Research with the IOTA Electron Lens: Overview

Giulio Stancari
Fermilab

IOTA/FAST Collaboration Meeting
Fermilab, October 27-29, 2021

indico.fnal.gov/event/50565

Contributors

C. Boffo, A. Burov, K. Carlson, B. Cathey, D. Crawford, R. Dhuley, N. Eddy, D. Franck, V. Kashikhin, V. Lebedev, S. Nagaitsev, M. Obrycki, A. Romanov, J. Ruan, V. Shiltsev, G. Stancari, E. Stern, A. Valishev, T. Zolkin (Fermilab)

A. Kolehmainen, D. Perini (CERN)

N. Banerjee, J. Brandt, Y.-K. Kim (U. Chicago)

B. Freemire (Euclid)

M. Chung (UNIST, Korea)

C. S. Park (Korea U. Sejong)

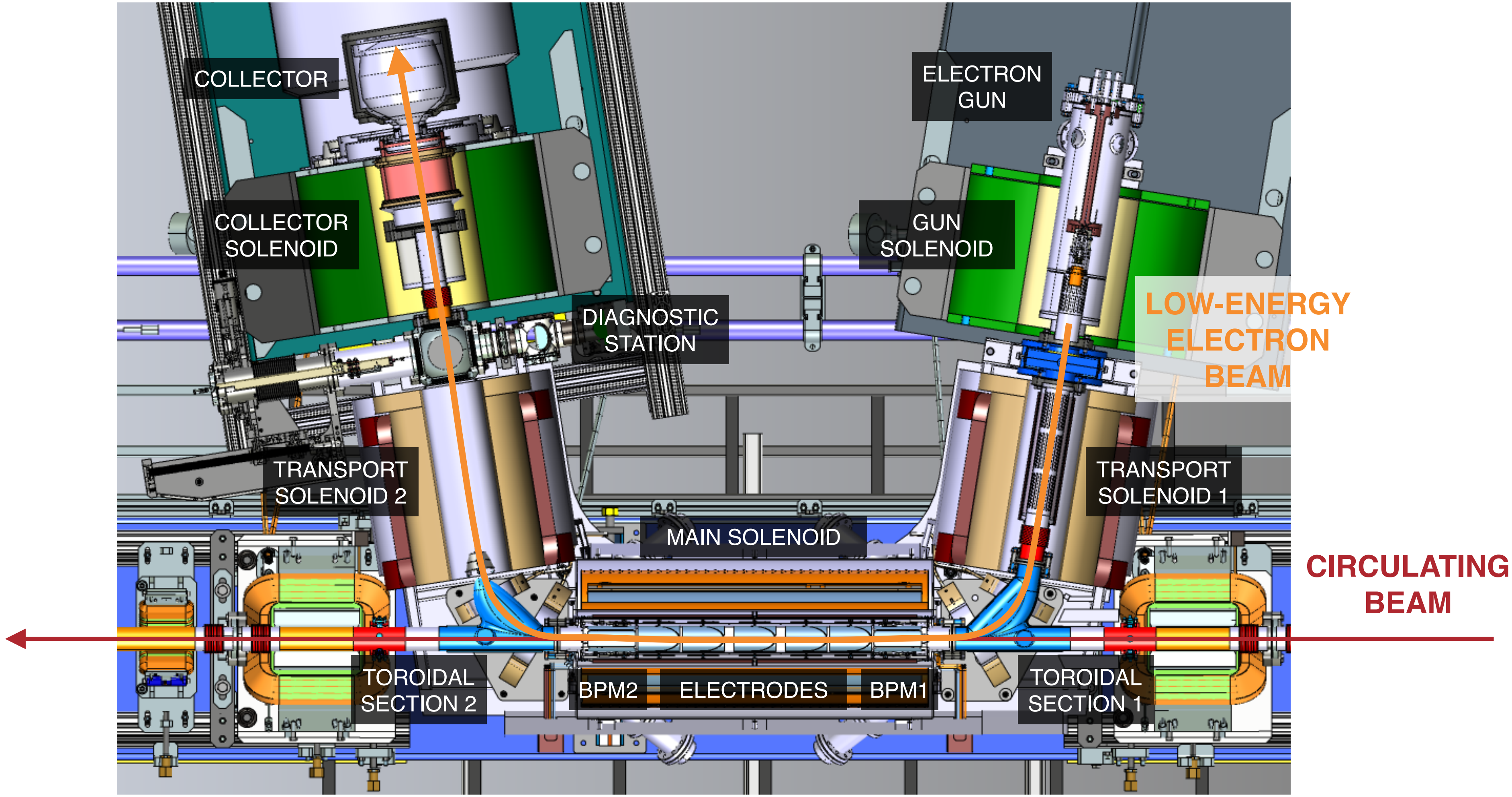
C. Mitchell (LBNL)

R. Agustsson, Y.-C. Chen, A. Murokh, A. Smirnov (RadiaBeam)

C. Hall (RadiaSoft)

What can an electron lens do?

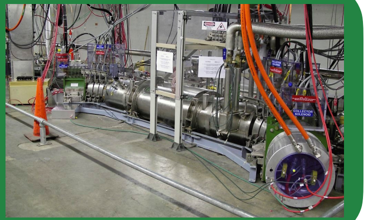
A **magnetically confined**, **low-energy electron beam** is used to affect the transverse and longitudinal **dynamics of the circulating beam** in a storage ring. **Energy**, **current**, **transverse profile** and **pulse structure** of the low-energy electron beam can be **precisely controlled**, making the electron lens a **very flexible tool** in beam physics.

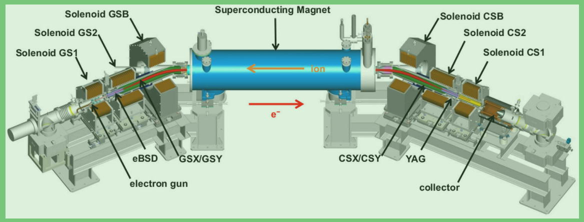


What can an electron lens do?

Fermilab Tevatron collider (2001-2011)

- head-on and long-range beam-beam compensation
- abort-gap clearing
- first studies of halo scraping with hollow beams



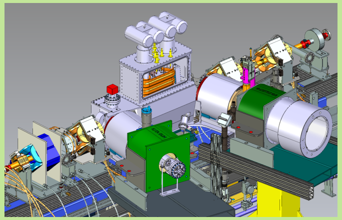


RHIC at BNL (2015-present)

- head-on beam-beam compensation
- further studies of halo scraping

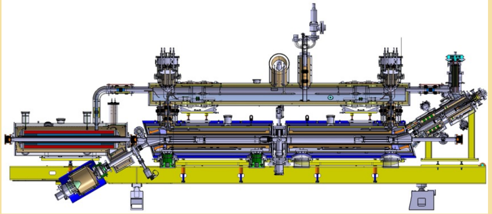
IOTA

- nonlinear integrable optics
- electron cooling
- tune-spread generation
- space-charge compensation



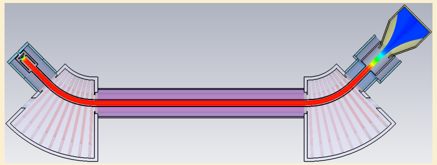
LHC at CERN (2025-2027 installation)

