Status of the IOTA proton injector

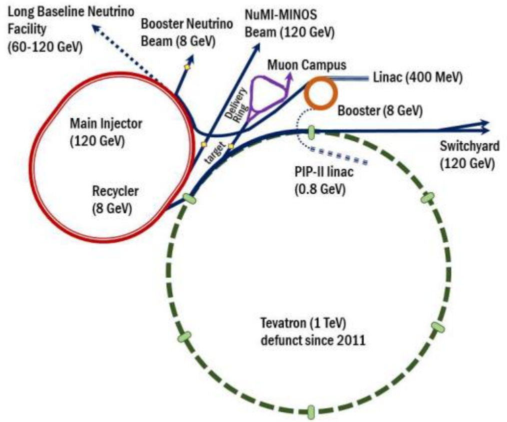
D. Edstrom Jr. , A. Romanov, D. Broemmelsiek, K. Carlson, J.-P. Carneiro, H. Piekarz, A. Shemyakin, A. Valishev

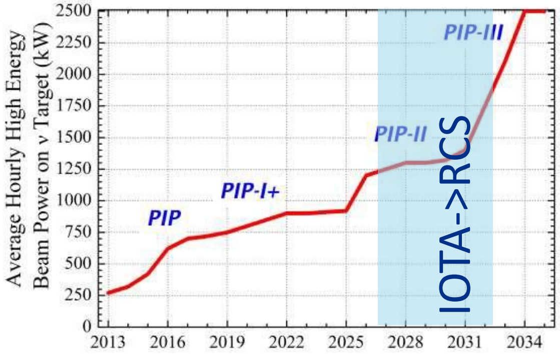
13 October 2023, Geneva, HB 2023

Motivation for IOTA

Of particular interest to us:

- Mitigation of beam losses at high-intensity:
  - Booster, Recycler and MI are intensity-limited by losses (~1 W/m).
- Mitigation of instabilities in high-brightness beams:
  - Fast instabilities which can not be suppressed by external dampers, e.g. an “electron cloud” instability (observed in the Recycler)
- Beam cooling
  - Future colliders
  - Quantum limits/properties of beams
- System integration and optimization





Instability mitigation – Landau damping with nonlinear magnets

COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

B. Richter

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

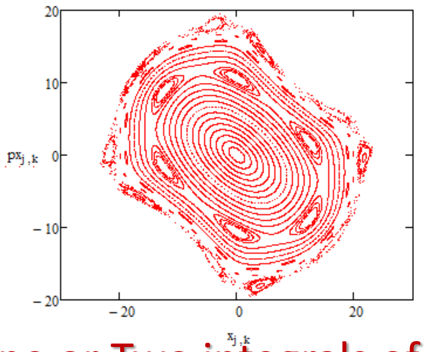
Report at HEAC 1971

- Landau damping – the beam's "immune system". It is related to the spread of betatron oscillation frequencies. The larger the spread, the more stable the beam is against collective instabilities.
  - The spread is presently achieved by adding special magnets -- octupoles
- External damping (feed-back) system – presently the most commonly used mechanism to keep the beam stable.

Are there “magic” nonlinearities with zero resonance strength?

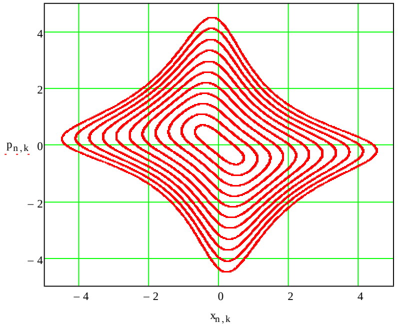
Yes, we call them “integrable”

Chaotic motion

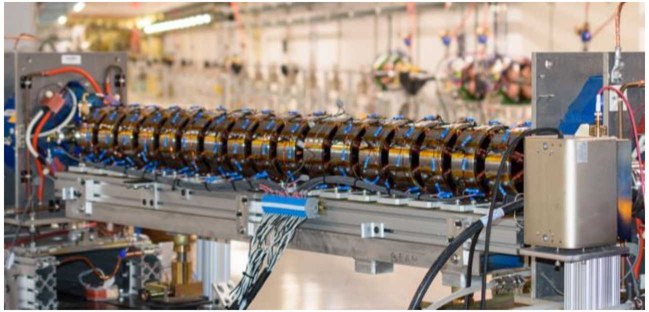


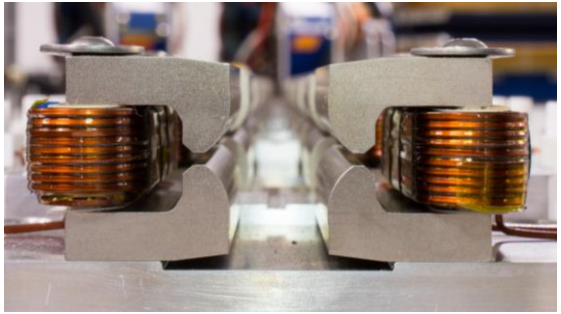
Nonlinear beam dynamics:
A new concept for nonlinear focusing in rings

Integrable motion



One or Two integrals of motion :





Parameter	Max error
Betas at the insertion	1%
Beta beating	3%
Dispersion	1 cm
Closed orbit at insertion	0.05 mm
Phase advanc	0.001

[1] V. Danilov and S. Nagaitsev, PRAB 13, 084002 (2010)

