Welcome!

Cockcroft Institute Lectures – Register Attendance

CI-ACC-221: Ion Sources and Secondary Beams
Dan Faircloth (DF) RAL/STFC

CI-RF-222: RF Linear Accelerators
Graeme Burt (GB) CI/Lancaster University

CI-ACC-225: Electron Sources
Boris Militsyn (BM) CI/ASTeC

CI-ACC-226: Machine Learning Methods for Particle Accelerators
Andrea Santamaria Garcia (ASG) CI/University of Liverpool

Date/time	10:30	11:45	14.00
9 Feb 2026	Ion Sources		Penning Magnetron
16 Feb 2026	High Voltage		Secondary Beams

QR code will take you to a Google form

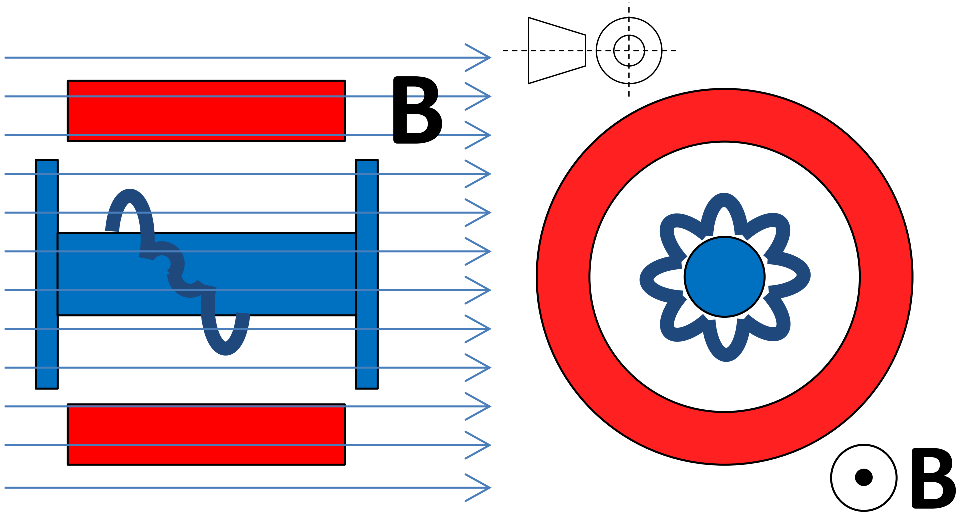
Record attendance for each day of lectures

Magnetron and Penning

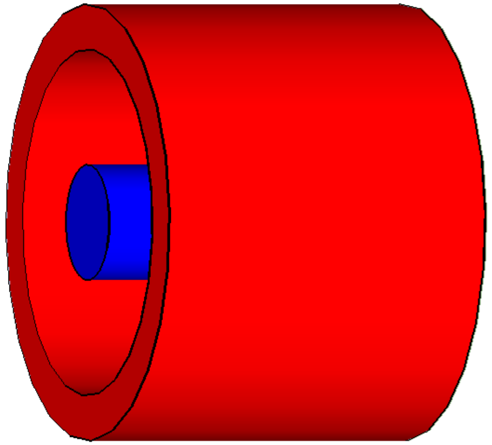
Dan Faircloth
ISIS Low Energy Beams Group Leader
Rutherford Appleton Laboratory
STFC-UKRI

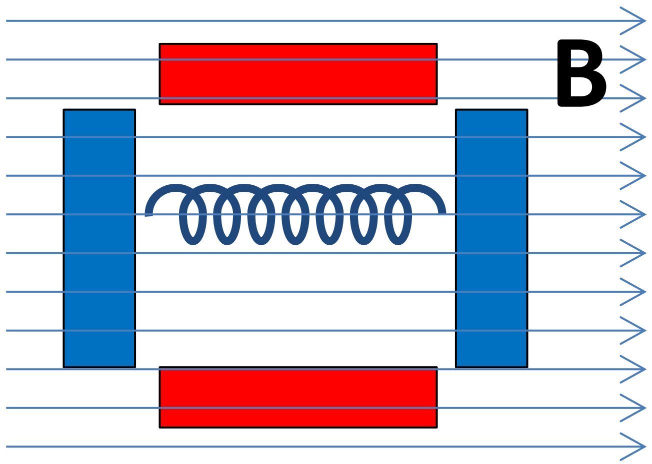
CI Lectures 2026 Daresbury

Fundamental Topology

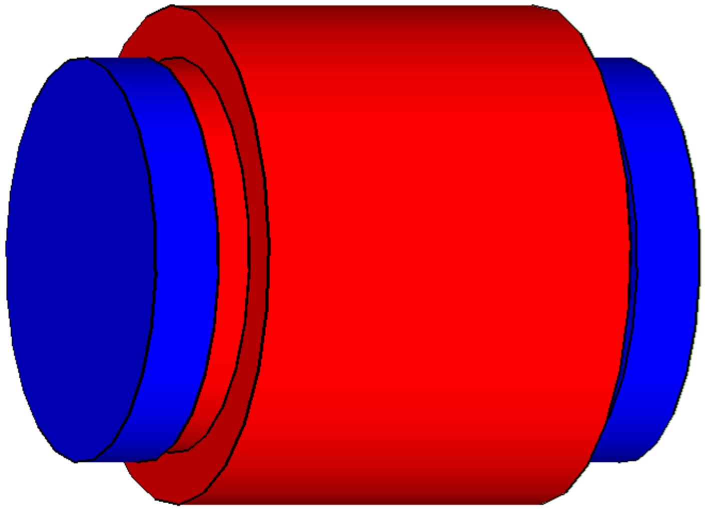


Magnetron

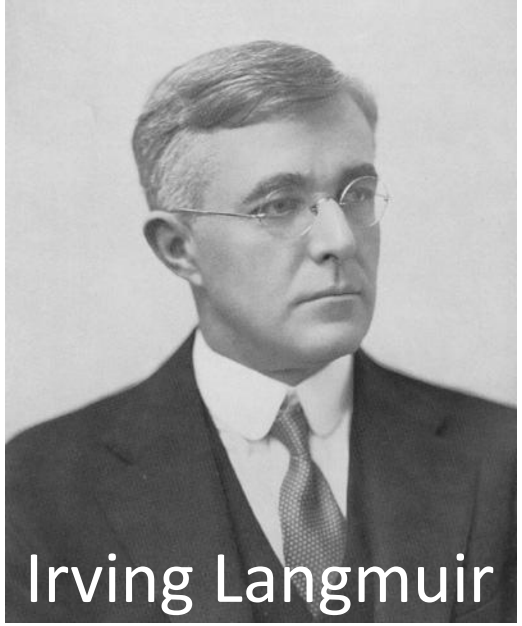




Penning



GE Research Lab, Schenectady, NY 1916



Albert Hull

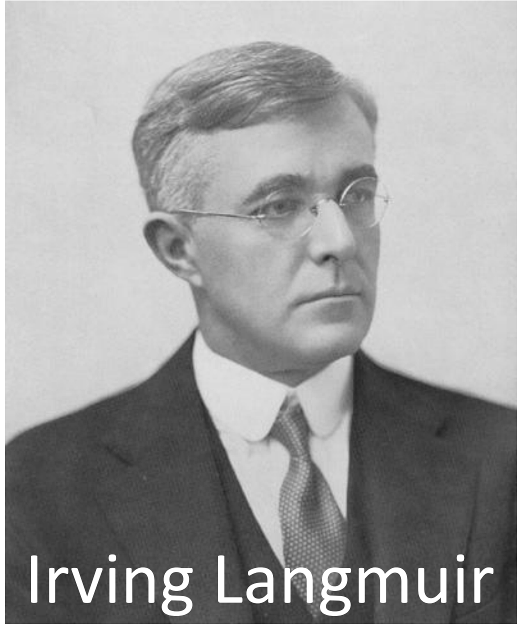
Using magnetism to find alternatives to patented electrostatic control of valves

E x B

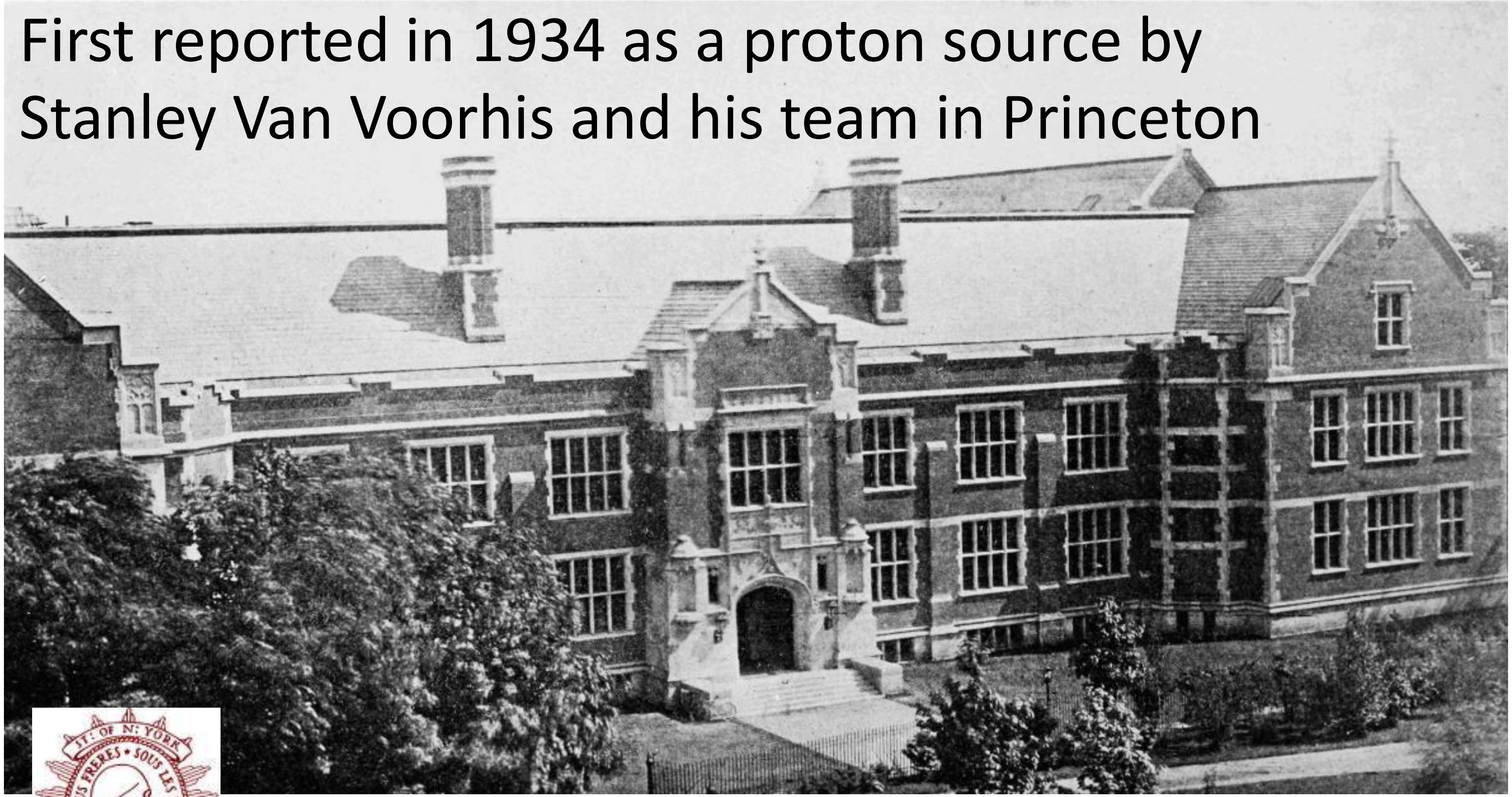
1920 Comet valves?
Boomerang valves?
Ballistic valves?
MAGNETRON VALVES

1920's Starts adding gasses to his valves and going to high powers.

Langmuir talks to his fellow New England scientists


Irving Langmuir

Magnetron Ion Source

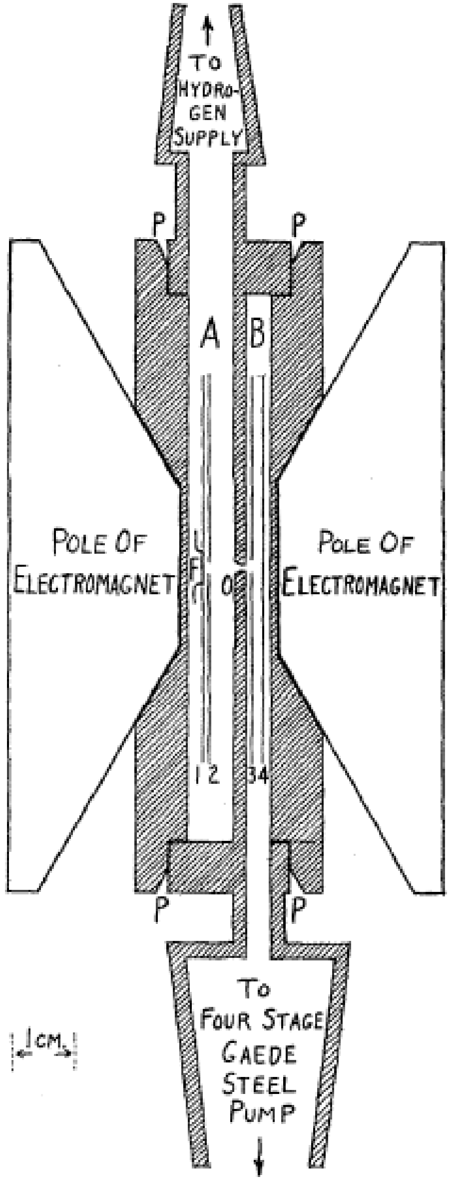


First reported in 1934 as a proton source by Stanley Van Voorhis and his team in Princeton

Also developed by Overton Luhr and others at MIT and Union College

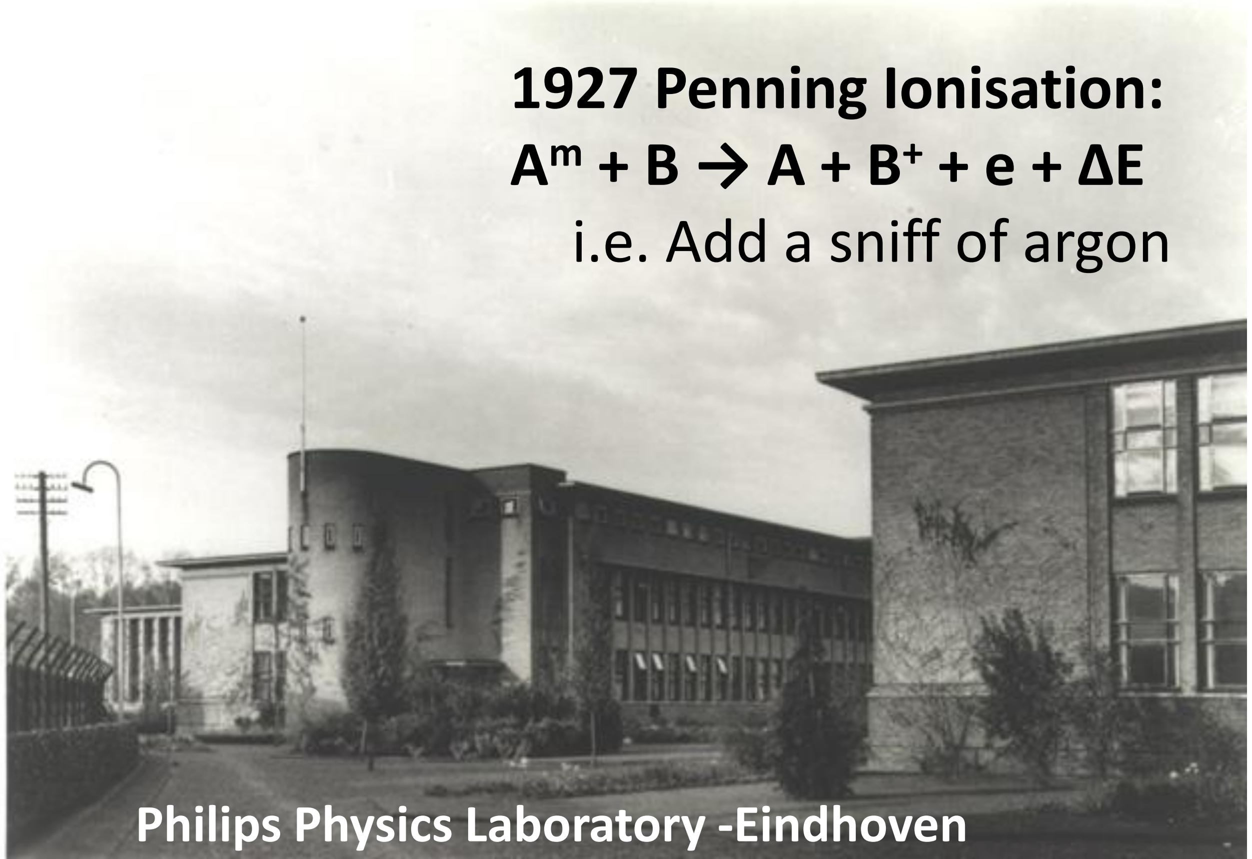
Louis Maxwell
The Franklin Institute
Philadelphia 1930

Penning Ion Source



1937 Penning Ionisation Gauge or
Philips Ionisation Gauge (PIG)

Frans Penning

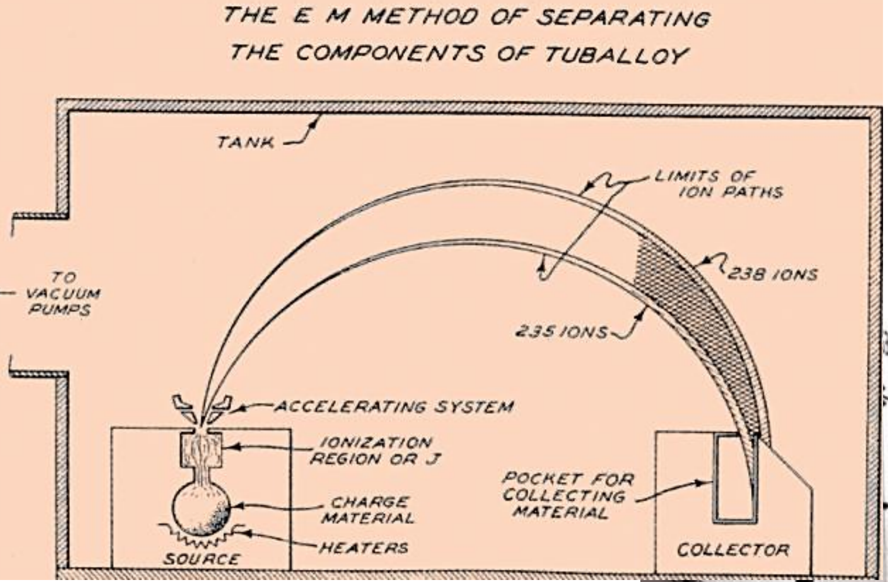


1927 Penning Ionisation:
$\mathbf{A^m + B \rightarrow A + B^+ + e + \Delta E}$
i.e. Add a sniff of argon

Philips Physics Laboratory -Eindhoven

Geometries similar to ‘Magnetron’ and ‘Penning’ are employed in a number of different sources:

Magnetron	- Freeman source
Penning	- Nielson source
	- Bernas source
	- Calutron source



The Penning geometry (Calutron) starts the Cold War

high-purity uranium-235

Magnetron and Penning ion sources are used in wide variety of applications:

- Mass separation
- Sputter coating
- Space thrusters
- Particle accelerators
  - Positive
  - Negative

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

Production of H^- ions by surface ionisation with the addition of caesium

Surface Plasma Sources (SPS)

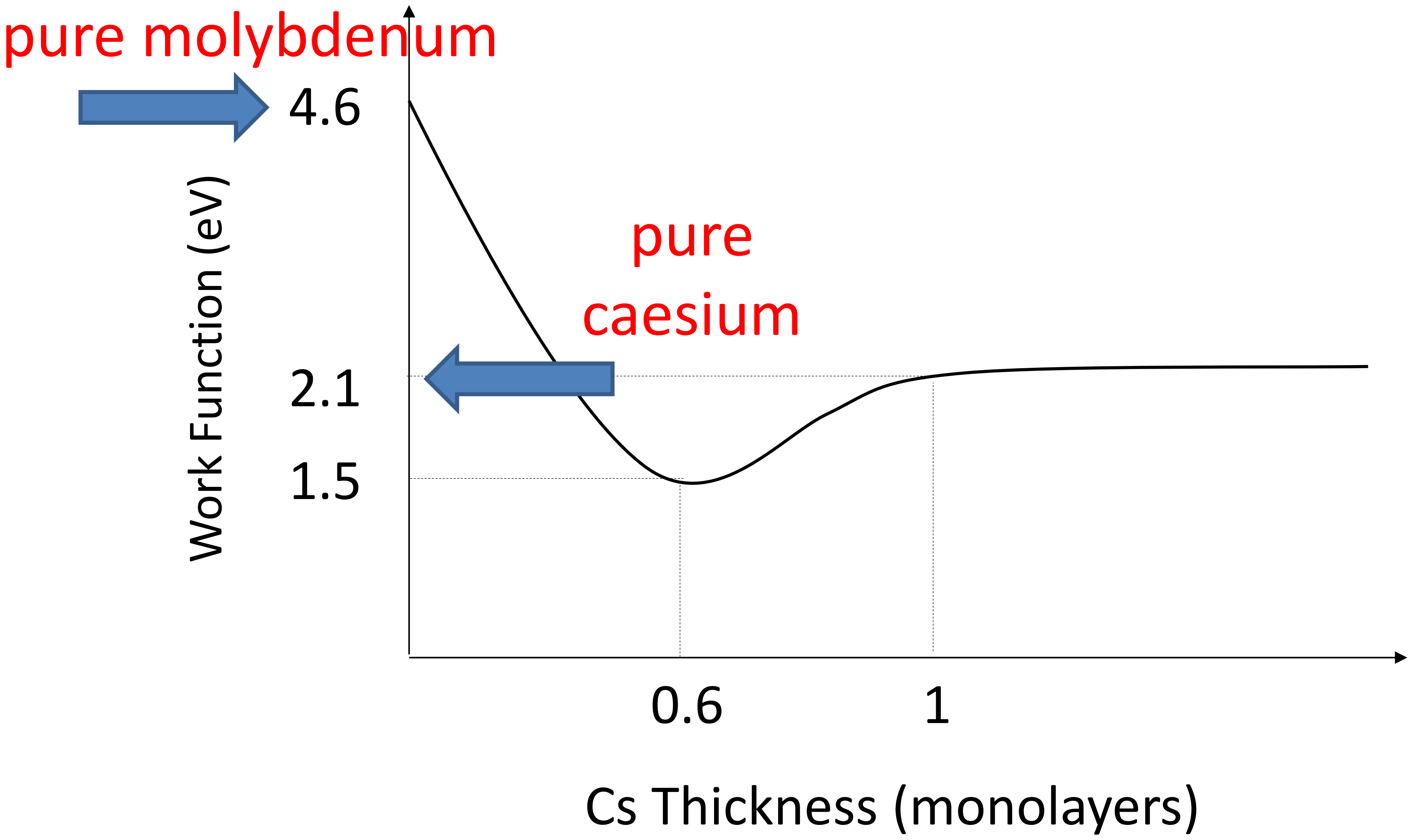
Gennady Dimov

Yuri Belchenko

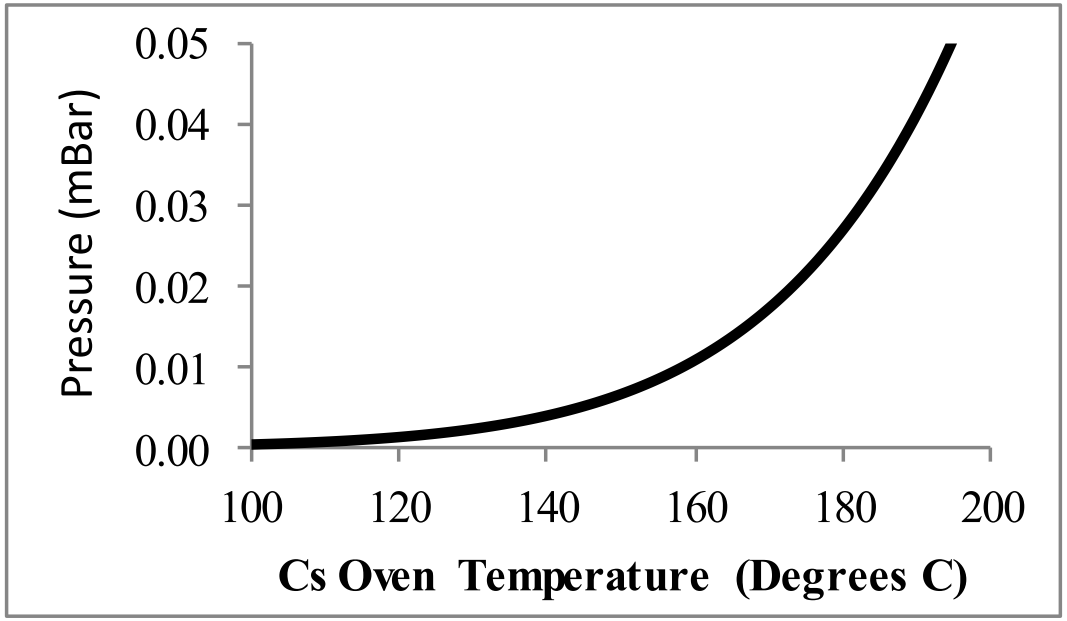
Vadim Dudnikov

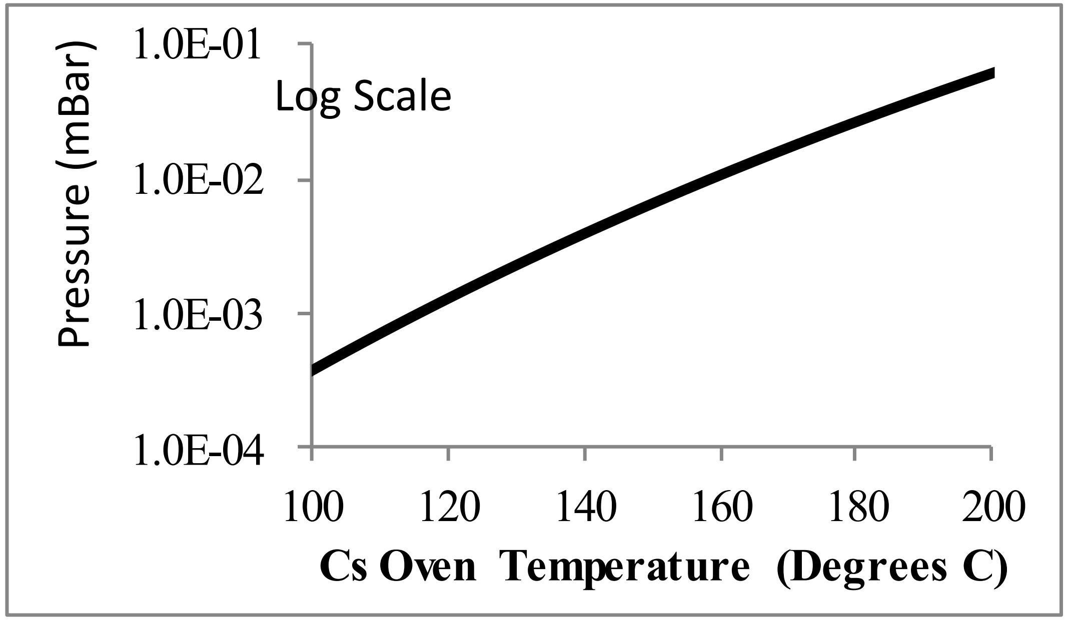

5 g
caesium
ampoule

Caesium Coverage



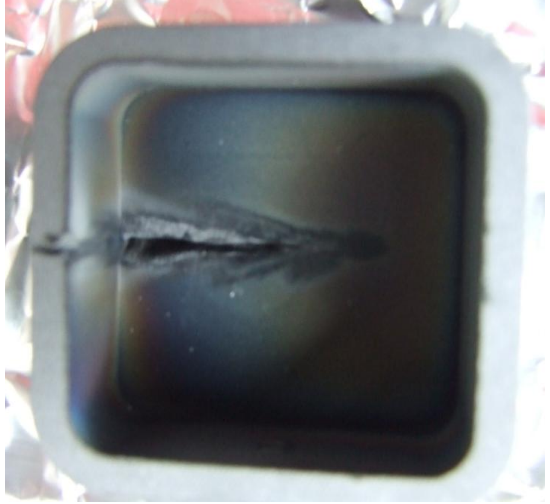
Vary caesium oven temperature to control vapor pressure to control caesium coverage:

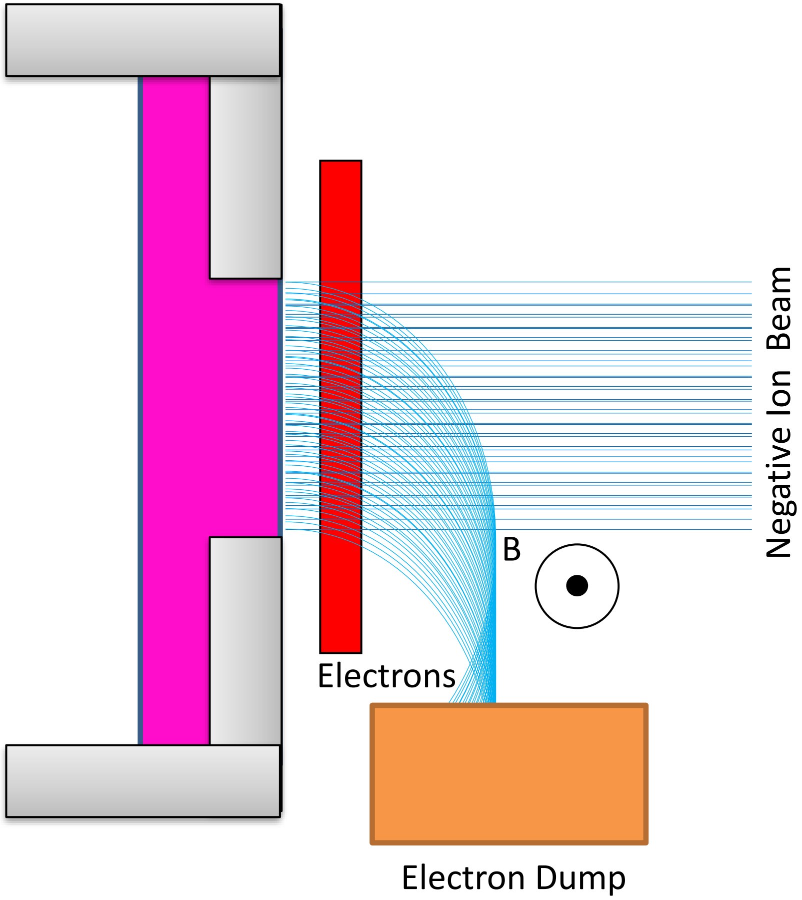




Negative Ion Extraction

CERN LINAC4
e-dump surface

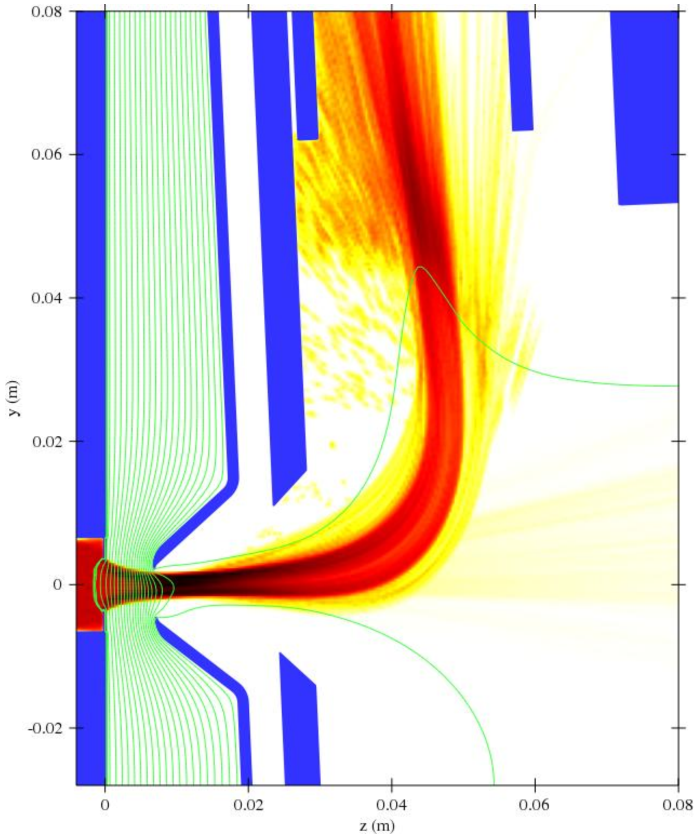




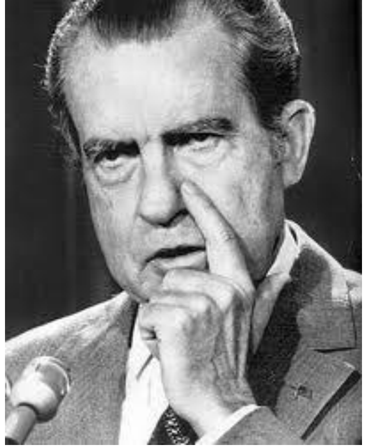
Electrons will also be extracted
Up to 1000 times the H^- current!
Use a magnetic field
Dump must be properly designed

SPS sources:

co-extracted electrons are only 0.5 to 10 H^- current

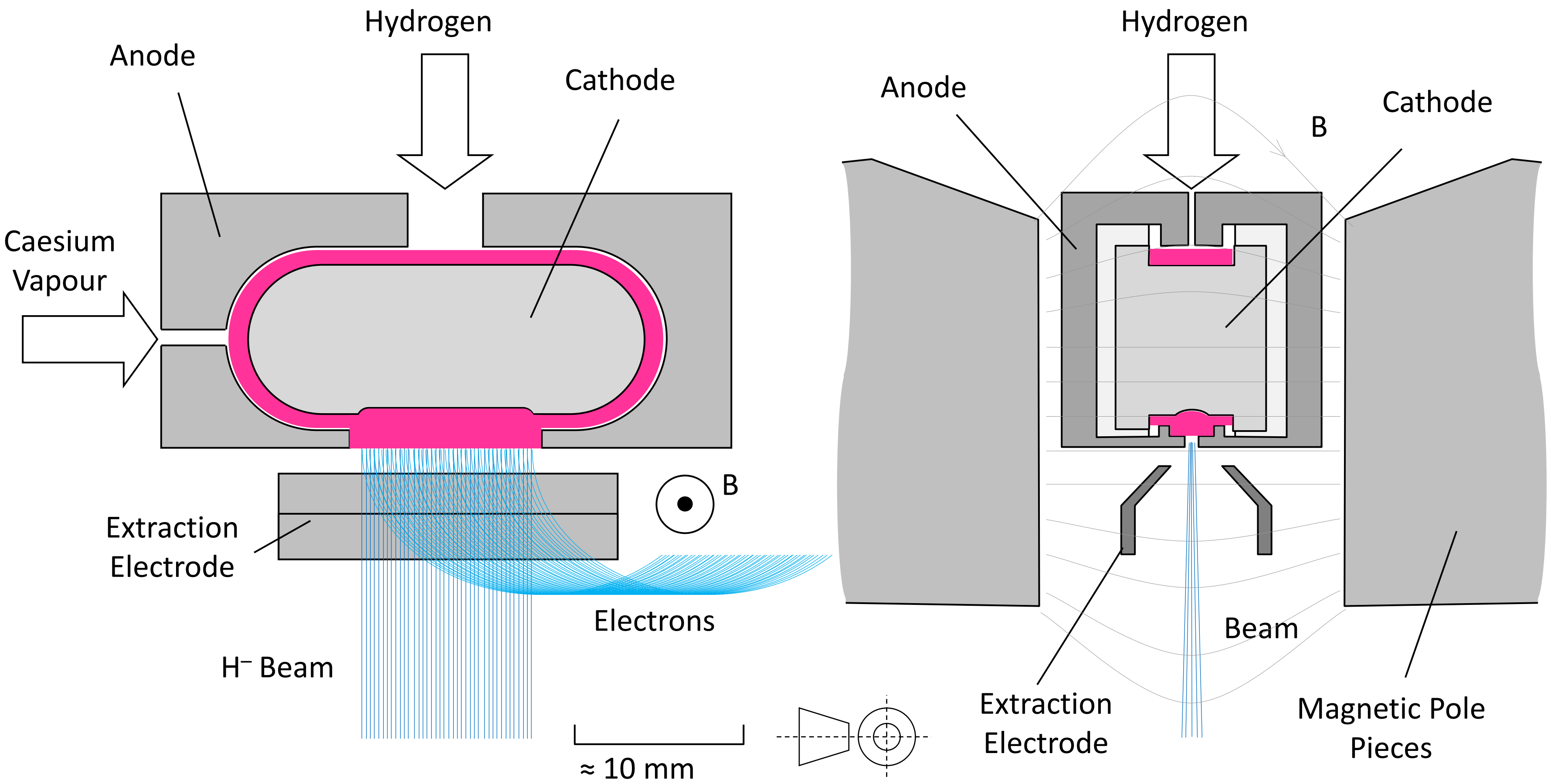


1970s Caesium Revolution!

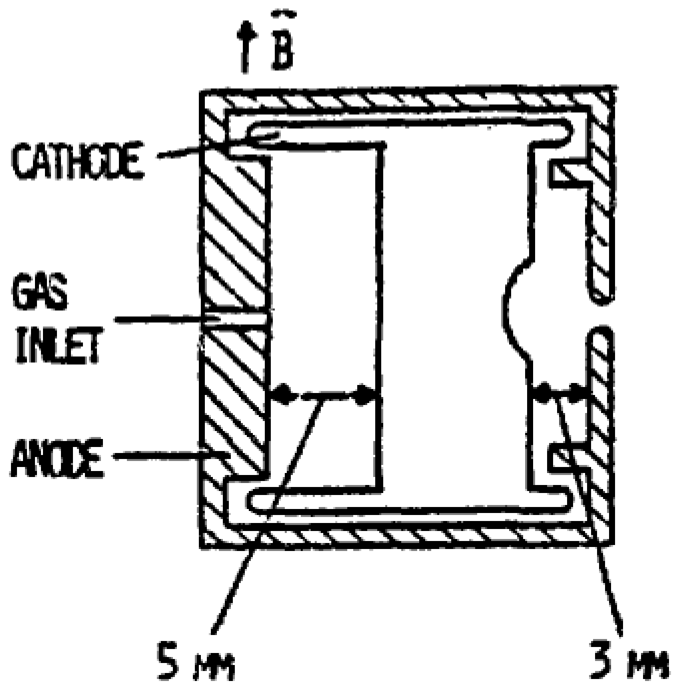


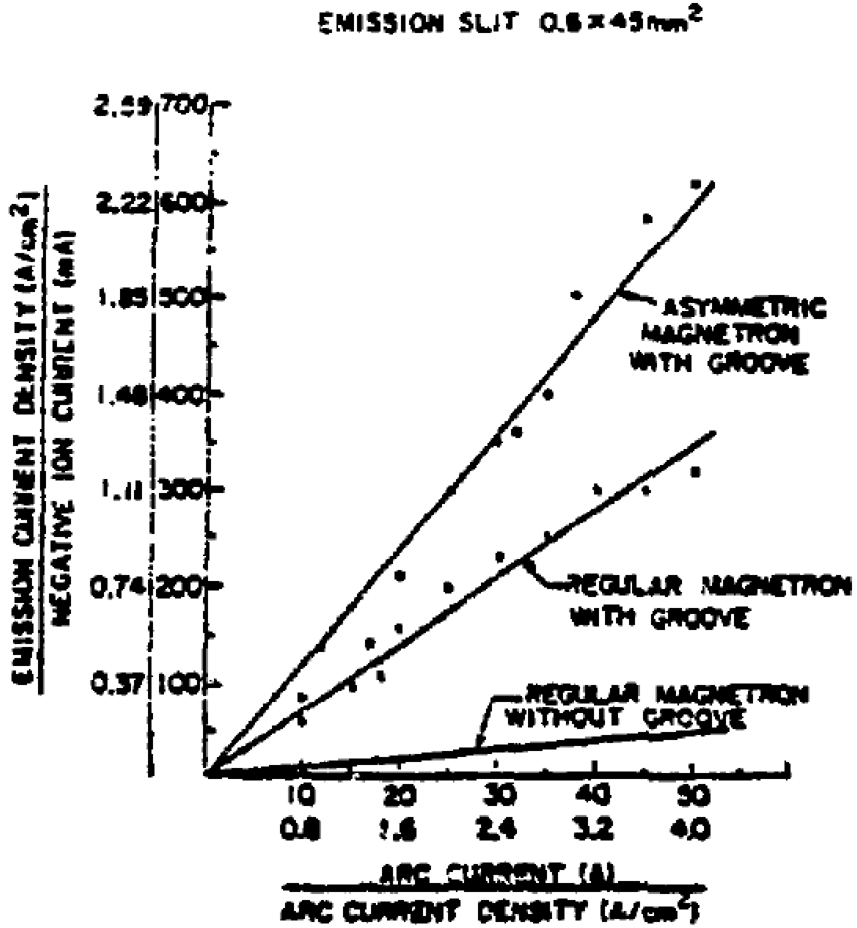
- BINP spreads the word and develops more sources
- BNL Krsto Prelec et al. develop the magnetron for NBI
- LANL Paul Allison et al. develop the Penning
- Berkley Ehlers+Leung develop Surface Converter sources
- Fermilab Chuck Schmidt et al. develop the BNL magnetron for accelerators

