The FAST/IOTA Project at Fermilab

Alexander Valishev

ICAP'18

October 20, 2018

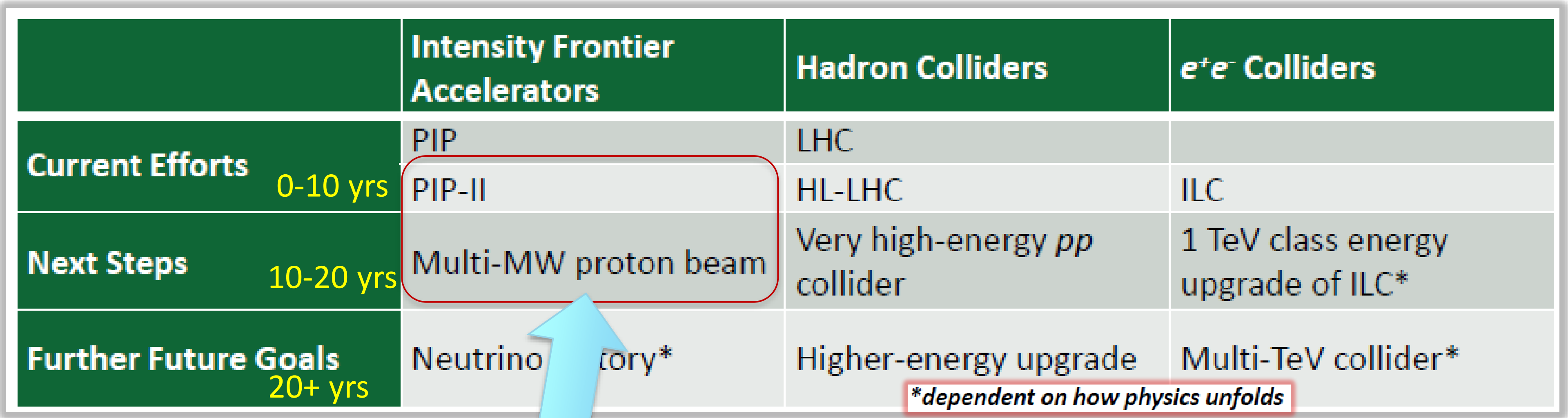
Acknowledgments

- R.Andrews, D.Barak, V.Bocean, D.Broemmelsiek, A.Burov, K.Carlson, D.Crawford, A.Didenko, N.Eddy, D.Edstrom, J.Eldred, R.Espinoza, D.Franck, J.Jarvis, V.Kashikhin, R.Kellett, M.Kucera, V.Lebedev, J.Leibfritz, C.Jensen, W.Johnson, P.Li, M.McGee, S.Nagaitsev, L.Nobrega, M.Obrycki, H.Piekarz, E.Prebys, I.Rakhno, A.Romanov, J.Ruan, J.Santucci, V.Shiltsev, G.Stancari, A.Valishev, J.VanBogaert, A.Warner, S.Wesseln(FNAL)
- M.Andorff, S.Chattopadhyay, B.Freemire, P.Piot, S.Szustkowski (NIU)
- D.Shatilov (BINP)
- S.Antipov, N.Kuklev (Univ. Chicago)
- D.Abell, D.Bruhwiler, N.Cook, C.Hall, S.Webb (RadiaSoft)
- C.Mitchell (LBNL)
- R.Agustsson, A.Murokh, F.O’Shea (RadiaBeam)
- H.Baumgartner, R.Kishek, K.Ruisard (UMD)

Outline

- Motivation
- Overview of FAST/IOTA facility
- FAST/IOTA science
- Status and plans

Context: US HEP Community Plan based on 2014 P5 Report



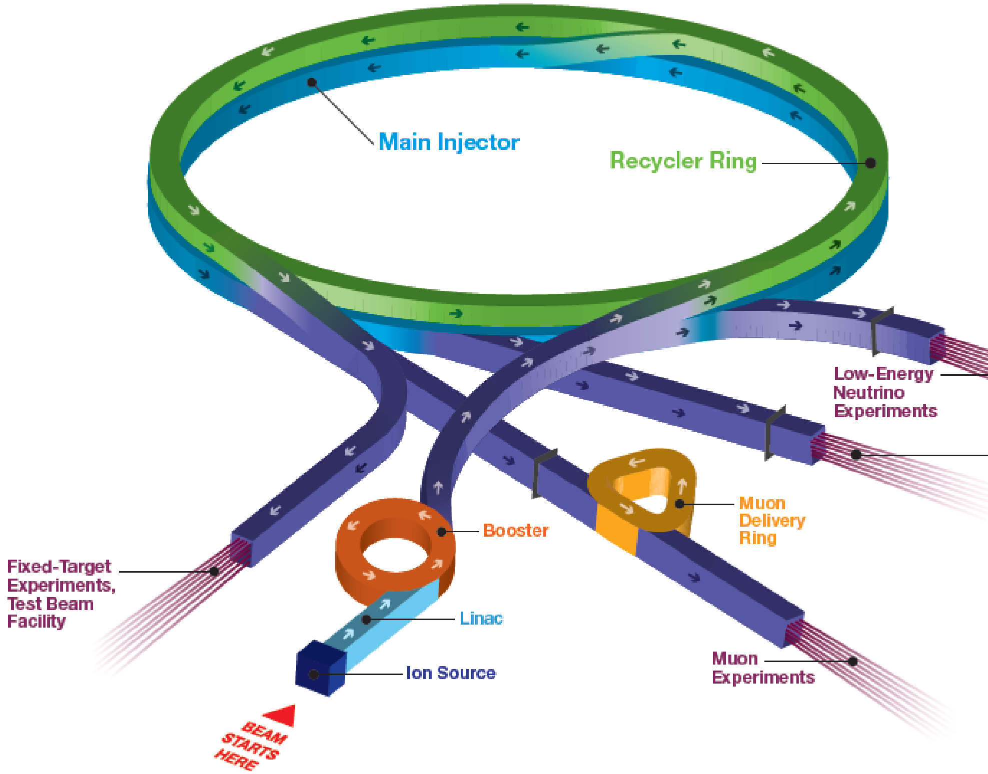
	Intensity Frontier Accelerators	Hadron Colliders	e^+e^- Colliders
Current Efforts 0-10 yrs	PIP	LHC	
	PIP-II	HL-LHC	ILC
Next Steps 10-20 yrs	Multi-MW proton beam	Very high-energy *pp* collider	1 TeV class energy upgrade of ILC*
Further Future Goals 20+ yrs	Neutrino tory*	Higher-energy upgrade	Multi-TeV collider*

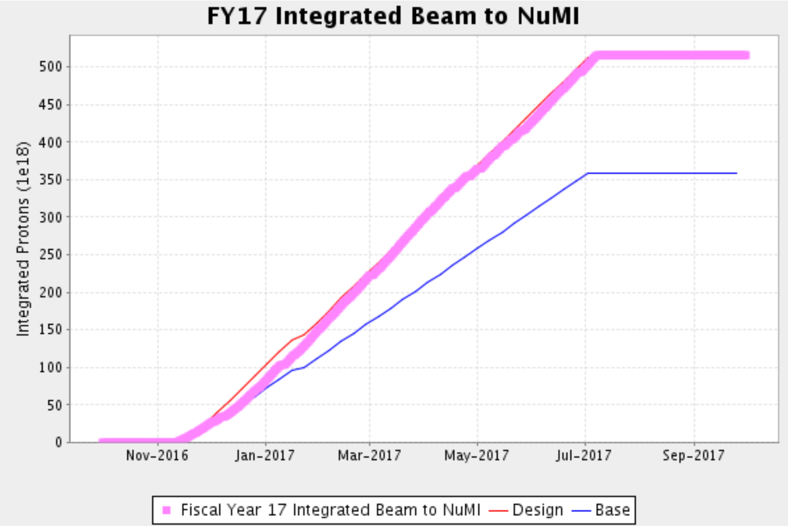
**dependent on how physics unfolds*

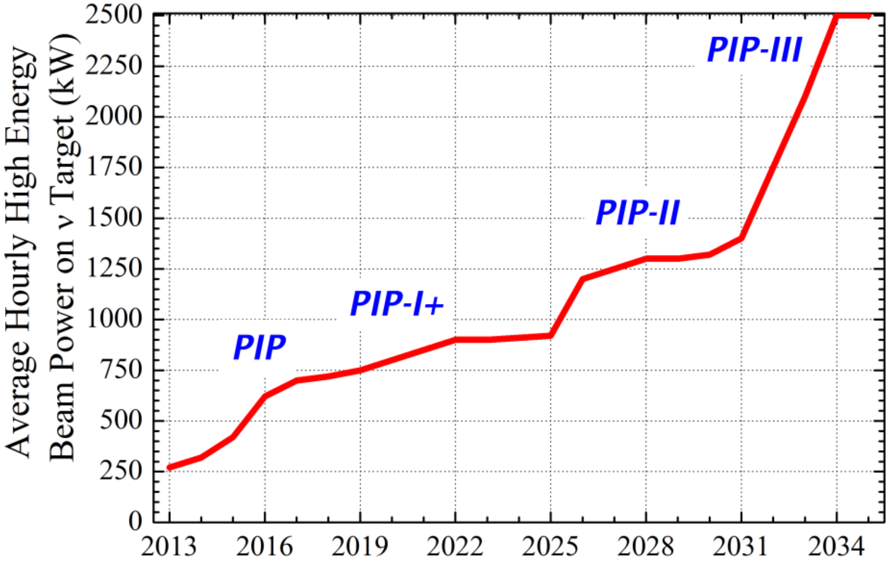
Key points on the Intensity Frontier HEP:

- “CP-violation sensitivity” ⇒ need **900 kt × MW × yrs**
- [R12] build LBNF/DUNE **40 kt LAr** detector
  - then 400kW⇒>50 years to get 900 kt × MW × yrs
- [R14] build PIP-II linac to **get >1 MW**
  - current plan 40 kt × 1 MW × **5 yrs** = > 200 kt × MW × yrs
- [R23/26] accelerator R&D (facilities) toward **multi-MW**
  - say, 40 kt × 2.5 MW × **7 yrs** = remaining 700 kt × MW × yrs

