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

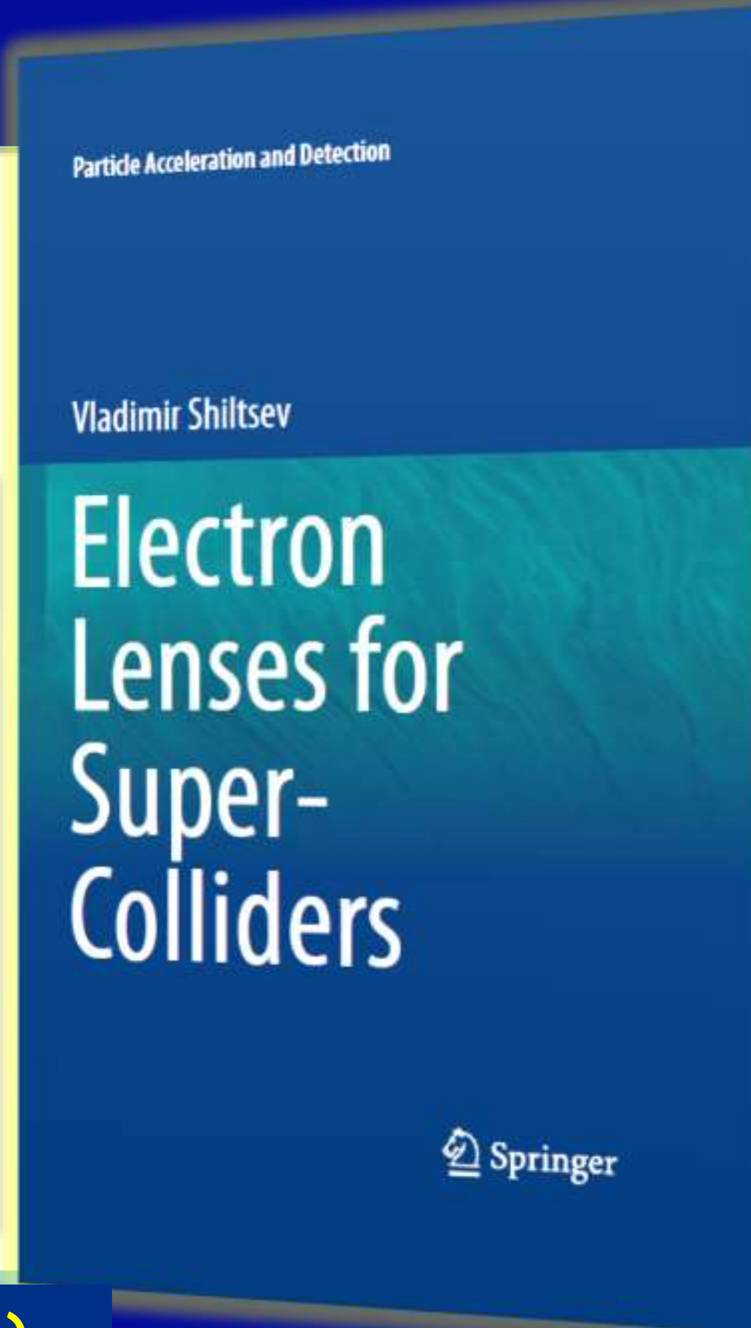
FUTURE

versatile applications depending on e-beam profile + pulsing

Book (2017)

Let me discuss here just one example: compensation of space-charge effects by electron lenses

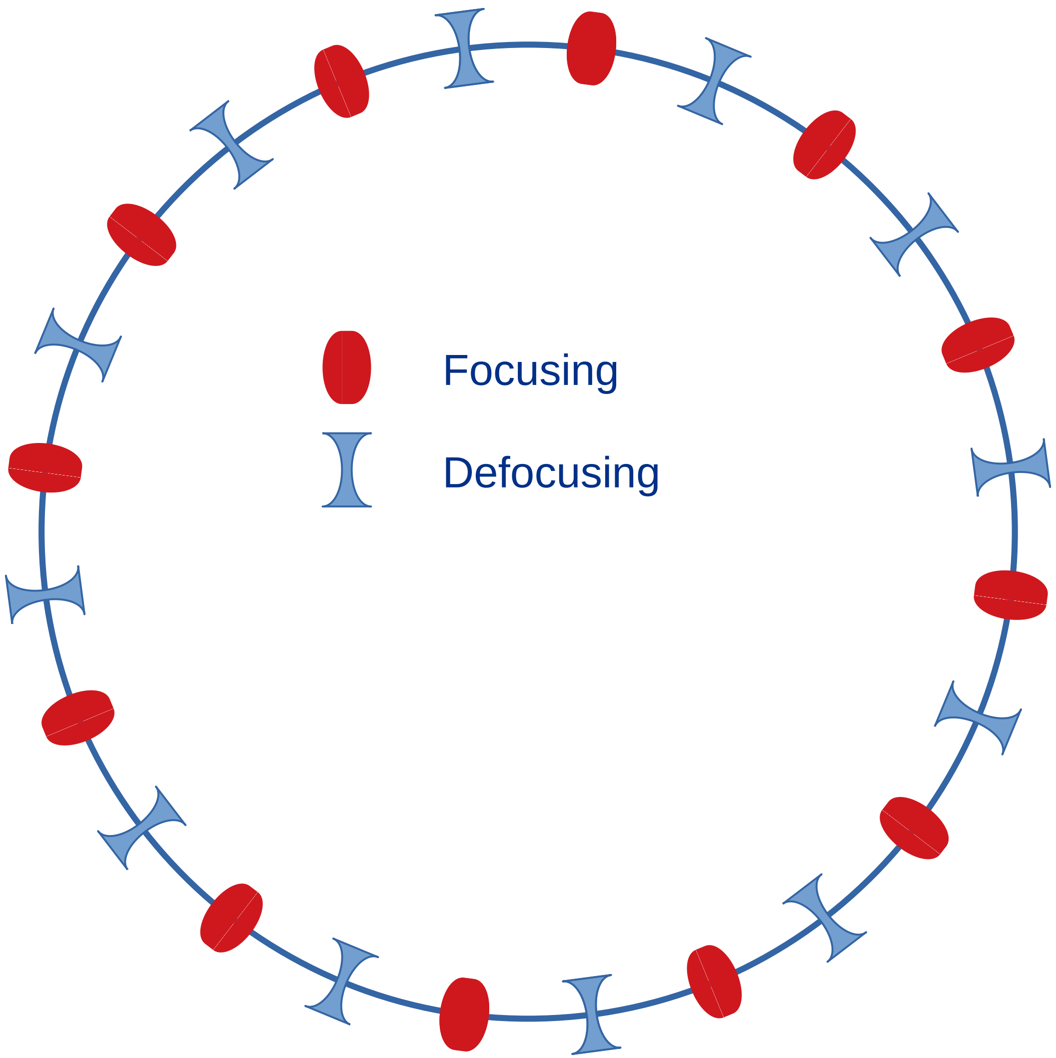




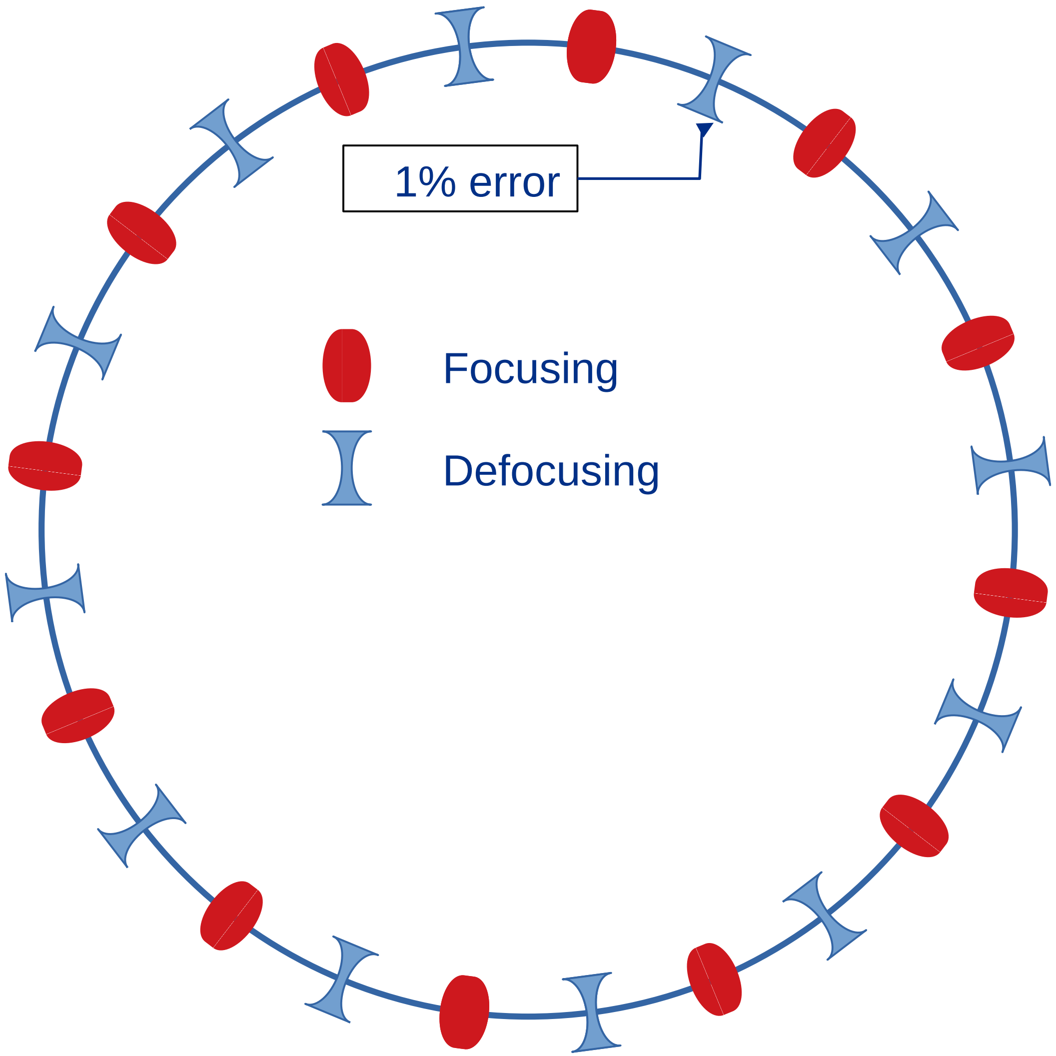
PIC simulations by E.Stern, et al (FNAL)

