Thermionic Sources for Electron Cooling at IOTA

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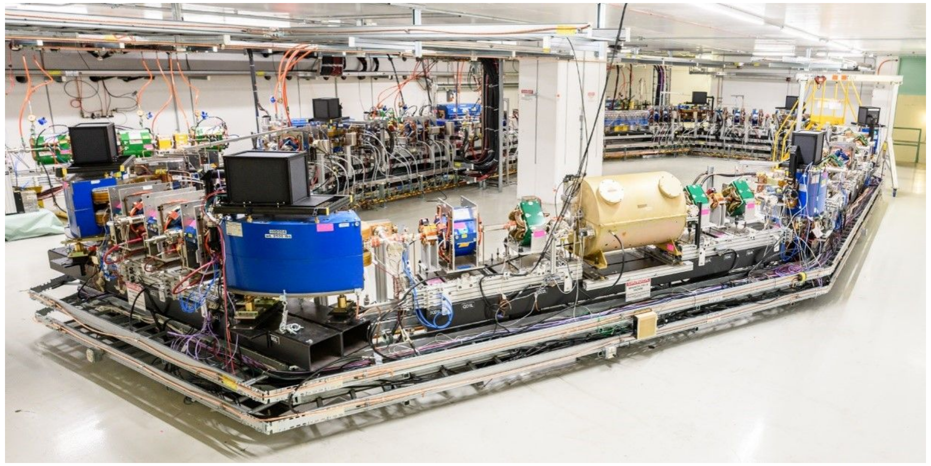
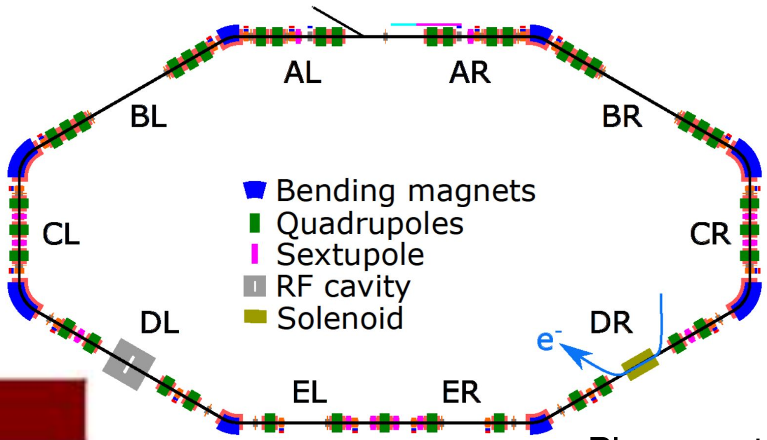
Overview

- IOTA at Fermilab
- Electron Lens
- Electron Cooling
- Thermionic Sources for Cooling
- Electron Source Test Stand
- Conclusions

IOTA at Fermilab

- Integrable Optics Test Accelerator (IOTA)
- Easily re-configurable 40 m storage ring.
- Test facility dedicated to research on intense beams:
  - Nonlinear Integrable Optics (NIO) - Experimental Studies of Nonlinear Integrable Optics, N. Kuklev
  - space-charge
  - beam cooling - J. Jarvis (FNAL) FRXD1
  - Single electron storage - A. L. Romanov (FNAL) TUZE1
- Circulates both electrons and protons.
  - **Focus: Circulating 2.5 MeV protons to investigate intense space-charge regime**

