FRIB

Electron Beam Commissioning of the High-Current Electron-Beam Ion Source Charge Breeder

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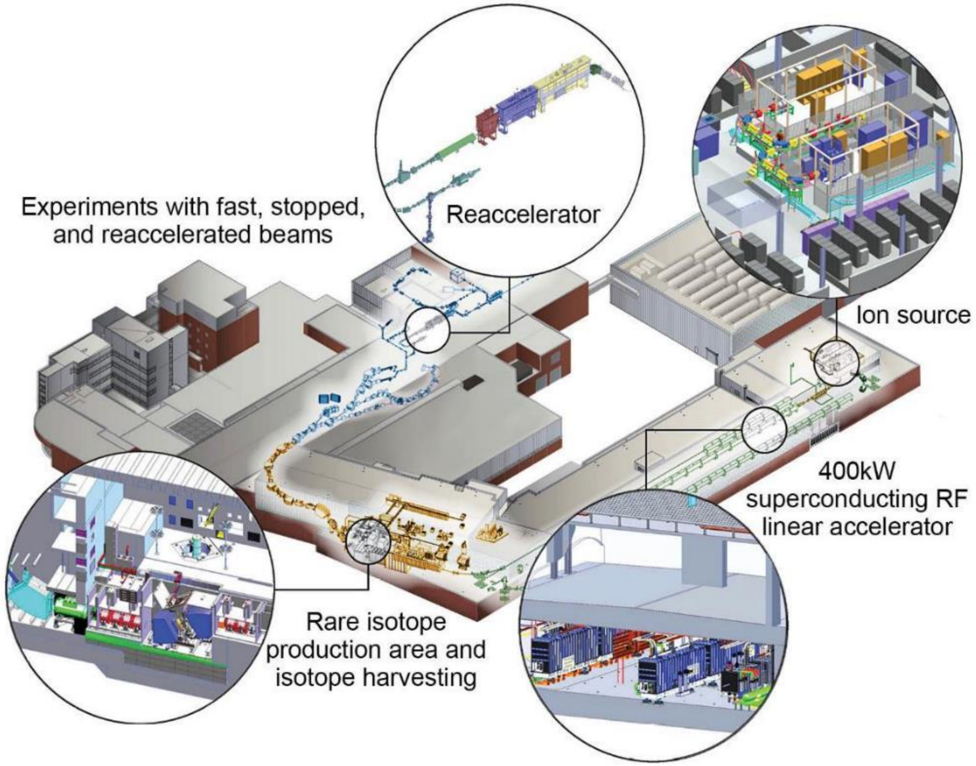
Outline

- The Facility of Rare Isotope Beams (FRIB) at MSU
- The ReA post-accelerator
- Need for increasing ReA capabilities in beam rate
- Electron beam commissioning result
- Cathode temperature measurements and cathode emissivity estimation
- Ion extraction and electron beam current density estimation
- Wien filter simulation for future charge state analyzer
- Path forwards and Summary

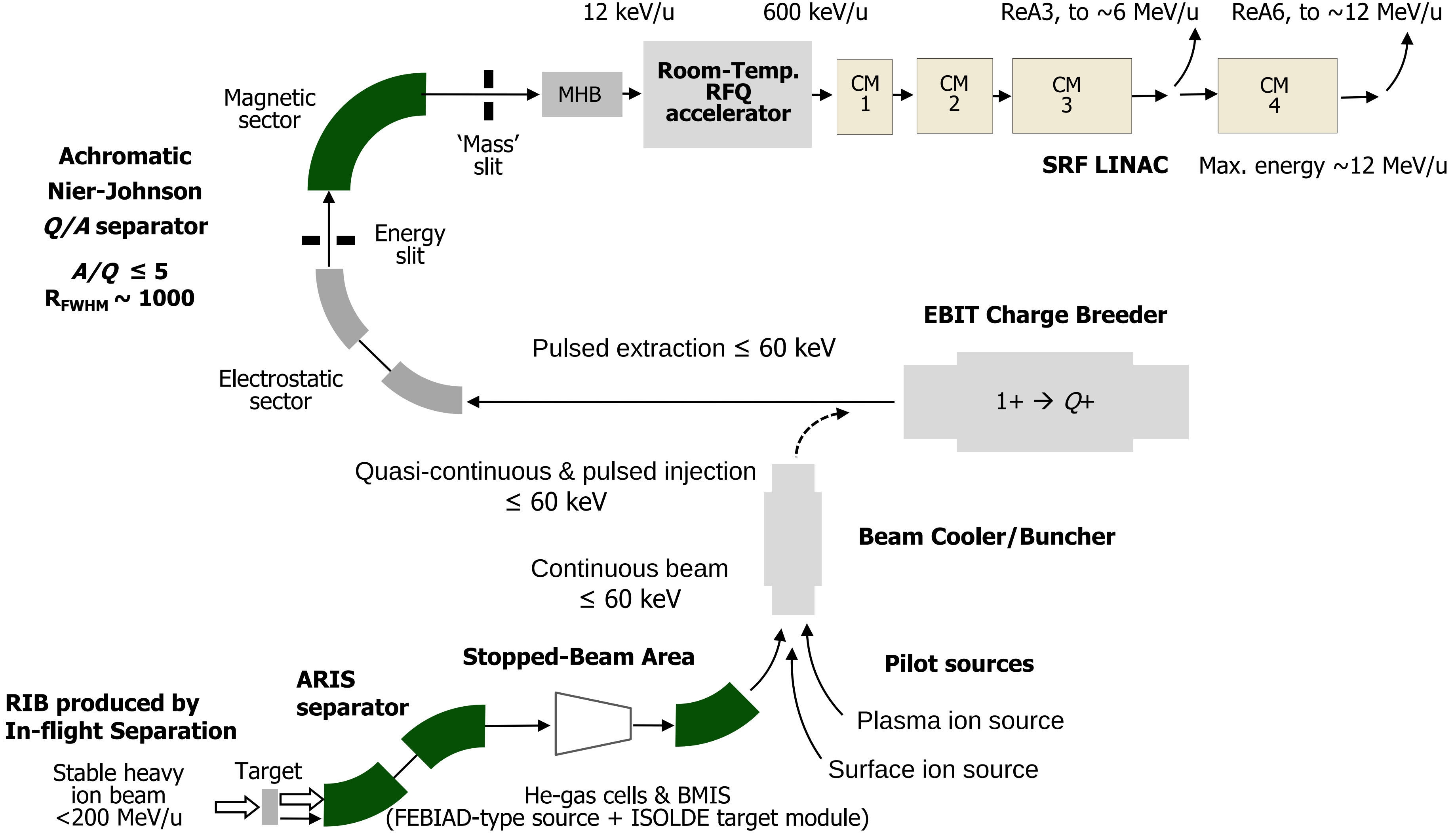
Facility for Rare Isotope Beams (FRIB)
with Fast, Stopped, and Reaccelerated Rare Isotope Beams

- FRIB construction completed on schedule in January 2022, end of the Coupled Cyclotron Facility (CCF) in November 2021, FRIB user operation started in May 2022
- Mission goal: 400-kW beam power on target from an SC LINAC for all ions (5x1013 238U/s)
- Power ramp up over several years - moving towards 20 kW
- Isotopes produced by “In-fight Separation” after projectile fragmentation & fission
- FRIB can provide beams of rare isotopes of all elements with Z < 83 and short half-lives
- FRIB provides fast, stopped, and reaccelerated beams
- Improvements projects, R&D, and new equipment increase FRIB’s capabilities for science
- Isotope harvesting capability from beam dump water



