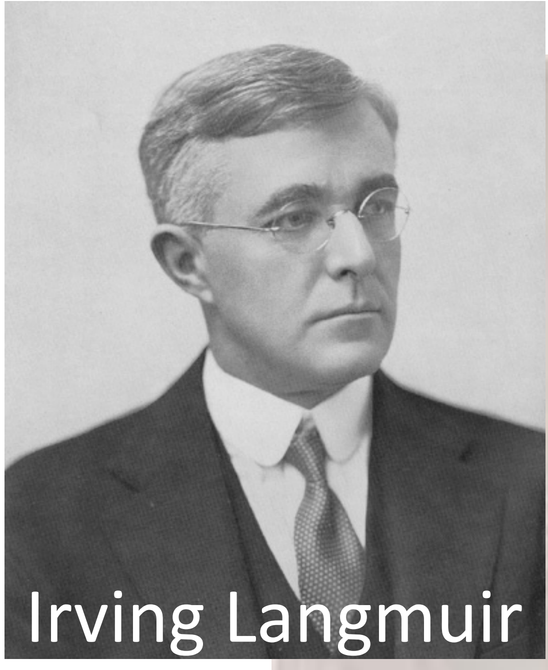
Negative Ion Sources: Magnetron and Penning

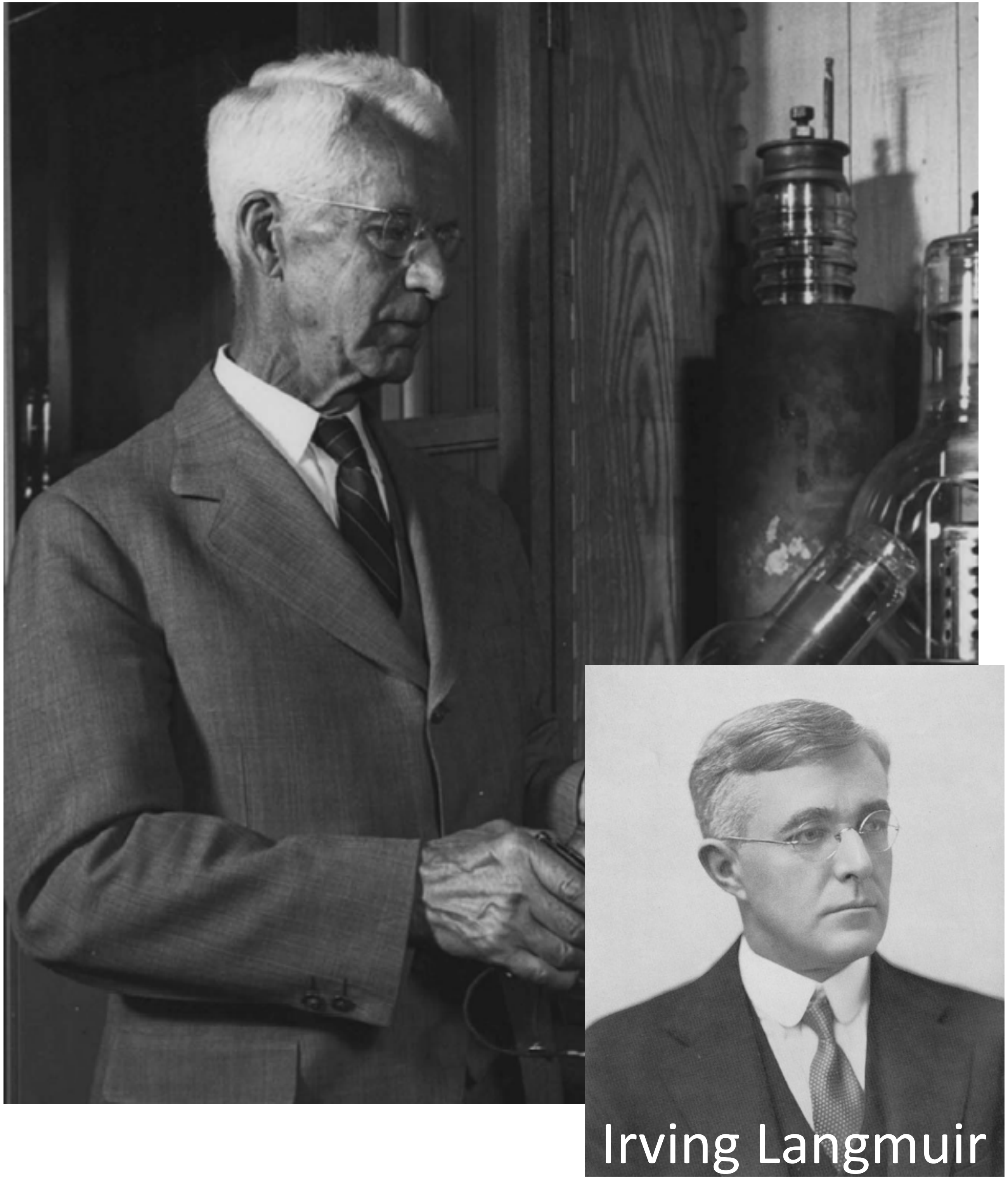
Dan Faircloth
Ion Source Section Leader
Rutherford Appleton Laboratory

Overview

- History
- The caesium revolution
- Magnetron sources
- Penning sources
- Failure modes and sputtering
- ISIS Developments

GE Research Lab, Schenectady, NY 1916





Irving Langmuir

Albert Hull

Using magnetism to find alternatives to patented electrostatic control of valves

E x B

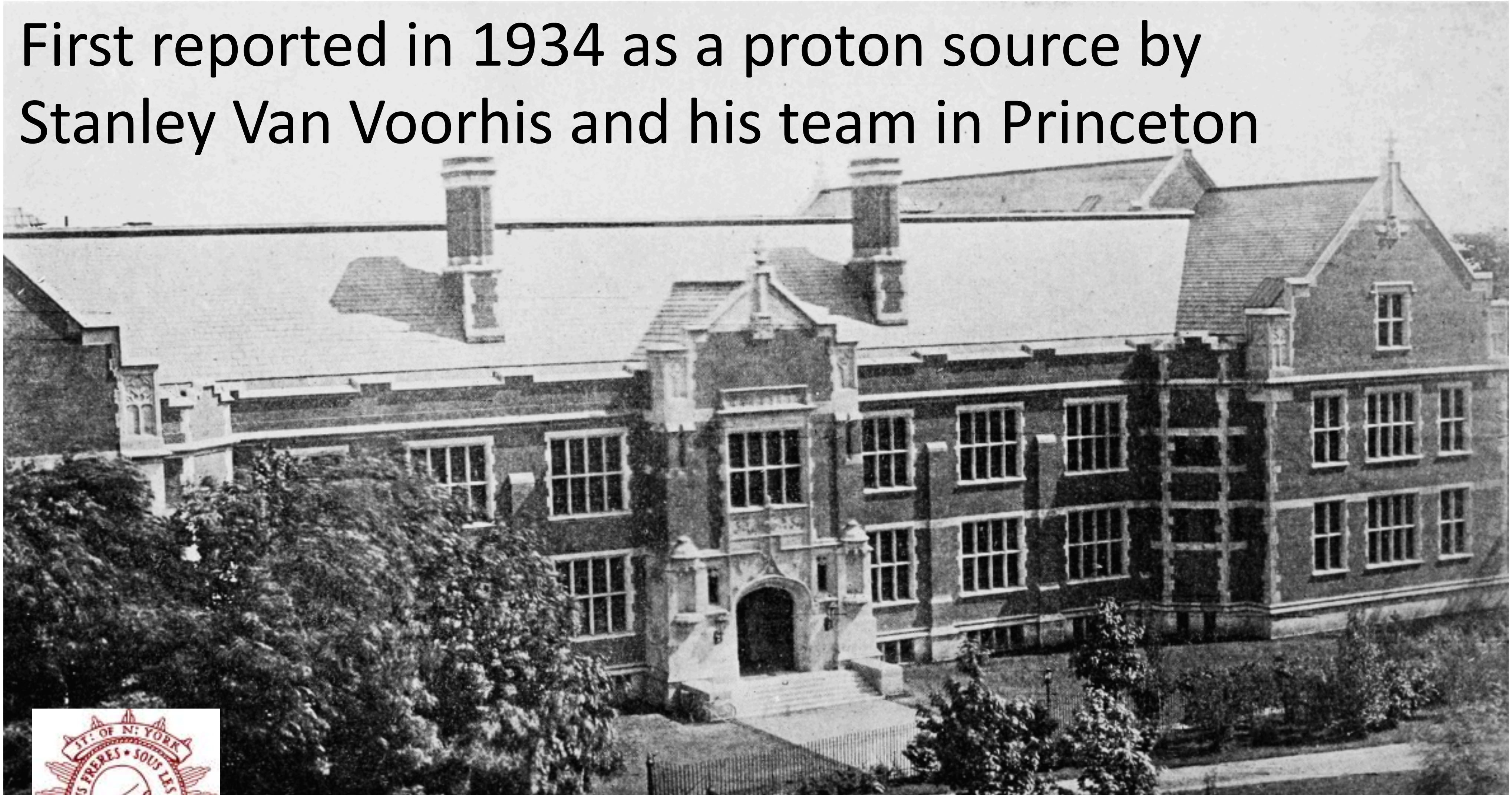
1920 Comet valves?
Boomerang valves?
Ballistic valves?
MAGNETRON VALVES

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

Langmuir talks to his fellow New England scientists

Magnetron Ion Source

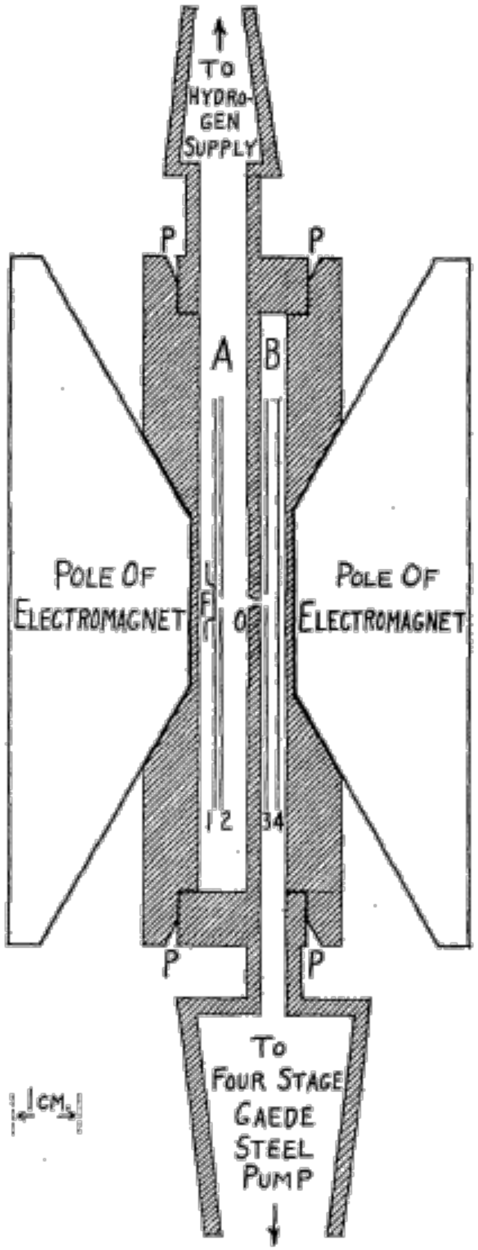
First reported in 1934 as a proton source by Stanley Van Voorhis and his team in Princeton



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

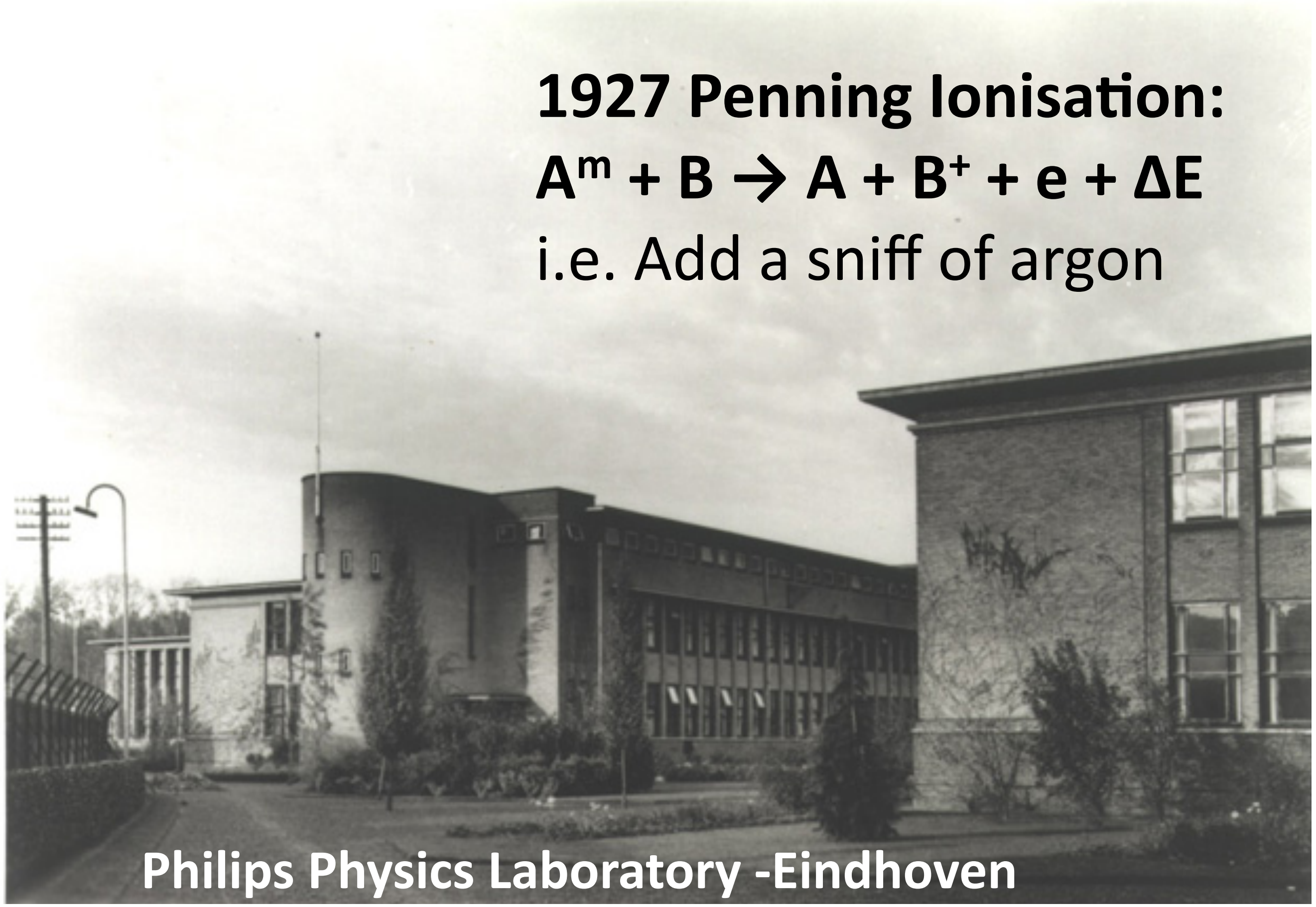
Penning Ion Source

Louis Maxwell
The Franklin Institute
Philadelphia 1930



Frans Penning

1937 Penning Ionisation Gauge or Philips Ionisation Gauge (PIG)



1927 Penning Ionisation:

$$\mathbf{A^m + B \rightarrow A + B^+ + e + \Delta E}$$

i.e. Add a sniff of argon

Philips Physics Laboratory -Eindhoven

Spawn a series of variations:

Penning Source

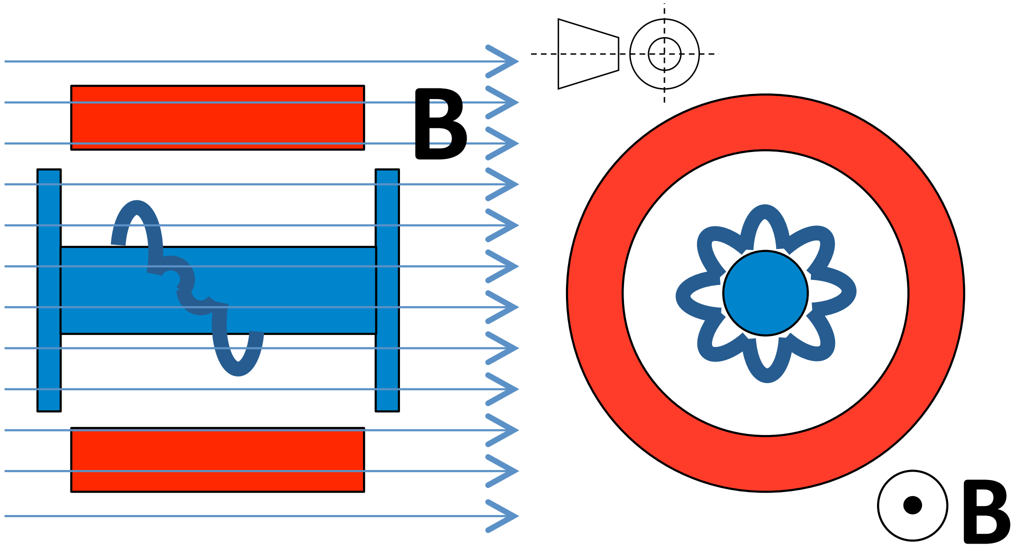
- Calutron source
- Bernas source
- Nielson source

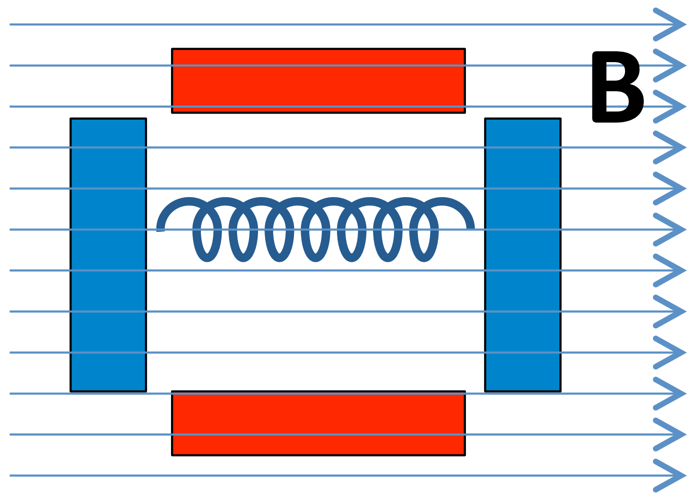
Magnetron Source

- Freeman source

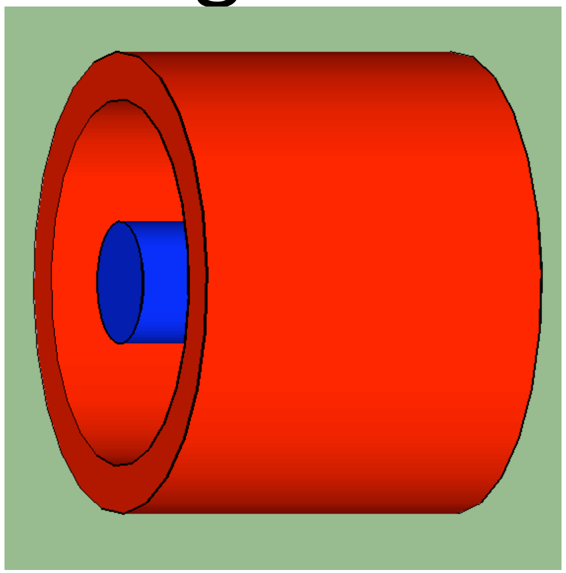
The Penning style source (Calutron) starts the Cold War

Fundamental Geometry

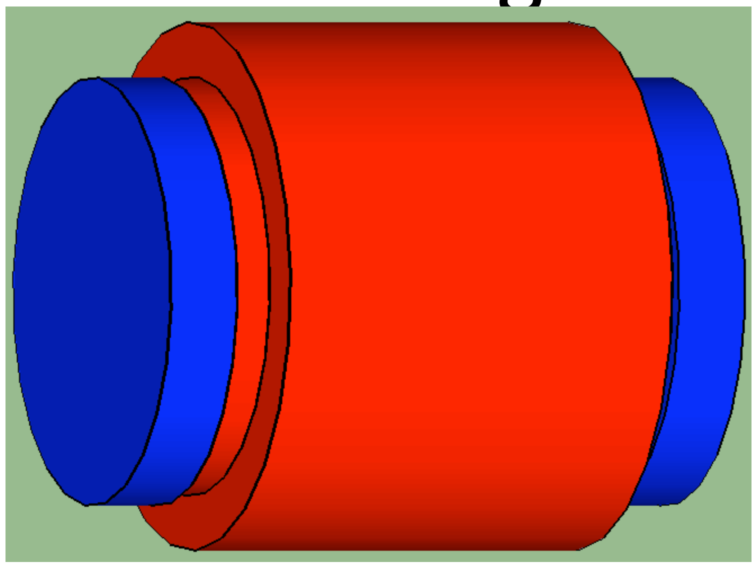




Magnetron

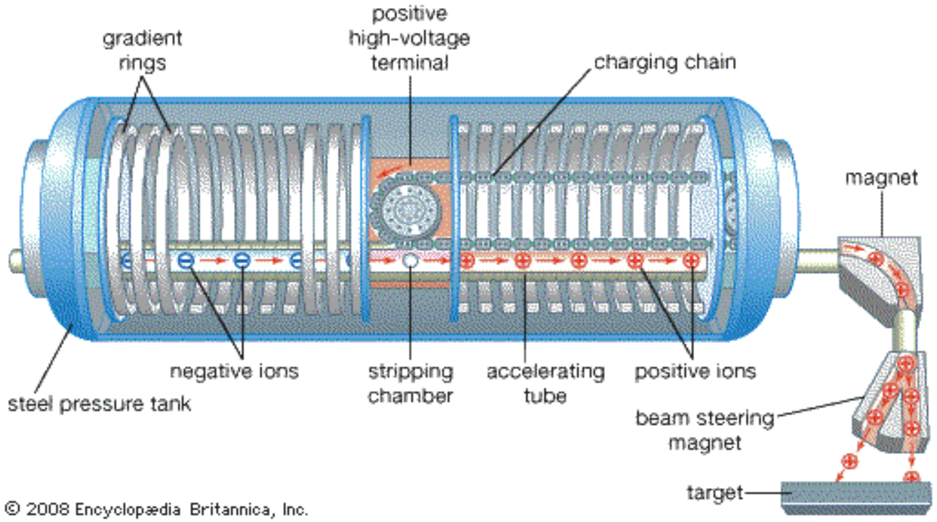


Penning

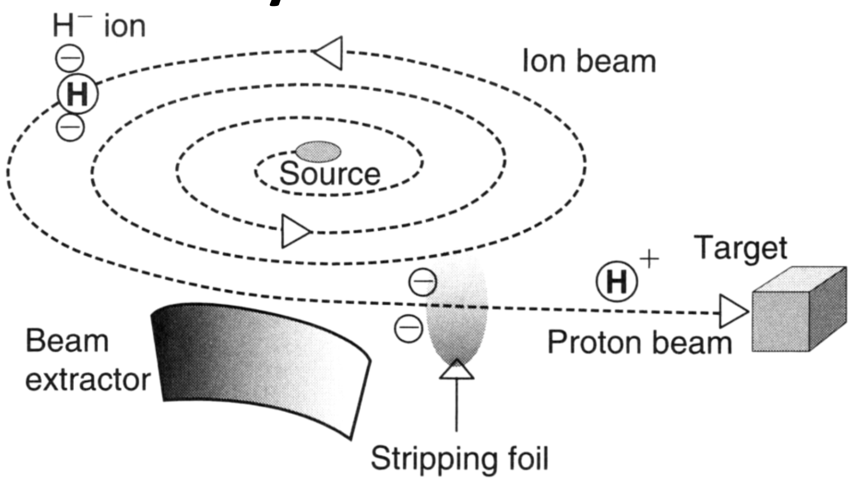


Increasing Need for Negative Ion Beams

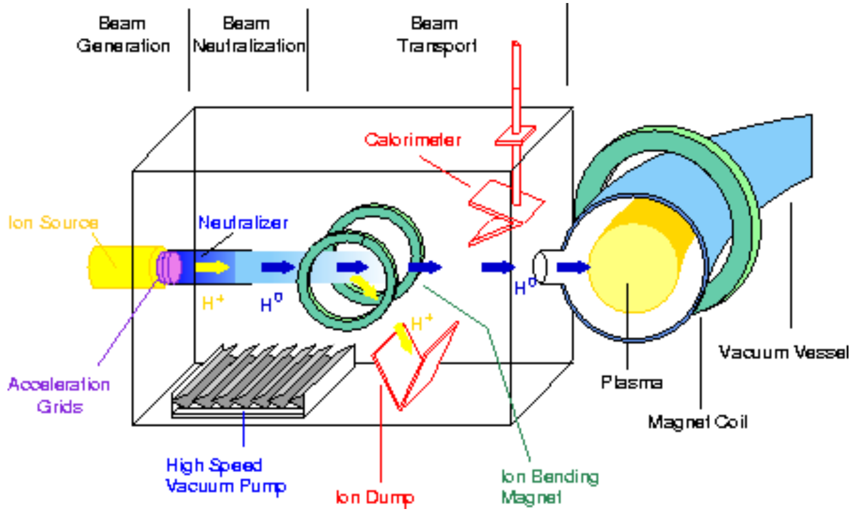
Tandem accelerators



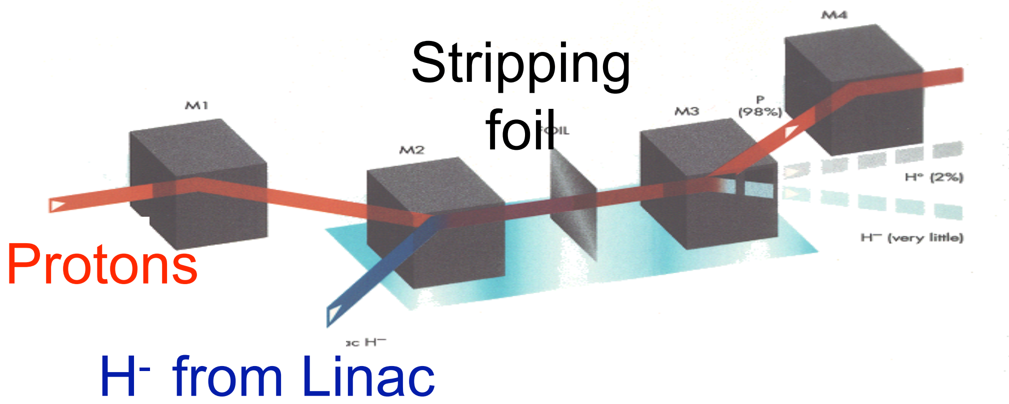
Cyclotron extraction



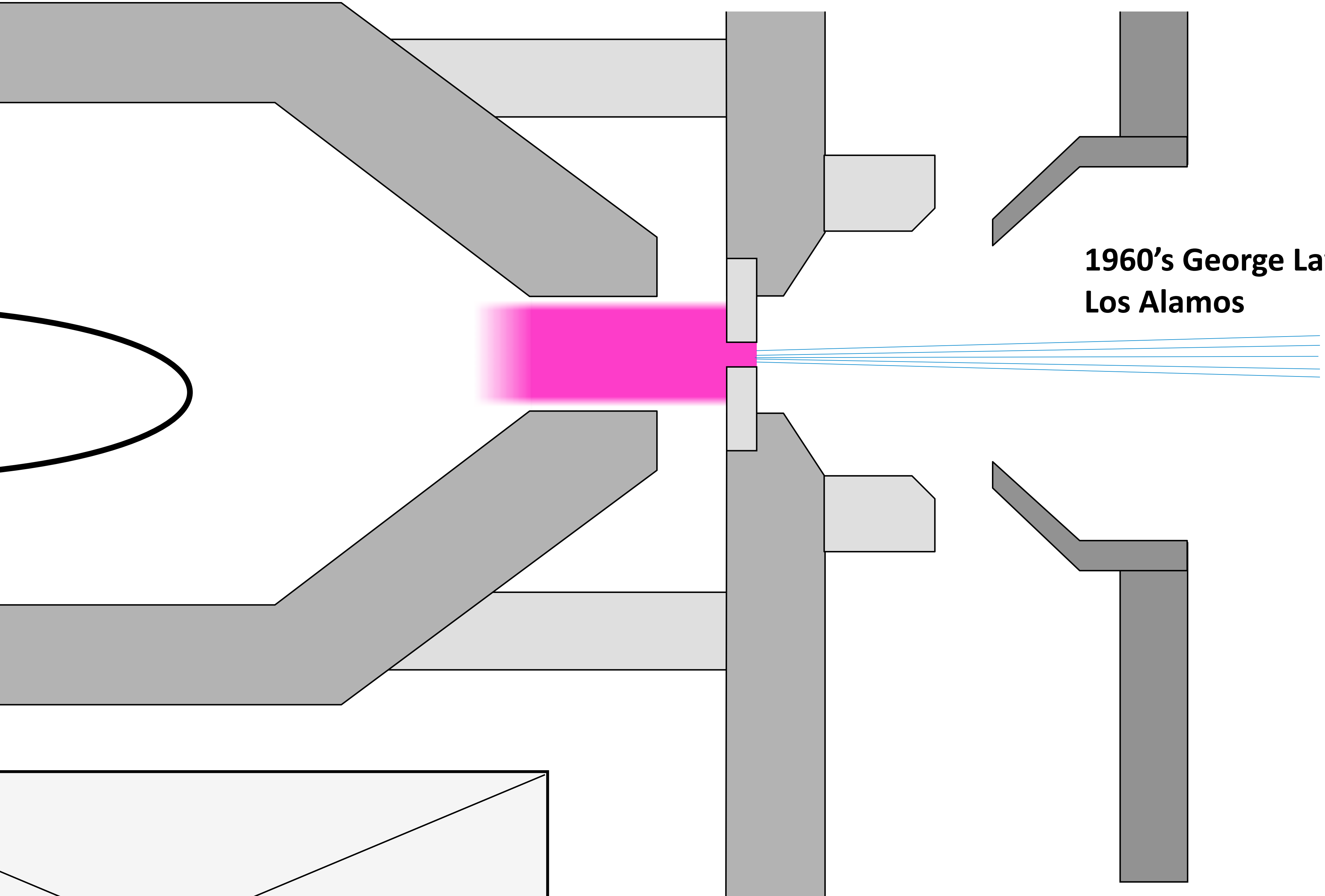
Neutral Beams



Multi-turn injection into rings

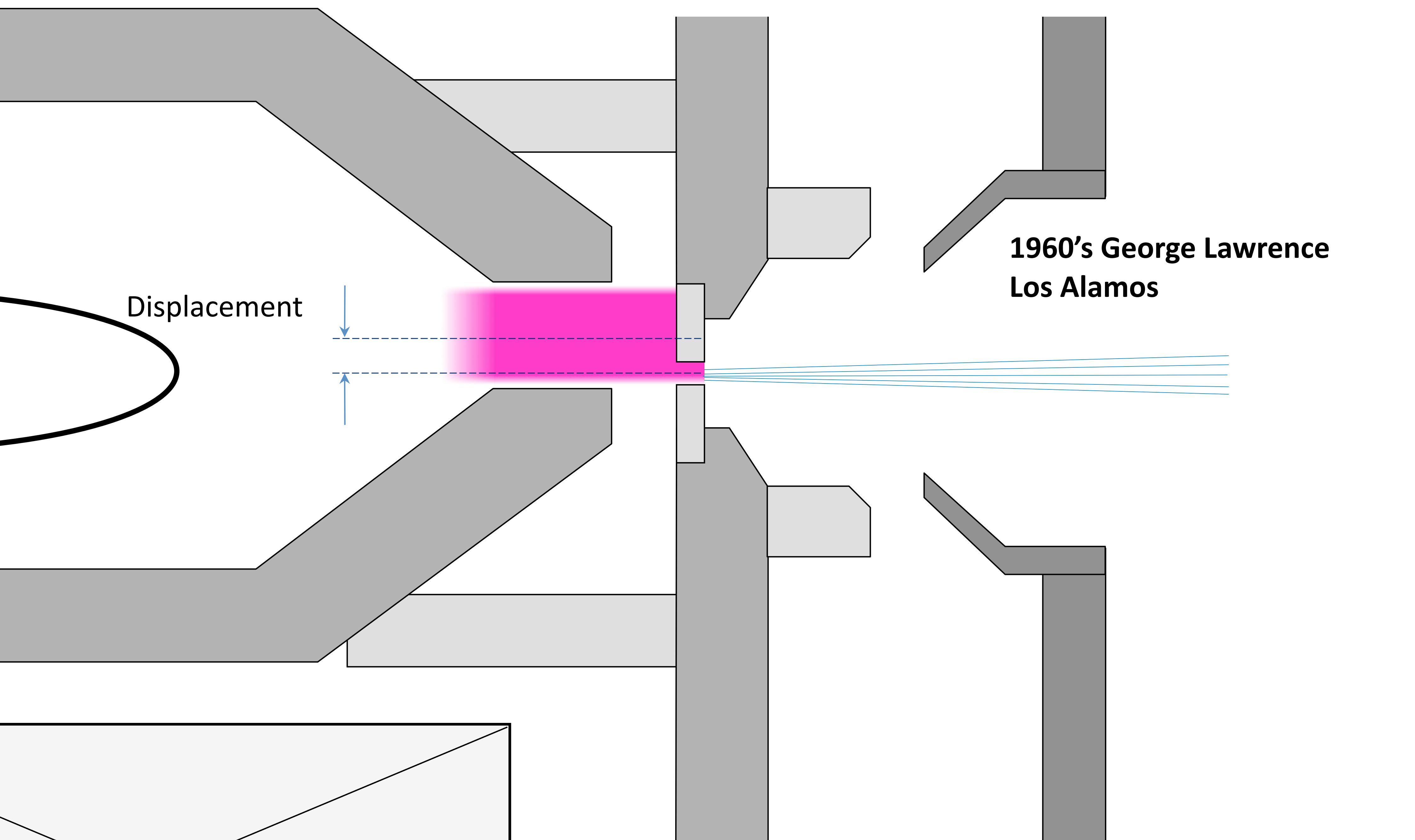


Off Axis Duoplasmatron Extraction

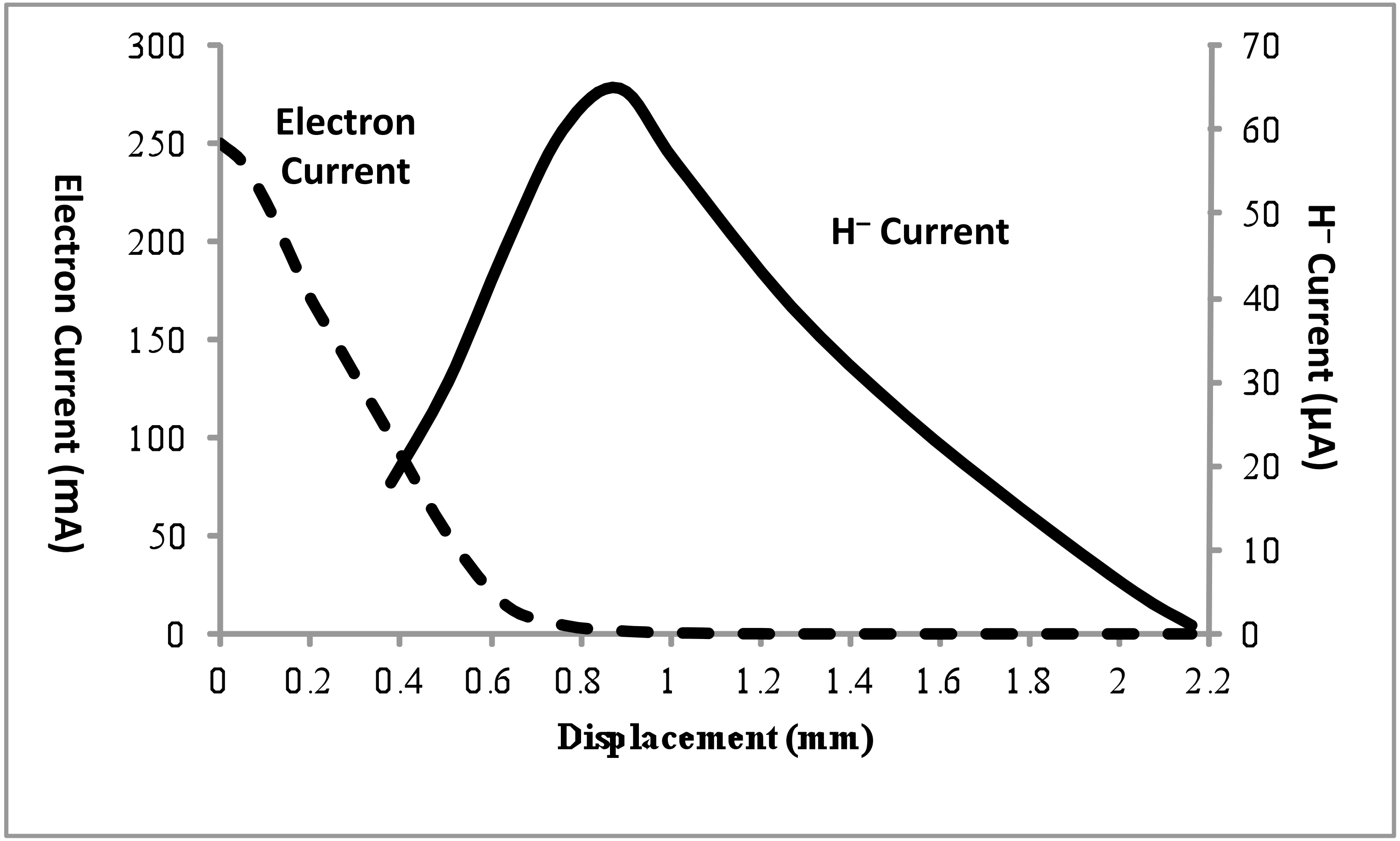


1960's George Lawrence
Los Alamos

Off Axis Duoplasmatron Extraction



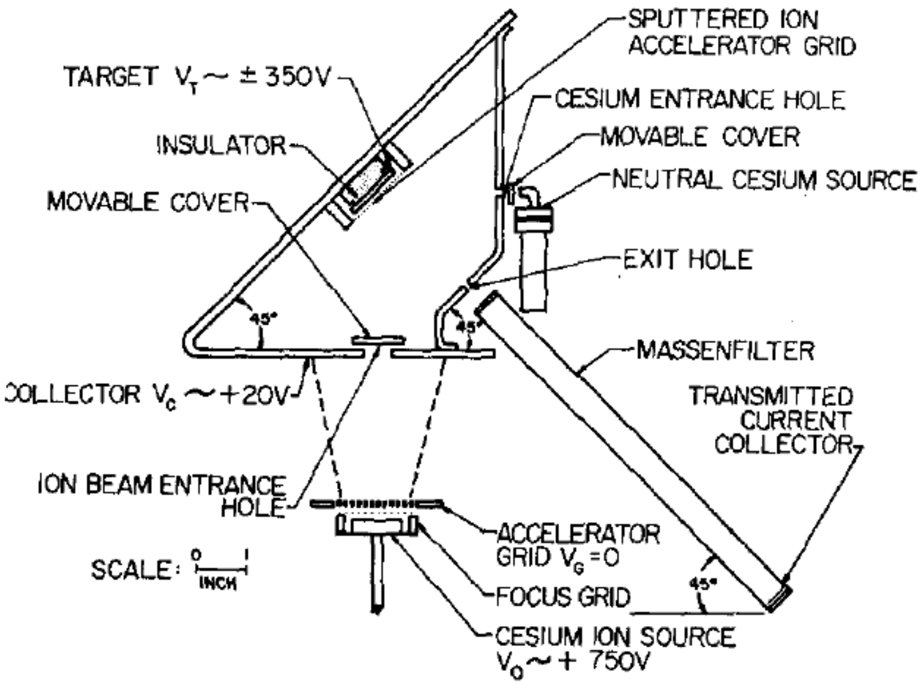
Off Axis Duoplasmatron Extraction



1962 Victor Krohn

Space Technology Laboratories inc.
Redondo Beach, California

Cs^+ ions on a metal target
increase yield of sputtered
negative ions
by an order of magnitude



Early 1970s Budker Institute of Nuclear Physics Novosibirsk

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

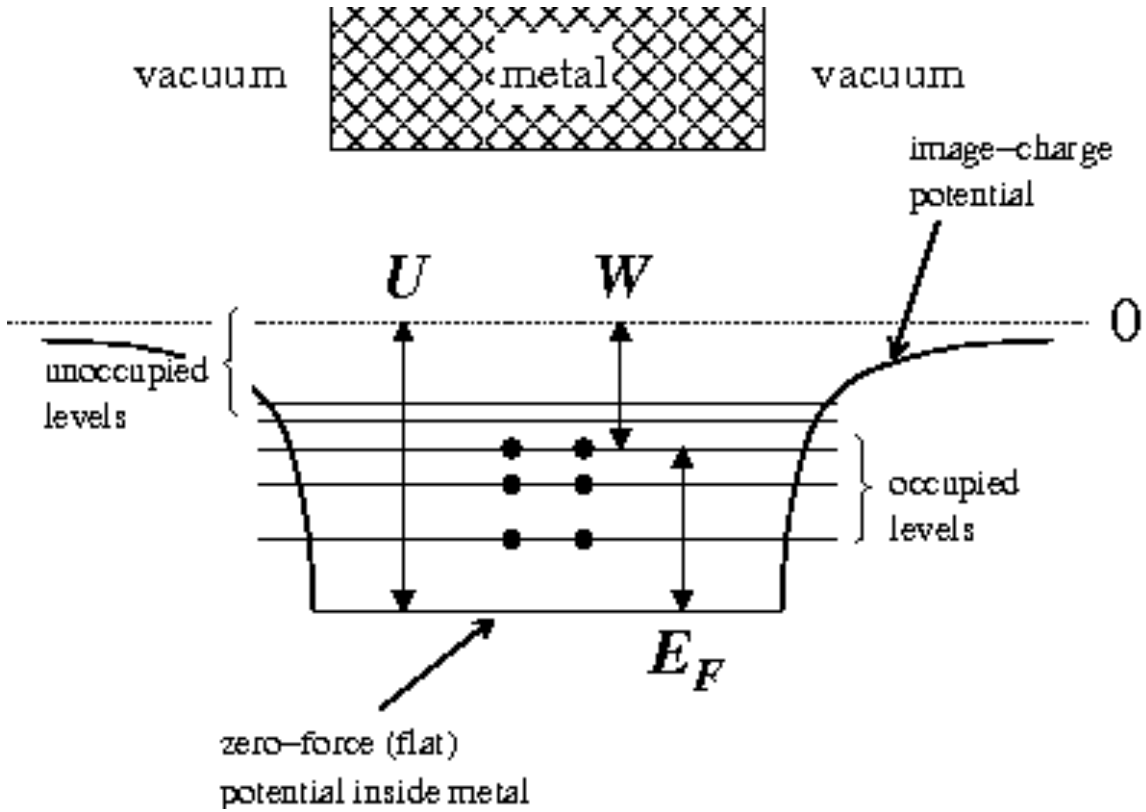
Surface Plasma Sources (SPS)

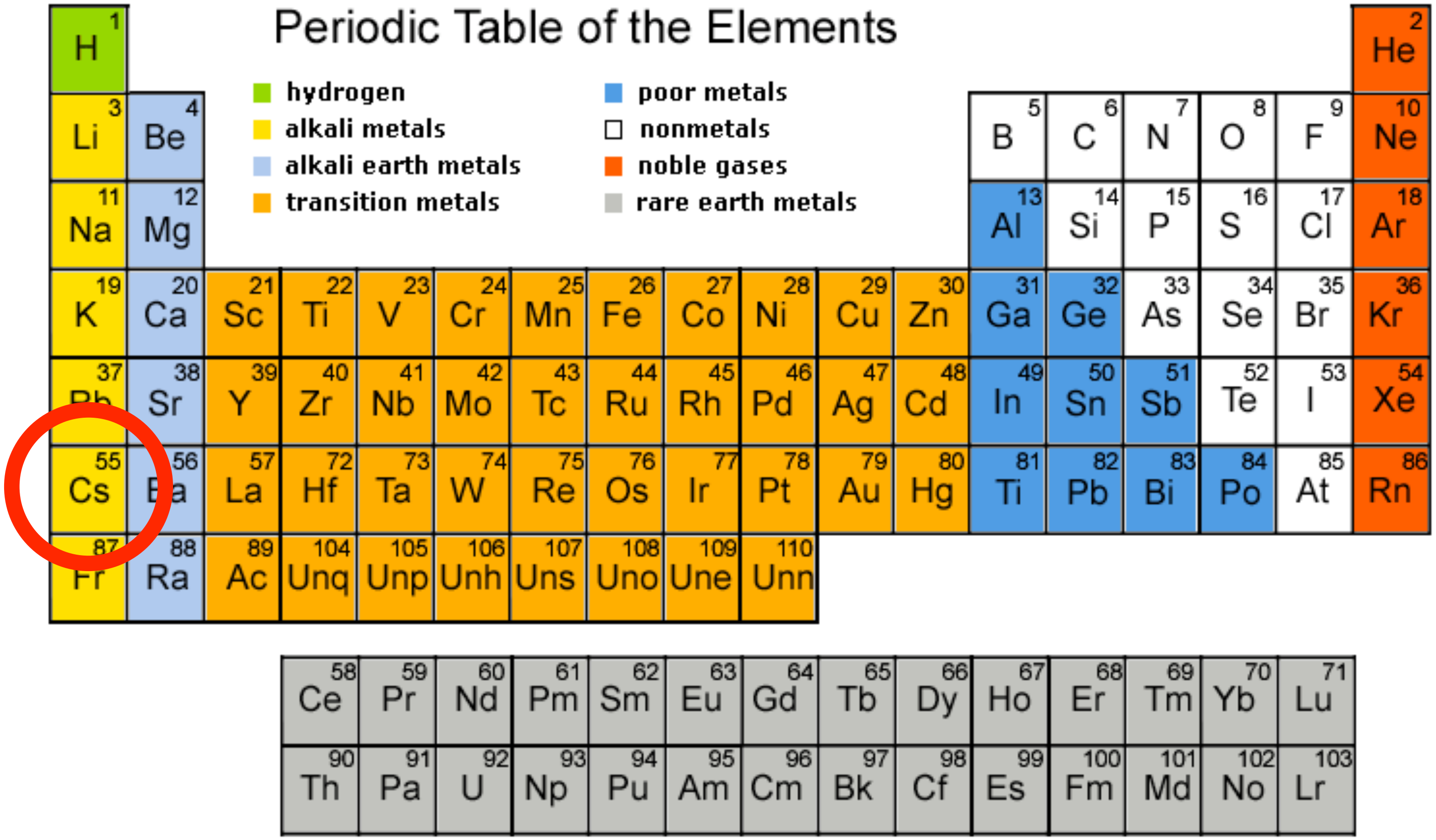
Gennady Dimov   Yuri Belchenko   Vadim Dudnikov


5 g
Caesium
Ampoule

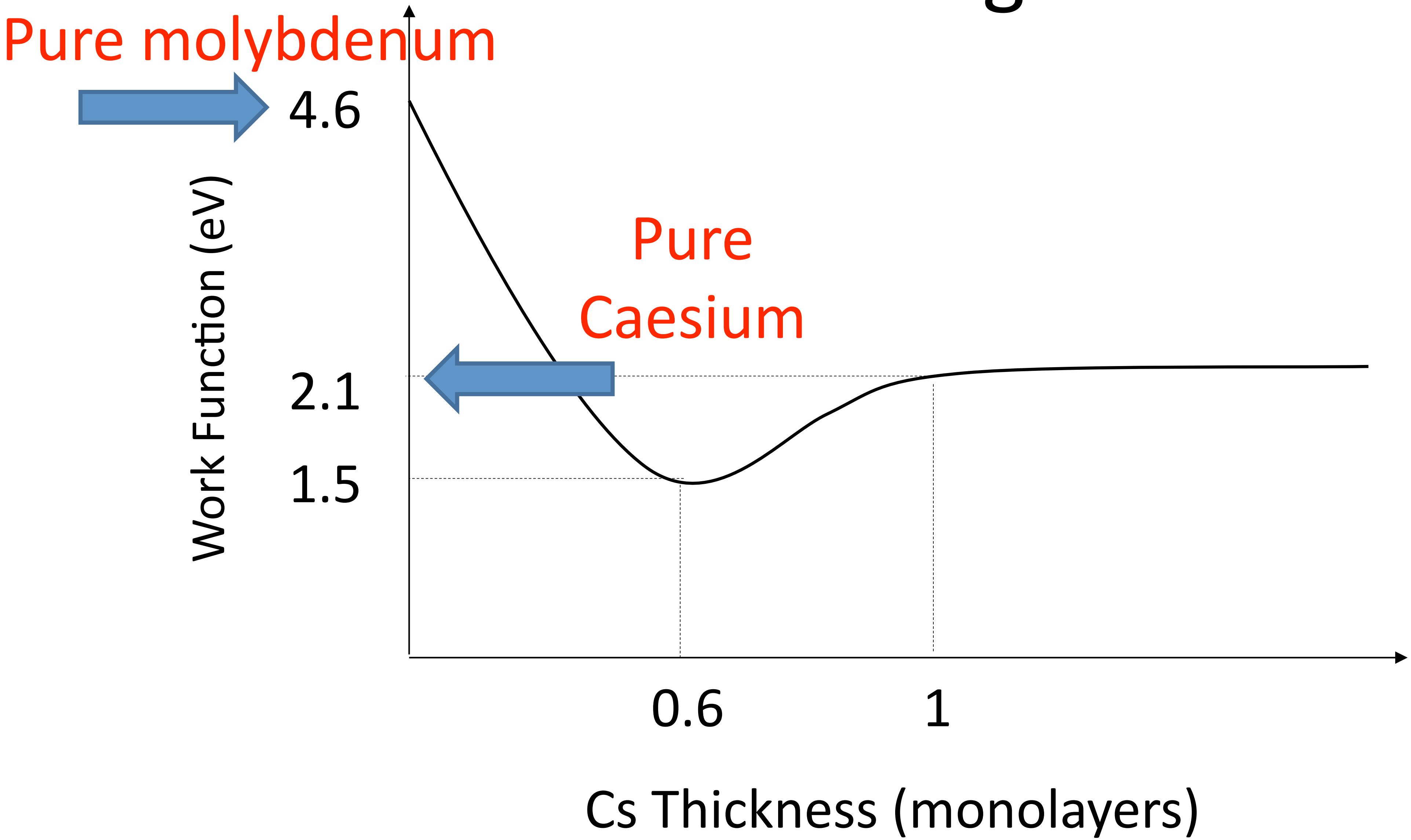
Electrodes...

