Future Accelerator Based Neutrino Beams

Vladimir SHILTSEV (Fermilab) - APT Seminar, August 6, 2019

Based on presentation at the CERN Council Open Symposium on the Update of European Strategy for Particle Physics

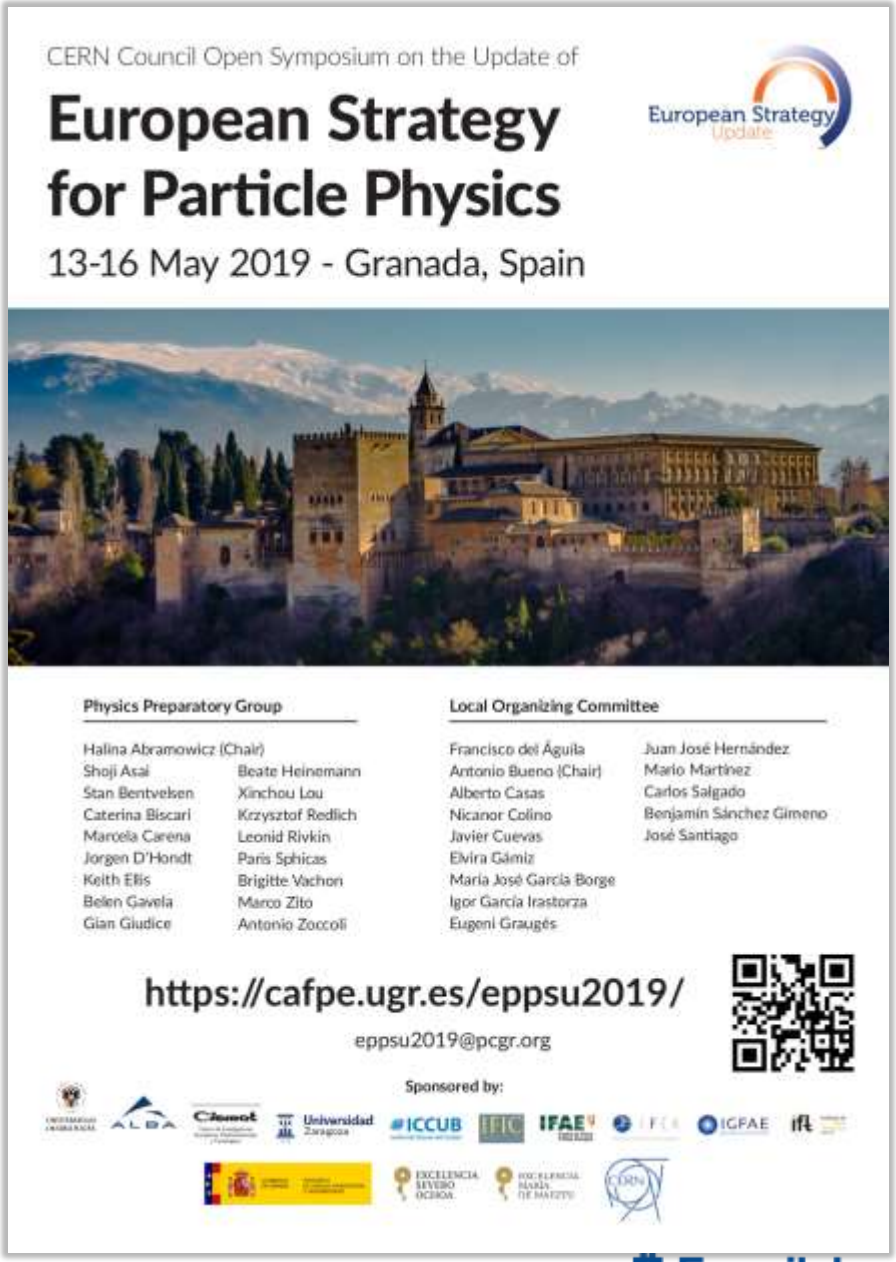
13-16 May 2019 - Granada, Spain

Content:

1. **What is Granada and how powerful are accelerators**
2. **Super-Beam Facilities and Upgrades** - how to achieve the ultimate energy and performance, R&D required :
   - Fermilab — Input #167, Input #150
   - J-PARC — Input #76, Input #158
3. **New Proposals** – opportunities and synergies **:**
   - Protvino/ORKA — Input #124
   - ESSνSB — Input #98
   - ENUBET — Input #57
   - νSTORM — Input #154

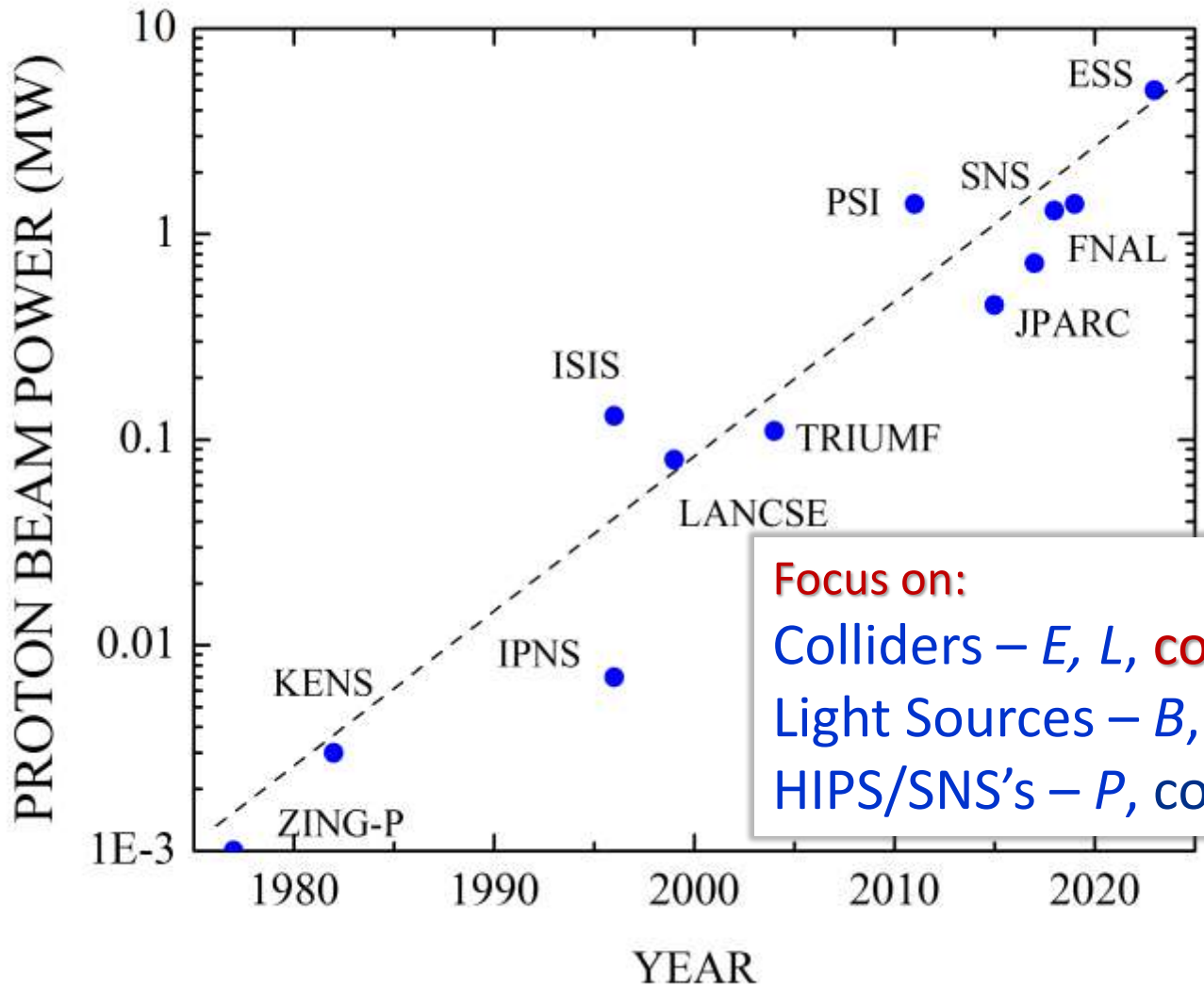
Granada'2019

- **HEP Int'l Community planning:**
  - European Strategy 2012-2013
  - US "Snowmass", P5, HEPAP 2013-2014
  - European Strategy Update 2019-2020
  - ILC250 in Japan? Decision by Feb. 2020
  - Potential of CepC in China?
  - US "Snowmass", P5, HEPAP 2019-2022
- **Planning for longer term HEP future in general (20-50 yrs) and "Post-2026" Era in particular (next cycle)**
  - Colliders: Higgs Factories and EF
  - Accel. for Neutrinos and PBC



World Scene of High-P Accelerators

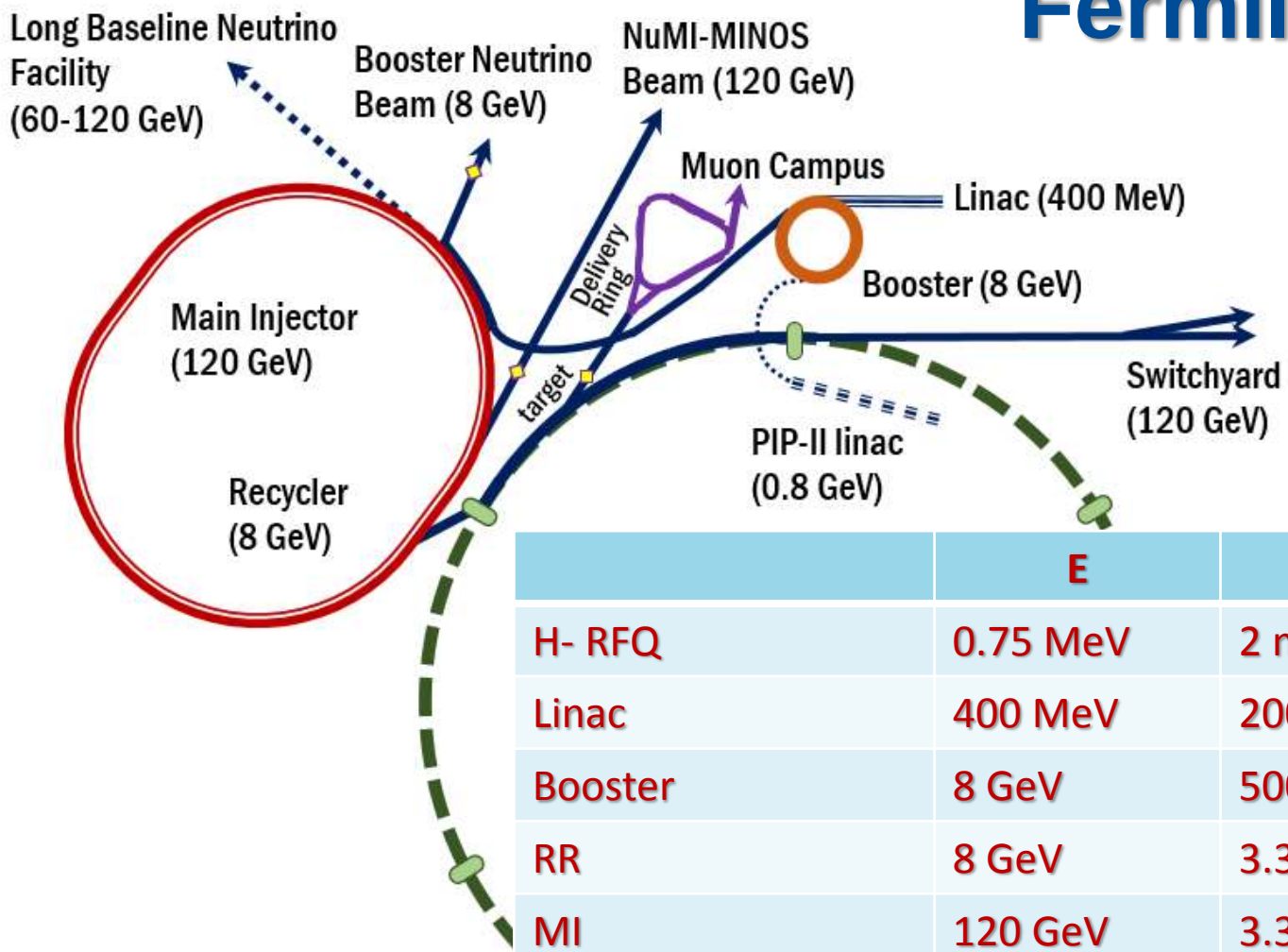
avg. doubling time 4 yr



Overarching:
Power
Cost
Energy Efficiency

Focus on:
Colliders – *E, L*, cost (5-25 BCHF)
Light Sources – *B*, cost (0.3-1 BCHF)
HIPS/SNS's – *P*, cost (1-2 BCHF)

Fermilab Proton Complex



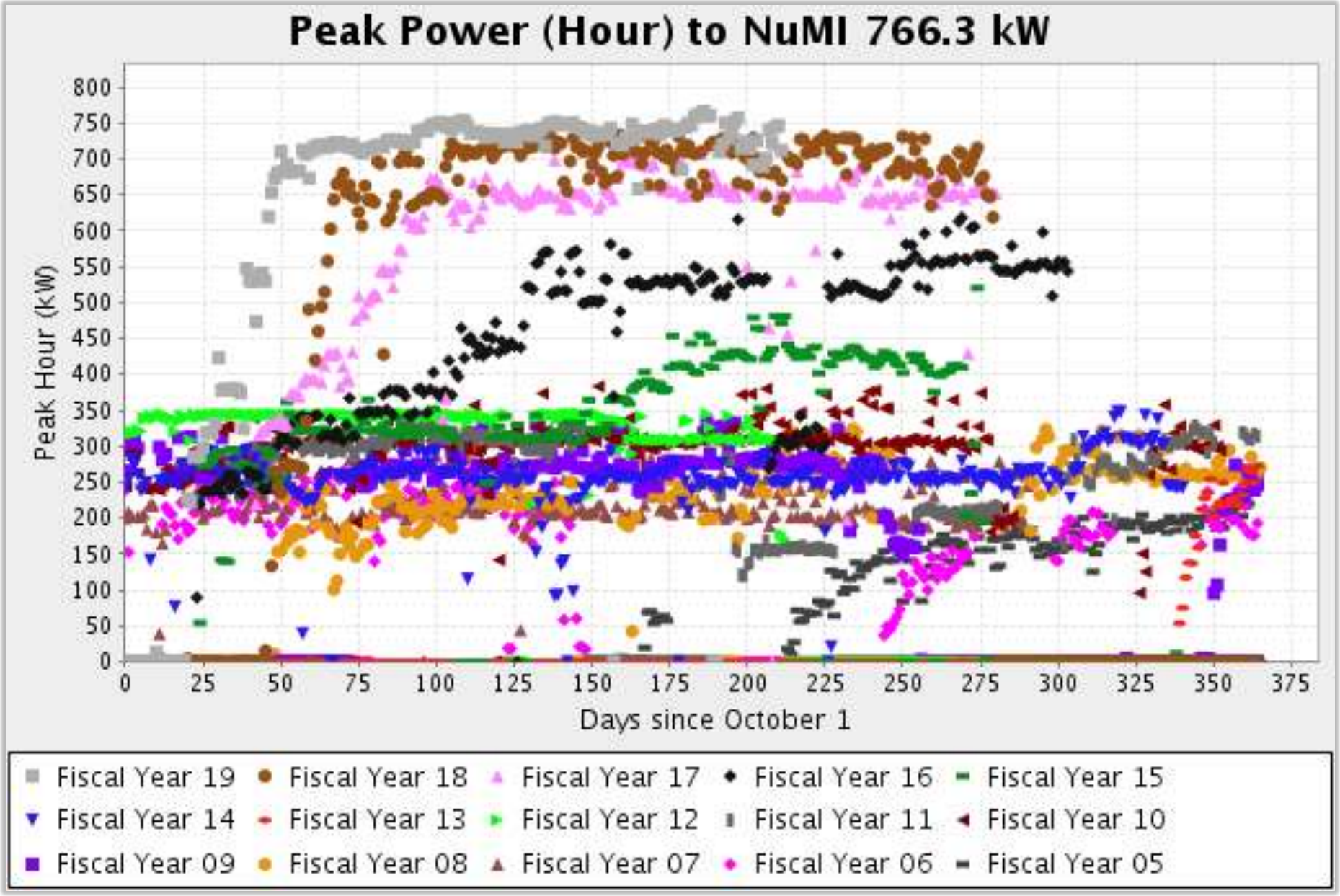
	E	L	Costr.
H- RFQ	0.75 MeV	2 m	2013
Linac	400 MeV	200 m	1970/93
Booster	8 GeV	500 m	1971
RR	8 GeV	3.3 km	1999
MI	120 GeV	3.3 km	1999
Delivery Ring	3.8-8 GeV	500 m	1985/2014
Beamlines	3-120 GeV	3.5 km	1970's-now
Upgr: PIP-II	800 MeV	240 m	2026
Upgr :PIP-III	8 GeV	500 m	Ca 2032
Upgr: beamlines	0.8-8 GeV	500 m	2026

Fermilab Accelerator Complex Users

- Proton Source (**400 MeV** Linac and **8 GeV** Booster ring):
  - 8 GeV Booster Neutrino Beam (BNB)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
    - ICARUS
    - SBND

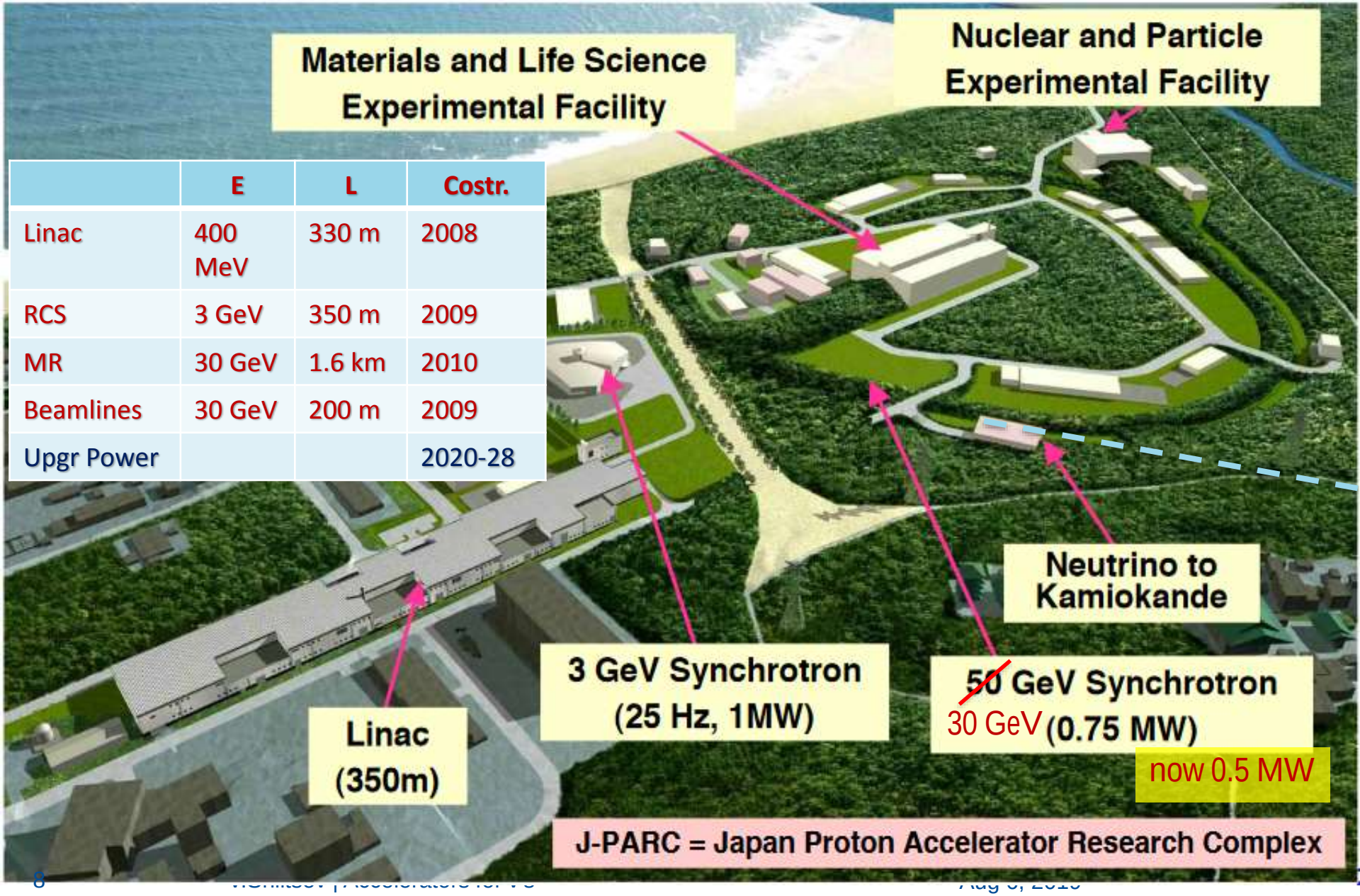
    8 GeV proton program expanding
  - Mucool Test Area (MTA, **400 MeV** beam test facility)
- **120 GeV** Main Injector / **8 GeV** Recycler:
  - NuMI: MINOS+, MINERvA, NOvA
  - LBNF/DUNE (future)
  - Fixed Target: SeaQuest, LArIAT, Test Beam Facility
  - Muon: g-2, Mu2e (future)