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

Case #1



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

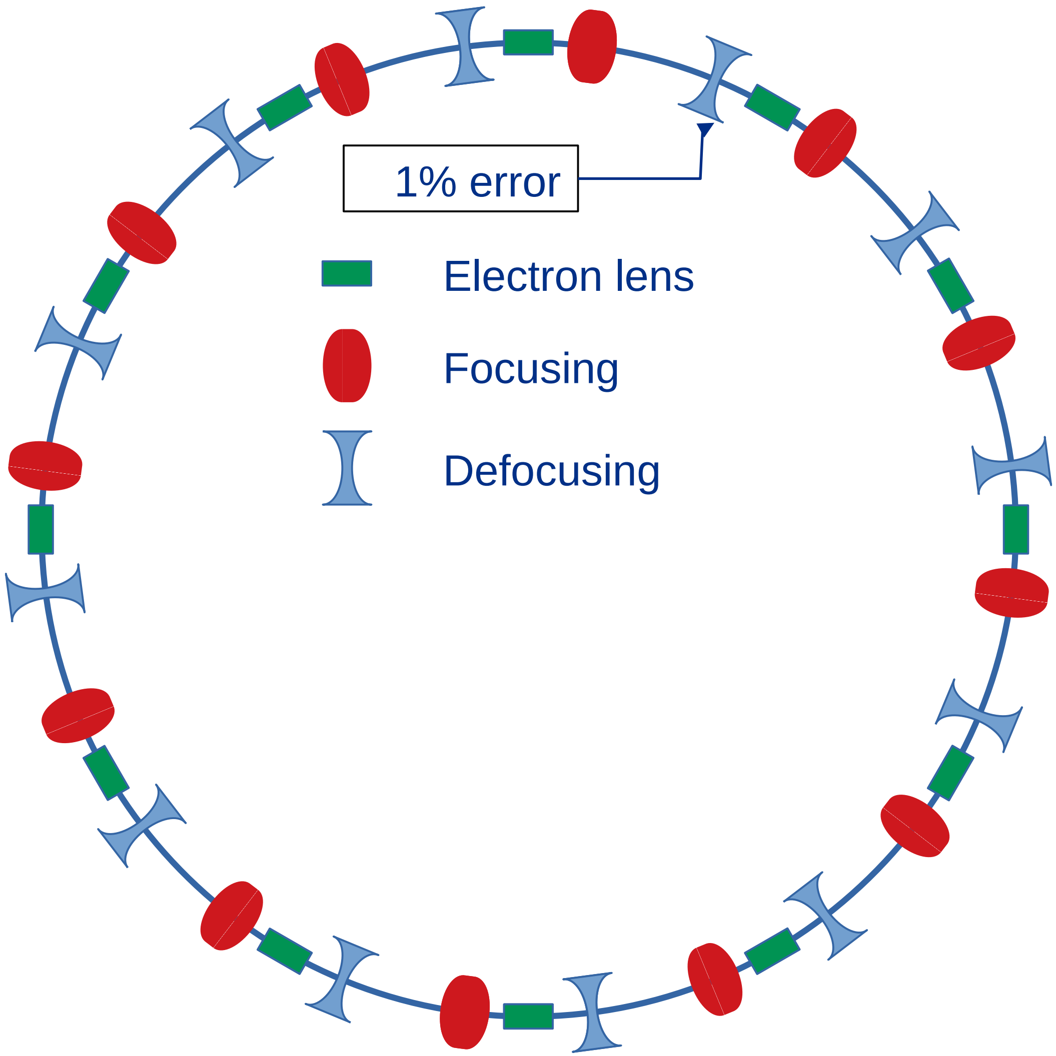


Case #2

Fermilab

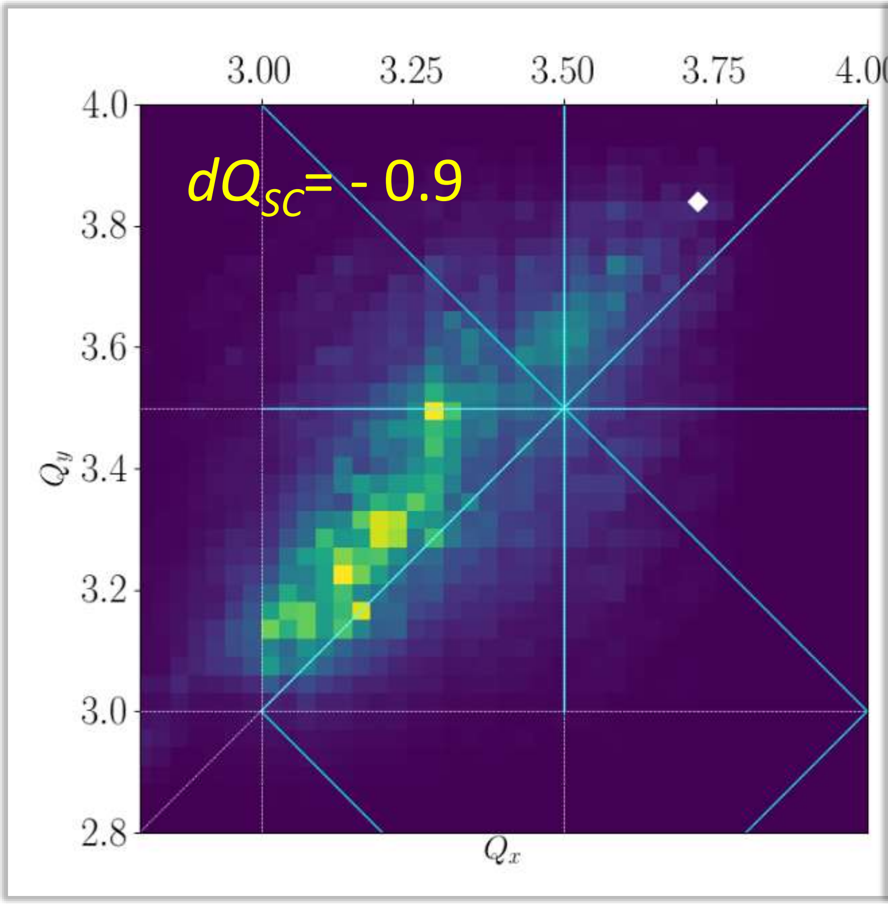
1000 Turns in a Ring with dQ_{SC}=-0.9

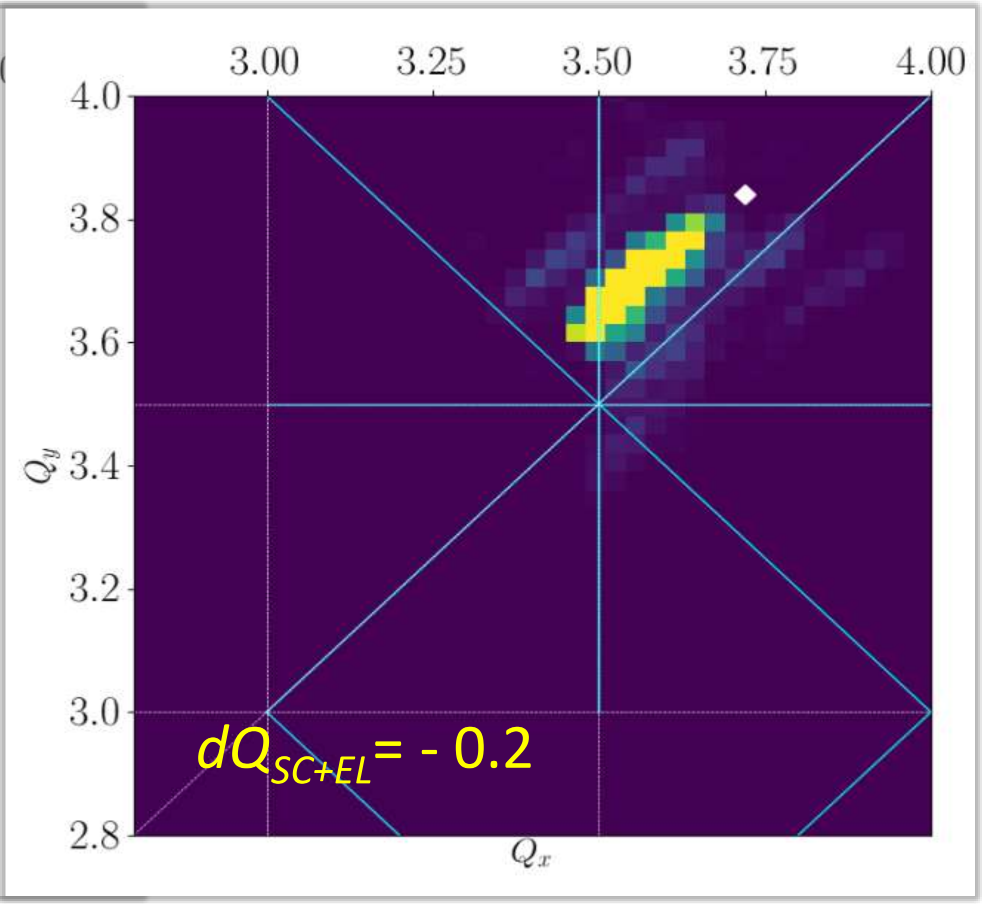
Case #3



Fermilab

Tune Footprint dQ_{SC}=-0.9



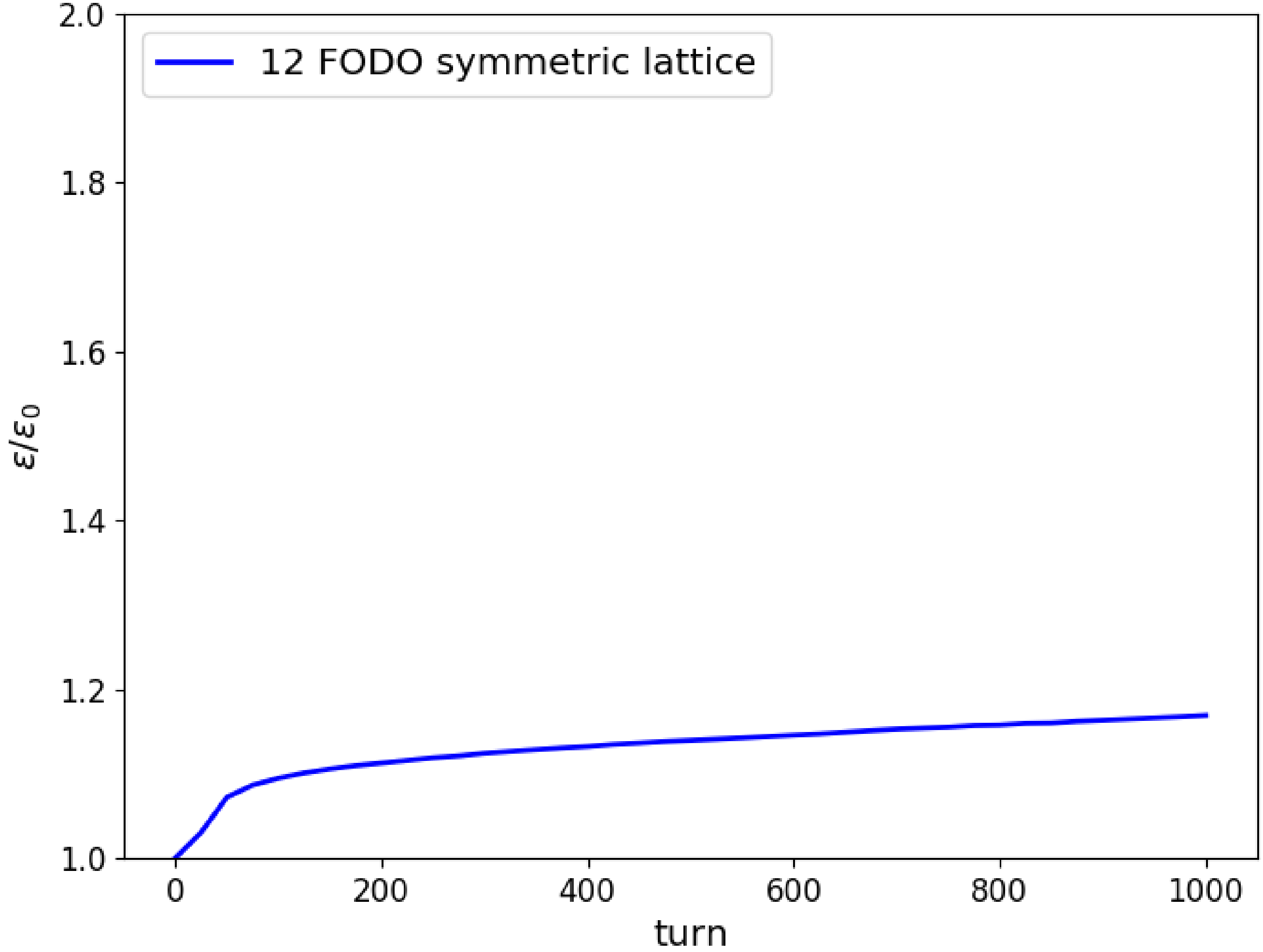


no e-lenses **~75% e-lens compensation**

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

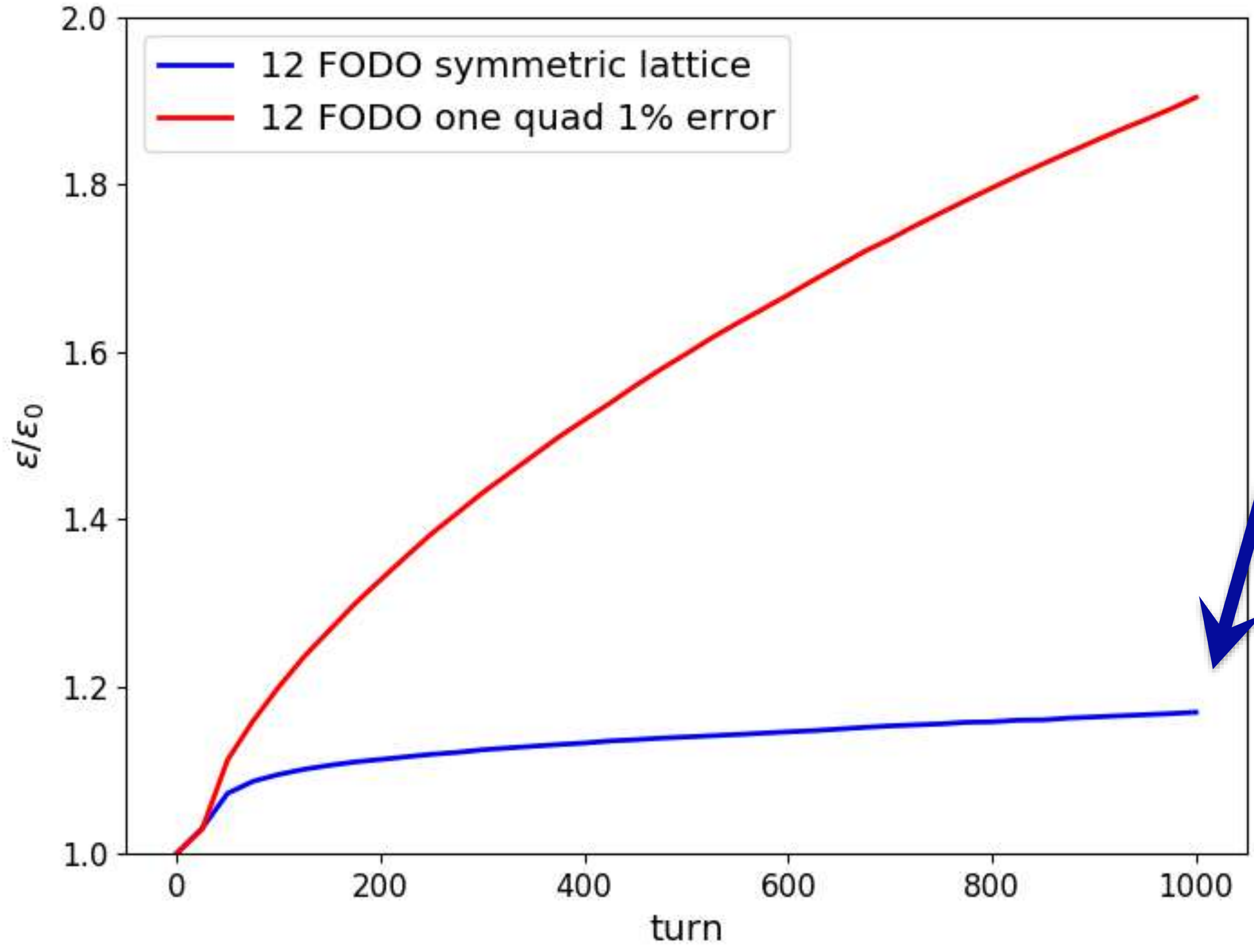
Emittance Growth – Case #1

