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
THE FIRST MEETING OF THE US-JAPAN COMMITTEE ON HIGH ENERGY PHYSICS
SLAC - 1979
Shin-Ichi KUROKAWA
Chair of IPAC19 Prize 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 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
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 $E \sim 0.3$ MV/m
Two Electron Lenses Were Installed in Tevatron

TEL-1 in 2001
TEL-2 in 2004
(till 2011)

In the Fermilab Tevatron Collider:

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

- abort gap collimation (for 10 years in regular operation);
  

- studies of head-on beam-beam compensation;
  
  \textit{Shiltsev et al, NJP (2008); Stancari et al., PRL 107, 084802 (2011)}

- demonstration of halo scraping with hollow electron beams;
  
What Electron Lenses Are Good For (2)

Presently used in RHIC at BNL for head-on beam-beam compensation with significant luminosity gain \( \sim x2 \)


Current areas of research:

- **hollow electron beam collimation** of protons in the HL-LHC;

- **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., IPAC’15*

- 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*

**versatile applications depending on e-beam profile + pulsing**
Let me discuss here just one example: compensation of space-charge effects by electron lenses.
1000 Turns in a Ring with $dQ_{SC} = -0.9$

Case #1
1000 Turns in a Ring with $dQ_{sc} = -0.9$

**Case #2**

Focusing

Defocusing

1% error
1000 Turns in a Ring with $dQ_{sc} = -0.9$

Case #3

1% error

Electron lens

Focusing

Defocusing
Tune Footprint $dQ_{SC}=-0.9$

$\text{no e-lenses}$
Tune Footprint $dQ_{SC} = -0.9$

- $dQ_{SC} = -0.9$
- $dQ_{SC+EL} = -0.2$

no e-lenses

~75% e-lens compensation
Emittance Growth – Case #1

no error, no e-lenses
Emittance Growth – Case #2

1% error, no e-lenses

- 12 FODO symmetric lattice
- 12 FODO one quad 1% error
Emittance Growth – Case #3

1% error, 12 e-lenses

Graph showing the emittance growth with 1% error and 12 e-lenses.
Particle Losses at $4\sigma$ – Case #2 and #3

Integrated particle loss

- 12 FODO one quad 1% error
- 12 FODO one quad 1% error, 12 ideal lenses

% loss

0.25

0.20

0.15

0.10

0.05

0.00

turns

0

200

400

600

800

1000

e-lenses reduce losses ~6 fold!
Optimal Compensation ~75% (emitt. growth)

RCS Model, SYNERGIA, 16 M
Q_{x,y} = 3.7/3.8, dQ_{sc} = -0.9, Q_s = 0.08
1% lattice error, 12 electron lenses
E. Stern, et al.

Degree of e-Lens Compensation (%)
RMS Emittance Growth (% after 1000 turns)

no compensation
optimal compensation
Optimal Compensation ~70\% (beam losses)

RCS Model, SYNERGIA, 16 M
$Q_{x,y} = 3.7/3.8$, $dQ_{sc} = -0.9$, $Q_s = 0.08$
1\% lattice error, 12 electron lenses

E. Stern, et al.

Fractional Beam Loss (%) vs Degree of e-Lens Compensation (%)
IOTA: Integrable Optics Test Accelerator

C = 40 m
150 MeV/c e-
and 70 MeV/c p+
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

- 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
Linear $\mu^+\mu^-$ Crystal X-ray Collider

1 PeV = 1000 TeV

$n_\mu \sim 1000$

$n_B \sim 100$

$f_{rep} \sim 10^6$

$L \sim 10^{30-32}$

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

IPAC19 Shiltsev | Nishikawa Prize
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
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[Image of Dmitri Mendeleev]

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[Image of a science magazine cover]
Thank You for Your Attention!