Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Accelerator and Beam Physics :
our vision in high intensity/high brightness beams

Vladimir SHILTSEV

DOE GARD Review, Fermilab

July 31, 2018

Biographical Sketch

- *Distinguished Scientist* at Fermilab
- Director of *Accelerator Physics Center* in FNAL Accelerator Division
- Chair of APS *Division of Physics of Beams*
- PhD in beam physics from Novosibirsk ('94)
- At Fermilab since 1996 :
  - Wilson Fellow, electron lens project
  - Tevatron Dept Head 2001-2006
- EPS Prize, APS Robert Siemann Prize, APS Fellow, APS Outstanding Referee; George Gamow Award, etc
- 2 books and > 300 papers

Outline

- Introduction: Strategic Context and Relevance to HEP
- Program Elements : High Level Goals and Recent Accomplishments
- Principal Program Goals: FY19-FY24
- Conclusion

Fermilab GARD Program on
Accelerator and Beam Physics
in the US HEP Strategic Context

US HEP Community Plan: *2014 P5 Report*

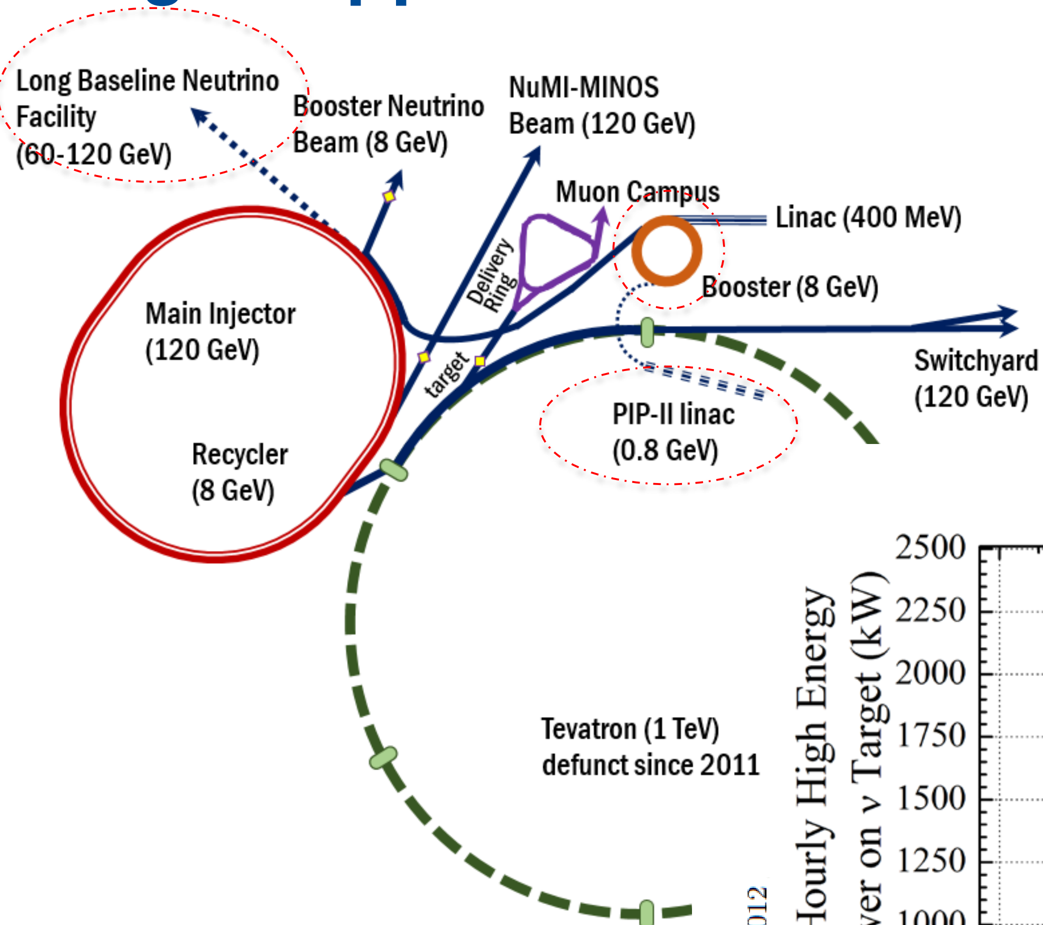
	Intensity Frontier Accelerators	Hadron Colliders	e^+e^- Colliders
Current Efforts 0-10 yrs	PIP	LHC	
	PIP-II	HL-LHC	ILC
Next Steps 10-20 yrs	Multi-MW proton beam	Very high-energy *pp* collider	1 TeV class energy upgrade of ILC*
Further Future Goals 20+ yrs	Neutrino [illegible]tory*	Higher-energy upgrade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

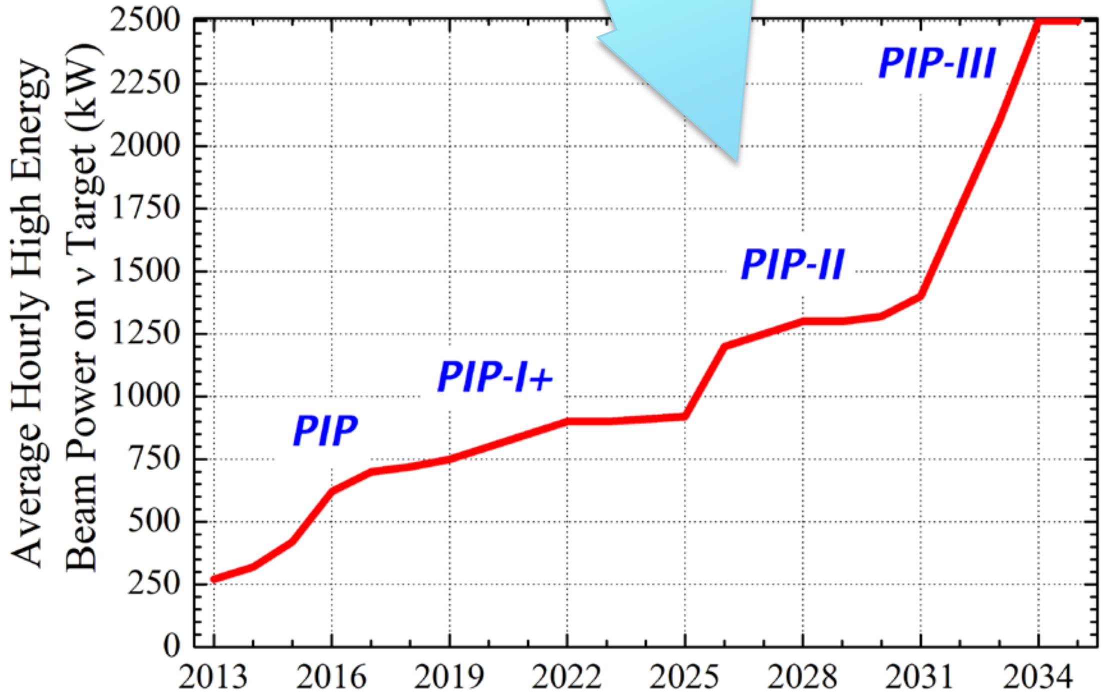
**dependent on how physics unfolds*

- 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*

Staged Approach to ***Multi-MW*** Beams :

Proton Improvement Plan(s)

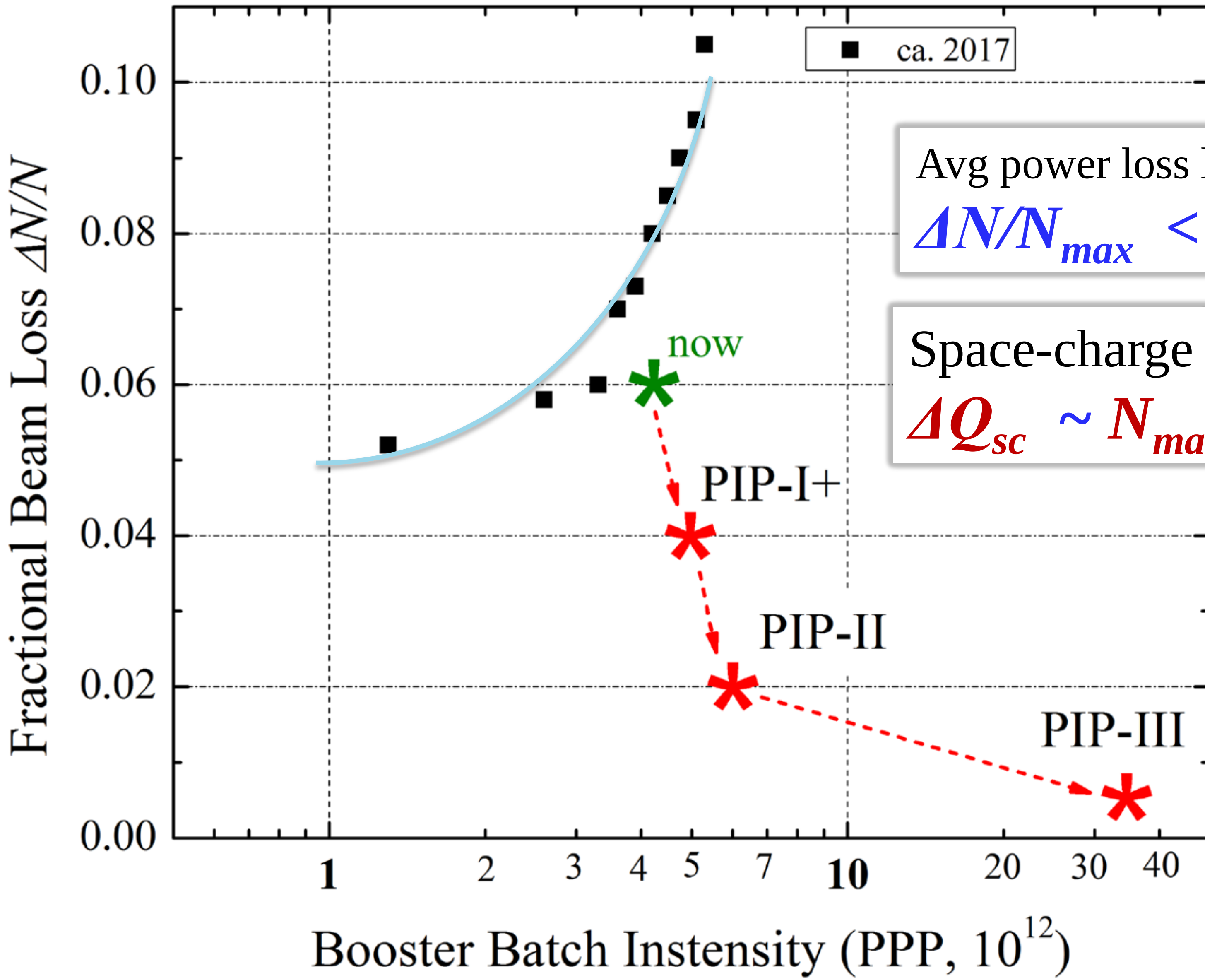




Modern Physics Letters A Vol. 32, No. 16 (2017) 1730012

Among Key Challenges - *Beam Physics*

e.g., limits on the Booster *Protons Per Pulse (PPP)*



Avg power loss limit (500W) :

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

Space-charge limit scales:

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

High Intensity Proton Beam Physics Issues

- Space-charge effects (losses, emittance growth, …)
- Longitudinal dynamics (capture, transition, …)
- Injection (notching, capture, painting, …)
- Coherent instabilities (resistive wall, e- cloud, …)
- RF optimization (acceleration, efficient loading, …)
- Focusing optics (noises, periodicity, …)
- Halo control (collimation, protection, …)
- Beam instrumentation (fast, large range, feedbacks, …)
- Theory and modeling (3D, cross-check wrt operation, …)

2015 *Accelerator R&D Subpanel* Recommendations

- maintain accelerator science core competence and support high intensity proton beam physics R&D:

[R2] Construct the IOTA ring, and conduct experimental studies of high-current beam dynamics in integrable non-linear focusing systems.

[R3] Support a collaborative framework among laboratories and universities that assures sufficient support in beam simulations and in beam instrumentation to address beam and particle stability including strong space charge forces.

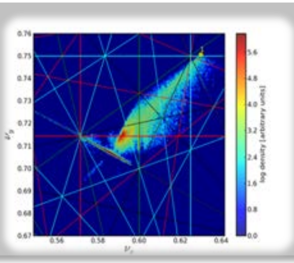
[R14] Continue ABP R&D aimed at developing the accelerators defined in the Next Steps and the Further Future Goals.

[R15] Ensure a healthy, broad program in accelerator research, allocate a fraction of the budget of the ABP thrust to pursue fundamental accelerator research outside of the specific goals.