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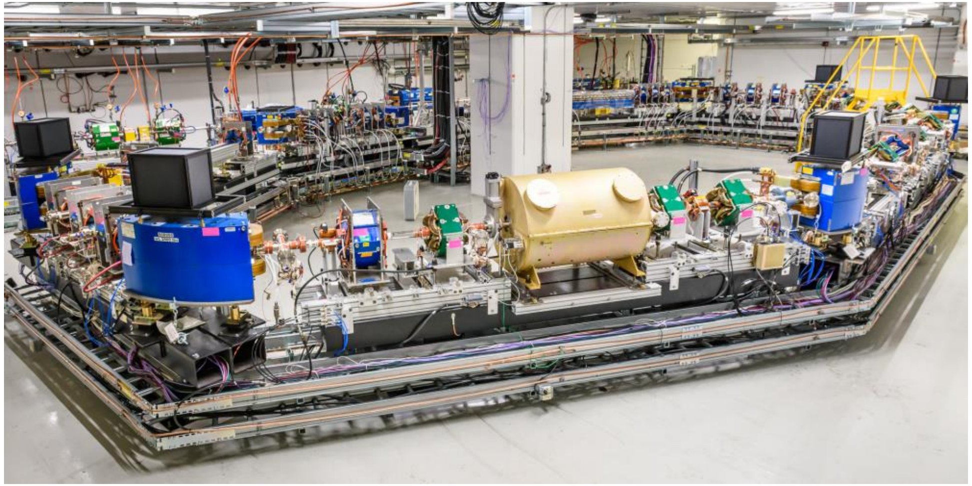
Why protons at IOTA?

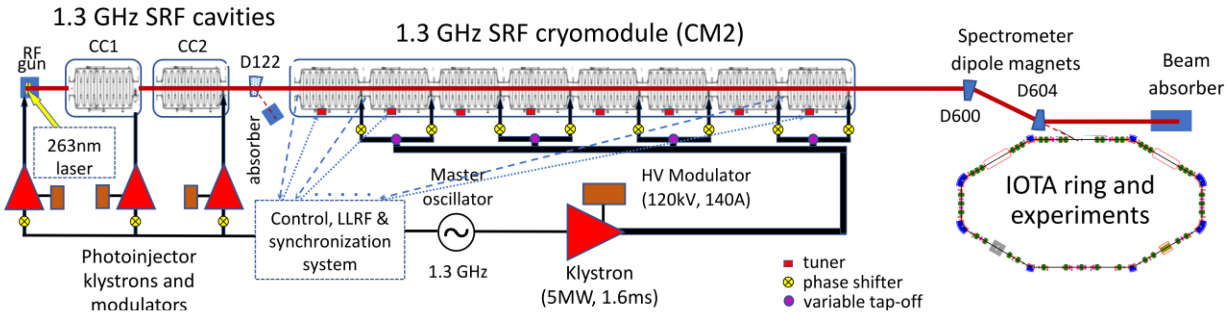
- It is the only viable option to study beams with strong space charge effects.

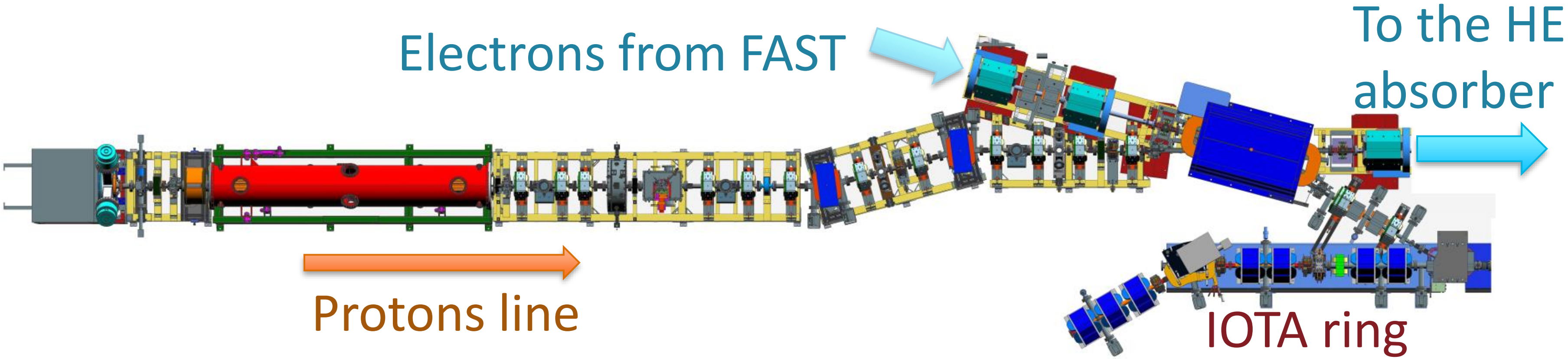


Lambertson magnet		1	Horizontal, injection in vertical plane
Kickers		1 hor. & 1 vert.	Horizontal for studies only
Main dipoles		4x60 deg & 4x30 deg	Sector type
Quads		39	Powered in pairs with individual shunts
Trims	Hor.	8	In main dipoles
	Vert.	2	For injection bump
	Hor.	20	Combined correctors
	Vert.	20	
Skew-quads		20	
Pickups		21	Turn-by turn position
Sync. light monitors		8	Shape and position
RF		1	Dual frequency
Sextupoles		12	In six families
DCCT		1	Precision calibrated DC beam current
Wall current monitor		1	Bunch currents and longitudinal shape

