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

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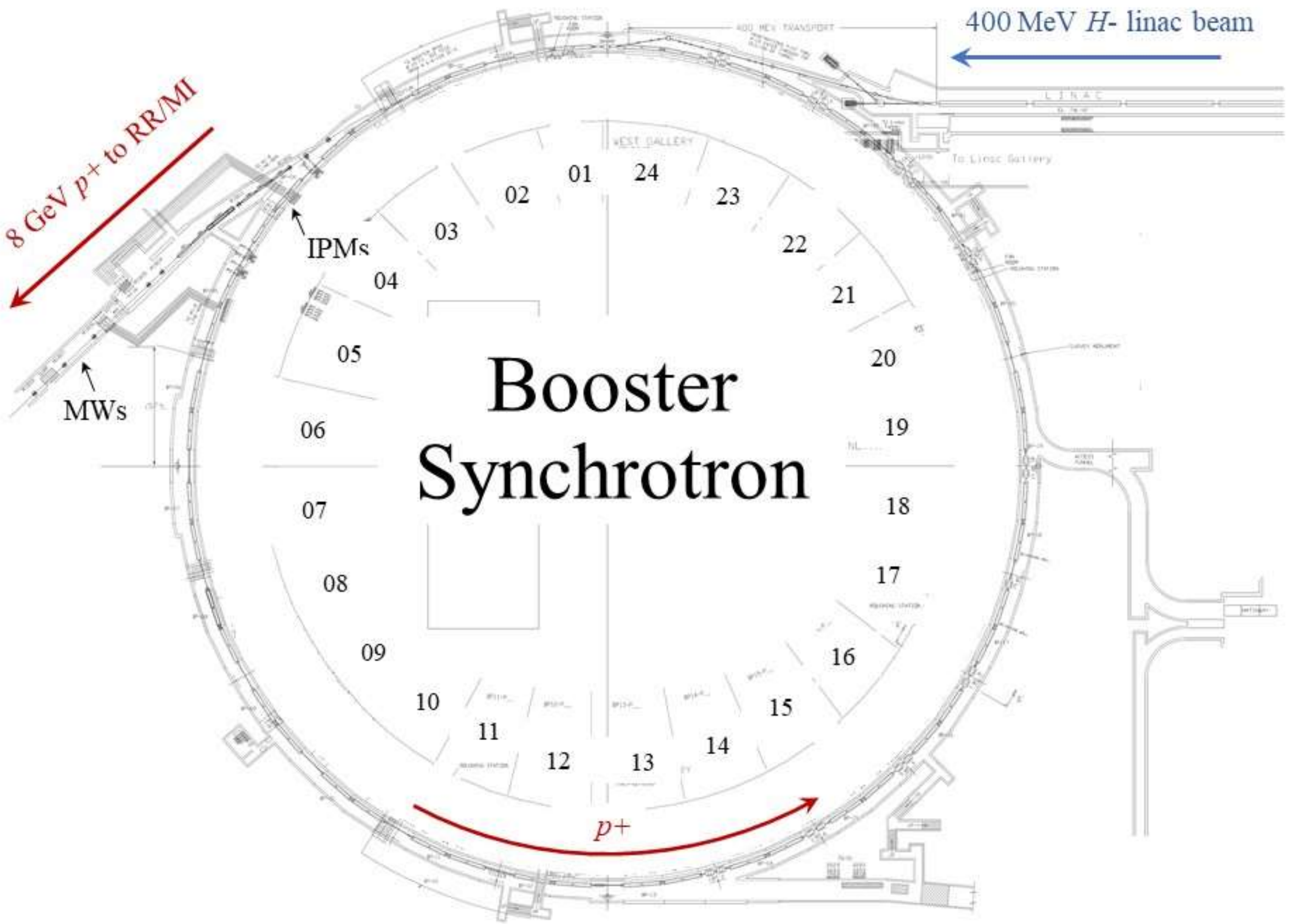
Yu.Alexahin, A.Burov, E.Stern, G.Stancari.

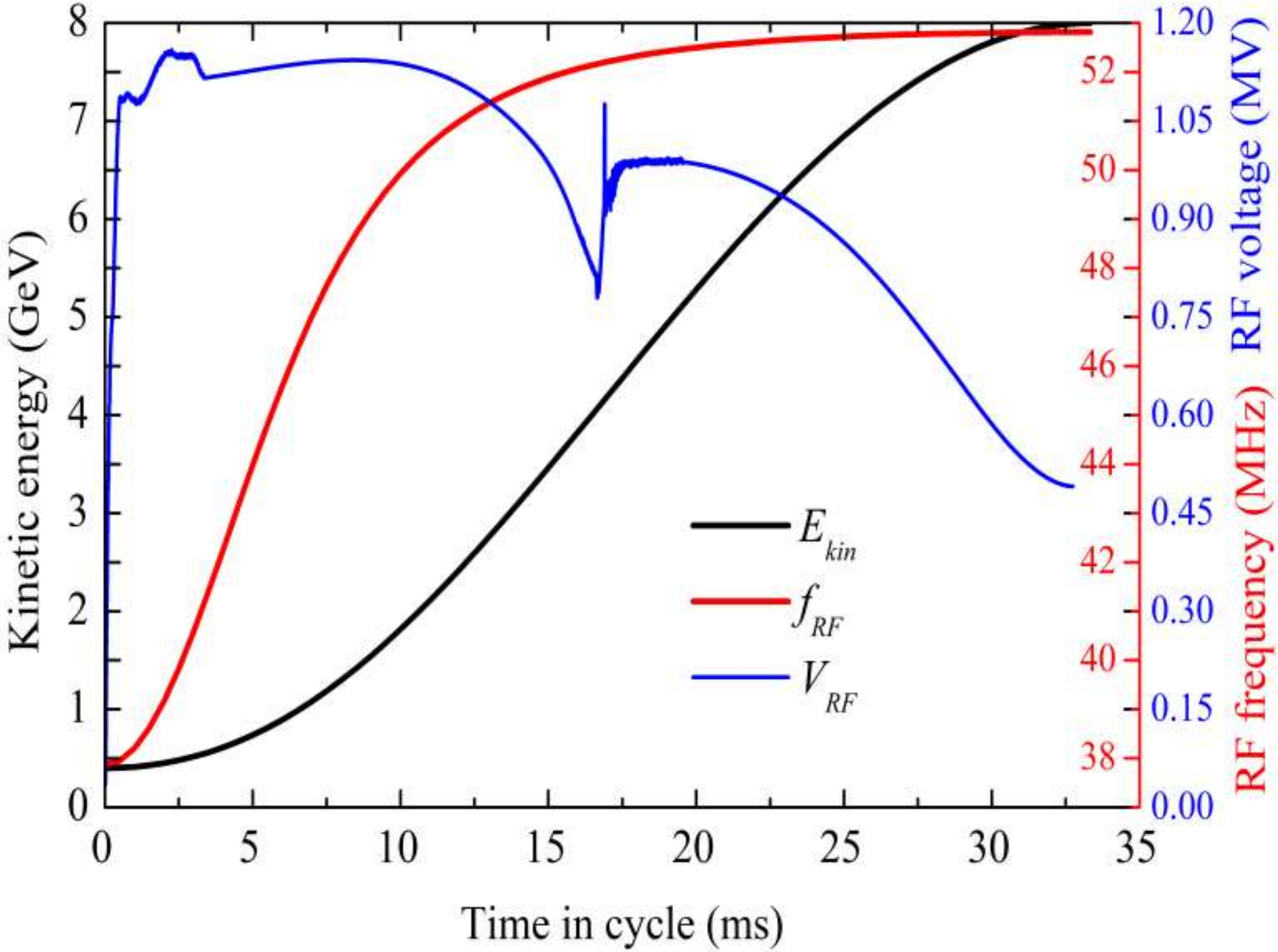
IOTA/FAST Collaboration Meeting 2020

June 17, 2020

Part I - Booster : C=474 m, 400 MeV → 8 GeV, 15 Hz



Complicated Dynamics – esp. Early in the Cycle



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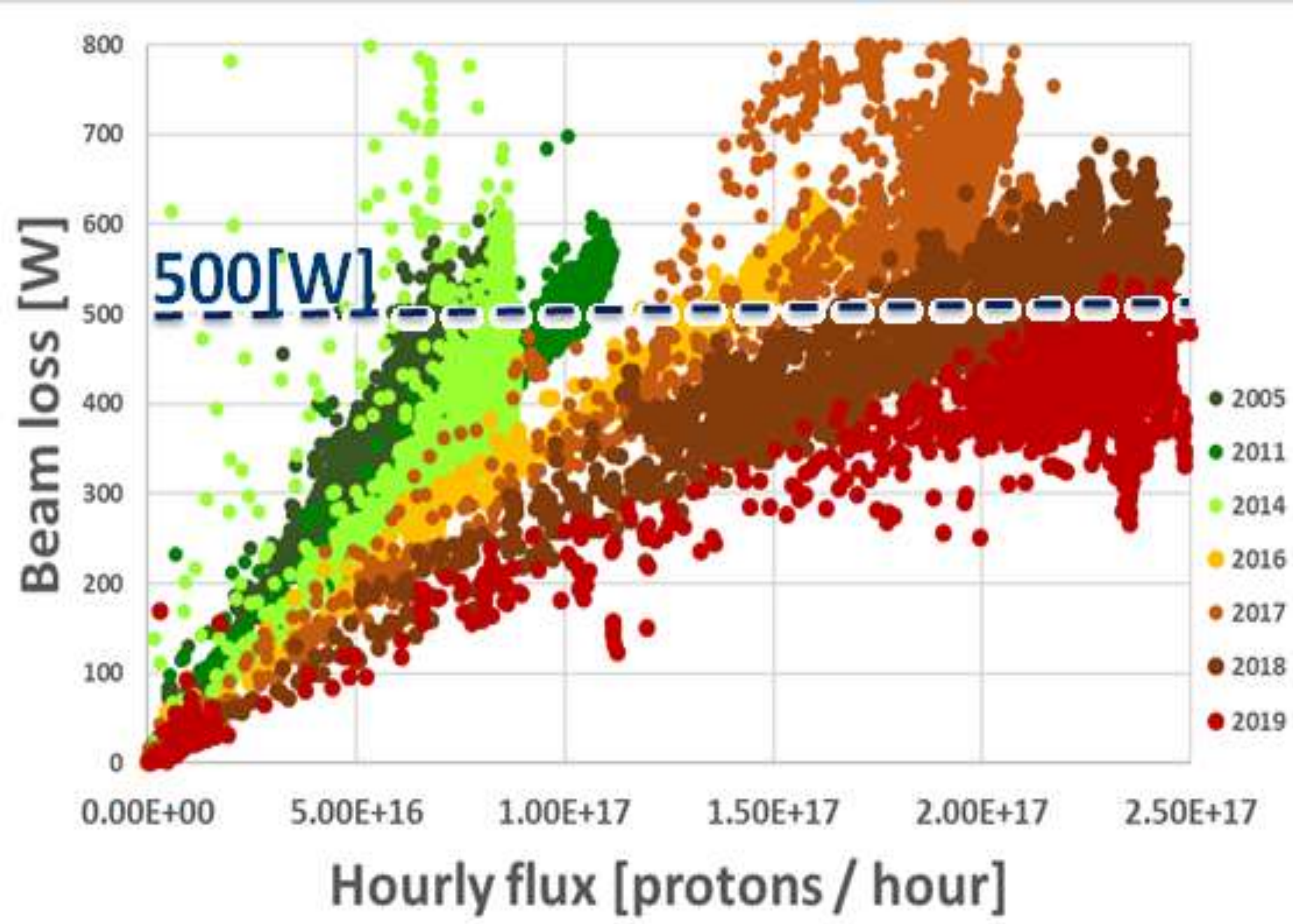
Losses vs Flux : 1 W/m Limit → Flux Limit