Accelerator and Beam Physics at Fermilab

Experimental Accelerator R&D Program at IOTA/FAST

- Develop and explore transformative concepts and technologies for next-generation high-intensity proton accelerators



Beam Physics Modeling and Simulations

- Contribute to the fundamental understanding of beam dynamics through simulation and theory

Collaborative ABP Framework among Universities and Labs

- Educate the next generation of accelerator designers and builders through the USPAS and Fermilab programs

Operational Support of IOTA/FAST/NML (Fermi-CARD)

- Support for the operating beams for General Accelerator R&D at GARD facility, and the Large Hadron Collider at CERN

Accelerator and Beam Physics Session

10:20 **Accelerator and Beam Physics (our vision in high intensity/brightness beams)** Vladimir Shiltsev *40'*

11:00 **Transformational R&D in nonlinear beam dynamics** Alexander Valishev *20'*

11:20 **Beam stability and loss control through electron lenses** Giulio Stancari *20'*

11:40 **Toward high brightness: optical stochastic cooling** Johnathan Jarvis *20'*

12:00 – 13:00 **Lunch** *60'*

13:00 **Grad. student report (IOTA)** Nikita Kuklev (U Chicago) *15'*

13:15 ***Synergia* high intensity beam dynamics simulations** Alex Macridin *30'*

13:45 **FAST beam facility operations** Jerry Leibfritz *30'*

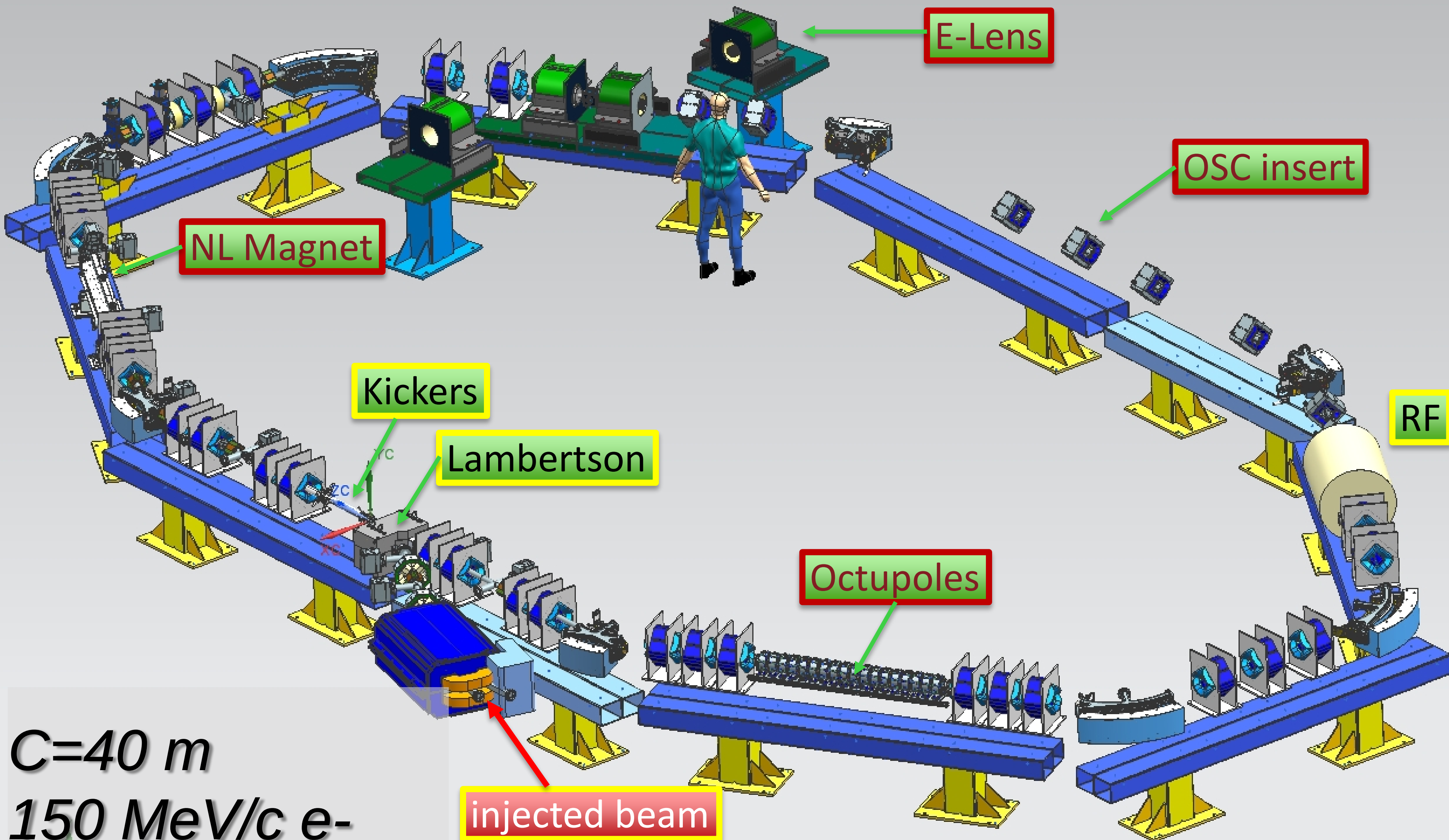
16:20 **Tour of FAST/IOTA and CMTF** *45'*

Accelerator and Beam Physics

Program Elements (1):

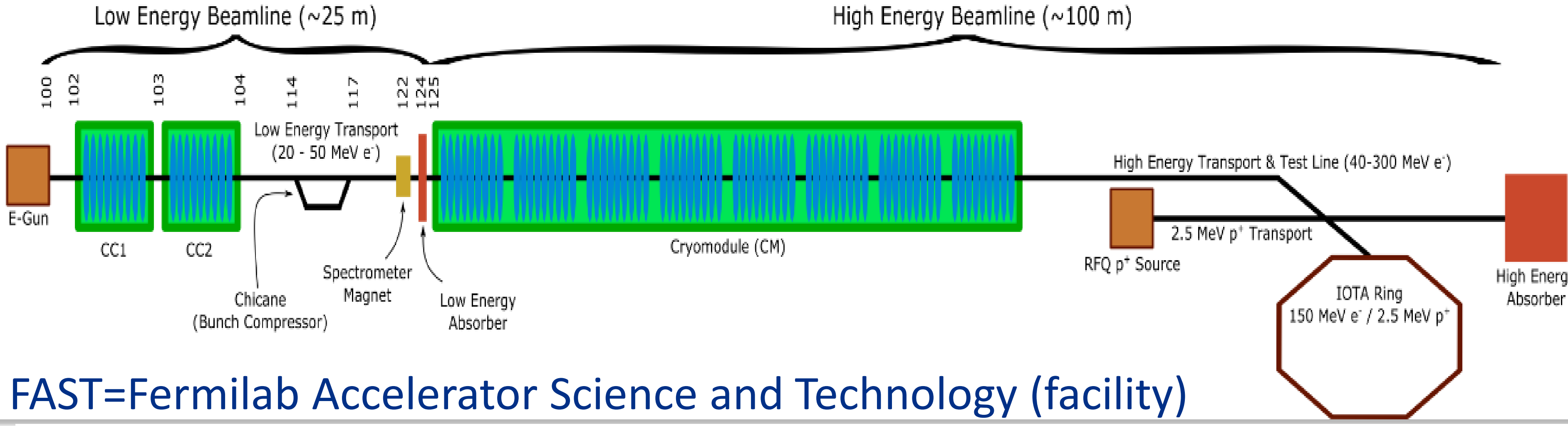
IOTA/FAST

IOTA: *Integrable Optics Test Accelerator*



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

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

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

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

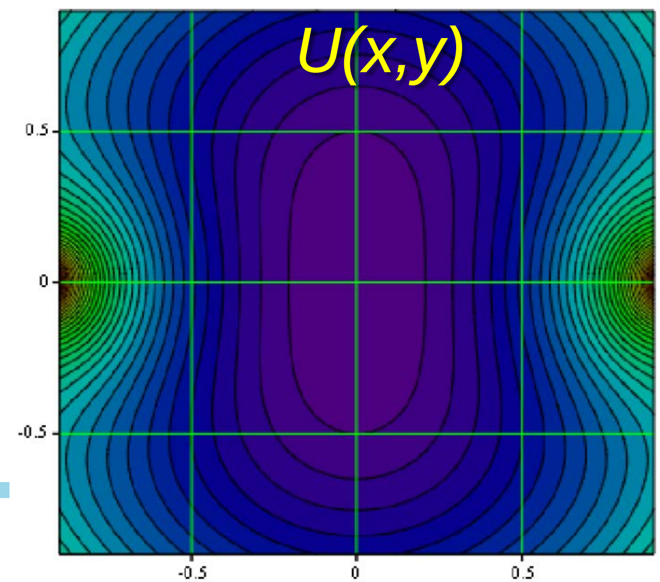
first invariant

[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

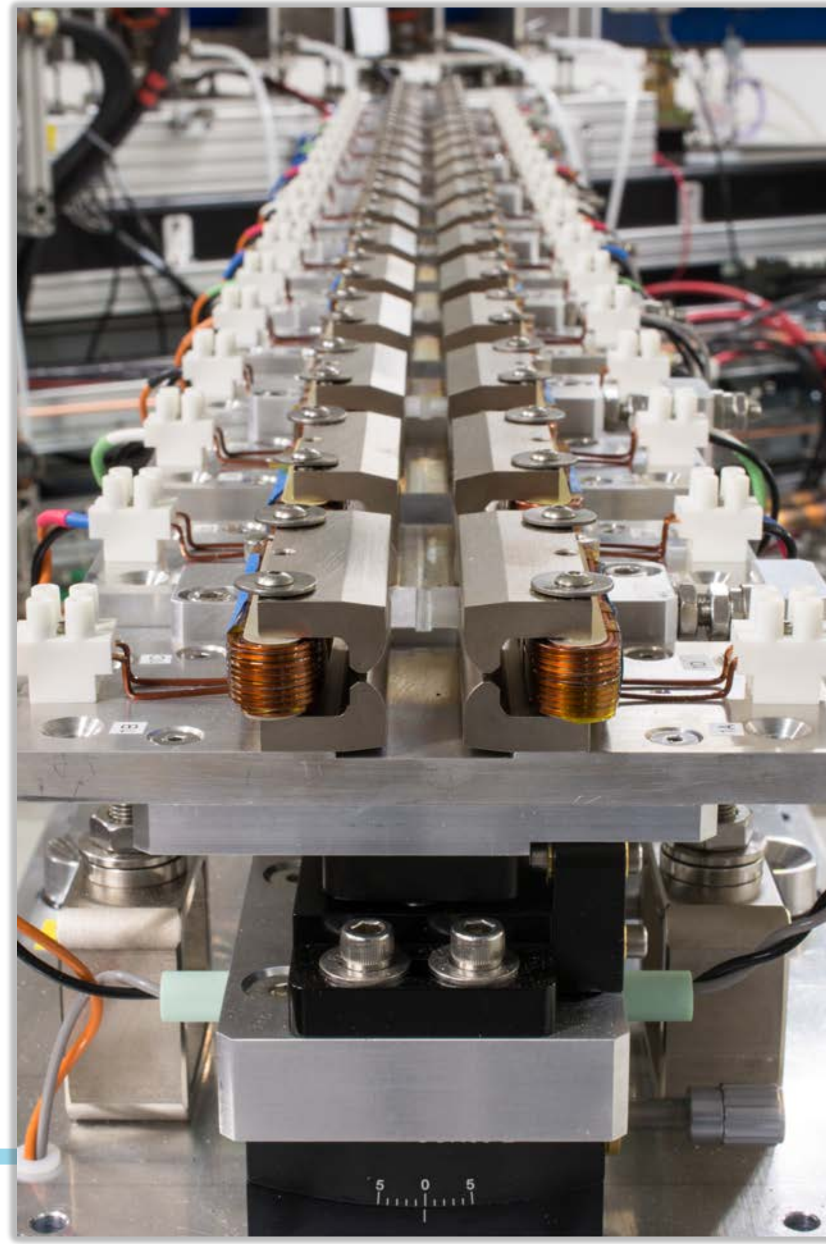
$$I = \left(xp_y - yp_x\right)^2 + c^2 p_x^2 + \frac{2c^2 t \cdot \xi\eta}{\xi^2 - \eta^2} \times$$