Electron and proton injectors for IOTA

- Up to 150 MeV can be injected from tha FAST superconducting linac





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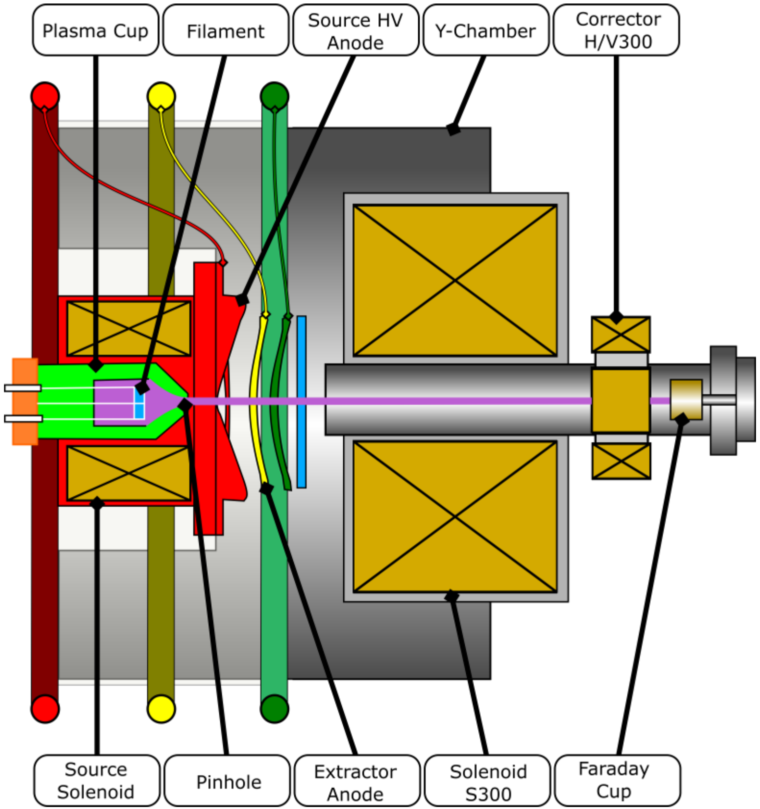
IOTA proton injector parameters

	Parameter	Nom.	Unit
LEBT	Energy	50	keV
	Proton beam current	20	mA
	Pulse length (99 %)	350	µs
	Source pulse rate	1	Hz
	Transverse beam size	0.7	mm
MEBT	Energy	2.5	MeV
	RF pulse rate	1	Hz
	RFQ frequency	325.0±0.5	MHz
	RFQ duty factor	< 0.002	%
	Phase/Amp. stability	1°/1 %	
	Beam pulse length	2	µs
	Bunch length (1σ)	0.3	ns

	Parameter	Nom.	Unit
IOTA with protons	Proton beam energy	2.5	MeV
	Relativistic β	$2.66 \cdot 10^{-3}$	keV
	Circumference	40	m
	Proton RF frequency	2.19	MHz
	Revolution period	1.83	µs
	RF voltage	1	kV
	Geometric emittance	3.5	µm
	$\Delta p/p$ (RMS)	0.07	%
	Beam current	8	mA
	Momentum compaction	0.07	
	Betatron tunes (Q_x, Q_y)	5.3, 5.3	

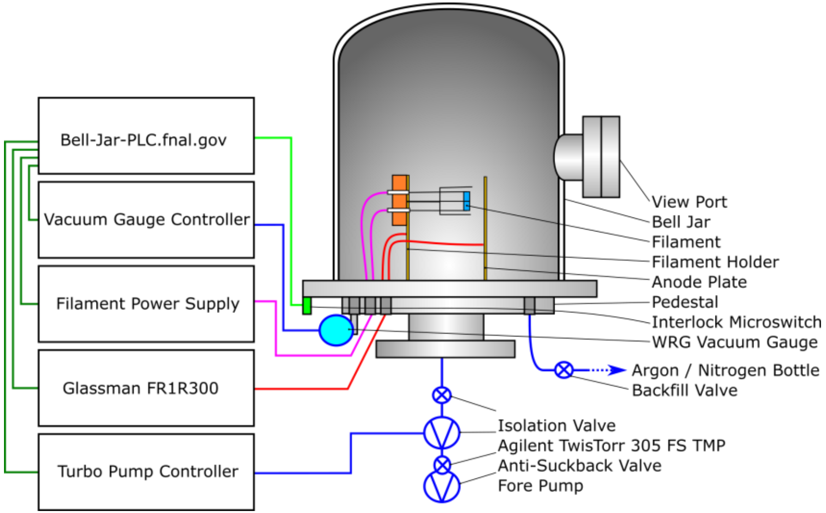
Proton source: Duoplasmotron ion source

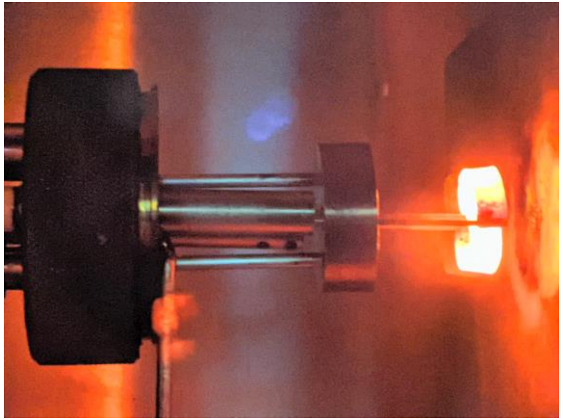
- A schematic view of the ion source in a test configuration.
- For extraction of 50 keV protons, the Source High Voltage
- Anode is charged to a static +50 kV
- The Extractor Anode is set to 40 kV, and the green anode is at ground potential.
- The S300 Solenoid is the first element of the LEBT