Magnetron SPS

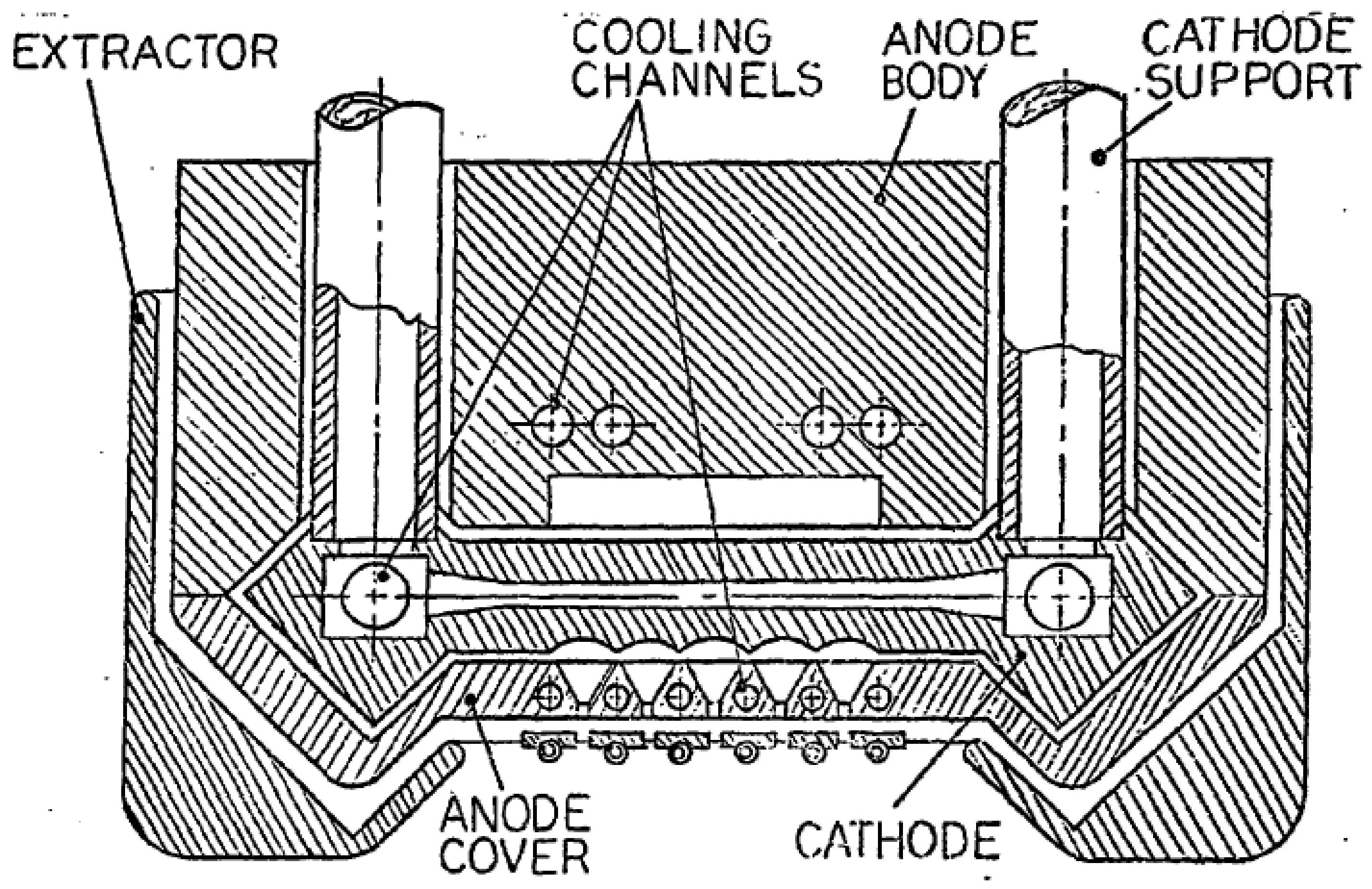


1980 BNL Developments

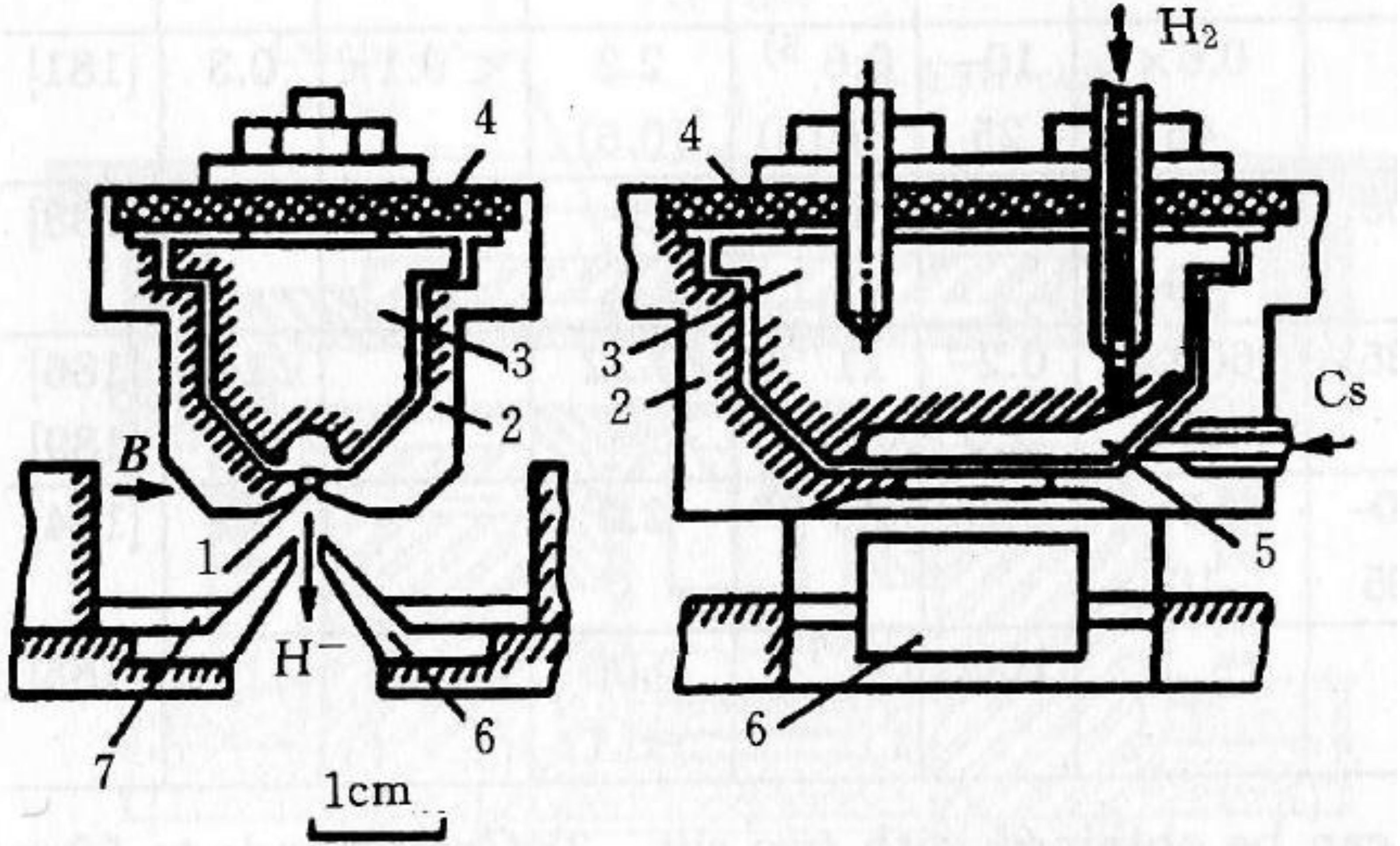




BNL 2 A Beam H^- Magnetron for NBI

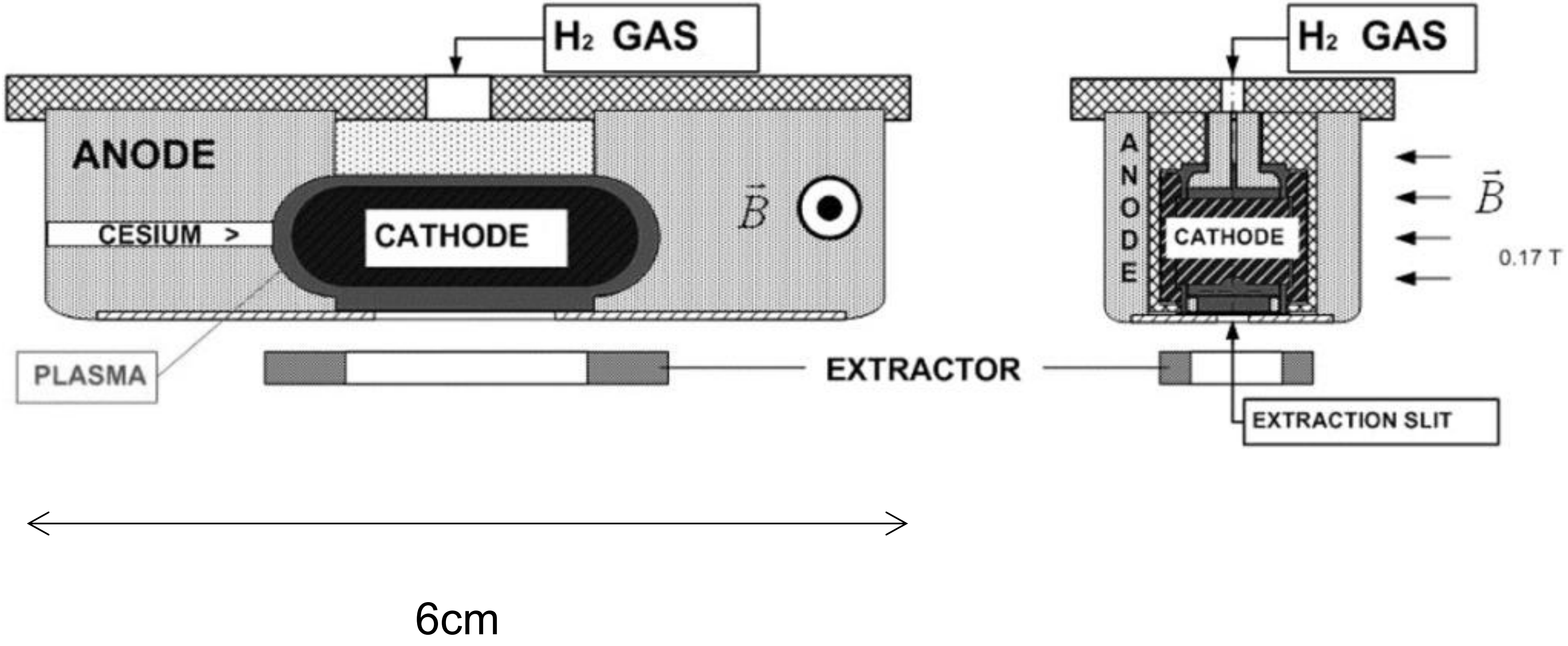


11 A Budker Semiplanotron

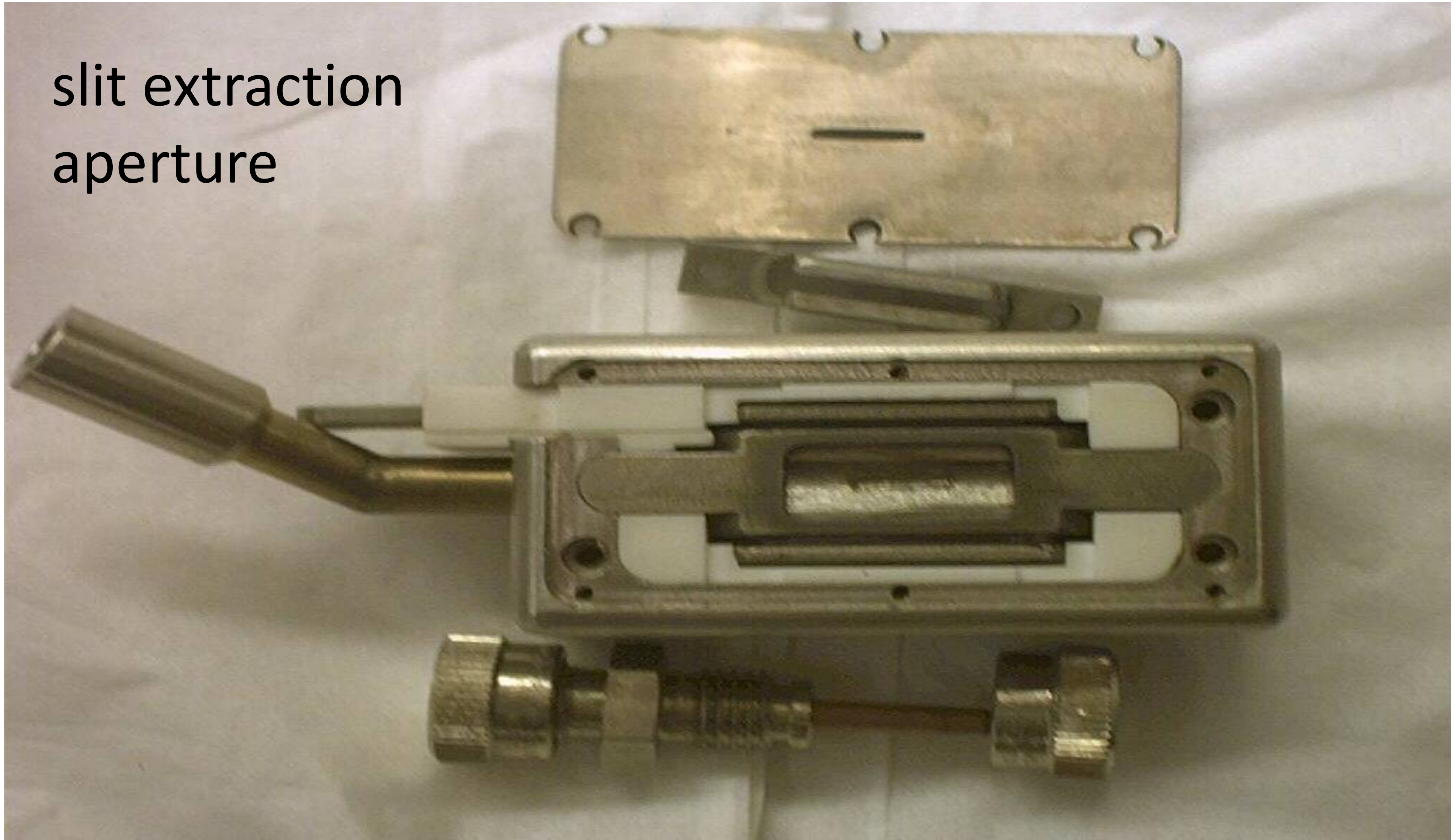


1—Emission slit, 2—Anode, 3—Cathode, 4—Insulator, 5—Cathode cavity, 6—Extracting electrode, 7—Iron inserts.

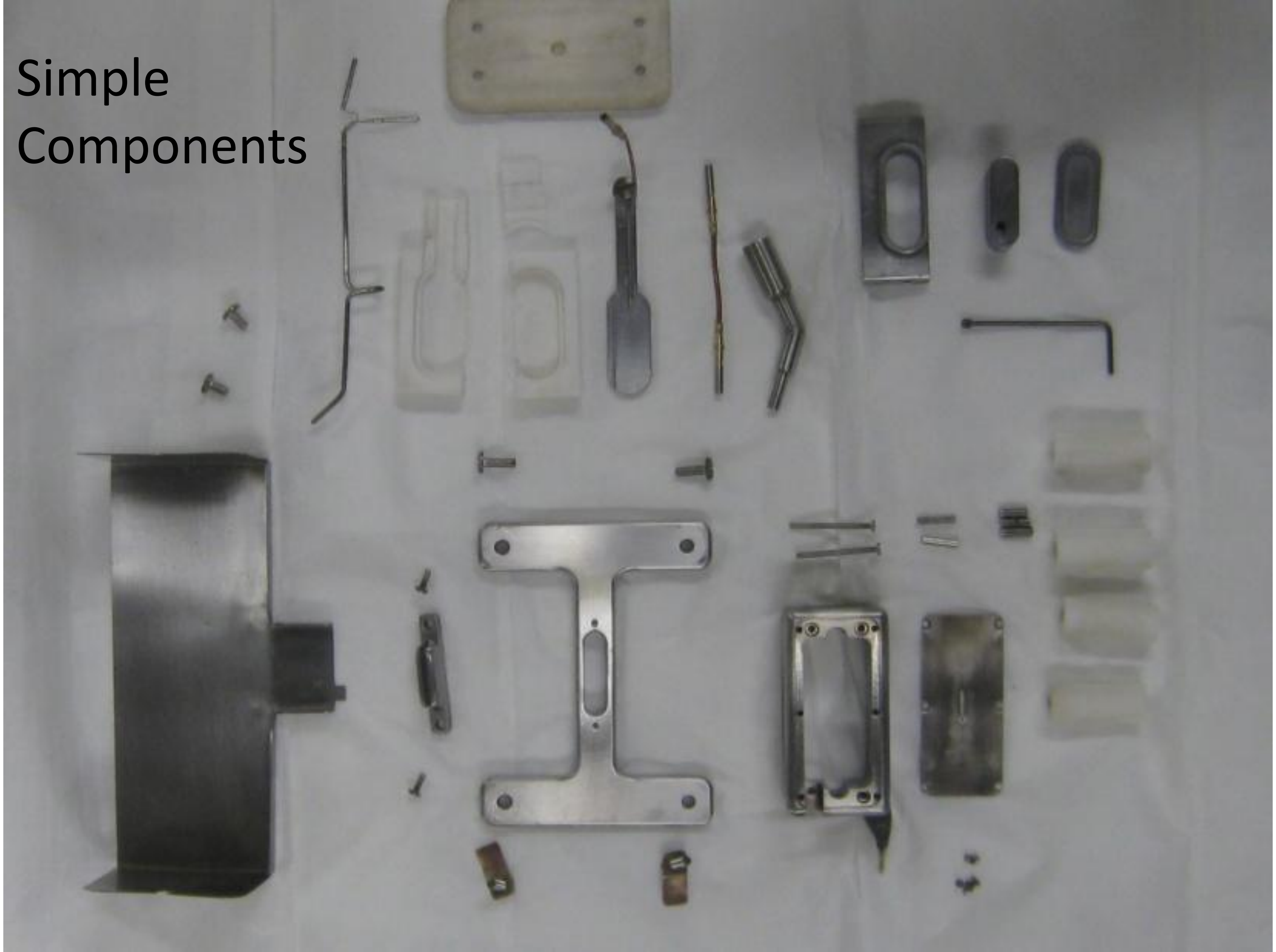
Late 1970s Fermilab Magnetron



Fermilab Magnetron

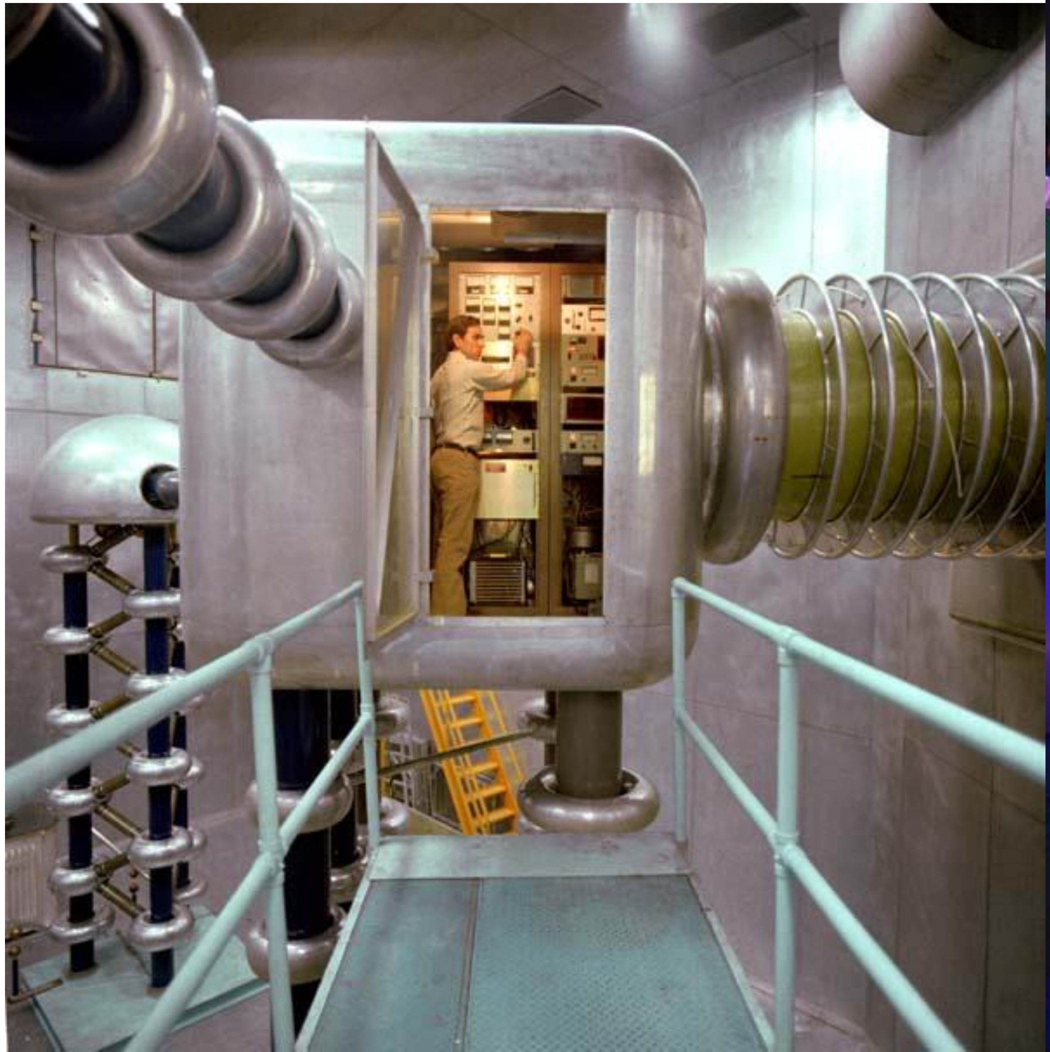


Simple Components



Fermilab Magnetron

750 kV Acceleration Column



Fermilab Magnetron

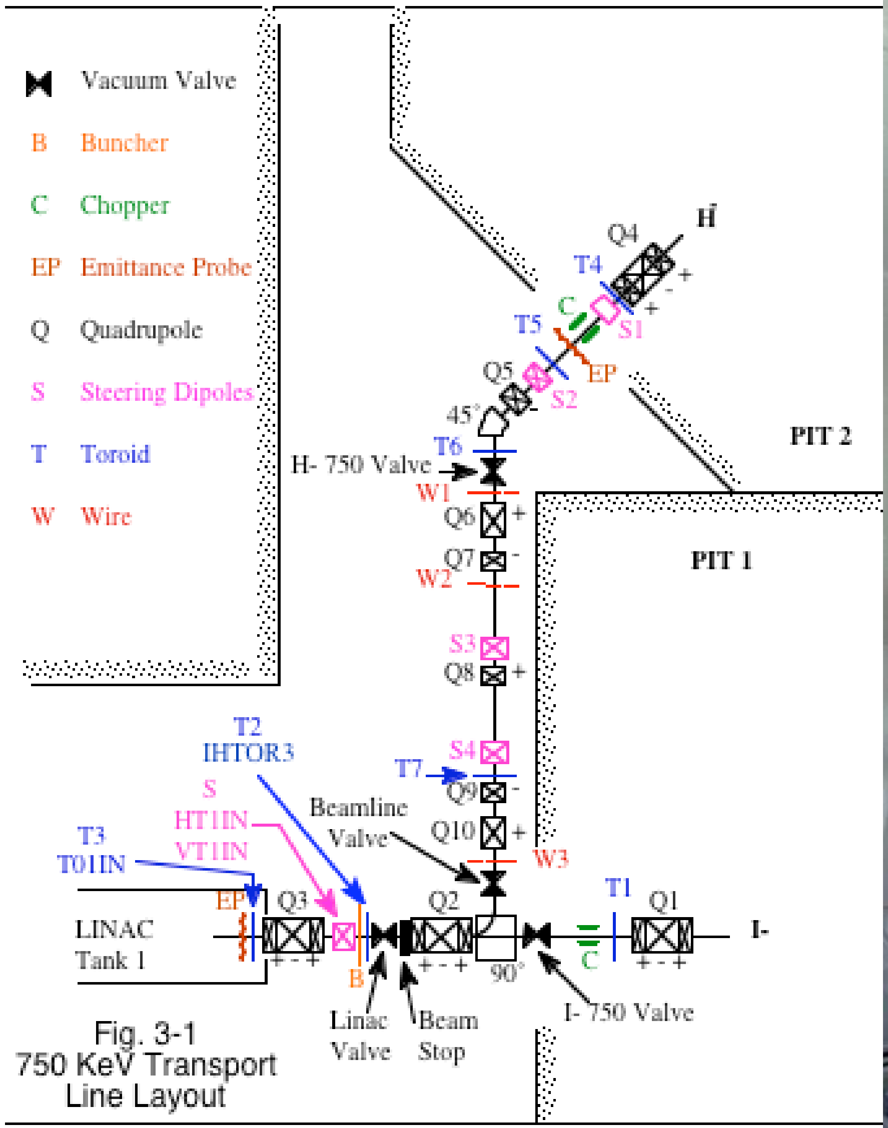
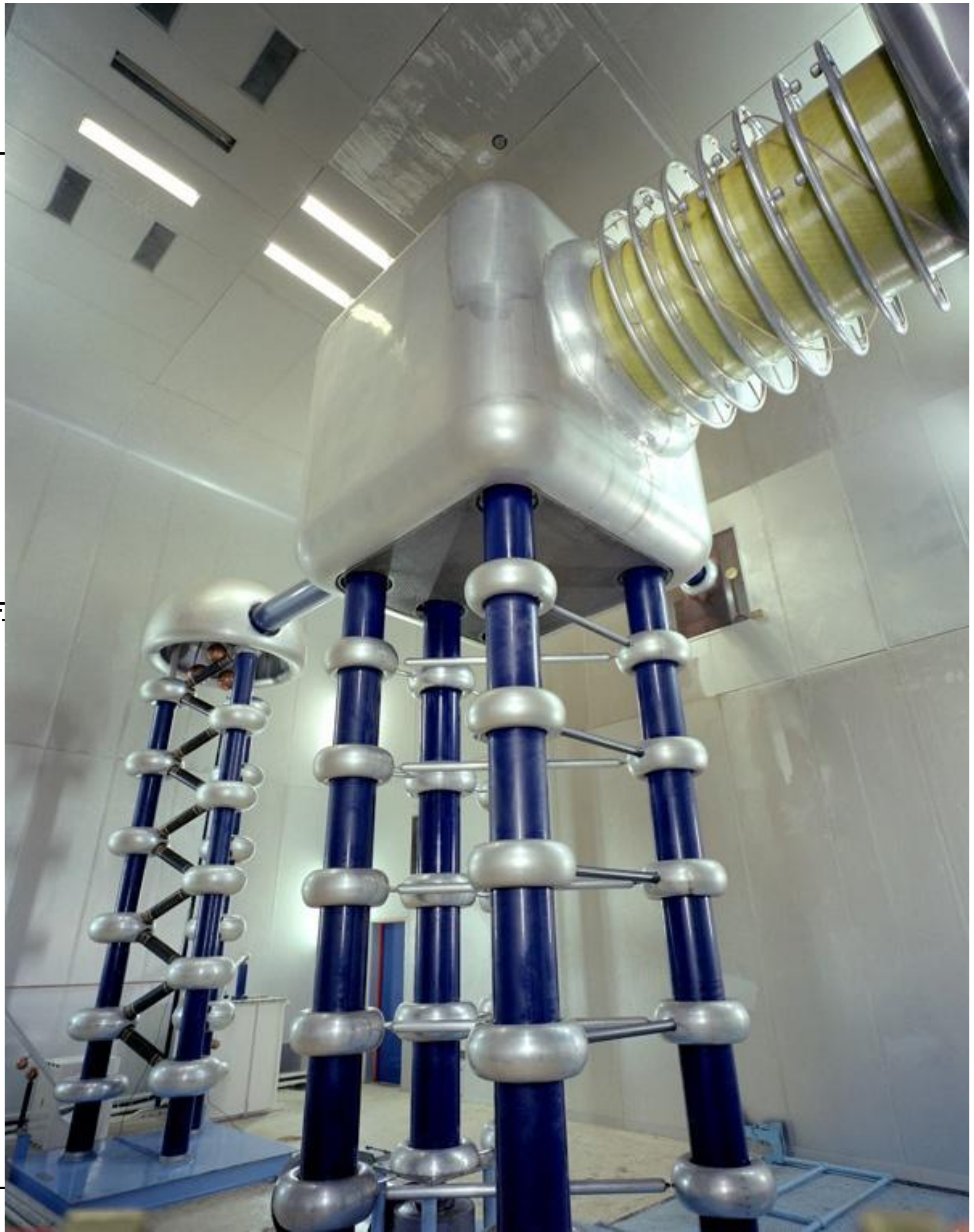
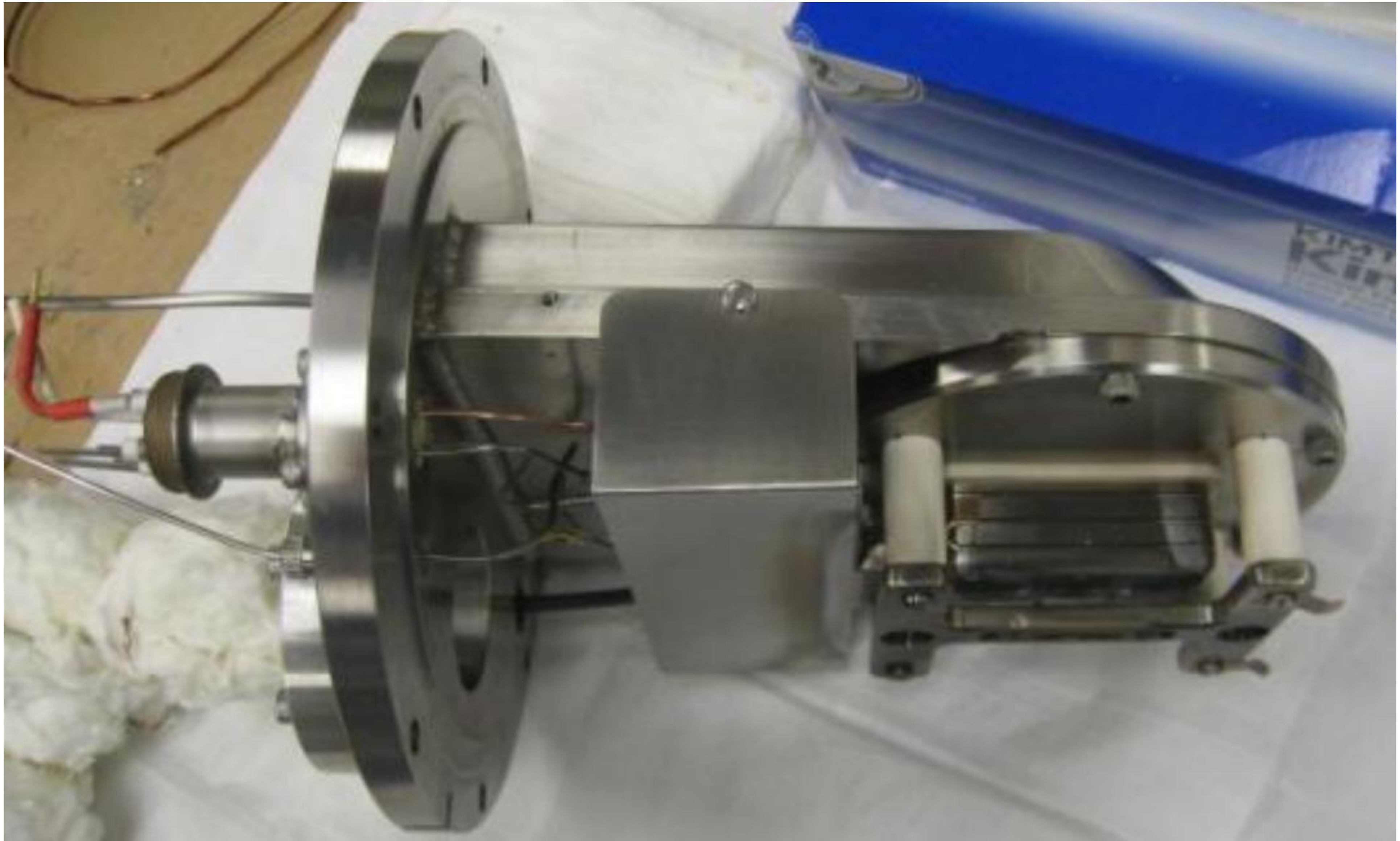


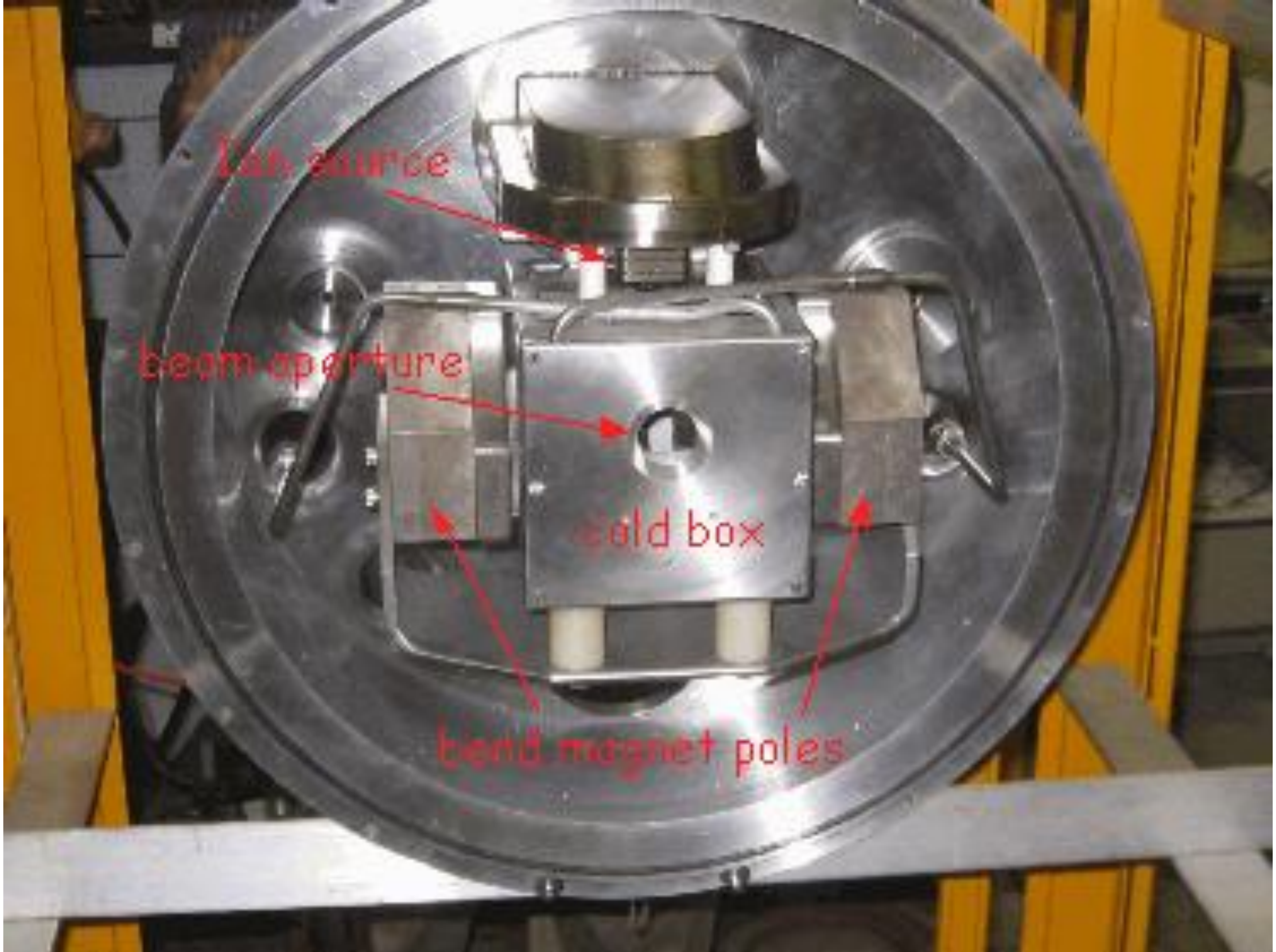
Fig. 3-1
750 KeV Transport
Line Layout

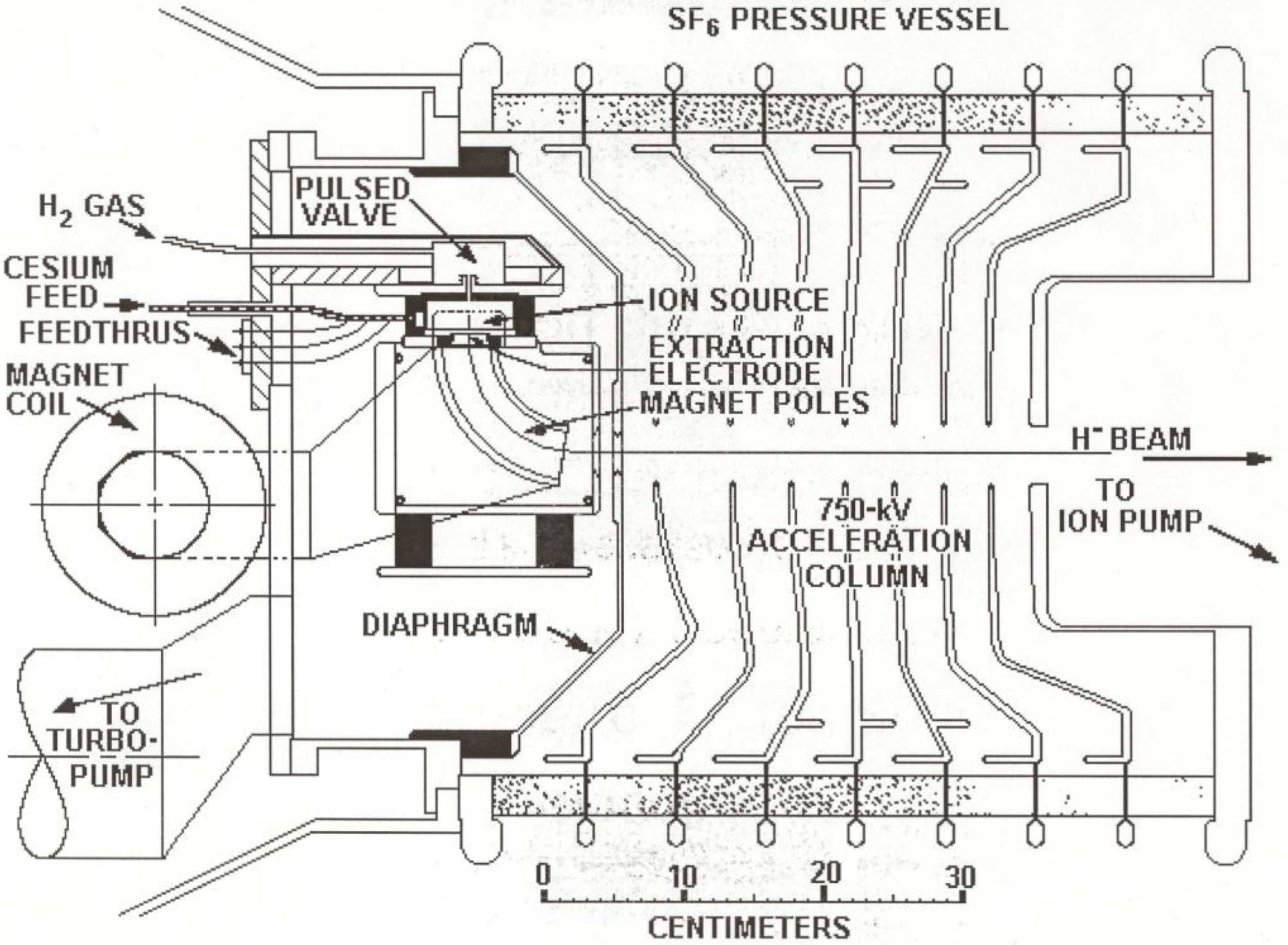


Fermilab Magnetron



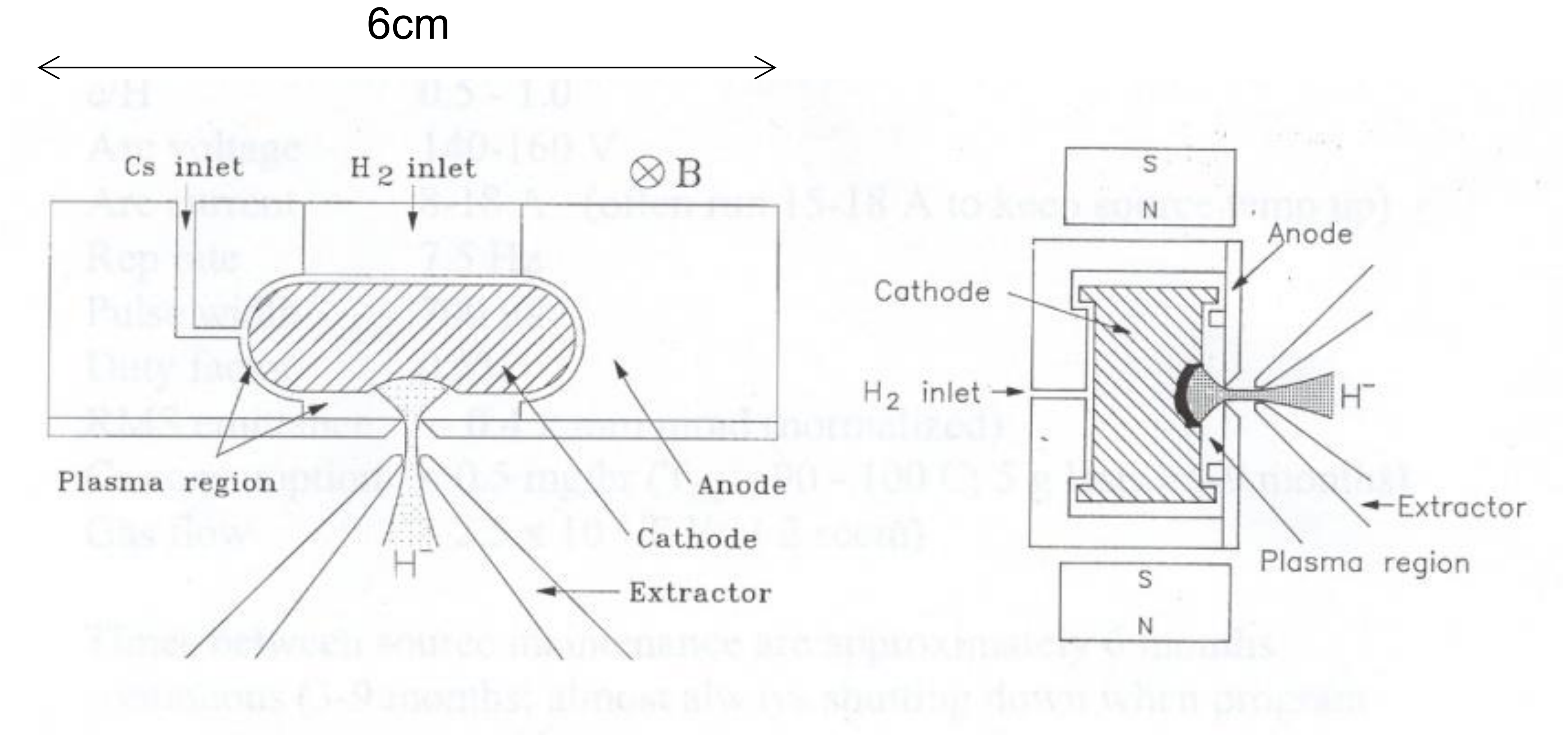
Caesium:
Friend of H^-
but
mortal enemy
of high voltage


beam aperture
cold box
bend magnet poles



H⁻ ION SOURCE ASSEMBLY

1989 BNL Magnetron

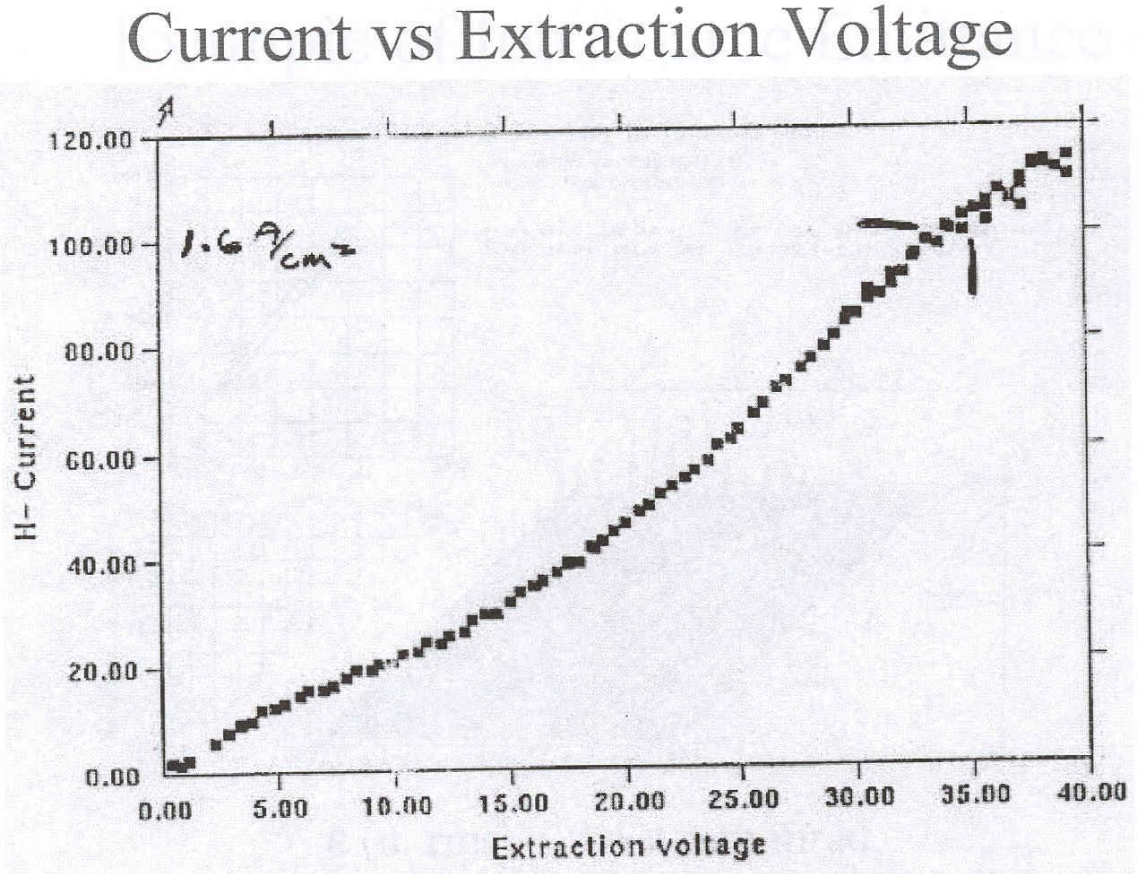


Circular Extraction Aperture

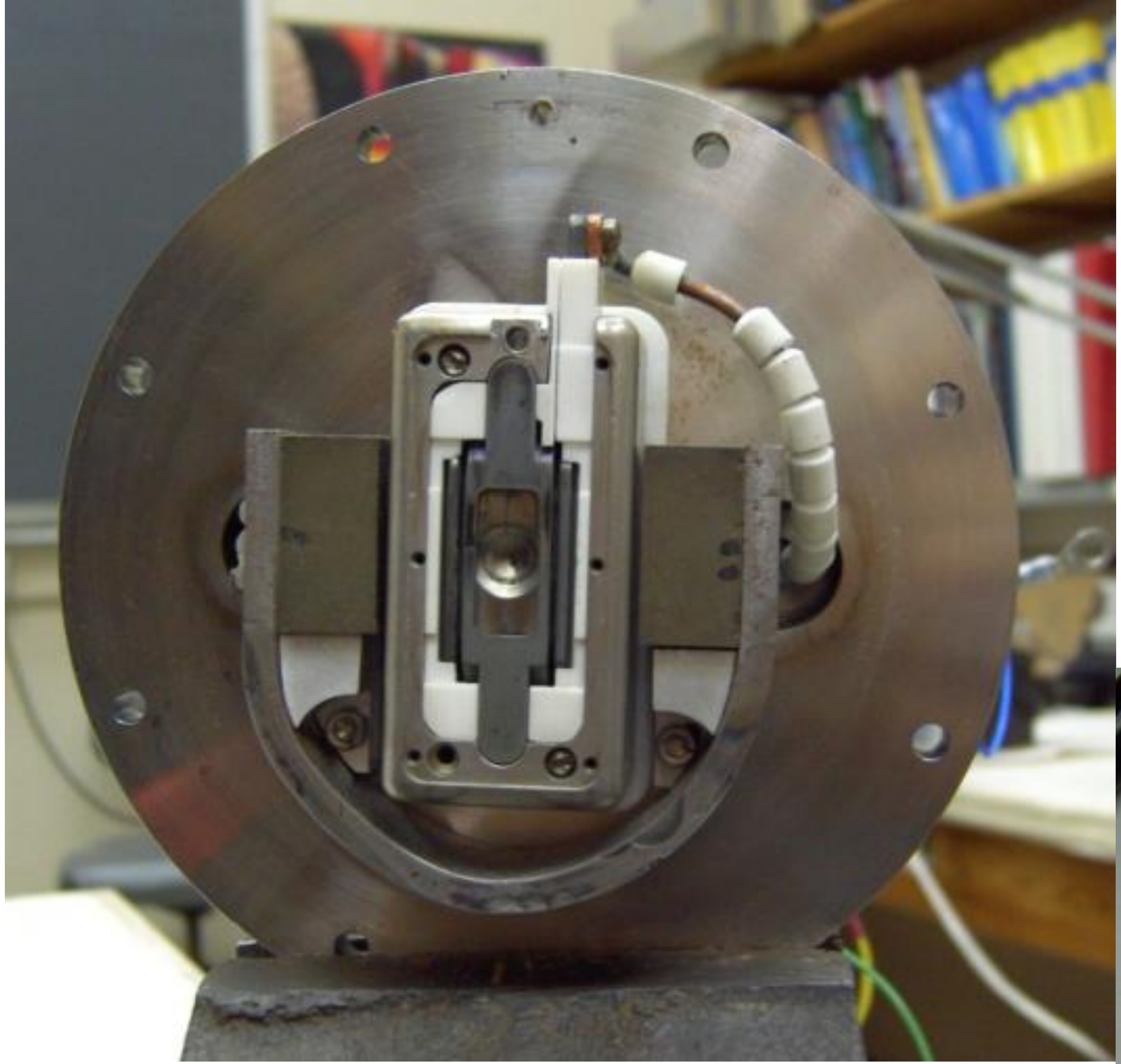
1989 BNL Magnetron

Lifetime, typically 9 months
Very good power efficiency ~ 67 mA/kW
High beam currents ~ 100 mA

