Accelerator expertise at Fermilab
and EIC - 10 reasons to call Chicago

Vladimir SHILTSEV , Fermilab

EIC Collaboration Meeting, October 10-12, 2017

Fermilab is the US leading accelerator laboratory

Our expertise is based on 5 decades of experience in design, construction, operation and upgrades of particle accelerators for High Energy Physics

In particular, in colliders, our knowledge and expertise is upon:

1. **Tevatron Collider:** design, SC and PM magnet technology, upgrades, collimation, electron lenses, electron cooling, electron cloud, stochastic cooling, beam-beam, instabilities, diagnostics, operation
2. **LHC contributions**: SC IR magnets, instrumentation, irradiation and collimation
3. **LARP/High Luminosity LHC**: SC IR magnets, SC RF CC, e-lenses
4. **MAP:** SC magnets, NC RF, advanced optics, ionization cooling, MDI
5. R&D and design work on next generation colliders **VLHC, ILC, FCC:** SC RF, optics, space-charge, beam-beam, Landau e-lenses, collimation, MDI, polarization

Now - US HEP Community Plan (“*P5-2014*”)

	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 factory*	Higher-energy upgrade	Multi-TeV collider*

***dependent on how physics unfolds*

Accelerator R&D Thrusts:

- Accelerator and Beam Physics
  - Experimental R&D at IOTA/FAST
  - Theory, modeling & studies
- MW+ Targetry R&D
- High-Field Magnets and Materials
- SRF Accelerator Technology

HEPAP GARD Plan (2015)

Topics of Relevance to EIC

- Spin Dynamics
- Optics : IR and control
- Shielding, collimation and MDI
- Beam-beam and mitigation
- Electron cloud and instability simulations
- Cooling : design , systems
- SRF development
- SC magnet development
- Electron photoinjectors and tests at FAST
- Experimental R&D at IOTA

#1: Spin Dynamics (see also Eliana's talk Tuesday)

Fermilab contribution to eRHIC studies: achievable polarization in the eRHIC storage ring. It determines the time between refills.

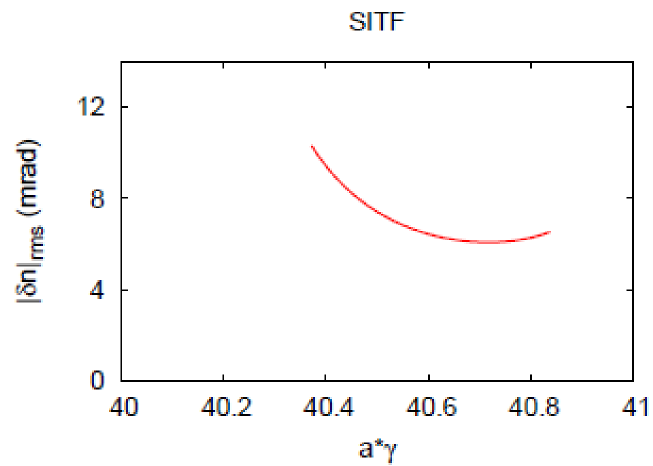
Two levels of contribution

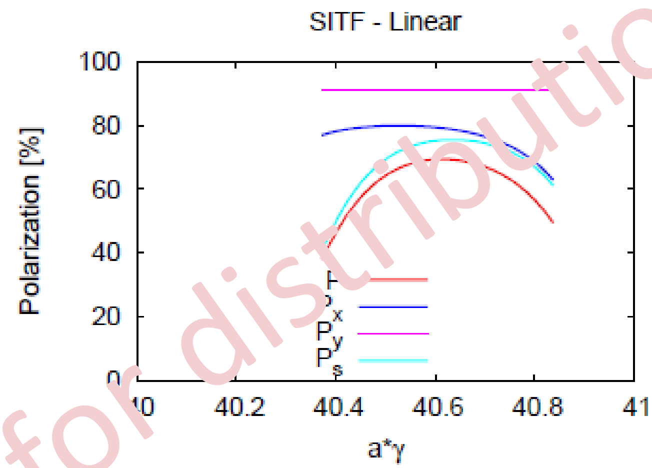
- Optics simulations
  - validation of optics from the Polarization point of view
  - simulations in the presence of misalignments
  - assess effect of corrections
- Suggestions on maintaining high level of Polarization routinely (cfr. HERAe experience)

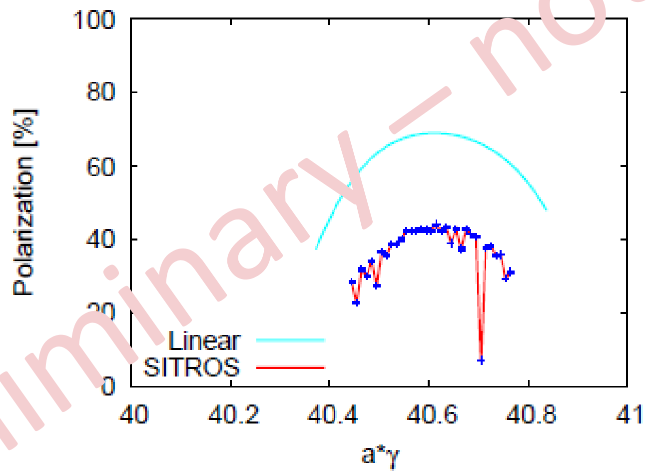
Tools for polarization simulations: SITROS (by J. Kewisch), BMAD (by D. Sagan). SITROS has been used for HERAe for which delivered sensible results in fairly good agreement with observations.

Promising results – more work to follow

Preliminary results for a not yet fully optimized eRHIC storage ring optics w/o misalignments:







Solenoids settings fixed at 18 GeV.

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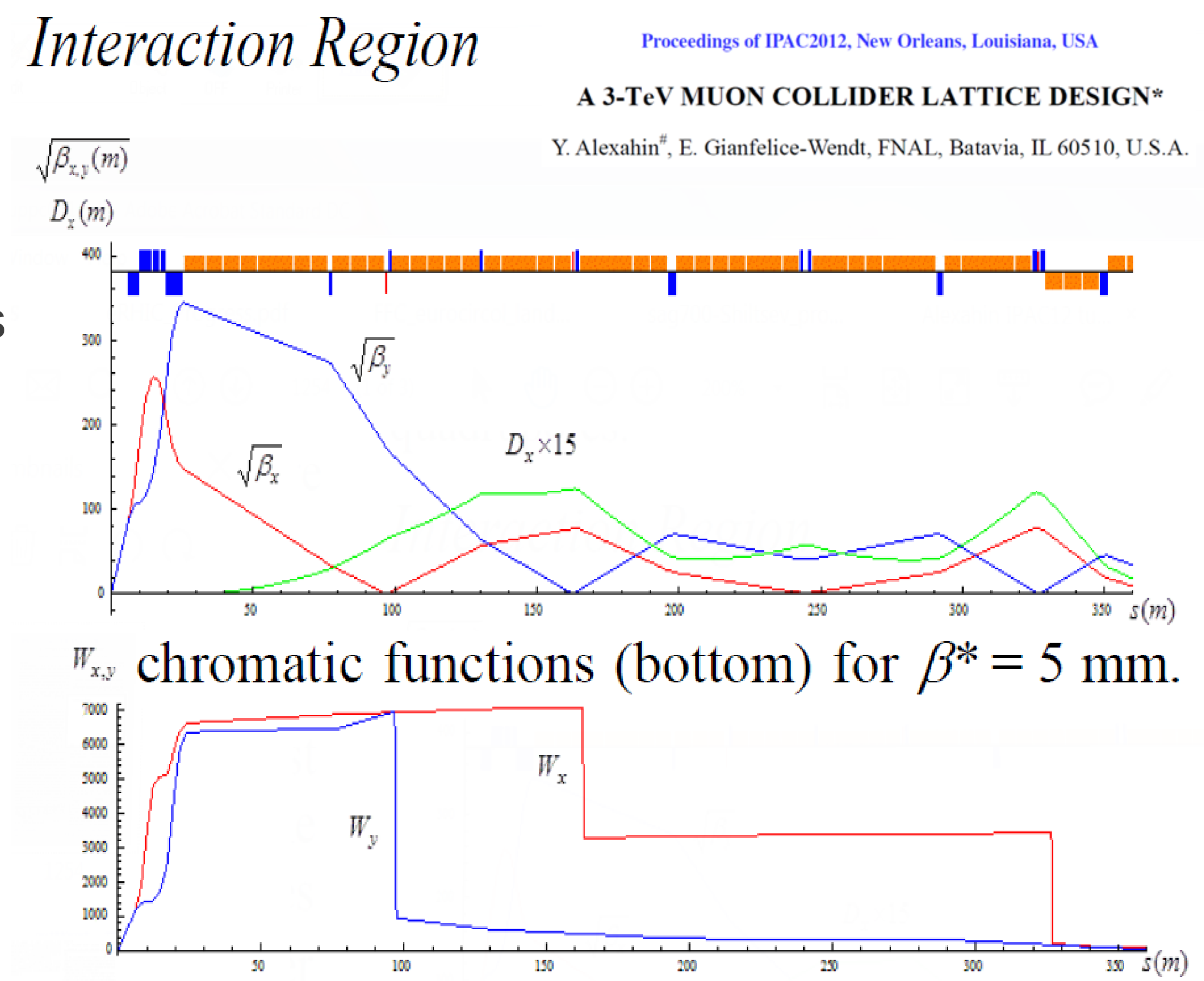
#2: Advanced IR Optics (Yu.Alexahin, D.Neuffer, et al)

Practical collider optics/IR designs:

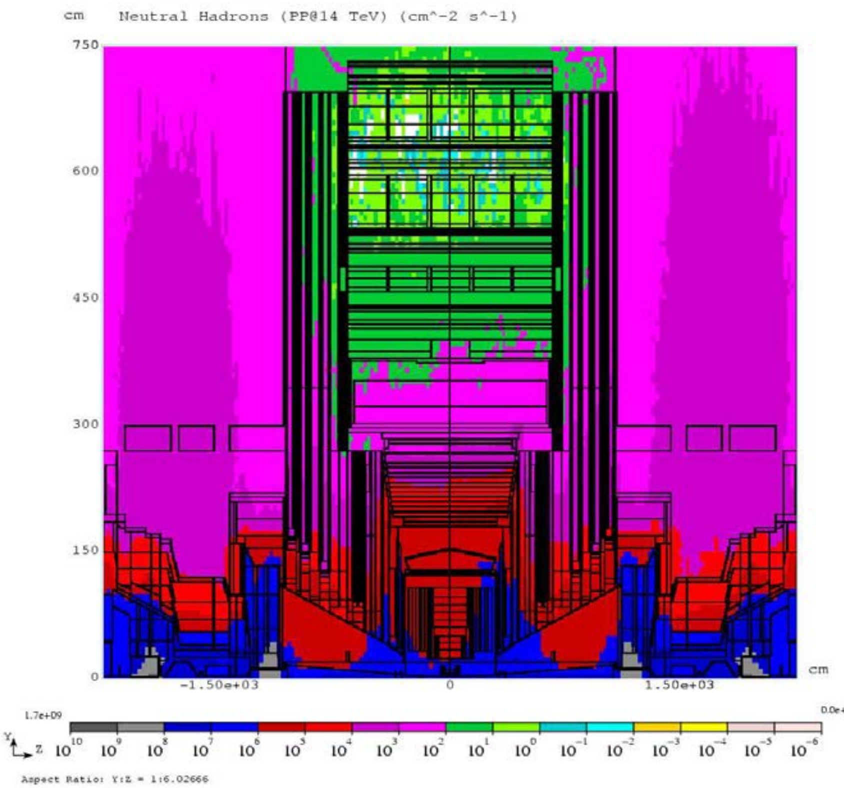
- Tevatron (many iterations)
- LHC/HL-LHC
- *ee* & *μμ* Higgs factories
- Muon Collider
- Real-life complications:
  - Chromatic corrections
  - Dynamic aperture
  - Neutrino radiation
  - Detector background
  - Magnet irradiation by debris
  - Real magnets/errs