Preparing filament

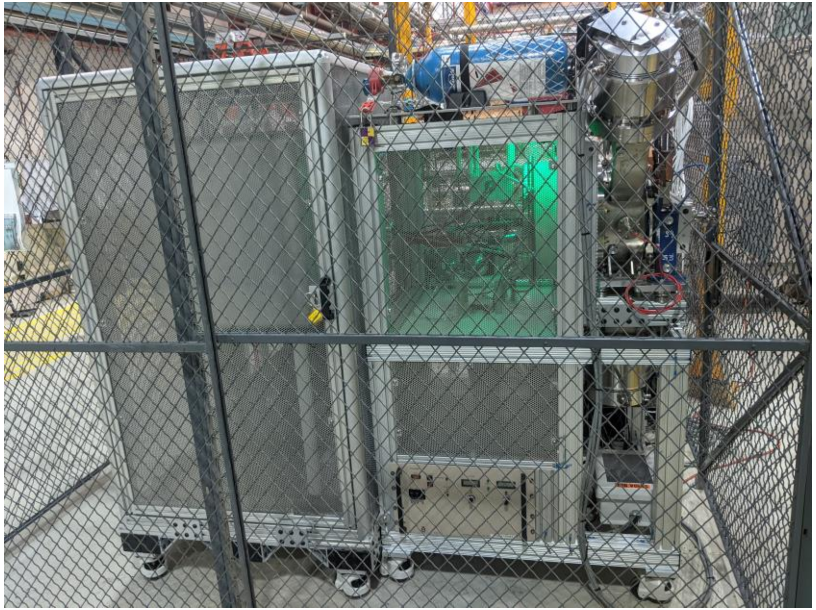
- Filaments are prepared on-site using a mixture of Barium, Calcium, and Strontium Carbonates along with Isoamyl Acetate to assist in binding the mixture to the filament.
- The mixture is dissolved in Acetone to form a thin solution
- Cleaned Nickel filament is dipped to deposit a modest coating of the carbonate mixture.
- It is then activated in a filament activation station.

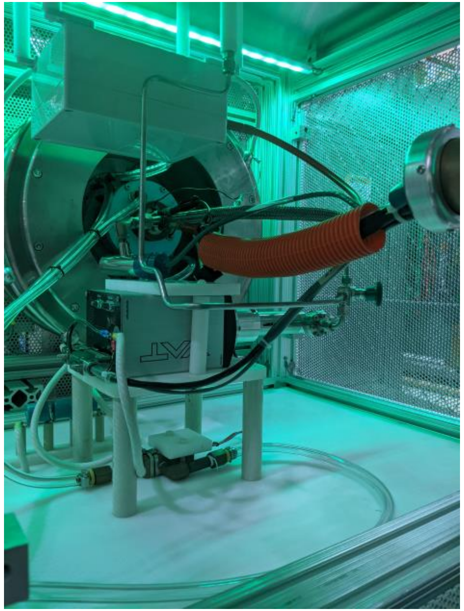




High voltage assembly for proton source

- The high voltage cabinets were assembled to test proton source. That includes gas distribution system and all necessary interlocks.

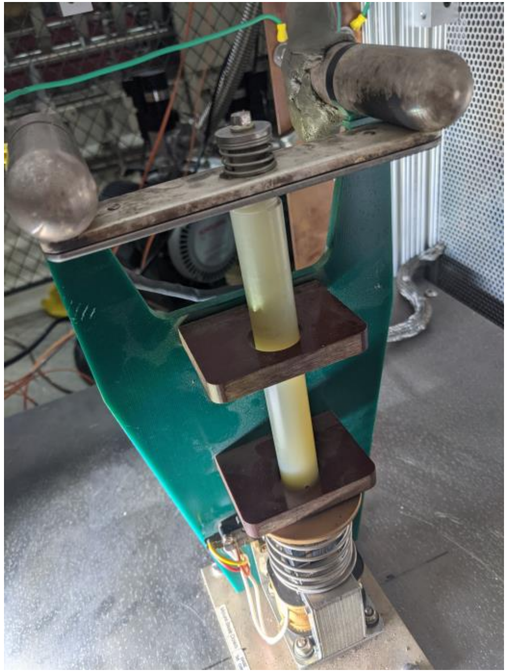


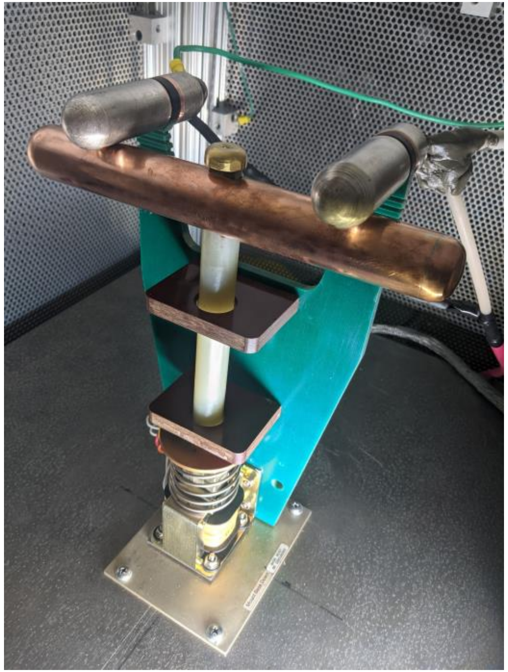


Then came a tedious process of looking for sparks

One of the improvement examples

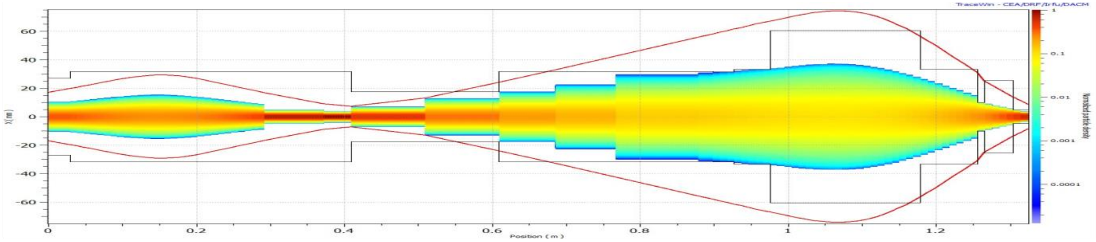
- A commercial contactor was used to ground high voltage components when necessary
  - Rated 60kV DC
- Had to be modified extensively to hold 51kV
  - Sharp-cornered nut and washer were replaced with rounded oversized nut
  - Contactor plate was replaced with tube
  - Fixed contactor electrodes were rounded near G10 interface planes
- Eventually demonstrated 51kV for 3 minutes without breakdown
  - Need more work as it didn't hold the next day (with nearly the highest humidity in the test area).