Fermilab Accelerator Complex

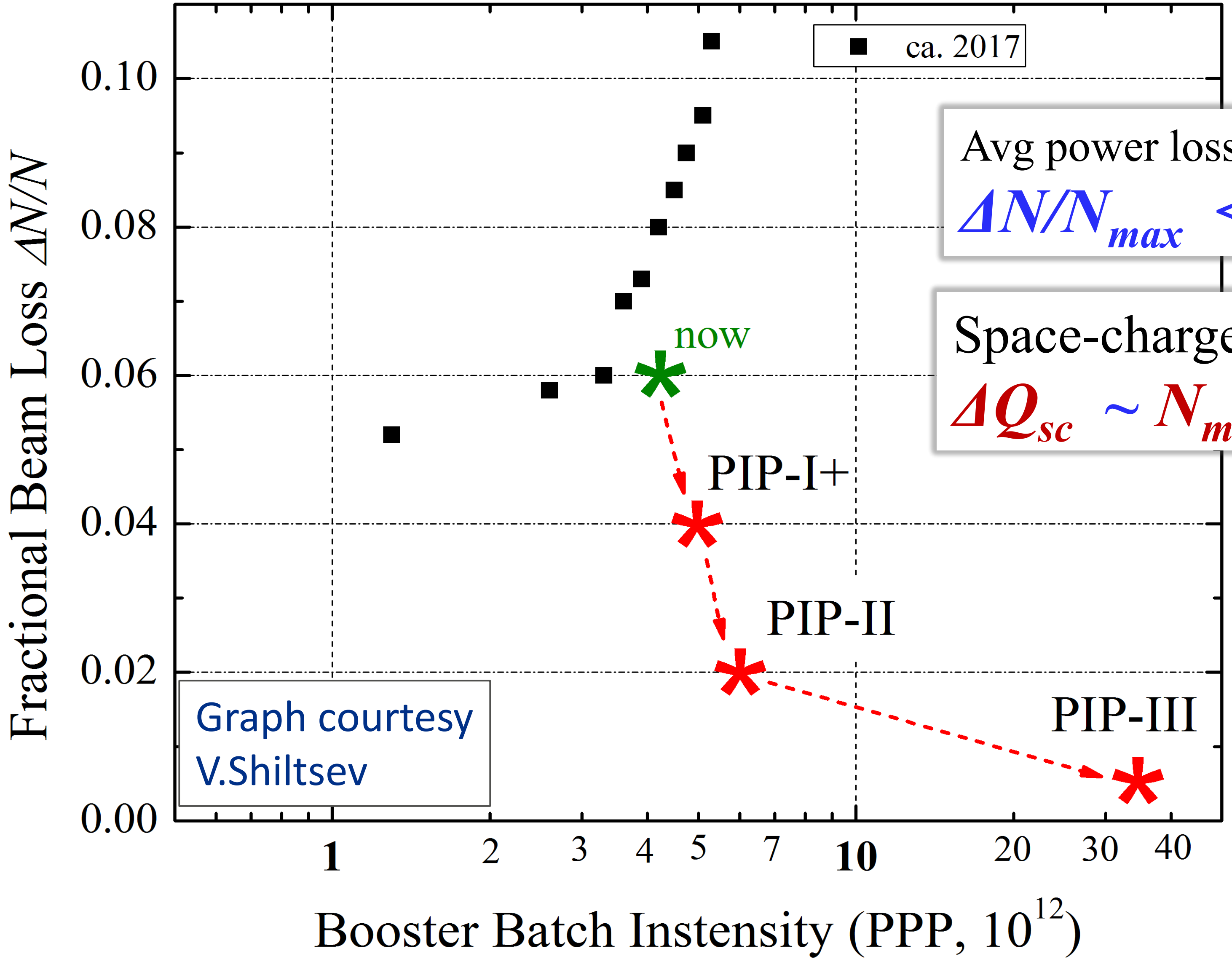






Key Challenge – Beam Brightness → Particle Losses

Example: limits on the Fermilab Booster *Protons Per Pulse (PPP)*



Graph courtesy V.Shiltsev

Avg power loss limit (500W) :

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

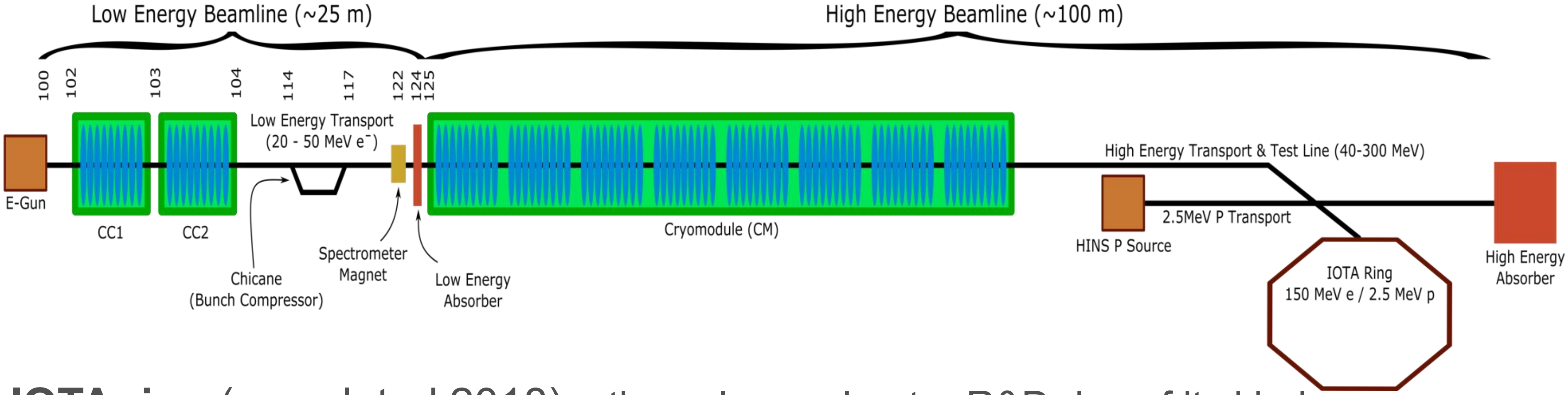
Space-charge limit scales:

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

Why Dedicated Facility?

- Need for experimental beam physics research especially in circular accelerators
  - Many challenges on the way to higher beam intensity and brightness
- Impossible to conduct R&D in main complex
  - Production machines must operate 24/7 for HEP users
  - Disruptive studies difficult if at all possible
- Dedicated R&D facility is an efficient way to conduct proof-of-principle experiments, train researchers

Fermilab Accelerator Science and Technology FAST facility – unique set of capabilities



IOTA ring (completed 2018) – the only accelerator R&D ring of its kind

- Protons or electrons
- Highly flexible, precise

SRF electron linac (completed 2017)

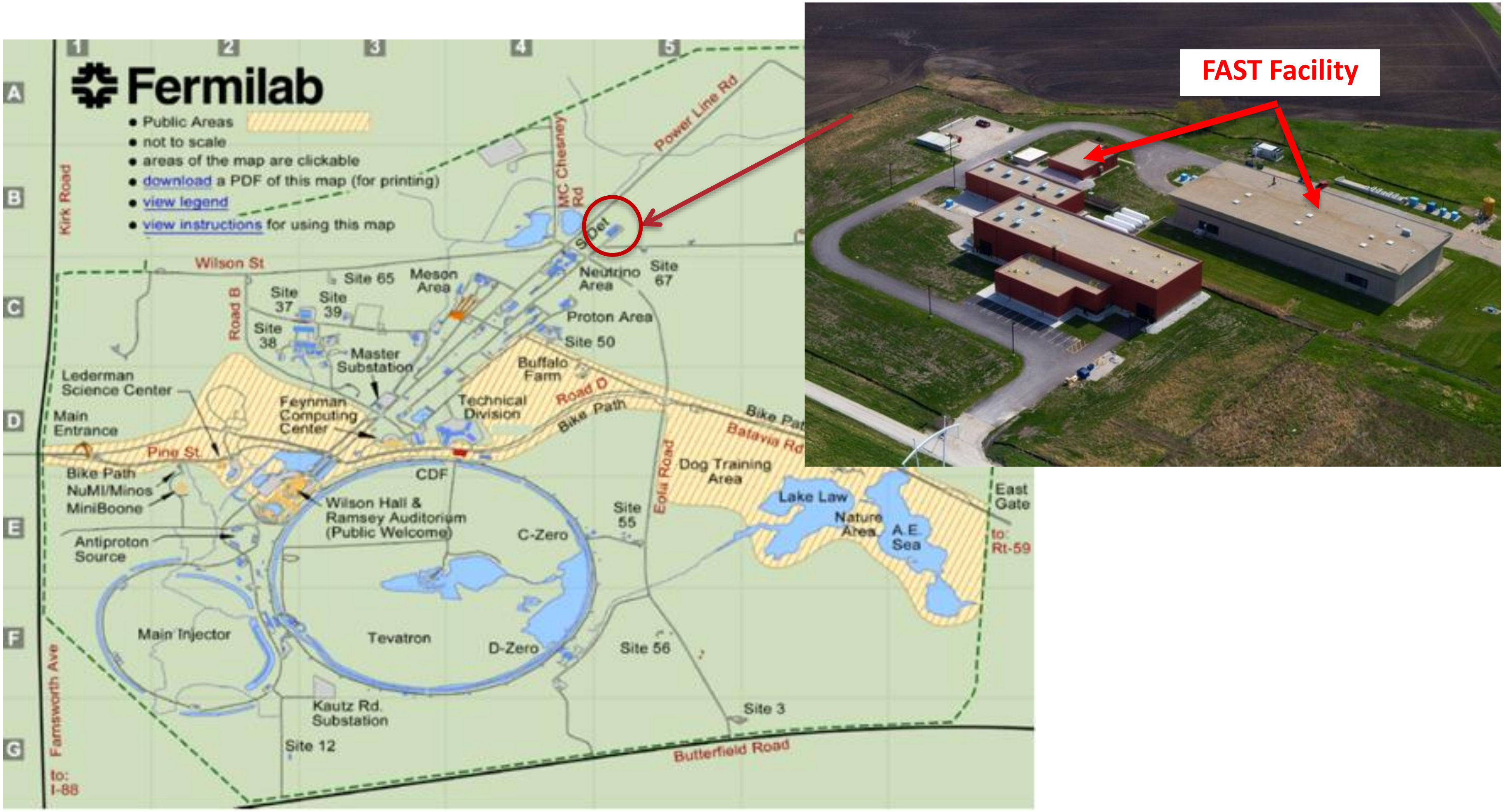
- Full ILC beam parameters
- World record accelerating gradient > 31.5MV/m

Proton RFQ (future addition)