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



Non-Linear Integrable Optics Test

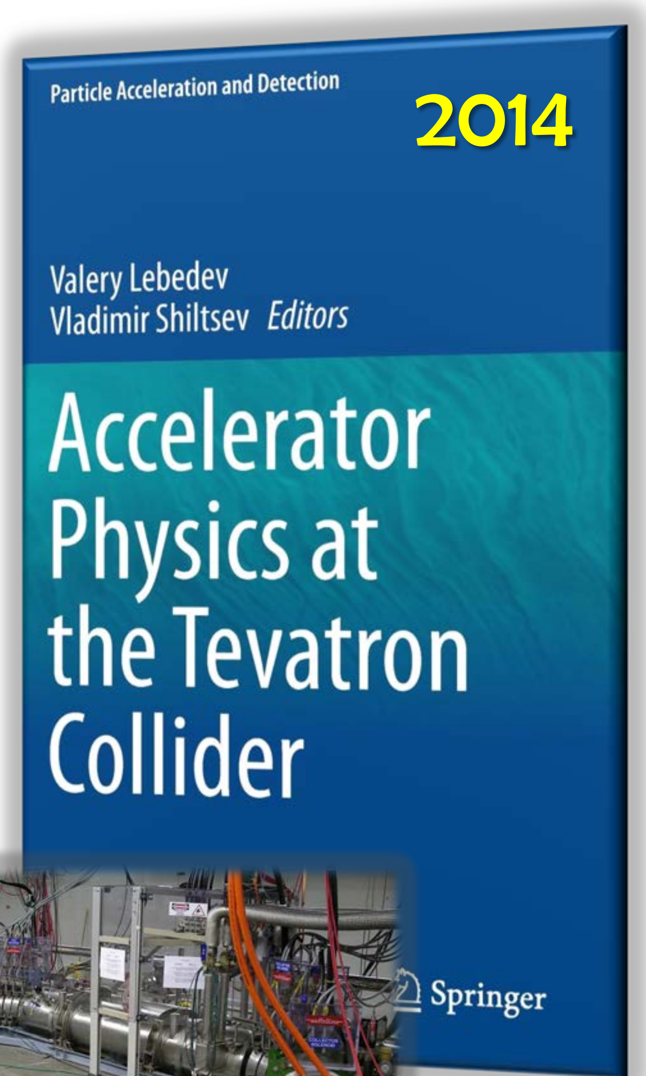
- Such a magnet is built and installed in IOTA
- Additional integral will be confirmed – first with “pencil” electron beam in IOTA
- Later, with high brightness, space-charge dominated proton beam
- Expect to demonstrate greatly improved coherent and incoherent beam stability
- (in greater detail – see Alexander Valishev’s talk)

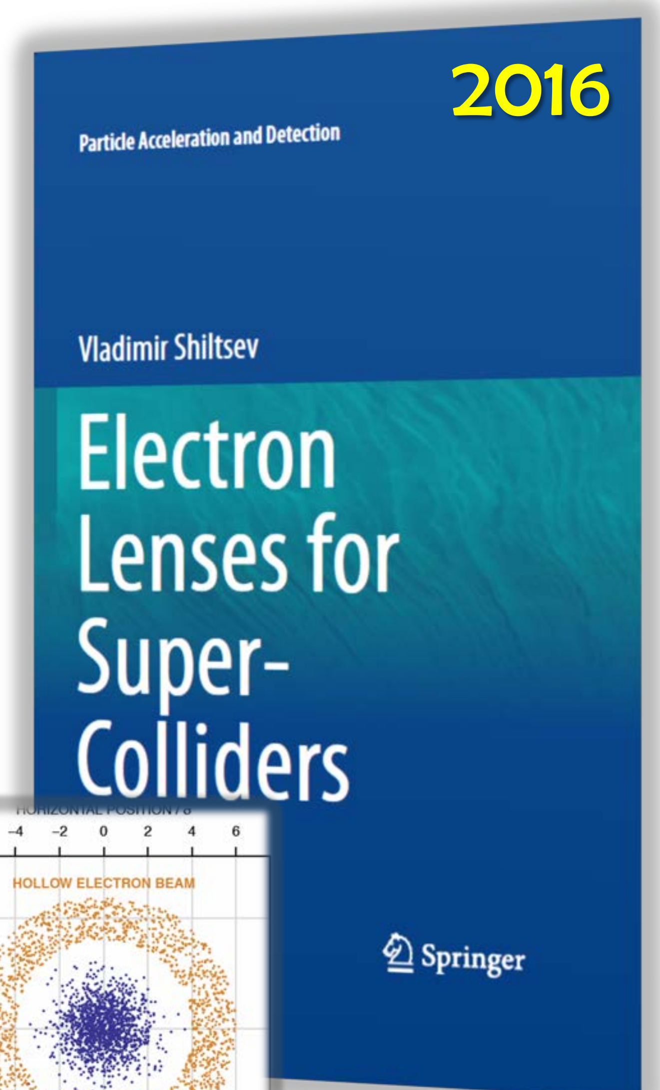


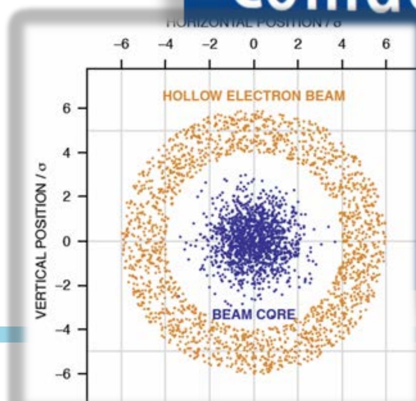
#1: IOTA GARD Experiment (2018-)

- ***Physics of Intergrable Optics***:
  - PIs: A.Valishev and S.Nagaitsev
  - Will start in 2018 – first, limited integrability (with octupoles), then with NL magnets, then with protons
- Experiment planning:
  - Stage (1) – theory, modeling, physics specs – mostly done, continue IOTA specific simulations
  - Stage (2) – technical specs and design - done
  - Stage (3) – fabrication and construction – mostly done
  - Stage (4) – installation and commissioning – 2018
  - Stage (5) – physics research – 2019-
- Collaboration:
  - Very strong (simulations, fabrication, beam diagnostics, etc)
  - Fermilab, NIU, U.Chicago, RadiaSoft, LBNL, RadiaBeams, et al
  - Regular meetings

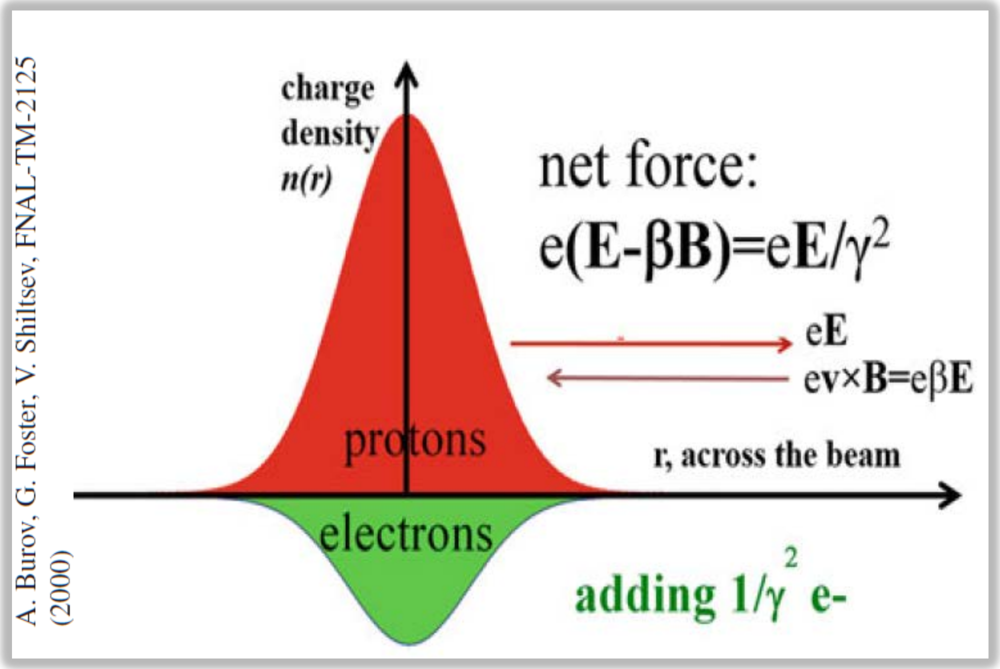
Electron Lenses : Introduced in *2000*'s

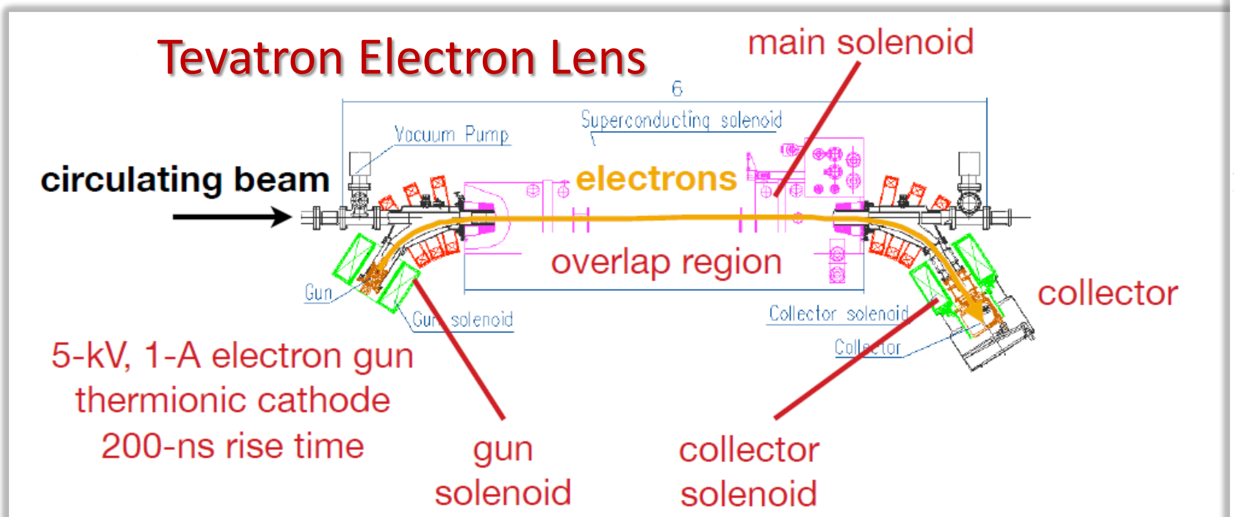


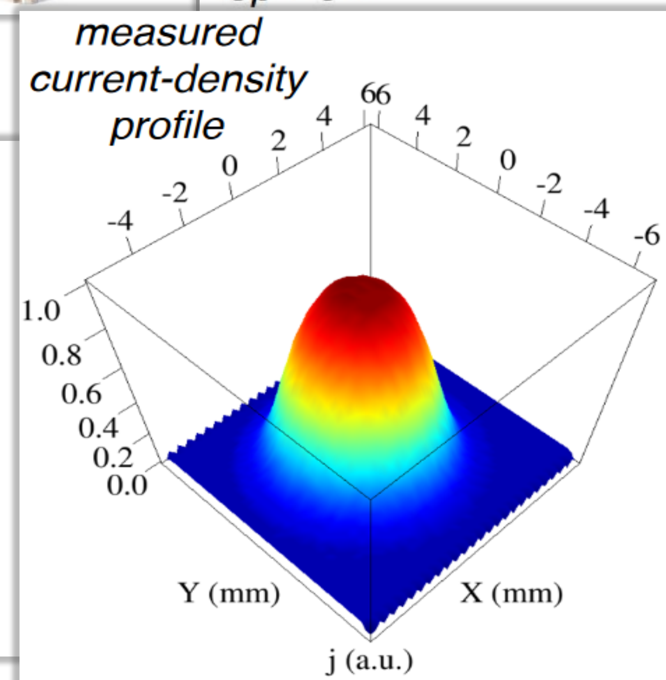




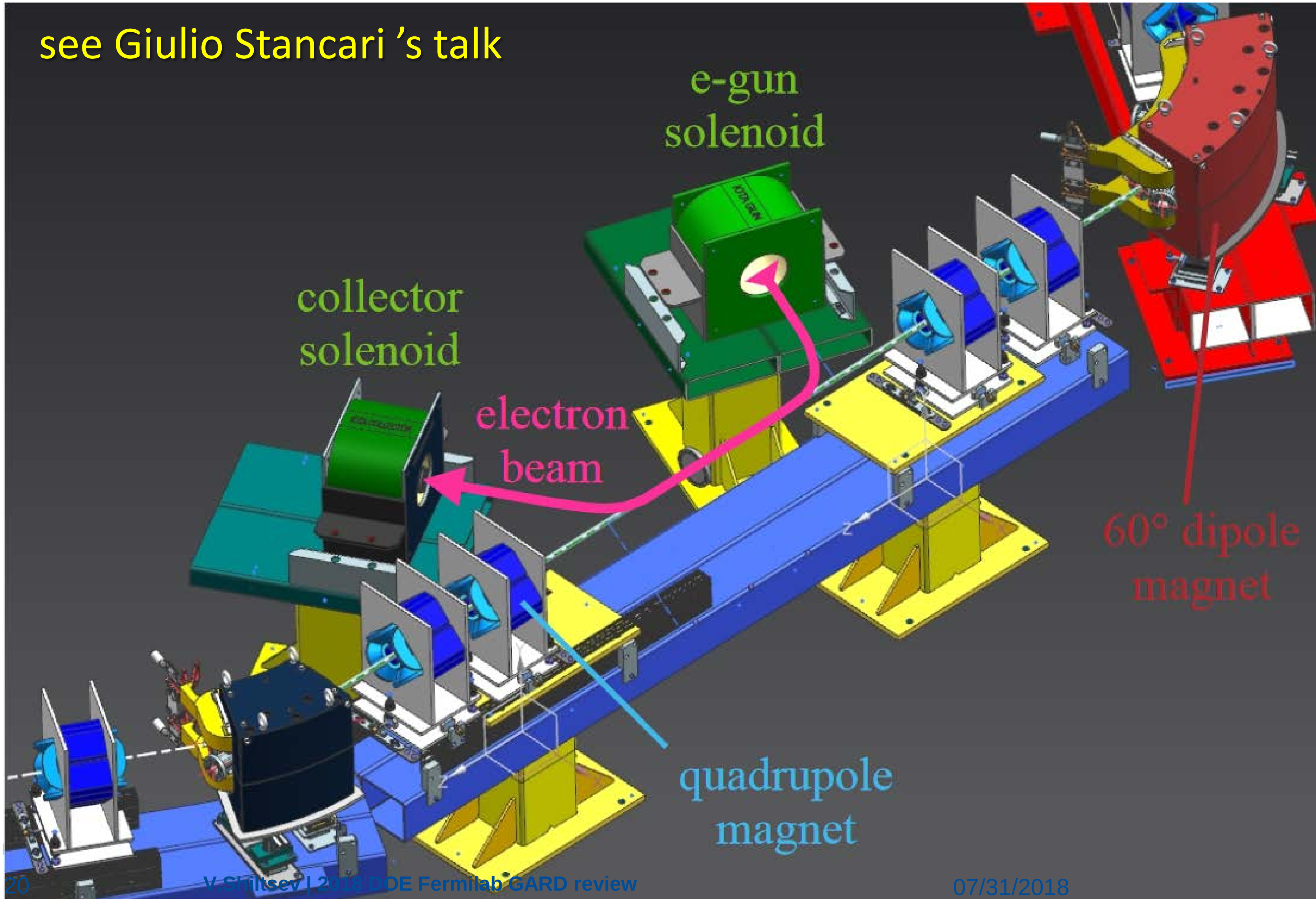
Proton Space-Charge: Compensated by Electrons







