Future Accelerator Based Neutrino Beams

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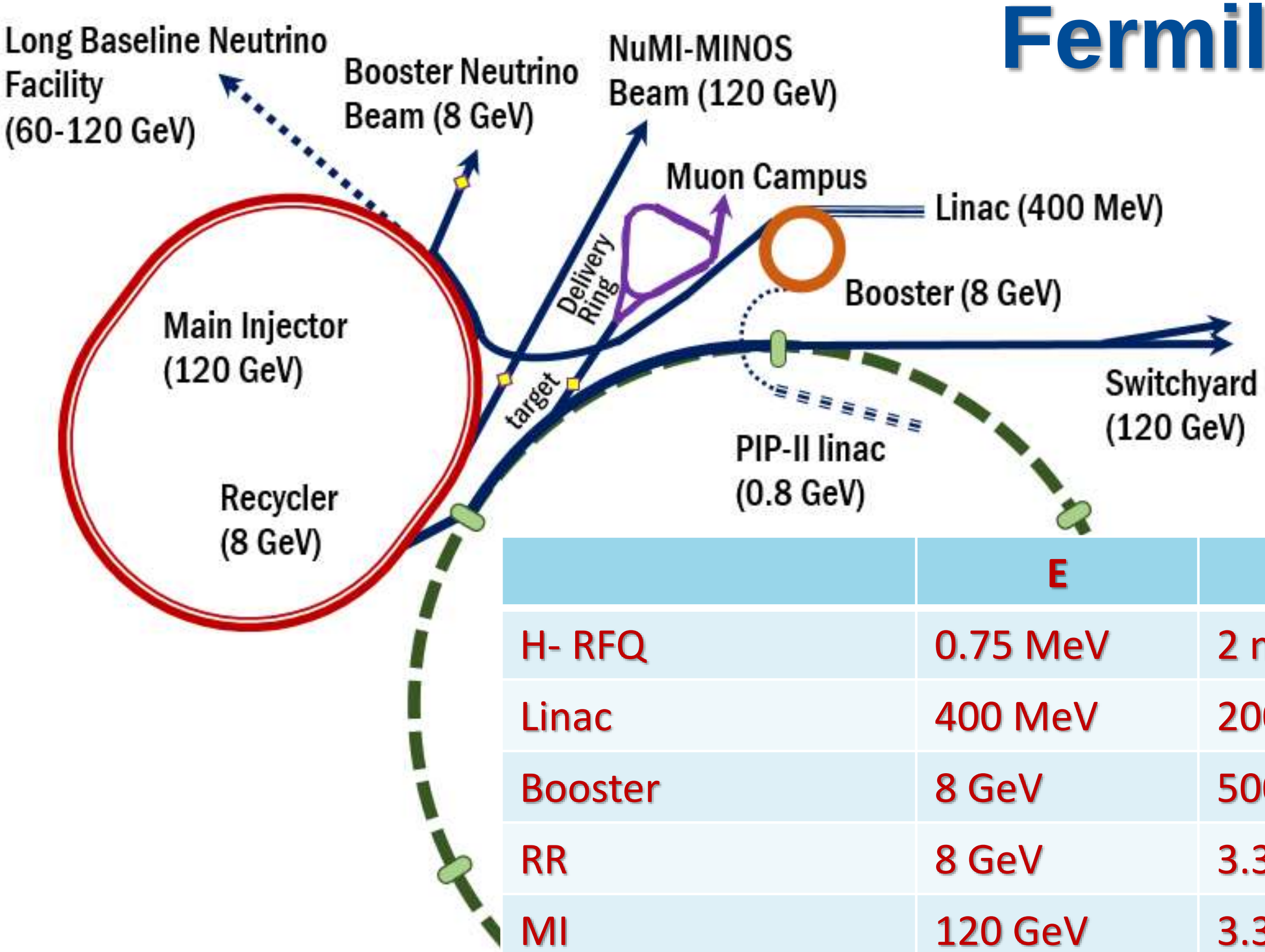
Content:

1. **Super-Beam Facilities and Upgrades** - how to achieve the ultimate energy and performance, R&D required :
    - Fermilab
    - J-PARC

2. **New Proposals** – opportunities and synergies :
    - Protvino/ORKA
    - ESSνSB
    - ENUBET
    - νSTORM

Fermilab Proton Complex



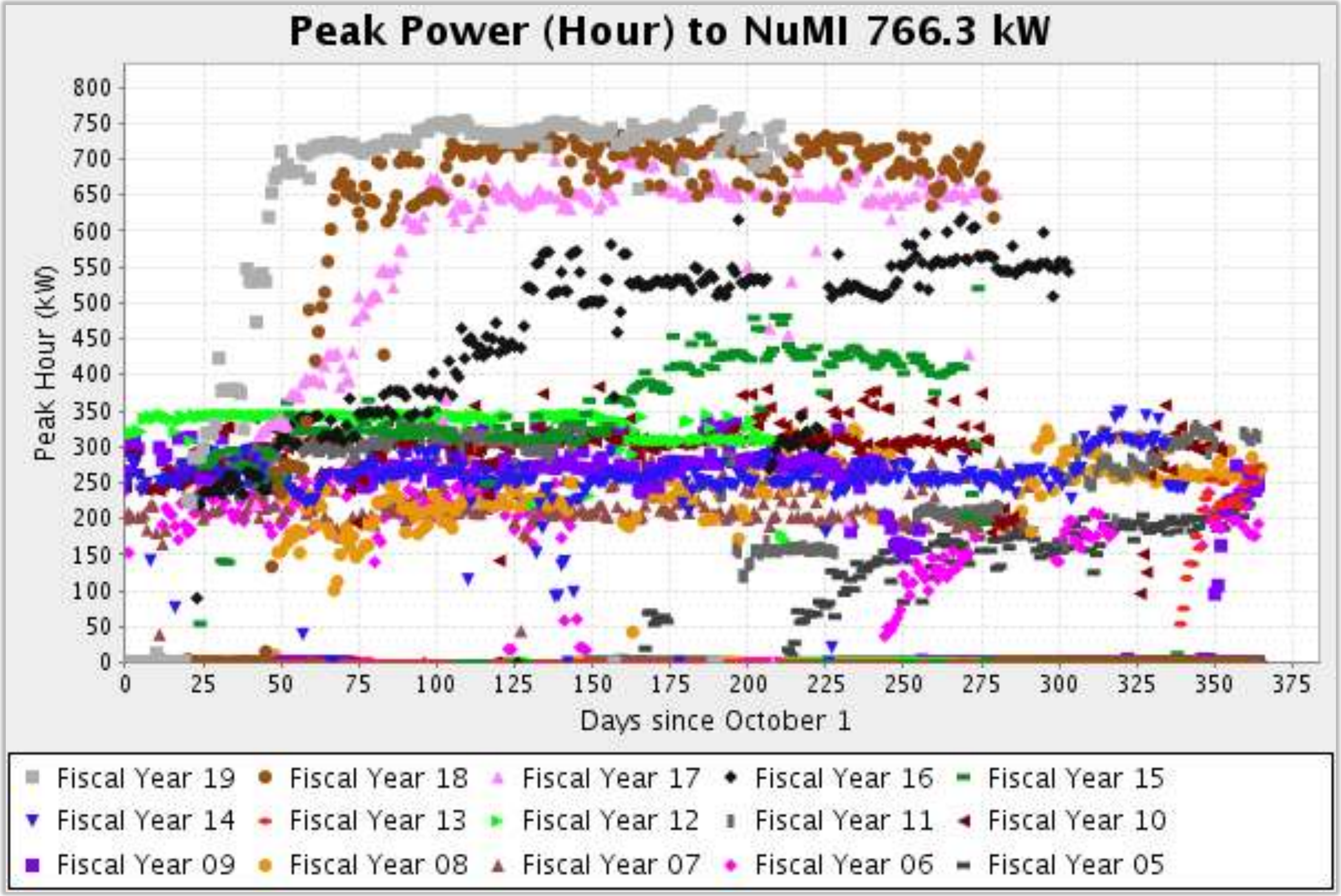
	E	L	Costr.
H- RFQ	0.75 MeV	2 m	2013
Linac	400 MeV	200 m	1970/93
Booster	8 GeV	500 m	1971
RR	8 GeV	3.3 km	1999
MI	120 GeV	3.3 km	1999
Delivery Ring	3.8-8 GeV	500 m	1985/2014
Beamlines	3-120 GeV	3.5 km	1970's-now
Upgr: PIP-II	800 MeV	240 m	2026
Upgr :PIP-III	8 GeV	500 m	Ca 2032
Upgr: beamlines	0.8-8 GeV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

Fermilab Accelerator Complex Users

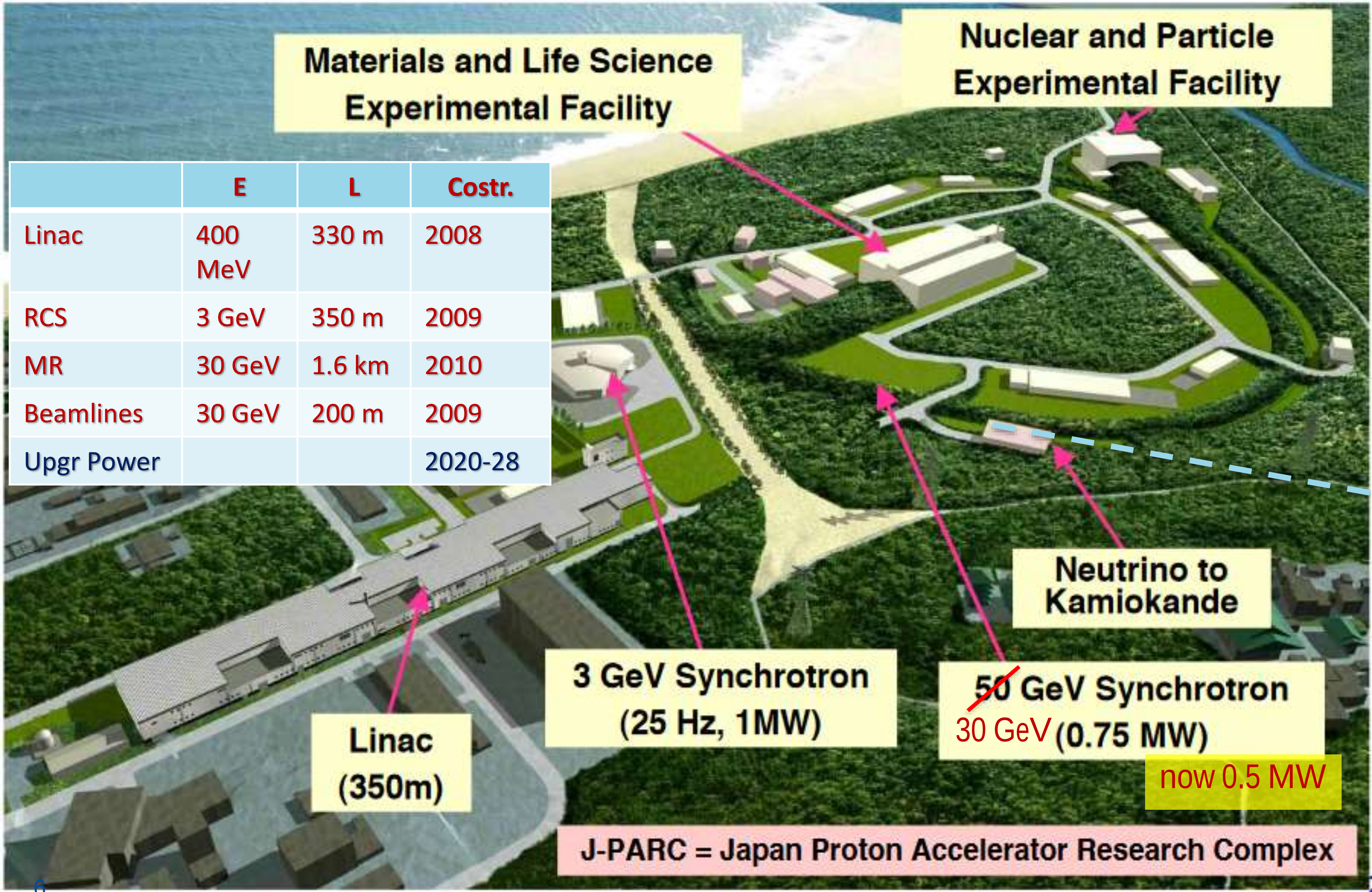
- Proton Source (**400 MeV** Linac and **8 GeV** Booster ring):
  - **8 GeV** Booster Neutrino Beam (BNB)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
    - ICARUS
    - SBND