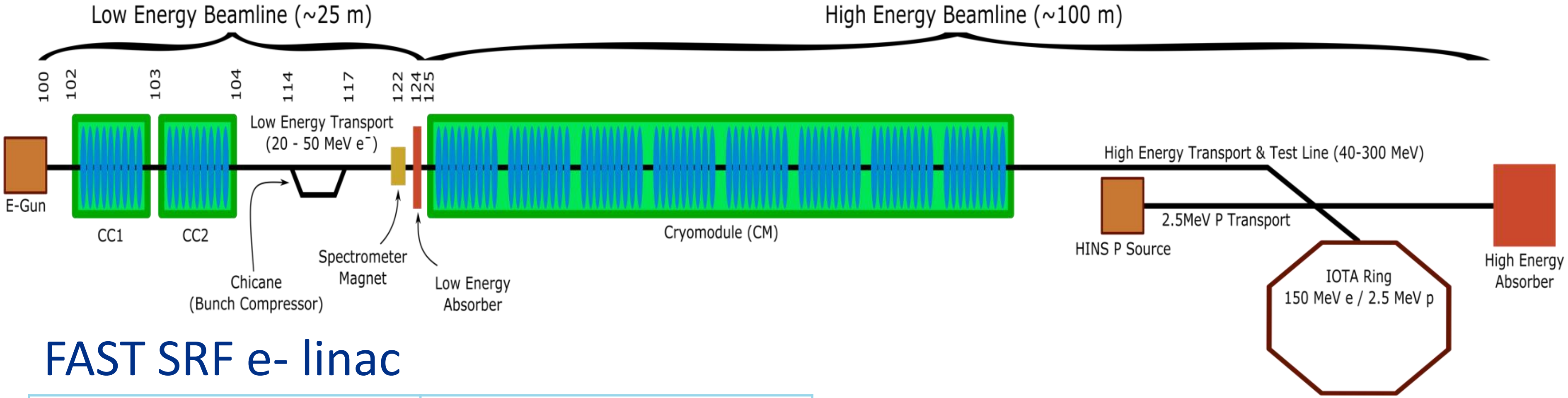
- High current / high space-charge

Together – positioned to advance beam brightness and intensity

FAST Location



Fermilab Accelerator Science and Technology FAST facility - Injectors



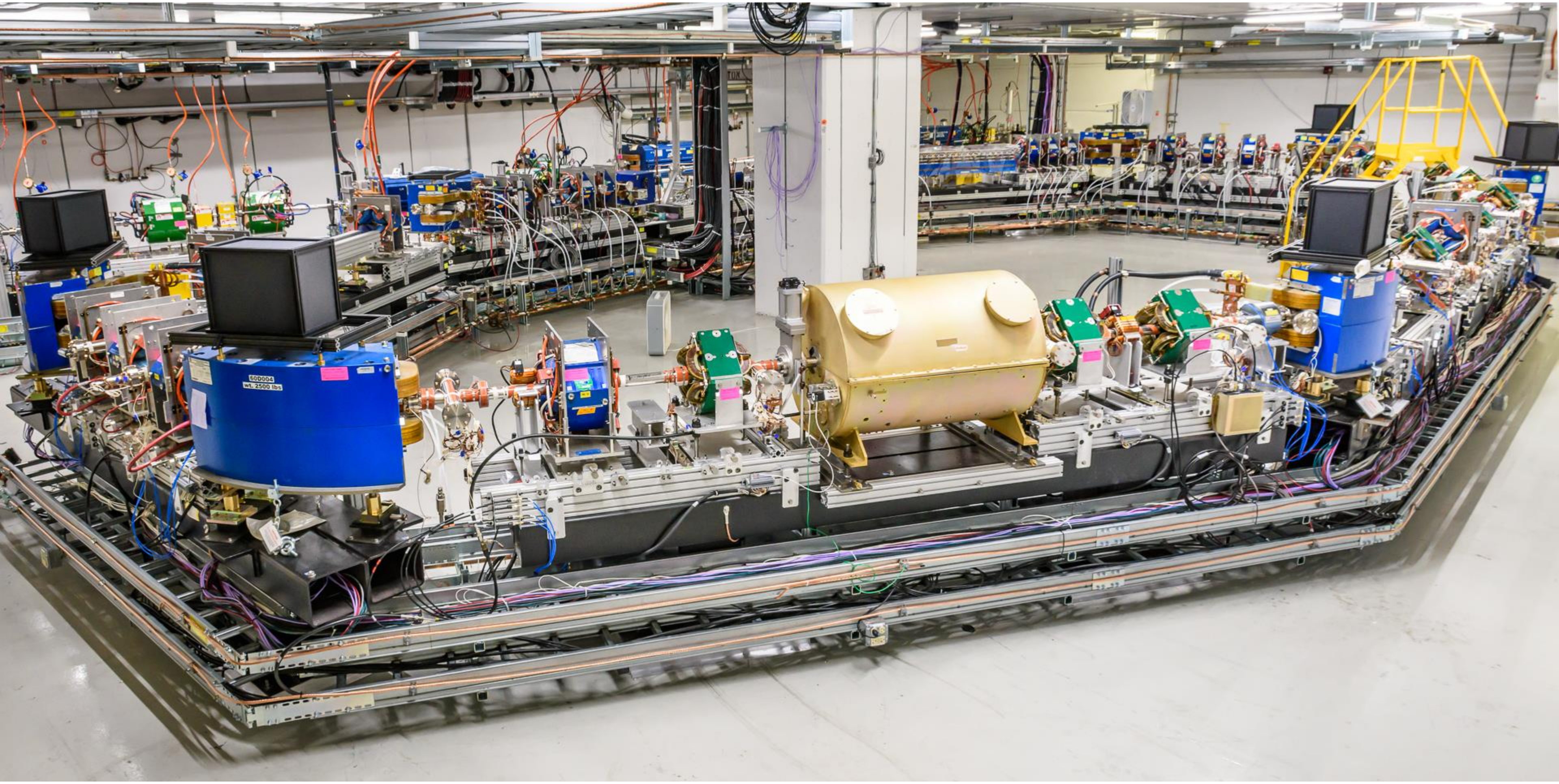
FAST SRF e- linac

Bunch charge	up to 2 nC
Gun gradient	45 MV/m
CC1 gradient	26 MV/m
CC2 gradient	15 MV/m
CM2 gradient	up to 31.5 MV/m
Beam energy	150 (up to 300) MeV
Bunch length	6-8 ps (rms)
Pulse length	1 ms
Bunch freq.	3 MHz
Rep. rate	1 Hz (5 Hz)

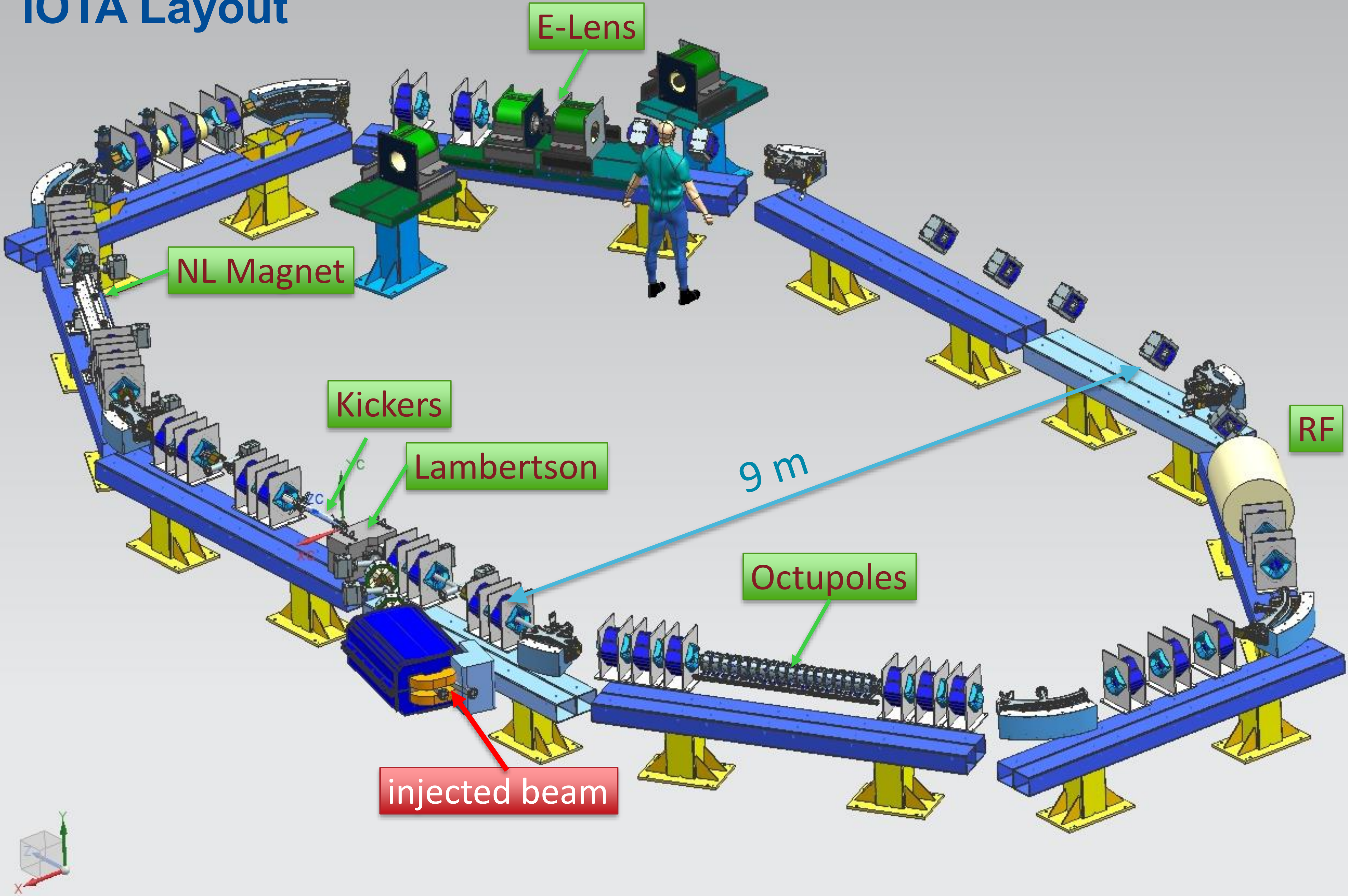
FAST proton injector

Particles	proton
Kinetic Energy	2.5 MeV
Momentum	69 MeV/c
β	0.073
RF Structure	325 MHz
Beam current	10 mA
Emittance	0.3 mm mrad
Rep. rate	1 Hz
Pulse length	1.5 us
ΔQ_{sc} in IOTA	-0.5