no error, no e-lenses



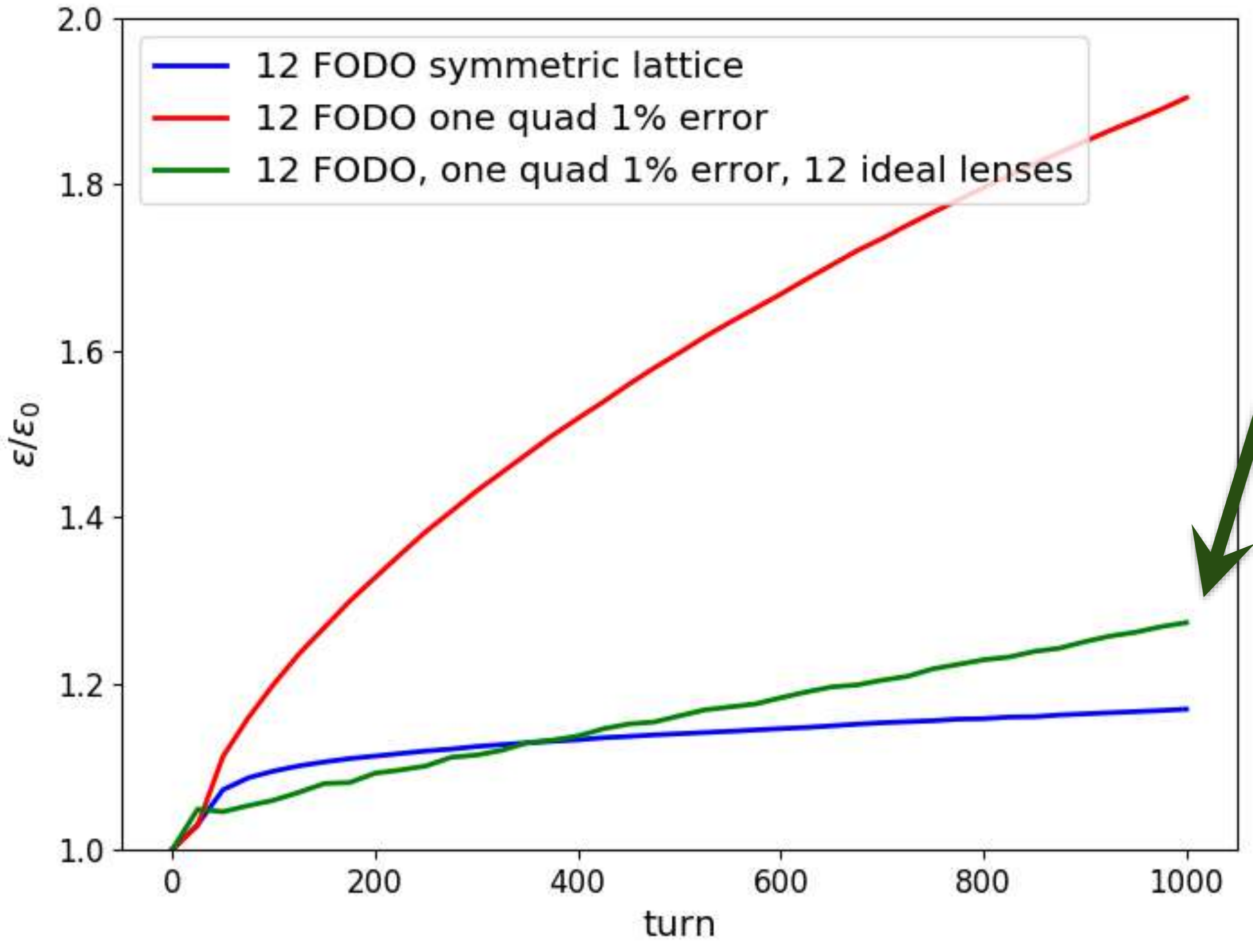
Emittance Growth – Case #2

1% error, no e-lenses

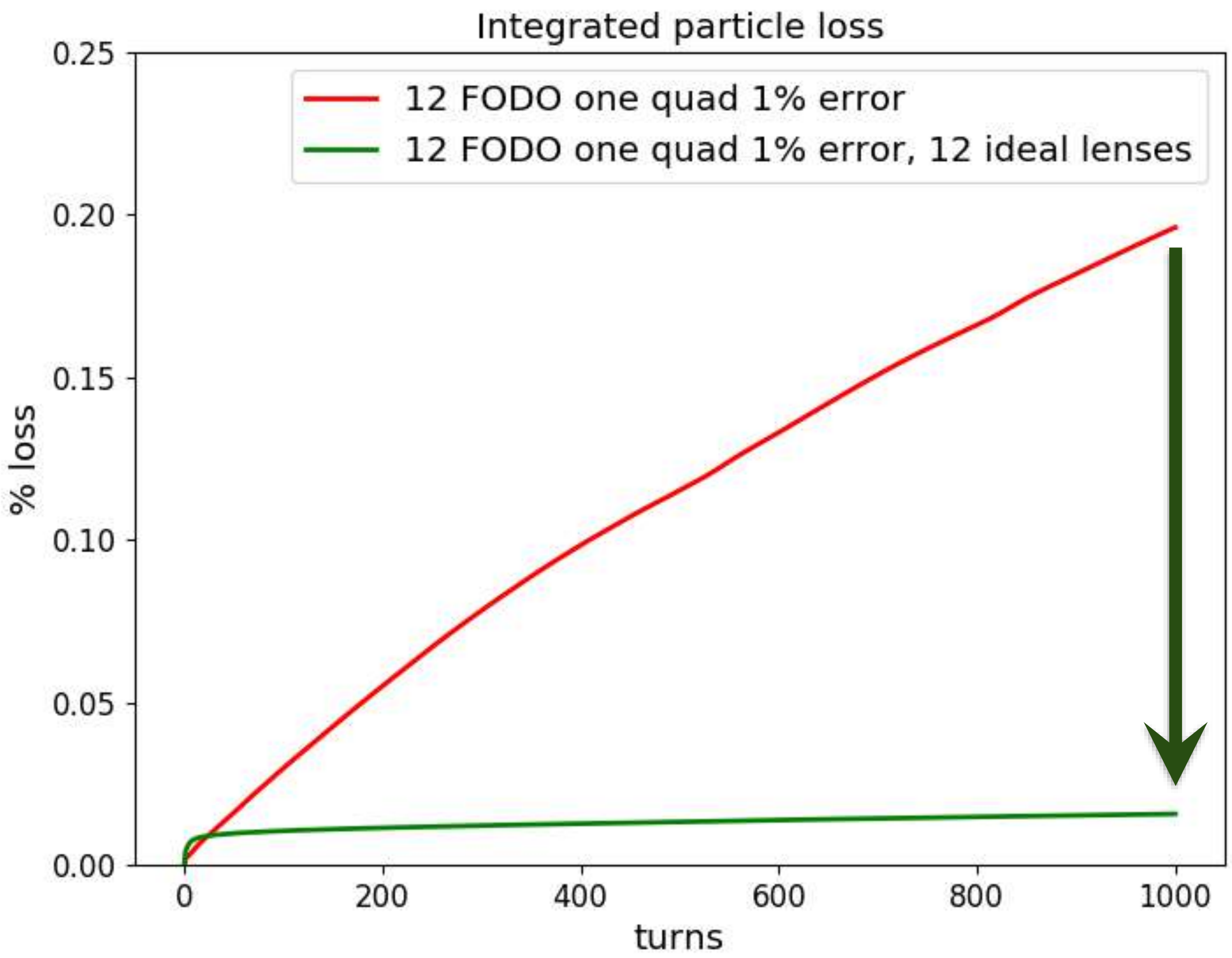


Emittance Growth – Case #3

1% error, 12 e-lenses

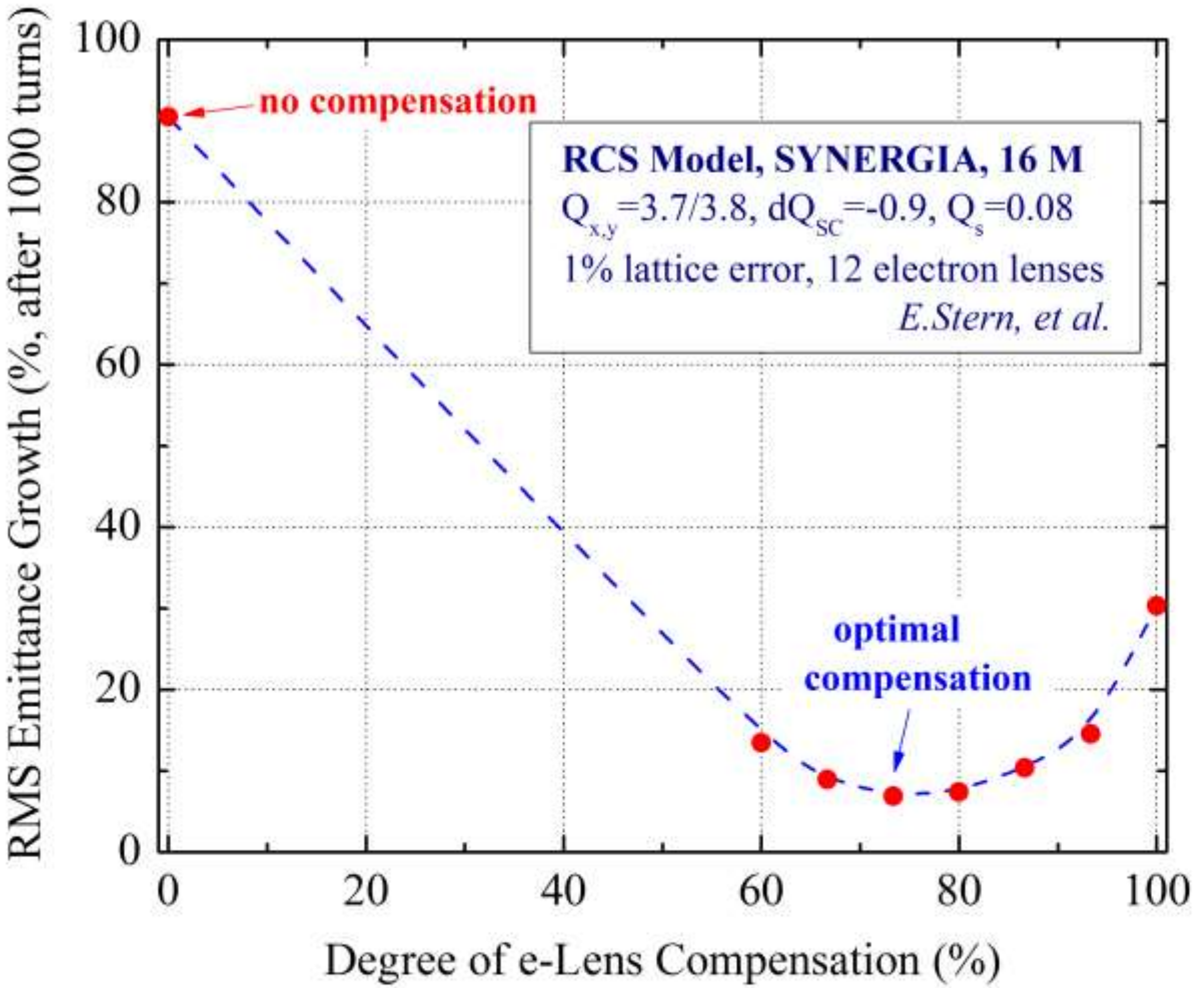


Particle Losses at 4σ – Case #2 and #3

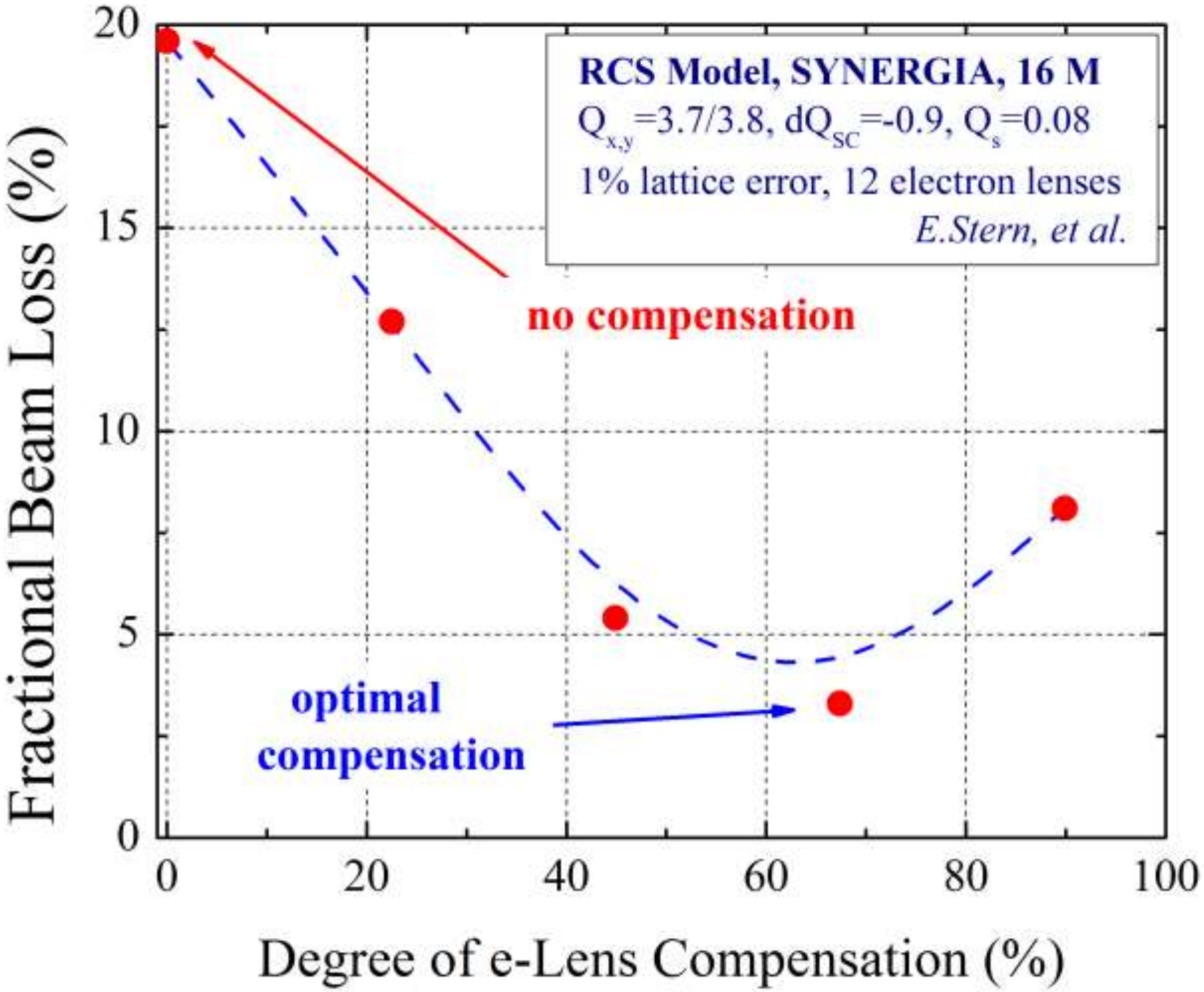


e-lenses reduce losses ~6 fold !

Optimal Compensation ~75% (emitt. growth)



Optimal Compensation ~70% (beam losses)



IOTA: *Integrable Optics Test Accelerator*

IOTA/FAST 2018/2019 Research Run

Real-time image of radiation of a single electron in the IOTA ring, courtesy A.Romanov