...have work functions

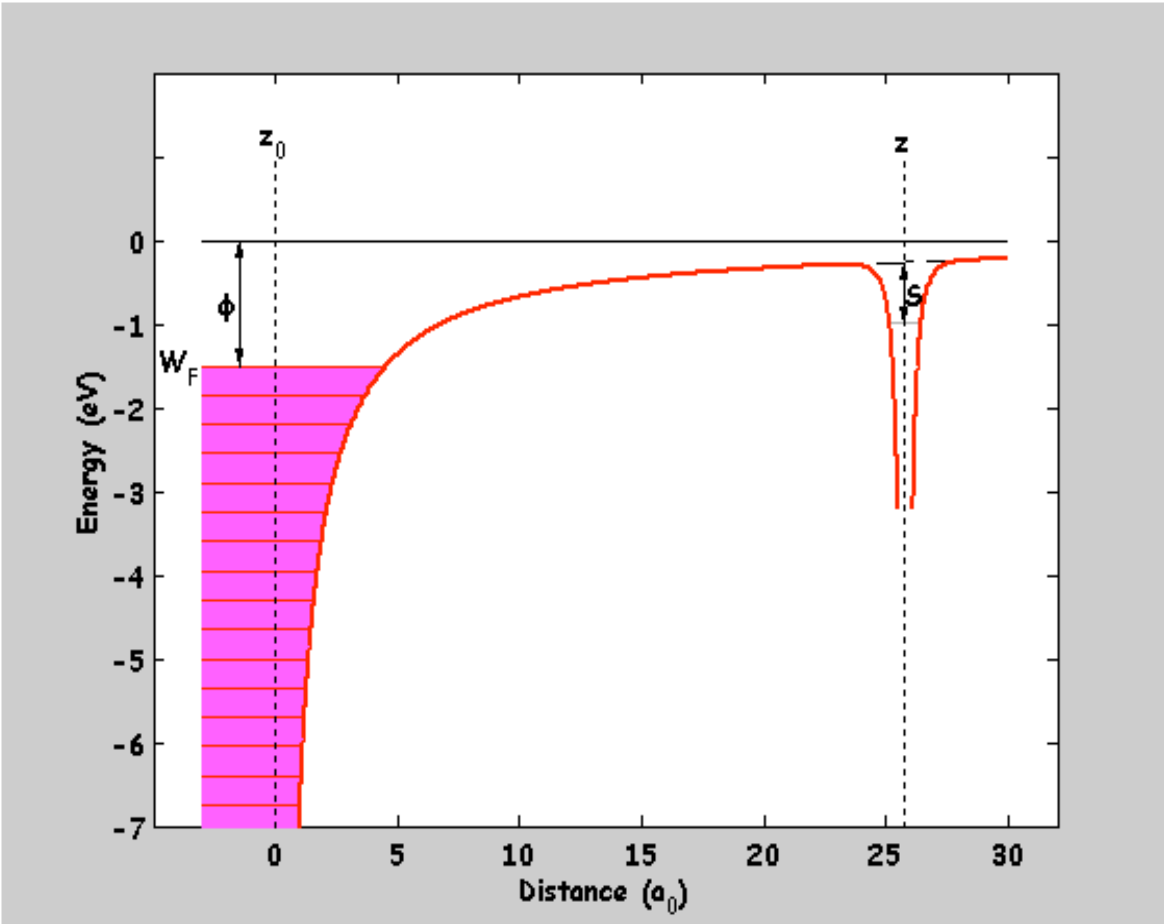


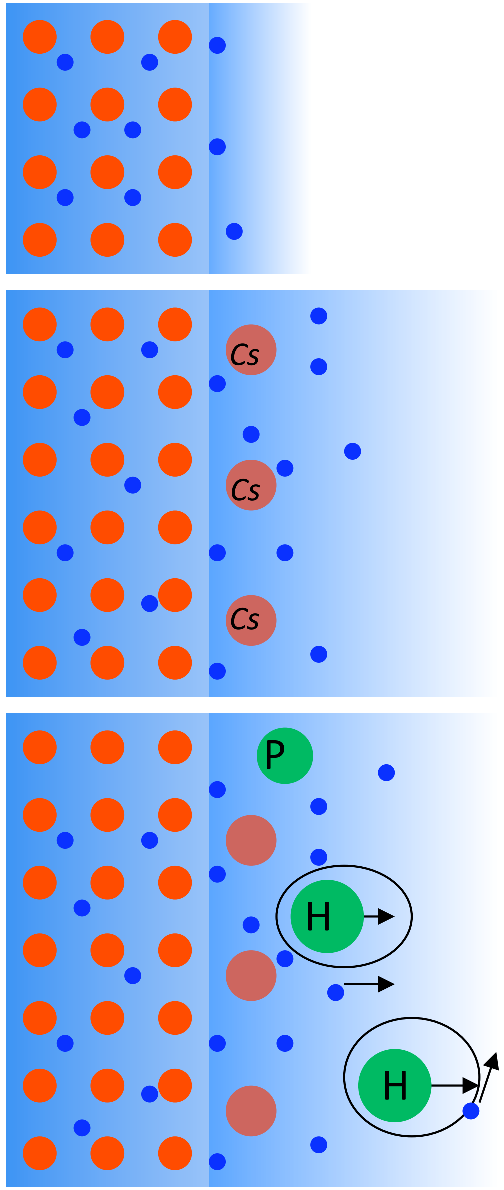

Periodic Table of the Elements
hydrogen
alkali metals
alkali earth metals
transition metals
poor metals
nonmetals
noble gases
rare earth metals
1 H
2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 57 La 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Ti 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 88 Ra 89 Ac 104 Unq 105 Unp 106 Unh 107 Uns 108 Uno 109 Une 110 Unn
58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr

Caesium Coverage

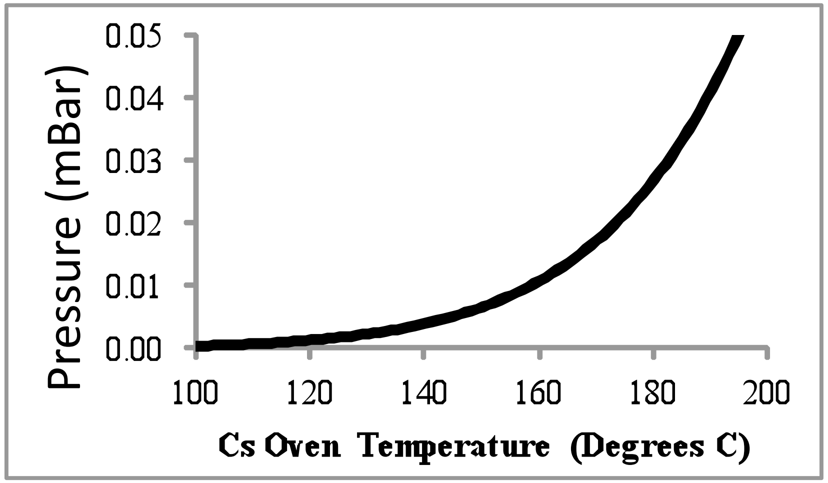


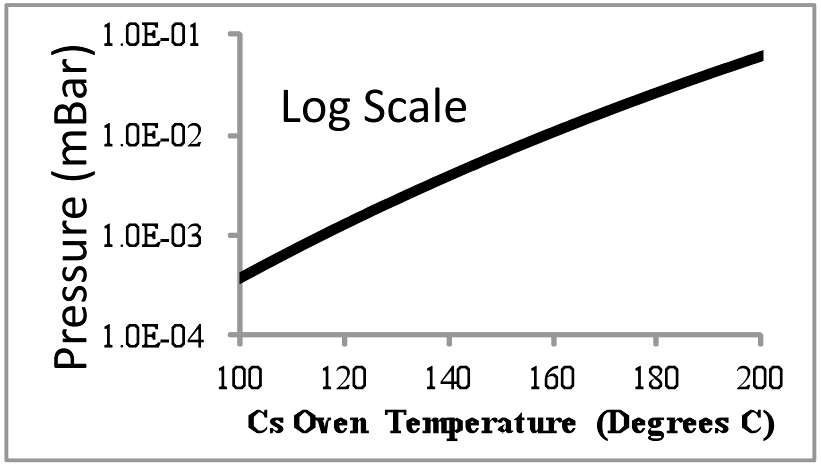
Fermilevels



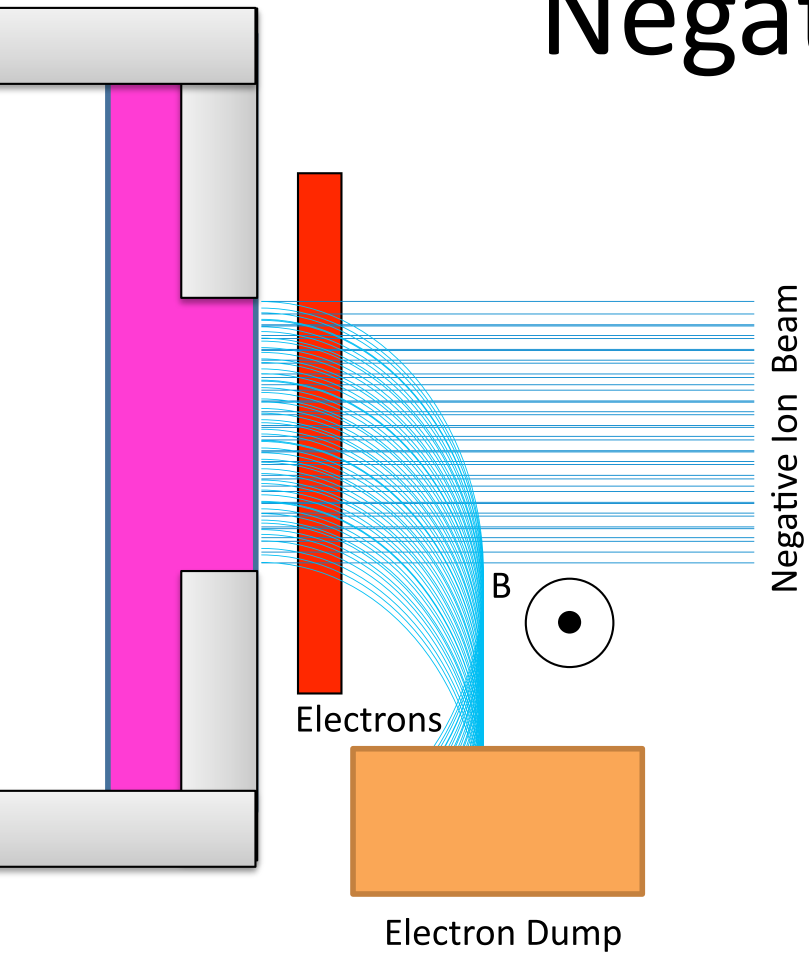


Vary Caesium Vapour Pressure to Control Caesium Coverage





Negative Ion Extraction



Electrons will also be extracted

Up to 1000 times the H^- current!

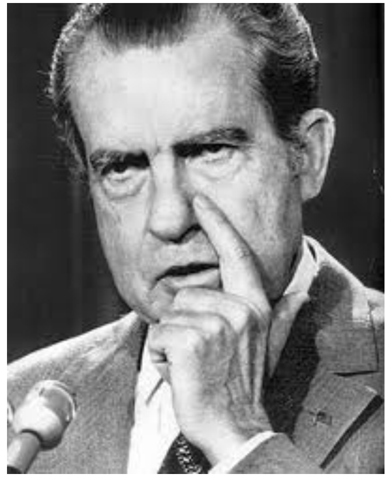
Use a magnetic field

Dump must be properly designed

SPS sources:

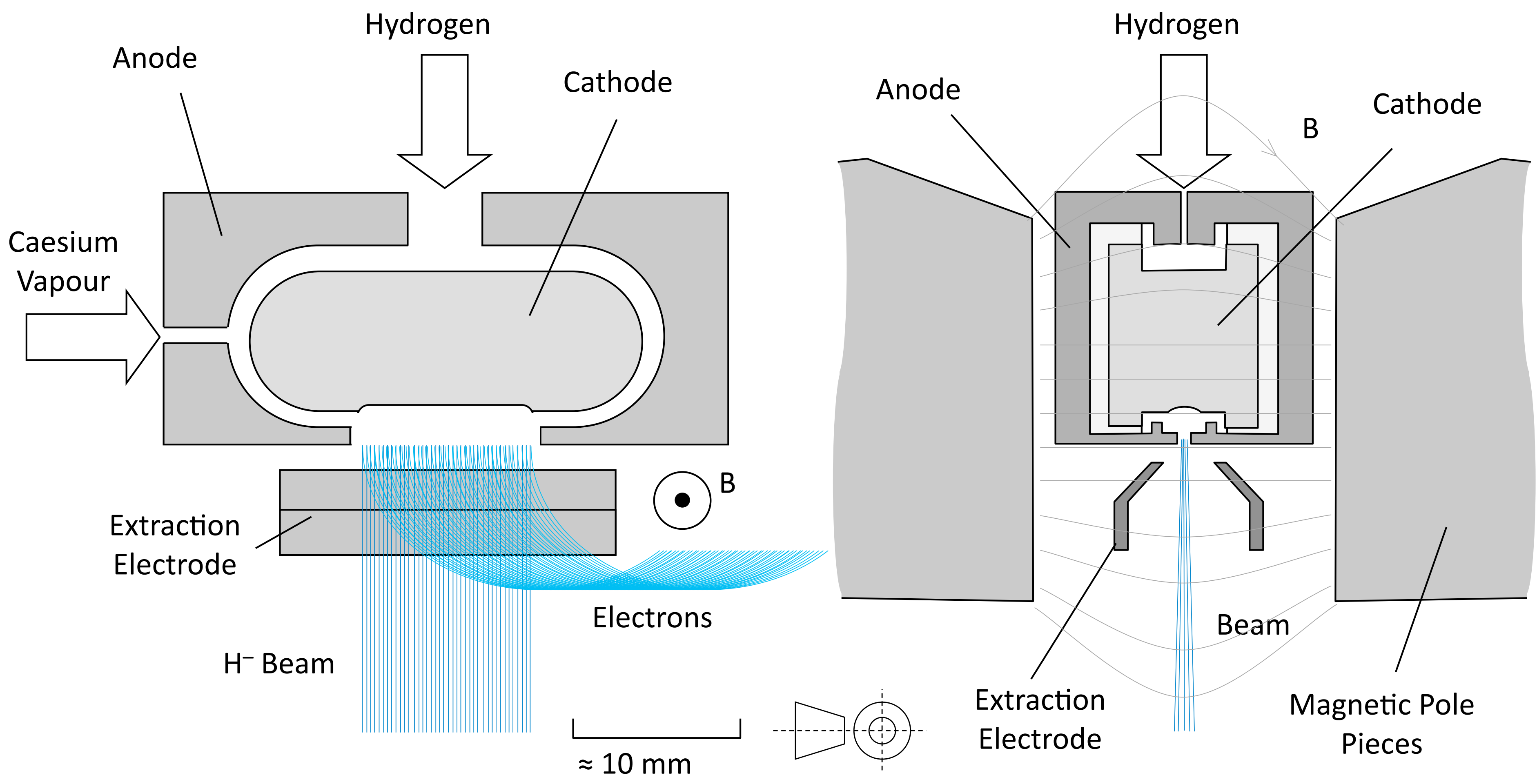
only 0.5 to 10 times H^- current

1970s Caesium Revolution!

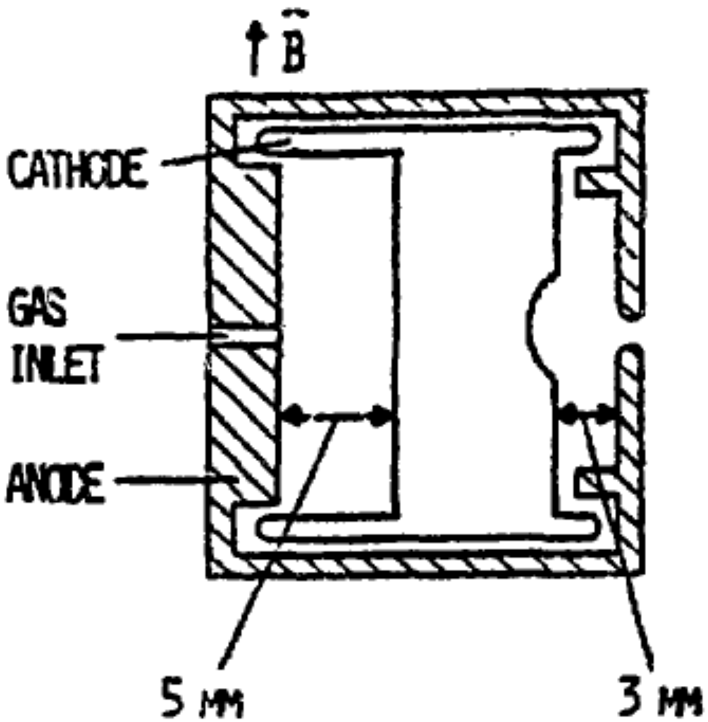


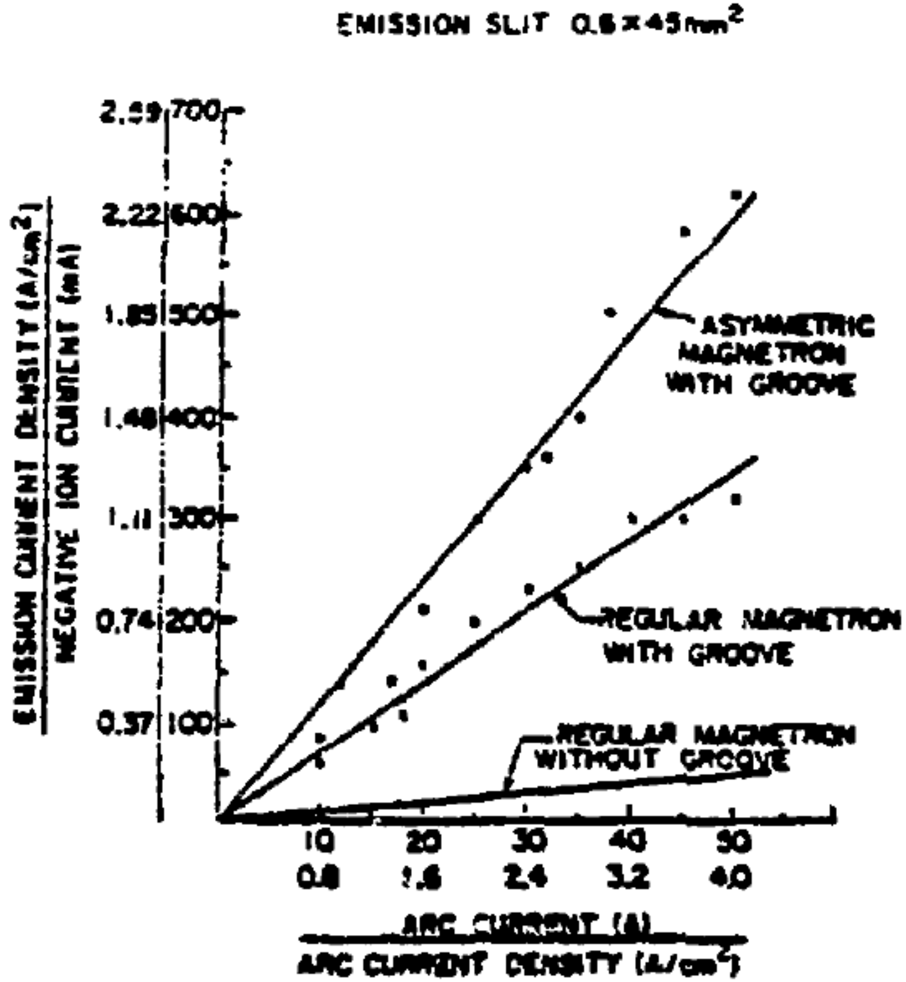
- Soviets spread the word and develop sources
- BNL Krsto Prelec et al. develop the magnetron for NBI
- LANL Paul Allison et al. develop the Penning
- Berkley Ehlers+Leung develop Surface Converter sources
- Fermilab Chuck Schmidt et al. develop the BNL magnetron for accelerators

Magnetron Source

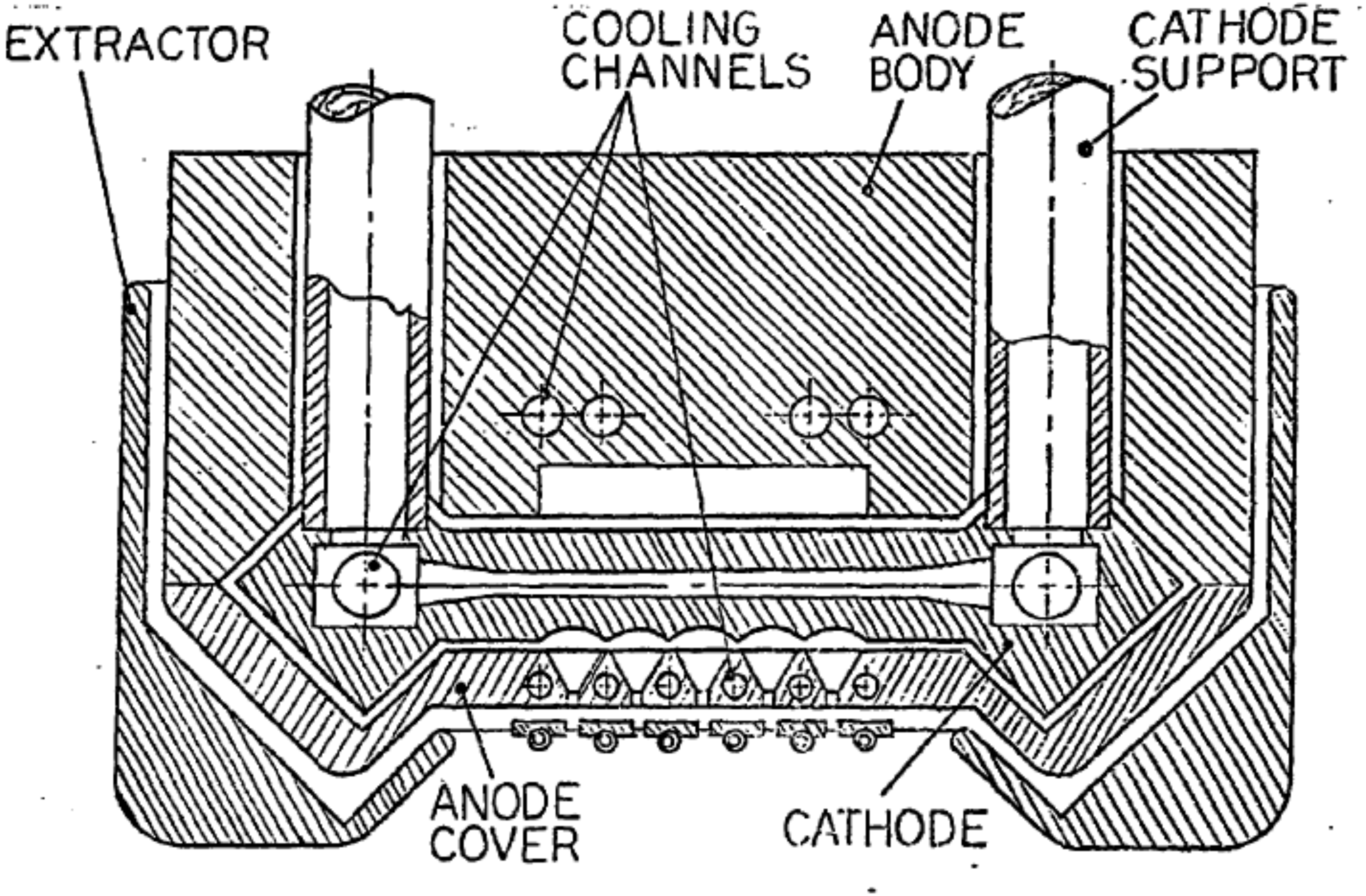


1980 BNL Developments

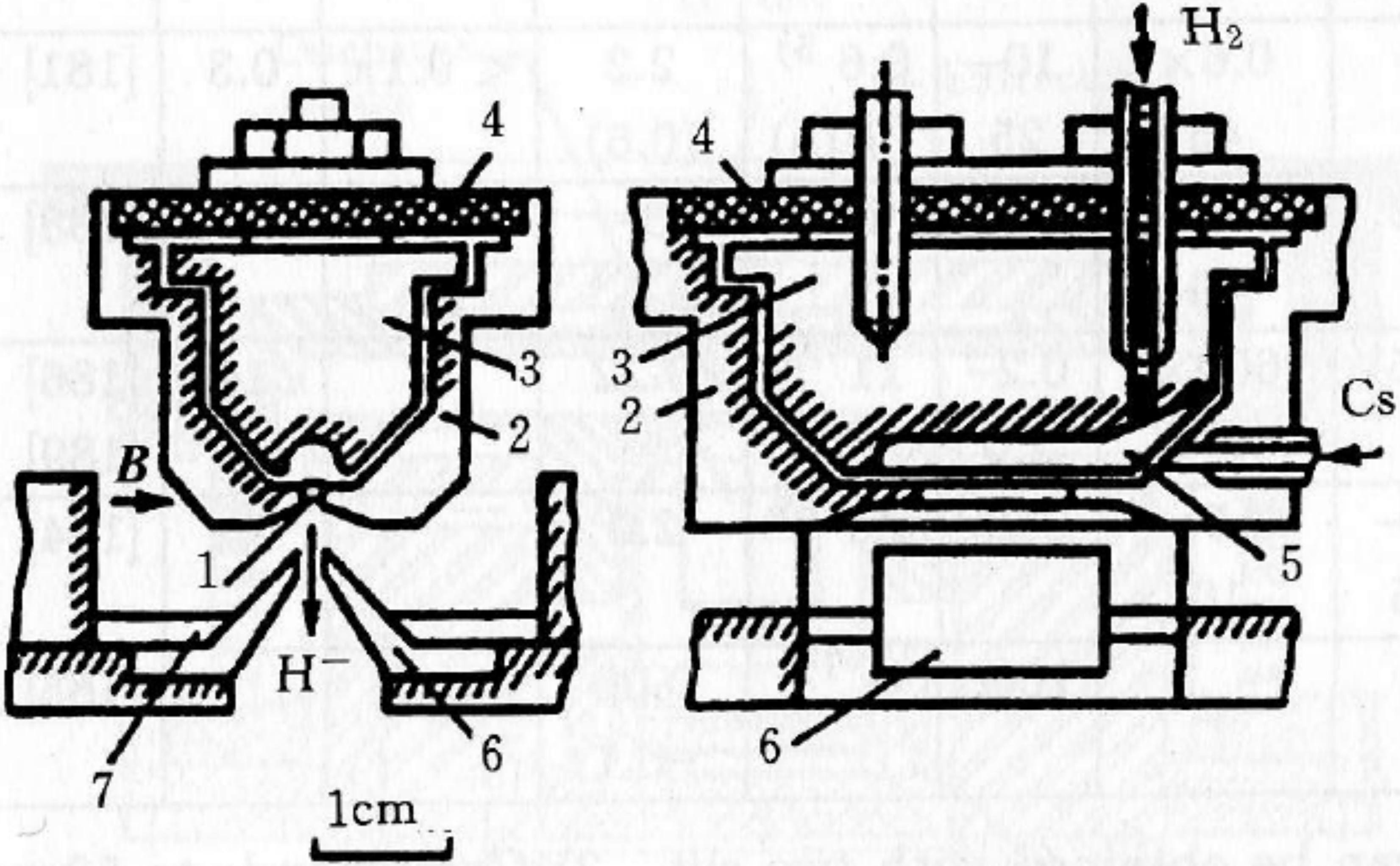




BNL 2 A Beam H^- Magnetron for NBI

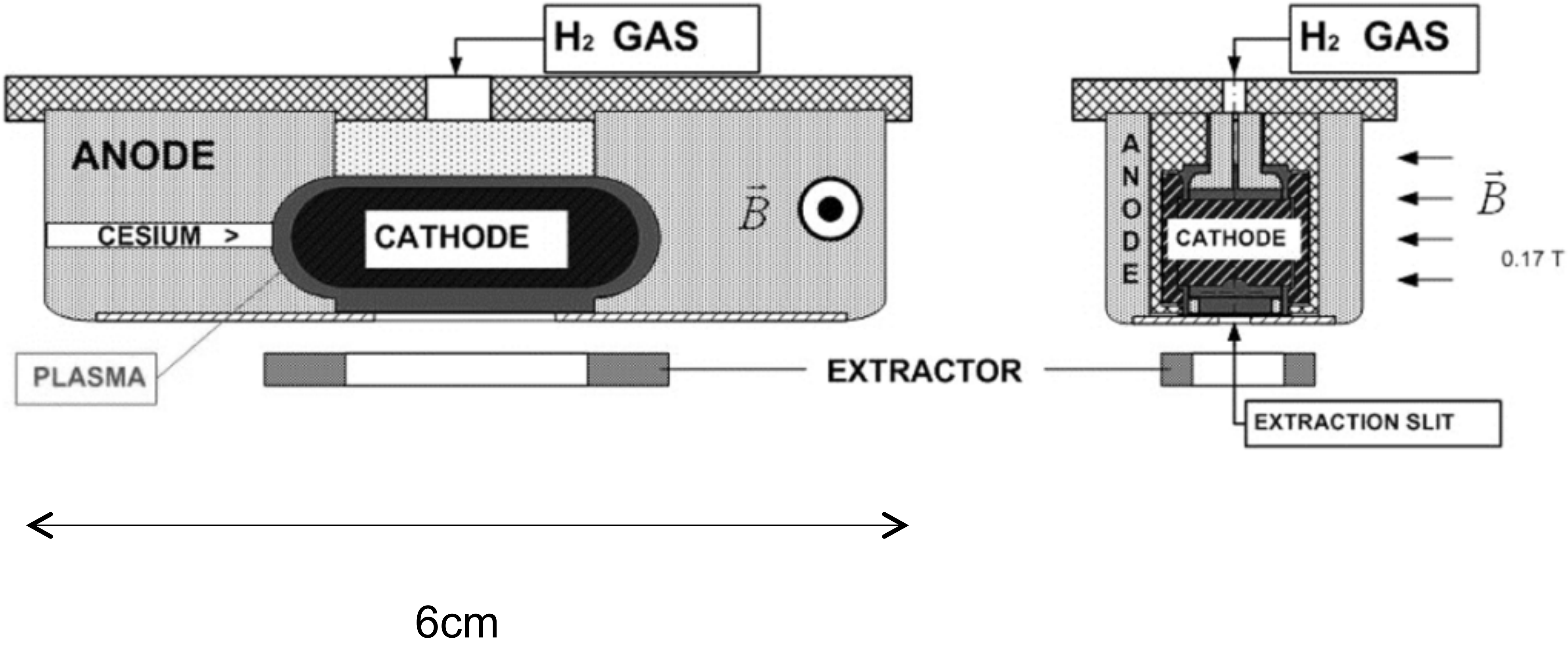


11 A Budker Semiplanotron

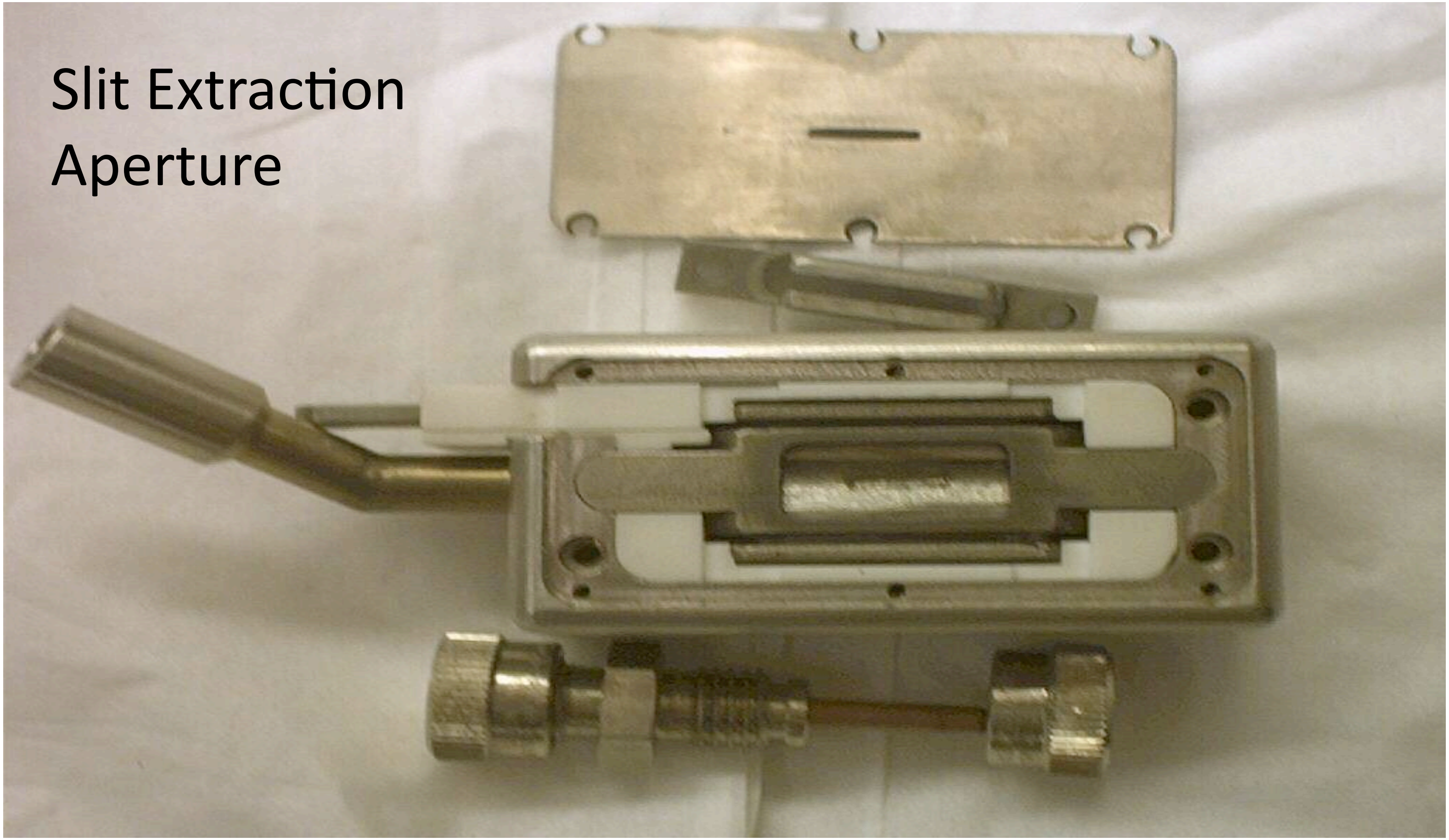


1—Emission slit, 2—Anode, 3—Cathode, 4—Insulator, 5—Cathode cavity, 6—Extracting electrode, 7—Iron inserts.

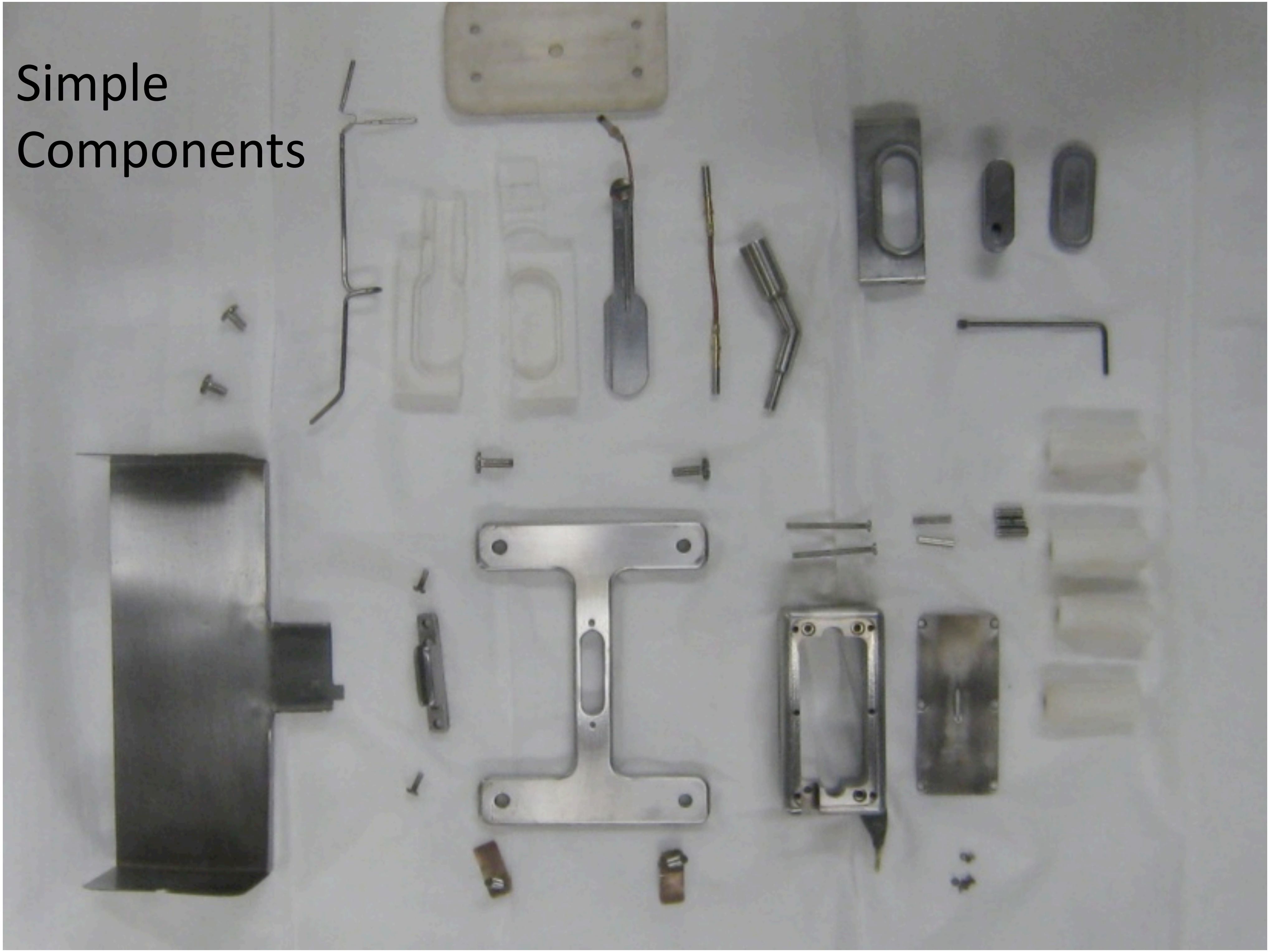
Late 1970s Fermilab Magnetron



Fermilab Magnetron

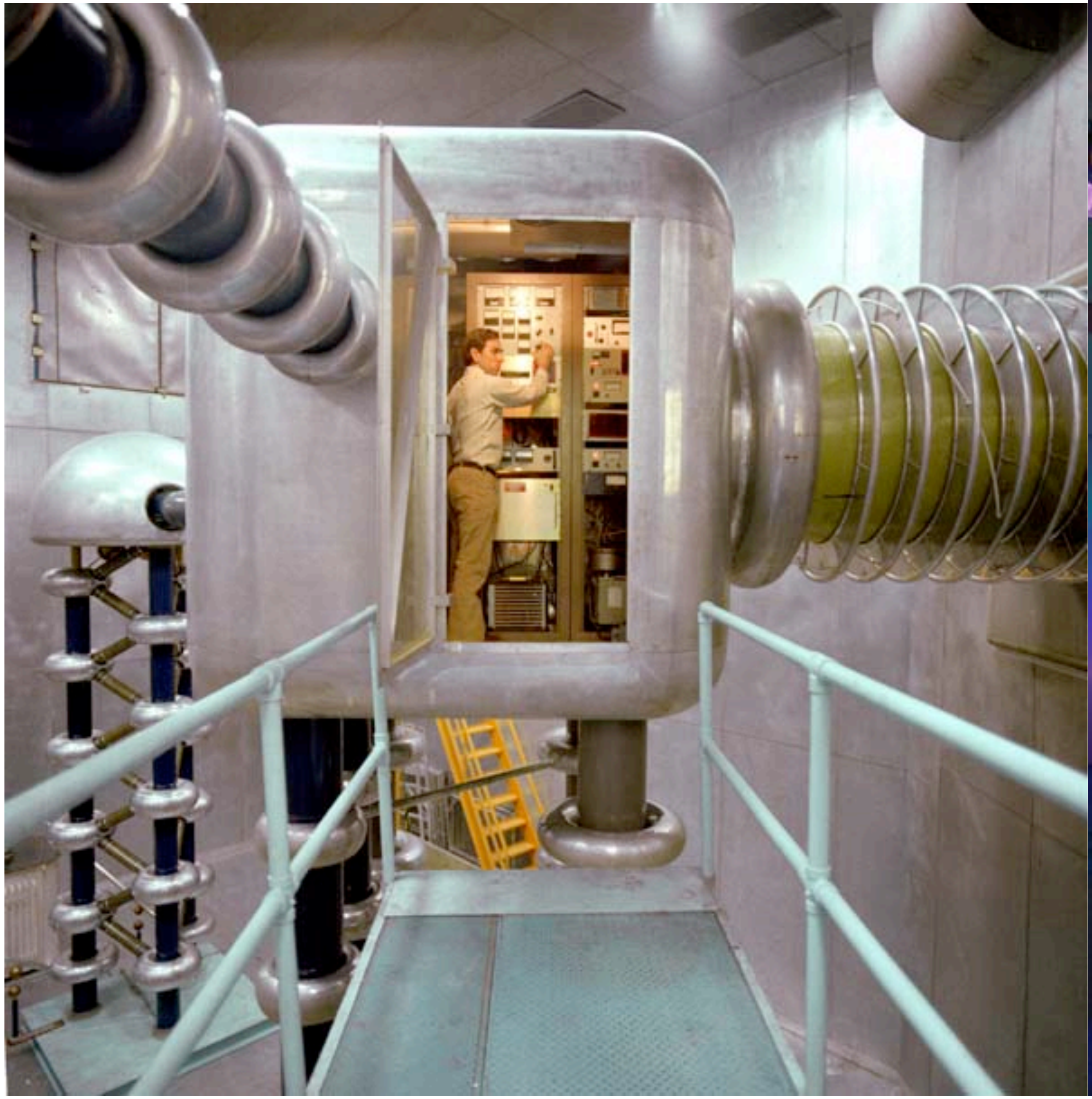


Simple Components



Fermilab Magnetron

750 kV Acceleration Column



Fermilab Magnetron

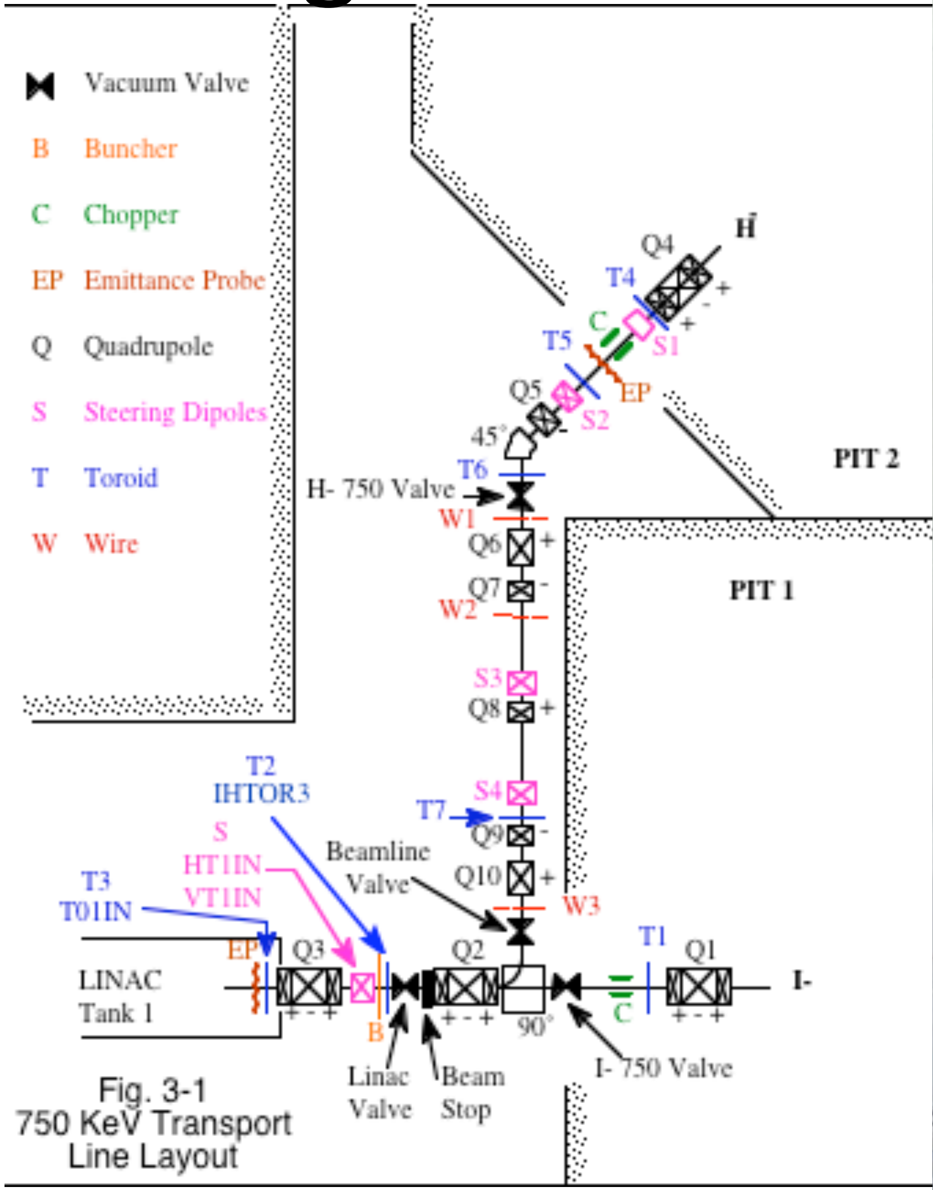
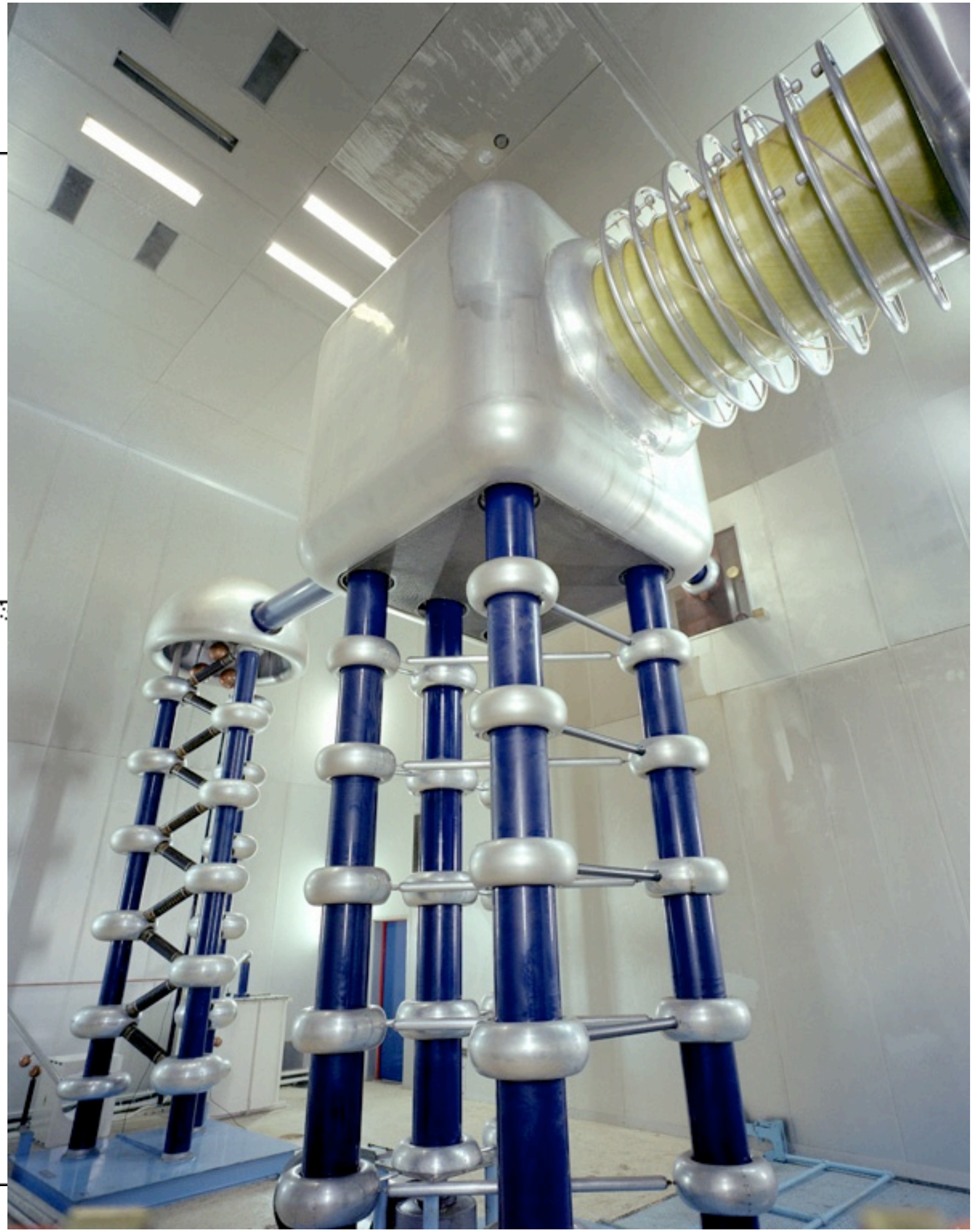
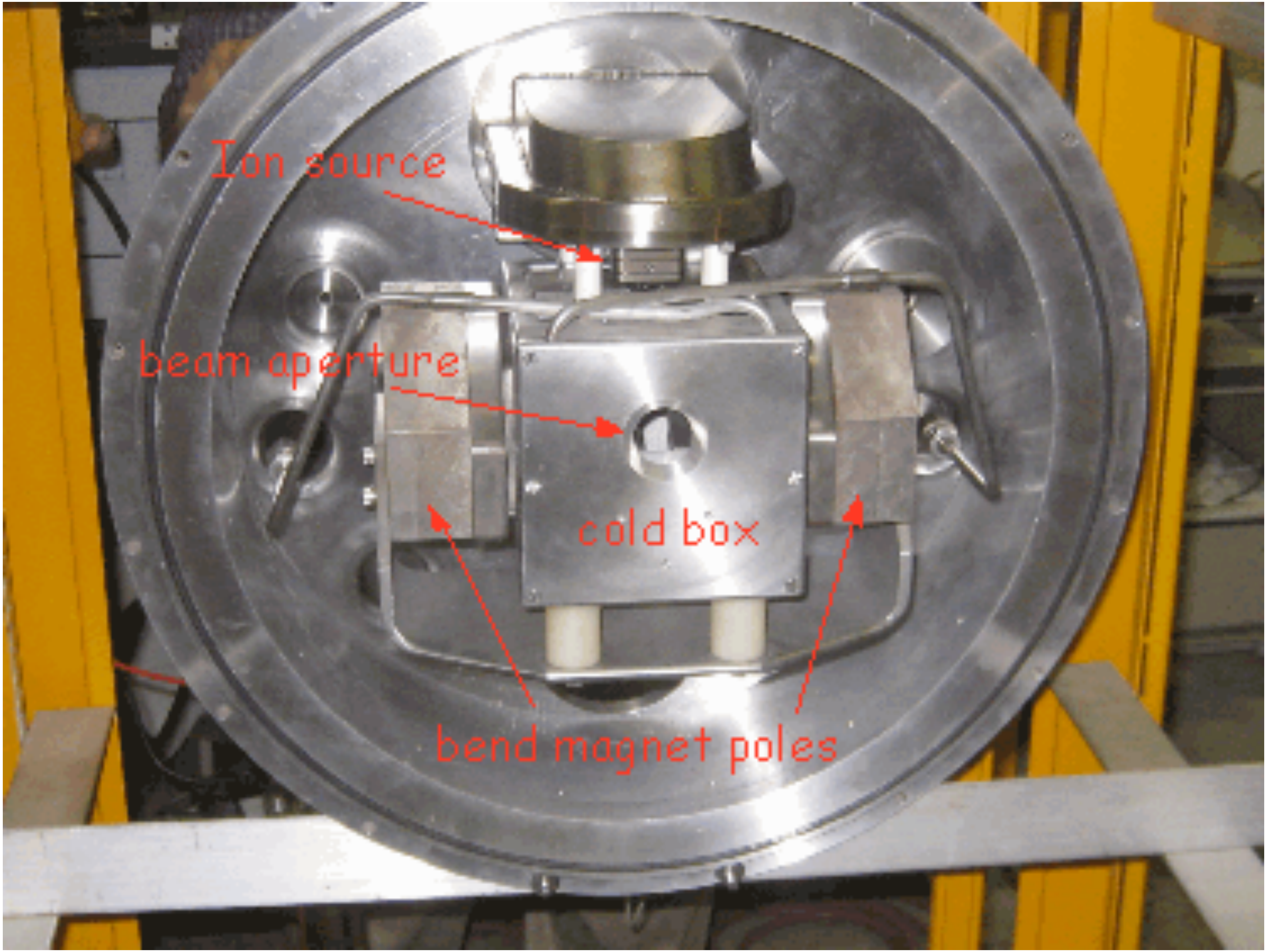