- active halo control with hollow beams
- option for tune-spread generation

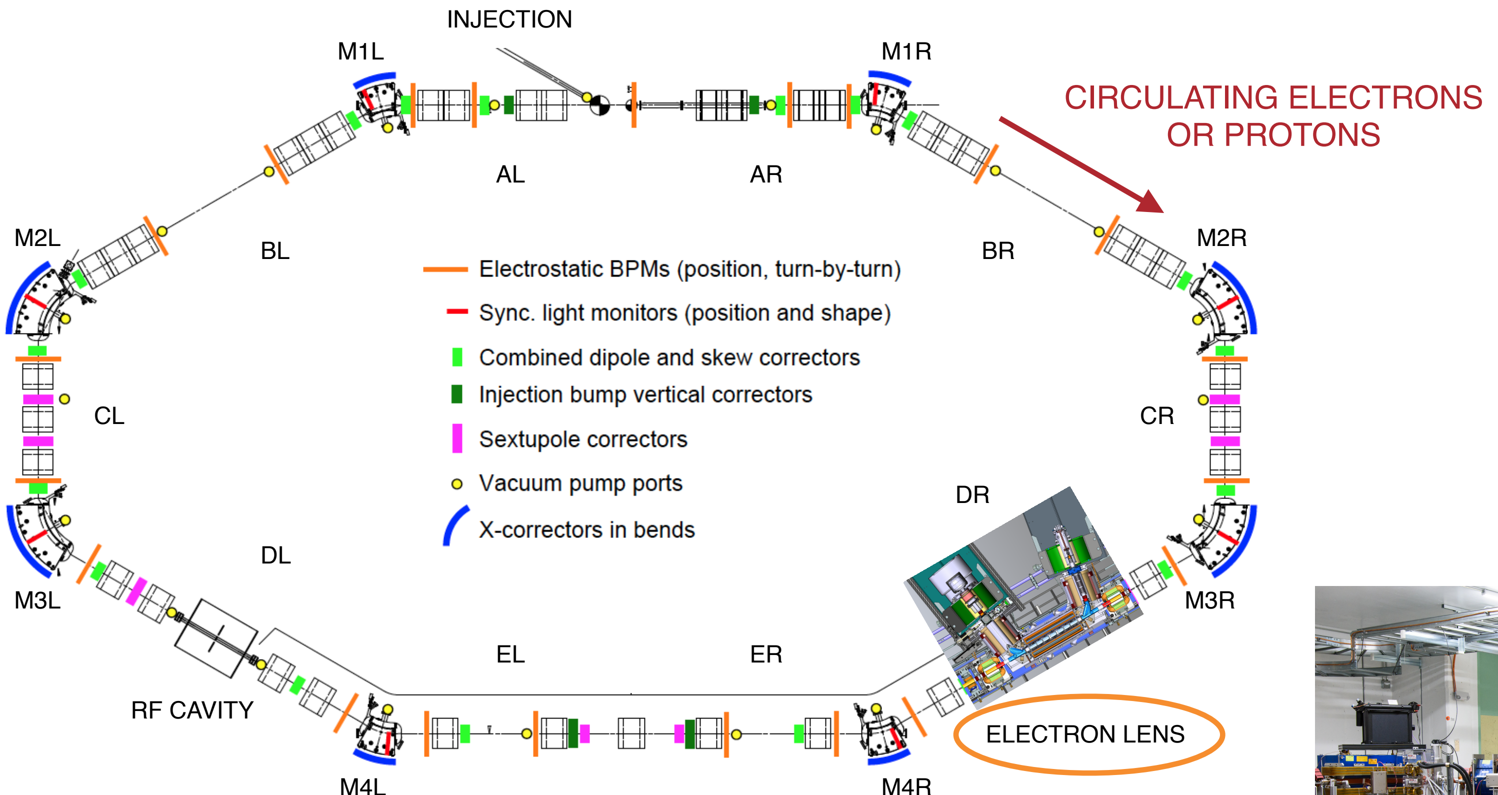


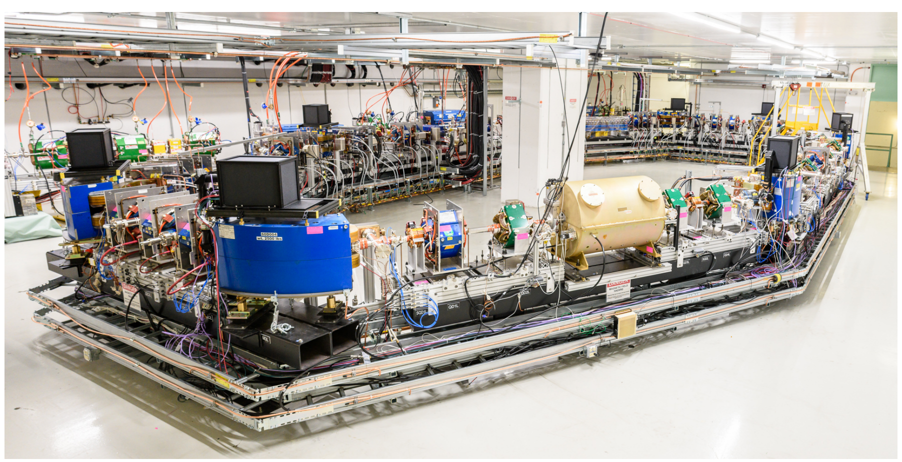
SIS18 and SIS100 at FAIR

- space-charge compensation



Electron lens layout in IOTA





What research can we do in IOTA with an electron lens?

Nonlinear Integrable Optics (NIO): Use the electron lens as a nonlinear focusing element to create integrable lattices.

Electron Cooling: Enable experimental program on high-intensity beams with protons, providing a wide range of lifetimes and brightnesses.

Tune-Spread Generation: Demonstrate the benefits of Landau damping under controlled excitations.