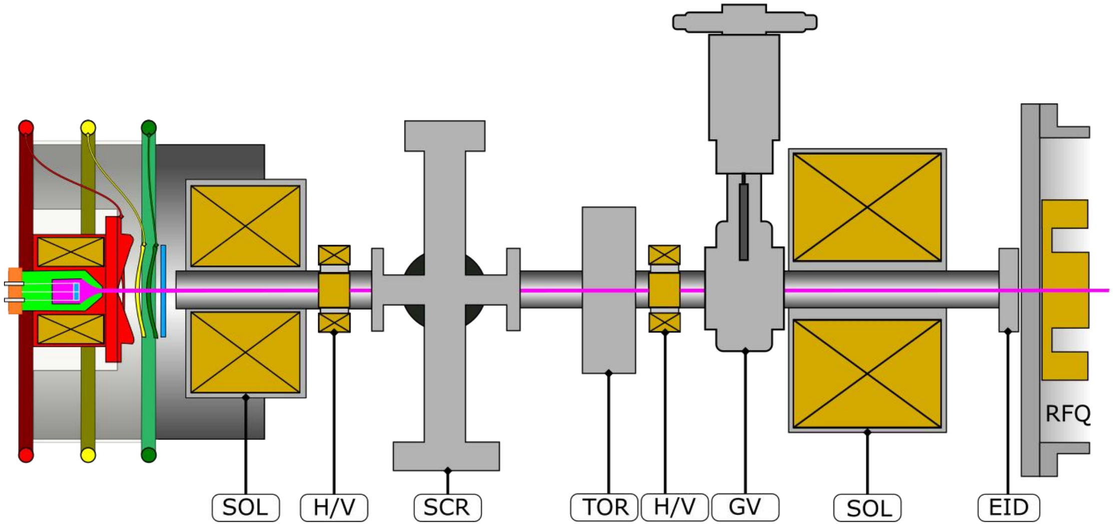




Low Energy Beam Transport line

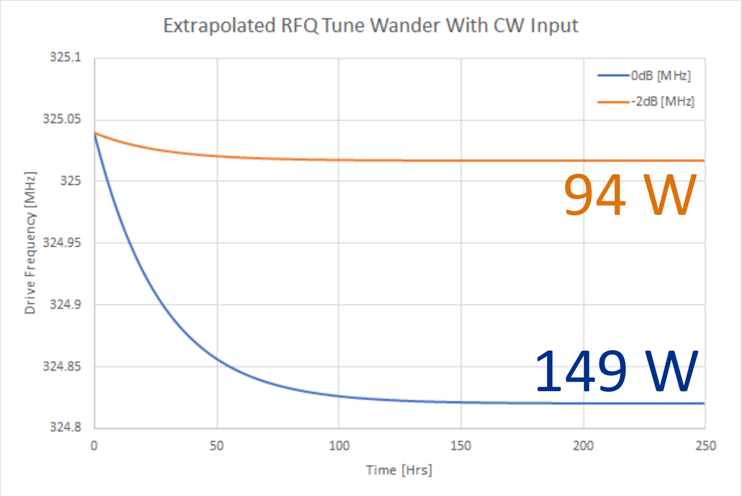
- The IPI LEBT, as seen in Figure 5, is a short section of beamline designed to transport beam from the IS to the RFQ. Its key komponents are:
  - Two solenoids (SOL) that provide focusing to allow for injection into the RFQ
  - Gate valve (GV) to isolate the IS from the RFQ
  - Toroid (TOR) to monitor beam current from the source
  - Electrically isolated diaphragm (EID).
- The EID has two primary roles:
  - Measure the intensity of the beam intercepted, allowing for tuning of the solenoids to maximize beam transmission to the RFQ or to perform other beam studies
  - Assist with beam space charge neutralization.





RFQ

- Like the IS, the RFQ was also adopted from the HINS experiment and is tasked with accelerating the proton beam from 50 keV to 2.5 MeV.
- Due to a cooling-to-vacuum leak, it cannot currently be temperature-regulated. The low duty factor will assist in mitigating the effects of frequency shift, and a test performed in 2020 indicates that the net effect will be a ≈5.6 kHz drop in the resonant frequency over the first 8 hours for an average CW power of 100W.
- Currently we plan to operate FRQ in self-excited loop with the bunching cavity following it.