Fermilab Proton Complex Now: ~0.6e21 POTs/Year on ν target

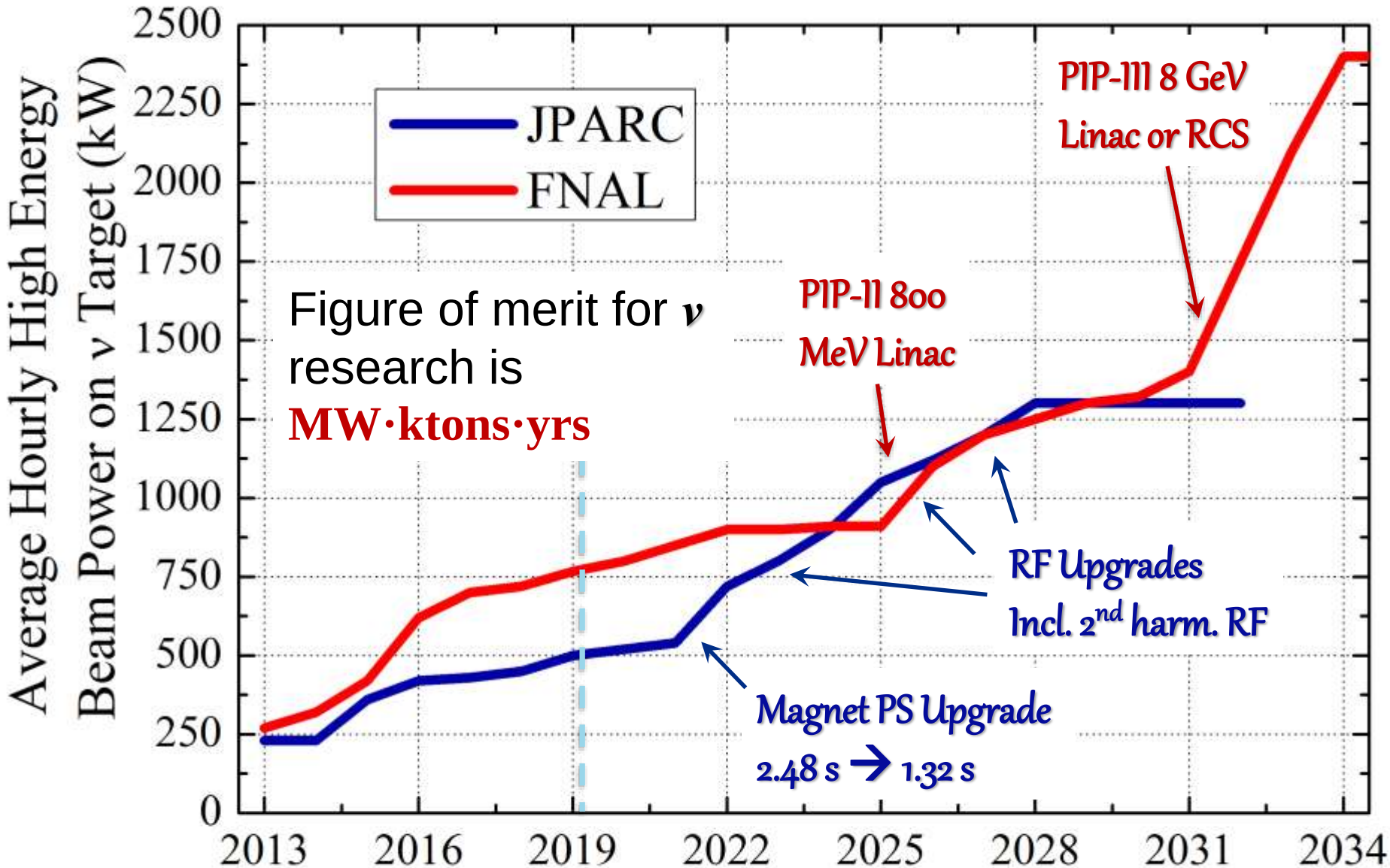


J-PARC sends neutrinos to Super-K (Hyper K)

	E	L	Costr.
Linac	400 MeV	330 m	2008
RCS	3 GeV	350 m	2009
MR	30 GeV	1.6 km	2010
Beamlines	30 GeV	200 m	2009
Upgr Power			2020-28

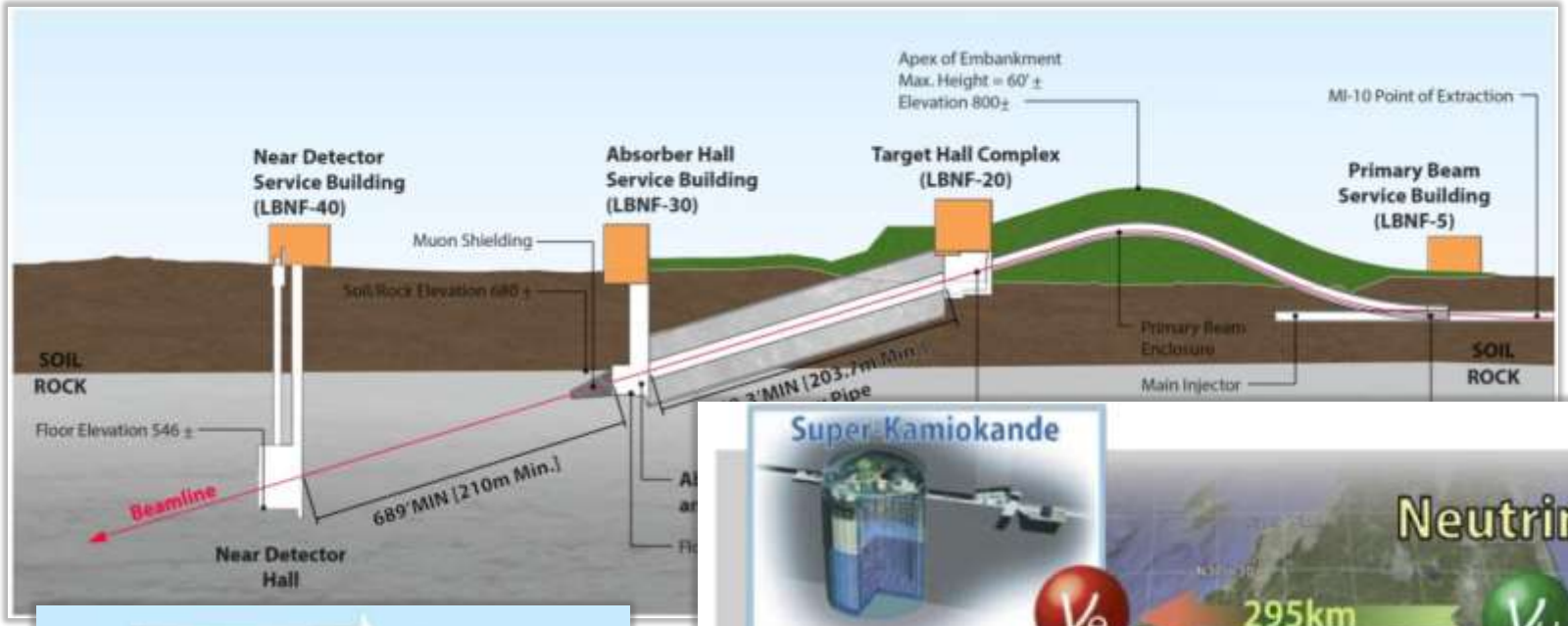


Fermilab and J-PARC Power Upgrades



40 kt LAr DUNE @ 2.4 MW & 1000 kt water Hyper-K @ 1.3 MW

** complimentary in terms of CPV sensitivity because of different ν's spectrum, different baseline (1300 km vs 295 km) and detector technology*



Ways to Increase Beam Power on Target

Particles per pulse

Particle energy [eV]

$$P_{beam} = \frac{N_{pulse} E}{T_{cycle}}$$

Accelerator cycle period

- **Brute force** :
  - increase the energy *E* – *magnets, RF*
  - decrease the cycle time *T* – *magnets, RF*
  - key challenge : cost (e.g., J-PARC TPC ~$1.7B) and power
- **Increase PPP** (protons per pulse) $\boldsymbol{N_p}$:
  - key challenges : many beam dynamics issues & cost
- In both cases – **need reliable horns and targets :**
  - key challenge : *lifetime* gets worse with power

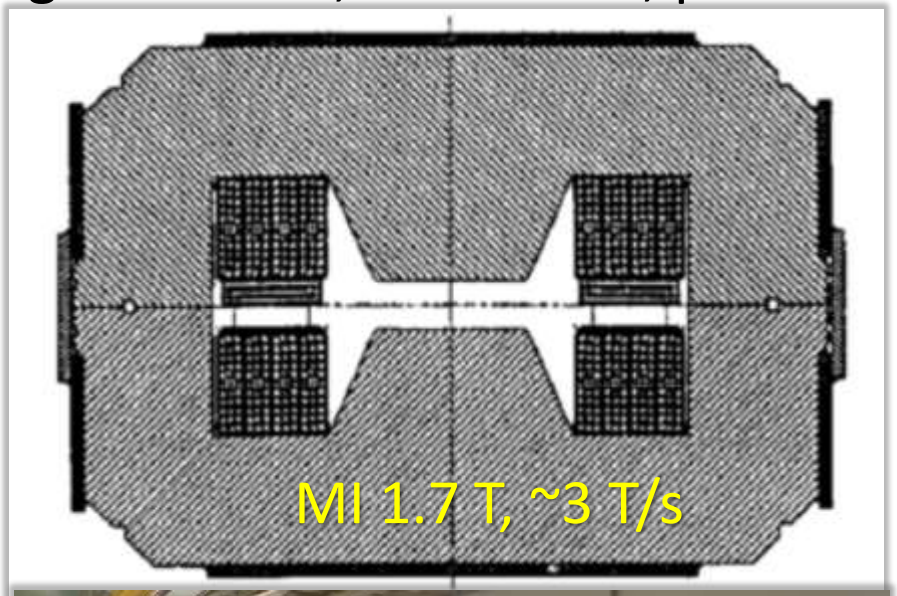
Fast Cycling Magnets + RF Cavities = 40-50% + 15-25% Cost *

** incl. magnet PSs and RF sources*

Major power consumers : e.g. FNAL MI:

Magnets 9 MW, RF 2.5 MW, pulsed 1 MW

Tunable frequency *O*(5%)



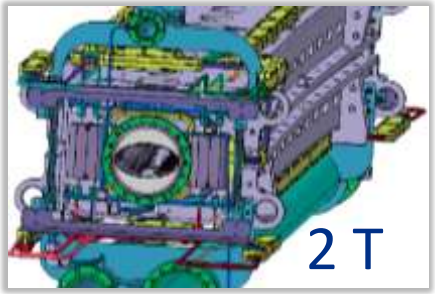
RF cavity loaded with magnetic alloy cores

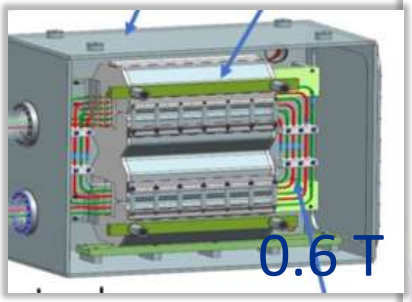
Power Efficiency – Huge Issue

Key R&D:

Efficient magnets :

- NbTi SC 4 T/s for FAIR
- HTS 12 T/s at FNAL





- FFAG accelerators *

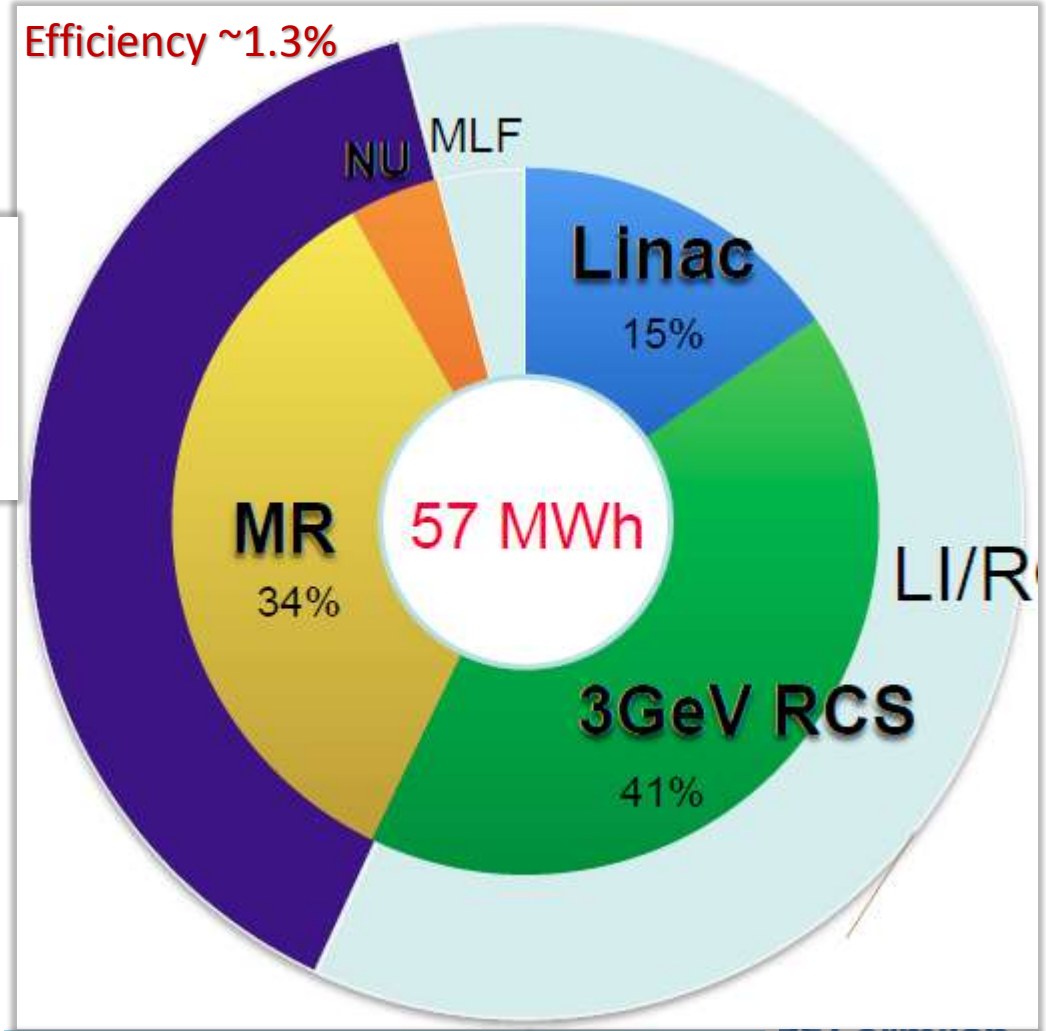
Efficient power supplies :

- Energy storage, e.g. capacitive, and recovery

Efficient RF power sources:

- η=55% → over 80%
- klystrons, magnetrons, solid-state, etc

J-PARC : 0.5 MW beams vs ~40 MW site power



- MR Magnets: 10.4 MWh per hour
- MR RF: 3.8 MWh per hour
- RCS Magnets: 9.6 MWh per hour
- RCS RF: 7 MWh per hour

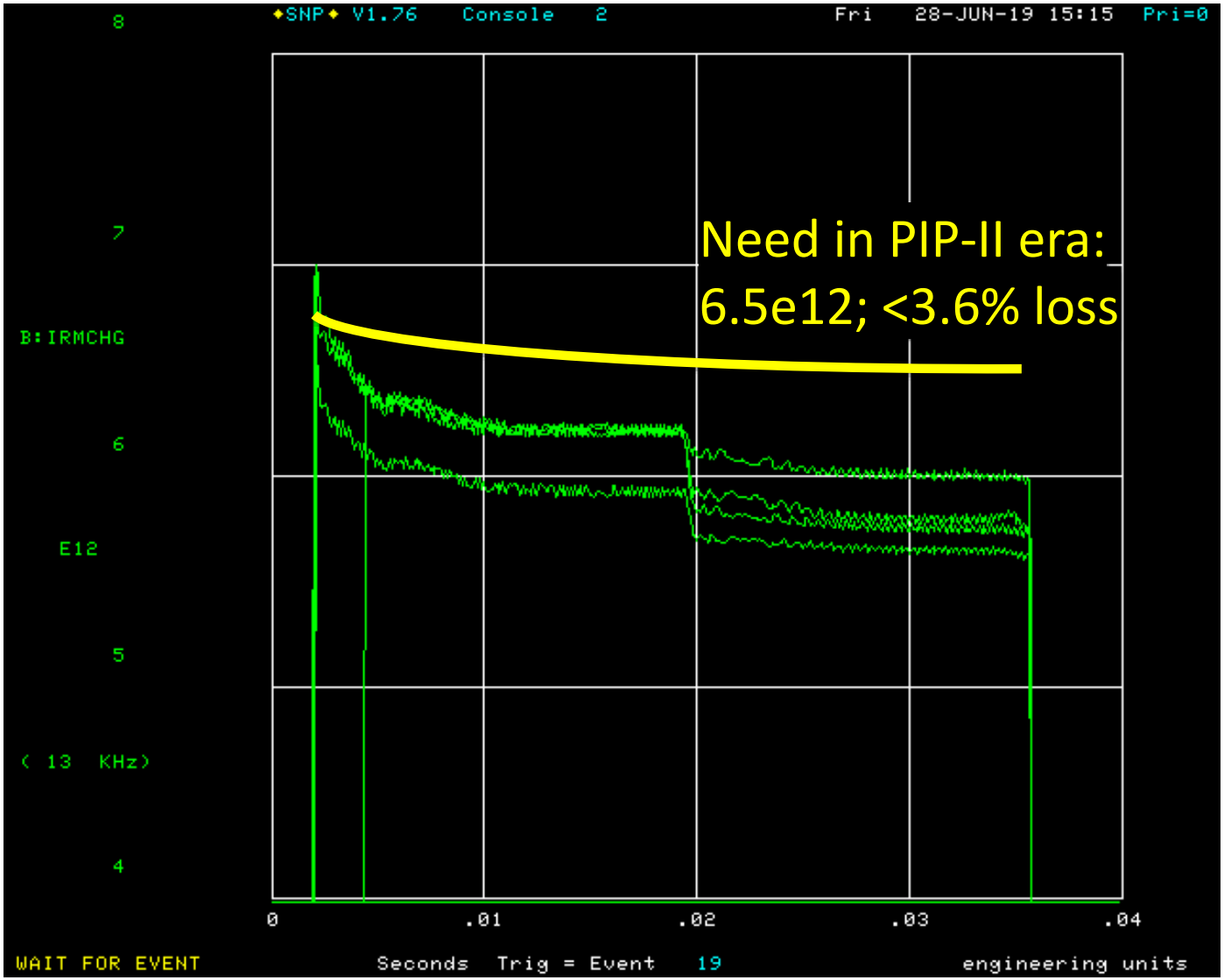
Protons Per Pulse Challenge : (June'19 Booster Studies) – Extracted 6e12 ppp – Booster record?

(per Jeff)

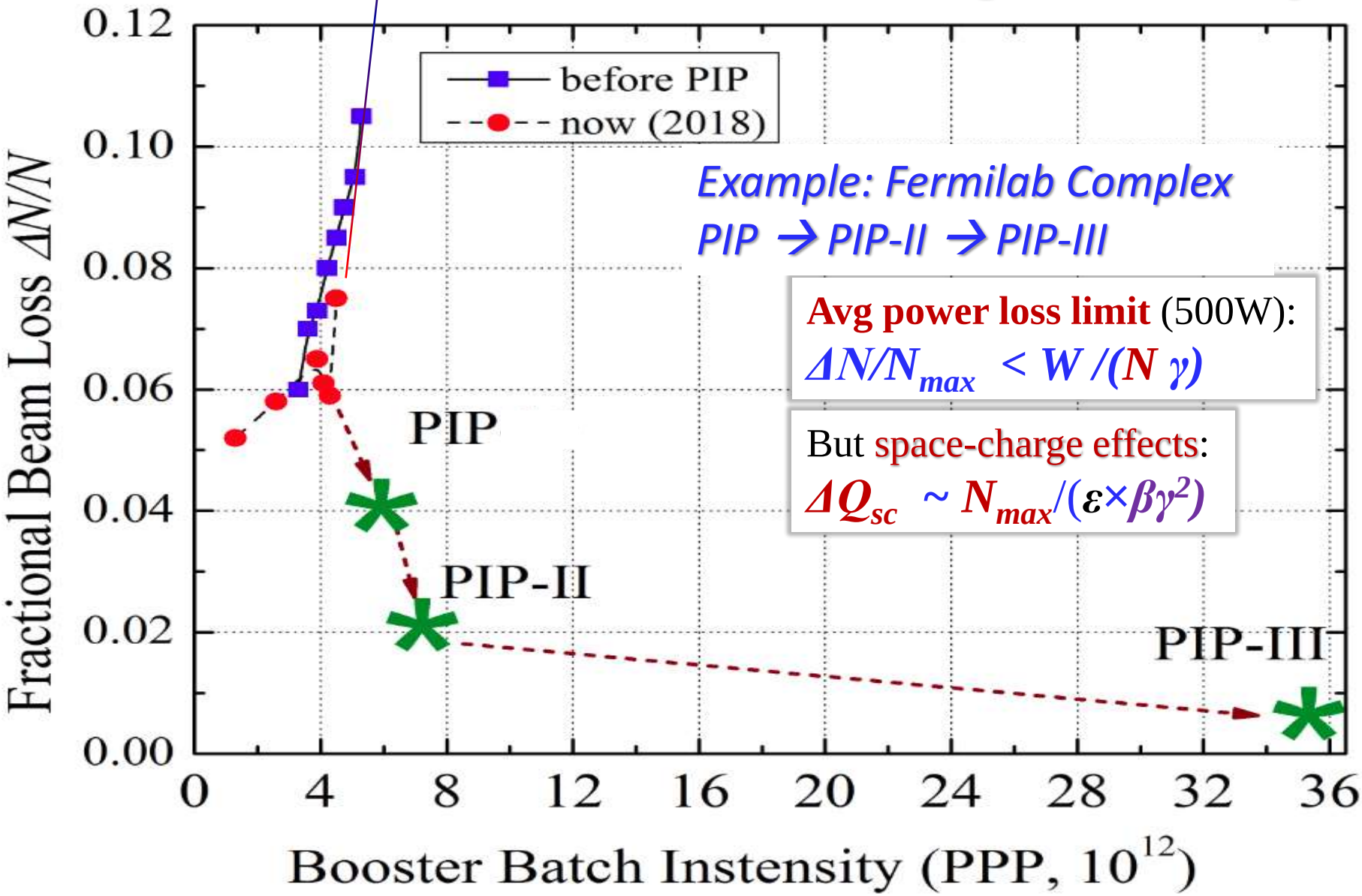
"…I went through some Elog history and Datalogger data, and I think it is a record.
I could not find any prior occasion in which the Booster successfully extracted above 6e12."