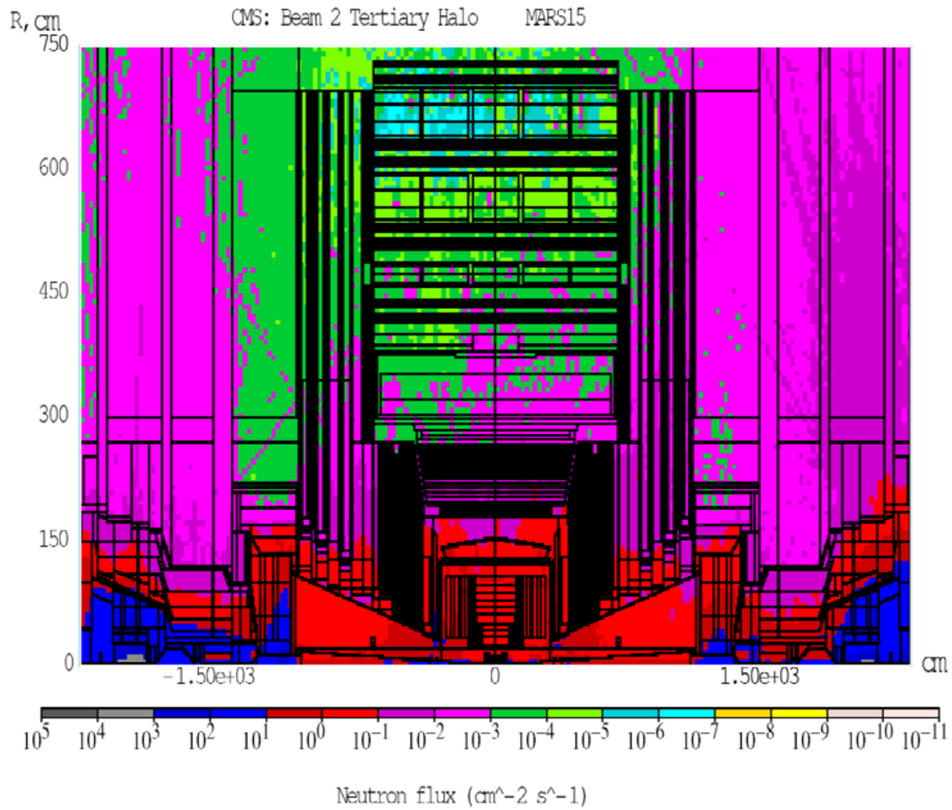
#3: Machine-Detector Interface and Detector Background MARS15 Modeling (N.Mokhov et al)

LHC pp *vs* Halo: Neutron Flux in CMS

pp "EIC: Heavy Ion Side"

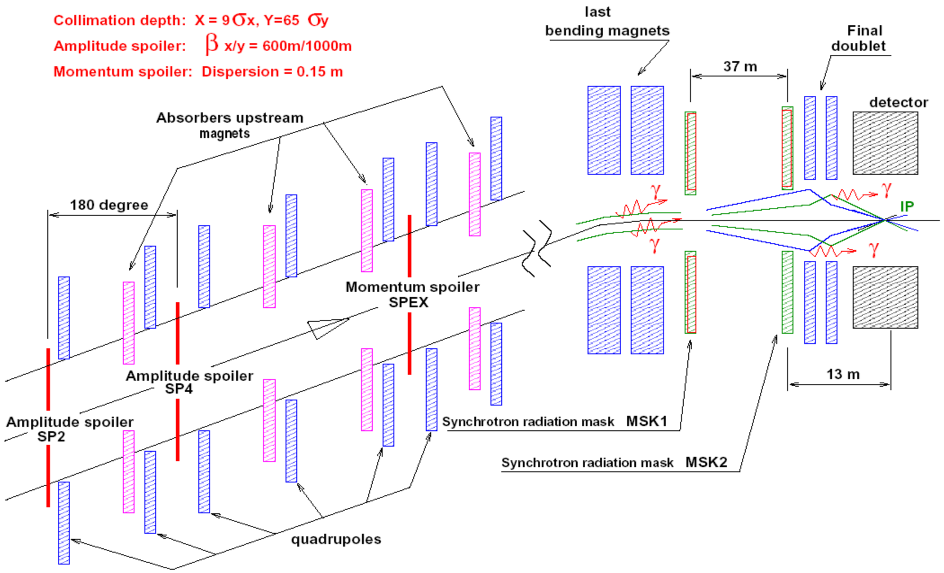


Machine-induced background (MIB)

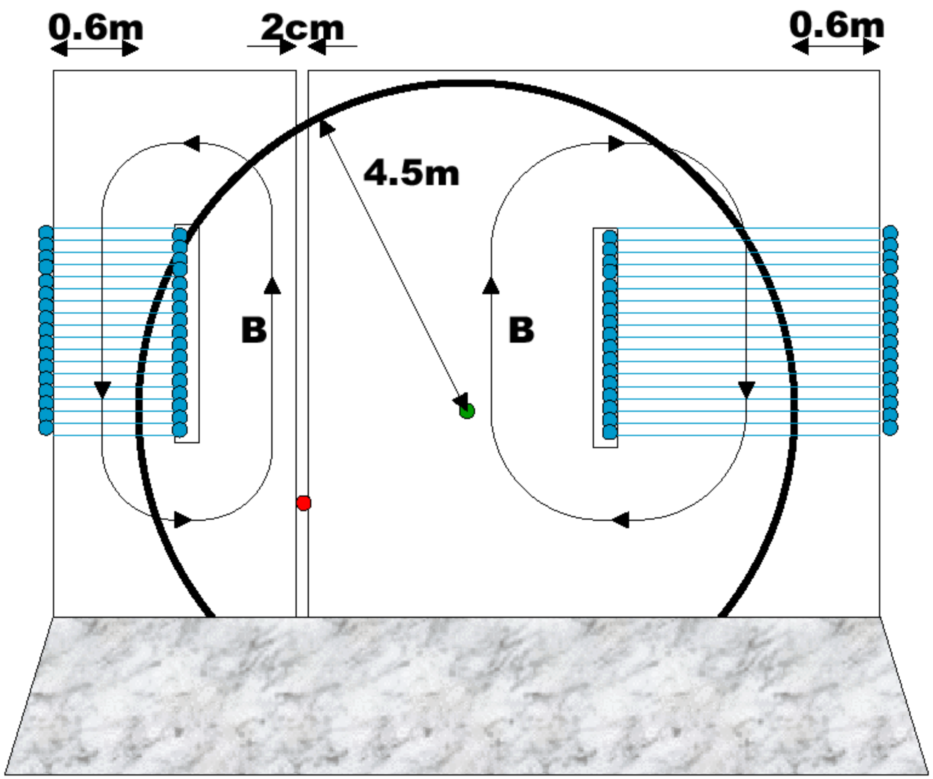


- Barrel Si tracker at r=4 cm: Φ_n**(pp) ≈ 10**^{5} Φ_n**(MIB**$_{total}$**), but can differ by only a factor of 10 or so at startup conditions**

MARS ILC BDS:
Collimation System and Magnetic Spoilers

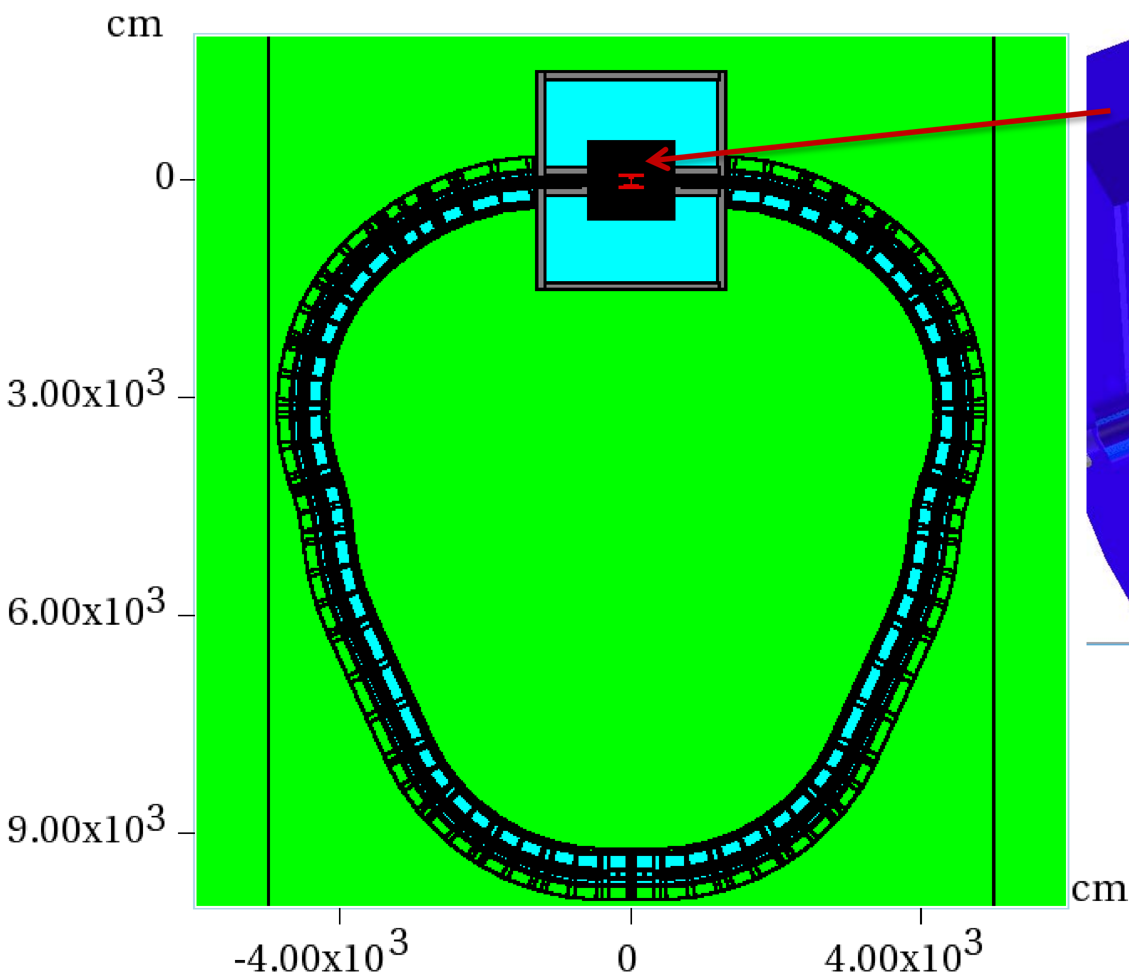


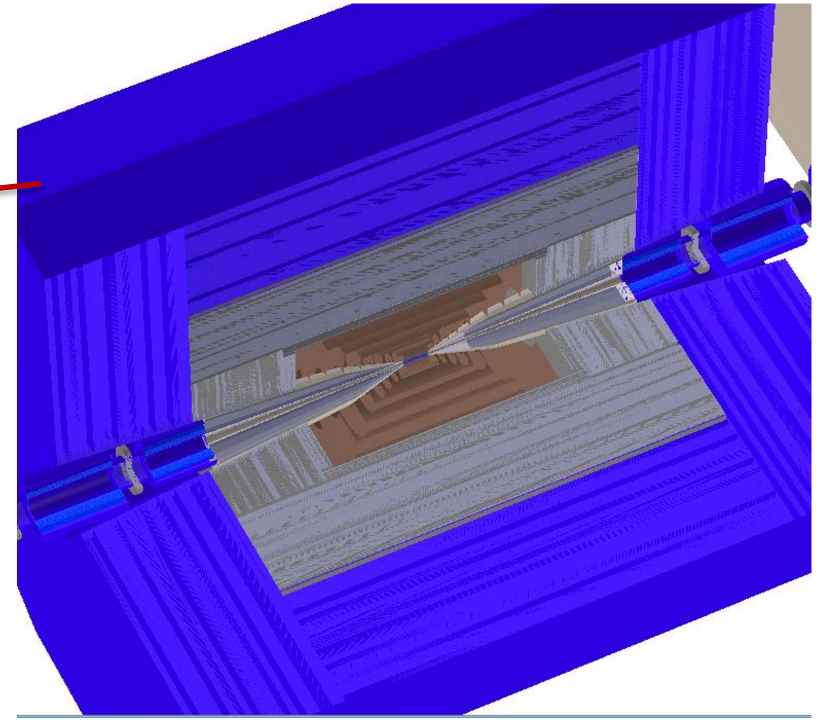
Thick steel 1.5-T magnetic wall sealing tunnel x-section, to spray the muons out of the tunnel