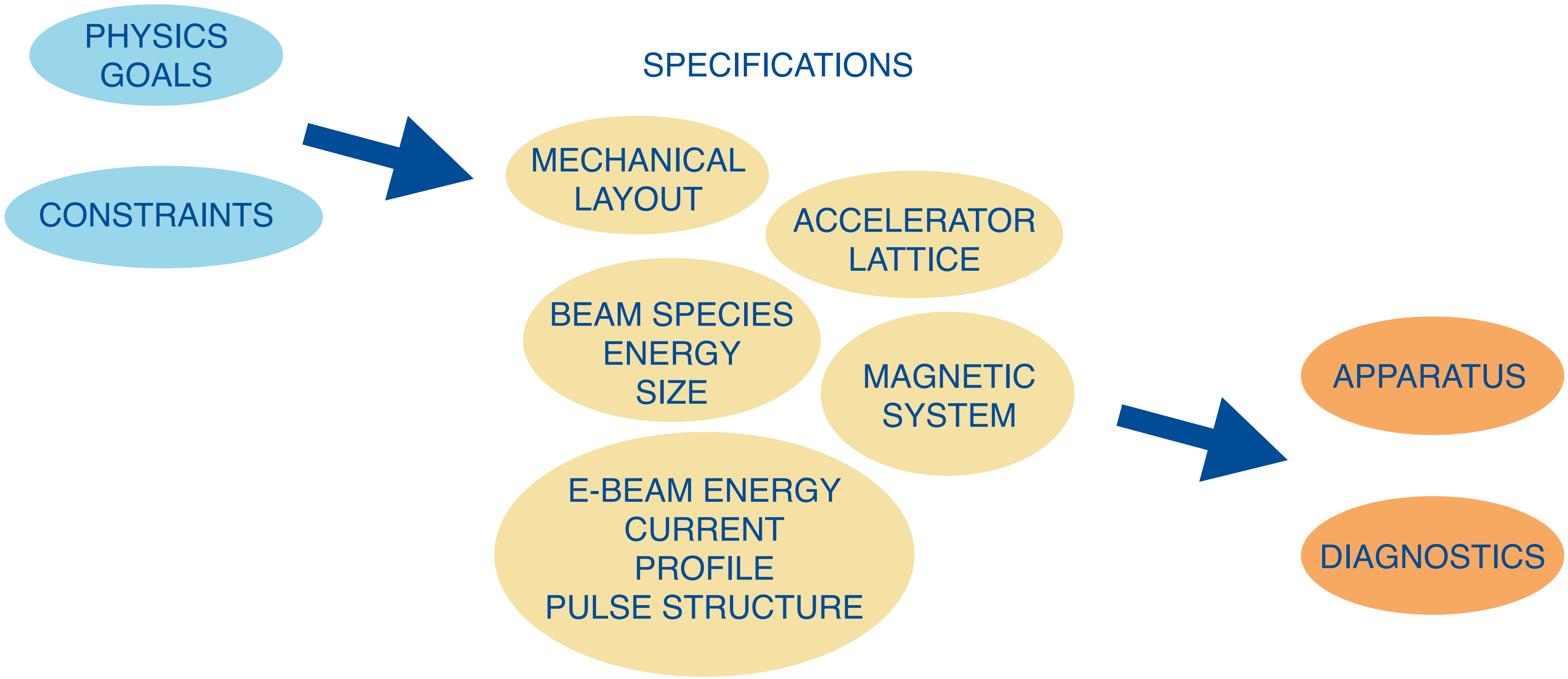
Space-Charge Compensation (SCC): Mitigate the effects of space charge on lifetime and emittance growth with an "e-column" or a "SCC e-lens".

Advanced Studies on Beam Stability: Observe the interplay between destabilizing mechanisms (space charge, controlled impedances) and mitigation strategies (electron cooling, Landau damping, active feedback).

G. Stancari et al., *Beam Physics Research with the IOTA Electron Lens*, JINST **16** P05002 (2021)
https://doi.org/10.1088/1748-0221/16/05/P05002

See also the next talks in this session: Cathey, Banerjee, Burov and Stern

Baseline design: from physics to specifications to apparatus



Challenge: several functions combined in a compact electron lens (too many?). Baseline design completed. However, careful **review of experimental designs** is required before construction. *Input from collaborators and users is needed.*

Core physics groups

Nonlinear Integrable Optics
Cathey, Romanov, Stancari, Valishev

Electron Cooling
Banerjee, Burov, Lebedev, Nagaitsev, Stancari

Tune-Spread Generation for Landau Damping
Burov, Shiltsev, Stancari, Valishev

Space-Charge Compensation
Chung, Freemire, Park, Shiltsev, Stancari, Stern

Advanced Beam Stability
(interplay of space charge, impedances, cooling, Landau damping and feedback)
Ainsworth, Banerjee, Burov, Eddy, Lebedev, Nagaitsev, Stancari, Valishev

Each group is responsible for **formulating physics goals**, preparing **experimental proposals**, and providing **specifications for the apparatus**.

Collaborators are very welcome.

Typical IOTA parameters with stored electrons or protons

	Electrons	Protons
Circumference, C	39.96 m	39.96 m
Kinetic energy, K_b	100–150 MeV	2.5 MeV
Revolution period, τ_{rev}	133 ns	1.83 µs
Revolution frequency, f_{rev}	7.50 MHz	0.547 MHz
Rf harmonic number, h	4	4
Rf frequency, f_{rf}	30.0 MHz	2.19 MHz
Max. rf voltage, V_{rf}	1 kV	1 kV
Number of bunches	1	4 or coasting
Bunch population, N_b	$1\ e^- - 3.3 \times 10^9\ e^-$	$< 5.7 \times 10^9\ p$
Beam current, I_b	1.2 pA – 4 mA	< 2 mA
Transverse emittances (rms, geom.), $\epsilon_{x,y}$	20–90 nm	3–4 µm
Momentum spread, $\delta_p = \Delta p/p$	1–4×10^{-4}	1–2×10^{-3}
Radiation damping times, $\tau_{x,y,z}$	0.2–2 s	–
Max. space-charge tune shift, $\lvert\Delta\nu_{\mathrm{sc}}\rvert$	$< 10^{-3}$	0.5

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IOTA electron lens parameters

Parameter	Value
Lattice amplitude functions, $\hat{\beta}$	2–4 m
Circulating beam size (rms), e^-	0.4–0.6 mm
Circulating beam size (rms), p	0.9–4 mm
Circulating beam divergence (rms), e^-	0.15–0.21 mrad
Circulating beam divergence (rms), p	0.3–1.4 mrad
Cathode-anode voltage, V	0.5–10 kV
Peak current, I_e	5 mA – 3 A
Pulse width	200 ns to DC
Pulse repetition rate	DC to 10 kHz
Cathode radius, r_c	< 15 mm
Current-density distributions	McMillan, Gaussian, flat, semi-hollow
Length of the main solenoid, L	0.7 m
Main solenoid field, B_m	0.1–0.5 T
Gun and collector solenoid fields, B_g and B_c	0.1–0.4 T
Beam size compression, $\sqrt{B_m/B_g}$	0.5–2.2
Current-density magnification, B_m/B_g	0.25–5

IOTA electron-lens experimental requirements (examples)

	NIO McM	NIO axially symm.	e-cool	tune-spread generator	SCC e-lens	e-column	other?
max. solenoid fields (e-gun, main, coll.) [T]	0.4 / 0.5 / 0.4	0.4 / 0.5 / 0.4	0.4 / 0.2 / 0.4	0.4 / 0.5 / 0.4	0.4 / 0.5 / 0.4	— / 0.1 / —	
kinetic energy [keV]	5-10	5-10	1.36	1-10	1-10	—	
peak current [A]	0.1-2	0.1-2	0.01	0.01-1	0.1-2	—	
current-density profile	McMillan	Gaussian, McMillan	flat, semi-hollow	Gaussian	Gaussian	—	
pulse duration [us]	10^4 turns or DC	10^4 turns or DC	DC	< 1 ms and DC	DC, pulsed?	—	
pulse frequency [Hz]	< 5 Hz	< 5 Hz	DC	< 5 Hz	DC, intra-bunch modulation?	—	

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When will we have an electron lens in IOTA?

Depends on resources. At least 1 year from now.

The electron lens is **essential to enable the proton program** on the stability of high-brightness beams (IOTA Run 5 and beyond) in terms of research topics, range of achievable brightnesses, and diagnostic tools.

Very valuable contributions were received from internal and external collaborators. Also, a substantial part of the **equipment can be reused** from previous projects.