Electron Lens in IOTA



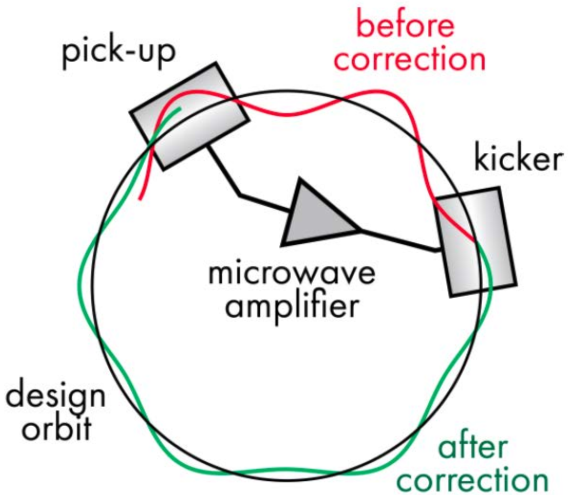
#2: IOTA GARD Experiment (2019-)

- ***Space-charge compensation by electron lenses:***
  - PIs: G.Stancari and V.Shiltsev
  - Will start in 2019 – first with e-lens commissioning
- Experiment planning:
  - Stage (1) – theory, modeling, physics specs – IOTA specific simulations started
  - Stage (2) – technical specs and design – to be finished in 2019
  - Stage (3) – fabrication and construction – 2019 *
  - Stage (4) – installation and commissioning – 2019 *
  - Stage (5) – physics research – 2020-
- Collaboration:
  - Strong on simulations (FNAL SCD and APC)
  - Fabrication and construction $$ *contingent on resources* available after IOTA/FAST constr'n/commiss'ng and IO exp't

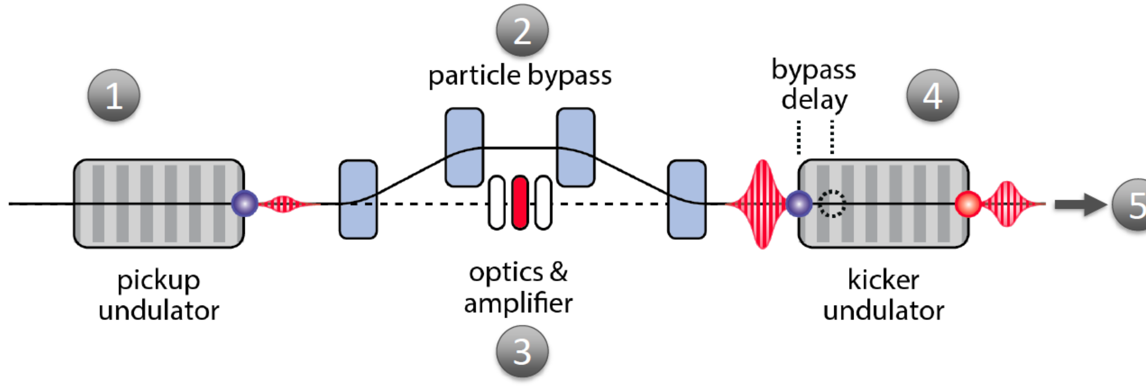
*

Optical Stochastic Cooling
from ~10 cm to 1 um wavelength

van der Meer, 1980's



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



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
- IOTA is designed to accommodate the OSC insert and proof-of-principle study with electrons
- (see Johnathan Jarvis's talk)

[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)

#3: IOTA GARD Experiment (2019-)

- ***Optical Stochastic Cooling:***
  - PIs: V.Lebedev, J.Jarvis and S.Chattopadhyay
  - Will start in 2019 – though first test of synchrotron light optics and measurements in IOTA will take place in 2018
- Experiment planning:
  - Stage (1) – theory, modeling, physics specs – done
  - Stage (2) – technical specs and design – to be finished in 2018
  - Stage (3) – fabrication and construction – 2018-19
  - Stage (4) – installation and commissioning – 2019
  - Stage (5) – physics research – 2020-
- Collaboration:
  - Strong on simulations, technical design and fabrication
  - NIU, Fermilab, U.Chicago, etc
  - External funding thru DOE/NSF grants; regular meetings

#4: Experimental Studies of Fundamental Physics of Space-Charge Dominated Beams

- 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:
  - Effects of linear and non-linear resonances
  - Magnet noise effects
  - Importance of lattice periodicity
  - Coherent instabilities, eg TMCI, and space-charge interplay
  - Landau damping and halo dynamics
  - High-order, eg, quadrupole, octupole, coherent SC modes
  - Etc, etc… plus, testbed for advanced beam diagnostics

(see more below, on ”Modeling/Theory/Simulations”)

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
  - 1st IOTA experiments begin
- 1st *p+* beam in IOTA – 2019
- Experimental R&D program
  - For ~5+ 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, 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.

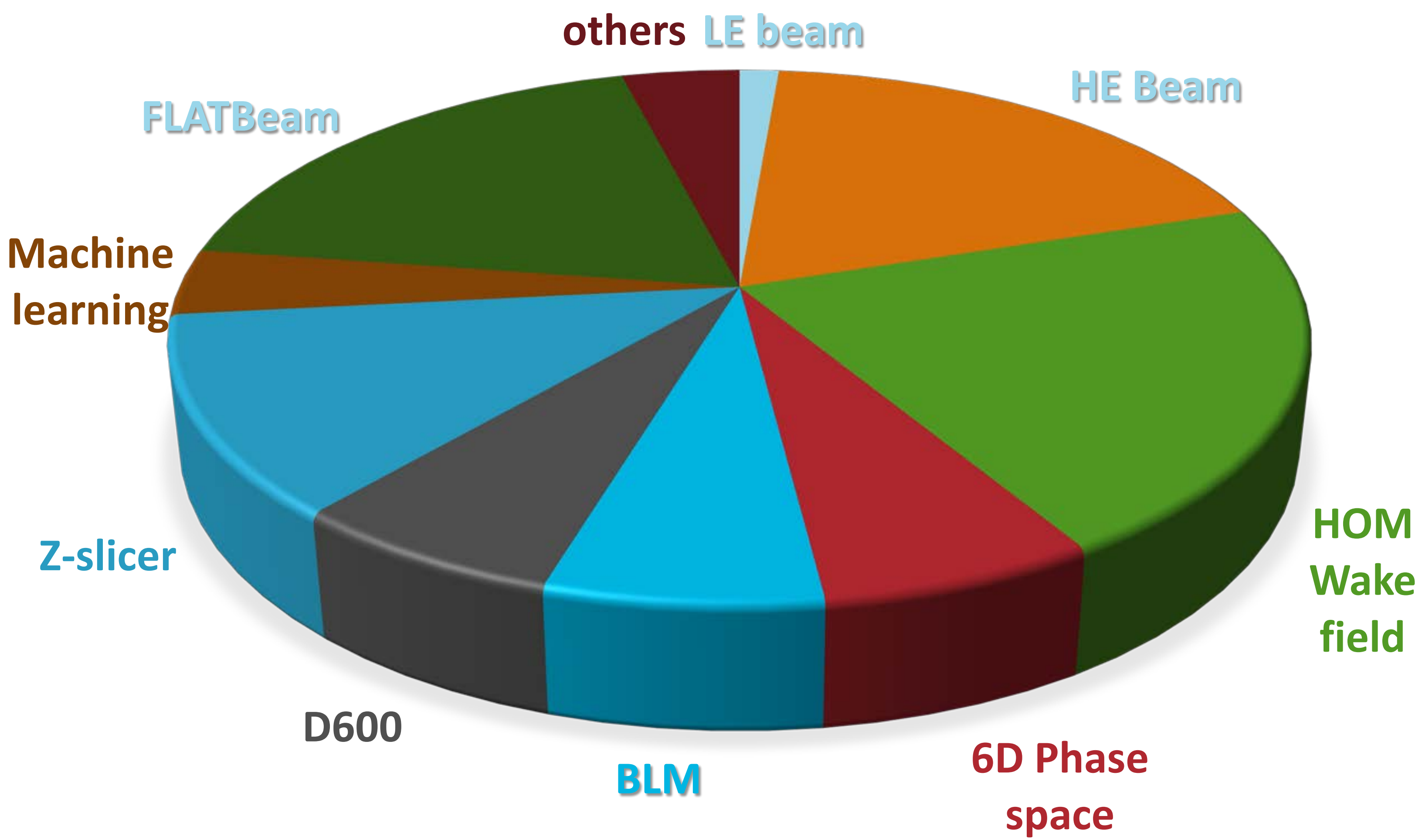
KEYWORDS: Accelerators, Synchrotrons, Magnets, Integrable Optics, Electron Lenses, Space-charge Effects, Instabilities, Collimation, Beam Instrumentation, Photo-injectors, Neutrino.

(CDR-type document)

300 MeV e- Injector – Nov. 15 , 2017

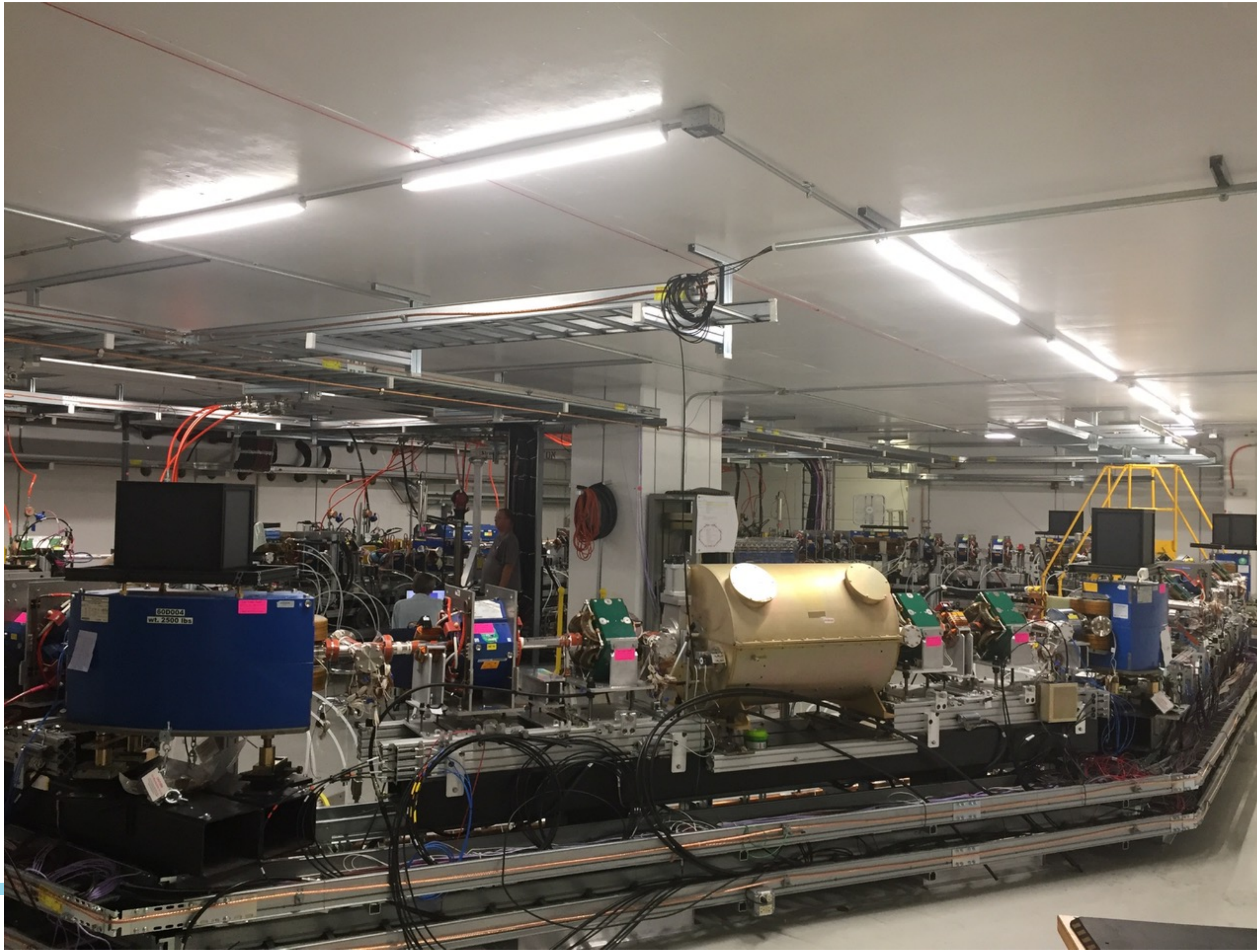
- ILC-type cryomodule acceleration by 255±5 MeV
  - Over 31.5 MV/m (world record and upto the ILC specification)
- Total beam energy 300 MeV in the HE beam absorber