https://fast.fnal.gov/

- Nonlinear Integrable Optics
- Single-electron tomography
- Initial experiments towards Optical Stochastic Cooling, Quantum Science
- Higher-Order Mode Measurements in the ILC SRF Cryomodule
- Magnetized beam manipulation technique (for the EIC project)
- Short-range wakefields studies
- **IPAC19: Invited talk T.Zolkin** (FRXPLS1)+17 posters: MOPGW113, MOPRB088, MOPGW107 , MOPGW127, MOPRB089, MOPTS115 , WEPTS068, WEPTS070, WEPTS074, WEPTS078, WEPTS073, MOPGW109, WEPGW100, WEPGW163, MOPGW108, THPRB106 ,TUPRB089

Li er

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

TeV

~1000

~100

, ~10^6

$0^{30\text{-}32}$

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

ilab

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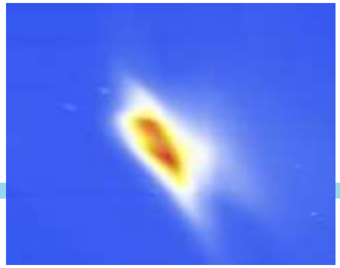
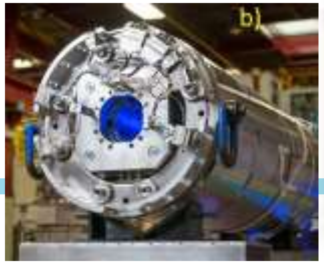
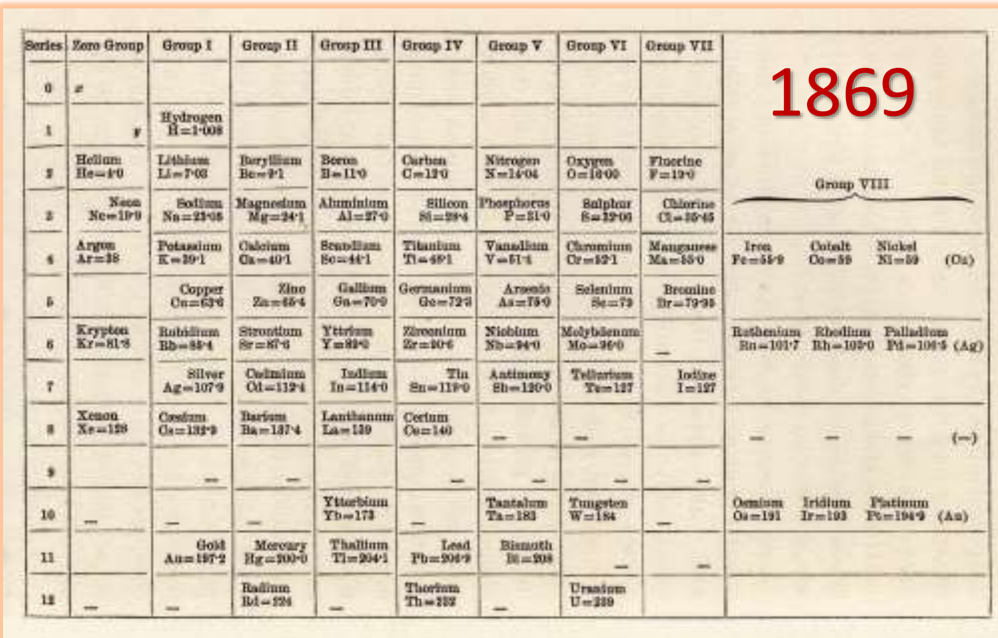



Celebrate Science! – 2019 is UNESCO's

Int'l Year of Periodic Table (150 yrs)



1869

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					

Dmitri Mendeleev

https://www.iypt2019.org/

Thank You for Your Attention!