Current critical needs:
- a project engineer, to oversee the design and integration
- funding for the main components of the magnetic system
- committed collaborators to take responsibility of subsystems

The IOTA/FAST team has been very successful in completing projects (facility construction, NIO installation, OSC experiment, etc.), but the size of the group does not allow for progress on several parallel fronts. Next priorities: IOTA proton injector, Run 4 operations, and electron lens.

Recently published scientific and technical reports in JINST

Special Issue of Journal of Instrumentation on electron lenses (ICFA Beam Dynamics Newsletter #81), edited by V. Shiltsev and I. Hofmann

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Journal of Instrumentation

ICFA Beam Dynamics Panel Newsletters Special Issue

ICFA

The International Committee for Future Accelerators (ICFA) was created in 1976 by the Particle and Fields Division of the International Union of Pure and Applied Physics (IUPAP) to promote international collaboration towards construction and use of accelerators for high energy physics.

The Beam Dynamics Panel of ICFA encourages and promotes collaboration on beam dynamics studies for present and future accelerators via Workshops and regularly appearing Newsletters dedicated to selected themes –coordinated by an Issue editor. The spectrum of beam dynamics themes includes medium energy and high energy / high luminosity electron facilities / colliders as well as medium energy and high energy / high intensity hadron facilities. The series of such Newsletters started in 1987.

Publication of the Beam Dynamics Newsletter as Special Issue of the Journal of Instrumentation started in 2020 with Newsletter #79. It includes a general report with forewords/news from the Panel Chair (editor in chief) and the Issue editor as well as reports from past workshops/conferences, PHD thesis abstracts and other reports; followed by papers submitted from individual authors on the special theme of the Issue. Current and previous Newsletters are available on the Beam Dynamics Panel website, which also includes information on relevant workshops (formal ICFA Advanced Beam Dynamics Workshops, ICFA Mini-Workshops), guidelines for Workshops and Newsletters and a list of Panel members.

Ingo Hofmann, Panel Chair, GSI Darmstadt and Technical University Darmstadt, Germany

Previous issues of Newsletters and further information by the ICFA Beam Dynamics Panel are available at: http://www.icfa-bd.org/

ICFA Beam Dynamics Newsletter#82 – Advanced Accelerator Modelling
+ View Newsletter#82

ICFA Beam Dynamics Newsletter#81 – Electron Lenses for Modern and Future Accelerators
+ View Newsletter#81

ICFA Beam Dynamics Newsletter#80 –Medium Energy Heavy Ion Facilities
+ View Newsletter#80

ICFA Beam Dynamics Newsletter#79 –Space Charge
+ View Newsletter#79

Several articles about the IOTA e-lens program

https://iopscience.iop.org/journal/1748-0221/page/ICFA_Beam_Dynamics_Panel_Newsletters_Special_issue

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Published several articles about the IOTA e-lens program

Electron lenses: historical overview and outlook
V. Shiltsev 2021 *JINST* **16** P03039
+ Open abstract View article PDF

Electron lenses in RHIC: status and prospects
W. Fischer *et al* 2021 *JINST* **16** P03040
+ Open abstract View article PDF

Design of a compact, cryogen-free superconducting solenoid for the electron lens of the Fermilab Integrable Optics Test Accelerator (IOTA)
R.C. Dhuley *et al* 2021 *JINST* **16** T03009
+ Open abstract View article PDF

Calculations of detuning with amplitude for the McMillan electron lens in the Fermilab Integrable Optics Test Accelerator (IOTA)
B. Cathey *et al* 2021 *JINST* **16** P03041
+ Open abstract View article PDF

Hollow electron lenses for beam collimation at the High-Luminosity Large Hadron Collider (HL-LHC)
S. Redaelli *et al* 2021 *JINST* **16** P03042
+ Open abstract View article PDF

Electron dynamics for high-intensity hollow electron beams
A. Rossi *et al* 2021 *JINST* **16** P03043
+ Open abstract View article PDF

Design of high-performance guns for the HL-LHC HEL
D. Perini *et al* 2021 *JINST* **16** T03010
+ Open abstract View article PDF

Pulsed electron lenses for space charge compensation in the FAIR synchrotrons
S. Artikova *et al* 2021 *JINST* **16** P03044
+ Open abstract View article PDF

Self-consistent PIC simulations of ultimate space charge compensation with electron lenses
E. Stern *et al* 2021 *JINST* **16** P03045
+ Open abstract View article PDF

Landau Damping with Electron Lenses in Space-Charge Dominated Beams
Y. Alexahin *et al* 2021 *JINST* **16** P03046
+ Open abstract View article PDF

McMillan electron lens in a system with space charge
S. Nagaitsev *et al* 2021 *JINST* **16** P03047
+ Open abstract View article PDF

Progress in space charge compensation using electron columns
C.S. Park *et al* 2021 *JINST* **16** P03048
+ Open abstract View article PDF

Beam physics research with the IOTA electron lens
G. Stancari *et al* 2021 *JINST* **16** P05002
+ Open abstract View article PDF

In memoriam: Yuri Alexahin (1948-2020)

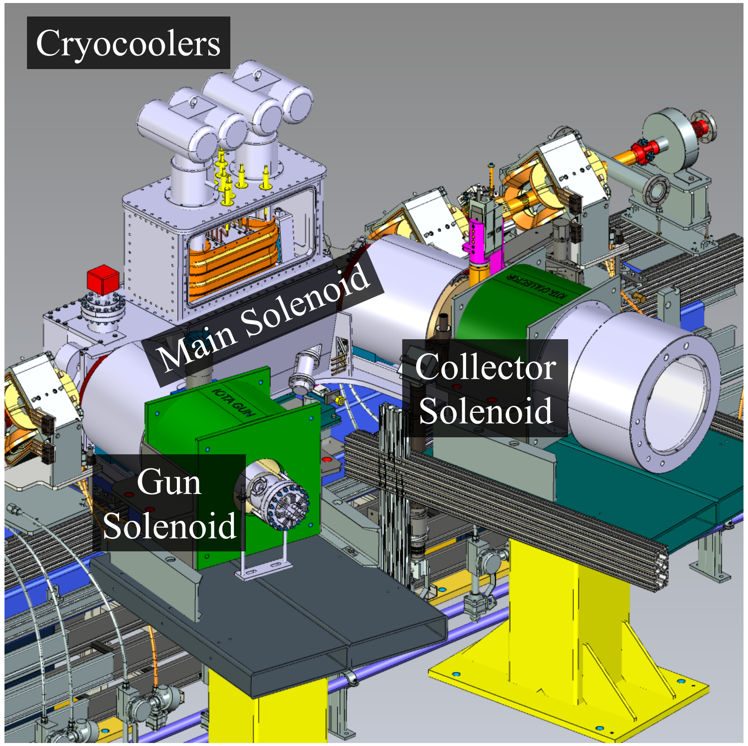
On possibility of space-charge compensation in the Fermilab Booster with multiple electron columns
Yu. Alexahin and V. Kapin 2021 *JINST* **16** P03049
+ Open abstract View article PDF