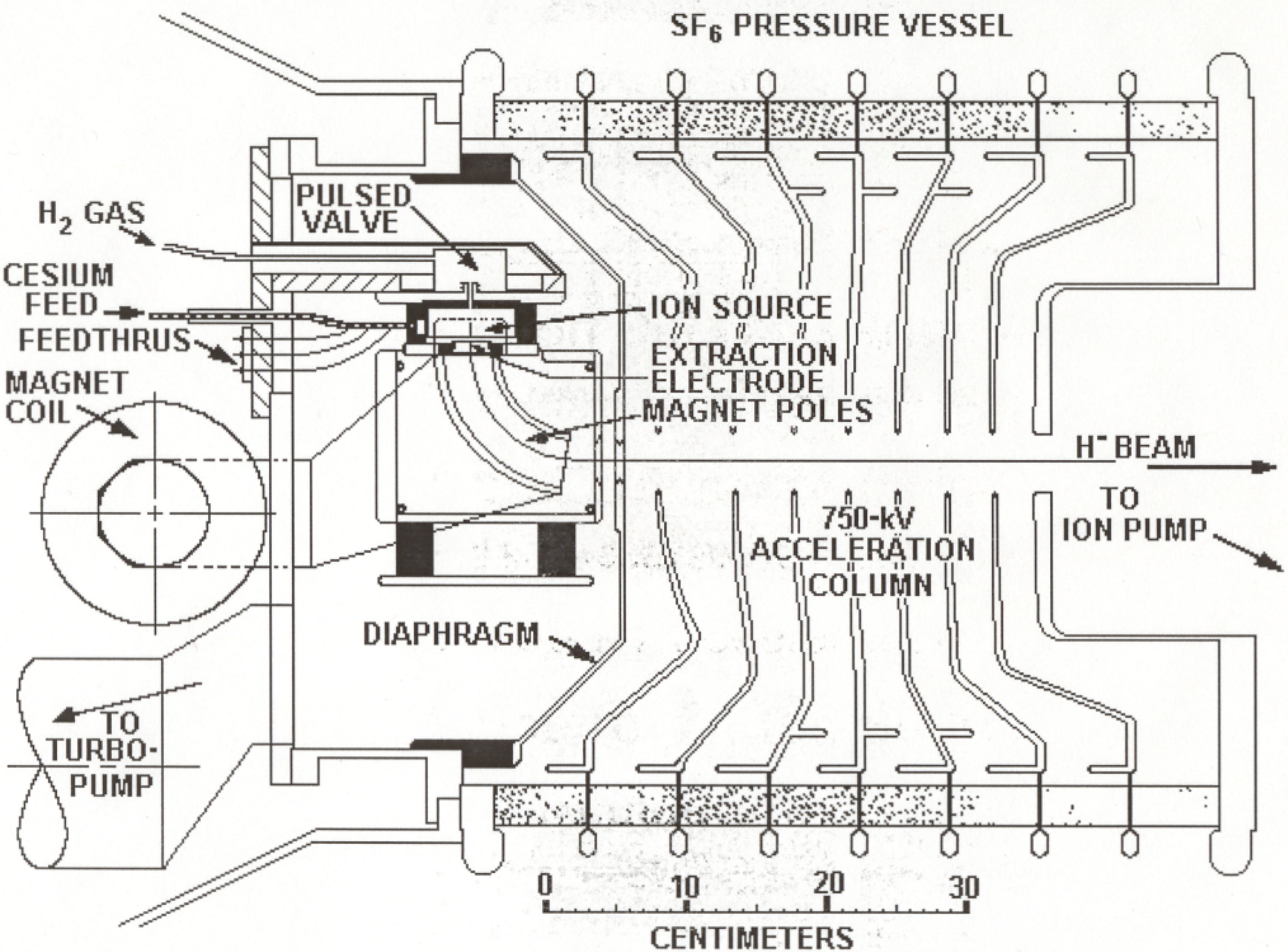
Fig. 3-1
750 KeV Transport
Line Layout



Fermilab Magnetron

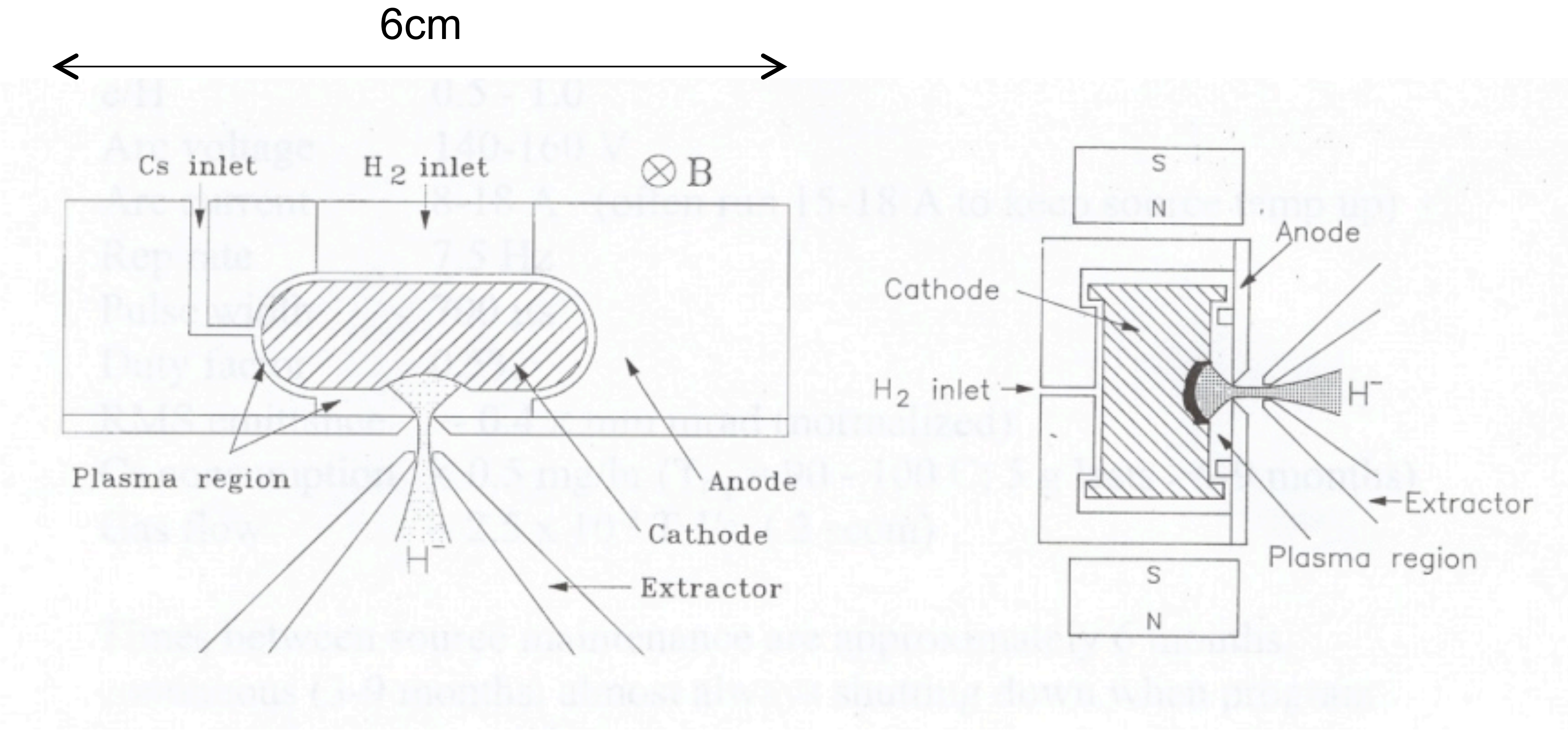
Caesium:
Friend of H^-
but
mortal enemy
of high voltage


Ion source
beam aperture
cold box
bend magnet poles



H⁻ ION SOURCE ASSEMBLY

1989 BNL Magnetron

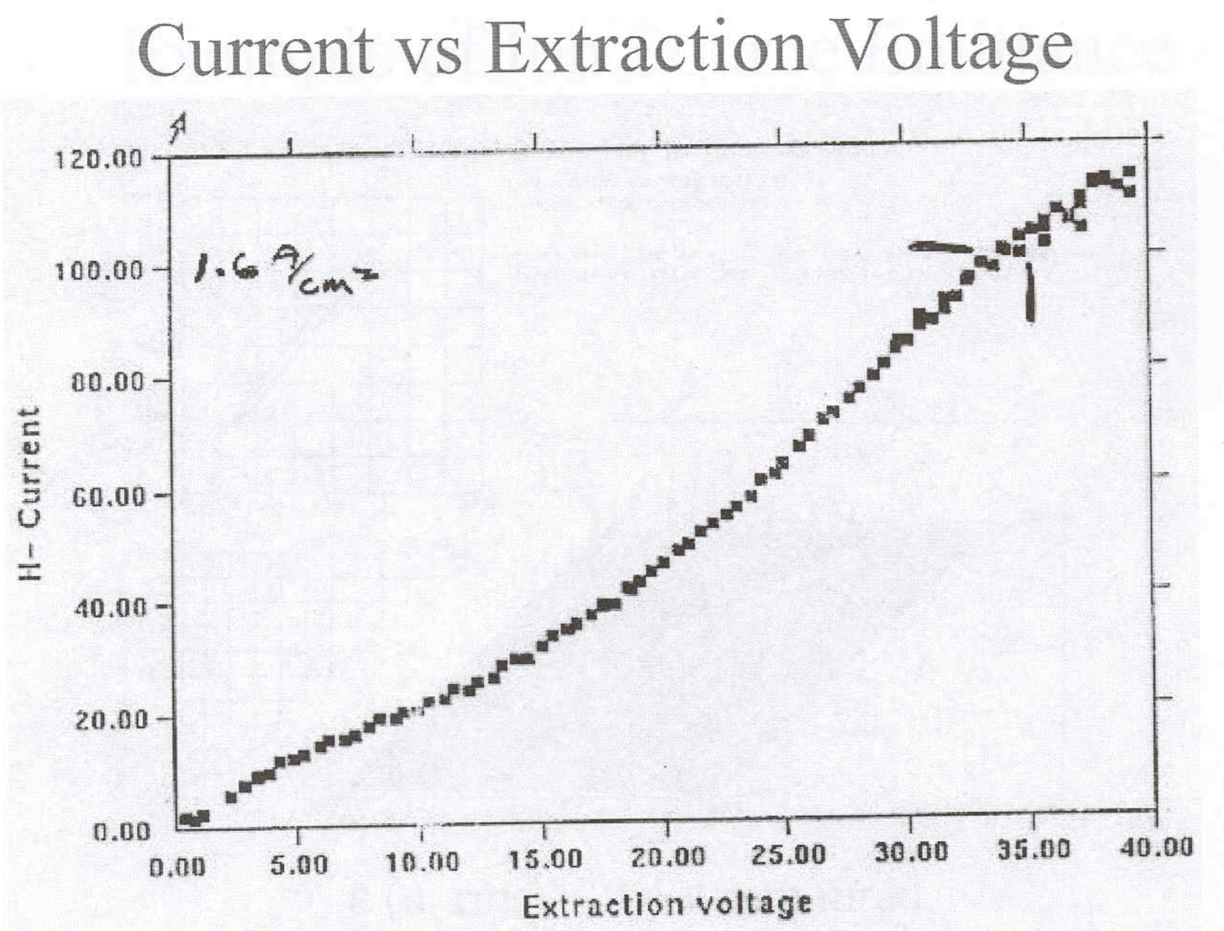


Circular Extraction Aperture

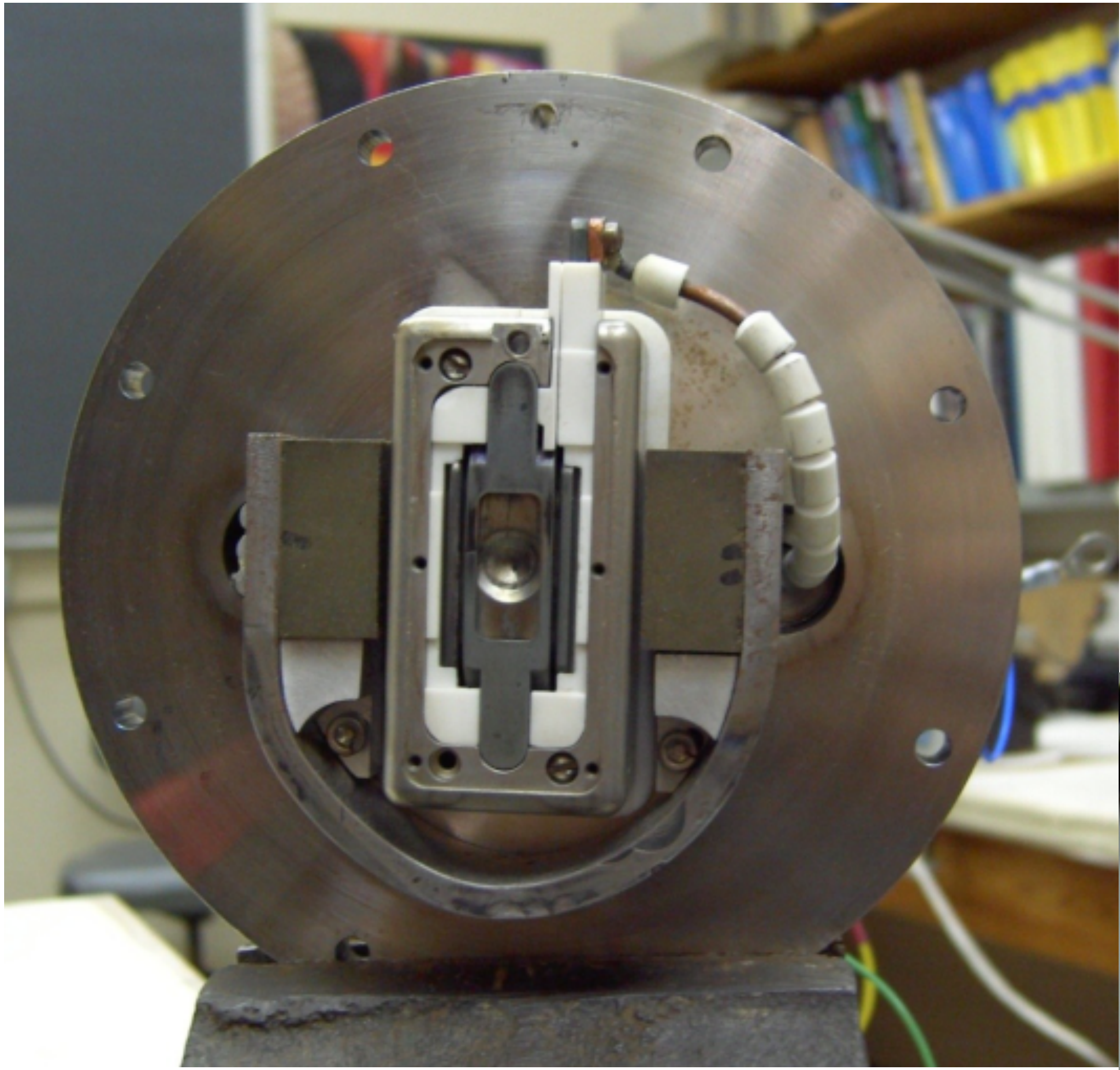
1989 BNL Magnetron

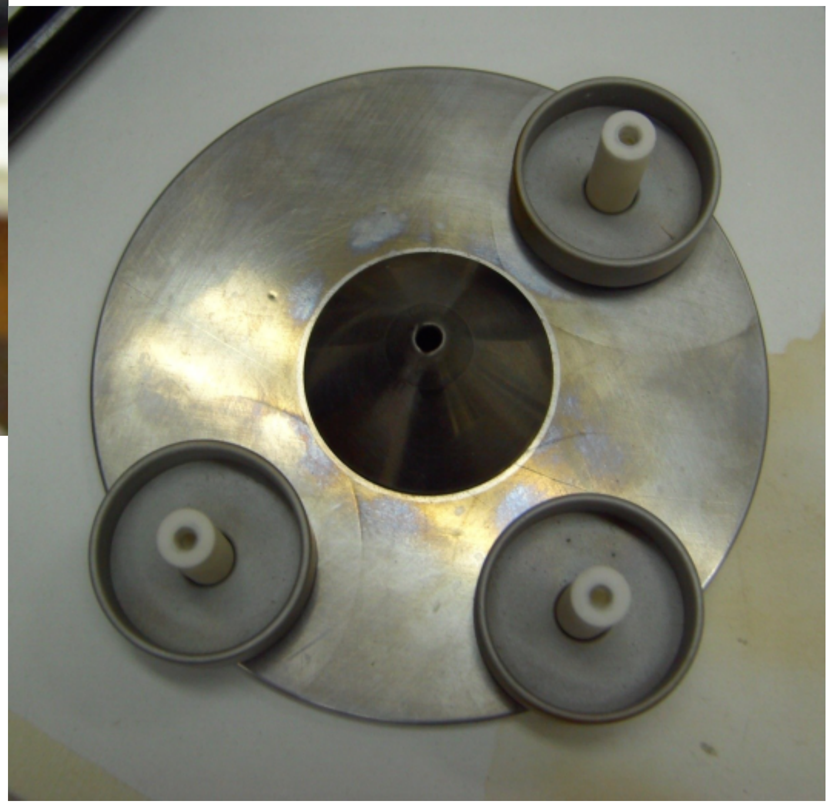
Lifetime, typically 9 months
Very good power efficiency ~ 67 mA/kW
High beam currents ~ 100 mA

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)

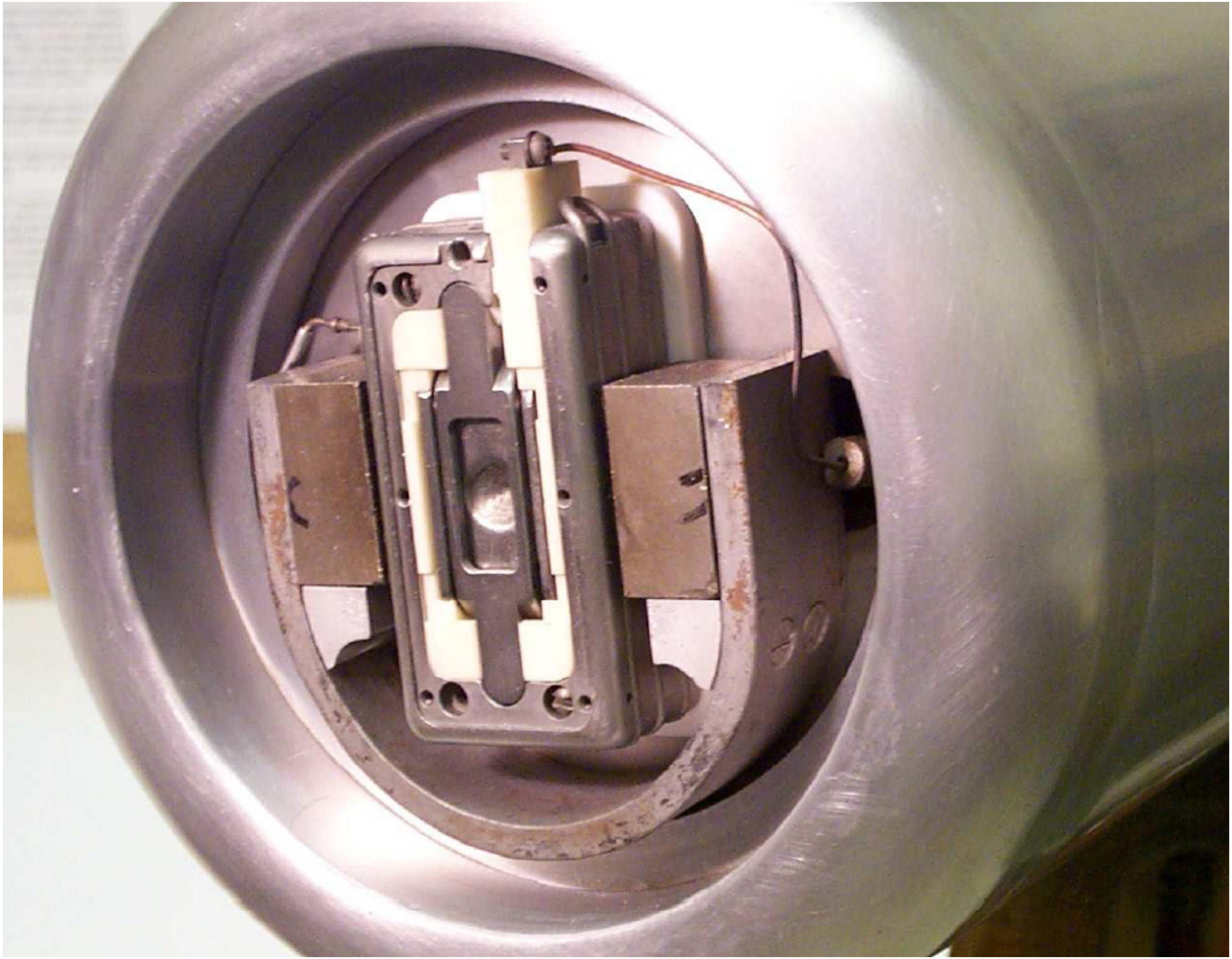


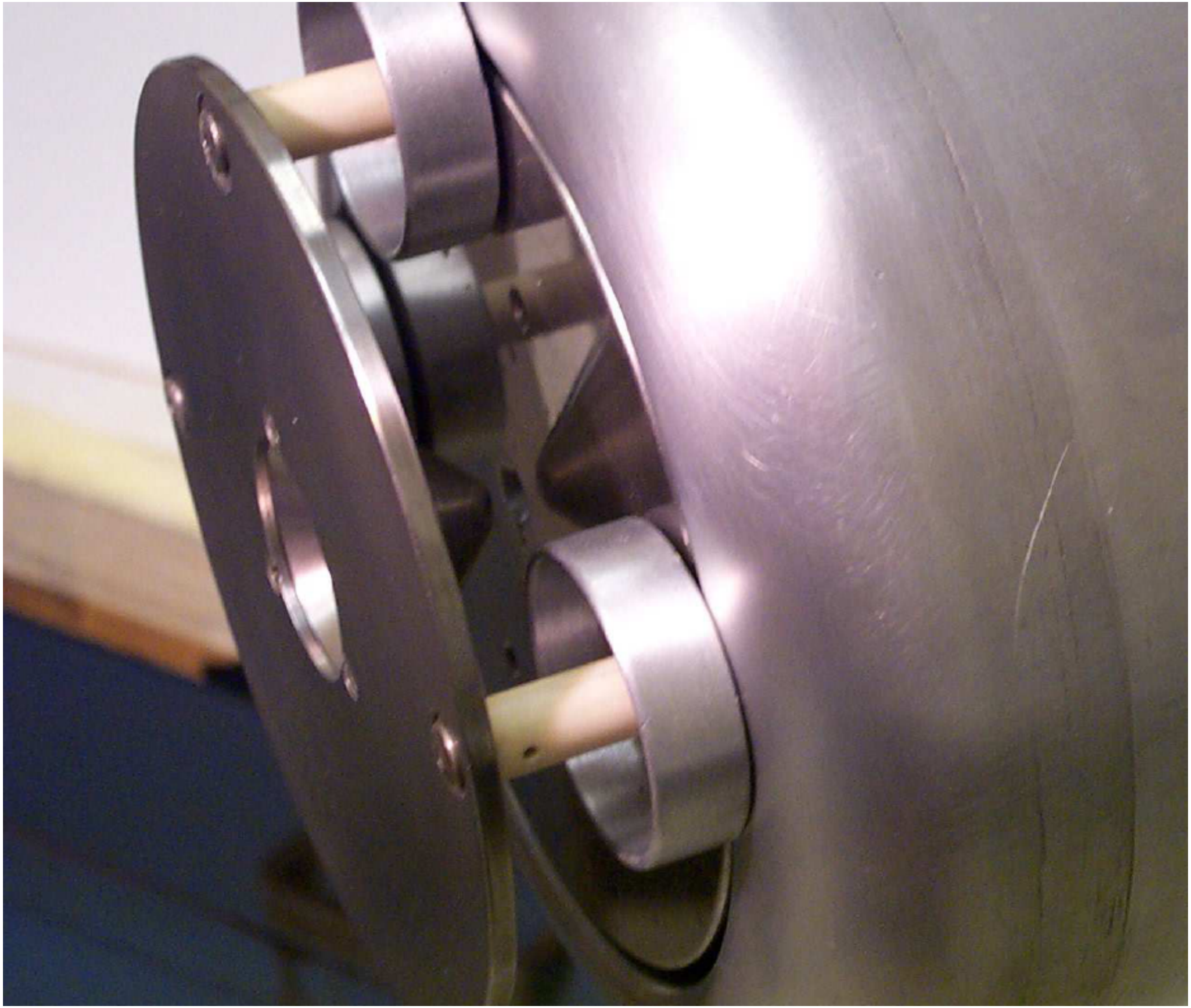
BNL Magnetron



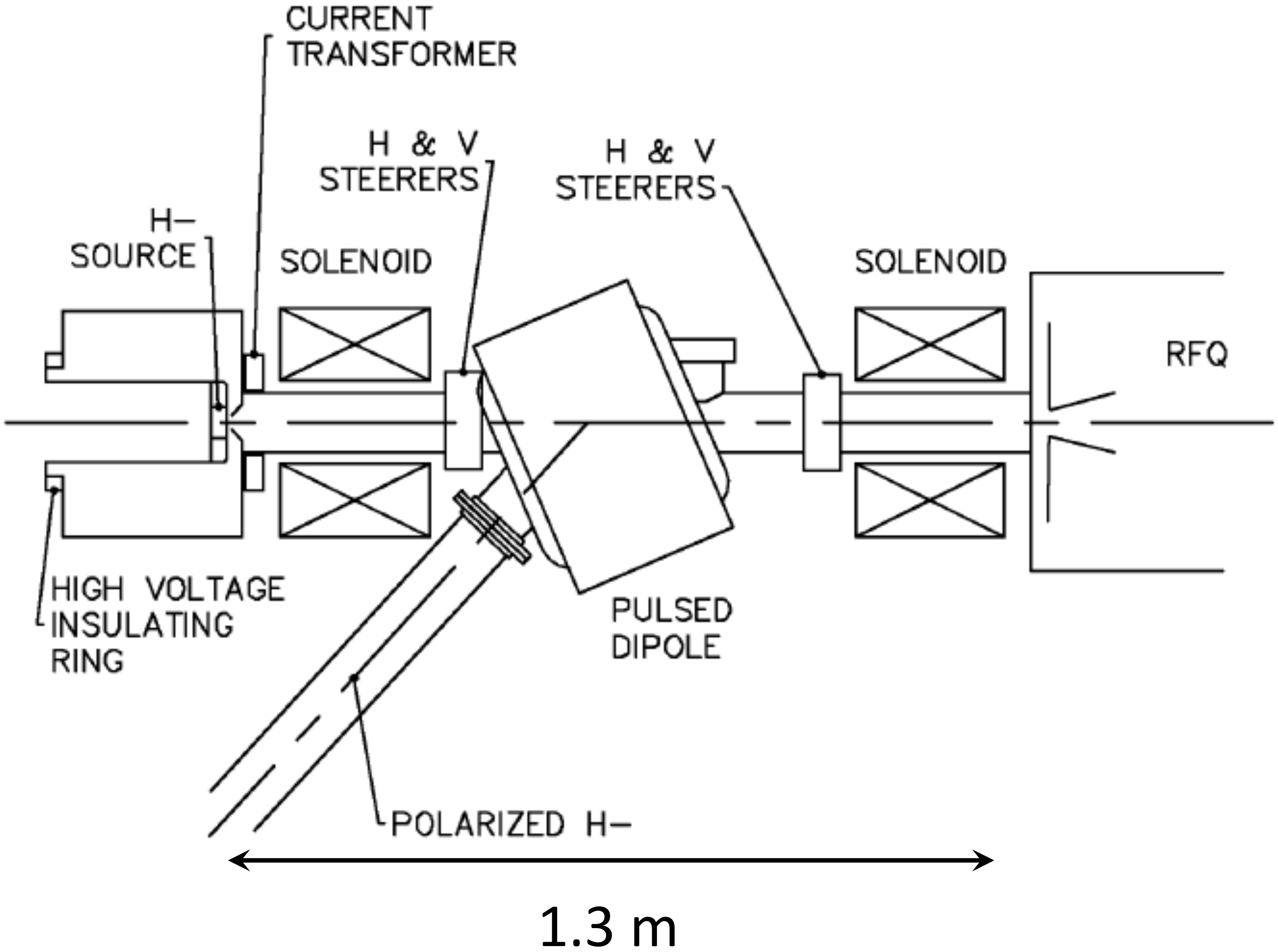


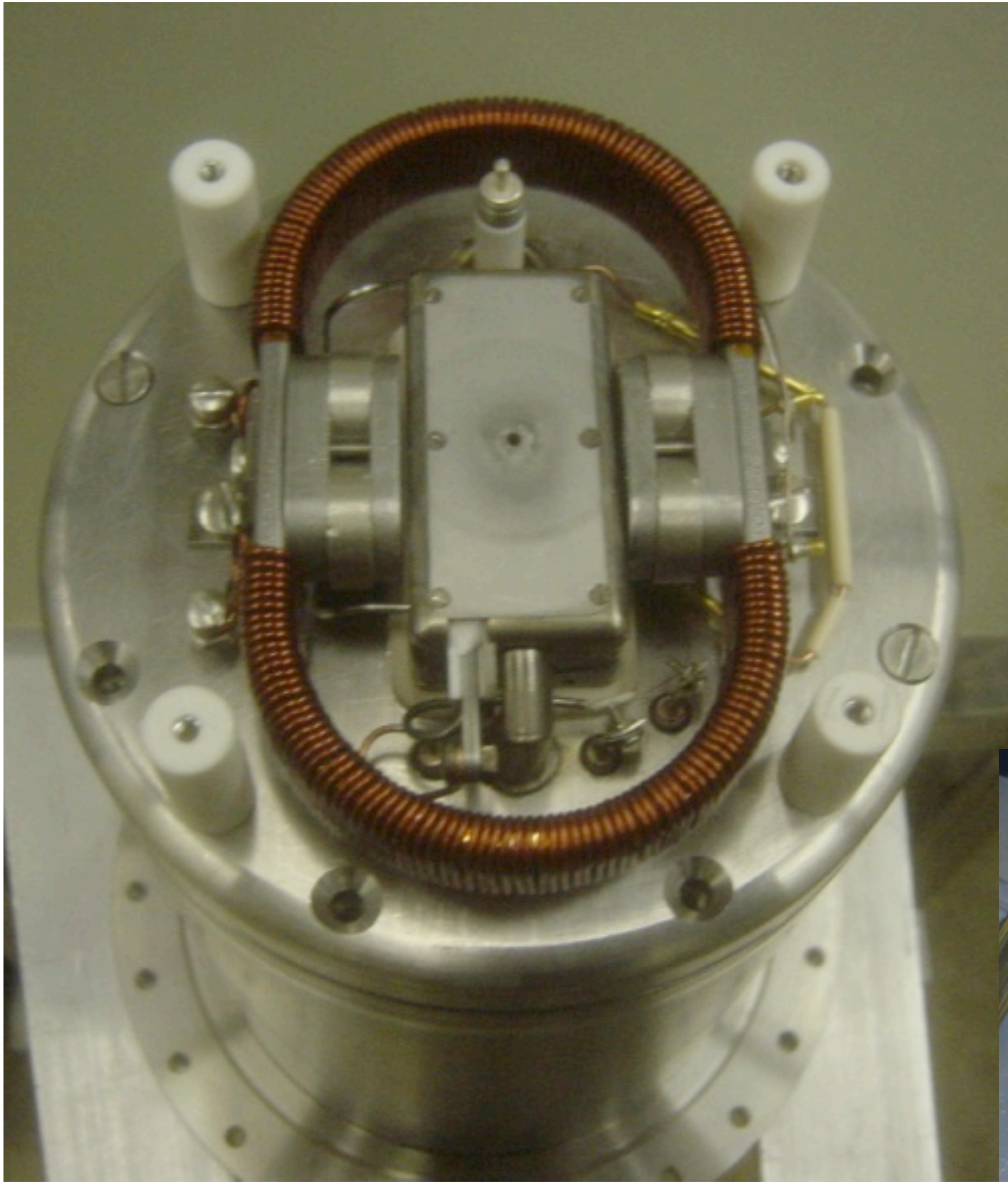
Extraction cone:
45deg angle
3.2 mm aperture





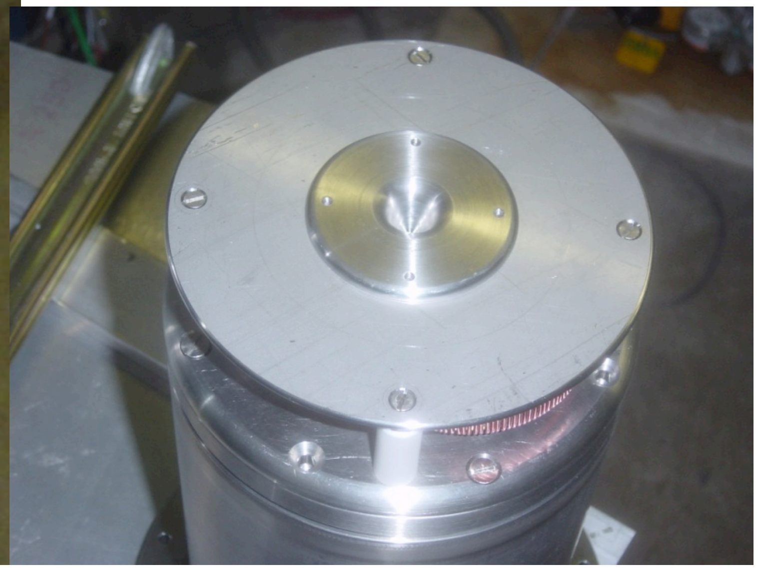
BNL Magnetron



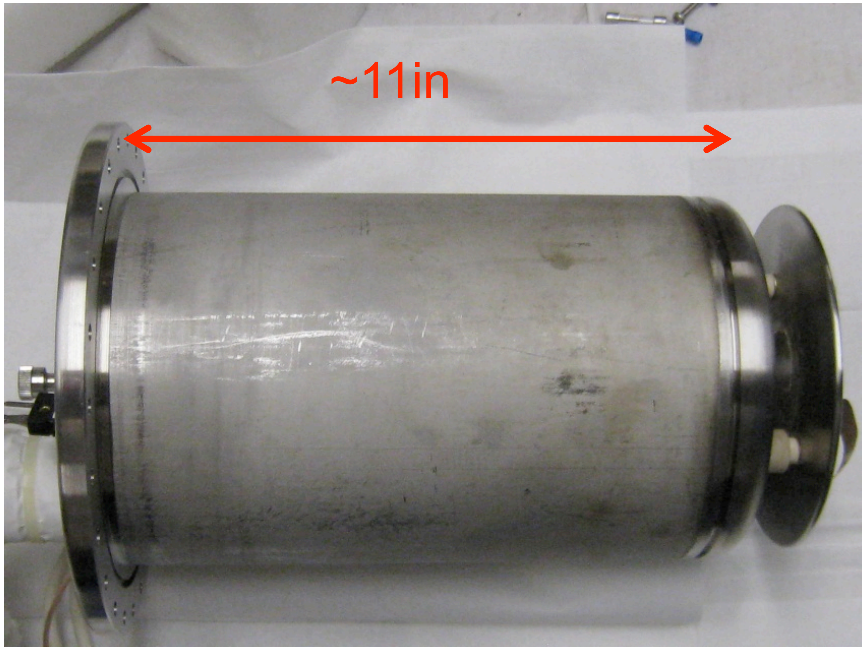


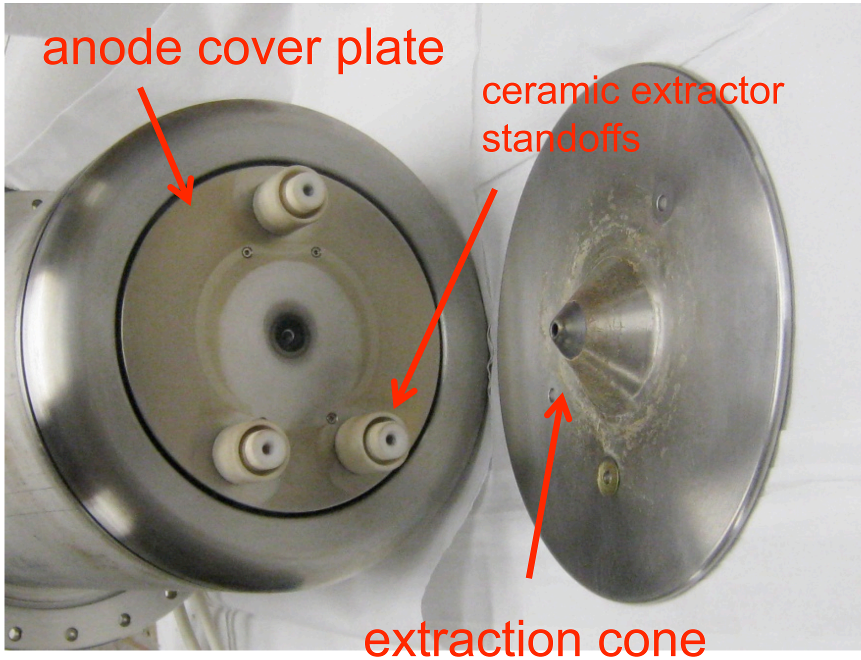
2012 New Fermilab Magnetron

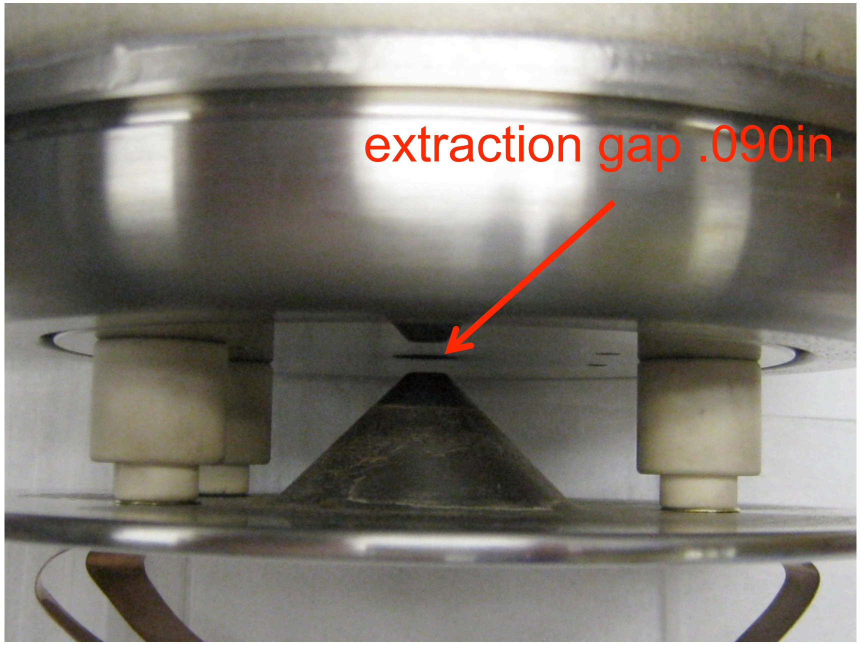
(Based on BNL design)

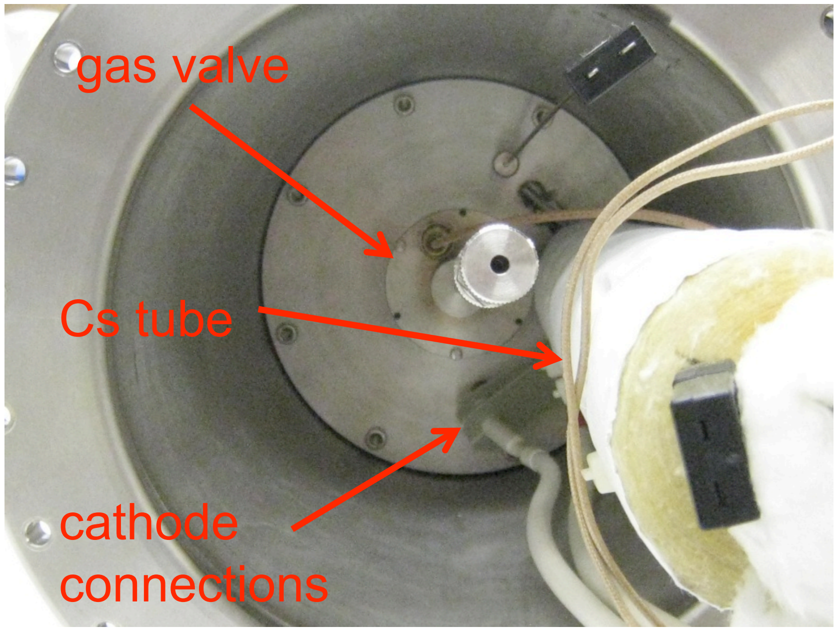


New Fermilab Magnetron



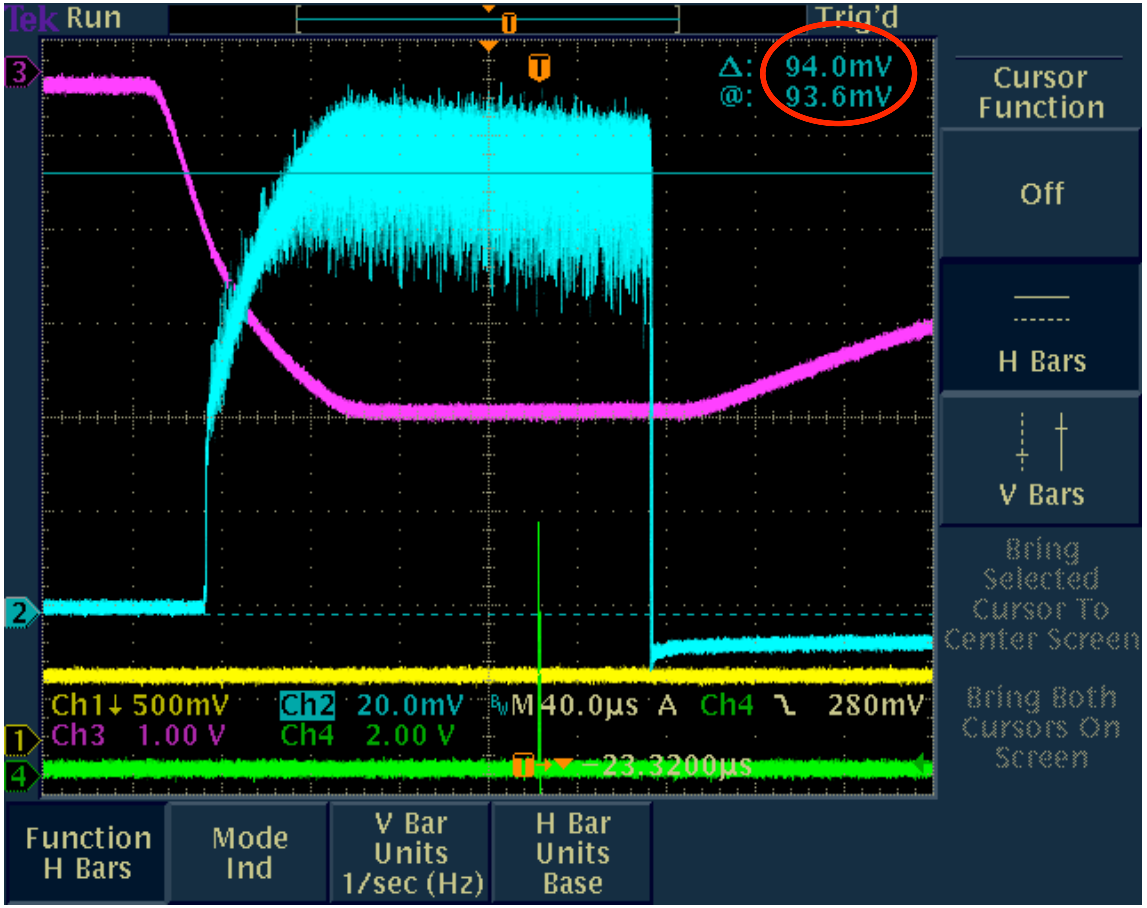






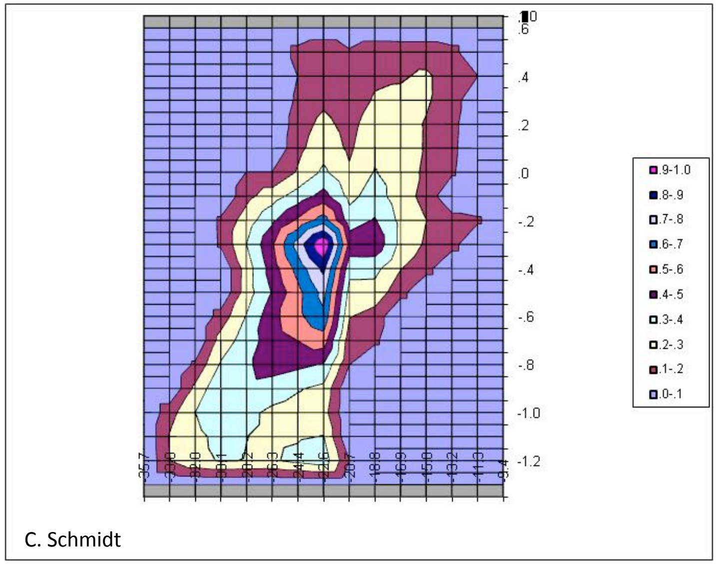
Fermilab HINS Magnetron

94 mA

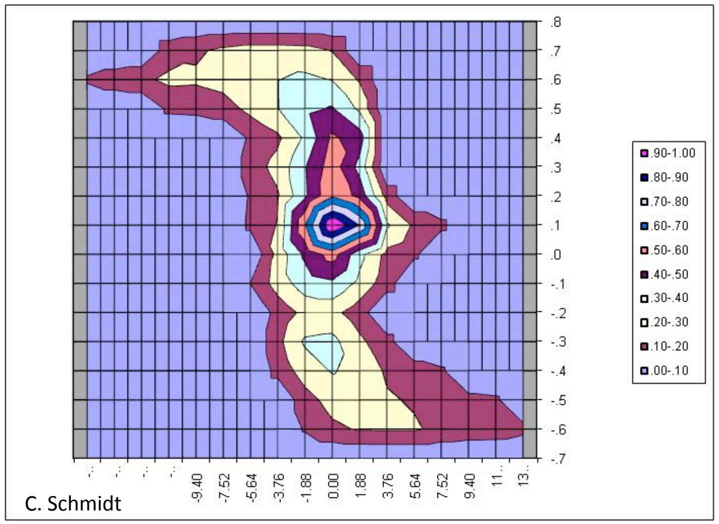


Magnetrons are noisy!