"EIC: Electron Side"

MARS15 Model of $\mu+\mu-$ Higgs Factory





MARS model of SiD-like detector with CMS upgrade-type tracker

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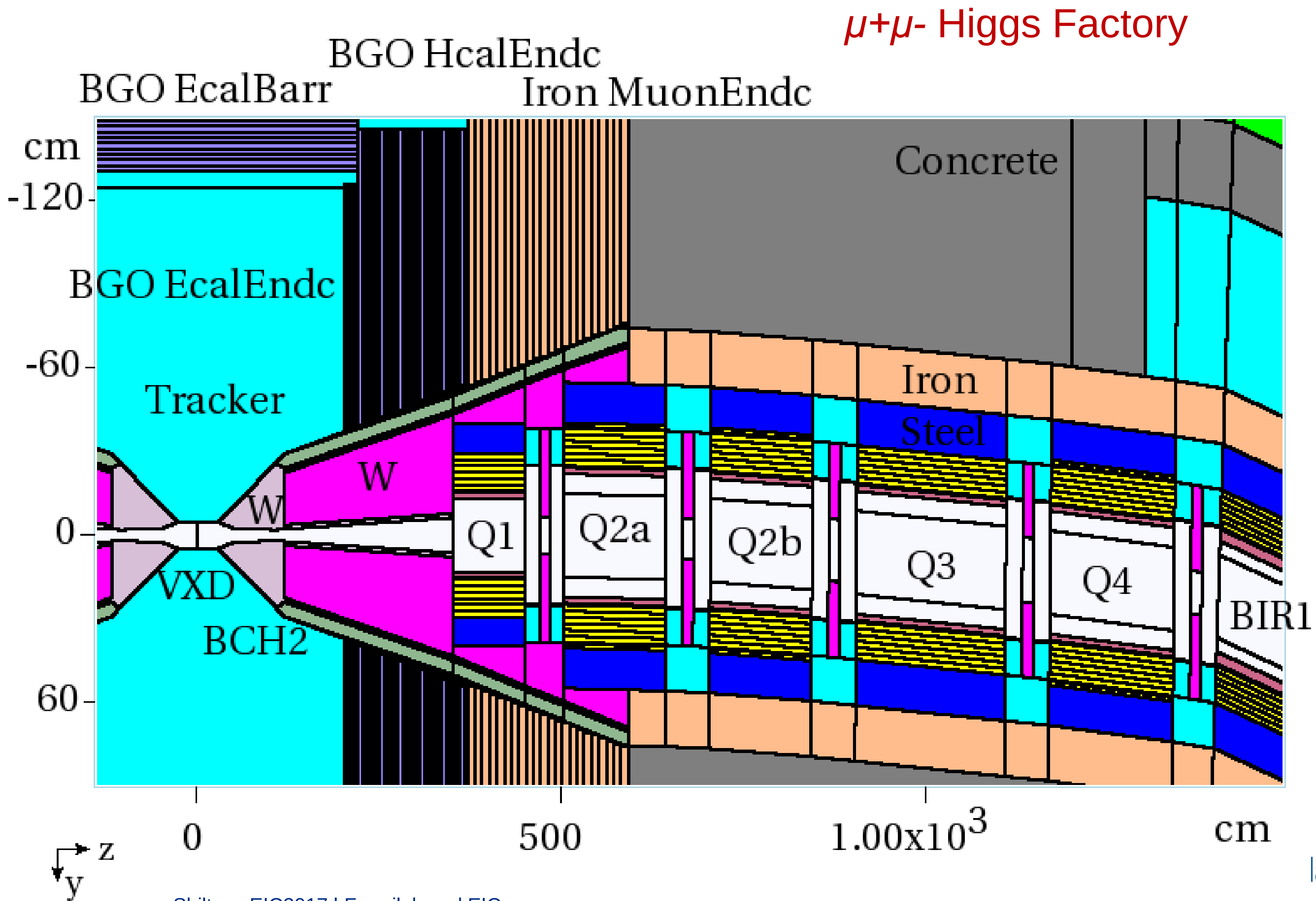
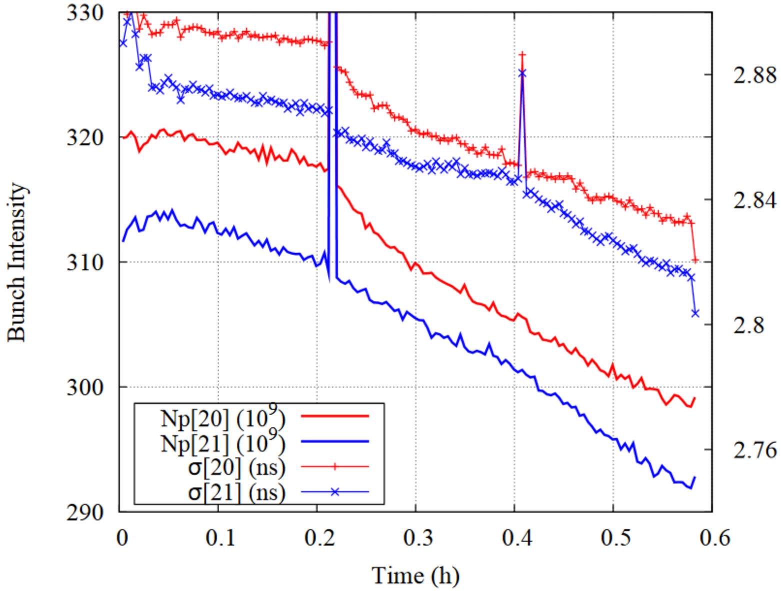
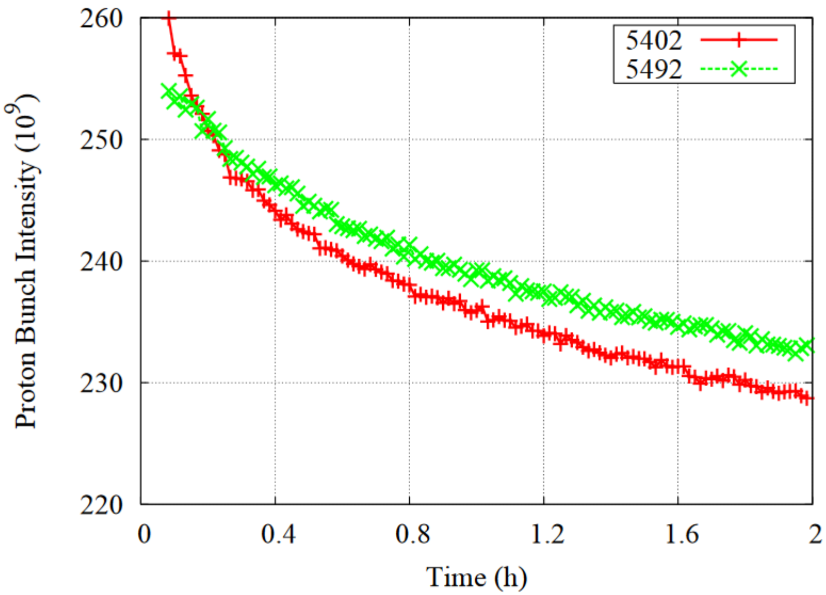
MARS15 Design & Optimization of MDI



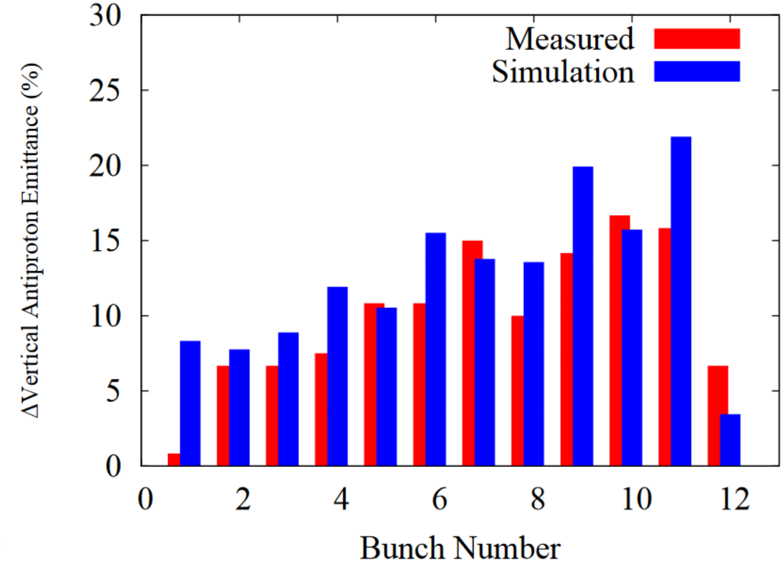
#4: Beam-beam and e-lenses (A.Valishev, et al)