BACK UP SLIDES

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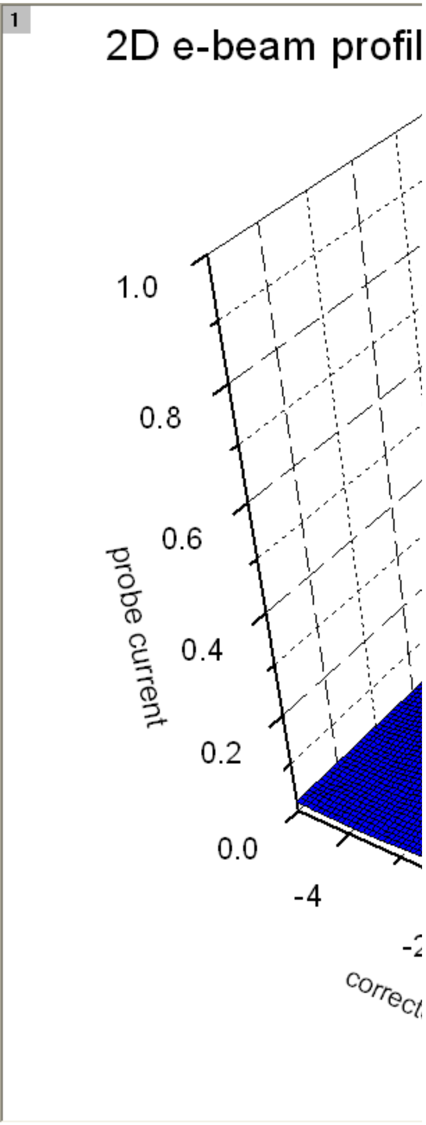
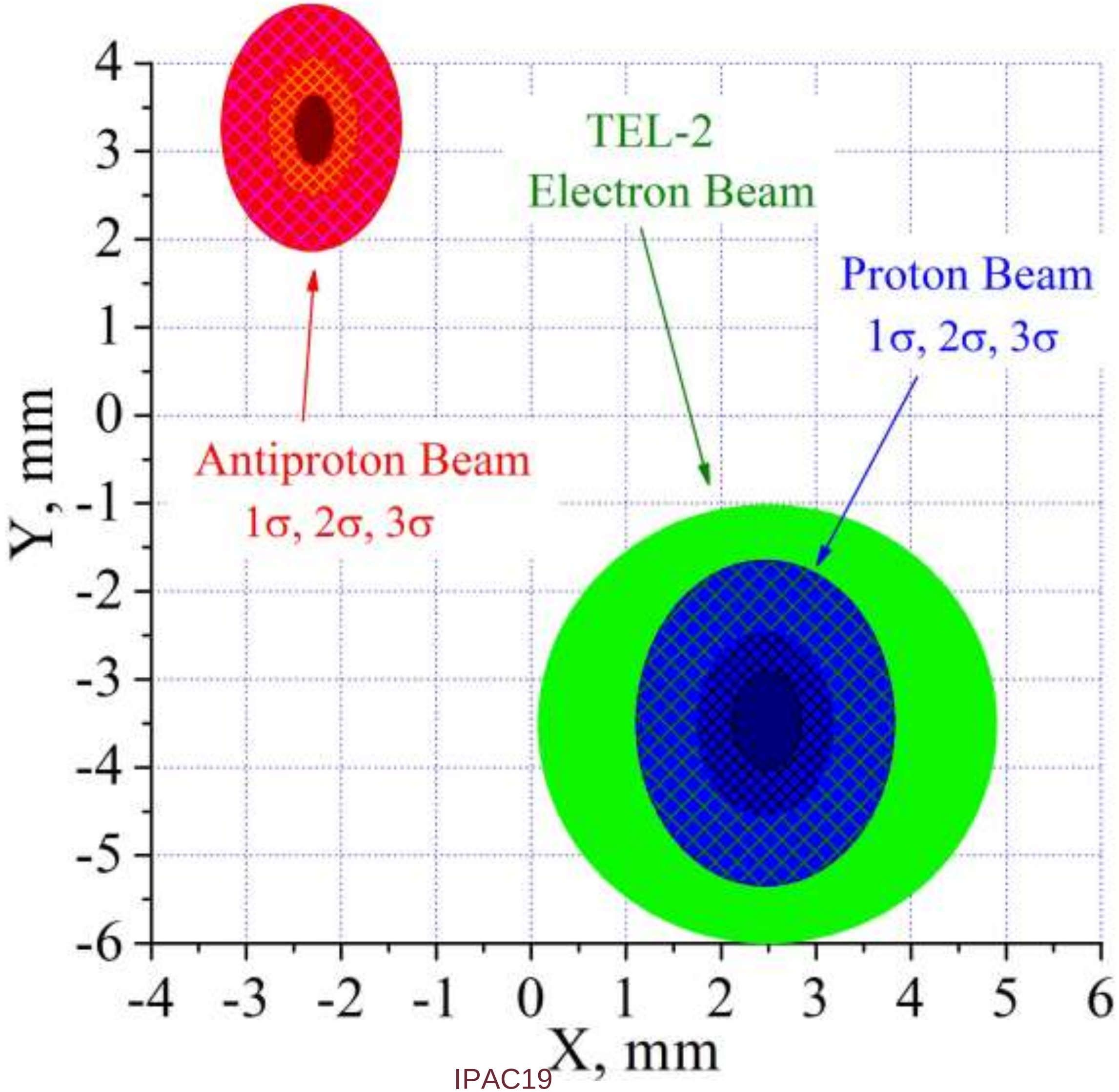
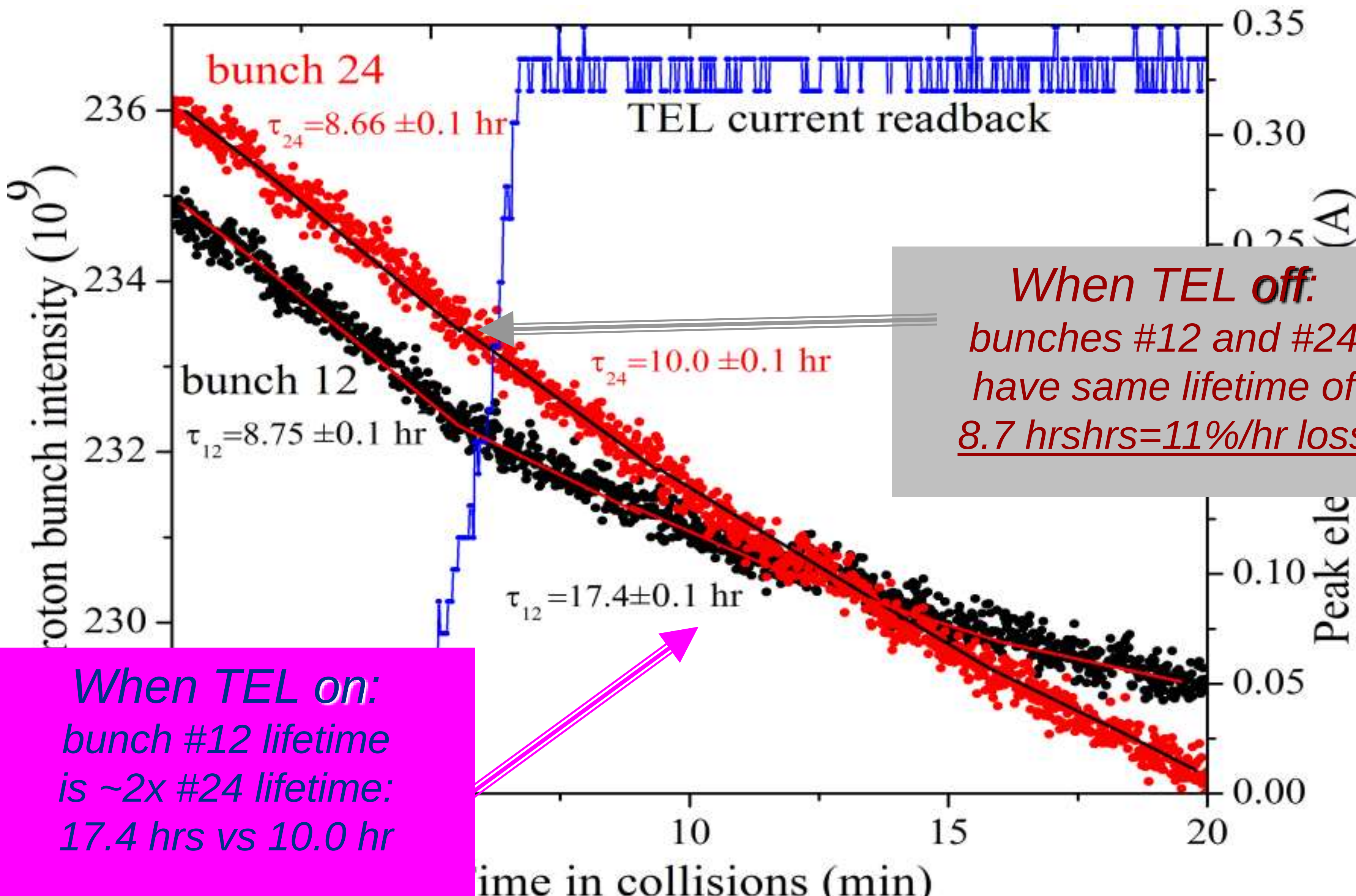
Beam-Beam Compensation

in Tevatron operation - TELs compensated of long range BB effects





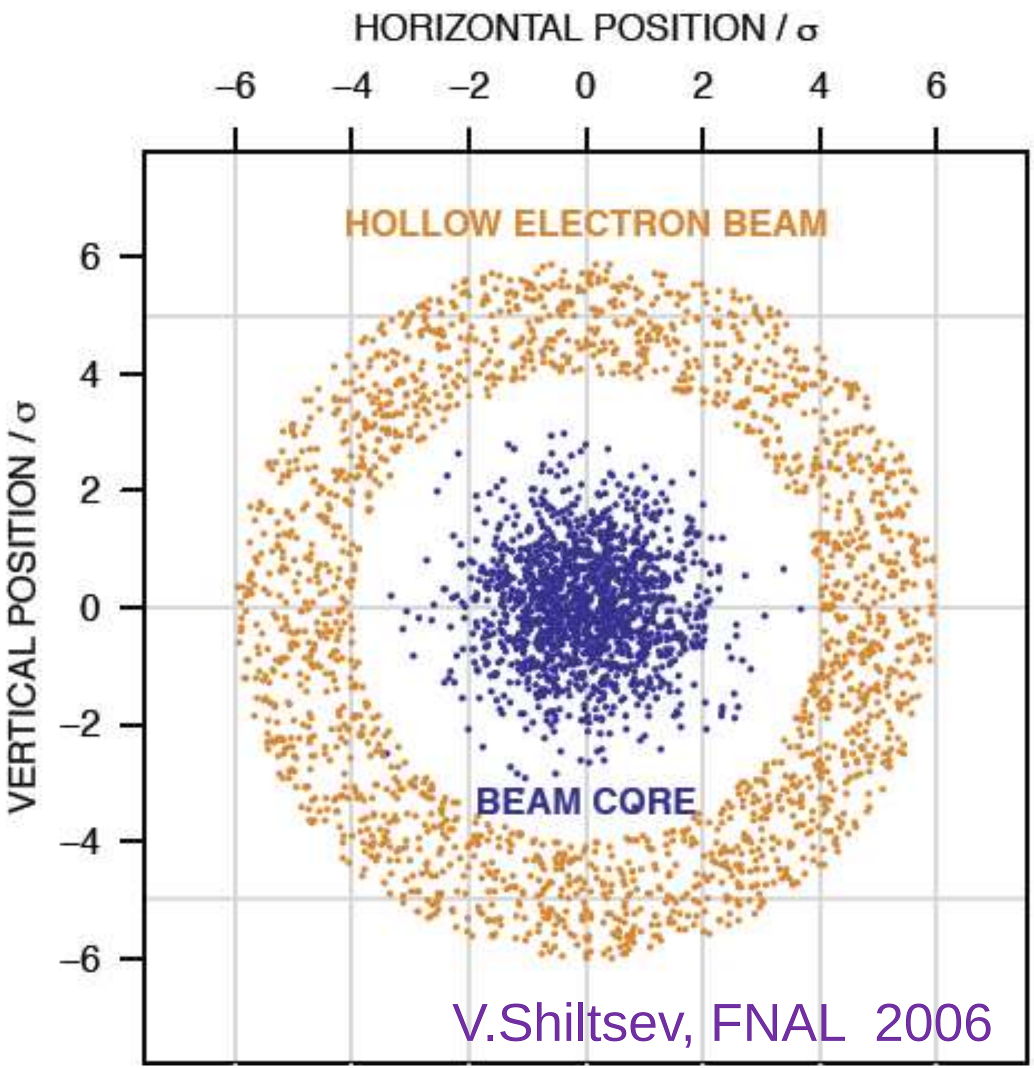
TEL2 on One “Bad” Bunch (P12)