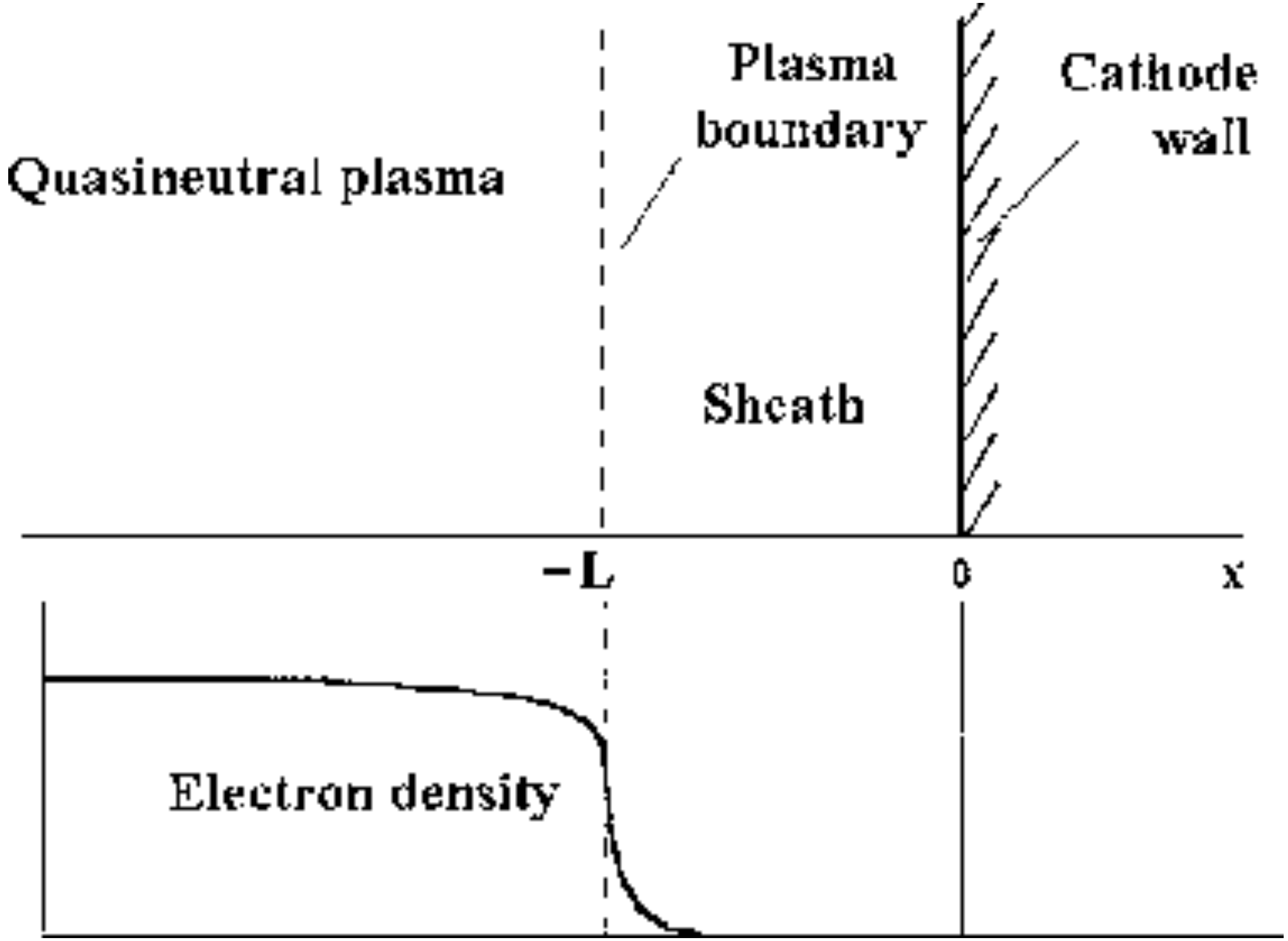
Vertical en rms = 0.18 mm.mRad

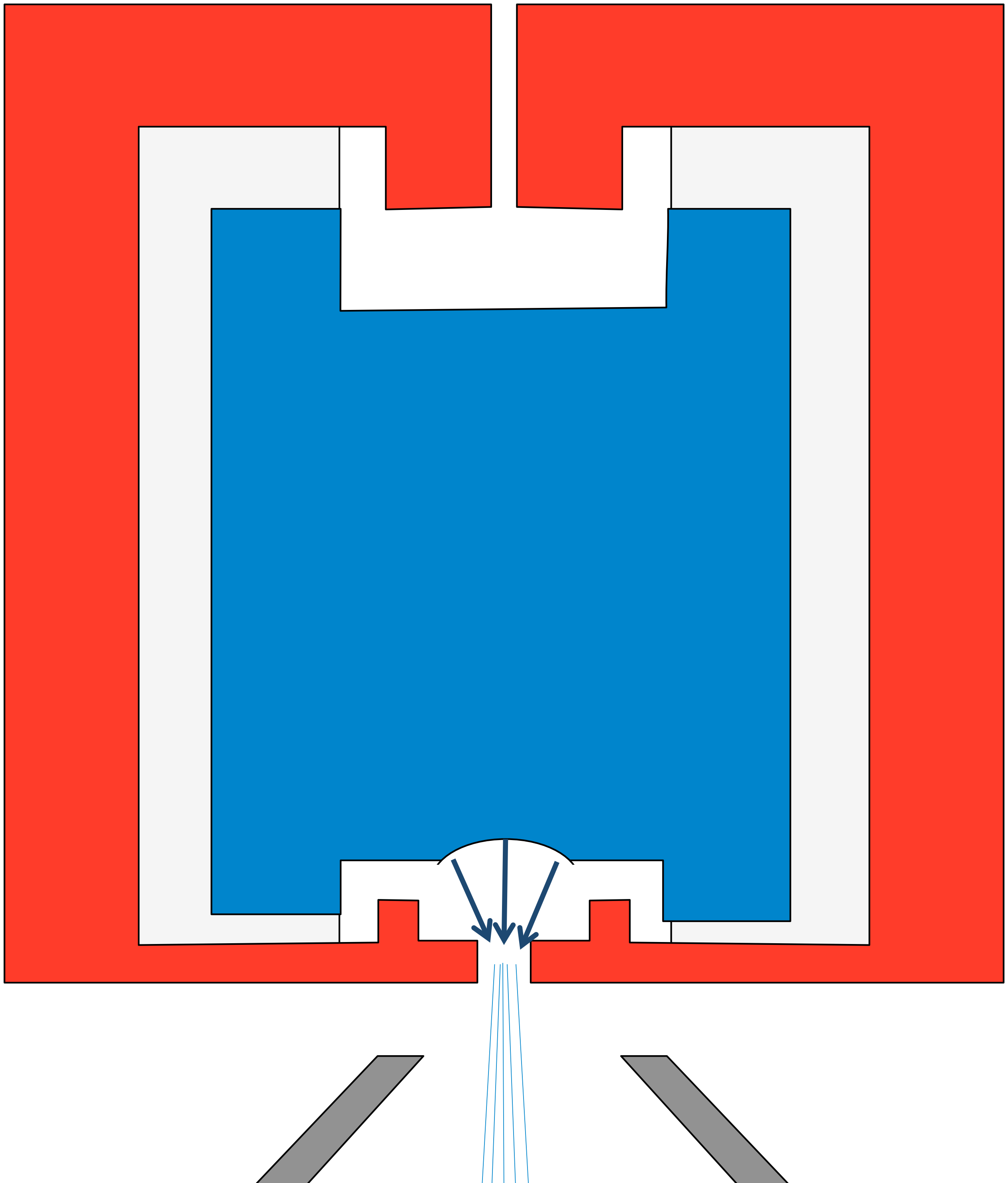


Horizontal en rms = 0.12 mm.mRad



Plasma 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^-

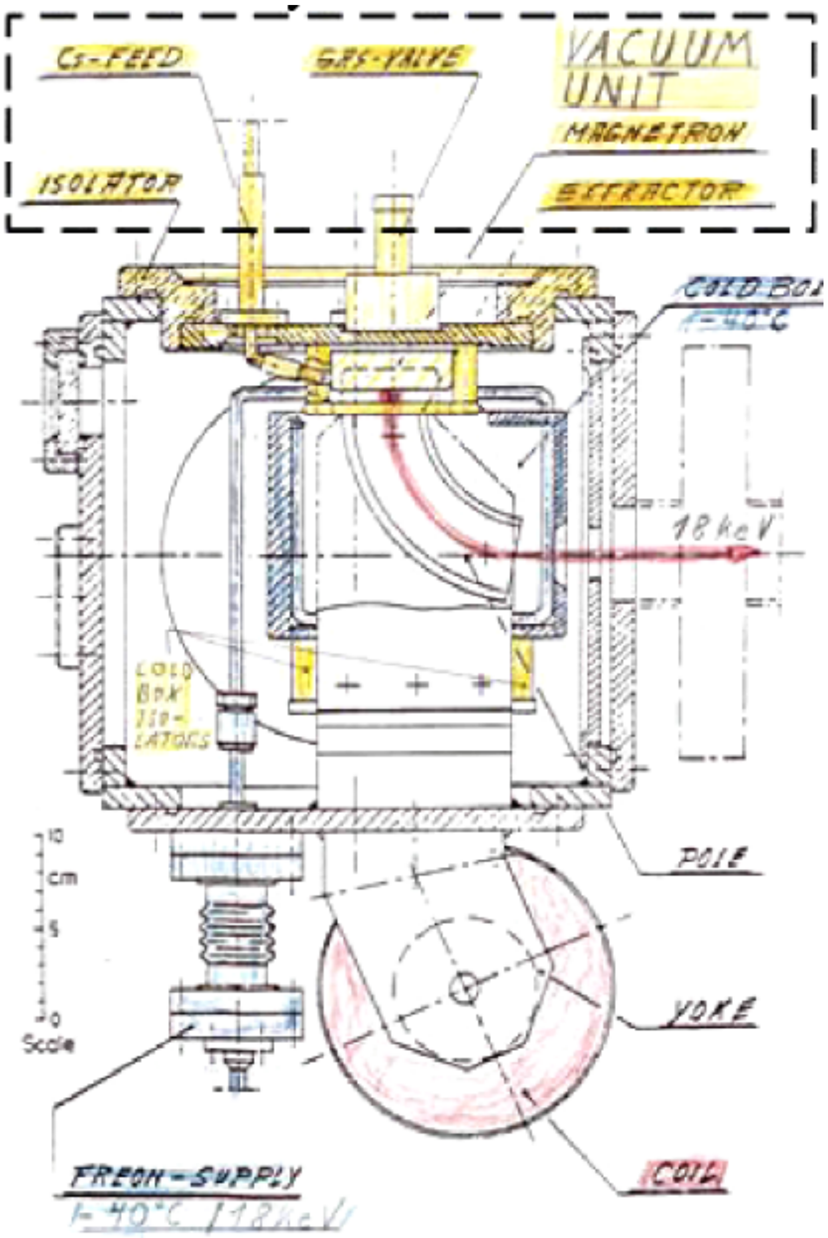
$$H^-_{(fast)} + H^0_{(slow)} \rightarrow H^0_{(fast)} + H^-_{(slow)}$$

Magnetrons are noisy because some H^- come directly from the cathode and some undergo charge exchange

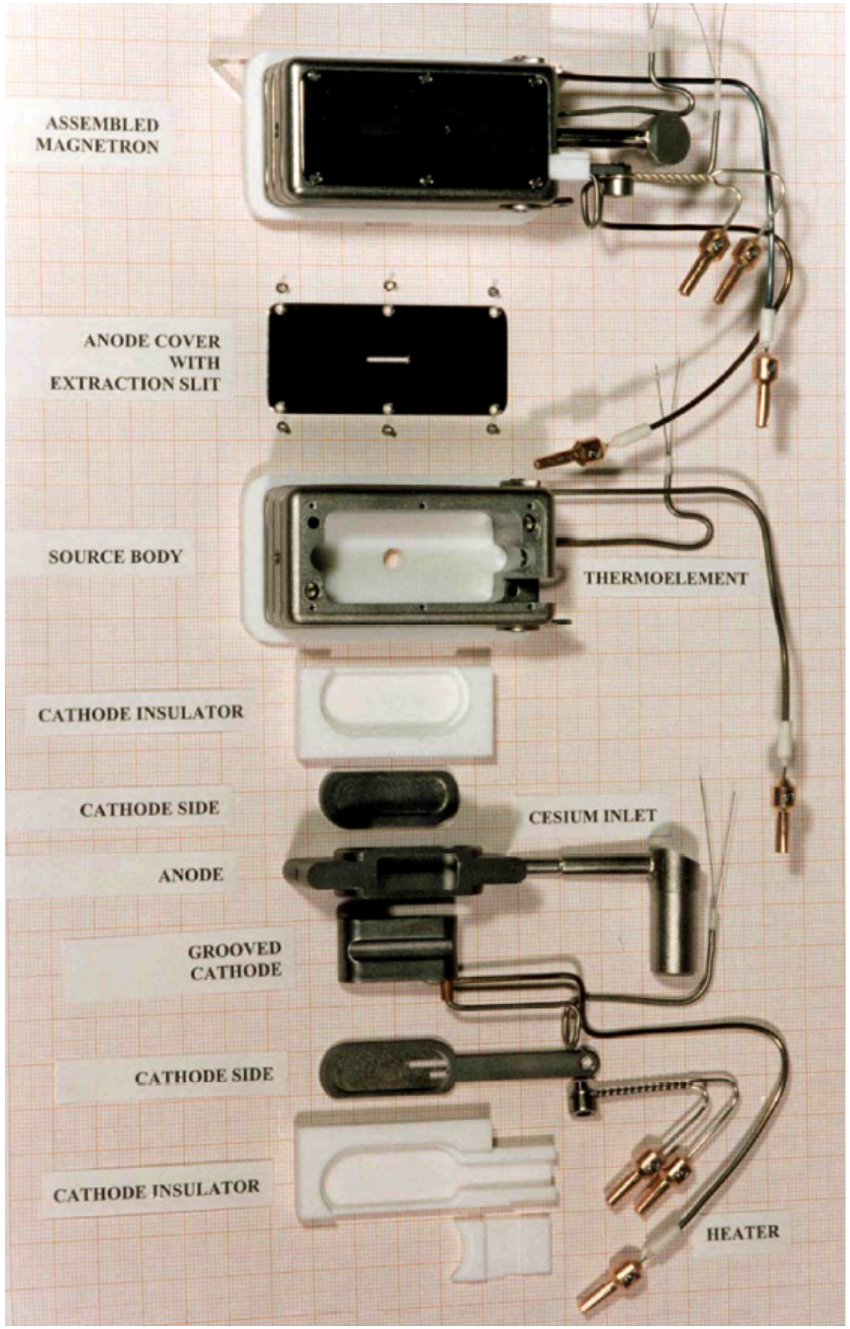
Slow thermal H^0 produced in the plasma (≈ 0.1 eV)

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

DESY HERA Magnetron Source

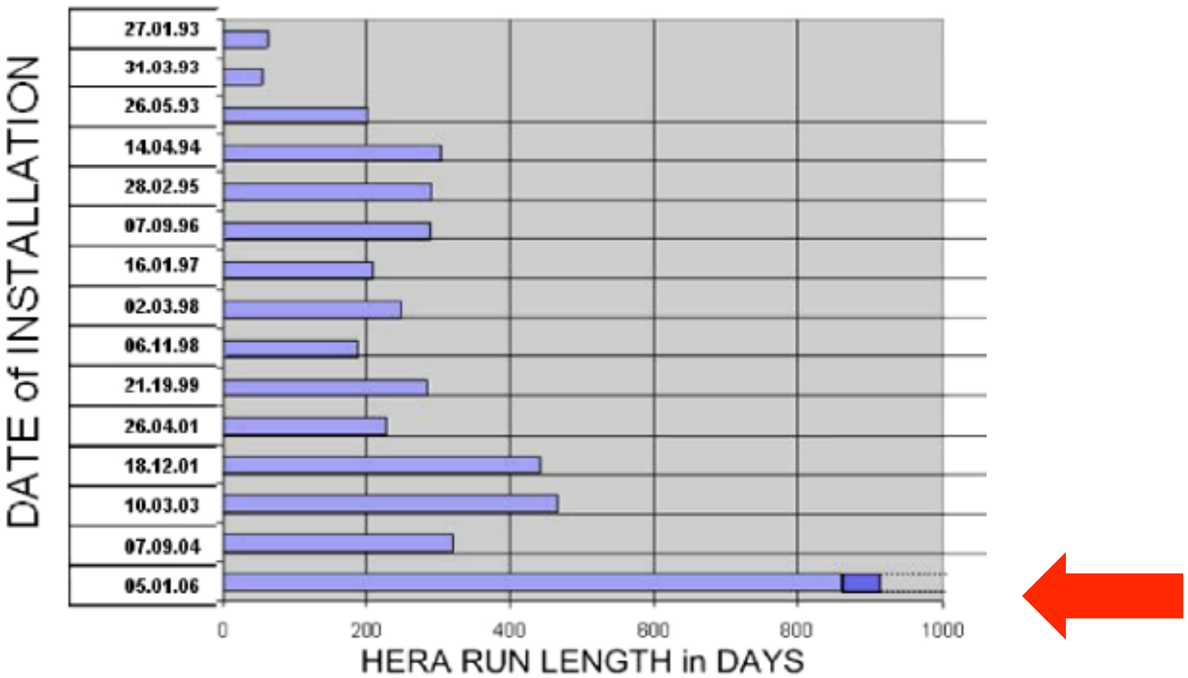


Source Box with Magnet



DESY HERA Magnetron Source

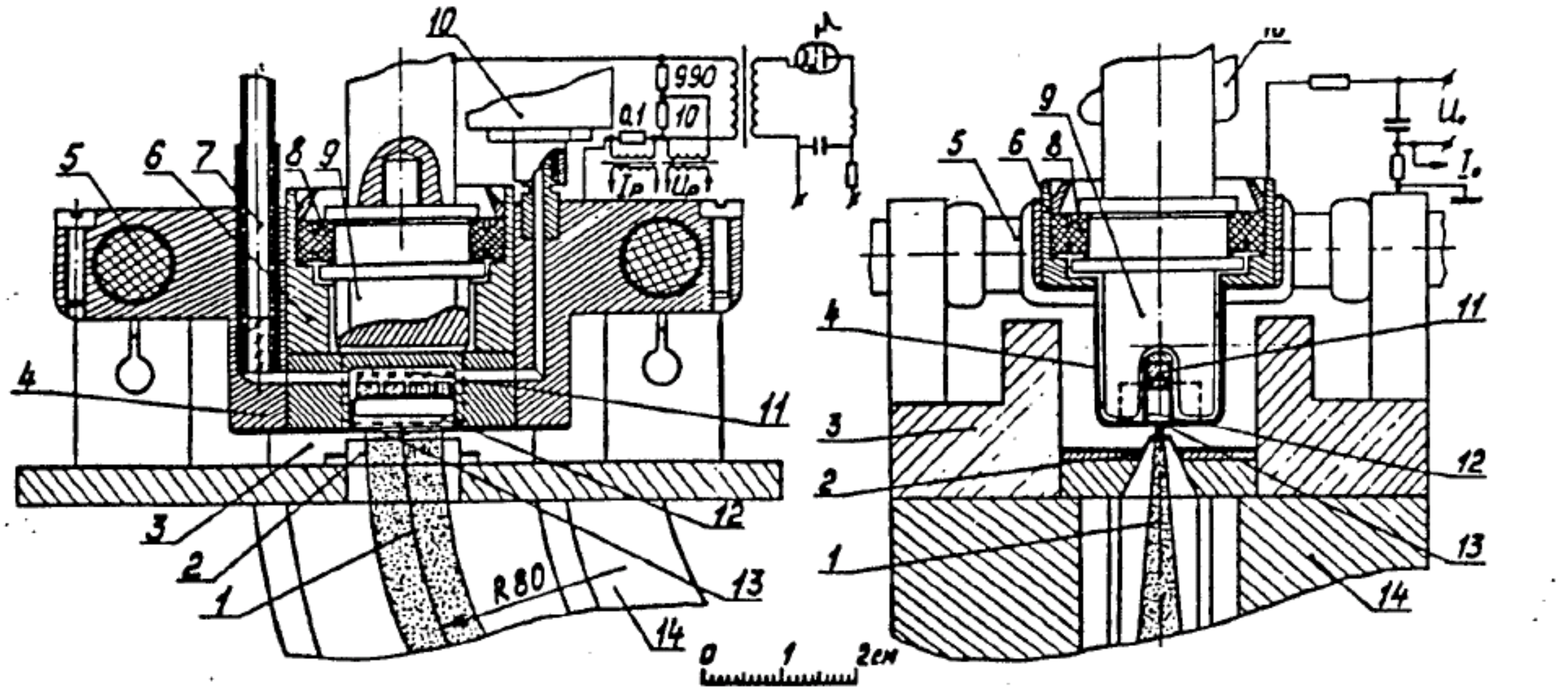
beam energy	18 keV	arc voltage	140 V
H^- beam current	60 mA	arc current	47 A
emittance		arc pulse width	75 μsec
$\varepsilon_{x\ rms,norm}$ ($\varepsilon_{x\ 90\%,norm}$) (35mA beam)	0.28(1.35) π mm mrad	extraction repetition rate	1/4 Hz -1Hz
$\varepsilon_{y\ rms,norm}$ ($\varepsilon_{y\ 90\%,norm}$) (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!

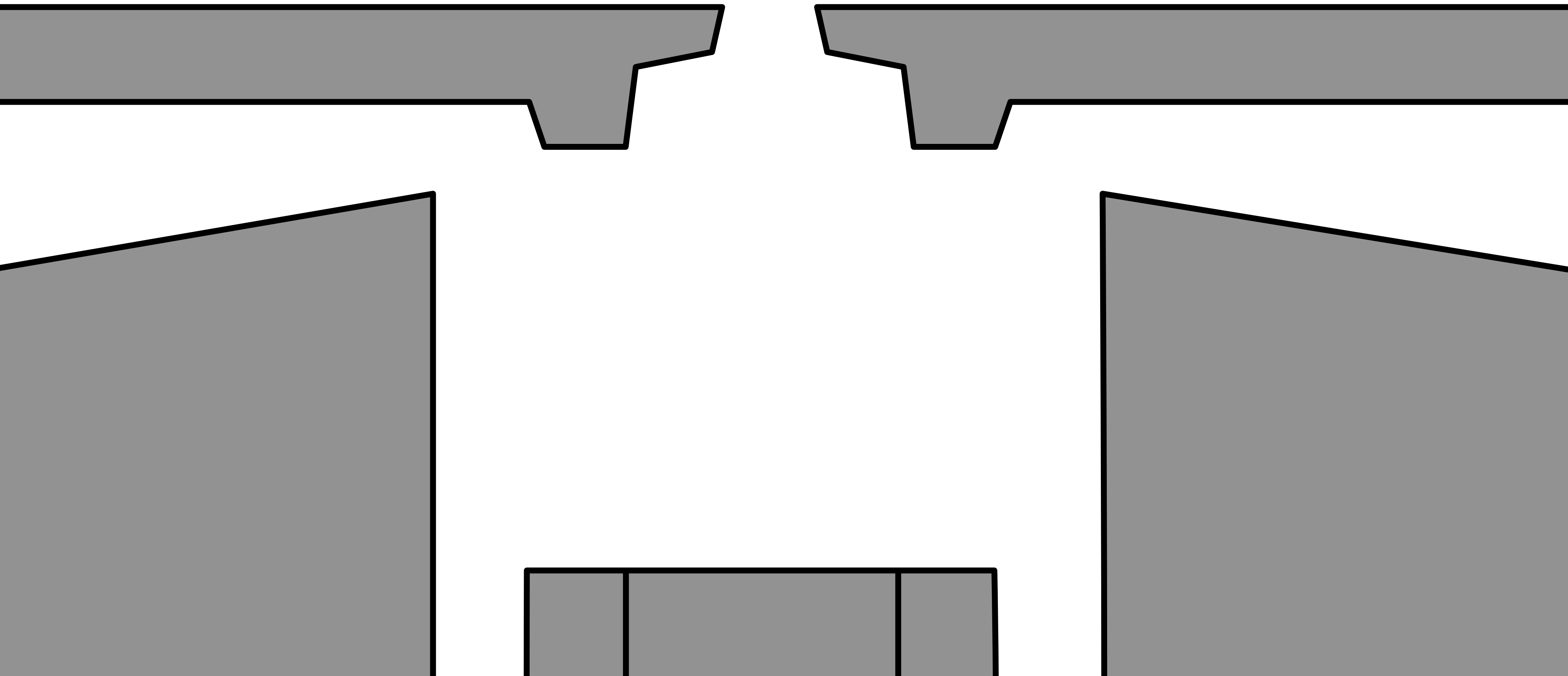
Penning Ion Sources

- Invented by Dudnikov in the 1970’s
- Very high current density > 1 Acm^{-2}
- Low noise
- Will not work without caesium



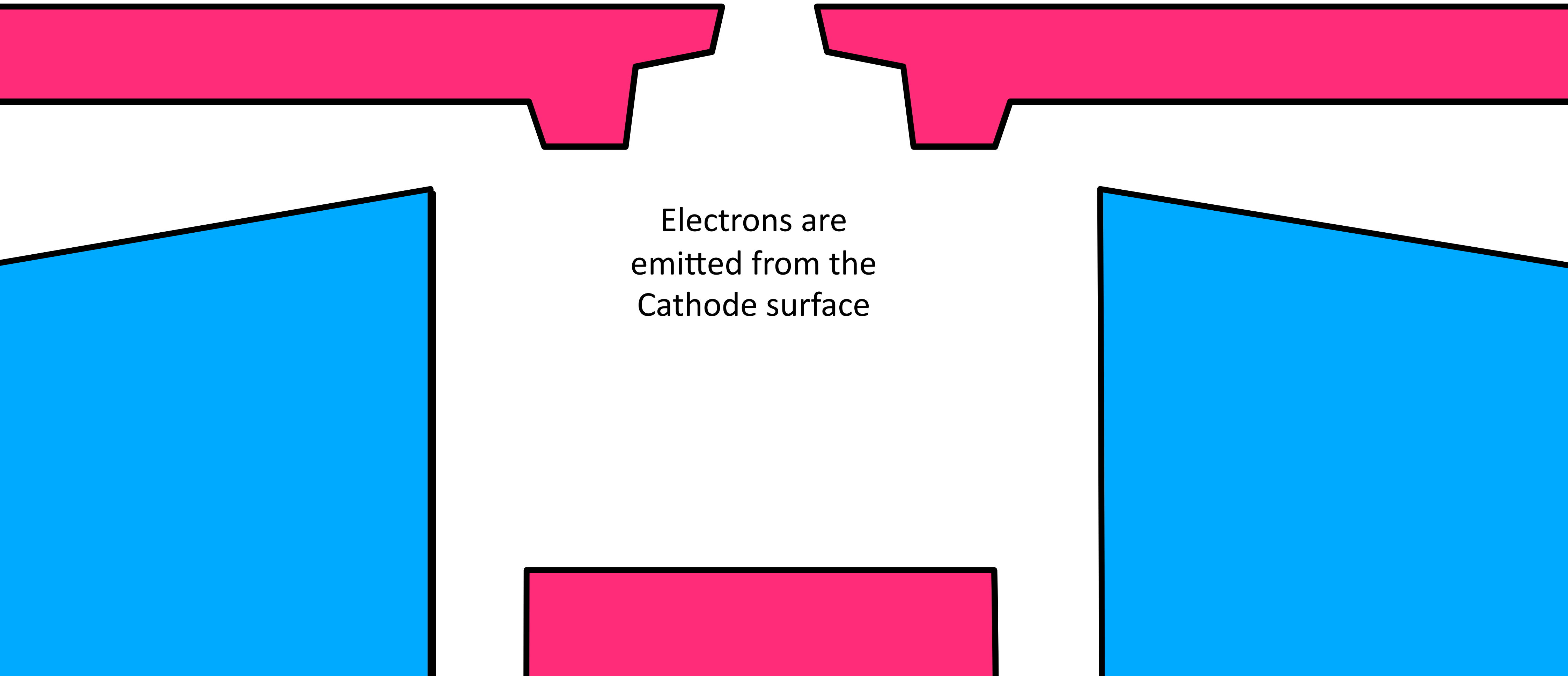
Key Design Points for H^- Production:

Electrodes are made of Molybdenum 4.5 eV work function and a high melting point



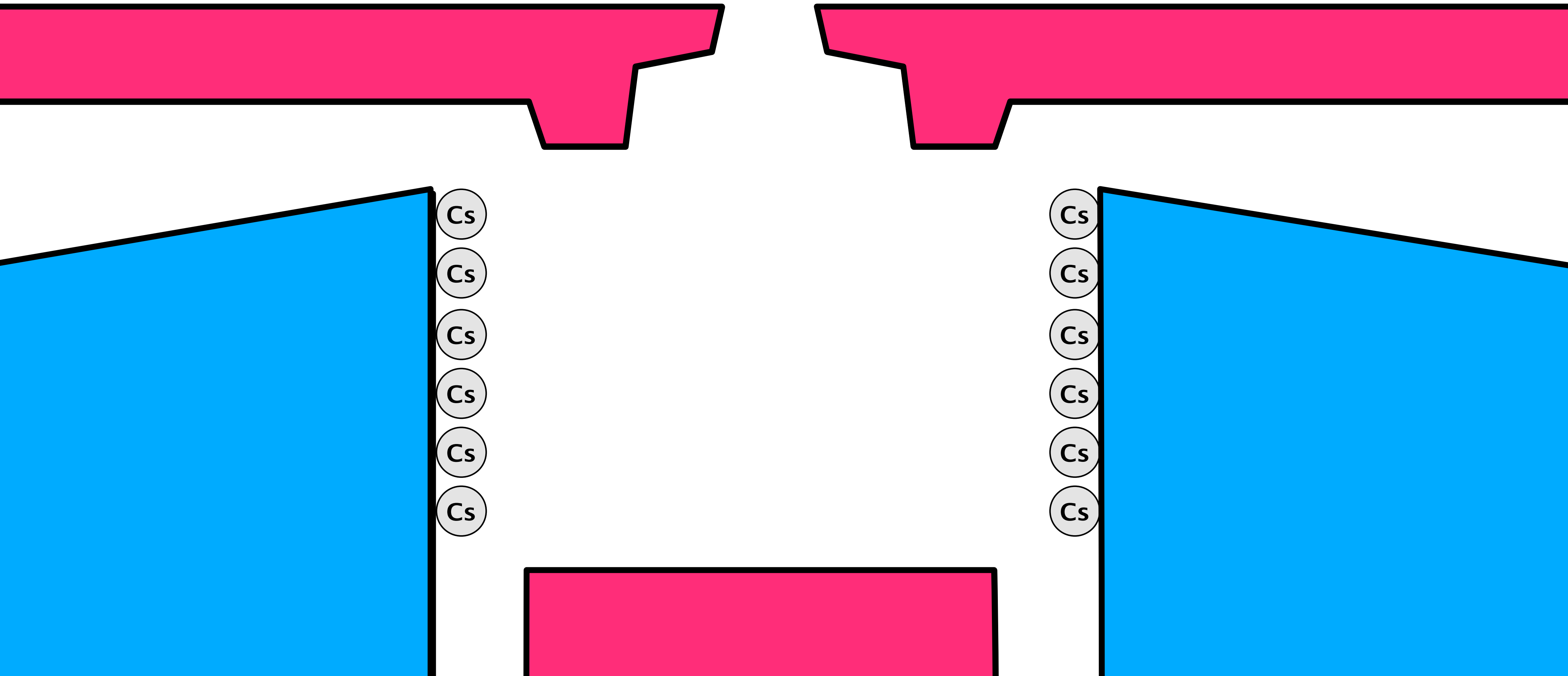
Key Design Points for H^- Production:

Electrodes are made of Molybdenum (4.5 eV work function) and a high melting point



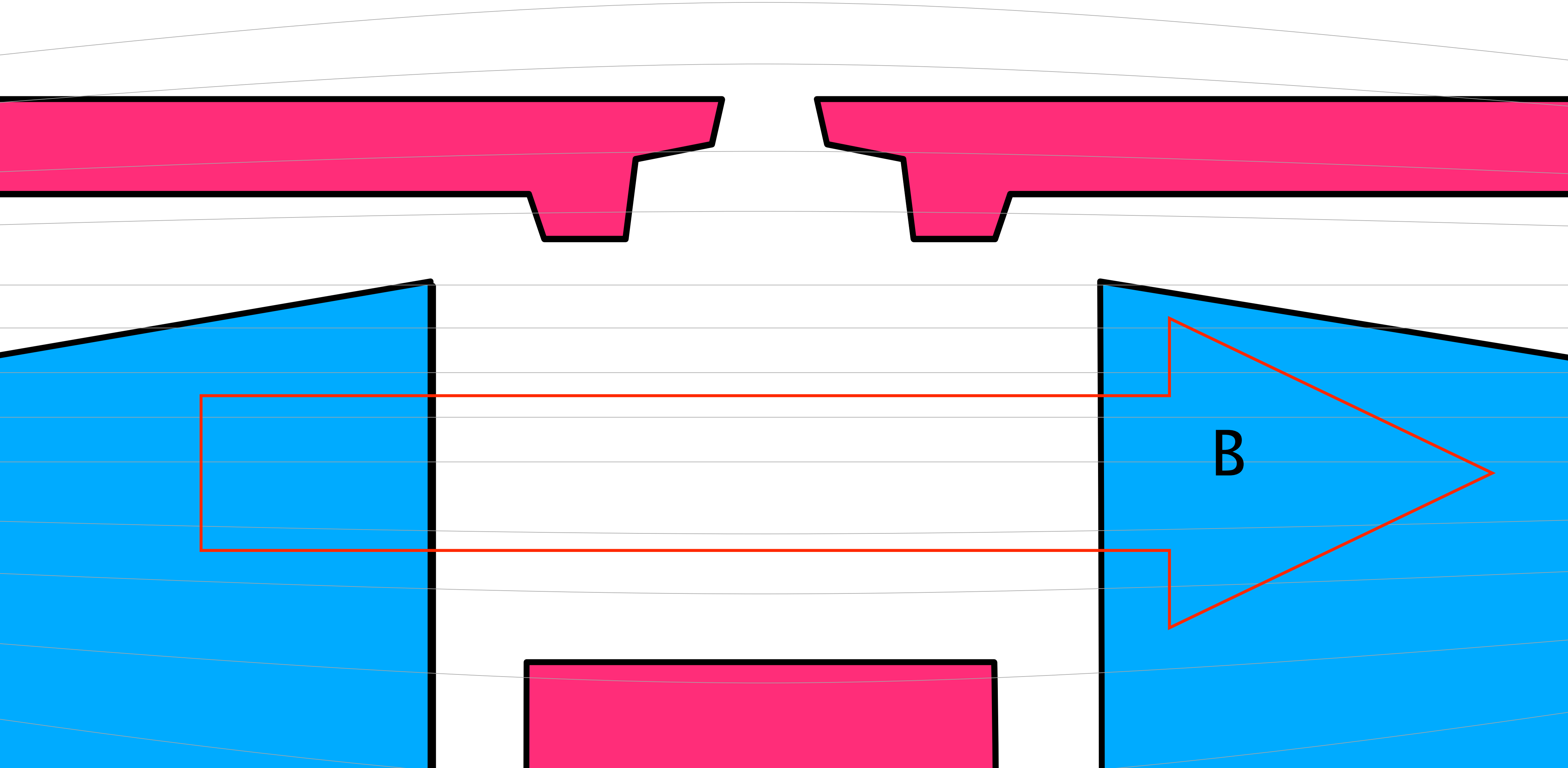
Key Design Points for H^- Production:

Caesium vapour further lowers the cathode work function (1.5 eV)



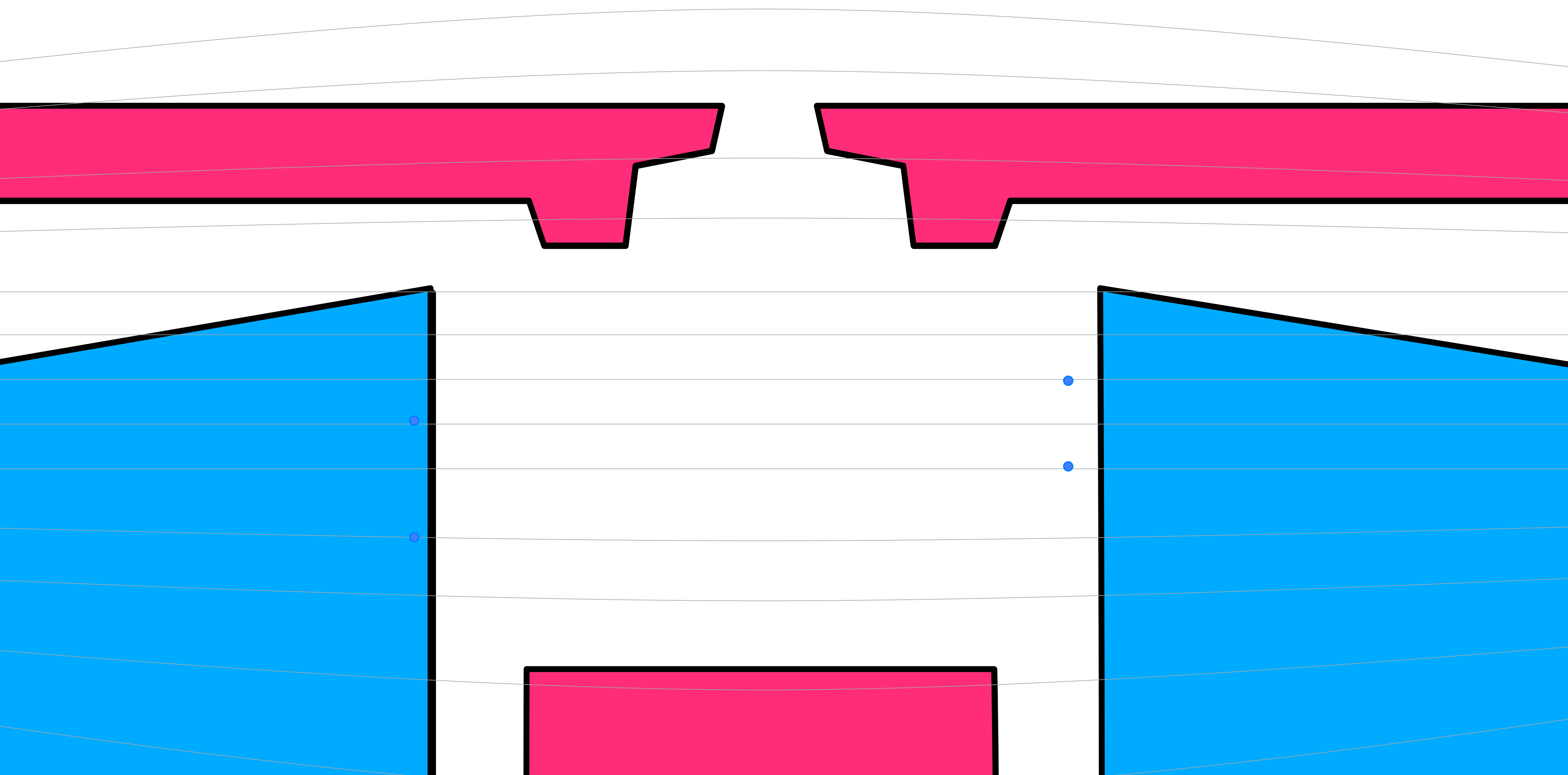
Key Design Points for H^- Production:

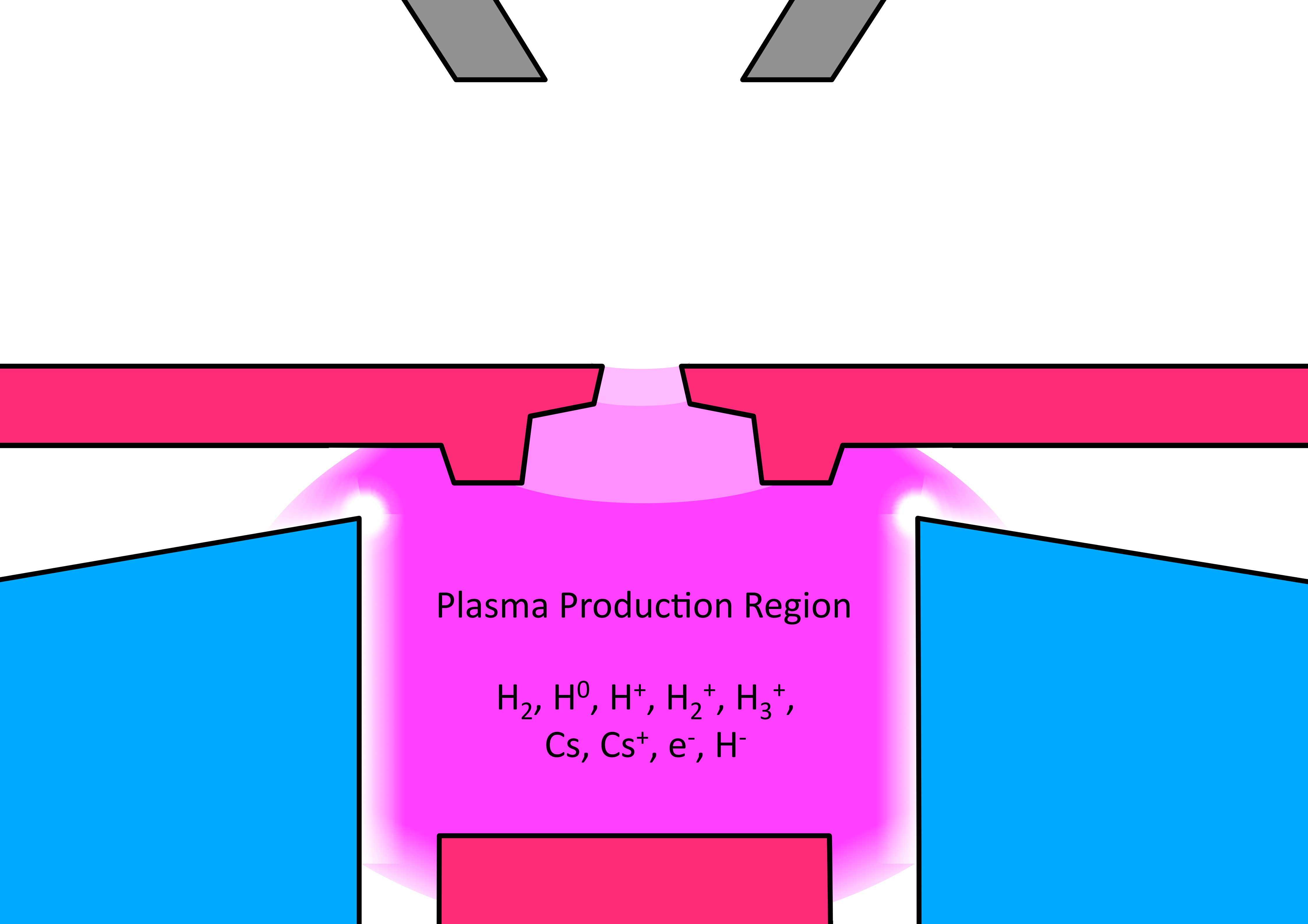
Penning Field confines the electrons increasing the number of ionisations

