Accelerator and Beam Physics :

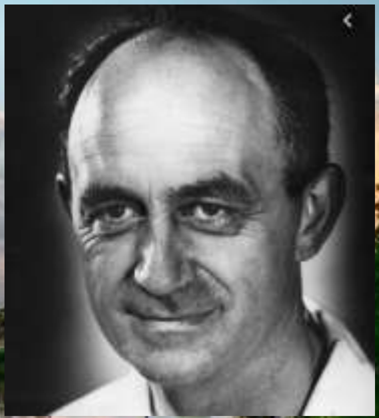
Needs and Opportunities at Fermilab

Vladimir SHILTSEV

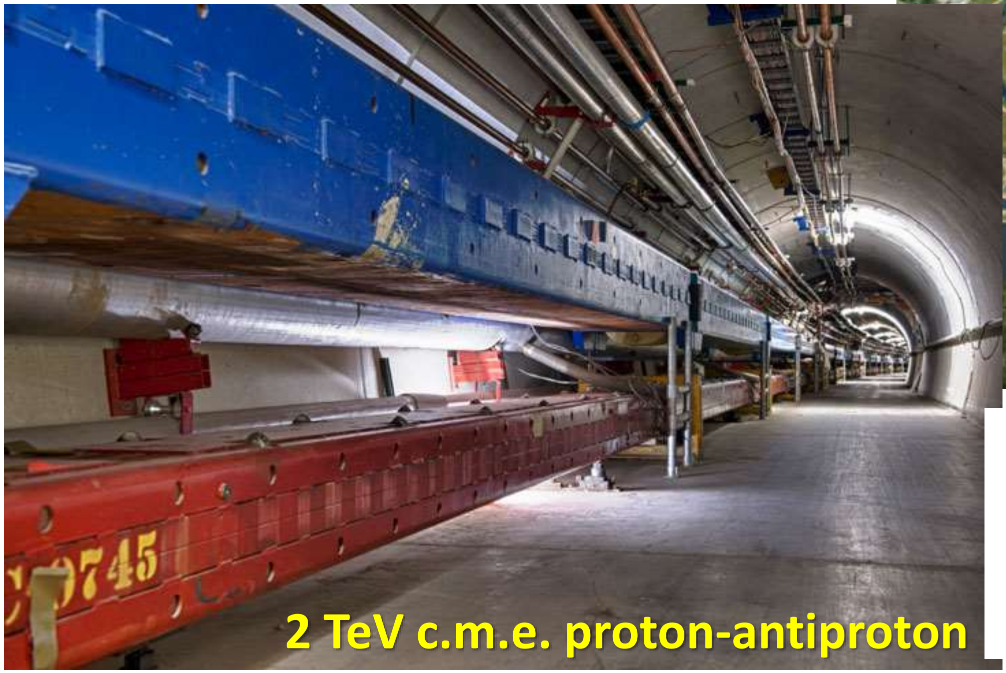
MSU

December 5, 2019

PhD (1994) – Novosibirsk (Russia)
Fermilab (Batavia, IL) – since 1996



- **Head of the Tevatron Collider 2001-2006**



- **Invented *electron lenses* for supercolliders (Tev, RHIC, LHC)**
- **Director of Accelerator Physics Center 2007-2018**

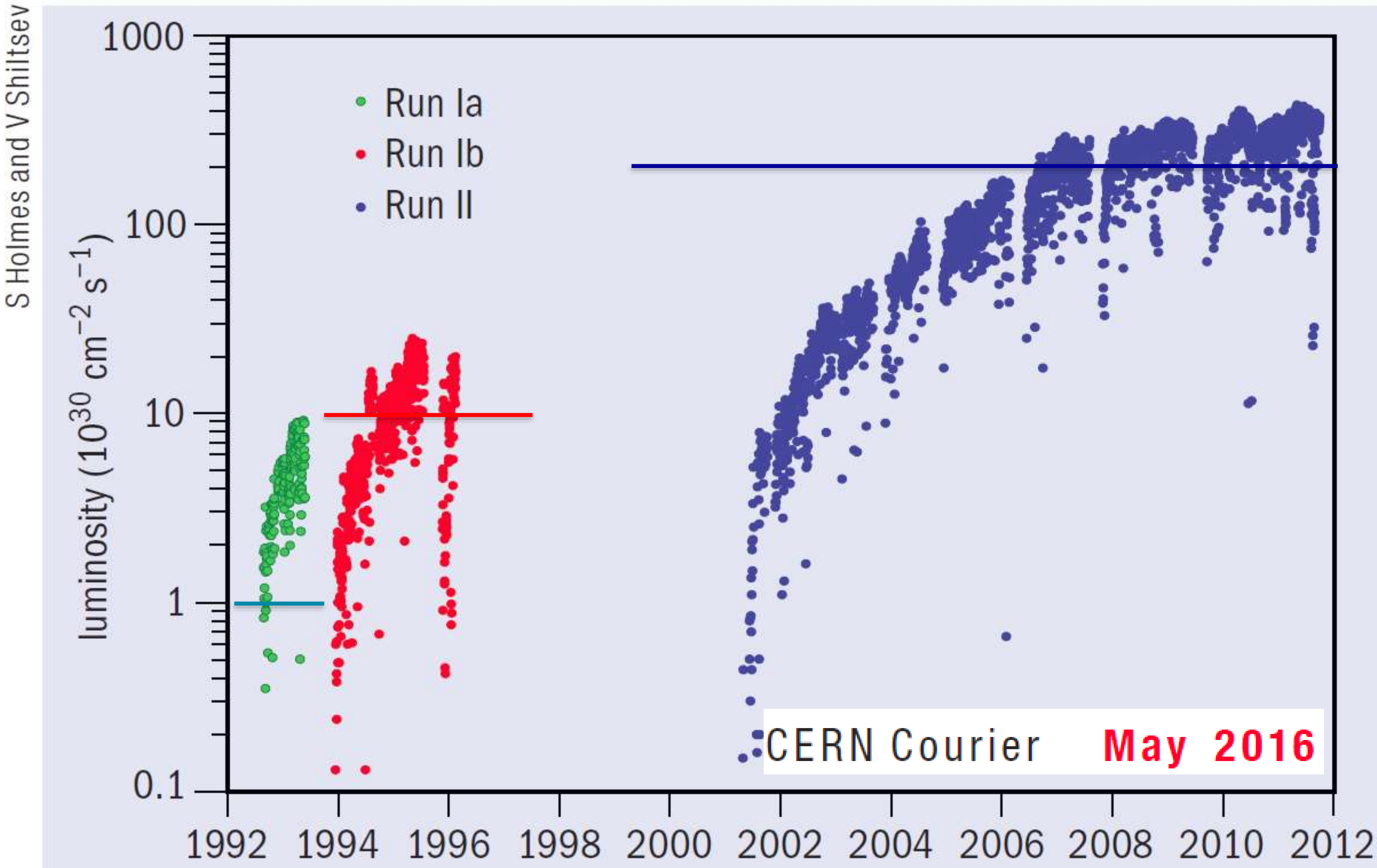
Outline

- **Fermilab Accelerators: Past, Present, Future**
- **Accelerator R&D Needs and Opportunities:**

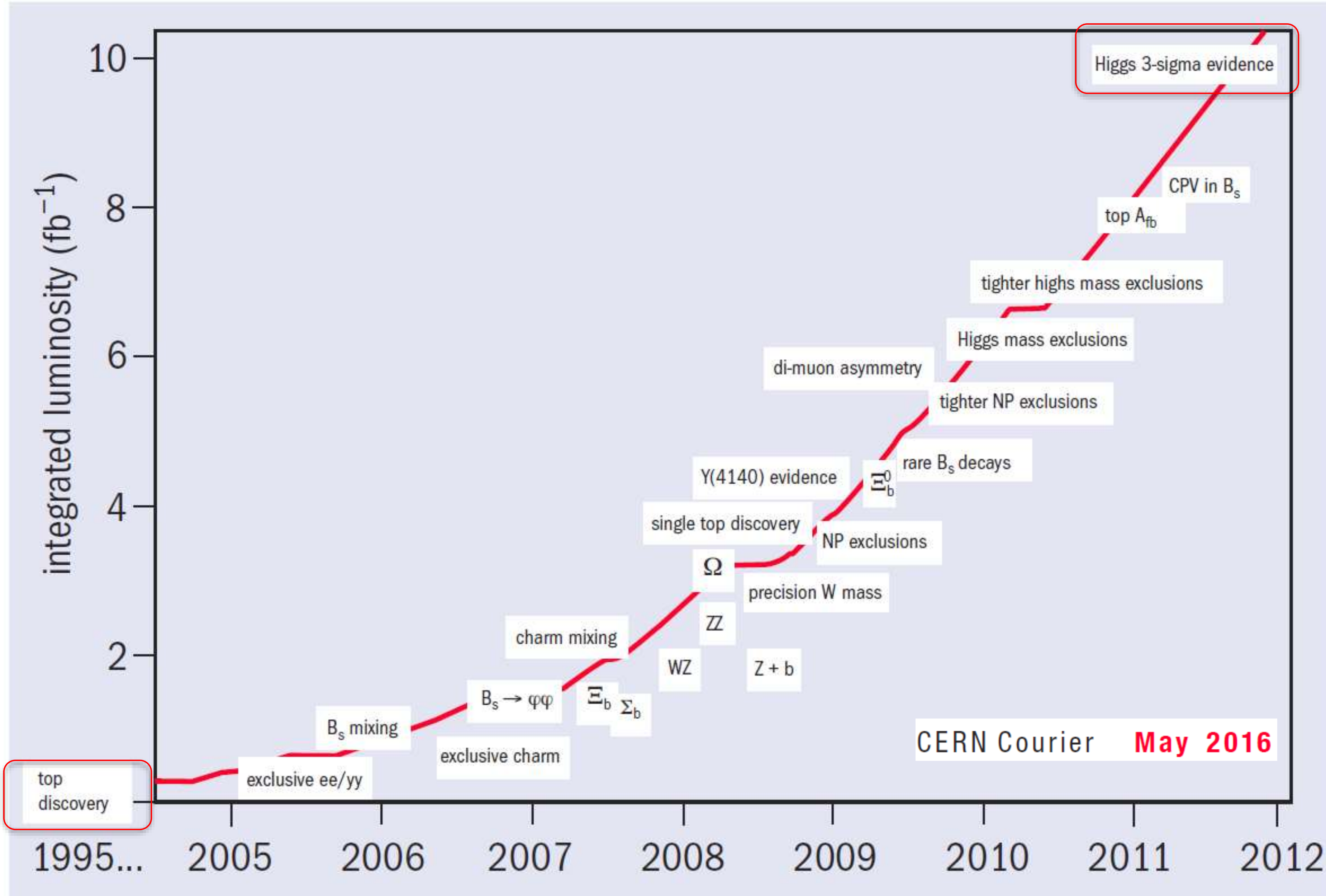
1. IOTA and FAST
2. Fermilab complex upgrades
3. Fermilab accelerator complex operation and power increase
4. Theory/Modeling/Simulations
5. Superconducting magnets
6. Superconducting RF
7. Other (QIS, dark matter searches, etc)

Fermilab Complex : 16 km of accelerators and beamlines, two high power targets, several low power target stations…

Tevatron Collider: 1985-2011

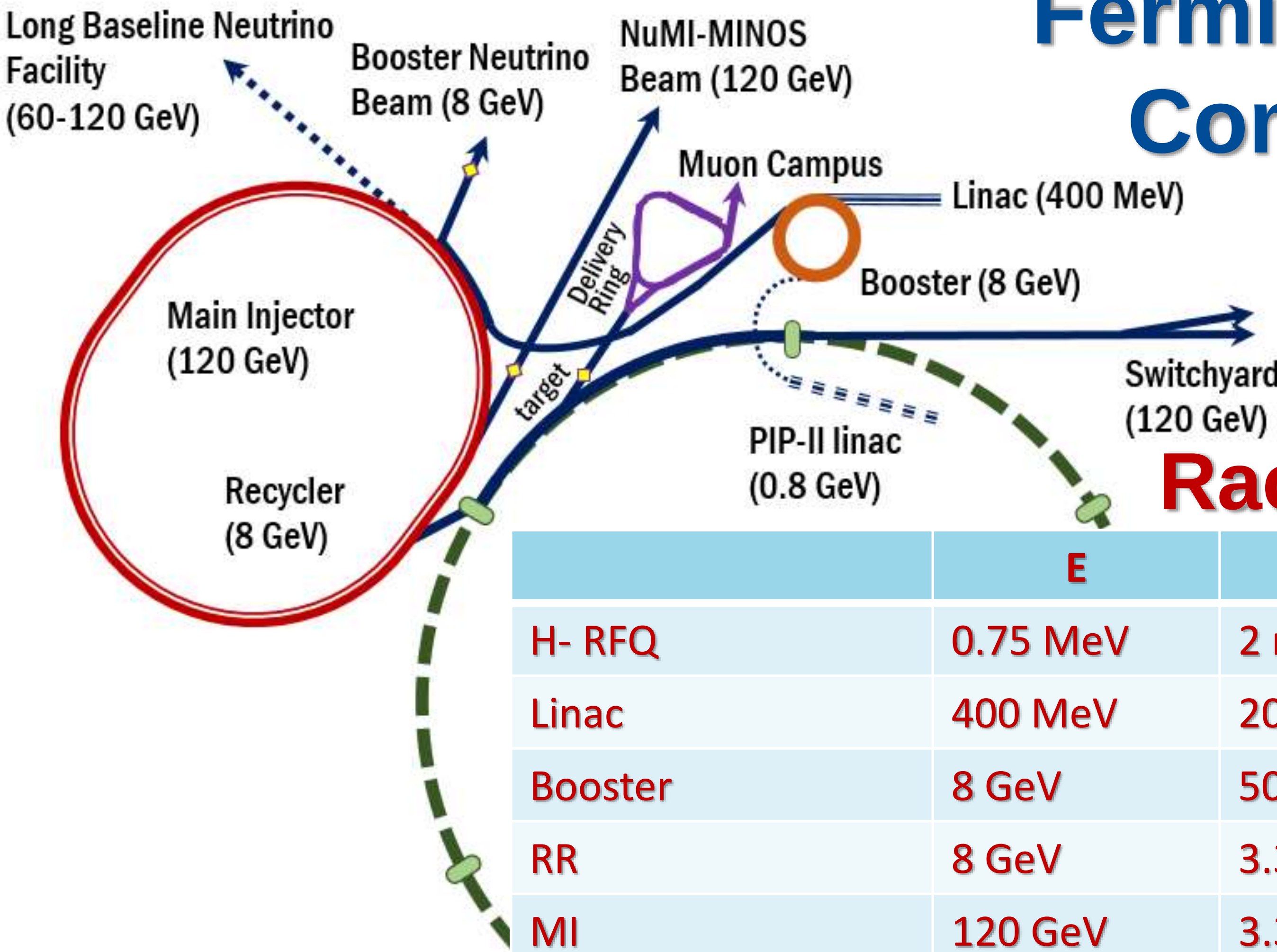


Tevatron



integrated luminosity (fb^{-1})
10
8
6
4
2
1995... 2005 2006 2007 2008 2009 2010 2011 2012
top discovery
exclusive ee/γγ
B_s mixing
$B_s \to \varphi\varphi$
exclusive charm
charm mixing
Ξ_b
Σ_b
WZ
ZZ
Ω
Z + b
precision W mass
single top discovery
Y(4140) evidence
NP exclusions
Ξ_b^0
rare B_s decays
tighter NP exclusions
di-muon asymmetry
Higgs mass exclusions
tighter highs mass exclusions
top A_{fb}
CPV in B_s
Higgs 3-sigma evidence
CERN Courier May 2016