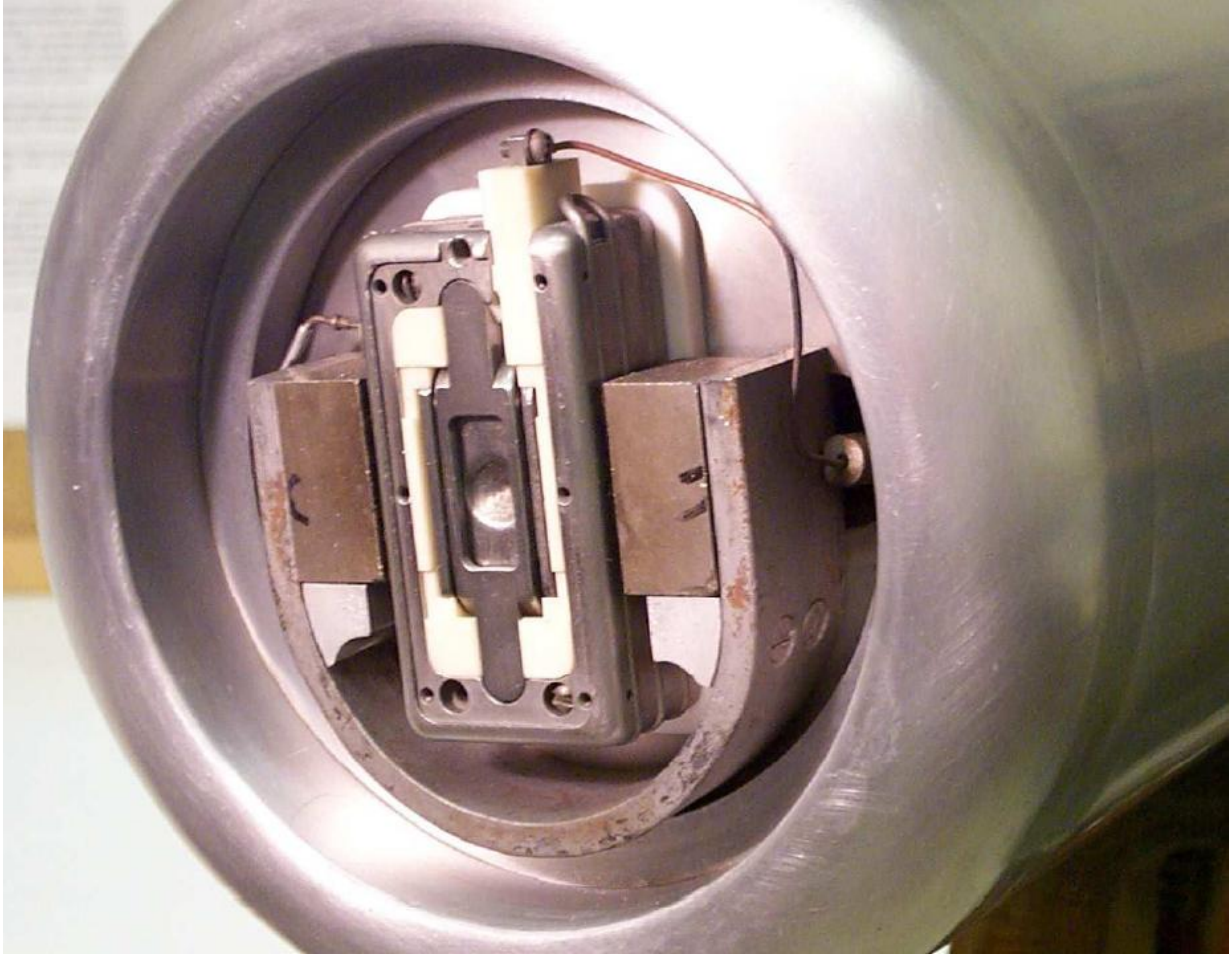
H- current	90-100 mA
Extraction Voltage	35 kV
Arc Voltage	140-160 V
Arc Current	8-18 A
Rep Rate	7.5 Hz
Pulse width	700 µs
Duty Factor	0.5%
Cs consumption	0.5 mg/hr
Gas Flow	3 sccm
RMS emittance	0.4 πmm.mrad (normalized)



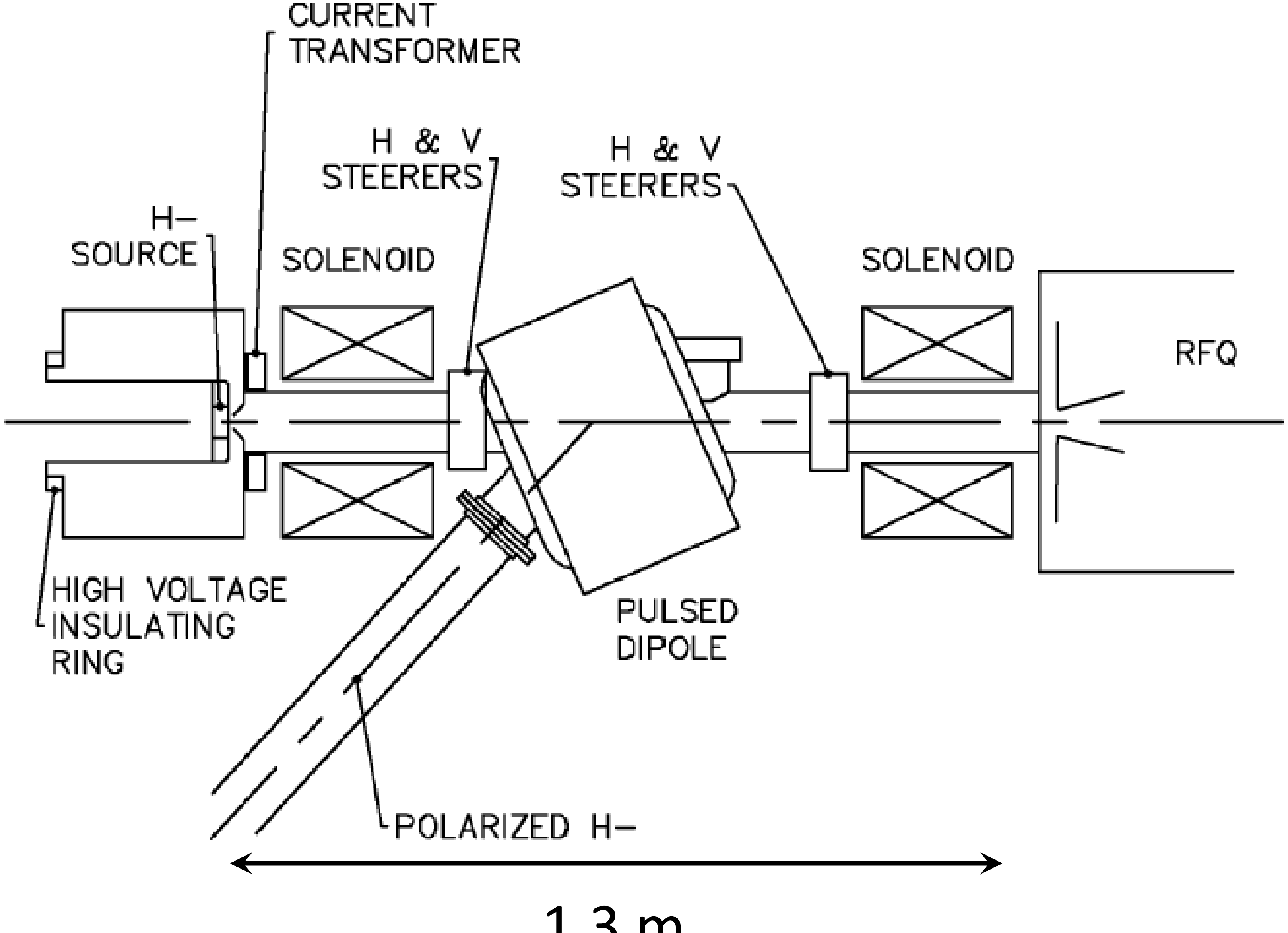
BNL Magnetron

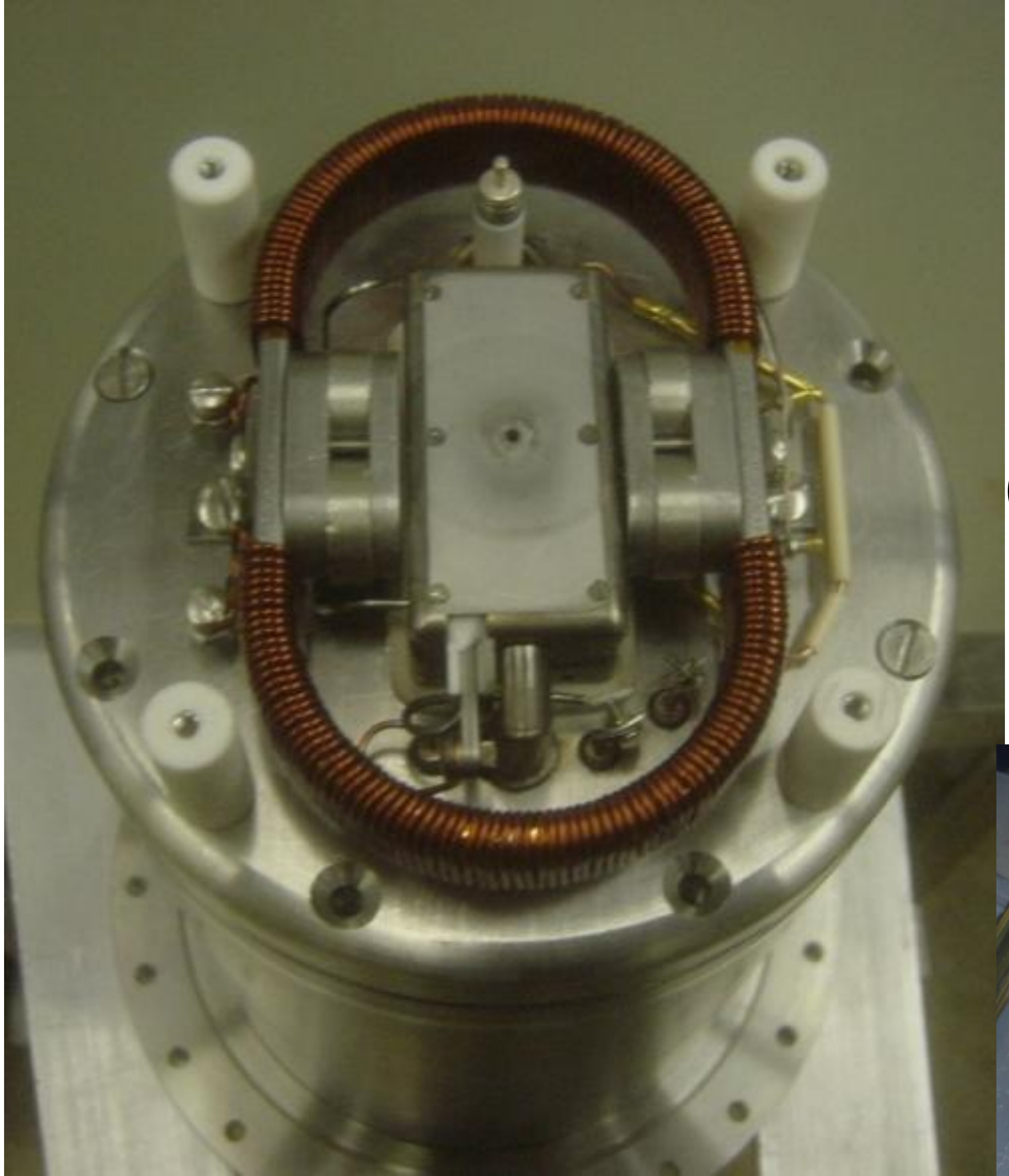


Extraction cone:
45deg angle
3.2 mm aperture



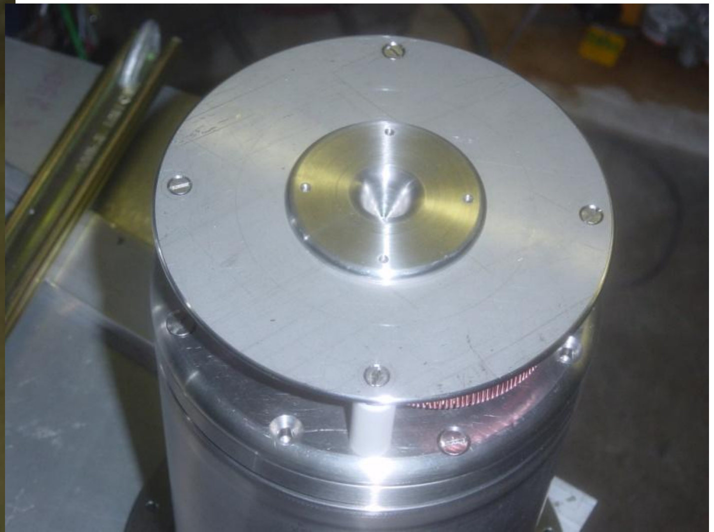
BNL Magnetron



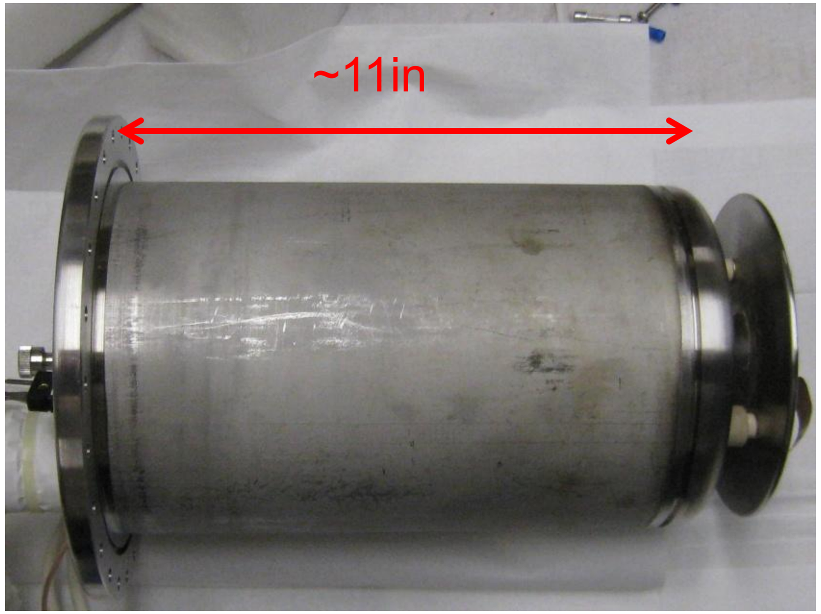


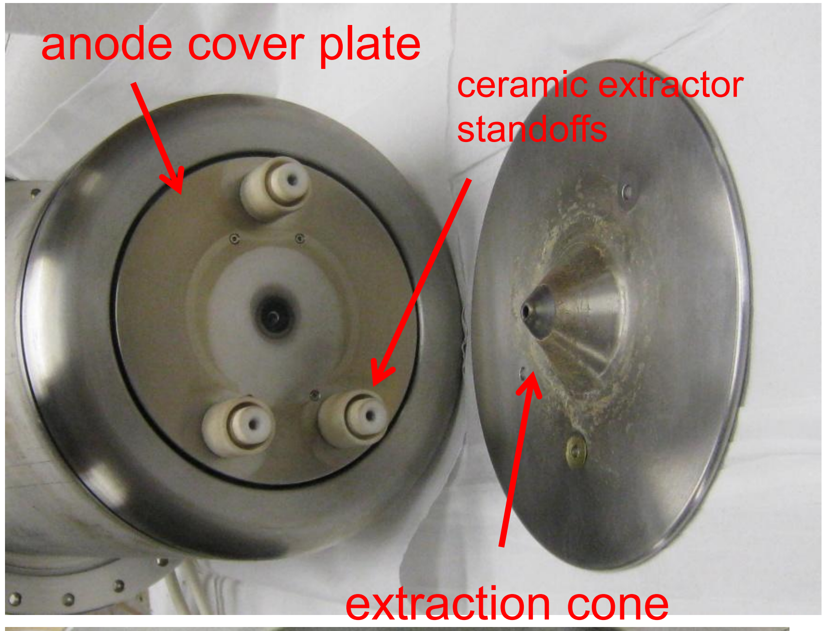
2012 Fermilab Magnetron

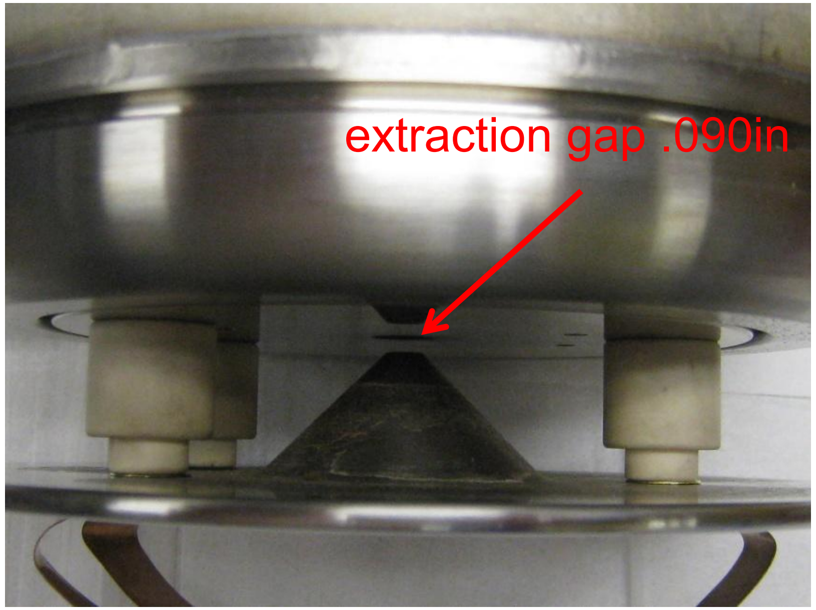
(Based on BNL design)

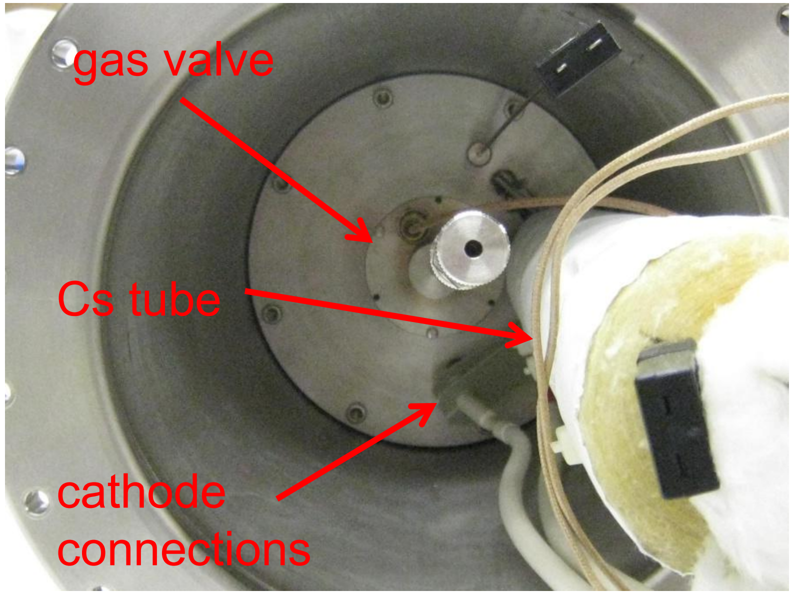


New Fermilab Magnetron



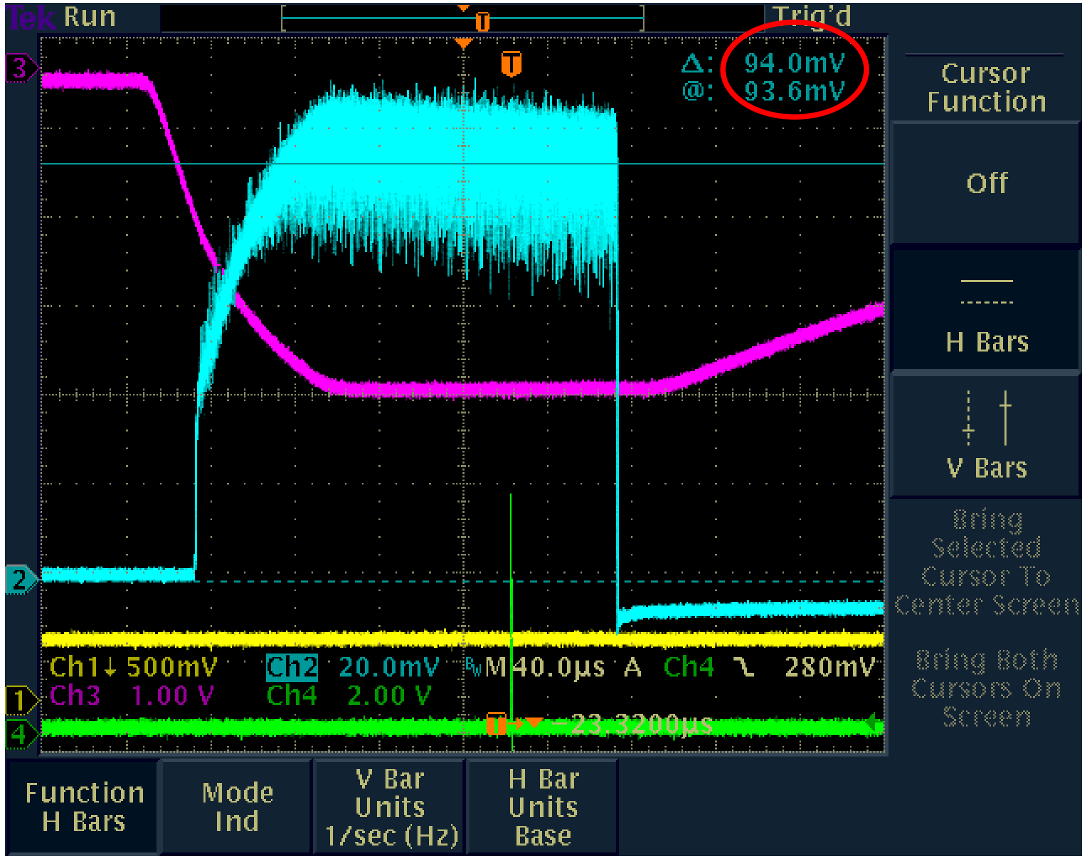






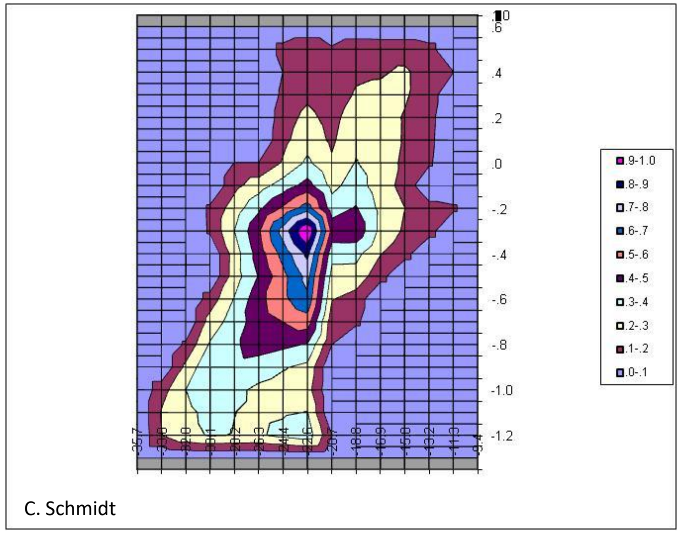
Fermilab HINS Magnetron

94 mA

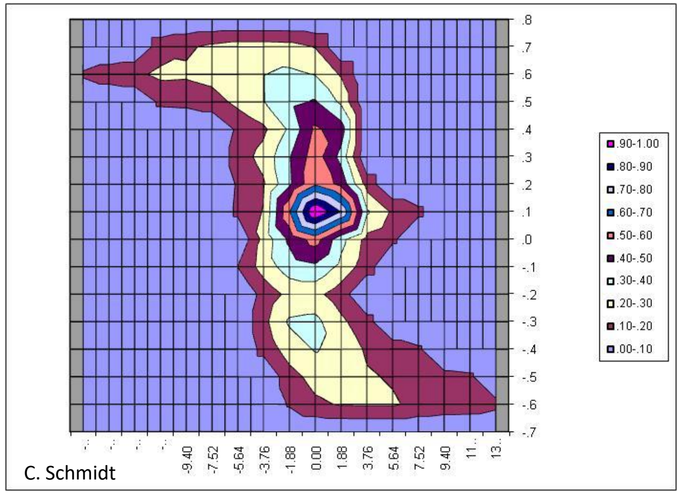


Magnetrons are noisy!

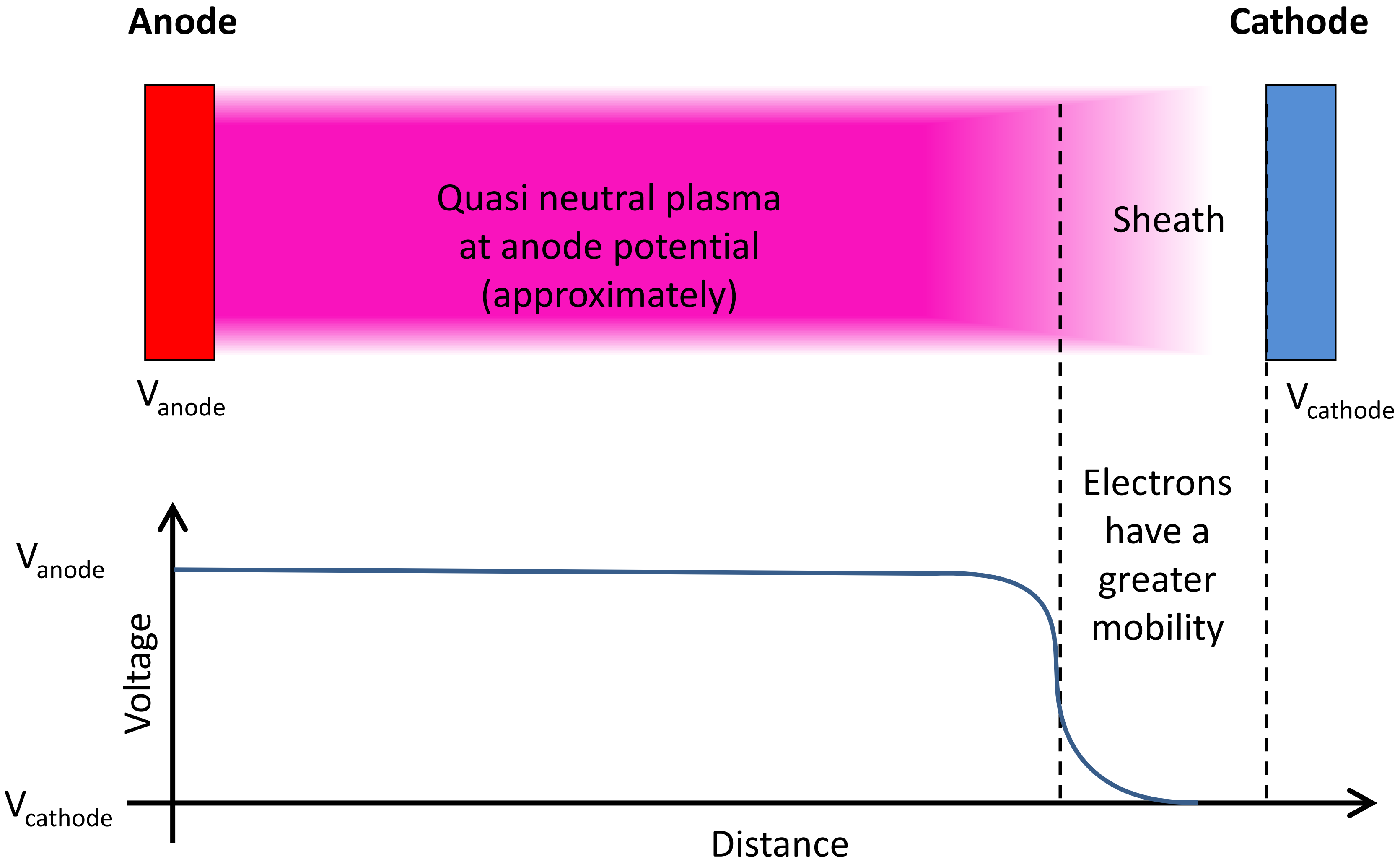
Vertical en rms = 0.18 mm.mRad

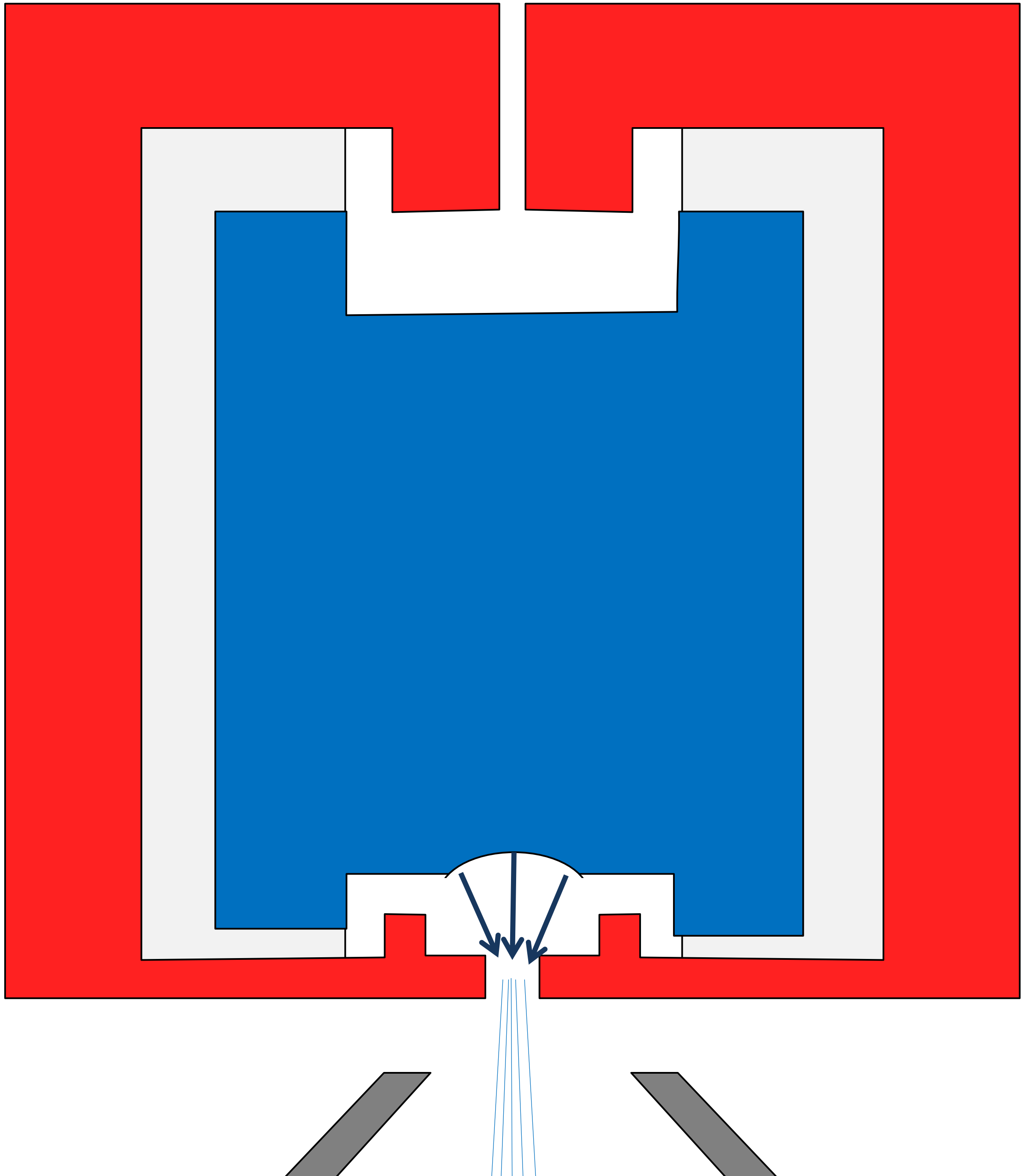


Horizontal en rms = 0.12 mm.mRad



Cathode Sheath





Magnetron Source

H^- produced on the cathode surface are accelerated by the cathode plasma sheath towards the extraction aperture

Resonant Charge Exchange

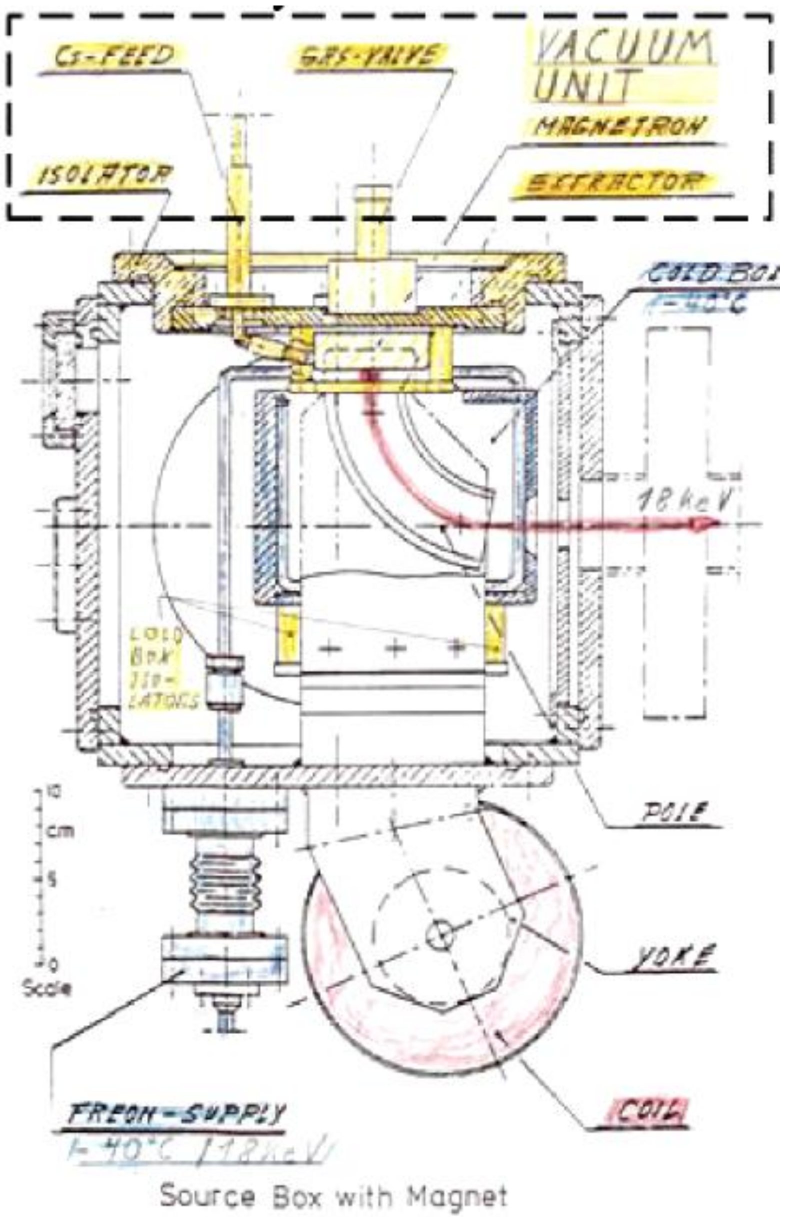
Leaving slow H^-

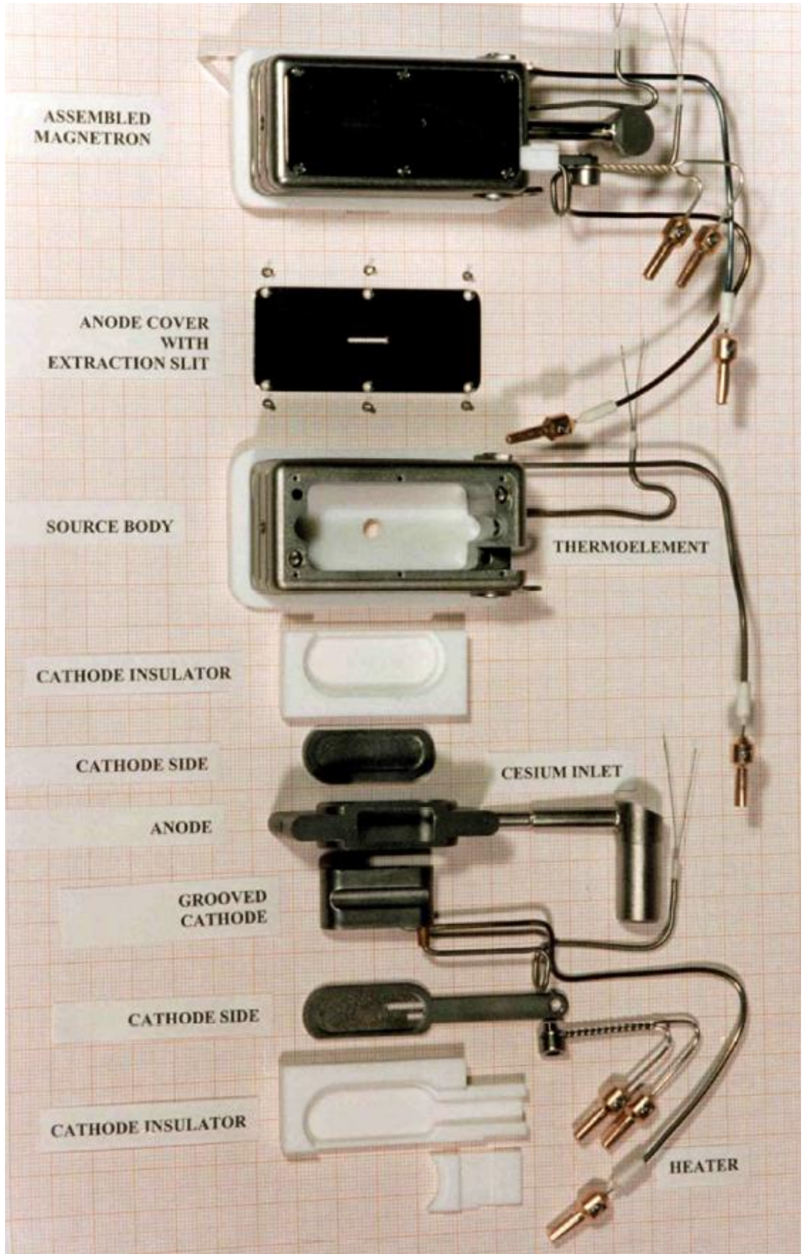
$$H^-_{(fast)} + H^0_{(slow)} \rightarrow H^0_{(fast)} + H^-_{(slow)}$$

Slow thermal H^0 produced in the plasma (≈ 0.1 eV)

Can undergo resonant charge exchange with fast H^- (≈ 80 eV) produced at the cathode surfaces