2017 Operation/Studies Period
~ 2 mos, 75 shifts (x 8 hrs), 86% uptime



(in detail – in Jerry Leibfritz's talk)

IOTA: Ready for the 1st (electron) Beam



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 2013-2018

DOE Early Career Research Proposals

2016 Award

Dr. Chad Mitchell –

our collaborator from the *Lawrence Berkeley National Laboratory*, Berkeley, CA - selected by the *Office of High Energy Physics* for the Early Career Research Proposal award *"Compensation of Nonlinear Space Charge Effects for Intense Beams in Accelerator Lattices"*

• IOTA/FAST at IPAC18 (Vancouver)

- *Contr Oral:* TUXGBF2 Higher-Order-Mode Effects in Tesla-Type SCRF Cavities on Electron Beam Quality (A.Lumpkin et al)
- *Contr Oral:* THYGBD4 Landau Damping by Electron Lenses: Outperforming Thousands of Octupoles (A.Burov et al)
- *Contr Oral:* THYGBE2 Results and Discussion of Recent Applications of Neural Network-Based Approaches to the Modeling and Control of Particle Accelerators (A.Morin et al)

– *Posters (25):*

- TUPAF073 Simulation of Integrable Synchrotron with SC and Chromatic (J.Eldred)
- TUPAL043 e-Column in IOTA (B.Freemire)
- WEPAF040, *SUSPL054* Neural Network Virtual Diagnostic & Tuning for FAST LEBL (A.Edelen)
- WEPAG005, *SUSPF100* Synchrotron Radiation Beam Diagnostics IOTA (N.Kuklev)
- WEPAL065, *SUSPL050* Development of a Gas Sheet Beam Profiler for IOTA (S.Szustkowski)
- THPAF067 Effects of Synchrotron Motion on Nonlinear Integrable Optics (J.Eldred)
- THPAF068 Suppression of Instabilities by an Anti-Damper in IOTA (A.Macridin)
- THPAF071 McMillan Lens in a System with Space Charge (S.Nagaitsev)
- THPAF073 Tomography FAST (A.Romanov)
- THPAF075 SCC with an Electron Lens (E.Stern)
- THPAK082 Perturbative Effects in IOTA (N.Cook)
- THPAK083 An s-Based Symplectic SC (N.Cook)
- THPAK036 Accurate Modeling of Fringe Field Effects on Nonlinear Integrable Optics in IOTA (C.Mitchell)
- THPAK061 Magnetized and Flat Beam Generation at the Fermilab's FAST Facility (A.Halavanau)
- THPAK062 Compression Flat Beams (A.Halavanau)
- THPMF024 Commissioning and Operation of FAST Electron Linac at Fermilab (A.Romanov)
- THPMF025 Emittance Study at FAST (J.Ruan)
- THPMF027 Electron-Beam Characterization in Support of a γ-Ray ICS at the FAST (J.Ruan)
- THPMF028 Coherent Stacking Scheme for ICS at MHz Repetition Rates (J.Ruan)
- THPMF029 Studies of the Novel MCP Based Electron Source (V.Shiltsev)
- THPMK036 Final Focus for a Gamma-Ray Source Based on ICS at FAST (A.Murokh)
- THPML063 Micro-Bunched Beam Production at FAST for Narrow Band THz (J.Hyun)
- THPAK057 Simulation of OSC (M.Andorf)
- THPAK058 Detection and amplification of infrared synchrotron radiation (M.Andorf)
- THPAK035 Modeling Nonlinear Integrable Optics in IOTA with Intense SC Using the Code IMPACT-Z (C.Mitchell)

IOTA/FAST @ IPAC18 - Authorship

- **65 co-authors**
- **32 collaborators:**
  - 13 from Universities
    - *U.Chicago:* PI's – Y.K. Kim, S.Nagaitsev
    - *CSU:* PI – S.Biedron
    - *NIU:* PI's – S. Chattopadhyay, P.Piot
  - 5 from abroad: *France, UK, Japan, Korea*
  - 4 from *LBNL*
  - 2 from *LANL*
  - 6 from *RadiaSoft LLC*
  - 2 from *RadiaBeam*
- **33 from *Fermilab***

Recent IOTA/FAST Peer-Reviewed Publications

- A. H. Lumpkin, B. E. Carlsten et al, *Submacropulse electron-beam dynamics correlated with higher-order modes in Tesla-type superconducting rf cavities* PRAB, 21, 064401 (2018);
- M.B. Andorf, V.A. Lebedev, P. Piot, J. Ruan, *Wave-Optics Modeling of the Optical-Transport Line for Passive Optical Stochastic Cooling*, NIM-A 883 119 (2018);
- M. B. Andorf, V. A. Lebedev, J. Jarvis and P. Piot, *Computation and Numerical Simulation of Focused Undulator Radiation for Optical Stochastic Cooling*, (submitted to PRAB, 2018) ;
- D.Broemmelsiek, et al, *Record High-Gradient SRF Beam Acceleration at Fermilab,* (submitted to NJP, 2018);
- D. Mihalcea, A. Murokh, P. Piot, J. Ruan, *Development of a Watt-level Gamma-Ray Source based on High-Repetition-Rate Inverse Compton Scattering* NIM-B 402 212 (2017);
- V. Shiltsev, Y. Alexahin, A. Burov, *Landau Damping of Beam Instabilities by Electron Lenses* and A. Valishev Phys. Rev. Lett. 119, 134802 (2017);
- A. Halavanau et al., *Analysis and Measurement of the Transfer Matrix of a 9-cell 1.3-GHz Superconducting Cavity* PRAB, 20, 040102 (2017);
- S. Antipov, S. Nagaitsev, A. Valishev, *Single-particle dynamics in a nonlinear accelerator lattice: attaining a large tune spread with octupoles in IOTA,* JINST, V.12 (2017);
- S.Antipov, et al *IOTA (Integrable Optics Test Accelerator): Facility and Experimental Beam Physics Program* JINST 12 T03002 (2017).

Accelerator and Beam Physics

Program Elements (2):

Beam Physics Modeling,

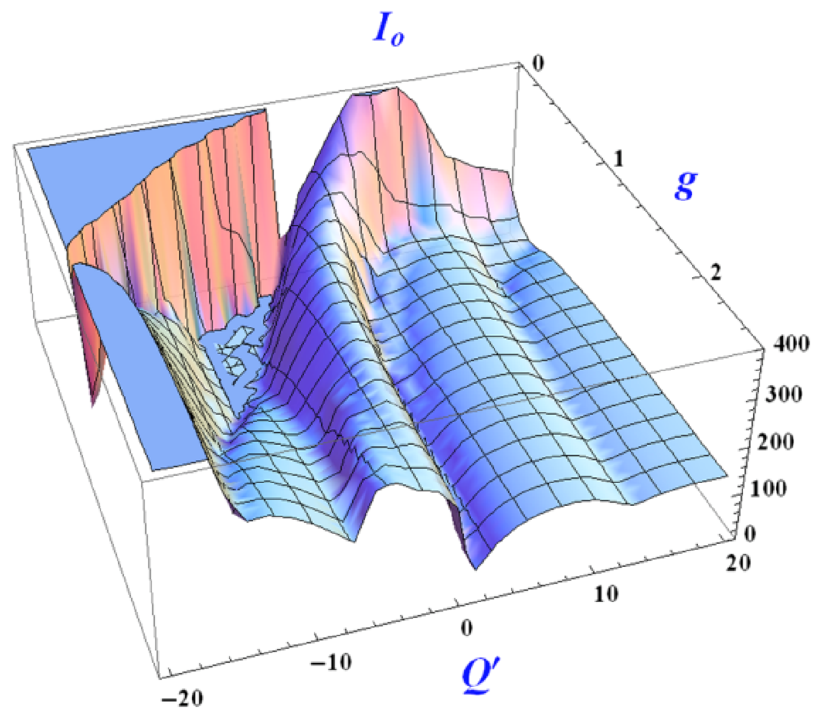
Theory and Simulations

i) Integrable optics (in A.Valishev's talk)
ii) Coherent beam stability
iii) Landau damping with electron lenses and space-charge
iv) Electron cloud studies
v) Beam phase-space manipulations
vi) Development of *MADX-SpaceCharge* code
vii) Development and applications of SYNERGIA (in more detail – see Alexandru Macridin's talk)

2013-now: Seminal Works on Theory of Collective Instabilities in High-Intensity Beams

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, K.Y. Ng, V. Balbekov, Y. Alexahin, S. Antipov, V. Lebedev, S. Nagaitsev, A. Macridin, E. Stern, V.Shiltsev, A. Valishev, T. Zolkin et al.

Coherent Stability with Electron Lenses

PRL **119,** 134802 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Landau Damping of Beam Instabilities by Electron Lenses

V. Shiltsev, Y. Alexahin, A. Burov, and A. Valishev
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA
(Received 23 June 2017; published 27 September 2017)

Modern and future particle accelerators employ increasingly higher intensity and brighter beams of charged particles and become operationally limited by coherent beam instabilities. Usual methods to control the instabilities, such as octupole magnets, beam feedback dampers, and use of chromatic effects, become less effective and insufficient. We show that, in contrast, Lorentz forces of a low-energy, magnetically stabilized electron beam, or "electron lens," easily introduce transverse nonlinear focusing sufficient for Landau damping of transverse beam instabilities in accelerators. It is also important to note that, unlike other nonlinear elements, the electron lens provides the frequency spread mainly at the beam core, thus allowing much higher frequency spread without lifetime degradation. For the parameters of the Future Circular Collider, a single conventional electron lens a few meters long would provide stabilization superior to tens of thousands of superconducting octupole magnets.

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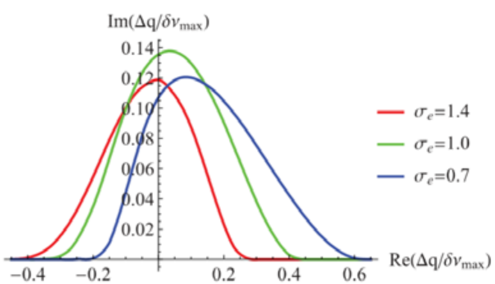

FIG. 3. Electron lens stability diagrams are presented for various electron beam sizes (noted in units of the proton beam rms size), assuming the same current density at the center.

"…For the parameters of the Future Circular Collider, a single conventional electron lens a few meters long would provide stabilization superior to *tens of thousands of superconducting octupole* magnets."

arXiv.org > physics > arXiv:1709.10020

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Physics > Accelerator Physics

Landau Damping with Electron Lenses in Space-Charge Dominated Beams

Yuri Alexahin, Alexey Burov, Vladimir Shiltsev

(Submitted on 28 Sep 2017)

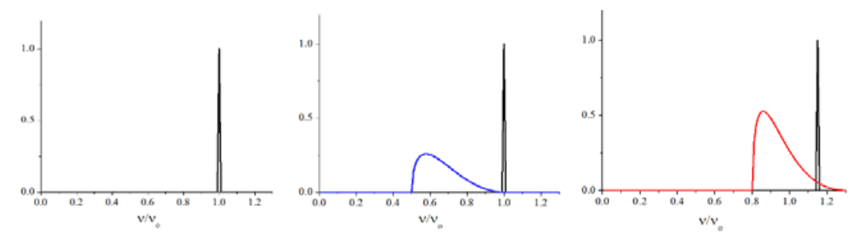


Figure 1: Illustrative dynamics of the spectra of coherent and incoherent betatron oscillations: a) left plot – in the absence of space charge forces; b) center – with strong space charge effect, but no electron lens, blue line – for incoherent frequencies, black one – for coherent; c) right - with an electron lens and in the presence of strong space charge effect, red line – for incoherent frequencies, black one – for coherent.