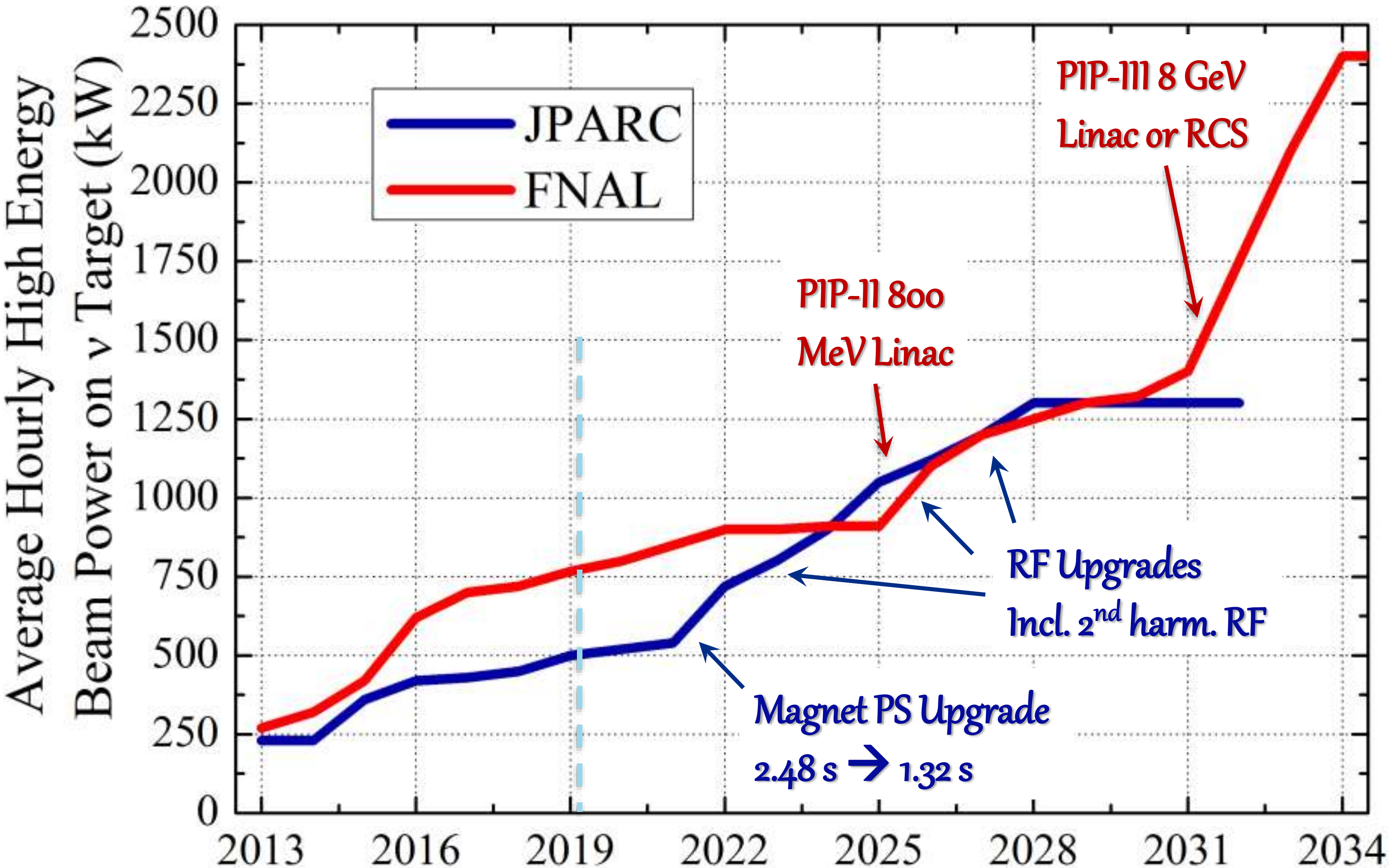
Fermilab Proton Complex Now



Race for power

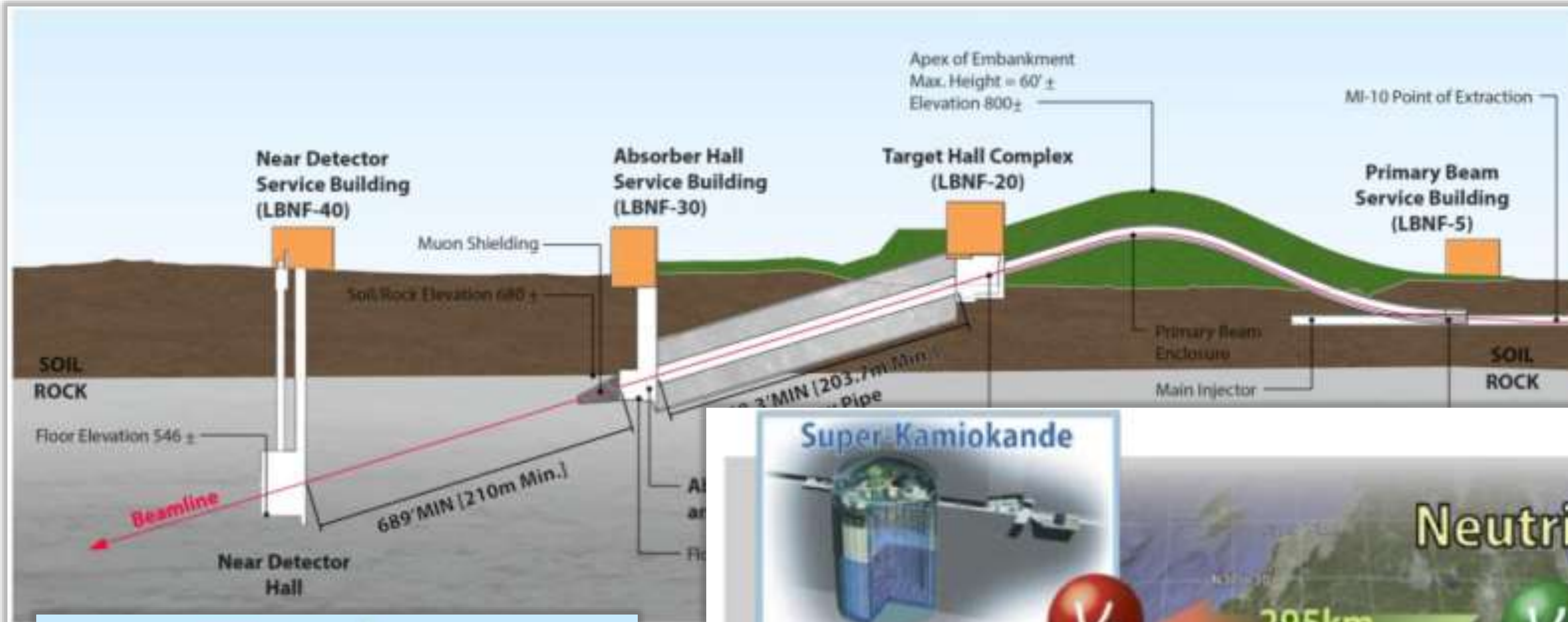
	E	L	Costr.
H- RFQ	0.75 MeV	2 m	2013
Linac	400 MeV	200 m	1970/93
Booster	8 GeV	500 m	1971
RR	8 GeV	3.3 km	1999
MI	120 GeV	3.3 km	1999
Delivery Ring	3.8-8 GeV	500 m	1985/2014
Beamlines	3-120 GeV	3.5 km	1970's-now
Upgr: PIP-II	800 MeV	240 m	2026
Upgr :PIP-III	8 GeV	500 m	Ca 2032
Upgr: beamlines	0.8-8 GeV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

Fermilab - JPARC Power Race (ν-Physics)



Goal: 40 kt LAr DUNE @ 2.4 MW

** compete with Hyper-K in Japan in terms of CPV sensitivity because of different ν's spectrum, different baseline (1300 km vs 295 km) and detector technology*



Idea #1 : Proton Improvement Plan-II

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

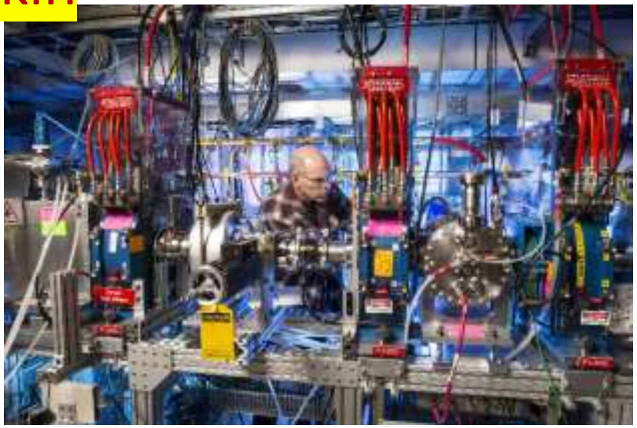
- ~100 kW @ 800 MeV
  - Arbitrary bunch structure
  - Muons (*mu2e**)

Fermilab

PIP-II : Topics for Studies/Development

Eduard Pozdeev

- PIPII injector tests facility Sasha Shemyakin
  - Experimental beam acceleration dynamics studies (2.5 →25 MeV)
  - Ultra-fast beam chopping
  - Novel beam diagnostics (emittance, halo)



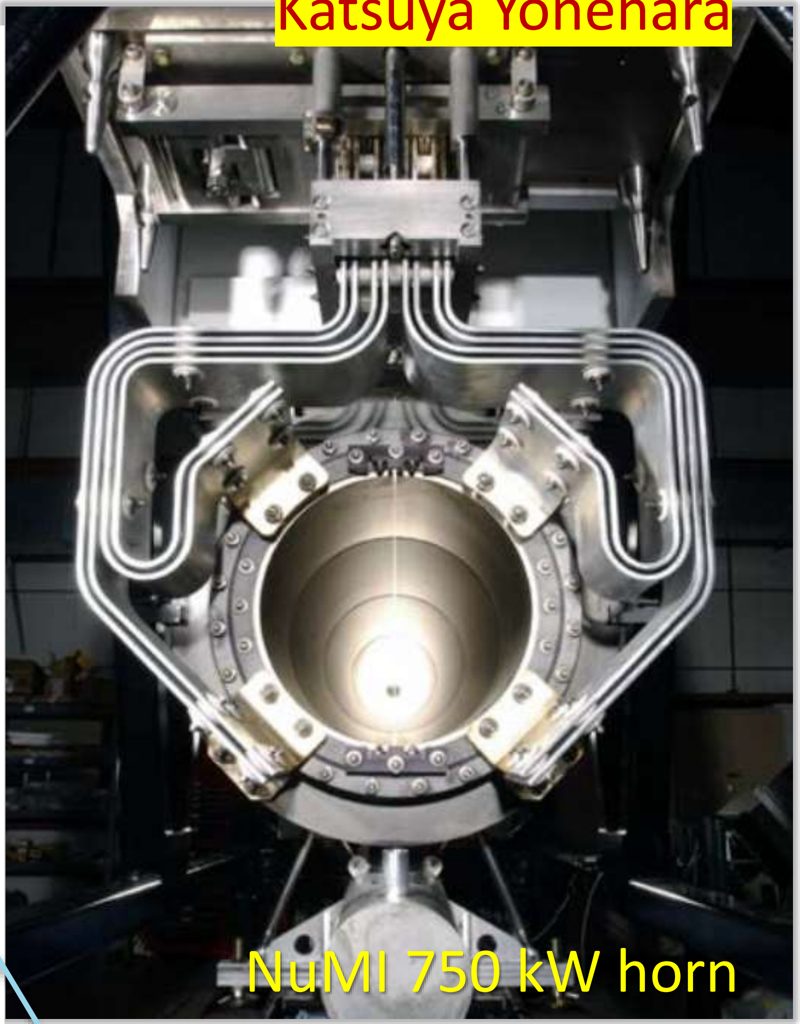
- Simulations
  - Dynamics in linac Arun Saini, Slava Yakovlev
  - Dynamics at injection to Booster Ioanis Kourbanis
- Microphonics in SRF cavities
  - Electromechanical tuner design
  - Feedback controller

Yuri Pischalnikov

Very Important : Targetry, Foils

Robert Zwaska
Katsuya Yonehara

- 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), diagnostics
- Also under development: **injection of high power beams** (stripping foils, laser stripping)
- We learn from lower energy high power machines **PSI** and **SNS** (1.4 MW), **RAL/ISIS**, etc



RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

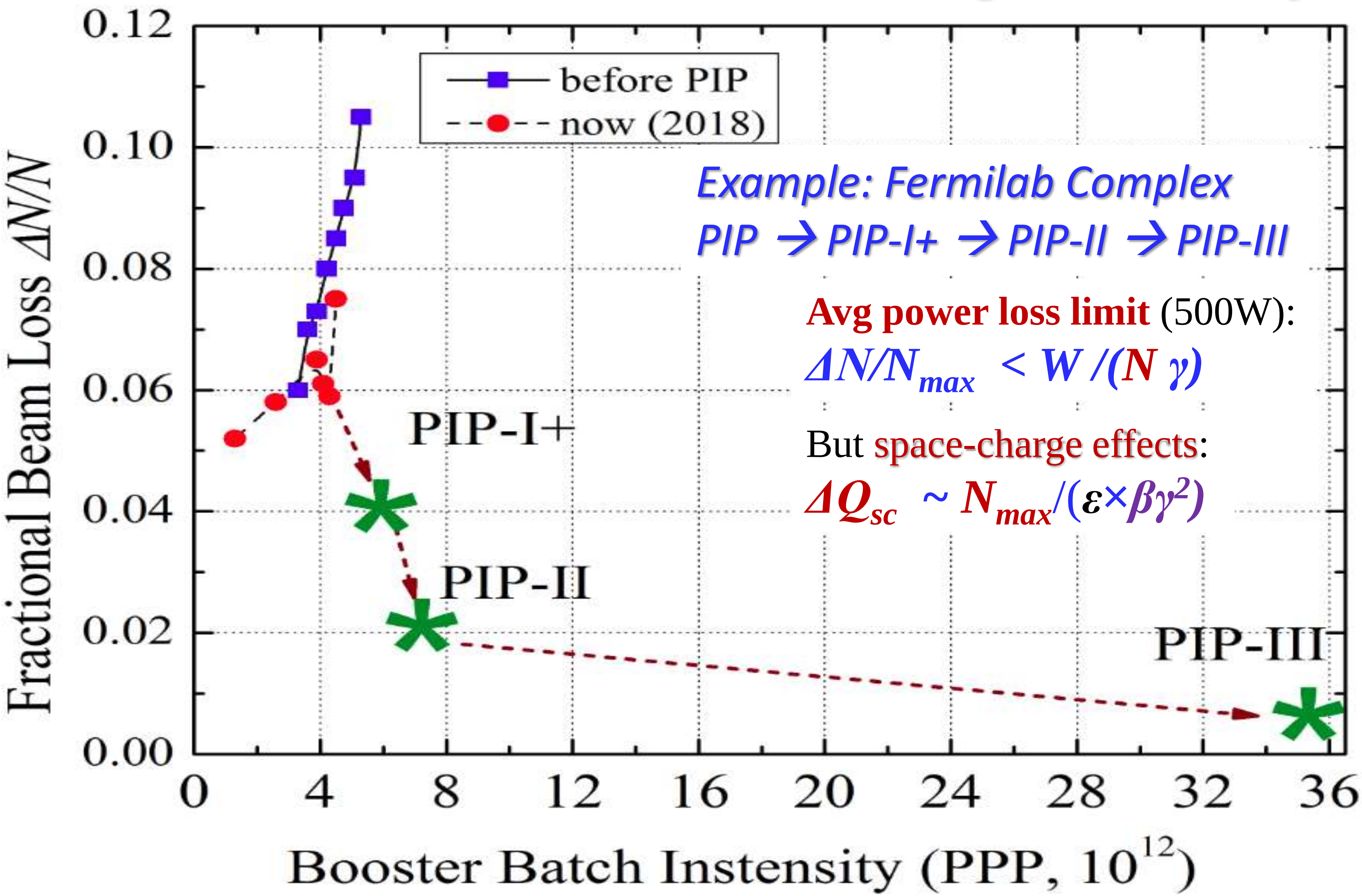
Ways to Increase Beam Power on Target

Particles per pulse → N_{pulse}; Particle energy [eV] → E; Accelerator cycle period → T_{cycle}

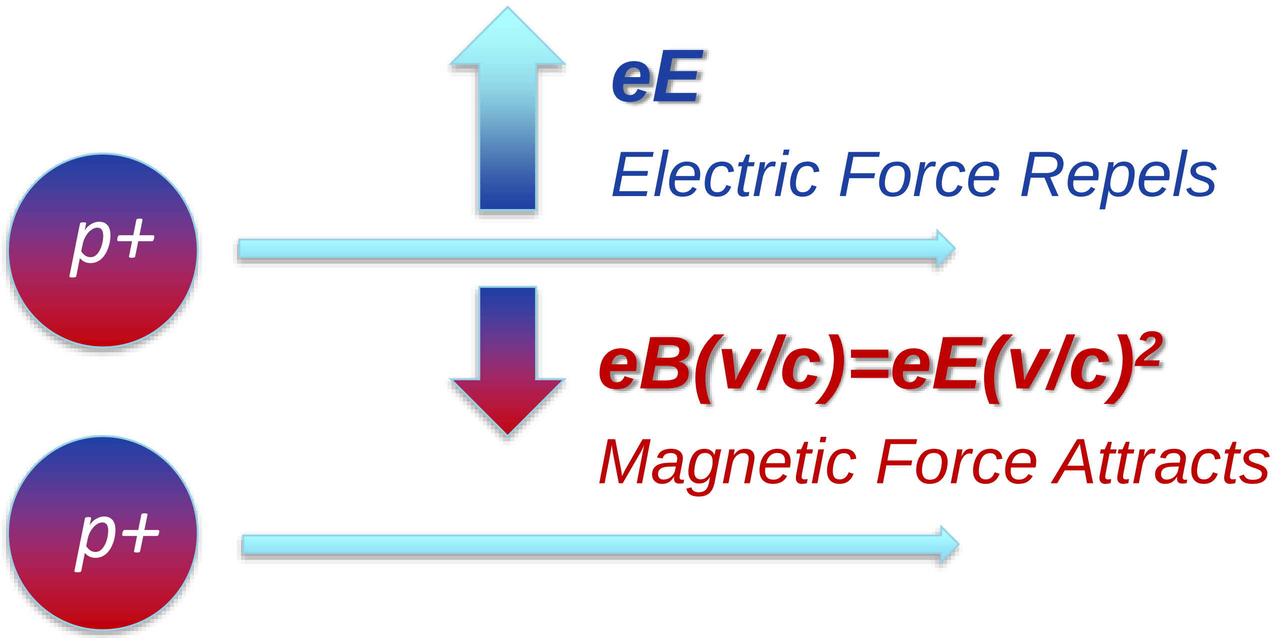
$$P_{beam} = \frac{N_{pulse} E}{T_{cycle}}$$

- **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

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



Intense Beams : Forces and Losses (1)

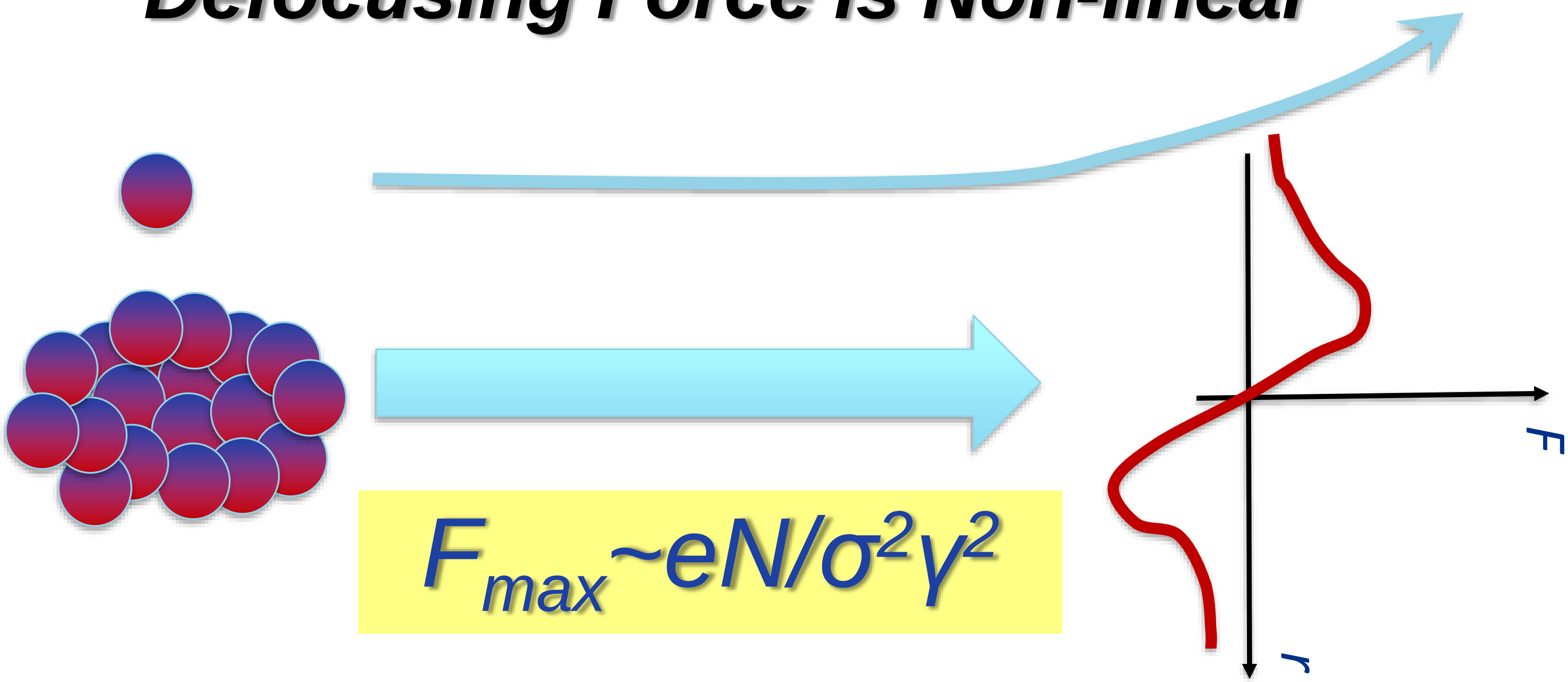


Net Force: Repels

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

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)

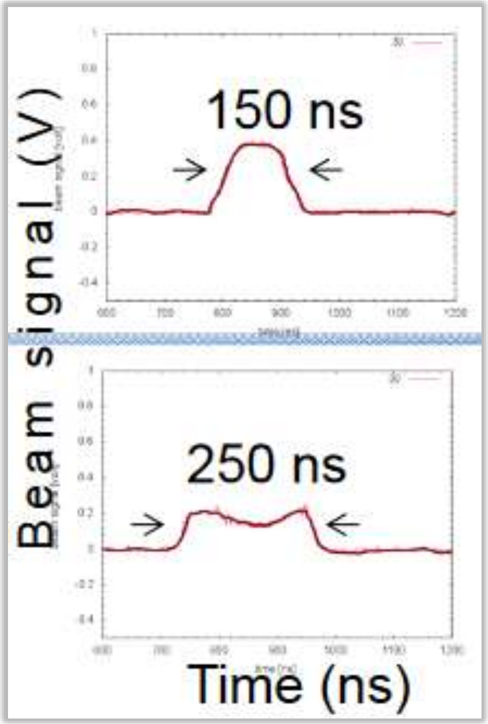
b) scale inversely with beam size (σ)

c) scale with time at low energies (γ)