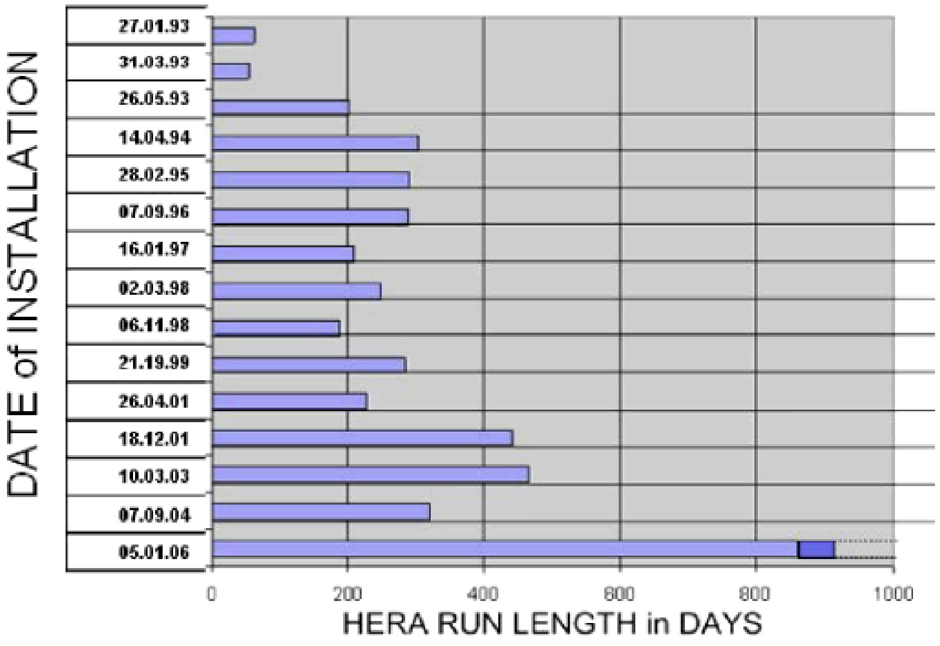
DESY HERA Magnetron Source





DESY HERA Magnetron Source

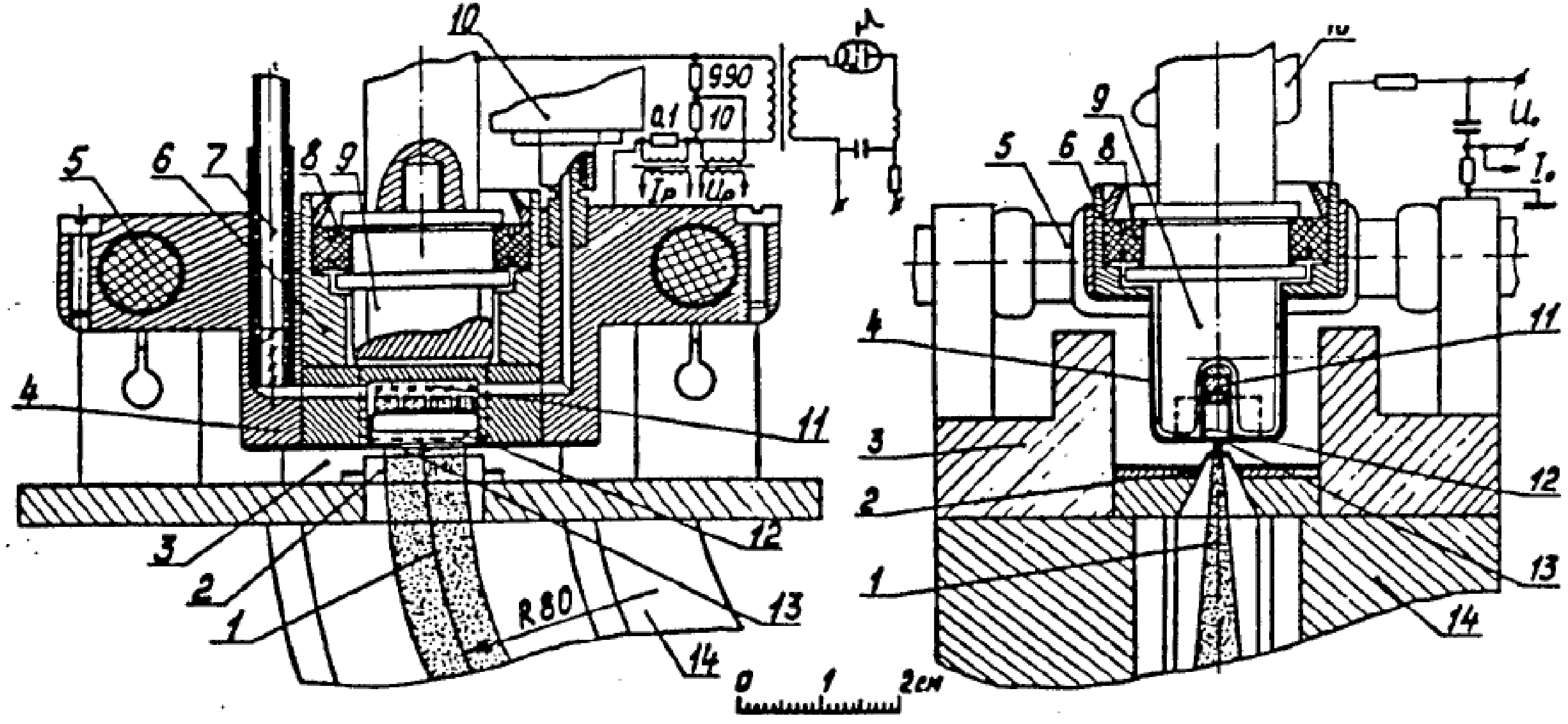
beam energy	18 keV	arc voltage	140 V
H^- beam current	60 mA	arc current	47 A
emittance		arc pulse width	75 μsec
$\varepsilon_{x\ rms,norm}$ ($\varepsilon_{x\ 90\%,norm}$) (35mA beam)	0.28(1.35) π mm mrad	extraction repetition rate	1/4 Hz -1Hz
$\varepsilon_{y\ rms,norm}$ ($\varepsilon_{y\ 90\%,norm}$) (35mA beam)	0.25(0.81) π mm mrad	magnetron repetition rate	1/4 Hz / 6.25 Hz
cathode temperature	249 °C	Cs boiler temperature	70 °C
anode temperature	147 °C	Cs consumption	3mg /day-0.5mg/day
		6 Hz magnetron repetition	



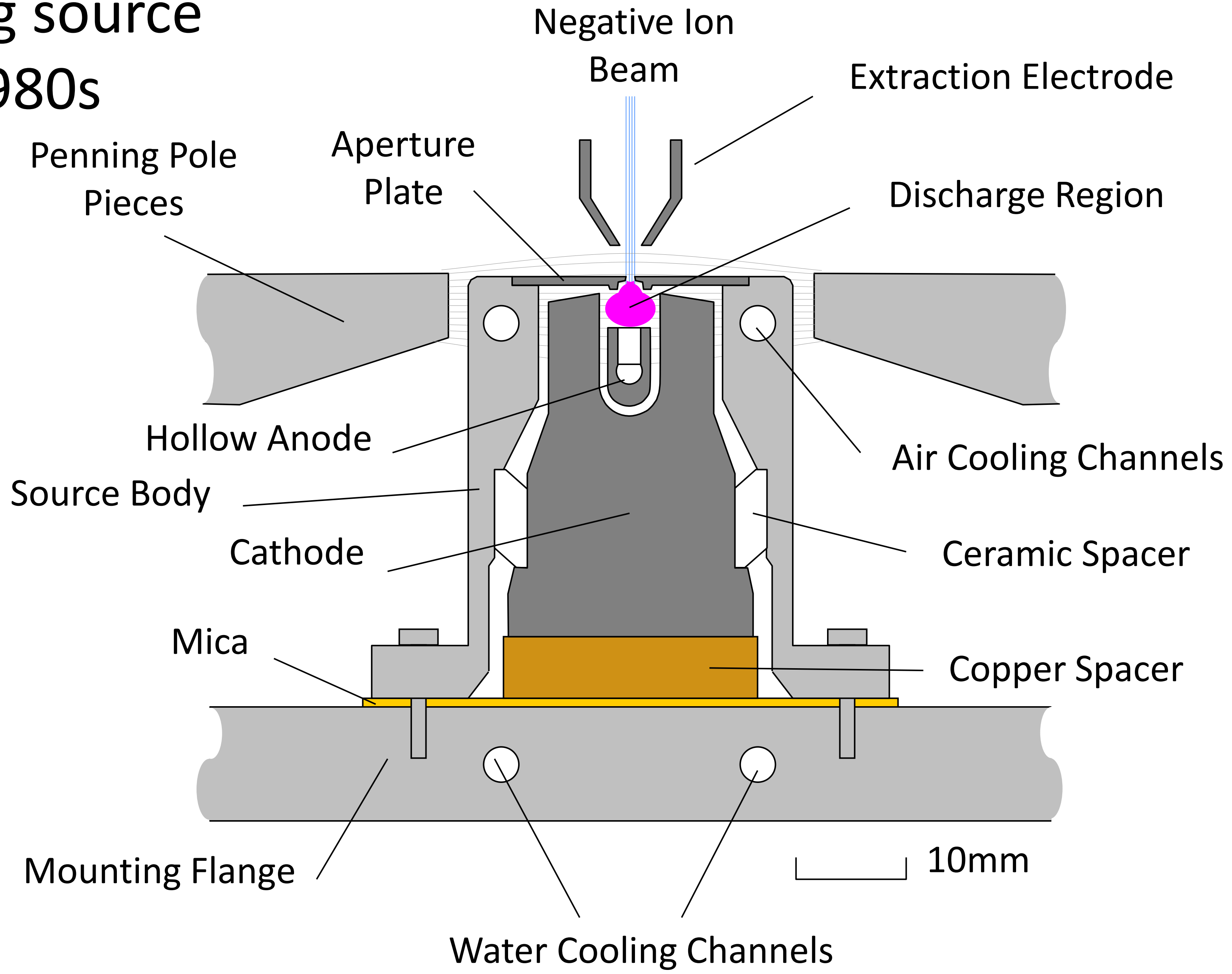
Almost Three Years!

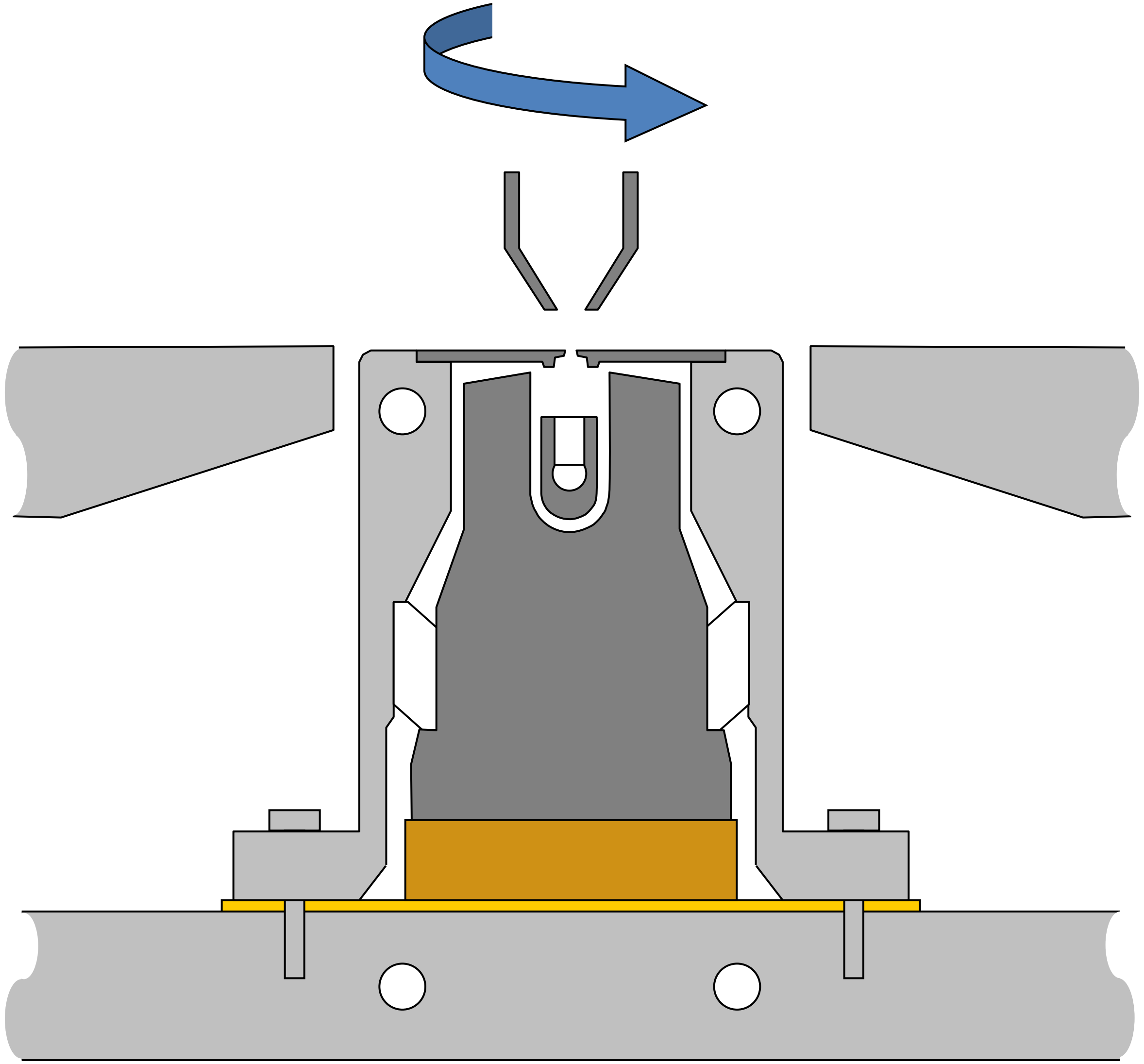
Penning SPS Ion Sources

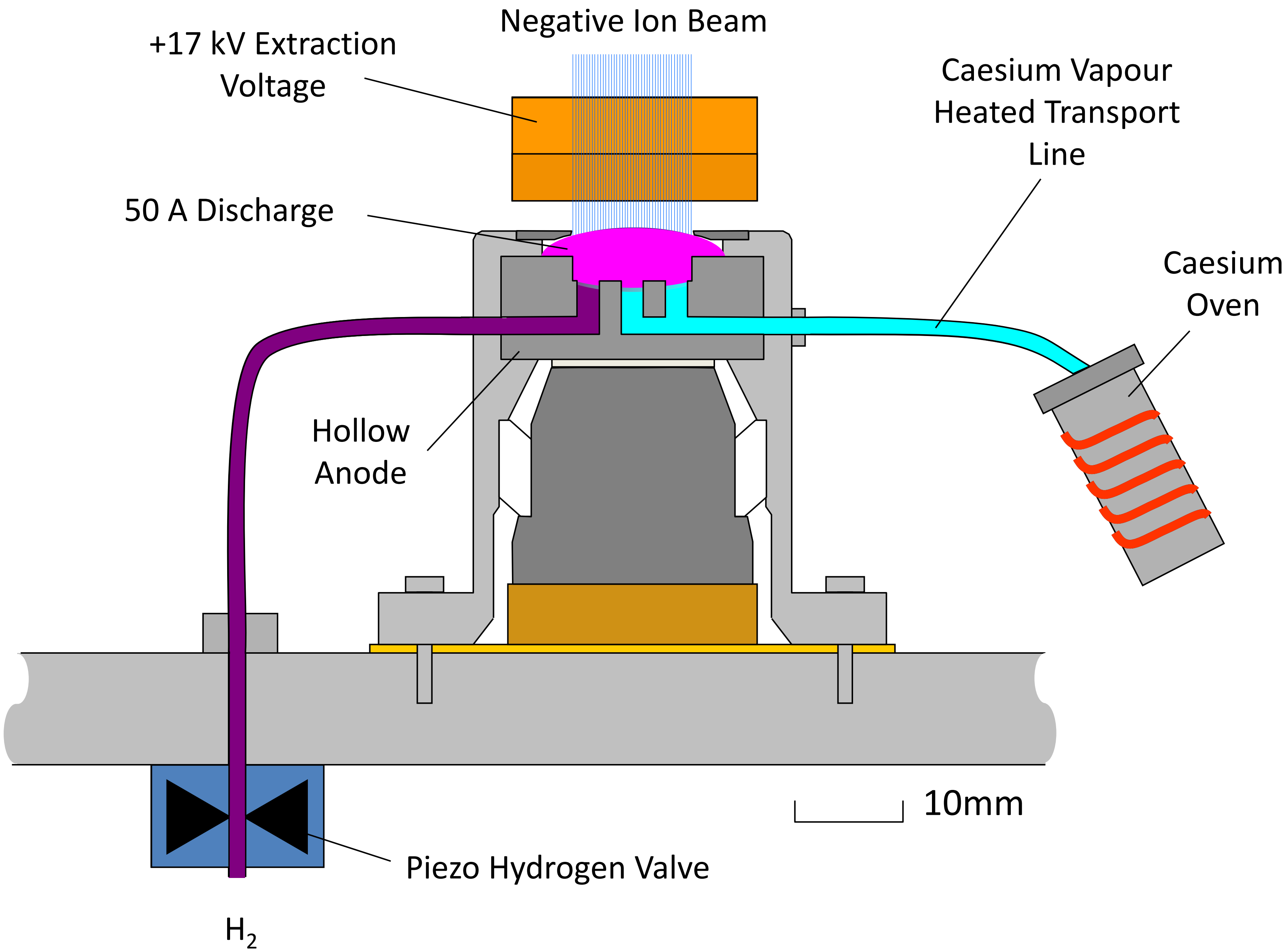
- Invented by Dudnikov in the 1970's
- Low noise

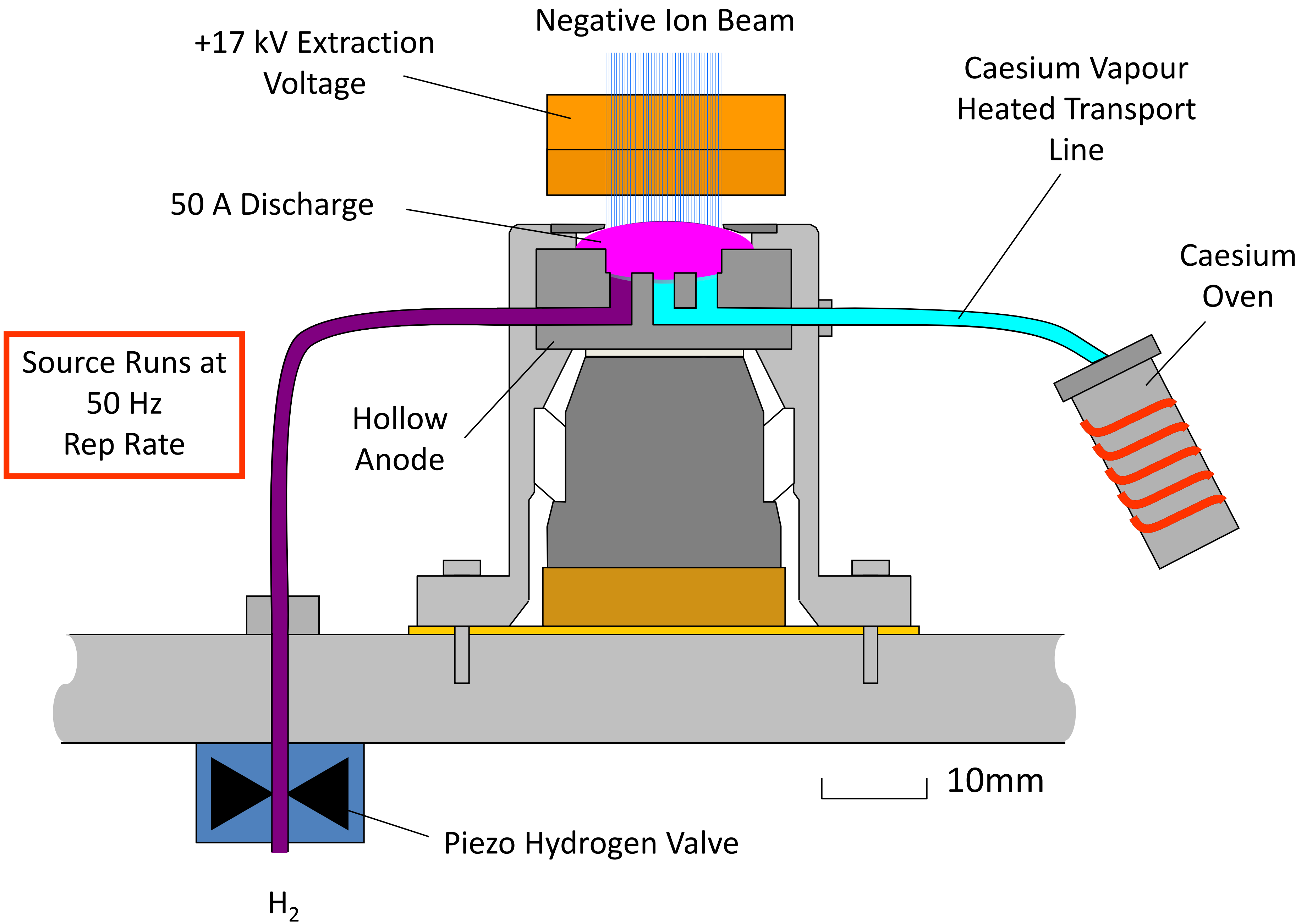


ISIS Penning source early 1980s

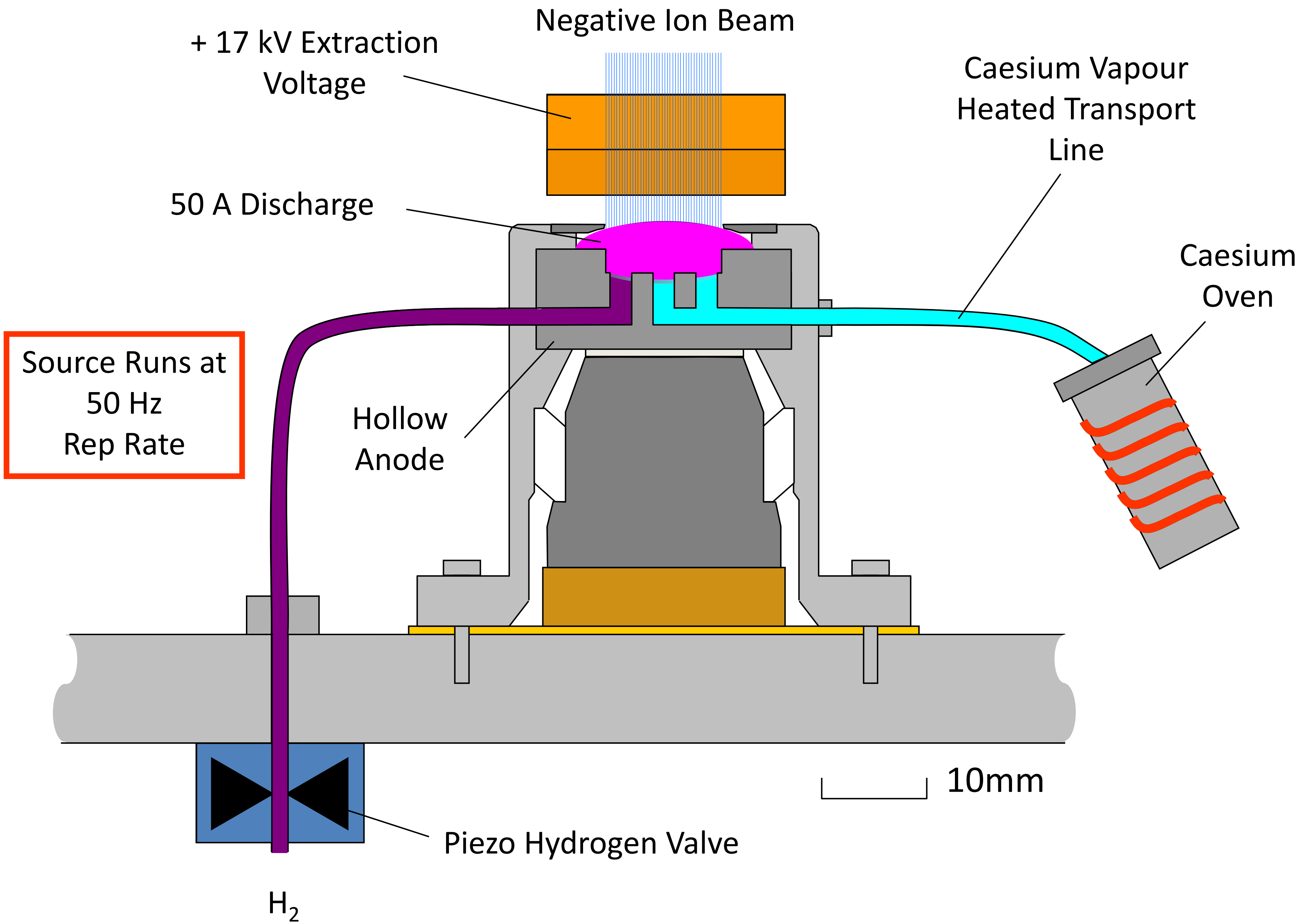





Negative Ion Beam
+17 kV Extraction Voltage
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Hollow Anode
10mm
Piezo Hydrogen Valve
H_2

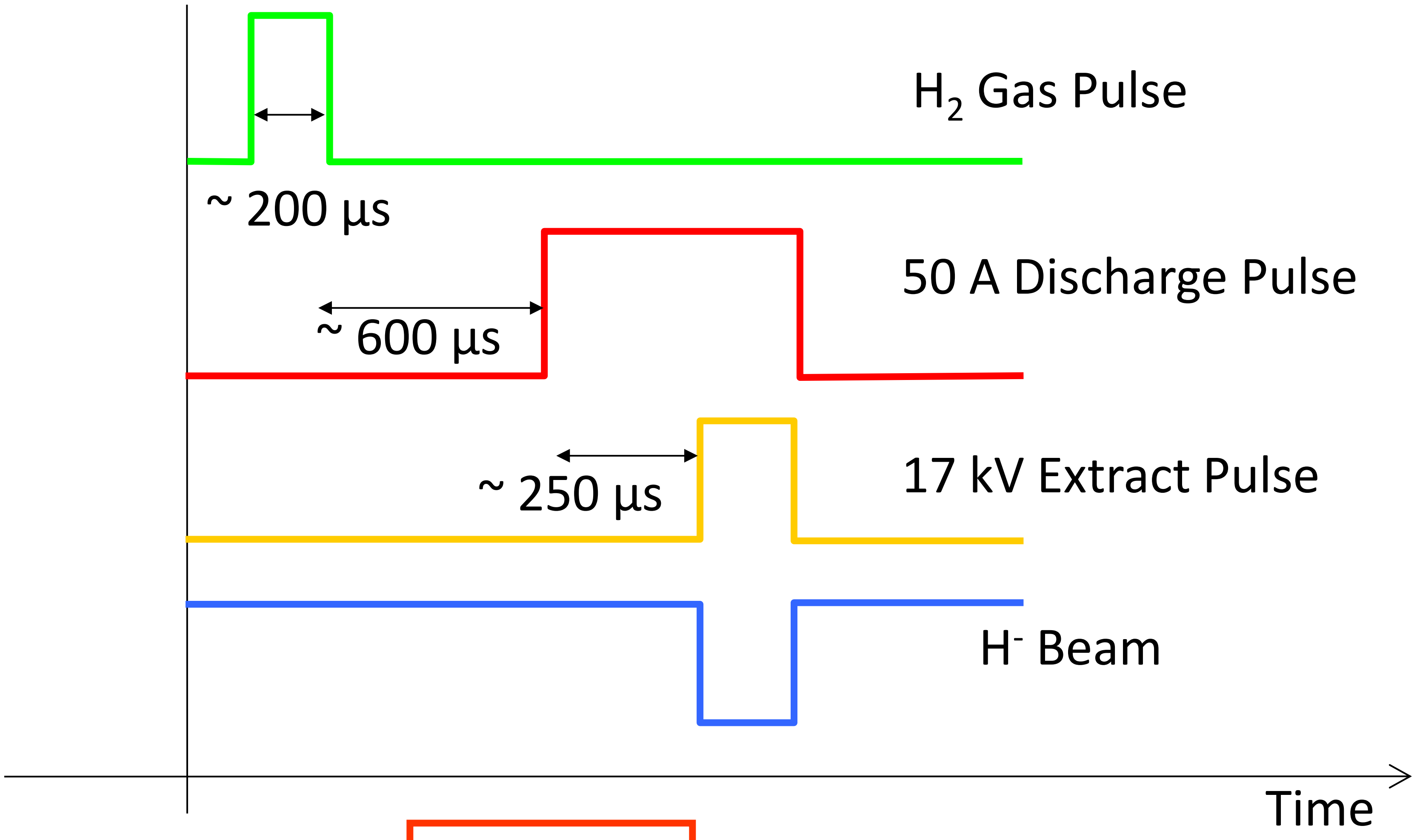


Negative Ion Beam
+17 kV Extraction
Voltage
Caesium Vapour
Heated Transport
Line
50 A Discharge
Caesium
Oven
Source Runs at
50 Hz
Rep Rate
Hollow
Anode
10mm
Piezo Hydrogen Valve
H_2

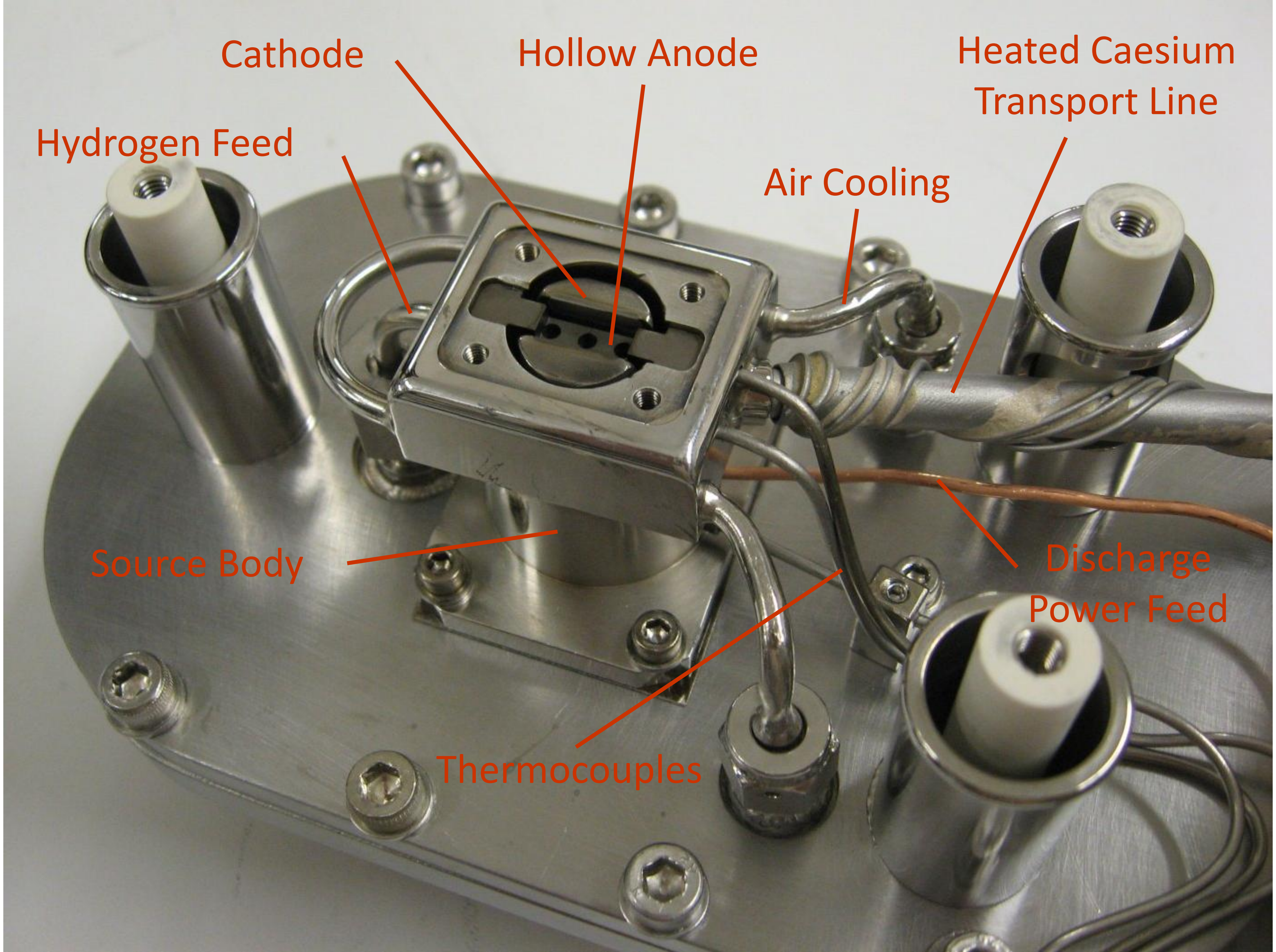


Negative Ion Beam
+ 17 kV Extraction Voltage
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Source Runs at 50 Hz Rep Rate
Hollow Anode
10mm
Piezo Hydrogen Valve
H2

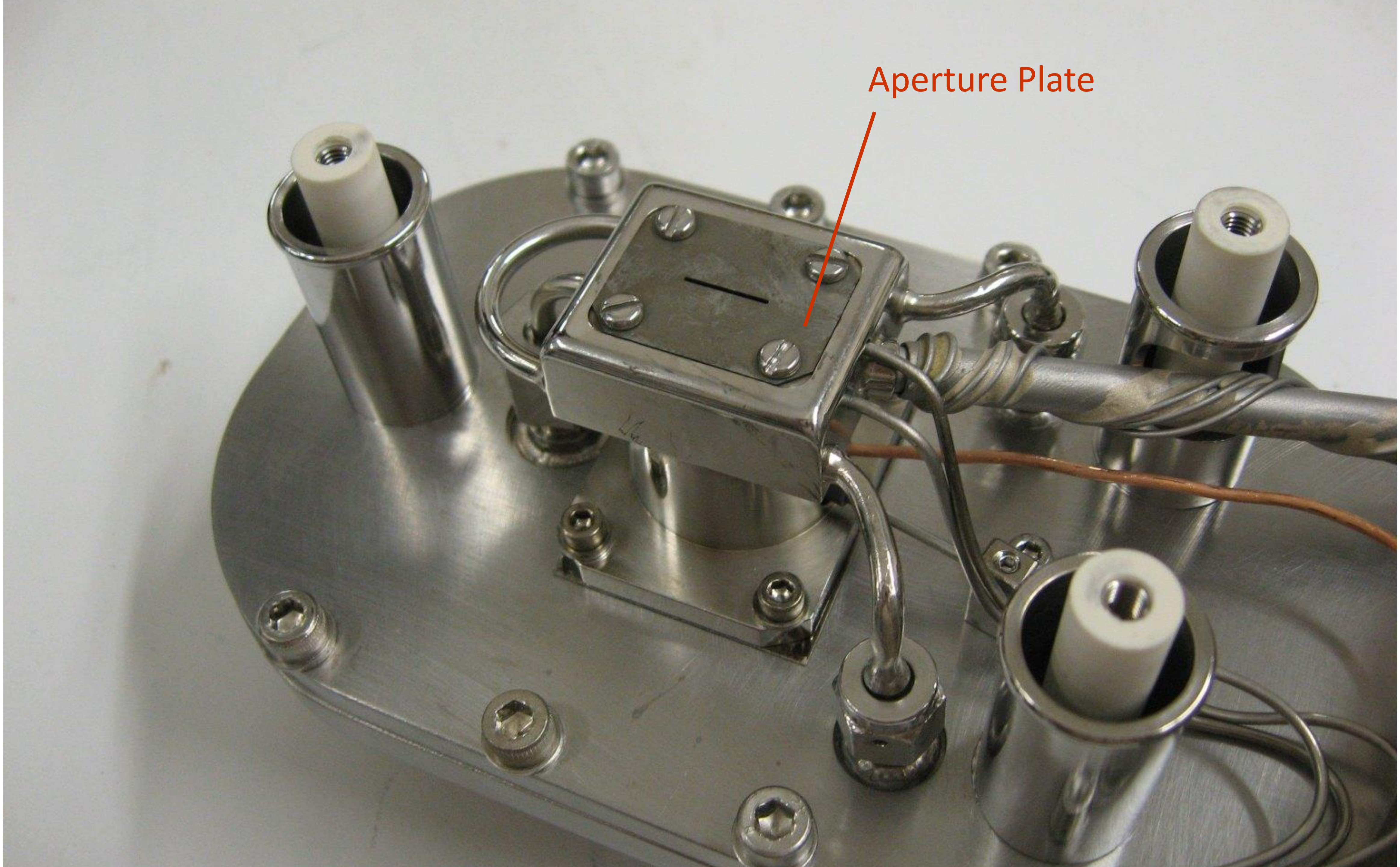
Timing

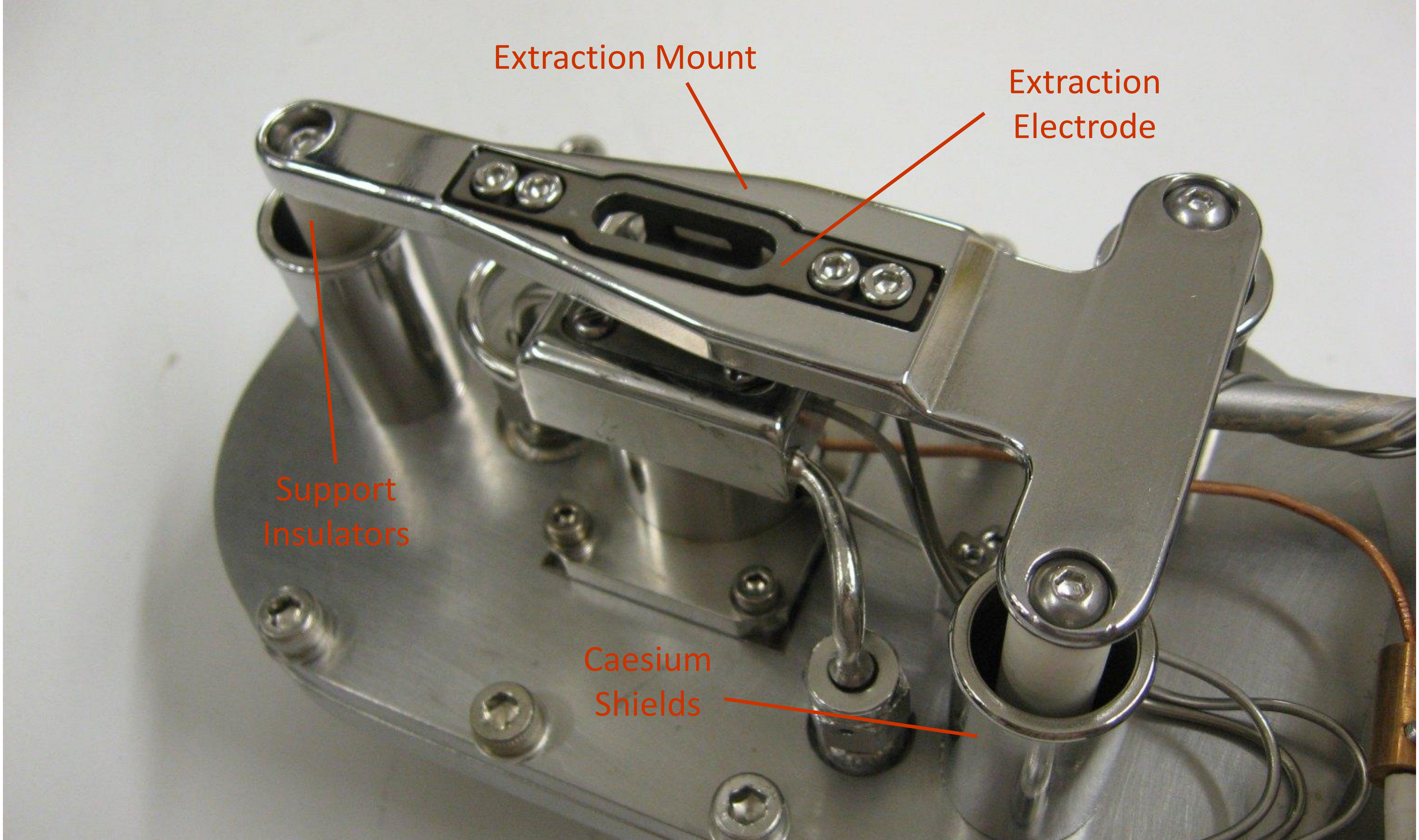


Source Runs at
50 Hz
Rep Rate

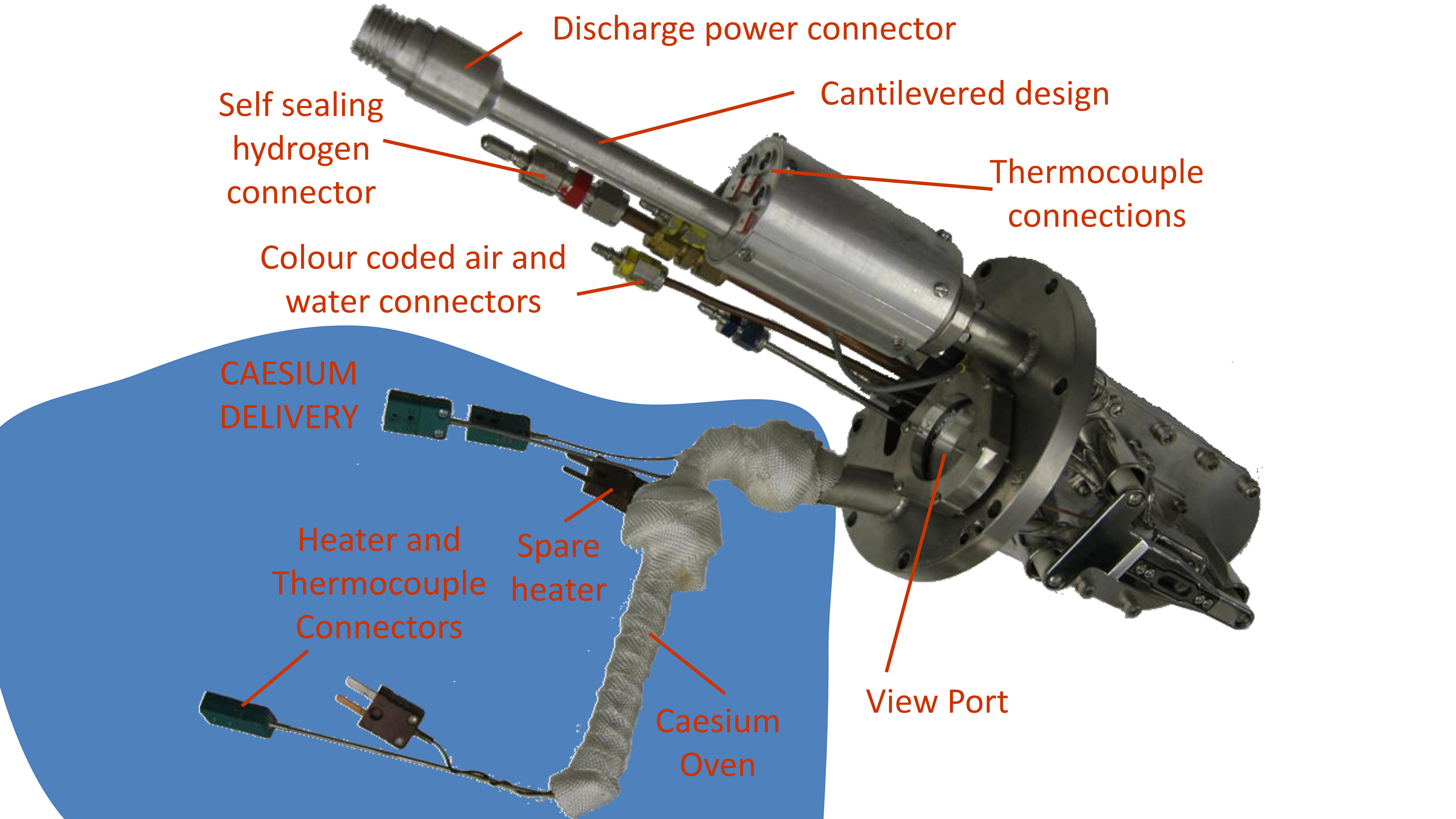


Cathode
Hollow Anode
Heated Caesium
Transport Line
Hydrogen Feed
Air Cooling
Source Body
Discharge
Power Feed
Thermocouples