ReA Post-Accelerator

Reaccelerates of Stable and Rare Isotope Beams from the Stopped Beam Area



ReA Post-Accelerator

Reaccelerates Stable and Rare Isotope Beams from the Stopped Beam Area

In operation since 2015

ReA3

Light ions: 0.3 - 6 MeV/u

Heavy ions: 0.3 - 3 MeV/u

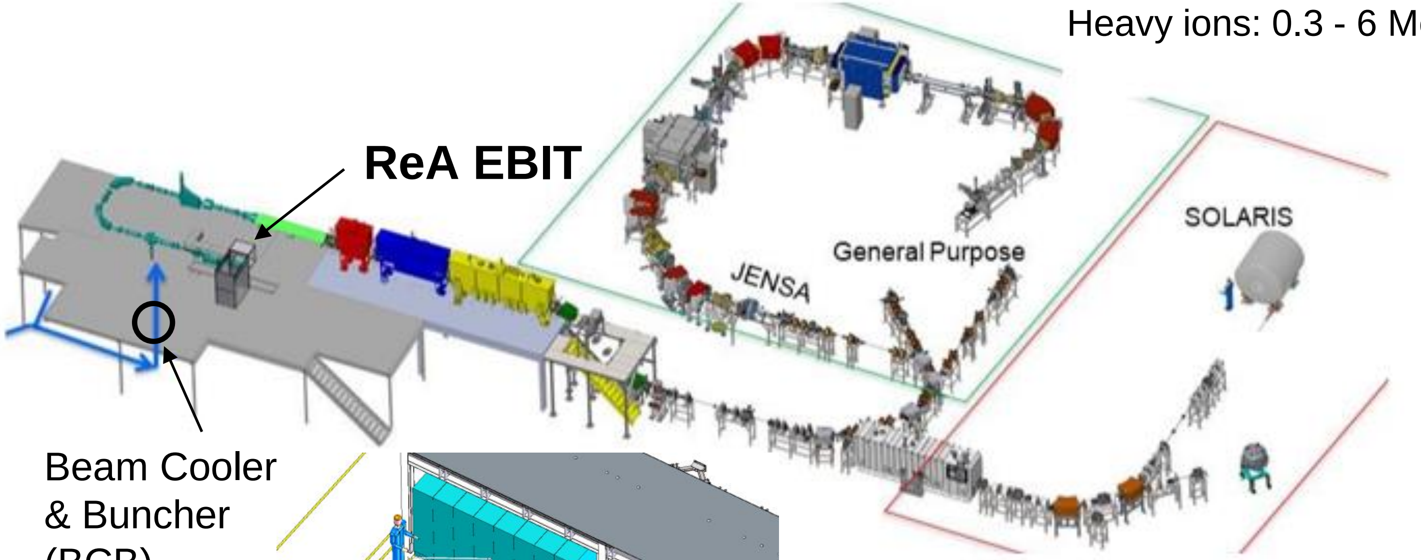
ReA6

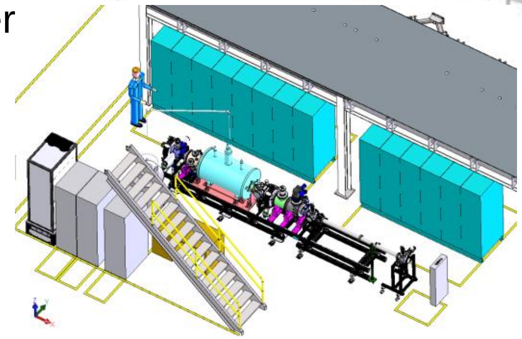
Light ions: 0.3 - 12 MeV/u

Heavy ions: 0.3 - 6 MeV/u

ReA EBIT

Beam Cooler & Buncher (BCB)





HCEBIS is being commissioned; test stand under the ReA platform.

Need for Increasing ReA Beam Rate Capabilities

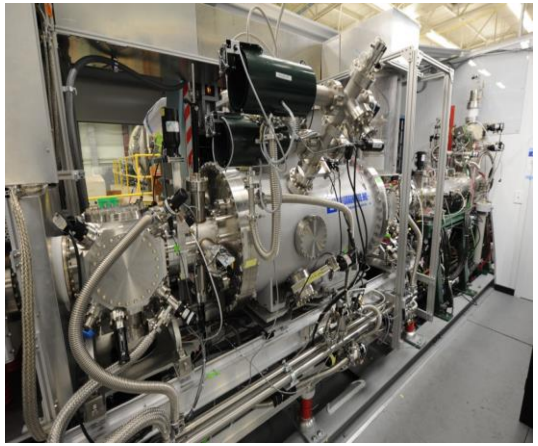
- Challenges
  - FRIB production rates expected to exceed 10^{10} pps (1.6 pnA) for some isotopes
  - Strong demands for stable-isotope beams of high intensities for nuclear astrophysics expt. (e.g., Recoil Separator SECAR, $\gtrsim 1\text{x}10^{10}$ pps (1.6 pnA))
  - The present electron current density achieved in the existing EBIT limits its capacity to provide maximum rates of < $2\text{x}10^{10}$ pps (3.2 pnA)
  - Designing a high-current, high-density electron gun for breeding at high repetition frequencies is technically challenging
- Two solutions in parallel to upgrade the charge breeding system
  - Increasing the electron current of the existing EBIT charge breeder
  - Implementing a high-current EBIS (also provides redundancy)

Key Parameters of ReA EBIT and HCEBIS

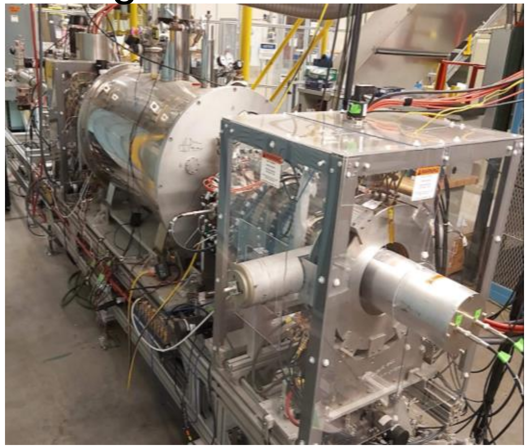
	ReA EBIT	HCEBIS
Maximum magnetic field	6 T	5 T
Bore type	Cold	Warm
E-beam current	**0.3 – 0.6 A** (Planning to upgrade up to 2 A)	**4 A**
E-beam current density	**170 – 340 A/cm^2** (Planning to upgrade up to 430 A/cm^2)	**300 A/cm^2**
E-beam energy	30 keV	20 keV
Trap length	800 mm	700 mm
Trap capacity [charges]	**1·10^{10}** (Planning to upgrade up to 5·10^{10})	**2.4·10^{11}**

- Electron beam current → Trap capacity
- Electron beam current density → Charge breeding efficiency