Pellico, et al

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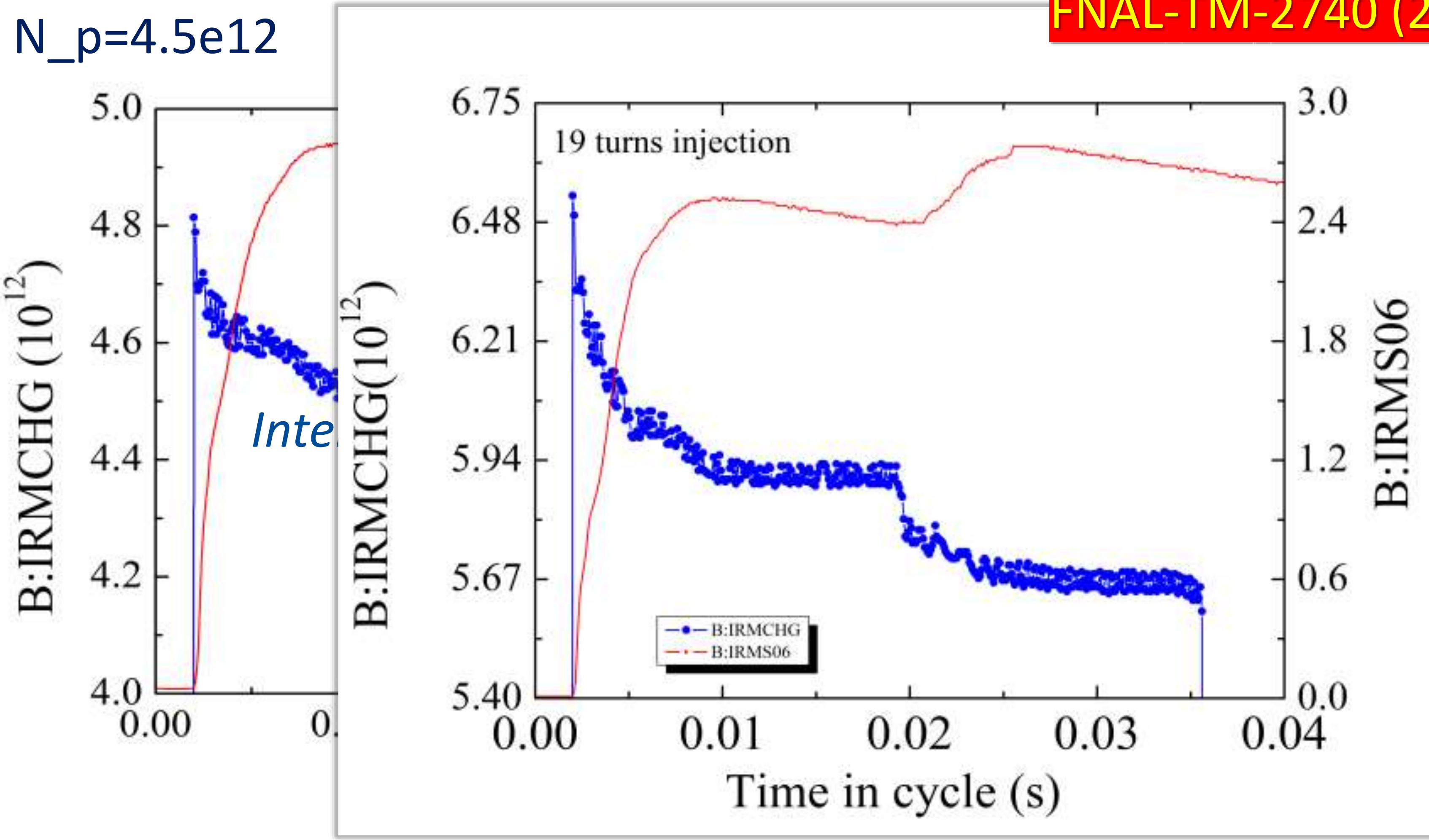
Two Occurrences of Losses in the Cycle

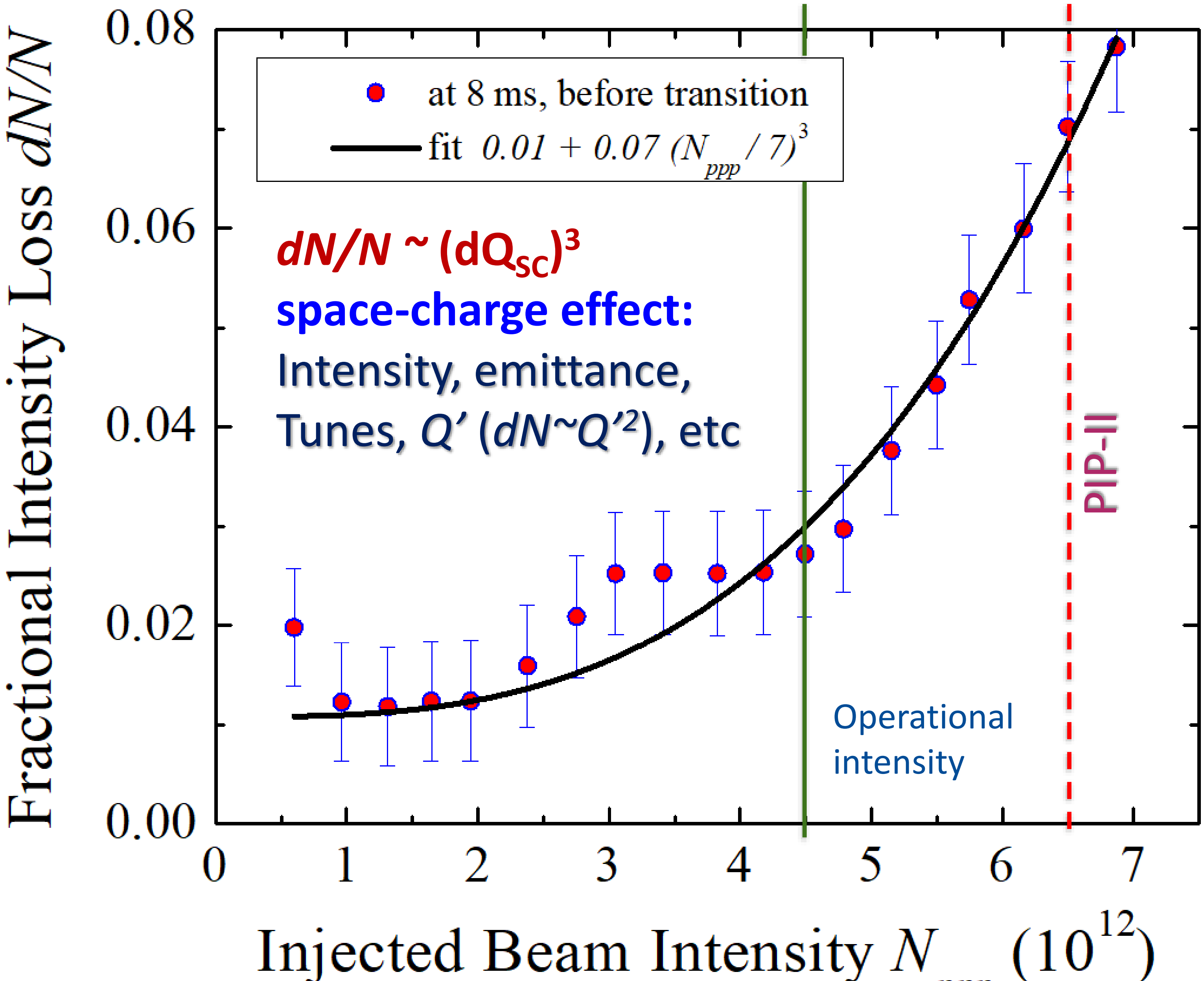
FNAL-TM-2740 (2020)