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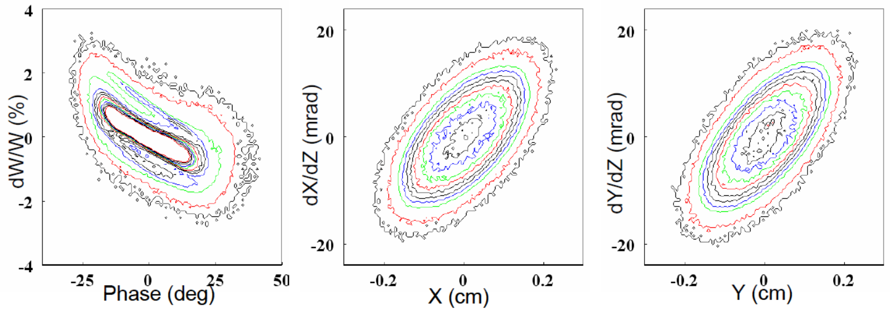
Beam parameters out of RFQ

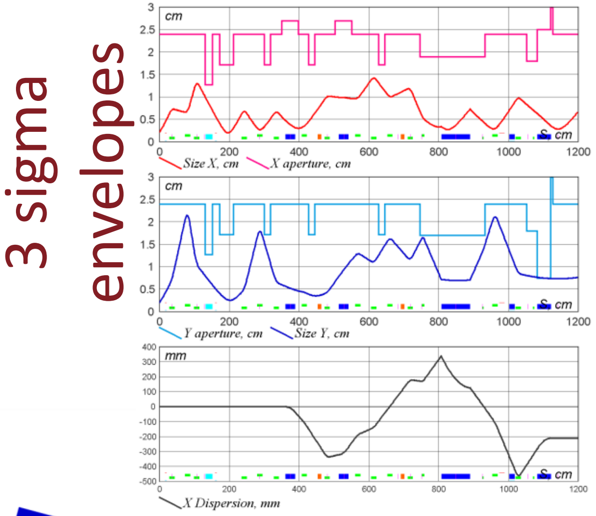
- Beam parameters after RFQ are strongly dependent on the input matching
- Tracewin is used for the simulations done by Jean-Paul Carneiro
- Data is cross-checked with the 2006 paper by P.N. Ostroumov, V.N. Aseev and A.A. Kolomiets

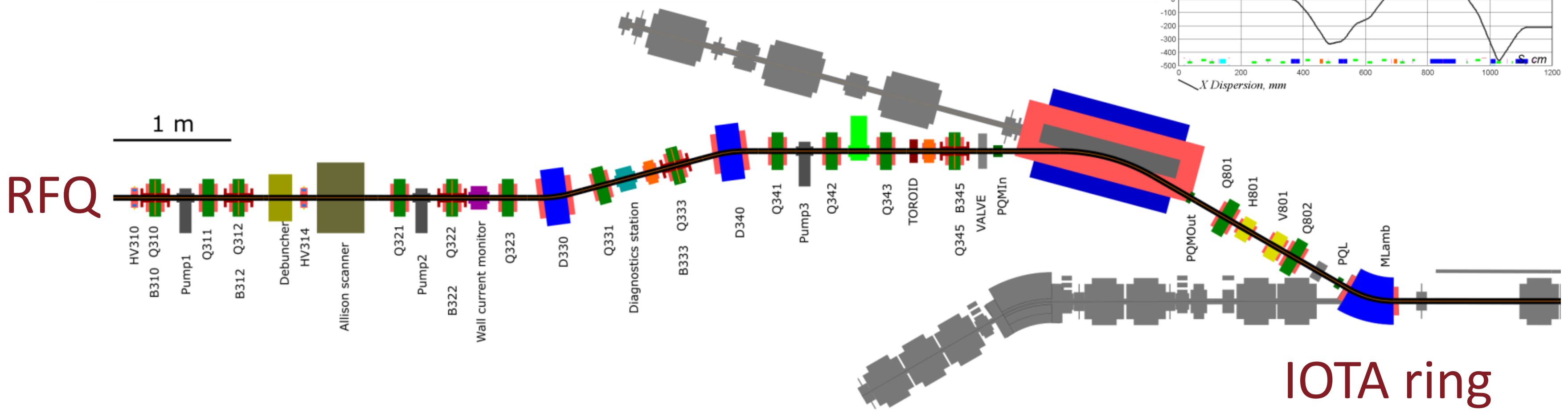
ε_x	β_x	α_x	ε_y	β_y	α_y	ε_s	β_s	α_s
3.5 um	15 cm	-0.7	3.5 um	15 cm	-0.7	173 keV*deg	45 deg	-2.3



MEBT line: layout

- First triplet matches beam out of RFQ, followed by debuncher RF cavity and diagnostics tools
- Three quads match beam into dispersion-excitation chicane
- Matching beam in and out of D600 dipole is done with 4 quads before and 2 after it
- Initial vertical bend for injection to steer beam into the Lambertson magnet is done with the last vertical trim