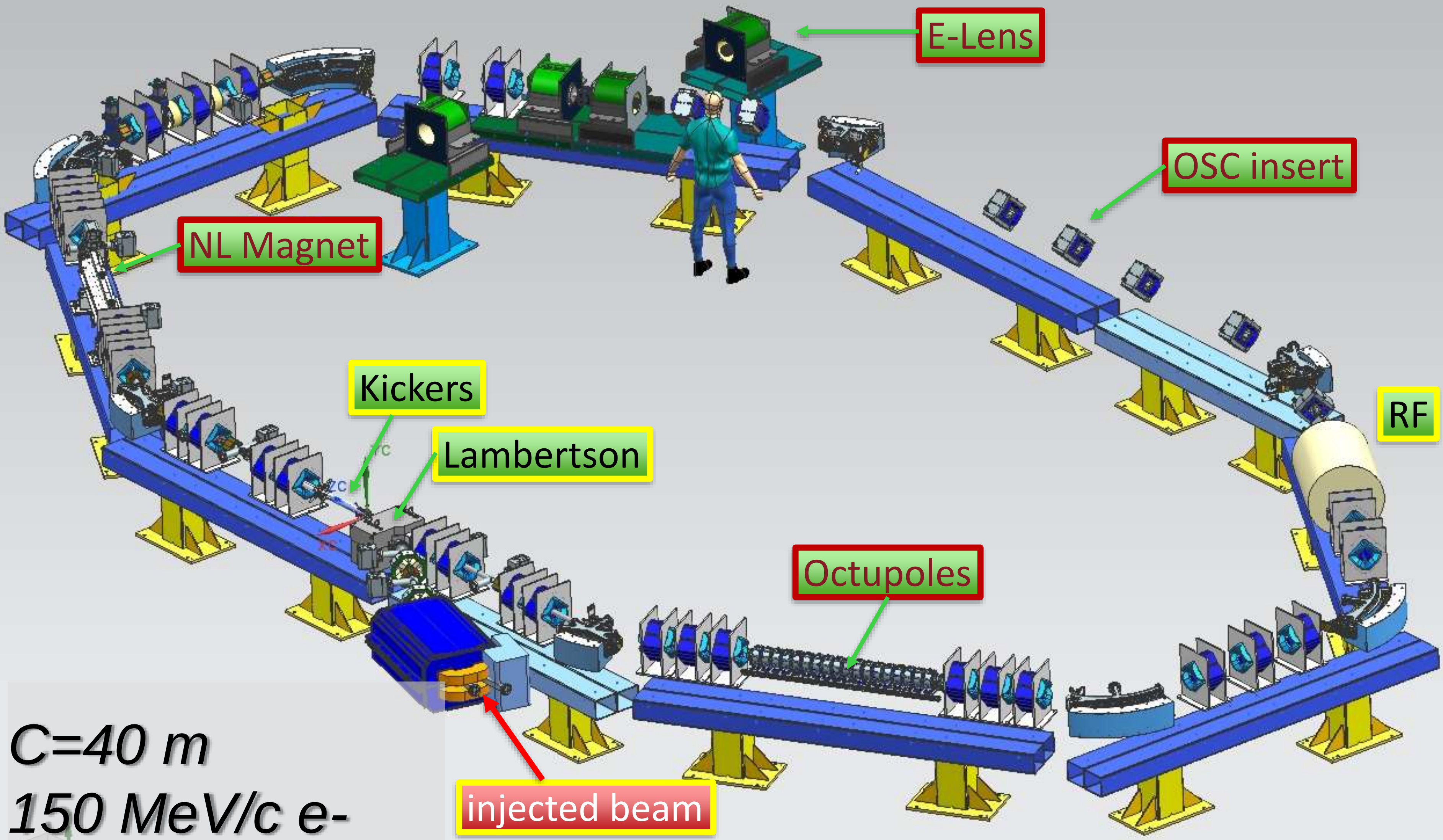
Linacs 5-20 MeV/m
Rings 0.002-0.01 MeV/m

Ways to Increase "Protons Per Pulse"

- **Increase the injection energy (PIP-II):**
  - 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



IOTA: *Integrable Optics Test Accelerator*



C=40 m
150 MeV/c e-
and *70 MeV/c p+*

Alexander Valishev

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

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

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

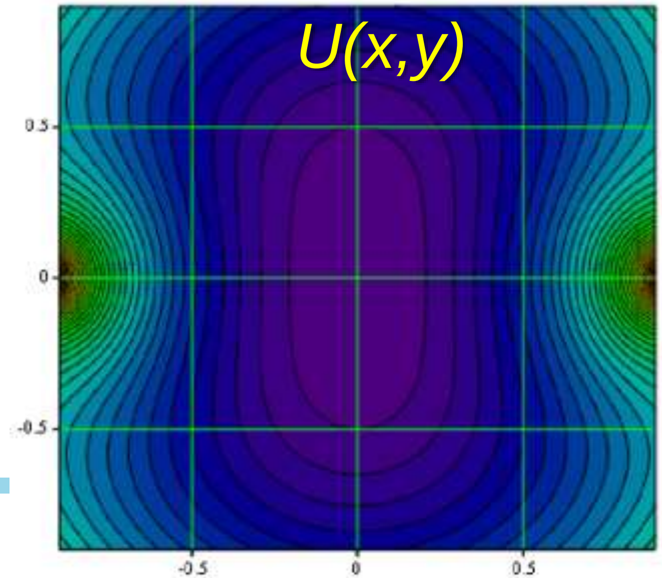
In accelerators :

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

Courant-Snyder transformation, scaling

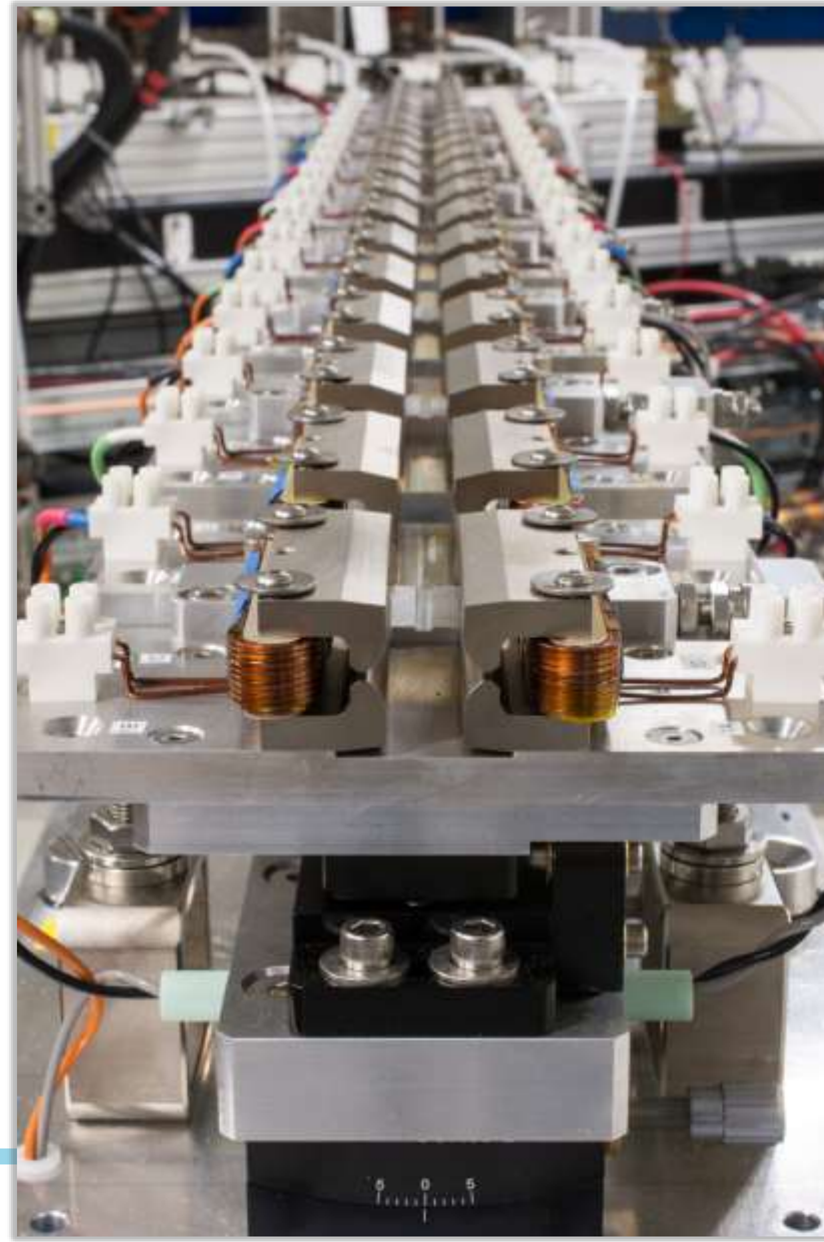
$$H_N = \frac{1}{2}(P_{xN}^2 + P_{yN}^2 + X_N^2 + Y_N^2) - \tau U(X_N, Y_N)$$

first invariant



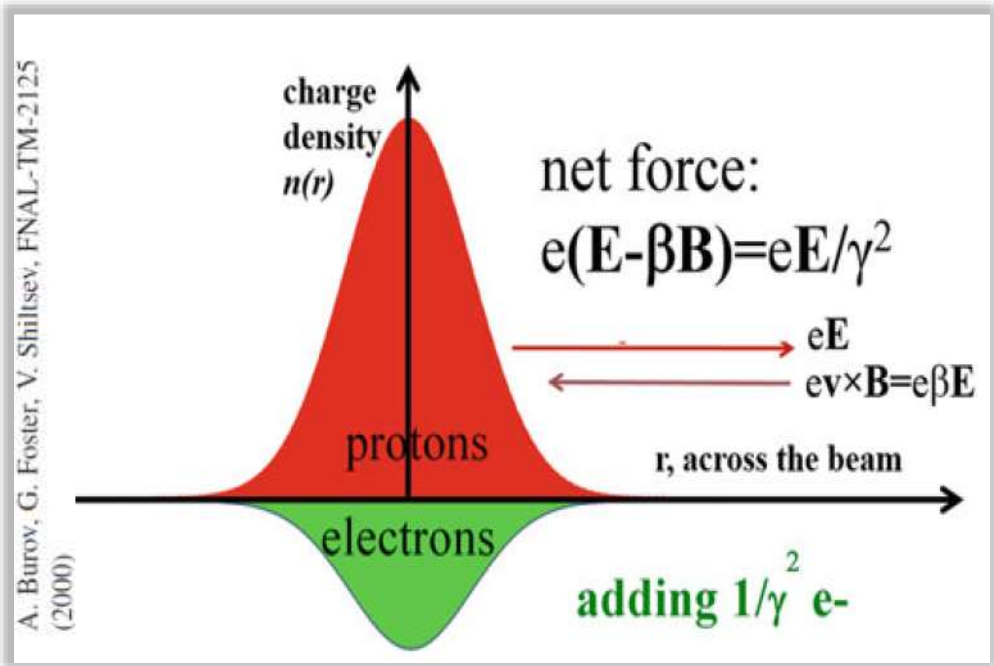
Non-Linear Integrable Optics Test

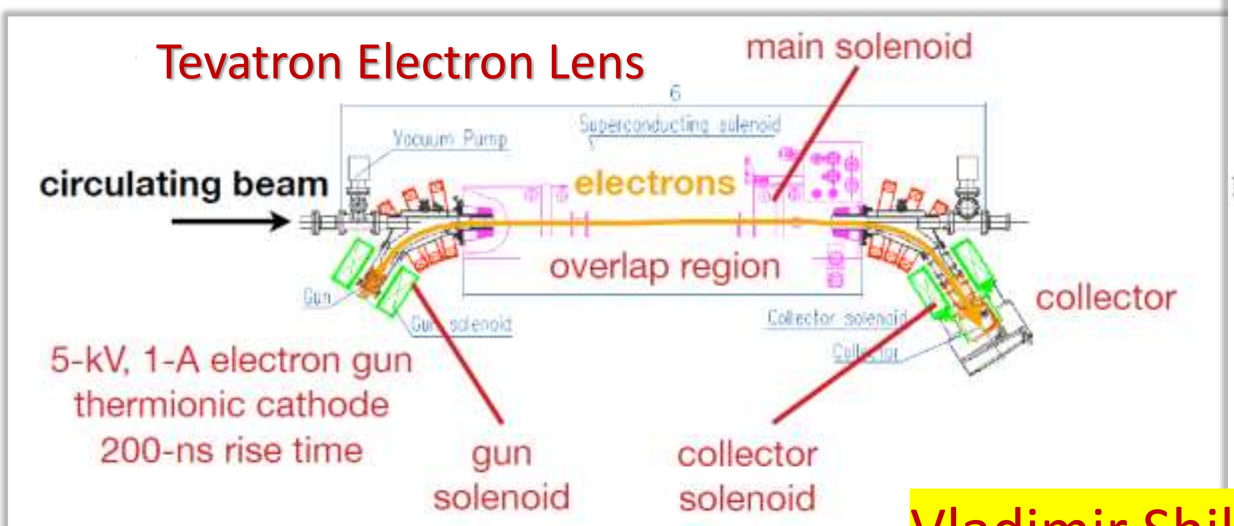
- Such a magnet is built and installed in IOTA
- Additional integral will be confirmed – first with “pencil” electron beam in IOTA
- Later, with high brightness, space-charge dominated proton beam
- Expect to demonstrate greatly improved coherent and incoherent beam stability

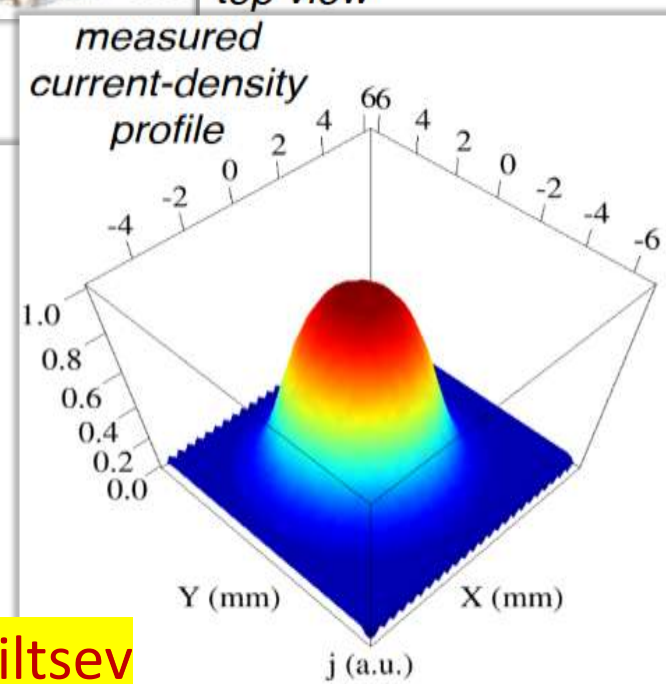


Alexander Romanov
Sergei Nagaitsev

Proton Space-Charge: Compensated by Electrons

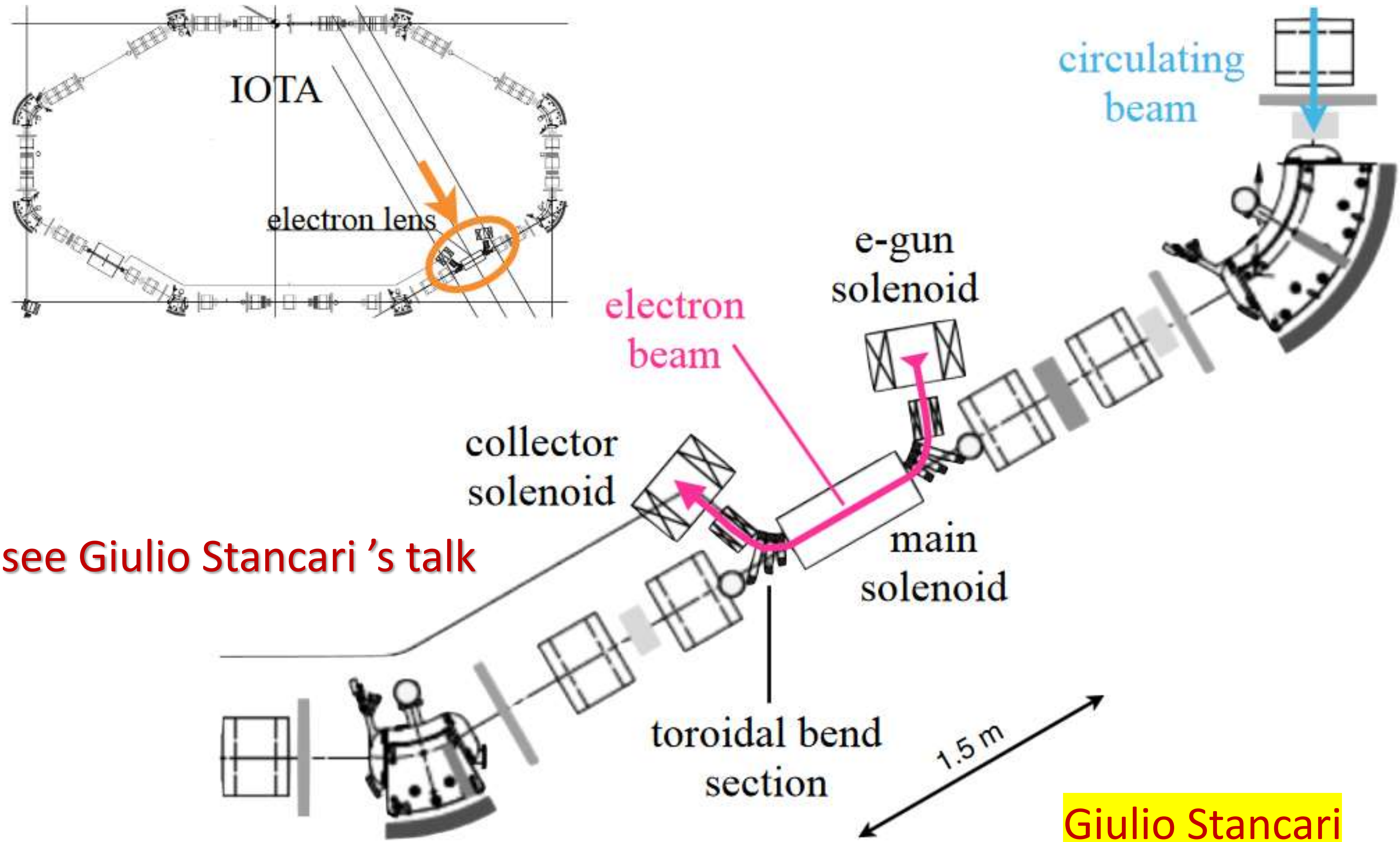






Vladimir Shiltsev

Electron Lens in IOTA

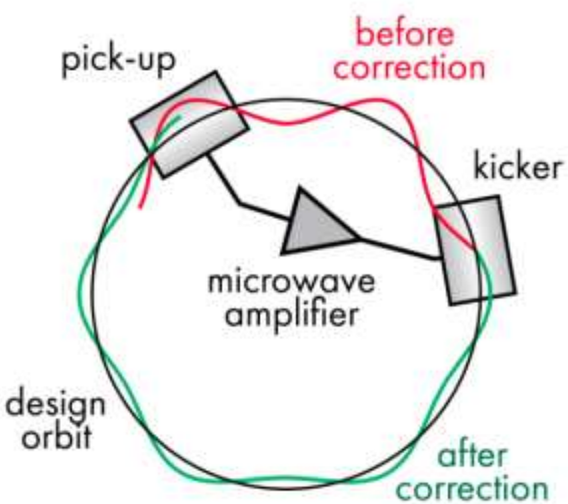


see Giulio Stancari 's talk

Giulio Stancari
Vladimir Shiltsev

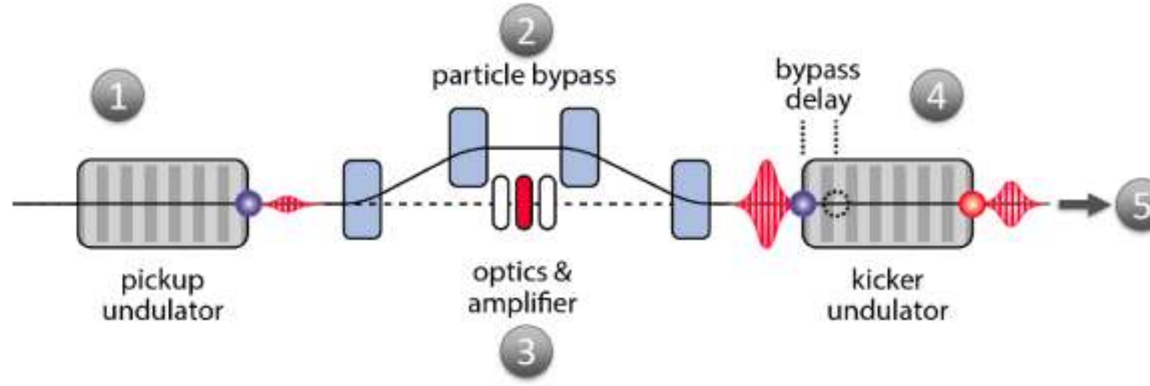
Optical Stochastic Cooling
from ~10 cm to 1 um wavelength

van der Meer, 1980's



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

cooling heating



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

- OSC promises new cooling scheme of relevance for high energy, high brightness proton bunches