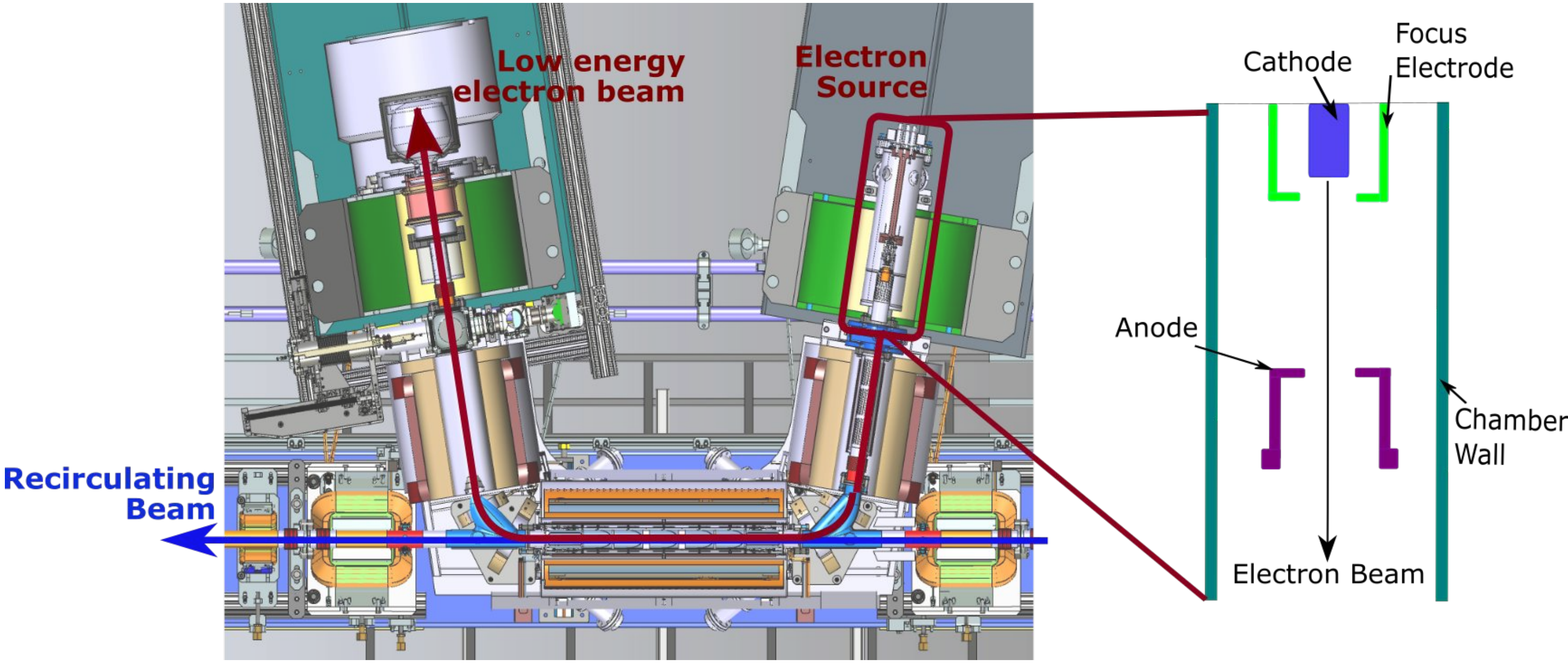




C	KE	τ_{rev}	h	N_{bunch}	$\nu_{x,y}$
39.96 m	2.5 MeV	1.83 μs	4	Coasting or 4	4.117, 3.632

Electron Lens

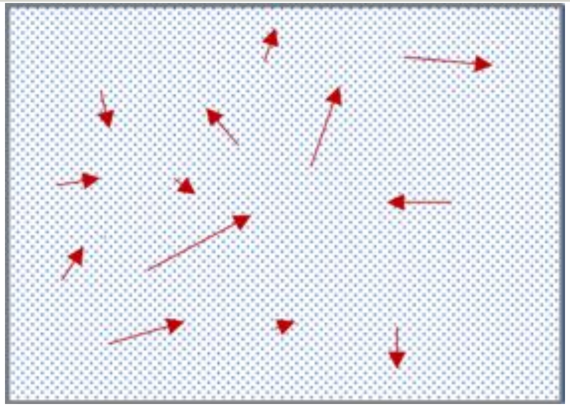
- **Electron Lens:**
  - Low-energy, magnetically confined electron beam
  - Overlap with circulating beam
    - Field from the electrons can shape the phase space structure of the beam
    - Magnetic field in beam overlap enhances stability of two-beam system