N_p=4.5e12



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

"After Injection" beam losses quickly grow with intensity *N*



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

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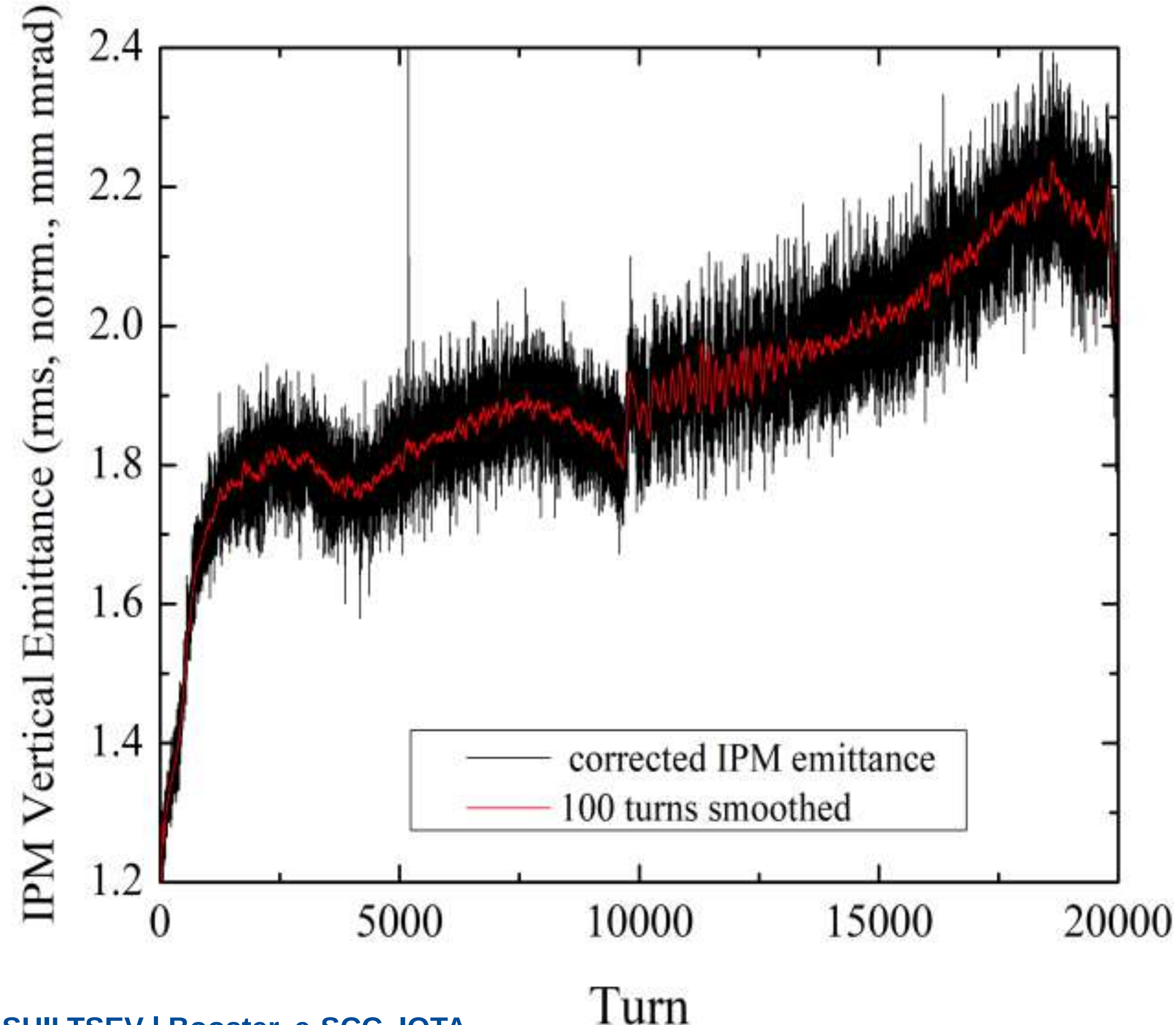
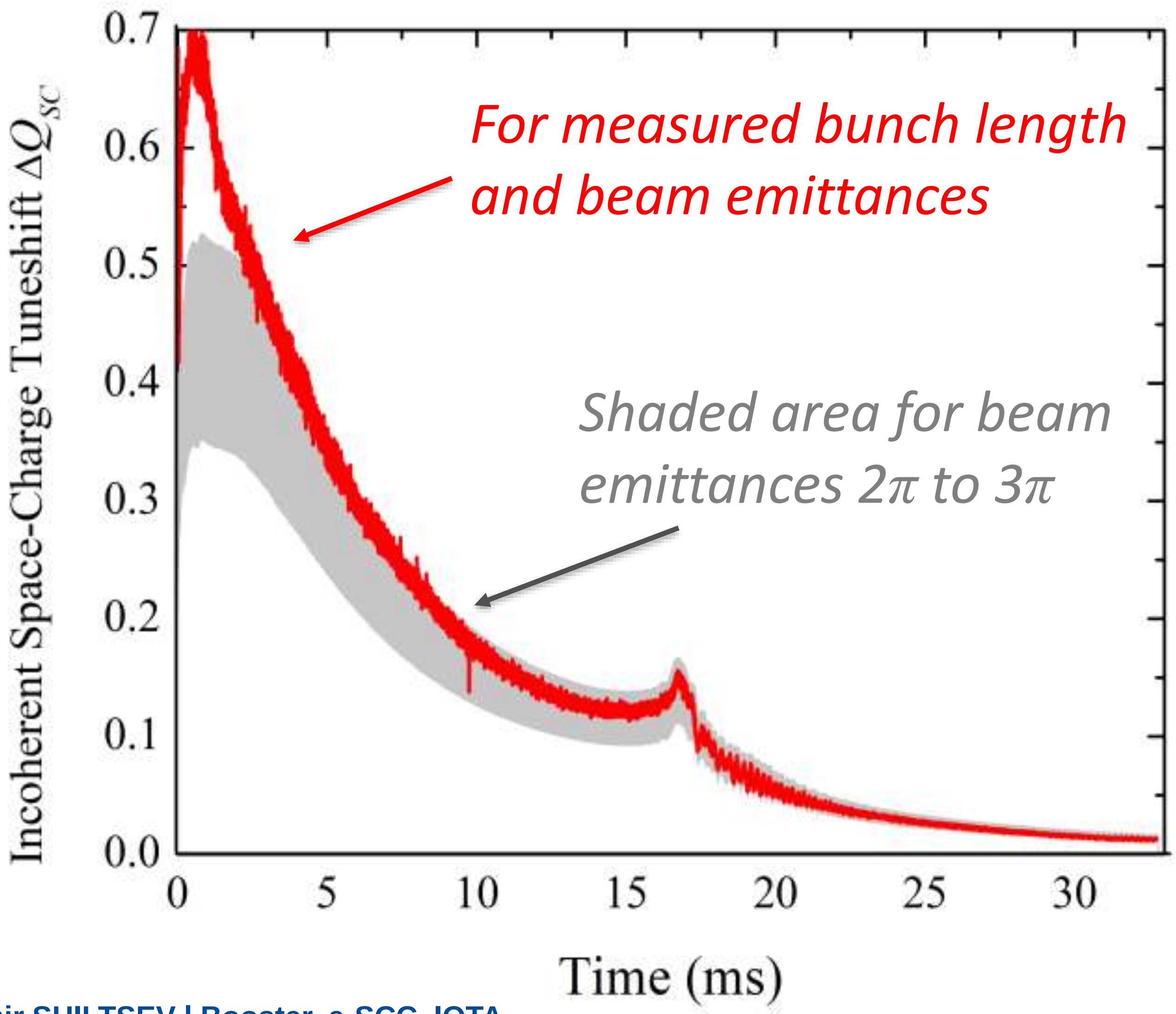
Booster emittance evolution at nominal intensity

FNAL-TM-2741 (2020)



Space-Charge Tune Shift Parameter $dQ_{SC} \sim NB_f/\varepsilon\beta\gamma^2$

at nominal intensity N_p=4.4e12



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± 0.4% , not depending on intensity
- **Losses at the transition energy (5.2 GeV)**
  - Usually small (<1%) for operational intensities *N*<4.6e12, 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 W

$$\frac{\Delta N_p}{N_p} \leq \frac{W}{(1-\eta) N_p E_k f_0}$$

$$\frac{\Delta N_p}{N_p} \sim \alpha \Delta Q_{sc}{}^{\kappa}$$

$$\Delta Q_{sc} = \frac{N_p r_p B_f}{4\pi\varepsilon\beta\gamma^2}$$

To increase the maximum intensity:

i) better collimation to increase η

ii) larger emittance (machine aperture)

iii) flatten the bunches to reduce B_f

iv) increase the injection energy

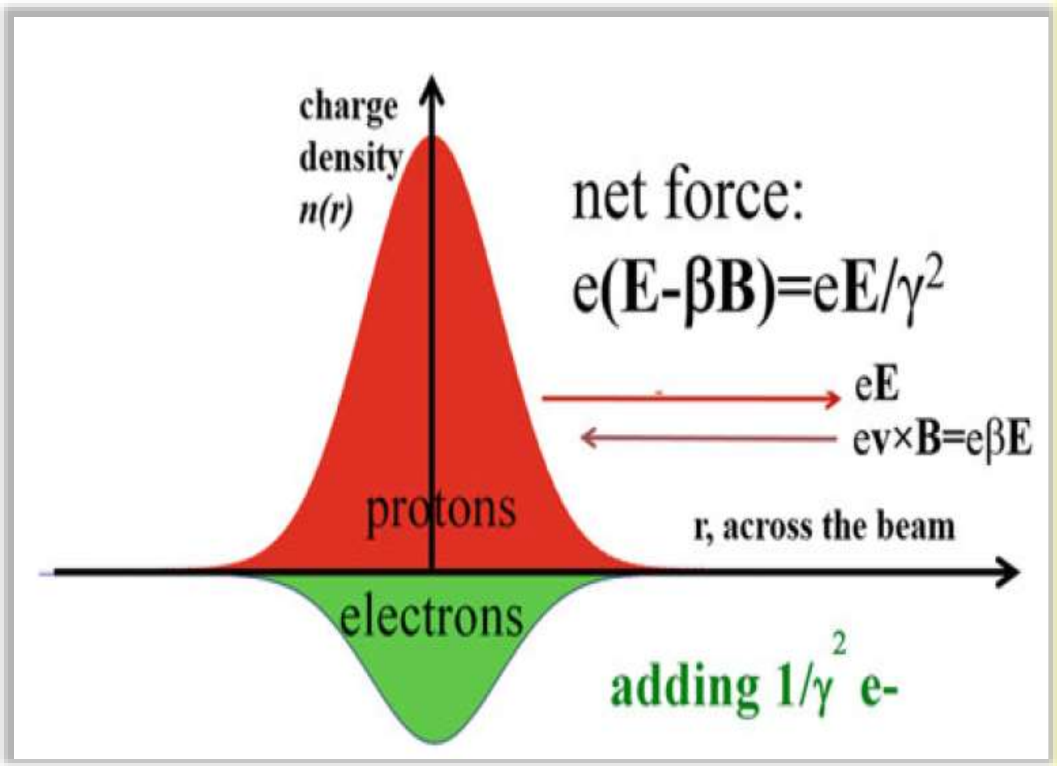
v) improve the beam dynamics to make α and κ smaller