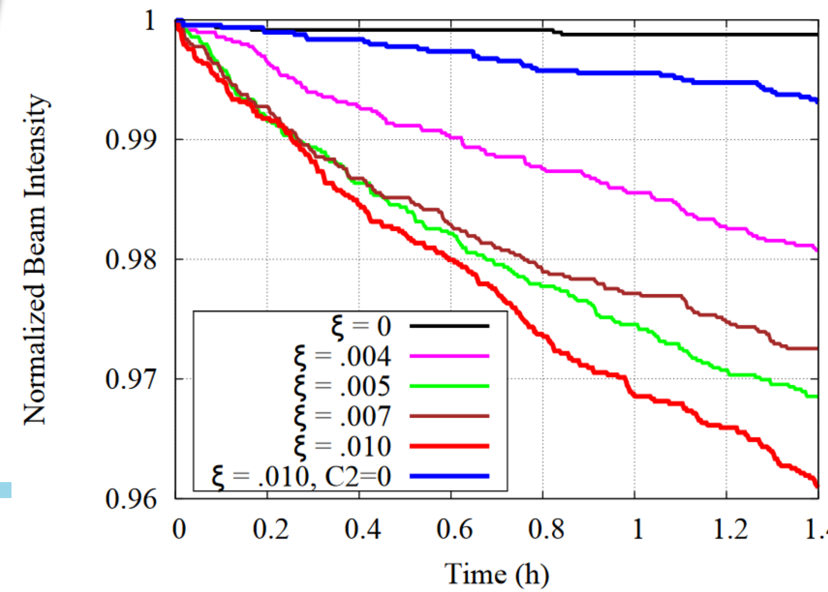
Tevatron stores





Simulated Tevatron stores



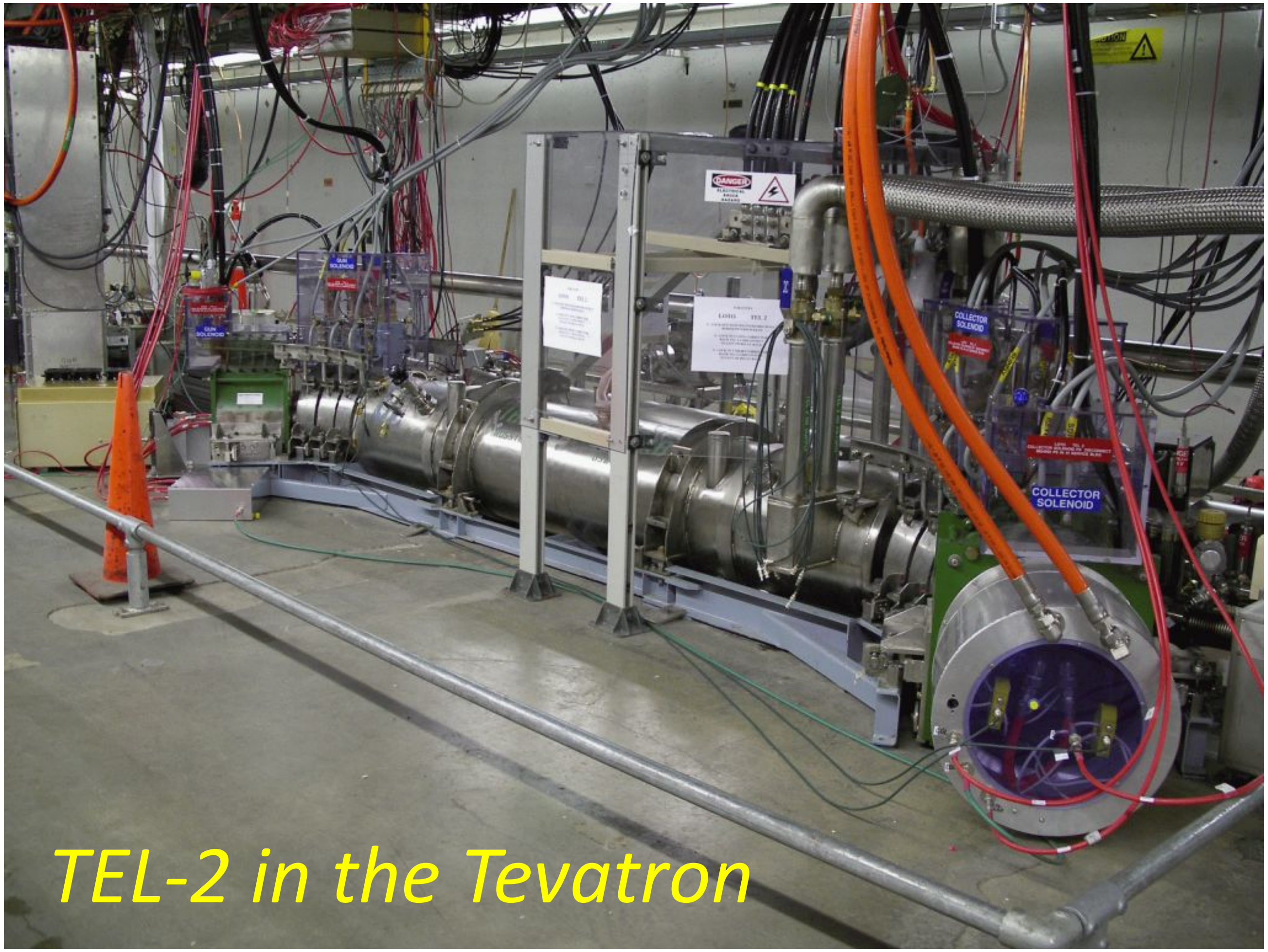


Electron Lenses (G.Stancari, V.Shiltsev, et al)

"Swiss knife"

e-lenses for:

- Long-range beam-beam compensation
- Head-on BBC
- Hollow beam collimation
- Landau damping
- Space-charge compensation



* Experimental studies of e-lens in IOTA (see below)

#5: Accelerator Modeling/Simulations/Tools

Synergia: self-consistent 3D Particle-in-cell accelerator simulation C++ code developed at Fermilab

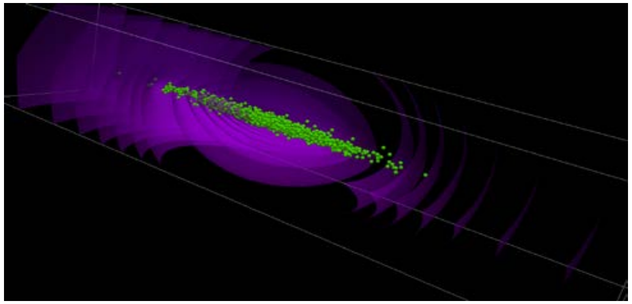
- Specifically to simulate collective effects in accelerators and to take advantage of supercomputers *when available*
- Space charge, impedance, nonlinear single-particle optics
- Collective effects can be extended
- Single bunch, multi-bunch, multi-train simulations

Synergia is being developed as part of the SciDAC ComPASS4 collaboration, which Fermilab leads

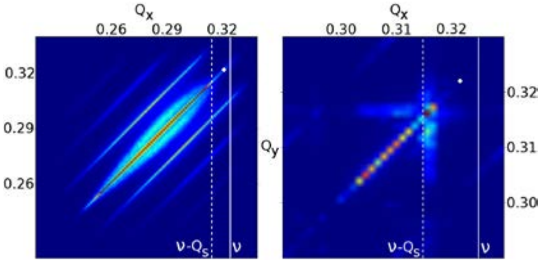
https://compass.fnal.gov

Synergia simulation activities at Fermilab include:

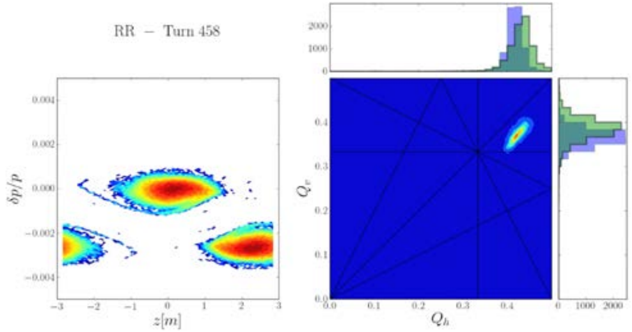
- Fermilab Booster space charge and impedance
- Fermilab Main Injector and Recycler space charge, impedance, slip stacking, transition Xing
- IOTA space charge, impedance and more



Synergia particle-in-cell simulation



Landau damping study



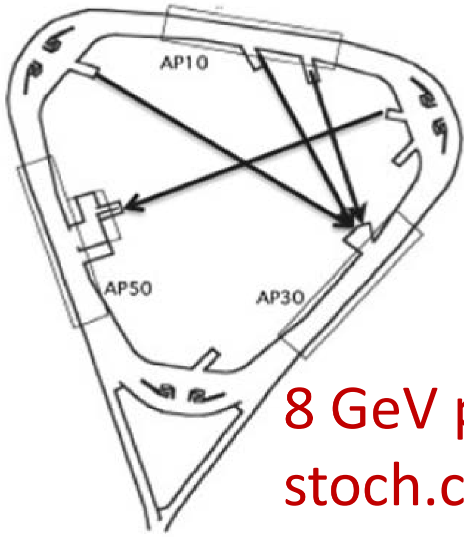
Slip-stacking phase space and tune footprint

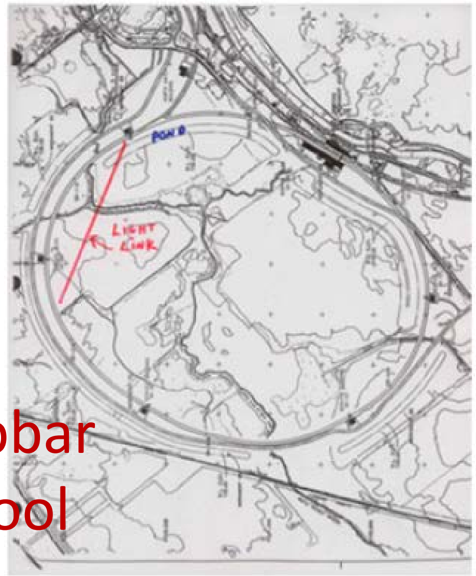
#6: Cooling

- Electron cooling
- Stochastic cooling
- Ionization cooling
- Cooling by instability
- Optical stochastic cooling

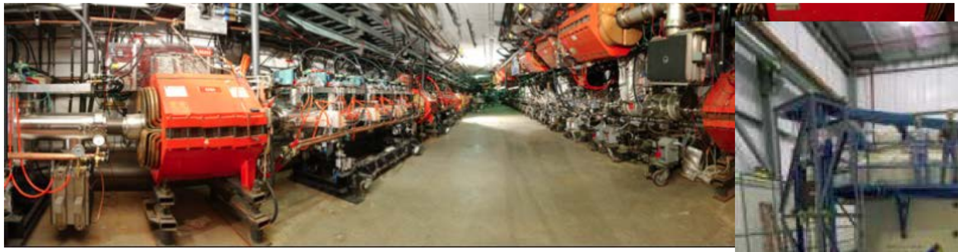
Fermilab could take on the entire EIC hadron cooling system:

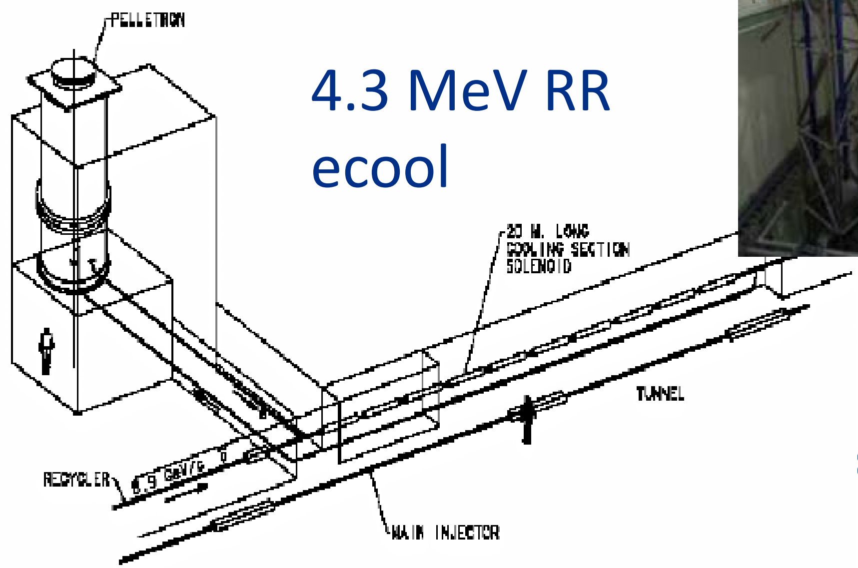
- *design, prototyping*
- *construction, commiss’g*