    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

30 GeV

now 0.5 MW

Fermilab and J-PARC Power Upgrades

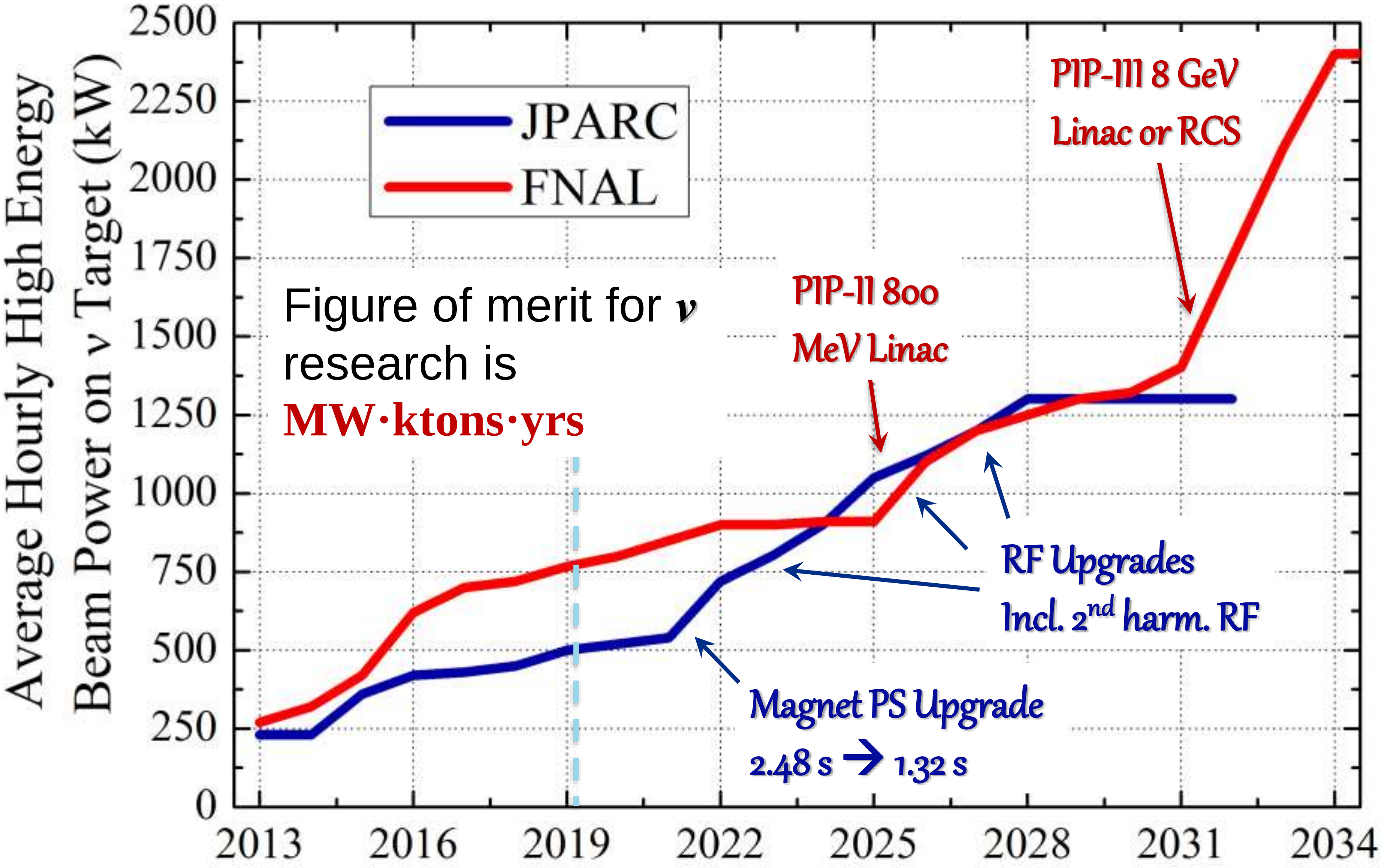


Figure of merit for ***ν*** research is **MW·ktons·yrs**

PIP-II 800 MeV Linac

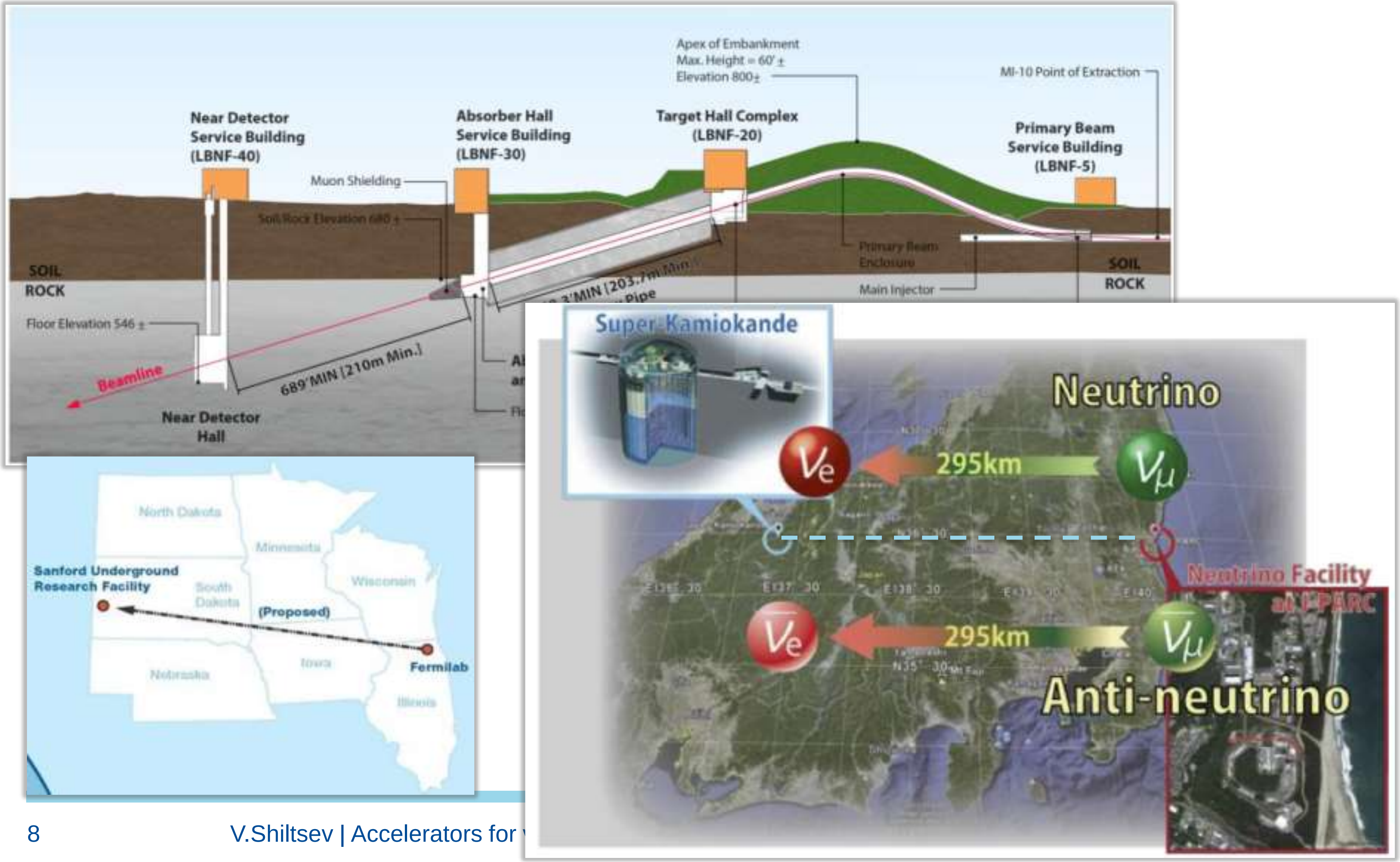
PIP-III 8 GeV Linac or RCS

RF Upgrades Incl. 2nd harm. RF

Magnet PS Upgrade 2.48 s → 1.32 s

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

** actually, comparable 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) N_p :
  - key challenges : many beam dynamics issues & cost
- In both cases – **need reliable horns and targets :**
  - key challenge : *lifetime* gets worse with power

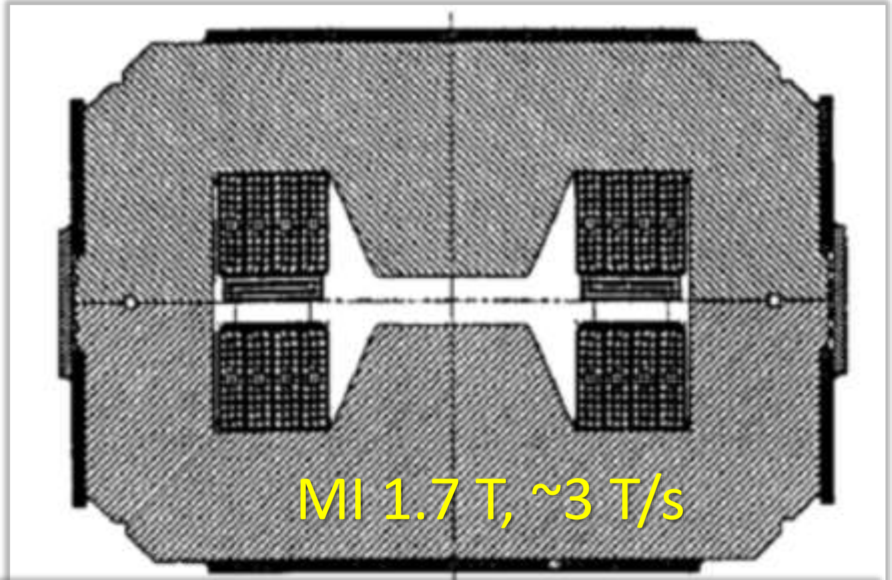
Fast Cycling Magnets + RF Cavities = 40-50% + 15-25% Cost *

** 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 1-5%



MI 1.7 T, ~3 T/s

MI 52.8 MHz

RF cavity loaded with magnetic alloy cores

JPARC MR 1.1 T, ~1 T/s

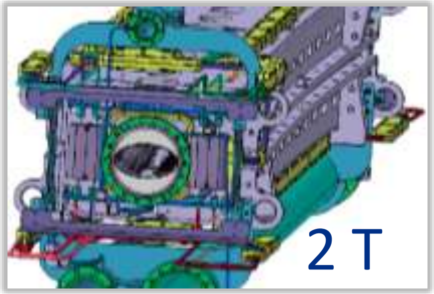
JPARC MR 1.7 MHz x harm.