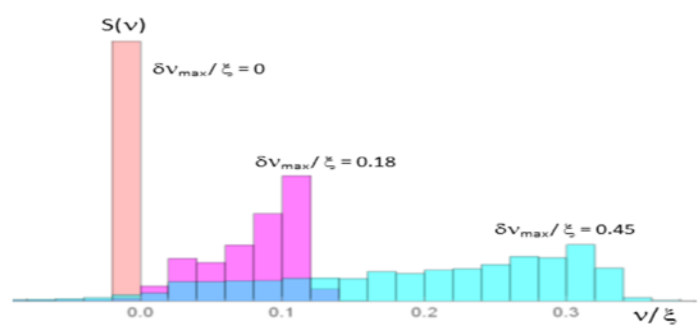


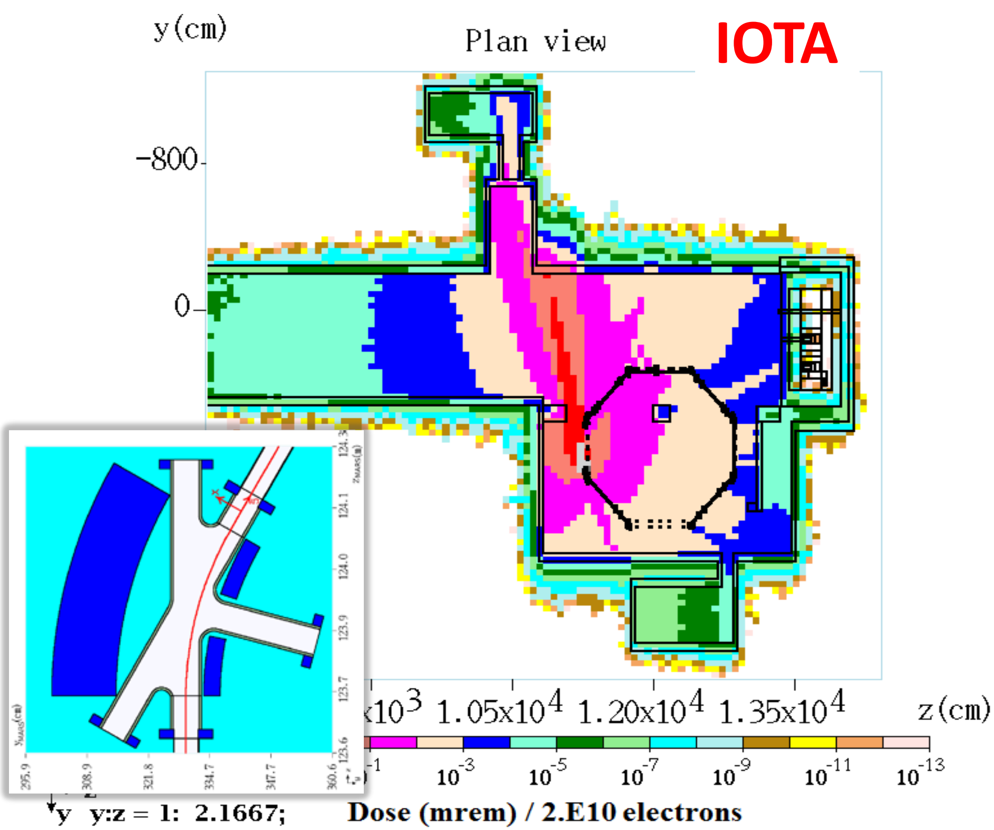
Figure 2. Spectral density of transverse oscillations in a bunch with space charge at indicated values of the maximum tuneshift due to a hollow electron lens.

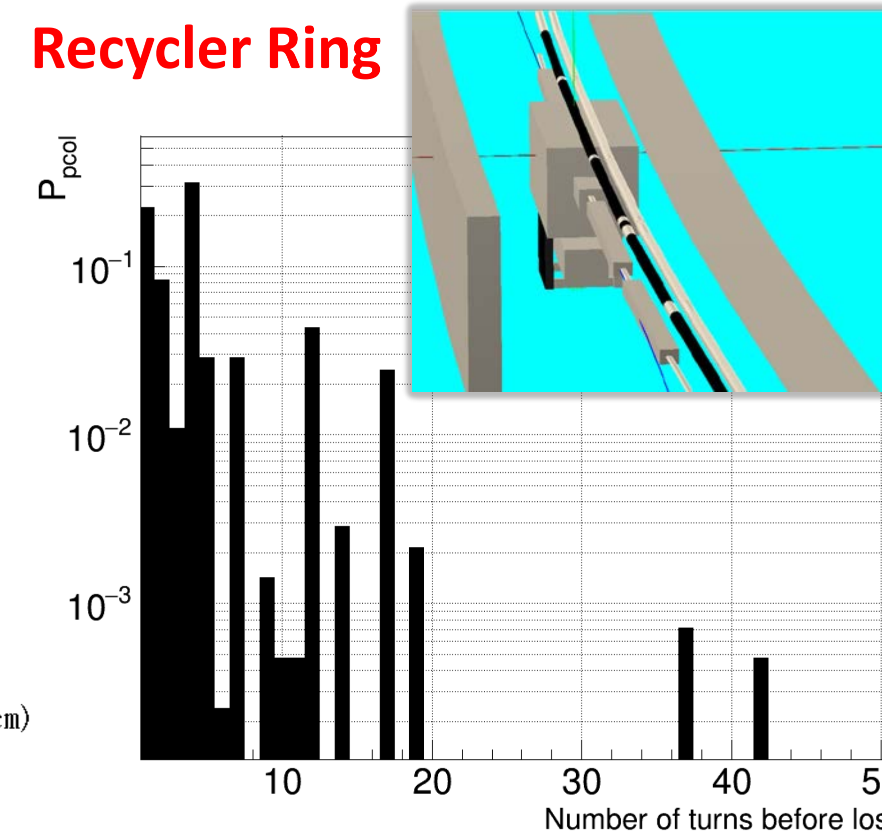
A.Burov, Y.Alexahin, V.Shiltsev, A.Valishev

Integrated Halo Collimation Analysis Tool

MADX/PTC - MARS15

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.

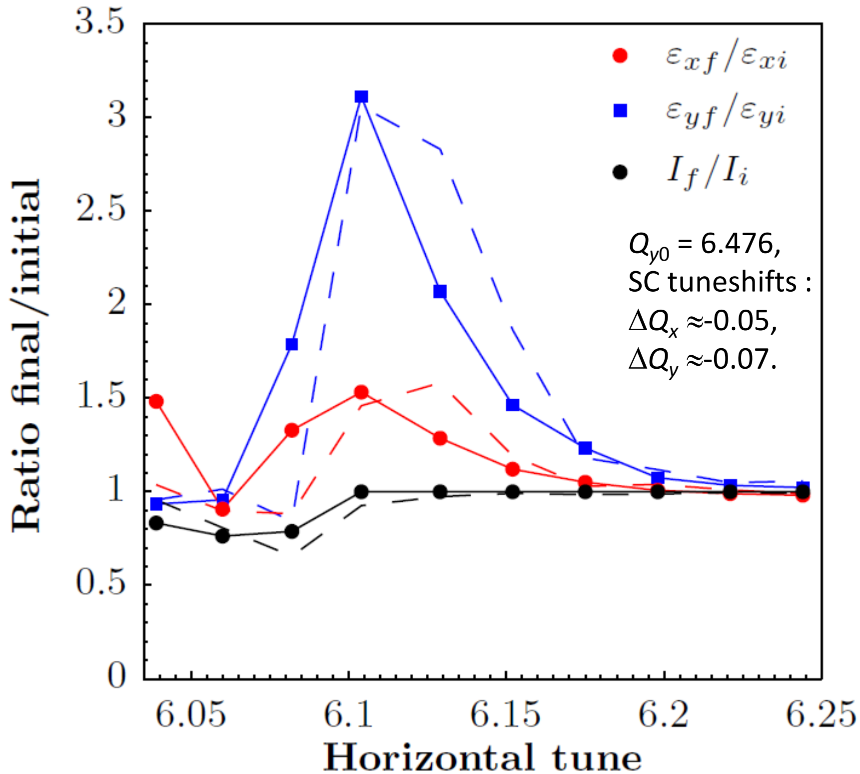




I.Tropin, F.Schmidt, N.Mokhov

MADX-SC Development : in Collaboration with CERN

- Based on algorithm proposed by Y. Alexahin and with participation from V. Kapin and A. Valishev the MADX code was modified to allow simulations with space charge
- The code uses Gaussian fit of particle distribution and requires small number of particles, hence it is rather fast.
- Figure on the right shows the results of code benchmarking of the *adaptive mode* [1] when beam emittances are updated every turn.
- The code is extensively used now for SC simulations at CERN and FNAL (IOITA, RR, etc)
- This year : implemented new algorithm for 6D Gaussian fit [1] and new formulas for symplectic SC kick [2].
- MADX-SC does not require stable optics to exist (can be used for study of half-integer resonance crossing) and allows for nonstate-onary distribution so that envelope resonances can be simulated.



Code benchmarking vs. experiment @ PS: beam emittance and intensity change over $5\cdot10^5$ turns at 2GeV vs. Q_{x0}. Dashed lines present experimental results, solid lines with dots present MADX simulations with adaptive SC (1000 particles used in simulations).

Y.Alexahin, V.Kapin, F.Schimdt

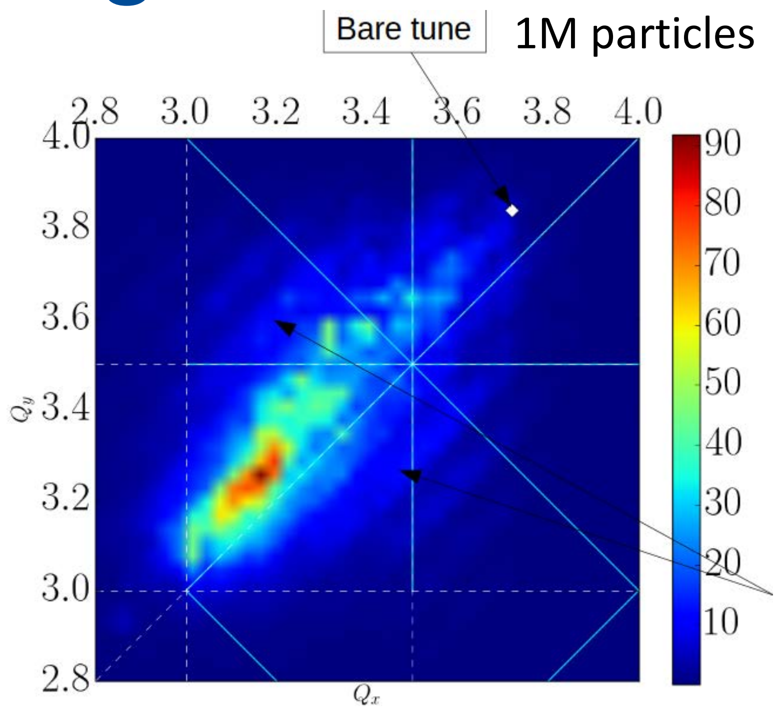
Intl SC Collab'n: FNAL, CERN, GSI, RAL, LBNL, IMP, UMD,..

[1] Y. Alexahin, New developments on adaptive SC methods. Space Charge 2017 workshop. Darmstadt, October 2017.
[2] Y. Alexahin, Progress on the symplectic 3D Space Charge Kick Development. 2nd CERN Space Charge Collaboration Meeting, March 2018.