8 GeV pbar
stoch.cool

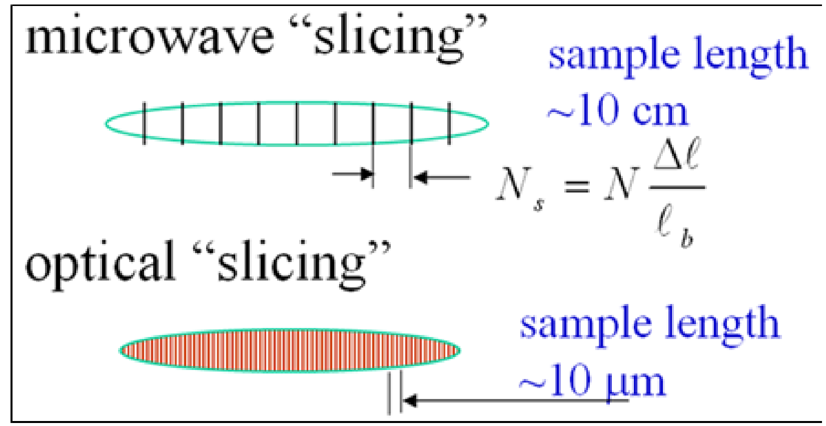




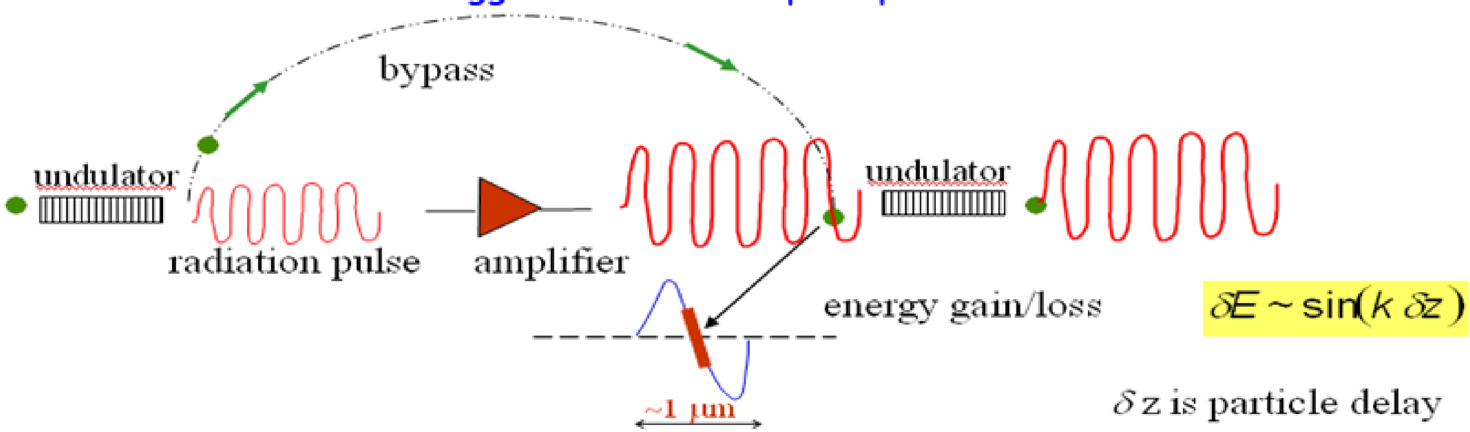
4.3 MeV RR
ecool

Optical Stochastic Cooling (V.Lebedev, et al)

- OSC was suggested by Zolotorev, Zholents and Mikhailichenko (1994)
- OSC obeys the same principles as the microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~ 10^{14} Hz
  - can deliver damping rates ~3 orders of magnitude larger than usual (microwave) stochastic cooling



- Pickup and kicker must work in the optical range and support the same bandwidth as the amplifier
  - Undulators were suggested for both pickups and kickers



- **Test of OSC will be carried out at IOTA ring in Fermilab**
  - Its results and developed technology can be scaled to a real hadron collider

EIC: OSCooling Parameters

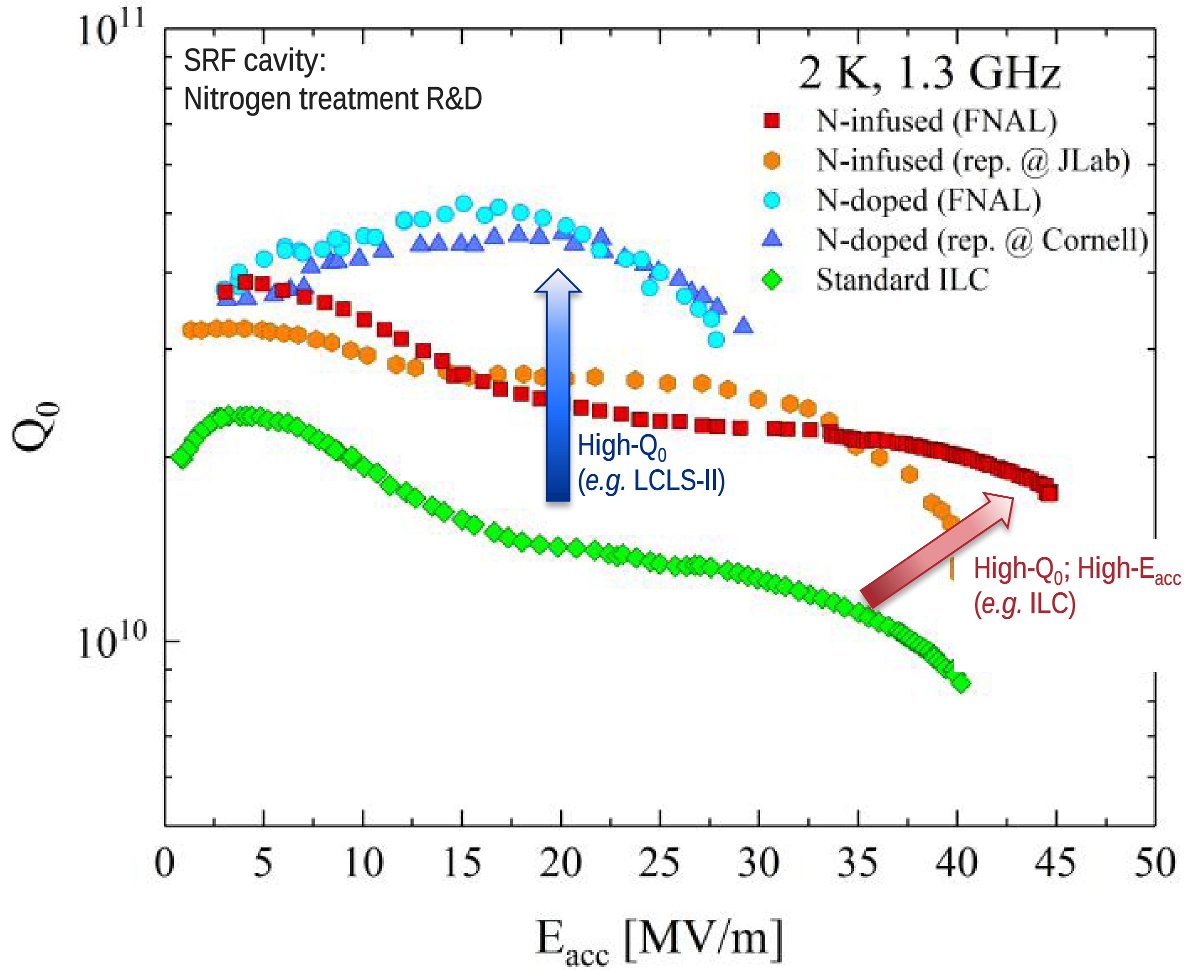
Major parameters for the IOTA OSC and tentative parameters for eRHIC OSC

	IOTA	RHIC
Particle type	electrons	protons
Energy	100 MeV	250 GeV
Relativistic factor, γ	196.7	267.5
Rms momentum spread, σ_p	$1.06 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$
Hor. rms emittance, ε, nm	2.62	0.6
Delay in the cooling chicane, Δs, mm	2	2.7
Cooling ranges measured in rms sizes, $n_{\sigma x} / n_{\sigma s}$	10 / 4.4	5.7/4
Basic radiation wavelength, $2\pi/k$, μm	2.2	2.2
Cooling type	Passive	Active
Number of wiggler periods, n_w	7	50
Wiggler length, $L_u = \lambda_w n_w$ [m]	0.774	15.46
Peak magnetic field of the wiggler, B_0 [kG]	1.005	120.8
Optical amplifier gain [dB]	0	30
Power of optical amplifier	N/A	≤1 W
Hor. emittance cooling time, λ_x	0.05 s	0.28 hour
Longitudinal emittance cooling rate, λ_s	0.06 s	0.57 hour

#7: SRF development at Fermilab

- Fermilab performs a **full cycle of work** related to R&D, design, manufacturing and testing of SRF cavities and cryomodules for High Energy Physics and other DoE programs and projects.
- Fermilab has world-recognized specialists in SRF – scientists, engineers and technicians – in all these areas as well as world-class facilities.
- Fermilab's SRF team performs a wide spectrum of **R&D related to SRF**:
  - materials research;
  - development of new cavity processing methods;
  - development of SRF cavities made from Nb/Cu, Nb_3Sn and other alternative materials;
  - development of new types of SRF cavities and components;
  - design of new types of cryomodules;
  - resonance control of the SRF cavities.

Highlights of the SRF technology at Fermilab

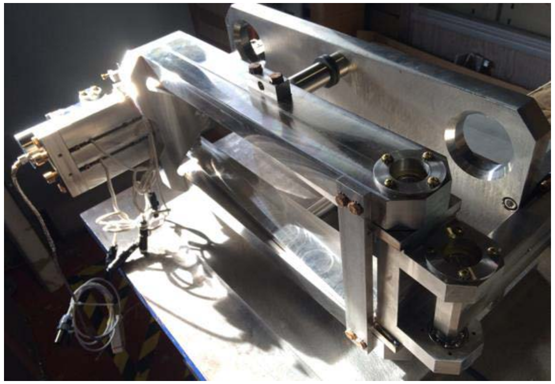


Nitrogen treatment of SRF cavities developed at Fermilab allows significant increase of the cavity quality factor (N-doping) for CW applications or increase of both the quality factor and accelerating gradient for pulsed applications (N-infusion).

- Fermilab is a world leader in R&D on new cavity processing methods, which include basic materials research and technology development.
- Revolutionary methods and technologies were developed, which allowed decrease of RF losses in the SRF cavities by 3-4 times. These methods were transferred from discovery to industry.

Highlights of the SRF technology at Fermilab: PIP-II

PIP-II HB650 cavity inside a high-pressure water rinsing (HPR) setup



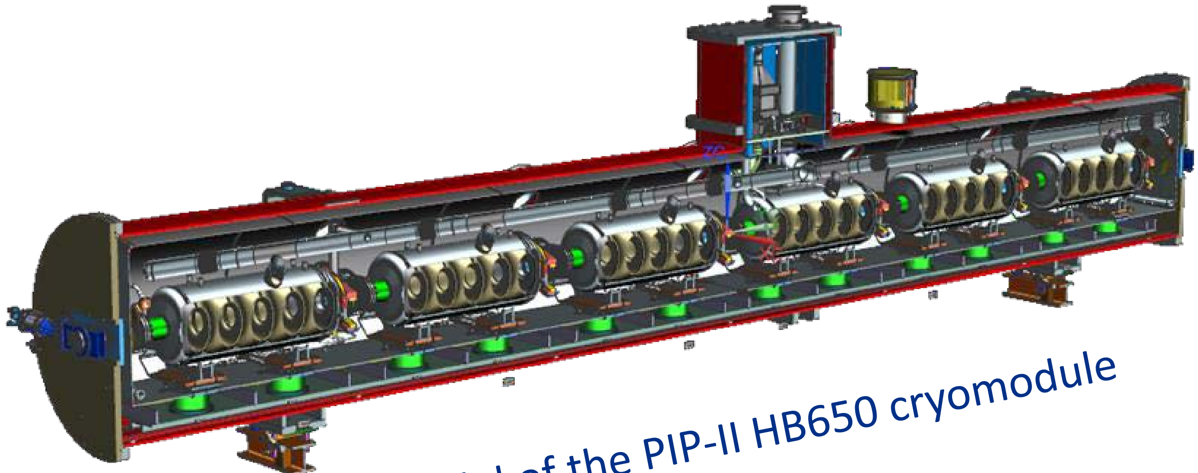
Prototype PIP-II 650 MHz frequency tuner during bench testing

PIP-II SSR1 cavities

- Major activities in SRF include RF design and optimization of the cavities and components, resonance control, mechanical design of the cavities and cryomodules, and supervision of the manufacturing, inspection, testing, and assembly of the cryomodules.

Highlights of the SRF technology at Fermilab

Prototype LCLS-II cryomodule on a test stand at Fermilab



3D model of the PIP-II HB650 cryomodule

- Fermilab SRF team plays a key role in development of superconducting linacs for **LCLS-II** at SLAC and **PIP-II** projects at Fermilab.
- Fermilab is responsible for the RFD crab cavity manufacturing for **HL-LHC** in the framework of AUP program.