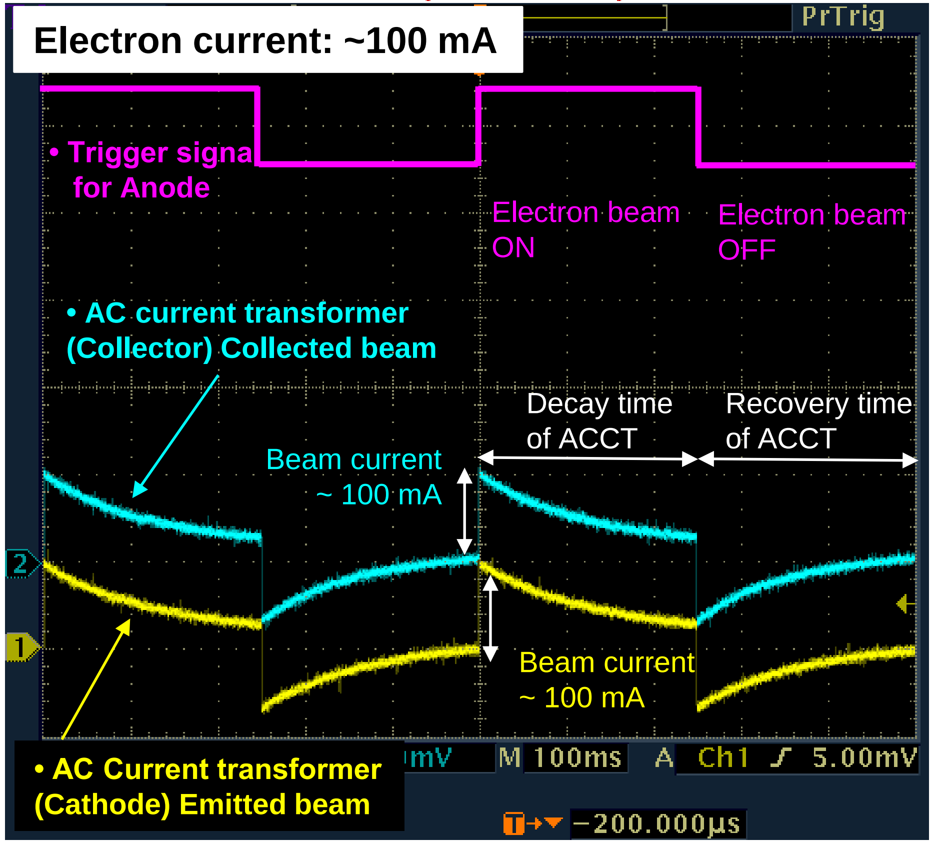
ReA EBIT

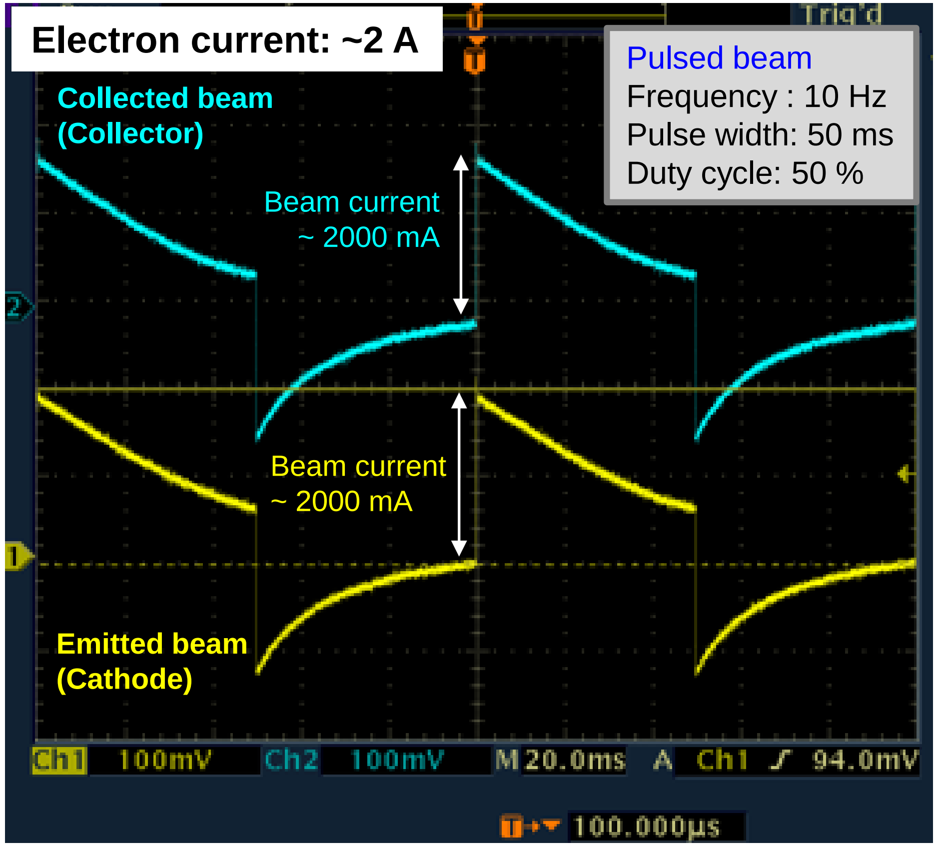


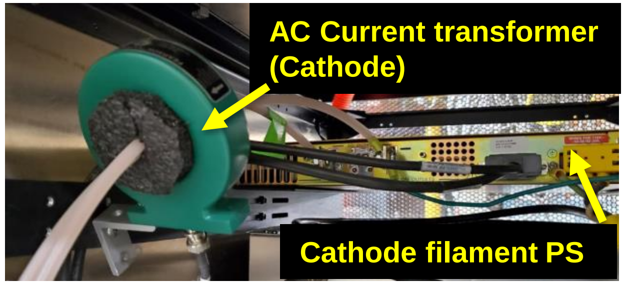
High-Current EBIS

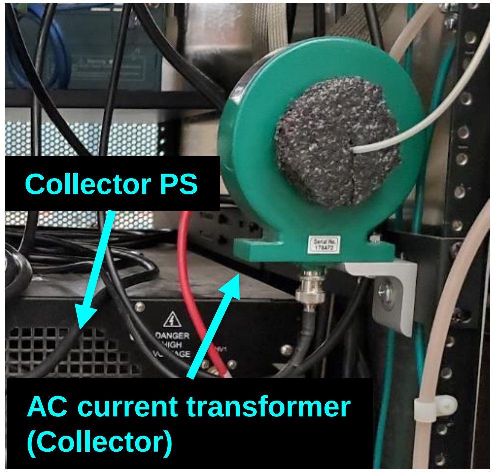


Electron Beam Commissioning
2 A of Electron Beam Current Achieved in HCEBIS



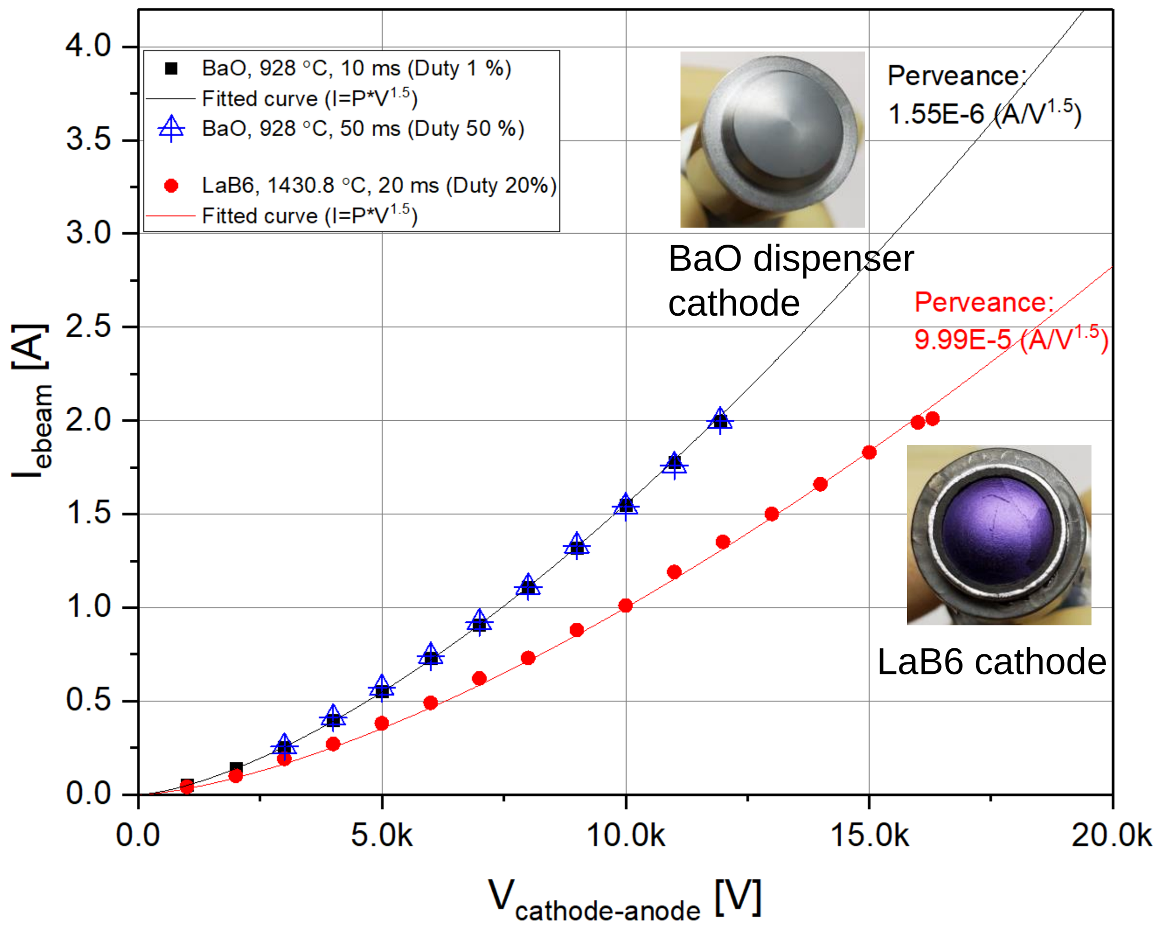




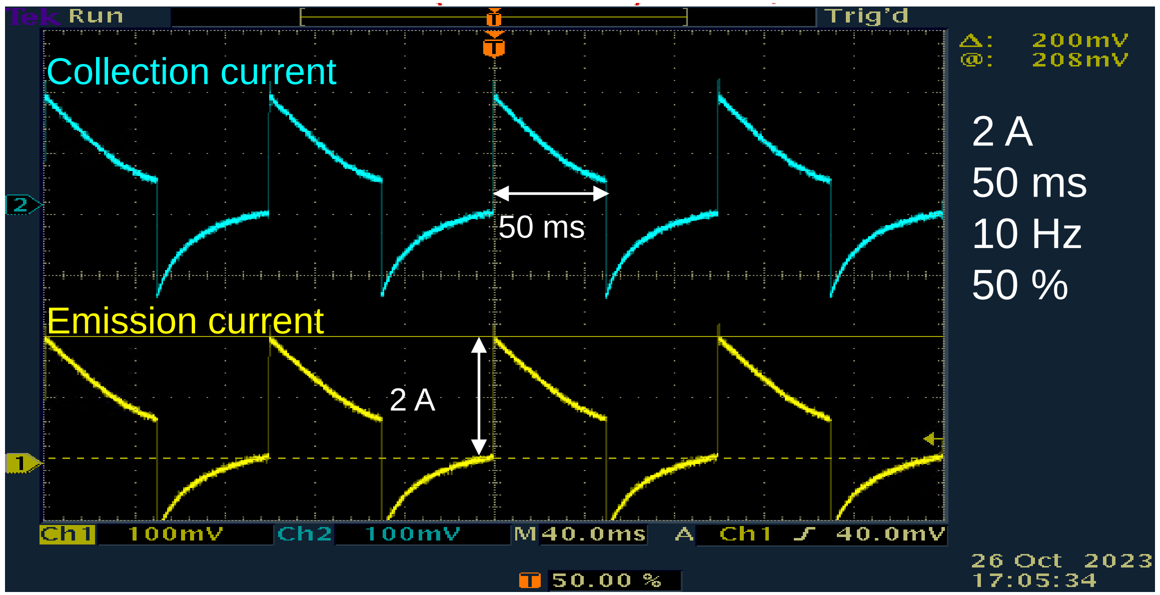


Electron beam current measurement signals on the oscilloscope

Electron Beam Commissioning
BaO Dispenser Cathode Shows Stable Electron Beam Current