Aperture Plate

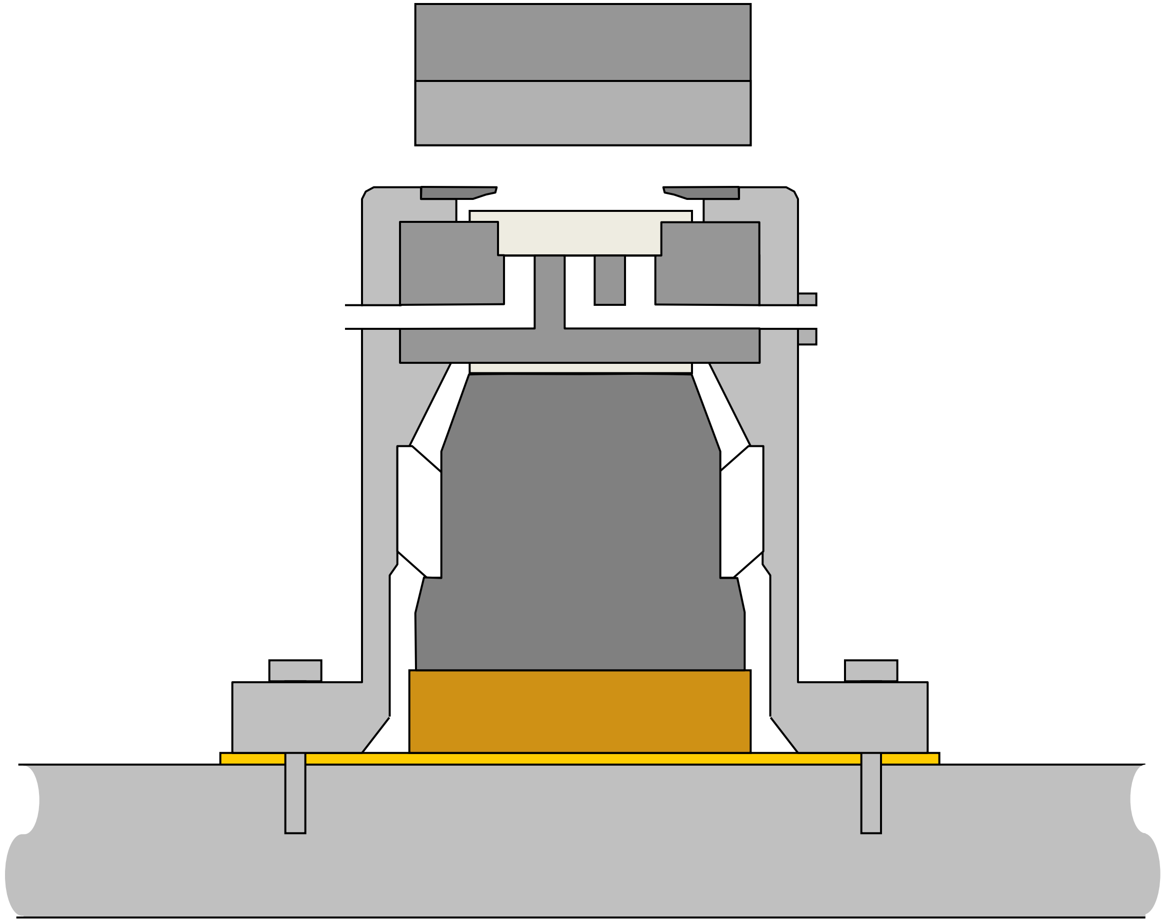


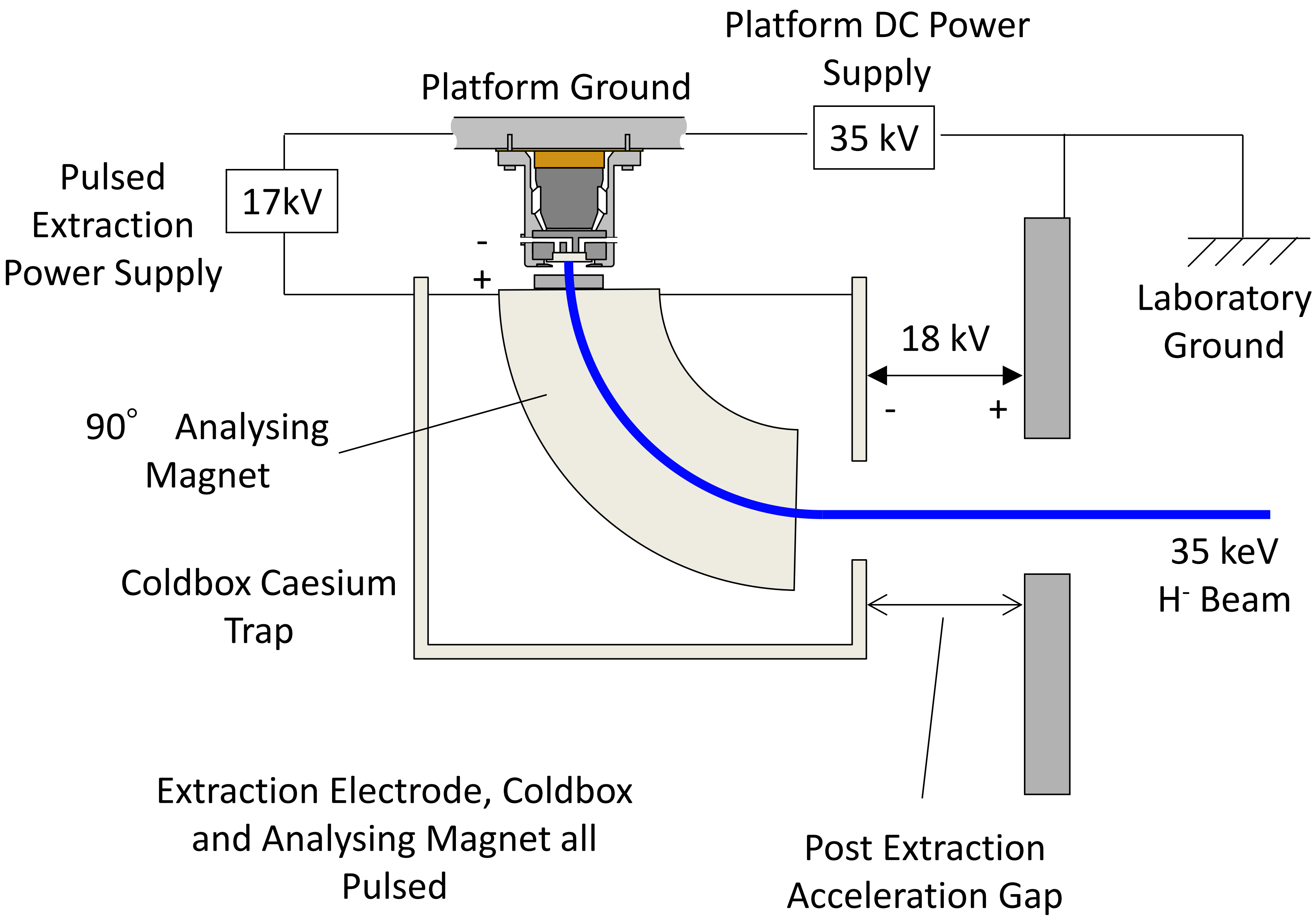
Extraction Mount
Extraction Electrode
Support Insulators
Caesium Shields

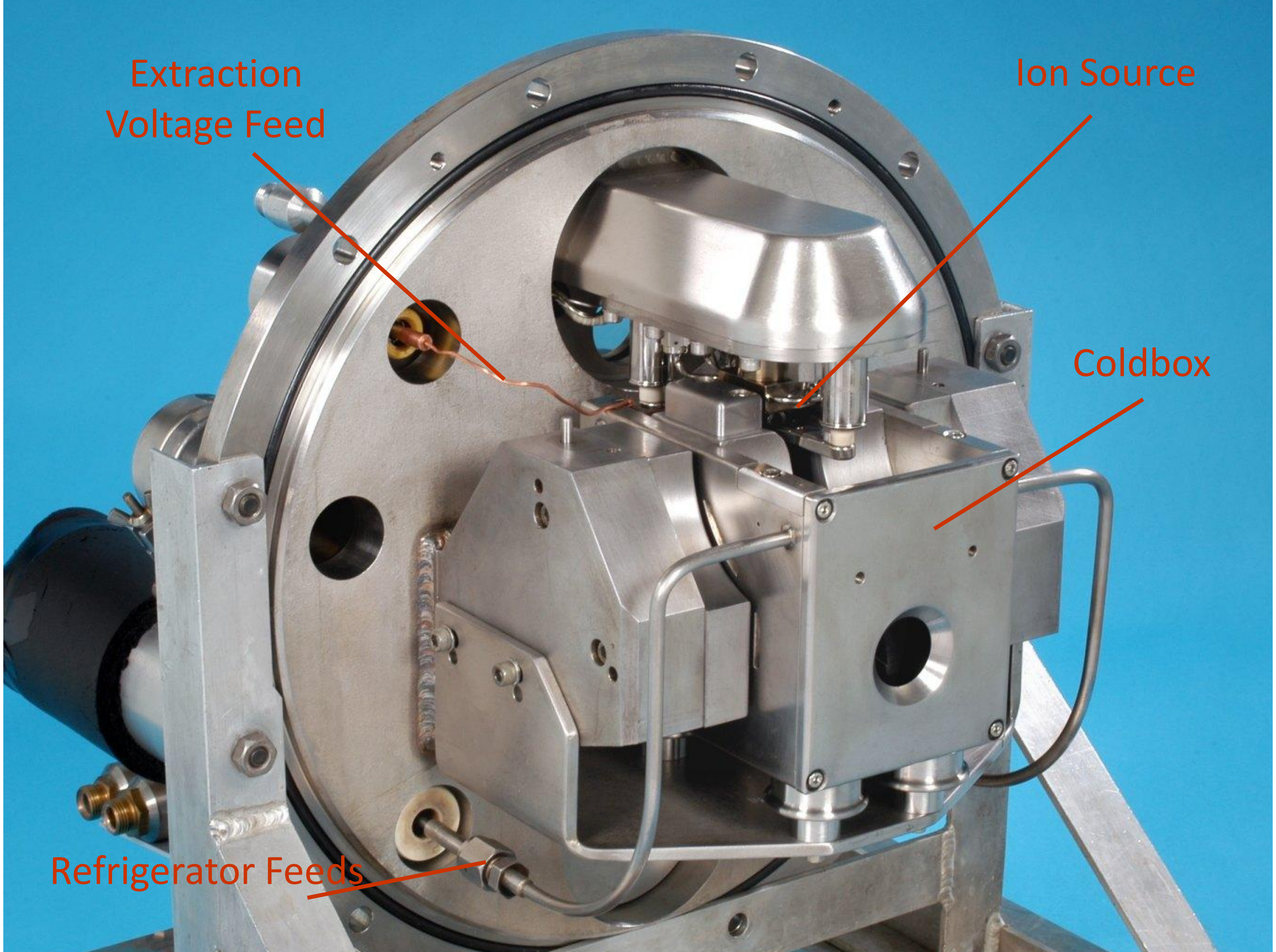


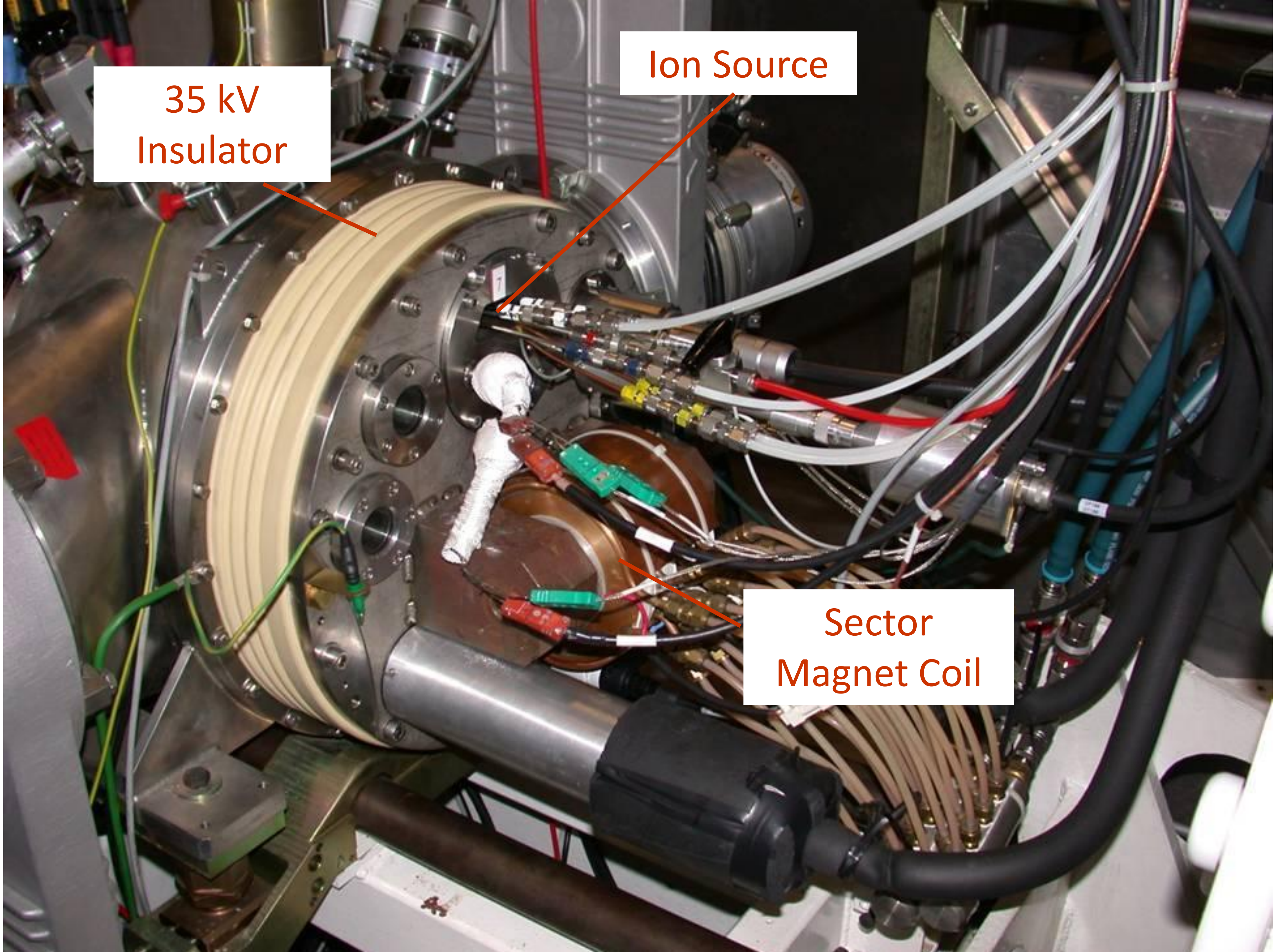
Discharge power connector
Cantilevered design
Self sealing hydrogen connector
Thermocouple connections
Colour coded air and water connectors
CAESIUM DELIVERY
Heater and Thermocouple Connectors
Spare heater
Caesium Oven
View Port

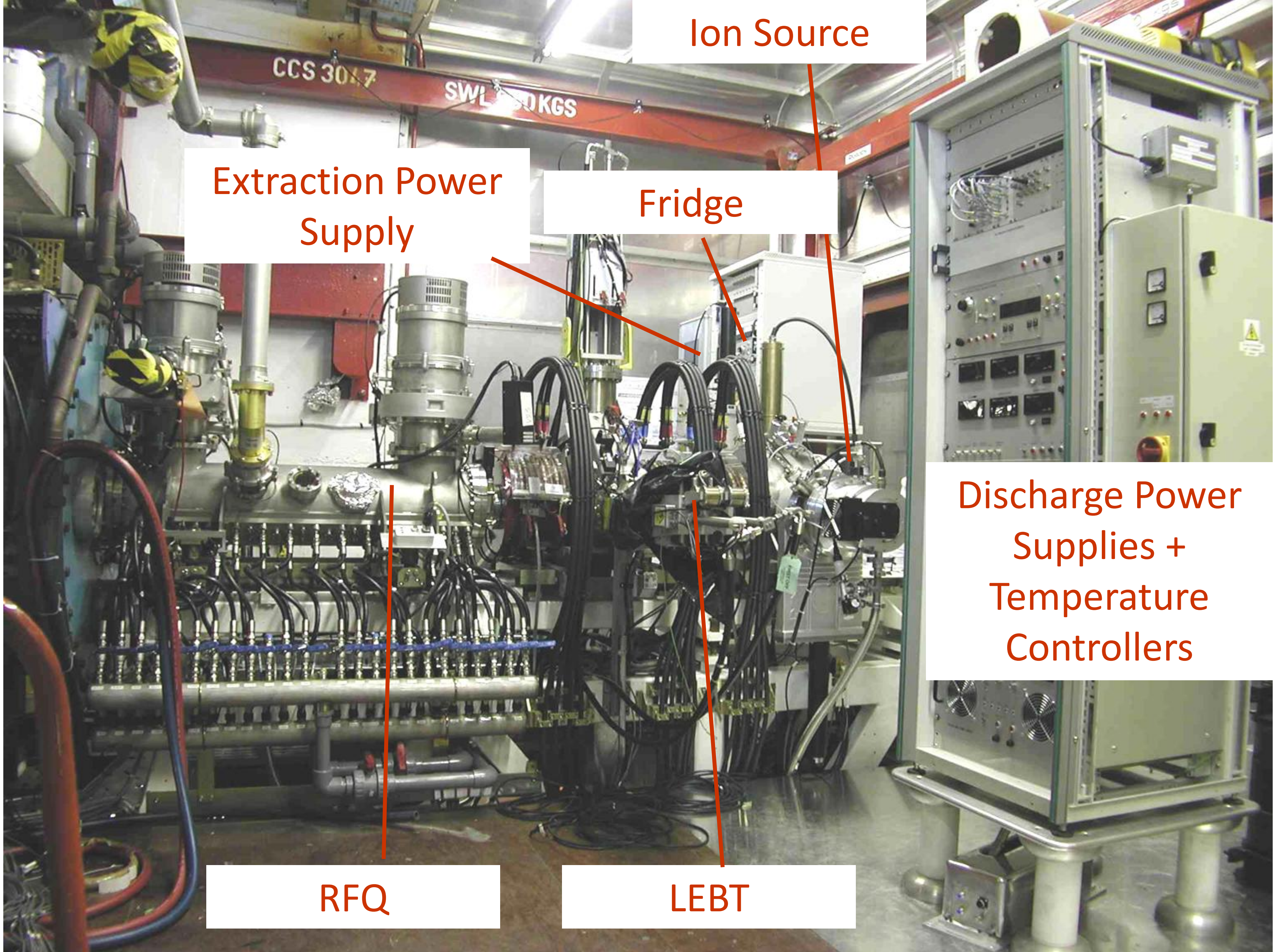
Caesium Oven



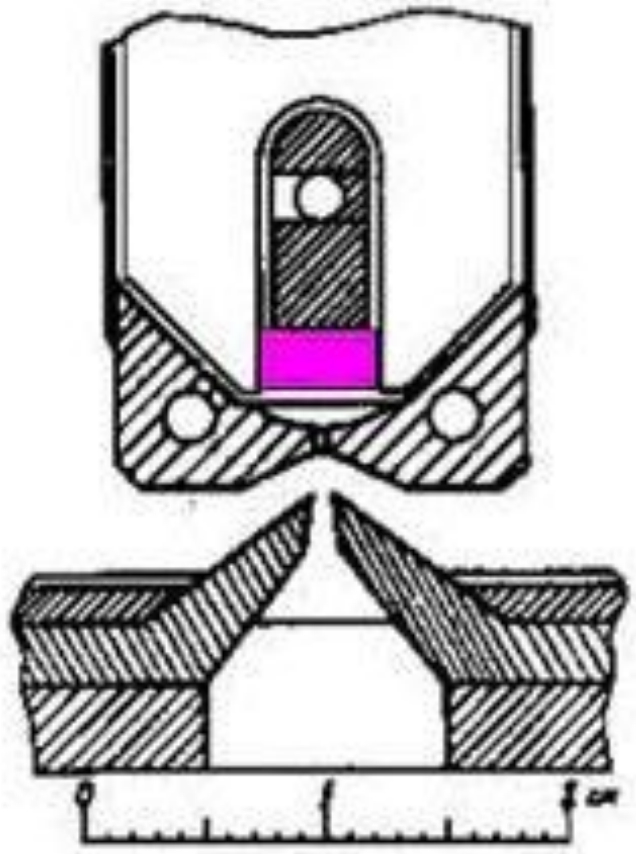

Platform DC Power Supply
Platform Ground
35 kV
Pulsed Extraction Power Supply
17kV
-
+
Laboratory Ground
18 kV
-
+
90° Analysing Magnet
35 keV H^- Beam
Coldbox Caesium Trap
Extraction Electrode, Coldbox and Analysing Magnet all Pulsed
Post Extraction Acceleration Gap


Extraction
Voltage Feed
Ion Source
Coldbox
Refrigerator Feeds


35 kV Insulator
Ion Source
Sector Magnet Coil


Ion Source
Extraction Power Supply
Fridge
Discharge Power Supplies + Temperature Controllers
RFQ
LEBT

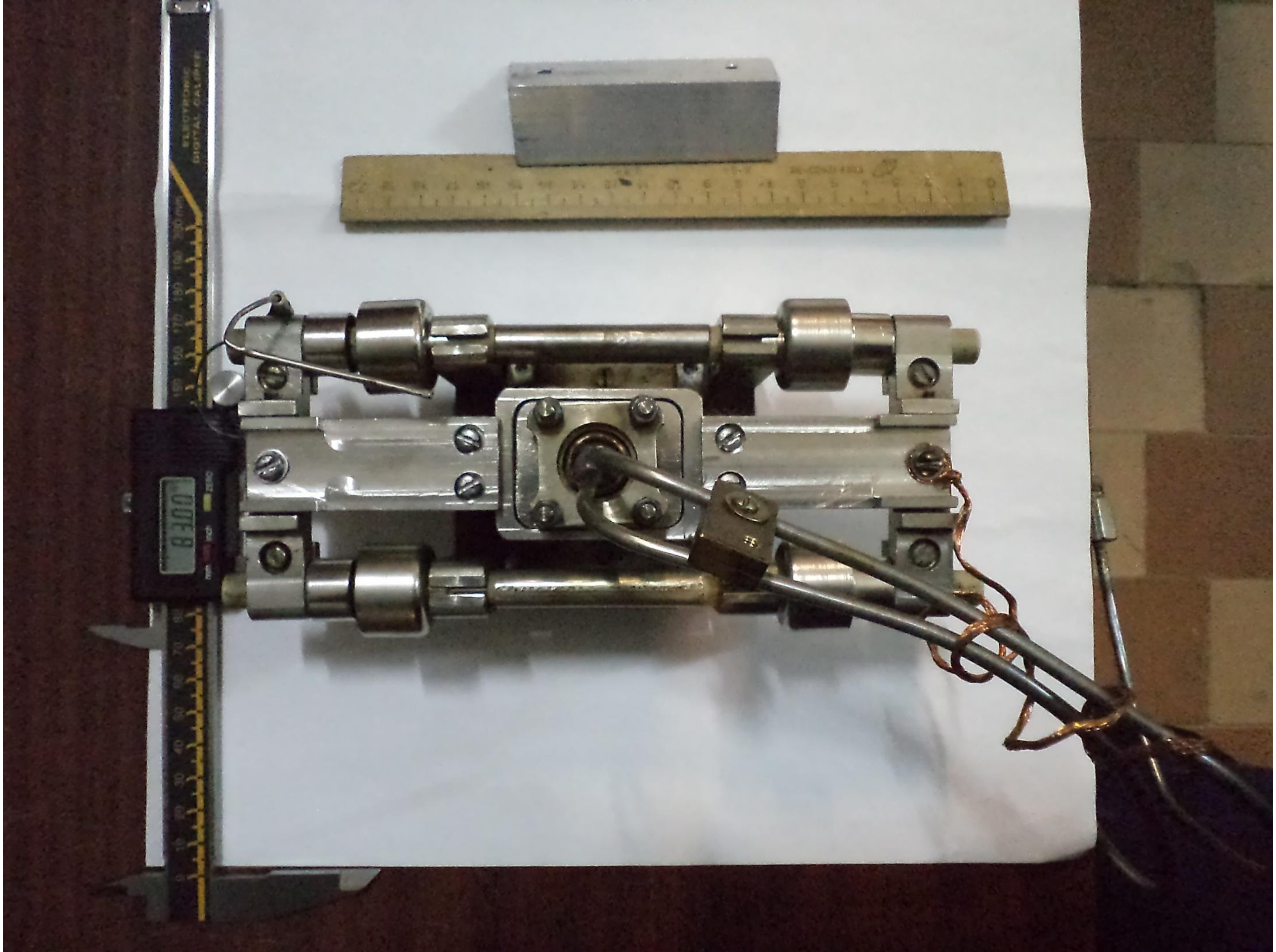
INR Moscow Penning

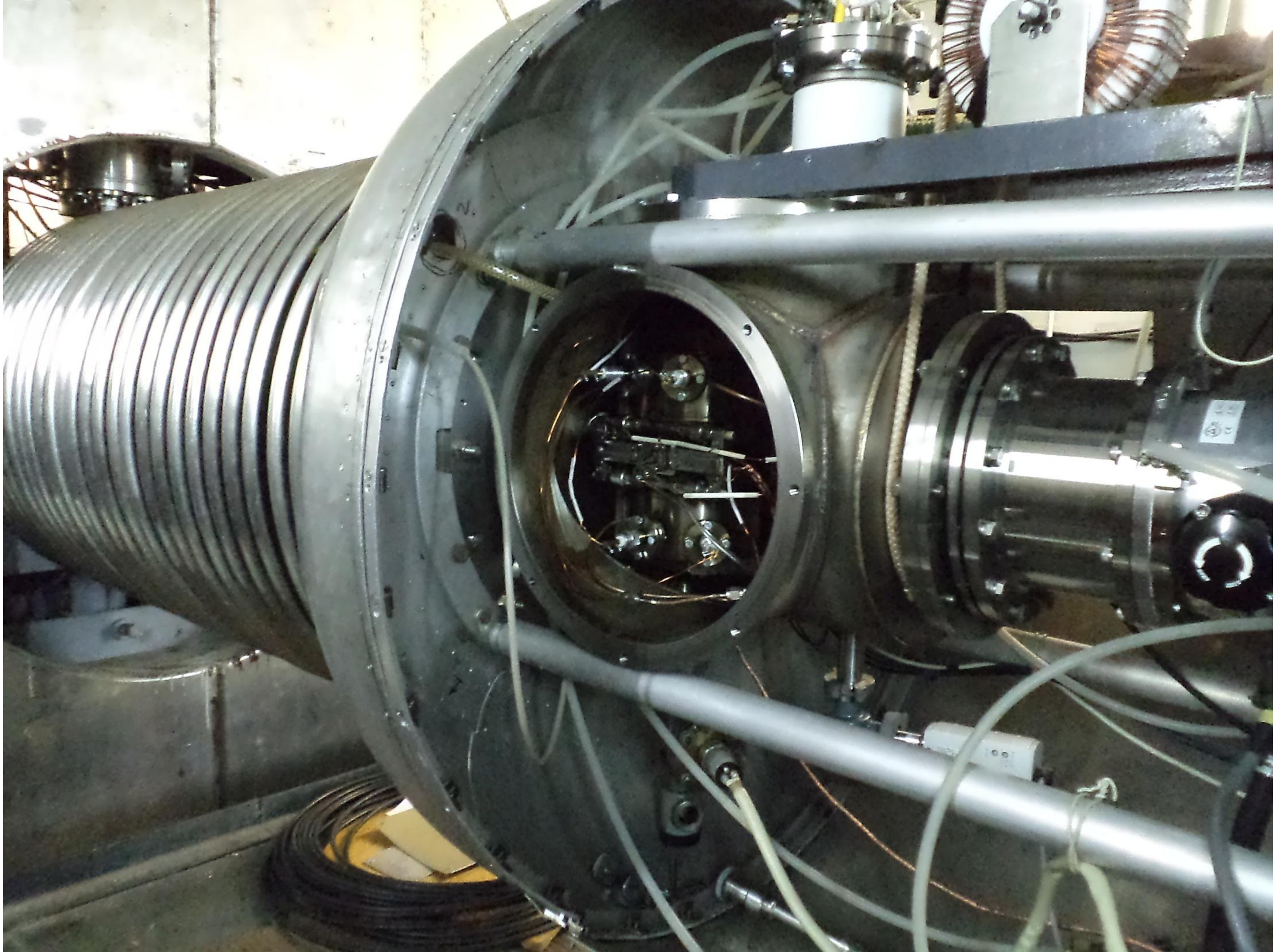


Pulse beam current 40 mA
Pulse repetition rate (PRR) 2 – 50 Hz
Macro-pulse beam current duration 60 – 200 μs
Normalized emittance ≤0.35 π·mm·mrad

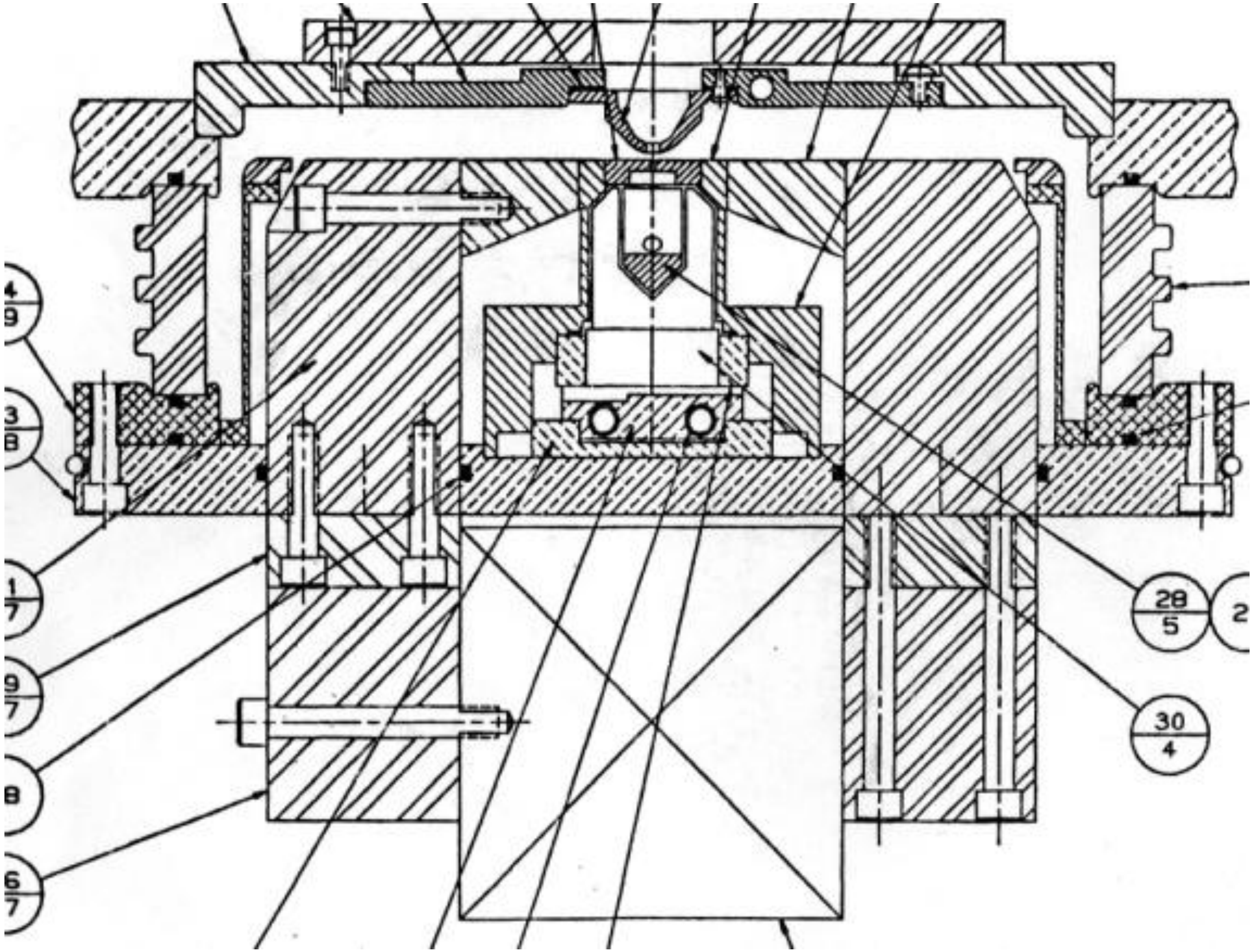
Novosibirsk design

INR Moscow Penning

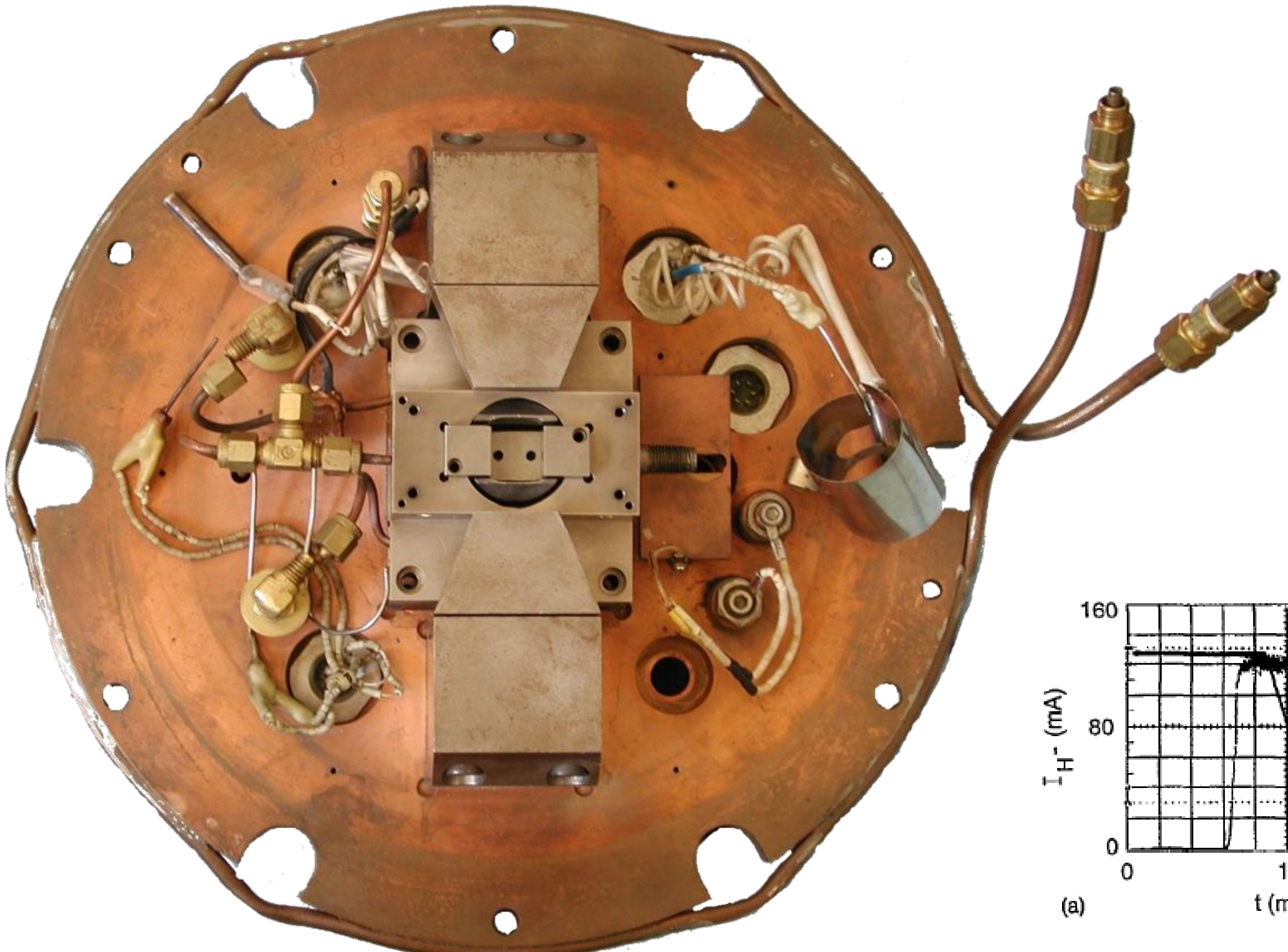




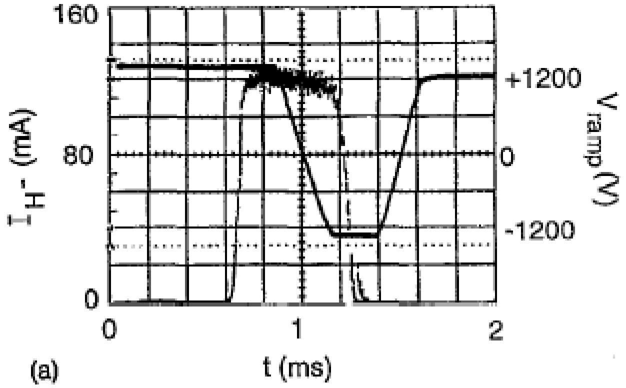
Los Alamos Scaled Penning source



Los Alamos Scaled Penning source



120 mA
500 µs
60 Hz



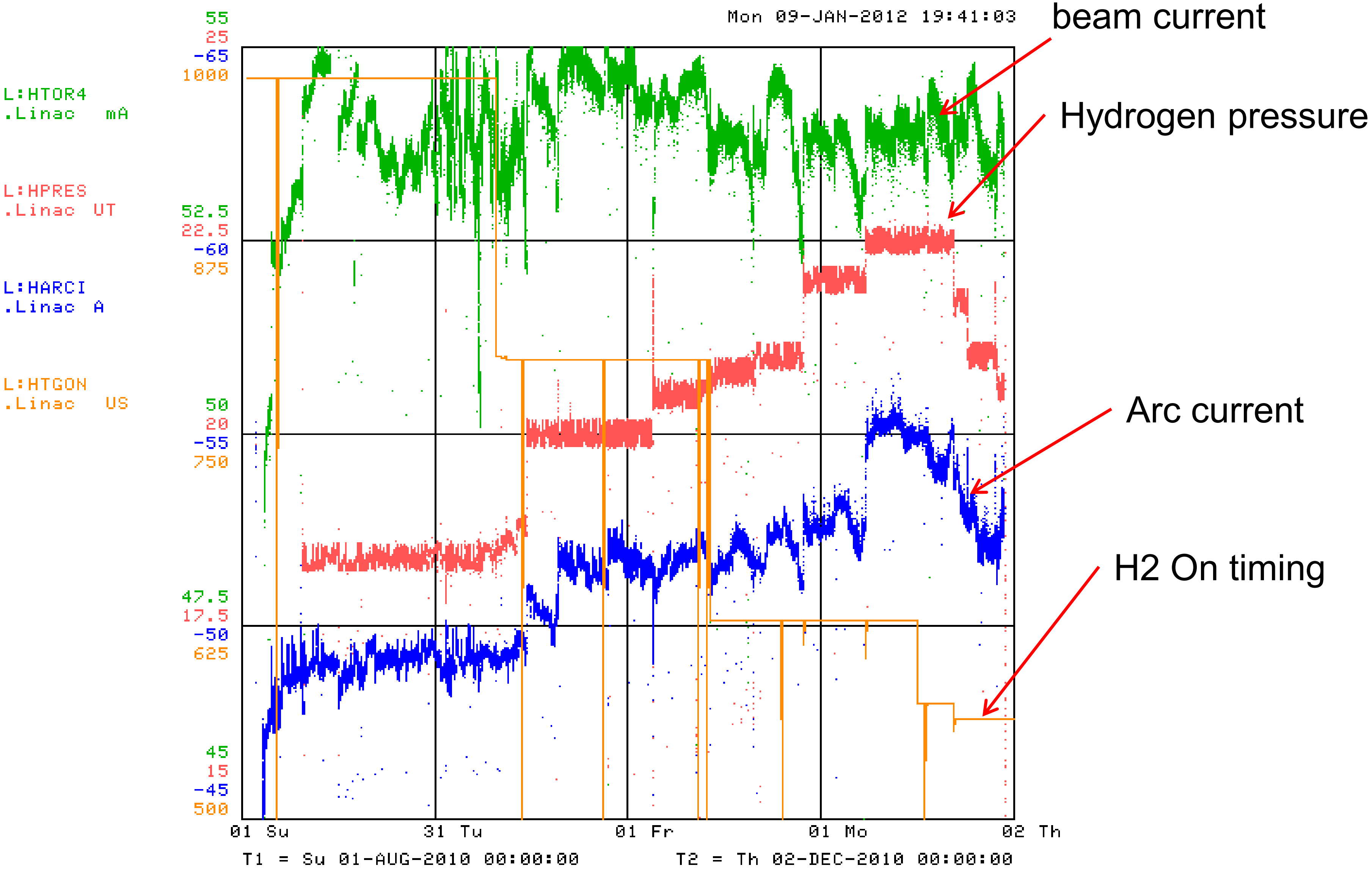
SPS Failure Modes

- Blocked caesium transport
- Failed heaters
- Failed piezo hydrogen valve
- Ancillary equipment failure
- Sputtering
  - Blocked Aperture Plate
  - Shorted Electrodes

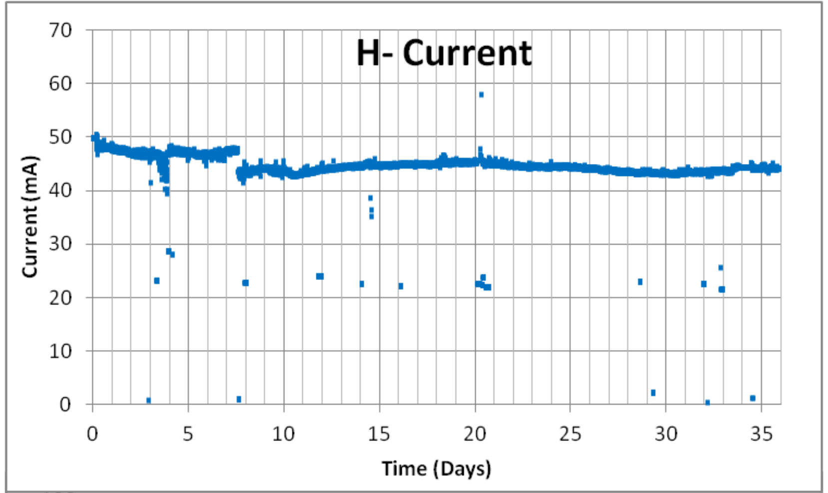
Compare SPS Lifetimes

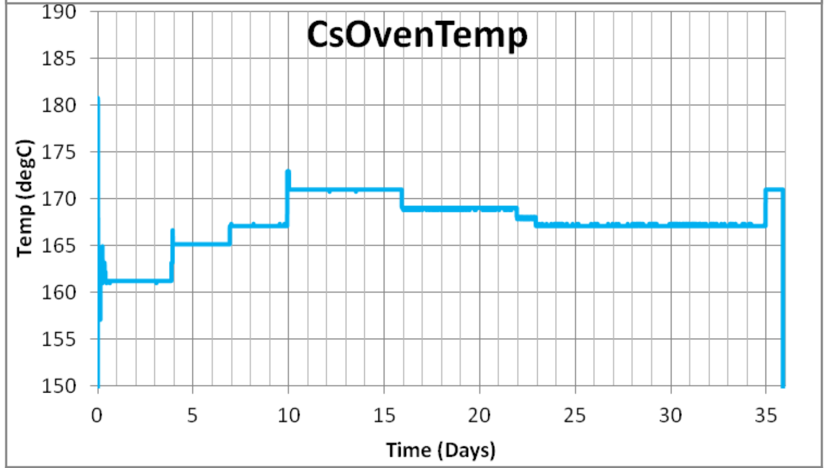
	DESY	FNAL	BNL	ISIS
Discharge Current (A)	47	50	18	55
Pulse length (µs)	75	80	700	800
Rep rate (Hz)	6.25	15	7.5	50
Plasma Duty Factor (%)	0.047	0.12	0.525	4
Lifetime (Days)	900	200	270	30
Lifetime (Plasma Days)	0.42	0.24	1.42	1.2