6e12/7e12=
86%

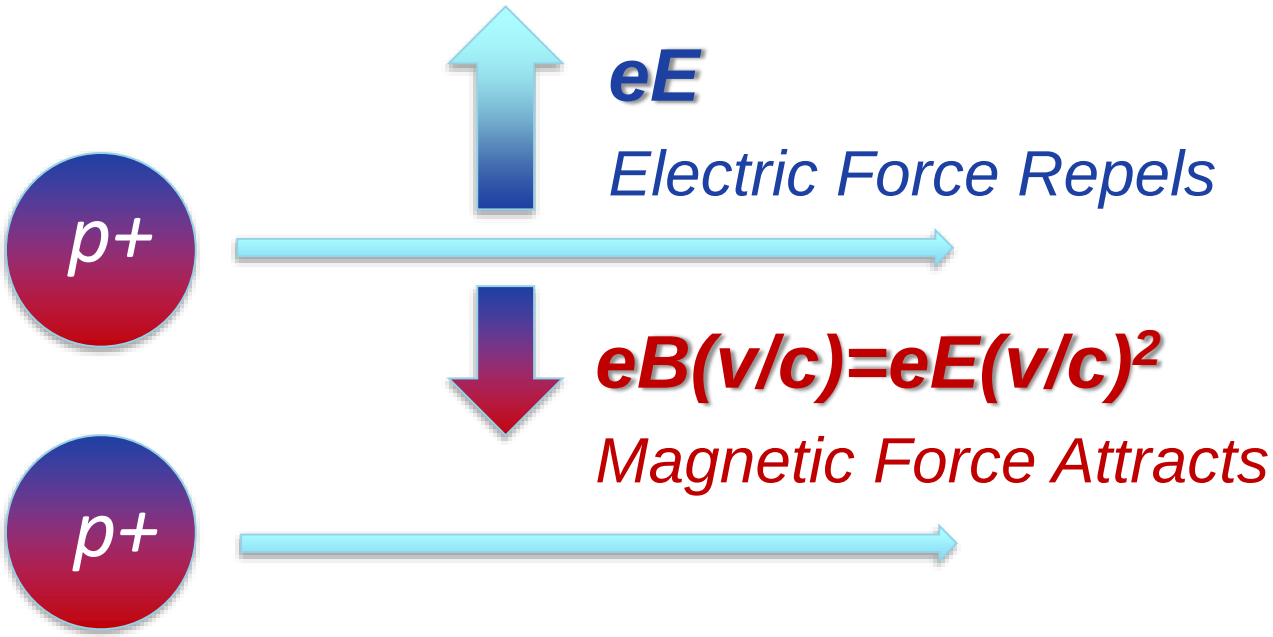
Transmission efficiency



Protons Per Pulse Challenge: to lower beam losses while increasing intensity



Intense Beams : Forces and Losses (1)

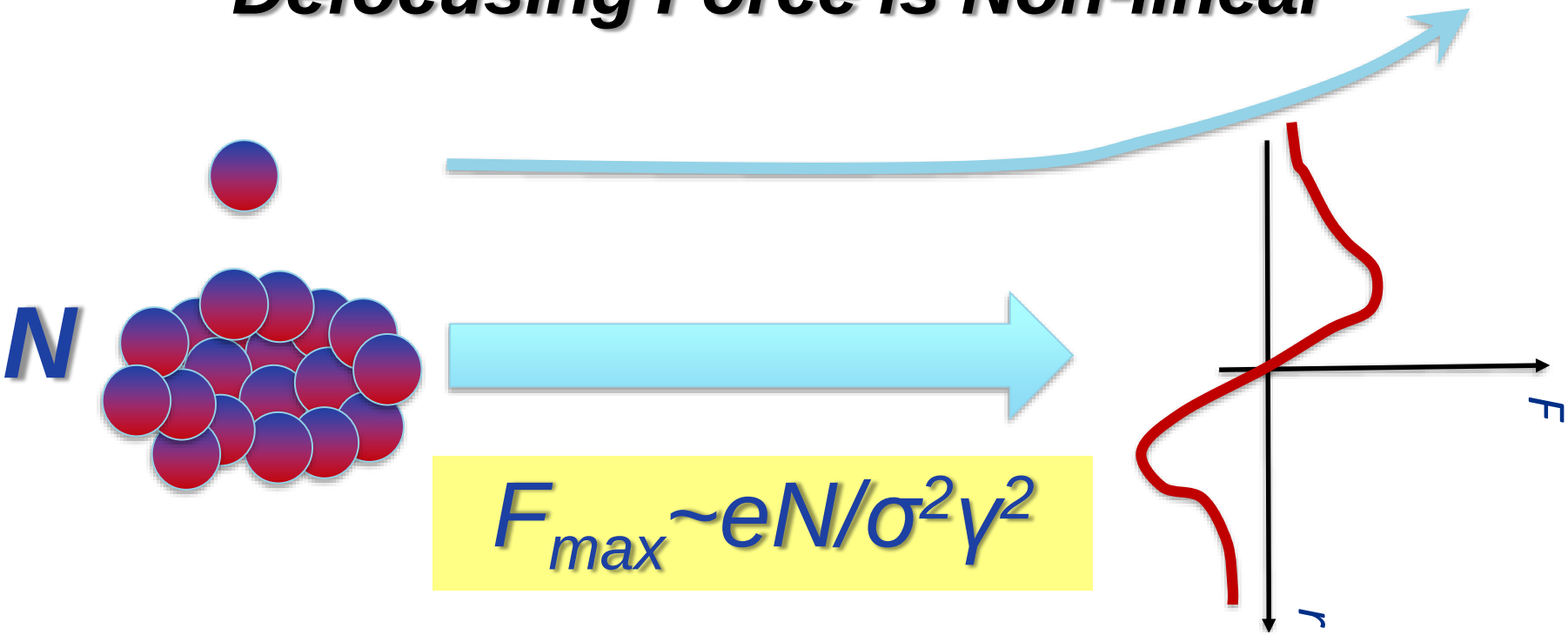


Net Force: Repels

$$eE - eE(v/c)^2 = eE\,(1-\beta^2) = eE/\gamma^2$$

Intense Beams : Forces and Losses (2)

Defocusing Force is Non-linear



$$F_{max} \sim eN/\sigma^2\gamma^2$$

Space-charge effects (emittance growth, losses):

a) proportional to current (N)

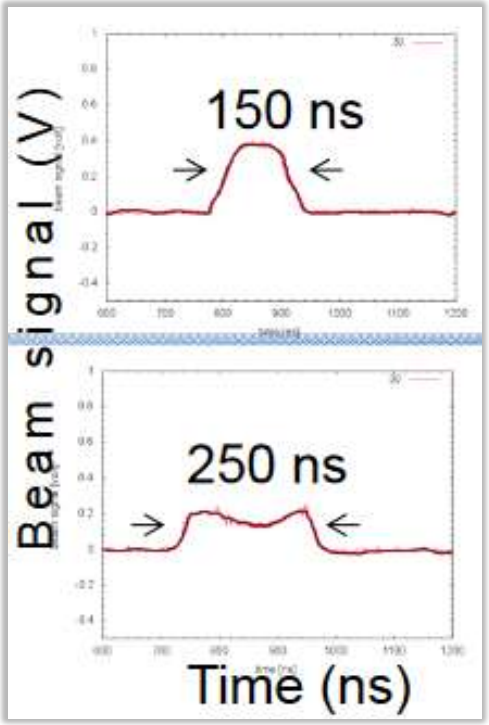
b) scale inversely with beam size (σ)

c) scale with time at low energies (γ)

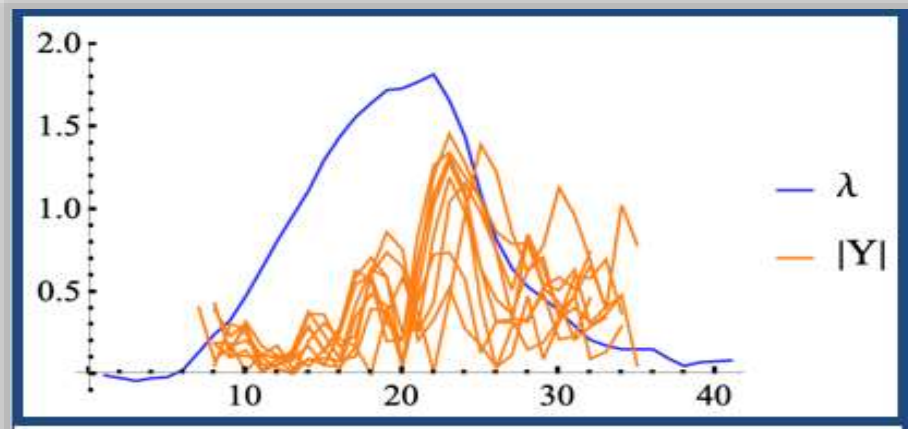
Linacs 5-20 MeV/m
Rings 0.002-0.01 MeV/m

Ways to Increase "Protons per Pulse"

- **Increase the injection energy**:
  - Gain about $N_p \sim \beta\gamma^2$, need (often - costly) linacs
- **Flatten the beams** (using 2nd harm, RF) :
  - Makes peak SC force smaller, $N_p \sim$ x2
- **"Painting" beams** at injection:
  - To linearize SC force across beams $N_p \sim$x1.5
- **Better collimation system beams:**
  - From η~80% to ~95% $N_p \sim$x1.5
- **Make focusing lattice perfectly periodic**:
  - Eg P=24 in Fermilab Booster, P=3 in JPARC MR → $N_p \sim$ x1.5
- **Introduce *Non-linear Integrable Optics*** :
  - Reduces the losses, $N_p \sim$ x 1.5-2
- **Space-Charge Compensation** by electron lenses **:**
  - Electrons focus protons $N_p \sim$x1.5 - 2

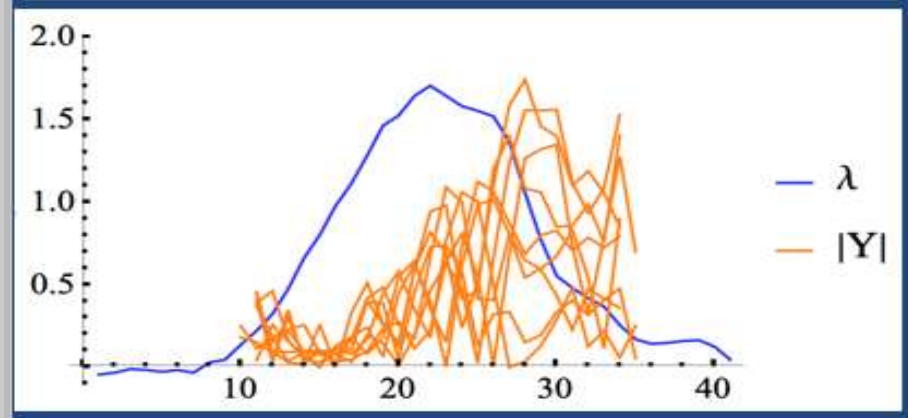


Instabilities: Yet Another One ("convective", A.Burov)

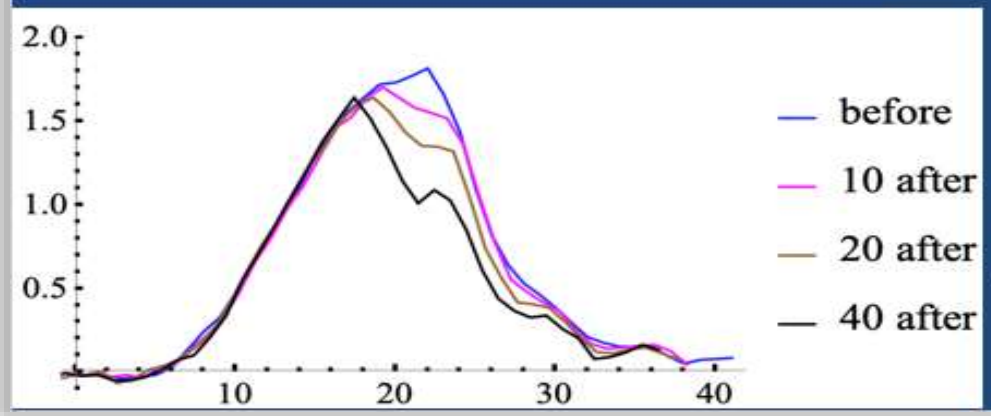


Line density (blue) and overlapped offset abs. value (orange), 8 next turns after the beam loss began, bunch #36.

May 2019, Booster studies



8 more turns after



Same bunch, just before and some turns after the beam loss began.

Option #1 : Proton Improvement Plan-II

- **Key elements:**
  - Replace existing 400 MeV linac

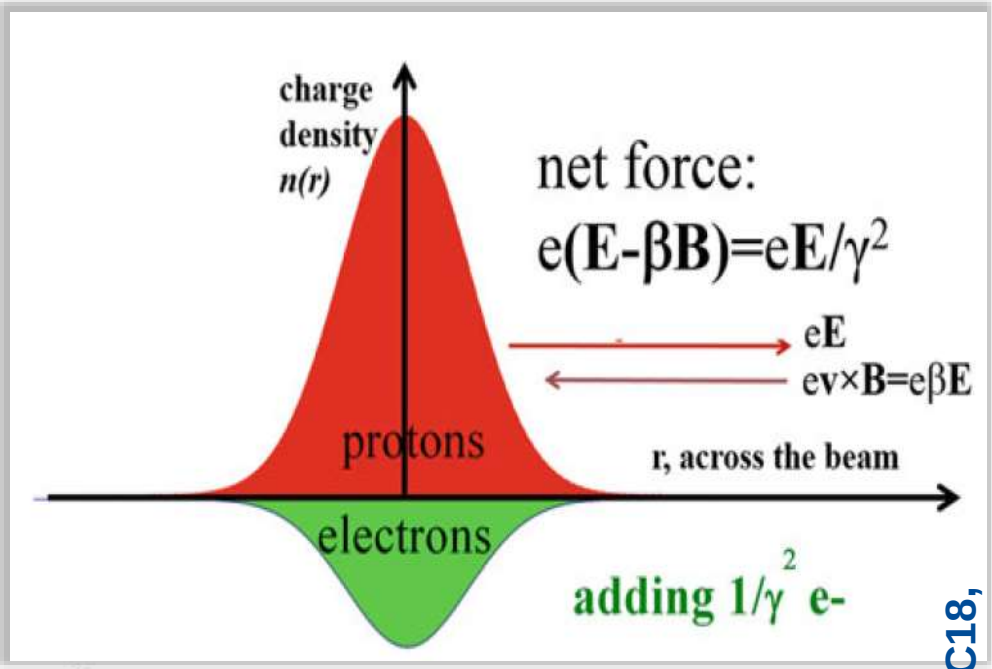
- ~100 kW @ 800 MeV
  - Arbitrary bunch structure
  - Muons (*mu2e**)

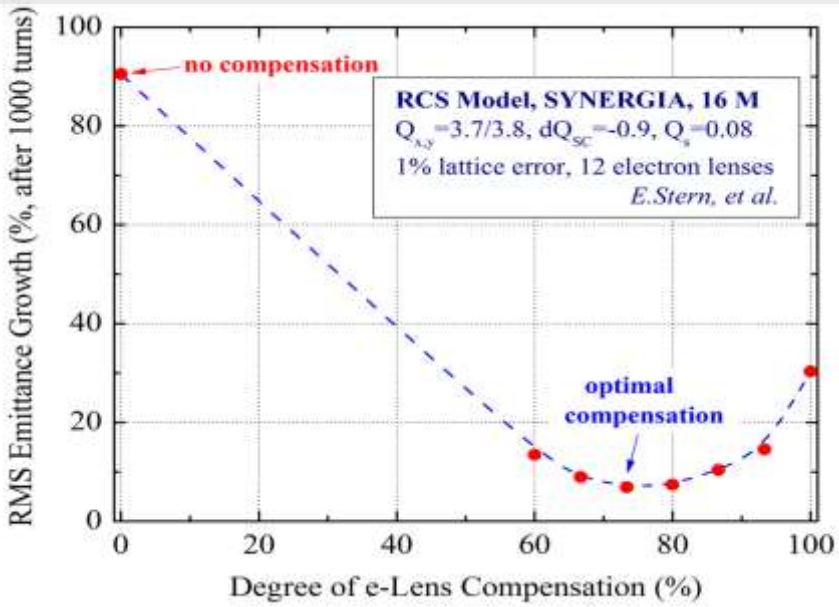
Fermilab

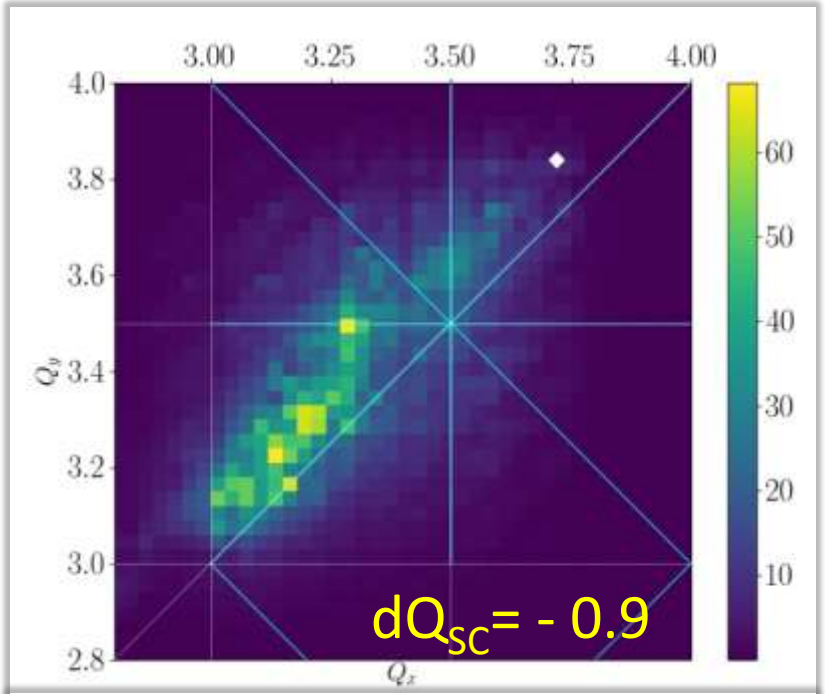
Note that linacs have their limitations, too – eg *H-* intrabeam stripping

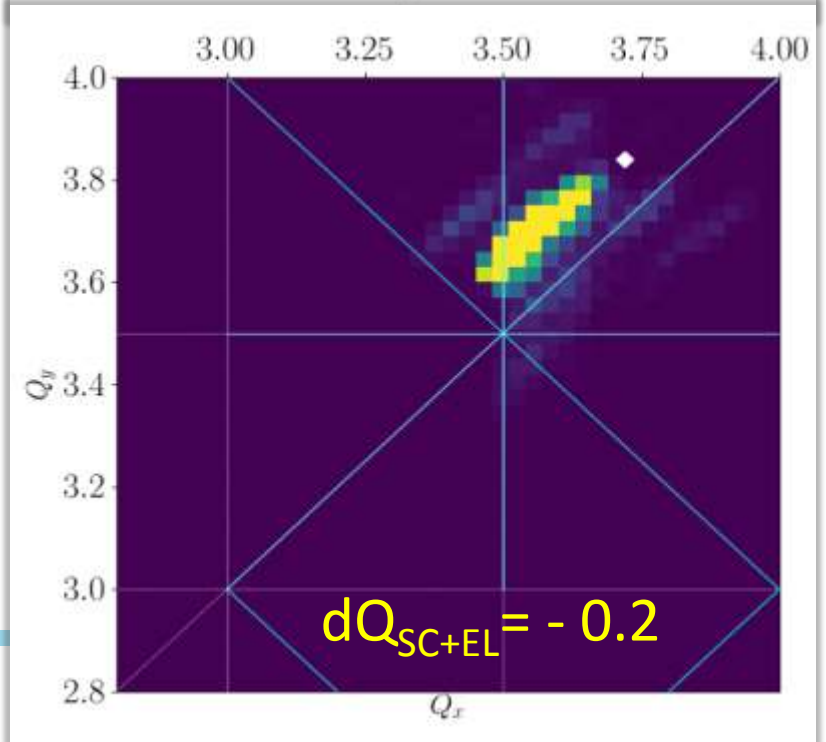
IOTA: *Integrable Optics Test Accelerator*

Space-Charge Compensation R&D









E.Stern et al, THPAF075, IPAC18, Beams Document 6790-v1 FNAL

Very Important : Targetry, Foils, e-clouds

- Existing ν targets and horns are good to ~0.8 MW, MW and multi-MW targets are under development
  - Issues depend on pulse structure and include **radiation damage and thermal shock -waves**
  - **R&D program** to study material properties, new forms (foams, fibers, etc), new target designs (rotating, etc)
- Also under development: injection of high power beams (stripping foils, laser stripping), e-cloud effects, etc
- We learn from lower energy - but record power - **machines PSI and SNS (1.4 MW), RAL/ISIS**, etc

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Proposed Facilities for Neutrino Research

Protvino-to-ORKA: L=2590km, E_ν ~5 GeV

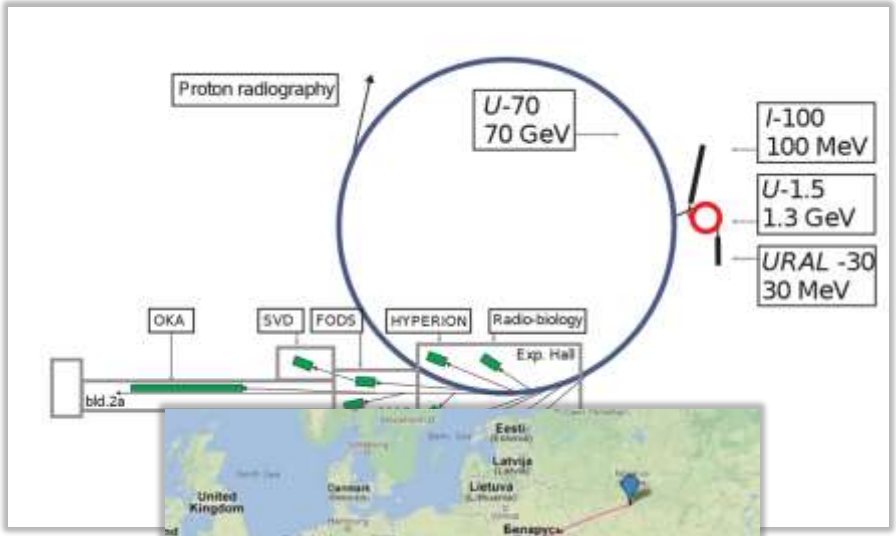
Input #124

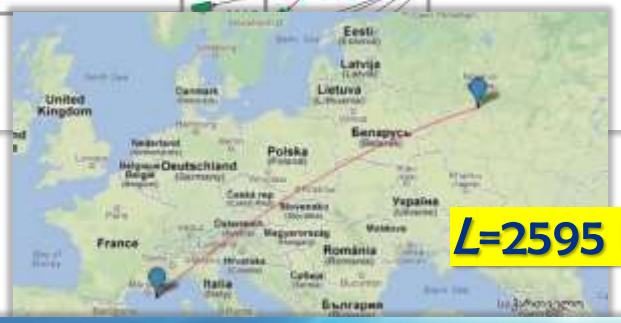
U-70 *p*+ synchrotron:

70 GeV protron beam

1.5 10^{13} *p*+ per pulse, T_{cycle}=10s

5μs (fast extraction), P_{avg} =15kW





Needed upgrades:

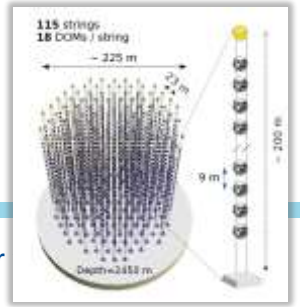
Decay pipe ~180 m long

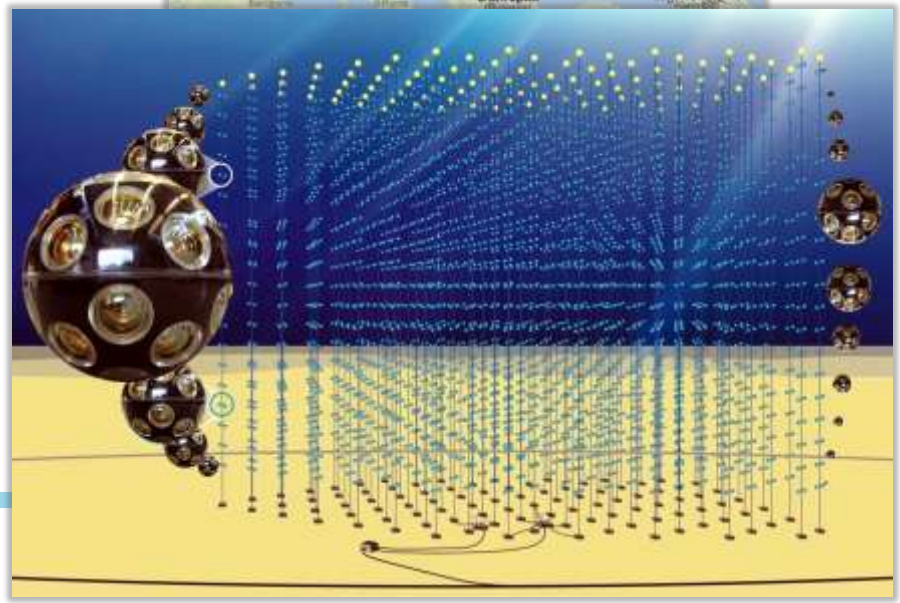
Power to 90 kW by 2026:

- 5 10^{13} *p*+ per pulse, T_{cycle}=7 s
- 5 yrs of ORCA data taking

Then to 450 kW by 2035

- (no details yet)
- Super-ORCA





ESS Neutrino Super Beams

ESSνSB **Input #98**

European Spallation Source:

~600 m SC linac, 1.83 B Euros

2 GeV x 62.5 mA x (η=4%) = **5 MW**

2.8 ms pulses

32 MW site power after all the measures

ESSνSB

CDR 2021, TDR 2024

Construction start 2026-2029

Linac upgrade 14 Hz → 28 Hz (η → 8%)

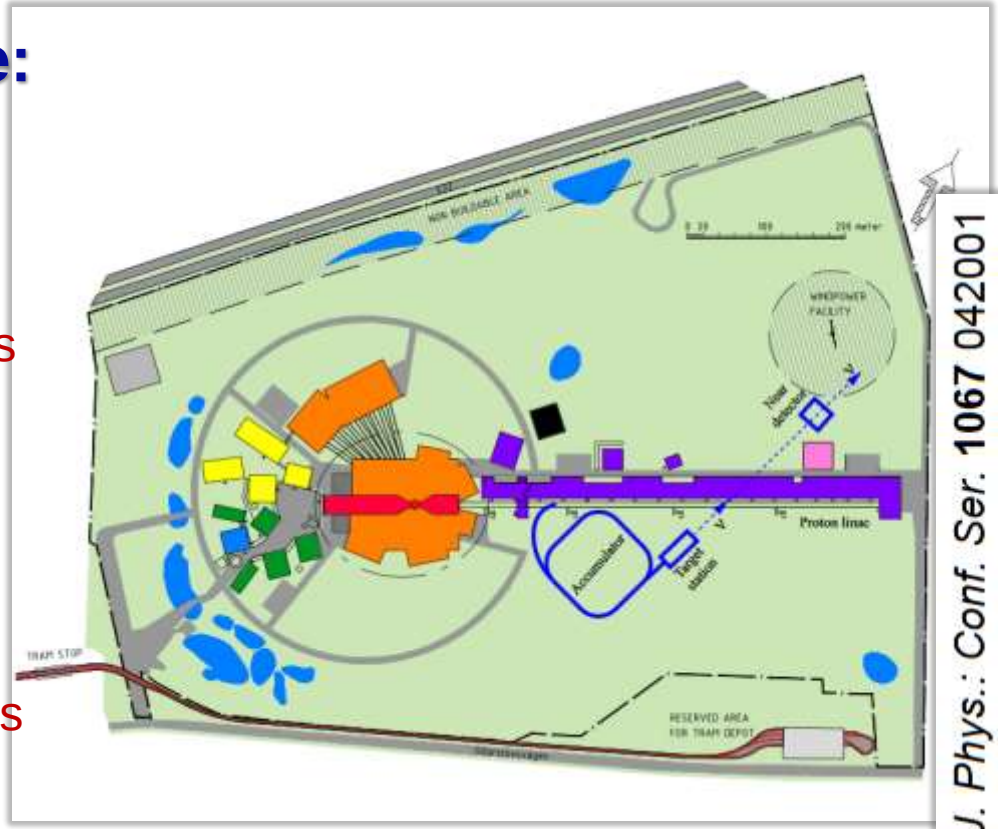
Accumulator C~400 m to compress to μs

H- instead of p+, space charge effects

Target station

Cost estimate 1.3 B Euro

Linac upgrade	230 MEUR
Accumulator ring	150 MEUR
Target Station	170 MEUR
Near and Far Detector	750 MEUR



Marcos Dracos 2018 *J. Phys.: Conf. Ser.* **1067** 042001

~0.3 GeV neutrino beam is directed towards the north in the direction of the Garpenberg mine, 540 km away, which could host the far 1 megaton water Cerenkov detector

ENUBET : SPS-based Short base-line ν's

Input #57

- to measure the cross sections as *f*(energy) with much better precision

SPS at CERN (max CNGS):

E=400 GeV protron beam

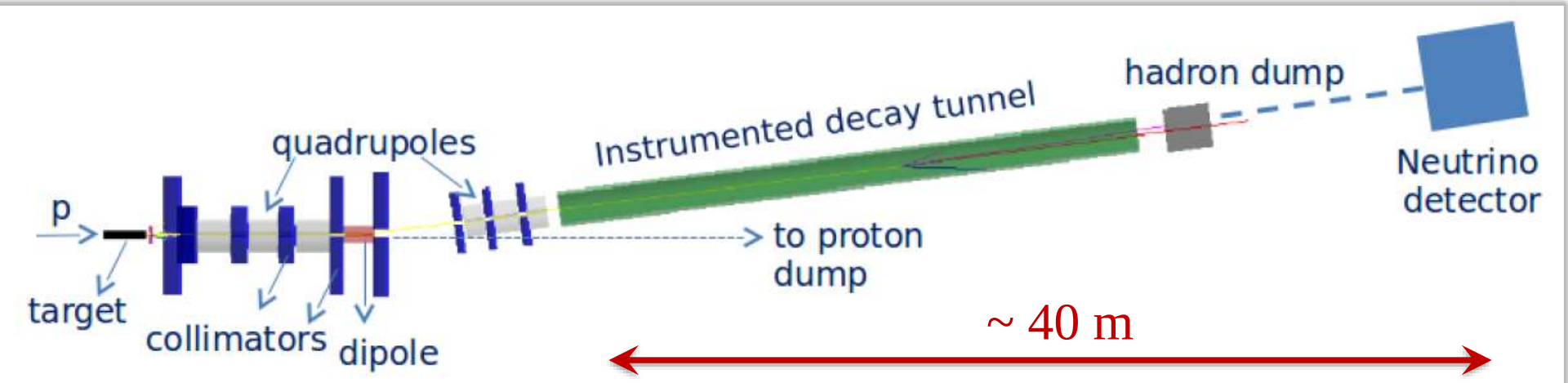
2.25 10^{13} *p*+ per pulse,

T_{cycle}=5.8s, 10 μs (fast extr.)

→ avg. *P*_beam = 510kW

8.5 GeV central energy of secondaries (pions, kaons)

0.5-3.5 GeV neutrino's



νSTORM

Input #154 2017 *JINST* **12** P07018 2017 *JINST* **12** P07020

SPS at CERN :

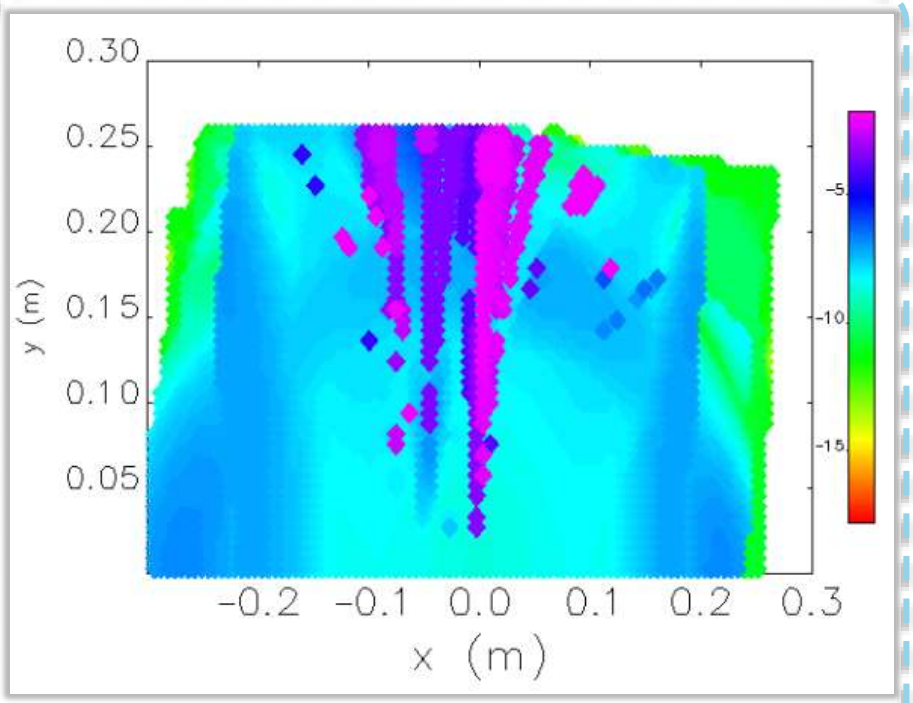
E=100 GeV *P*_beam =**156kW**

4 10^{13} *p*+ per pulse

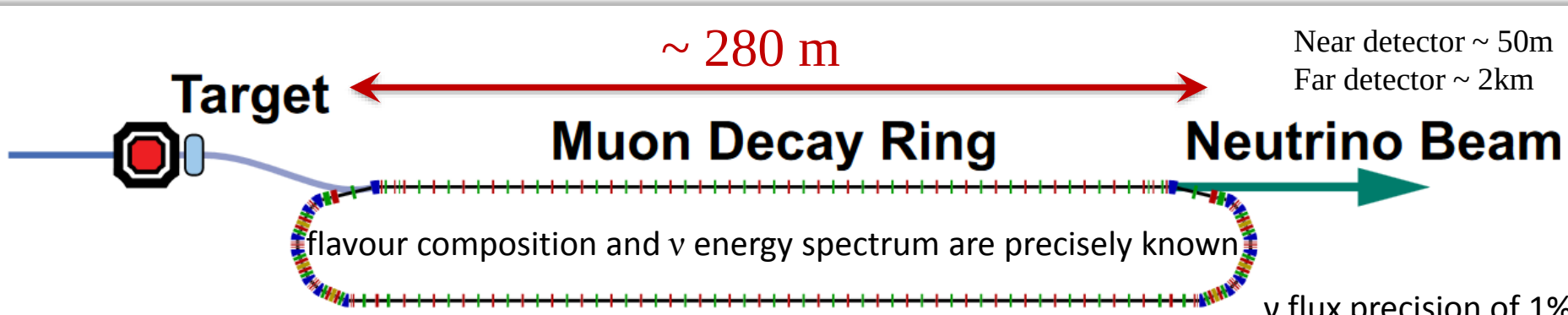
T_{cycle}=3.6 s, 2 x 10 μs (fast extr.)

$\mu\pm$ beams 1 GeV/c - 6 GeV/c
momentum spread of 16%

Cost est. 160 MCHF @ CERN



Challenge: a) 300 μmrad emittance → 0.5 dia magnets; b) survival ~60% after 100 turns for $\delta P/P$ ~10%



ν flux precision of 1%

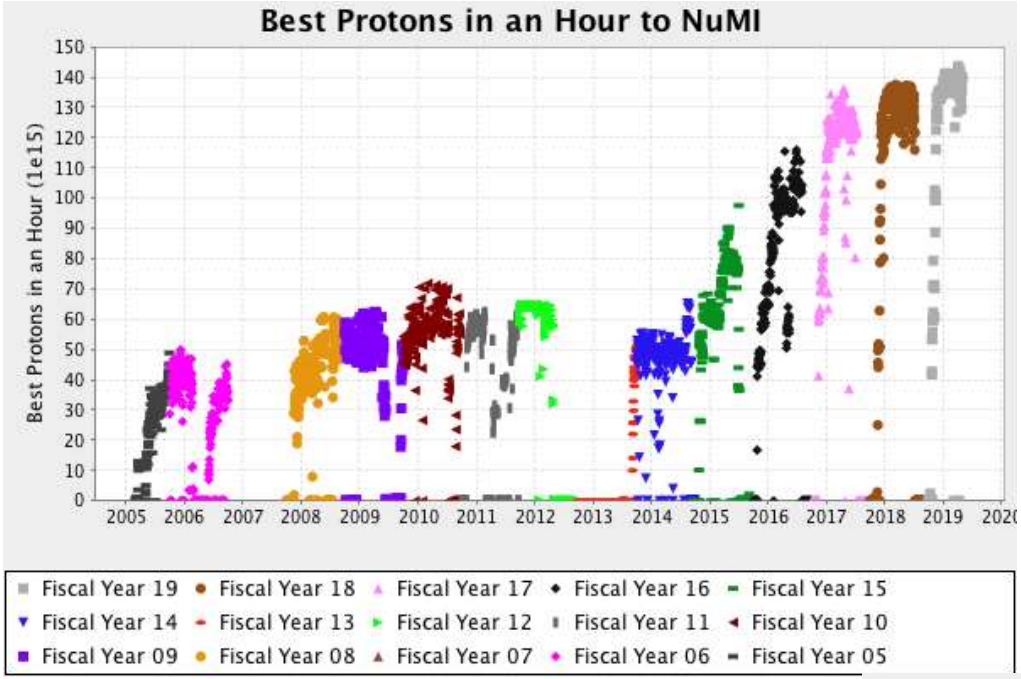
Summary:

- Over the past decade we witness impressive progress of high energy high power accelerators for *ν* research:
  - J-PARC achieved ~500 kW of 30 GeV beam, Fermilab MI over 750 kW of 120 GeV
- Neutrino physics demands multi-MW facilities:
  - some of them in progress – Fermilab's PIP-II linac upgrade
  - in general, many challenges faced beyond 1 MW
- Accelerator R&D is required and in many cases started:
  - On cost saving technologies (magnets, RF sources, etc)
  - On control of space-charge effects, instabilities and losses
    - to be tested at operational machines and IOTA ring
  - On MW and multi-MW neutrino targets and horns
- New proposals show promise and should be further studied :
  - Protvino-to-ORKA; ESSνSB; ENUBET; νSTORM

Thanks for Your Attention !

Acknowledgements

Yuri Alexahin, Paul Czarapata, Paul Derwent, Jeff Eldred, Steve Holmes, Valeri Lebedev, Sergei Nagaitsev, Bill Pellico, Eric Stern, Cheng-Yan Tan, Alexander Valishev, Bob Zwaska (all – Fermilab), Eric Prebys (UCD), Frank Schmidt (CERN), David Bruhwiler (RadiaSoft)


Best Protons in an Hour to NuMI
Best Protons in an Hour (1e15)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Fiscal Year 19
Fiscal Year 18
Fiscal Year 17
Fiscal Year 16
Fiscal Year 15
Fiscal Year 14
Fiscal Year 13
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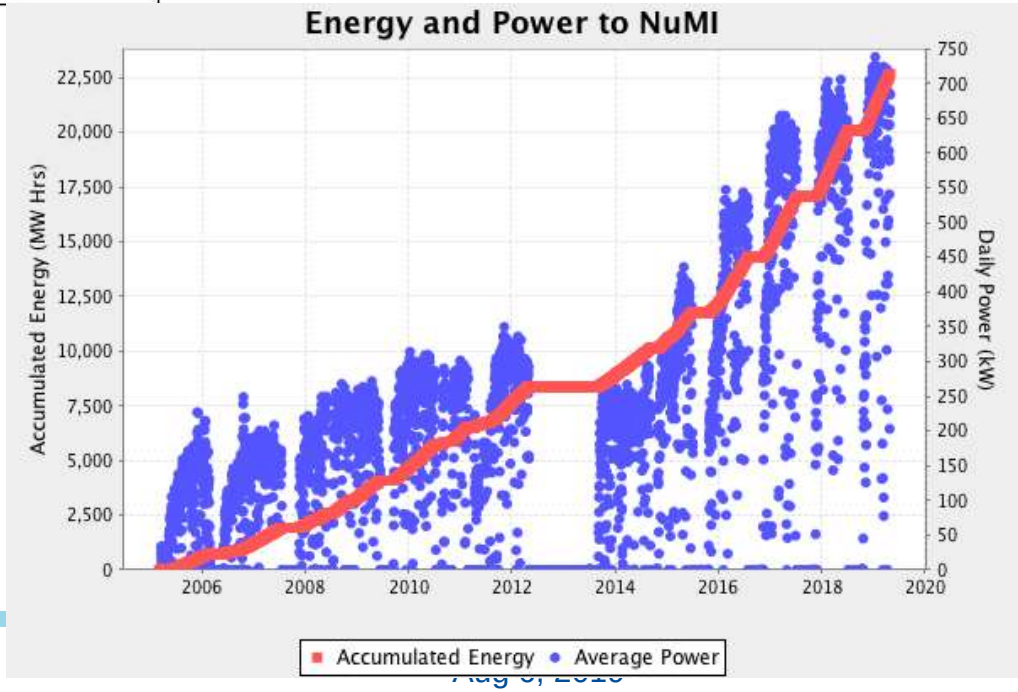
Fiscal Year 06
Fiscal Year 05


Energy and Power to NuMI
Accumulated Energy (MW Hrs)
22,500
20,000
17,500
15,000
12,500
10,000
7,500
5,000
2,500
0
Daily Power (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
2006
2008
2010
2012
2014
2016
2018
2020
Accumulated Energy
Average Power

Slow and Painful Understanding of Reality

- TIER I Issues (feasibility of):

ENERGY **COST** **POWER**

- TIER II Issues:

Luminosity **Detectors** **Backgrounds** **Availability of Experts**

R&D required **Polarization** **Timeline** **Re-use** **etc.**

PIP-II Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	**400**	**800**	**MeV**
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.6	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Booster Protons per Pulse	**4.3×10^{12}**	**6.5×10^{12}**	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max; MI @ 120 MeV)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	**0.7***	**1.0-1.2**	**MW**
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*NOvA operations at 120 GeV

(How to Get Around) Space Charge Limit

- The maximum useful injected charge into the Booster is limited by the *space charge tune-shift*, which can drive harmonic instabilities.

total protons

"Bunch factor" = I_{peak}/I_{ave}
(Reduce with higher RF harmonics)

$$\Delta\nu \approx \frac{N r_0}{2\pi\epsilon_N \beta\gamma^2} FB \lesssim .3$$

normalized emittance
$\epsilon_N = \epsilon\beta\gamma = \text{constant}$

= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

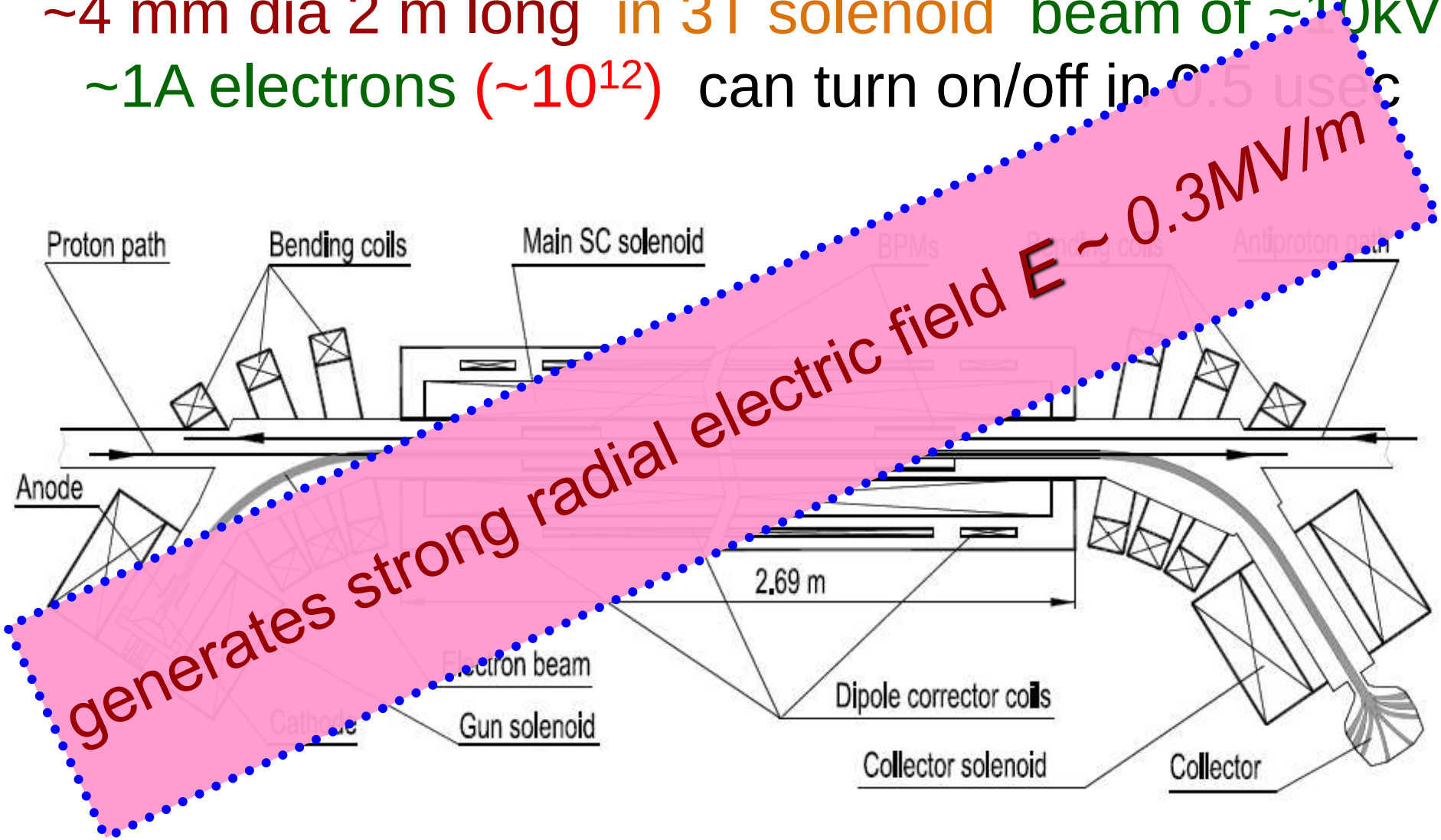
(if not straightforward solution – double the energy - then)

- Two novel approaches to increase the SC tune-shift:
  - "Integrable Non-Linear Optics"
  - Space-Charge Compensation with Electron Lenses
- Possibly augmented with Superperiodic Focusing Lattice and "flat long bunches" (multiple harmonics RF)