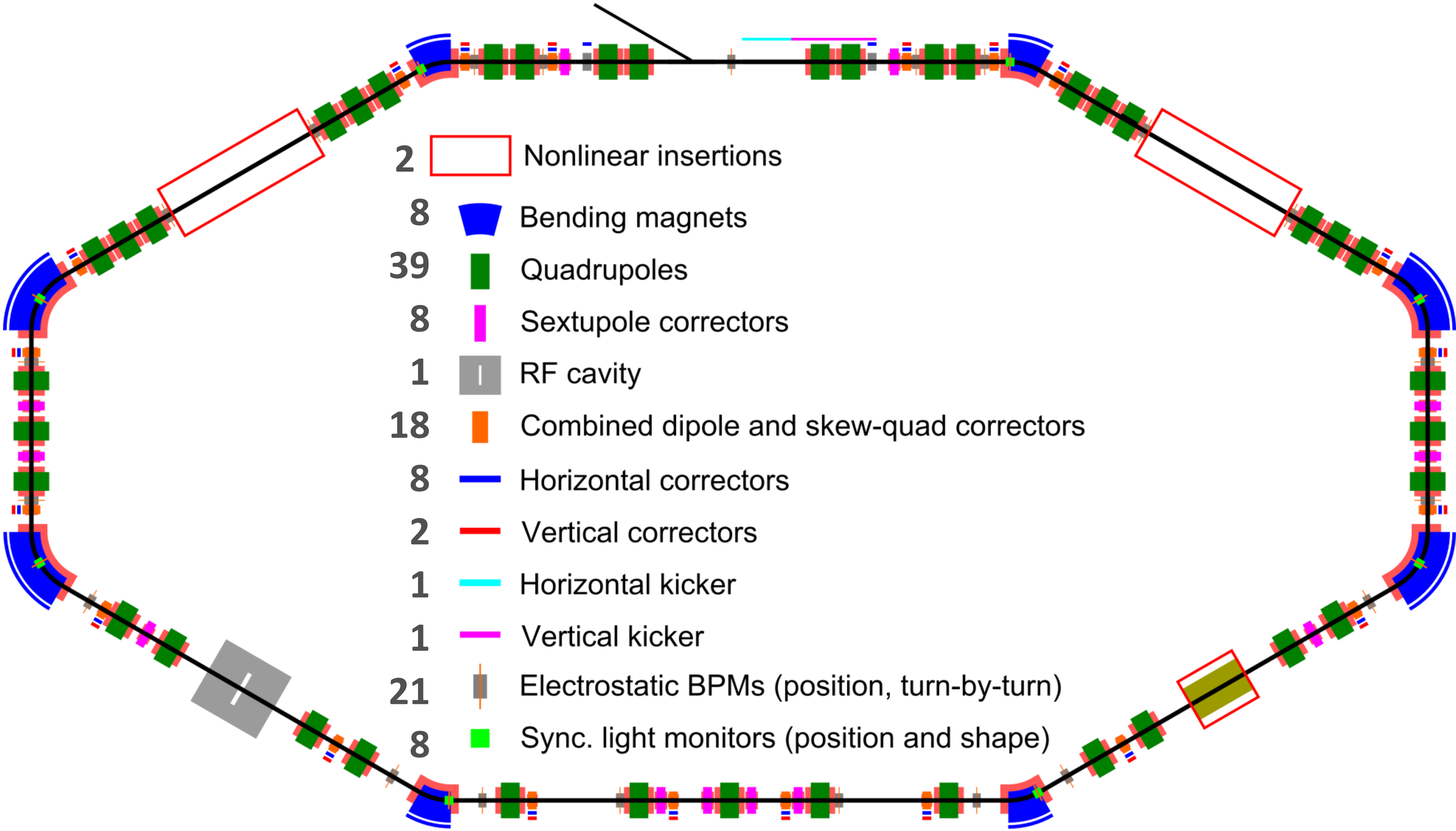
Center Piece of FAST – Integrable Optics Test Accelerator



IOTA Layout


E-Lens
NL Magnet
Kickers
Lambertson
9 m
RF
Octupoles
injected beam

IOTA Layout - Elements



2	▭	Nonlinear insertions
8	▬	Bending magnets
39	🟩	Quadrupoles
8	▮	Sextupole corrector
1	▨	RF cavity
18	🟧	Combined dipole and skew-quad correctors
8	—	Horizontal correctors
2	—	Vertical correctors
1	—	Horizontal kicker
1	—	Vertical kicker
21	▮	Electrostatic BPMs (position, turn-by-turn)
8	🟩	Sync. light monitors (position and shape)

IOTA Parameters

	Electrons	Protons
Nominal kinetic energy	150 MeV	2.5 MeV
Nominal intensity	1×10^9	1×10^{11}
Circumference	40 m	
Bending dipole field	0.7 T	
Beam pipe aperture	50 mm dia.	
Betatron tune	3÷5	
Beam size (rms, x,y)	0.05 ÷ 0.5 mm	5 ÷ 15 mm
Transverse emittance r.m.s.	0.04 μm	2 μm
Synchrotron Radiation damping time	0.6s, 5×10^6 turns	
Synchrotron tune	$2\div5\times10^{-4}$	
Bunch length, momentum spread	12 cm, 1.4×10^{-4}	
Beam pipe vacuum	$2\div4\times10^{-10}$ Torr	
Beam lifetime	1÷10 hour	1÷10 min

Integrable Optics Test Accelerator – Unique R&D Machine

- **Adaptable**
  - Can operate with either electrons or protons
  - Easily reconfigurable – quick-change experimental equipment
  - Significant flexibility
- **Accurate**
  - Precise control of the optics quality and stability
  - Comprehensive set of precision instrumentation
  - Set up for very high intensity operation (with protons)
- **Affordable**
  - Cost-effective solution, re-use existing parts whenever possible
  - Mostly based on conventional technology (magnets, RF)
  - Balance between low energy (low cost) and research potential

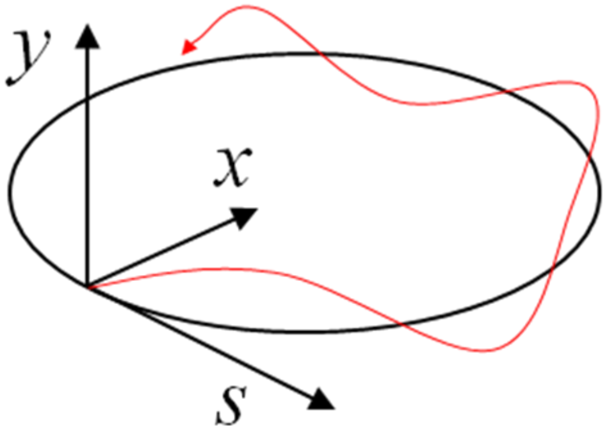
Summary of High-Intensity / High-Brightness Beam Physics Issues – FAST/IOTA Research

- Space-charge effects (Coulomb interaction inside the beam)
  - Particle losses
  - Beam quality (emittance) degradation
- Coherent instabilities
  - Very fast beam loss
  - Losses, emittance degradation
- Beam cooling
- Halo control
  - Halo formation
  - Halo collimation
- Beam diagnostics and control tools

IOTA Experiments

1. **Nonlinear Integrable Optics** – Experimental demonstration of NIO lattice in a practical accelerator
2. **Beam Cooling**
   - **Optical Stochastic Cooling** – Proof-of-principle demonstration
   - **Electron Cooling** – Advanced techniques
3. **Space Charge Compensation** – Suppression of SC-related effects in high intensity circular accelerators
   - Nonlinear Integrable Optics
   - Electron lenses
   - Electron columns
   - Circular betatron modes
4. **Quantum Physics** – Localization of single electron wave function

Beam Focusing in Accelerators



$$H = c\left[m^2c^2 + \left(\mathbf{p} - \frac{e}{c}\mathbf{A} \right)^2 \right]^{\frac{1}{2}} \qquad H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

$$K_{x,y}(s+C) = K_{x,y}(s)$$

- Equilibrium orbit – closed circular trajectory of the particle with ideally matched energy
- Beam – particles which have a spread in coordinates, momenta (both transverse x,y) and longitudinal (s)
  - Beam emittance – volume in phase space
- Need to contain beam particles
  - Focusing with Lorentz force from magnets and accelerating structures
    - Longitudinal focusing – synchrotron principle (Veksler 1944, McMillan 1945)

Strong Focusing - Limitations

- The key principle of everything we considered so far – linear focusing

$$H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

- What about higher order terms?
  - Imperfections in magnet construction
  - Chromatic aberrations ∝ quadrupole gradient
  - Coulomb self-interaction inside beams
  - E/M interaction of beam with environment (image charges, etc)
  - E/M interaction between beams
  - Intentionally introduced multipole magnets (e.g. sextupoles to correct chromaticity)

$$F \propto \frac{e}{(p_0 + \Delta p)c} \frac{\partial B_y}{\partial x} x$$

- All are aberrations to the initially decoupled system of two linear oscillators
  - Since the 60ies, thousands of papers on mitigation
  - Accelerator physics on crossroads of plasma, nonlinear dynamics, etc.