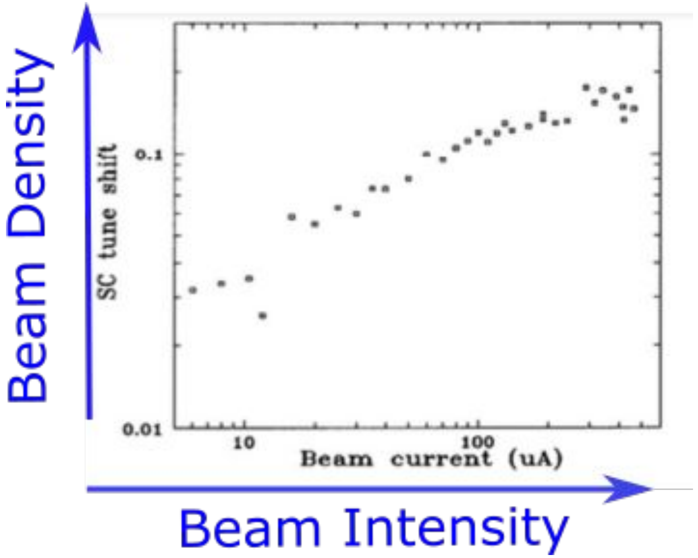


- **Electron Lens at IOTA:**
  - Nonlinear element to create integrable lattices McMillan Lens : B. Cathey **MOPA17**
  - Electron cooler - for experiments with proton beams requiring range of lifetimes, emittances, and brightness

Electron Cooling at IOTA

- **Electron cooling:** Ion beam exchanges thermal energy with a co-propagating electron beam.
- Goals at IOTA:
  - Counter emittance growth in 2.5MeV proton beam and other beam manipulations
  - Explore cooling in intense space-charge regime.
  - Study interplay between wakefields, space charge and electron cooling. A. Burov, Phys. Rev. Accel. Beams 22, 034202, 2019
- Need two coolers:
  - Simple Electron Source:Cooling the Proton beam at IOTA. Tool for other experiments at IOTA.
  - Strong Electron Source: Studying effects of electron cooling in ion beams with intense space-charge.