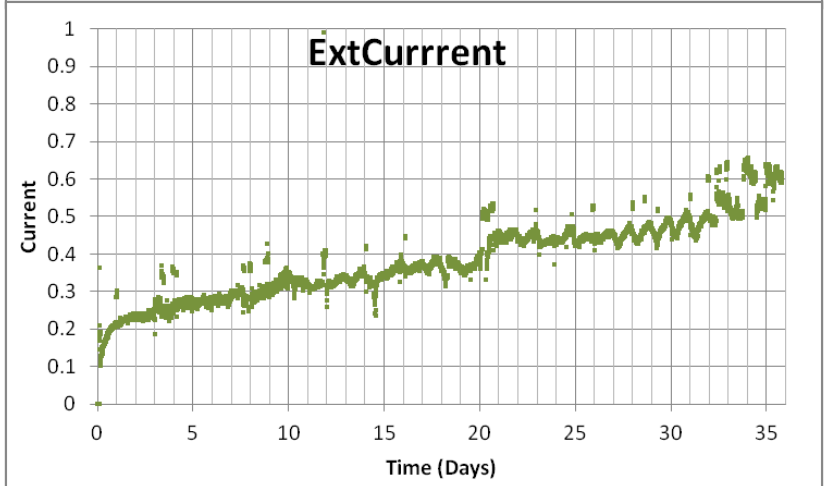
Fermilab Magnetron Ageing

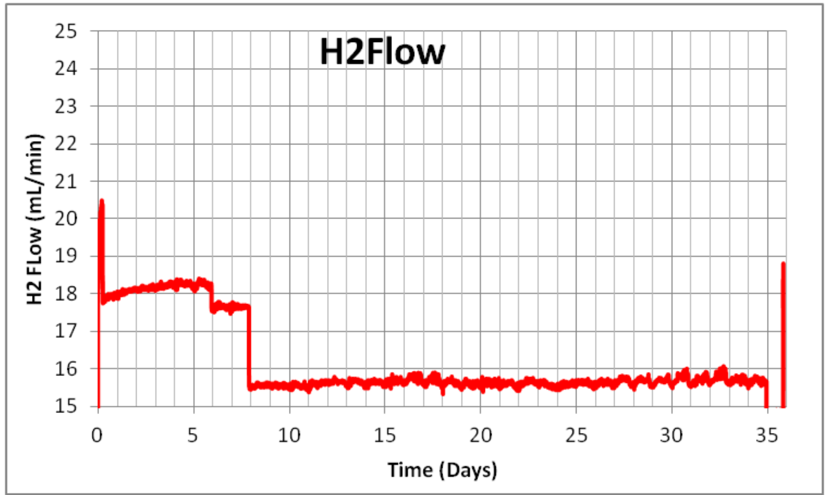


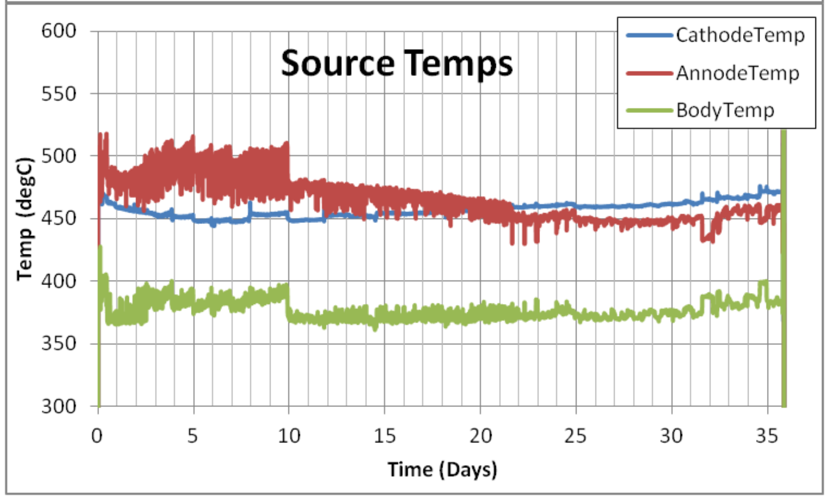
ISIS Penning Ageing



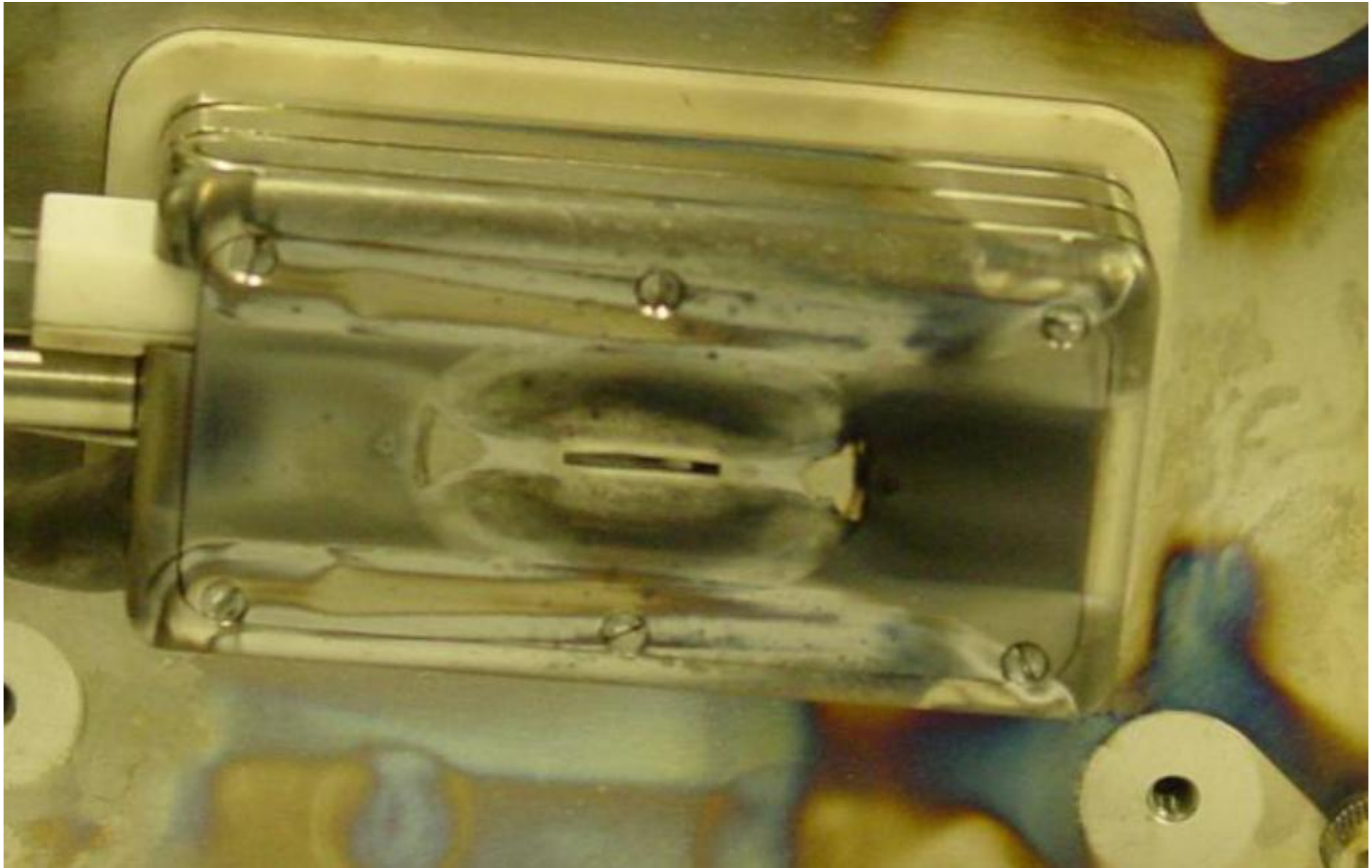






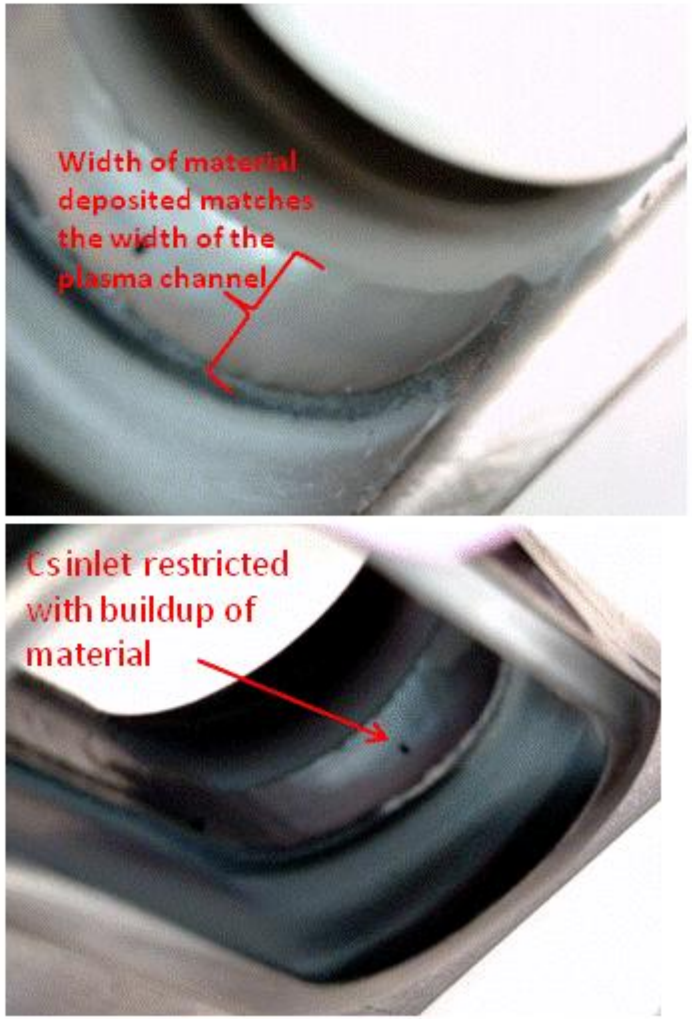


Fermilab Magnetron



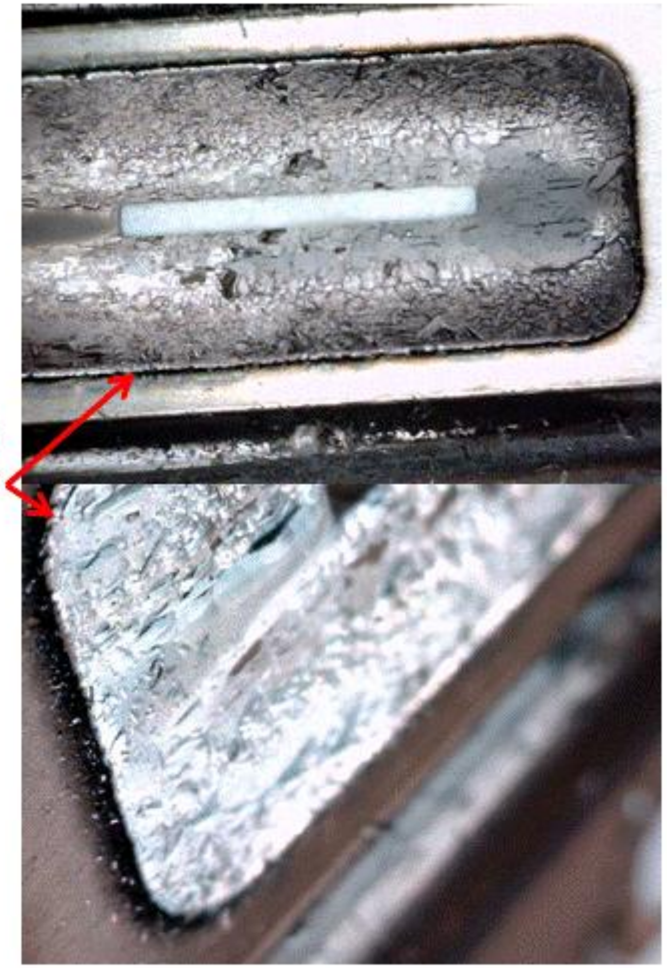
Fermilab Magnetron

Anode



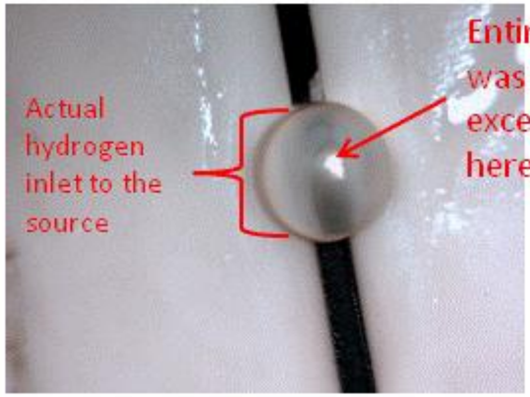
Anode cover plate

Thicker than usual buildup of material on near the source aperture

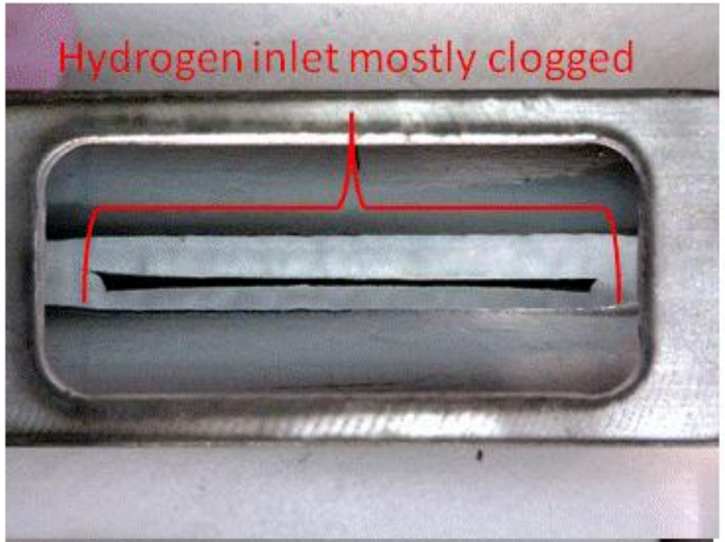


Fermilab Magnetron

Ceramic source body insulator



Anode

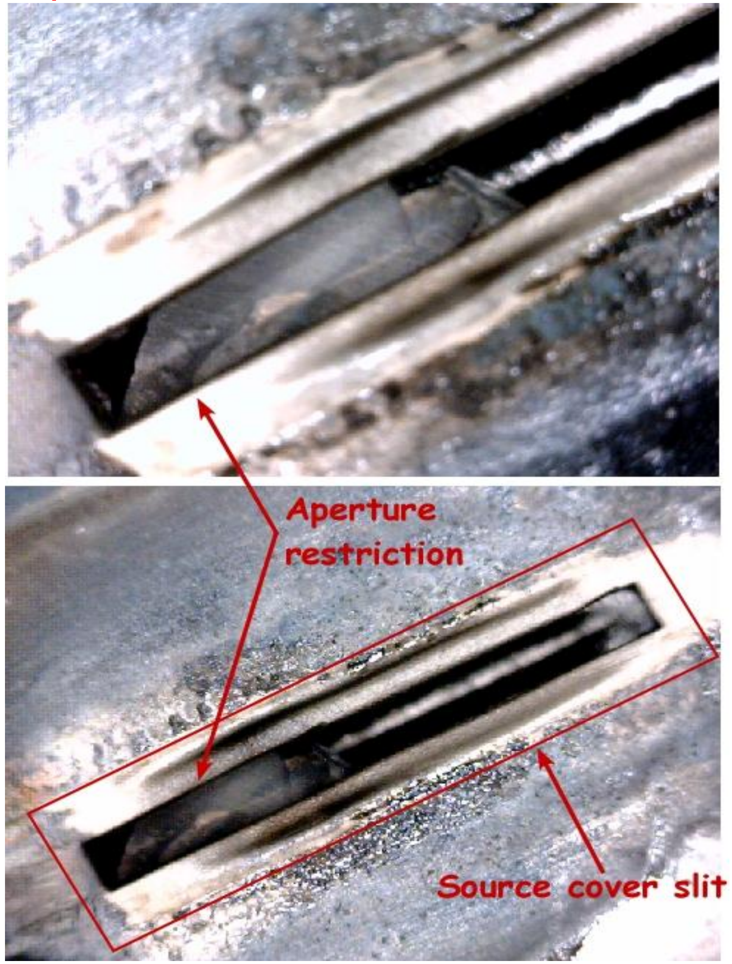


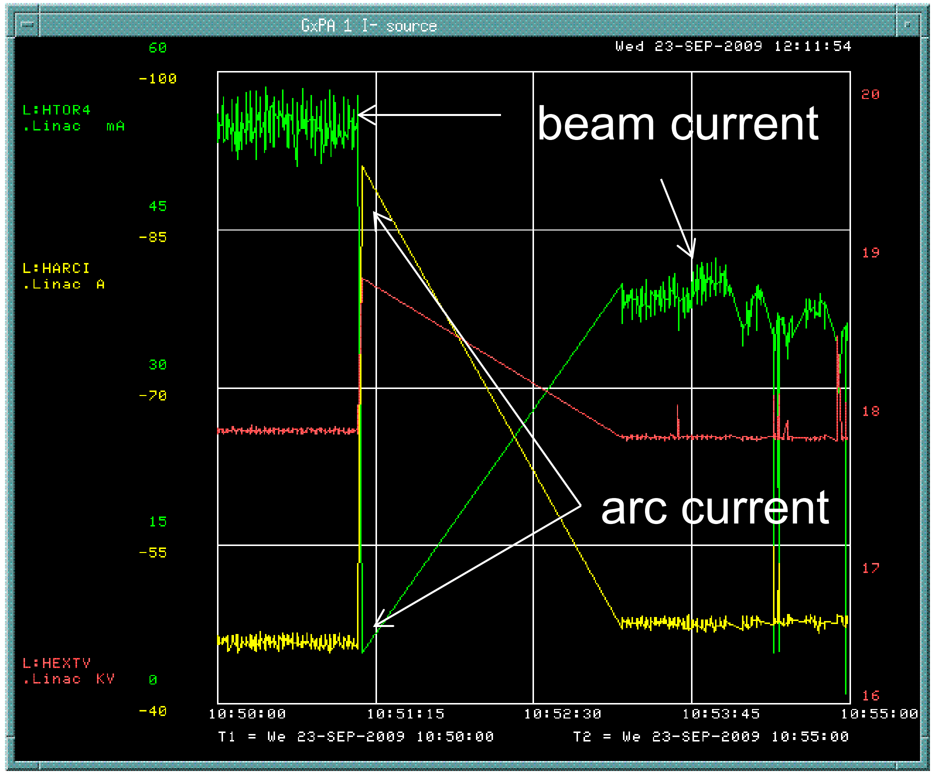
Material clogging the anode hydrogen inlet was a few mm thick. This is the most that we have ever seen.

Fermilab Magnetron

Typical Source Failures

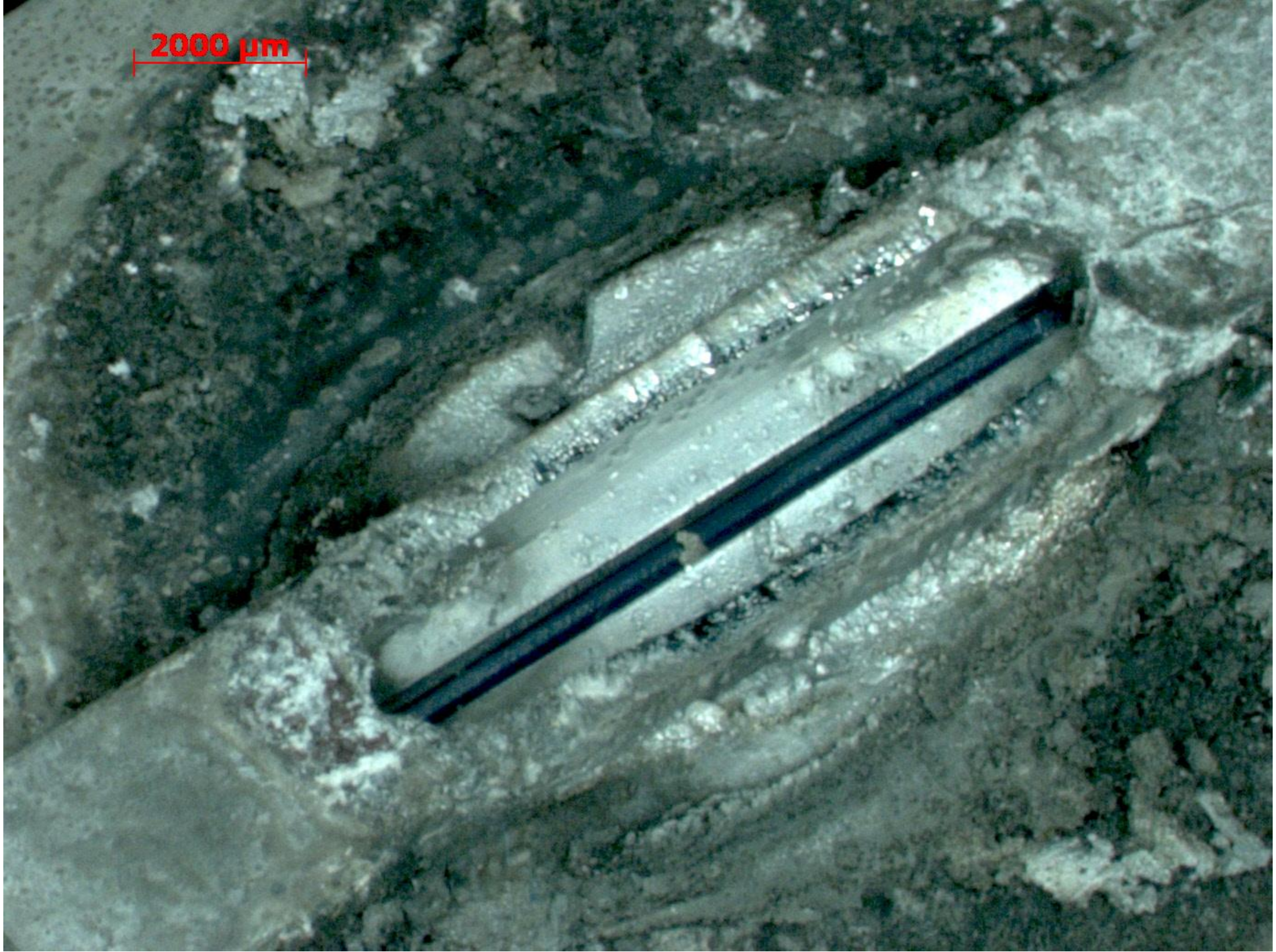
Cathode material flakes blocking source extraction aperture

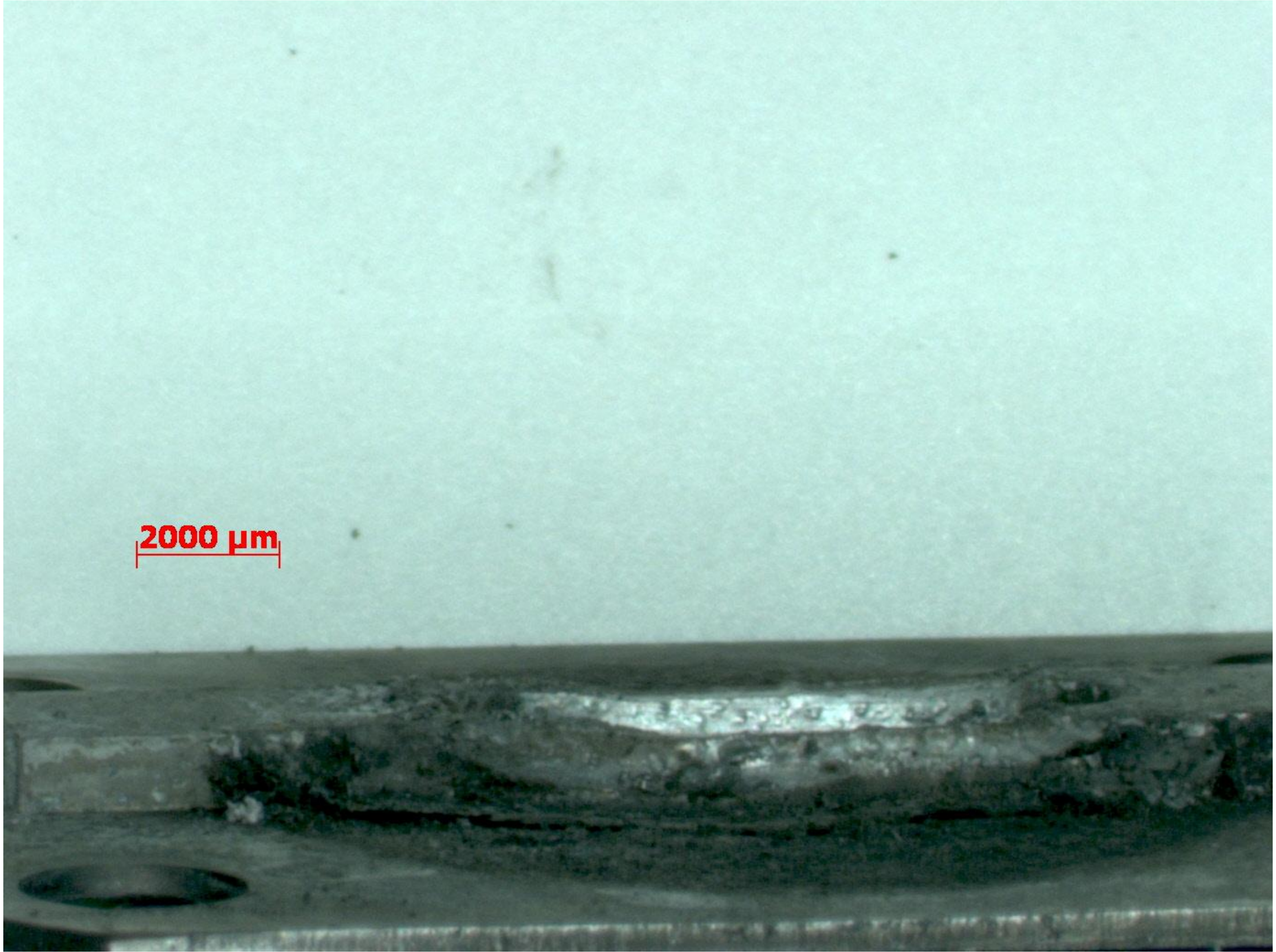


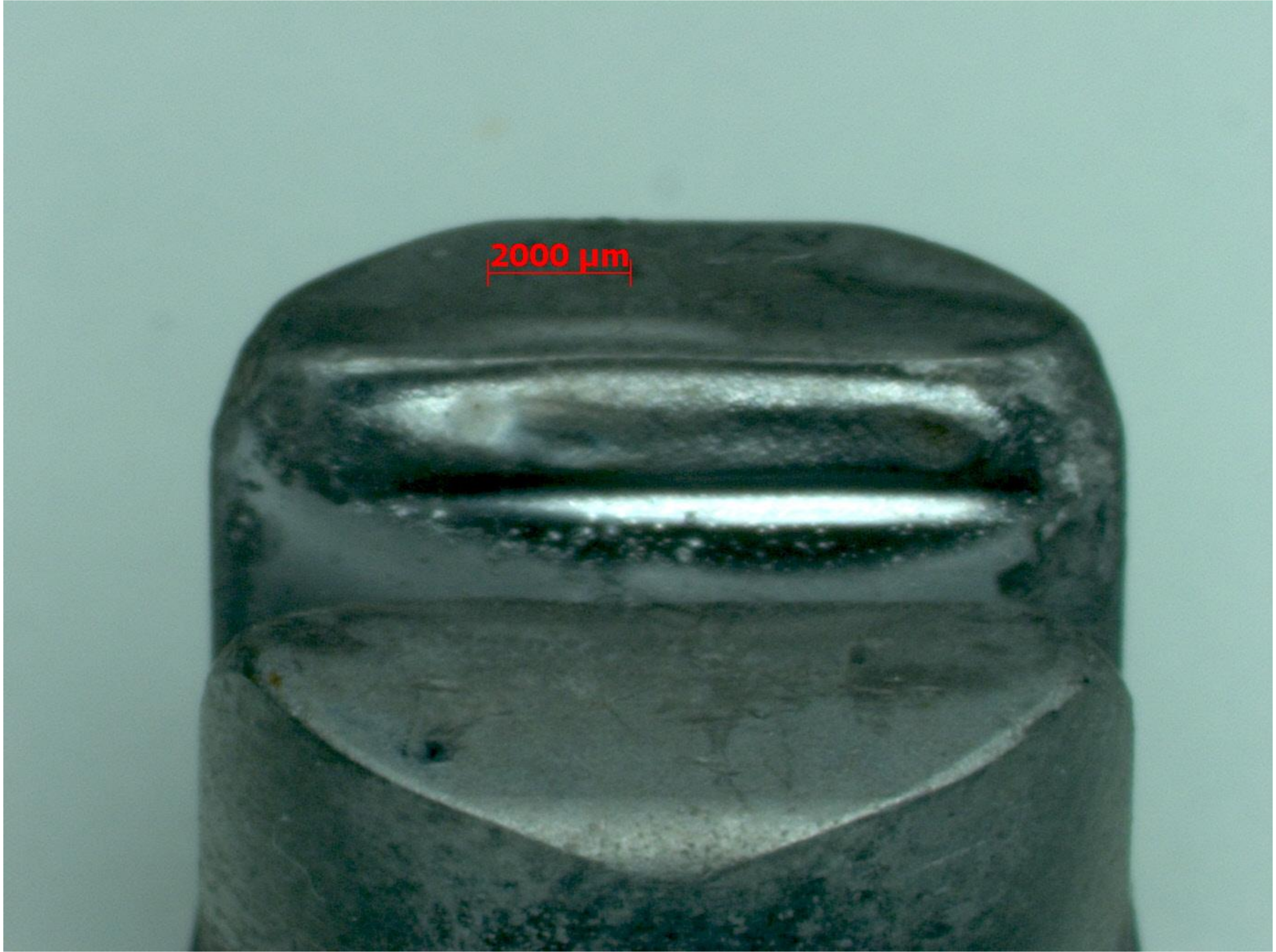


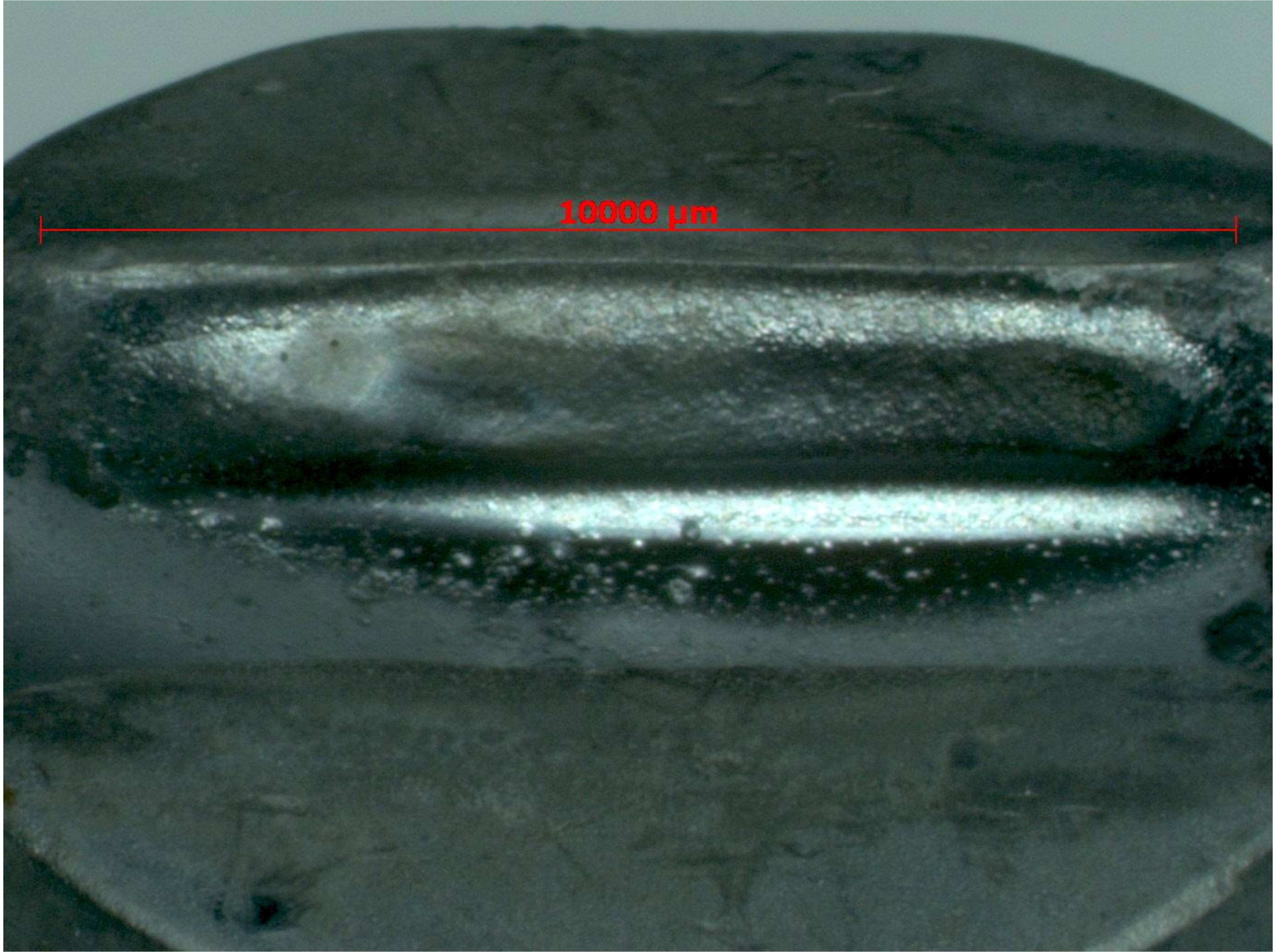
Cathode material flakes off and causes cathode/anode shorts

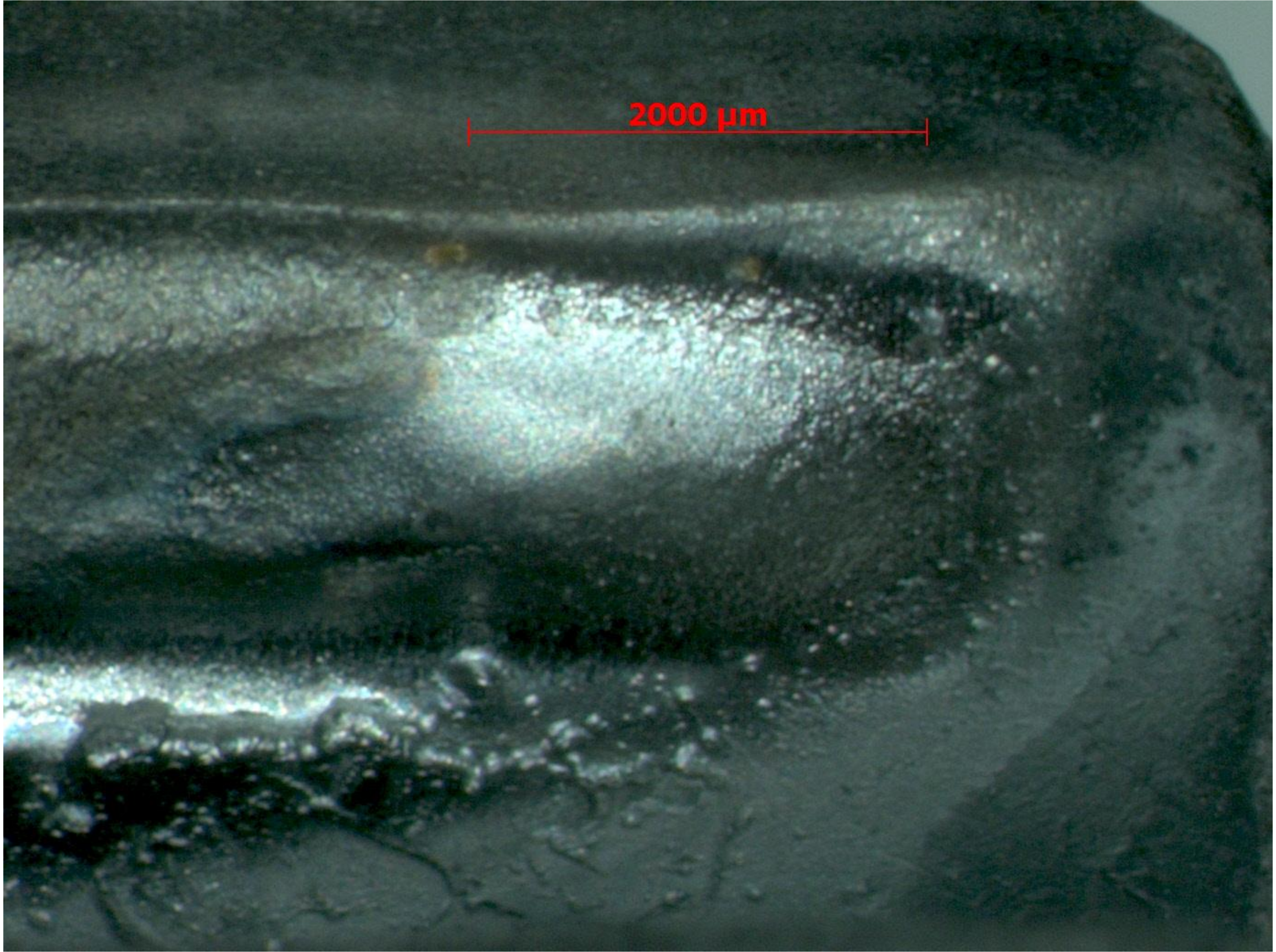
ISIS Penning 26 Day Electrode Wear

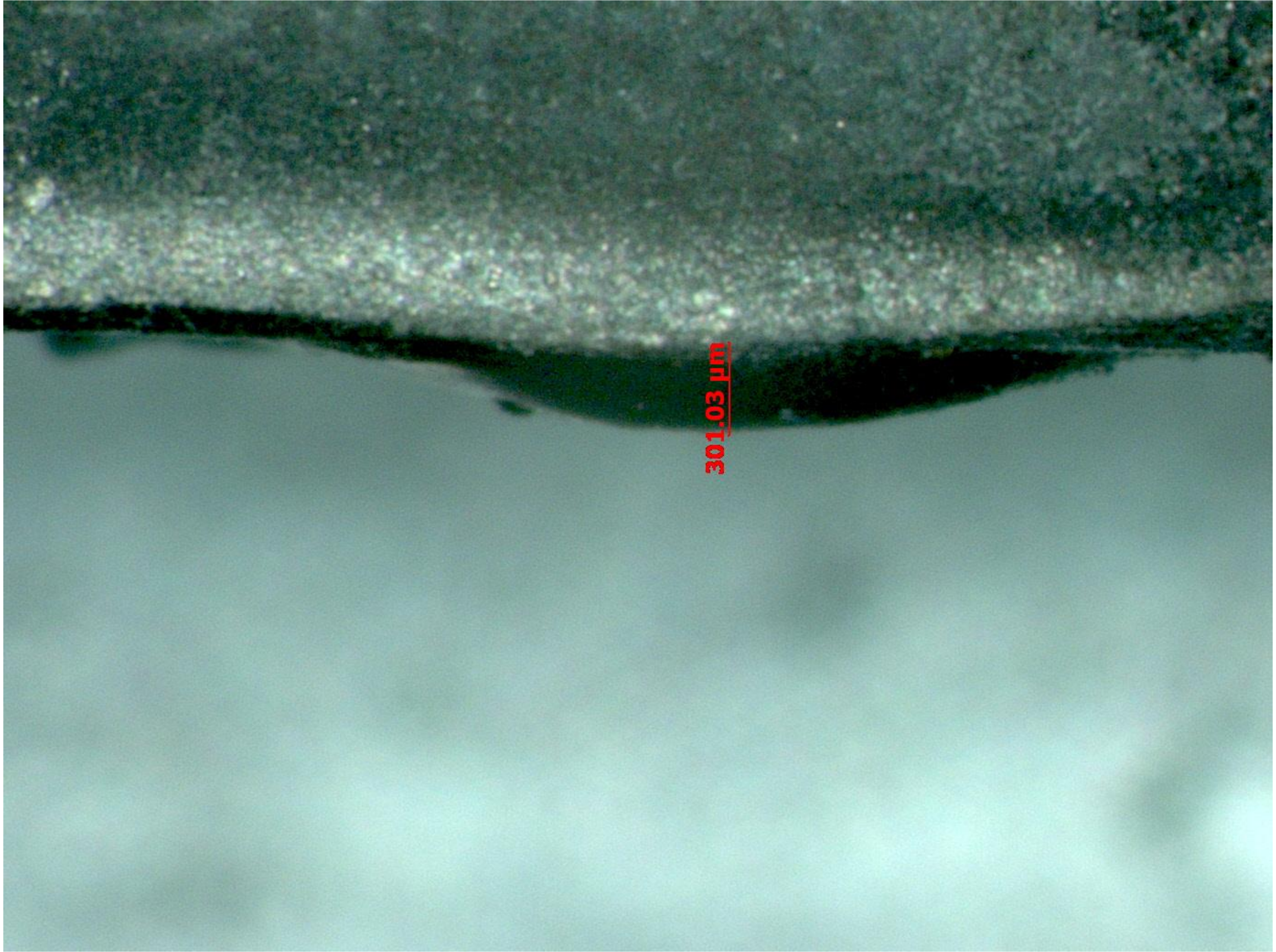

2000 µm

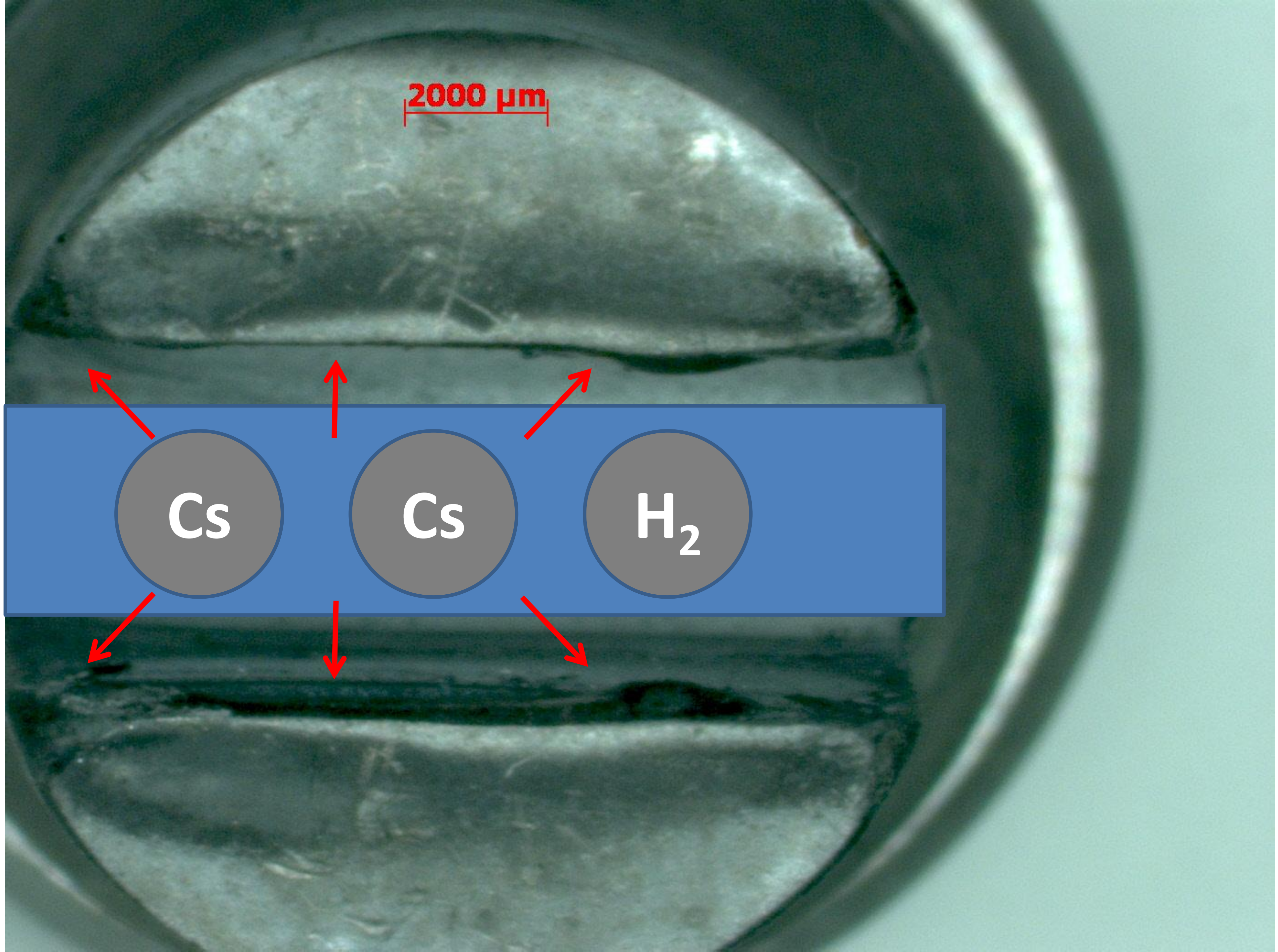

2000 µm


2000 µm


10000 µm


2000 µm

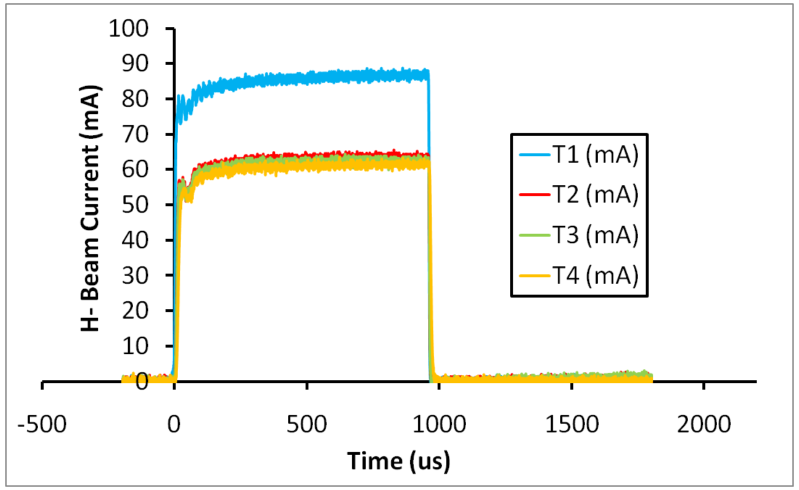

301.03 µm



2000 µm
Cs
Cs
H2

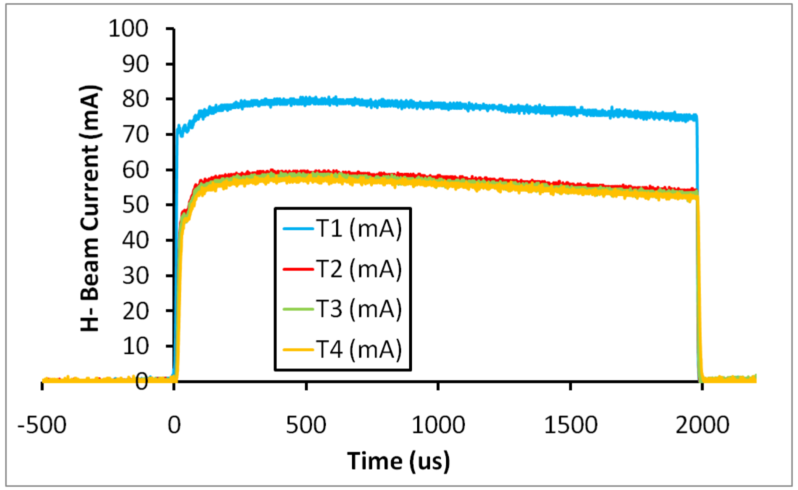
Duty cycle limit of the standard ISIS source