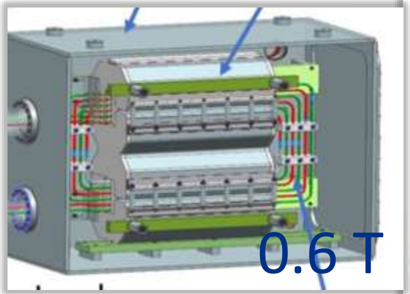
Power Efficiency – Huge Issue

Key R&D:

Efficient magnets :

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





- FFAG accelerators *

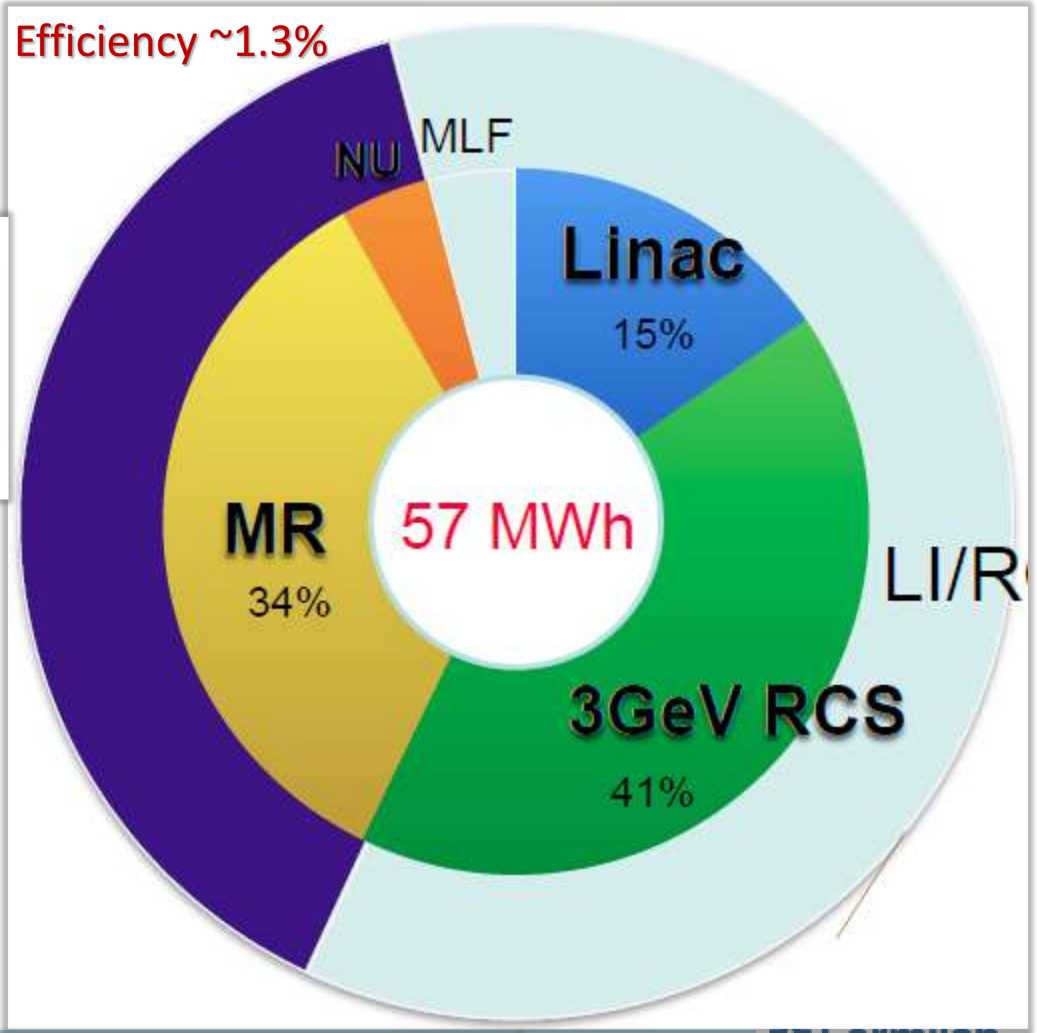
Efficient power supplies :

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

Efficient RF power sources:

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

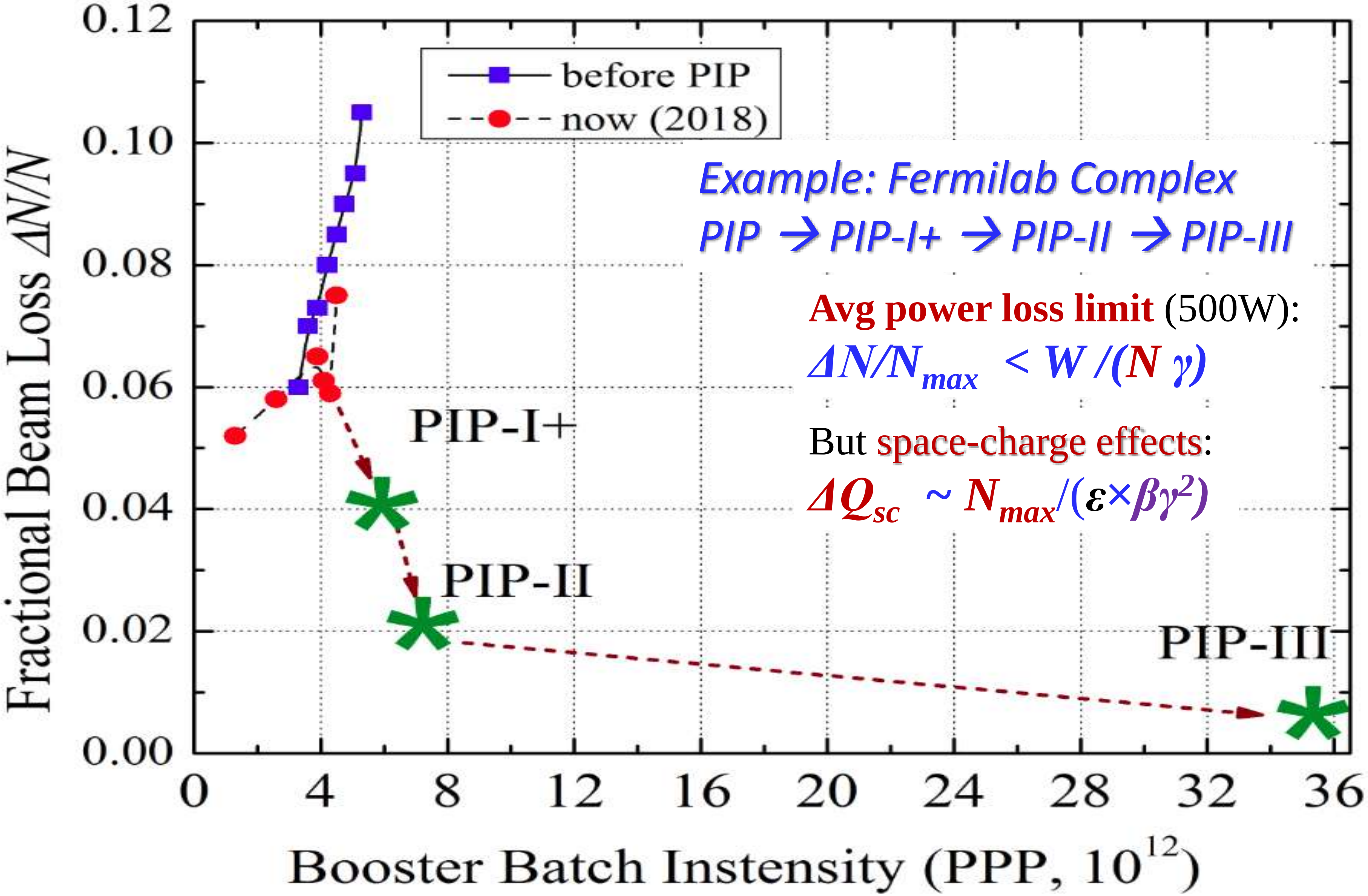
J-PARC : 0.5 MW beams vs ~40 MW site power


Efficiency ~1.3%

- 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: to lower beam losses while increasing intensity



Example: Fermilab Complex

PIP → PIP-I+ → PIP-II → PIP-III

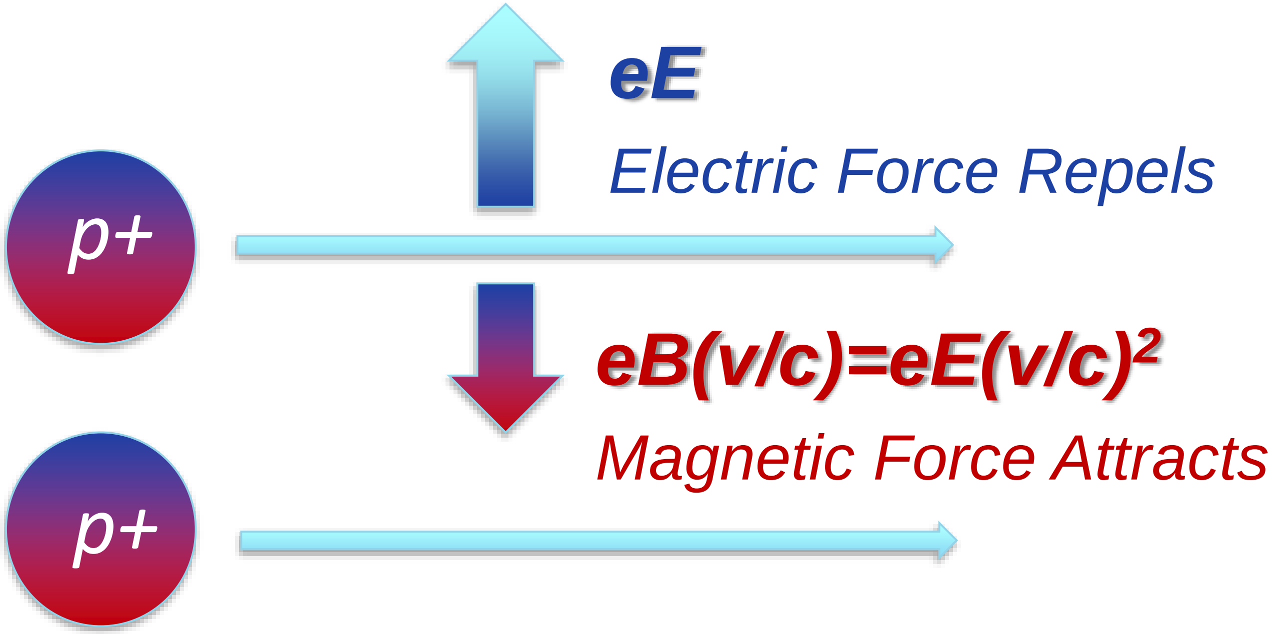
Avg power loss limit (500W):

$\Delta N/N_{max} < W/(N\gamma)$

But space-charge effects:

$\Delta Q_{sc} \sim N_{max}/(\varepsilon\times\beta\gamma^2)$

Intense Beams : Forces and Losses (1)



eE

Electric Force Repels

$eB(v/c)=eE(v/c)^2$

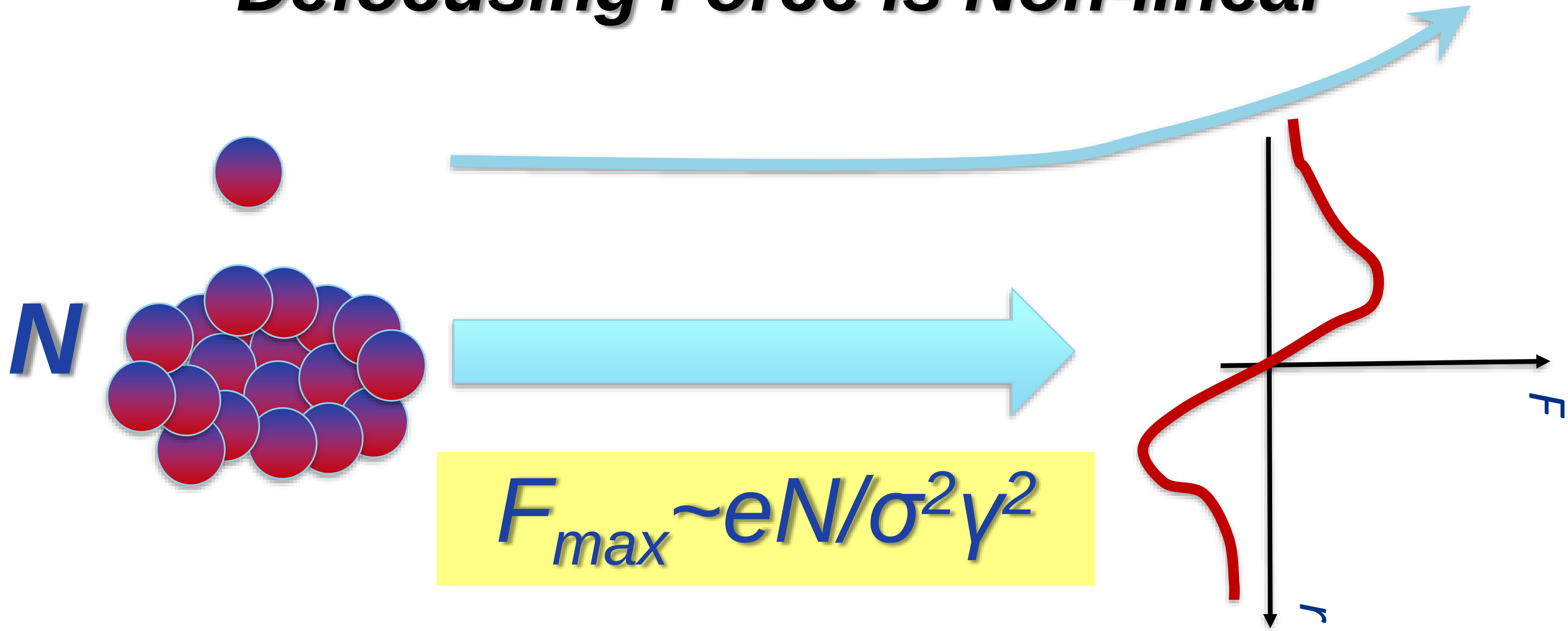
Magnetic Force Attracts

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):

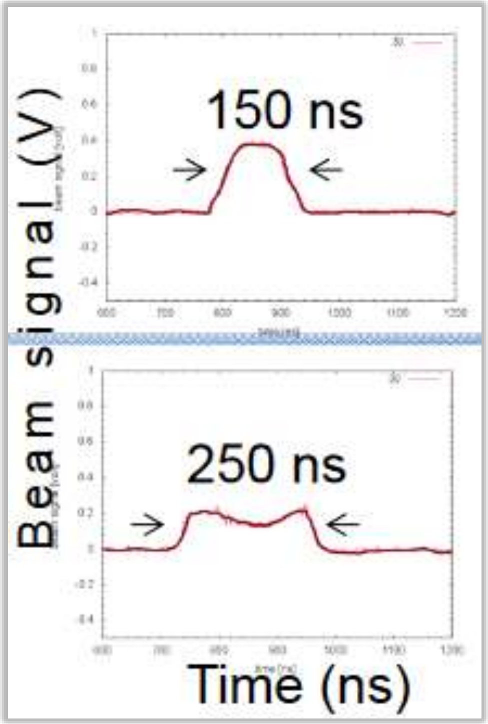
a) proportional to current (N)

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 SC force uniform, $N_p \sim$ x2
- **"Painting" beams** at injection:
  - To linearize SC force across beams $N_p \sim$x1.5
- **Better collimation system beams:**
  - From $\eta \sim 80\%$ 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, allows $N_p \sim$ x 1.5-2
- **Space-Charge Compensation** by electron lenses :
  - Electrons to focus protons, $N_p \sim$x1.5 - 2

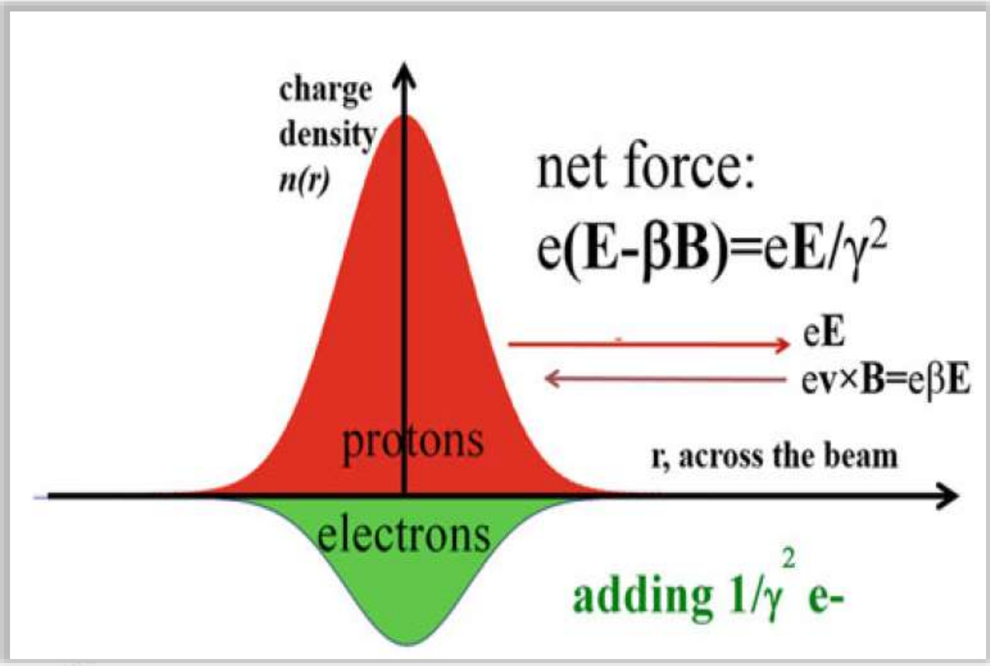
Option #1 : Proton Improvement Plan-II

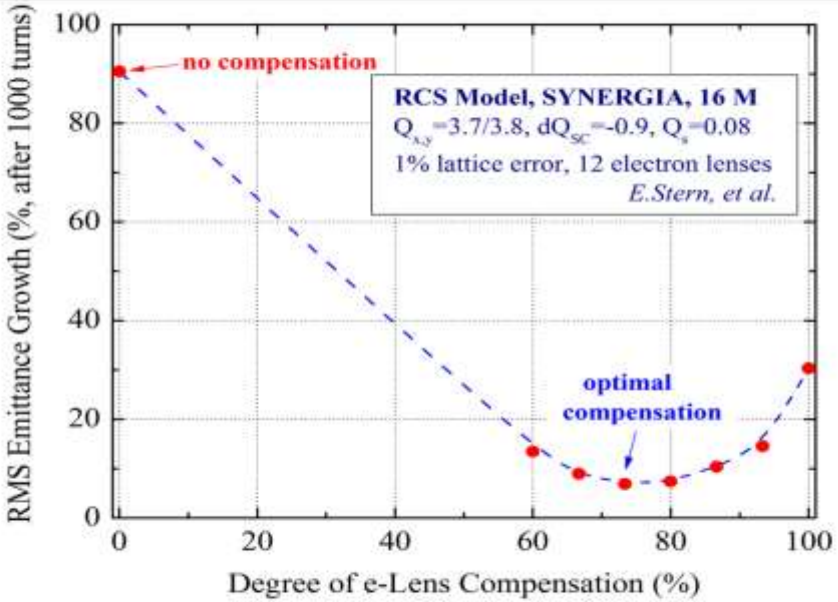
- **Key elements:**
  - Replace existing 400 MeV linac

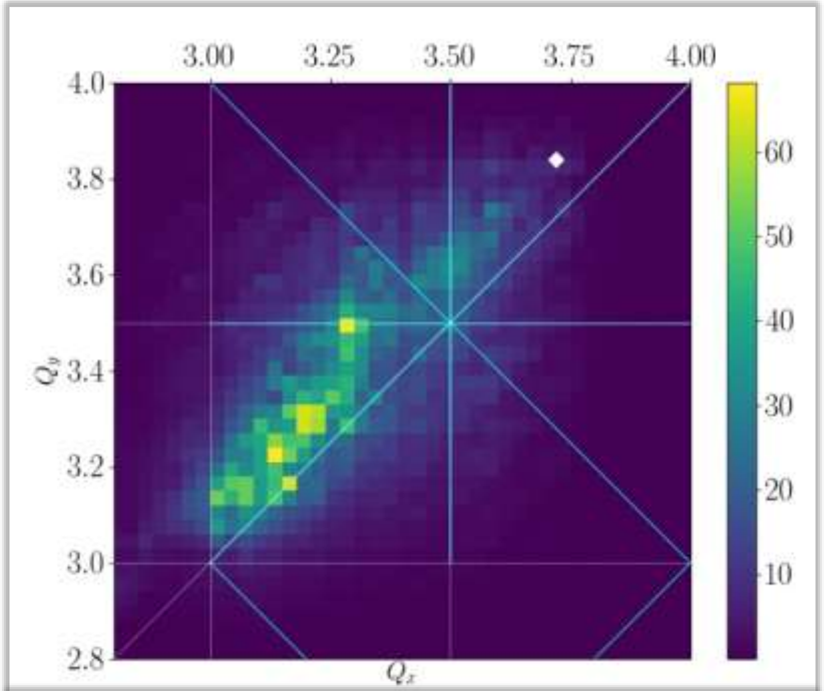
  - ~100 kW @ 800 MeV
    - Arbitrary bunch structure
    - Muons (*mu2e**)

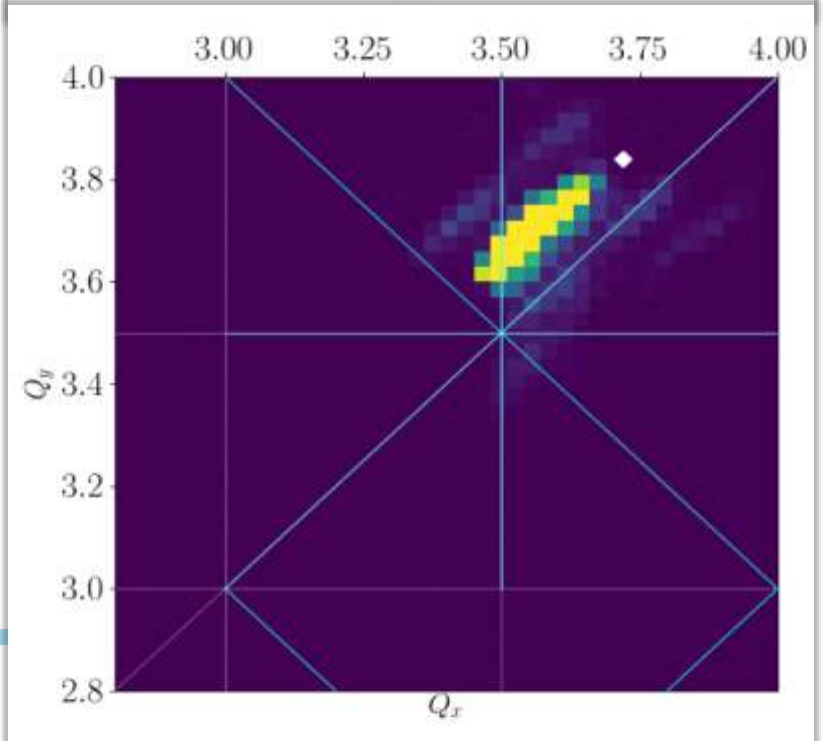
IOTA: *Integrable Optics Test Accelerator*