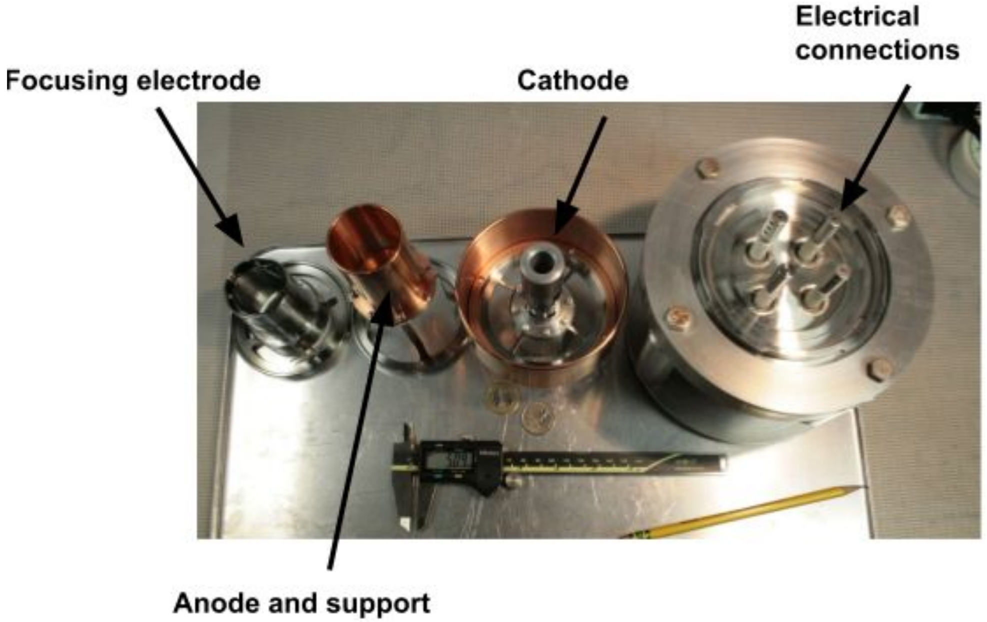


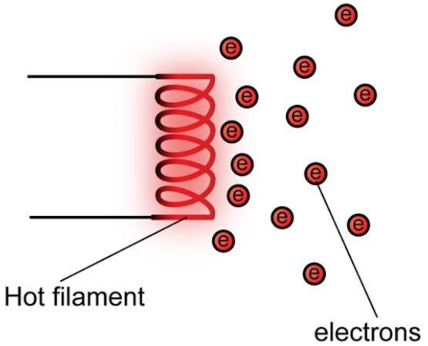


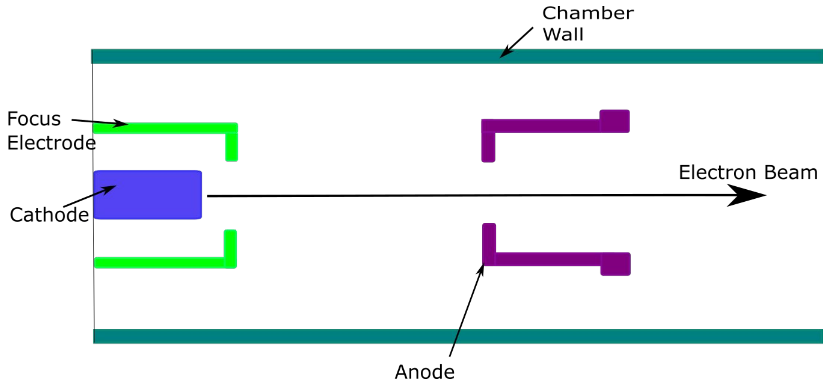
S. Nagaitsev et al., Proceedings Particle Accelerator Conference, 1995, pp. 2937-2939

Electron Sources

- **Thermionic Emission:** Cathode heated by filament, supplying thermal energy to electrons
  - Emission occurs when electrons overcome work function of cathode surface (Temp near 1400K)
- Collimated beam: electrons perform cyclotron motion in high B-field line.
- Sources for IOTA:
  - Similar to others developed at Fermilab
  - B-field of both source and main solenoid: 0.1 T.