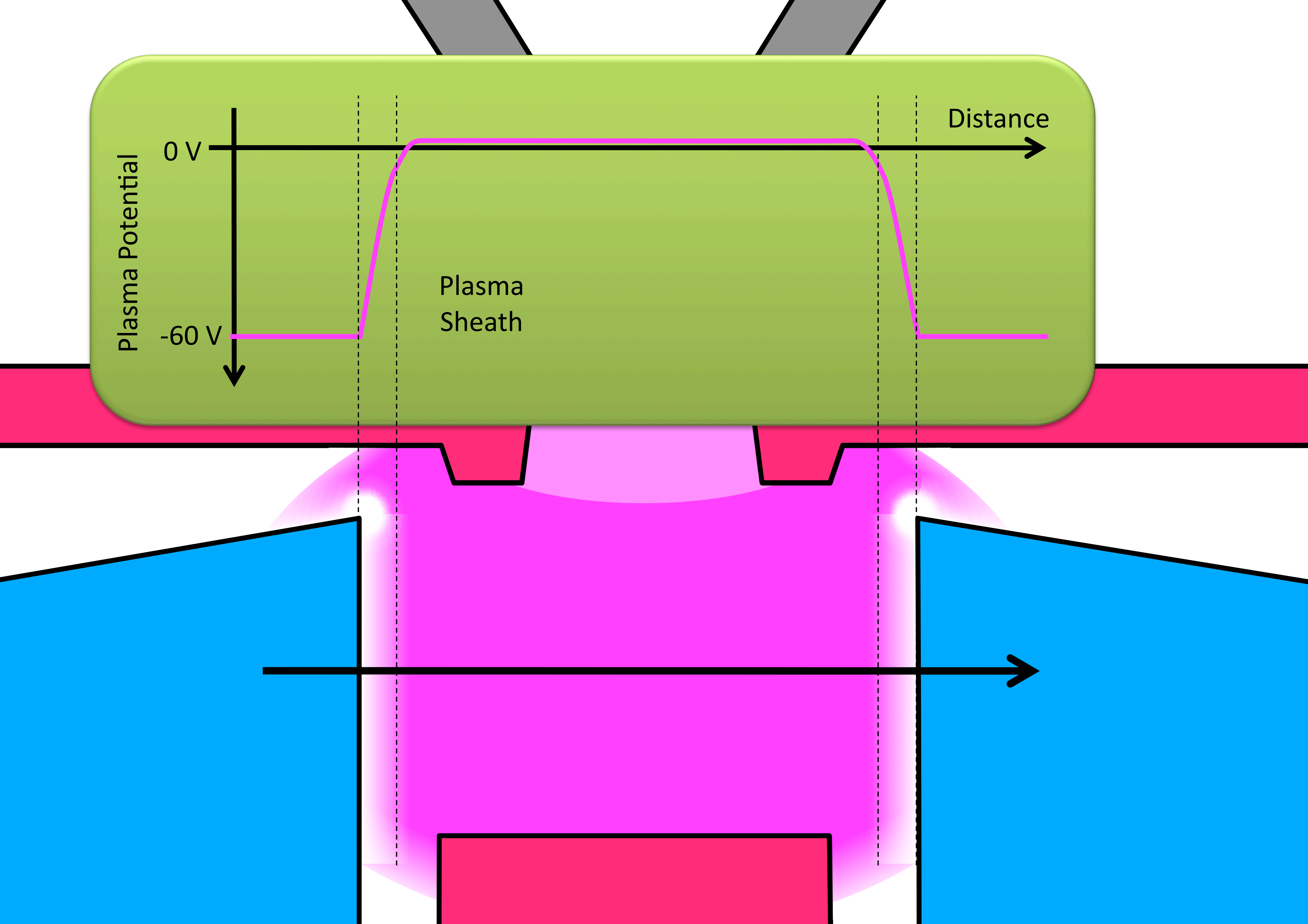


Key Design Points for H^- Production:

Cathode geometry causes the electrons to reflex back and forwards

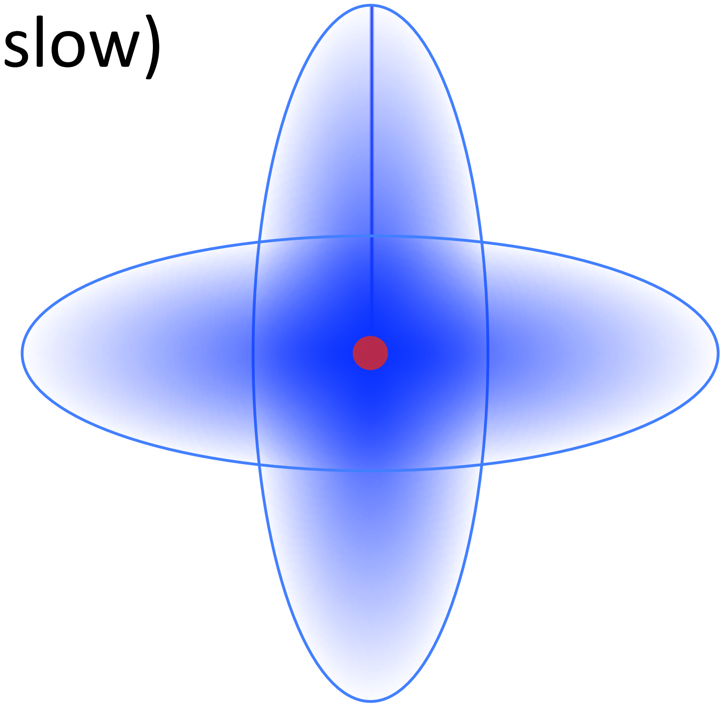



Plasma Production Region
H2, H0, H+, H2+, H3+,
Cs, Cs+, e-, H-


Distance
0 V
-60 V
Plasma Potential
Plasma
Sheath

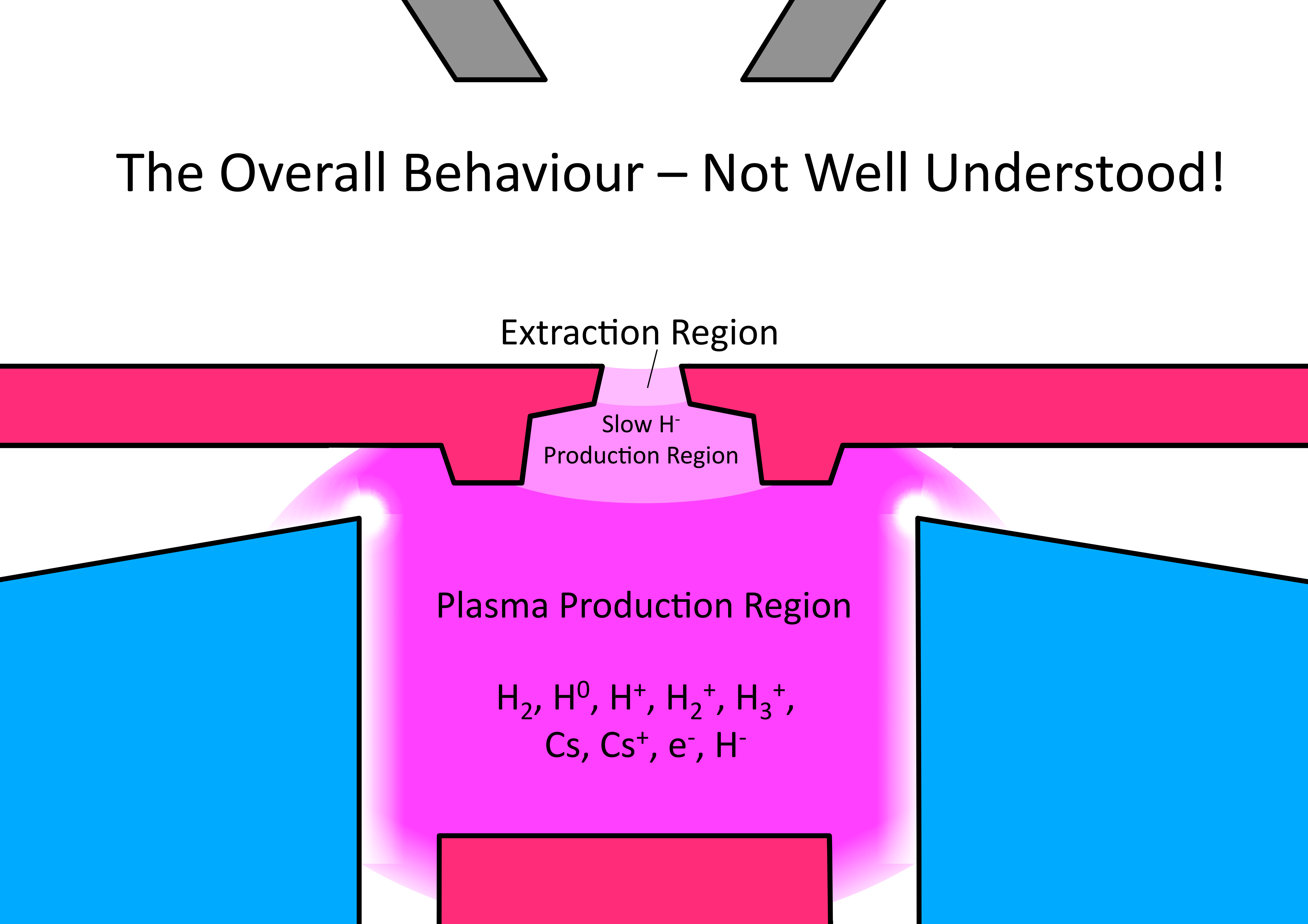
Resonant charge exchange near the extraction region

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

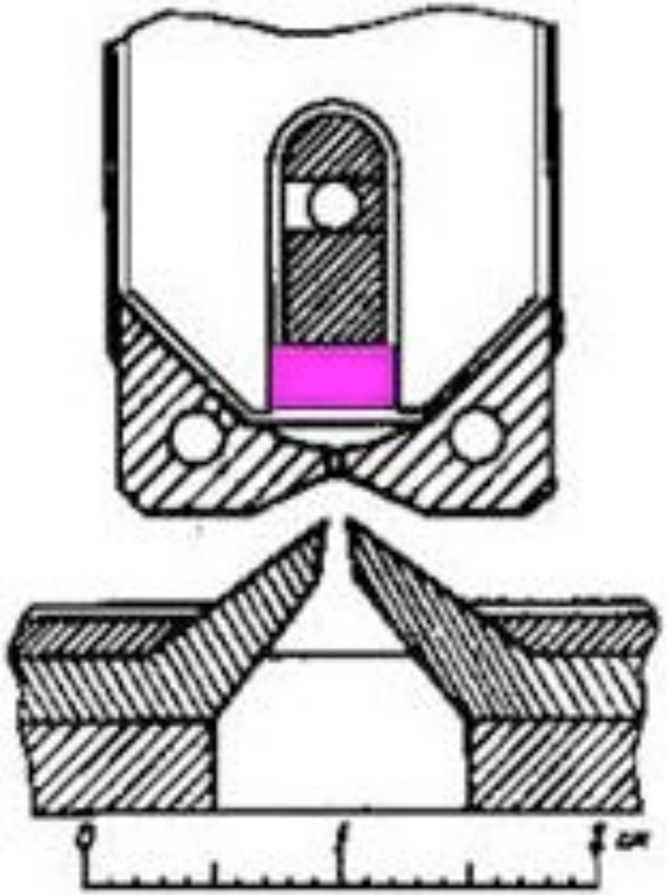


Essential to producing
low noise beams

The Overall Behaviour – Not Well Understood!



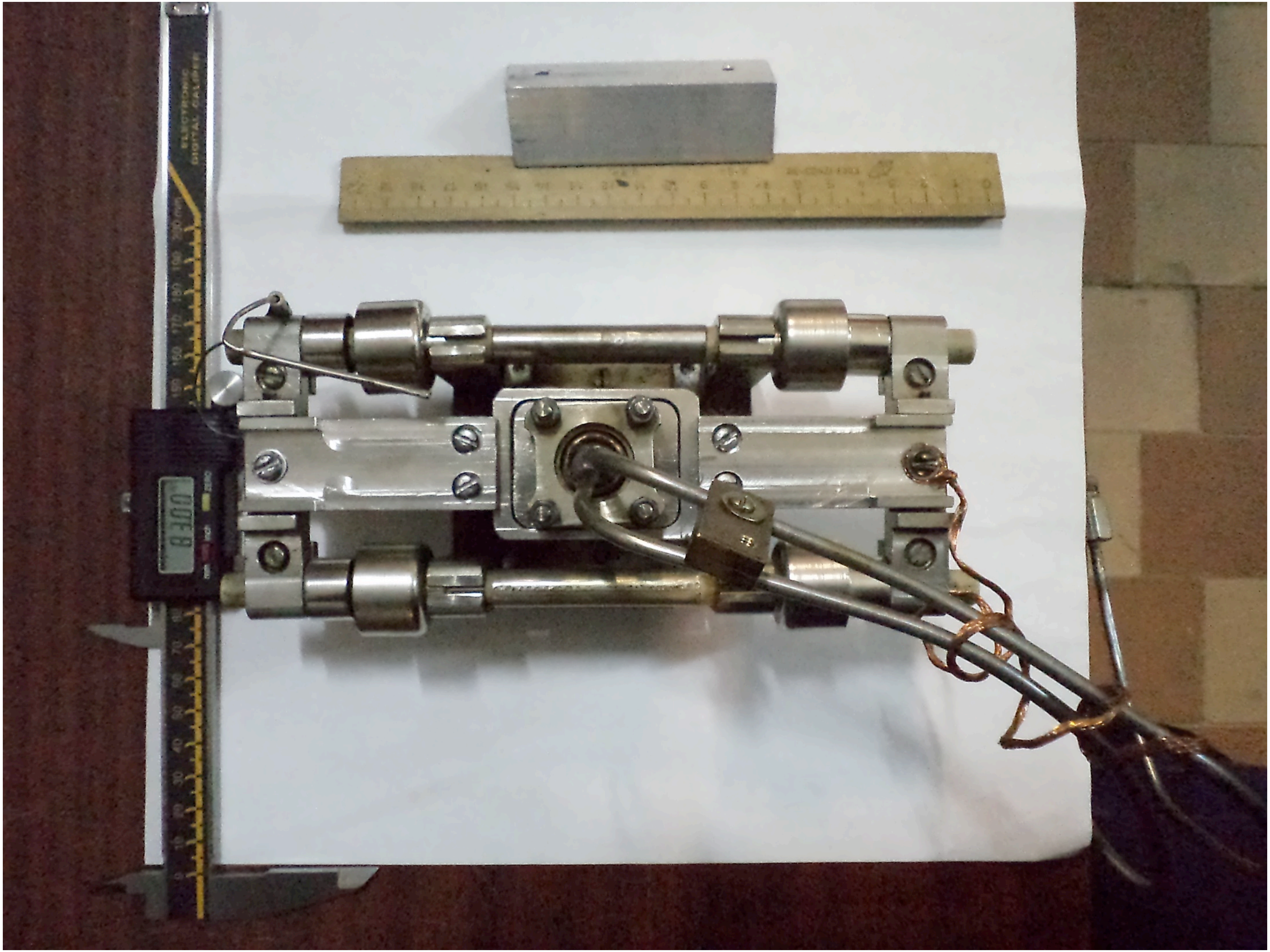
INR Moscow Penning

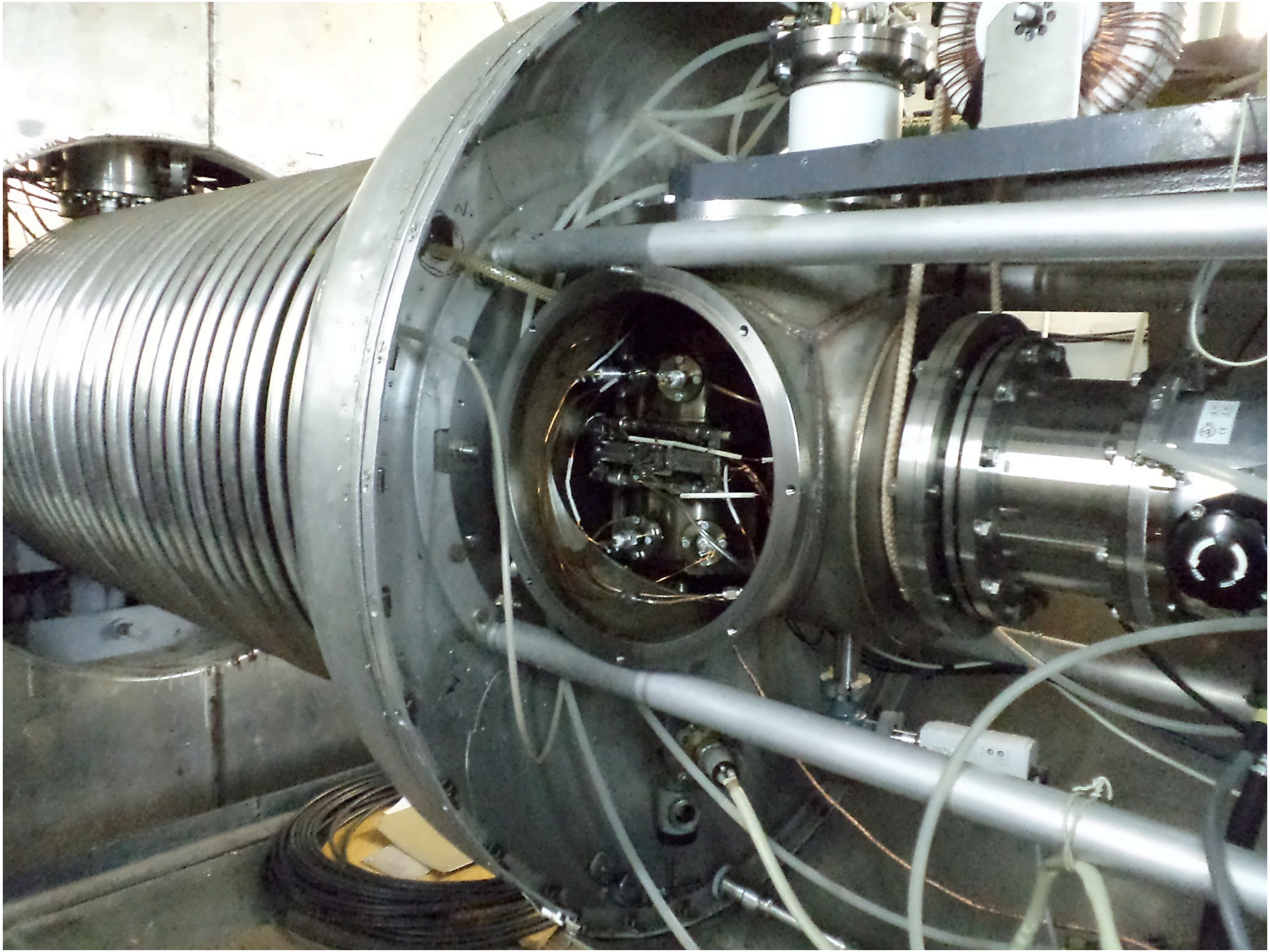


Pulse beam current 40 mA
Pulse repetition rate (PRR) 2 – 50 Hz
Macro-pulse beam current duration 60 – 200 µs
Normalized emittance ≤0.35 π·mm·mrad

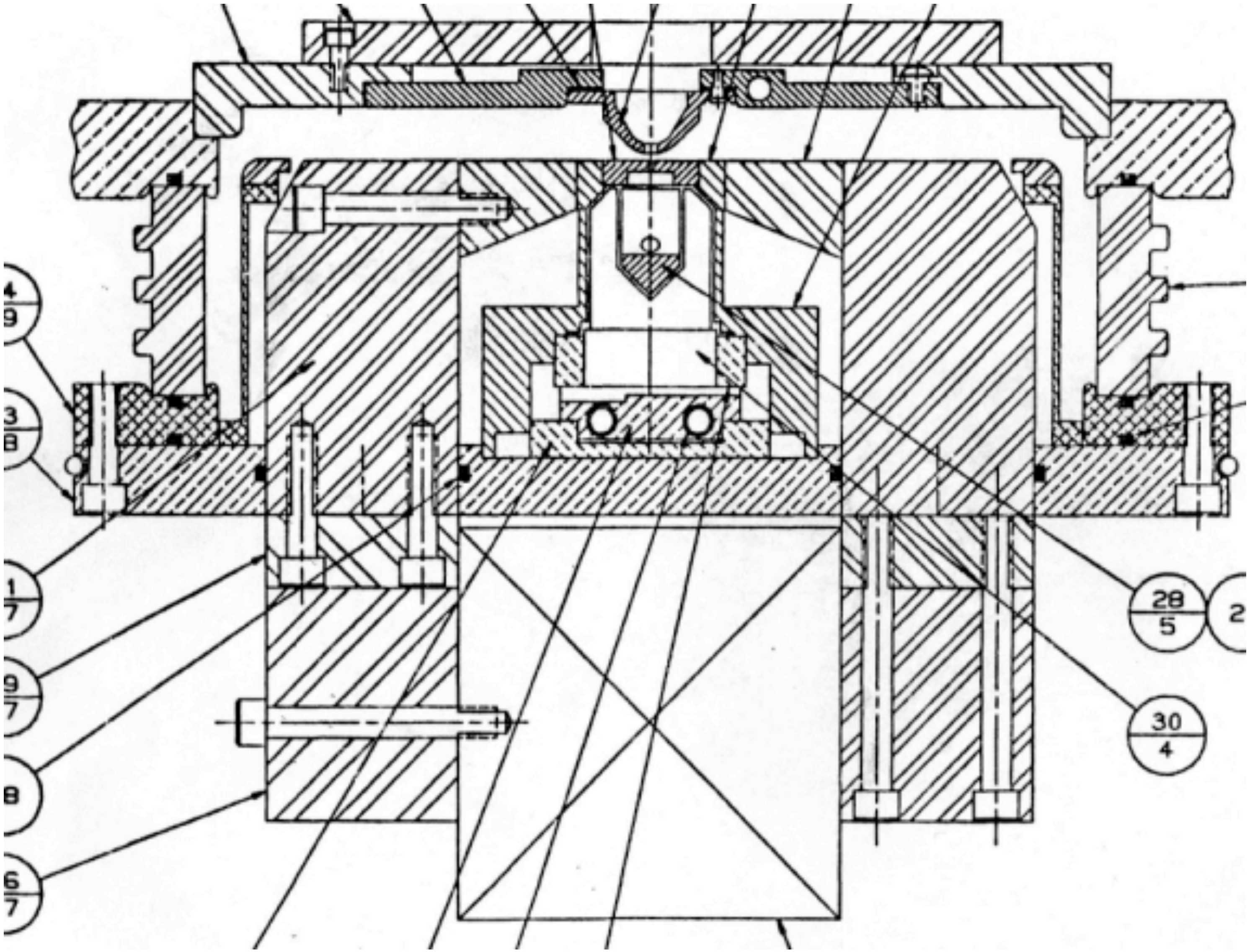
Novosibirsk design

INR Moscow Penning

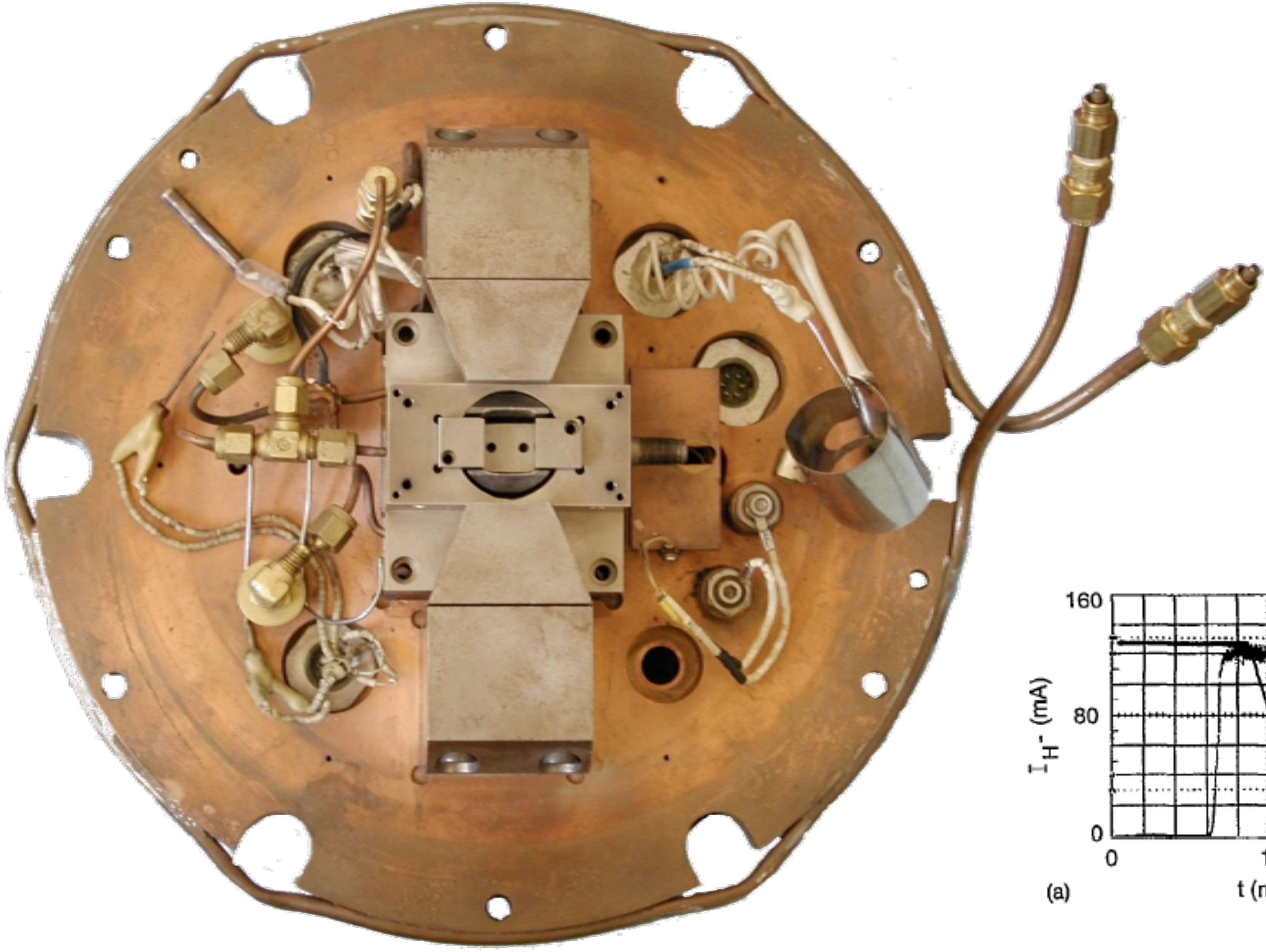

ELECTRONIC DIGITAL CALIPER



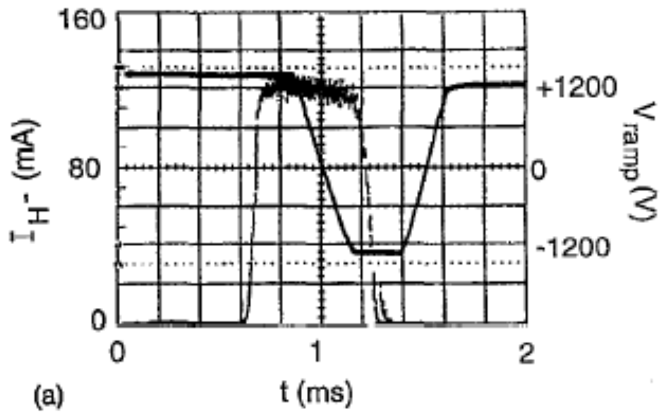
Los Alamos Scaled Penning source



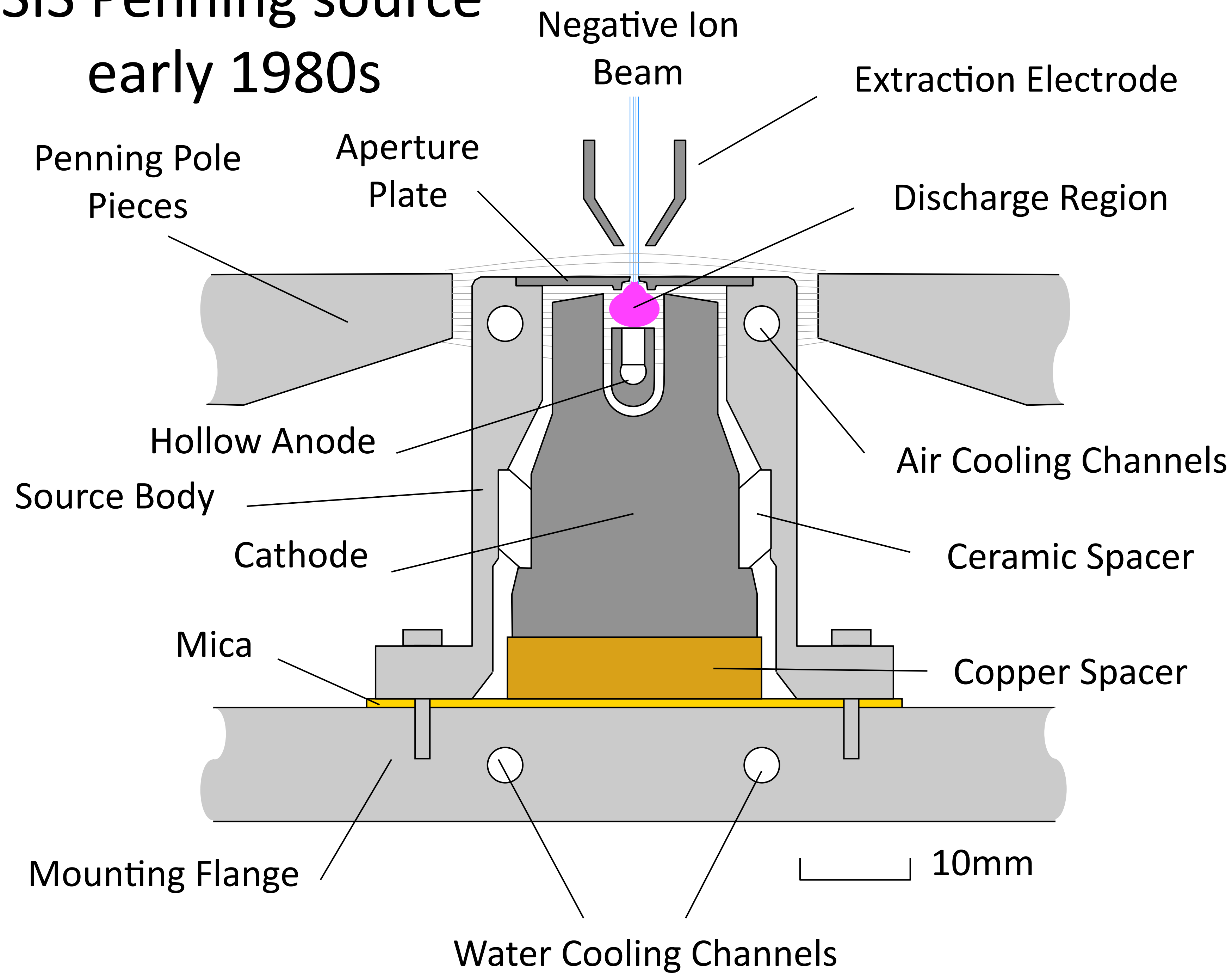
Los Alamos Scaled Penning source

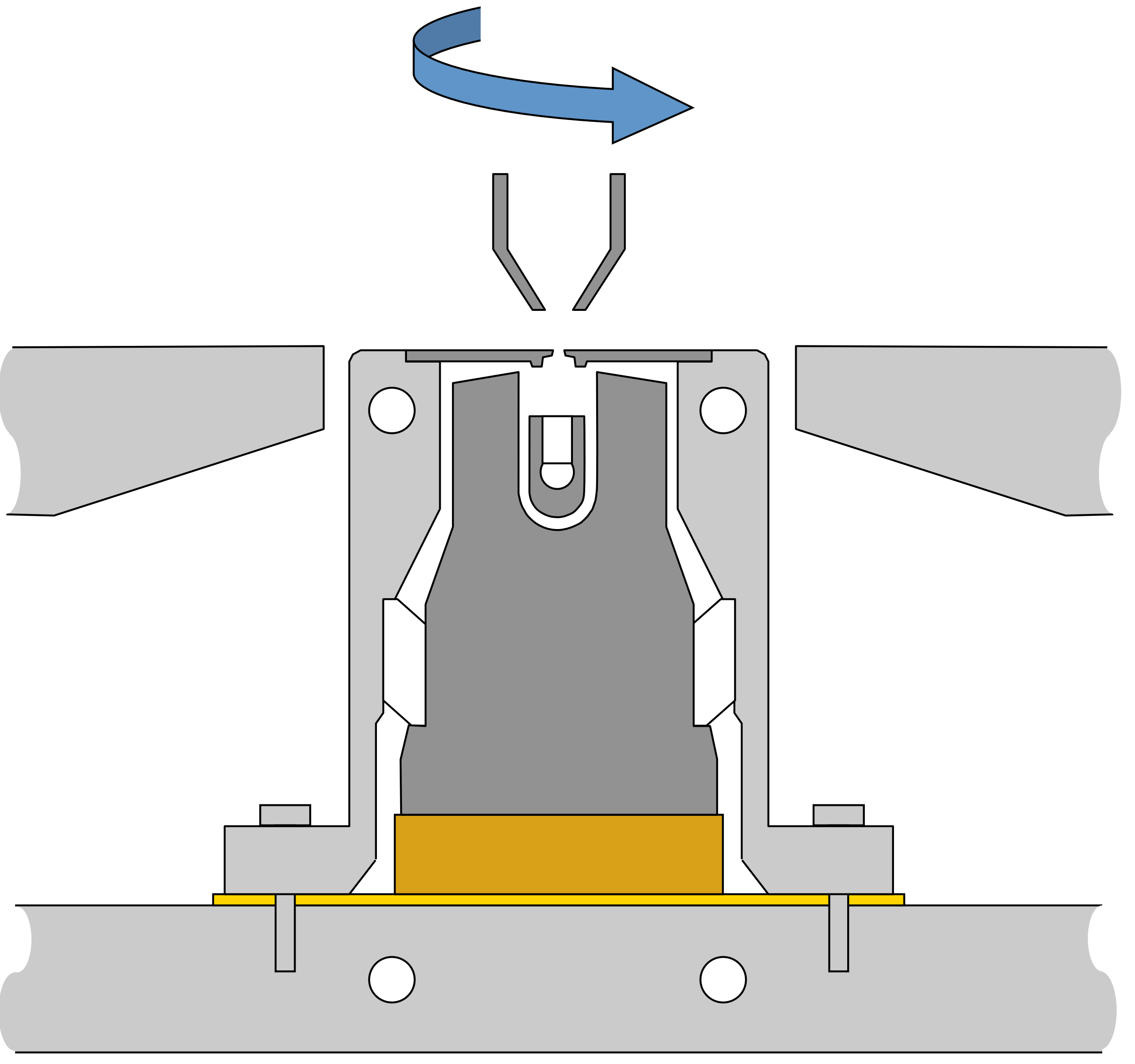


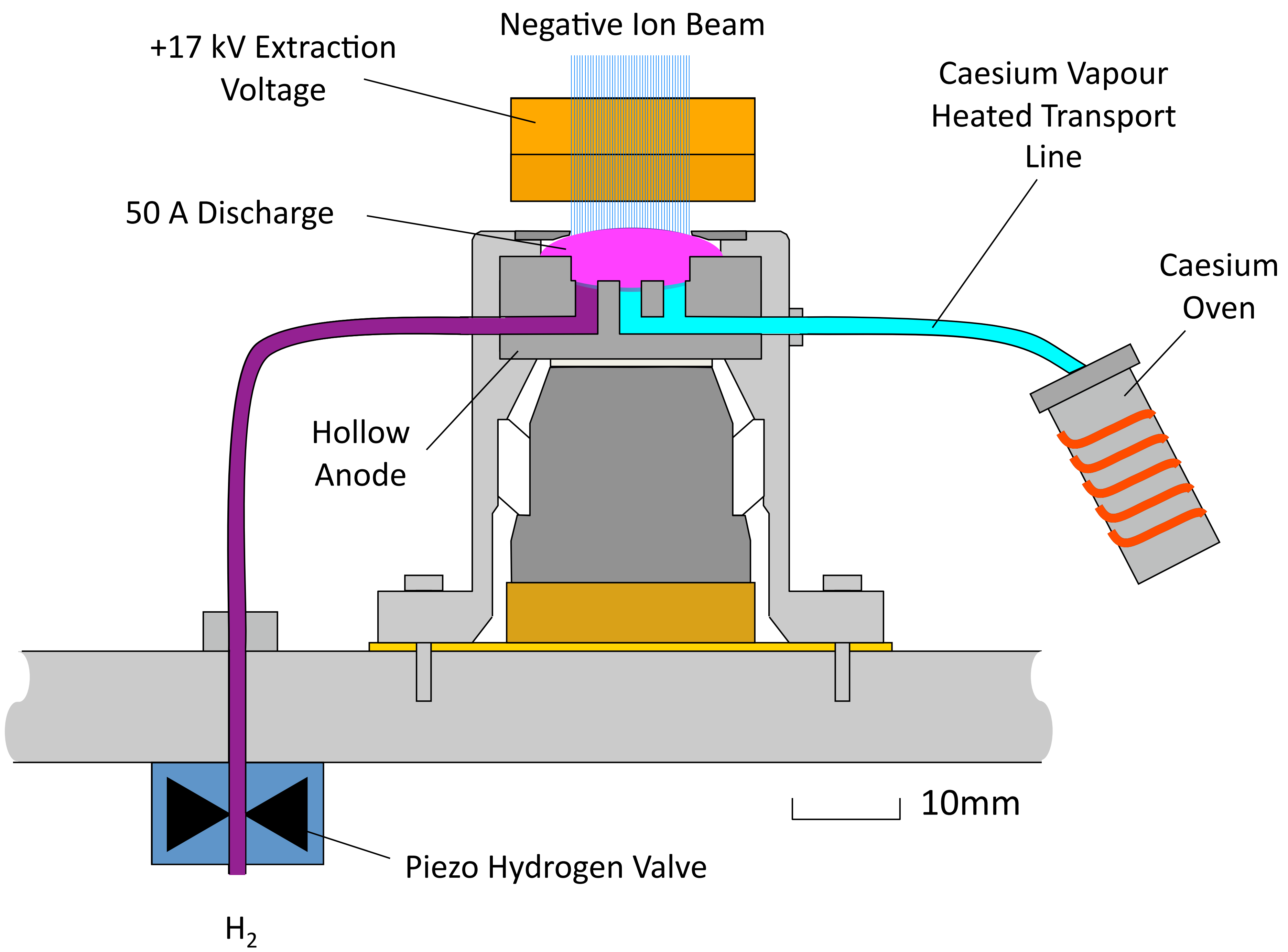
120 mA
500 µs
60 Hz



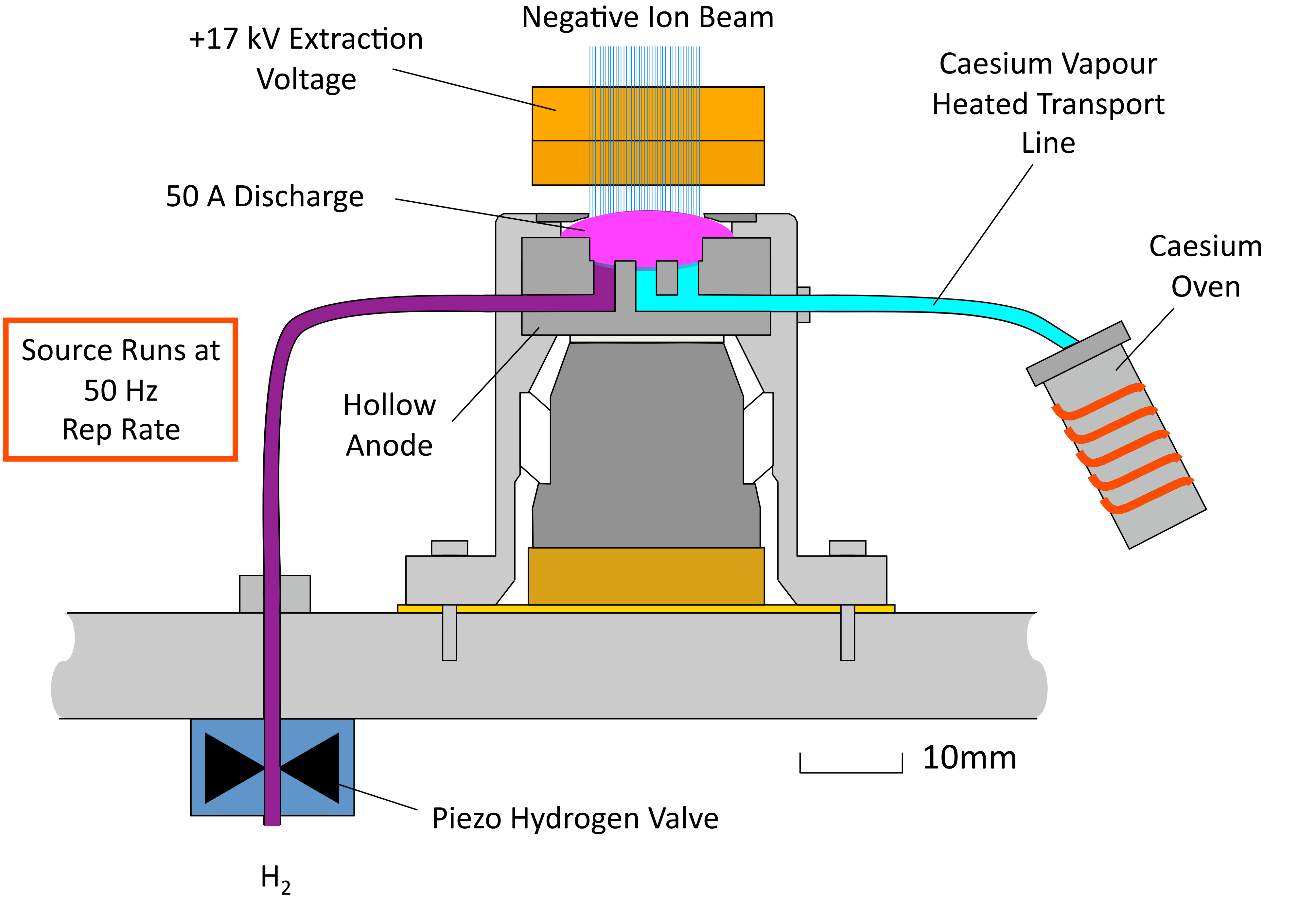
ISIS Penning source early 1980s

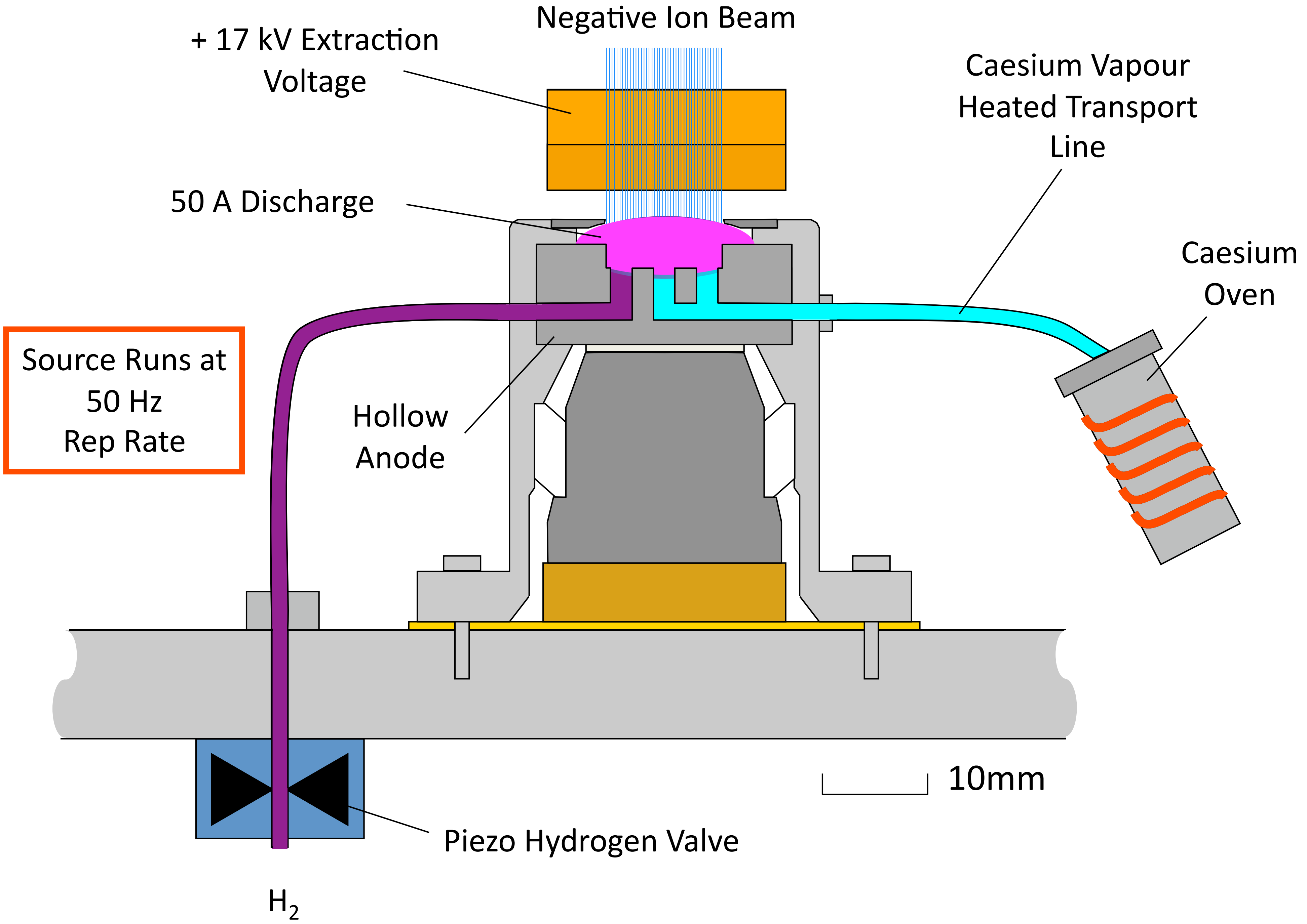




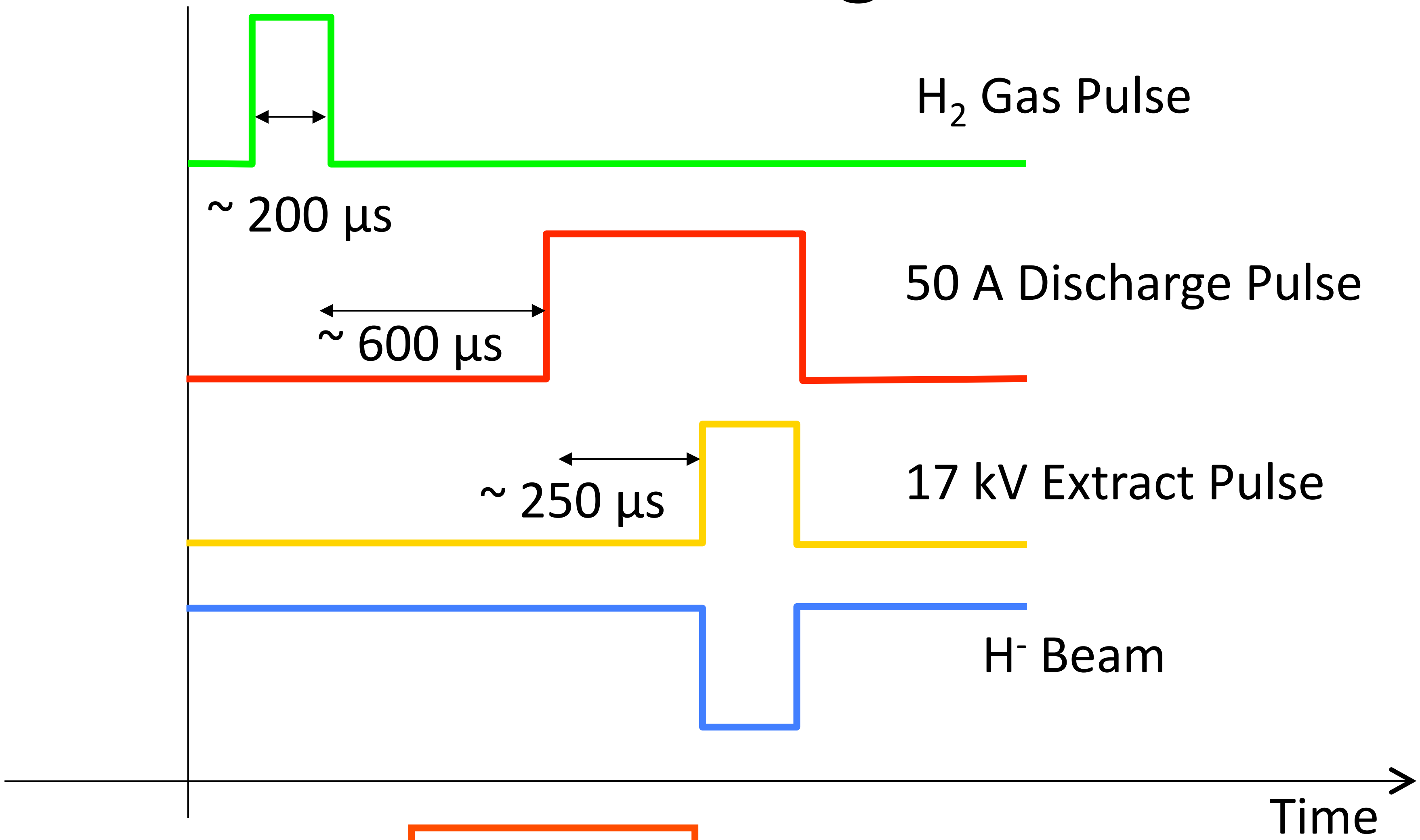


Negative Ion Beam
+17 kV Extraction Voltage
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Hollow Anode
10mm
Piezo Hydrogen Valve
H2