Electron Lens

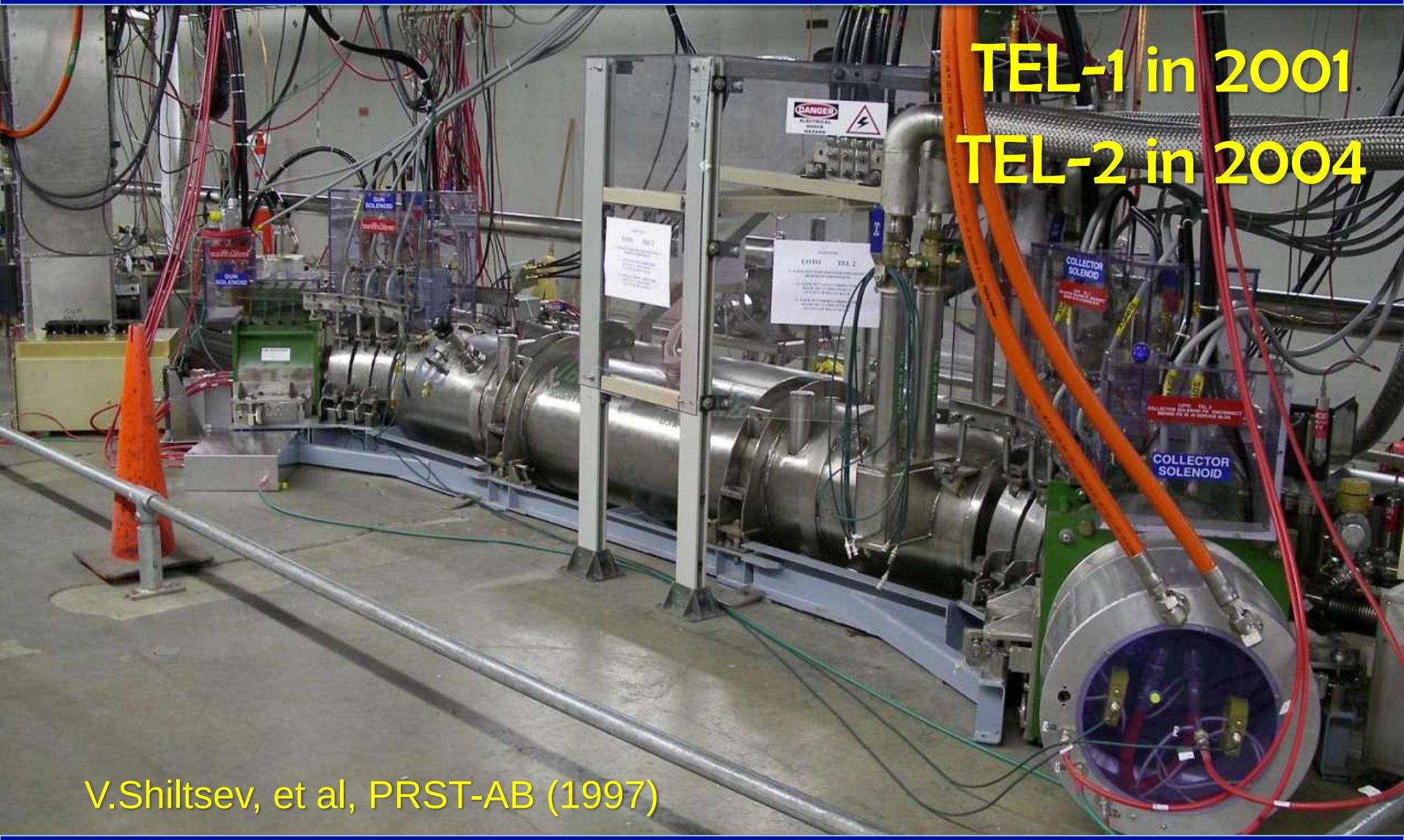
~4 mm dia 2 m long in 3T solenoid beam of ~10kV

~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



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

What Electron Lenses Are Good For (1)

In the Fermilab Tevatron Collider:

- **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)

PAST

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

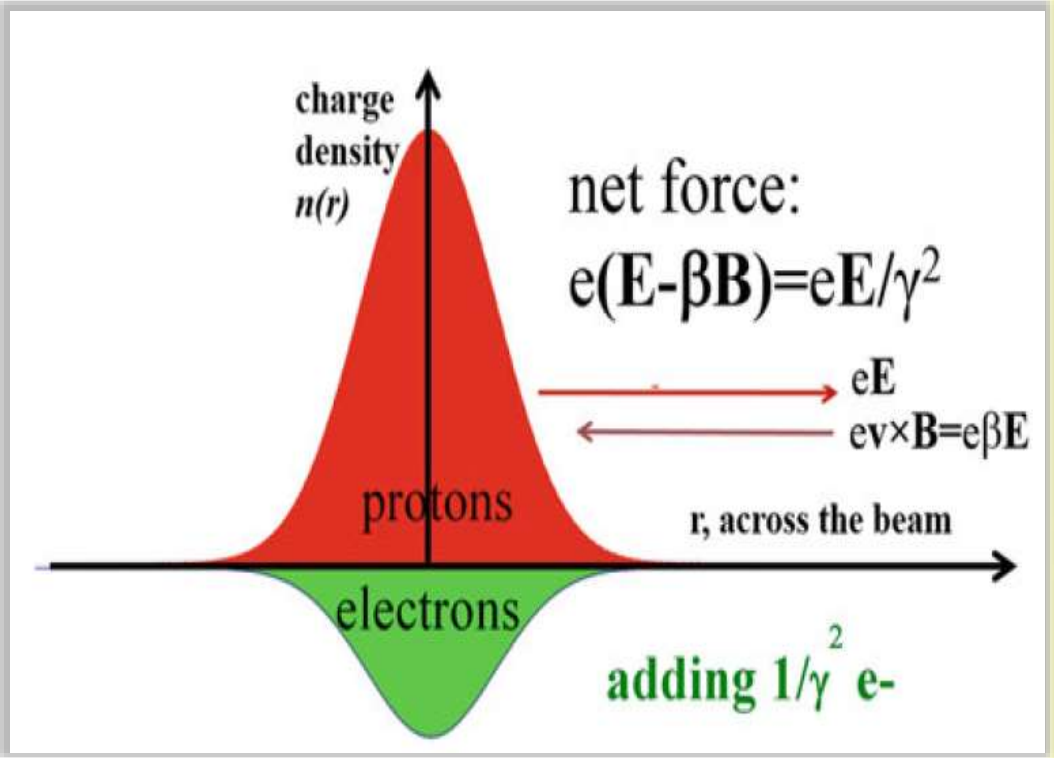
FUTURE

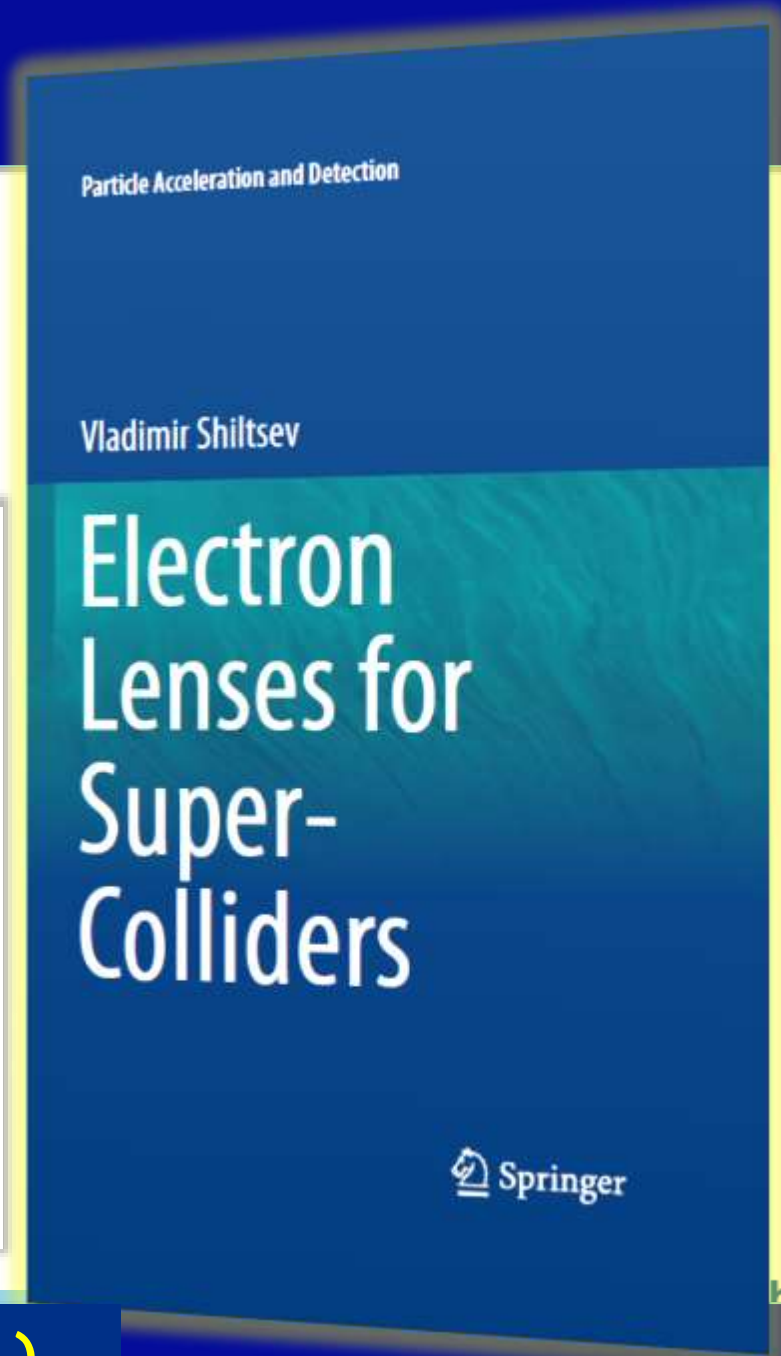
Fermilab

versatile applications depending on e-beam profile + pulsing

Book

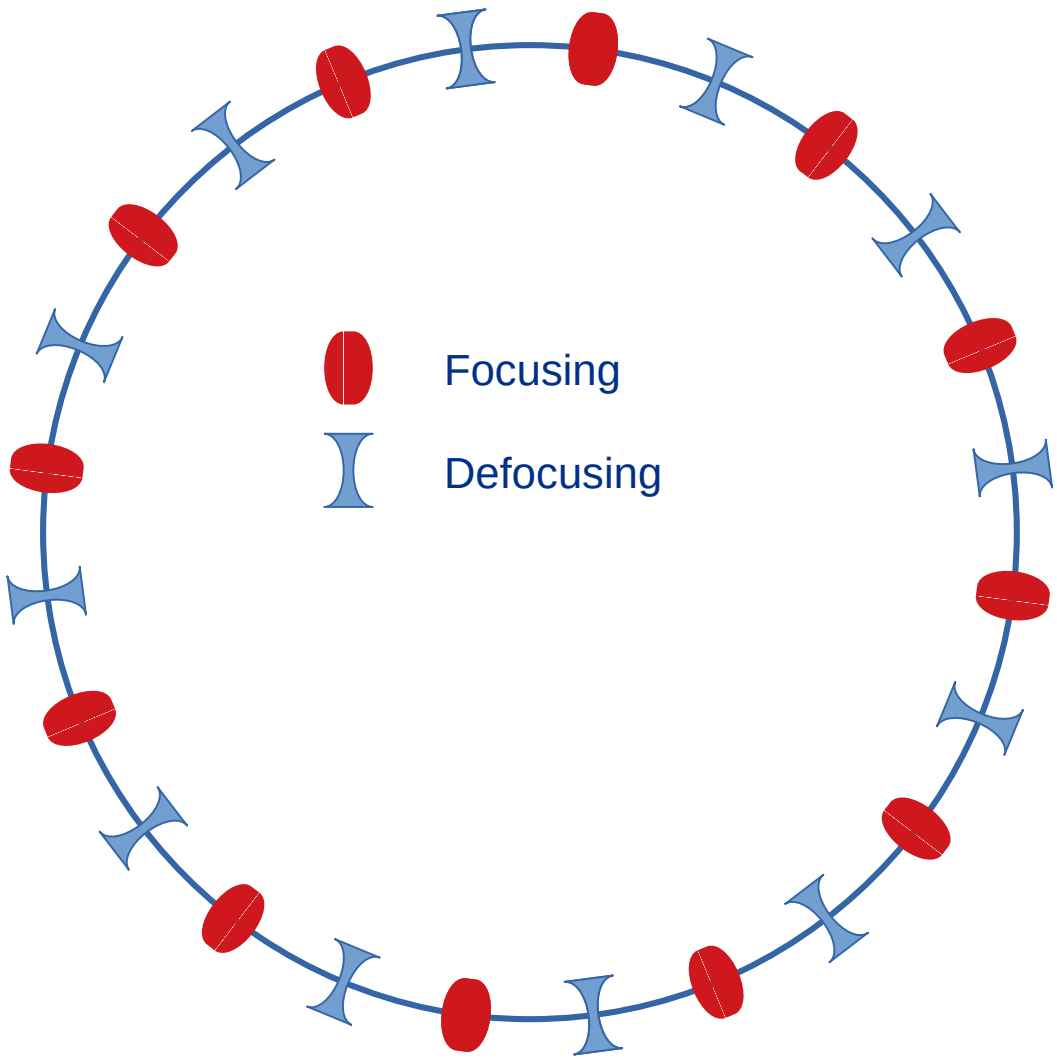
Below I present just one example of compensation of space-charge effects by electron lenses





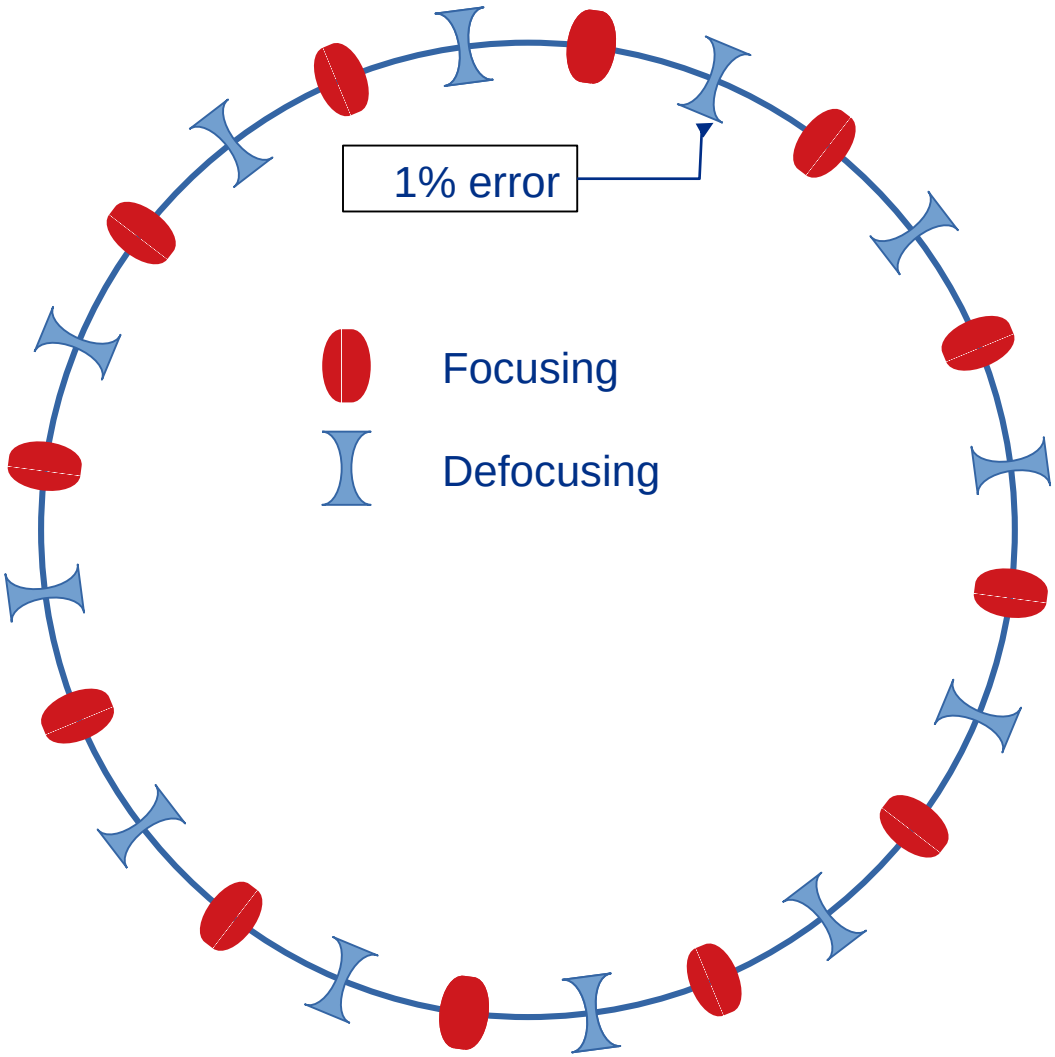
PIC simulations by E.Stern, et al (FNAL)