EIC: Areas for collaboration on SRF

Fermilab can contribute to:

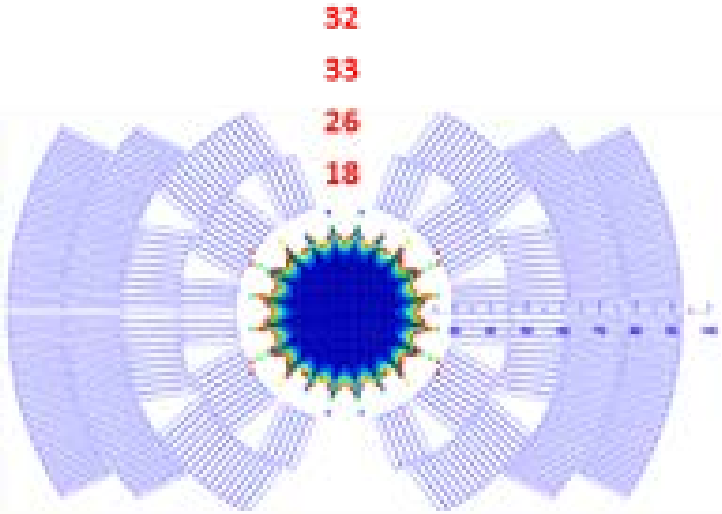
- **SRF cavity processing**: Adapting of the best cavity processing methods to EIC cavities in order to dramatically reduce RF losses;
- The cavity **high Q_0 preservation** in cryomodule. In particular, the work on cryomodule magnetic "hygiene", magnetic shielding, and component demagnetization
- **EIC SRF accelerating cavity design**: Developing cavities with improved mechanical properties (microphonics), reduced HOM impedance, etc.;
- Development of new components for SRF cavities:
  - **High power couplers** with reduced losses (static and dynamic);
  - Cavity frequency **tuners** (slow and fast);
  - **HOM dampers;**
- **Resonance control** algorithms for microphonics suppression in narrow-band SRF cavities for EIC ERLs;
- Development of **new types of crab cavities**;
- Design of cryomodules with improved properties.

#8: Superconducting Magnets at Fermilab

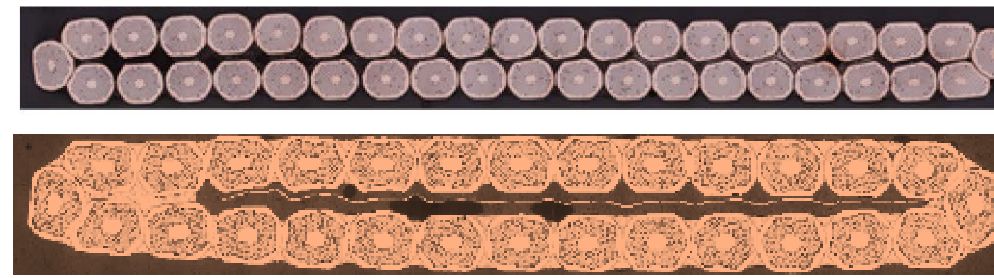
Fermilab has been designing, building, and testing superconducting accelerator magnets for ~ 40 years.

- Energy Doubler/Saver → **Tevatron** → 774 NbTi (4.2 T) dipoles and another 216 focusing quadrupoles.
- **Low beta** quadrupoles for the Tevatron – complex magnets with high gradient of 140 T/m
- **SSC dipole** prototypes (2 left on is in the Smithsonian, one in the backyard of Fermilab)
- **Low beta quadrupoles for LHC** – operational until 2024, until HL upgrade
- Torus coils for **JLab** – 4x2 m^2, detector magnet
- LCLS-II – splittable quadrupoles
- **LARP → HL-LHC** Accelerator Upgrade Project (Nb_3Sn) – Fermilab is leading organization, in collaboration with BNL and LBNL
- High field magnet program (Nb_3Sn) – **15 T dipole R&D** as a part of the U.S. Magnet Development Program (MDP)

Current R&D – 15 T dipole demonstrator



Inner L1-L2

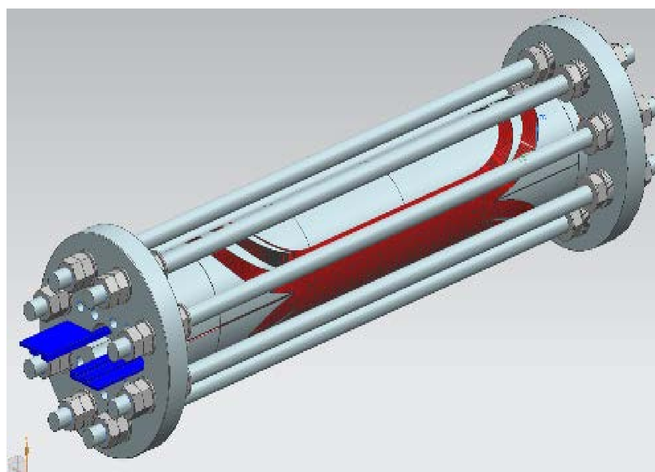


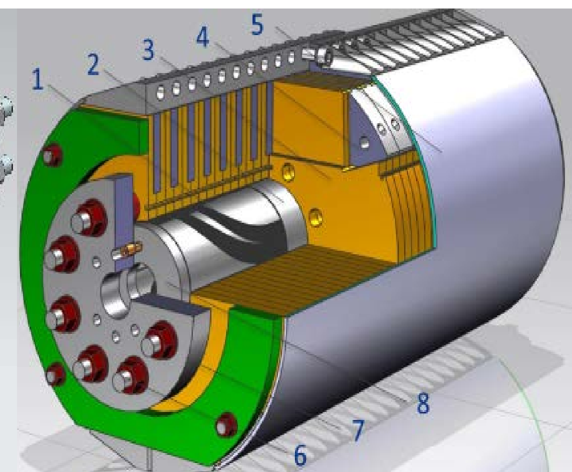
Outer L3-L4

- Coil:
  - 60-mm aperture
  - 4-layer graded coil

- Cable:
  - L1-L2: 28 strands, 1 mm RRP150/169
  - L3-L4: 40 strands, 0.7 mm RRP108/127
  - SS core

- Mechanical structure:
  - Thin SS coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick SS skin
  - Thick end plates and SS rods
  - Cold mass OD < 610 mm (VMTF Dewar limit)





- Magnet ready for test in Spring/Summer 2018

1000 T/s HTS Magnet Test stand (LDRD)

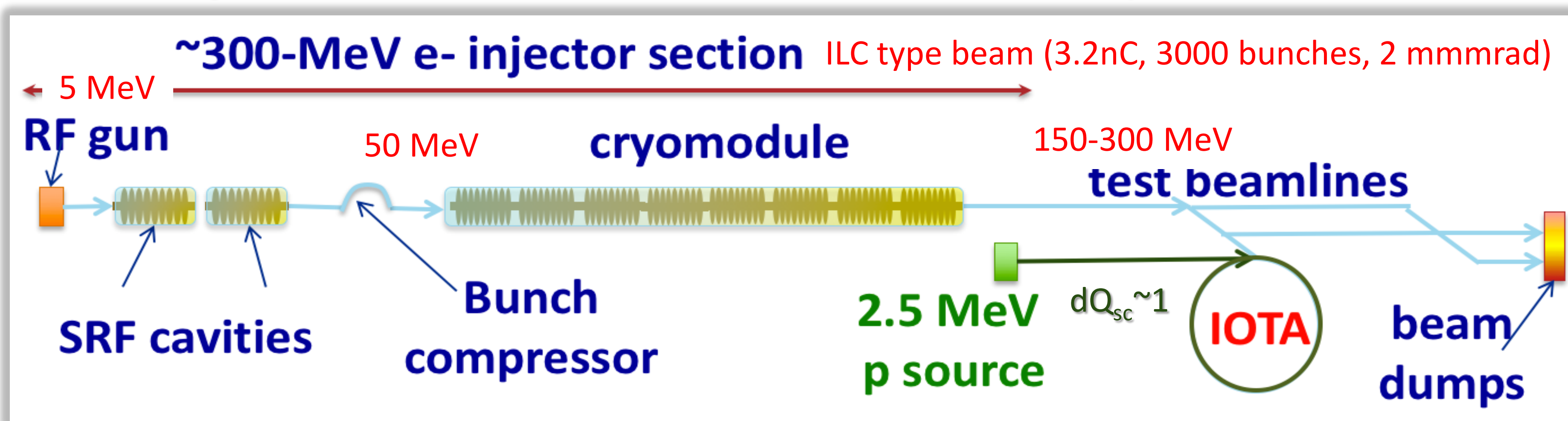
EIC: Topics for magnet collaboration

Fermilab can contribute to:

- **IR quadrupoles** – based on the current HF magnet R&D and HL-LHC (LARP) experience
- **SC transport magnets** based on different technologies – from permanent magnets to Nb_3Sn dipoles and quadrupoles
- Specialized magnets needed for beam transport: **Kickers, Lambertson and Septum magnets**
- **SC detector** magnets for experiments

#9-10: FAST & IOTA : Overarching Motivation – R&D on Intensity Frontier Accelerators for HEP

- To enable multi-MW beam power, losses must be kept well <0.1% at the record high intensities:
  - Need <0.06% for the post PIP-II ~2.5 MW upgrade
  - Present level ~3-5% in Booster and MI synchrotrons @0.7MW
- Need to develop tools for:
  - Space-charge countermeasures
  - Beam halo control
  - Single-particle and coherent beam stability



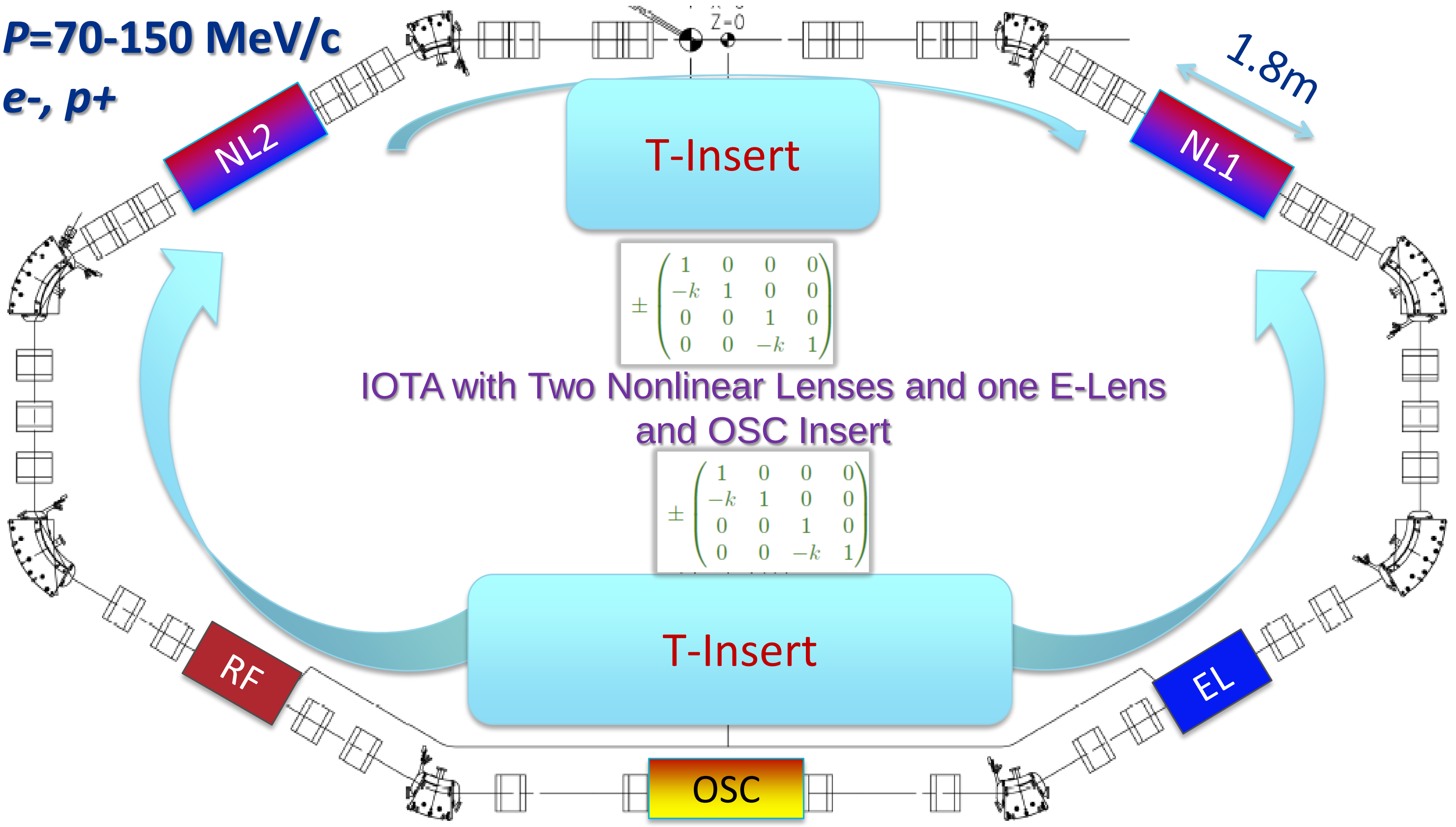
IOTA (Integrable Optics Test Accelerator): Uniqueness