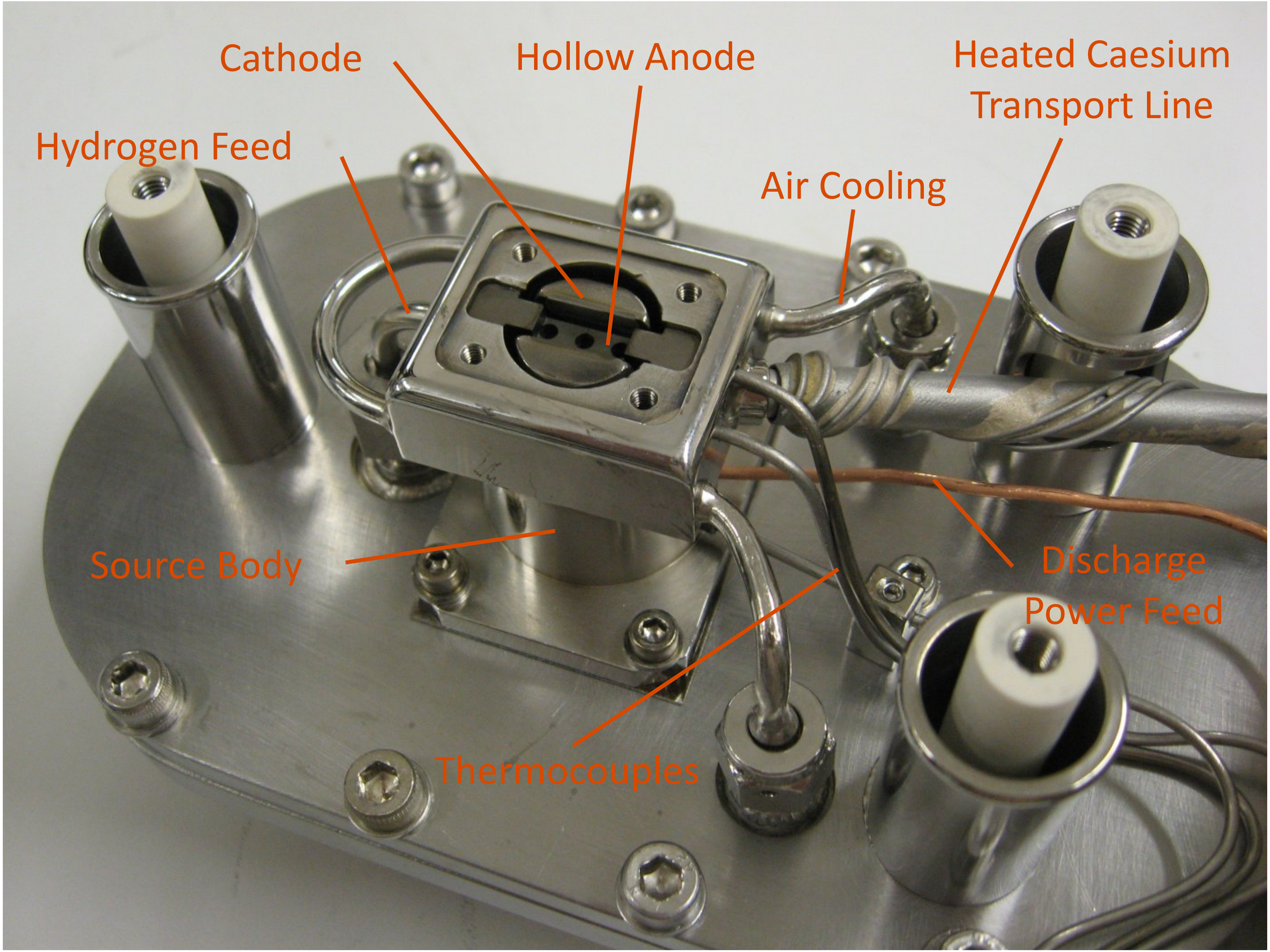

Negative Ion Beam
+17 kV Extraction Voltage
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Source Runs at 50 Hz Rep Rate
Hollow Anode
10mm
Piezo Hydrogen Valve
H_2

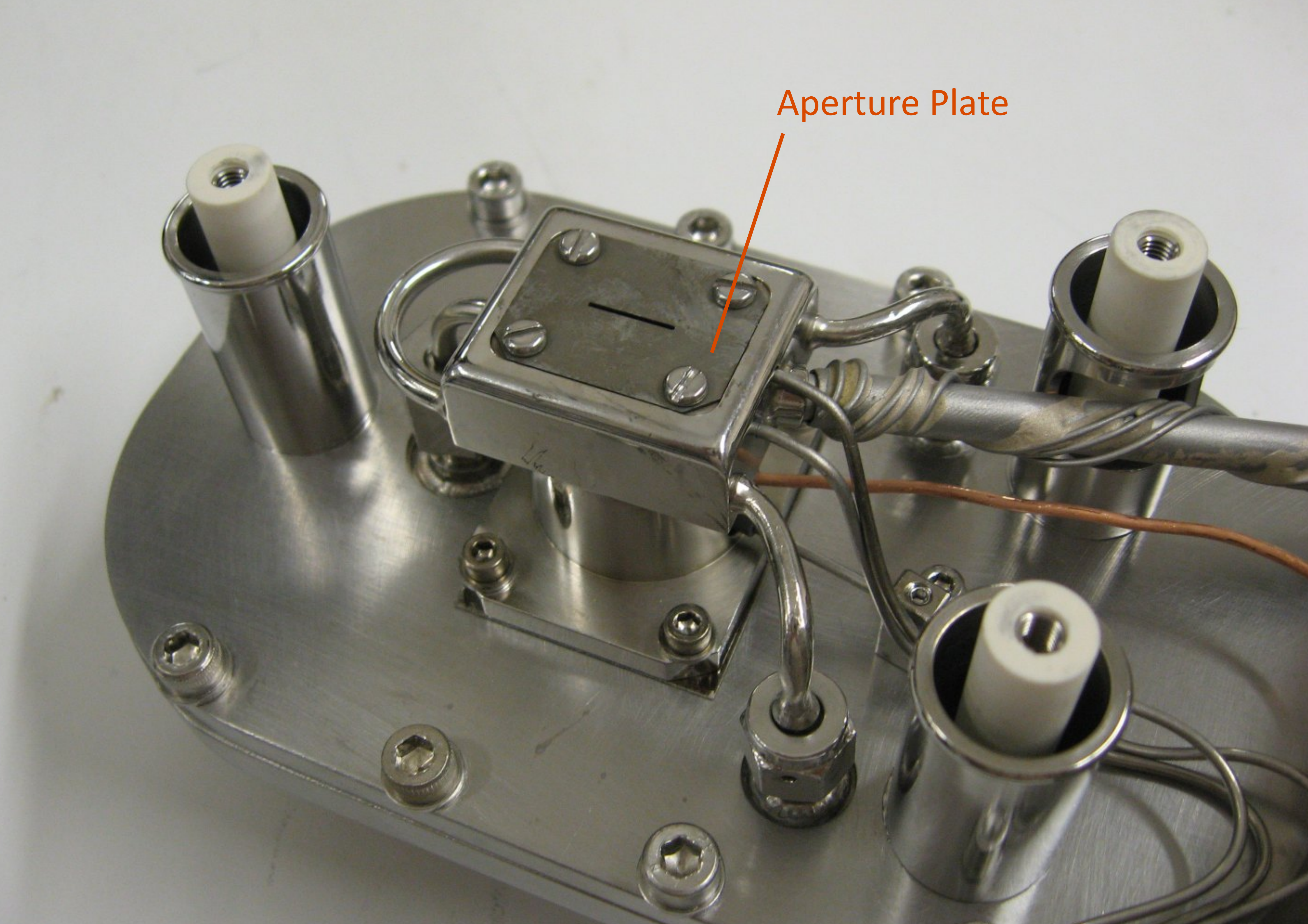

Negative Ion Beam
+ 17 kV Extraction Voltage
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Source Runs at 50 Hz Rep Rate
Hollow Anode
10mm
Piezo Hydrogen Valve
H_2

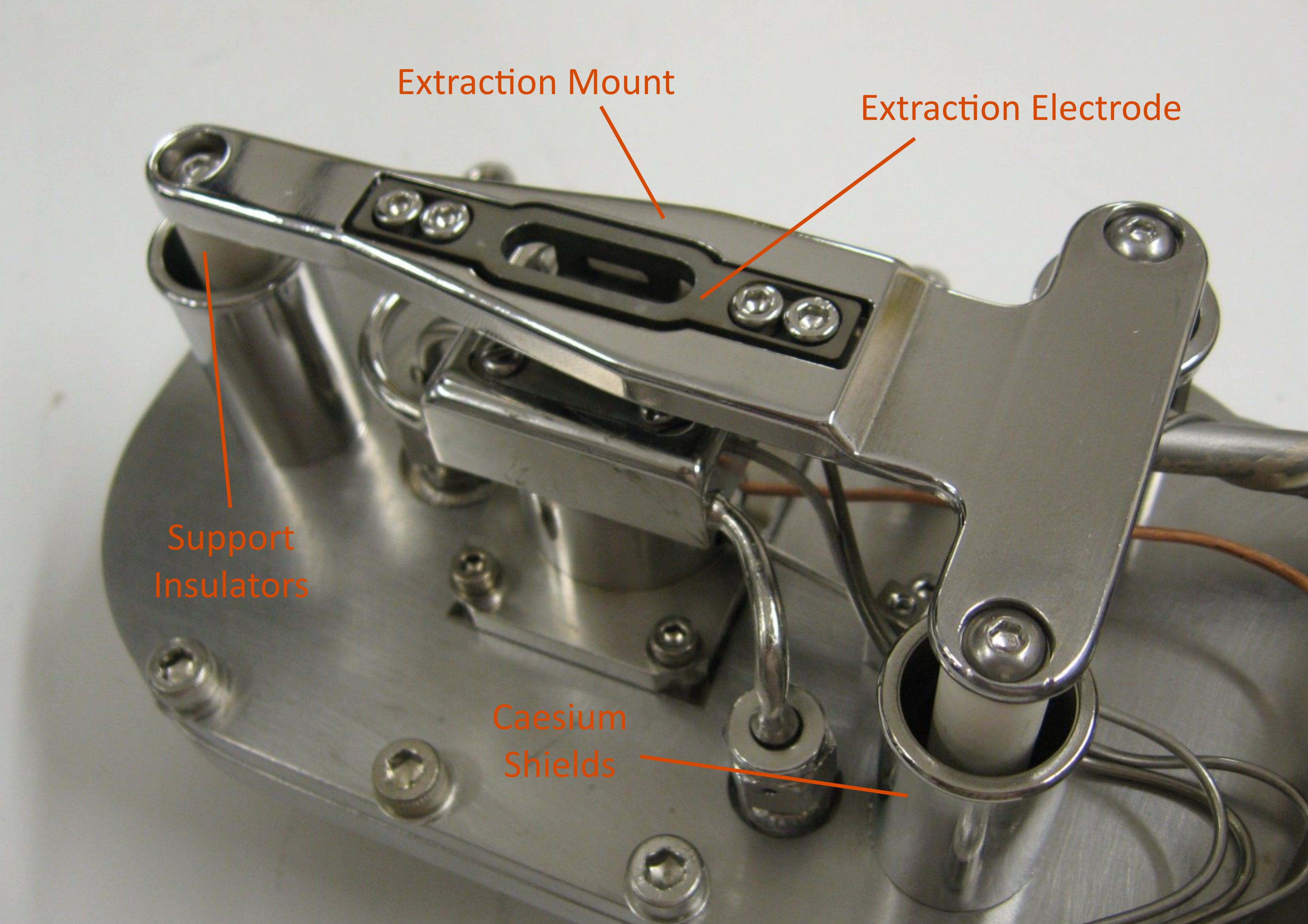
Timing

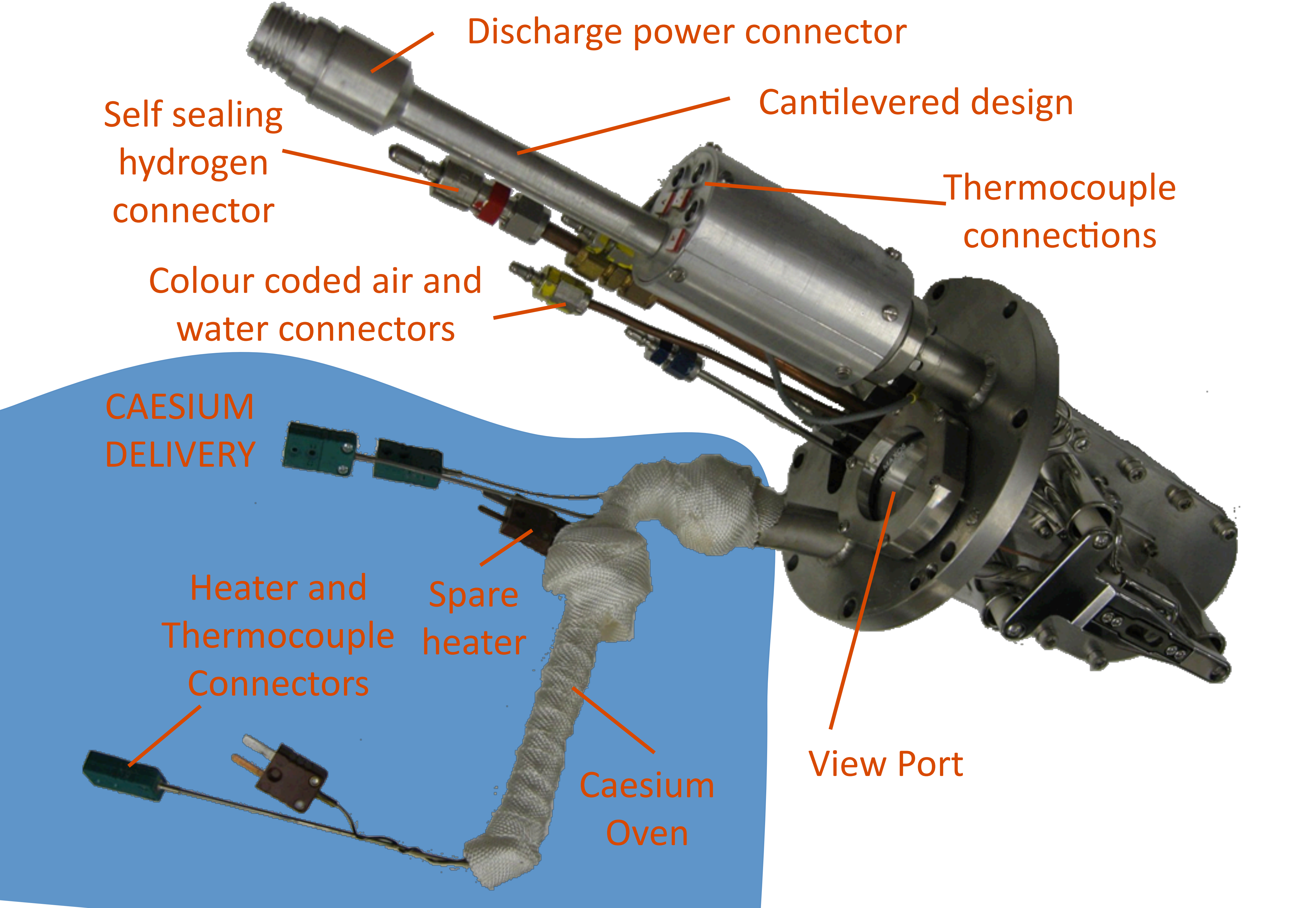


Source Runs at
50 Hz
Rep Rate

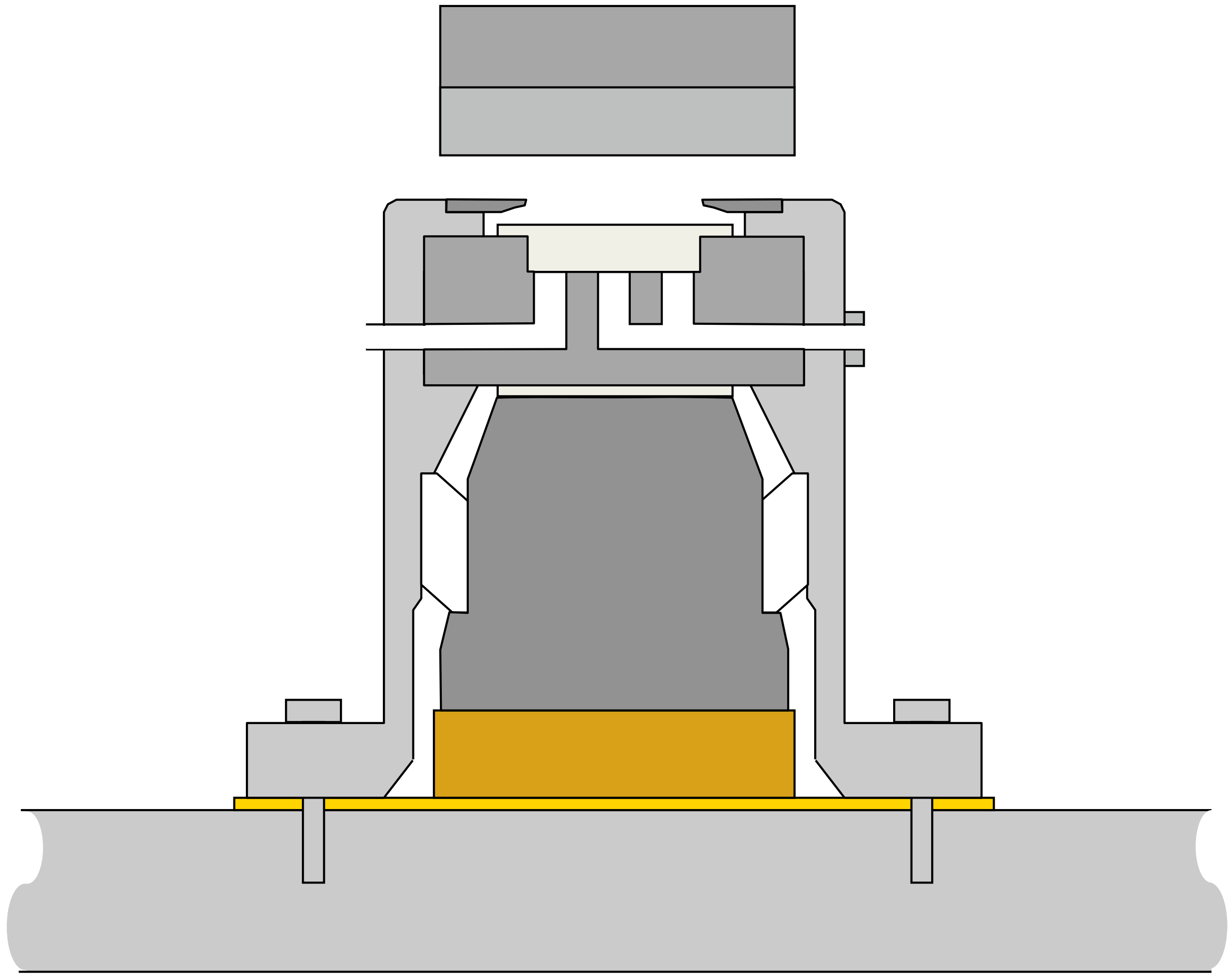

Cathode
Hollow Anode
Heated Caesium
Transport Line
Hydrogen Feed
Air Cooling
Source Body
Discharge
Power Feed
Thermocouples

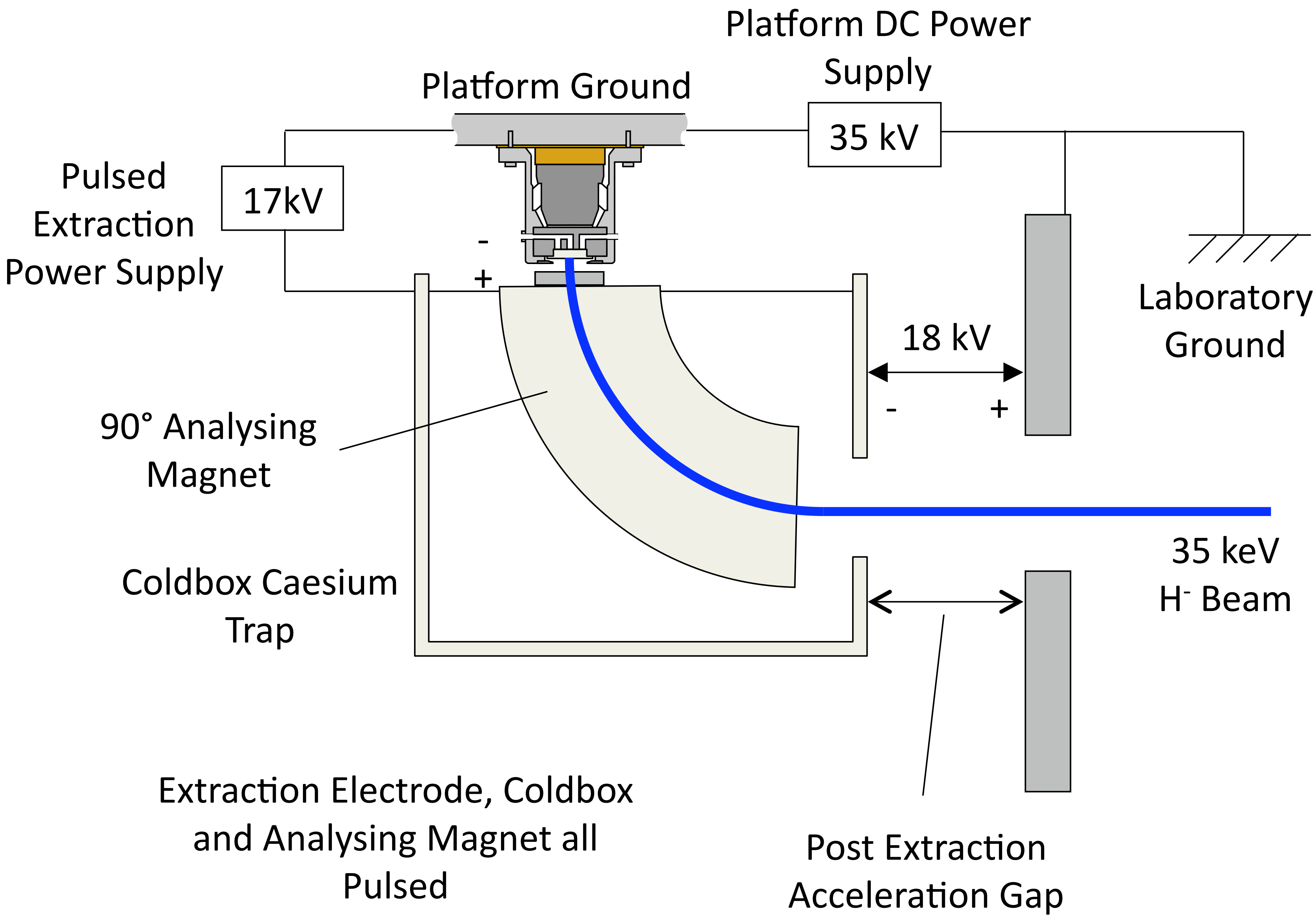

Aperture Plate

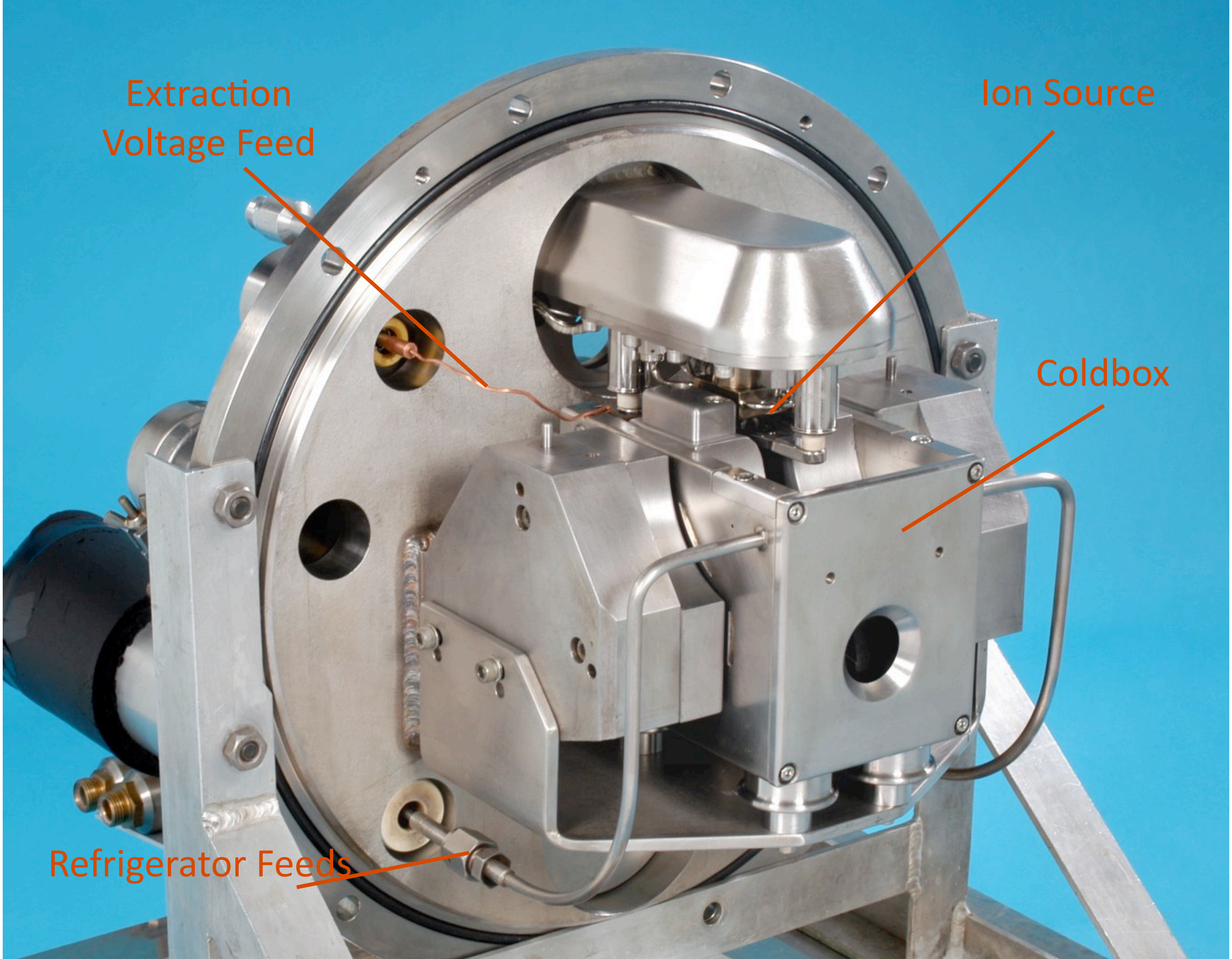

Extraction Mount
Extraction Electrode
Support
Insulators
Caesium
Shields

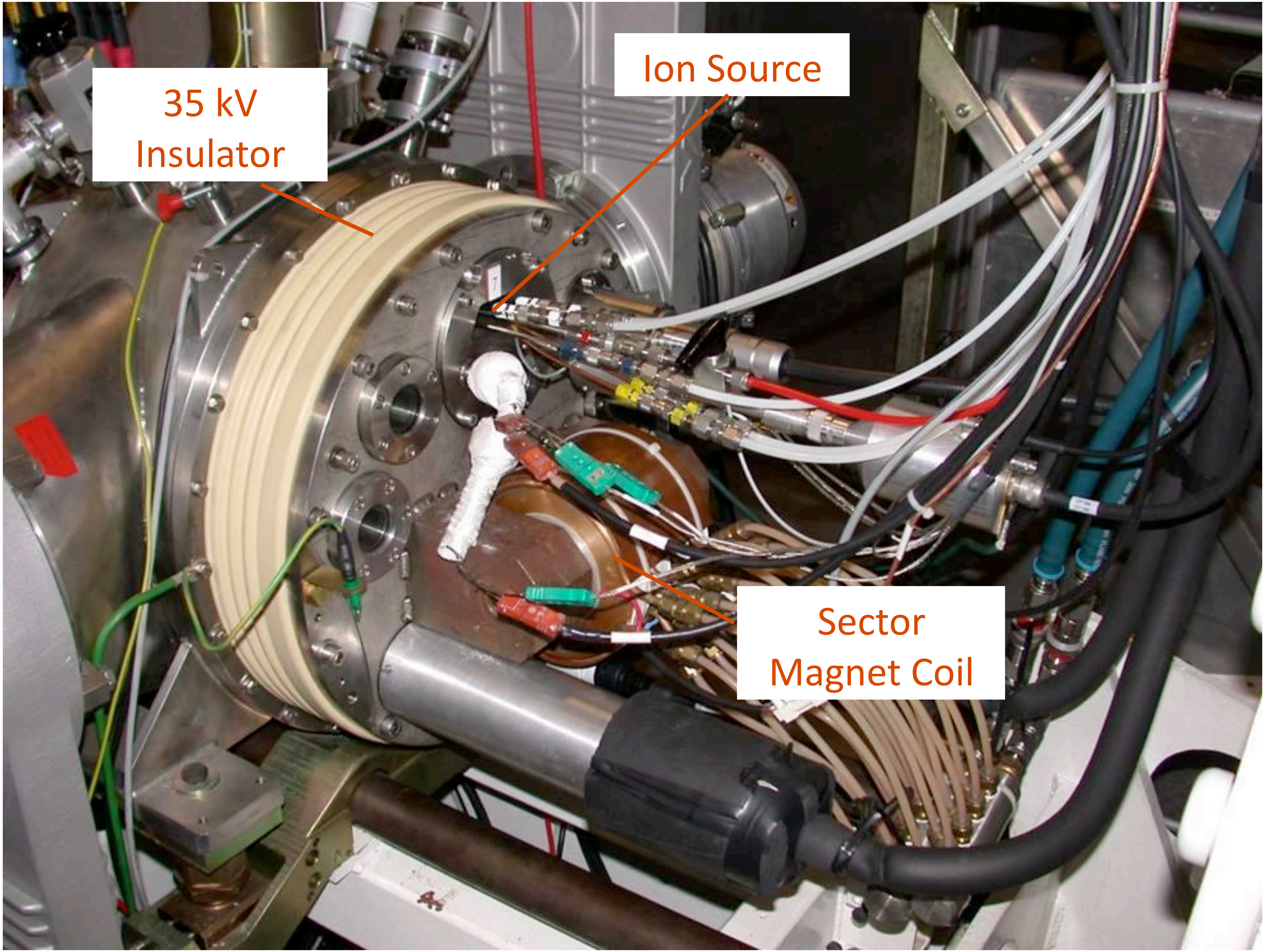

Discharge power connector
Cantilevered design
Self sealing hydrogen connector
Thermocouple connections
Colour coded air and water connectors
CAESIUM DELIVERY
Heater and Thermocouple Connectors
Spare heater
Caesium Oven
View Port

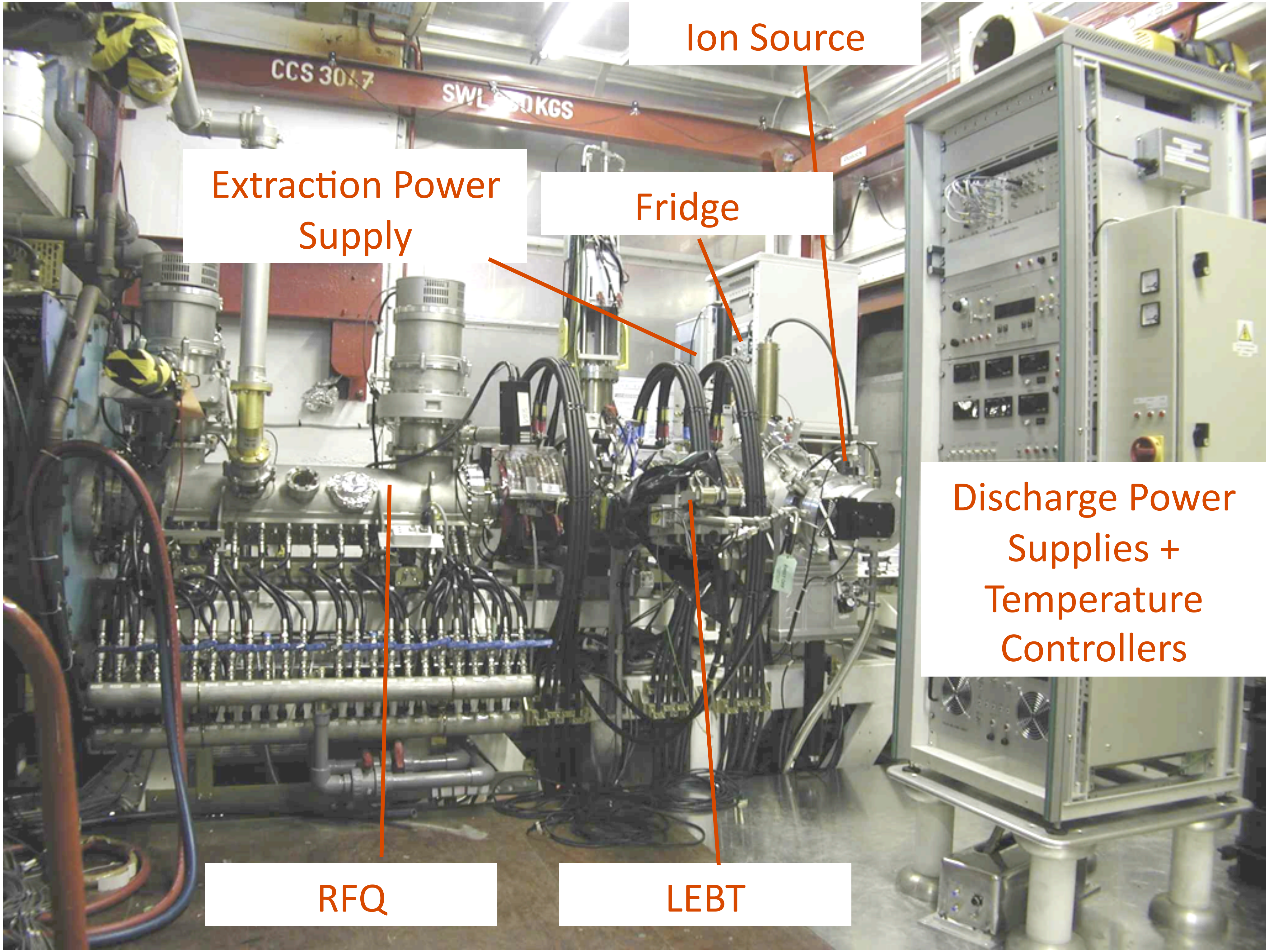

Caesium Oven

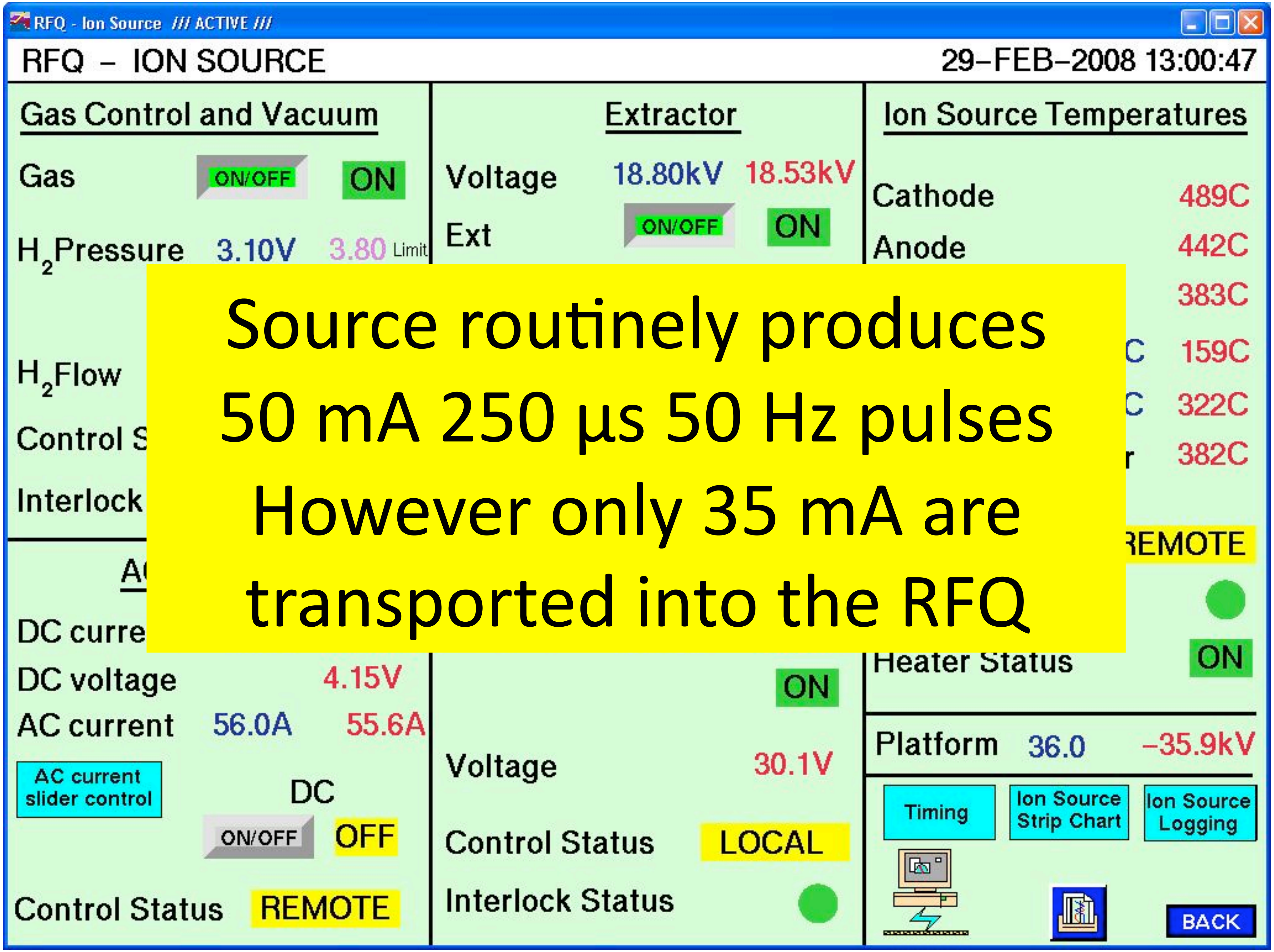



Platform DC Power Supply
Platform Ground
35 kV
Pulsed Extraction Power Supply
17kV
-
+
Laboratory Ground
18 kV
-
+
90° Analysing Magnet
35 keV
H- Beam
Coldbox Caesium Trap
Extraction Electrode, Coldbox and Analysing Magnet all Pulsed
Post Extraction Acceleration Gap


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



Source routinely produces
50 mA 250 µs 50 Hz pulses
However only 35 mA are
transported into the RFQ

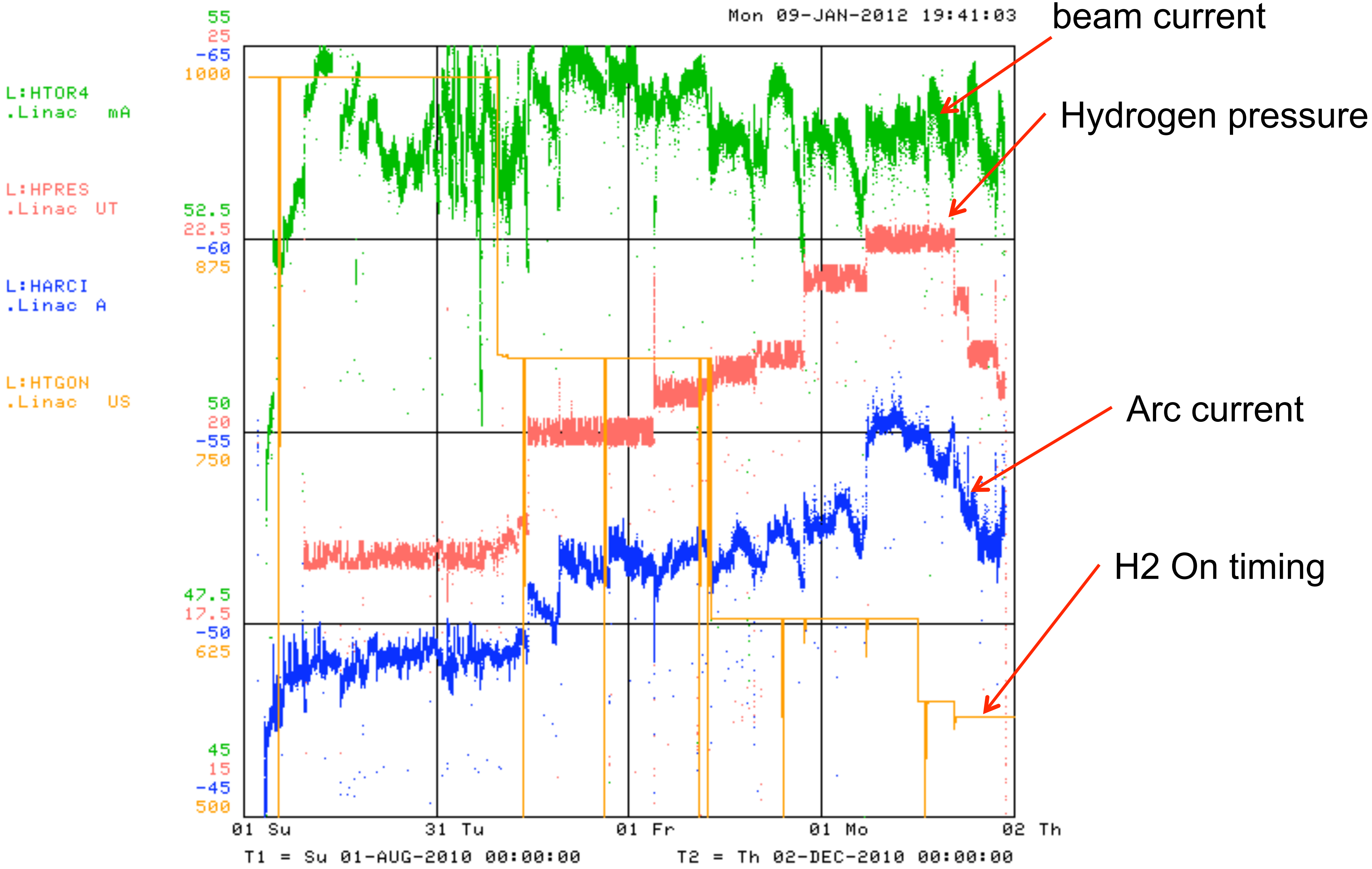
SPS Failure Modes

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

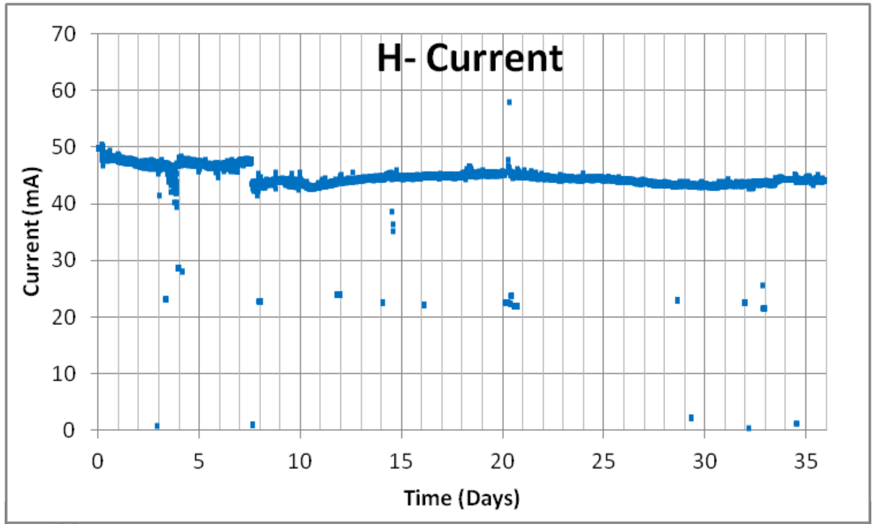
Compare SPS Lifetimes

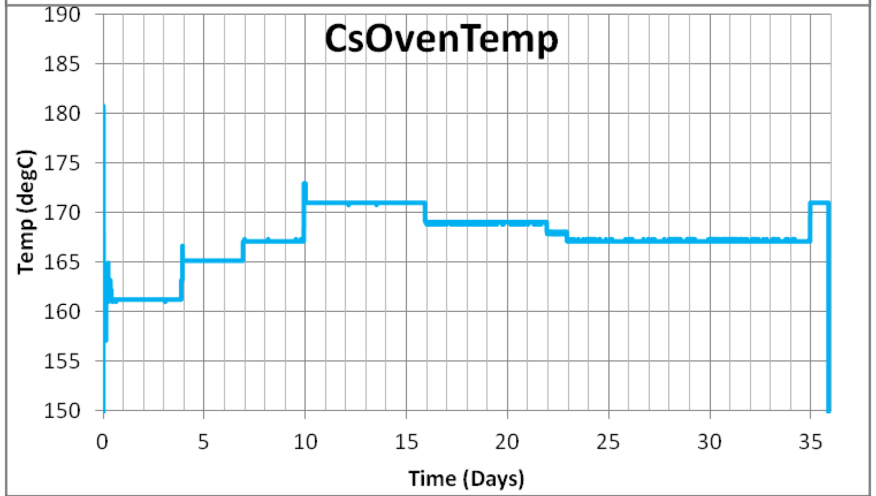
	DESY	FNAL	BNL	ISIS
Discharge Current (A)	47	50	18	55
Pulse length (µs)	75	80	700	800
Rep rate (Hz)	6.25	15	7.5	50
Plasma Duty Factor (%)	0.047	0.12	0.525	4
Lifetime (Days)	900	200	270	30
Lifetime (Plasma Days)	0.42	0.24	1.42	1.2