Aberrations of Linear Focusing

$$x'' + K_x(s)x = S(s)x^2 + O(s)x^3 + \cdots$$

- Nonlinearities result in dependence of oscillation frequency (tune) on amplitude
- Explicit time-dependence of multipole coefficients results in resonances
- Coupling between x and y further complicates the dynamics
- Ultimately, chaos and loss of stability
  - Beam quality degradation (blow-up)
  - Particle loss from accelerator
- We call this single particle stability or Dynamical Aperture

Collective Instabilities

- In addition to the single-particle chaos, the beam can become unstable as a whole if resonantly excited by external field or via self-interaction through environment
- These instabilities can be suppressed by
  1. External damping system – presently the most commonly used mechanism to keep the beam stable.
  2. Landau damping – the beam's own "immune system" related to the spread of betatron oscillation frequencies. The larger the spread, the more stable the beam is against collective instabilities.
     - **1965 Priceton-Stanford CBX: First mention of an 8-pole magnet**
       - Observed vertical resistive wall instability
       - With octupoles, increased beam current from ~5 to 500 mA
     - **CERN PS: In 1959 had 10 octupoles; not used until 1968**
       - At 10^{12} protons/pulse observed (1st time) head-tail instability. Octupoles helped.
       - Once understood, chromaticity jump at transition was developed using sextupoles.
       - More instabilities were discovered; helped by octupoles, fb
     - **LHC has 336 octupoles that run close to 500A to create 0.001 tune spread**
     - **FCC will require ~ 20,000 octupoles to retain stability**

Collective Instabilities

- In addition to the single-particle chaos, the beam can become unstable as a whole if resonantly excited by external field or via self-interaction through environment
- These instabilities can be suppressed by
  1. External damping system – presently the most commonly used mechanism to keep the beam stable.
  2. Landau damping – the beam's own "immune system" related to the spread of betatron oscillation frequencies. The larger the spread, the more stable the beam is against collective instabilities.
     - **1965 Priceton-Stanford CBX: First mention of an 8-pole magnet**
       - Observed vertical resistive wall instability
       - With octupoles, increased beam current from ~5 to 500 mA
     - **CERN PS: In 1959 had 10 octupoles; not used until 1968**
       - At 10^{12} protons/pulse observed (1st time) head-tail instability. Octupoles helped.
       - Once understood, chromaticity jump at transition was developed using sextupoles.
       - More instabilities were discovered; helped by octupoles, fb
     - **LHC has 336 octupoles that run close to 500A to create 0.001 tune spread**
     - **FCC will require ~ 20,000 octupoles to retain stability**

Nonlinear Integrable Optics

- We want to build an optical focusing system that
  a. Is strongly nonlinear = strong dependence of oscillation frequency on amplitude
  b. Is 2D integrable and stable
  c. Can be realized with magnetic fields in vacuum

- Mathematically, that means the system should
  – Possess two integrals of motion
  – Have steep Hamiltonian
  – Field potential satisfies the Laplace equation

- Practical benefits relevant to future HEP machines
  – Reduced chaos in single-particle motion
  – Strong immunity to collective instabilities via Landau damping

Nonlinear Integrable Optics Implementations at IOTA

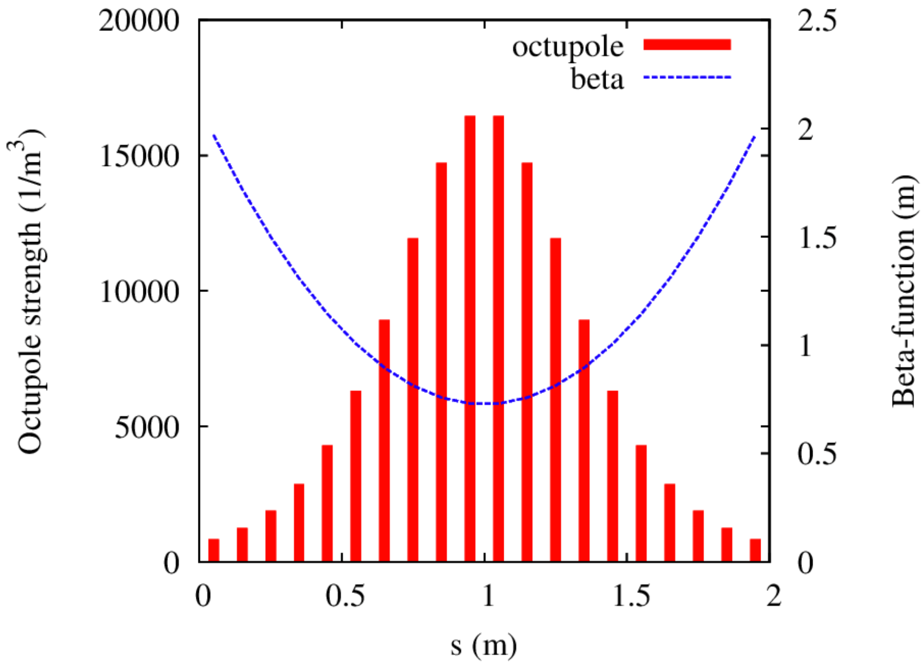
1. Henon-Heiles type system with octupoles
   - Provides one invariant (limited DA)
   - Can be implemented with common octupole magnets
2. Danilov-Nagaitsev system
   - Two invariants of the motion (infinite DA)
   - Requires unique magnet
3. 2D Expansion of McMillan mapping
   - Two invariants of the motion
   - Implementation with electron lens
   - The steepest Hamiltonian

Henon-Heiles Type Systems (N.Kuklev's Thesis)

- For example, build *V* with Octupoles

$$V(x,y,s)=\frac{\kappa}{\beta(s)^3}\left(\frac{x^4}{4}+\frac{y^4}{4}-\frac{3x^2y^2}{2}\right)$$

$$U=\kappa\left(\frac{x_N^4}{4}+\frac{y_N^4}{4}-\frac{3y_N^2x_N^2}{2}\right)$$



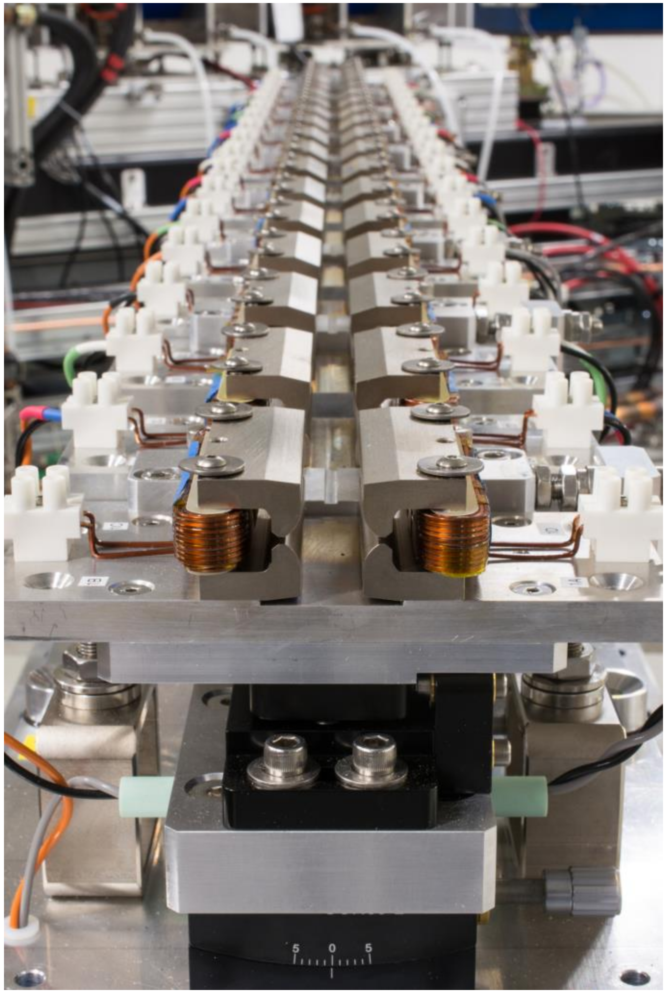
$$H=\frac{1}{2}(p_x^2+p_y^2)+\frac{1}{2}(x^2+y^2)+\frac{k}{4}\left(x^4+y^4-6x^2y^2\right)$$