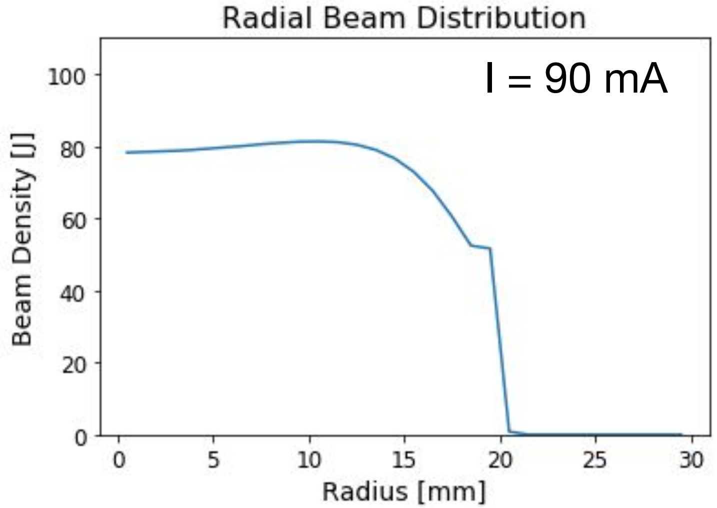


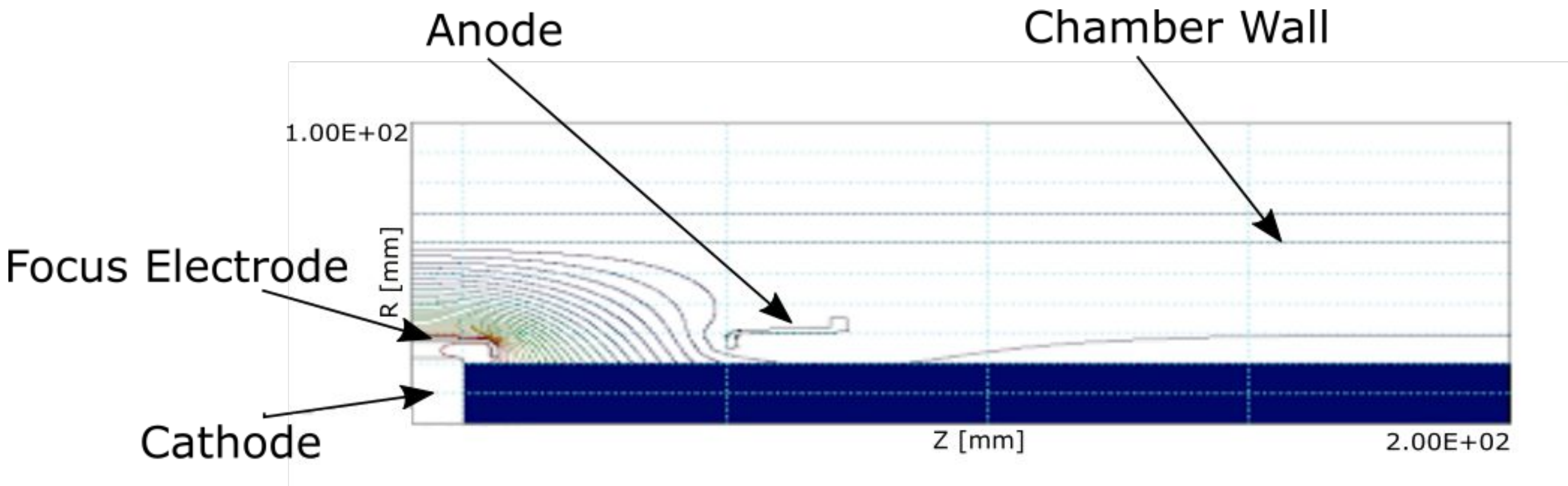


Basic Electron Source Design

- Same B-field at both source and cooler:
  - same beam parameters at the source.
- Simulations in **TRAK** "Trak Charged Particle Toolkit," Field Precision LLC, 2022.

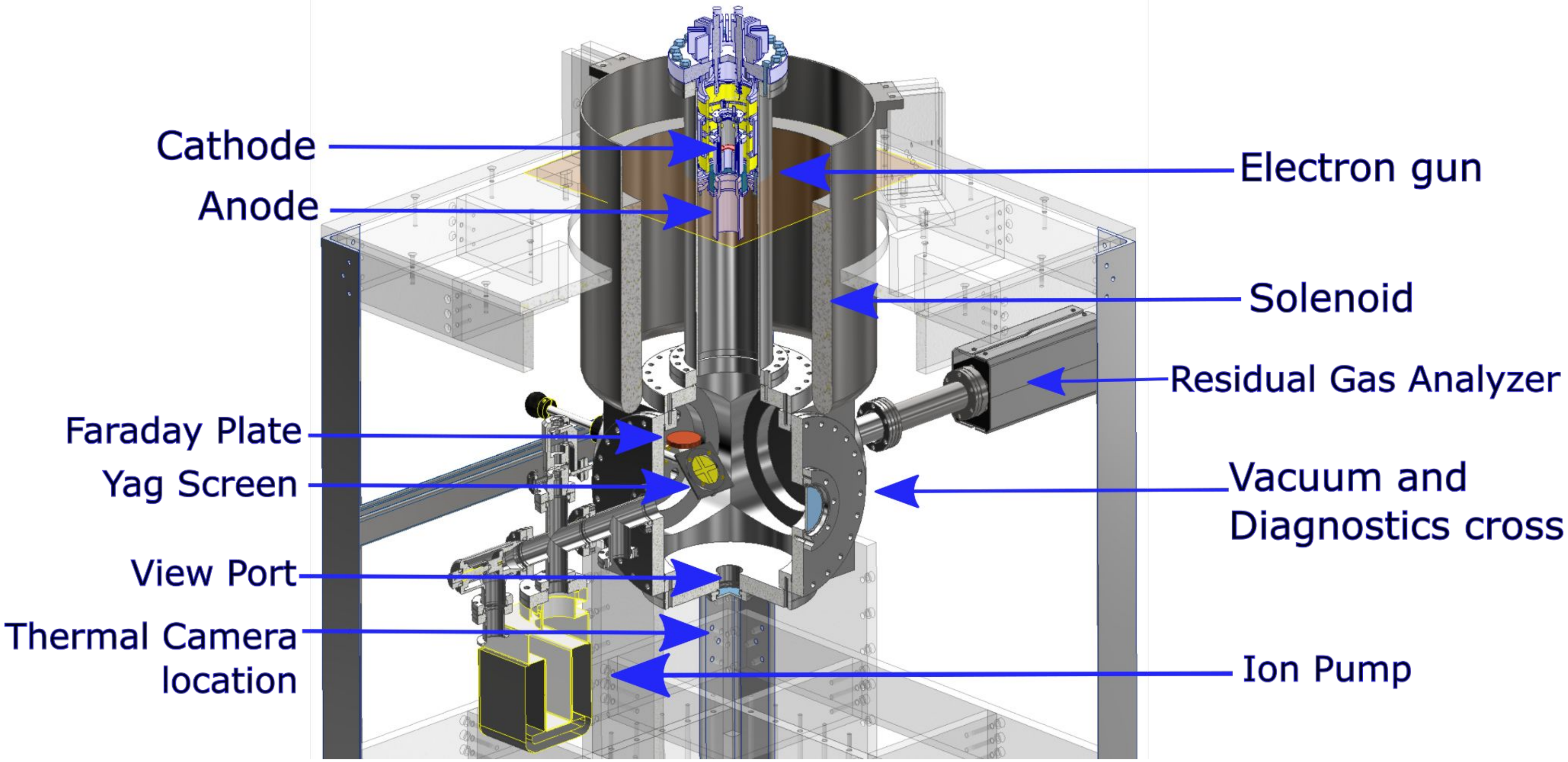
- **Specifications for Electron beam at the cooler:**
  - Beam energy: 1.36 KeV
  - Cathode ϕ: 40 mm
  - B-field: 0.1 T
  - Current: 1 mA
  - Flat beam distribution
- in process of designing strong source