[1] A.A.Mikhailichkenko, M.S. Zolotorev, "Optical stochastic cooling," Phys. Rev. Lett. 71 (25), p. 4146 (1993)
[2] M. S. Zolotorev, A. A. Zholents, "Transit-time method of optical stochastic cooling," Phys. Rev. E 50 (4), p. 3087 (1994)

- IOTA is designed to accommodate the OSC insert and proof-of-principle study with electrons

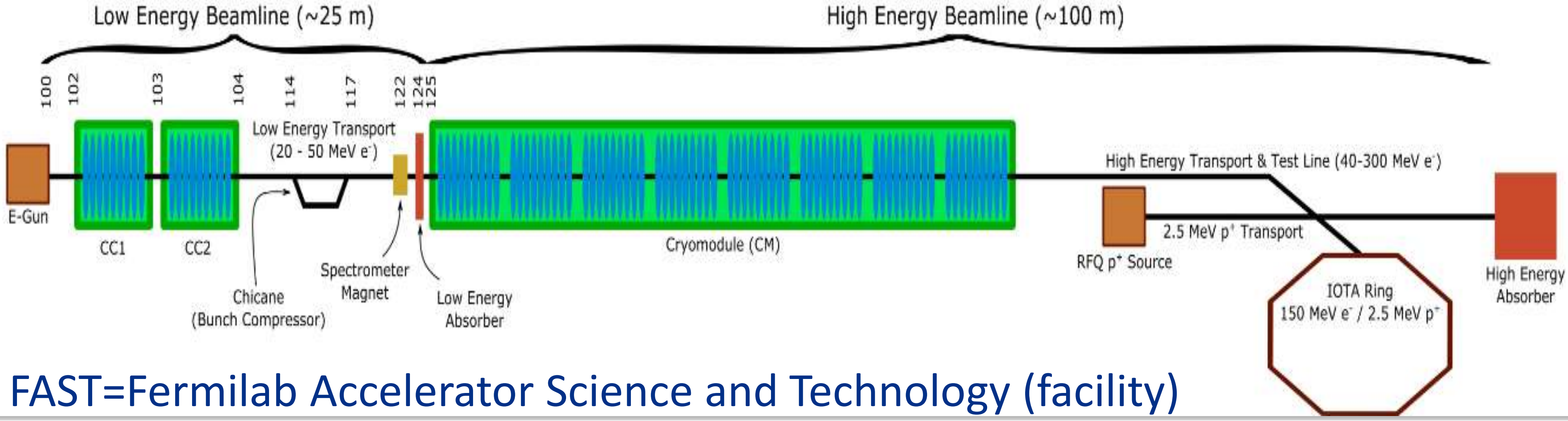
Jonathan Jarvis
Valery Lebedev

Experimental Studies of Fundamental Physics of Space-Charge Dominated Beams

Alexei Burov
Valery Lebedev

- In addition to the above high-impact innovative experiments, a number of beam studies toward deeper understanding of fundamental phenomena in SC-dominated beams will be carried out:
  - **Coherent instabilities, eg TMCI, and convective, with SC**
  - Landau damping and halo dynamics
  - Effects of linear and non-linear resonances
  - Magnet noise effects
  - Importance of lattice periodicity
  - High-order, eg, quadrupole, octupole, coherent SC modes
  - Etc, etc… plus, testbed for advanced beam diagnostics

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/SRF linacs*
- Accurate
- Affordable

http://fast.fnal.gov/

IOTA/FAST Timeline:

- 5 MeV e- beam – 2015
- 50 MeV e- beam – 2016
  - First experimental journal publications
- 300 MeV e- beam – 2017
  - Beam thru 1.3GHz CM to dump (record *MeV/m*); experimental program
- 1st e- beam in IOTA – 2018
  - Run I (NL optics, single *e*-)
  - Run II (OSC) - 2019
- 1st *p*+ beam in IOTA – 2020
- Experimental R&D program
  - For ~7 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
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** also at Northern Illinois University, DeKalb, Illinois, 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

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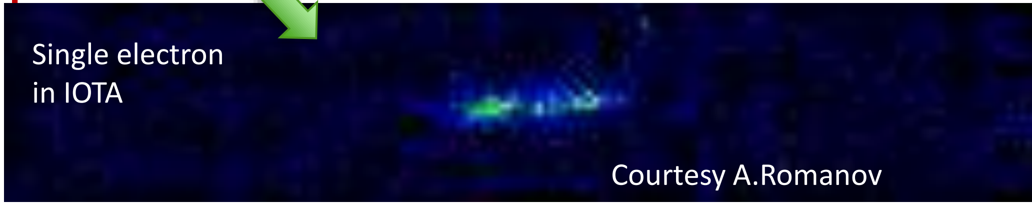
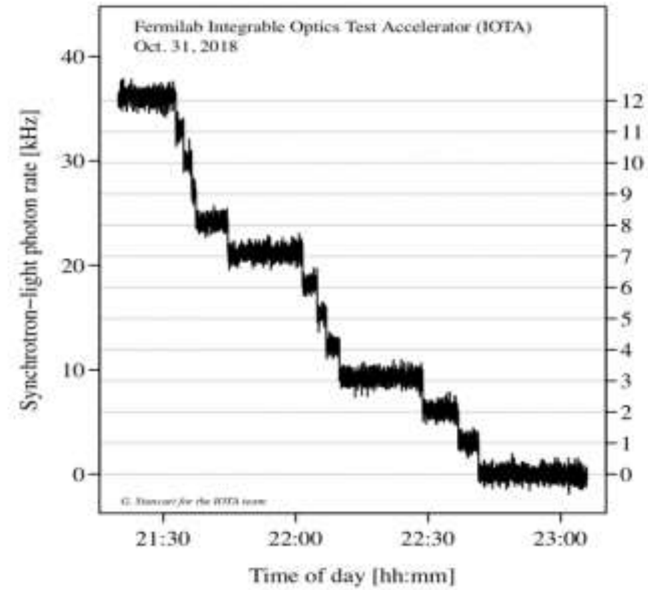
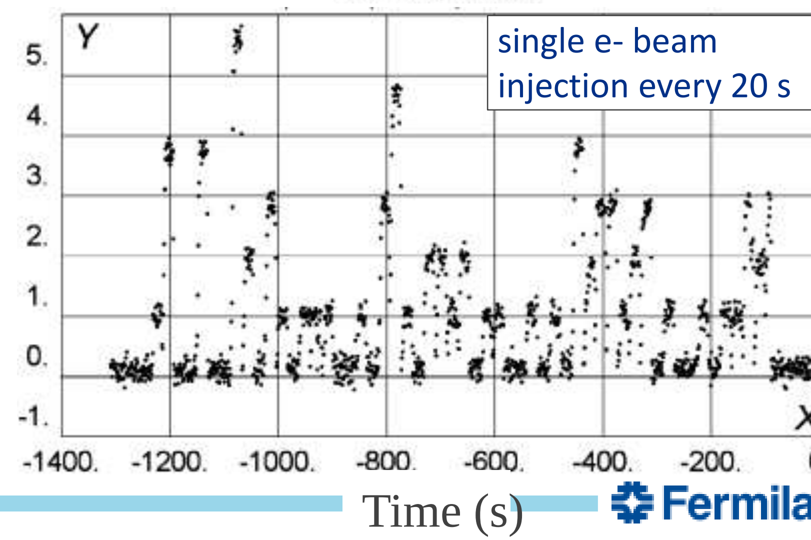


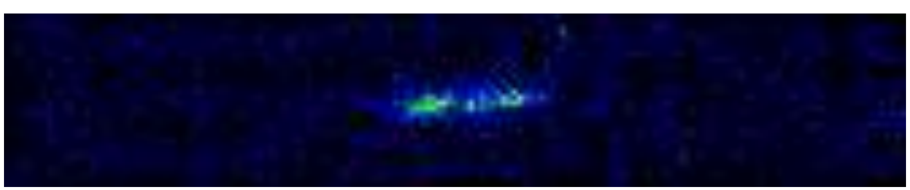
IOTA: unique opportunities in QS

Sasha Romanov,
Giulio Stancari, Sergei Nagaitsev

- IOTA demonstrated storage of a **single relativistic electron** for long periods of time (~10 minutes).
- High particle energy (100 MeV) enables observation of SR emission
- This opens the way to a wide variety of quantum experiments
- Recent One-day **Workshop on Single-Electron experiments in IOTA** – 30 participants from U.Chicago, LANL, SLAC, ANL, Princeton, RadiaBeam, BNL, UC Berkeley, Fermilab







IOTA/FAST Collaborators

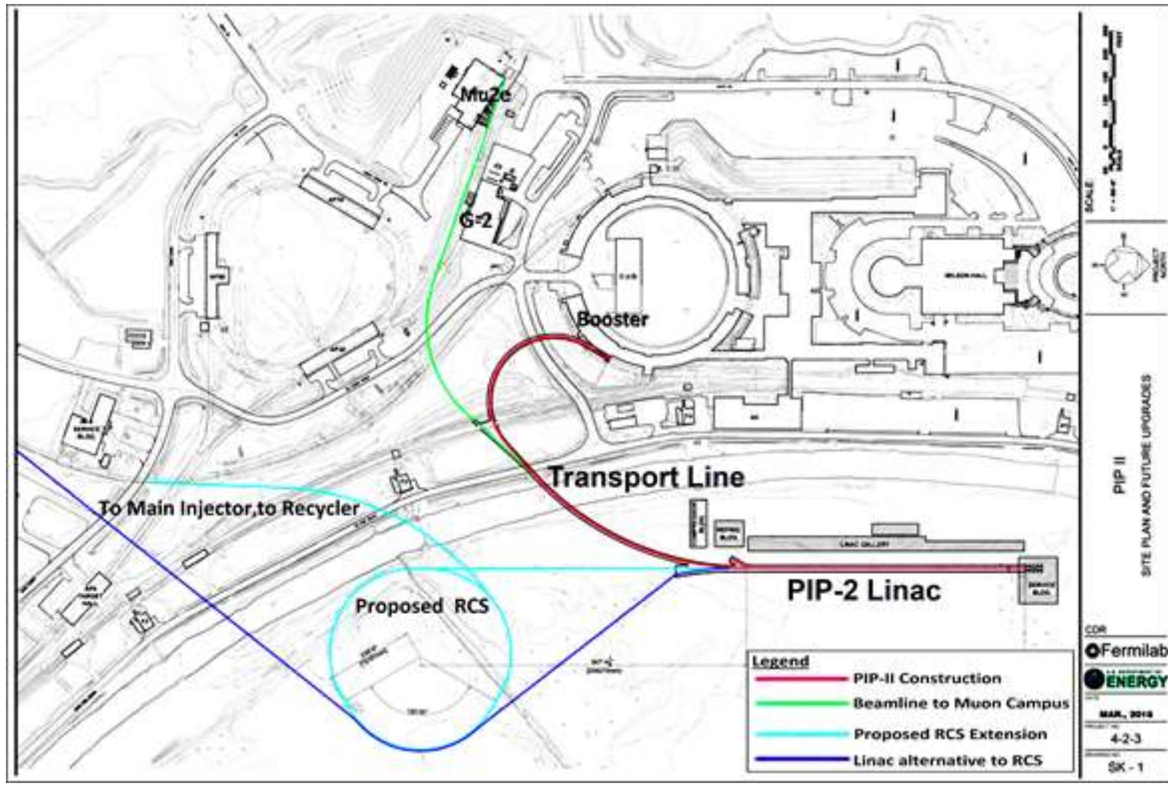
- **29 Partner Institutions:**
  – ANL, Berkeley, BNL, BINP, CEA/Saclay, CERN, Chicago, Colorado State, Fermilab, DESY, IAP Frankfurt, JAI, JLab, JINR, Kansas, KEK, LANL, LBNL, ORNL, Maryland, U. de Guantajuato Mexico, NIU, Michigan State, Oxford, Radia Beam Tech, RadiaSoft LLC, Tech-X, Tennessee, Vanderbilt
- **NIU-NICADD:** **strategic ties**
- **EIC/MARIE/BES:** many critical tests are possible
- Annual IOTA/FAST Workshops-Collaboration Mtgs 2013-2019

"PIP-III": Next-Generation Proton Complex at Fermilab

DUNE/LBNF long-baseline neutrino program calls for Fermilab beam power to be further doubled to **2.4 MW**. This will require a new particle accelerator!

Rapid-Cycling Synchrotron (RCS)
new proton ring
based on cutting-edge
beam dynamics

or New H- Linac
based on cutting-edge
SRF technology



The new accelerator would set the stage for Fermilab's post-DUNE future…

"PIP-III": R&D Topics

Jeff Eldred

Incorporate new Fermilab technologies into RCS design:

- **nonlinear integrable optics** mitigations beam instabilities and halo formation without introducing unwanted resonances.

- **electron lens** a versatile particle accelerator device with applications in collimation, nonlinear focusing, and direct space-charge compensation.

- **HTS superconductors** to design a high-energy, highly-efficient particle accelerator on a compact footprint.

Henryk Piekarz

Envision future rings & beamlines at Fermilab:

- **stored muon program (i.e. NuSTORM)** from 10-12 GeV RCS, provides a gateway to muon accelerator program.

Alan Bross

- **surface muon program (i.e. J-PARC MLF)** from 2-3 GeV linac, for a precision science and material science programs.

- **dedicated proton accumulators rings** at 1 GeV and/or 10-12 GeV, optimize for beam-stacking and slow-extraction techniques.

Accelerator R&D at FNAL Machines

Jeff Eldred, et al

Fermilab Linac Department

Laser Manipulation of H- Beams including **longitudinal collimation** and **pulse-shaping** techniques.

David Johnson

Neural Networks / Machine Learning of variable and complex **accelerator systems** including ion-sources, RF-accelerators, focusing elements, and power-supplies.

Kiyomi Seyia

Fermilab Booster Department

Jeff Eldred, CY Tan

Beam dynamics studies

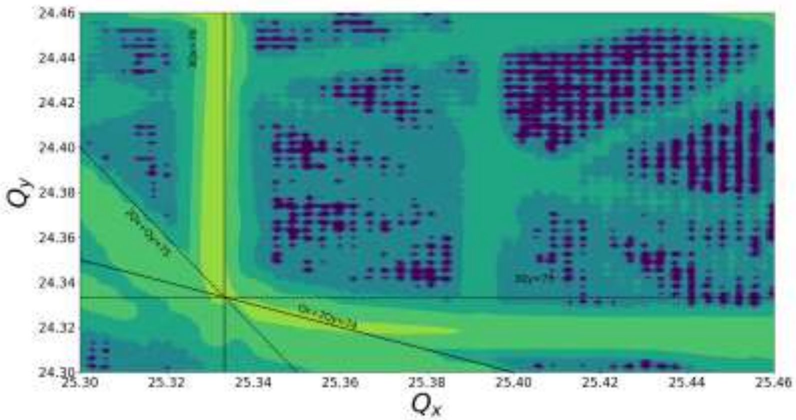
- **Cancellation of betatron resonances** for intense beam operation.
- **Develop new diagnostics** including ionization-profile monitors, PMT-based loss monitors, and high-bandwidth stripline.
- **Kalman filter (dynamic Bayesian modeling)** of Booster optics.

Simulations for Fermilab PIP-II intensity upgrade:

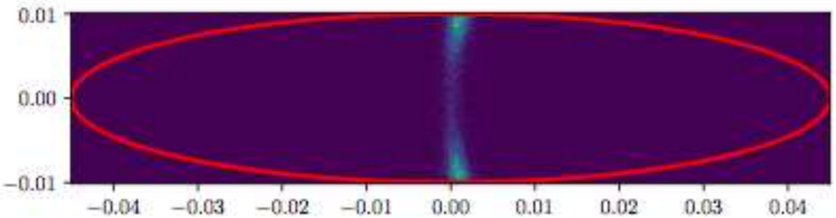
- **Transverse & Longitudinal Painted Injection**
- **Transition-Energy Loss** with novel crossing schemes.

Research topics in 8 GeV Recycler Ring and Main Injector

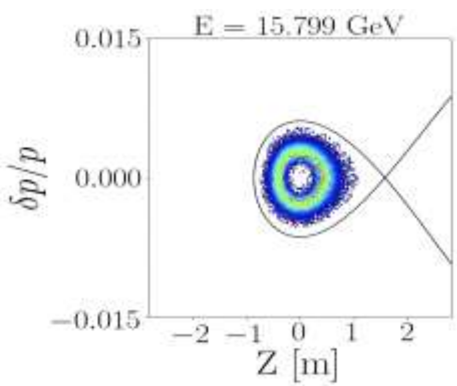
Rob Ainsworth



- Develop **compensation schemes** for detriemental lattice resonances



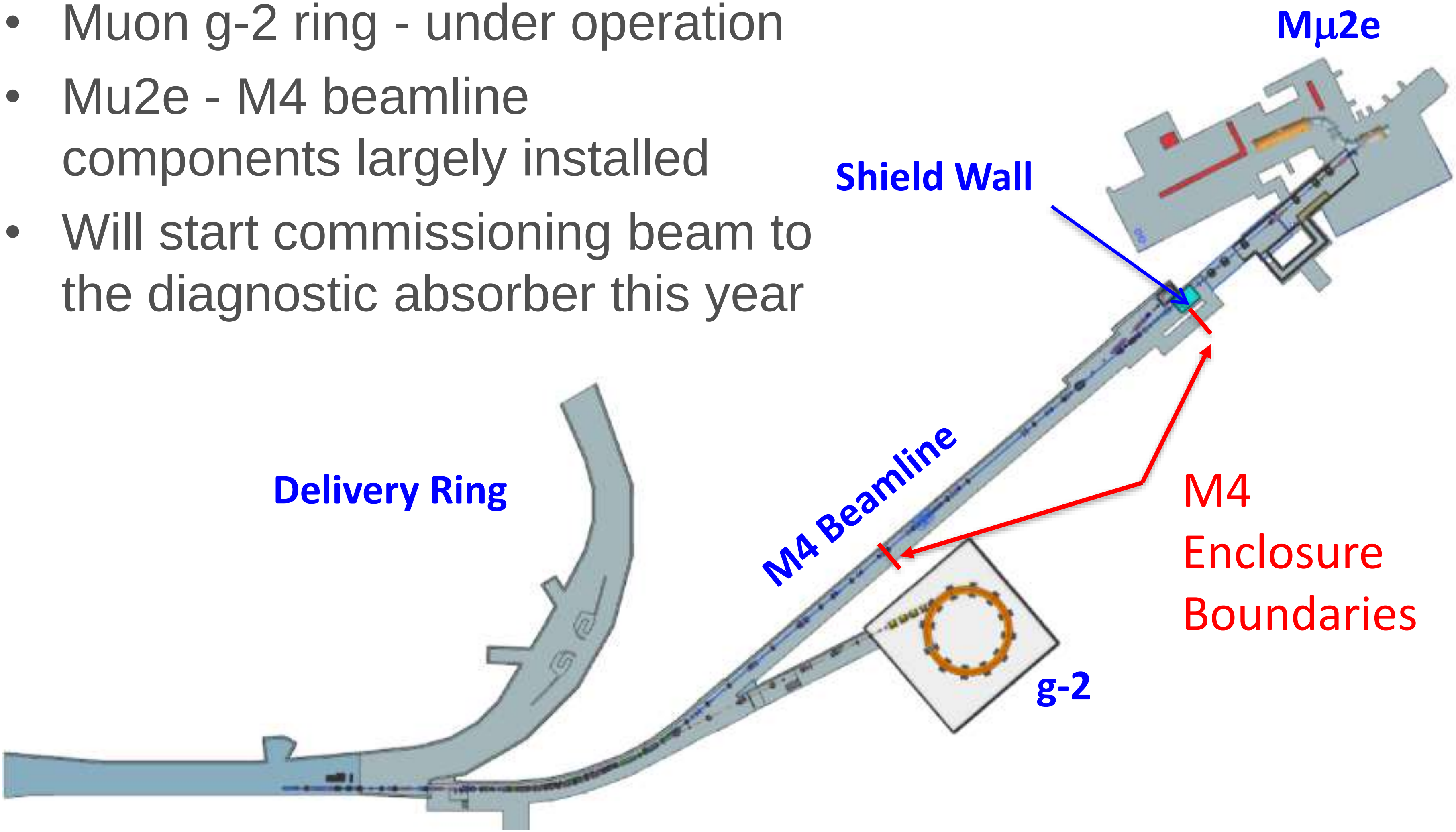
- **Electron cloud** simulations/measurements in RR