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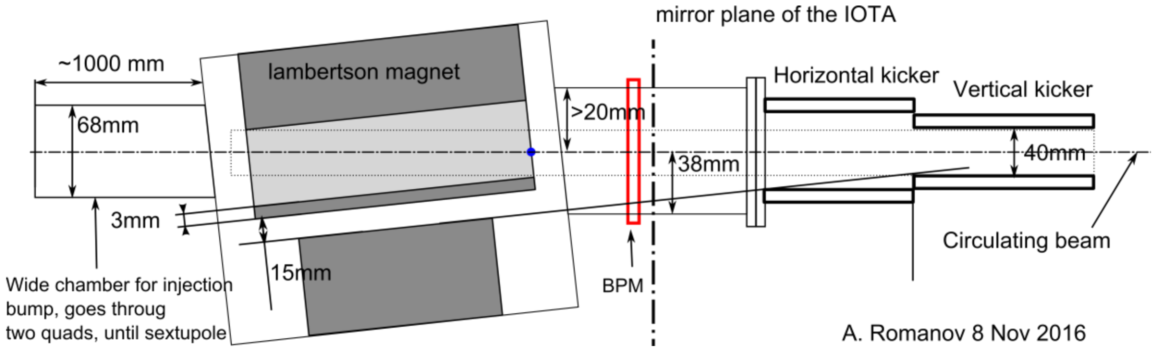
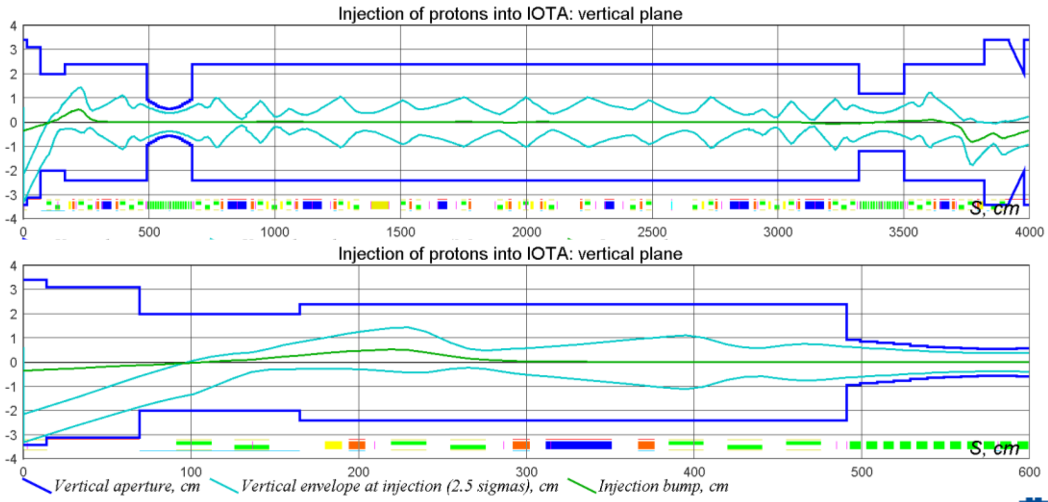
Injection configuration





25 kV at kicker

~26mRad kick

All trims are <1A,

up to 2A possible

Envelope is for 2.5 sigmas, same as horizontal limit

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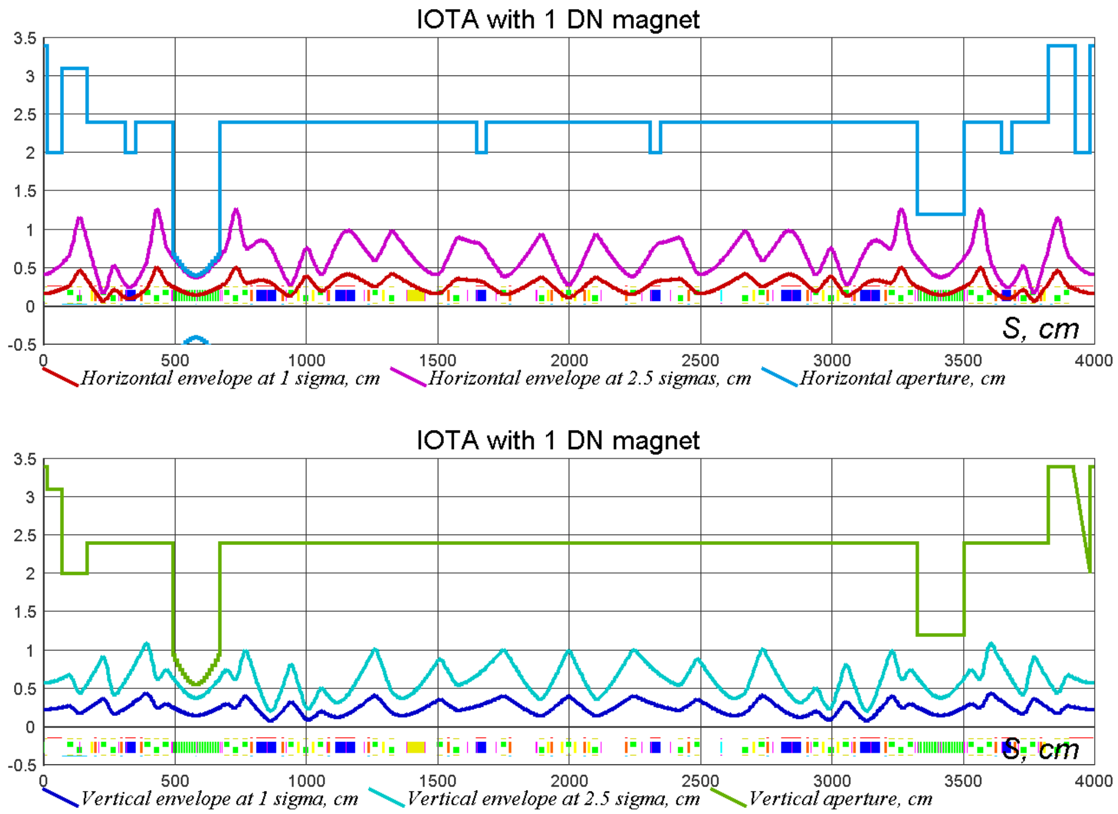
Aperture in IOTA