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

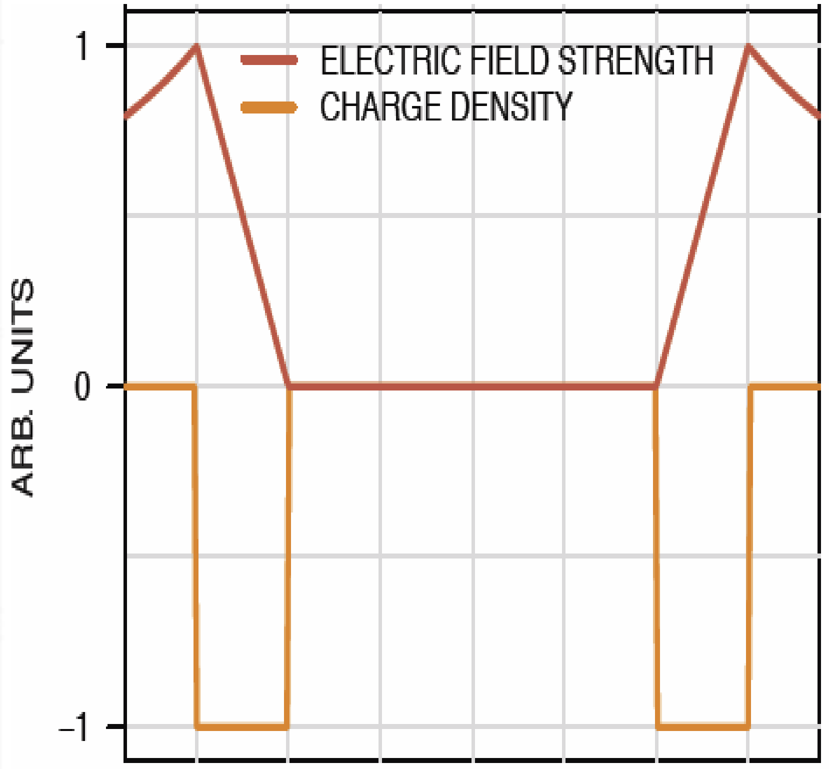
When TEL on:
bunch #12 lifetime
is ~2x #24 lifetime:
17.4 hrs vs 10.0 hr

Physics: Hollow Electron Beam Collimation



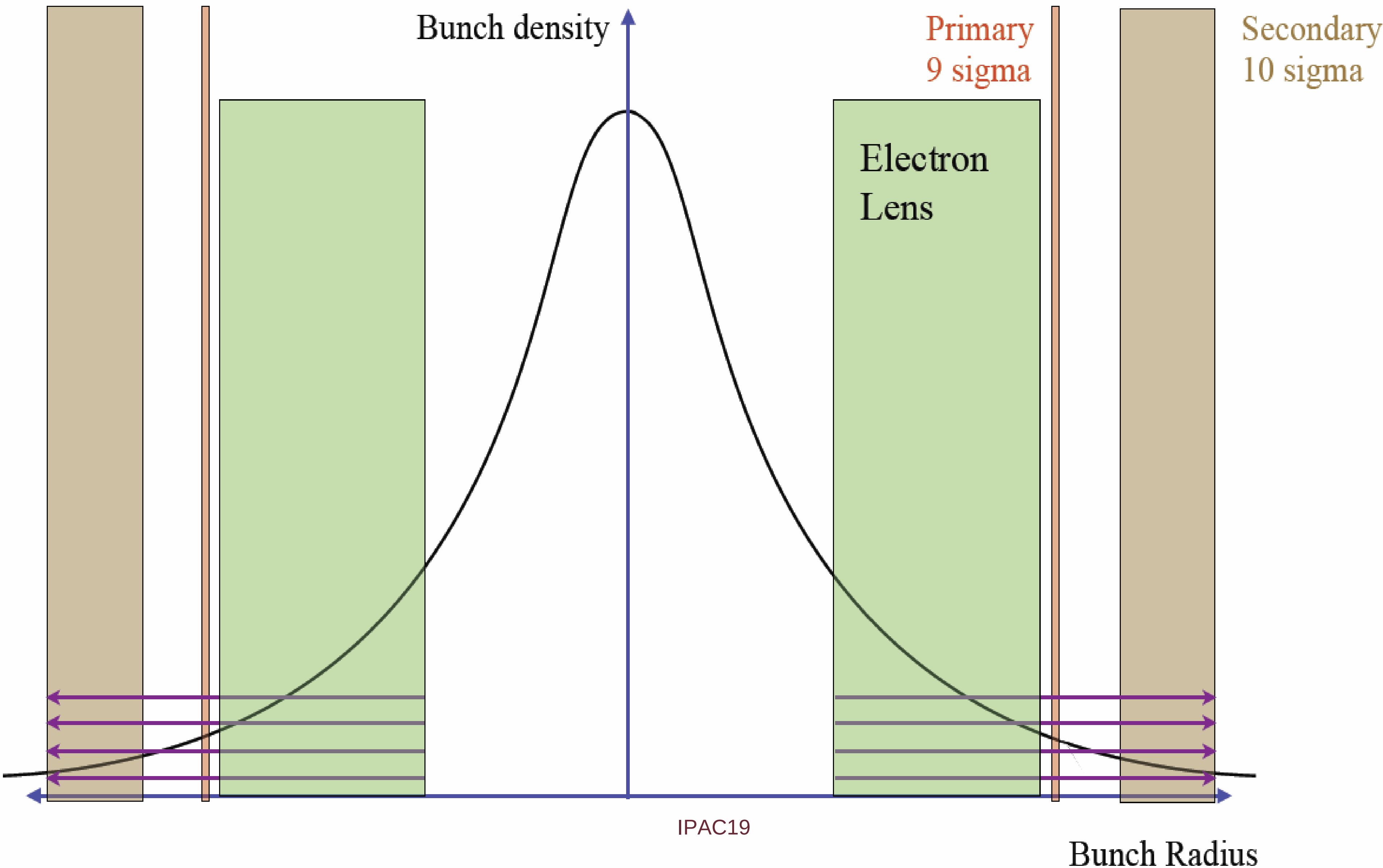
No EM field inside

Strong field outside



Concept Hollow Electron Beam Collimation

Tevatron – 2 MJ beams, LHC – 360 MJ beams

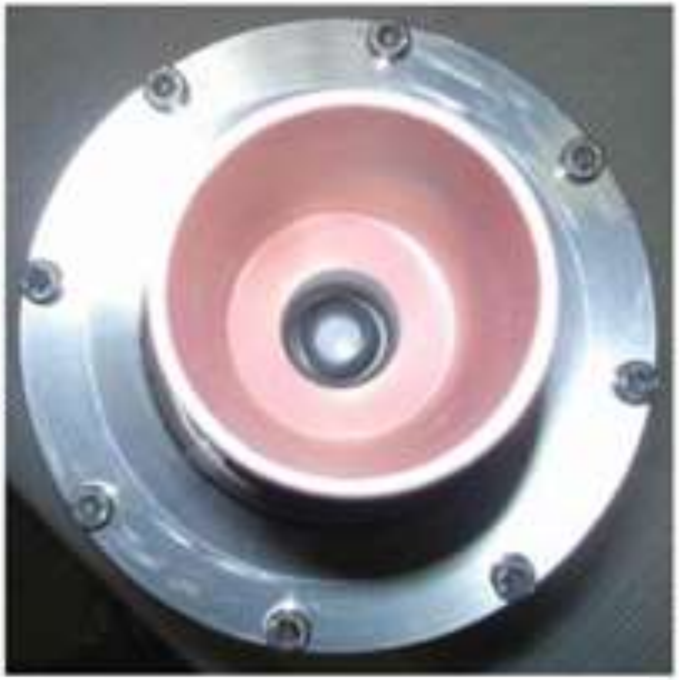


Tevatron Hollow e-Collimator

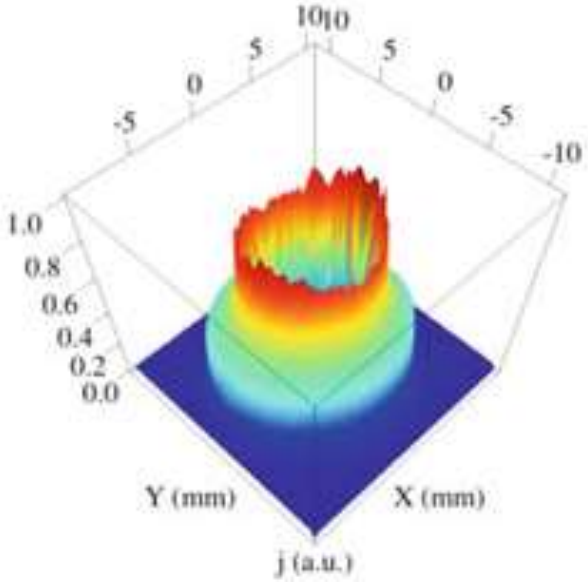
Advantages:

- 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

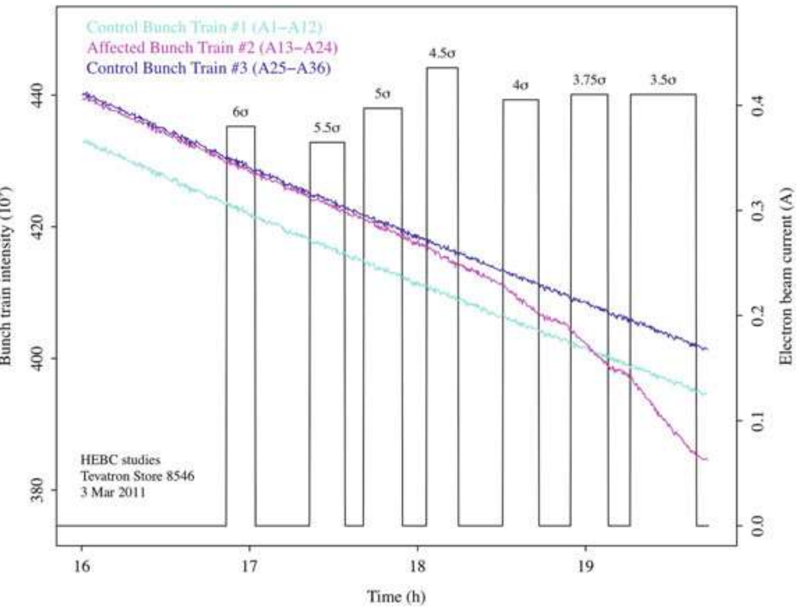
e



c

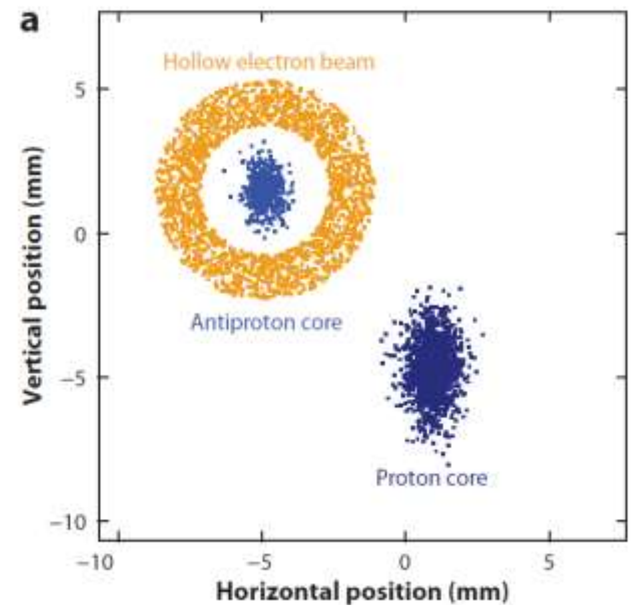


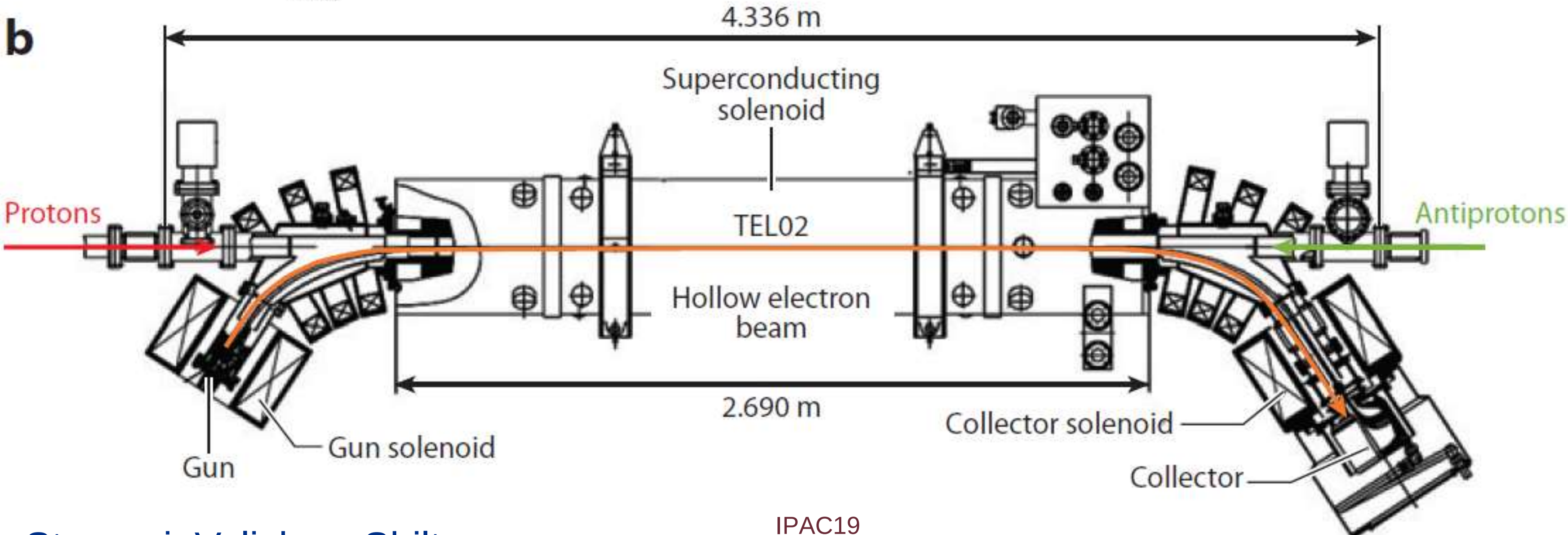
Hollow e-Beam in Tevatron



Tevatron Electron Lens:

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

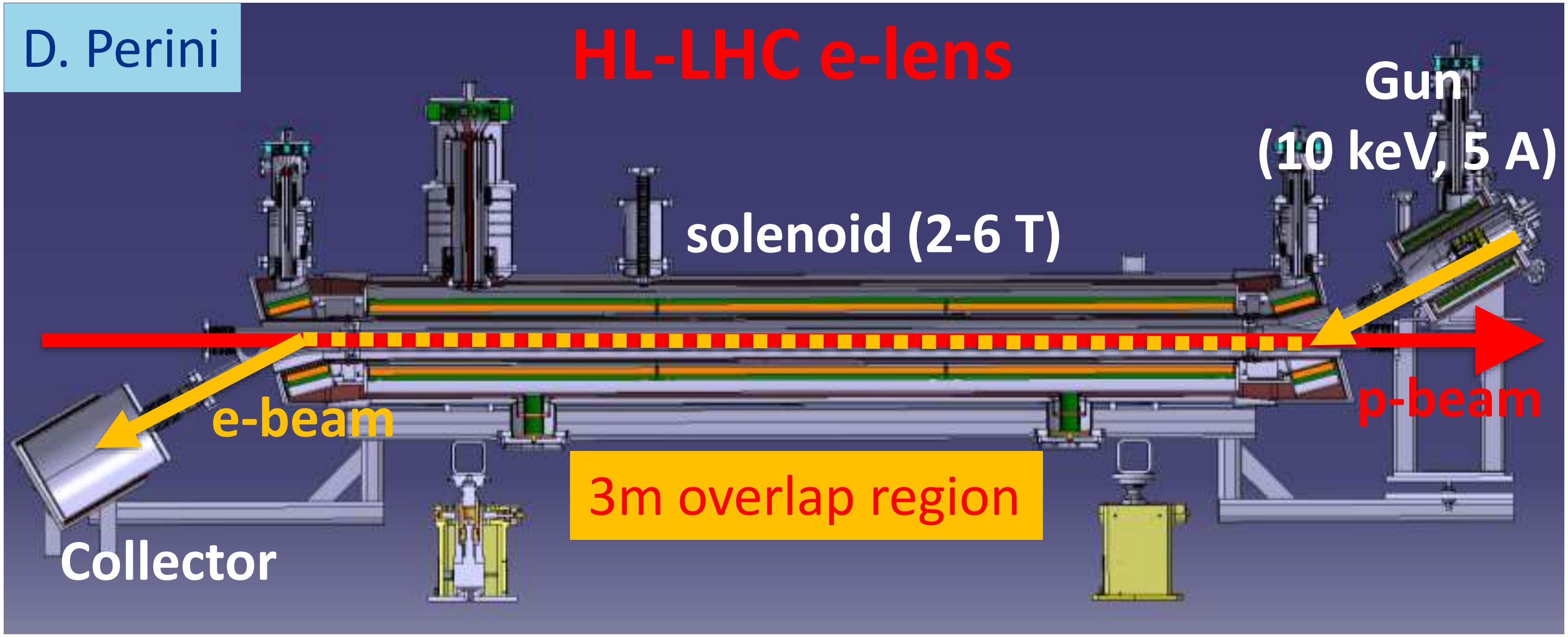




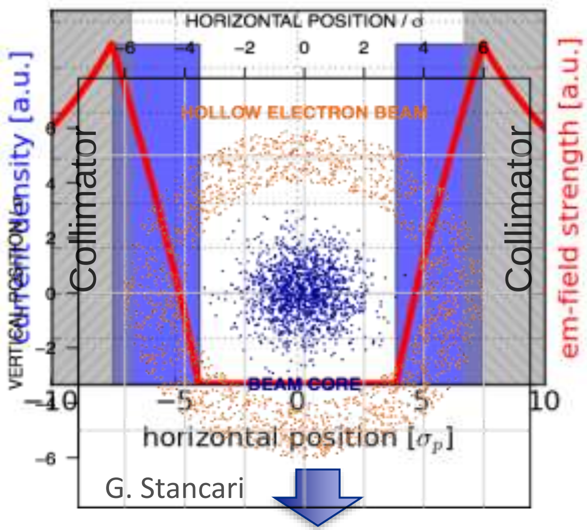
Stancari, Valishev, Shiltsev

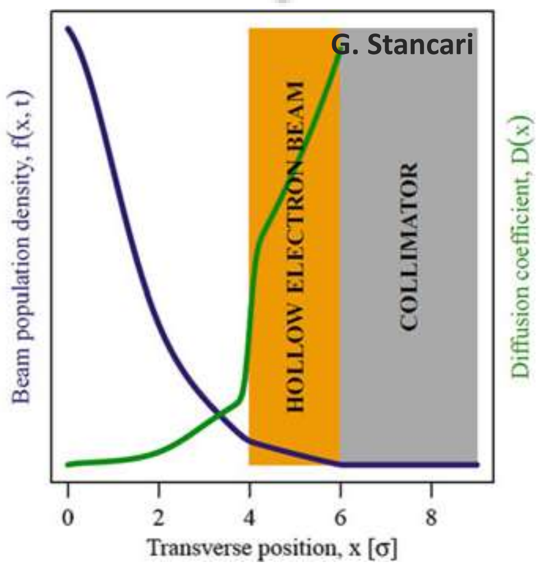
What is an electron lens?

- 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 nth order resonances)

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