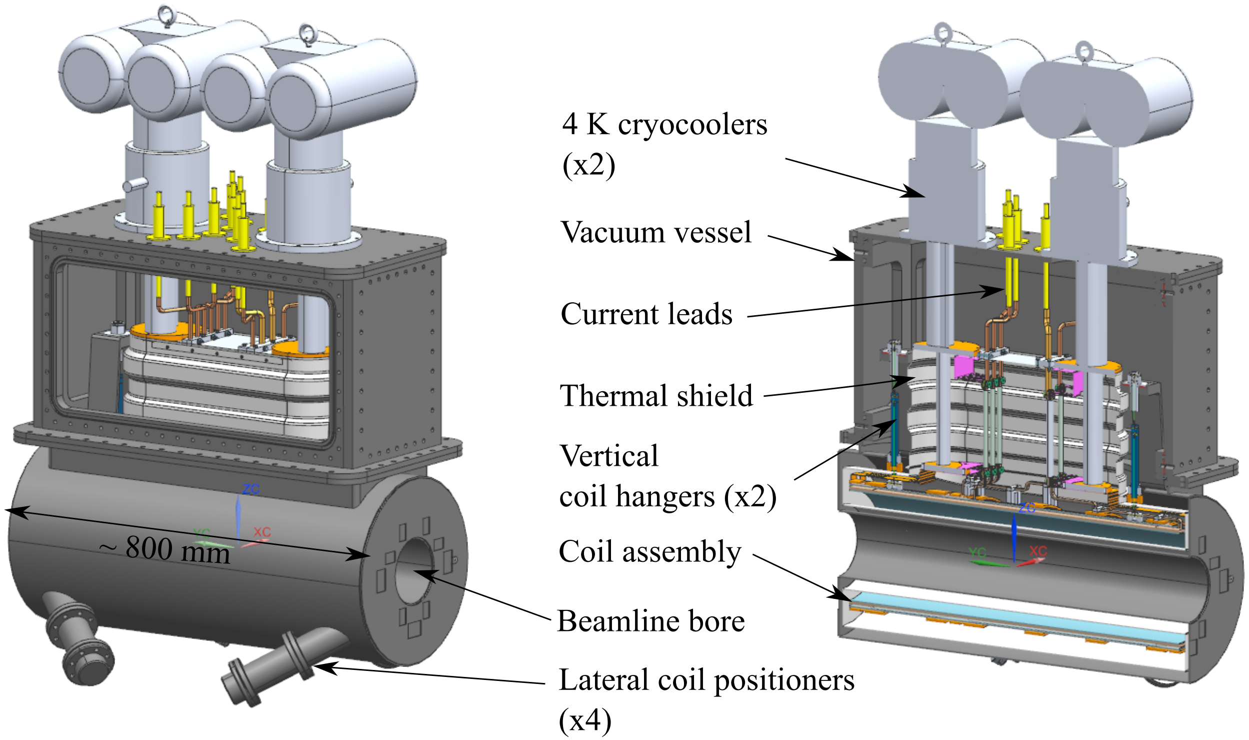
In memoriam: Slava Danilov (1966-2014)

On the possibility of footprint compression with one lens in nonlinear accelerator lattice
V. Danilov and V. Shiltsev 2021 *JINST* **16** P03050
+ Open abstract View article PDF

Designed a cryo-cooled main solenoid for the IOTA e-lens

R. C. Dhuley, C. Boffo, V. Kashikhin, A. Kolehmainen, D. Perini and G. Stancari,
Design of a Compact, Cryogen-Free Superconducting Solenoid for the Electron Lens of the Fermilab Integrable Optics Test Accelerator,
JINST **16** T03009 (2021), https://doi.org/10.1088/1748-0221/16/03/T03009



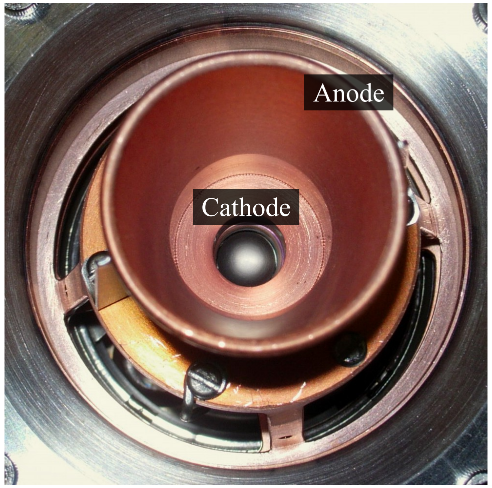


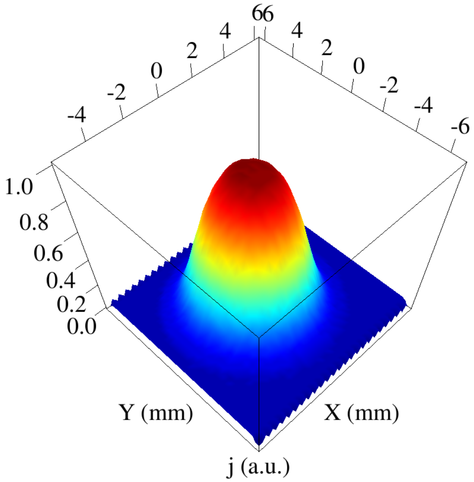
Stand-alone, compact and reliable system. Good field quality and low power consumption. Needs second design iteration on field straightness and quench protection.

Fermilab e-lens test stand upgrades and commissioning

Vacuum upgrades: new pumps and ion gauges, controls (Franck, Obrycki, Stancari)

Started tests of existing 10-mm Gaussian electron gun (1.6 A at 10 kV), reused from the Tevatron, for the IOTA research program (Banerjee, Cathey, Stancari)

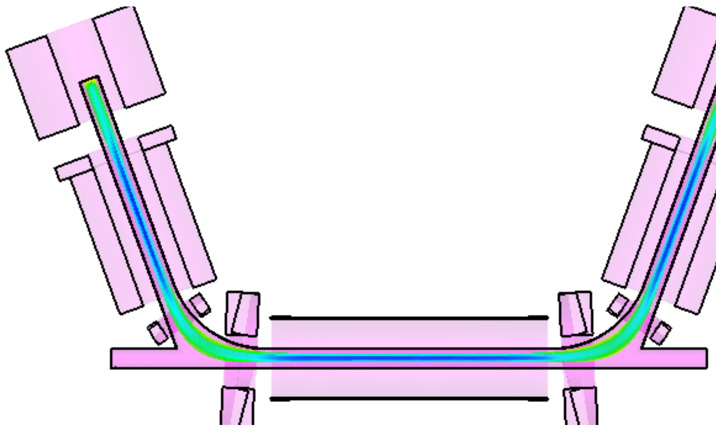




Collaborations

Completed DOE SBIR Phase I design study with RadiaBeam and RadiaSoft:

- R. Agustsson
- Y.-C. Chen
- C. Hall
- A. Murokh
- A. Smirnov (PI)



Conceptual design of the full magnetic system for the IOTA e-lens. Compared resistive and superconducting options.