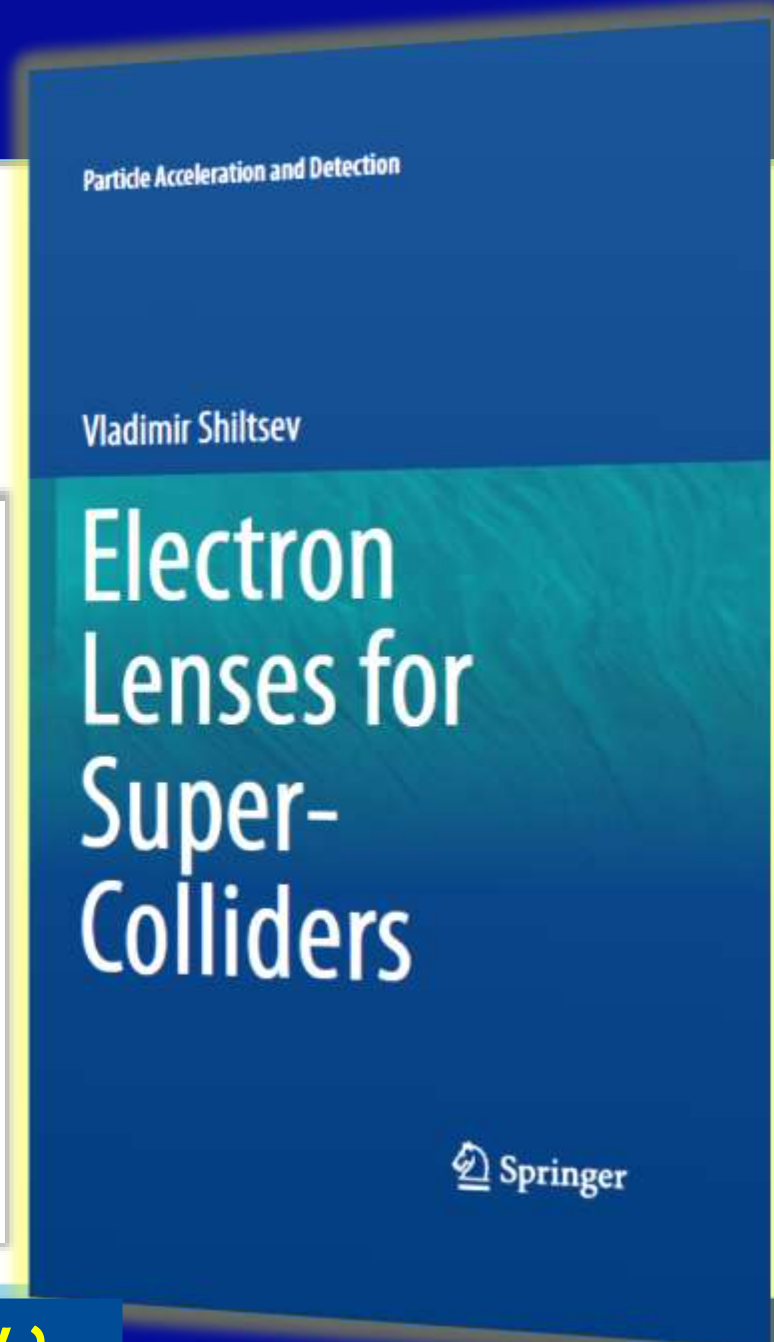
- by the injection "painting" to make the SC force more uniform
- by SC compensation by e-lenses
- via non-linear integrable optics, etc

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

Part II :