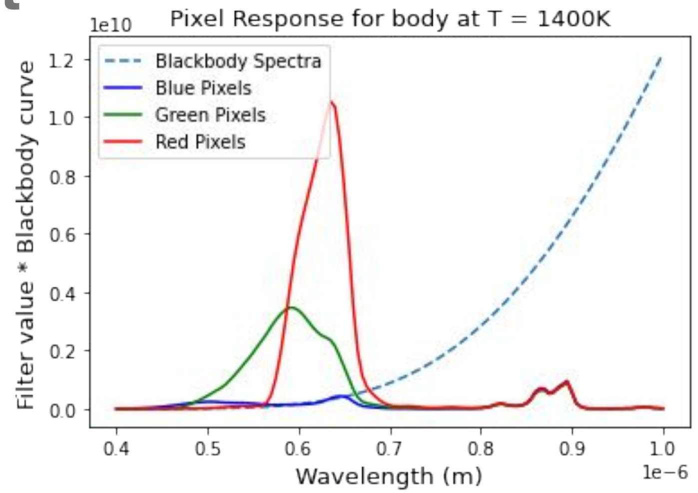
Test Stand for Thermionic Sources

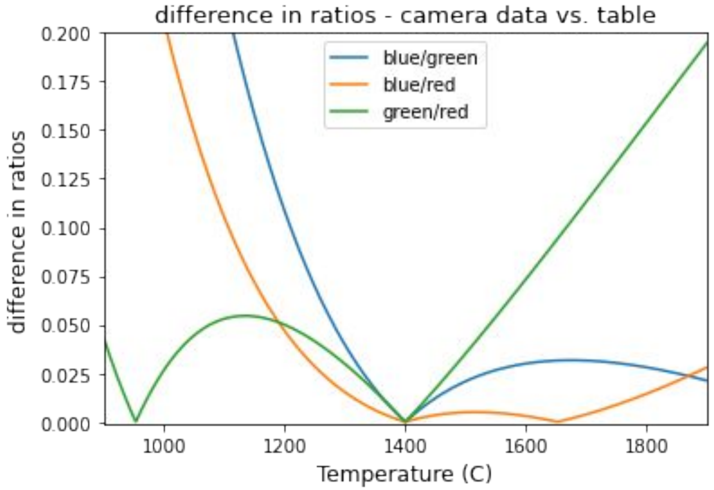
- **Constructing test stand** at the University of Chicago
- Test stand goals to validate electron source operations:
  - Vacuum performance
  - Thermal performance
  - Beam current
  - Beam distribution