Space-Charge Compensation R&D









Very Important : Targetry, Foils, *e*-clouds

- Existing ν targets and horns are good to ~0.8 MW; 1 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 high power machines **PSI** and **SNS** (1.4 MW), **RAL/ISIS**, etc


NuMI 750 kW horn

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Proposed Facilities for Neutrino Research

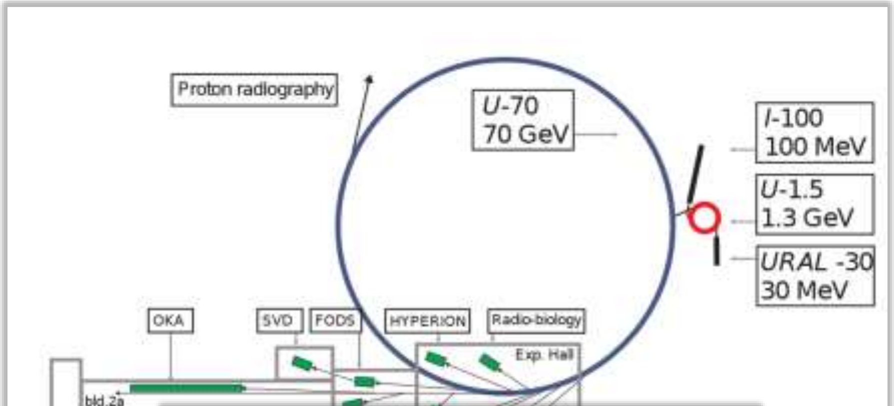
Protvino-to-ORKA: L=2590km, E_ν ~5 GeV

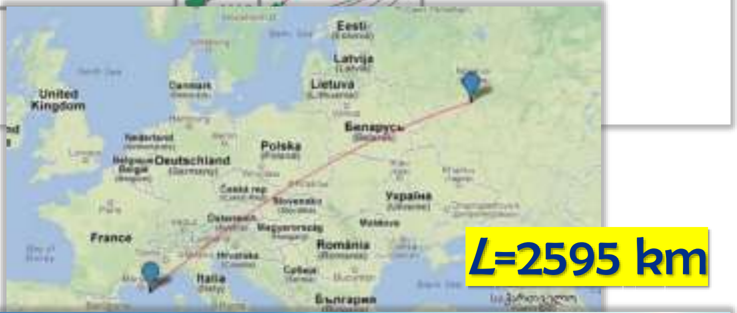
U-70 p+ synchrotron:

70 GeV protron beam

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

5μs (fast extraction), P_{avg} =15kW





L=2595 km

Needed upgrades:

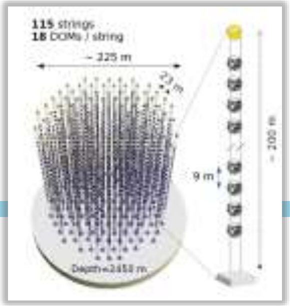
Decay pipe ~180 m long

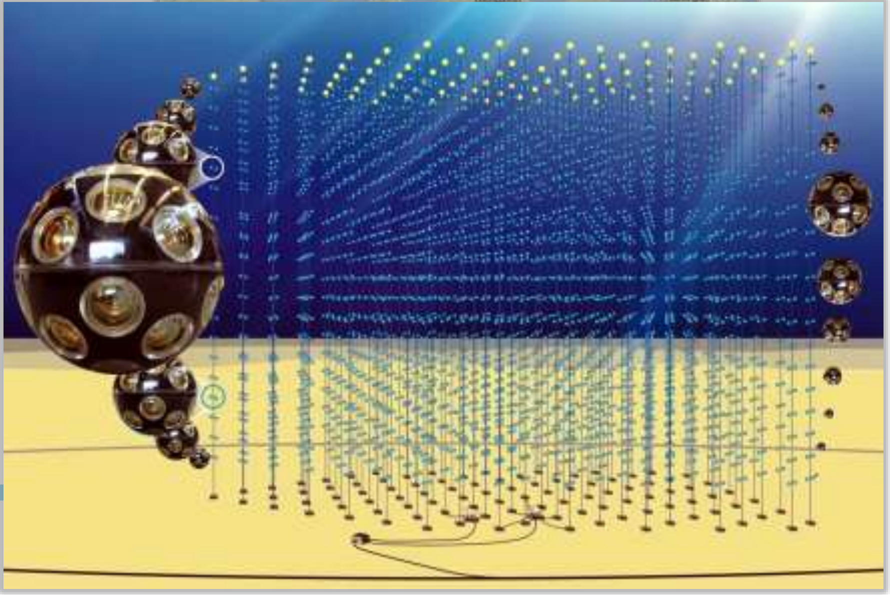
Power to 90 kW by 2026:

- 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

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%)

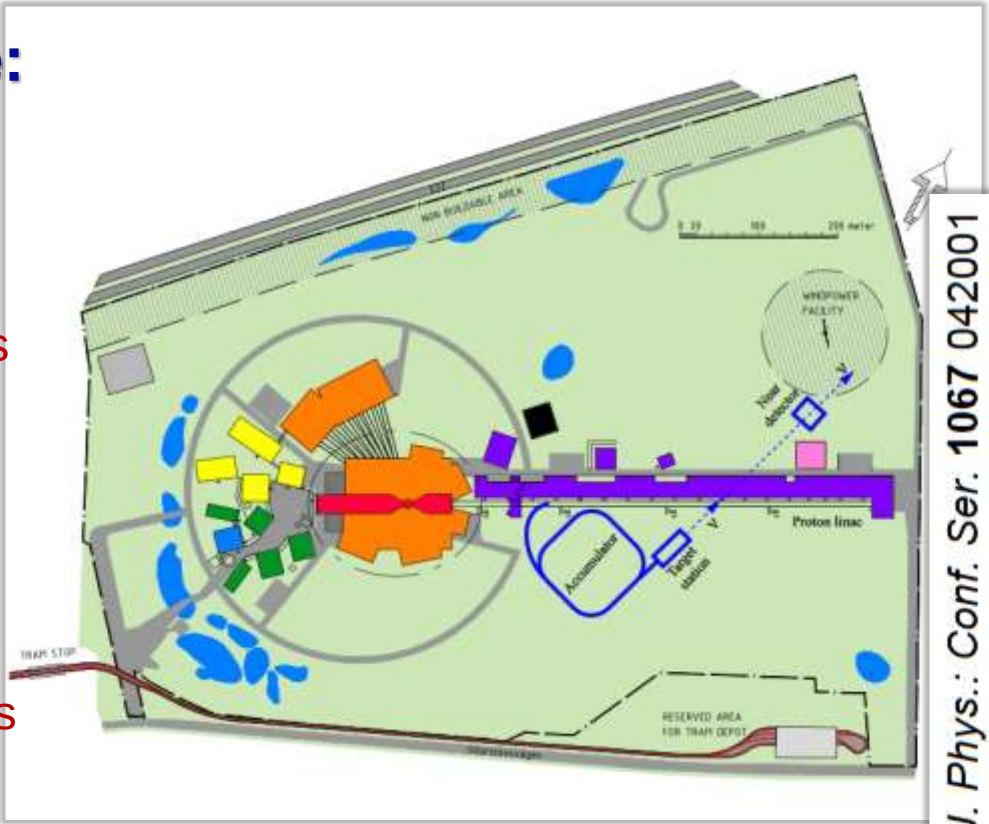
Accumulator *C*~400 m to compress to μs

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



~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

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

ENUBET : SPS-based Short Baseline ν's

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

SPS at CERN (max CNGS):

E=400 GeV protron beam

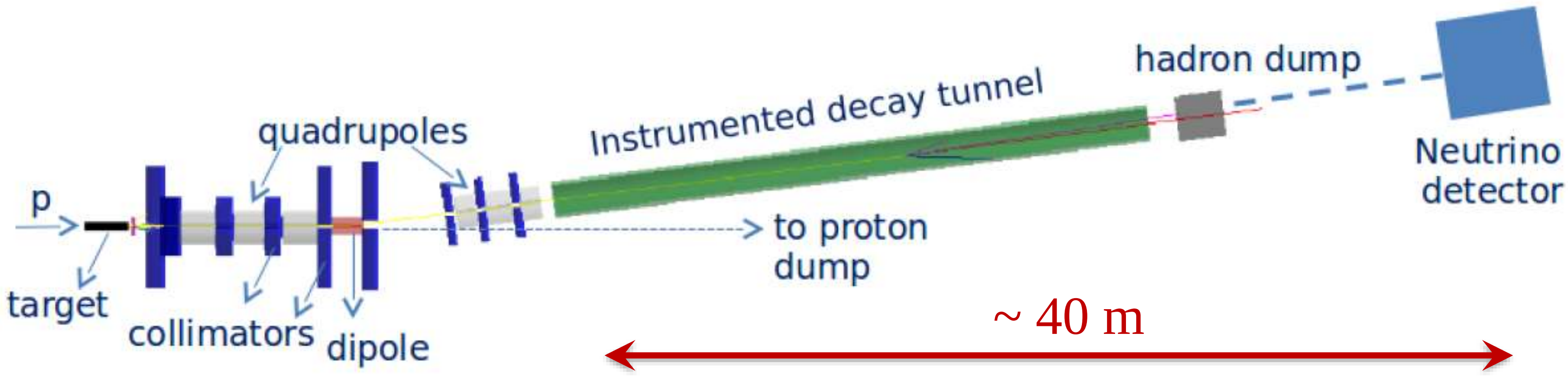
$2.25\ 10^{13}$ p+ per pulse,

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

2017 *JINST* **12** P07018 2017 *JINST* **12** P07020

SPS at CERN :

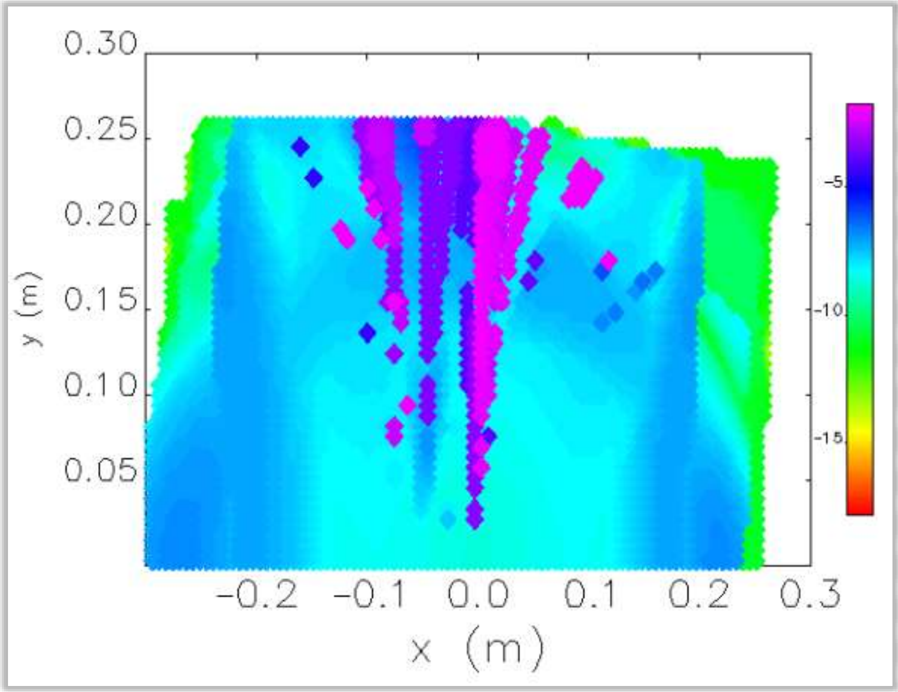
E=100 GeV *P*_beam =156kW

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

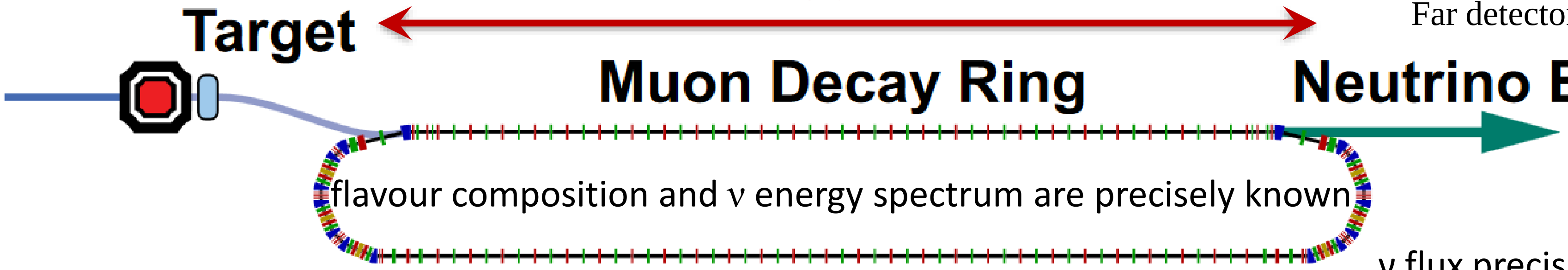
T_{cycle}=3.6 s, 2 x 10 μs (fast extr.)