- Only one integral of motion – *H*
- Tune spread limited to ~12% of Q_0

S. Antipov, S. Nagaitsev, A. Valishev, JINST 12 (2017) no.04, P04008

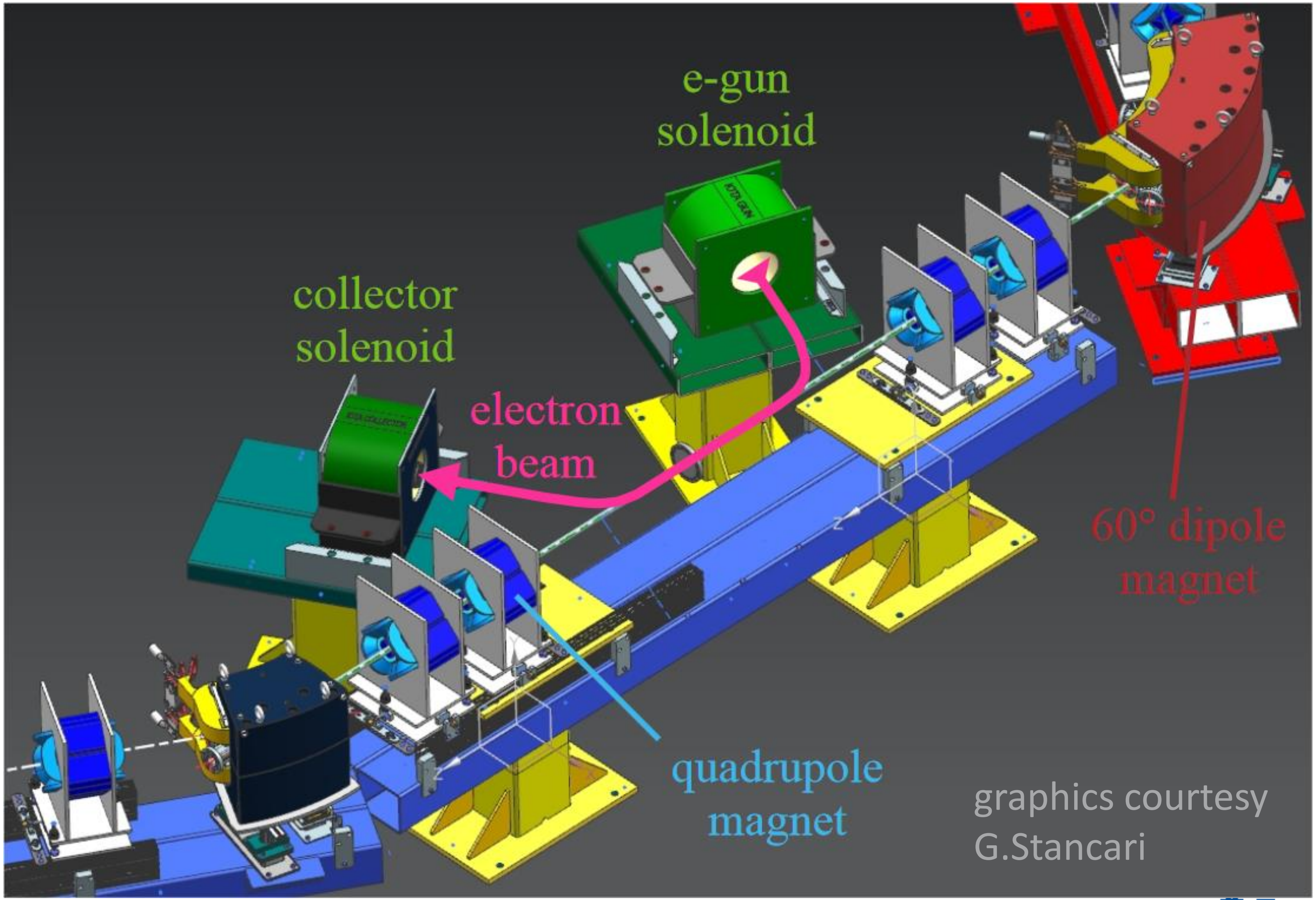
Nonlinear Optics Magnet

RadiaBeam Technologies



V. Danilov, S. Nagaitsev,
Phys. Rev. Spec. Topics –Accel. Beams.
13, 084002 (2010)

Electron lens in IOTA



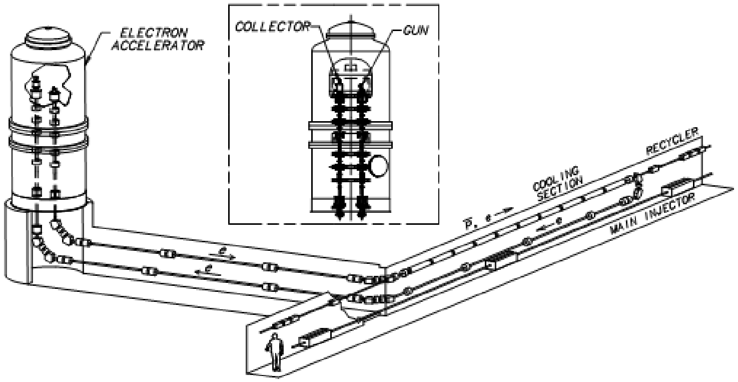
graphics courtesy G.Stancari

IOTA Physics

1. **Nonlinear Integrable Optics** – Experimental demonstration of NIO lattice in a practical accelerator
2. **Beam Cooling**
   - **Optical Stochastic Cooling** – Proof-of-principle demonstration
   - **Electron Cooling** – Advanced techniques
3. **Space Charge Compensation** – Suppression of SC-related effects in high intensity circular accelerators
   - Nonlinear Integrable Optics
   - Electron lenses
   - Electron columns
   - Circular betatron modes
4. **Quantum Physics** – Localization of single electron wave function

Beam Cooling in IOTA

- Fermilab is a world-recognized leader in beam cooling:
  - Both stochastic and electron cooling systems in the past
  - World’s highest energy electron cooler in operation, 2005-2011



PRL 96, 044801, 2006

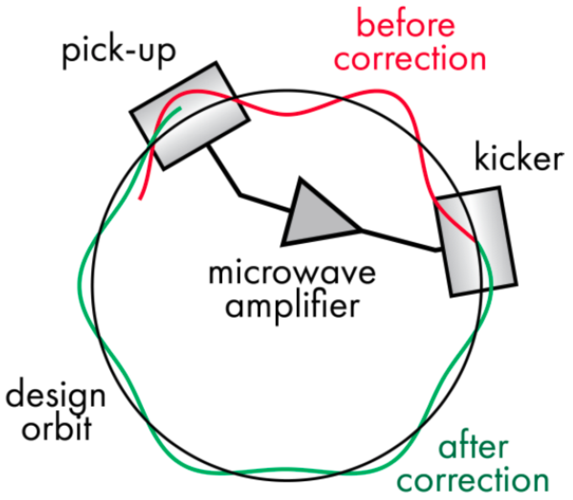
- Optical Stochastic Cooling
- Two cooling concepts for Electron Ion Collider
  - Development of Innovative, High-energy, Magnetized Electron Cooling for an EIC
  - Ring-based high-energy electron cooler

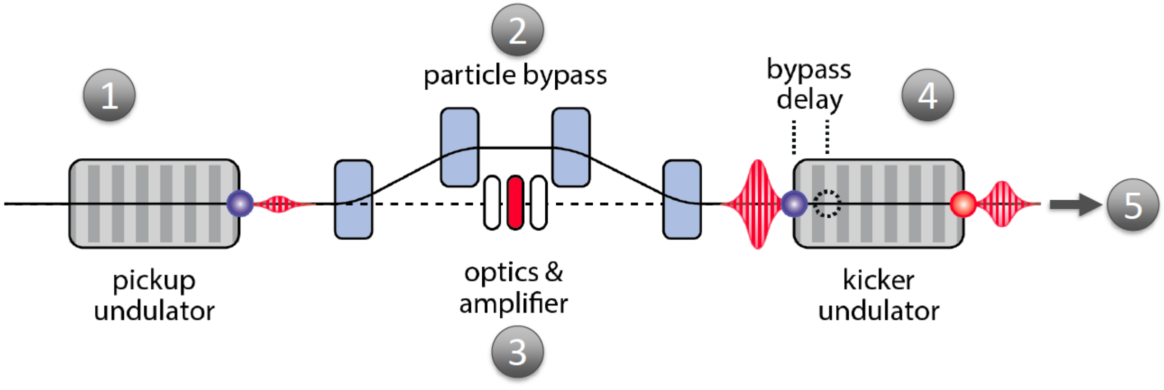
Optical Stochastic Cooling

from ~10 cm to 1 um wavelength

A.Mikhailichkenko, M.Zolotorev
Phys. Rev. Lett. 71 (25), p. 4146 (1993)

van der Meer, 1980's





1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates over many turns

$$\frac{1}{\tau}=\frac{2W}{N}(\underset{\text{cooling}}{2g}-\underset{\text{heating}}{g^2})$$

- OSC promises new cooling scheme of relevance for high energy, high brightness proton bunches
- IOTA is designed to accommodate the OSC insert and proof-of-principle study with e-

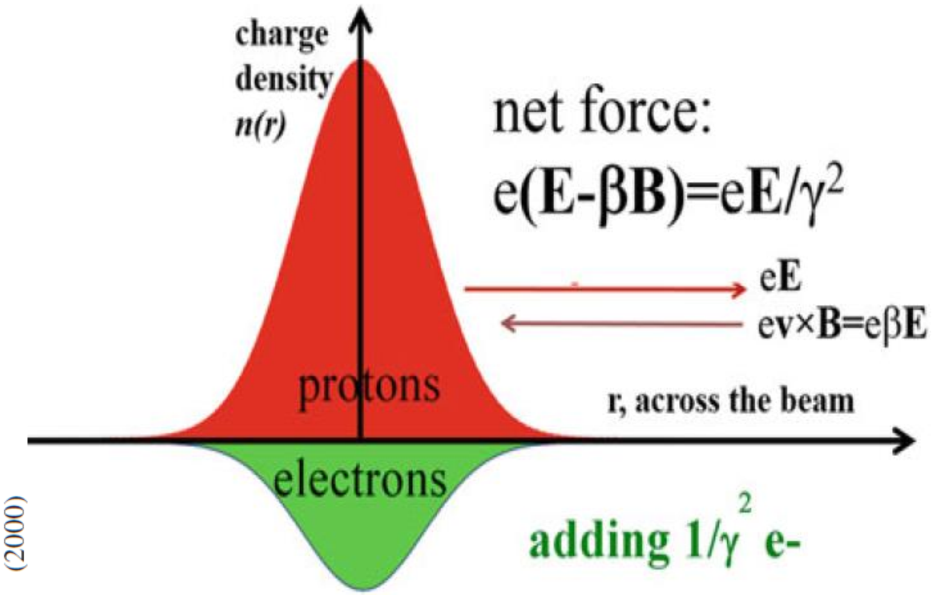
graphics courtesy
J.Jarvis

IOTA Physics

1. **Nonlinear Integrable Optics** – Experimental demonstration of NIO lattice in a practical accelerator
2. **Beam Cooling**
   - **Optical Stochastic Cooling** – Proof-of-principle demonstration
   - **Electron Cooling** – Advanced techniques
3. **Space Charge Compensation** – Suppression of SC-related effects in high intensity circular accelerators
   - Nonlinear Integrable Optics
   - Electron lenses
   - Electron columns
   - Circular betatron modes

- **More –** QED,

Proton Space-Charge: Compensated by Electrons



net force:

$e(E-\beta B)=eE/\gamma^2$

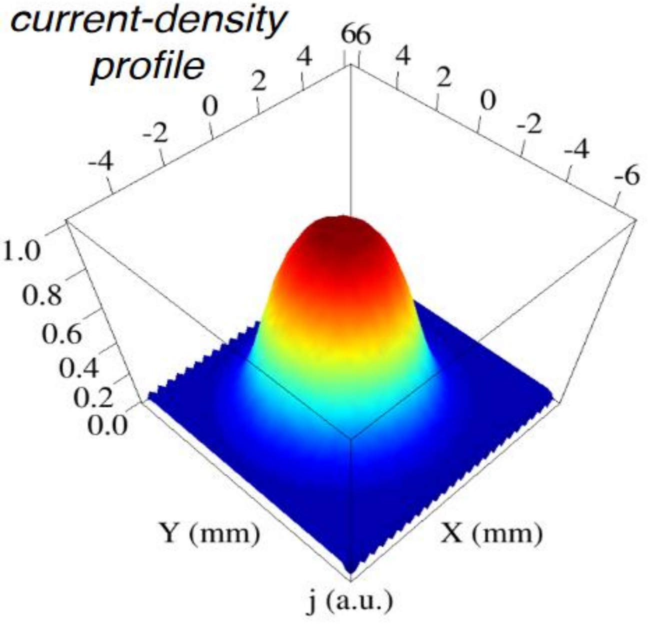
adding $1/\gamma^2$ e-

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

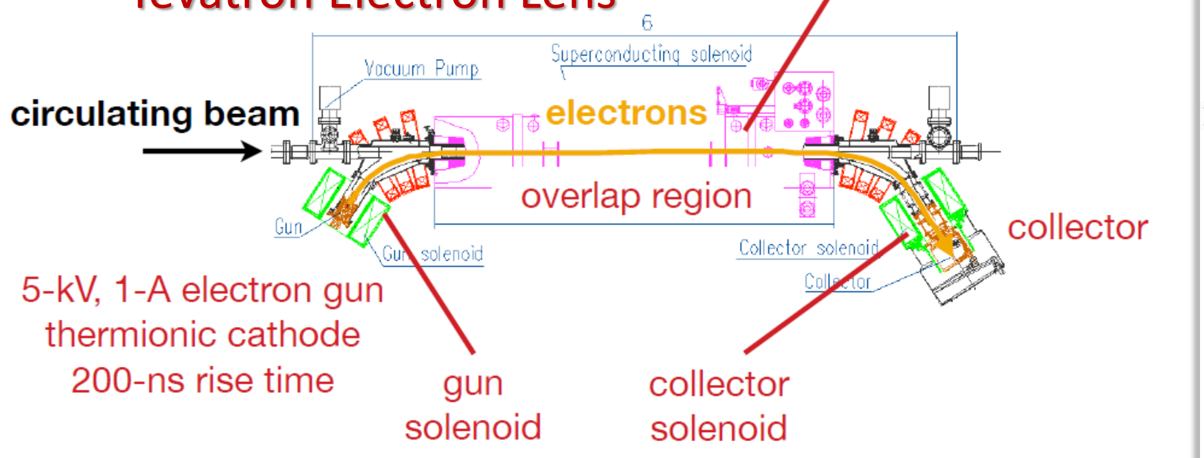

side view


top view

measured current-density profile



Tevatron Electron Lens



main solenoid

circulating beam

electrons

overlap region

collector

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

gun solenoid

collector solenoid

Beam Phase Space Manipulation in FAST e- linac

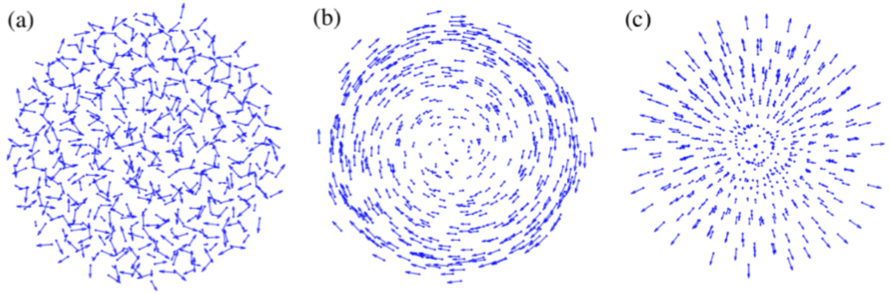
- Experiments on conversion of magnetized beam into asymmetric-emittance beams

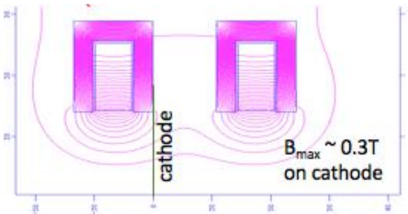
$$L = \gamma m r^2 \dot{\theta} + \frac{1}{2} e B_z(z) r^2$$

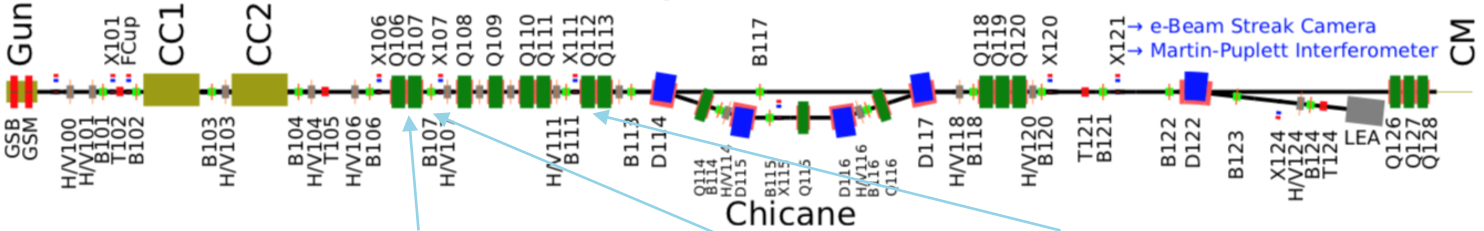
$$\mathcal{L} = L/2p_z$$

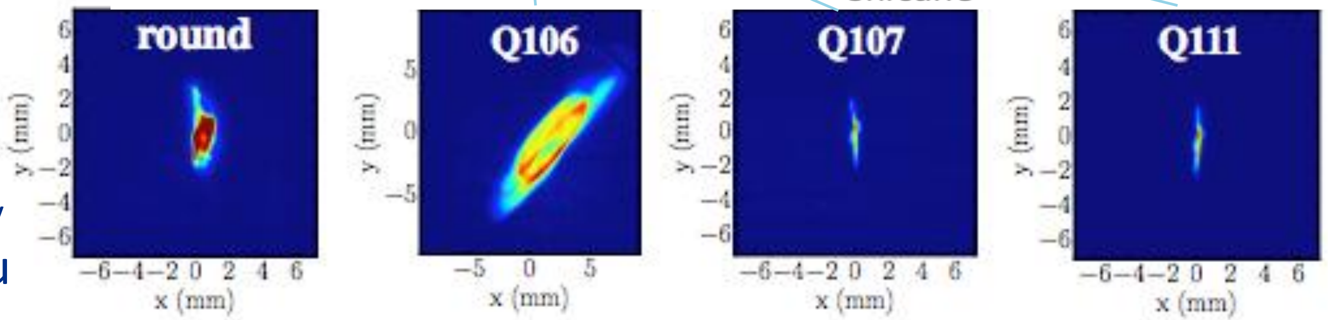
$$\epsilon_\pm = \sqrt{\epsilon_u^2 + \mathcal{L}^2} \pm \mathcal{L}$$

$$\epsilon_+ \approx 2\mathcal{L}; \quad \epsilon_- \approx \frac{\epsilon_u^2}{2\mathcal{L}}$$