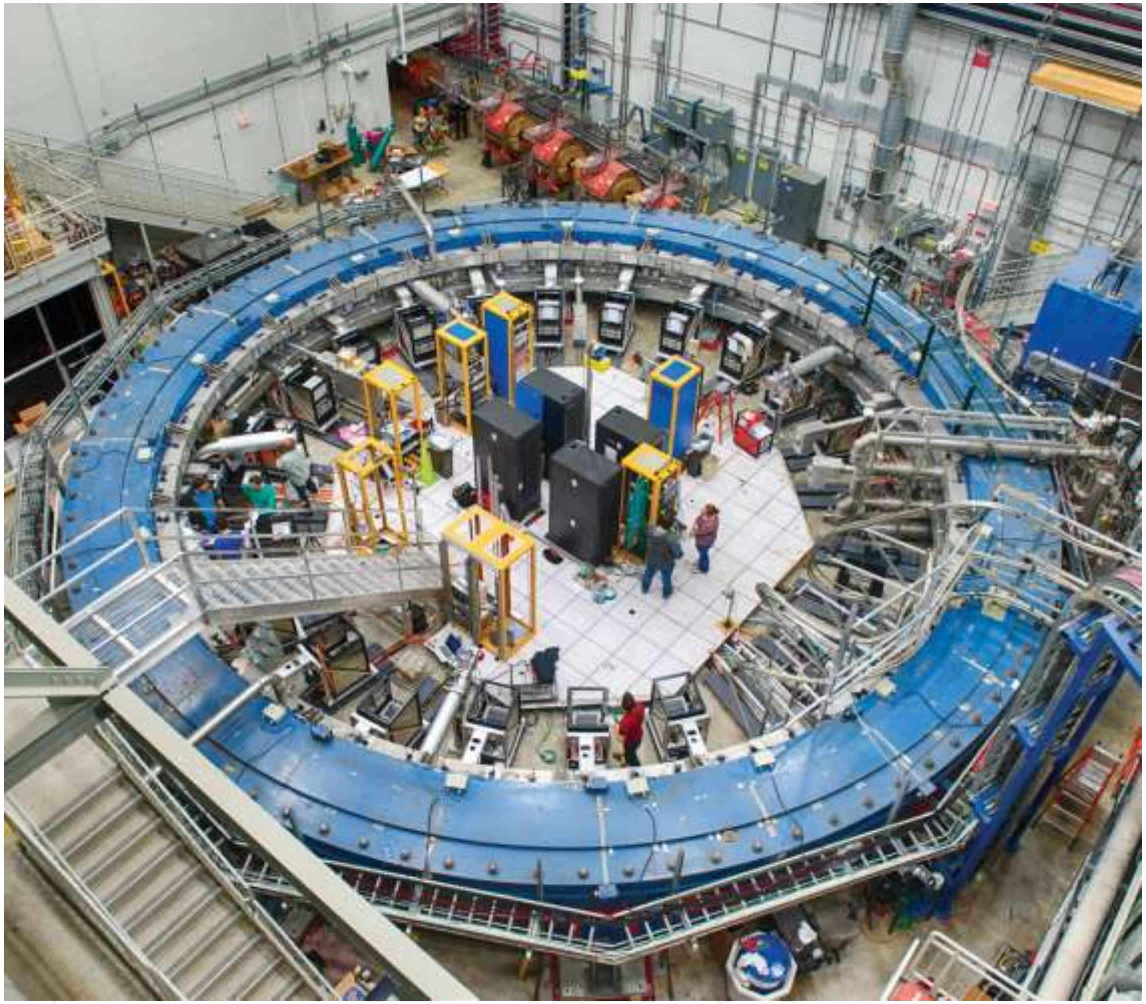
- **Impedance studies/control**
  - Instabilities in RR
  - Transition crossing in MI

Secondary beams (muons): Muon g-2 and Mu2e

- Muon g-2 ring - under operation
- Mu2e - M4 beamline components largely installed
- Will start commissioning beam to the diagnostic absorber this year



Muon g-2 experiment

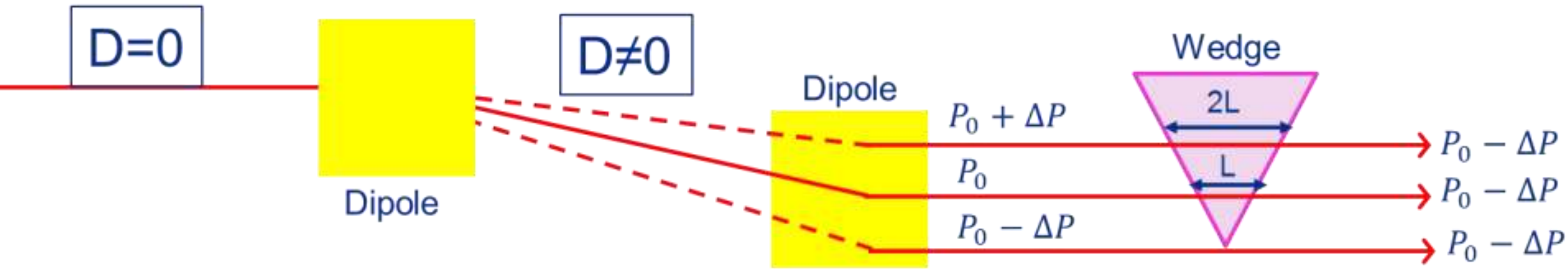


- Experiment began taking data in May 2017

Momentum control of secondary beams

Diktis Stratakis

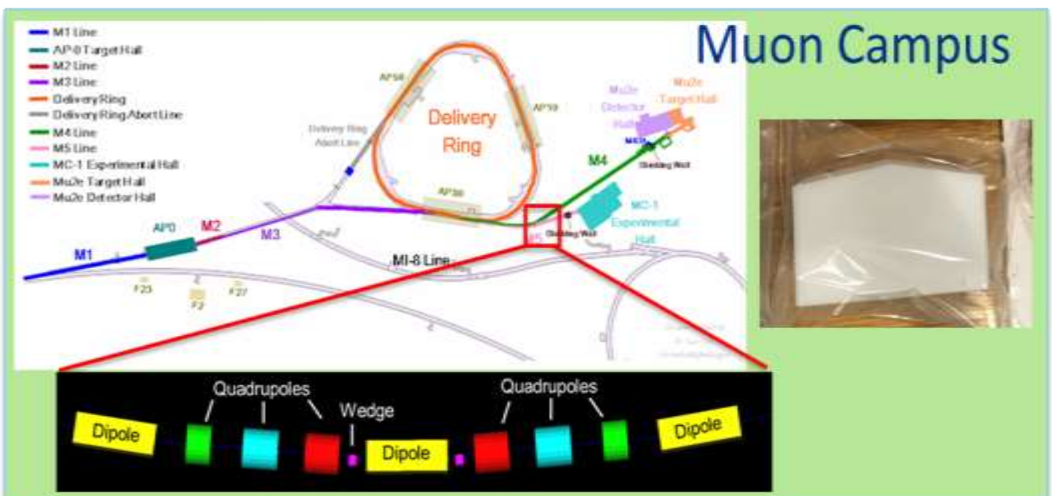
- Secondary beams can have a significant energy spread and users can benefit from increasing the particle count near the target energy
- The technique relies on inducing momentum dispersion by means of a dipole magnet and subsequently passing the beam through a wedge absorber so that faster particles will get decelerated more than the slower ones

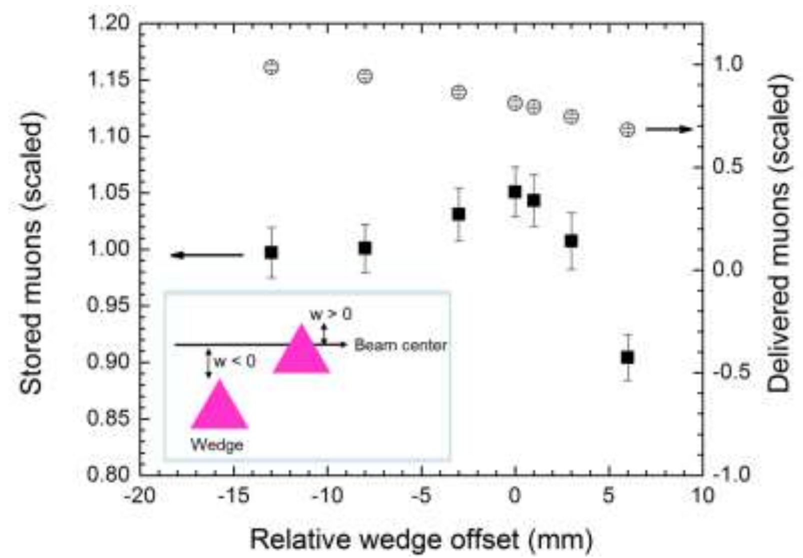


Application

Diktis Stratakis

- We found a practical implementation of this idea to the Fermilab Muon g-2 Experiment and performed a proof-of-principle demonstration.
- Ongoing work to extend the concept for other secondary beam based experiments at Fermilab, i.e. Mu2e, Mu2e-II.
- Three year funding received via Fermilab's LDRD program





Fermilab

Theory/Modeling/Simulations

- **Synergia – simulations of complex effects** Eric Stern
  - Space-charge modes and Landau damping
  - Impedances and wakes
  - Slip-stacking and transition crossings
  - Space-charge compensation
- **MARS – energy deposition simulations** Nikolai Mokhov
  - Targetry
  - Backgrounds
  - Halo collimation
- **Theory and experiments**
  - Instabilities, electron cloud & impedance
  - Beam-beam
  - Nonlinear systems

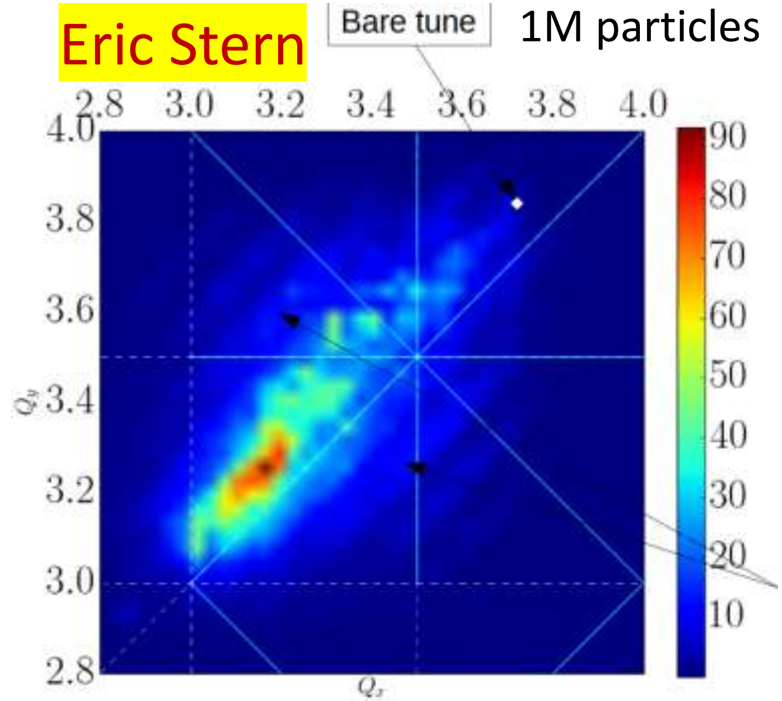
Alexei Burov
Yuri Alexahin
Tim Zolkin

Synergia - PIC "Heavyweight" Code

Self-consistent 6D Particle-in-cell ***"open source"*** code, unique:

- Simulate combined beam optics and collective effects (space charge and impedance).
- All the usual magnetic elements, RF cavities. Apertures and elements all agree with MAD-X.
- Now includes electron lens element
- Collective operations included with beam transport symplectically using the split-operator method.
- PIC space charge solvers 2.5D, 3D, B-E, KV
- Detailed impedance using wake functions
- Multiple bunch beams & coherent bunch modes

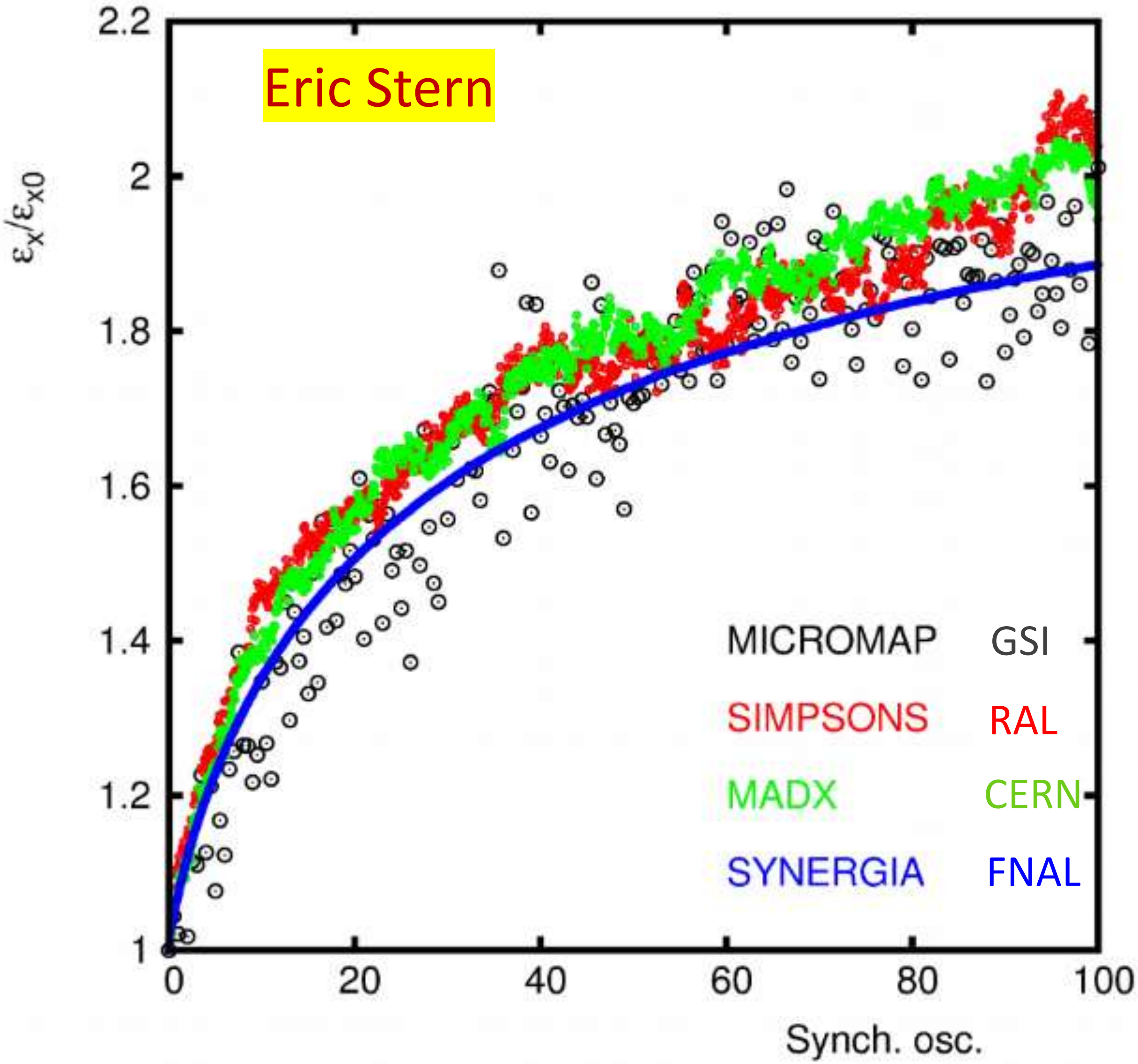
Eric Stern



Widely used for simulations of Fermilab machines and IOTA

- Code development supported by the DOE SciDAC program since 2001
- Synergia is currently part of the SciDAC4 ComPASS4 project
  - Collaboration led by FNAL and includes collaborators from ANL, LBL and UCLA. It is funded to enable simulation of beam dynamics for PIP-II and IOTA at Fermilab as well as plasma acceleration at FACET-II
- Parameteric Landau damping and other important scientific discoveries thru advanced computer simulations

Synergia Validated with *GSI Space Charge Benchmark*



Int'l Space-Charge Collaboration:

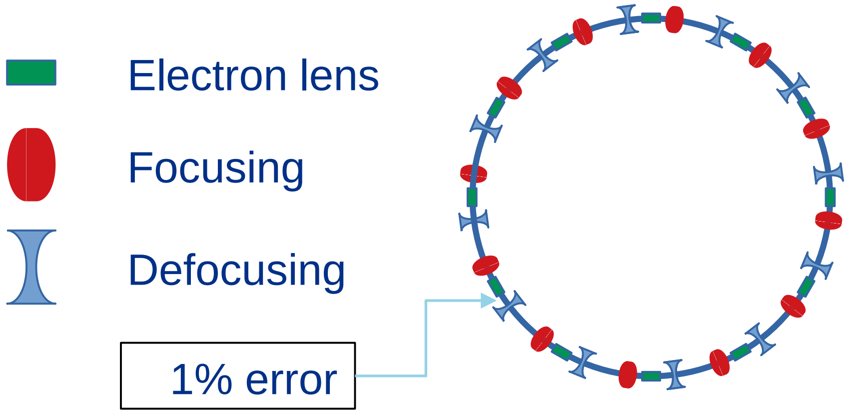
Fermilab, CERN, FAIR, ICFA, Berkeley Lab, GSI, University of Maryland, Technische Universität Darmstadt, Science & Technology Facilities Council Rutherford Appleton Laboratory

Synergia is "the best" – most precise and most stable

(state-of-the-art for beam dynamics – ran on 140,000 processors)