$\mu\pm$ 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%



~ 280 m

Near detector ~ 50m
Far detector ~ 2km

Target

Muon Decay Ring

Neutrino Beam

flavour composition and ν energy spectrum are precisely known

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/ORKA; ESSνSB; ENUBET; νSTORM

Thanks for Your Attention !

Acknowledgements

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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)

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

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

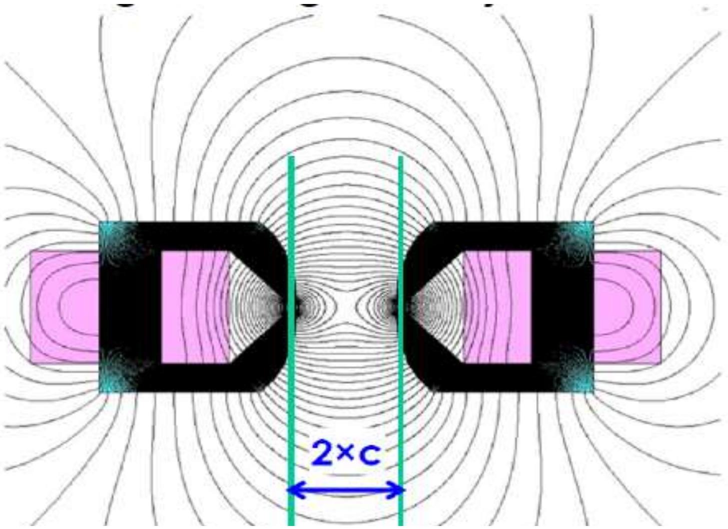
= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

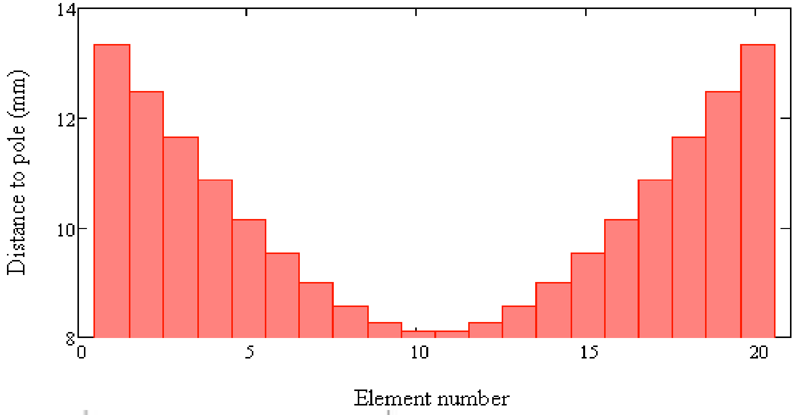
(if not straightforward solution – double the energy - then)

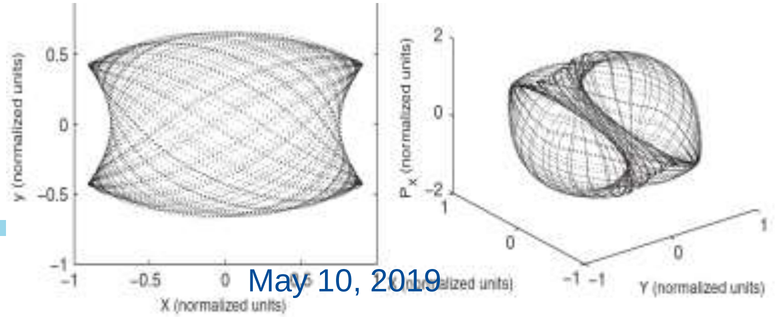
- Two novel approaches to increase the SC tune-shift:
  - "Integrable Non-Linear Optics"
  - Space-Charge Compensation with Electron Lenses
- Possibly augmented with Superperiodic Focusing Lattice and "flat long bunches" (multiple harmonics RF)