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

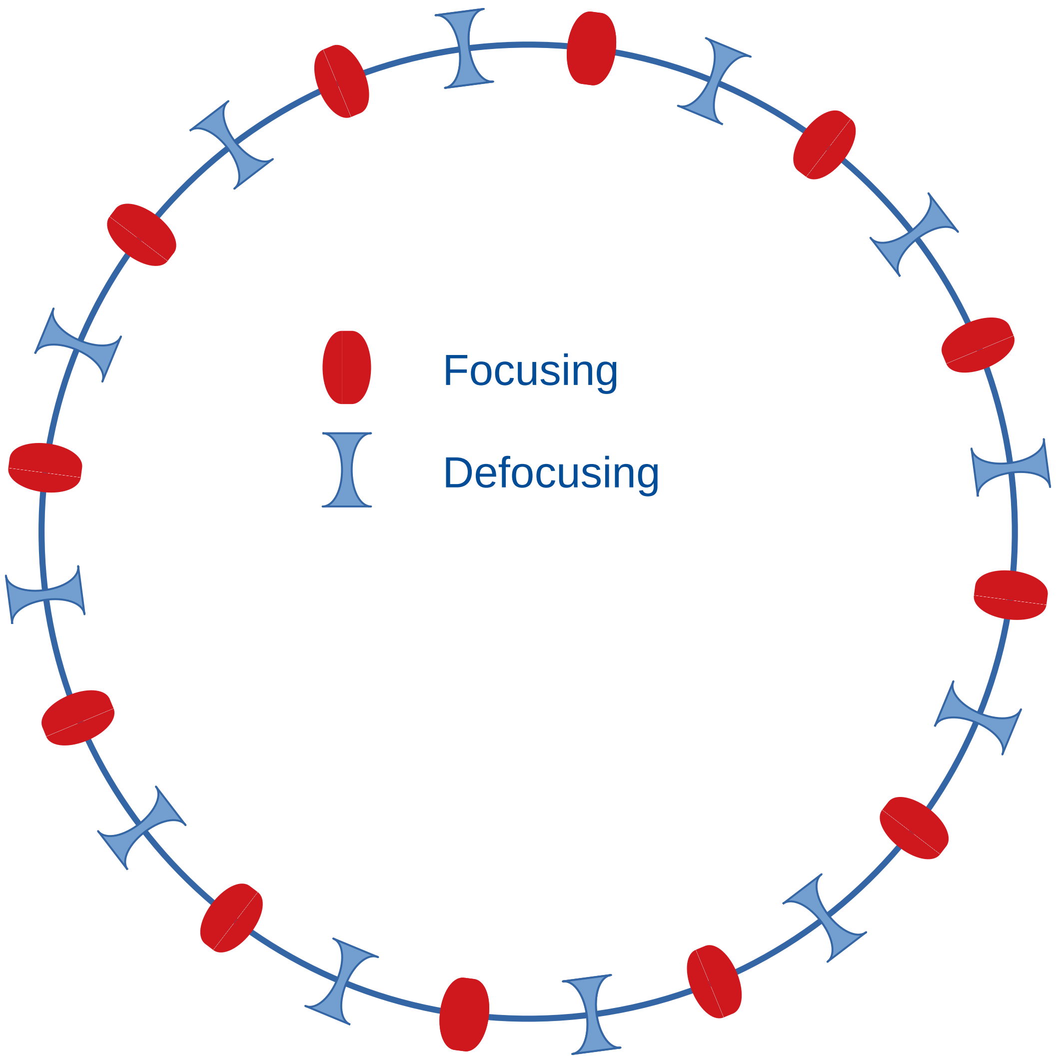




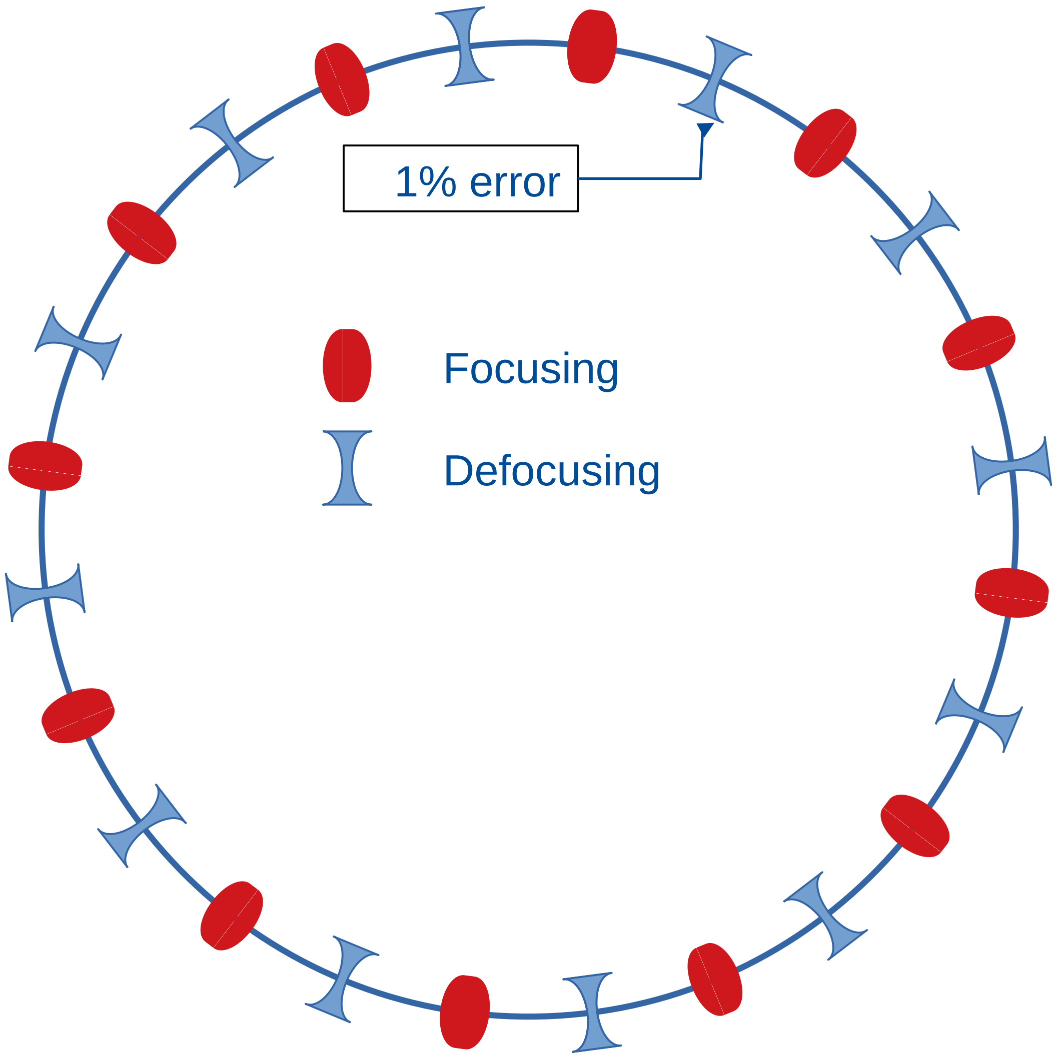
PIC simulations by E.Stern, et al (FNAL)