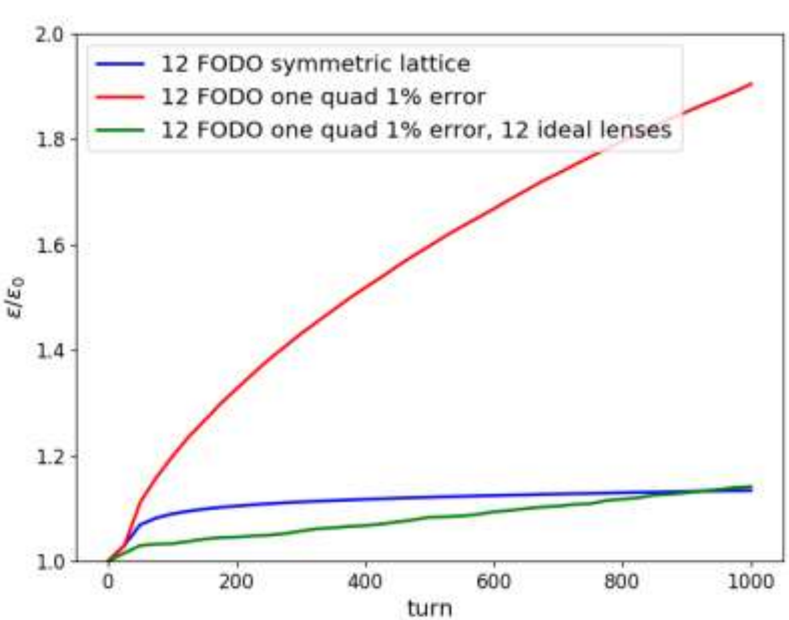
Extreme space charge dQ=-1 with elens compensation

Eric Stern, Vladimir Shiltsev
Yuri Alexahin, Alexei Burov

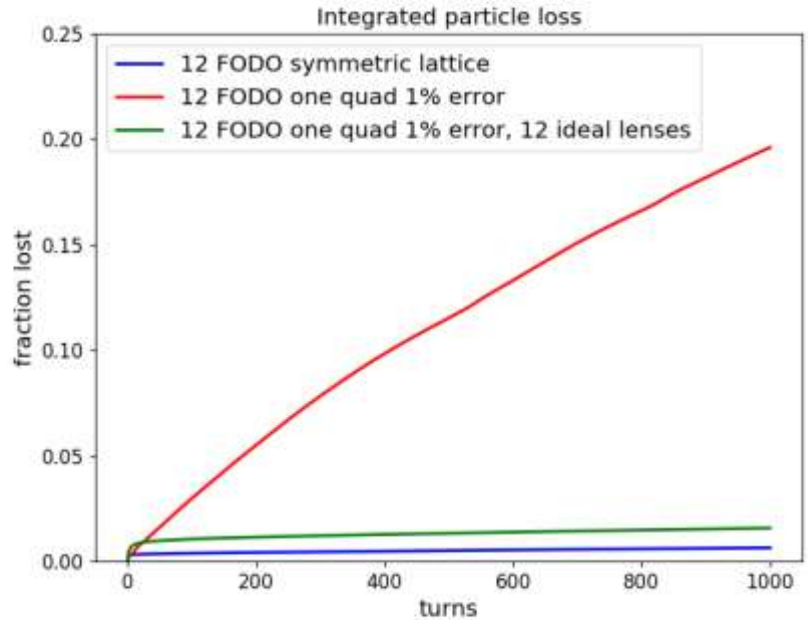


1000 turns
dQ_{SC} = -0.9
Lattice error in one element

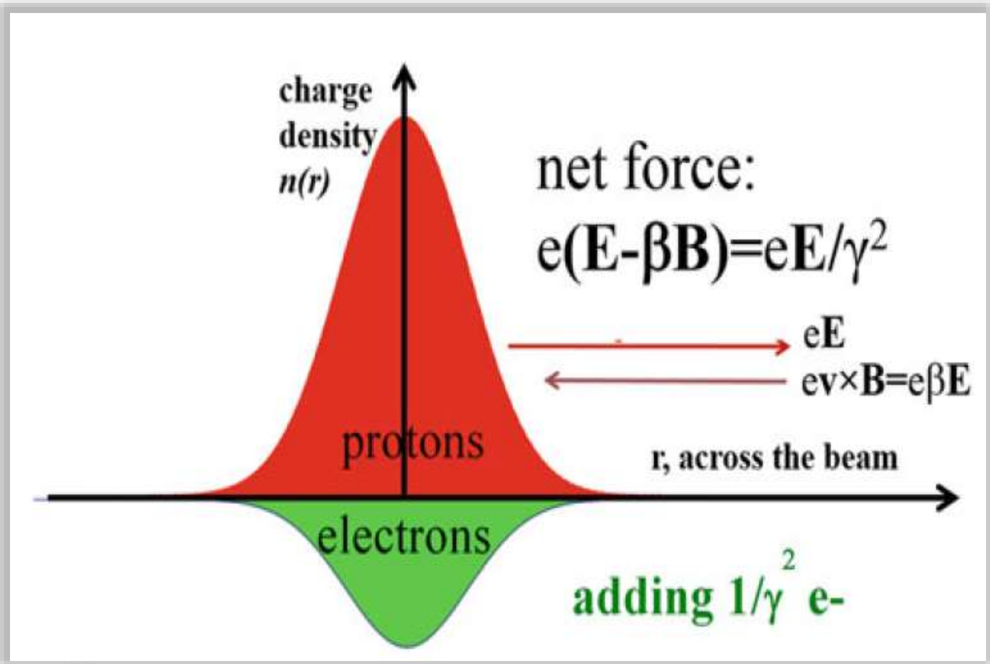
RMS x emittance growth

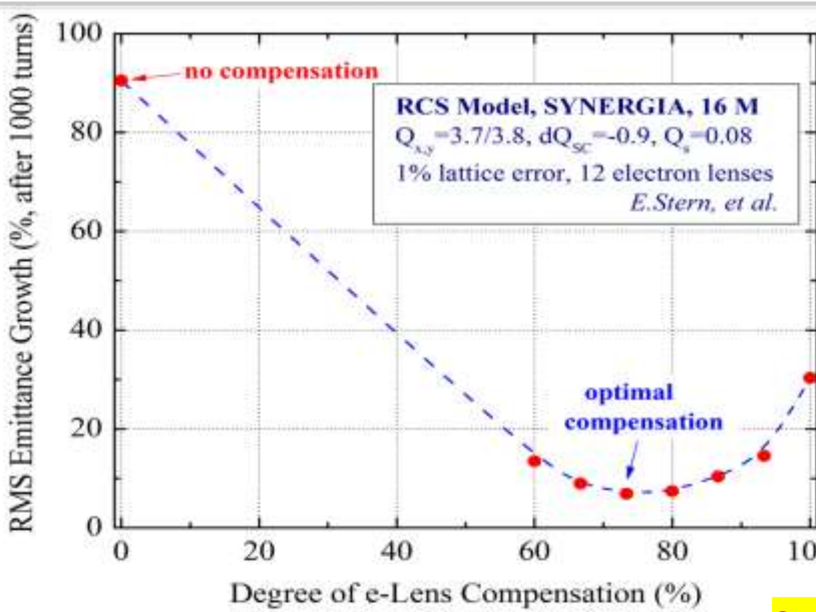


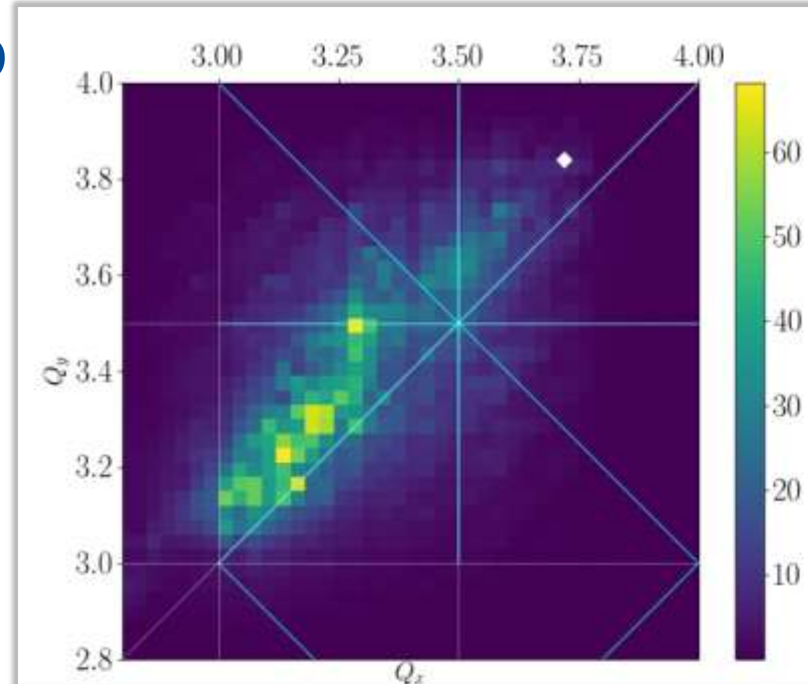
4 sigma aperture loss

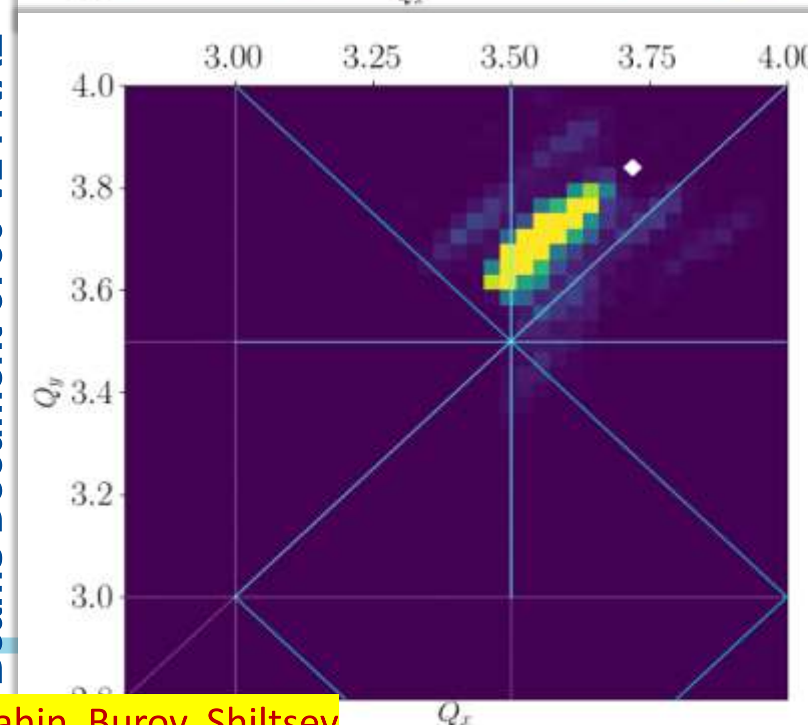


Space-Charge Compensation R&D









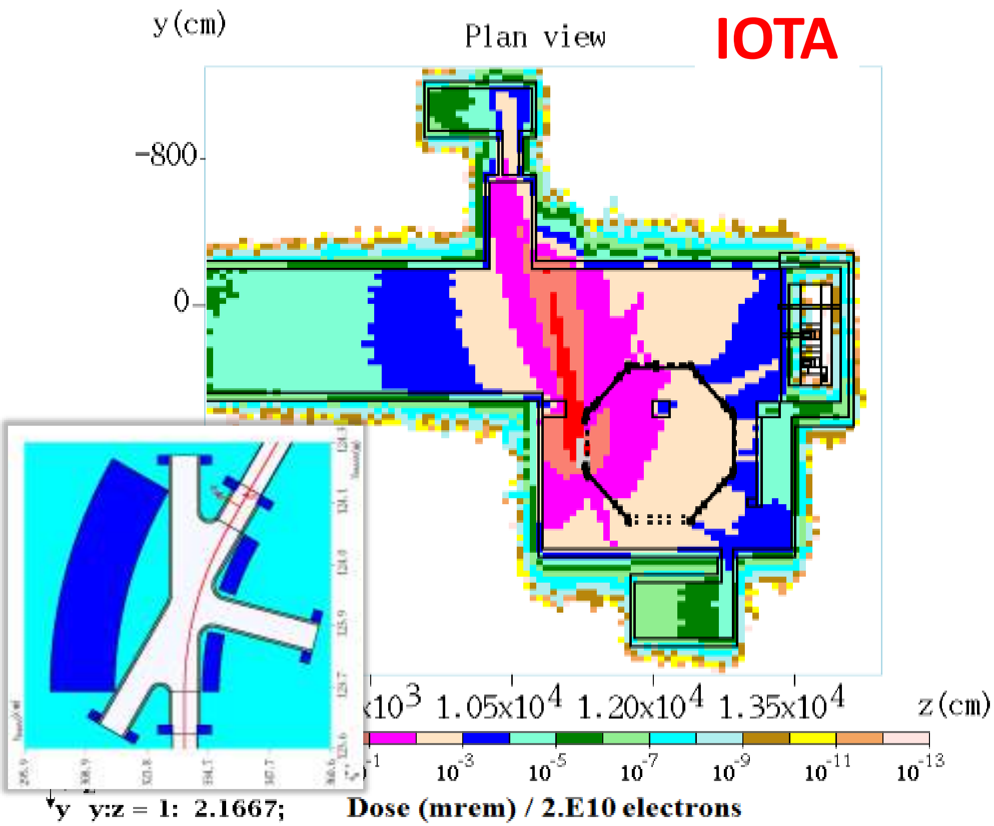
Stern, Alexahin, Burov, Shiltsev

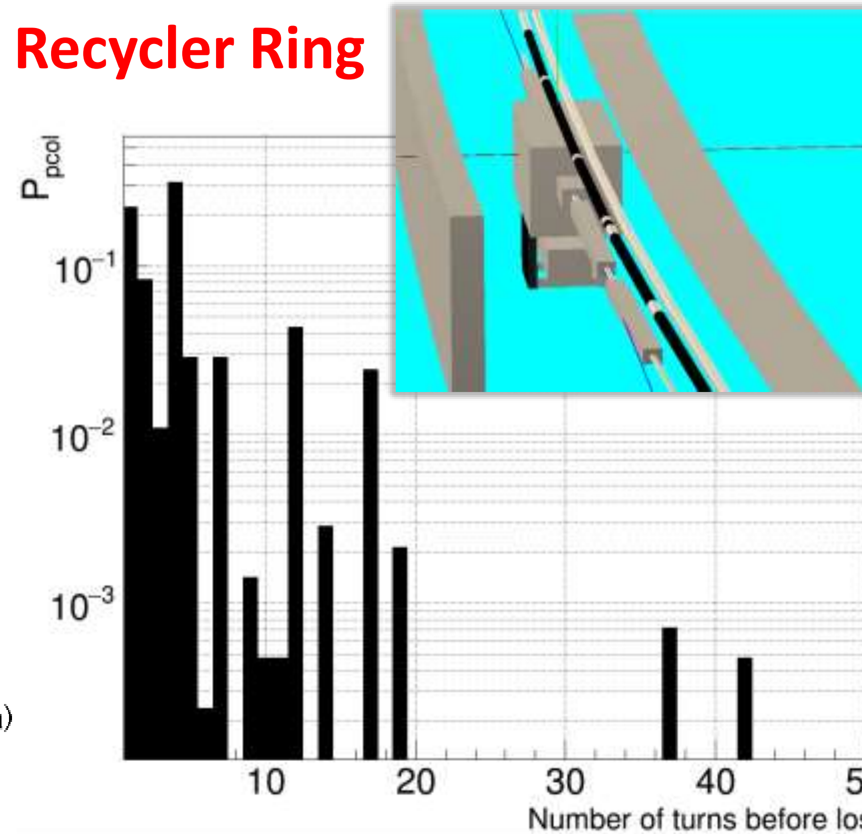
MARS: ED and Halo Collimation Analysis Tool

MARS15 - MADX/PTC

Nikolai Mokhov

The newest MARS15 version for particle interactions and transport in accelerator components integrated with MADX-Polymorphic Tracking Code (PTC) unit. This allows cross-talk between two codes for precise multi-turn modeling of beam loss and induced impact on accelerator components. Recent successful applications include ESH analysis of the IOTA beam accidents and design of the Recycle proton collimation.





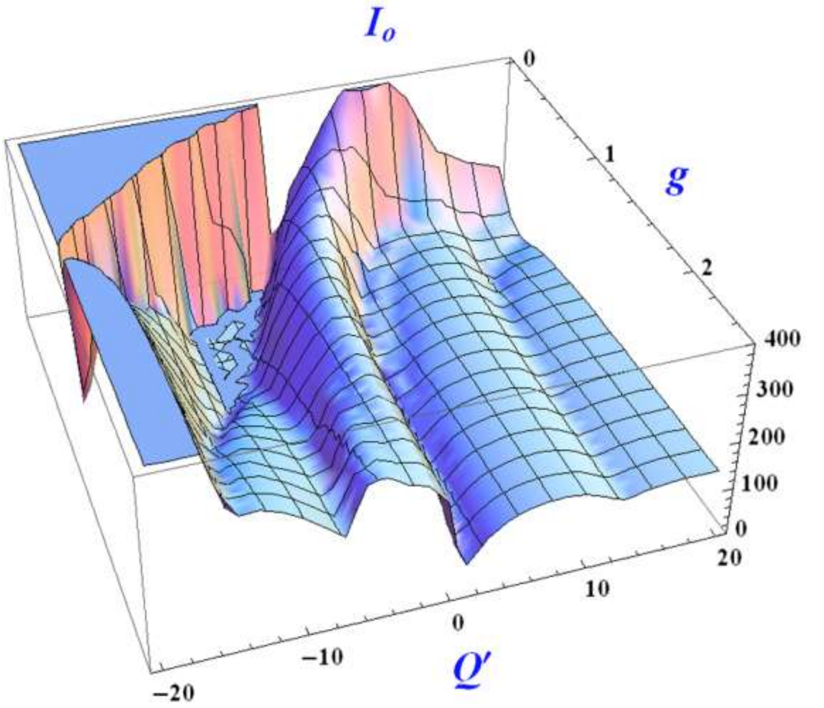
I.Tropin, F.Schmidt, N.Mokhov

Theory of Collective Instabilities in High-Intensity Beams

Alexei Burov

Topics covered:

- TMCI and space-charge effects
- SC and Landau damping
- SC and electron lenses
- SC or beam-beam and dampers
- Single- and coupled-bunch wakes and dampers
- Instabilities in PWA
- ***Convective instabilities***
- “Three beam” (BBB) effects (impedance, beam-beam and e-cloud)



TMCI threshold octupole currents vs chromaticity and feedback system gain

People:

A. Burov, V. Balbekov, Y. Alexahin, V. Lebedev, E. Stern, V.Shiltsev, A. Valishev, T. Zolkin et al.

Technology and Systems

- **Superconducting magnets**
  - Record breaking fields
  - Conductor studies and developments
- **Superconducting RF**
  - Quality factors and gradients
  - New materials (NB3Sn)
  - Cost saving ideas
- **Systems**
  - Industrial SRF electron accelerators
  - Qubit / QIS systems
  - RF for Dark matter search

Sasha Zlobin
Xingchen Xu
Tiziana Spina

Anna Grasselino
Alex Romanenko
Sam Posen

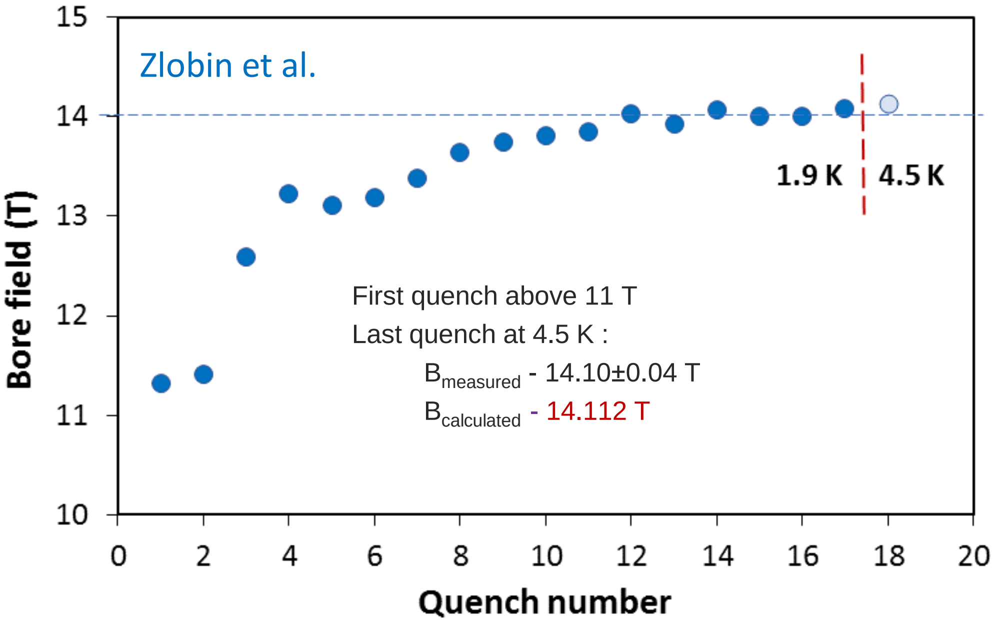
Charles Thangaraj
Eric Holland
Dan Bowring