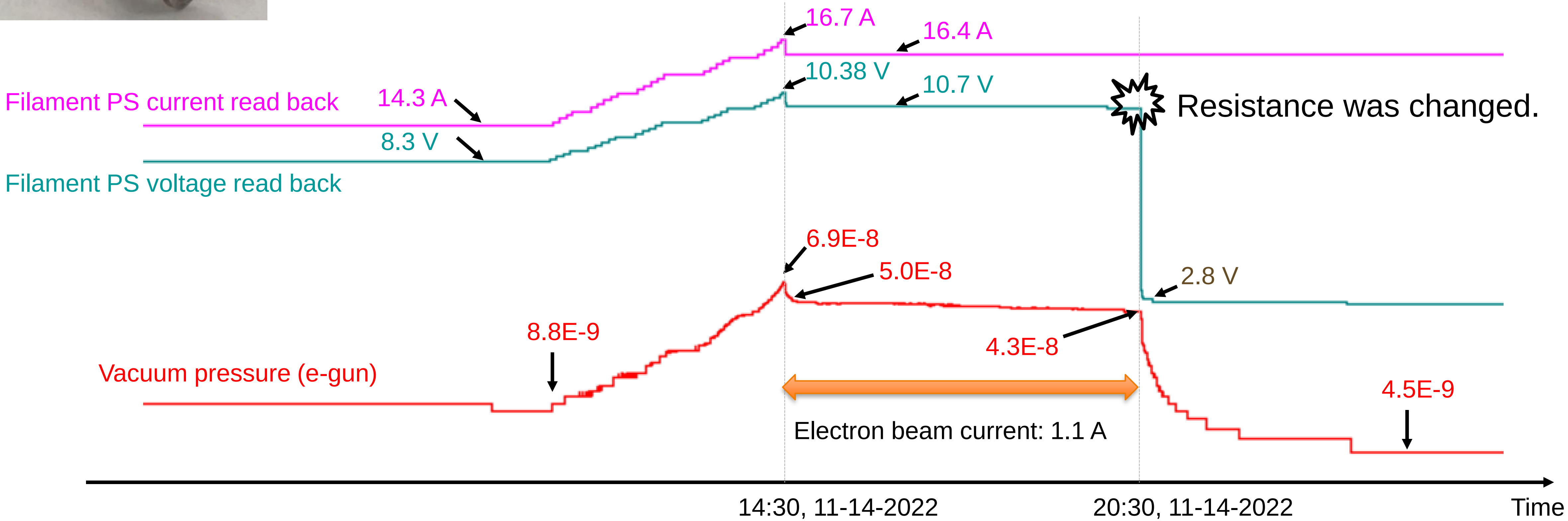
I-V curve of electron beam with different cathode current



- Perveance (1.55E-6 $A/V^{1.5}$) with BaO dispenser cathode is much improved, and this value agrees with the simulated value (1.45E-6 $A/V^{1.5}$).
- Electron beam with BaO dispenser cathode is very stable.
- Vacuum pressure in the e-gun section was improved with the dispenser cathode because of low cathode temperature

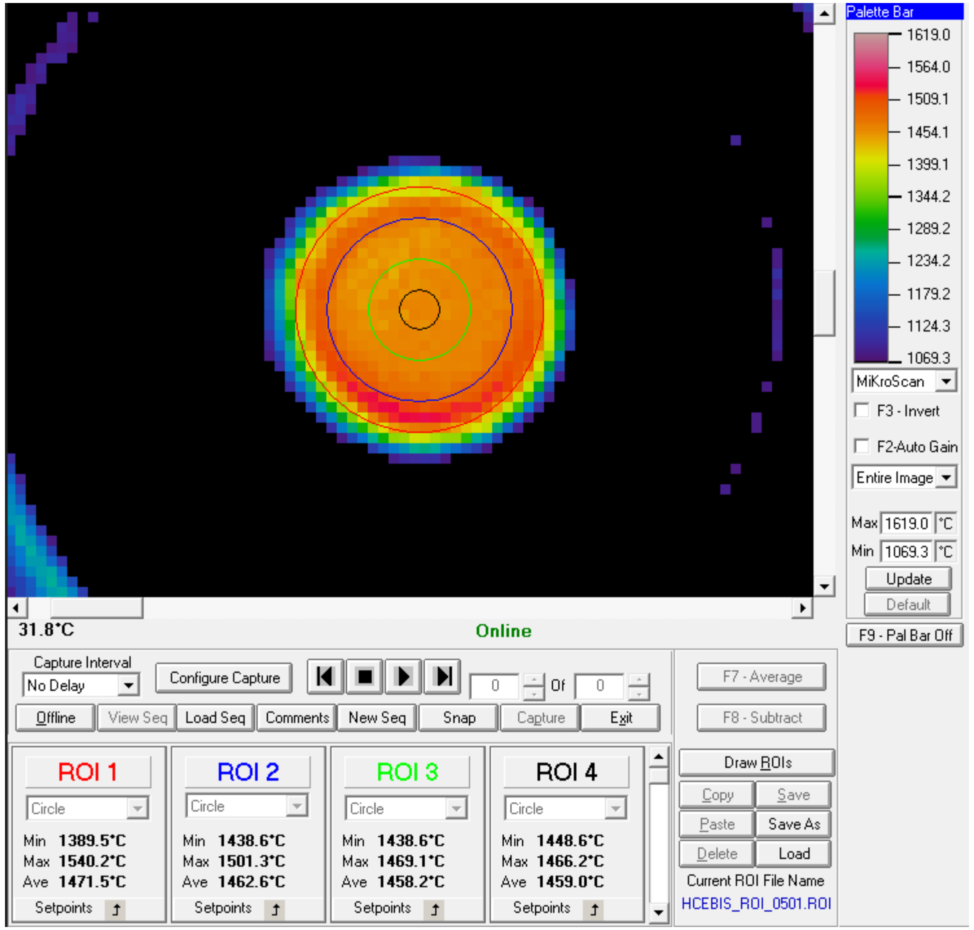
Issue: Filament failure inside cathode unit

- The filament inside the cathode unit was sagging down and touched to GND wall because the temperature was too high
- After this event, we decided to measure the cathode temperature more accurately for an optimal operation.