Synergia - PIC “Heavyweight” Code

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

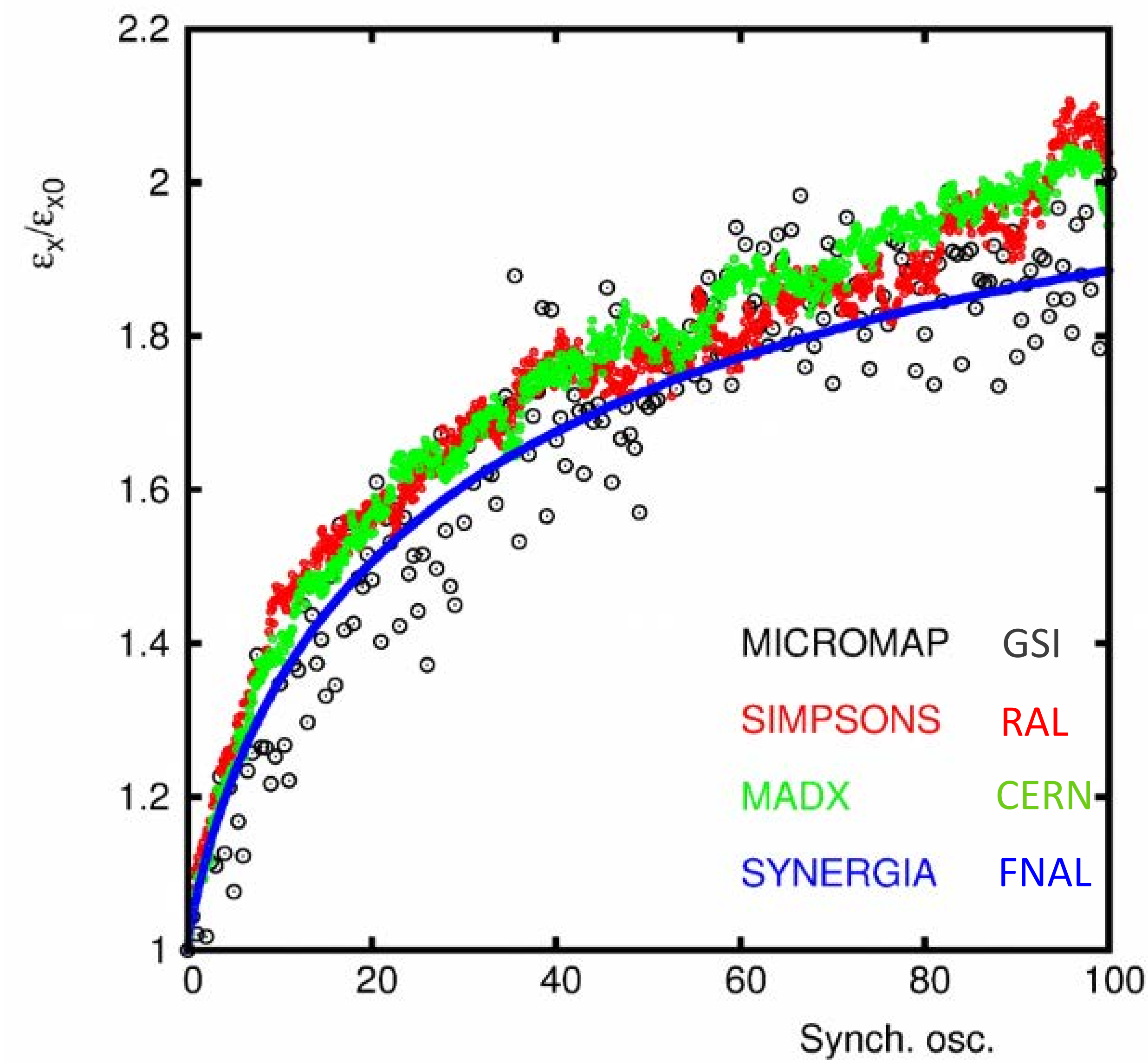
- Simulate combined beam optics and collective effects (space charge and impedance).
- All the usual magnetic elements, RF cavities. Apertures and elements all agree with MAD-X.
- Now includes electron lens element
- Collective operations included with beam transport symplectically using the split-operator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



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 and IOTA at Fermilab as well as plasma acceleration at FACET-II
- Parameteric Landau damping and other important scientific discoveries thru advanced computer simulations - more in Alexandru Macridin’s talk

SYNERGIA Validated with *GSI Space Charge Benchmark*

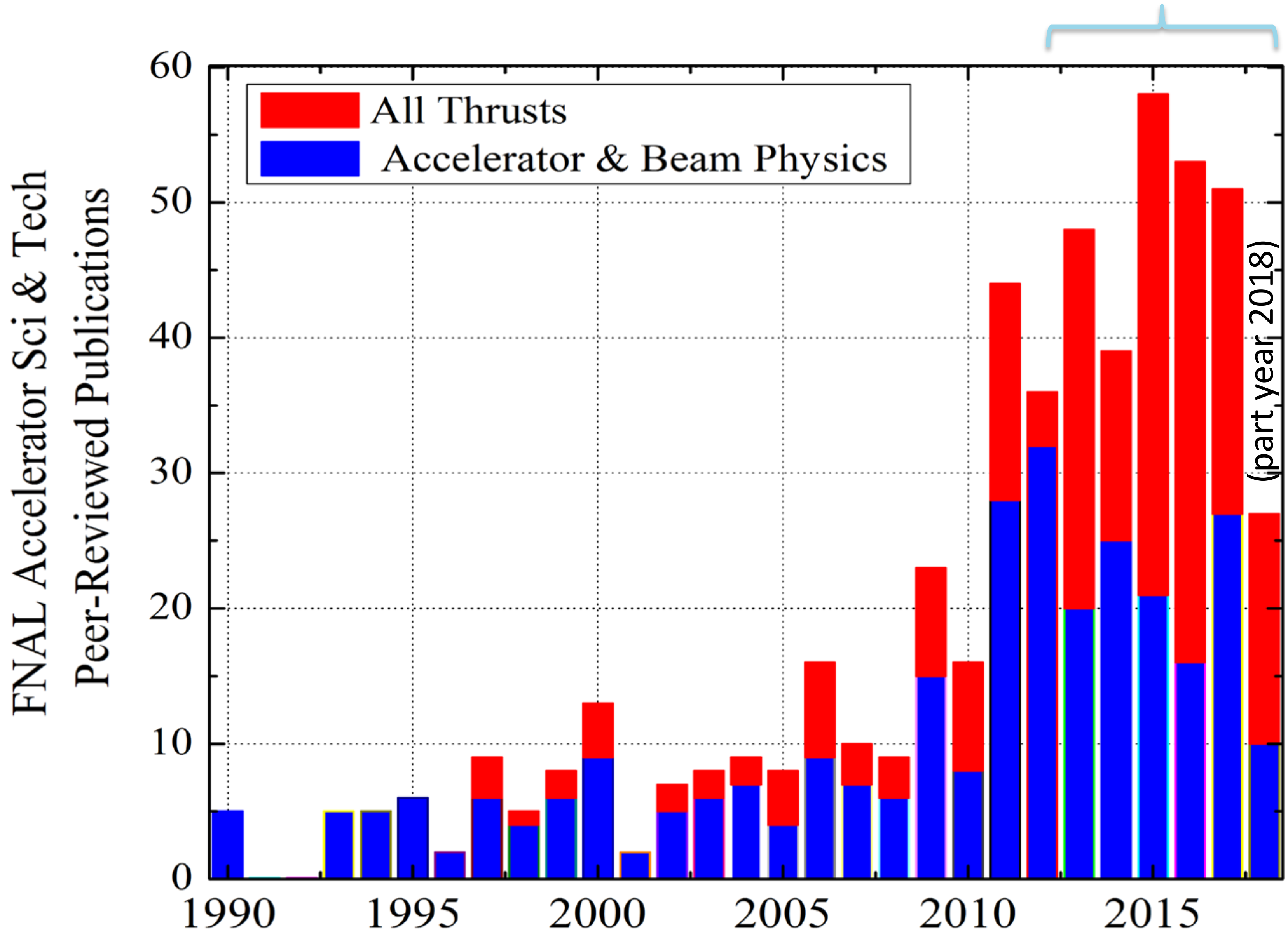


Int'l Space-Charge Collaboration:

Fermilab
CERN
FAIR
ICFA
BERKELEY LAB
GSI
UNIVERSITY OF MARYLAND 1856
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)

Fermilab Publications in Accelerator & Beam Physics



Publications in Accelerator and Beam Physics

- Strong peer-reviewed publication record: ***119*** papers in ***2013-2018***

2013	20	**3**
2014	25	**4**
2015	21	**2**
2016	16	**2**
2017	27	**4**
2018	10	**1**

- Incl. **14 high impact** publications (books, Nature, PRL, APL, Ann.Rev.Nucl.Sci., etc)