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

Case #1



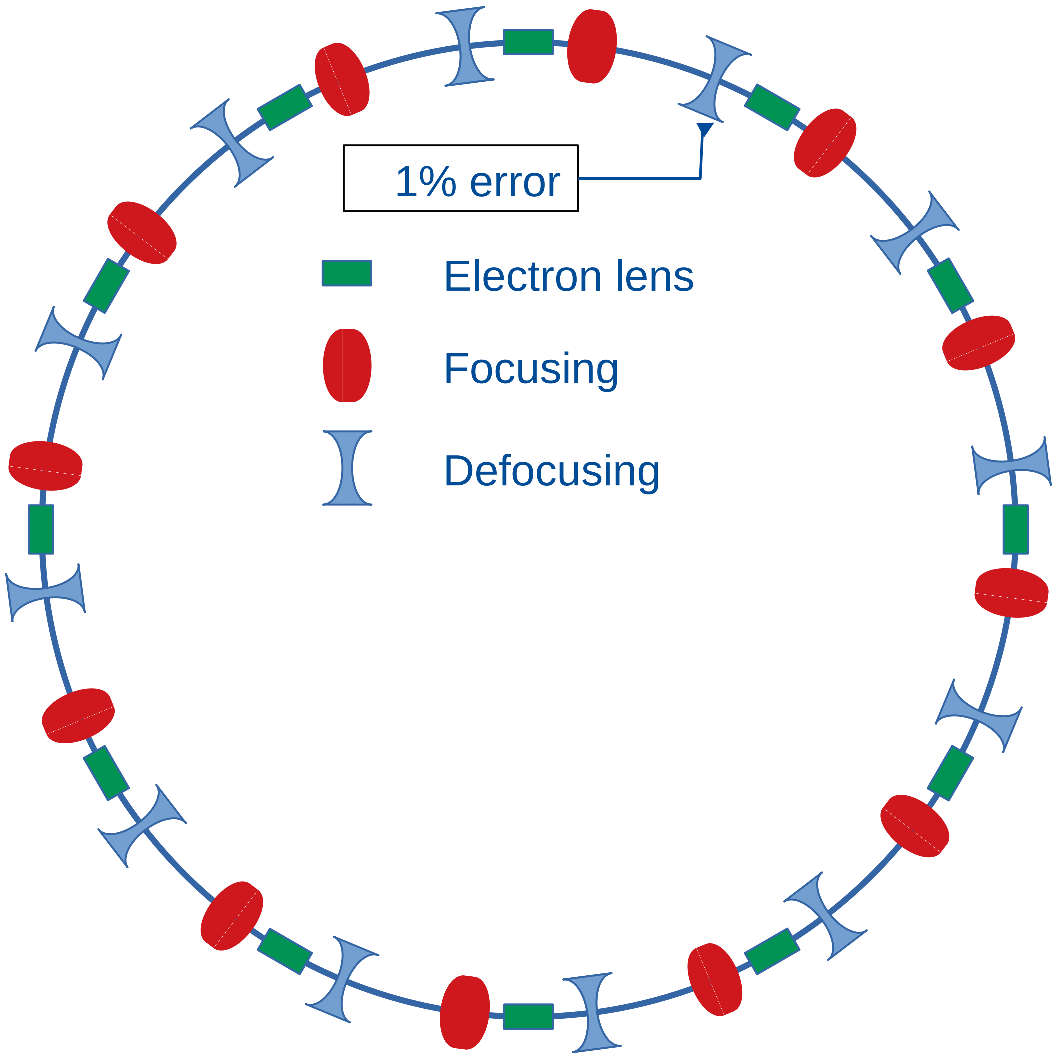
1000 Turns in a Ring with dQ_{SC}= -0.9



Case #2

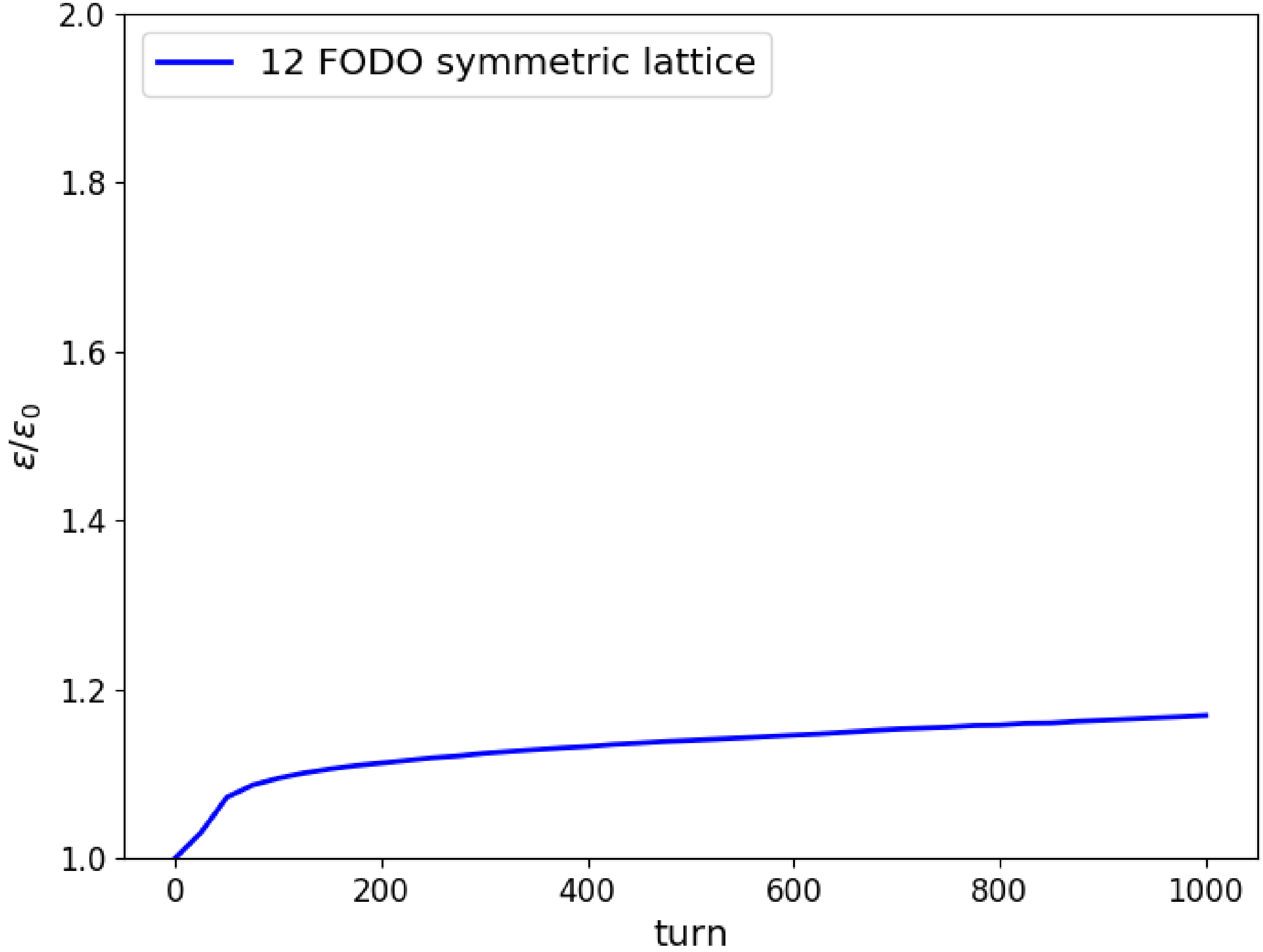
1000 Turns in a Ring with dQ_{SC}= -0.9

Case #3



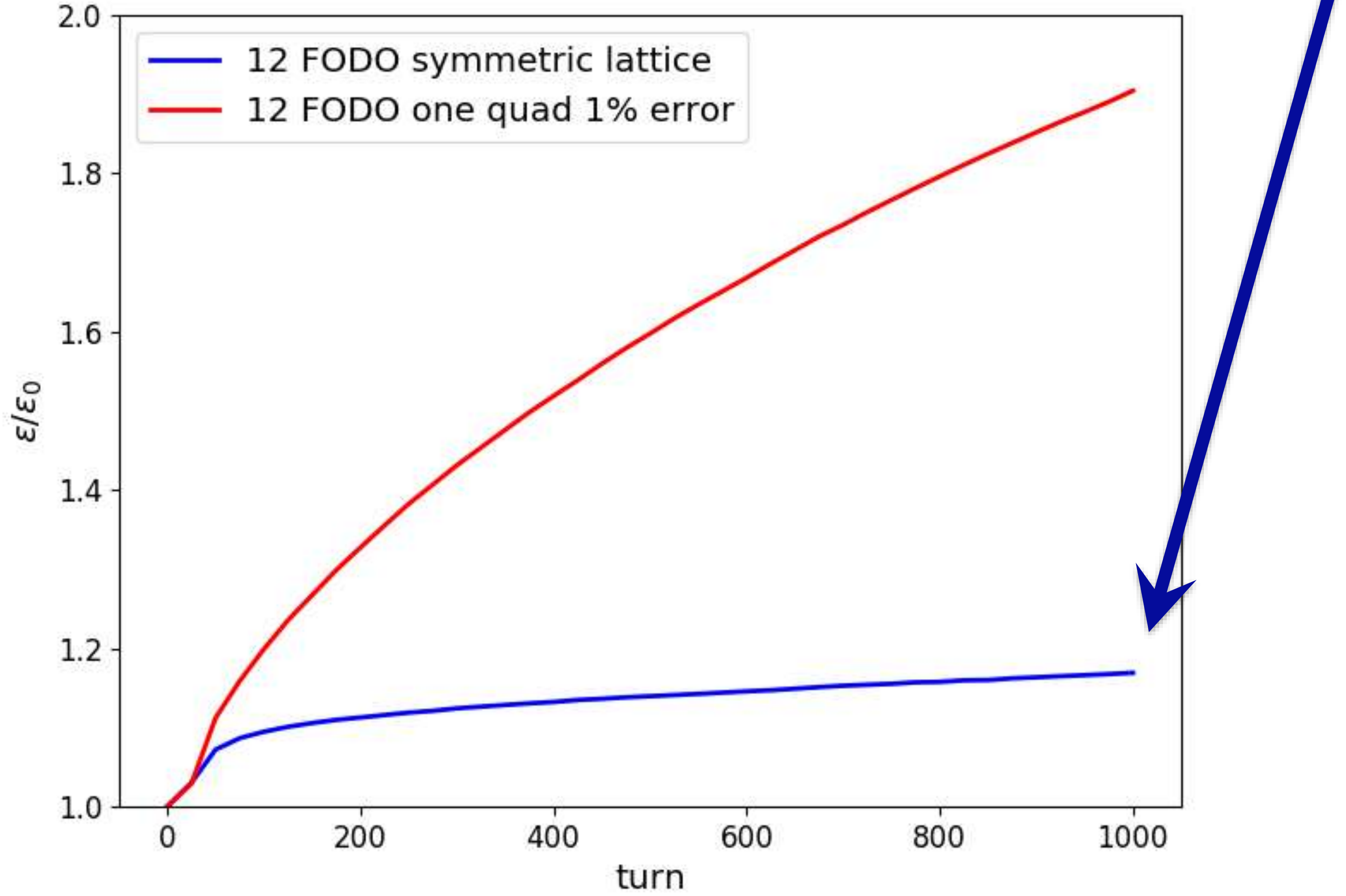
Emittance Growth – Case #1

no error, no e-lenses