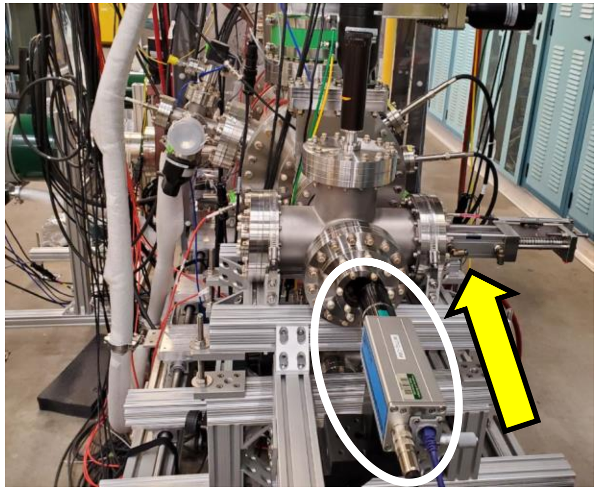


Cathode Temperature Measurement

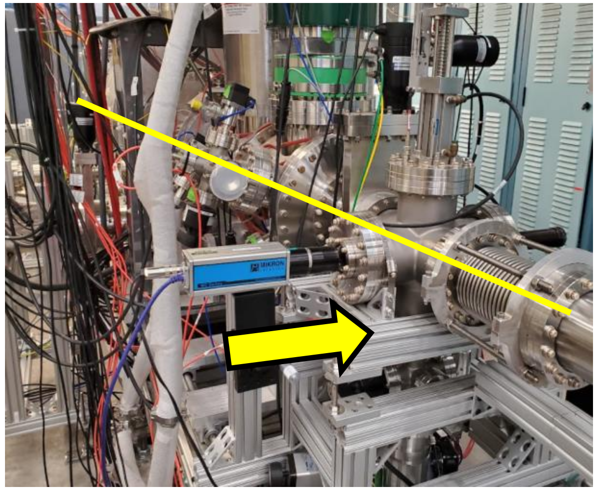
Cathode thermal image



On-axis setup

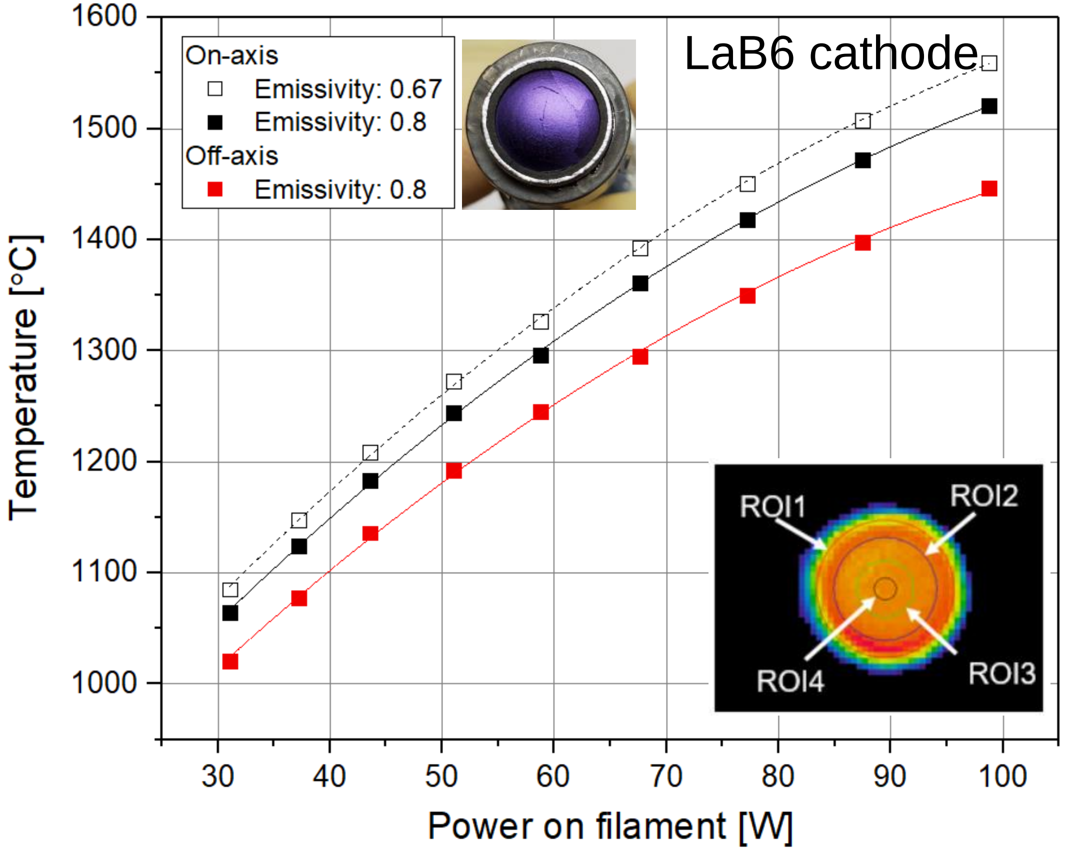


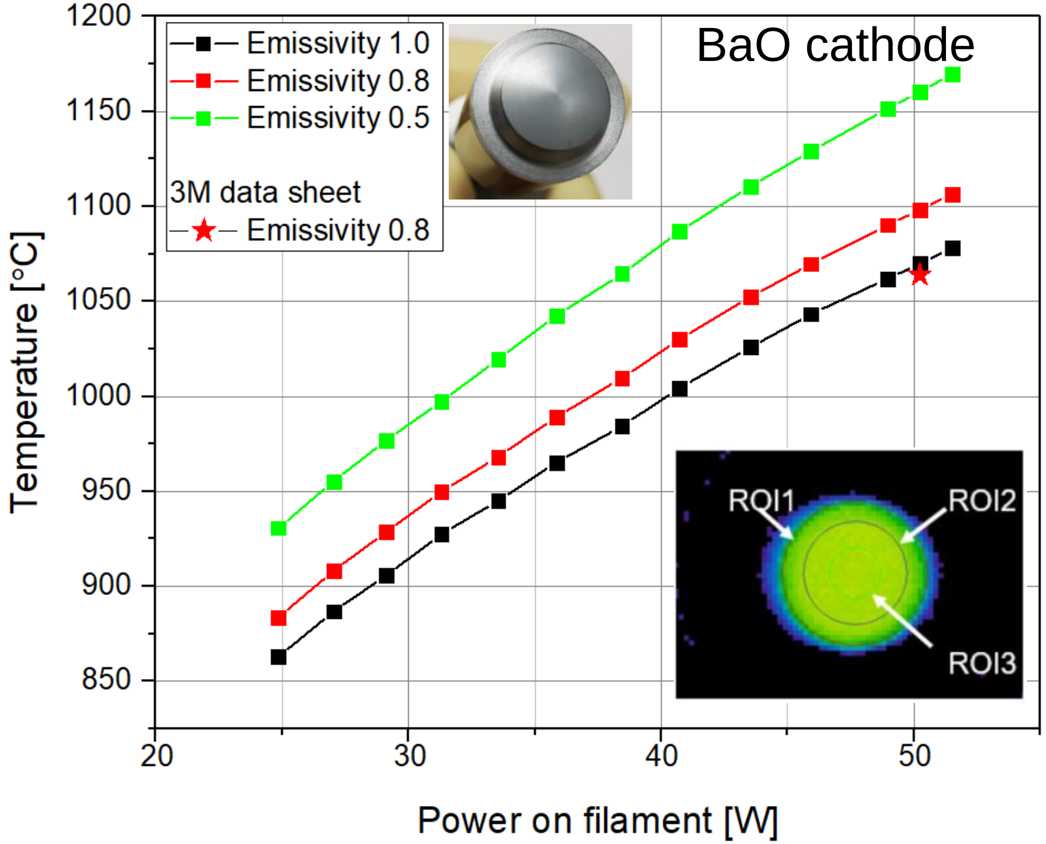
Off-axis setup



- Understanding the relation between power and temperature is important because we must not cross a limit temperature to avoid damage.
- Thermal camera (Mikron MSC640) has been calibrated with a black-body source at 1200 ° C
- There are two camera positions: On-axis and Off-axis with 45 ° mirror

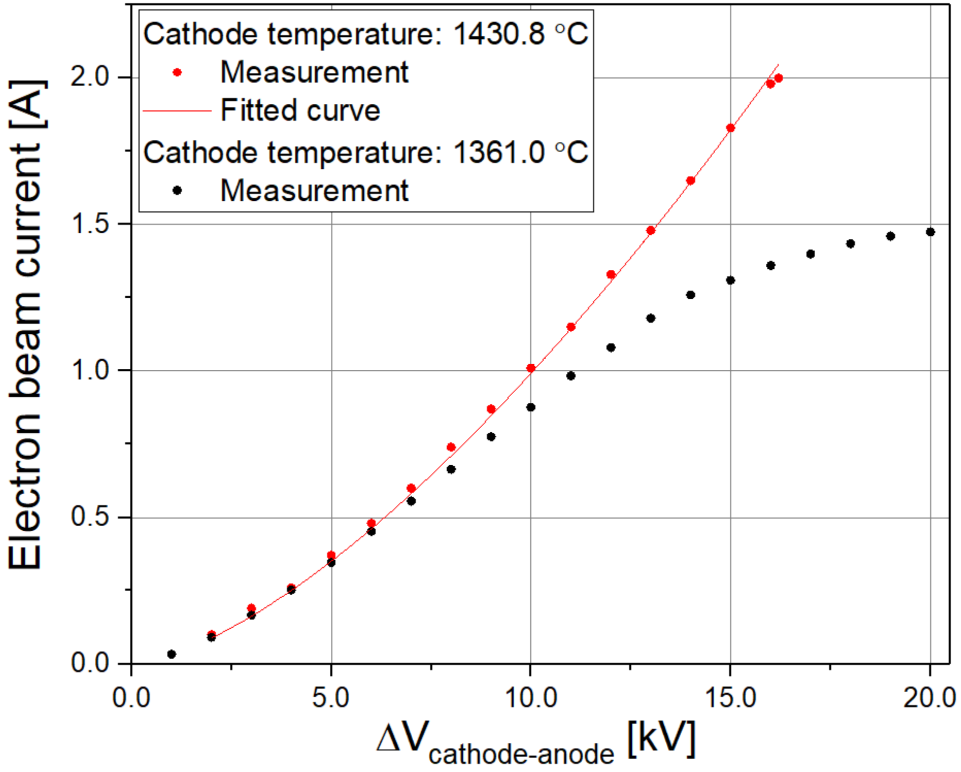
Cathode Temperature Measurement





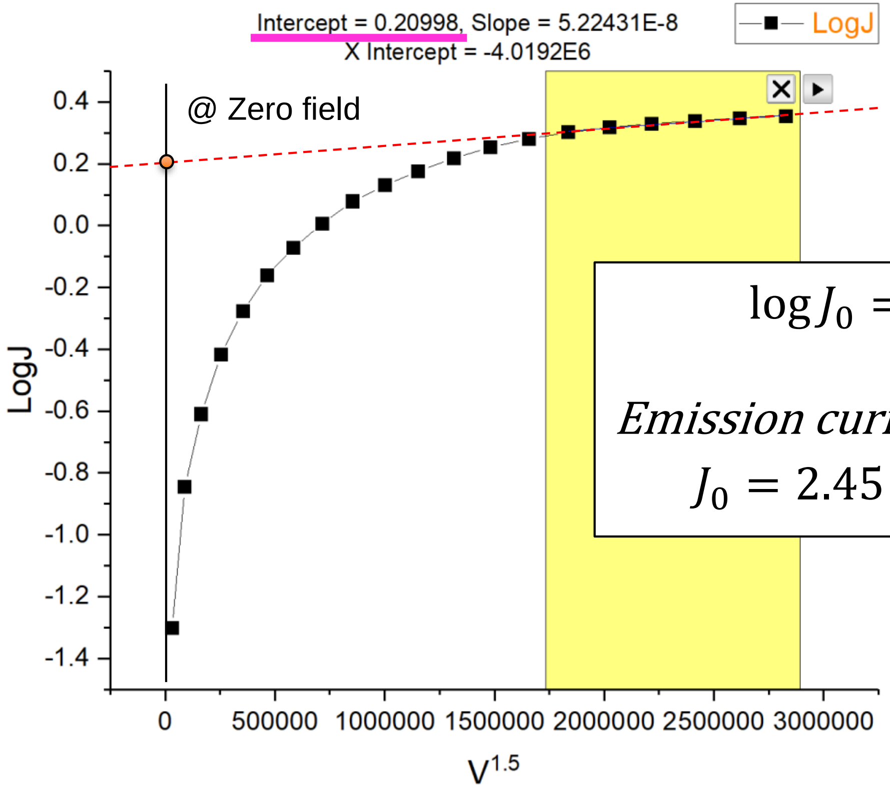
- We obtained the relation between power and temperature to understand optimal operation conditions for both cathodes.
- The temperature distribution of BaO dispenser cathode is more uniform than that of LaB6 cathode.