Strengthened collaboration with U. Chicago (Y.-K. Kim, S. Nagaitsev):

- Nilanjan Banerjee (post-doc)
- John Brandt (engineer)

Main topics: electron cooling, beam instabilities, design and construction of electron guns and instrumentation

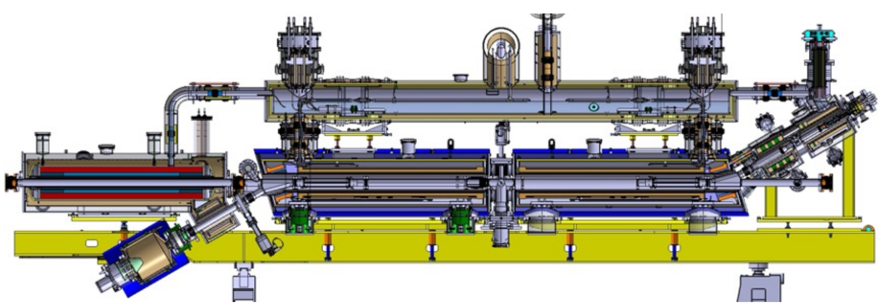
Collaborations

Continued to benefit from collaborations with the **growing international community of electron-lens experts**

W. Fischer, X. Gu (BNL) - Beam studies at RHIC, electron gun design

P. Hermes, D. Mirarchi, S. Redaelli, A. Rossi, S. Sadovich (CERN) - Hollow electron beams for halo control in LHC, e-lens test stand design and instrumentation, simulation codes

A. Levichev, D. Nikiforov (BINP) - electron beam dynamics, simulation codes



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 031001 (2020)

Halo removal experiments with hollow electron lens in the BNL Relativistic Heavy Ion Collider

X. Gu,[*] W. Fischer, Z. Altinbas, A. Drees, J. Hock, R. Hulsart, C. Liu, A. Marusic, T. A. Miller, M. Minty, G. Robert-Demolaize, Y. Tan, and P. Thieberger
Brookhaven National Laboratory, Upton, New York 11973, USA

H. Garcia Morales[†]
CERN, 1211 Geneva, Switzerland and Royal Holloway, University of London, Egham, TW20 0EX, United Kingdom

D. Mirarchi,[‡] S. Redaelli, and A. I. Pikin
CERN, 1211 Geneva, Switzerland

G. Stancari
Fermilab, Batavia, Illinois 60510, USA

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 021001 (2021)

Resonant and random excitations on the proton beam in the Large Hadron Collider for active halo control with pulsed hollow electron lenses

Miriam Fitterer, Giulio Stancari,[*] and Alexander Valishev
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

Stefano Redaelli and Daniel Valuch
CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 044802 (2020)

Probing LHC halo dynamics using collimator loss rates at 6.5 TeV

A. Gorzawski,[1,2,*,†] R. B. Appleby,[3,4] M. Giovannozzi,[1] A. Mereghetti,[1] D. Mirarchi,[1] S. Redaelli,[1] B. Salvachua,[1] G. Stancari,[5] G. Valentino,[2] and J. F. Wagner[1,6]
[1]*CERN, Beams Department, Esplanade des Particules 1, 1211 Geneva, Switzerland*
[2]*University of Malta, Msida, MSD 2080 Malta*
[3]*The University of Manchester, Manchester M13 9PL, United Kingdom*
[4]*The Cockcroft Institute, Warrington WA4 4AD, United Kingdom*
[5]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[6]*Goethe-Universität Frankfurt am Main, 60323 Frankfurt, Germany*

Conclusions

The **electron lens** is an integral part of the **IOTA research program**: it enables new experiments on **nonlinear dynamics**, **electron cooling**, **tune-spread generation** for stability, **space-charge compensation**, and **more advanced studies on instabilities and their mitigation**.

The project is **closely related to electron-lens applications in other machines** (RHIC at BNL, LHC at CERN, SIS18 and SIS100 at GSI/FAIR). Fermilab has been a leader in this field for 20 years.

Received **very valuable contributions** from **collaborators**.

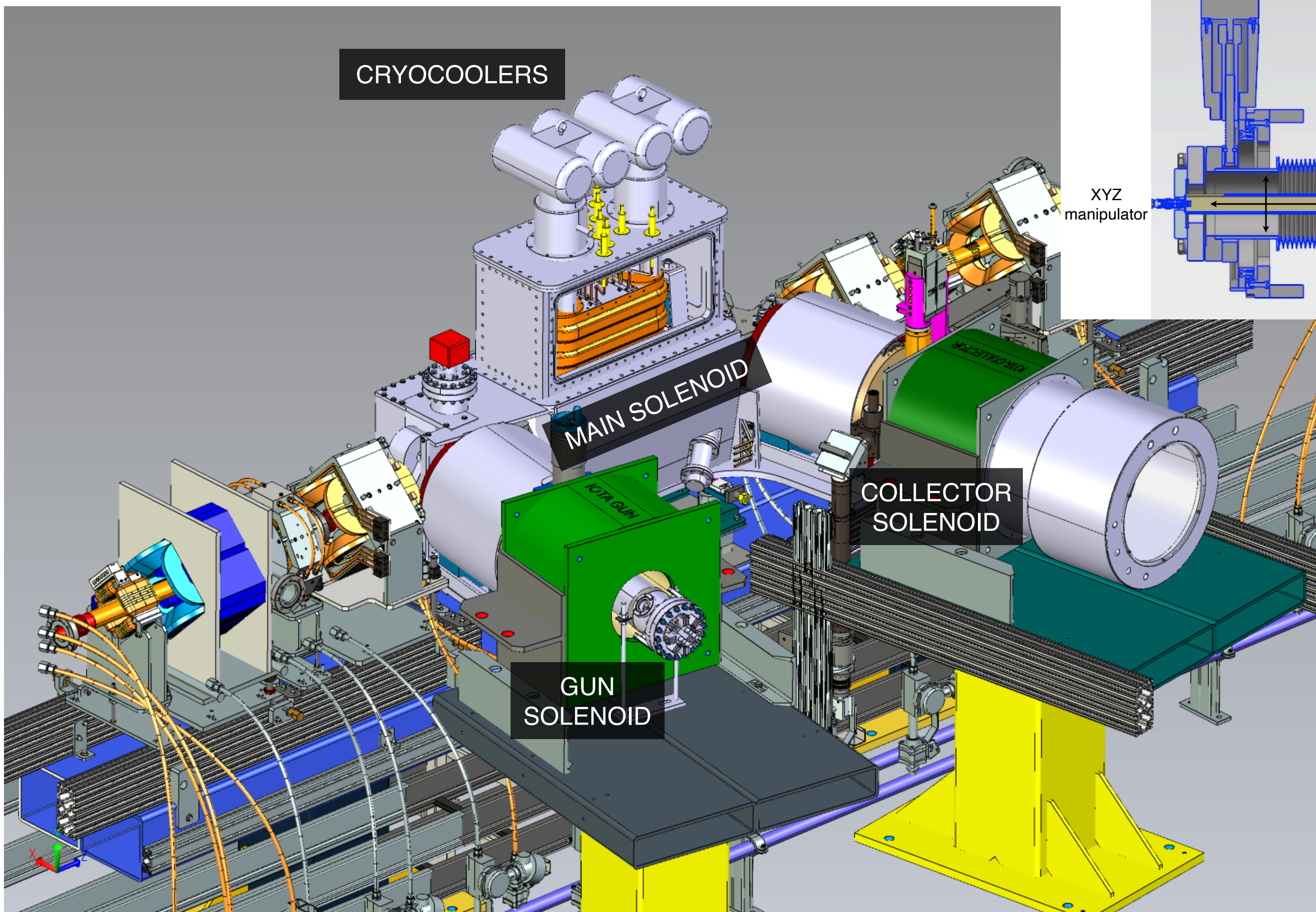
Now transitioning from baseline conceptual design to detailed experiment design. Input from all interested collaborators is needed before construction.