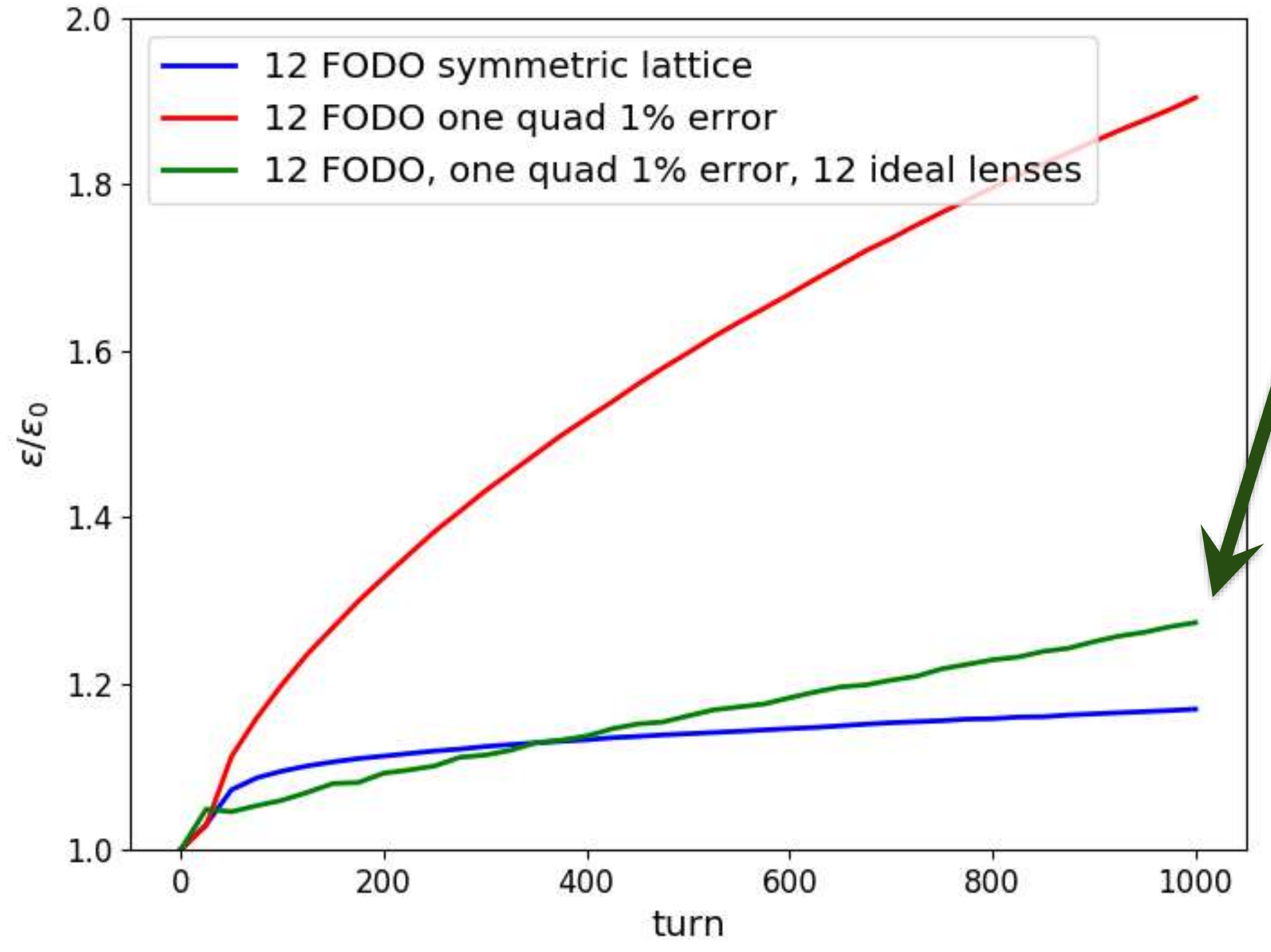
Emittance Growth – Case #2

1% error, no e-lenses

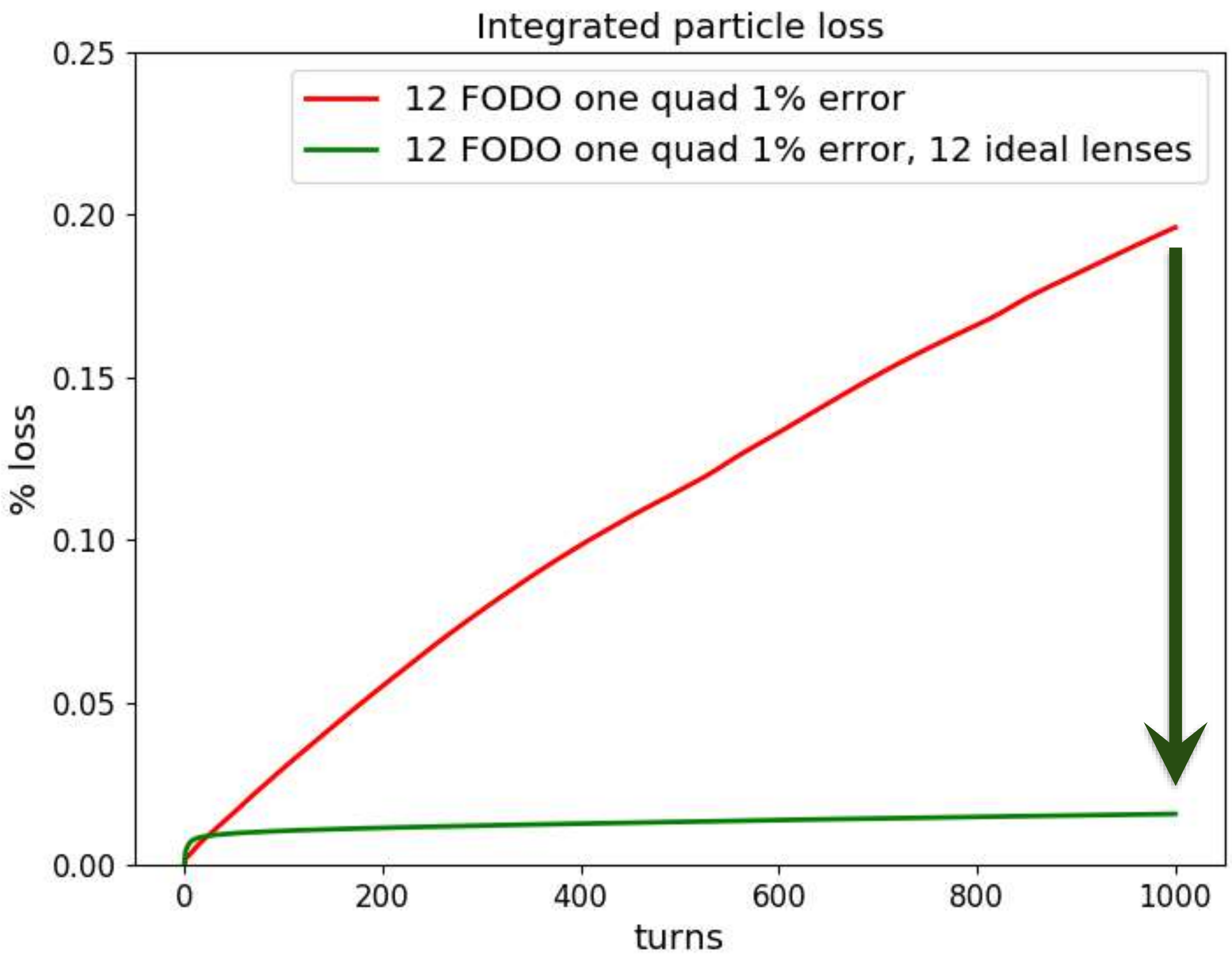


Emittance Growth – Case #3

1% error, 12 e-lenses

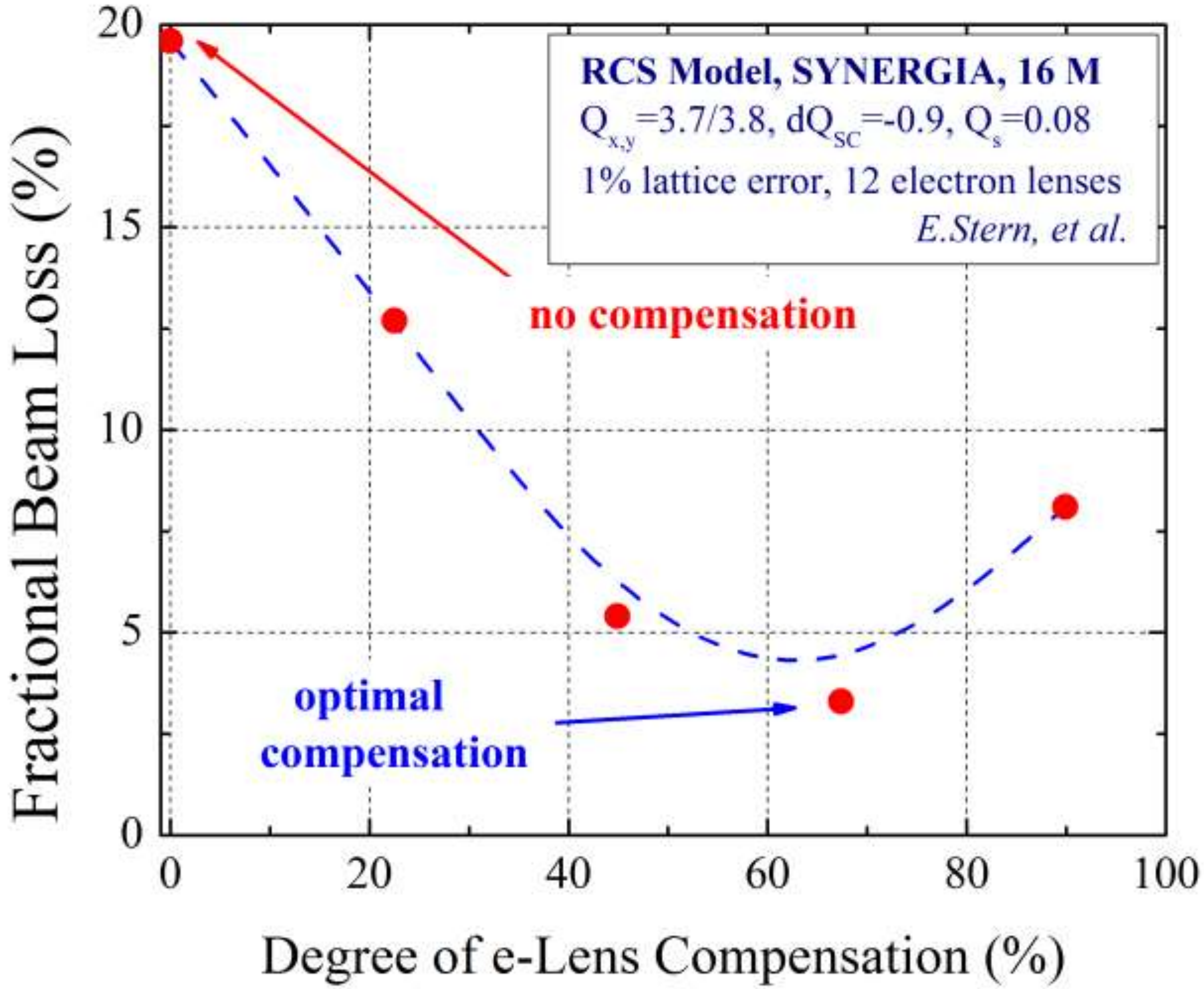


Particle Losses at 4σ – Case #2 and #3

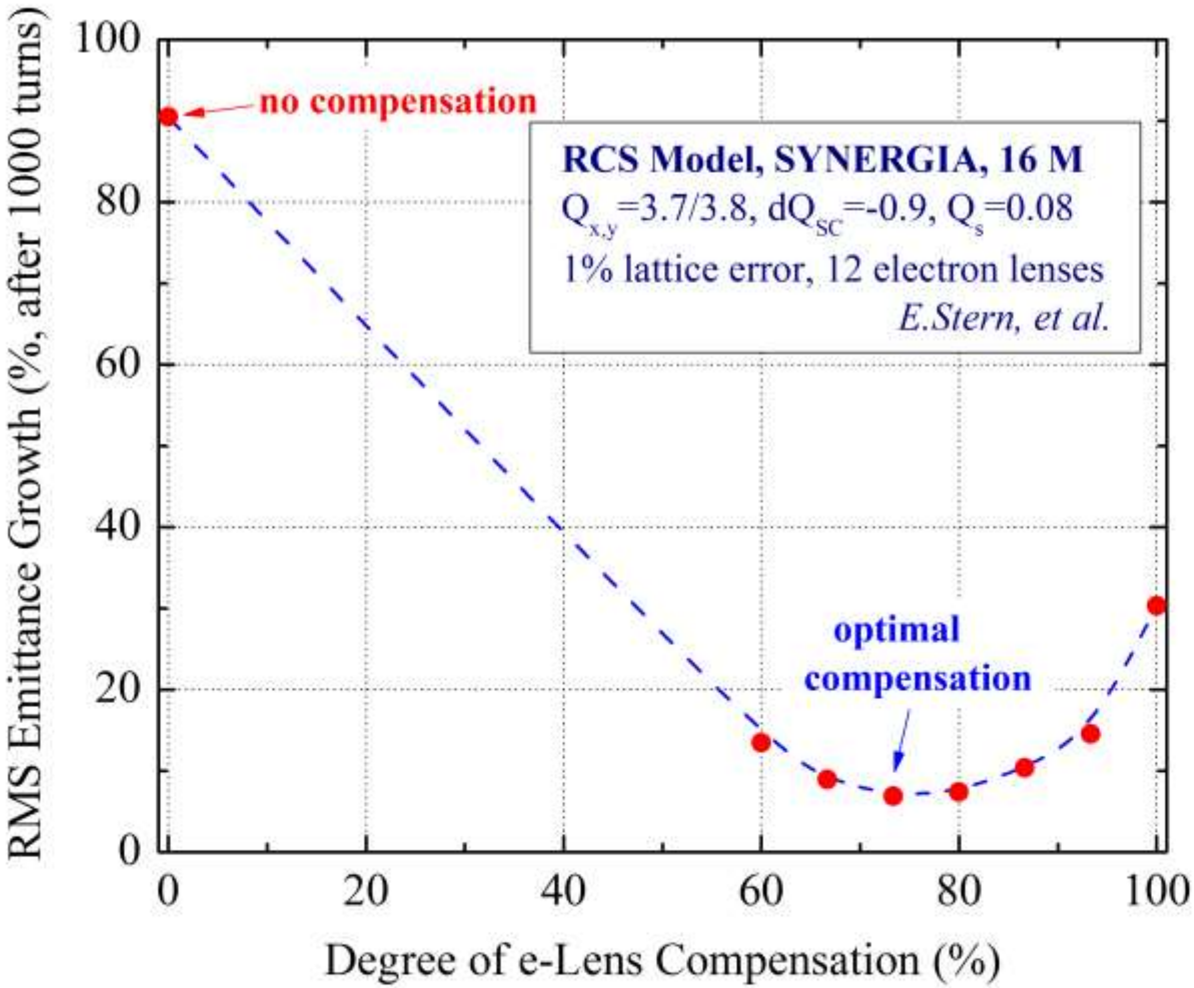


e-lenses reduce losses ~6 fold !