Emission density estimation: LaB_6 cathode



$$J = \frac{I_{beam}}{Area}$$

Emission area → 0.66 cm^2



$$\log J_0 = 0.21$$

Emission current density

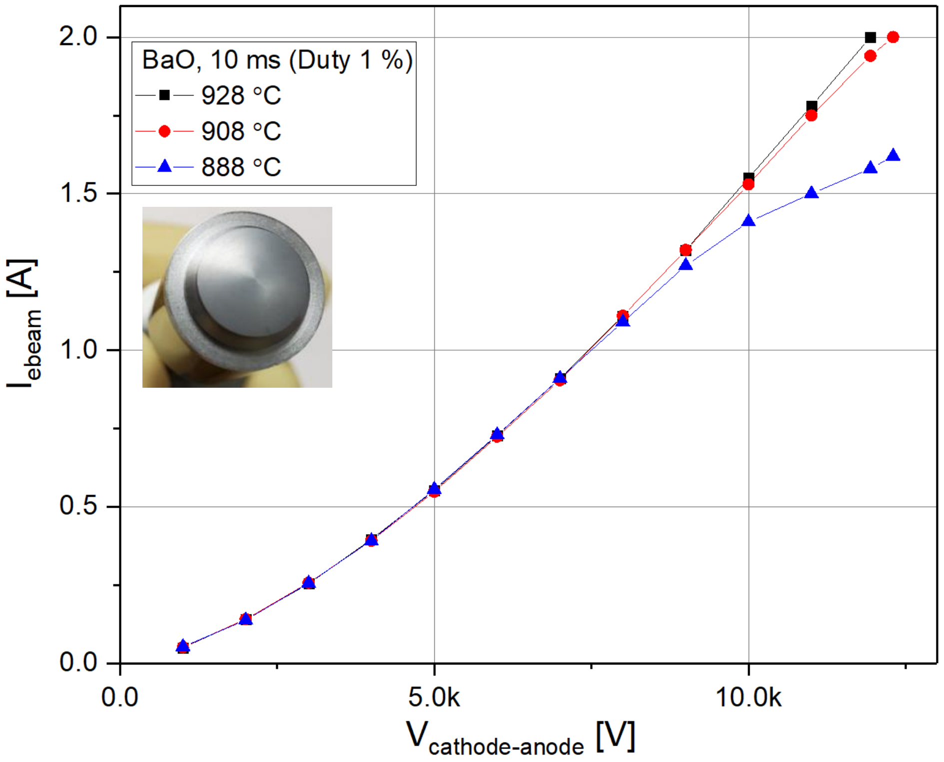
$$J_0 = 2.45\ [^A/_{cm^2}]$$

@1361 ℃	Ours	Ref.1	Ref.2	Ref. 3
Emission density [A/cm^2]	**2.45**	1.9	2.0	2.54

- Our measurement of the emission density agrees with literature values which confirms our temperature measurements

Ref.1: G.I. Kuznetsov 2004 *J. Phys. Conf. Ser.* **2** (35) / Ref.2: U. Kokal et al 2017 *8th Int. Conf. on Recent Advances in Space Technologies* (Istanbul) 47–53 / Ref.3: ES-423E LaB6 Crystal, KIMBALL PHYSICS

Emission density: BaO dispenser cathode



Typical Physical Properties

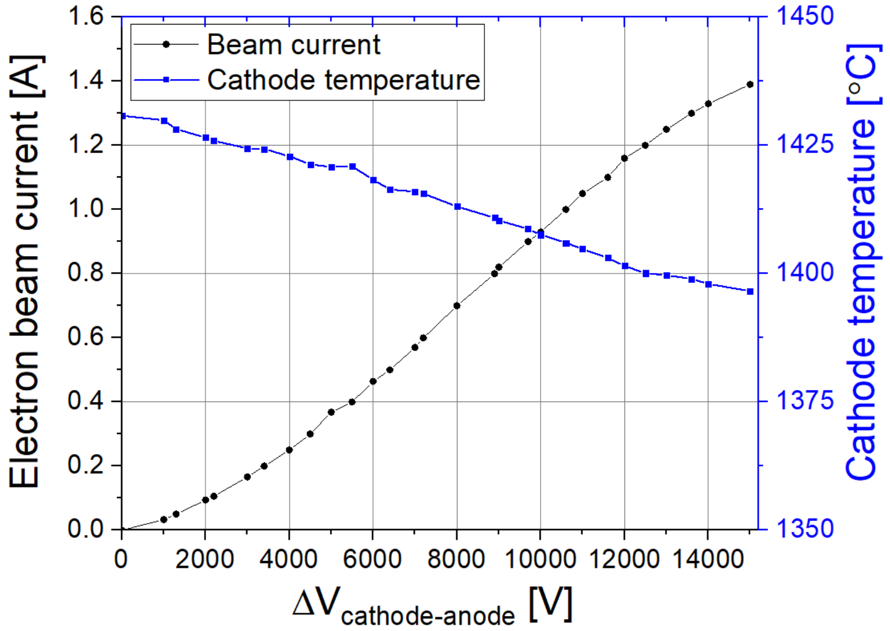
(Not for specification purposes)

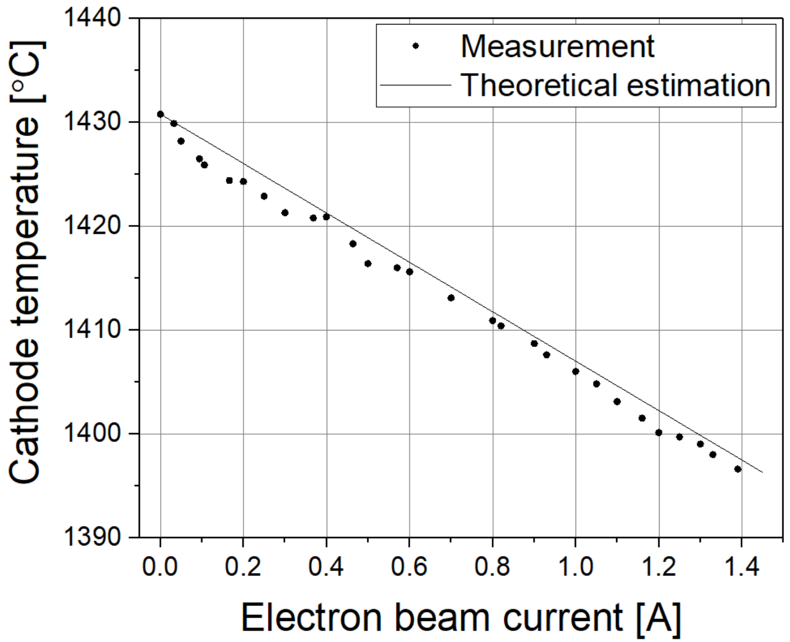
Commercial, Military or Space Qualification	
Size Range	0.010" – 8.00" (0.25 mm – 200 mm)
Tungsten Density Range	74% – 84%
Impregnant Types	4:1:1 (S), 5:3:2 (B), 6:1:2, 3:1:1 or any other required type
Sputter Coatings	Osmium Ruthenium (M), Iridium; other coatings possible
Materials	Tungsten, molybdenum, molybdenum-rhenium, rhenium, tungsten-rhenium, Kovar®, nickel, stainless steel, Monel® and others
Machined Tolerances	To ±0.0002" (±0.005 mm)
Brazes	Ranging from molybdenum-ruthenium (mp 1980°C) to low temperature alloys such as copper-gold (mp 910°C)
Operating Temperature	From 910°C_B to 1200°C_B
Emission Density	Continuous, as high as 20 A/cm², typically 2 – 5 A/cm²; pulsed, as high as 120 A/cm², typically 30 – 70 A/cm²
Life Expectancy	From 3,000 hours to 150,000 hours

* 3M data sheet / This cathode was built by 3 M

- The BaO dispenser cathode is expected to emit a 4-A electron beam at a much lower temperature range than that of LaB6 cathode.