either

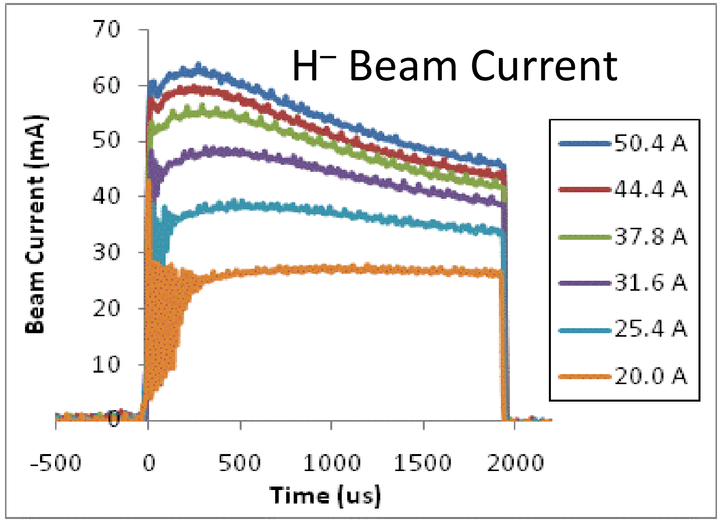


60 mA 1 ms 50 Hz

or



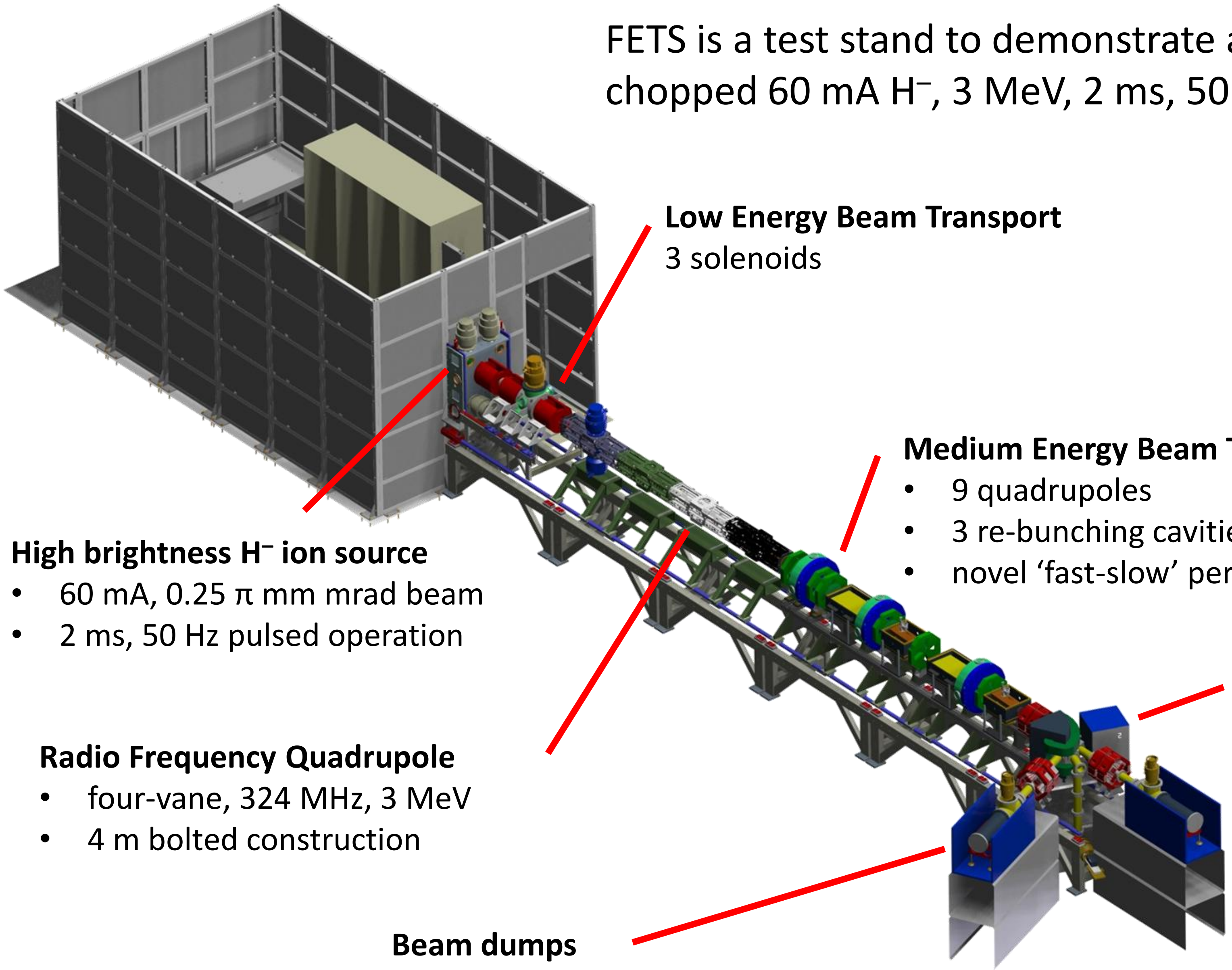
60 mA 2 ms 25 Hz



Droop is unavoidable at 50 Hz 2 ms

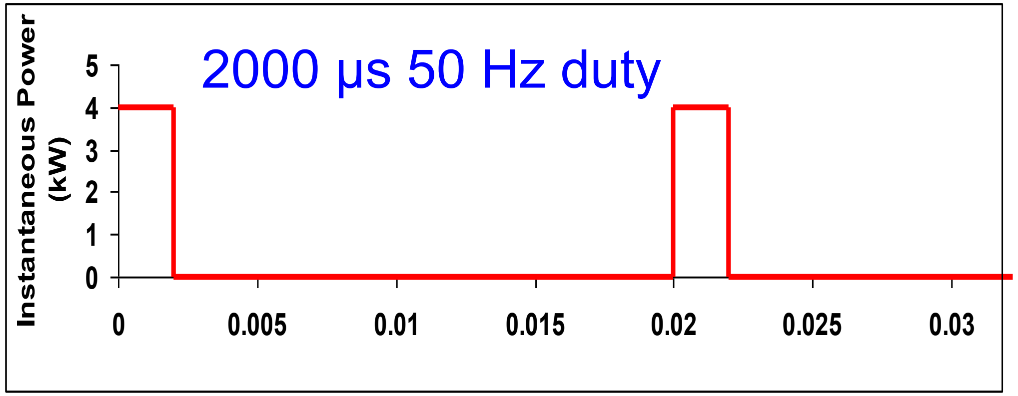
FETS Project needs
60 mA 2 ms 50 Hz

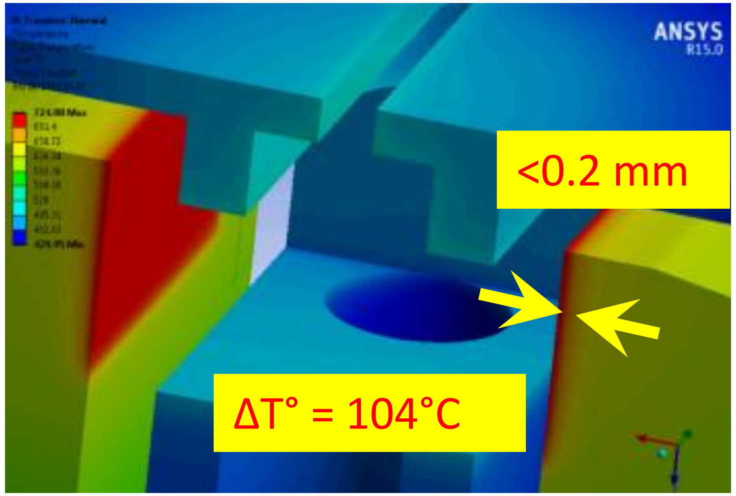
FETS is a test stand to demonstrate a perfectly chopped 60 mA H^-, 3 MeV, 2 ms, 50 Hz beam

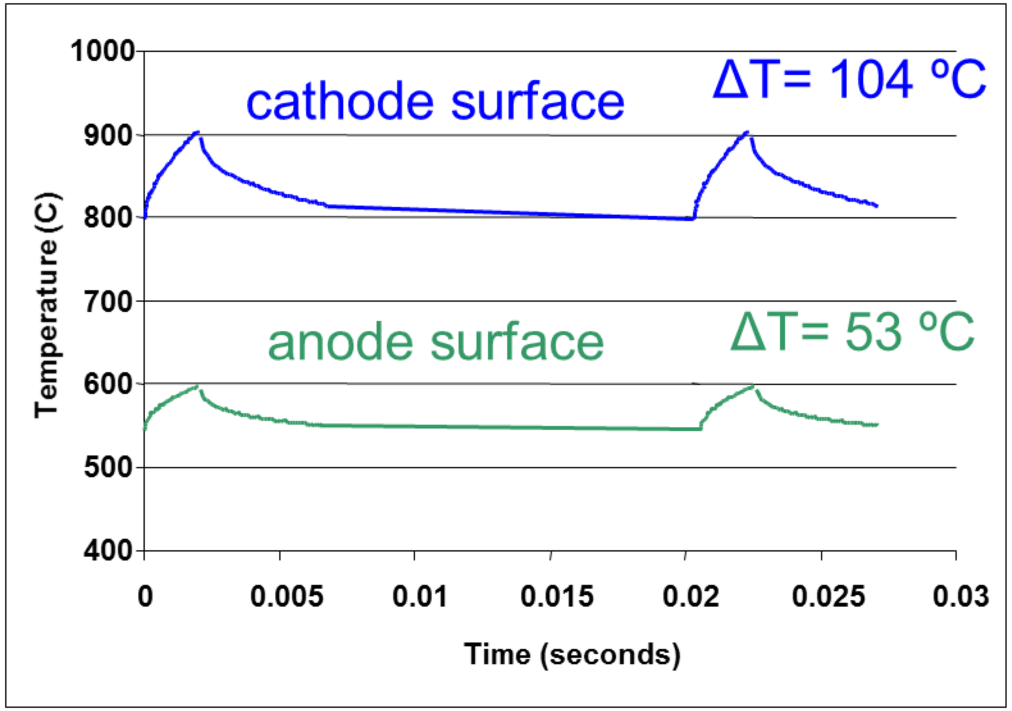


Duty factor limited thermal problems:

1. TRANSIENT PROBLEM







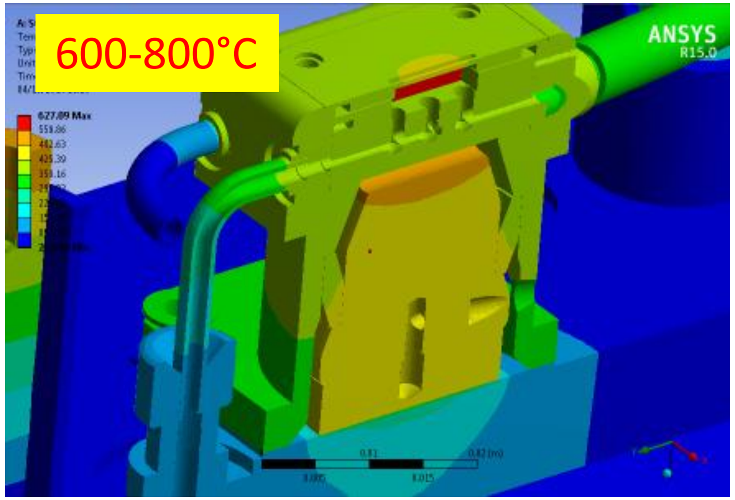
Transient surface temperature rise occurs in a very thin layer

SOLUTION

Reduce plasma power density by increasing surface area = Scaling

Duty factor limited thermal problems:

2. STEADY STATE PROBLEM

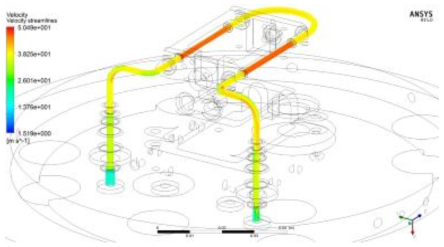


Average surface temperatures must be maintained at increased duty cycles

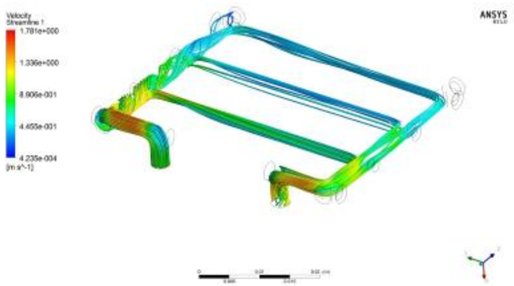
SOLUTION

Improve cooling:

CFD cooling simulations

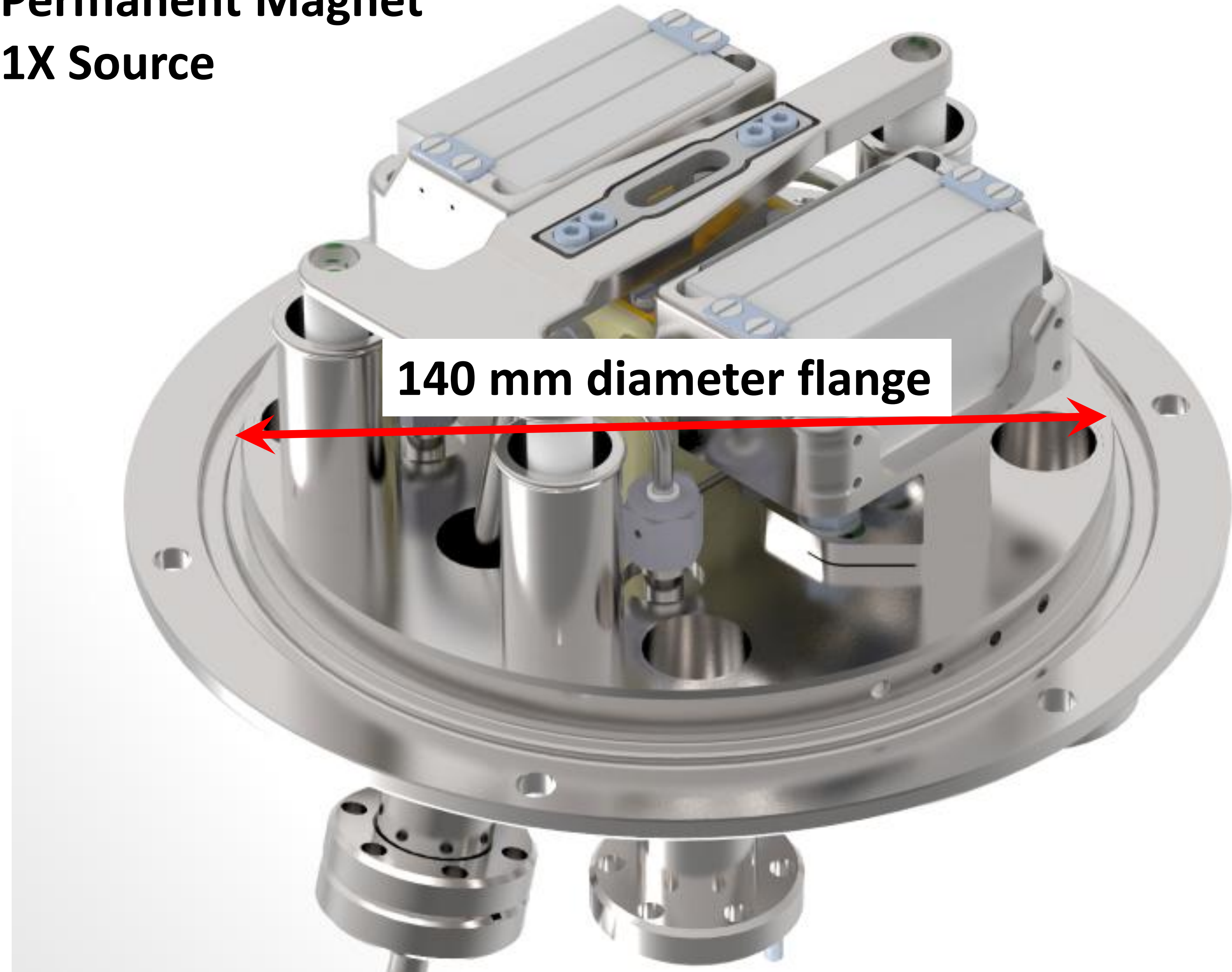


Head cooling- switched from air to water

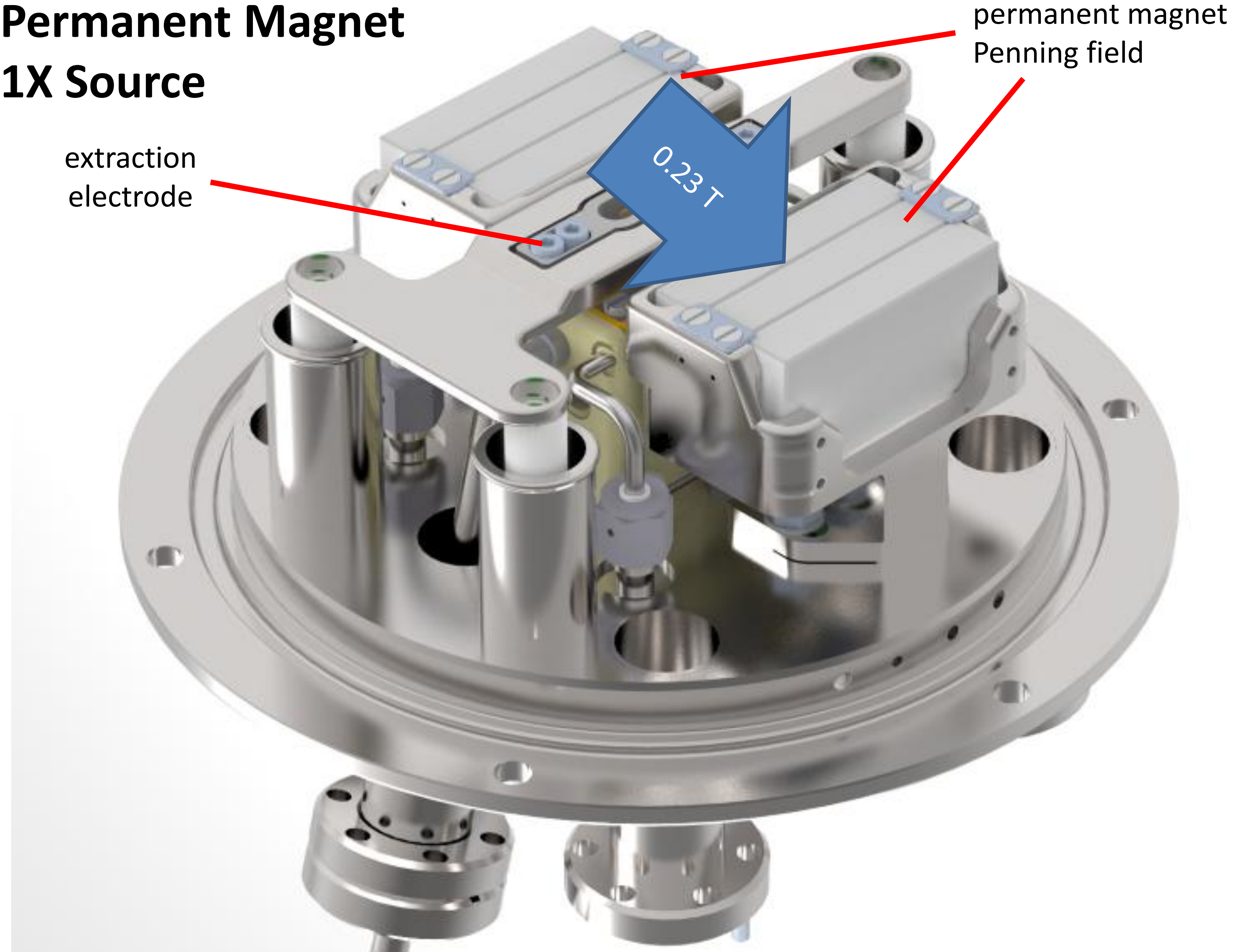


Flange cooling- extra parallel water channels

Permanent Magnet
1X Source

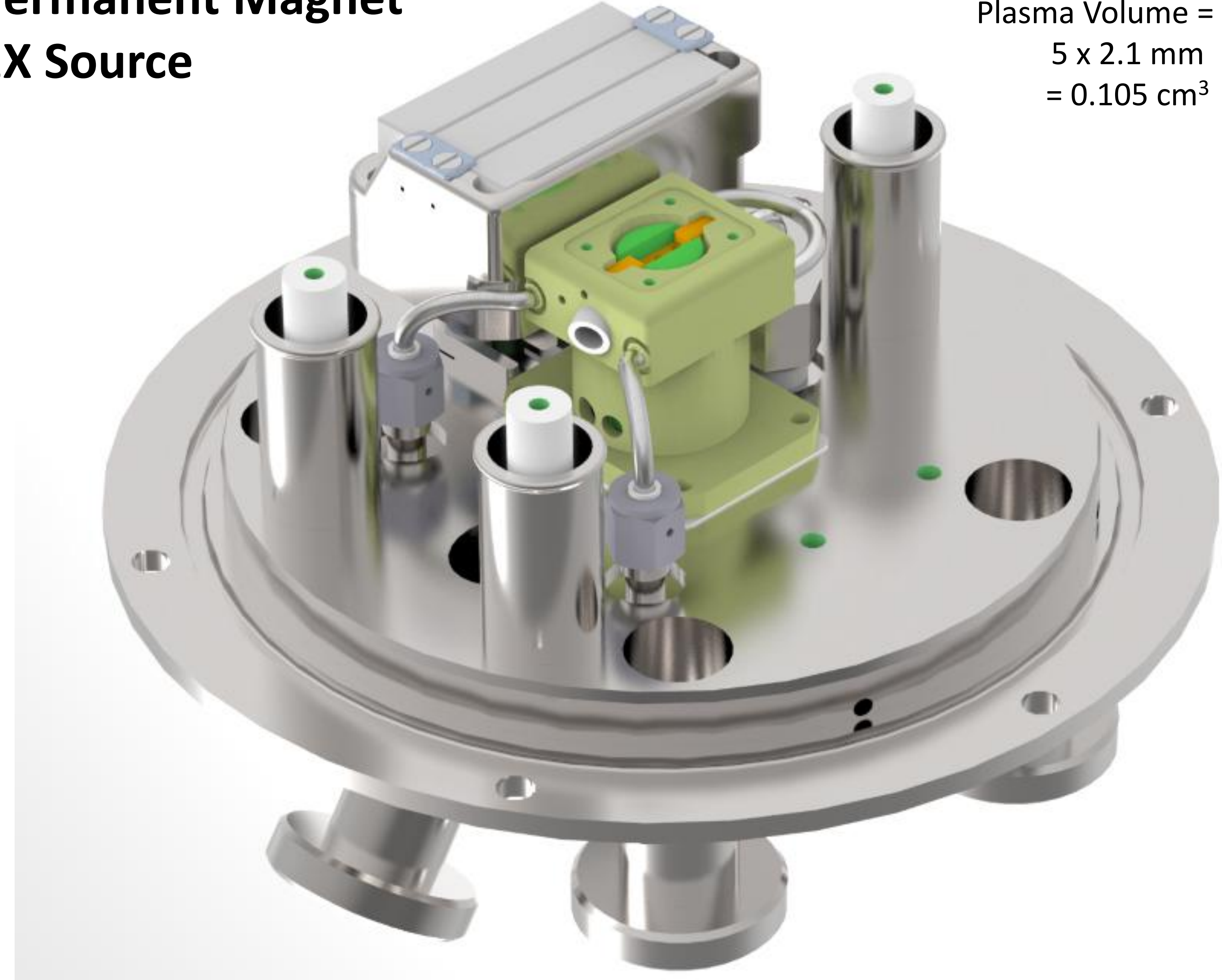


Permanent Magnet
1X Source

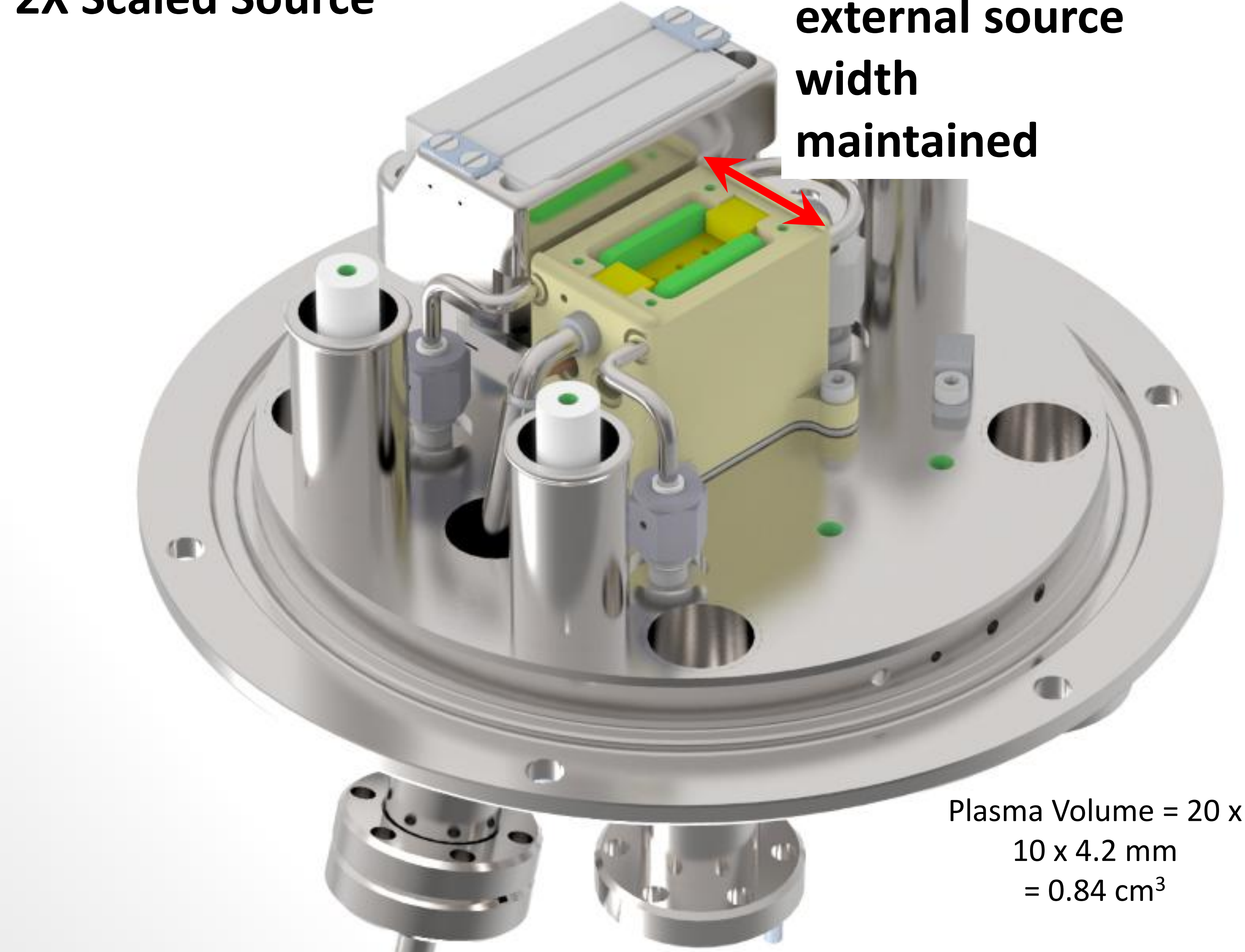


Permanent Magnet
1X Source

Plasma Volume = 10 x 5 x 2.1 mm = 0.105 cm^3

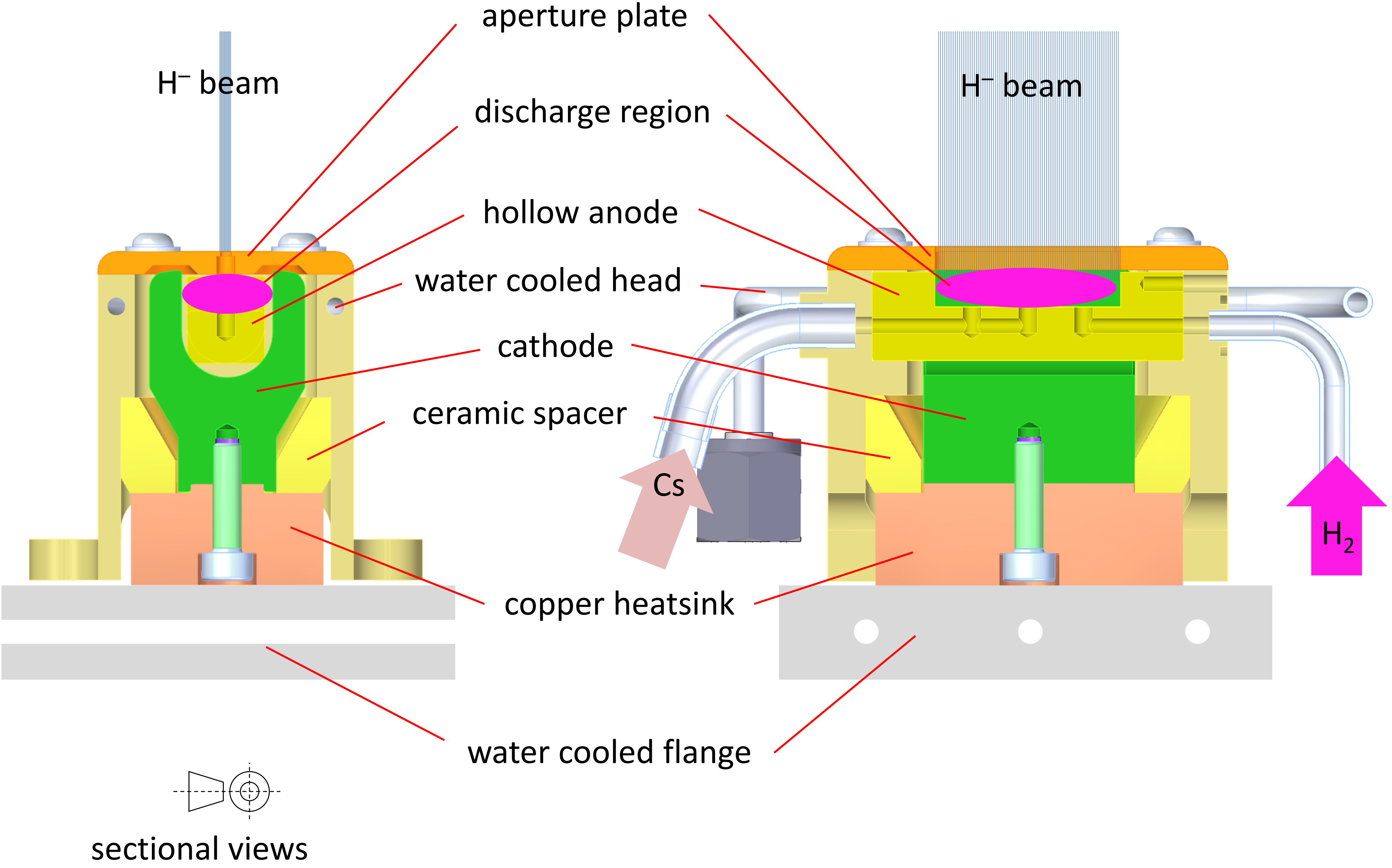


2X Scaled Source

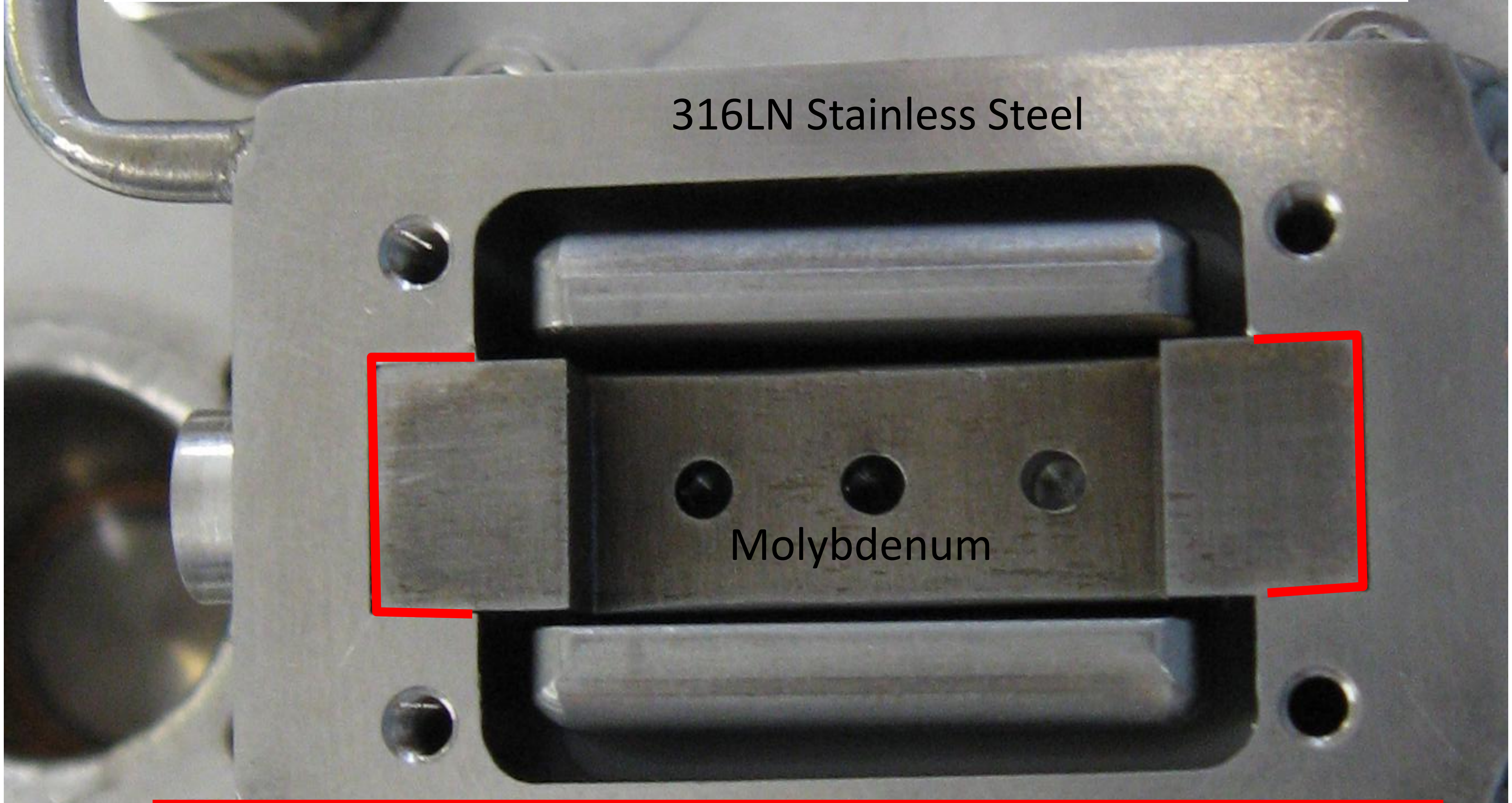


Plasma Volume = 20 x 10 x 4.2 mm = 0.84 cm^3

2X Source Cross-sections



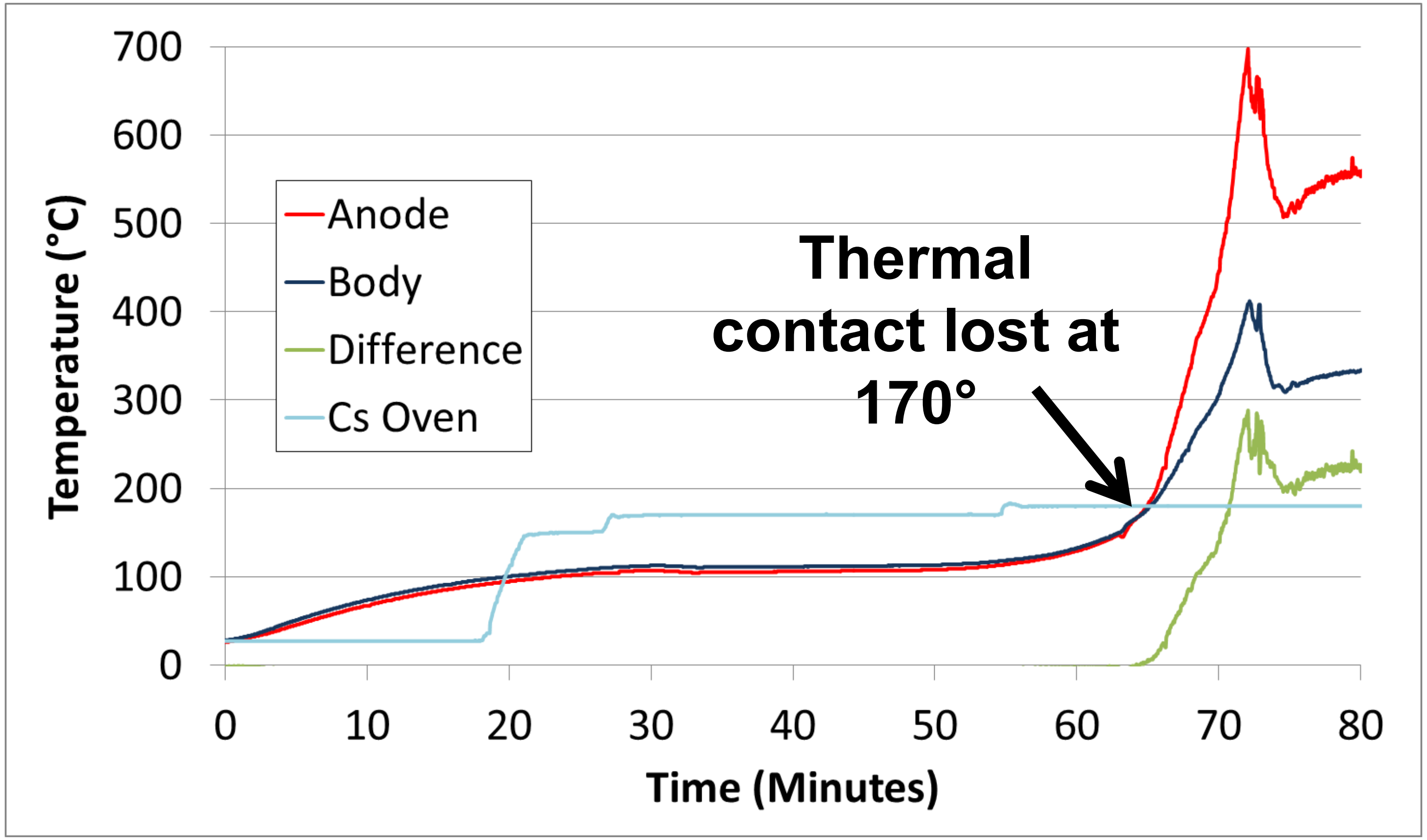
Thermal Contact Resistances



Anode cooling relies on good contact between the molybdenum anode and the stainless steel source body head

Anode Press

Anode Cooling



Dissimilar Expansion Coefficients and Mechanical Tolerances

Component	Length	Tolerance	Width	Tolerance
Anode	33.5	+0.02/+0.01	8.5	+0.028/+0.020
Source Body	33.5	+0.02/-0.00	8.5	+0.01/-0.00

20	C		
Most clearance		Length	Width
	Anode	33.51	8.52
	Source body	33.52	8.51
	Difference	0.01	-0.01
	Inter/Clear	Clearance	Interference
Least Clearance			
	Anode	33.52	8.528
	Source body	33.5	8.5
	Difference	-0.02	-0.028
	Inter/Clear	Interference	Interference