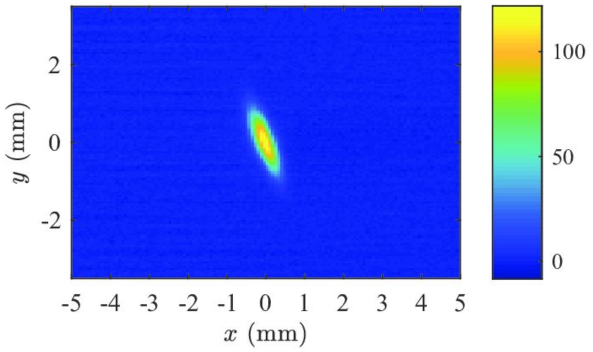


Test Stand Diagnostics

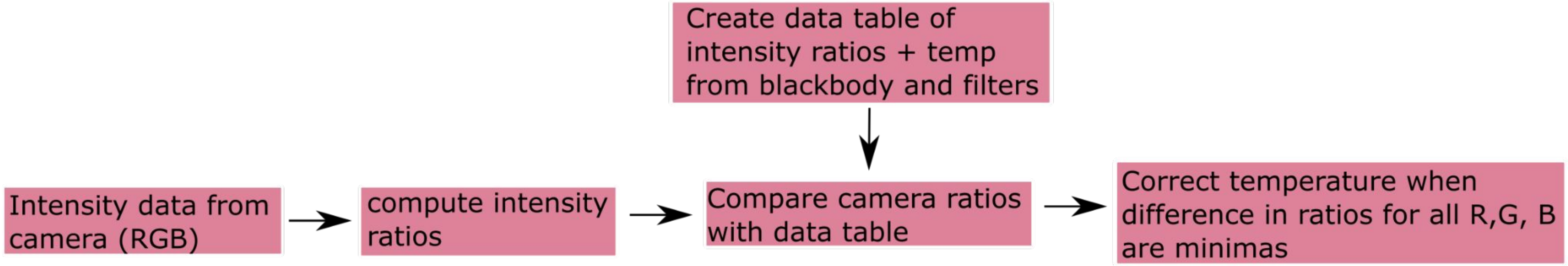
- **Cathode Temperature Measurement**
  - Algorithm to measure temperature of cathode in the test stand.
- **Yag Screen**
  - beam distribution measurement
- **Faraday Plate**
  - Beam current measurement





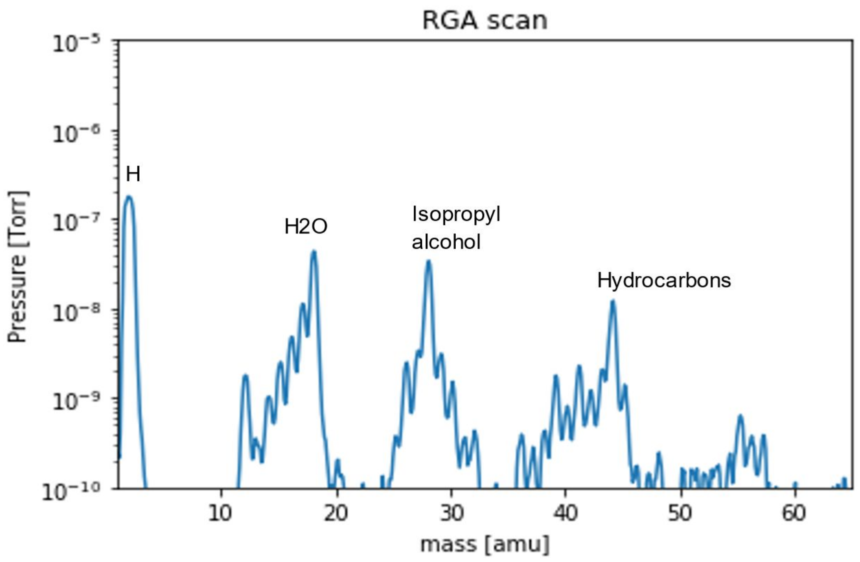


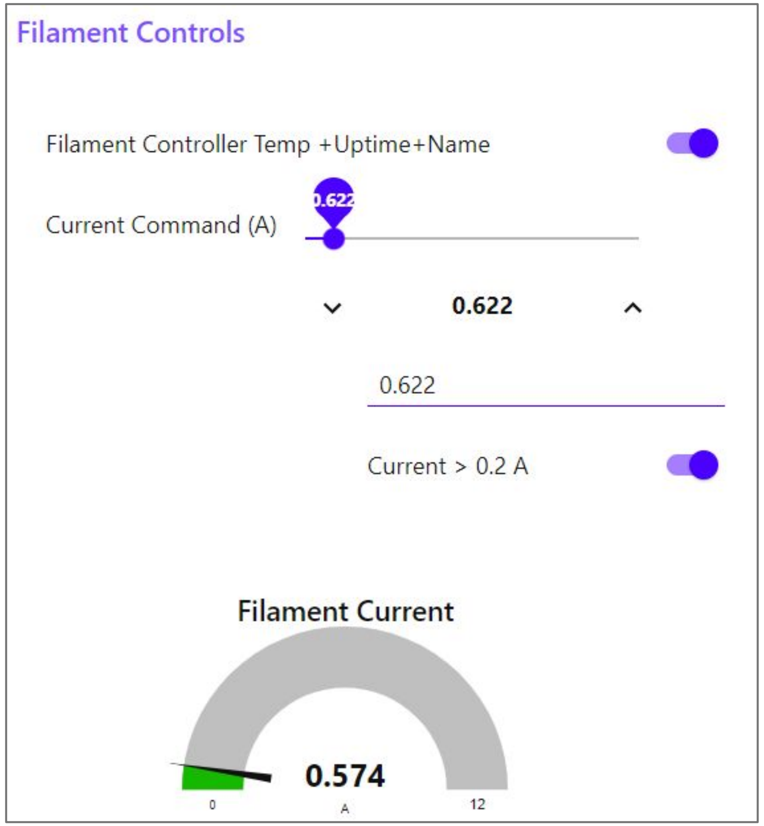
Kent Wootton, et al. Proceedings 8th International Beam Instrumentation Conference, 2020, DOI: 10.18429/JACoW-IBIC2019-TUPP039