8 APS Fellows Take Part In Accelerator & Beam Physics R&D

Alexei Burov

Eric Prebys **

including those elected in 2013-2017

Alan Bross **

Valery Lebedev

Nikolai Mokhov

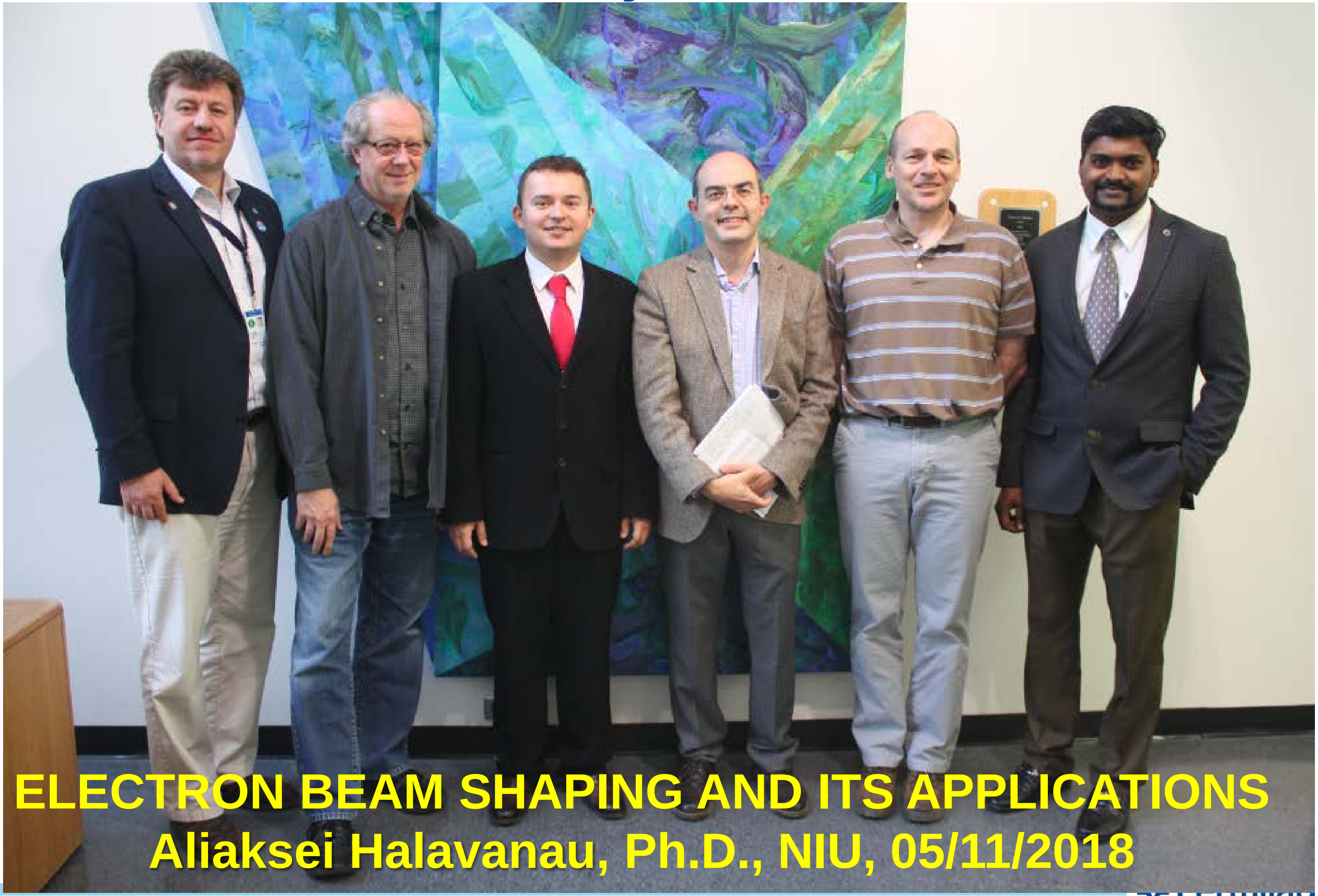
Sergei Nagaitsev

David Neuffer

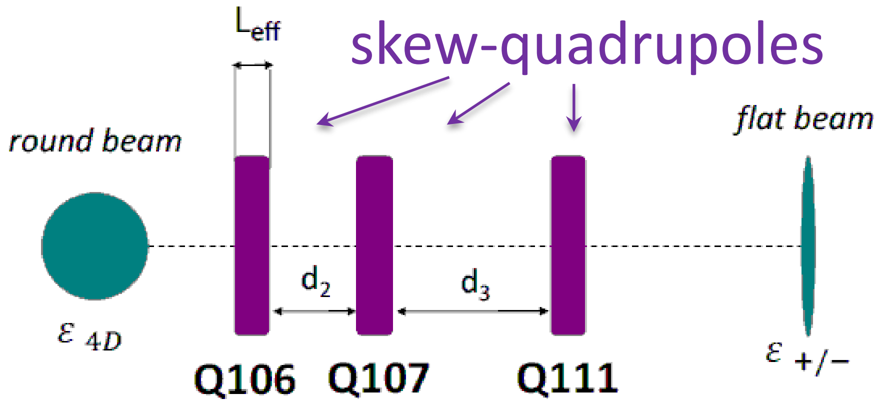
Vladimir Shiltsev

13 Students Got PhDs in 2013-2018 on base of Accelerator and Beam Physics Research at FNAL

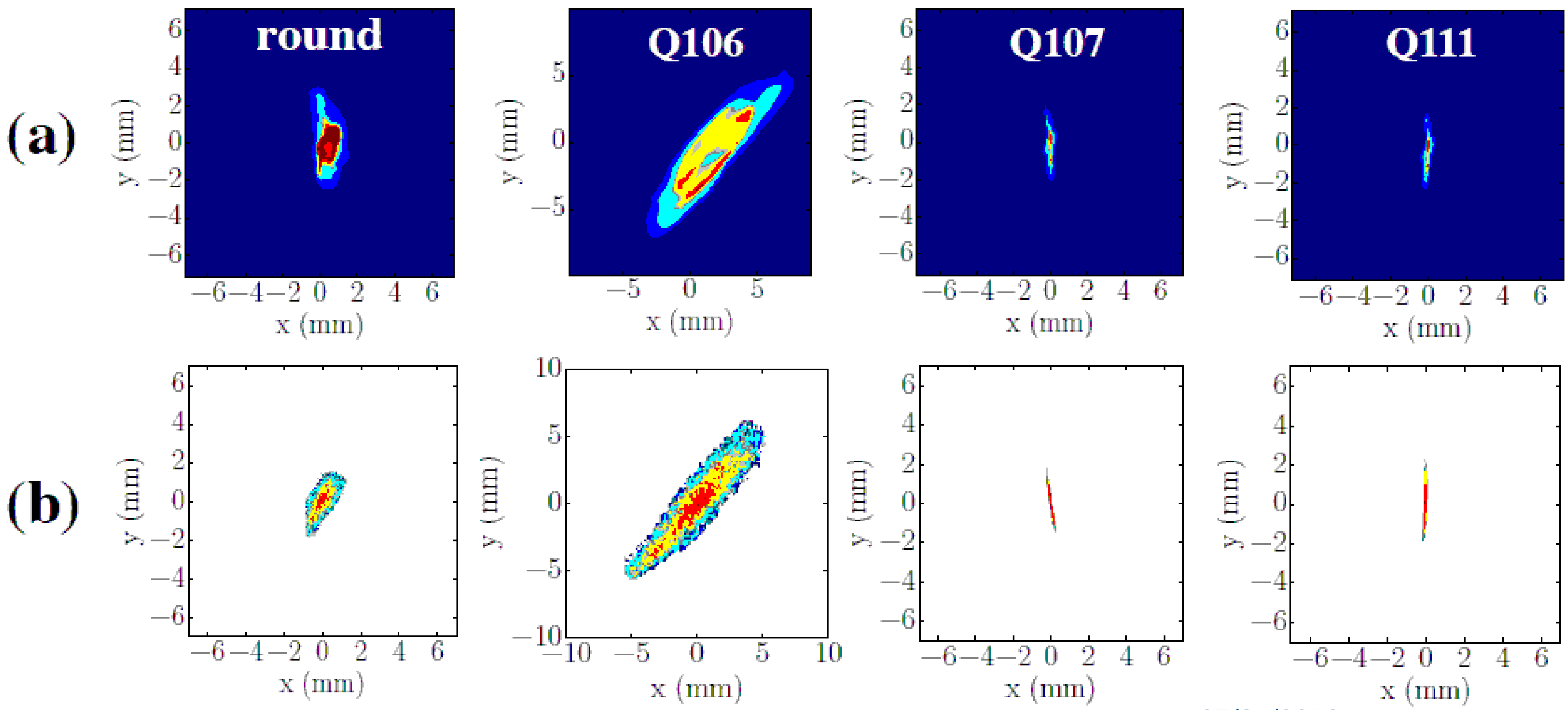
* see his talk in the Breakout Session 4



Beam Phase-Space Manipulation: Round-to-Flat



- (a) - Experimental, (b) - simulations in *Impact-T*
- both Vert. and Hor. flat beams
- First ever compressed Hor-flat-beam helps against CSR



10 Current PhD Students at Fermilab Doing Accelerator and Beam Physics R&D

* see also his talk

Nikita Kuklev	University of Chicago
Ihar Lobach	University of Chicago
Yichen Ji	IIT
David Tarazona	Michigan State University
Jibong Hyun	KEK
Saba Fatima	NIU
Matt Urfer	NIU
Asama Mohsen	NIU
Aaron Fewtterman	NIU
Sebastian Szustkowski	NIU

Fermilab GARD Program on

Accelerator and Beam Physics :

Goals for 2019-2024 and Beyond

Accelerator and Beams Physics : Plans for 2019-23

i. Over the next five years Fermilab will establish a fully operational test facility to address key questions related to intense beams for future, cost-effective accelerators The facility will enable transformative accelerator science. The central component of the test facility is the Integrable Optics Test Accelerator (IOTA), an innovative nonlinear storage ring that will include a proton and ion injector as well as a world-class high-brightness electron injector

ii. IOTA scientific output will be critical to define the next steps in high-intensity particle beam development beyond PIP-II, and to establish novel approaches to advanced beam physics research. Expect to demonstrate greatly improved coherent and incoherent beam stability"

ALP-2018: Accelerator Science Vision

- Over the next 5 years… the laboratory will strive to establish a ***national user facility*** for accelerator science based around the FAST facility and its IOTA ring.
- Do accelerator beam-based science to *advance all fields that use accelerators*: light sources; free-electron lasers; very-high-energy colliders; electron-ion colliders, high-intensity machines


Fermi National Accelerator Laboratory
Fermilab

Annual Laboratory Plan

Fermi National Accelerator Laboratory

Fiscal Year 2018

see Sergei Nagaitsev's talk

- Couple it with strong *student training* through the U.S. Particle Accelerator School (USPAS) and *engagements with universities*; leverage GARD, Accelerator Stewardship, and LDRD funding as well as CRADA and SPP research opportunities to : i) expand the Fermilab Accelerator PhD program; ii) lead and grow collaborations with local universities; iii) initiate and expand non-HEP accelerator initiatives; iv) lead and safeguard the USPAS; and v) lead and expand international initiatives together with DOE/HEP.

In particular, for Accelerator and Beam Physics (1):

I. Conclude construction of the IOTA R&D facility:

i. IOTA proton injector **2019 ***

II. Focus on experimental studies in IOTA

i. Nonlinear Integrable Optics

- Phase I: With electrons **2018-2020**
- Phase II: With protons **2020-2022**

Goal: ~(3-10) reduction in SC-dominated beam losses

ii. Space-charge compensation with e-lens

- With electron lens **2020-2022**
- With electron column **2022-2023**

Goal: factor of ~2 compensation of the SC limit

Accelerator and Beam Physics Goals (2):

II. Focus on experimental studies in IOTA

iii. Optical Stochastic Cooling

- Without optical amplifier **2019-2021**
- With optical amplifier **2021-2023**

Goal: proof-of-principle demo of OSC / measure rates

iv. Physics of space-charge dominated beams

- Imperfections and noise effects **2020-2023**
- Halo and collective modes dynamics **2022-2023**

Goal: confirm theory and benchmark simulation codes

v. Grow the IOTA collaboration

- Fermilab, Labs, Universities, Intl **2019-2023**

Goal: double the collaboration to ~130

vi. Provide cost-efficient operation **2018-2023**

Goal: 6 months a year of beam-time; >90% uptime

Accelerator and Beam Physics Goals (3):

III. Beam physics theory and simulations

i. Further insight into physics of IOTA tests

- Integr.Optics, SC Compens'n, OSC, etc **2019-2023**

Goal: complete modeling/explanation of results

ii. Additional studies at operational machines

- FNAL-CERN-GSI studies in Booster **2019**
- Benchmark theory/simulations vs ops **2019-2023**

Goal: better understanding and codes' benchmarking

iii. Further development of Synergia

- GARD and SciDAC4, couple with MARS **2019-2023**

Goal: broaden scope and "trust" in simulations

iv. Apply new knowledge to PIP-III design **2024-2027**

Goal: high performance & cost efficient options

Accelerator and Beam Physics Goals (4):

IV. Establish *Accelerator Science User Facility*

i. Provide opportunities for external users

- At both FAST and IOTA **2019-2023**

Goal: demonstrate opportunities and develop user base

ii. Establish National *Accelerator Science User Facility*

- Set up the program and organization by ~**2023**

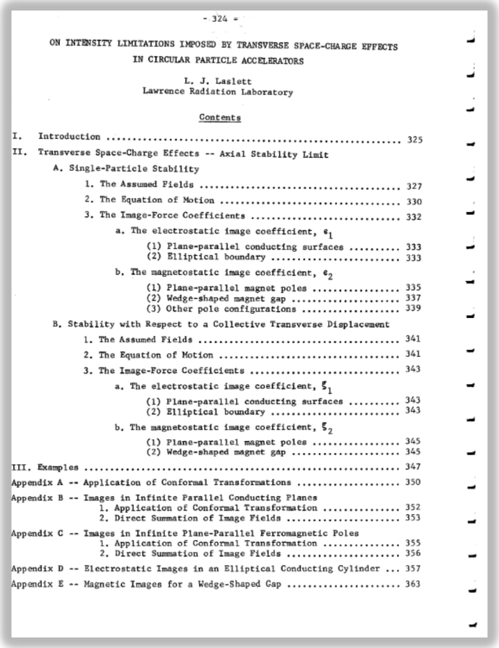
Goal: serve all Office of Sci offices and beyond

V. Operate *User Facility* **2024-**

Challenges (1) : Physics

- We carry out innovative research in the area where many smart people worked for over 50 years
- Truly “high risk – high reward” research

L.J. Laslett, BNL-7534 (**1963**)



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ON INTENSITY LIMITATIONS IMPOSED BY TRANSVERSE SPACE-CHARGE EFFECTS IN CIRCULAR PARTICLE ACCELERATORS

L. J. Laslett
Lawrence Radiation Laboratory

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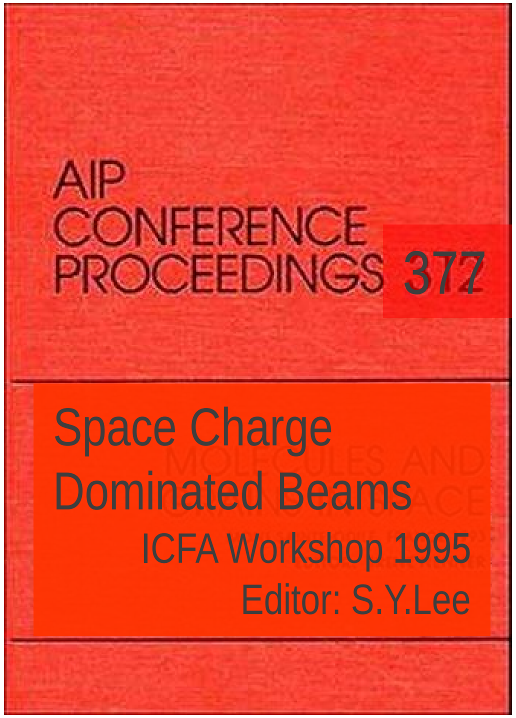

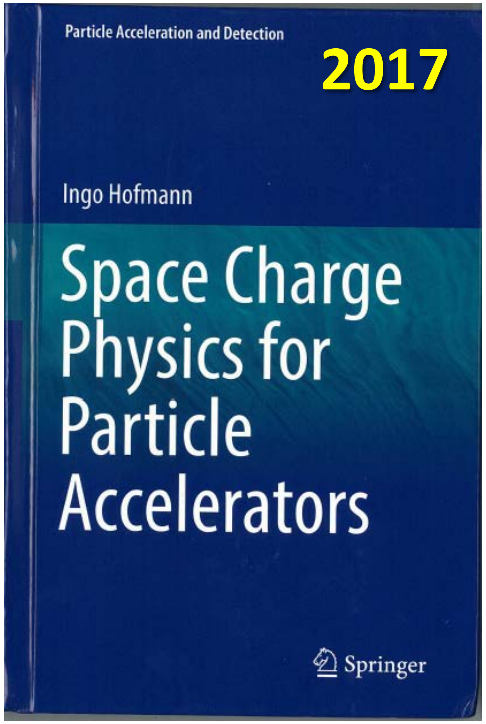

Challenges (2): Management and Planning

- In FY13-FY18 Accelerator and Beam Physics thrust funding has been absorbed by IOTA/FAST construction, commissioning and initial operation:
  - supplemental support from OHEP was critically important to accelerate the schedule and allow start the research sooner by ~1 yr (*thank you!)*
  - research per se (experiments) was lower funding priority for a while
  - e.g., additional request for FY19 is 800k$ of M&S to boost e-Lens & OSC
- "Release" of funds for the IOTA/FAST research in FY19-23 will be possible only if operations cost is fully picked by the Test Facilities Ops B&R:
  - e.g., requested 864k$ increase in FY19 (see J.Leibfritz talk)
- Transition from the GARD Accelerator and Beam Physics program at FAST/IOTA to the National Accelerator Science User Facility should be carefully planned:
  - GARD program should have schedule contingency to be finished/extended if necessary to conclude innovative studies towards record high brightness beams
  - the Accelerator Science User Facility program will need to be formed in close coordination with other SCI Offices and labs

Conclusion

- Fermilab's GARD program in accelerator and beam physics is perfectly aligned with the P5 plan, ARDS, and supports the US's and FNAL ambitions in the Intensity and Energy Frontiers
- We had tremendous success in the past 5 years:
  - Constructed IOTA/FAST facility : ring and two injectors
  - Established landscape-changing IOTA experiments & collaborations
  - Greatly progressed in beam theory and simulation tools
  - Record high 119 peer-review publications, 14 PhDs, 8 awards, etc
- Accelerator and Beam Physics program plan for FY19-23:
  - Is of highest relevance to HEP's mission and goals
  - Has IOTA/FAST research program as key element for Accelerator R&D in US, esp. for *Intensity Frontier Program*
  - Lays foundation for transition to Acc.Sci. User Facility in the future