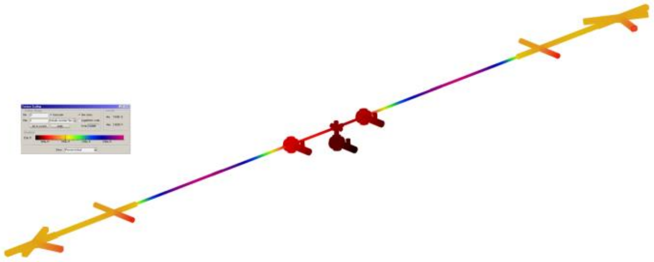


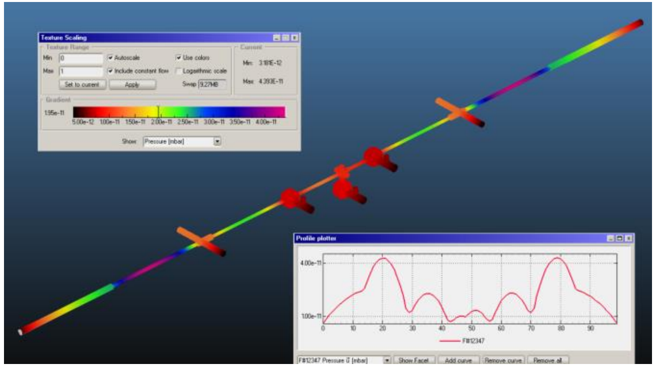
Proton beam diagnostics at IOTA

- DCCT
- Wall current monitor
- 21 button BPMs
  - at 1mA, 1s integration, 30% bunching factor at 30MHz we should get around 5 um resolution at IOTA button BPMs
- 3 strip-line BPMs
  - Used for damping/antidamping
  - Better sensitivity
- Gas sheet or gas ionization beam profile monitor

Vacuum after baking

- Vacuum level was ~10^{-9} torr towards the end of Run-3
- With low temperature bakeout (~100 C) we expect residual pressure of H_2 at the level of $5x10^{-11}$ torr.
  - Ion pumps with NEGs can be used to improve it





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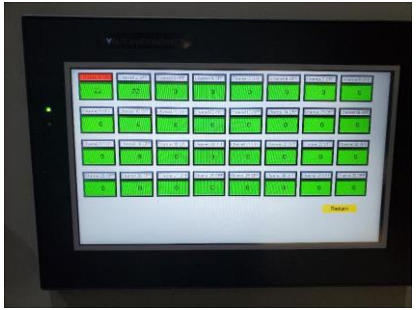
Bakeout system

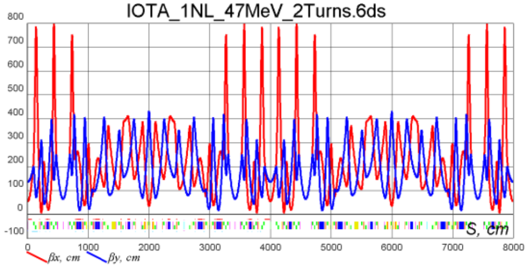
- Bake out system at IOTA is vital for the successful experiments with proton beams.
- A prototype system has been successfully tested
- A 160-channel system is close to completion
  - Up to 125 C
  - Individually controlled channels with thermocouple feedbacks
  - ACNET integration

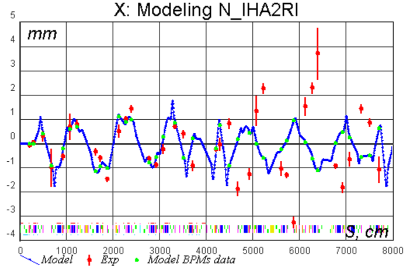


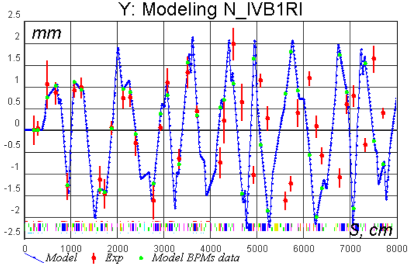
Lattice tuning (on an example of 47 MeV e- beam)

- Measured data: 21 BPMs x 20 trims
- Model adjusted to match measured data by tuning 39 quads

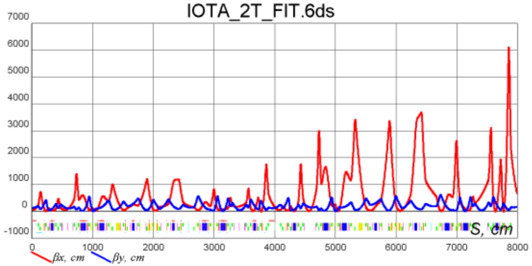
Model lattice and corresponding sample responses compared to measured

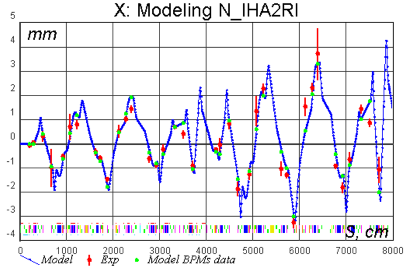


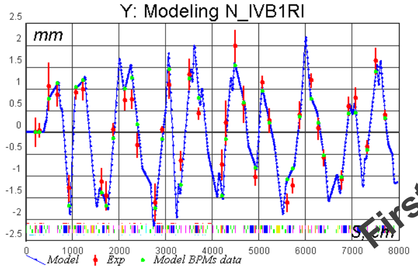




Fitted model has clear instability in X plane







First correction iteration made a stable betatron lattice

Experiments at IOTA

- Demonstration of integrable optics with Danilov-Nagaitsev nonlinear magnets (e, p)
- Demonstration of integrable optics with octupoles (e, p)
- Demonstration of integrable optics with non-linear electron lenses (e, p)
  - Thin radial kick of McMillan type
  - Axially symmetric kick in constant beta function
- Space-charge compensation with electron lenses (p)
- Space-charge compensation with electron columns (p)
- Optical stochastic cooling (e)
- Electron cooling (p)
  - Electron cooling of protons
  - Diagnostics through recombination
  - Electron cooling and nonlinear integrable optics

Summary

- IOTA proton injector is mandatory for the success of the proposed IOTA research program
- The IPI design is finalized and well thought through
- All necessary components are either on hands or purchased with delivery times within next few months
- Proton source HV tests and optimization is underway
- Active phase of construction will begin in a few weeks, right after conclusion of the current experimental run with electrons
- First protons in IOTA are planned at the end of the first quarter of 2024