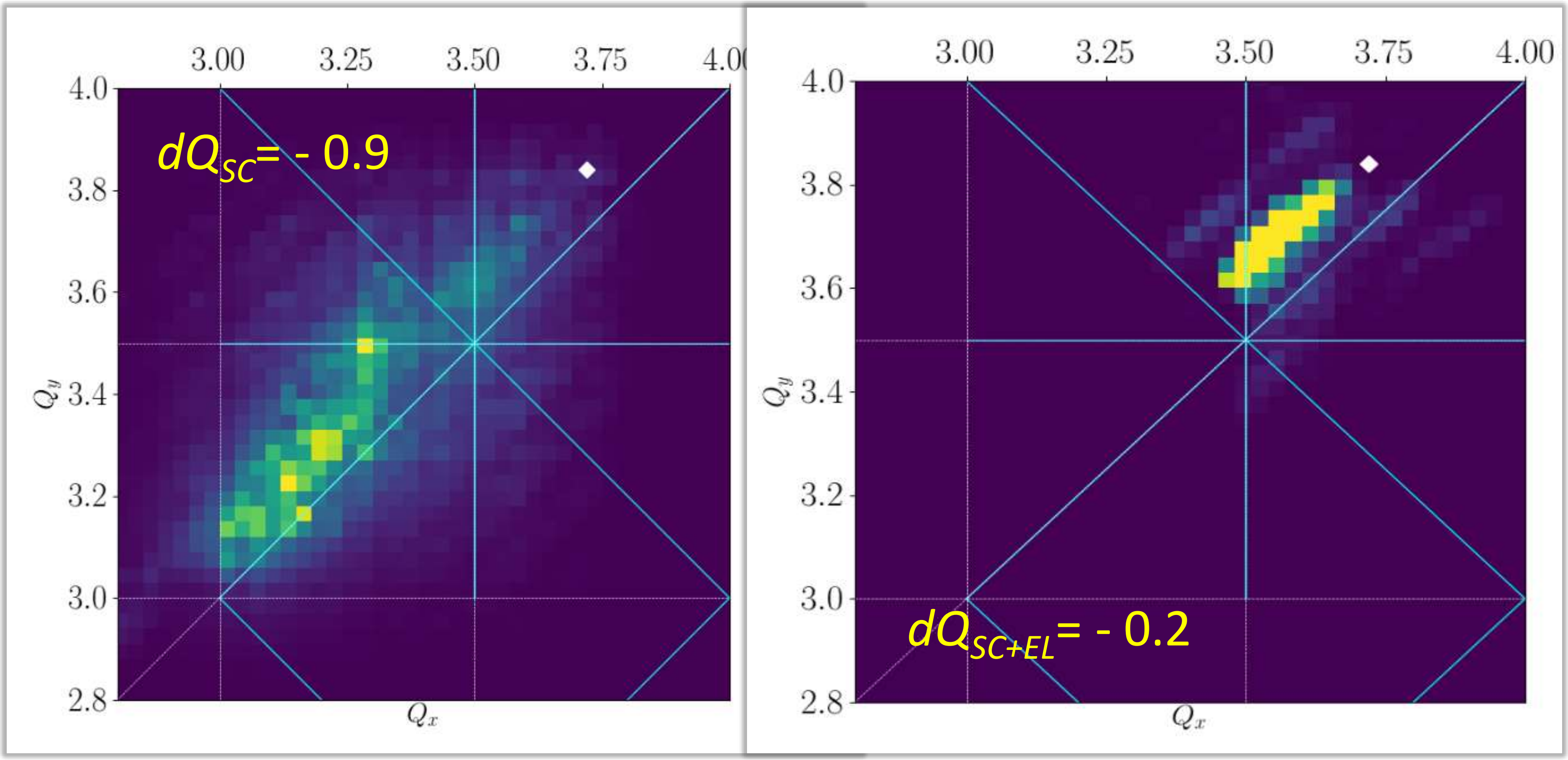
Optimal Compensation ~70% (beam losses)



Optimal Compensation ~75% (emitt. growth)



Tune Footprint dQ_{SC}= -0.9



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

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)

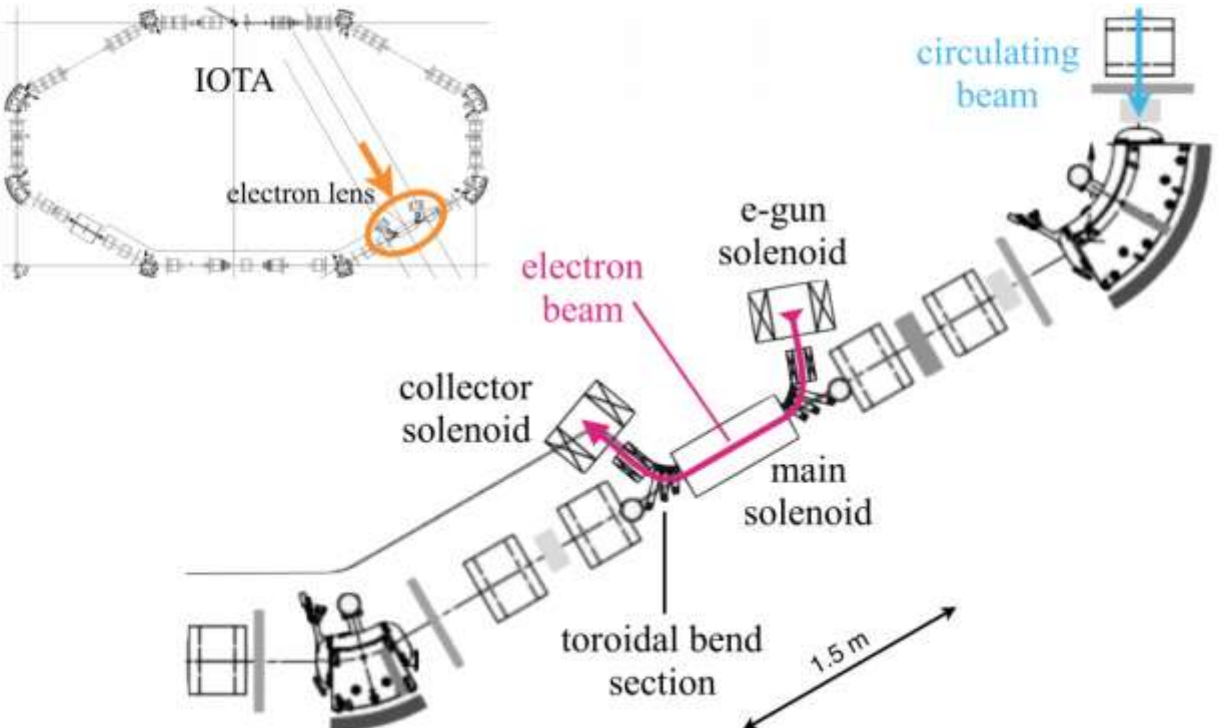
see *E.Stern, et al, Proc. 4th ICFA Mini-Workshop on Space Charge* (Nov. 2019)

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



see G.Stacari's talk earlier today

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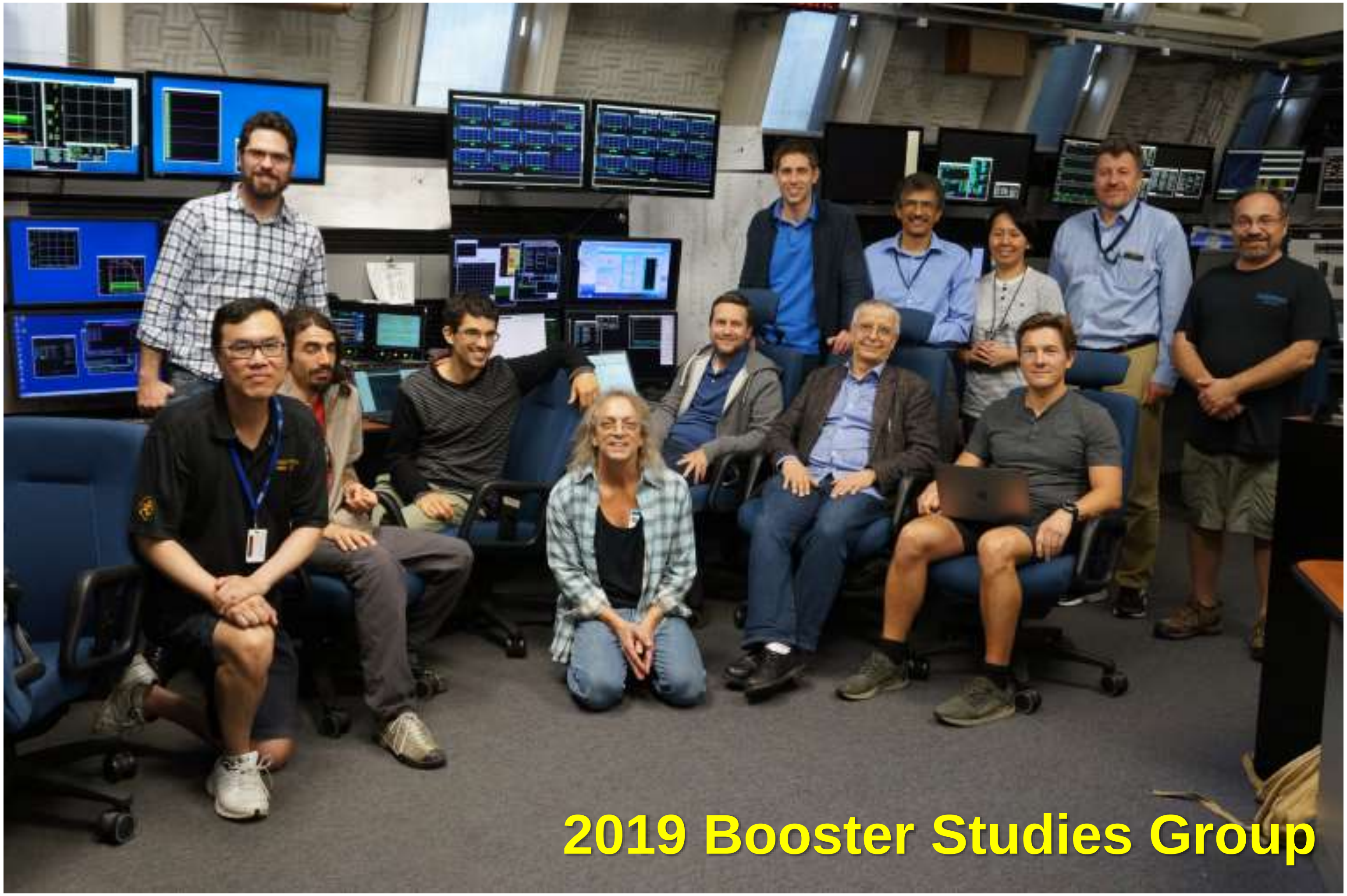
Summary and Next Steps – re: IOTA

- (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 !



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

Backup