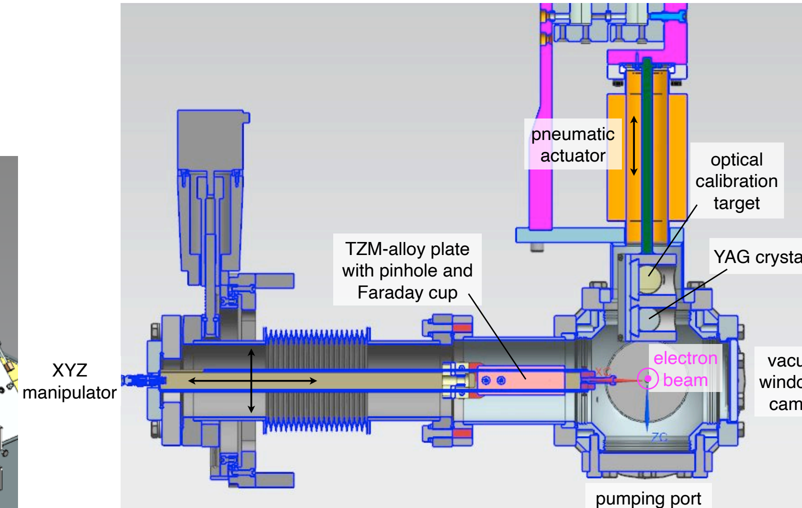
We look forward to interesting experiments in IOTA!

For more info: cdcvs.fnal.gov/redmine/projects/iota-e-lens/wiki

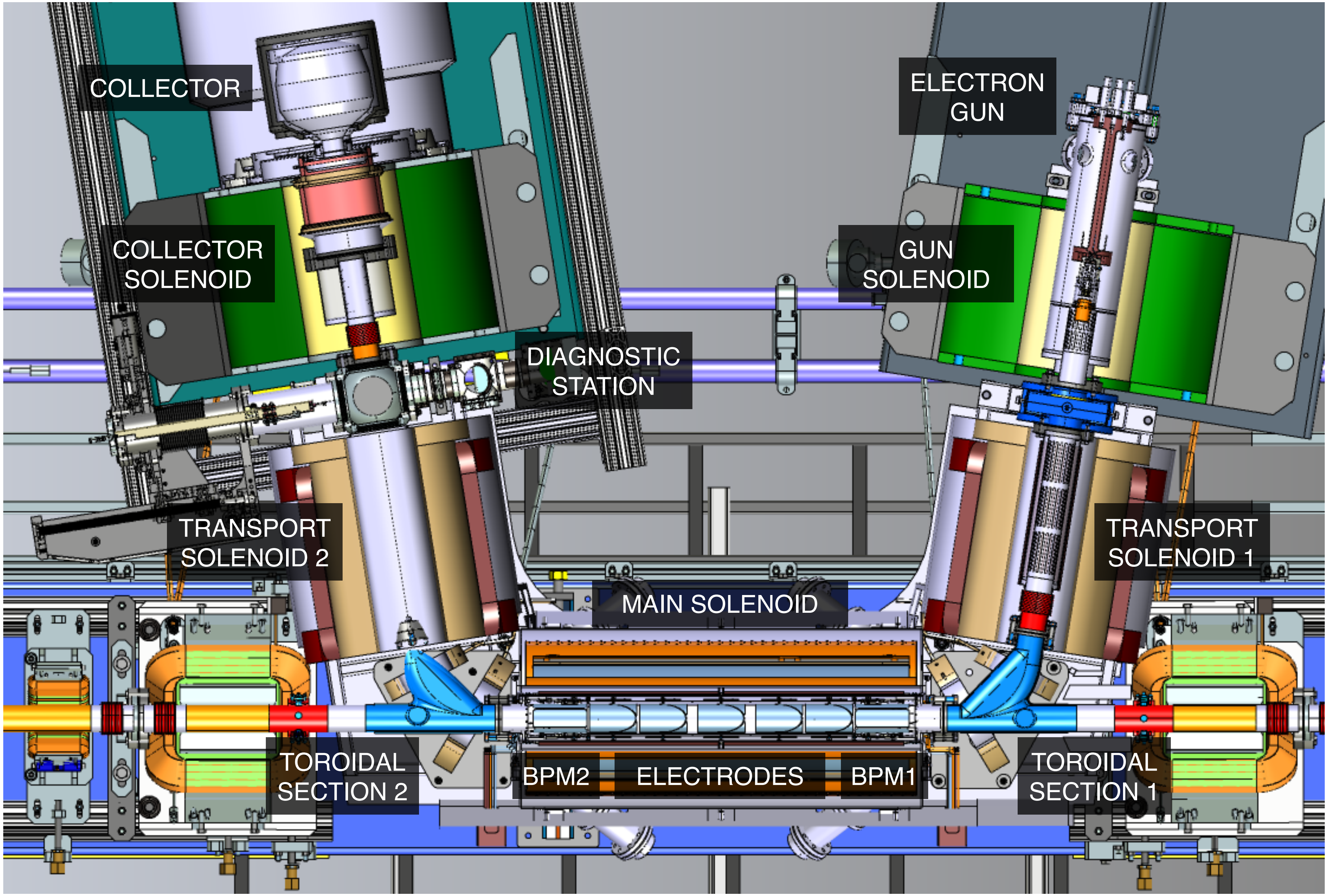
Backup slides

IOTA e-lens apparatus





IOTA Electron Lens Layout (top view)