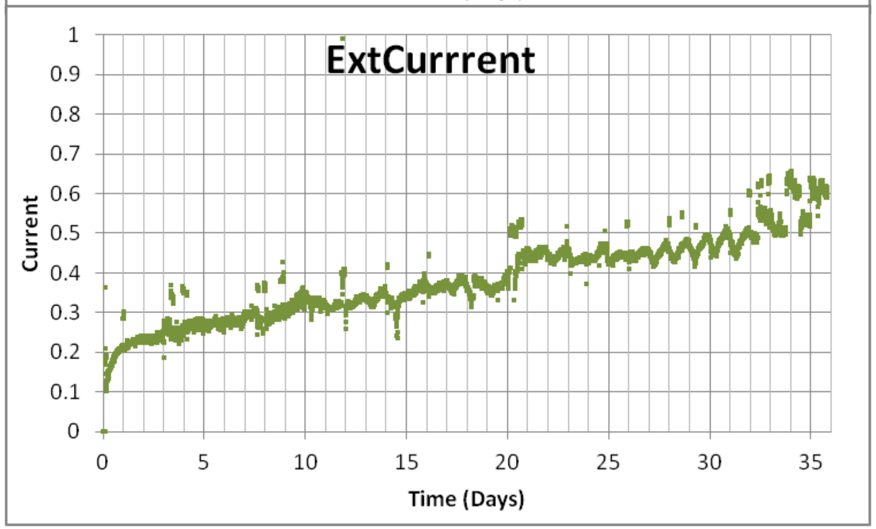
Fermilab Magnetron Ageing

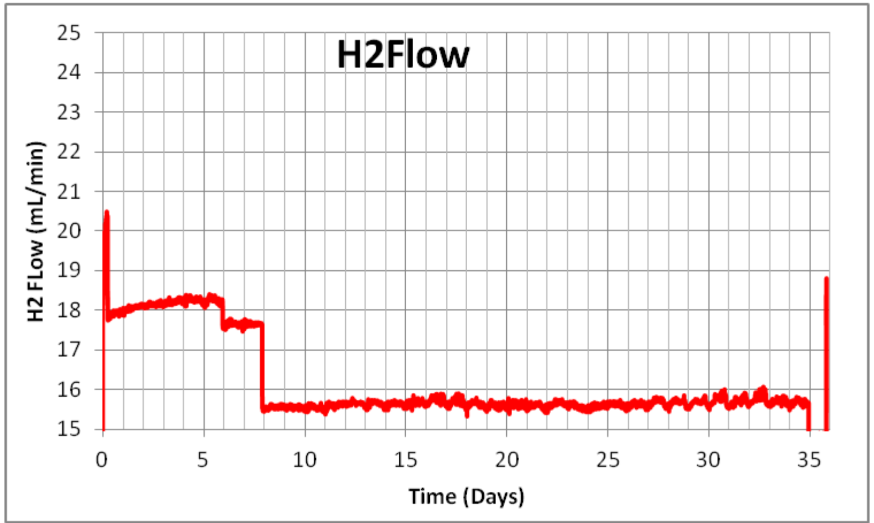


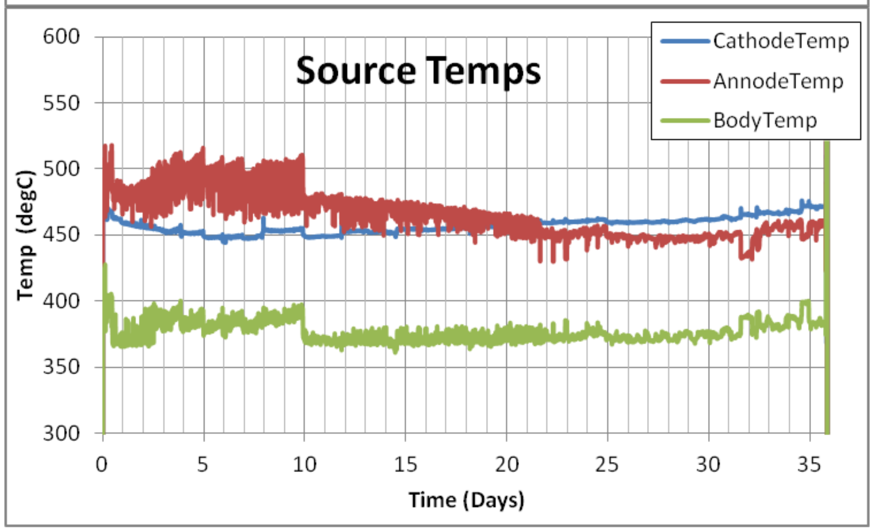
ISIS Penning Ageing



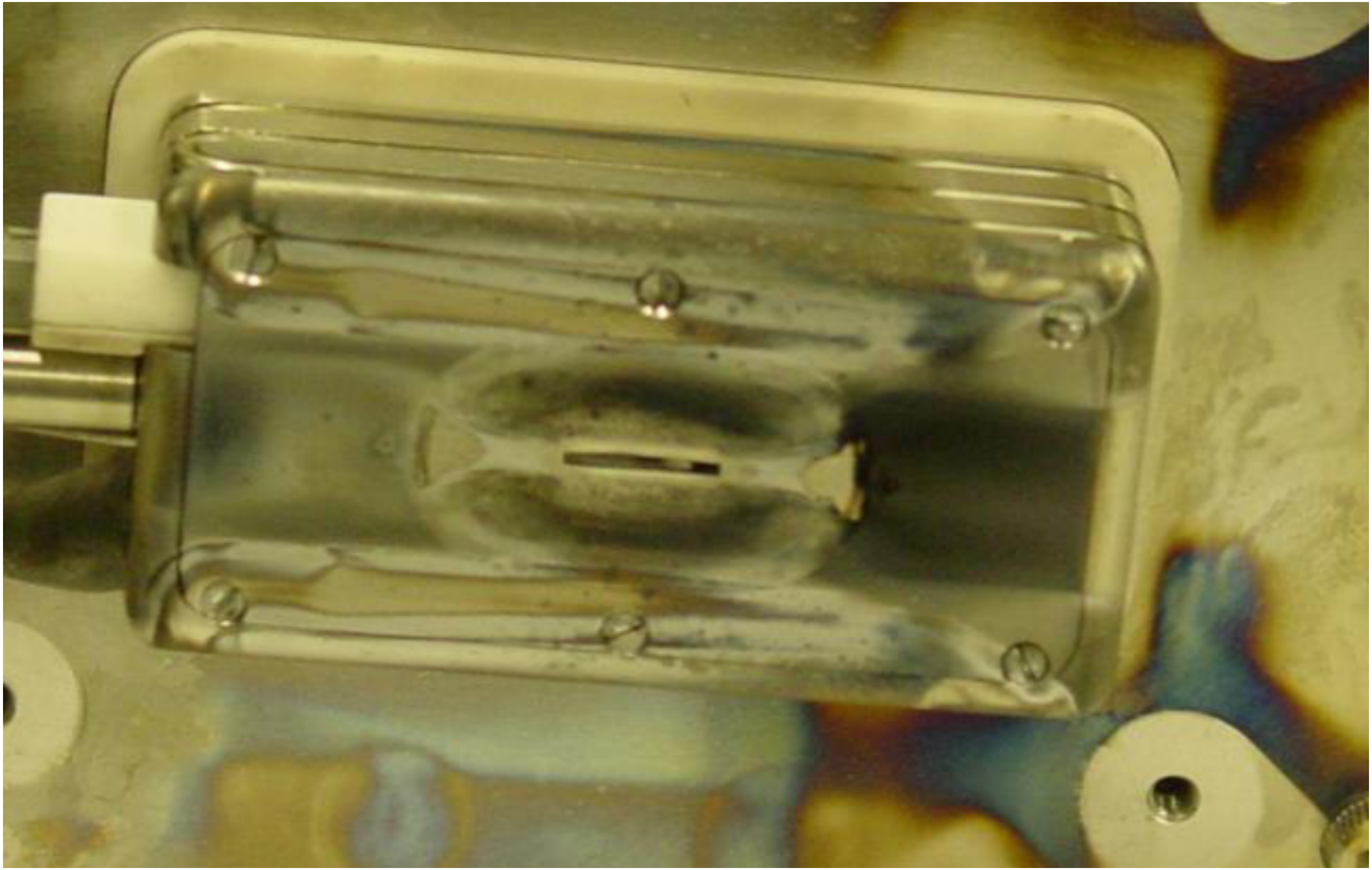






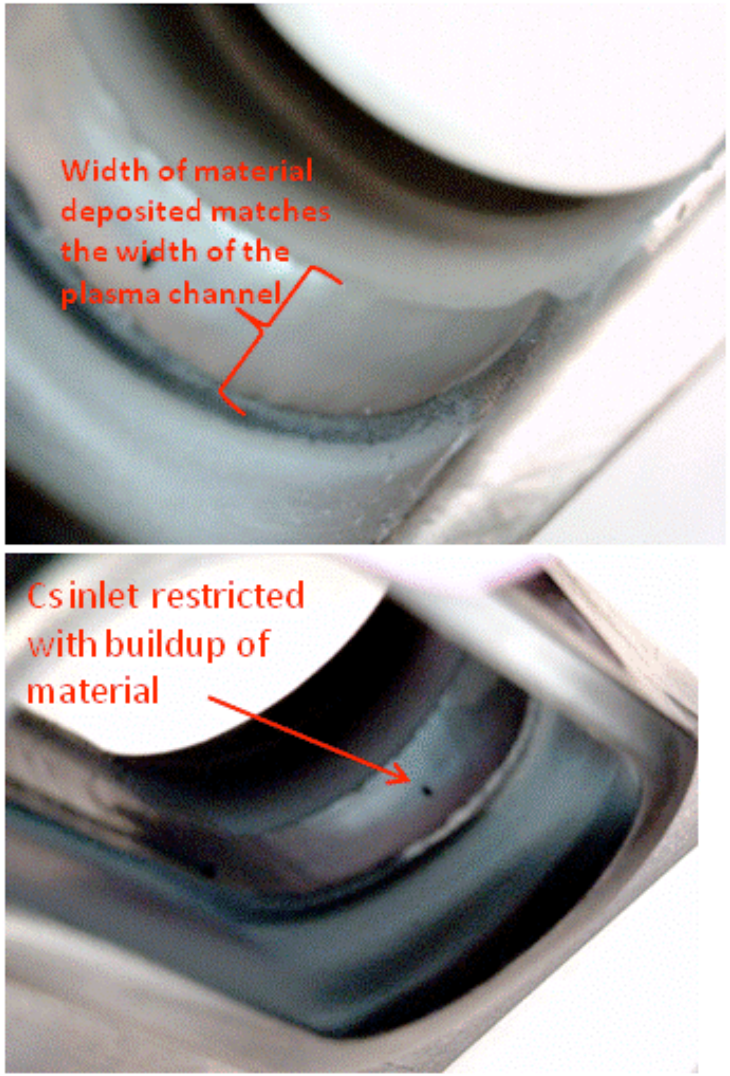


Fermilab Magnetron

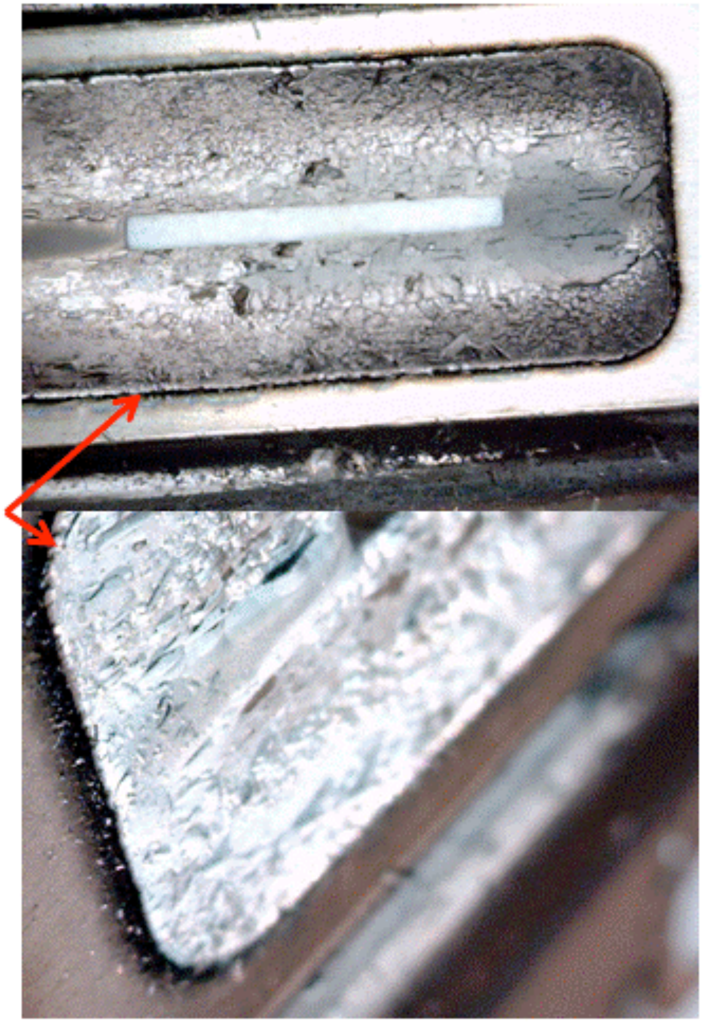


Fermilab Magnetron

Anode

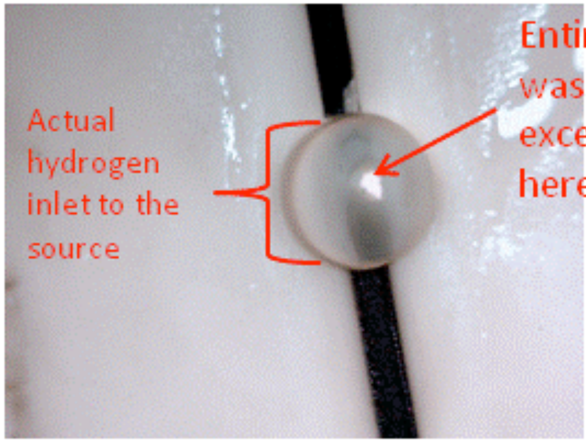


Anode cover plate

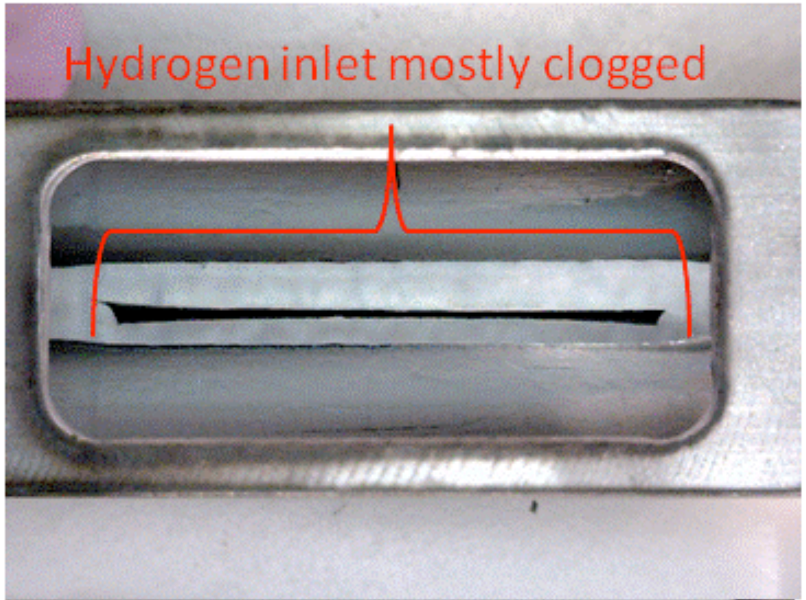


Fermilab Magnetron

Ceramic source body insulator

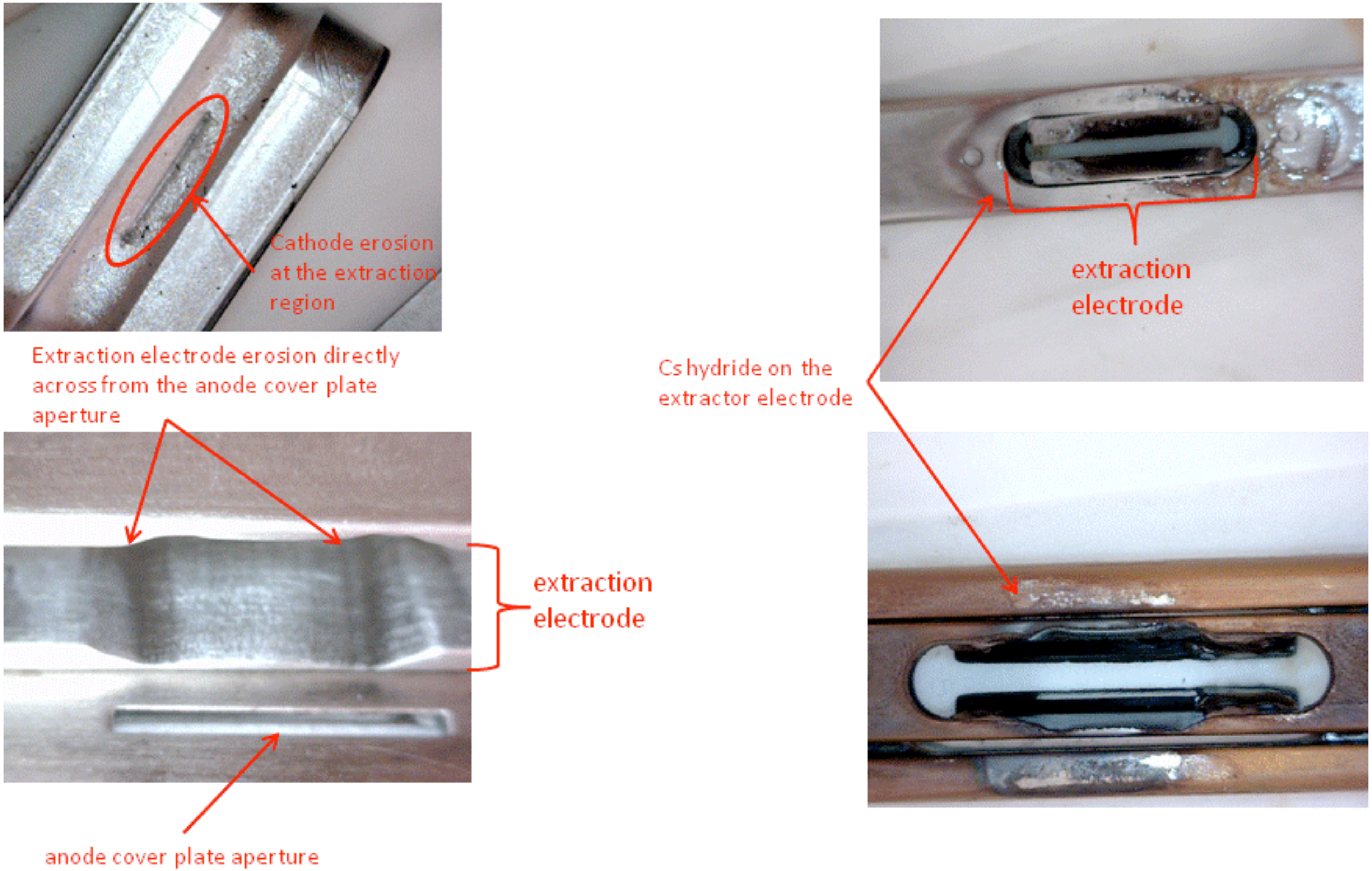


Anode



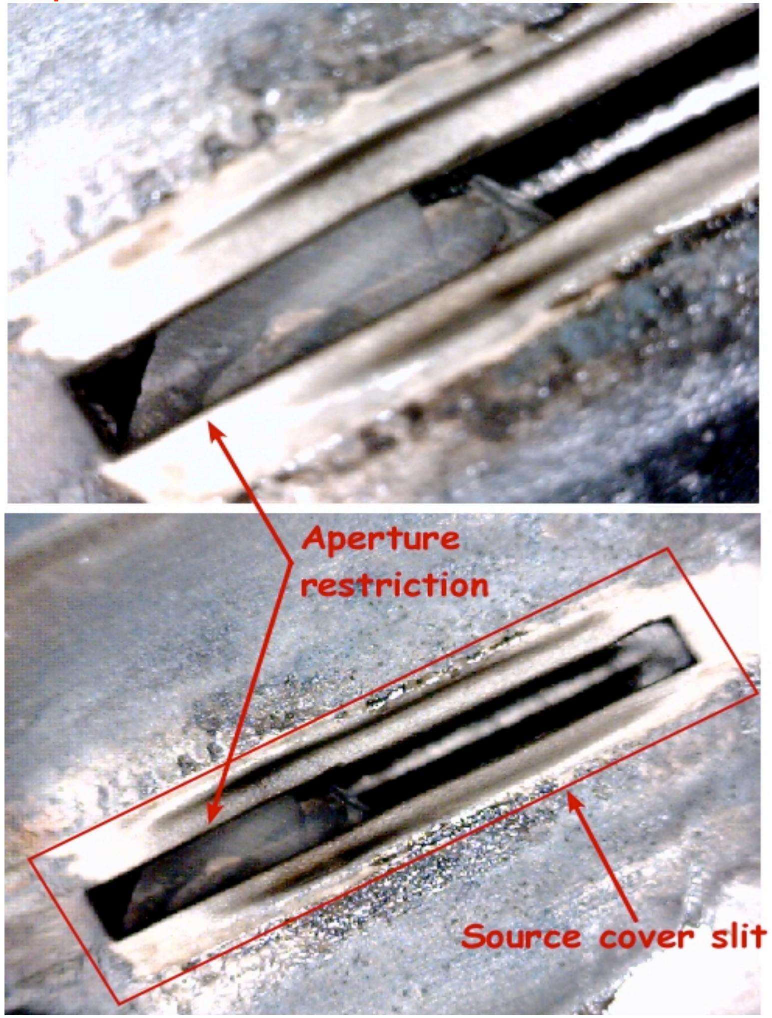
Material clogging the anode hydrogen inlet was a few mm thick. This is the most that we have ever seen.

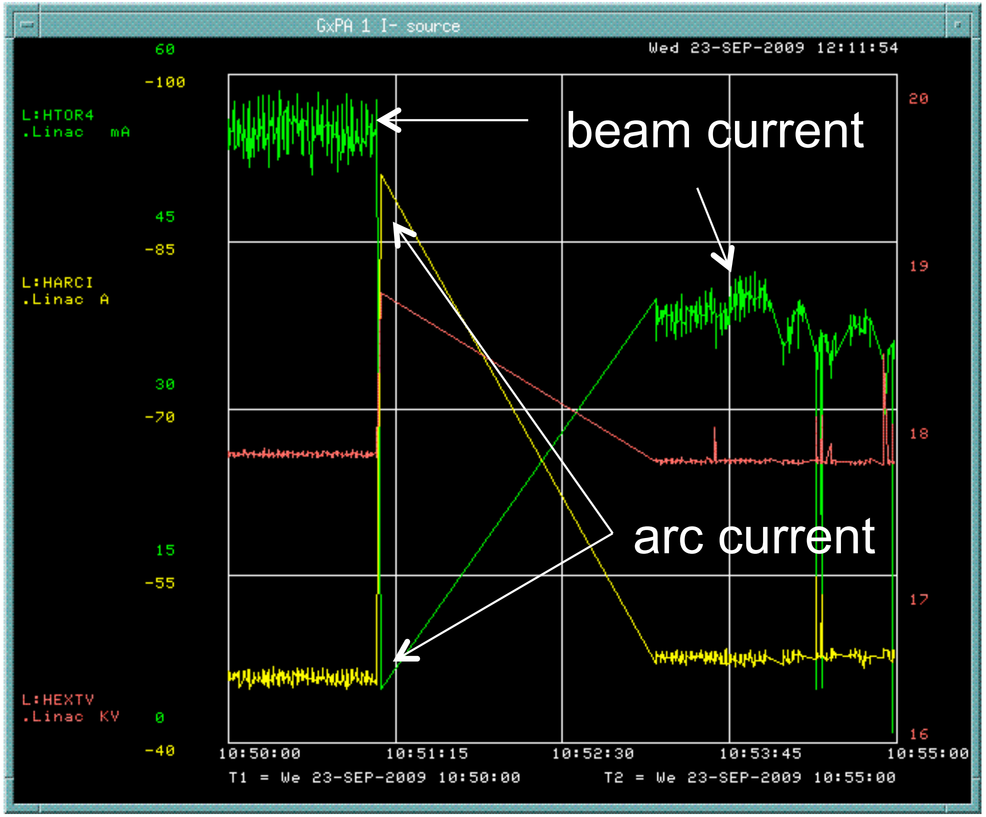
Fermilab Magnetron



Typical Source Failures

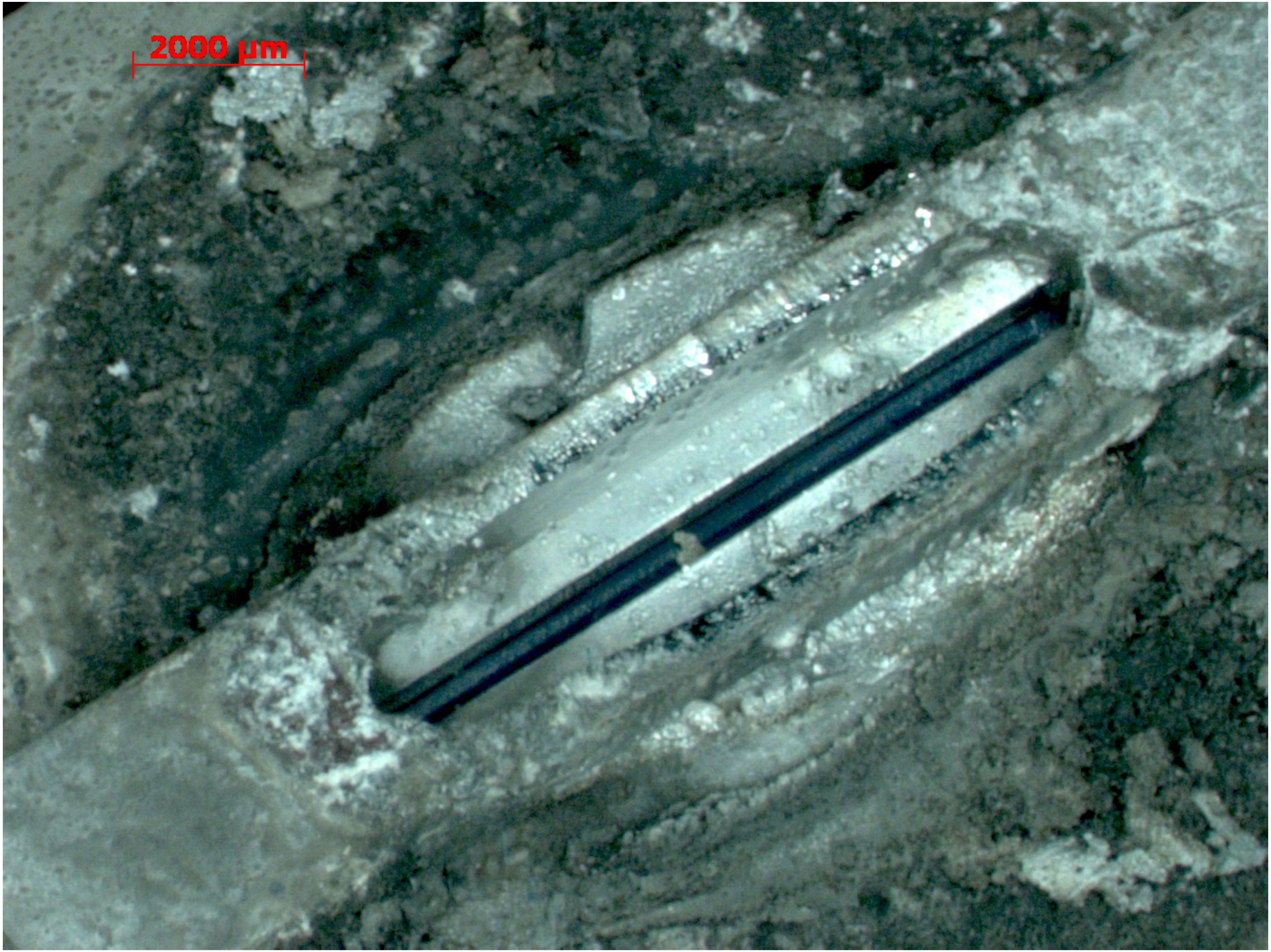
Cathode material flakes blocking source extraction aperture

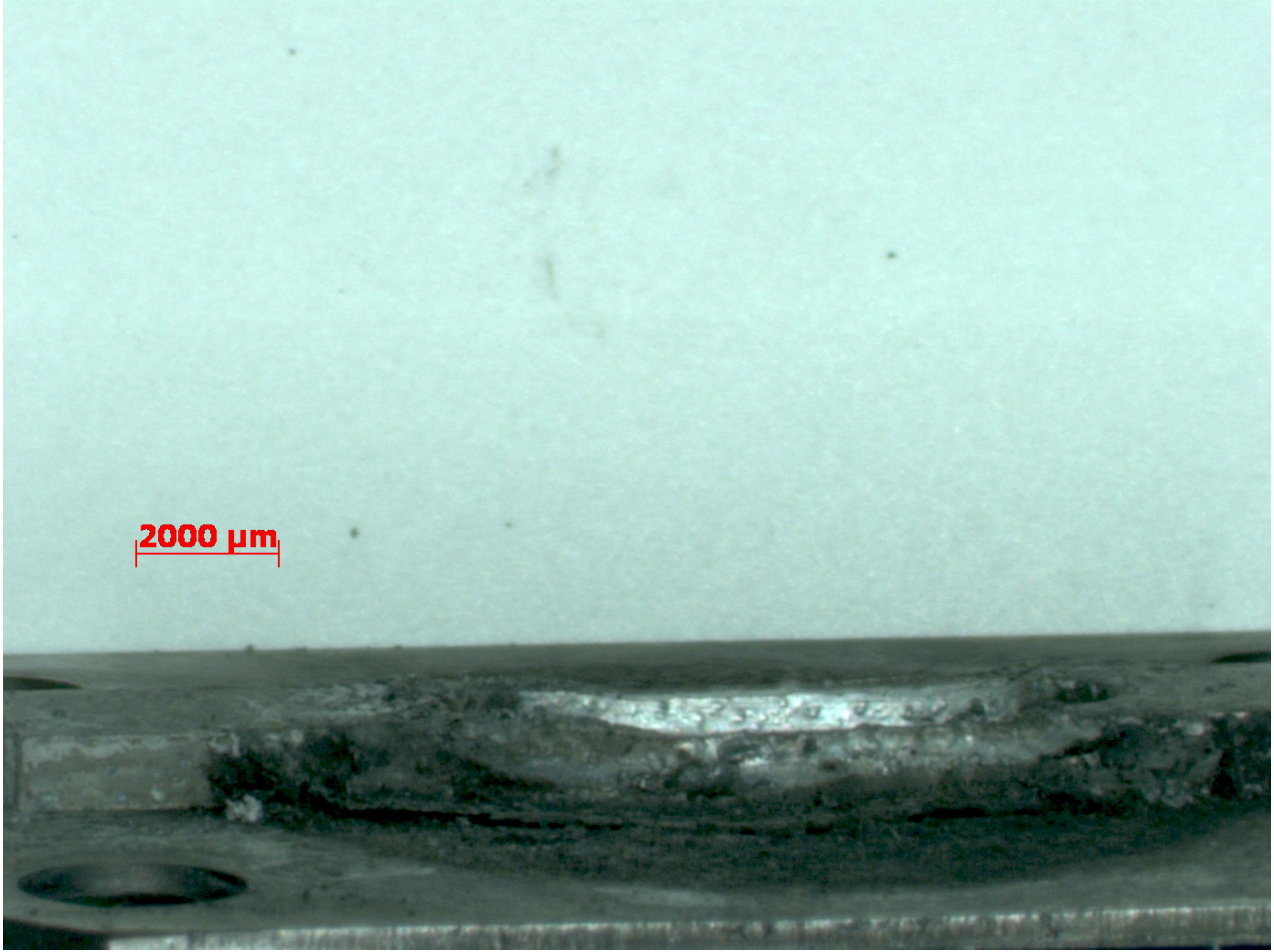


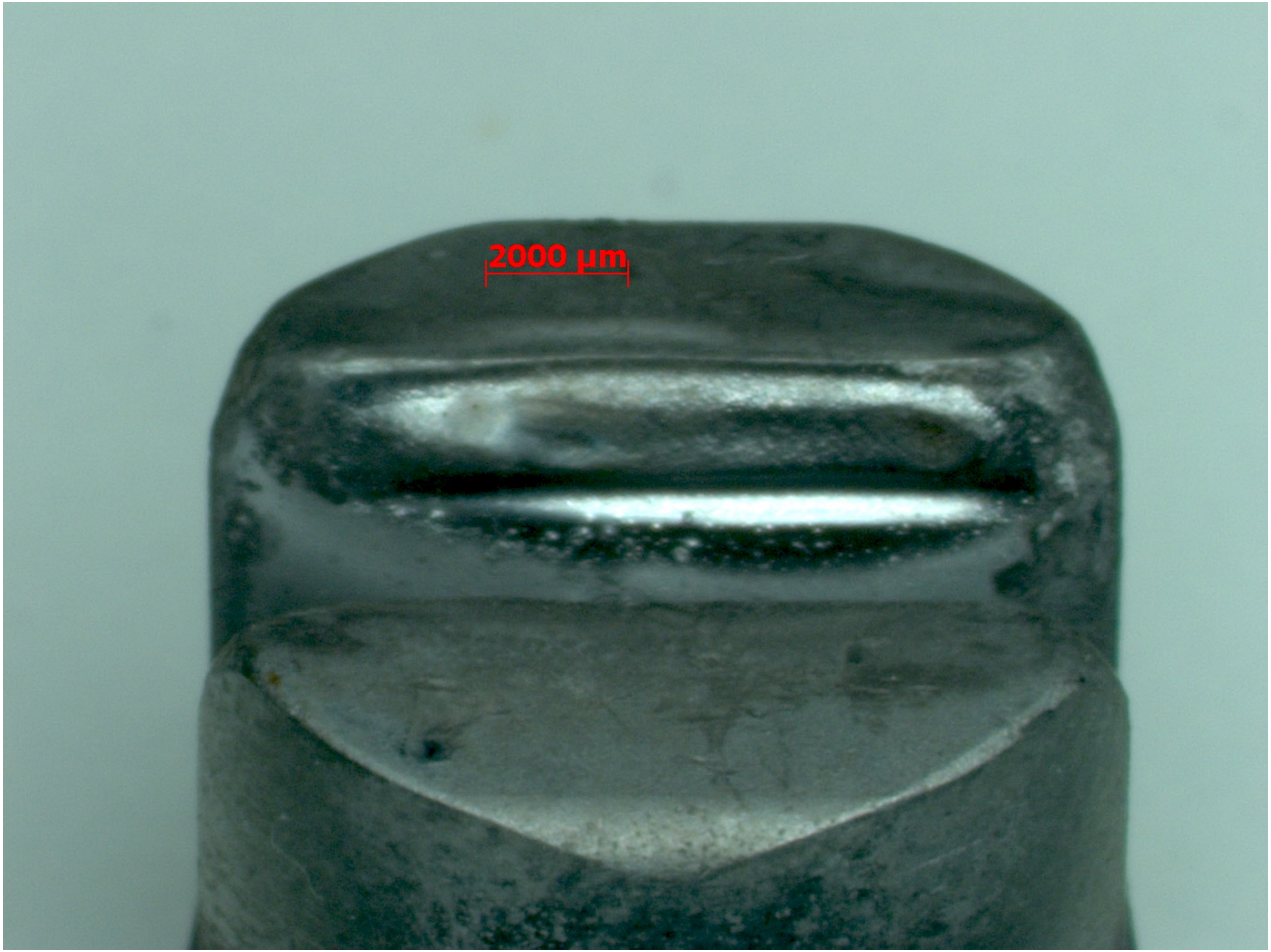


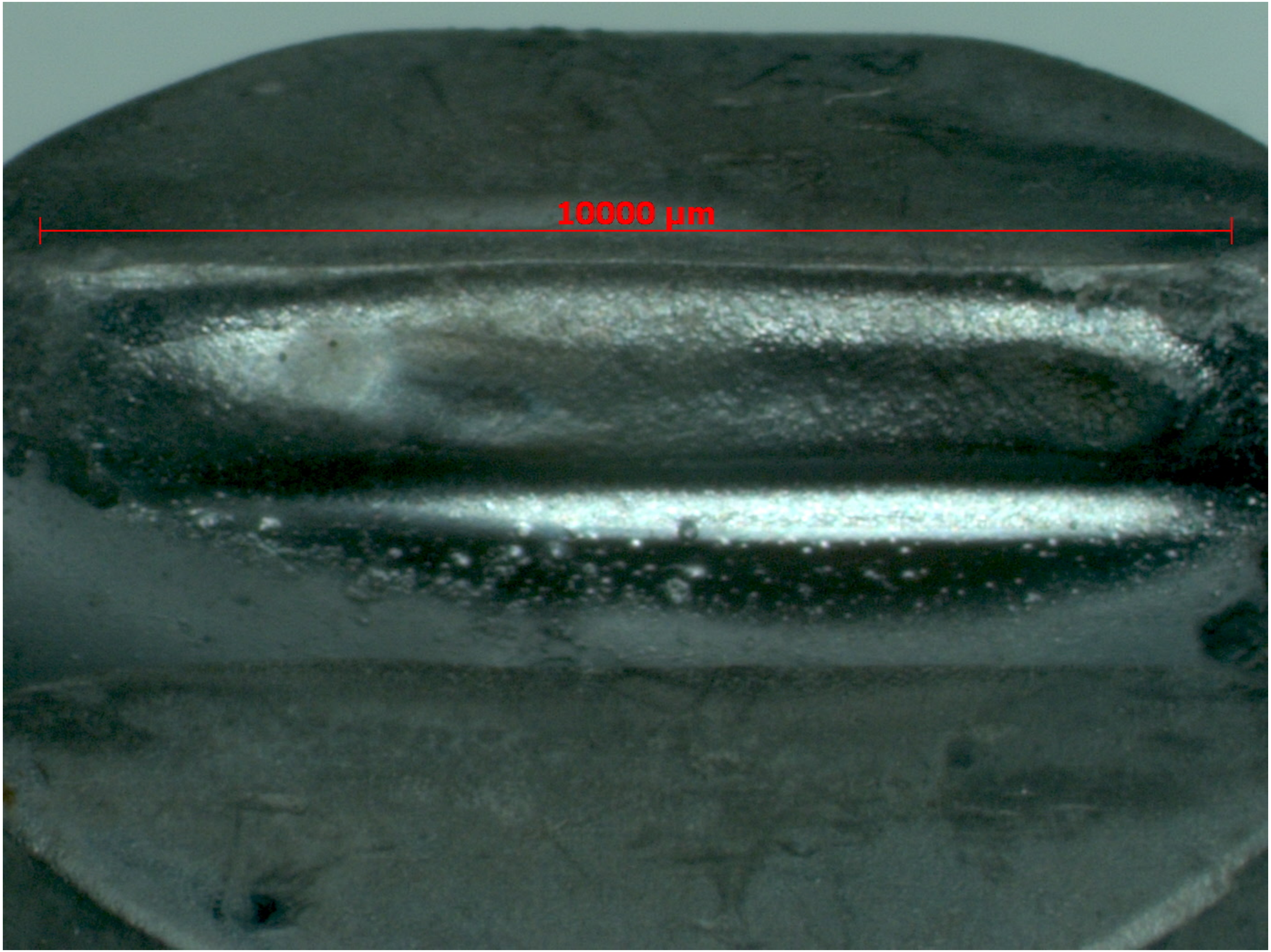
Cathode material flakes off and causes cathode/anode shorts

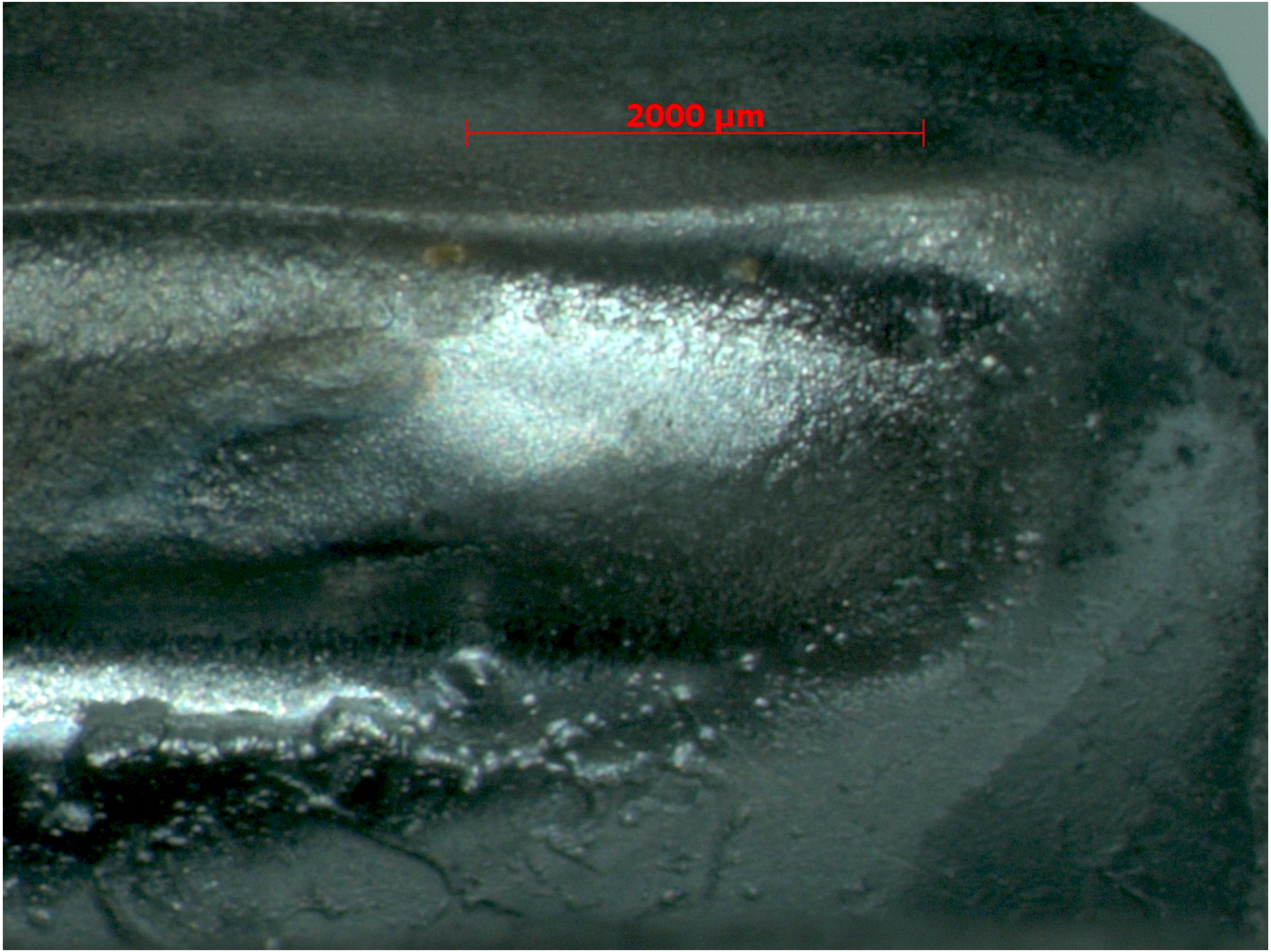
ISIS Penning 26 Day Electrode Wear

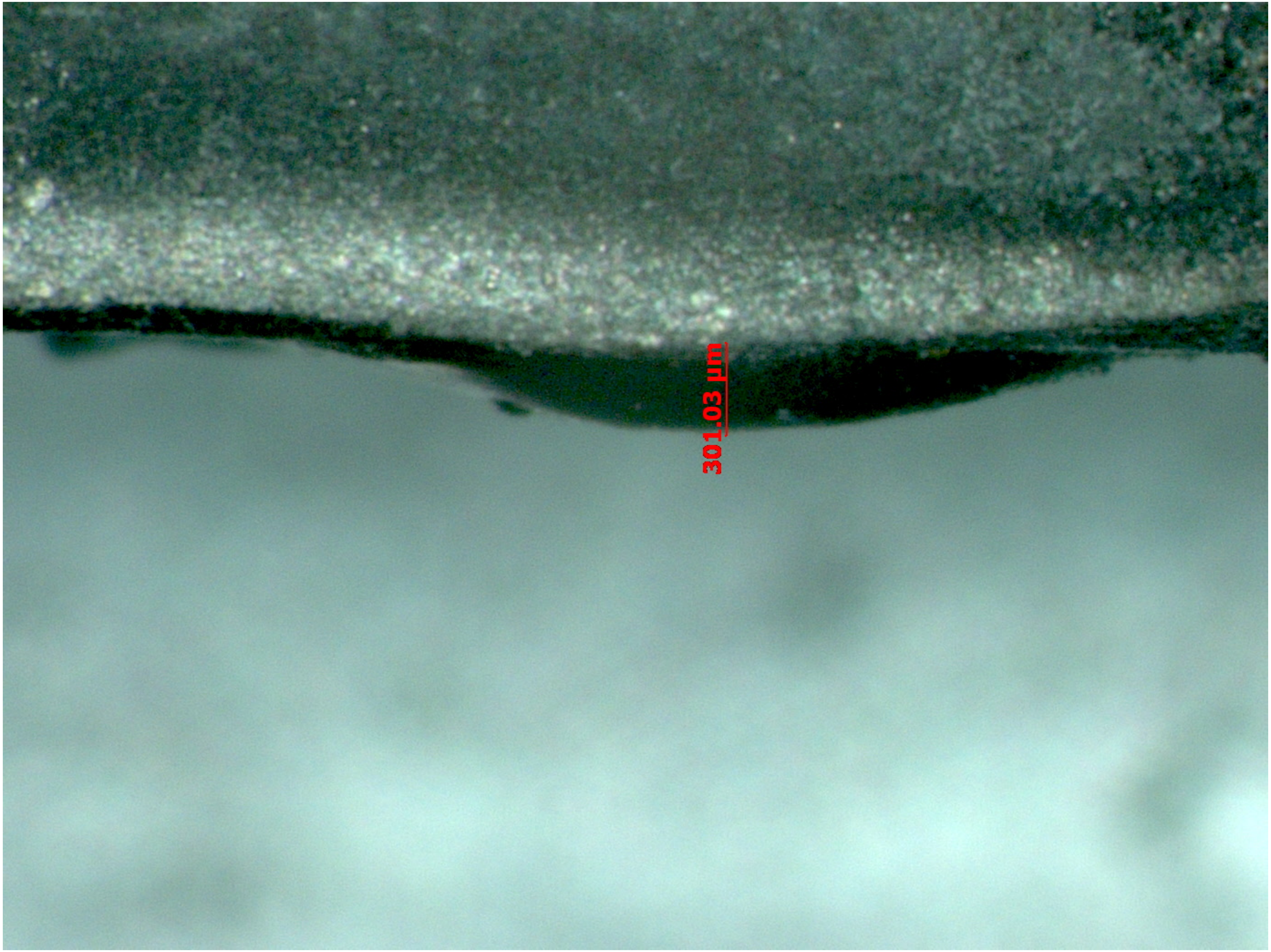

2000 µm

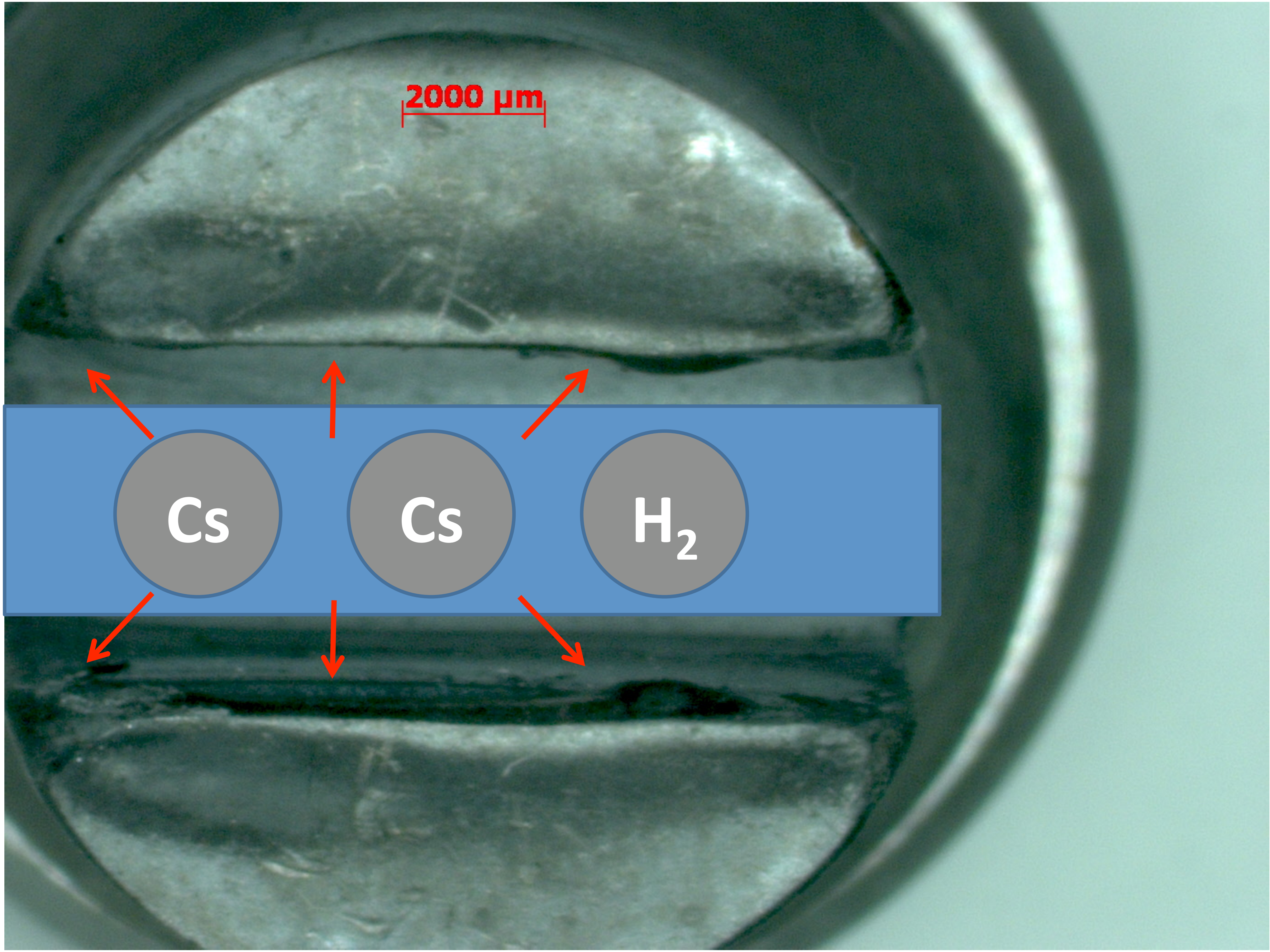

2000 µm


2000 µm


10000 µm


2000 µm


301.03 µm


2000 µm
Cs
Cs
H2

3 Sources at ISIS

Operational Source

24 x 7 operation
20 day average lifetime
200-300 μs pulse length
50 Hz
35 keV
35 mA @ RFQ