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) →

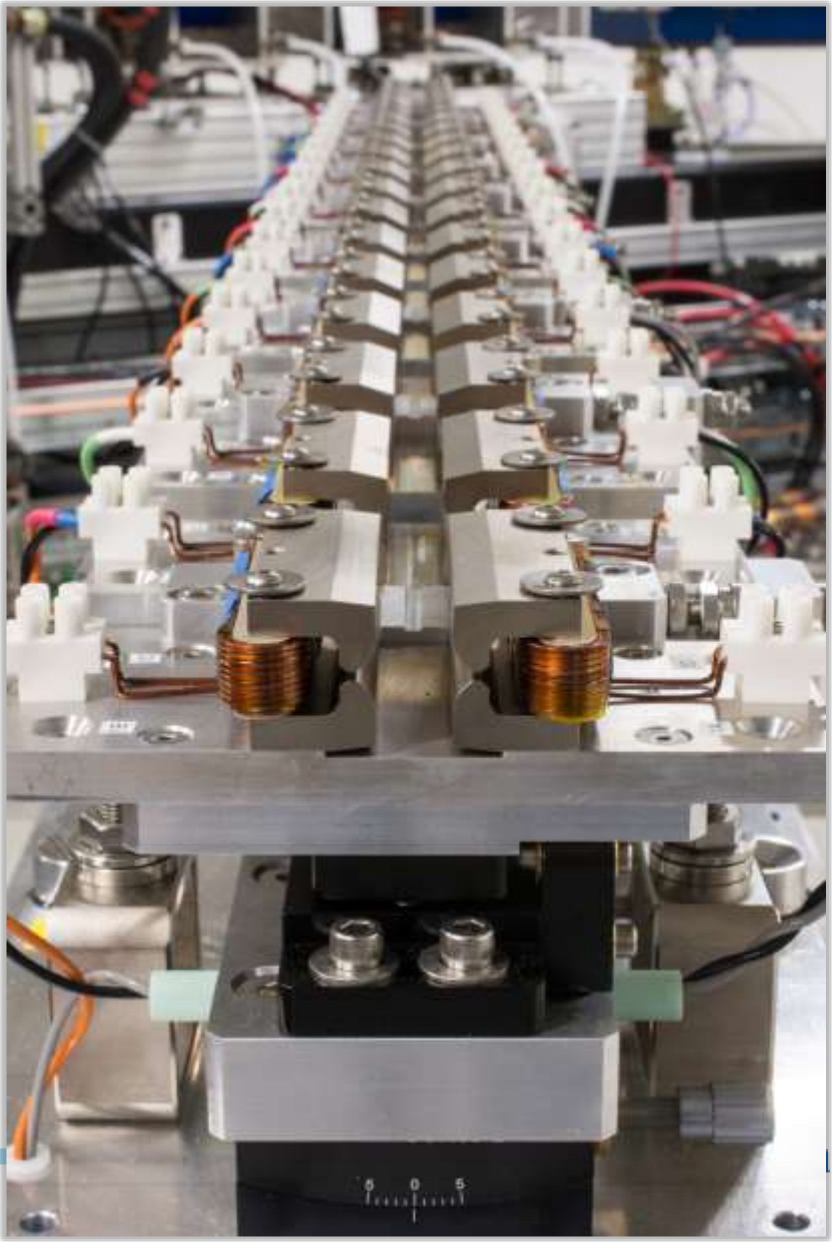






Non-Linear Integrable Optics Test

- 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

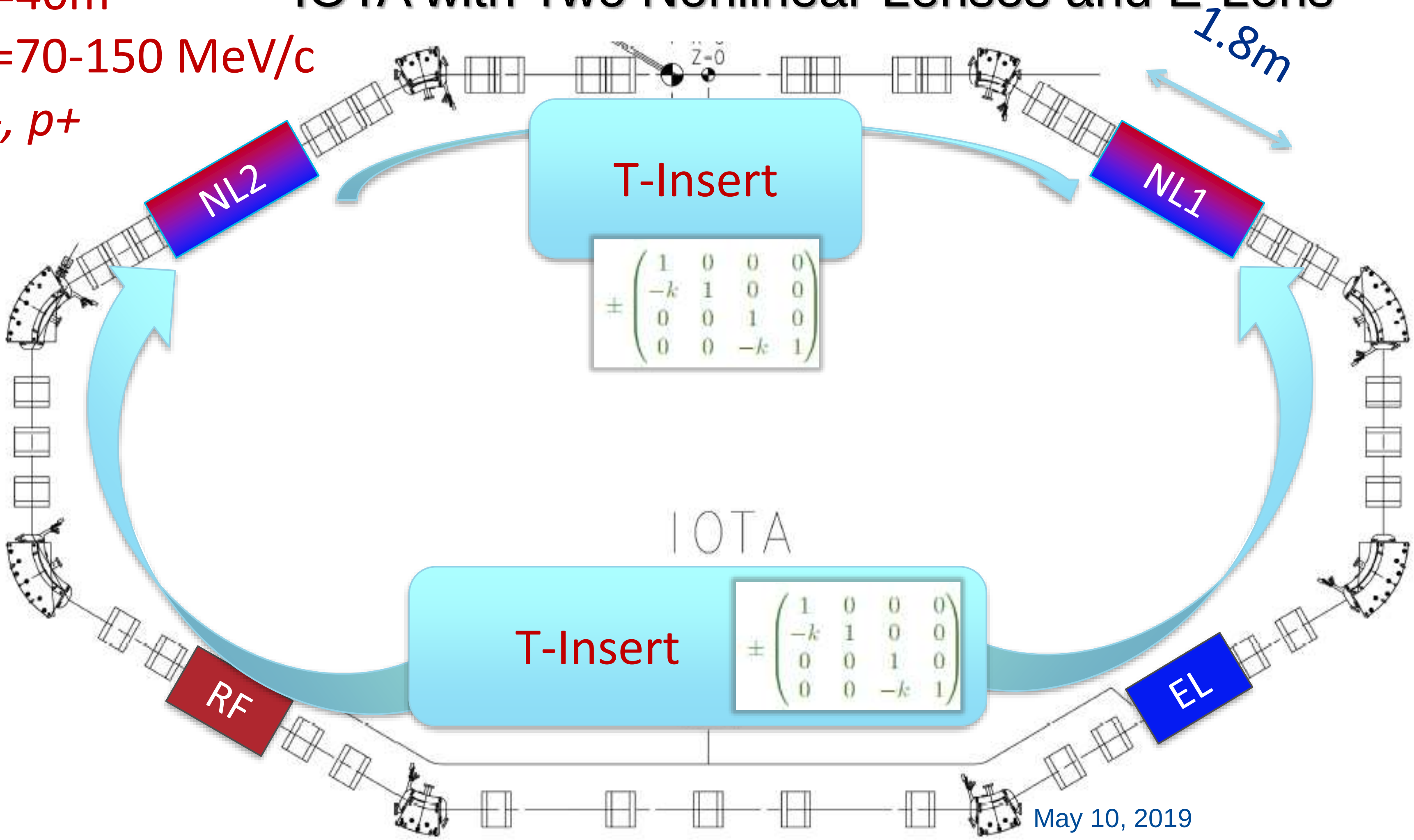
Integrable Optics Test Accelerator

C=40m

P=70-150 MeV/c

e-, p+

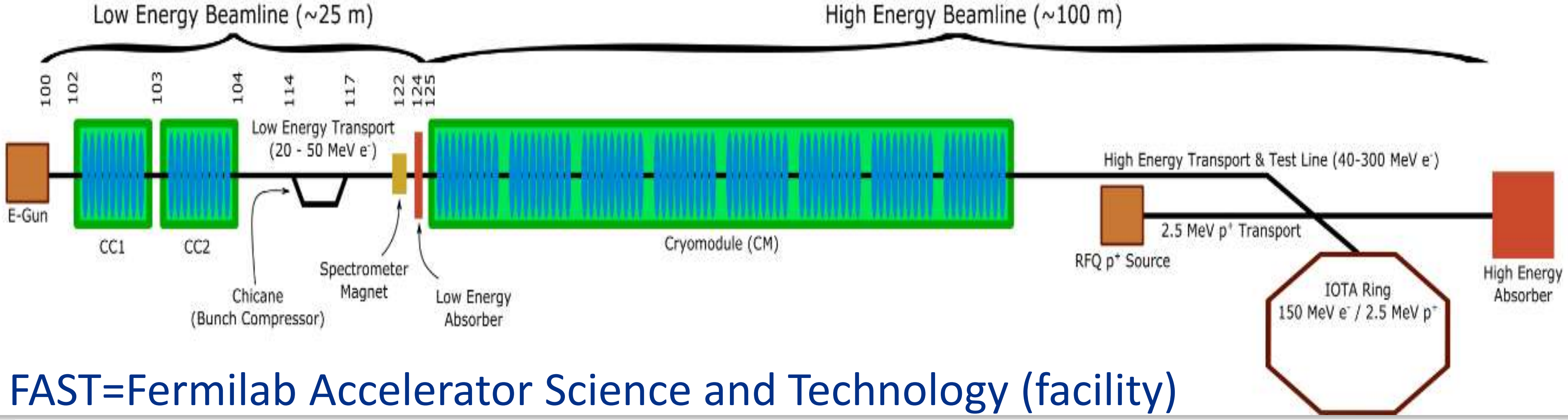
IOTA with Two Nonlinear Lenses and E-Lens



$$\pm\begin{pmatrix} 1 & 0 & 0 & 0 \\ -k & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -k & 1 \end{pmatrix}$$

$$\pm\begin{pmatrix} 1 & 0 & 0 & 0 \\ -k & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -k & 1 \end{pmatrix}$$

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

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

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

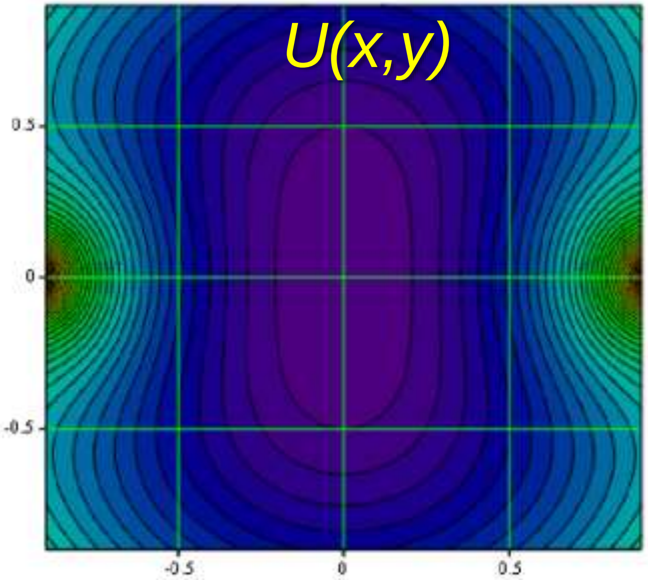
In accelerators :

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

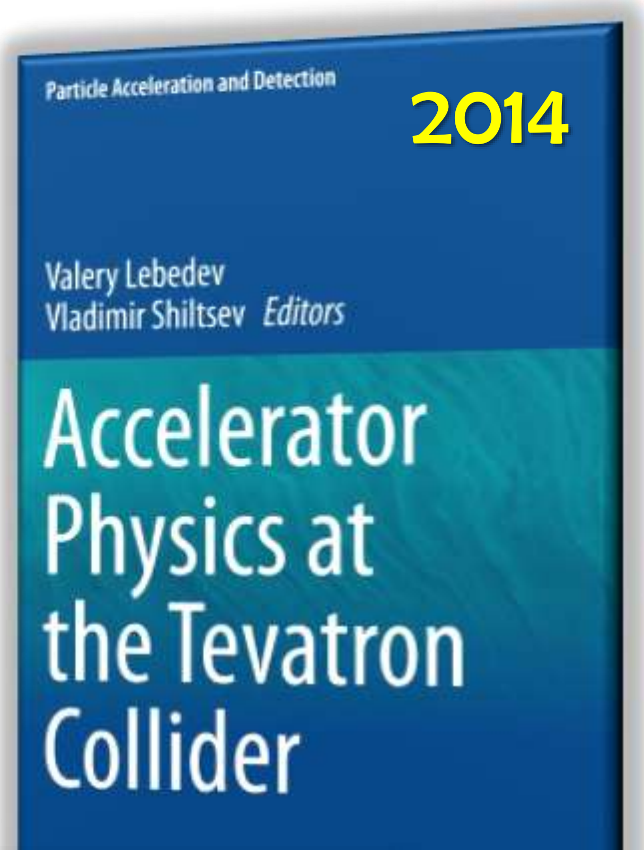
→ **Courant-Snyder transformation, scaling**

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

first invariant



Electron Lenses : Introduced in *2000*’s



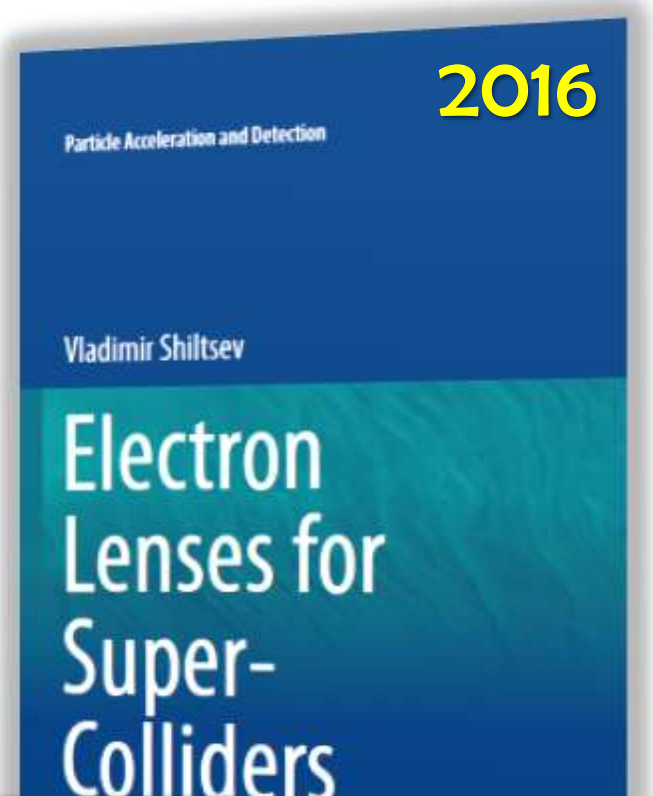
2014

Particle Acceleration and Detection

Valery Lebedev
Vladimir Shiltsev *Editors*

Accelerator Physics at the Tevatron Collider

Springer



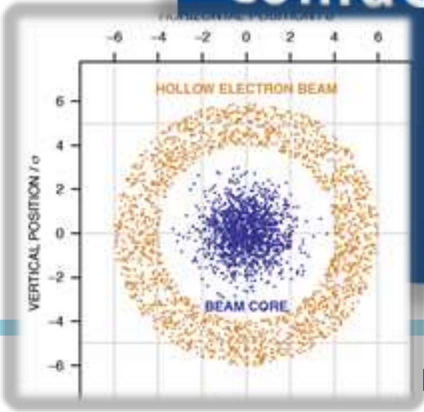
2016

Particle Acceleration and Detection

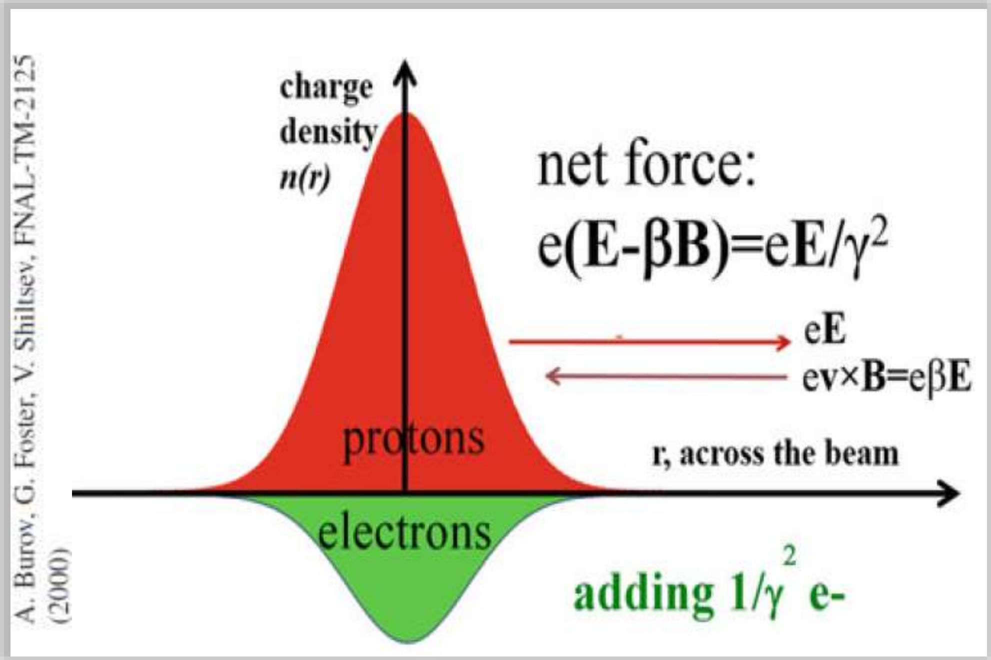
Vladimir Shiltsev

Electron Lenses for Super-Colliders

Springer



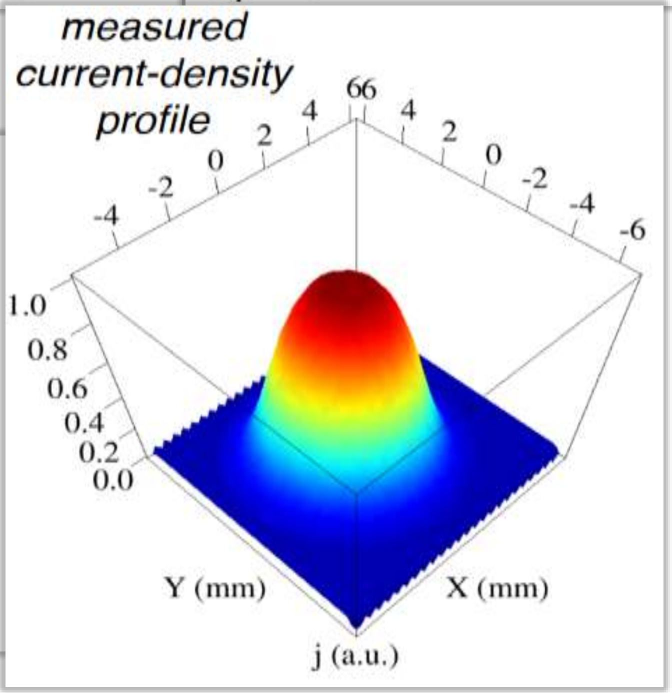
Proton Space-Charge: Compensated by Electrons