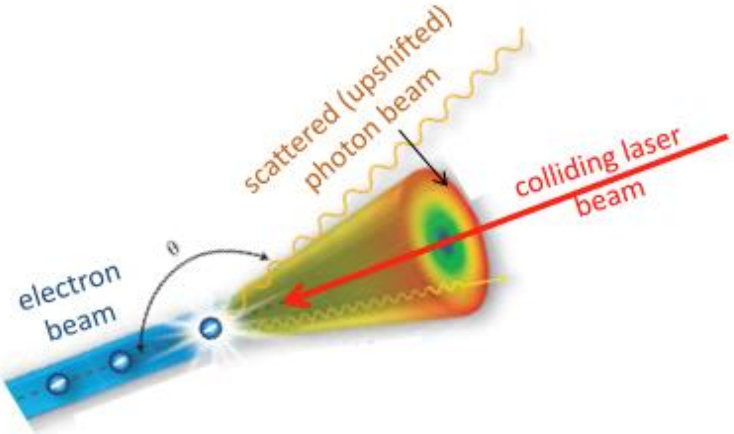

FAST injector beamline

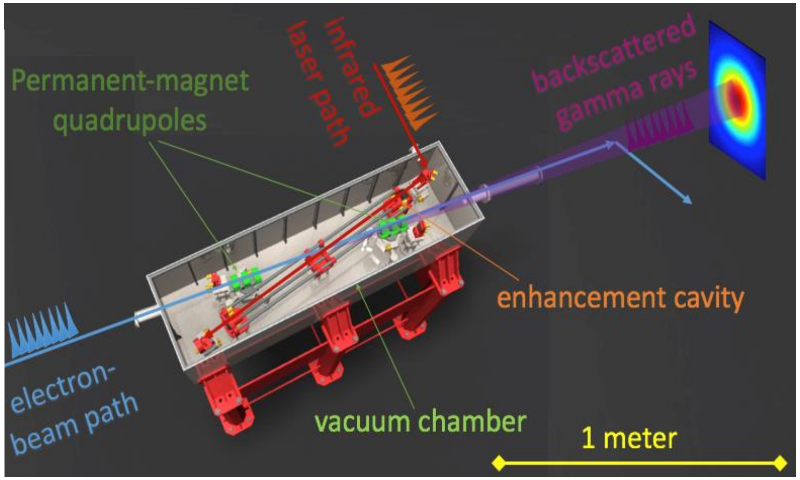


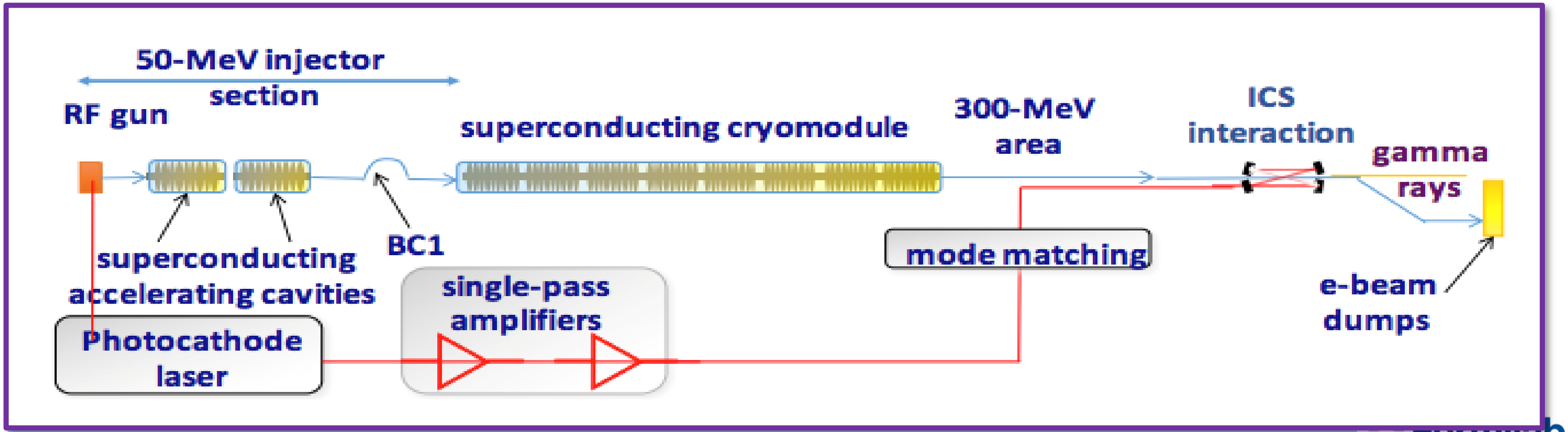
graphics courtesy
A.Halavanau

Beam Radiation – High-Flux γ-Ray Source via ICS

Combining e- linac beam with high-rep-rate laser



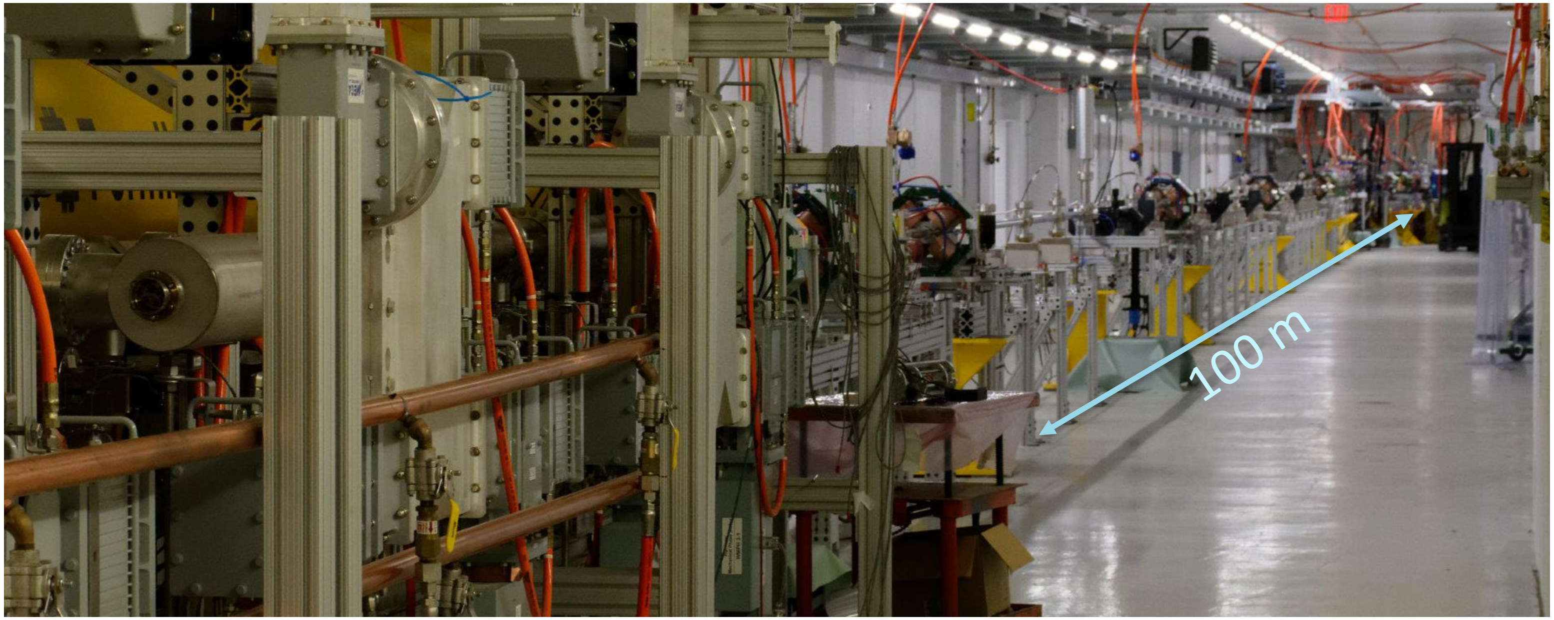




graphics courtesy P.Piot

Current Status

FAST Electron Linac Completed in 2017



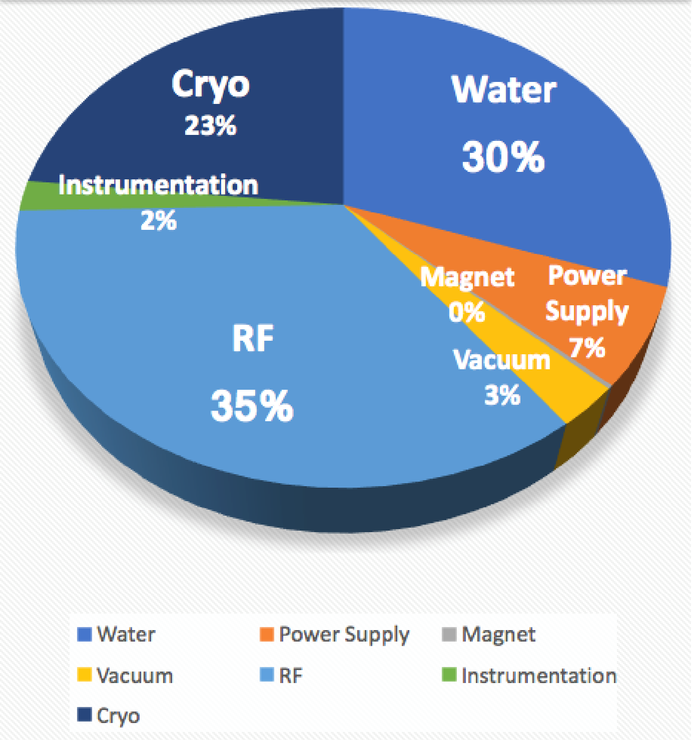
- 100m of High Energy FAST beam line constructed
- **19 October** – for the first time, beam accelerated through ILC-type cryomodule to energy **150 MeV**
  - Propagated to point of injection to IOTA
- **15 November** – beam accelerated to **301 MeV**
  - **World record ILC-type cryomodule acceleration of 255 MeV**
  - Over 31.5 MV/m

2 Months of FAST Linac Operations in 2017

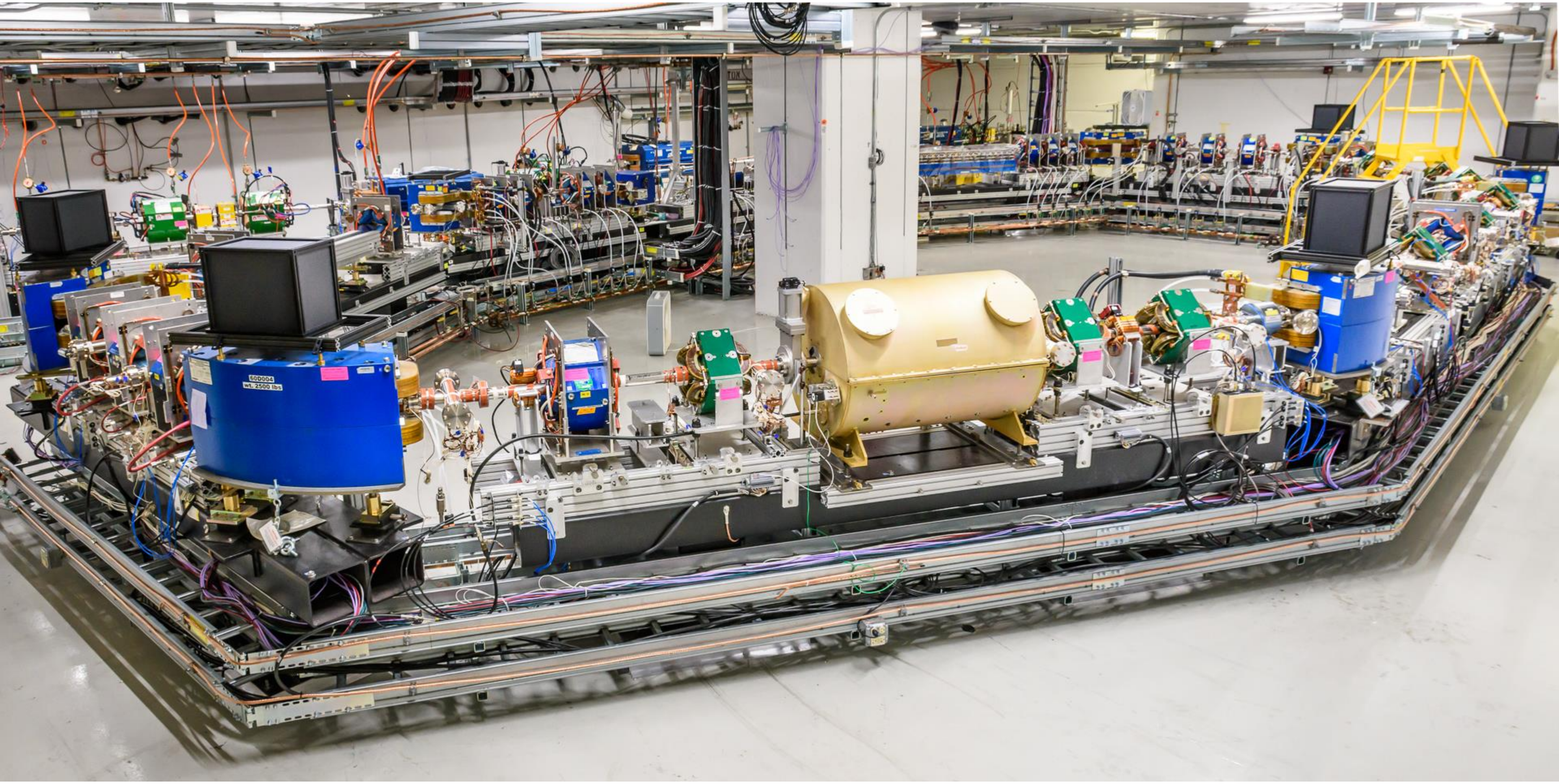
- **Primary goal – IOTA injector commissioning**
  - Acceleration in CM-2 to 150MeV
  - Instrumentation
  - Machine Protection System
  - Machine stability and reproducibility
  - Beam line tuning for injection to IOTA
- **Achievement of 300 MeV beam in SRF linac**
  - Conditioning and phasing of cavities
  - Low-Level RF tuning
- **Parasitically – collaboration-driven experimental program**

Overal uptime 85.6% normalized to planned hours of operation (2 shifts/day)

Downtime contributions



IOTA Construction Completed 7/31/2018



IOTA Commissioning

- First beam circulation – August 21
  - Linac: Gun+CC1+CC2 ~~CM2~~ ⇒ Injection energy of 47 MeV
  - IOTA: ~~RF~~ ⇒ beam lifetime limited by SR losses
    - SR damping time 20s
    - Expected circulation time ~50,000 turns = 75 ms
    - Observed 40ms
- Commissioning at nominal energy – October 9-
  - 100MeV beam captured in RF on October 16
  - Initial beam lifetime ~10 min
- Physics run November-January

Collaboration

- Beam physics calculations are critical for success of IOTA/FAST program
- We rely on collaborators in many aspects
  - RadiaSoft – NIO and space-charge, Synergia
  - LBNL – NIO, space-charge, Impact-z, Warp (C.Mitchell talk Wed.)
  - NIU – NIO, Radiation studies, COSY infinity (B.Erdelyi talk this afternoon)
  - UMD – NIO (K.Ruisard talk Tue.)
  - BINP (single-particle simulations, Lifetrac)

Summary

- Fermilab's FAST/IOTA is a flexible machine uniquely positioned to advance novel accelerator R&D
  - Nonlinear integrable optics
  - Space-charge effects and their suppression
  - Advanced beam cooling methods
  - High brightness beams and radiation sources
  - …
- Many opportunities for collaboration and training
  - Software for beam physics computations
- IOTA is entering first physics run
  - Commissioning started in Aug. 2018
  - Research Nov. 2018 – Jan. 2019