Space-charge and Its Compensation:
(i) Fermilab Booster Beam Studies and
(ii) e-Lens Compensation Modeling
(iii) IOTA as the next step

V. Shiltsev, J. Eldred, V. Lebedev, K. Seiya
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Part I - Booster: C=474 m, 400 MeV → 8 GeV, 15 Hz
Complicated Dynamics – esp. Early in the Cycle
Losses vs Flux: 1 W/m Limit → Flux Limit

![Graph showing losses vs flux with a 1 W/m limit and flux limit indicated.](chart.png)
Two Occurrences of Losses in the Cycle

N_p = 4.5e12

*data from the 2019 Booster Beam Studies, expt #S09

FNAL-TM-2740 (2020)
“After Injection” beam losses quickly grow with intensity $N$

$$\frac{dN}{N} \sim (dQ_{sc})^3$$

Space-charge effect:
Intensity, emittance, Tunes, $Q'$ ($dN \sim Q'^2$), etc

Operational chromaticities $Q'(x,y) = (-4/-16)$

Operational intensity

Injected Beam Intensity $N_{ppp} (10^{12})$
Booster emittance evolution at nominal intensity

![Graph showing booster emittance evolution over turns.](image)

- **Axis Labels:**
  - Y-axis: IPM Vertical Emittance (rms, norm., mm mrad)
  - X-axis: Turn

- **Legend:**
  - **corrected IPM emittance**
  - **100 turns smoothed**

**Note:**

- [FNAL-TM-2741 (2020)](https://example.com/12345)

**Author:**

Vladimir SHILTSEV | Booster, e-SCC, IOTA
Space-Charge Tune Shift Parameter $dQ_{SC} \sim NB_f / \varepsilon \beta \gamma^2$

at nominal intensity $N_p = 4.4e12$

For measured bunch length and beam emittances

Shaded area for beam emittances $2\pi$ to $3\pi$
Other losses (small but important)

- Losses due to imperfect clearing of a three bunch gap in the linac beam, needed for clean extraction
  - About $1.7 \pm 0.4\%$, not depending on intensity

- Losses at the transition energy (5.2 GeV)
  - Usually small (<1%) for operational intensities $N<4.6\times10^{12}$, can become $O(10\%)$ at higher intensities
  - Longitudinal tails may lead to losses in Recycler

- Losses at extraction
  - Usually small $O(1\%)$
If the total loss power is limited – eg $W=500 \text{ W}$

$$\frac{\Delta N_p}{N_p} \leq \frac{W}{(1-\eta)N_pE_kf_0}$$

To increase the maximum intensity:

i) better collimation to increase $\eta$

ii) larger emittance (machine aperture)

iii) flatten the bunches to reduce $B_f$

iv) increase the injection energy

v) improve the beam dynamics to make $\alpha$ and $\kappa$ smaller

- by the injection “painting” to make the SC force more uniform

- by SC compensation by e-lenses

- via non-linear integrable optics, etc

$$\Delta N_p \sim \alpha \Delta Q_{SC}^\kappa$$

$$\Delta Q_{SC} = \frac{N_pr_pB_f}{4\pi\varepsilon\beta\gamma^2}$$

$$N_p^{max} \sim \left(\frac{W}{1-\eta}\right)^{1/(\kappa+1)} \cdot \left(\frac{\varepsilon}{B_f}\right)^{\kappa/(\kappa+1)} \cdot \gamma^{3\kappa/(\kappa+1)} \cdot (\alpha f_0)^{-1/(\kappa+1)}$$
Part II:

compensation of space-charge effects by electron lenses (2001)

PIC simulations by E. Stern, et al (FNAL)
1000 Turns in a Ring with $dQ_{SC} = -0.9$

Case #1

Focusing

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

Focusing

Defocusing

1% error

Case #2
1000 Turns in a Ring with $d\Omega_{SC} = -0.9$

Case #3

1% error

Electron lens

Focusing

Defocusing
Emittance Growth – Case #1

no error, no e-lenses

12 FODO symmetric lattice

$\varepsilon/\varepsilon_0$ vs turn

0.0  0.2  0.4  0.6  0.8  1.0  1.2  1.4  1.6  1.8  2.0

0        200    400    600    800    1000

Vladimir SHILTSEV | Booster, e-SCC, IOTA
Emittance Growth – Case #2

1% error, no e-lenses

- 12 FODO symmetric lattice
- 12 FODO one quad 1% error

\[ \frac{\epsilon}{\epsilon_0} \]

<table>
<thead>
<tr>
<th>turn</th>
<th>[0, 200, 400, 600, 800, 1000]</th>
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<tr>
<td>(\frac{\epsilon}{\epsilon_0})</td>
<td>[1.0, 1.2, 1.4, 1.6, 1.8, 2.0]</td>
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Emittance Growth – Case #3

1% error, 12 e-lenses

12 FODO symmetric lattice
12 FODO one quad 1% error
12 FODO, one quad 1% error, 12 ideal lenses

ε/ε₀

0 200 400 600 800 1000

turn
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

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

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

$dQ_{SC} = -0.9$

$\sim 75\%$ e-lens compensation

no e-lenses

Stern et al, THPAF075, IPAC18, Beams Document 6790-v1 FNAL (2019)
More on the e-Lens SCC Simulations

We already know that:

- Effect is sensitive to longitudinal e-p matching
- Not so sensitive to transverse e-p matching
- Number of e-lenses matters (3…6…12 - more the better)

see E. Stern, et al, Proc. 4th ICFA Mini-Workshop on Space Charge (Nov. 2019)

Topics under/to study:

- Longitudinally flat proton bunch distributions may be more beneficial to compensation to allow DC lens current
- Adjusting lattice functions might improve lens operation
- Incorporate more realistic lattice including dipoles, sextupoles, dispersion, chromaticity, etc.
- Explore interplay between impedance and space charge
Part III: Electron lens experiment at IOTA

- Simulations will be part of the experiment planning and analysis
- Design underway with CERN and U. Lapland
- Construction planned for 2020–2021
Summary and Next Steps – re: IOTA

- **(Following commissioning of the IOTA proton injector)**
- **Studies of effects due to space-charge and impedances should be part of the IOTA program:**
  - Dependence of the losses and emittance growth on N, emittances, tunes, chromaticities, **longitudinal shape (higher harmonics RF), lattice periodicity (new lattice for P=2 with new/moved quadrupoles)**
  - Compare with the Booster’s and other machine observations (continue in-depth Booster beam studies)
  - Carry out SC simulations for IOTA and get predictive results
- **(Prior the installation of the IOTA e-lens)**
- **Carry out simulations of e-lens SC compensation:**
  - First, all remaining topics for model RCS
  - Then for realistic IOTA lattice and proton injector
- **At some moment, consider the second IOTA e-lens**
Thank You for Your Attention!

(2019 Booster Studies Group)

(also Angela, David, Jon, and many key Fermilab participants.)
Backup