Thermionic Cooling Effect
Measurements and Theoretical Predictions Agree





$$J = AT^2 e^{-W/kT}$$

$$\Rightarrow \frac{dJ}{J} = \left(2 + \frac{W}{kT}\right)\frac{dT}{T}$$

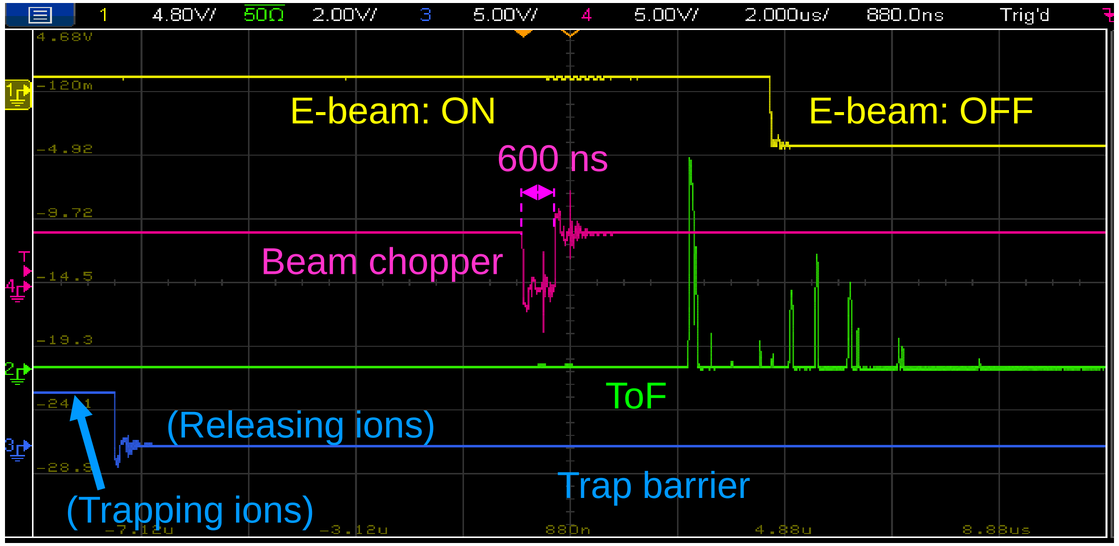
$$\Rightarrow \frac{dJ}{J} = 21.4\frac{dT}{T}$$

Work function: 2.85 eV,

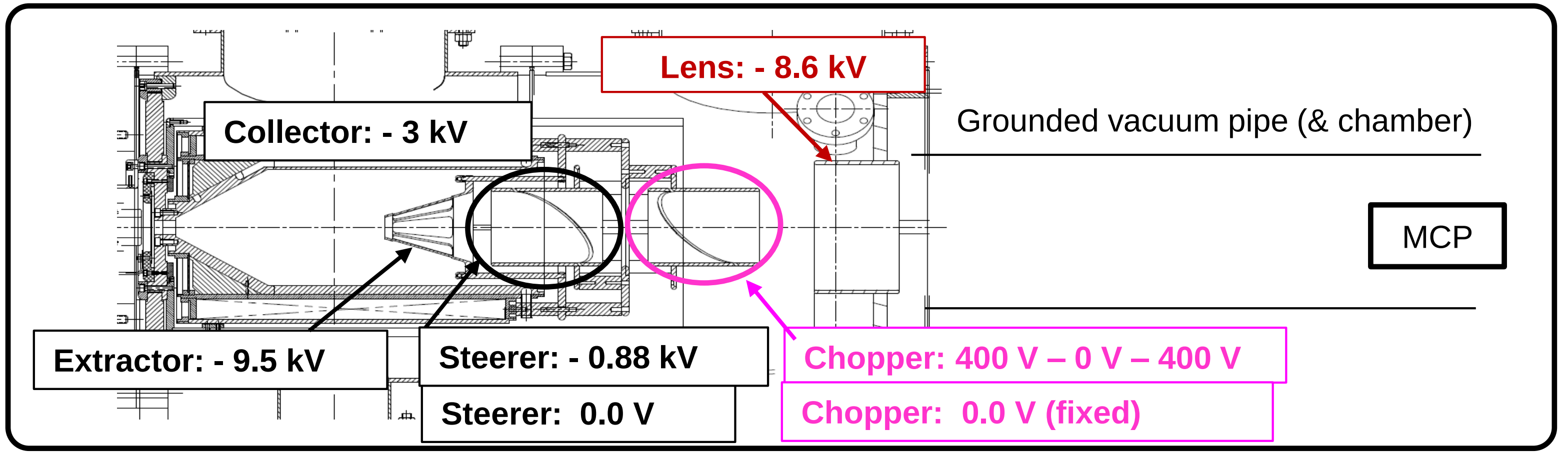
Initial temperature: 1430.8 ° C

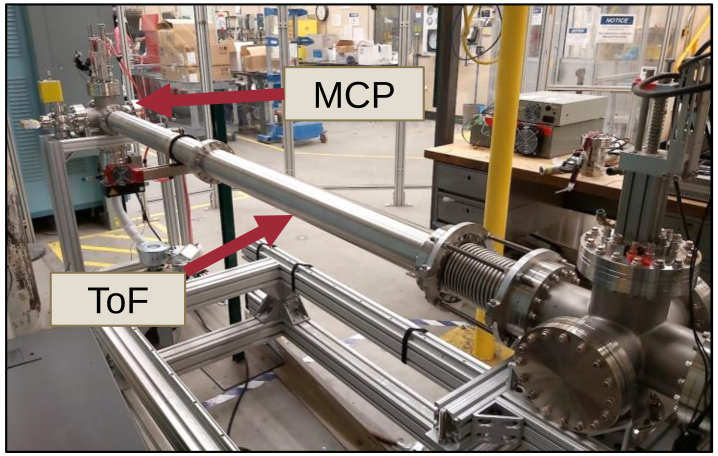
- Thermionic cooling effect was observed. When energetic hot electrons leave the thermionic cathode surface, the emitting electrons take thermal energy away from the cathode surface.
- Measured temperature decrease has been compared with theoretical estimation*. *Y. Liu *et al* 2008 *Sci. China Ser. E-Tech Sci.* 51 (9) 1497–1501
- According to the Richardson-Dushman equation, a 1% temperature decrease leads to a 21.4 % emission density (at zero electric field) decrease.
- With a high current EBIS/T charge breeder, an electron-beam current initially appears to be maintained, but over time, one may see a noticeable beam current drop by the thermionic cooling effect. It should be compensated by increasing the heater filament power.