Superconducting Magnets Frontier : 15 T Dipole

- Such magnets are critical for future colliders (FCC, Muon, e-i)
  - **Strong collaborations in the US, worldwide**

Sasha Zlobin

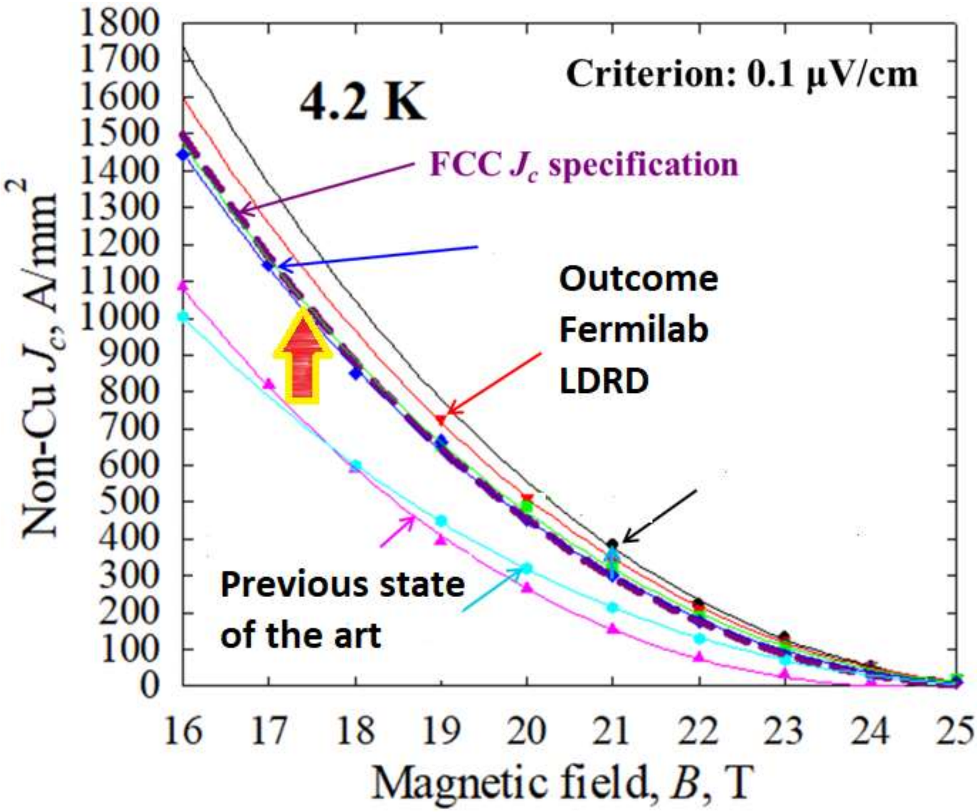
- Nb3Sn Dipole MDPCT1 was tested in June 2019
  - The magnet produced a **world record field of 14.1 T** (at 4.5 K) for an accelerator dipole (limited by mechanical pre-stress)
  - The magnet is being re-assembled with increased pre-stress to allow reaching the design filed of 15 T



Highlighted in *FermilabNews* and *CERN Courier* articles

Challenge Current Density in Type-II SC

Xingchen Xu



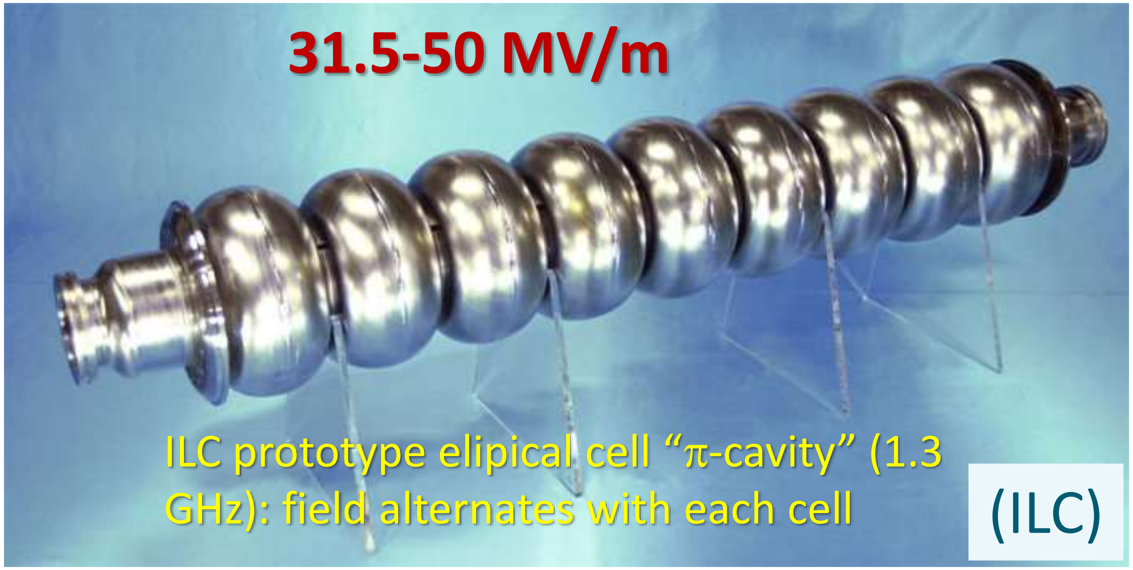
Nb_3Sn conductor R&D

Artificial Pinning Center (APC)

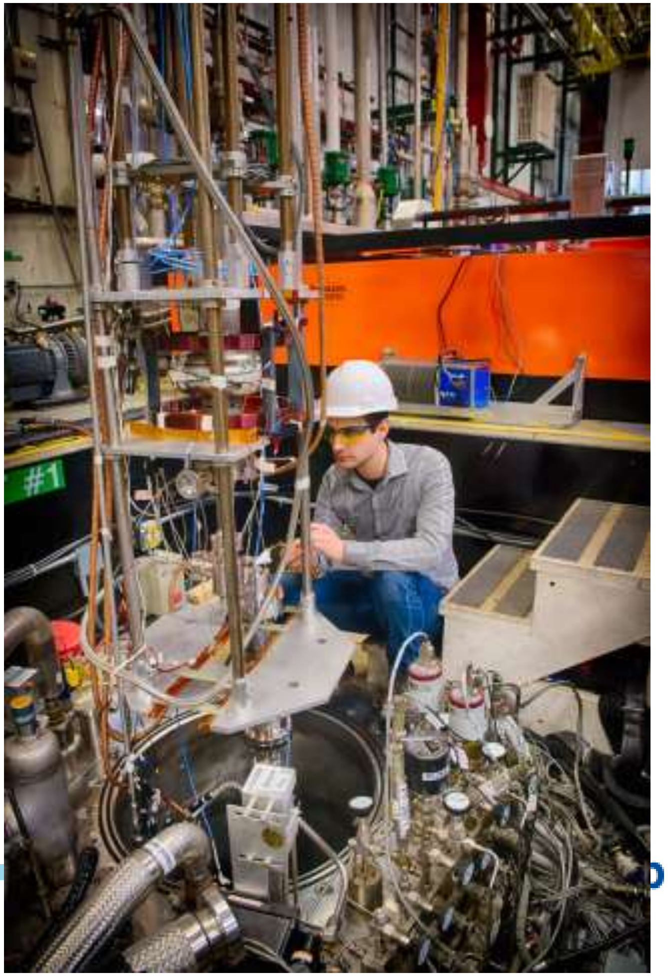
- Nb_3Sn wires, record J_c, meet or exceed the FCC specifications (X. Xu et al.)

Xingchen Xu received the prestigious DOE Early Career Award for the development of next-generation niobium-tin superconductors for energy frontier circular colliders

Superconducting RF : Backbone of Modern and Future Accelerators



Fermilab is world leader in cavity processing physics and techniques



Main R&D Thrusts:

New materials (*Nb3Sn*) –

higher gradients

New techniques (*Nb on Cu*) –

lower cost

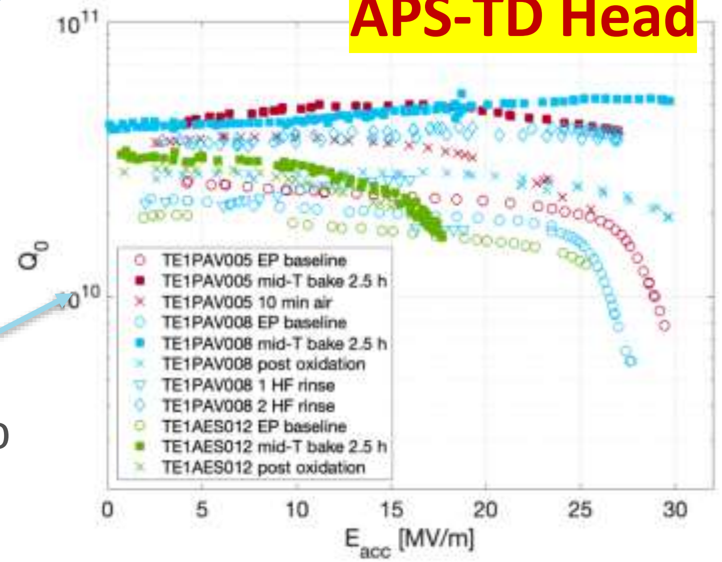
Surface treatment (*N2 doping*) –

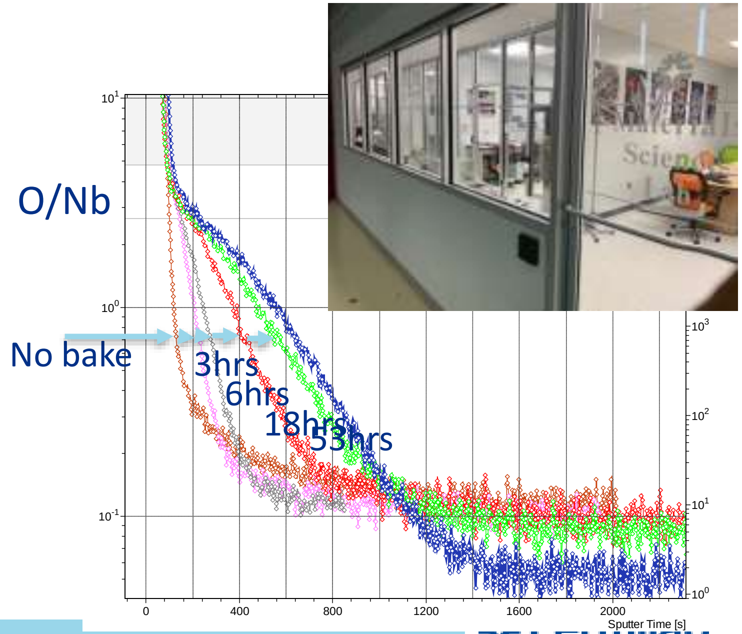
higher Q_0 and lower operation cost

SRF R&D: some recent highlights

Sergei Belomestnikh, APS-TD Head

- Continuing to push the performance envelope
  - Record Q factors at <u>higher</u> gradients
  - New mid-T heat treatments developed
    - Advance the quantum regime Q's
    - Produce doping effect without adding nitrogen
  - Successful plasma processing demonstrations to suppress field emission in situ
  - Nb_3Sn cavities - record gradient achieved
- Understanding the physics
  - Mild baking (120C) effect understood using the state-of-the-art MSL equipment
  - Material level drivers for flux expulsion being explored
- Employing SRF cavities as sensitive new physics detectors
  - Dark photon search started



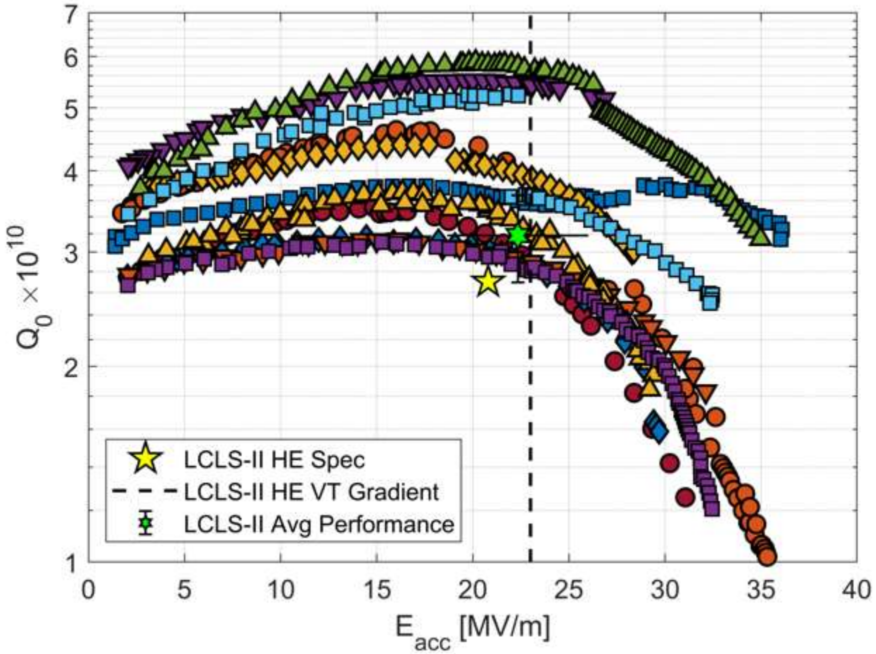


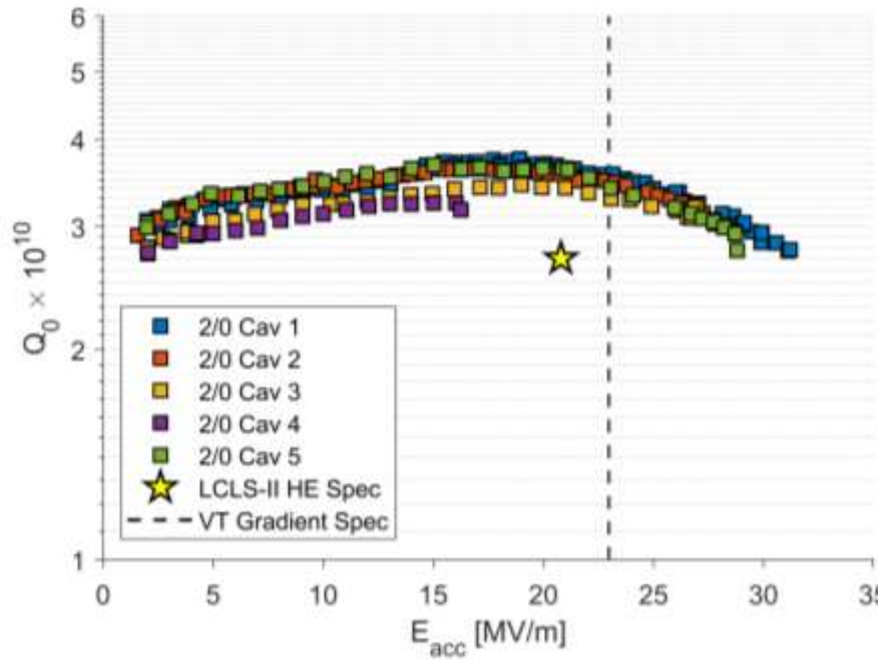
SRF R&D: pushing high Q to higher gradients

Anna Grasselino
Martina Martinello

- Research supported by HEP and BES (LCLS-II HE)
- Pushing nine-cell cavity performance from average 24 MV/m to > 30 MV/m with Q at mid field ~ 3e10 at 2 K
- Very important for increasing luminosity of ILC, and all CW SRF machines

Single-cell and nine-cell results with new doping process giving *E_{acc}* > 30 MV/m

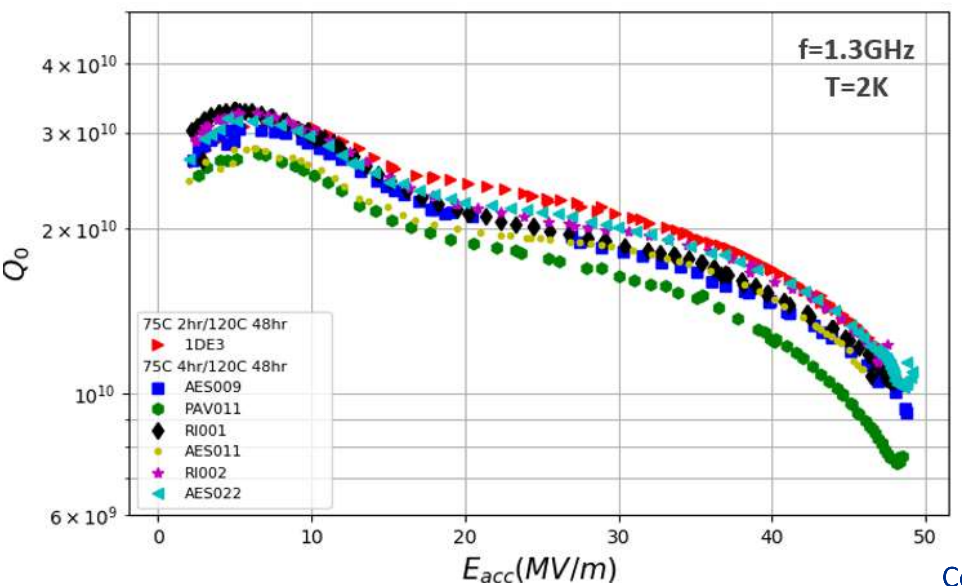


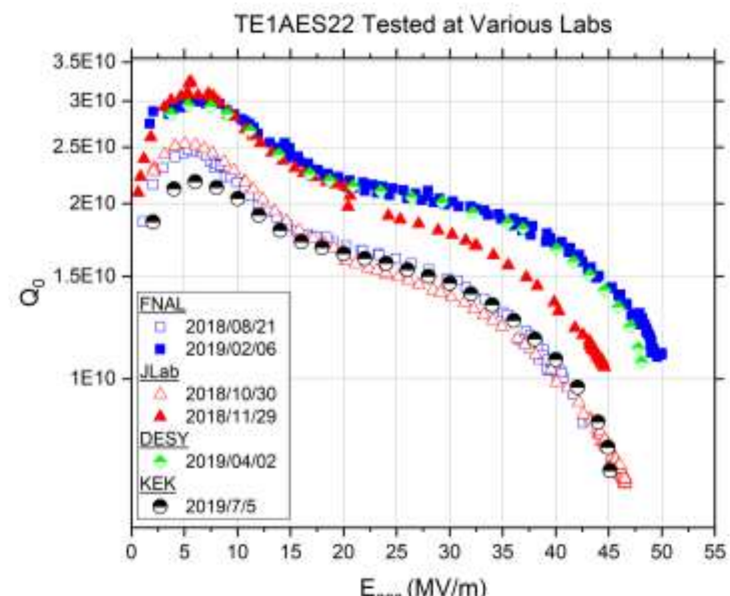


SRF Record : very high E_{acc} up to 50 MV/m

Anna Grasselino

- Recent advancements in low temperature bake and electropolishing are producing accelerating voltages never achieved before in tesla shape cavities
- Cavity sent for verification of performance in all major SRF labs worldwide show perfect agreement in performance (even in curious performance bifurcation)