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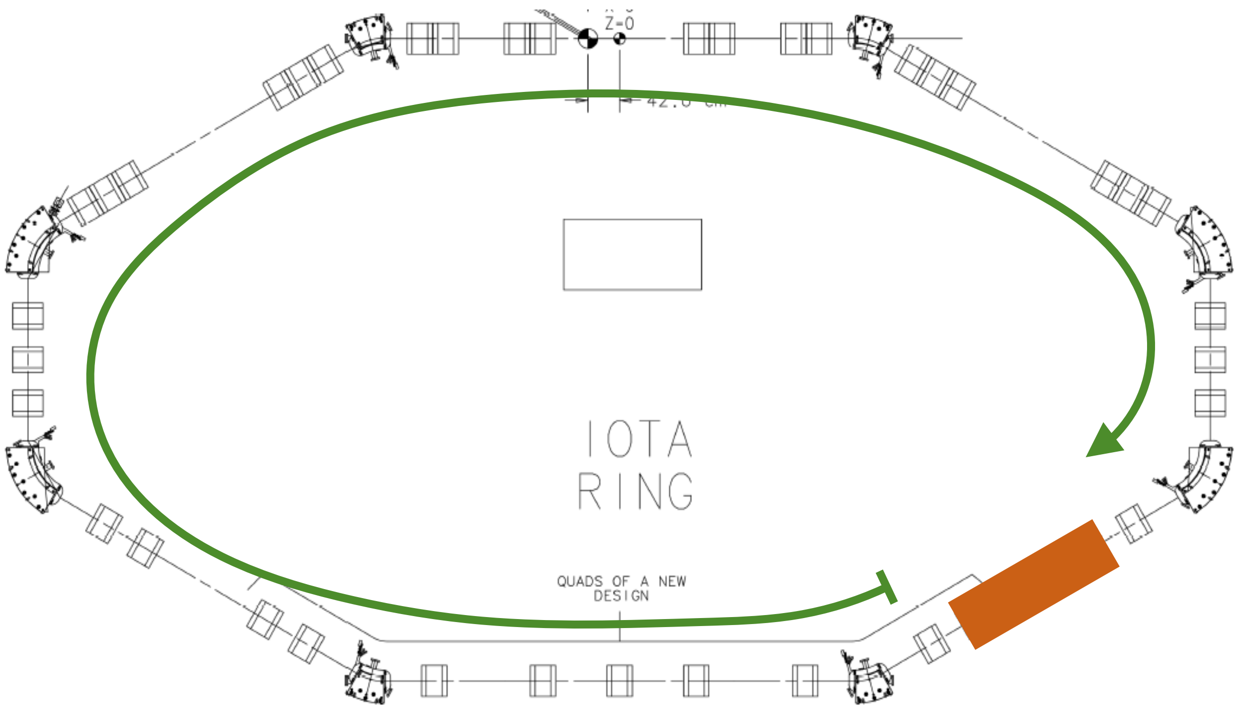
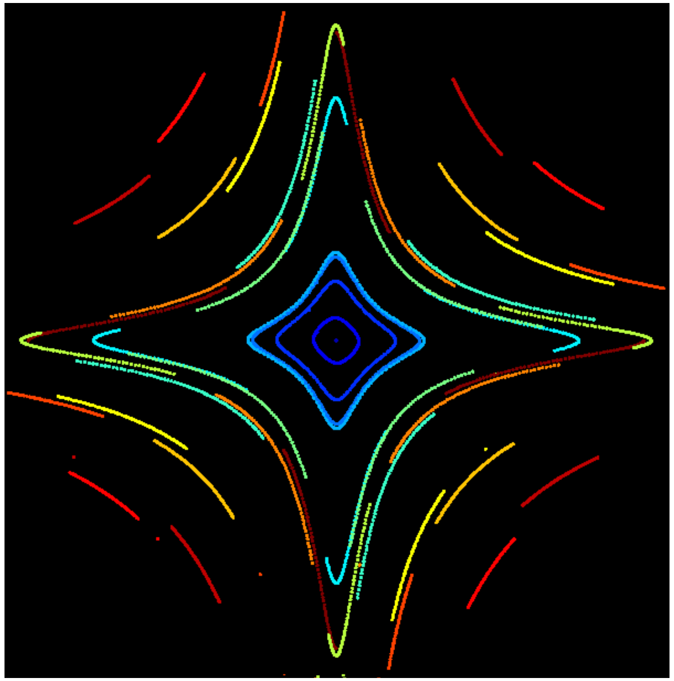
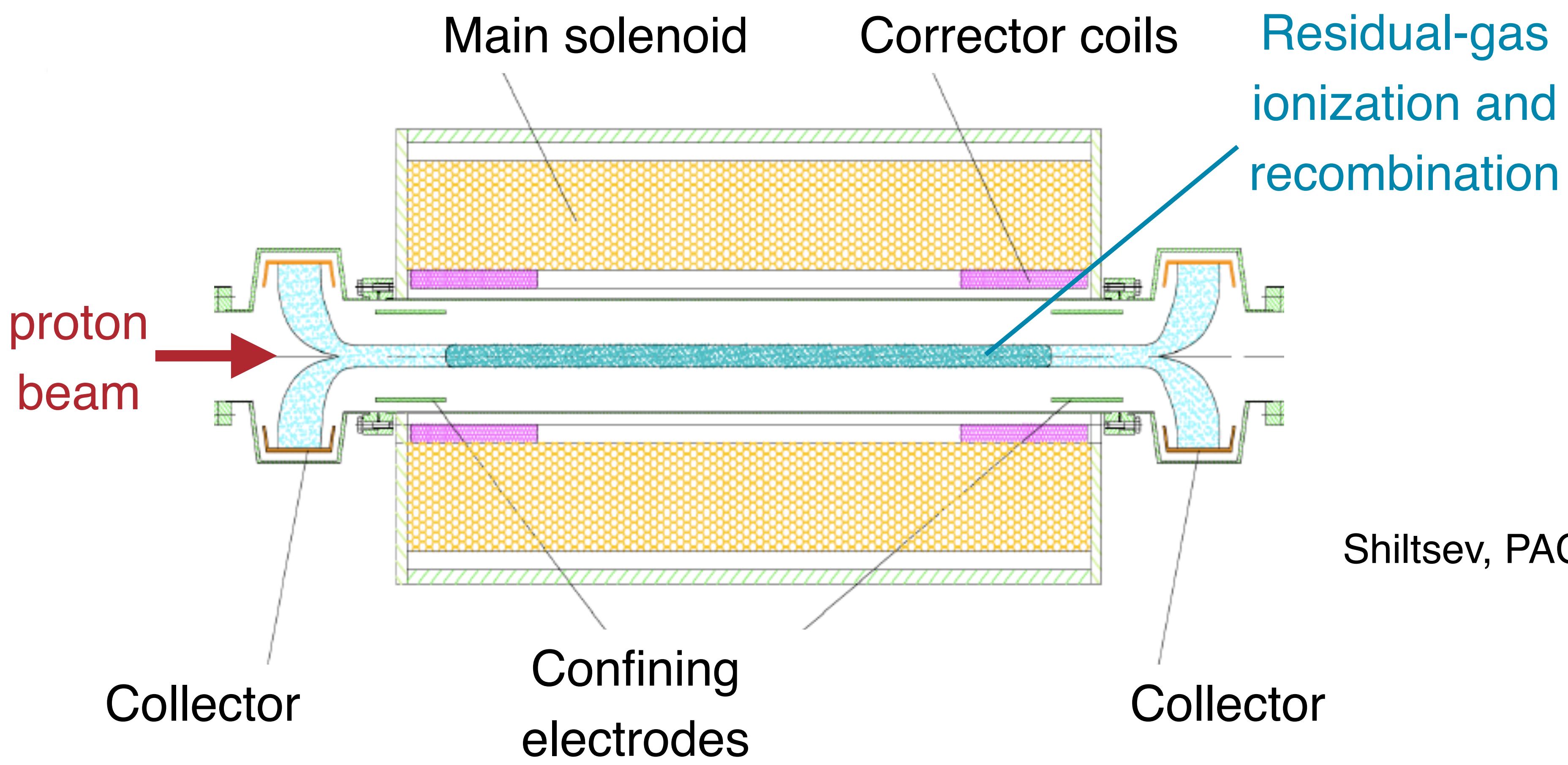
Nonlinear Integrable Optics Concept





Electron Column Concept



Shiltsev, PAC07