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



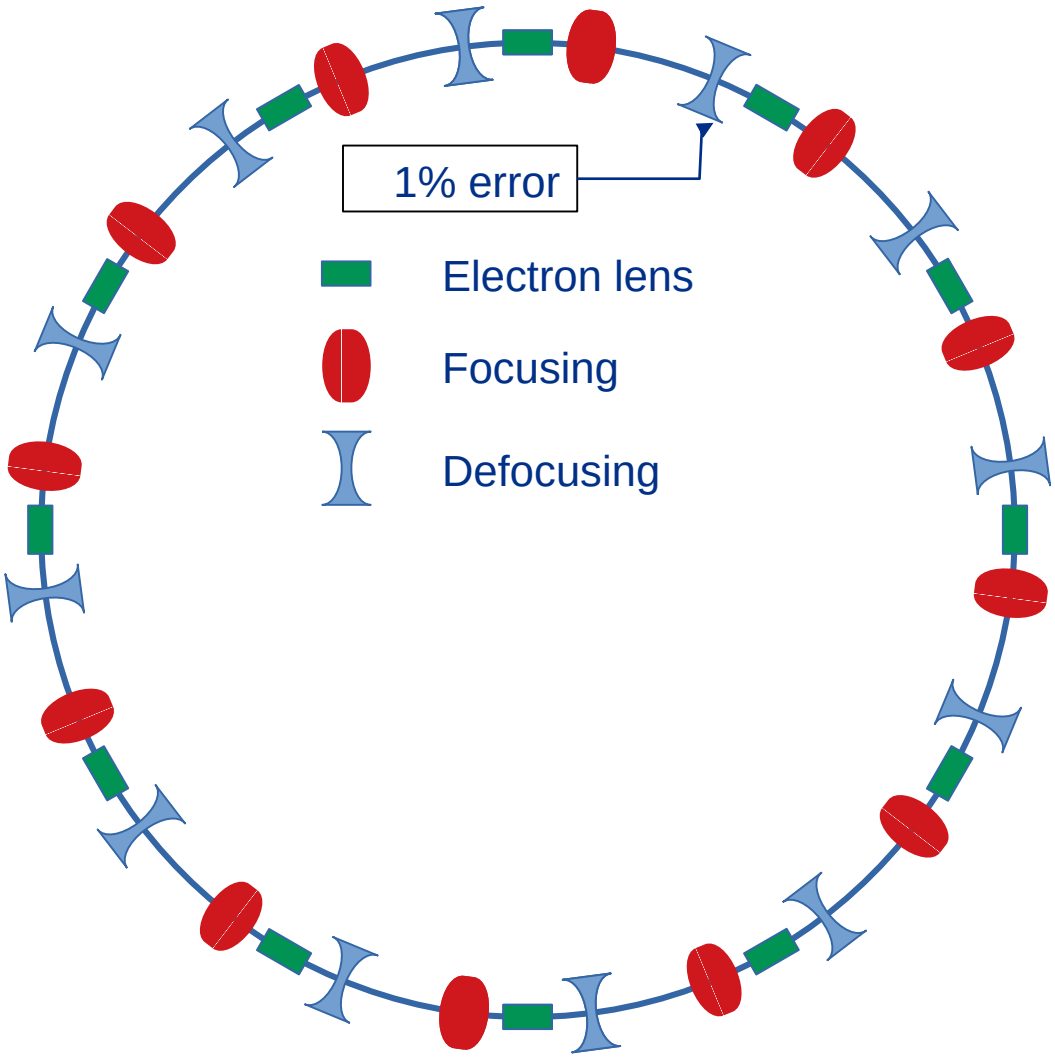
Case #1

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



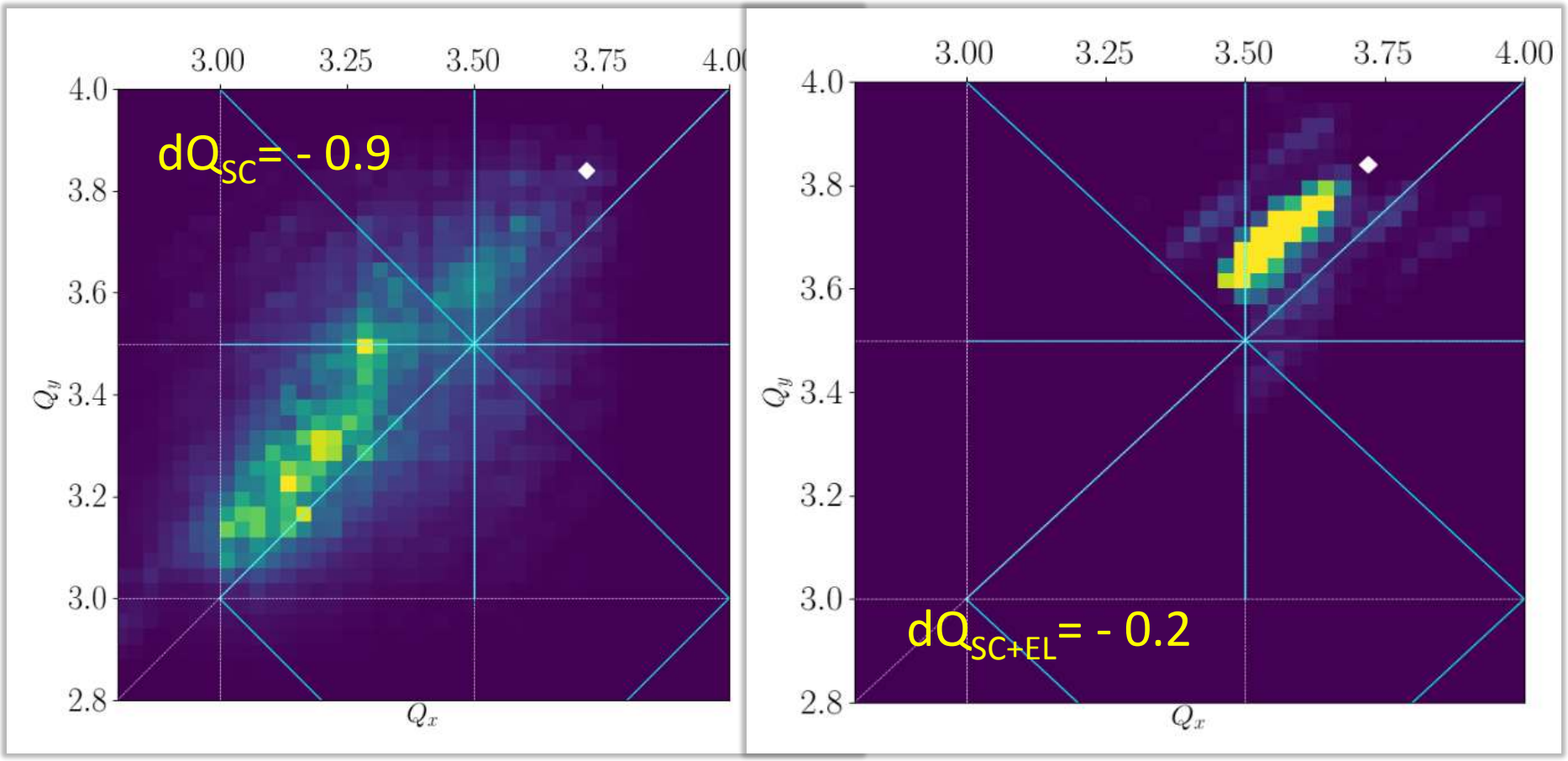
Case #2

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



Case #3

Tune Footprint dQ_{SC}=-0.9

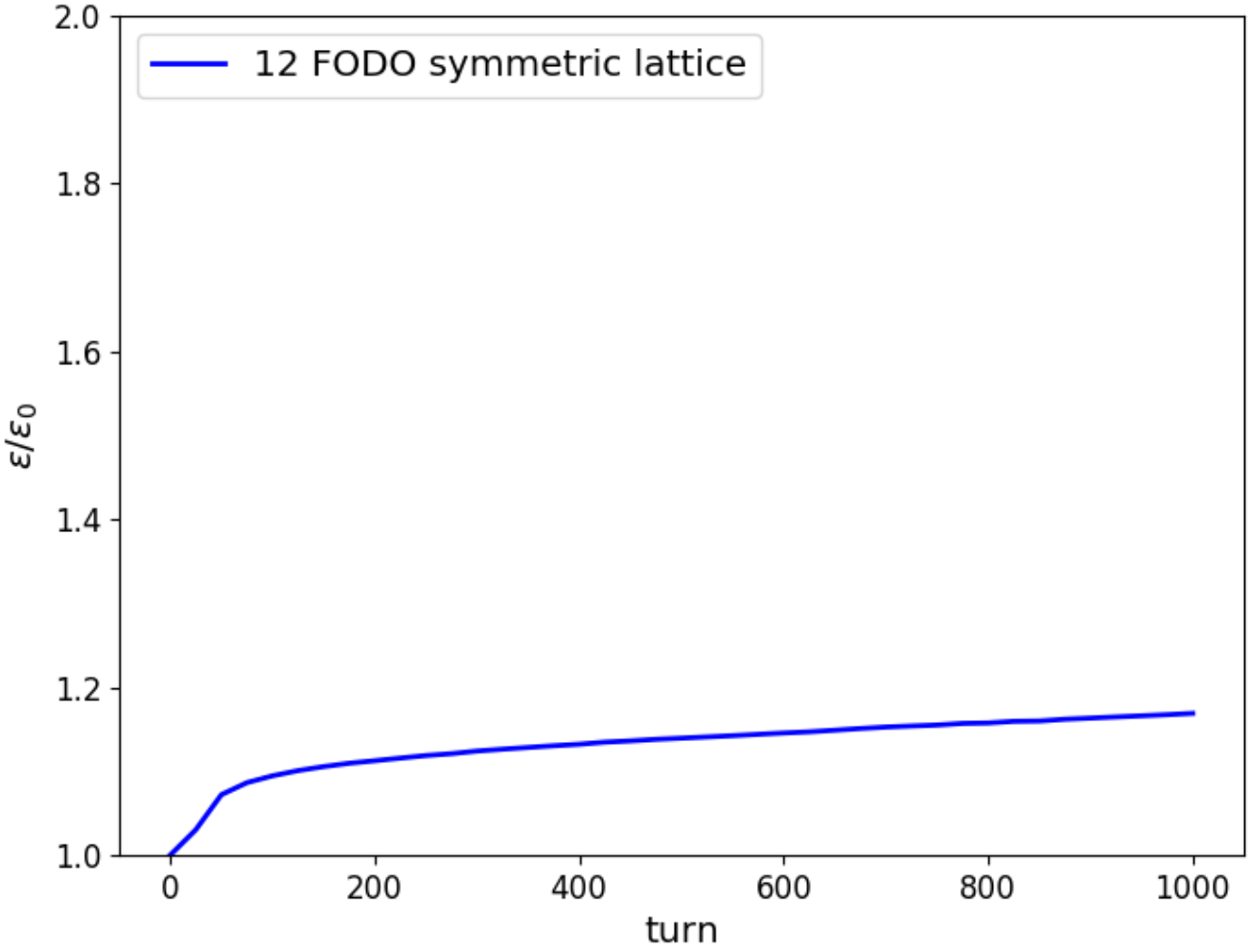


no e-lenses

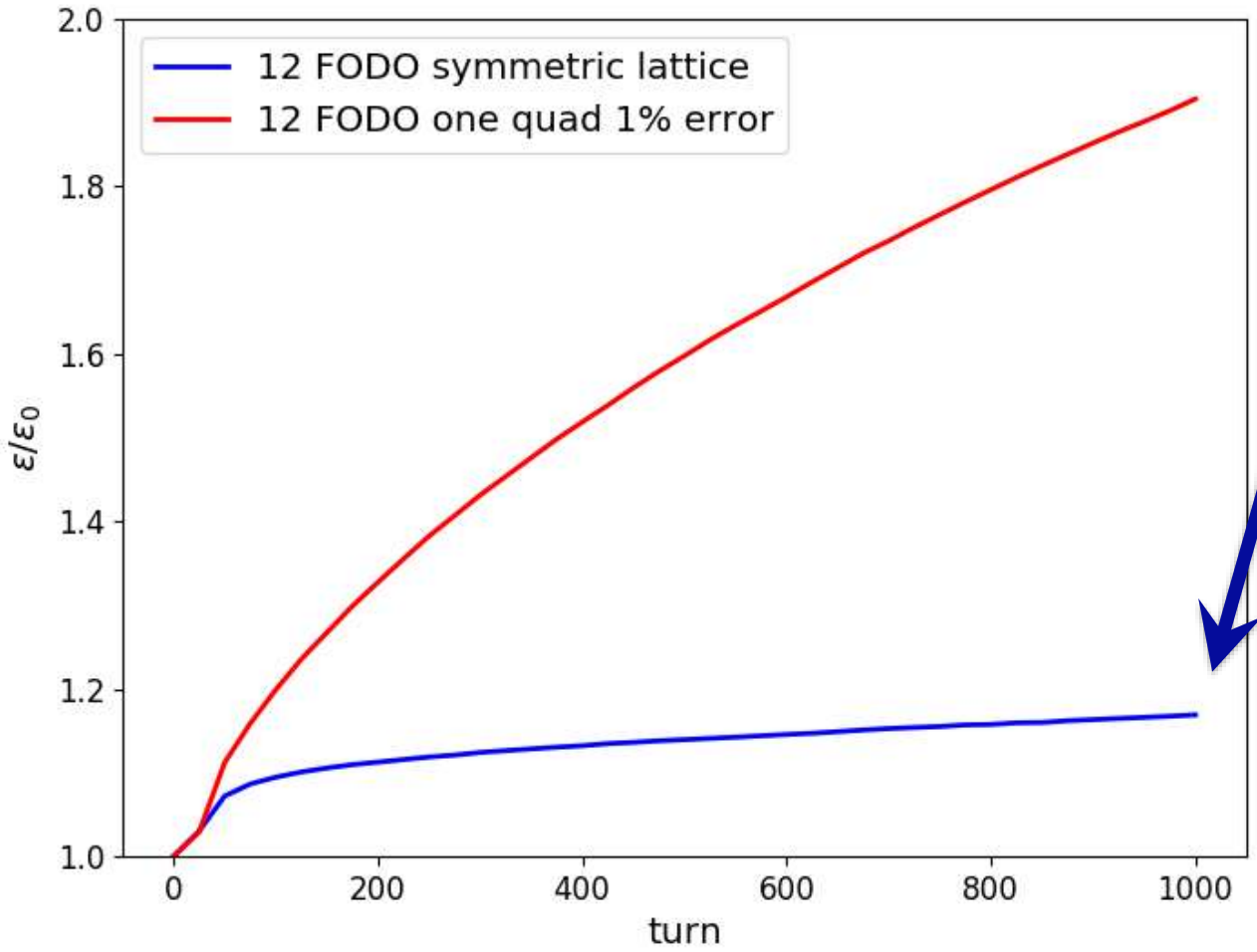
~75% e-lens compensation

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

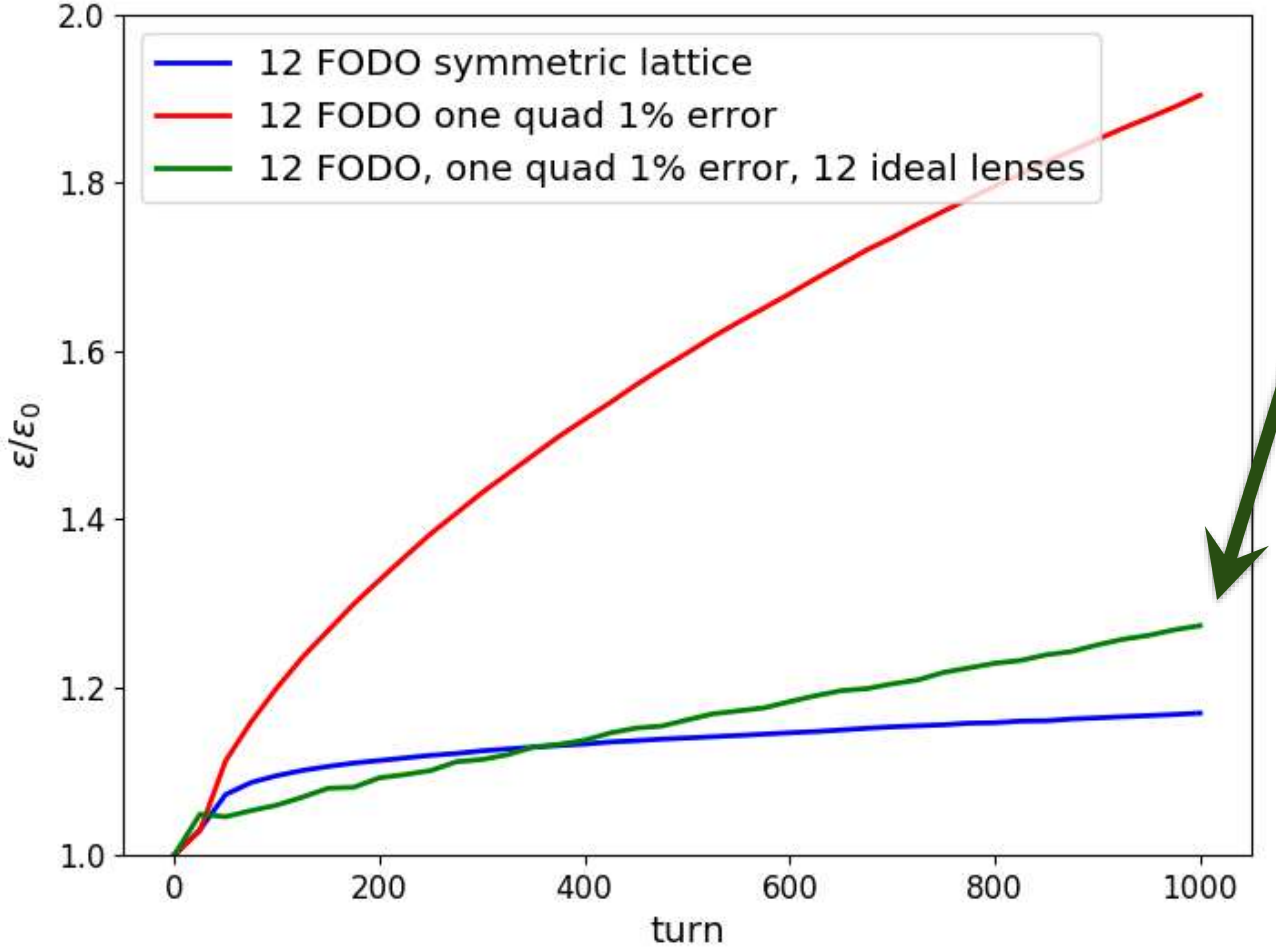
Emittance Growth – Case #1



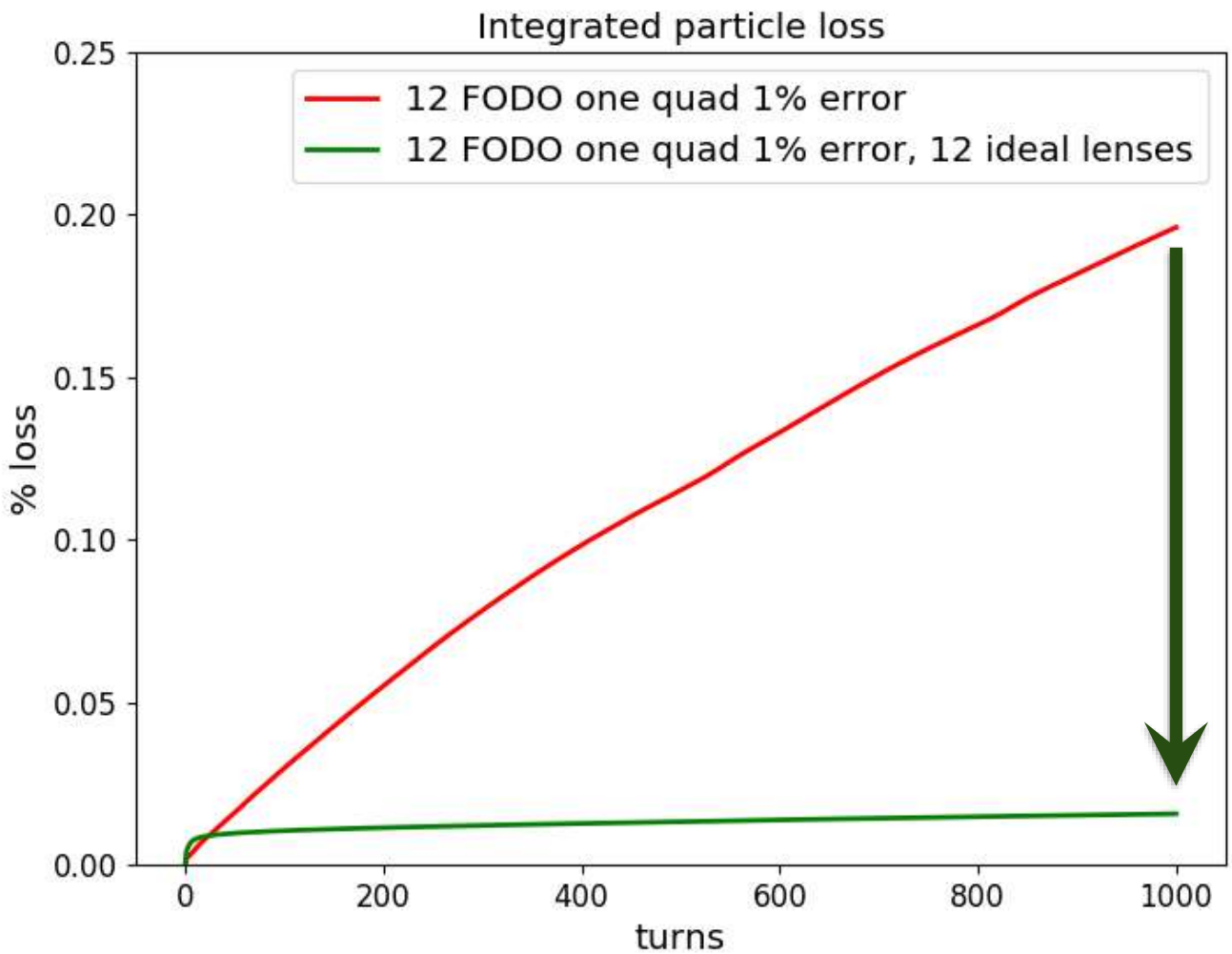
Emittance Growth – Case #2



Emittance Growth – Case #3

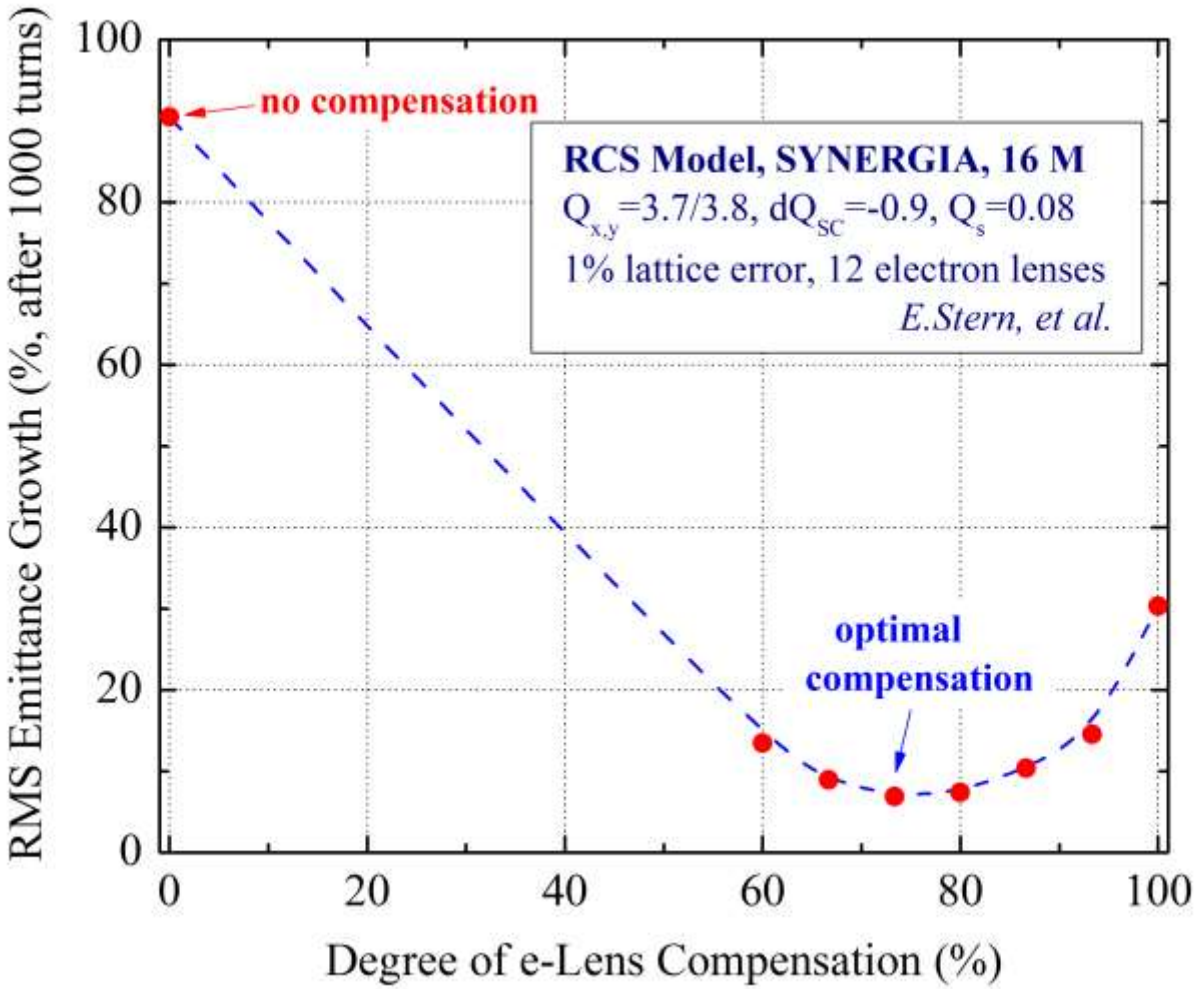


Particle Losses at 4σ – Case #2 and #3

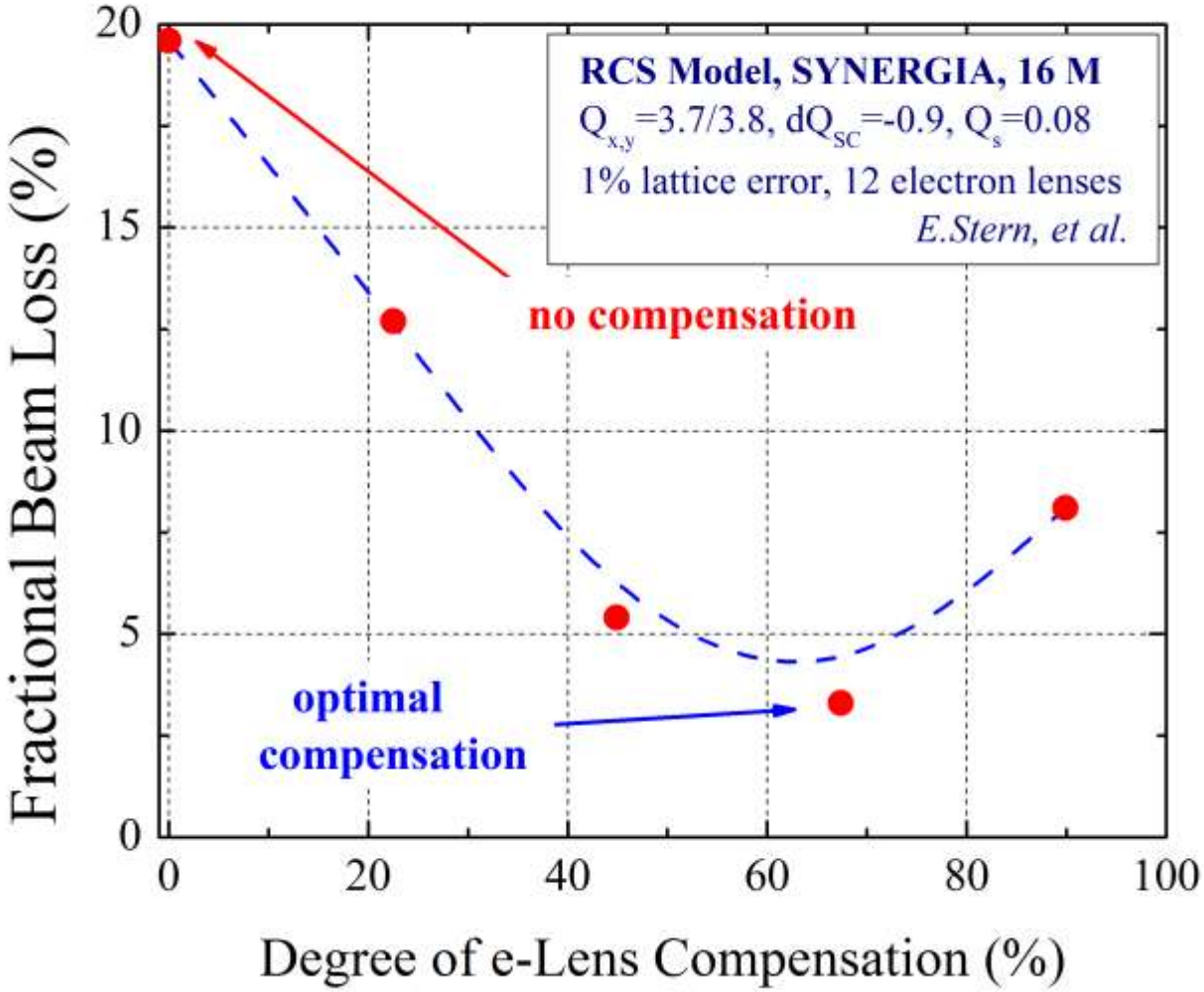


e-lenses reduce losses ~6 fold !