A. Burov, G. Foster, V. Shiltsev, FNAL-TM-2125 (2000)

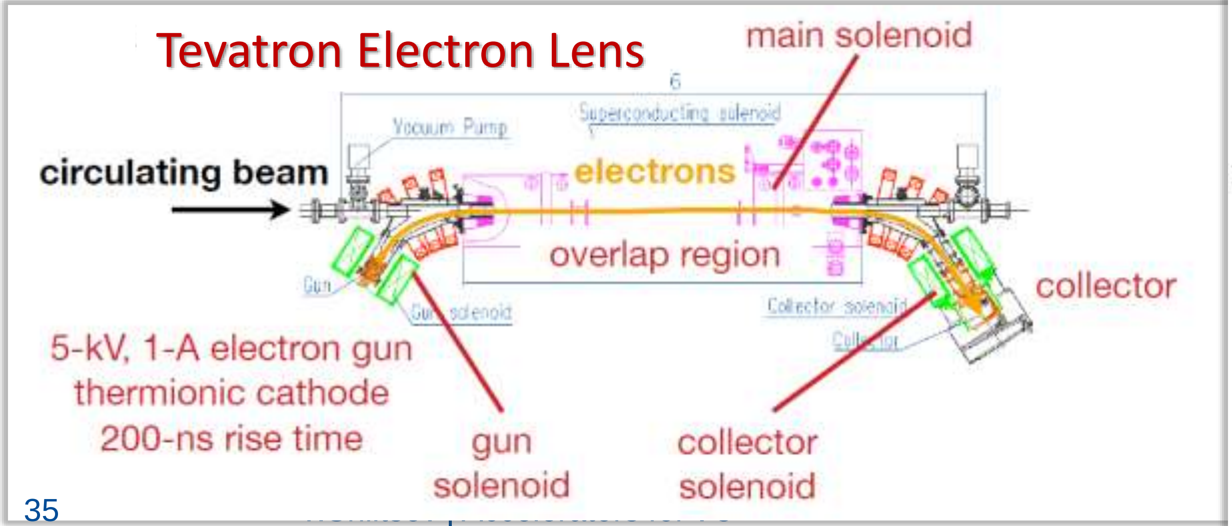
side view

top view



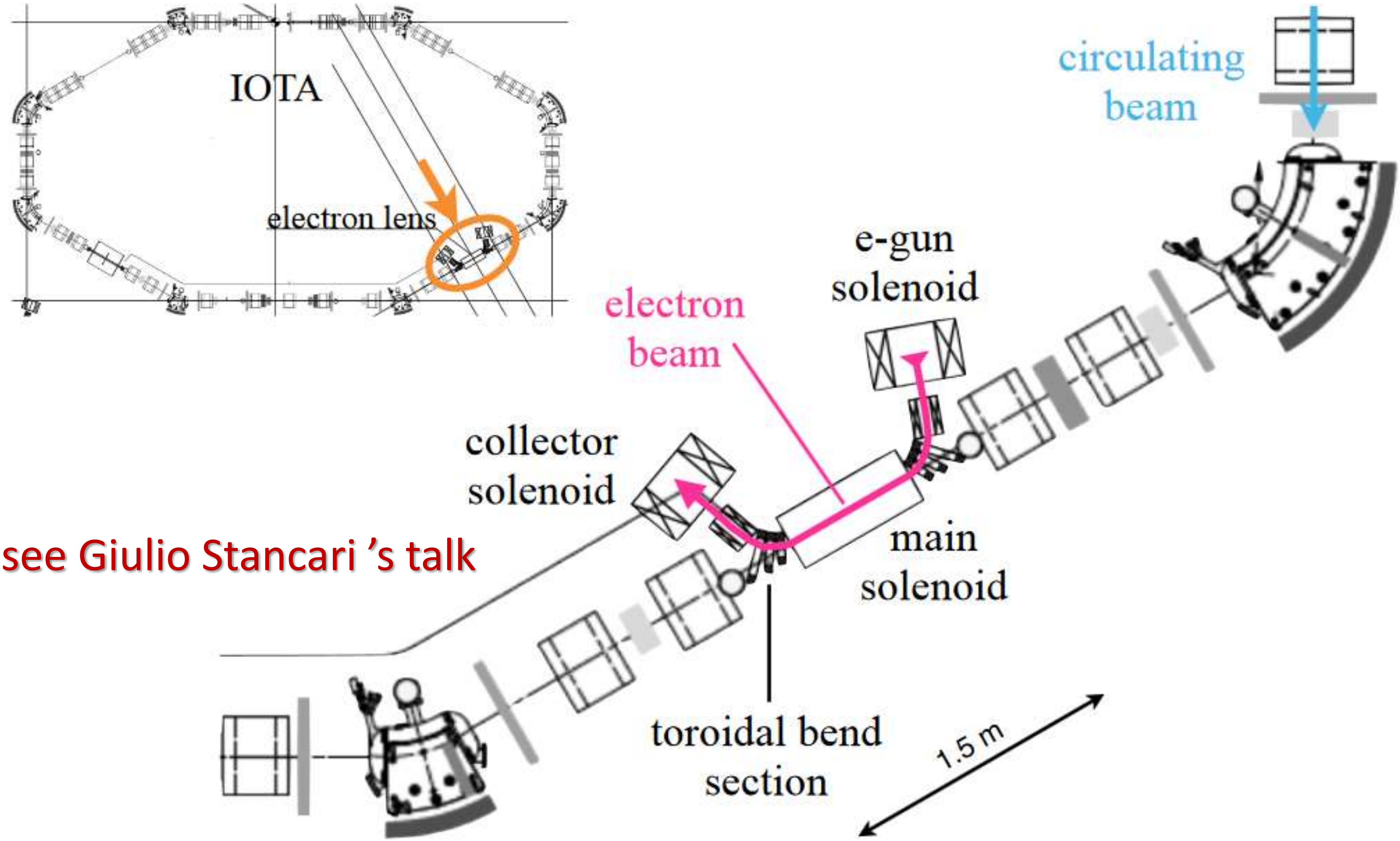
measured current-density profile

Tevatron Electron Lens



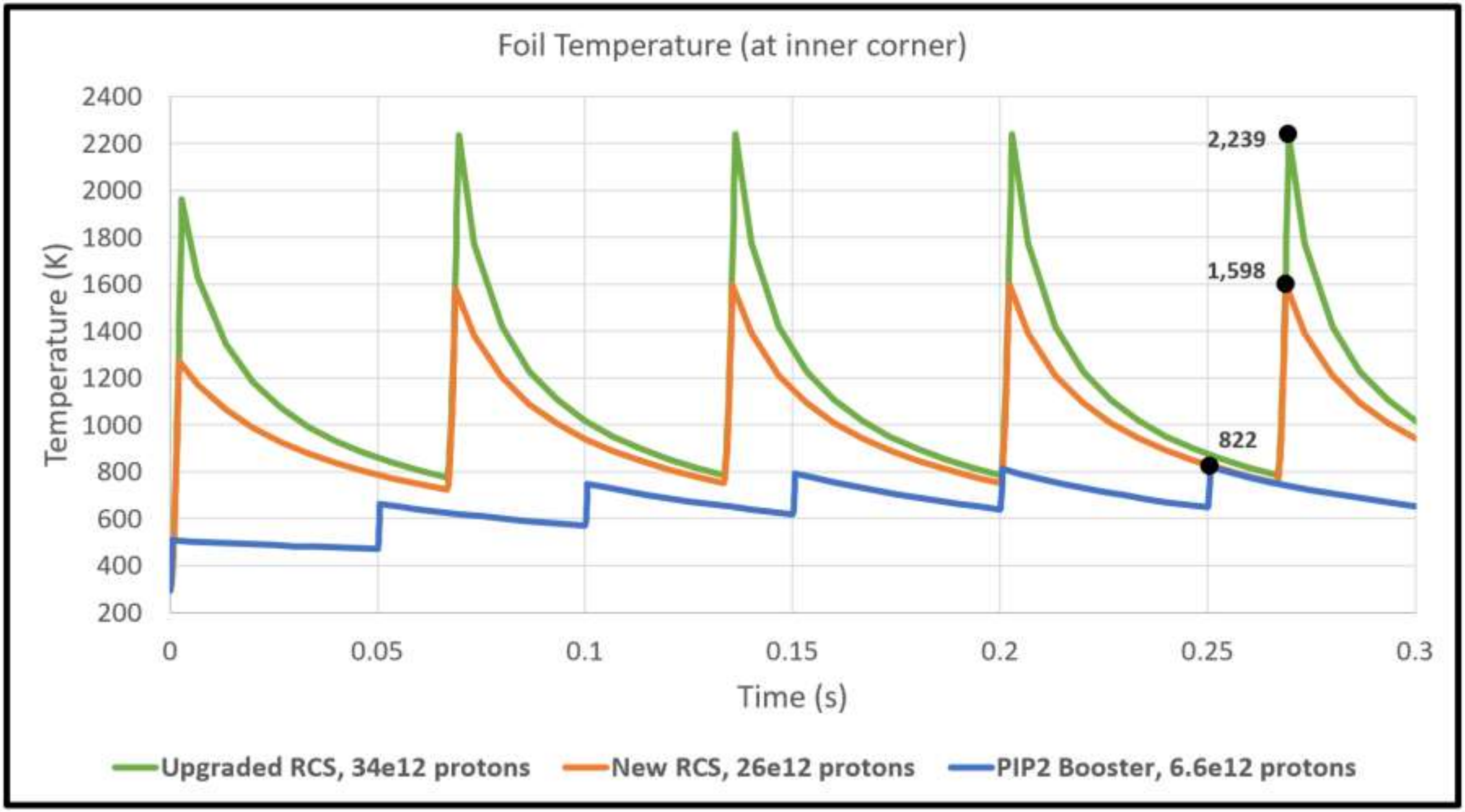
5-kV, 1-A electron gun
thermionic cathode
200-ns rise time

Electron Lens in IOTA



see Giulio Stancari ’s talk

H- Foil Heating



Coherent Stability

Mitigation of Electron Cloud:

Avoid combined function magnets.

Use **TiN** or **a-Carbon** beampipe coating.

Transverse Instabilities:

Much less impedance than current Booster.

Transverse and longitudinal dampers like Booster.

No transition crossing.

IOTA Technologies

Nonlinear integrable optics:
Provides incredible **nonlinear focusing** without the usual loss in dynamic aperture. Mitigates **halo formation** and **collective effects**.

Electron lens/column:
Directly compensates **space-charge effects**, R&D underway to determine the best way to implement.

Both technologies tested at IOTA over the next several years.

For **robustness** of performance?

Or for **upper-bound** of performance?

Loss Limit reaching PIP goal of 2.4E17 pph – running above 2.1E17 pph