- Has two injectors: can operate with either *e-* or *p+* up to 150 MeV/c momentum
- Super-flexible beam optics lattice
- Precise control of the optics quality (<1%) and stability
- Set up for very high intensity operation (*dQ_sc*~1 with protons)

***C*=40m**

***P*=70-150 MeV/c**

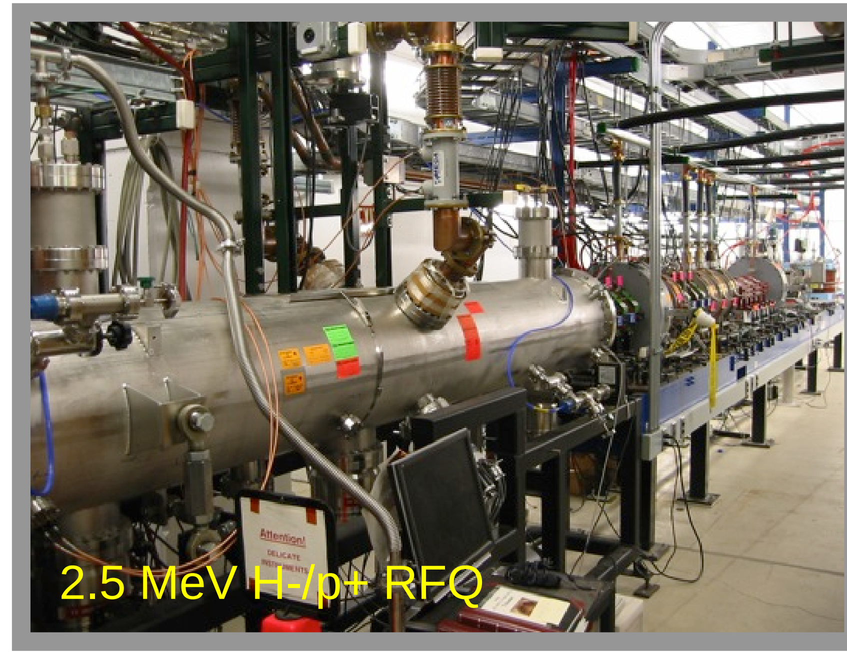
e-, p+

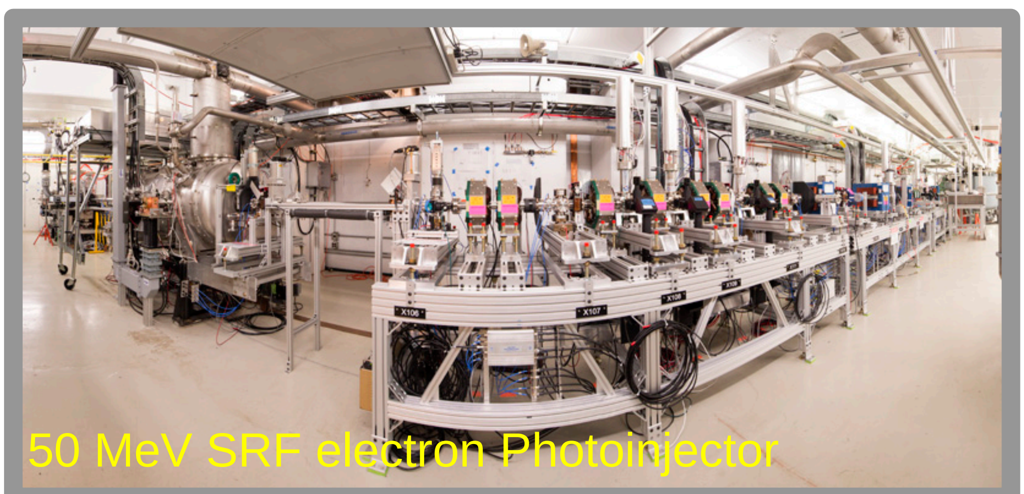


IOTA & FAST Accelerator R&D Program

- **IOTA** - **innovative ideas for the RCSs**:
  - *Integrable Optics*
    - *With strongly nonlinear magnets*
    - *With specially shaped electron beams in electron lens*
  - *Space Charge Compensation*
    - *With ~"Gaussian" electron lens*
    - *With neutralizing "electron columns"*
  - *Coherent Beam "Super"-Stability* *(NL & electron lenses, FB)*
  - *Optical Stochastic Cooling*
- **FAST** - **user-driven accelerator R&D**:
  - *Mostly with electrons*
    - *Beam dynamics in SRF linacs (ILC, MARIE, EIC)*
    - *Advanced electron sources, phase-space manipulations (EIC)*
    - *Novel e- and photon beam diagnostics (all)*


record gradient 31.5 MV/m
achieved in CM2
1.3 GHz SRF Cryomodule


2.5 MeV H-/p+ RFQ


50 MeV SRF electron Photoinjector


IOTA Ring Hall

IOTA Ring: Taking Shape (operational in 2018)

IOTA/FAST Timeline:

- 5 MeV e- beam – FY15
  - Period of studies
- 50 MeV e- beam – FY16
  - Period of studies
- 300 MeV e- beam – “now”
  - Beam 1.3GHz CM to dump
  - Period of studies
- 1st e- beam in IOTA – FY18
  - 1st experiments begin
- 1st *p*+ beam in IOTA – FY19
- Experimental R&D program
  - For several (5-8?) years
  - many experiments (*e*-, *p*+)

S. Antipov et al 2017 JINST 12 T03002

IOTA (Integrable Optics Test Accelerator): Facility and Experimental Beam Physics Program

Sergei Antipov, Daniel Broemmelsiek, David Bruhwiler*, Dean Edstrom, Elvin Harms, Valery Lebedev, Jerry Leibfritz, Sergei Nagaitsev, Chong-Shik Park, Henryk Piekarz, Philippe Piot**, Eric Prebys, Alexander Romanov, Jinhao Ruan, Tanaji Sen, Giulio Stancari, Charles Thangaraj, Randy Thurman-Keup, Alexander Valishev, Vladimir Shiltsev***

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
**RadiaSoft LLC, Boulder, Colorado 80304, USA*
*** also at Northern Illinois University, DeKalb, Ilinois, 60115, USA*

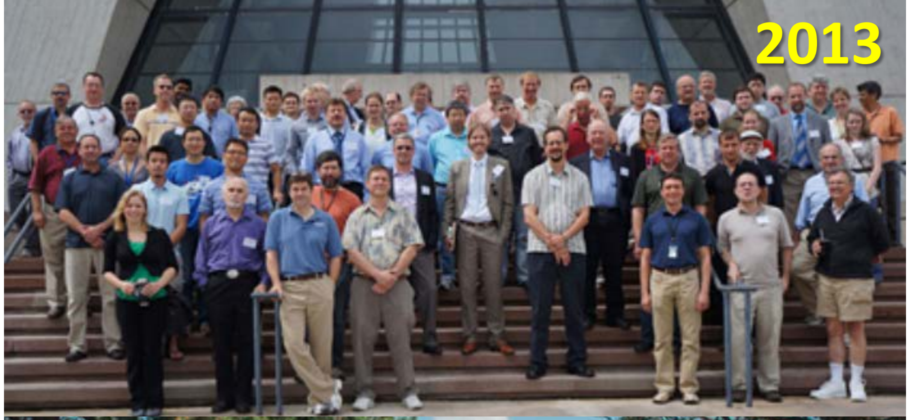
****E-mail:* shiltsev@fnal.gov

ABSTRACT: Integrable Optics Test Accelerator (IOTA) is a storage ring for advanced beam physics research currently being built and commissioned at Fermilab. It will operate with protons and electrons and, correspondingly, employ 70 – 150 MeV/c proton and electron injectors. The research program includes the study of nonlinear focusing integrable optical beam lattices based on special magnets and electron lenses, beam dynamics of ultimate space-charge effects and their compensation, optical stochastic cooling, and several other experiments. In this article we present the design and main parameters of the facility, outline progress to date and the timeline of the construction, commissioning and research, and describe the physical principles, design, and hardware implementation plans for the IOTA experiments.

KEYWORDS: Accelerators, Synchrotrons, Magnets, Integrable Optics, Electron Lenses, Space-charge Effects, Instabilities, Collimation, Beam Instrumentation, Photo-injectors, Neutrino.

IOTA Collaboration

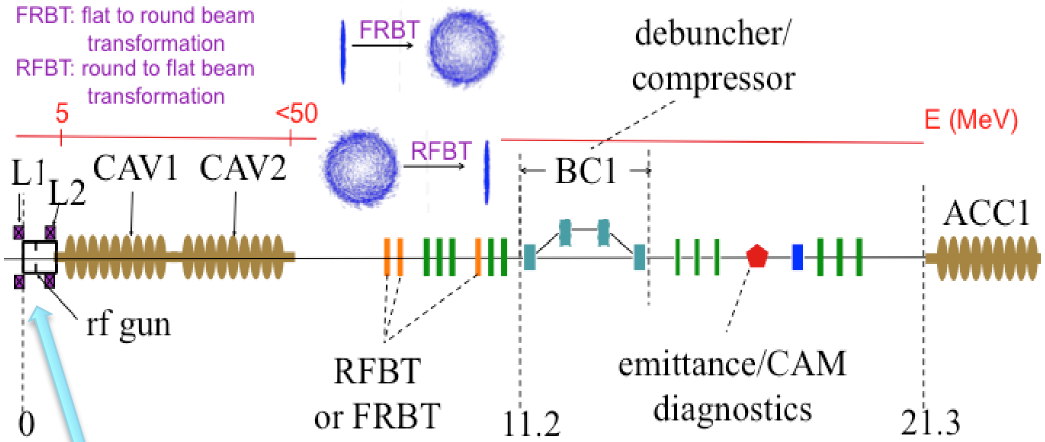
- **26 Partners:**
  - ANL, Berkeley, BNL, BINP, CERN, Chicago, Colorado State, IAP Frankfurt, JINR, Kansas, LANL, LBNL, ORNL, Maryland, Universidad de Guantajuato Mexico, JAI, Michigan State, NIU, Oxford, RadiaBeam Technologies, RadiaSoft LLC, Tech-X, Tennessee, Vanderbilt
- **NIU-FNAL:** Joint R&D Cluster
- Publications, presentations at conferences, workshops, etc
- **EIC :** many critical tests possible (some happening)