Optimal Compensation ~75% (emitt. growth)



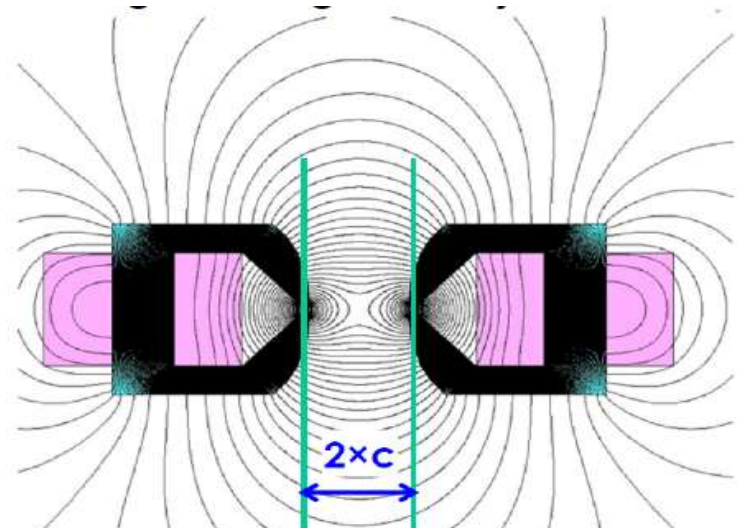
Optimal Compensation ~70% (beam losses)

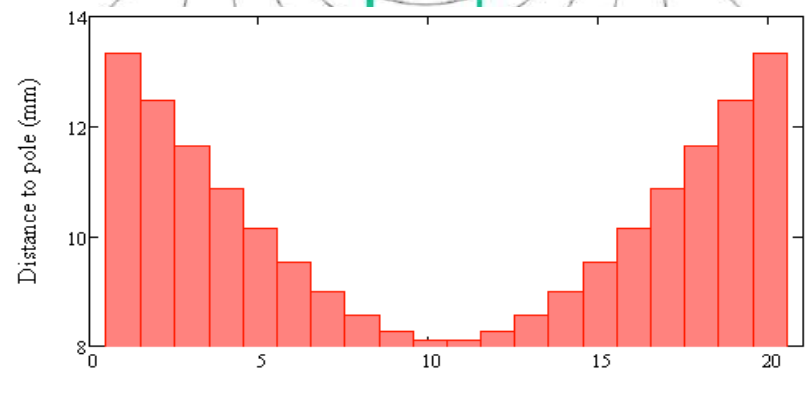


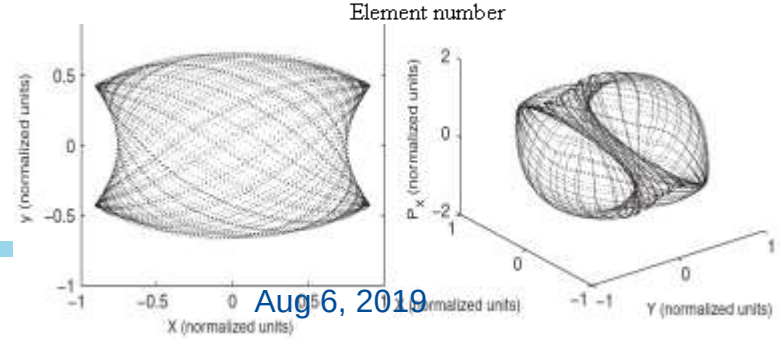
IOTA: *Integrable Optics Test Accelerator*

Integrable Optics with Non-linear Magnets

- Additional integrals of transverse motion possible:
  - Special NL magnets →
  - Special optics of the ring
  - Special longitudinal shape of the magnets (gap vs Z) →
  - Makes particle dynamics stable with very large tune-spread
    - Danilov, Nagaitsev, PRSTAB **13**, 084002 (2010) →



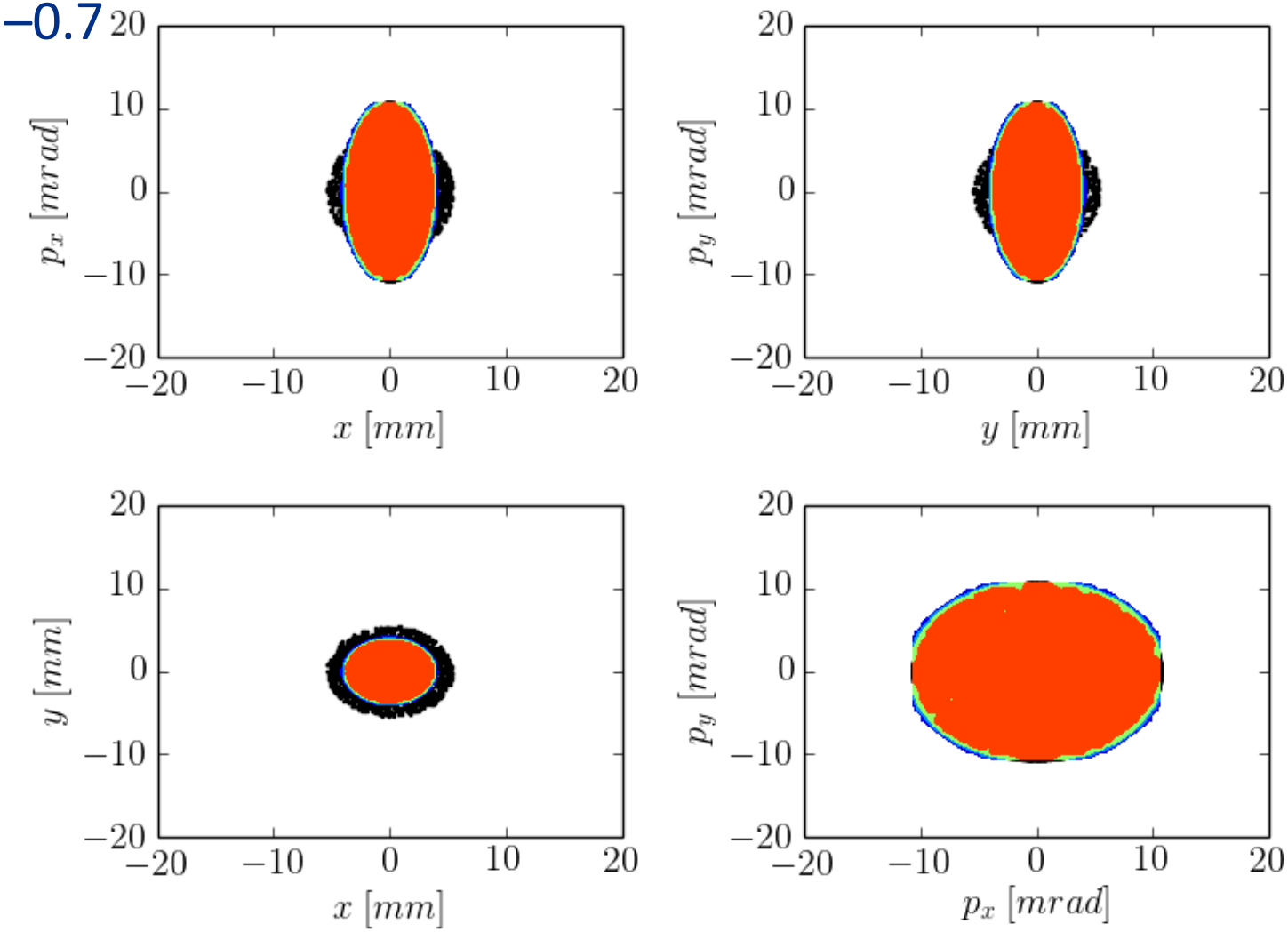




Space Charge Driven Halo in *Linear Optics*

- System: linear FOFO 100 A linear KV w/mismatch
- Result: quickly drives test-particles into the halo

$\Delta Q_{sc} \sim -0.7$

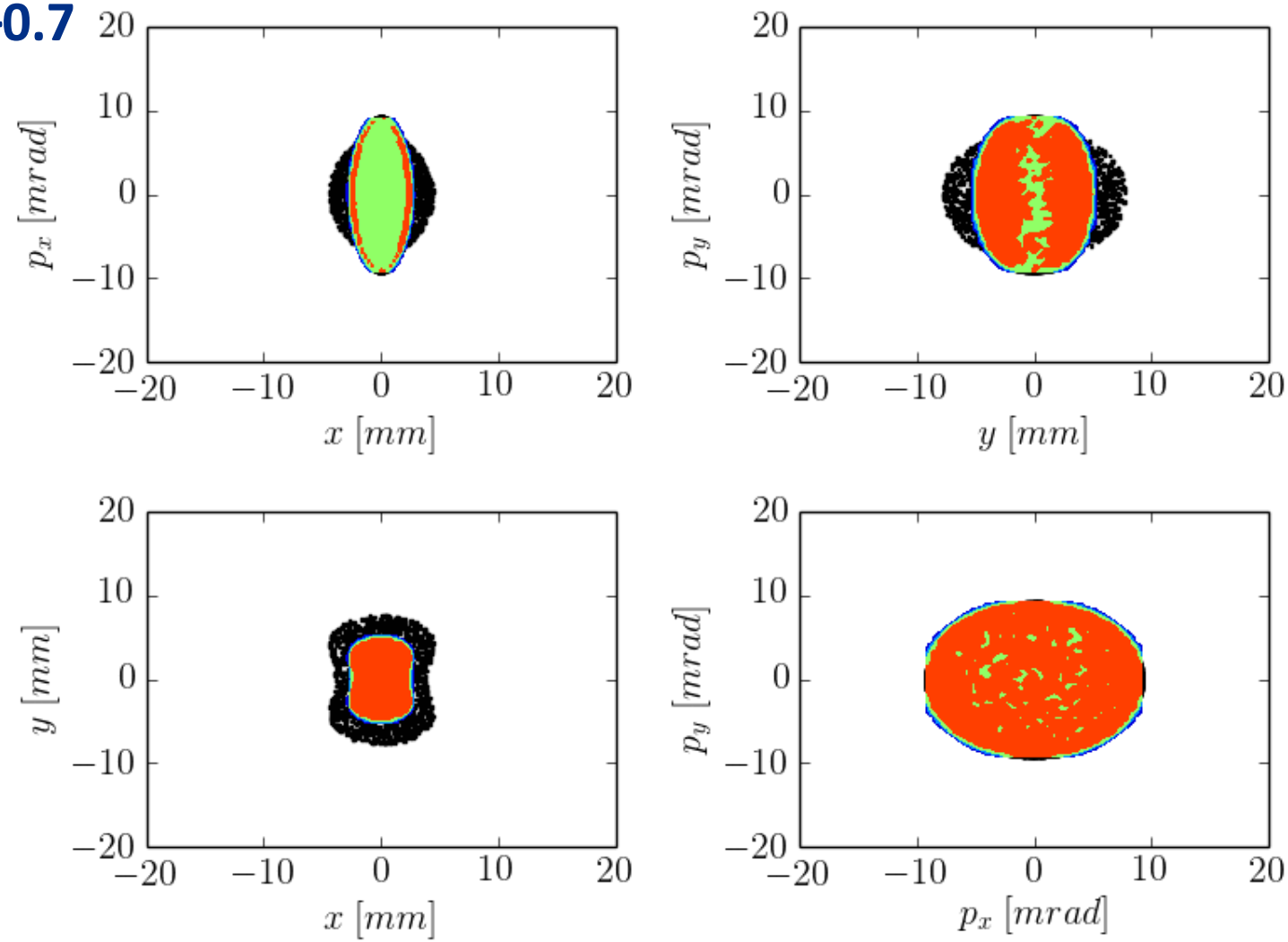


Tech-X, RadiaSoft simulation

Halo Suppressed in *NL Integrable Optics*

- System: linear FOFO 100 A linear KV w/mismatch
- Result: nonlinear decoherence suppresses halo

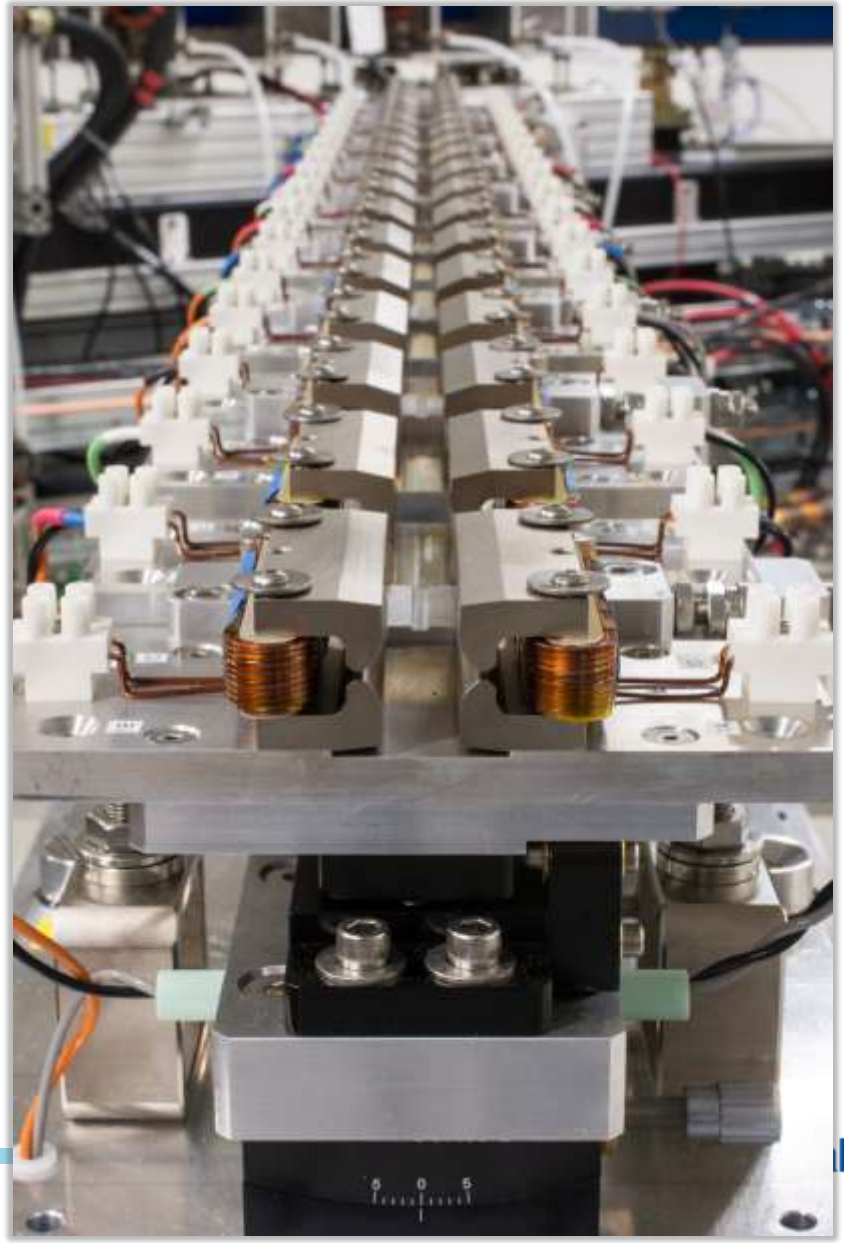
$\Delta Q_{sc} \sim -0.7$



Tech-X, RadiaSoft simulation

Non-Linear Integrable Optics Test

- Such a magnet is built and installed in IOTA
- Additional integral will be confirmed – first with “pencil” electron beam in IOTA
- Later, with high brightness, space-charge dominated proton beam
- Expect to demonstrate greatly improved coherent and incoherent beam stability



Both Nonlinear IO and E-Lens SCC work in Simulations!→ experimental verification at the

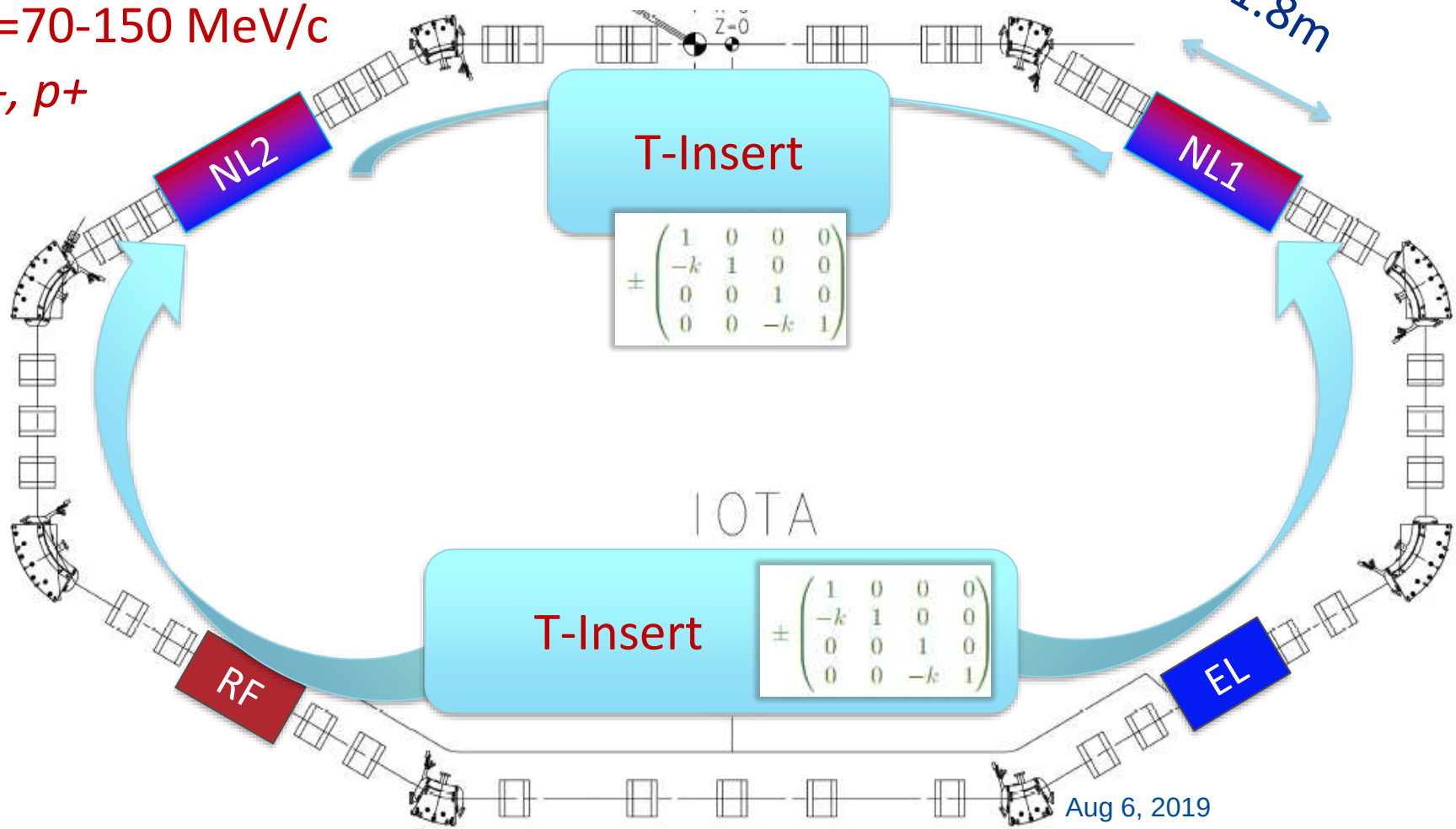
Integrable Optics Test Accelerator

C=40m

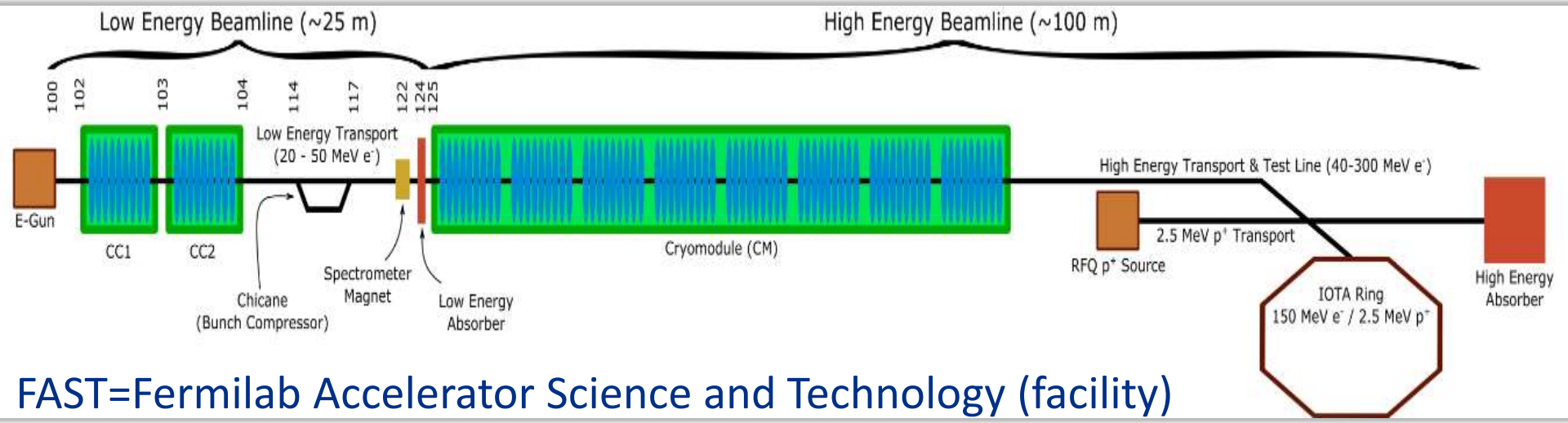
P=70-150 MeV/c

e-, p+

IOTA with Two Nonlinear Lenses and E-Lens



IOTA/FAST: Centerpiece of Beam Physics Innovation



FAST=Fermilab Accelerator Science and Technology (facility)