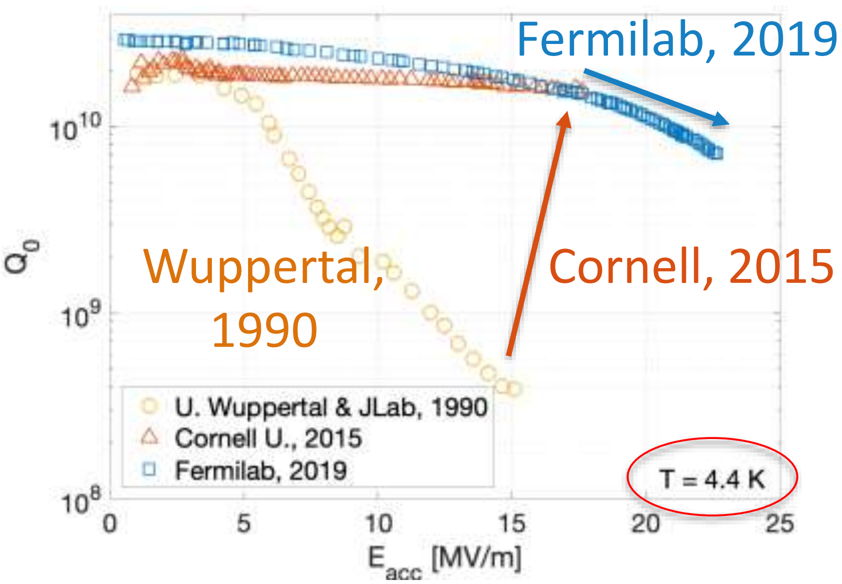


Courtesy of A. Grassellino, FNAL

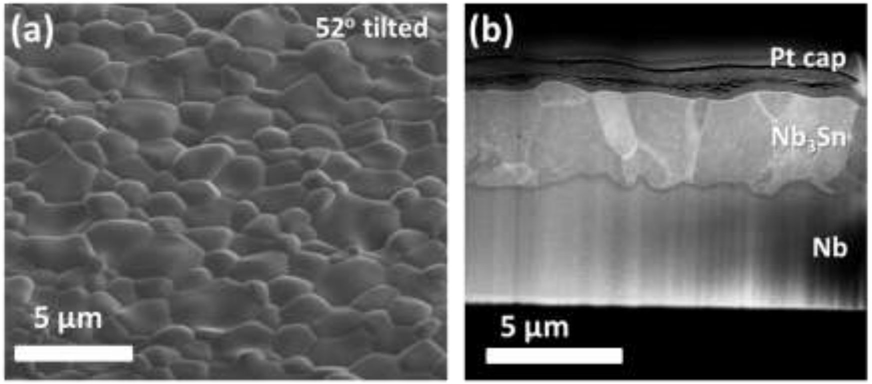
Nb_3Sn SRF cavities: recent results

Sam Posen

- Nb_3Sn coated cavities can operate at 4.4 K to reduce cost of cryogenics and enable new compact accelerator applications; in addition, theory predicts maximum gradient 2x niobium
- Not yet at ultimate potential, but substantial recent progress, including **world record gradient of 24 MV/m at Fermilab**



Progress in Nb_3Sn cavity performance

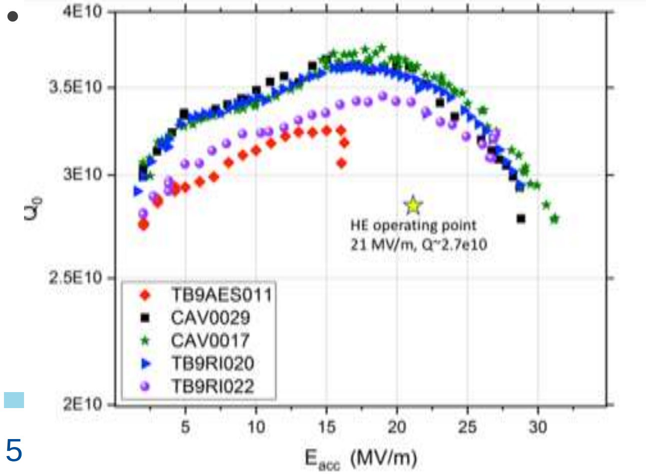


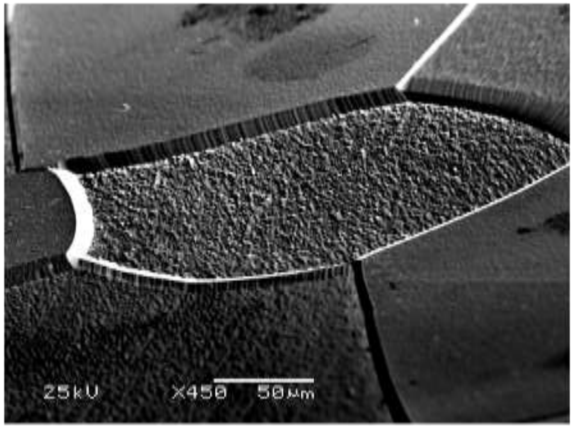
SEM images of Nb_3Sn film coated on Nb: a) surface, b) cross section

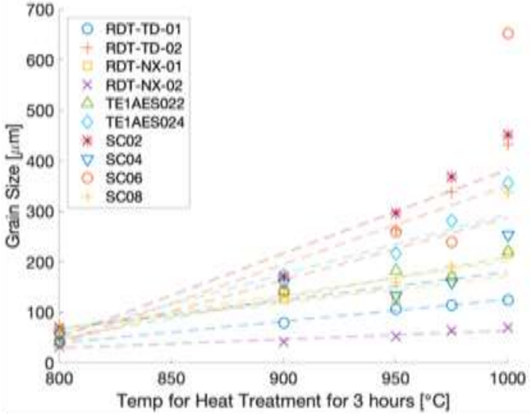
High Q Cavity and Material R&D

Alex Romanenko, Mattia Chechin

- FNAL has pioneered the key advances for high Q/high G: N doping and efficient flux expulsion, and continues to contribute with advancing these technologies – well aligned with our competences and core HEP mission
- HE R&D program on single and then nine cells demonstrated that quench field in nitrogen doped nine cells has systematically improved reaching gradients Eacc > 28 MV/m with 80% yield
- Key parameter found to improve gradient performance is the (lower) EP temperature post doping, in addition to other precautions taken
- New protocol is now being transferred to the vendor, results by end of the year, gating the prototype cryomodule cavities
- Material studies are now focused on understanding root cause of quench in N doped cavities and why colder EP helps
-





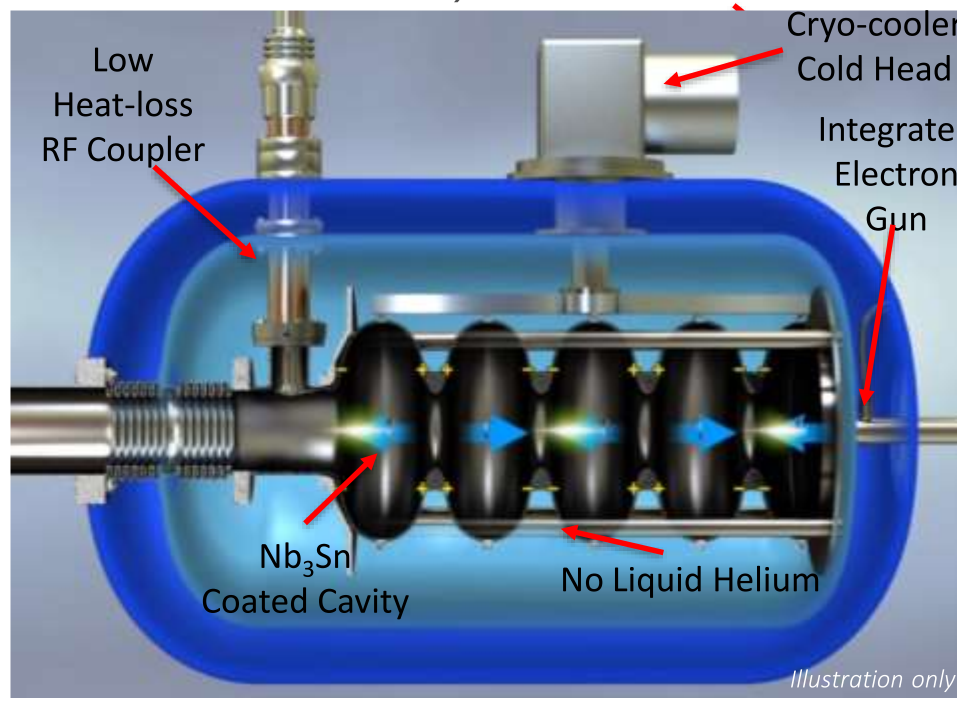


Compact, high power SRF industrial accelerator

Charles Thangaraj

- Combine state-of-the-art technology advances in SRF, RF sources, coupler and cathodes to create a simple, compact, high power, superconducting RF based industrial accelerator 10 MeV, > 250 kW for application (wastewater treatment, medical device sterilization, pavement application)
- First *experimental* demonstration of a Nb_3Sn coated cavity at 650 MHz > 5.5 MV/m using conduction cooling (US Patent #14/689,695;#16/054,942). Goal: 10 MV/m

Conduction cooling setup: A ringed 650-MHz cavity attached to a cryocooler*.



ENERGY Office of Science — Science Highlights

Cryogen-free Superconducting RF Cavity

A team from Fermilab has demonstrated cryogen-free operation of a niobium superconducting radiofrequency cavity

ColdFacts

Towards cryogen-free SRF particle accelerators

*R.C. Dhuley et al. "Thermal Link Design for Conduction Cooling of SRF Cavities Using Cryocoolers," *IEEE Transactions on Applied Superconductivity* Vol. 29-5 (2019)

Quantum Computing Lab

Eric Holland
Daniil Frolov

Qubit :
3 GHz RF cell
with Josephson
junction
Read-Write system

Dilution fridge
(down to 8 mK)

Quantum Sensors for Dark Matter Searches

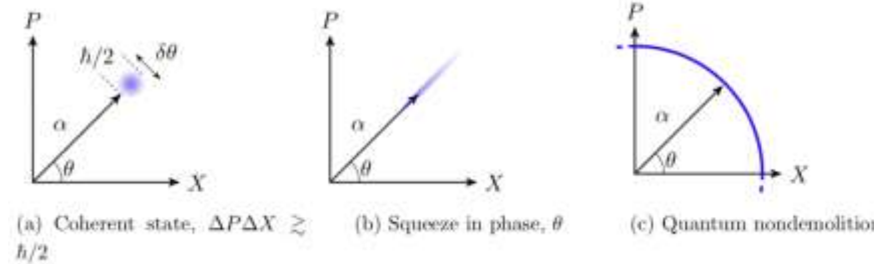
Daniel Bowring

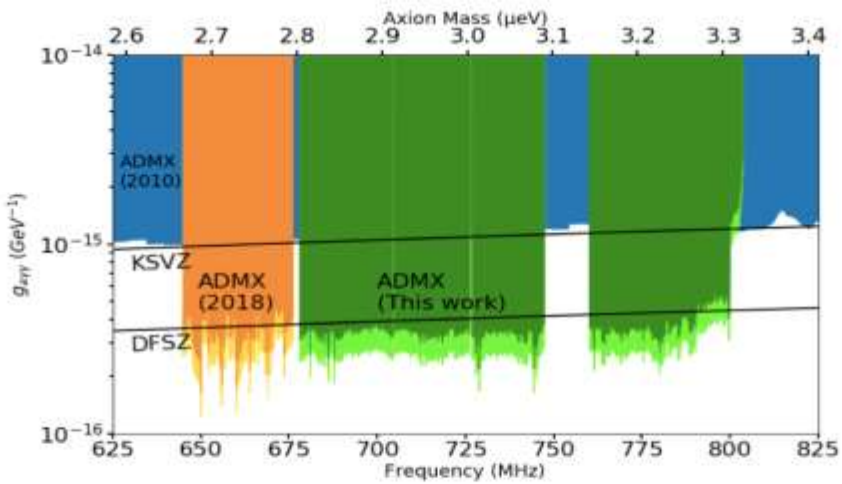
for FNAL axion R&D group and collaborators

Strong, recent interest in axion dark matter. Next-gen searches require new technology.

Dan Bowring

- New results from ADMX, the most sensitive axion search experiment!
- arXiv/1910.08638





- Superconducting qubits enable **quantum nondemolition** measurements of photon occupation in our detectors.

- Signal-to-noise issues motivate **new technology** for > 10 GHz searches.

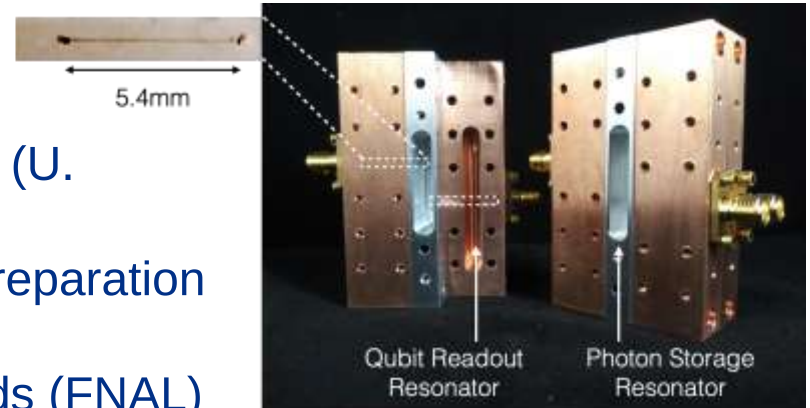
Fermilab

CHICAGO Yale University JILA HEISING-SIMONS FOUNDATION Argonne NATIONAL LABORATORY

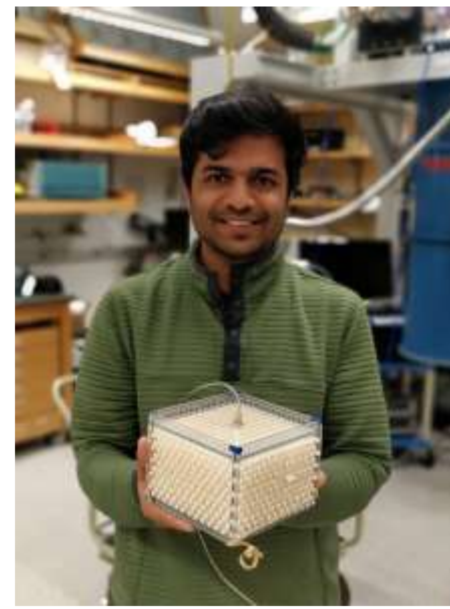
Significant R&D effort over the next 5 years!

Dan Bowring

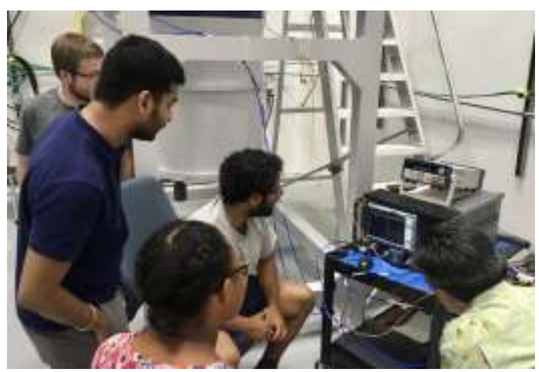
- Multi-qubit readout to reduce error.
- Enhance signal rates via:
  - High-Q photonic bandgap resonators (U. Chicago)
  - Stimulated emission via Fock state preparation (UC/NIST)
  - Entangled multi-qubit readout methods (FNAL)
- And for higher axion masses:
  - Rydberg atom QND (Yale)
  - Transition edge sensors (ANL)
- New collaborators to be announced soon!
- **We're hiring postdocs! Contact Daniel Bowring, dbowring@fnal.gov.**



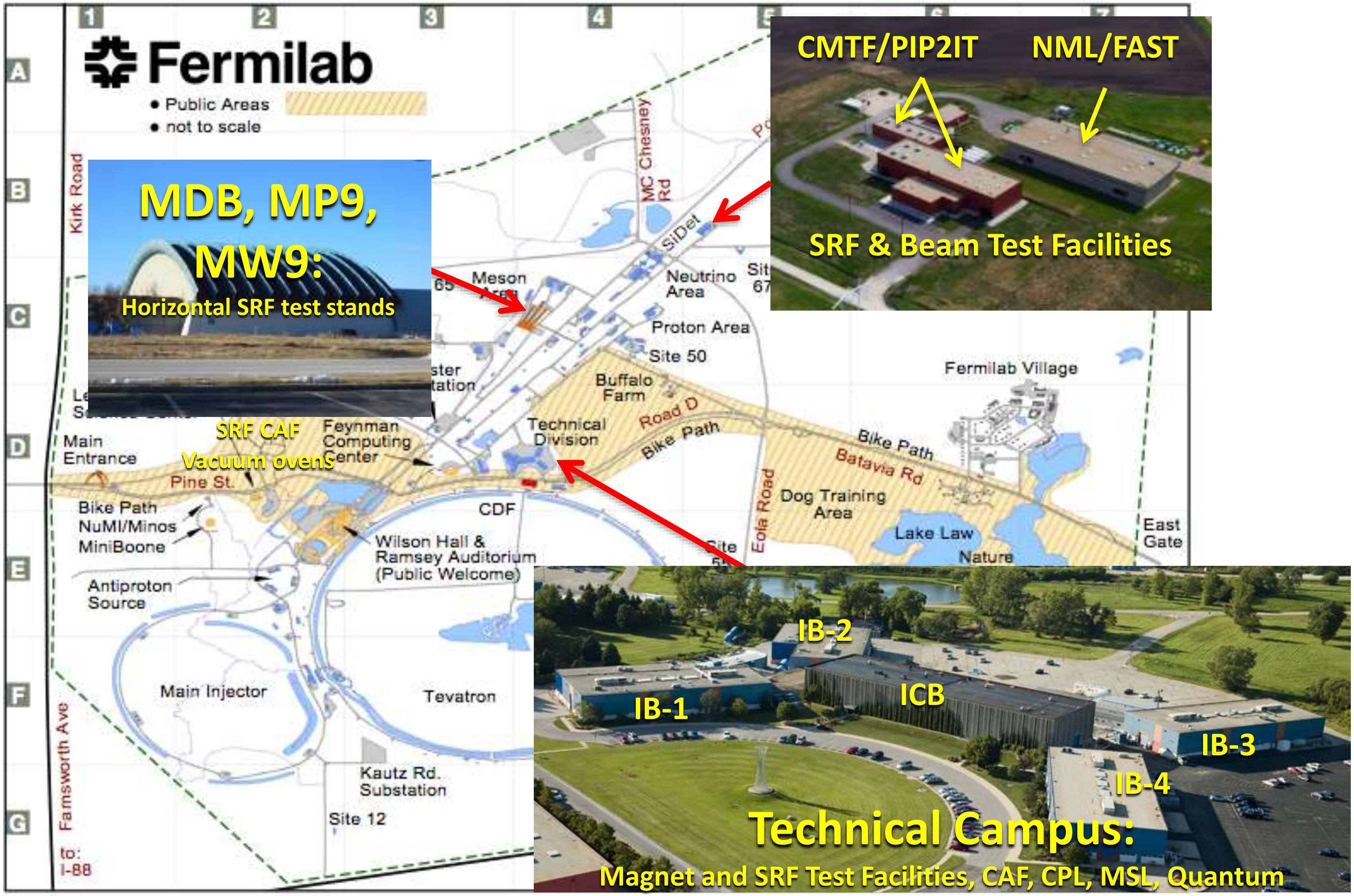
Akash Dixit, UC (Schuster Lab)



Ankur Agrawal, UC (Schuster Lab)



Advantages of Fermilab : People, Accelerators and Facilities



CAF = Cryomodule Assembly Facility, CPL = Cavity Processing Lab, MSL = Materials Science Lab

Your are very welcome to Fermilab!

Join forces, collaborate, do research !