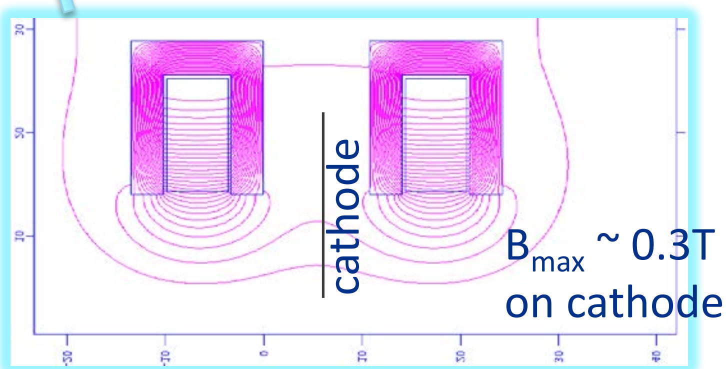


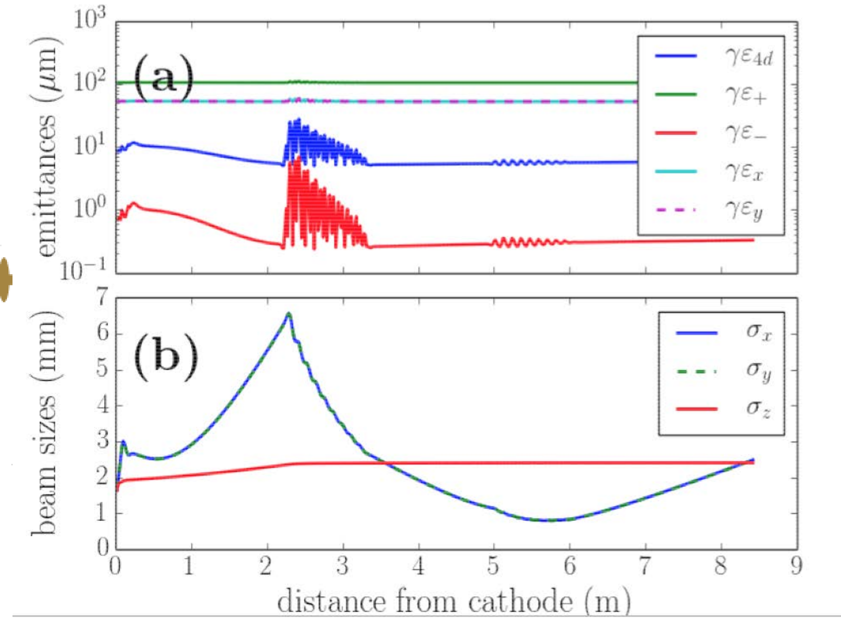
EIC R&D at FAST: Unique Capability and Aligned Need

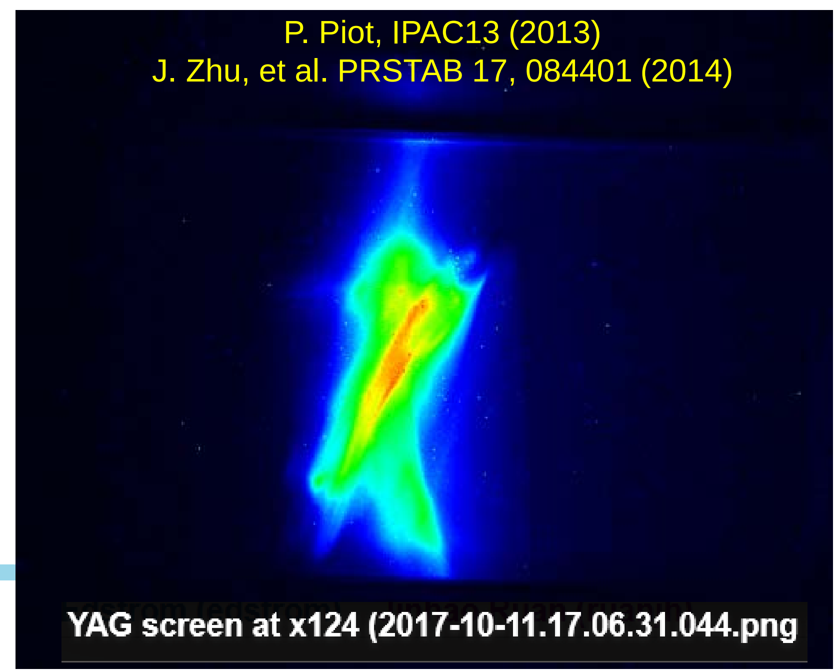
- FAST/IOTA is the only facility in operation/under construction that can
  - Generate a 3.2 nC magnetized beam
  - Accelerate it to 20-55 MeV
  - Test various classes of emittance exchange
- It is therefore offers unique capability to expand understanding of JLEIC cooler single-bunch dynamics
  - Evolution of magnetized bunch under influence of space charge, LSC, CSR; potential for microbunching
  - Explore emittance-exchange based architectures for coolers
- It also can be an unique and excellent test bed for beam studies and tests of various components of eRHIC hadron cooling system
  - Esp. at full electron energy of 150 MeV

Experiments at FAST ("now", P.Piot *et al*)







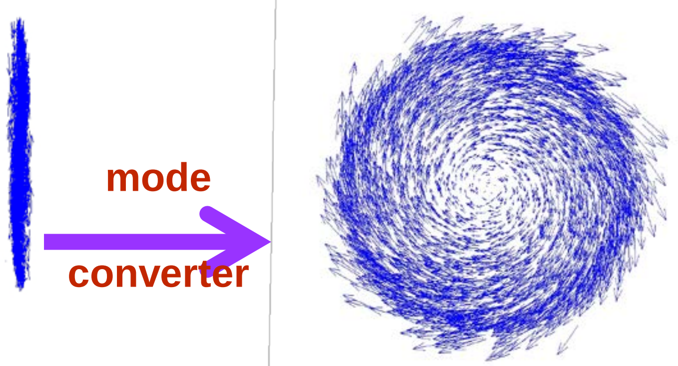


First round of studies:

- Experiment to focus on flat beam generation (after decoupling of magnetized beam with a skew-quad channel)
- Characterization of magnetized beams will be a byproduct

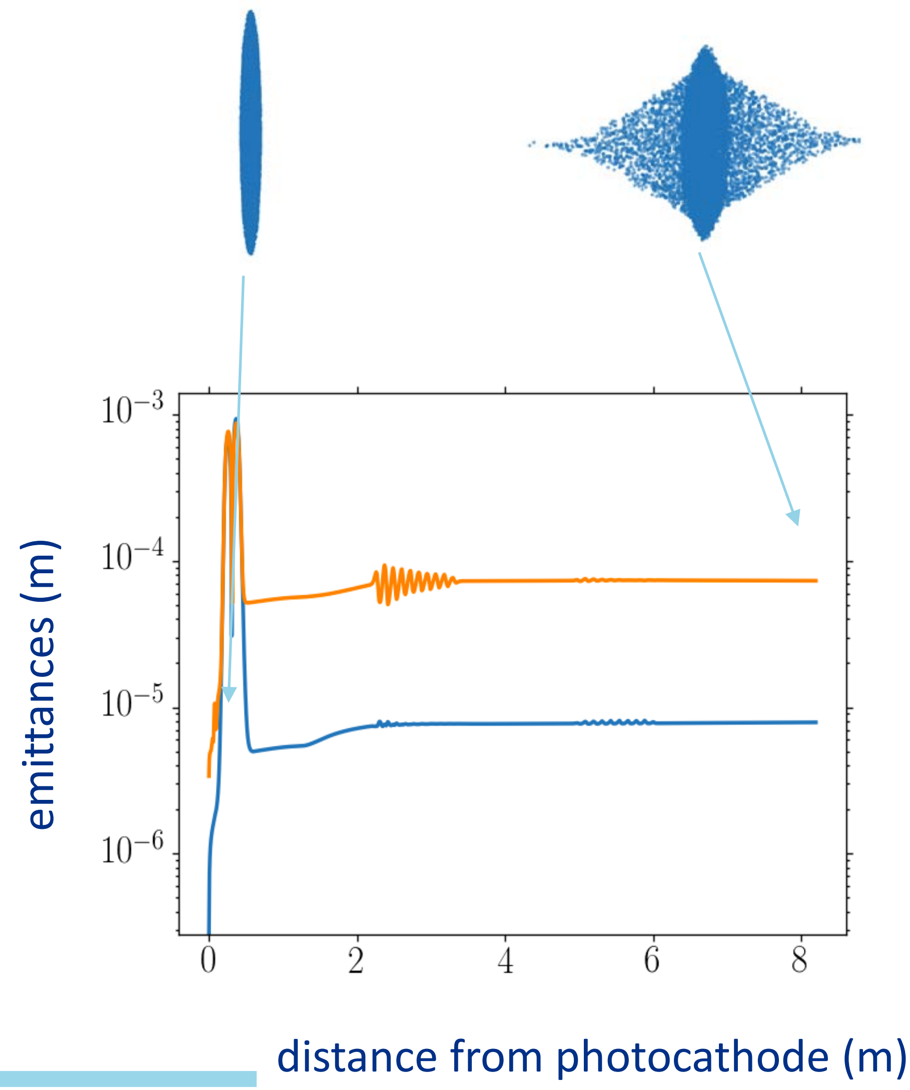
Next: Flat-to-round beam transformation

- **Reverse of flat beam transform:**
  - Illuminate photocathode with ribbon laser
  - Transform into a magnetized beam
- **Preliminary simulations (IMPACT-T)**



Y. Derbenev, University of Michigan
report UM-HE-98-04 (1998)

P. Piot, IPAC17



- At FAST/IOTA produced magnetized beam could be injected in IOTA (R. Li)

Proposed Tests (Ya.Debenev, Yu.Zhang, et al)

- Demonstrate generation and acceleration of 3.2 nC magnetized beam
  - phase space configuration consistent with that in JLEIC Cooler: long, low dp/p bunch (fill linac phase acceptance); 6D top-hat if possible
- Test/validate single-bunch dynamics in merger designs at 5 MeV
- Characterize evolution of 3.2 nC phase space over long distances (order 100 m straight-ahead, longer distances using IOTA) in energy range 20-55 MeV
  - Assess impact of space charge, CSR
    - Emttance v. distance, degradation of magnetization, …
  - Characterize microbunching dynamics, evaluate microbunching gain
  - Provide benchmark data on evolution of different initial distributions (Gaussian, super-Gaussian, top-hat, …)
- Test Derbenev accelerating-mode-based emittance exchange (JLAB-TN-17-008); characterize evolution of resulting quasi-magnetized beam
  - existence proof will support viable alternative cooler system architecture for JLEIC
- Study of the beam-beam kicker for cooling e-beam switching between ERL and Circulator-cooler ring

Summary

- Fermilab has unique expertise in Beam Physics and Accelerator Technology of direct relevance to EIC
- It is important to have that expertise available for and used by the entire US accelerator community
- EIC activity commends to us, Fermilab is very much open for collaboration and sees potential in:
  - Polarization, IR and optics design, MDI, collimation and coherent beam stability analysis and similar collider design work
  - Hadron beam cooling – various options:
    - in longer run – ready to take over building the system
  - Development/construction of the SRF systems and SC magnets for EIC
- We'd be glad to offer access to unique FAST/IOTA beams to carry out EIC-related research with electrons and protons

Interested? – *Call (630) 840-5241*

Contributions from:

Sergei Nagaitsev, Sergey Belomestrnykh, Valery Lebedev, Eliana Gianfelice-Wendt, Nikolai Mokhov, Philippe Piot, George Velev, Slava Derbenev, James Amundson, Eric Stern