Time-of-Flight Setting for Extracted Ion Charge State Analysis

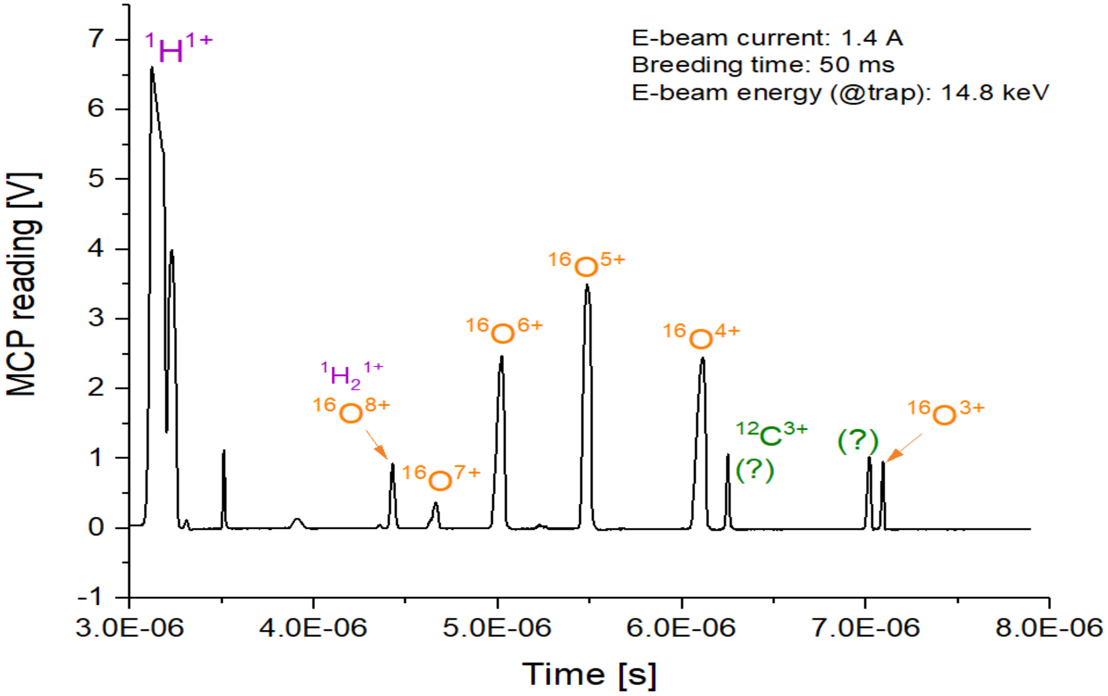


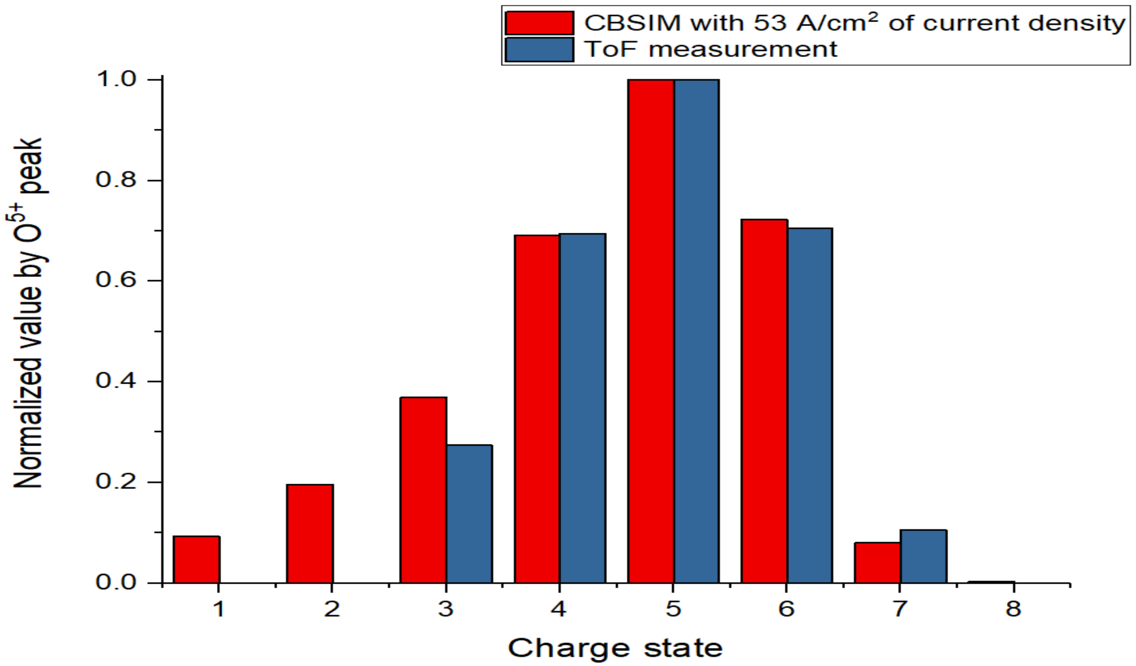
- Ion extraction by TOF by chopping the extracted beam.
- Allows us to study the charge breeding and charge state distribution (CSD).
- Also allows us to measure the e-beam current density.
- We performed charge breeding test with residual gas.





Ion Extraction and Electron Beam Current Density Estimation





- Beam current: 1.4 A
- Magnetic field at the trap center: 4 T
- Magnetic field at the cathode surface: 0.15T
- Cathode diameter: 9.2 mm

→ Estimated e-beam dia. In the trap: 1.78 mm

→ Estimated current density: 56 A/cm^2

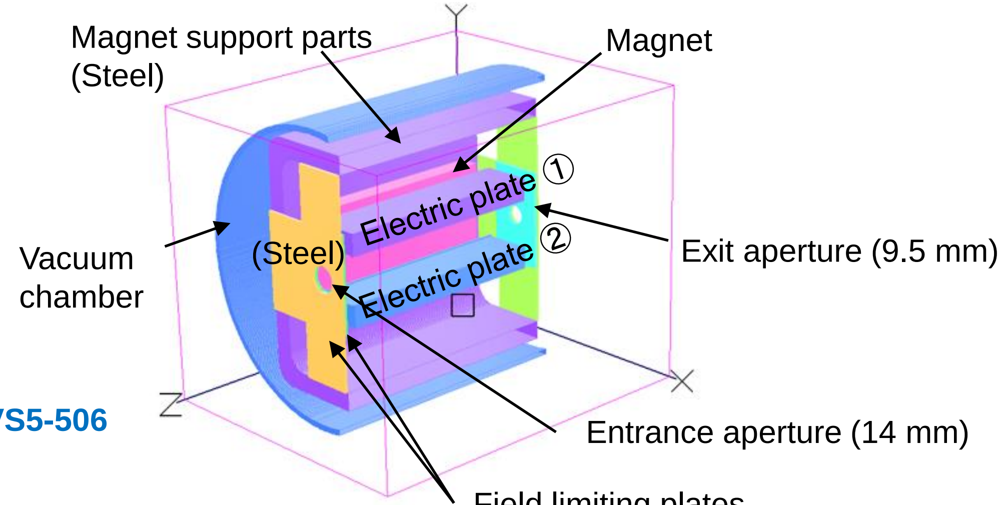
$$r_z = r_{cathode}\sqrt{\frac{B_{cathode}}{B_z}}$$

- We compared our CDS measurement with the CBSIM simulated CDS.
- Electron beam current density
  - Our estimation: 56 A/cm^2
  - CBSIM: 53 A/cm^2

Good agreement!

Wien Filter Simulation for Charge State Analyzer

- We are considering a Wien filter as charge state analyzer. To check capability of the Wien filter, we have performed simulations.

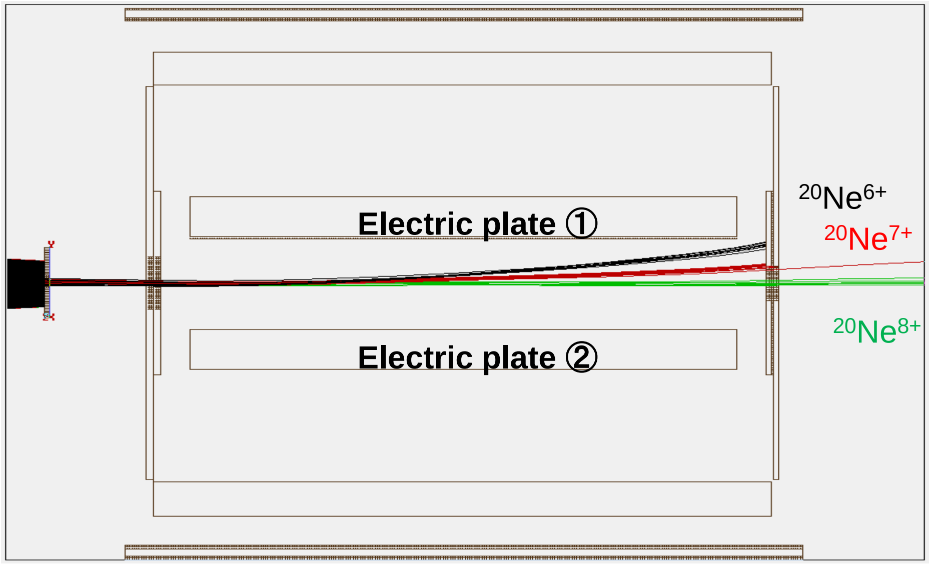


NEC: VS5-506

- Simulation parameters

Electrode ①	-2.2 kV
Electrode ②	2.2 kV
Magnetic field	2300 Gauss (fixed)
Aperture size (dia.)	14 mm (entrance), 9.5 mm (exit)
Acceleration voltage	7 kV

- Beam separation result



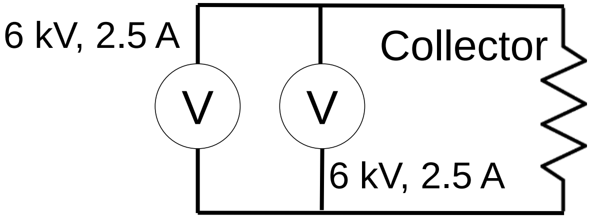
- Ion beam energy (average) at starting location

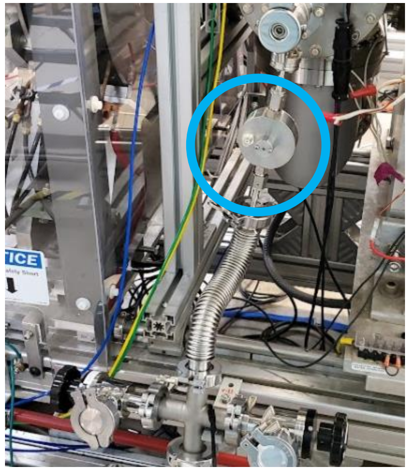
$^{20}Ne^{6+}$	42 keV
$^{20}Ne^{7+}$	49 keV
$^{20}Ne^{8+}$	56 keV

Path Forwards

- Electron beam commissioning up to 4 A
  - New collector power supplies are being installed. Two 2.5 A power supplies will be operated in parallel mode.
- Fast gas injection system for Ne charge breeding
  - We want to define a clean injection time for breeding time measurements with controlled amount of gas. The piezoelectric gas valve can operate within the several ms range for the fast gas injection.
  - Our goal is to produce intense Ne^{8+} beam (~10^{11}pps).

✓ Parallel mode
- Total output : 6 kV, 5 A





✓ Piezoelectric gas valve

Summary

- The Electron beam reached 2 A.
- We obtained a stable electron beam with the BaO dispenser cathode.
- We measured the cathode temperature to establish the optimal cathode operation.
- The thermionic cooling effect was observed, and theoretical predictions agree well with it.
- The residual gas charge breeding test was performed, and its charge state distribution (CSD) was obtained by TOF by chopping the extracted beam.
- The estimated electron beam current density is well agreed with the simulated value based on our CSD measurement.
- Wien filter simulation has been performed for the future charge state analyzer.
- New collector power supplies are being installed for 4-A electron beam.
- The fast gas injection system is being implemented for the Ne gas charge breeding

Thank you for your attention.