Test Stand Diagnostics

- **Vacuum Measurement**
- **Residual Gas Analyzer**
  - mass spectrometer
- **Mounts for cameras**
- **For analyzing the data:**
  - User Interface - Node Red
  - Will use to communicate with hardware and store data





Conclusions

- Electron Cooling can improve beam quality for hadron beams.
- IOTA will use electron cooling for research towards how cooling interacts with high space-charge and instabilities.
- We are designing two electron sources for cooling:
  - Proton beam cooling
  - Strong space-charge regime research
- Developing test stand to analyze these and other electron sources
- Next steps:
  - bake-out of test stand
  - develop optimization method for electron source electrode design

Acknowledgements

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Thank you!

Questions: mbossard@uchicago.edu

Appendix

Table 1: Typical Operation Parameters for Protons in IOTA

Parameter	Value		Unit
Circumference (C)	39.96		m
Kinetic energy (K_b)	2.5		MeV
Emittances ($\epsilon_{x,y}$)	4.3, 3.0		μm
Momentum spread (σ_p/p)	1.32×10^{-3}		
	Coasting	**Bunched**	
Number of bunches	-	4	
Bunch length (σ_s)	-	0.79	m
Beam current (I_b)	6.25	1.24	mA
Bunch charge (q_b)	11.4	0.565	nC
Tune shifts ($\Delta\nu_{x,y}$)	-0.38, -0.50		
$\tau_{\mathrm{IBS,x,y,z}}$	6.4, 4.2, 8.1	8.7, 6.0, 23	s

Table 2: Electron Cooler Parameters for IOTA

Parameter	Values		Unit
Proton parameters			
RMS Size ($\sigma_{b,x,y}$)	3.22, 2.71		mm
Main solenoid parameters			
Magnetic field ($B_\parallel$)	0.1 - 0.5		T
Length (l_{cooler})	0.7		m
Flatness ($\langle B_\perp \rangle / B_\parallel$)	2×10^{-4}		
Electron parameters			
Kinetic energy (K_e)	1.36		keV
Temporal Profile	DC		
Transverse Profile	Flat		
Source temp. (T_{cath})	1400		K
Current (I_e)	1	40	mA
Radius (a)	20	12	mm
$\tau_{\mathrm{cool,x,y,s}}$	37, 33, 18	3.4, 3.2, 1.7	s

Appendix

- Our system will enable study of magnetized electron cooling of proton beam with transverse incoherent space charge tune shifts approaching -0.5.
- e-cooling min beam size: corresponds to transverse space-charge tune shifts of 0.1-0.2.
- Setup capable of exploring dynamics due to space-charge in the regime of large transverse tune shifts up to $\Delta \nu x,y = -0.5$.
- Electron beam size is chosen to effectively cool at least 3σ of the transverse proton beam size.
- Maximum current of the cooler: the velocity depression at center of the electron beam due to space-charge forces is of the same order as the standard deviation of the velocity distribution of the ion beam.

Appendix

- Proton beam diagnostics: beam position monitors and a DC current transformer.
- The simple cooler configuration: low current regime, where space-charge tune shifts of the ions are less than 0.1 and IBS is the major driver of emittance growth.
- The strong cooler configuration is designed to cool proton beams where the transverse space-charge tune shift is more than 0.1.