Possible clearance above 130 °C

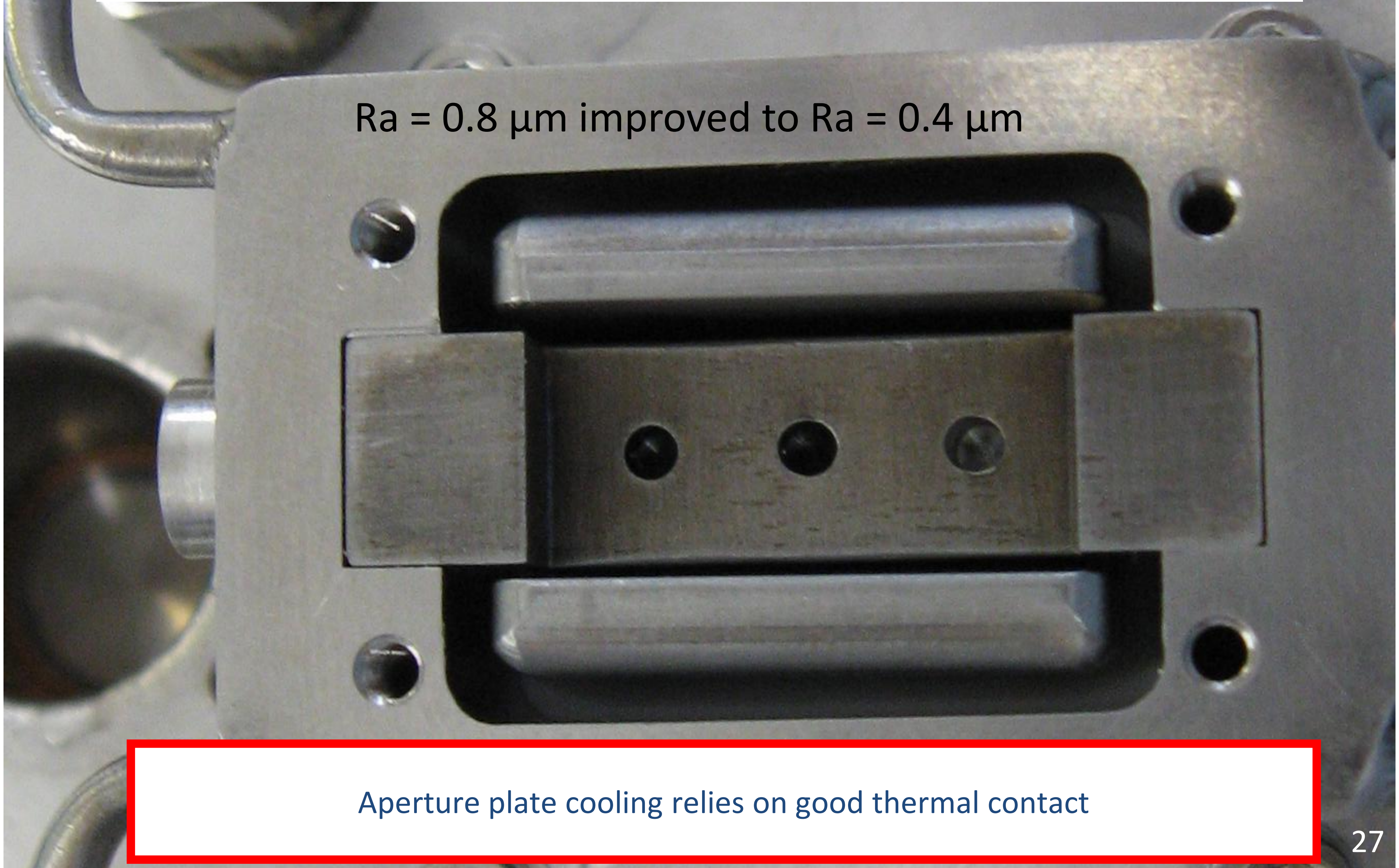
130	C		
Most clearance		Length	Width
	Anode	33.528	8.525
	Source body	33.579	8.525
	Difference	0.051	0.000
	Inter/Clear	Clearance	Clearance
Least Clearance			
	Anode	33.538	8.533
	Source body	33.559	8.515
	Difference	0.021	-0.018
	Inter/Clear	Clearance	Interference

Guaranteed clearance above 320 °C

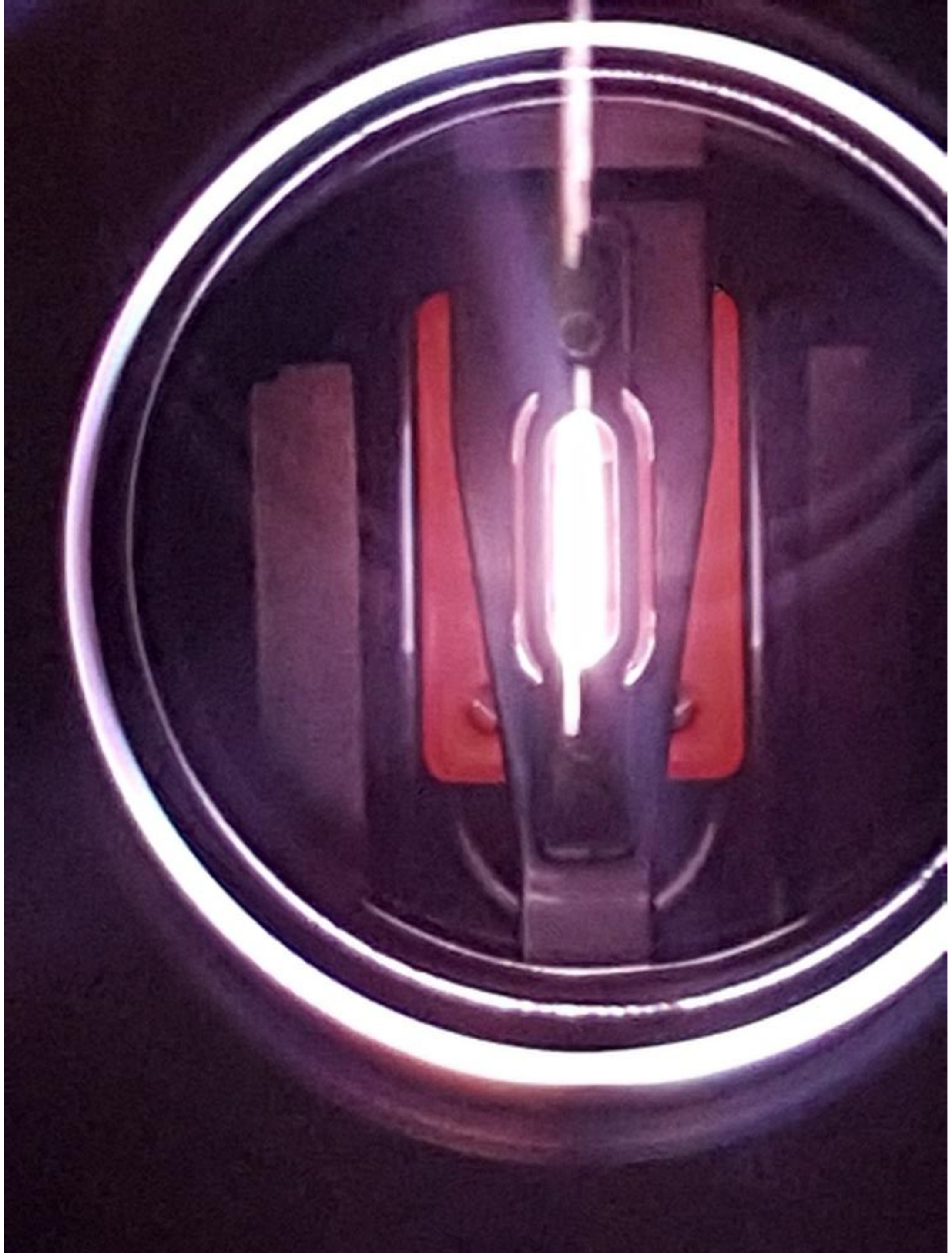
320	C		
Most clearance		Length	Width
	Anode	33.560	8.533
	Source body	33.681	8.551
	Difference	0.121	0.018
	Inter/Clear	Clearance	Clearance
Least Clearance			
	Anode	33.570	8.541
	Source body	33.661	8.541
	Difference	0.091	0.000
	Inter/Clear	Clearance	Clearance

Anode length and width tolerances modified to:
+0.04/+0.03 and +0.048/+0.038

Thermal Contact Resistances



Aperture plate cooling relies on good thermal contact

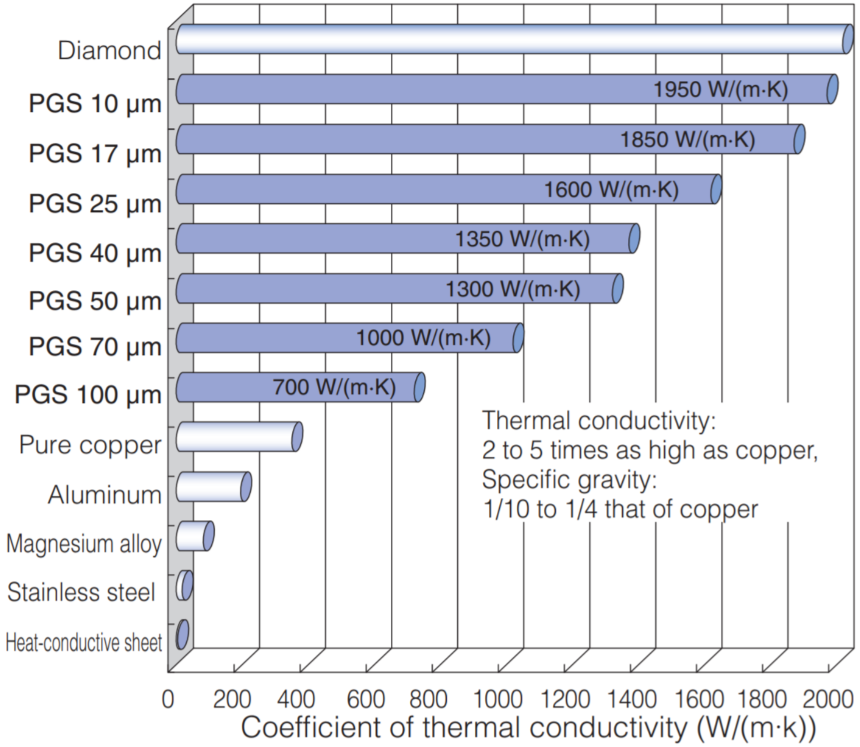


overheating aperture plate

“PGS” Graphite Sheets

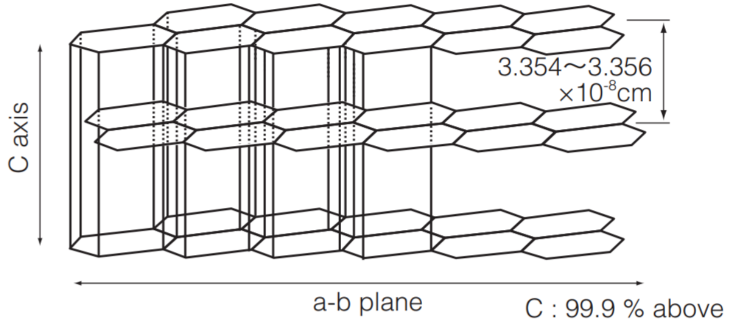
Panasonic

Comparison of thermal conductivity (a-b plane)



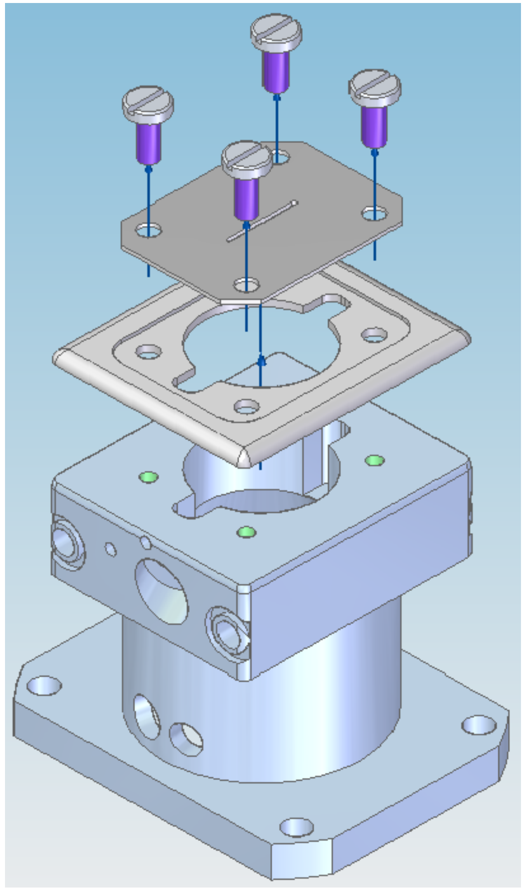
2.5x conductivity of copper!

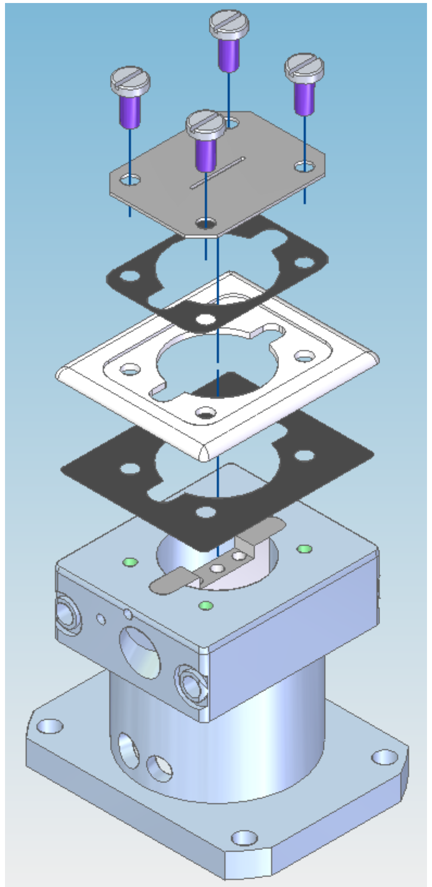
Layered structure of PGS

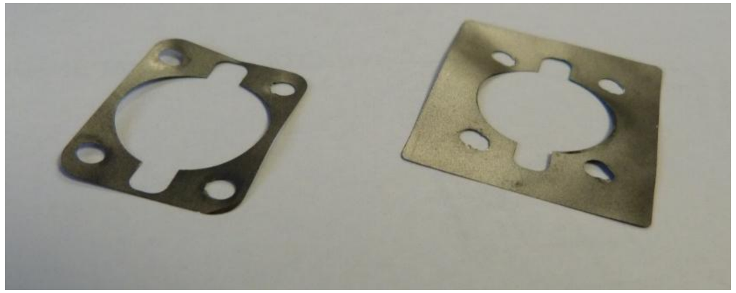


Laser cut 70 µm thick PGS thermal interface gasket

PGS allows biasable aperture plate



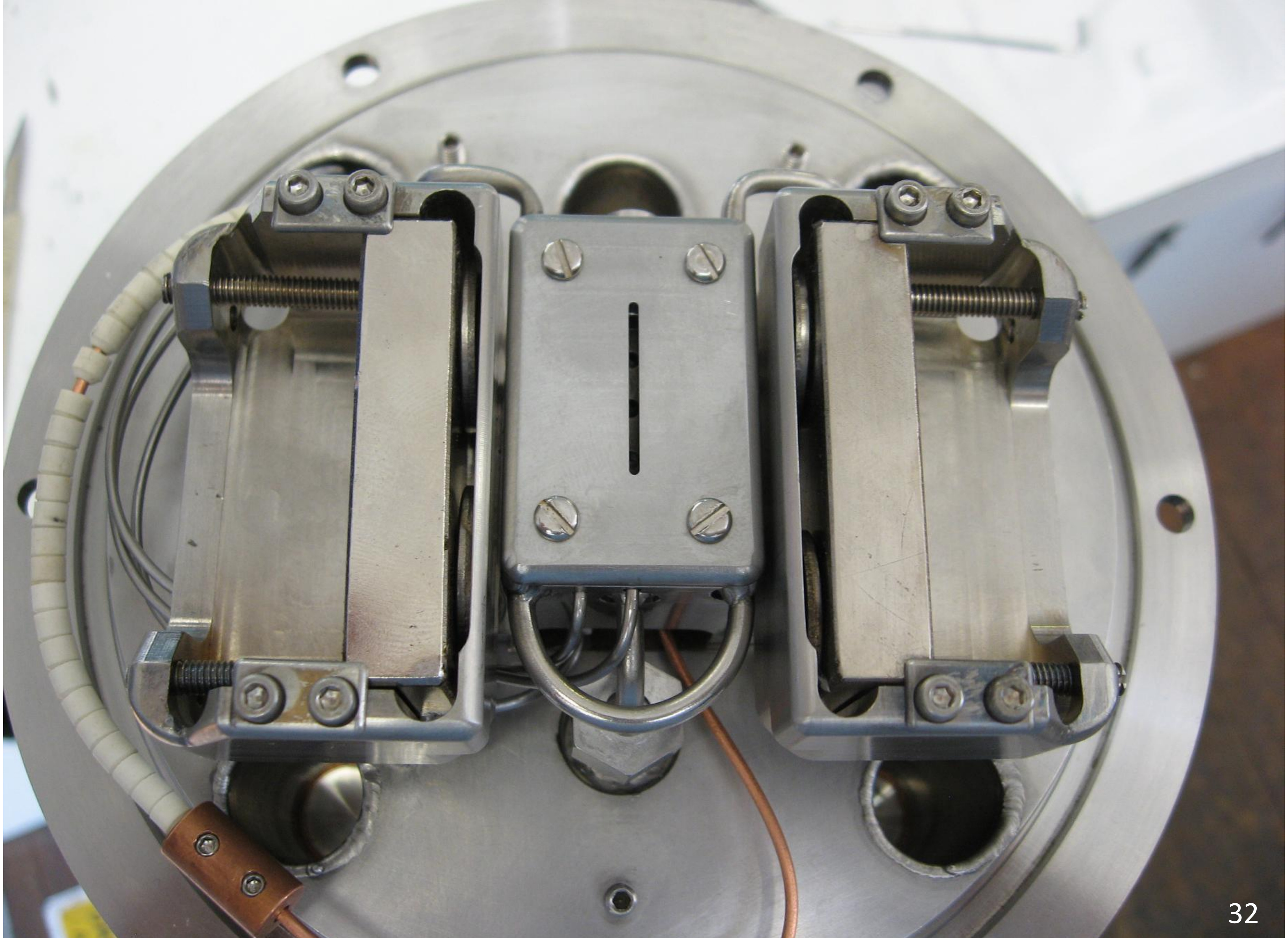




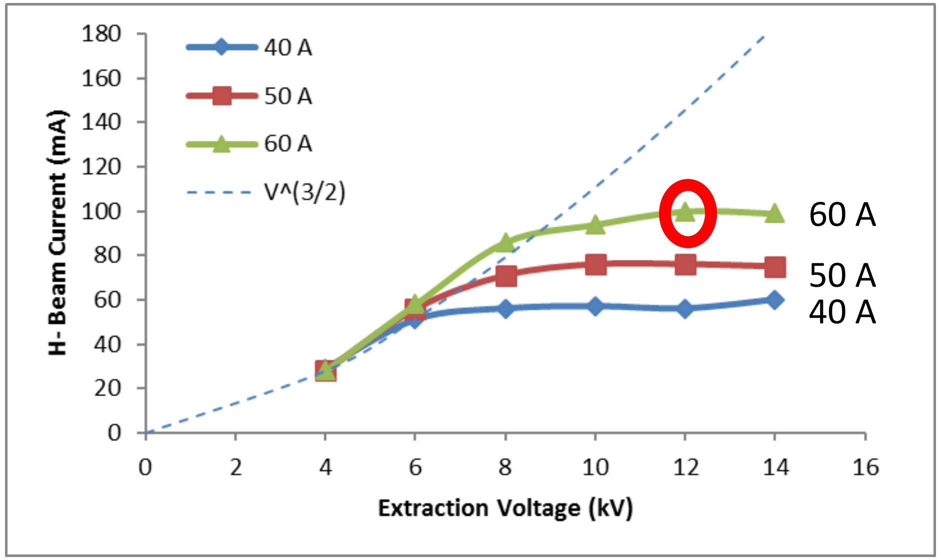
Not implemented on
scaled source

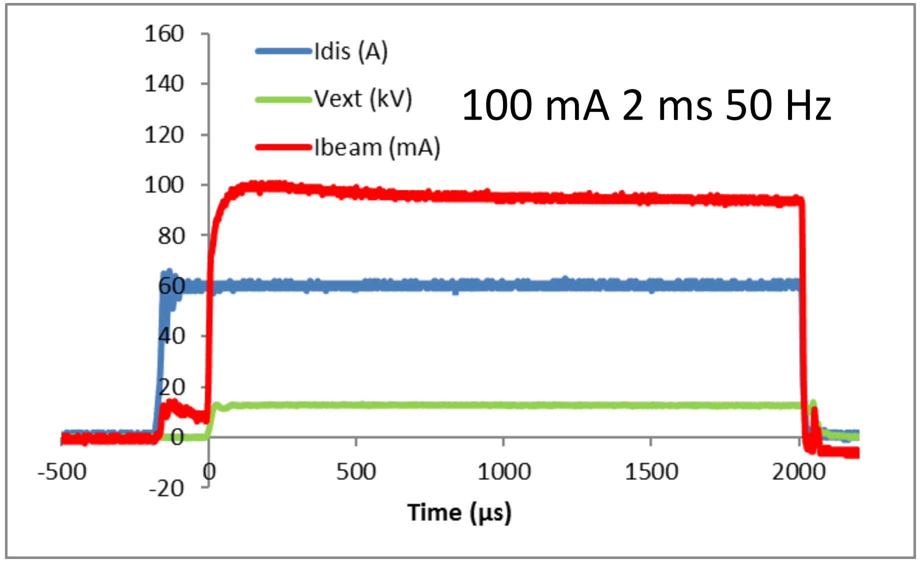
Magnetic Penning Field

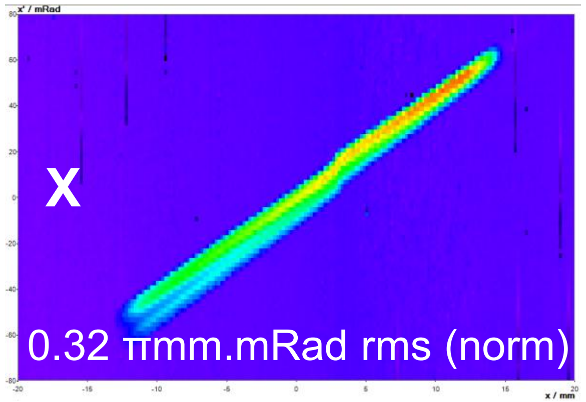
- Cathode separation is doubled in the 2X source
- Penning field should be halved
- 0.084 T found to be best after experimentation

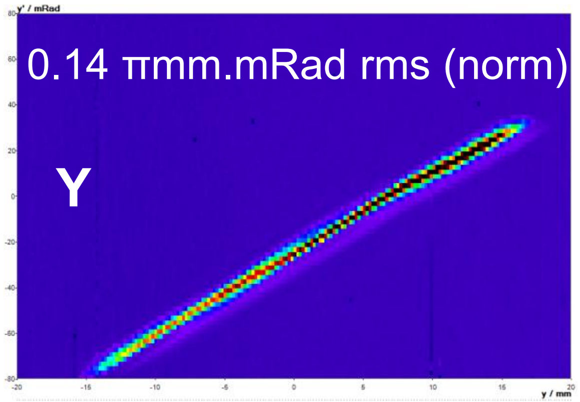


ISIS 2X Penning SPS Full Duty Cycle Results



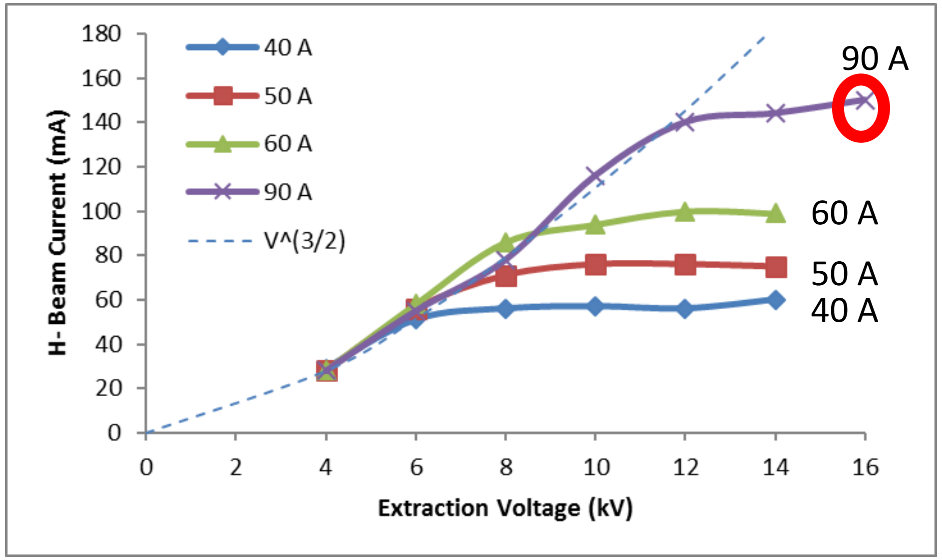


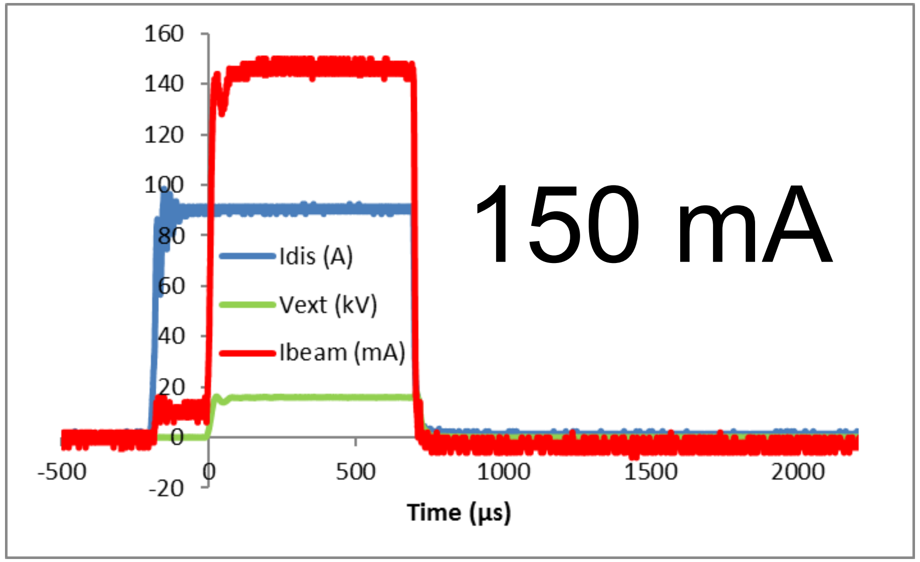




60 A discharge
12 kV extraction voltage
35 keV beam
210ºC Cs oven!

Shorter 700 µs Pulse at 90 A

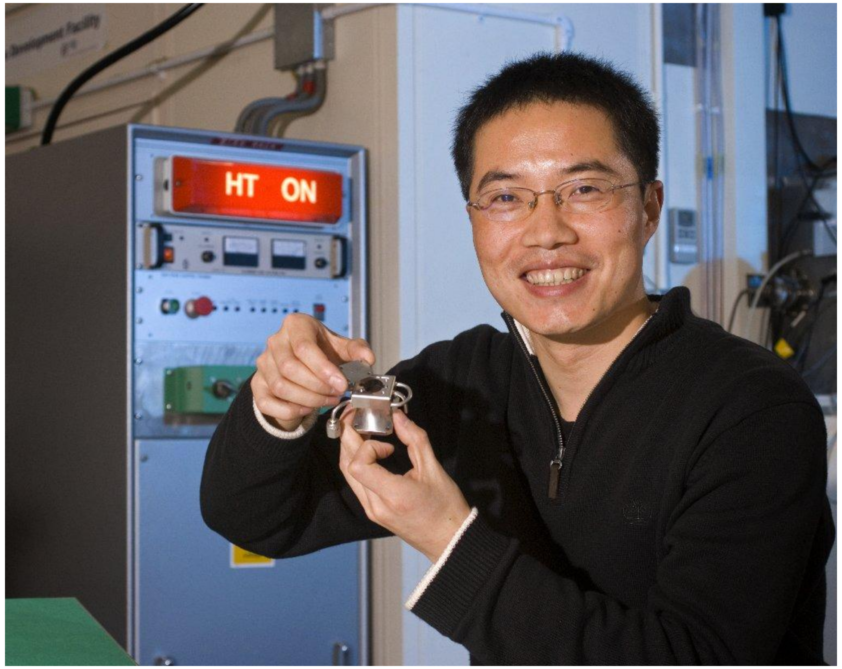


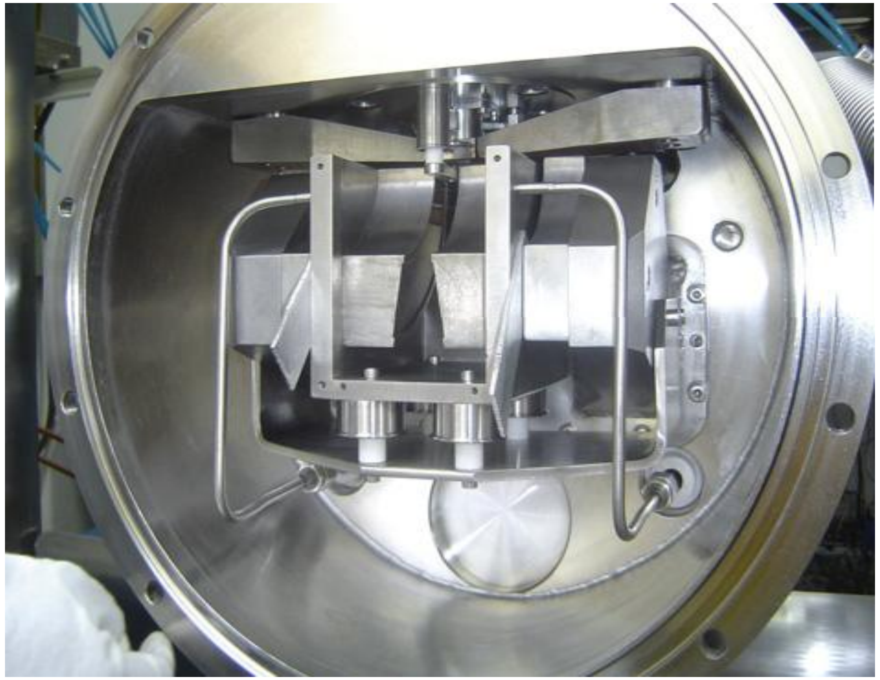


90 A discharge
16 kV extraction voltage
35 keV beam
210ºC Cs oven
150 mA 700 µs 50 Hz

ISIS Source Around the World

IHEP China copied the ISIS source on CSNS

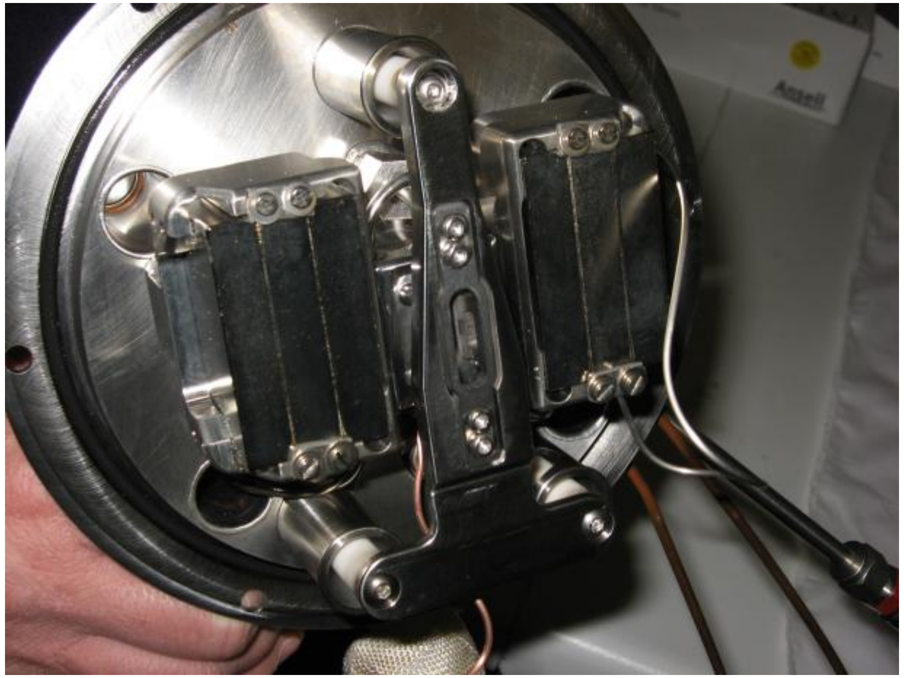




CSNS 中国散裂中子源
China Spallation Neutron Source

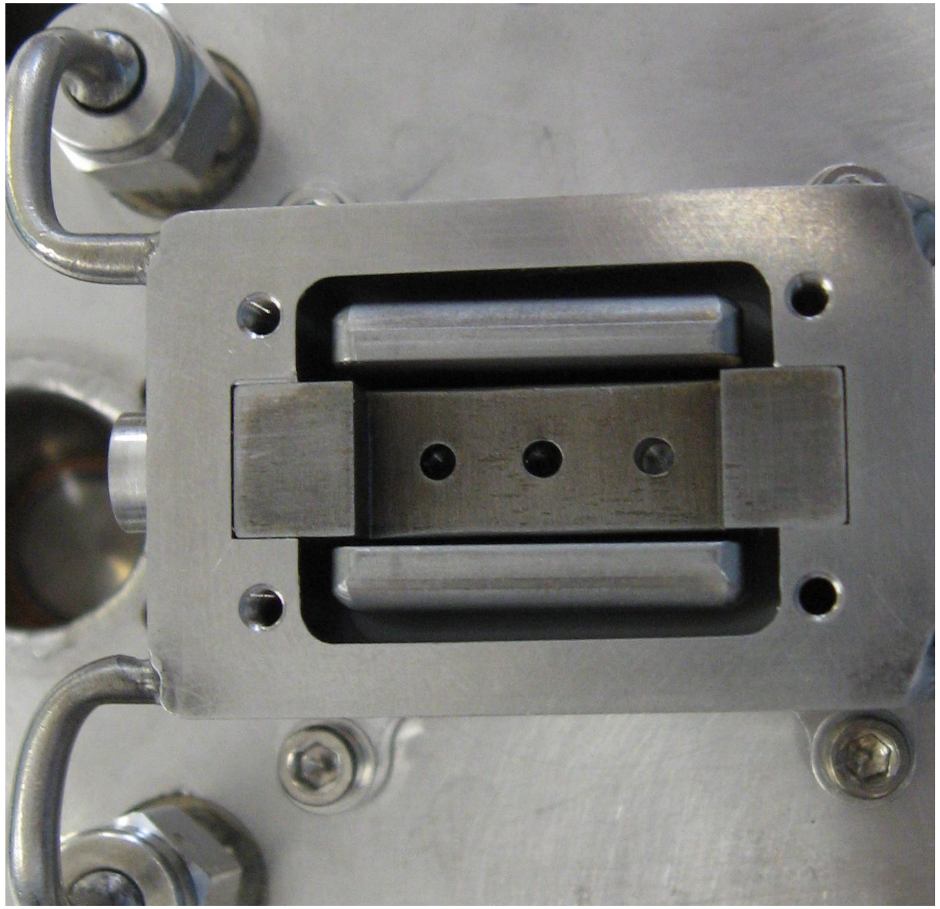
ISIS Source Around the World

University of the Basque Country developed an Ion Source Test Stand in collaboration with ISIS

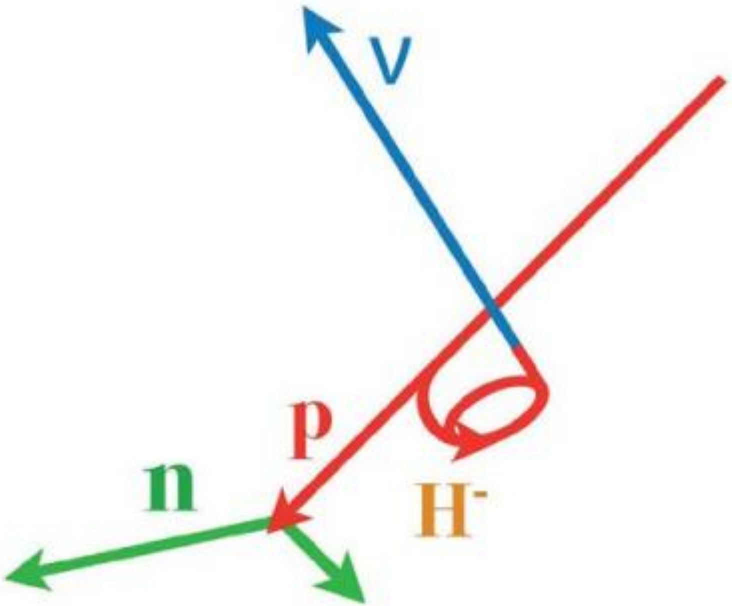


ESS Bilbao

ISIS Source Around the World



The 2X Penning is a source candidate



The ESS
Neutrino Super
Beam Project

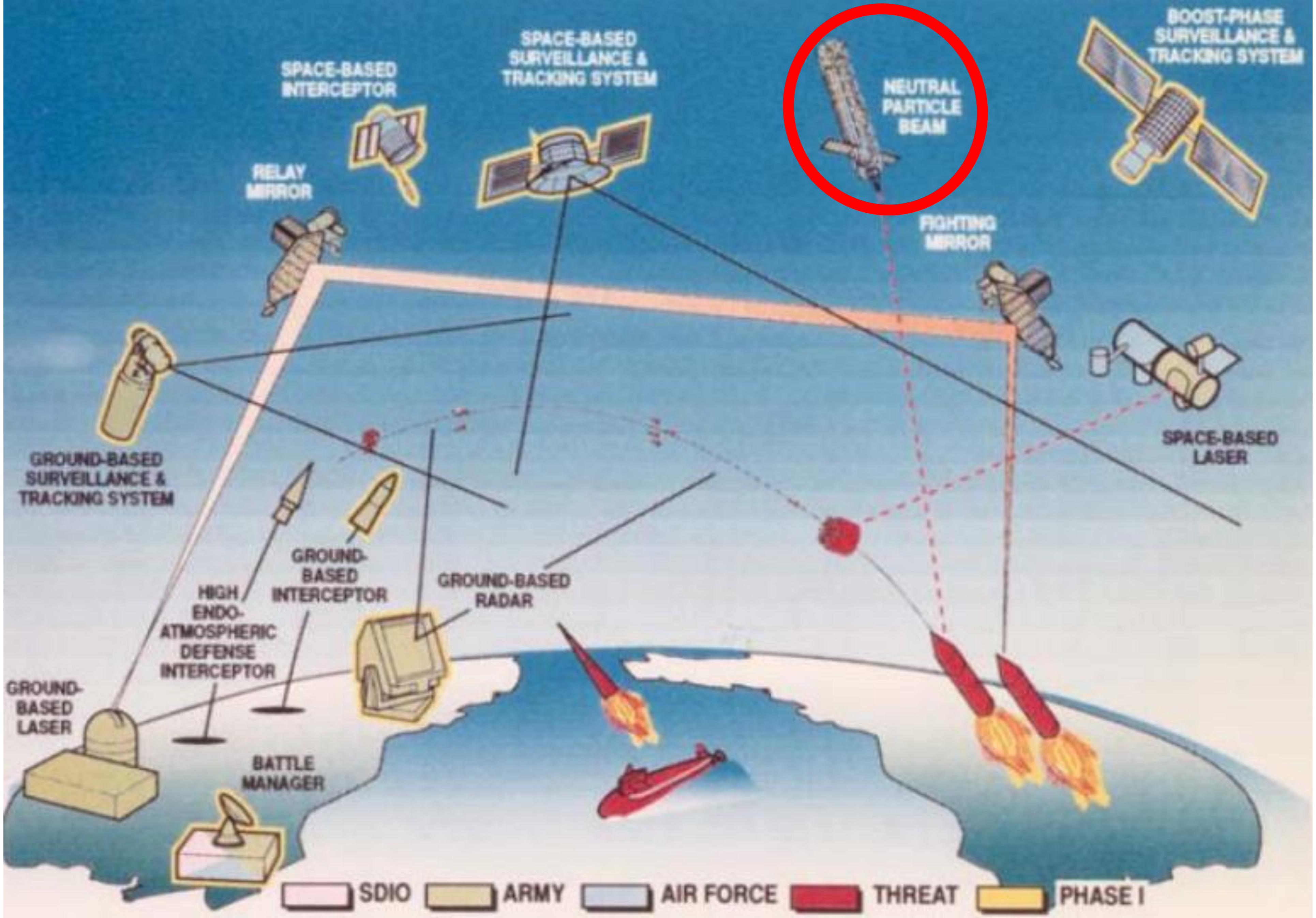
How the Penning Source Ended the Cold War

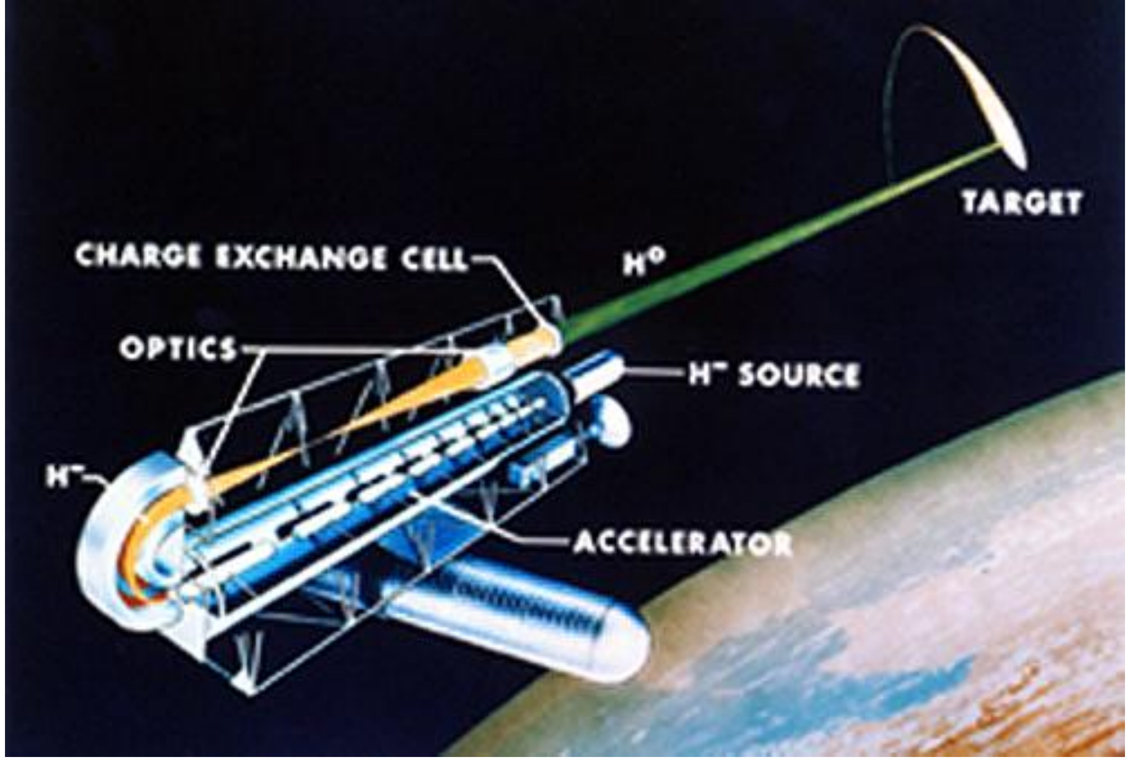
MAD Strategy:
Mutually
Assured
Destruction

Star Wars

STRATEGIC DEFENSE INITIATIVE
DEPARTMENT OF DEFENSE

23 March 1983:
Regan announces the Strategic Defence Initiative (SDI)


SPACE-BASED INTERCEPTOR
SPACE-BASED SURVEILLANCE & TRACKING SYSTEM
NEUTRAL PARTICLE BEAM
BOOST-PHASE SURVEILLANCE & TRACKING SYSTEM
RELAY MIRROR
FIGHTING MIRROR
SPACE-BASED LASER
GROUND-BASED SURVEILLANCE & TRACKING SYSTEM
GROUND-BASED INTERCEPTOR
GROUND-BASED RADAR
HIGH ENDO-ATMOSPHERIC DEFENSE INTERCEPTOR
GROUND-BASED LASER
BATTLE MANAGER
SDIO
ARMY
AIR FORCE
THREAT
PHASE I



Beam Experiment Aboard Rocket (BEAR)

13 July 1989:

H^- Ions from a Penning ion source
10 mA, 50 µs pulses at 5 Hz
425 MHz 1 MeV RFQ
Gas-cell neutralizer
Los Alamos National Laboratory

11-minute flight to a maximum altitude of 195 km

Less than 4 months later...

9 November 1989

The End

Thank you for listening

Questions?