IOTA designed and constructed as an R&D Facility :

- Adaptable: broad spectrum of research
  - *Nonlinear Integrable Optics*
  - *Space charge compensation*
  - *High-Bandwidth Beam Cooling*
  - *Beam Dynamics in High Brightness Rings*:
- Accurate
- Affordable

http://fast.fnal.gov/

Novel Ideas for IOTA: Non-Linear I-Optics

Value of extra integrals of motion

[1] V. Danilov and S. Nagaitsev, PRAB 13, 084002 (2010)

Danilov & Nagaitsev gave in [1] a realizable potential U such that H_N admits a second invariant I_N

$$I = \left(xp_y - yp_x\right)^2 + c^2p_x^2 + \frac{2c^2t\cdot\xi\eta}{\xi^2-\eta^2}\times$$

$$\left(\eta\sqrt{\xi^2-1}\cosh^{-1}(\xi) + \xi\sqrt{\eta^2-1}\left(\frac{\pi}{2}+\cosh^{-1}(\eta)\right)\right)$$

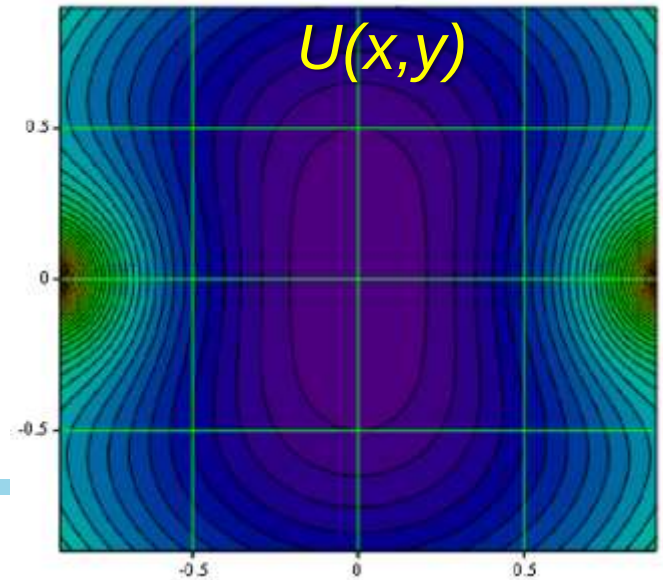
In accelerators :

$$H_\perp = \frac{1}{2}(P_x^2+P_y^2) - \frac{\tau c^2}{\beta(s)}U\left(\frac{X}{c\sqrt{\beta(s)}}, \frac{Y}{c\sqrt{\beta(s)}}\right)$$

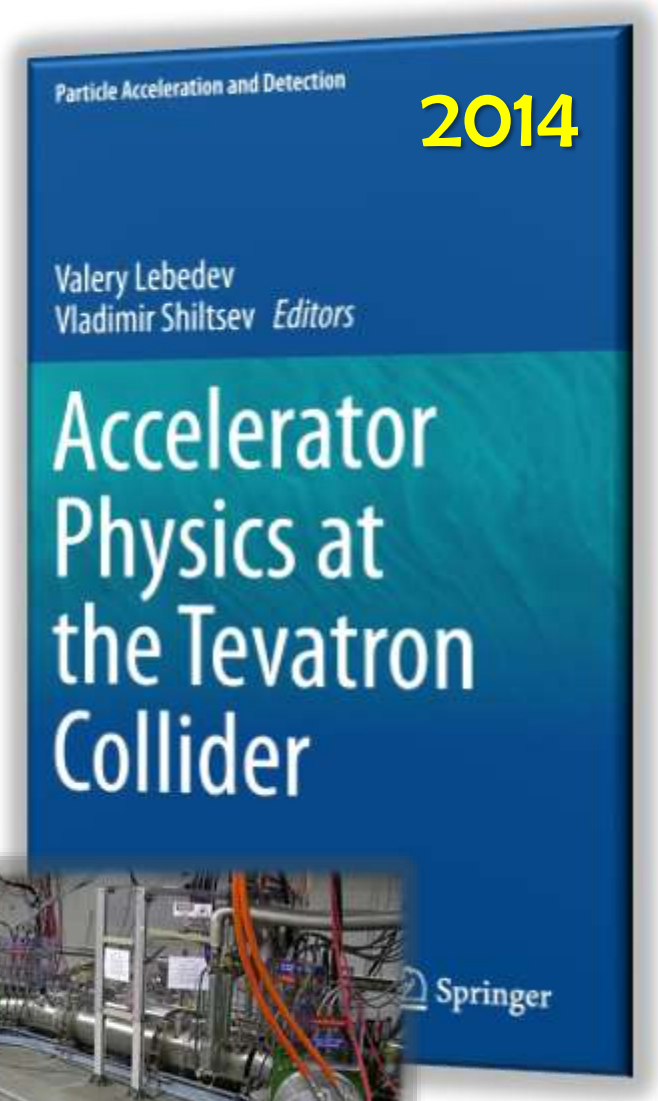
Courant-Snyder transformation, scaling

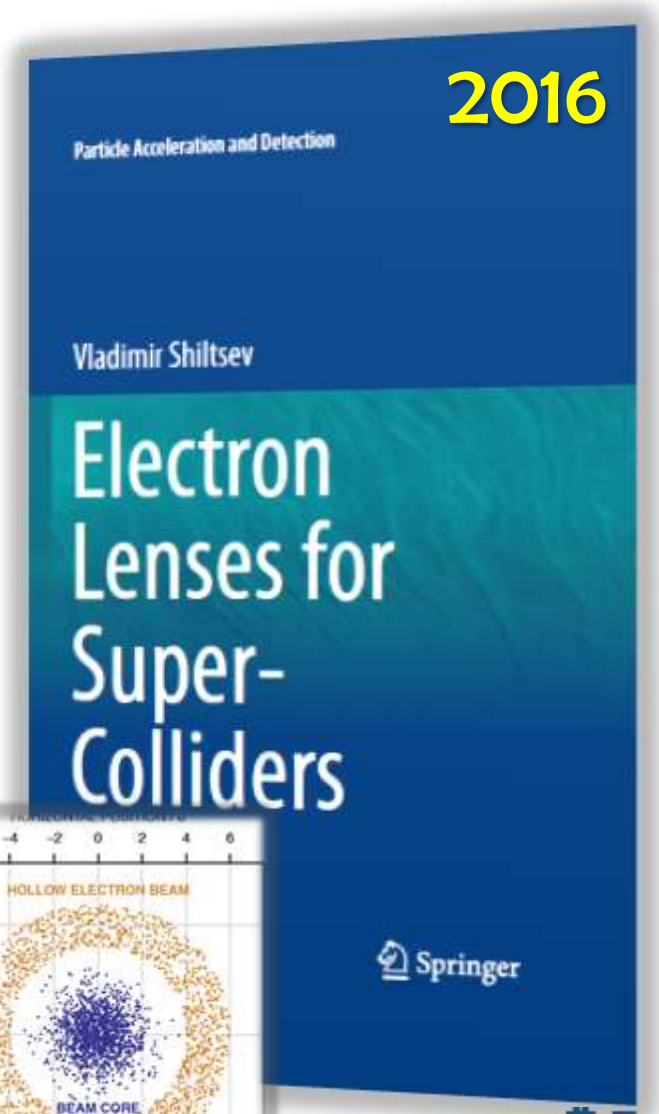
$$H_N = \frac{1}{2}(P_{xN}^2+P_{yN}^2+X_N^2+Y_N^2) - \tau U(X_N, Y_N)$$

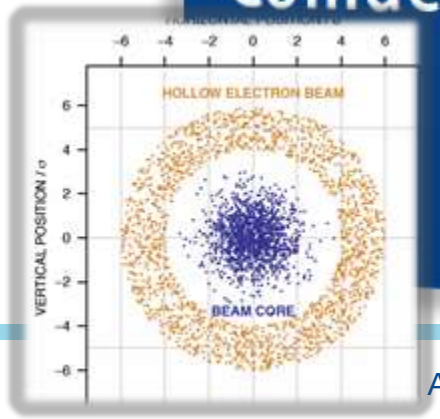
first invariant



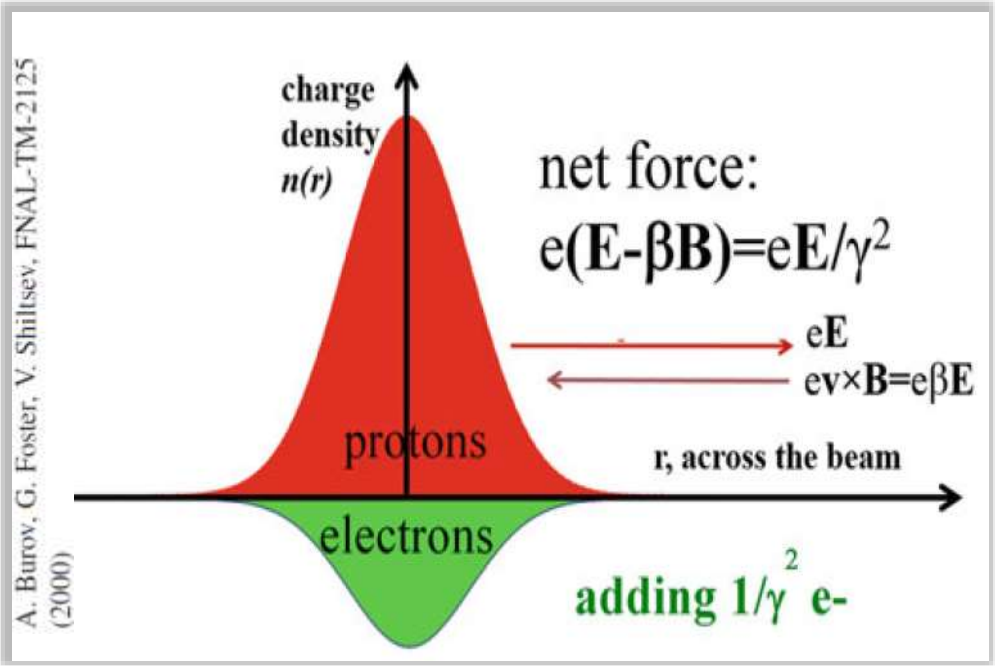
Electron Lenses : Introduced in *2000*'s

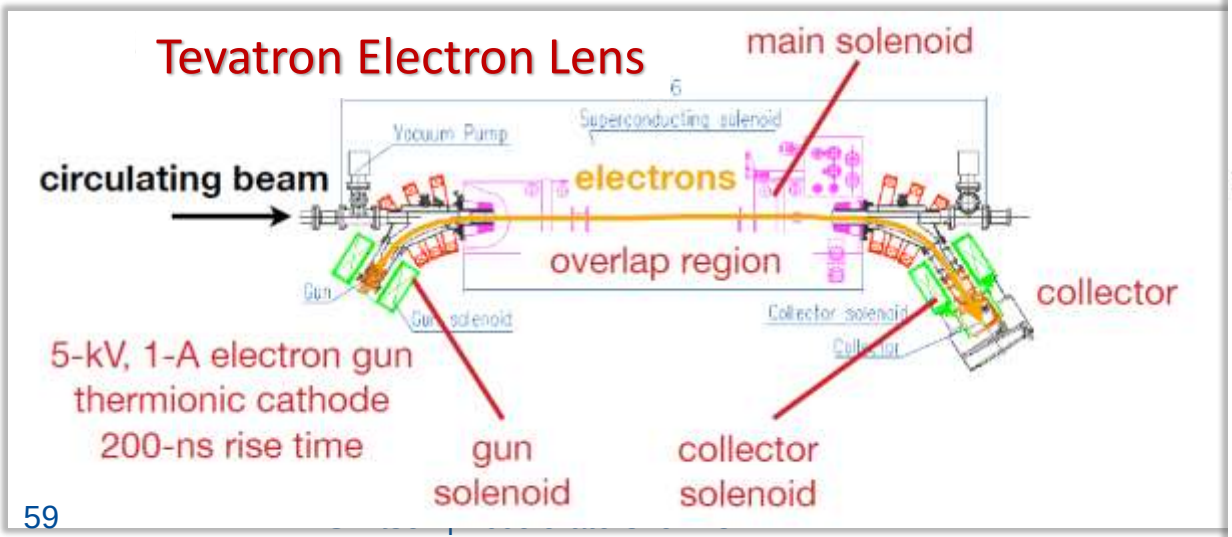


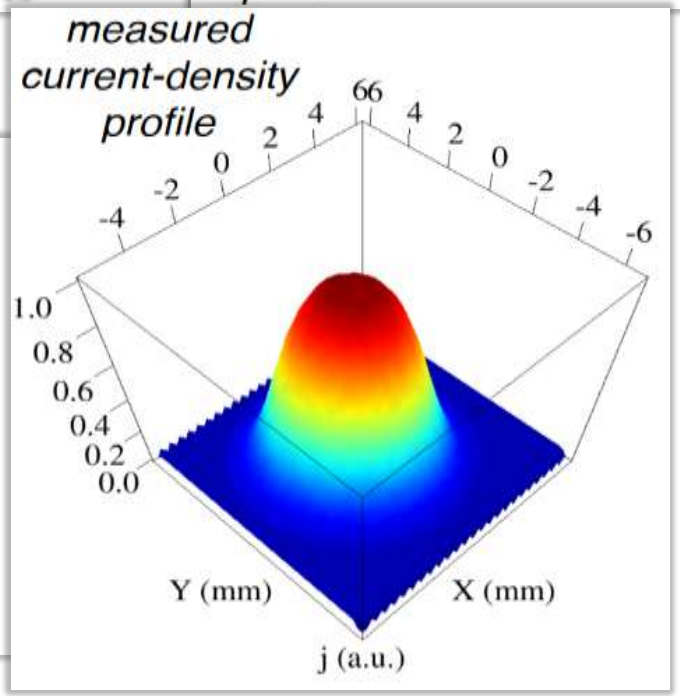




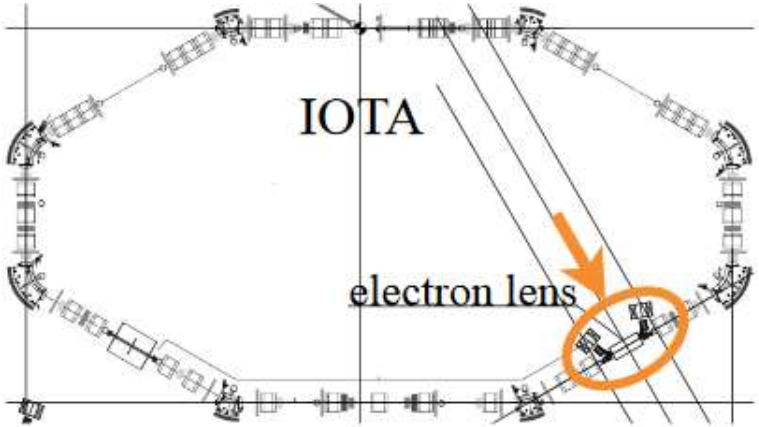
Proton Space-Charge: Compensated by Electrons

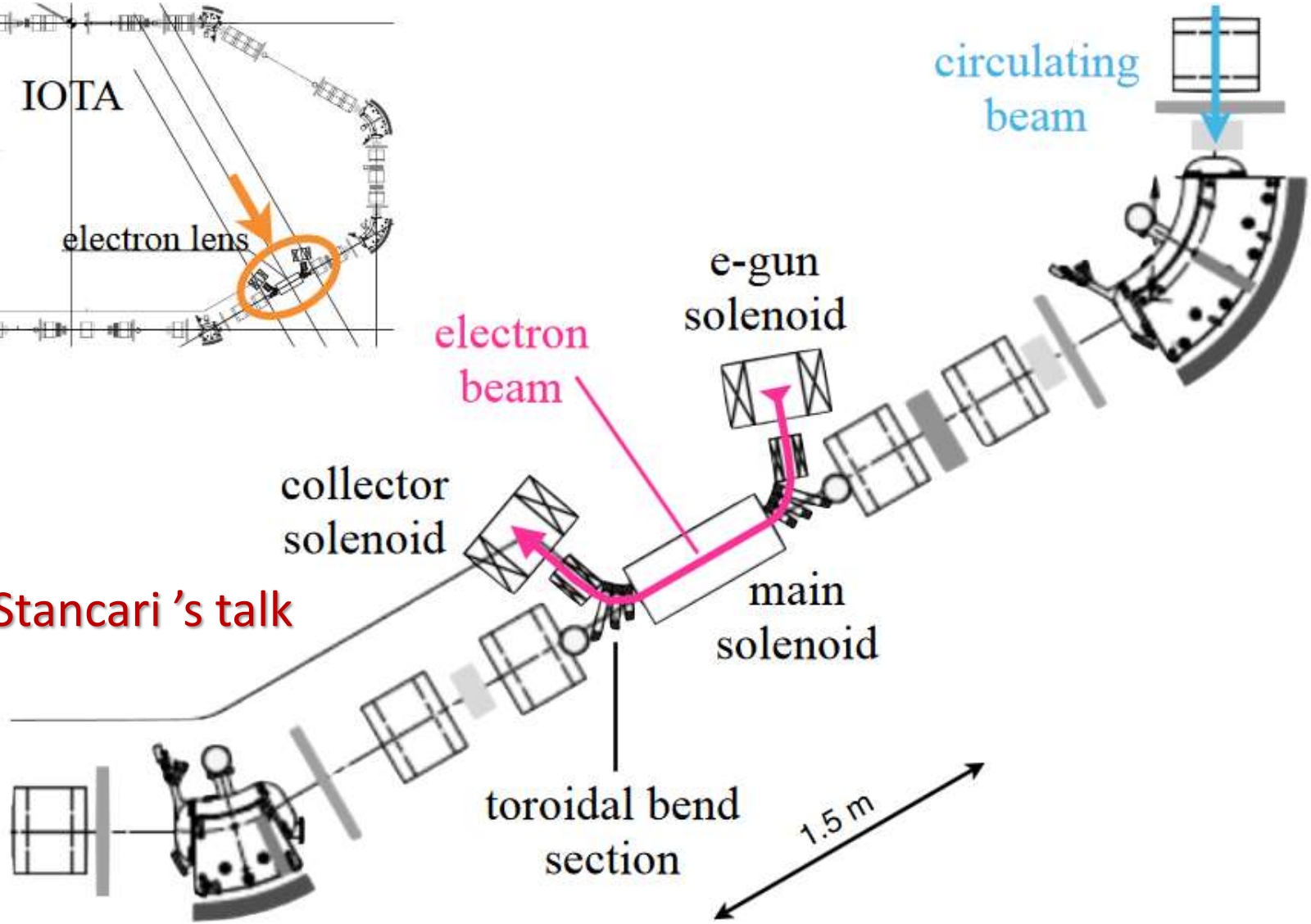




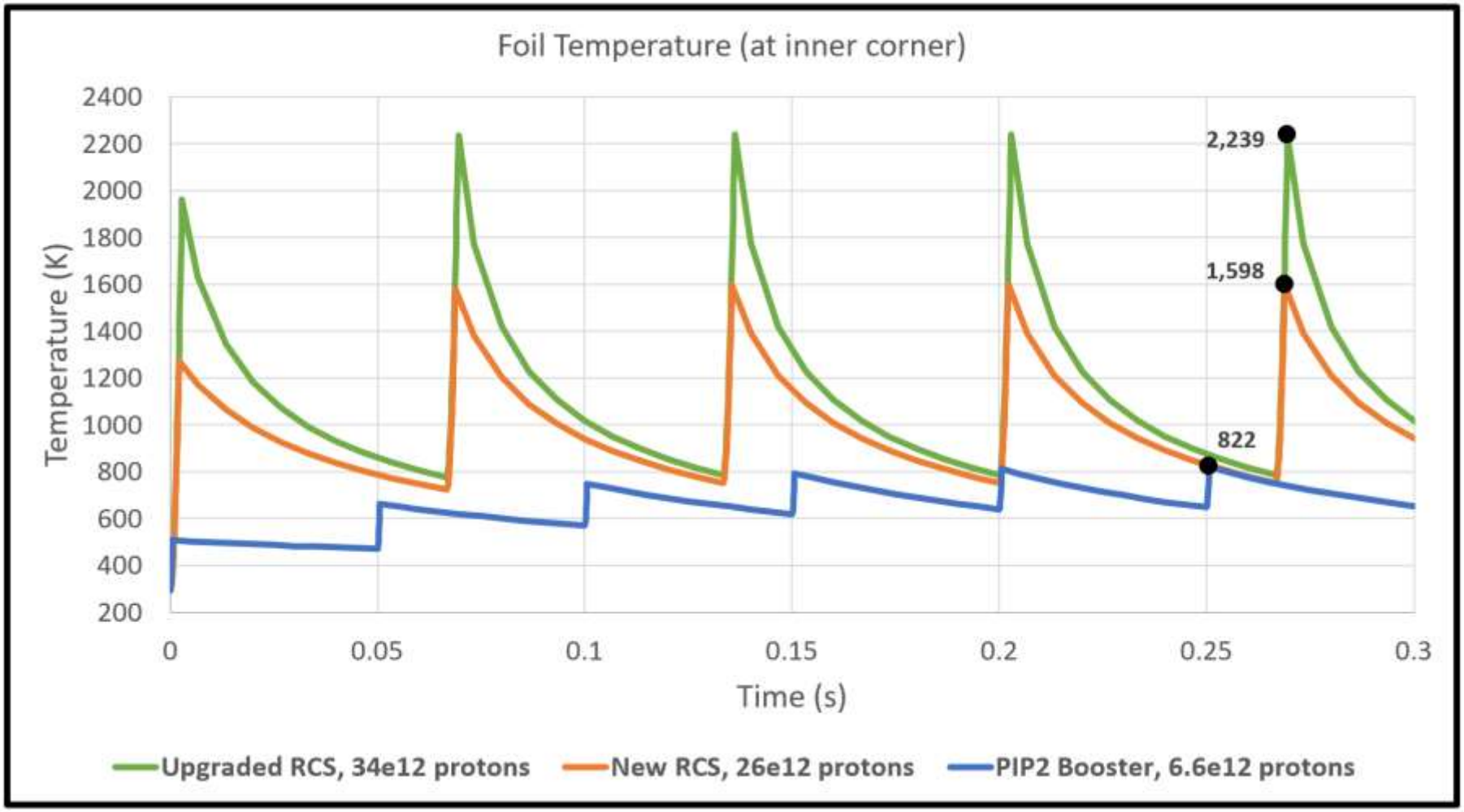


Electron Lens in IOTA





see Giulio Stancari 's talk

H- Foil Heating

J.Eldred et al