Ion Source Development Rig

Pre-test operational sources

Problem solving

FETS Source

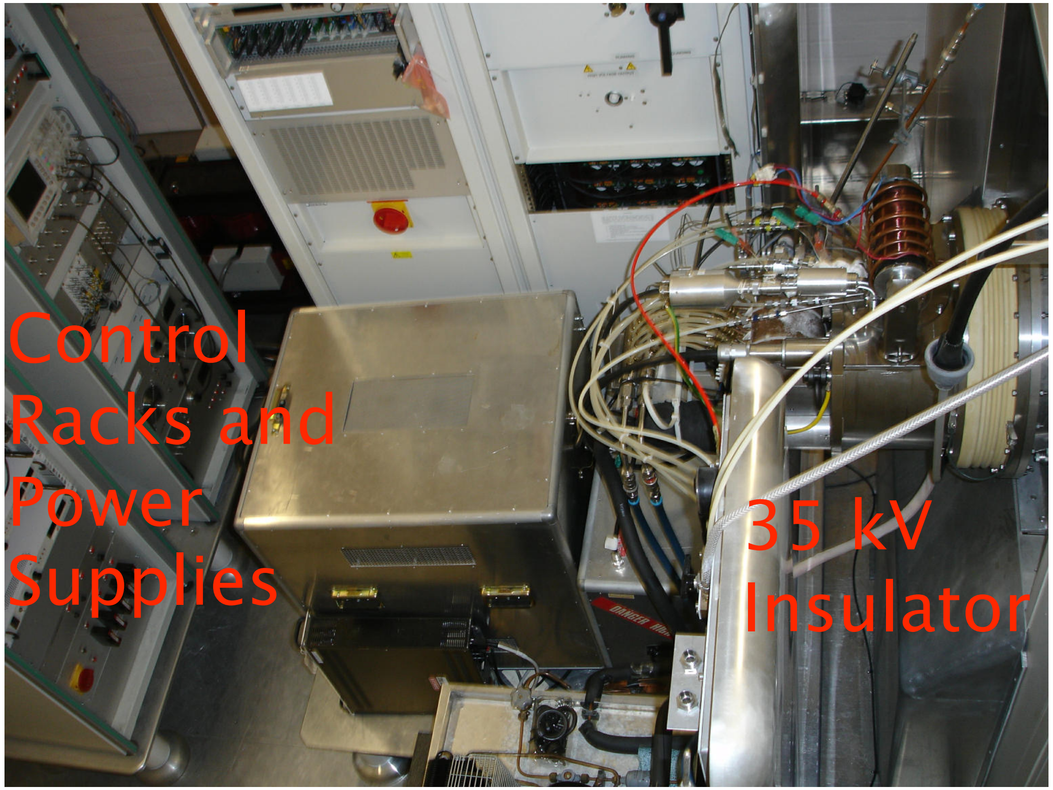
Experimental sources

High current

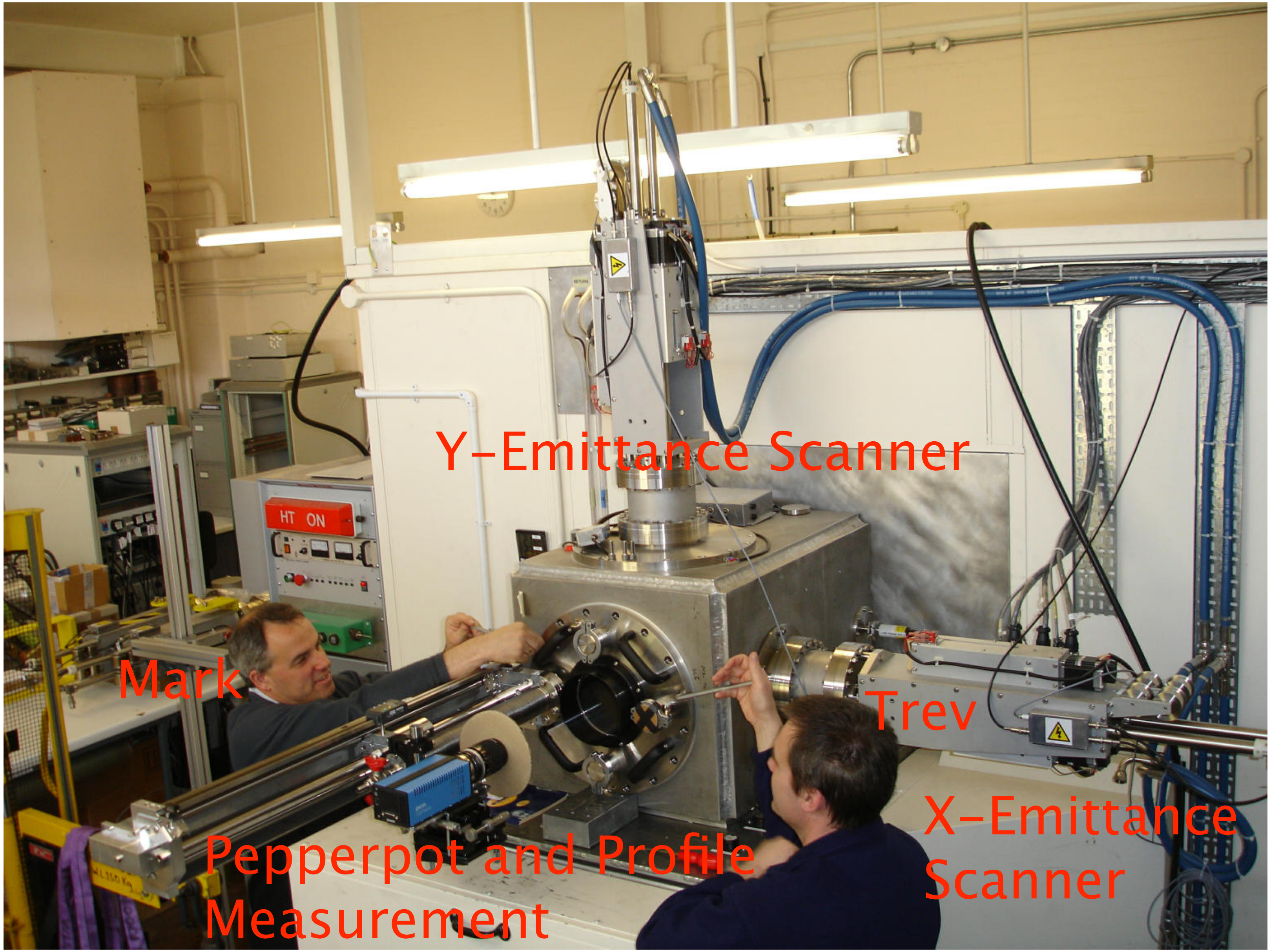
Long pulse

65 keV


Ion Source
No smoking or naked flames
FLOW
19 kV extract power supply
Cold Box Refrigerat or
Chiller Circulator


Control Racks and Power Supplies
35 kV Insulator

ISDR



Diagnostics Vessel

3 Sources at ISIS

Operational Source

24 x 7 operation
20 day average lifetime
200-300 μs pulse length
50 Hz
35 keV
35 mA @ RFQ

Ion Source Development Rig

Pre-test operational sources

Problem solving

FETS Source

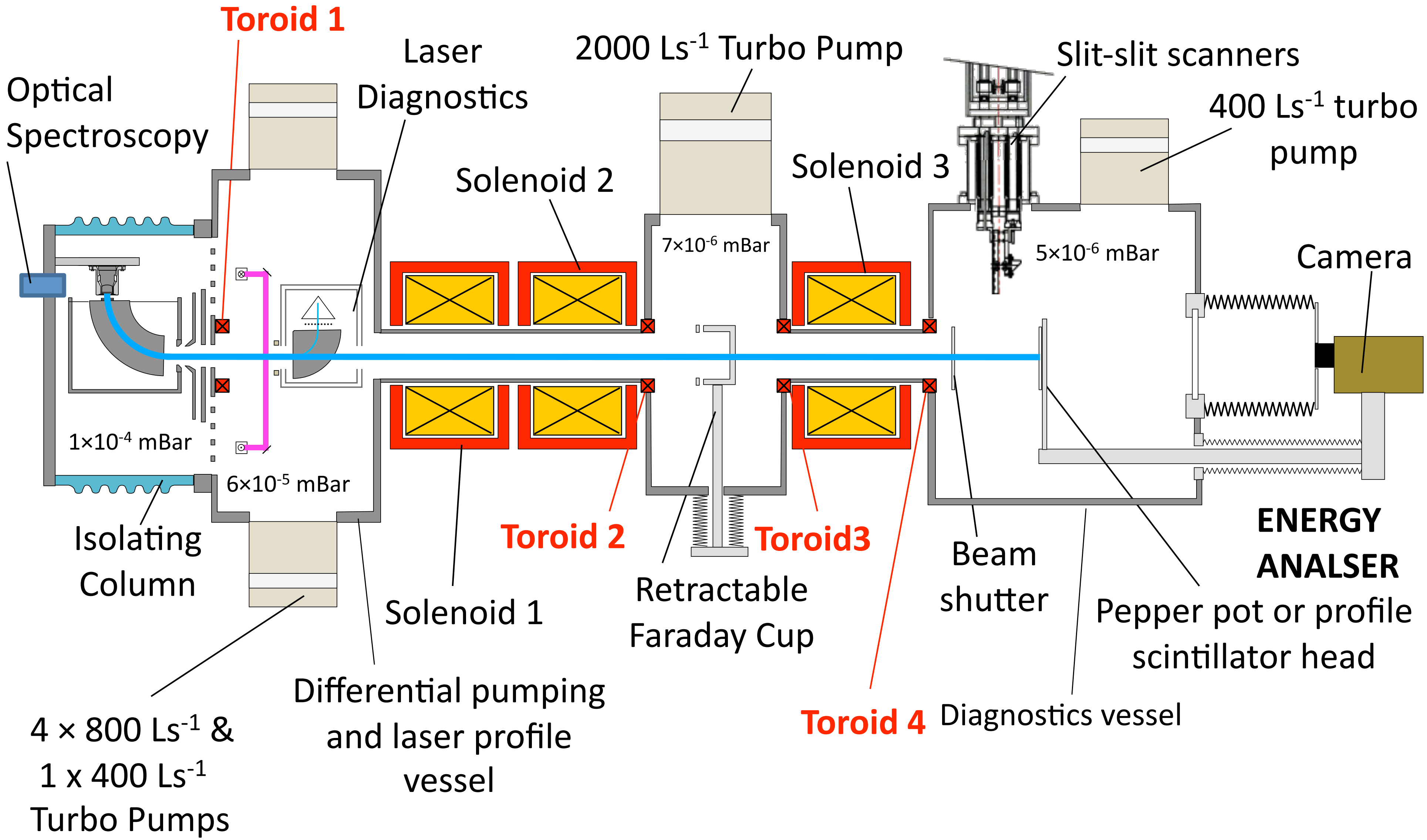
Experimental sources

High current

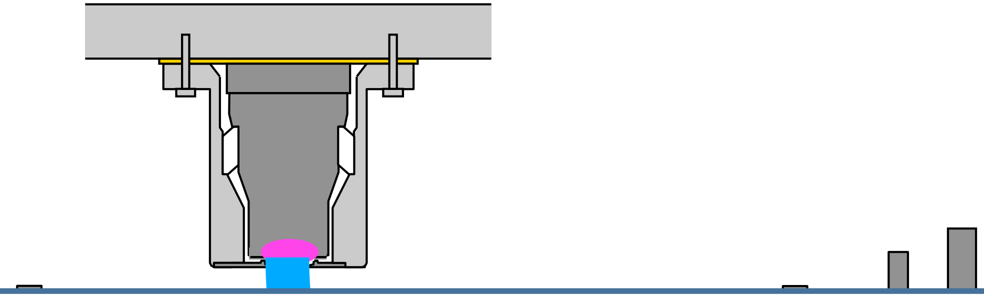
Long pulse

65 keV

Diagnostics and a LEBT are critical to Ion Source Development

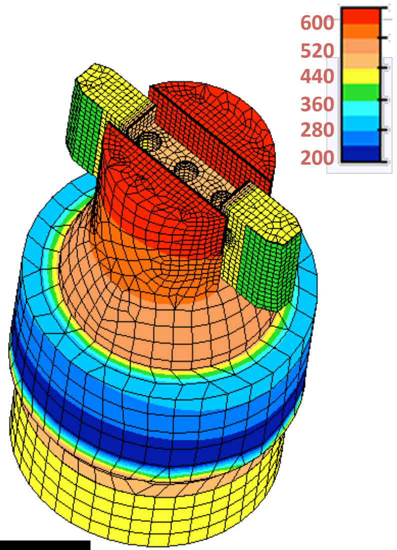


1. Extend discharge duty cycle

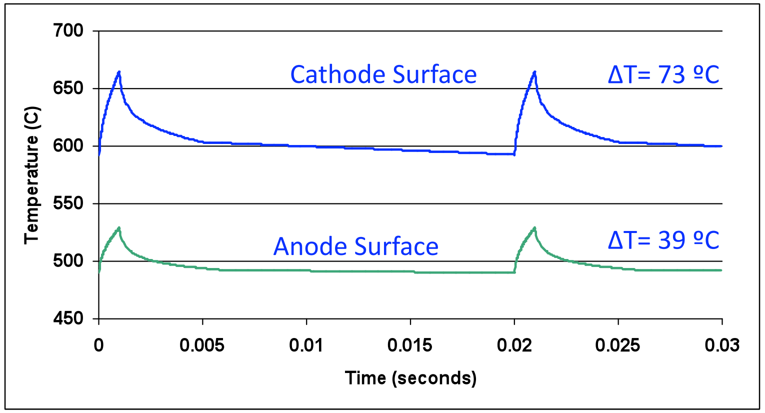


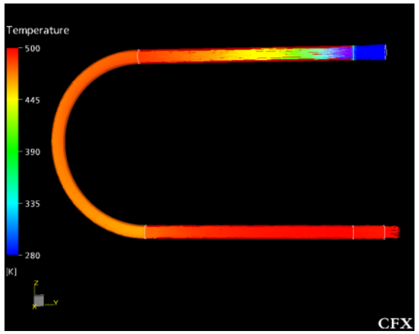
Finite Element Modelling

Steady state calculation



Transient Calculation



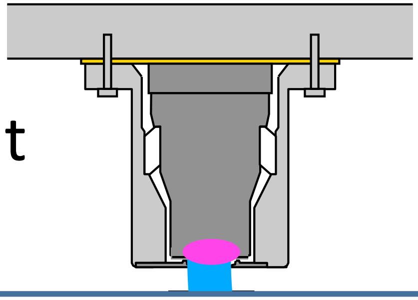


Computational fluid dynamic cooling calculation

2.2 ms discharge at 50 Hz achieved with simple design changes + new PS

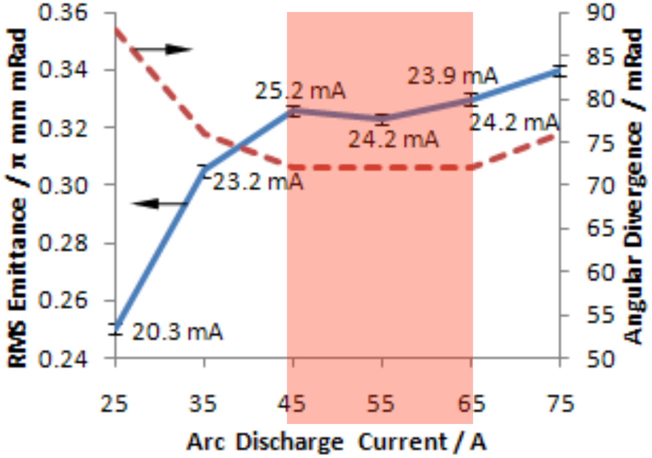
FE modifications

1. Extend discharge duty cycle



2. Discharge current

Discharge Current Experiments



14 kV extraction voltage
2.2 mm extraction gap

For each extraction condition

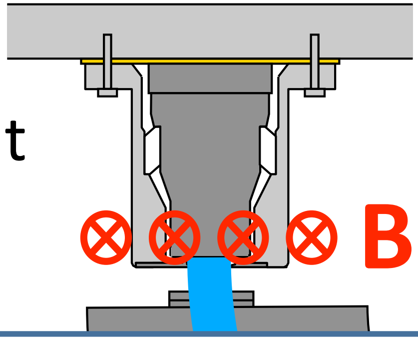
there is a range of discharge currents that give minimum beam divergence

FETS source modifications

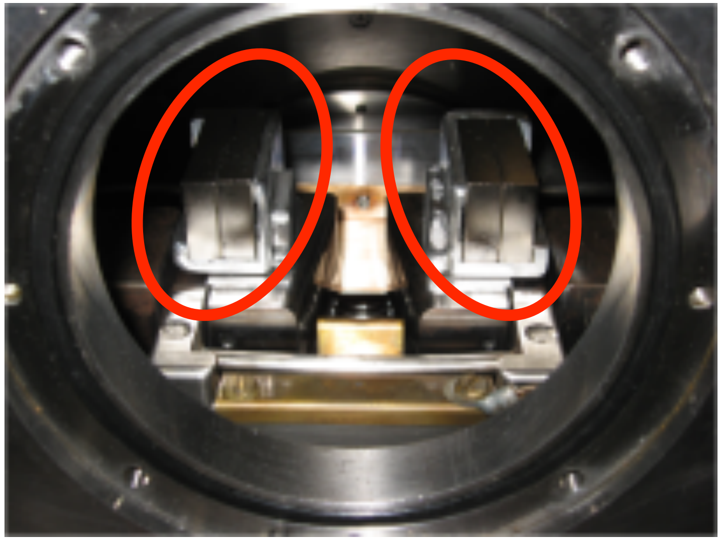
1. Extend discharge duty cycle

2. Discharge current

3. Permanent magnet
Penning field



$Nd_2Fe_{14}B$ Permanent Magnets



To allow different extraction voltages the Penning field must be decoupled from the sector magnet field

Permanent magnets are used to produce the produce the 0.15 – 0.25 T required for a stable discharge

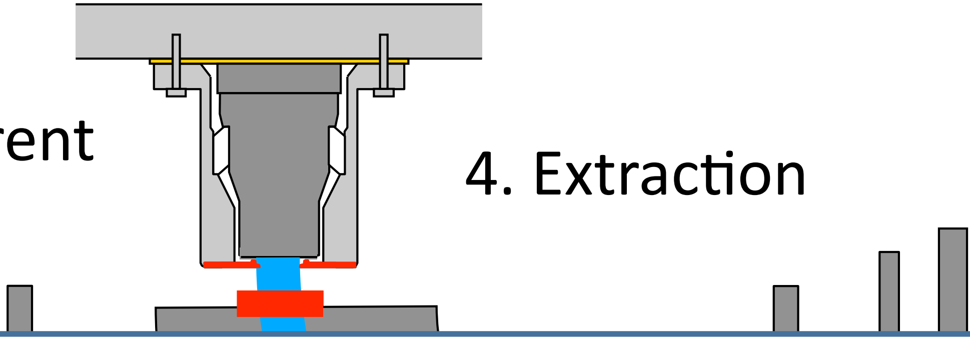
FETS source modifications

1. Extend discharge duty cycle

3. Permanent magnet Penning field

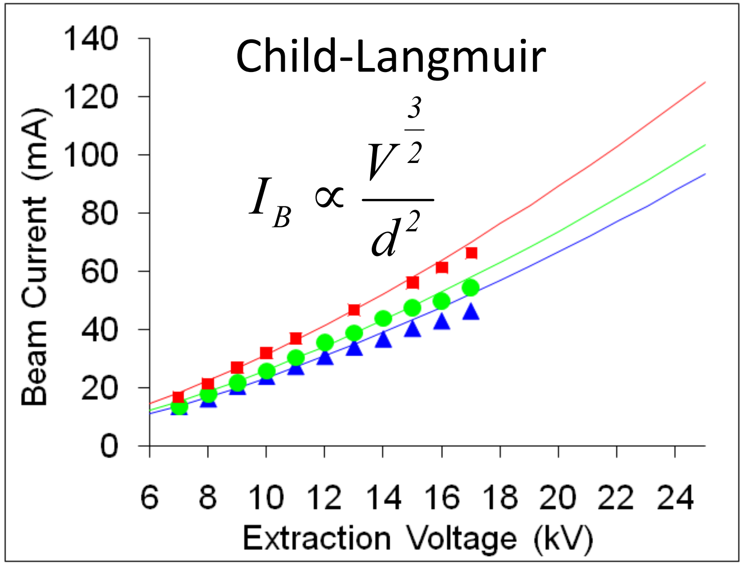
2. Discharge current

4. Extraction

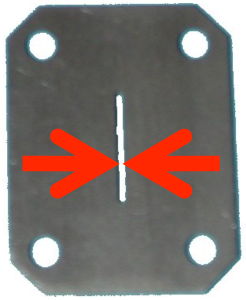


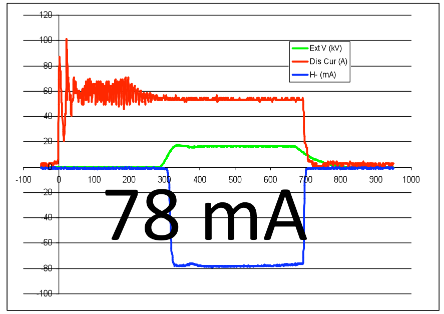
Voltage, Geometry and Meniscus

Increase voltage from 17 to 25 kV

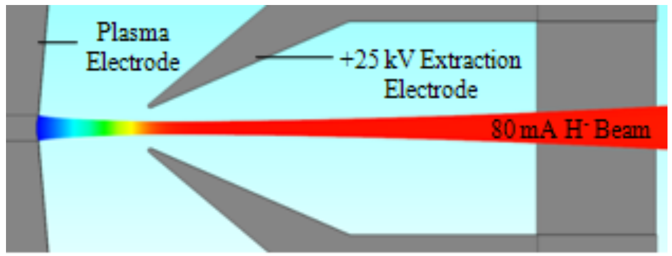


Widen plasma electrode aperture





Meniscus Studies



Work in progress…

FE

mo

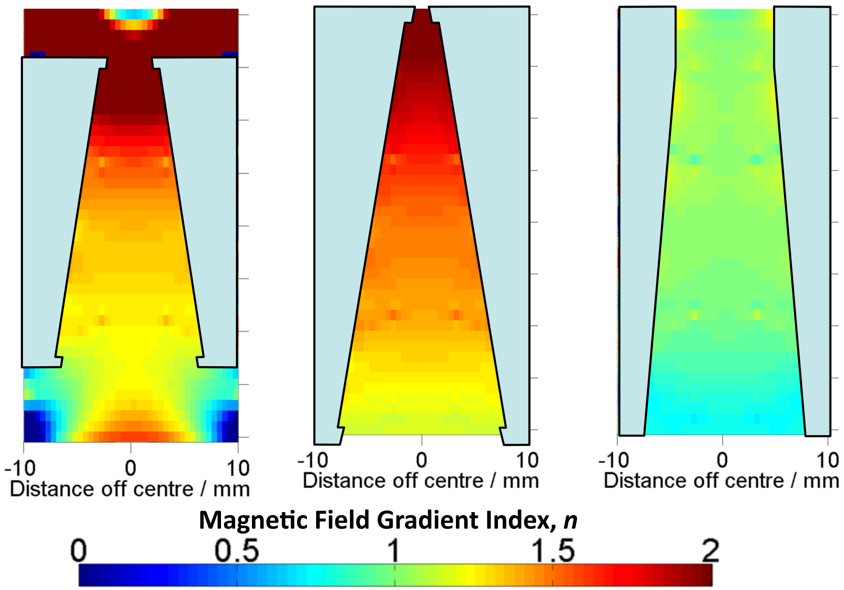
1.

2

Magnet Redesign

Dipole has a focusing component

Field gradient index $$n = -\frac{R_e}{B_e}\left(\frac{dB}{dR}\right)$$



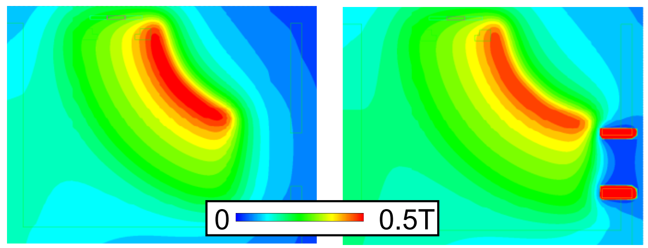
Beam expands under space charge

Exact degree of compensation unknown

Optimum field gradient index n = 1.2 determined by experiment

Size of good field region increased

Field must be adequately terminated



Significant improvement in emittance

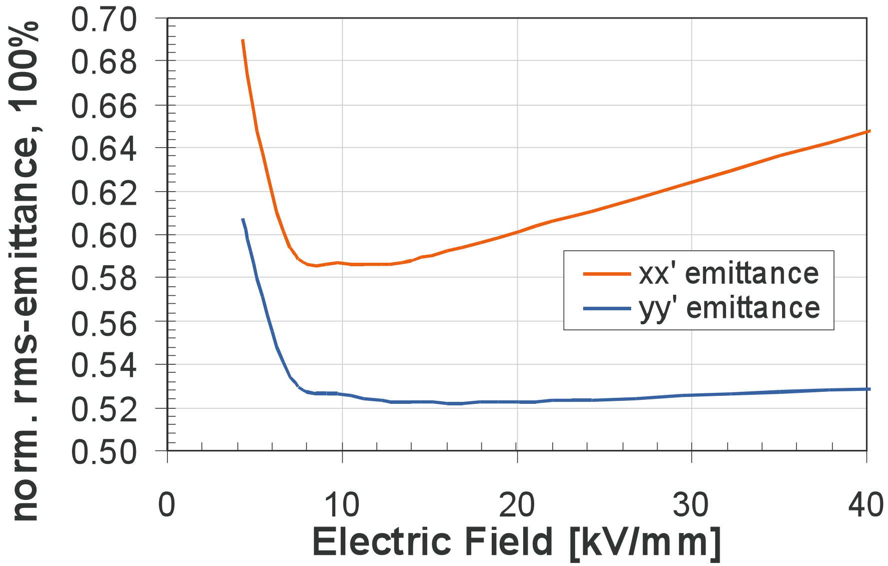
5. Analysing magnet

FETS source modifications

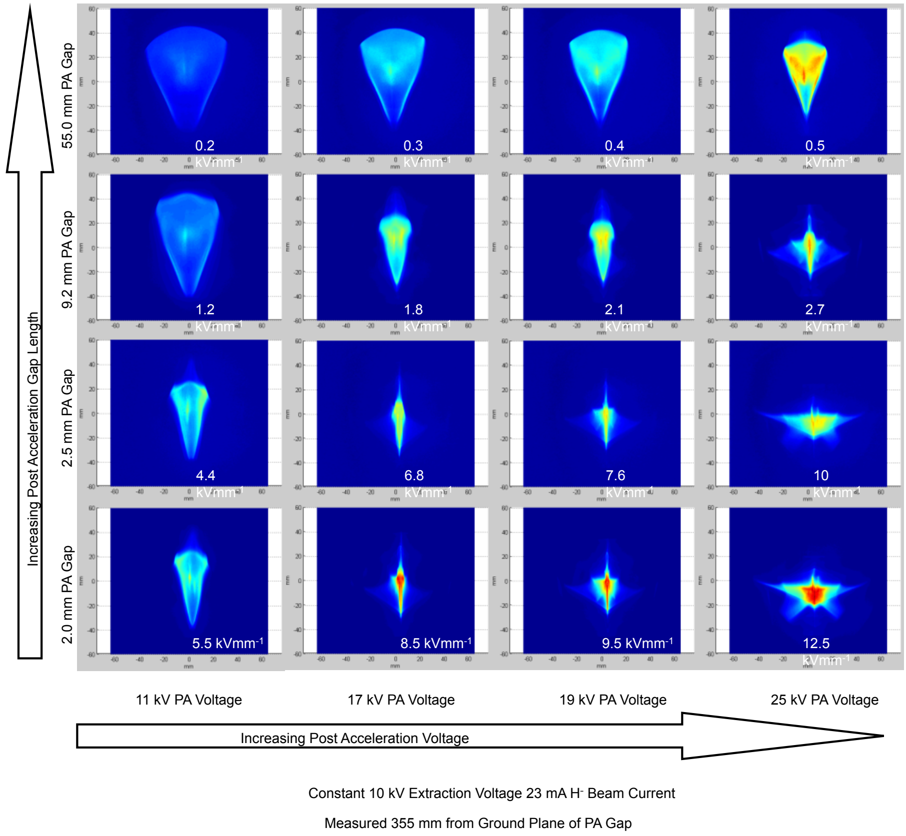
1.

2

Optimize Gap



Minimum emittance growth occurs for a post acceleration field of 9 kVmm^{-1}



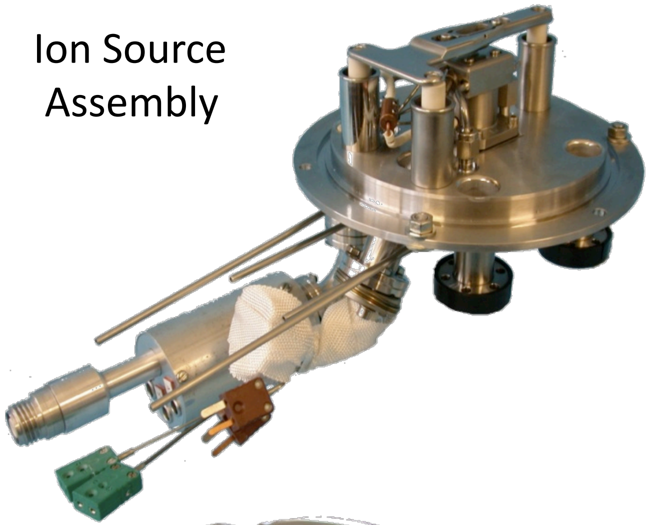
5. Analysing magnet

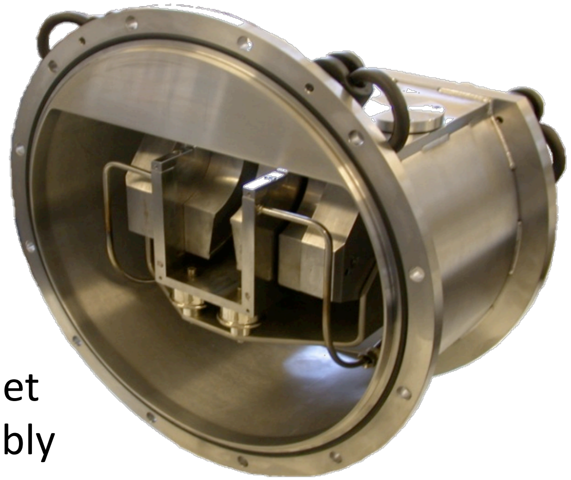
FETS source modifications

Experimental Source Configurations

Top Loading Ion Source

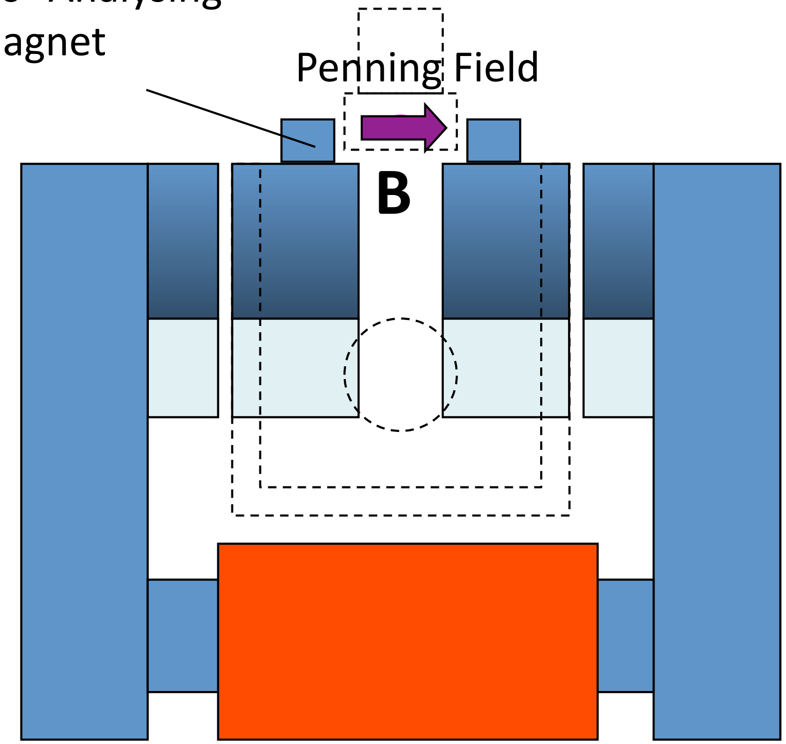
Ion Source Assembly

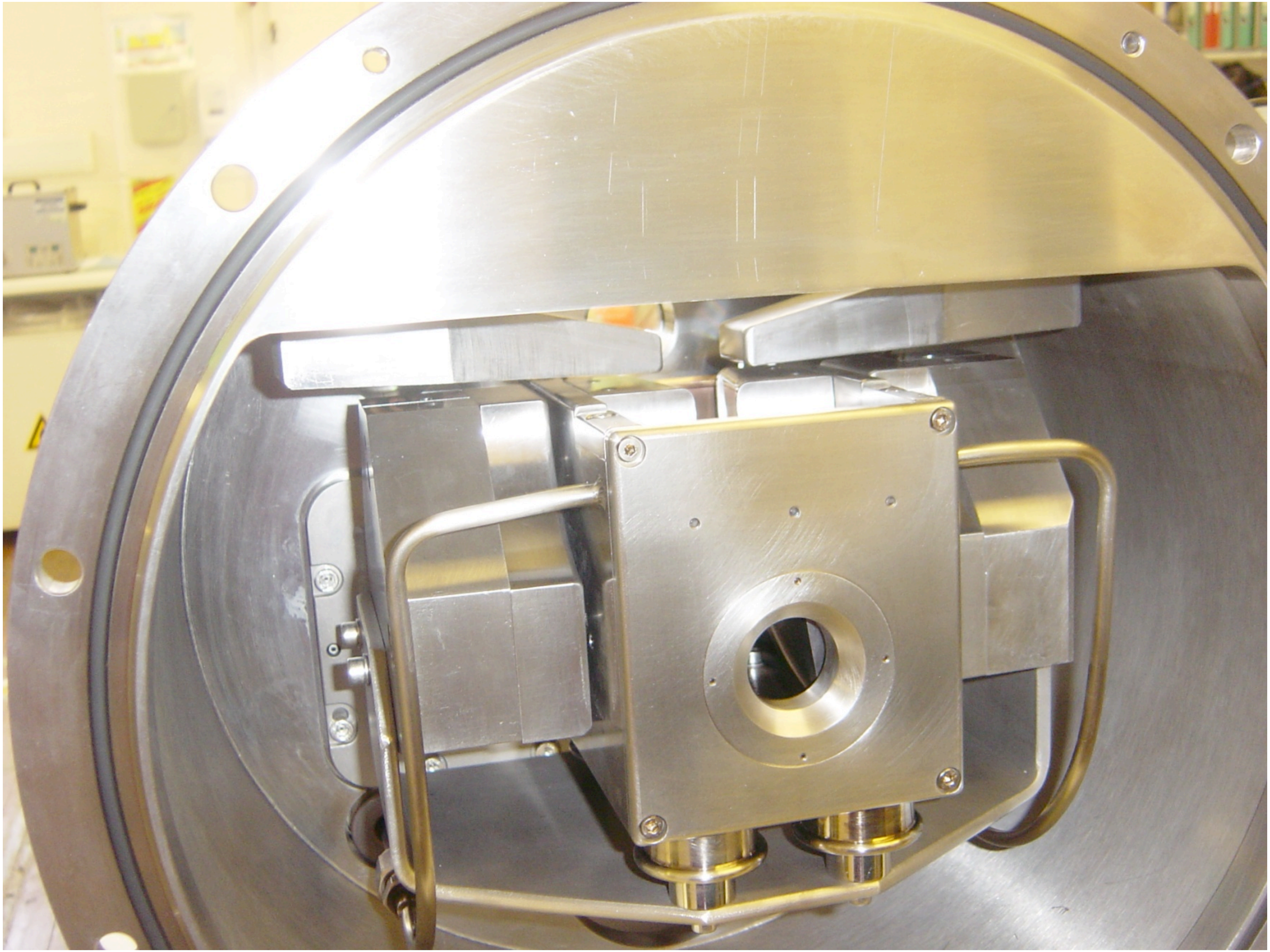




Magnet Assembly

Separate Penning Field





Many Experiments

Energy Spread

Extraction Voltage

Extraction Geometry

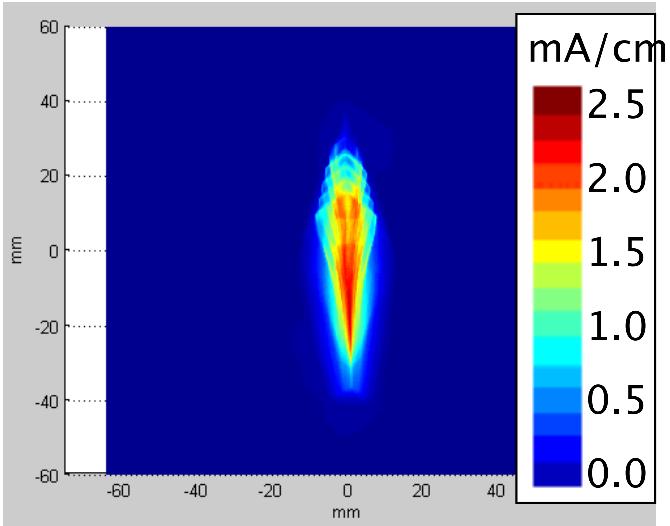
Post Acceleration Gap

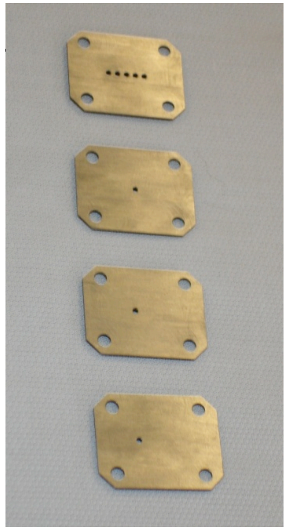
Post Acceleration Voltage

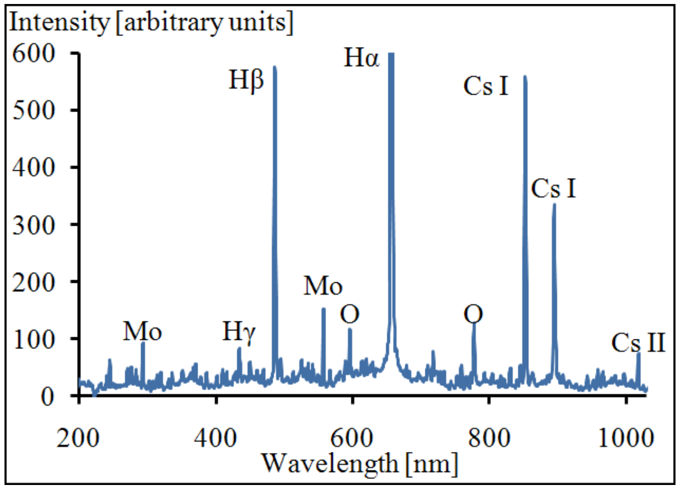
Anode Geometry

Operating Conditions

Multi Beamlett Extraction

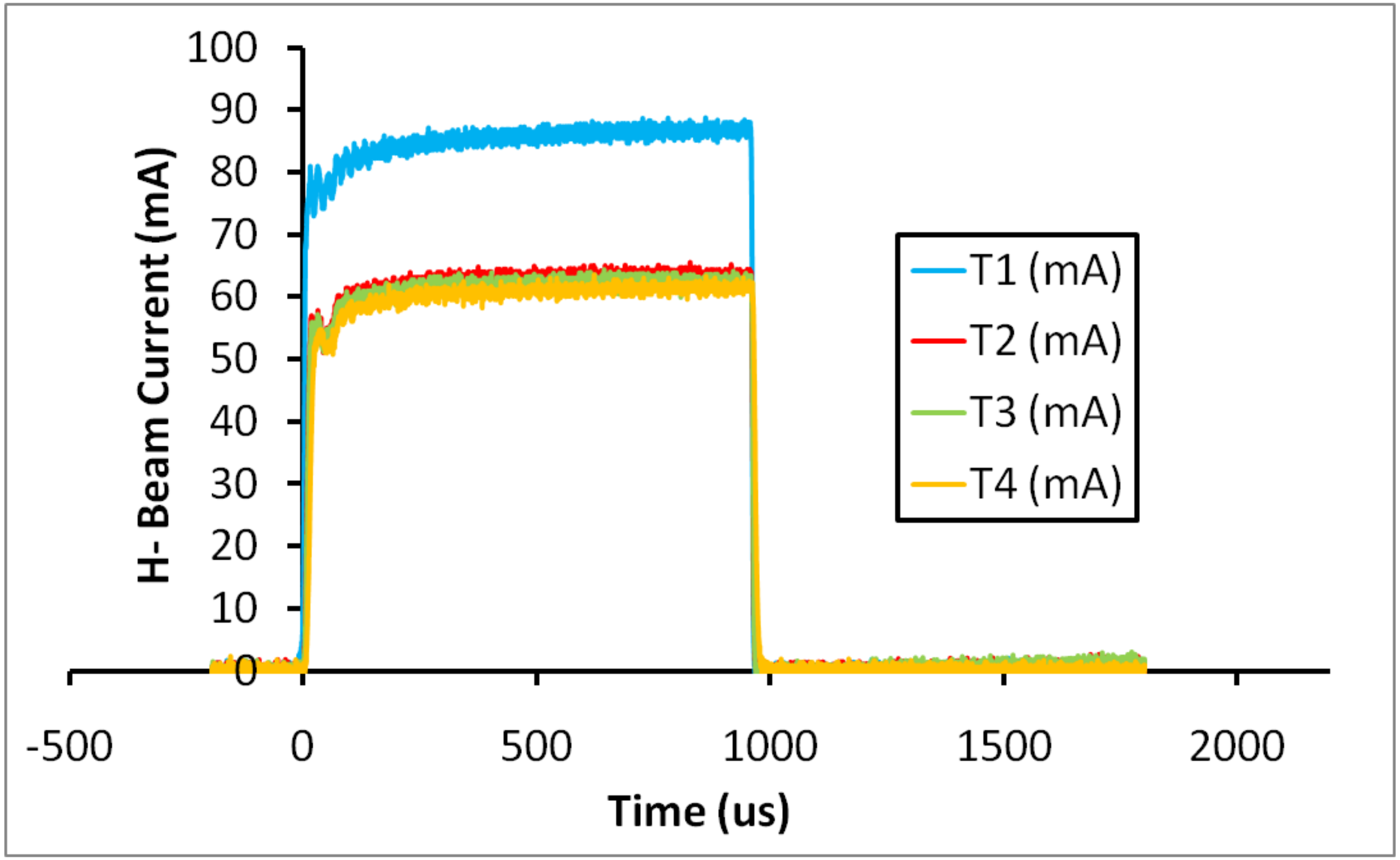






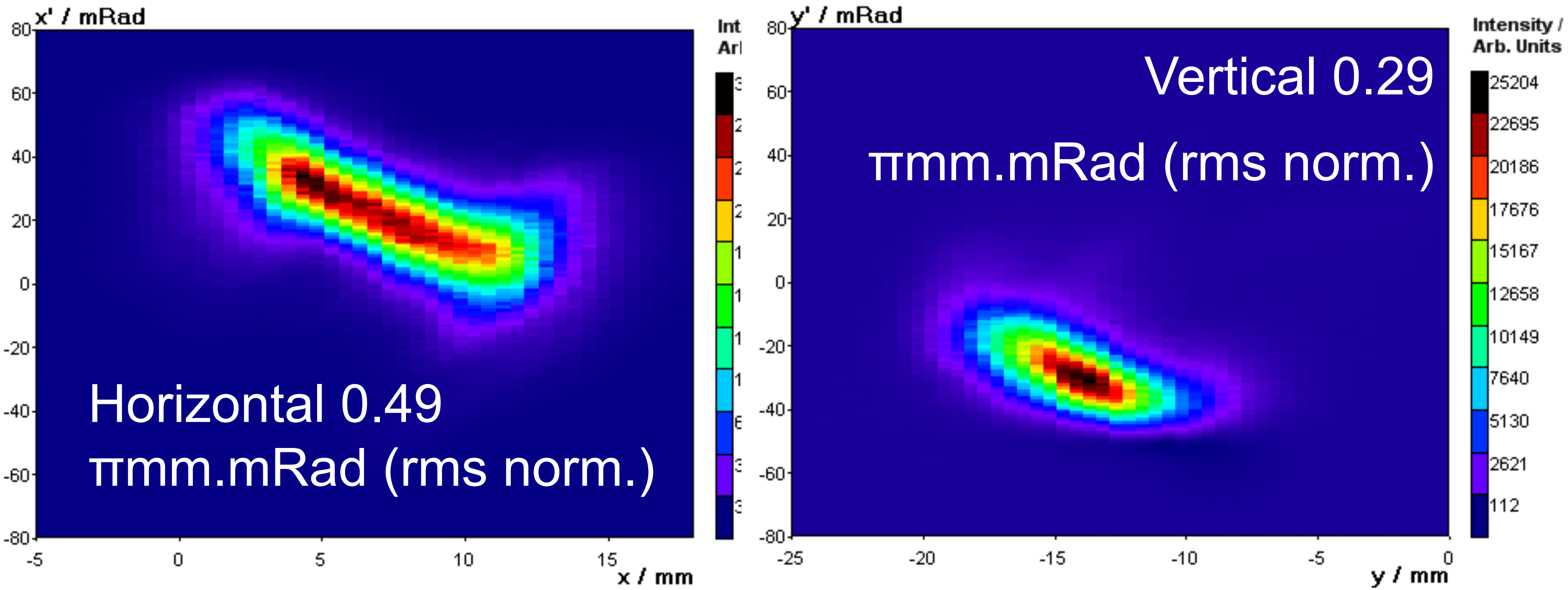
Optical Spectroscopy

62 mA 1ms 50 Hz Operation



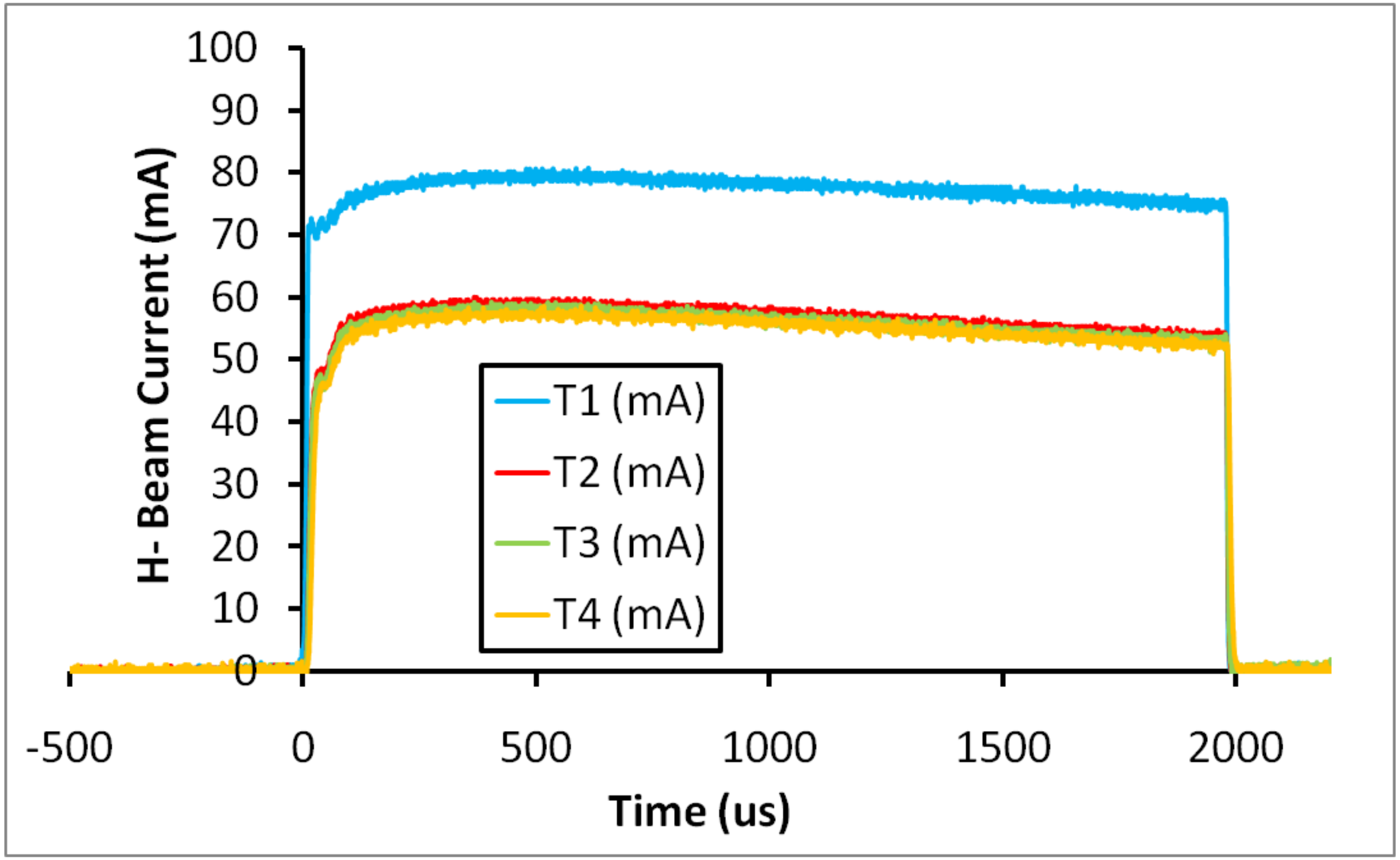
1.2 ms 60 A discharge, 19.6 kV extraction voltage, 65 keV beam, 180°C caesium oven, 16 $mLmin^{-1}$ H_2

Emittances



x' / mRad
x / mm
Horizontal 0.49
πmm.mRad (rms norm.)
y' / mRad
y / mm
Vertical 0.29
πmm.mRad (rms norm.)
Intensity / Arb. Units
25204
22695
20186
17676
15167
12658
10149
7640
5130
2621
112

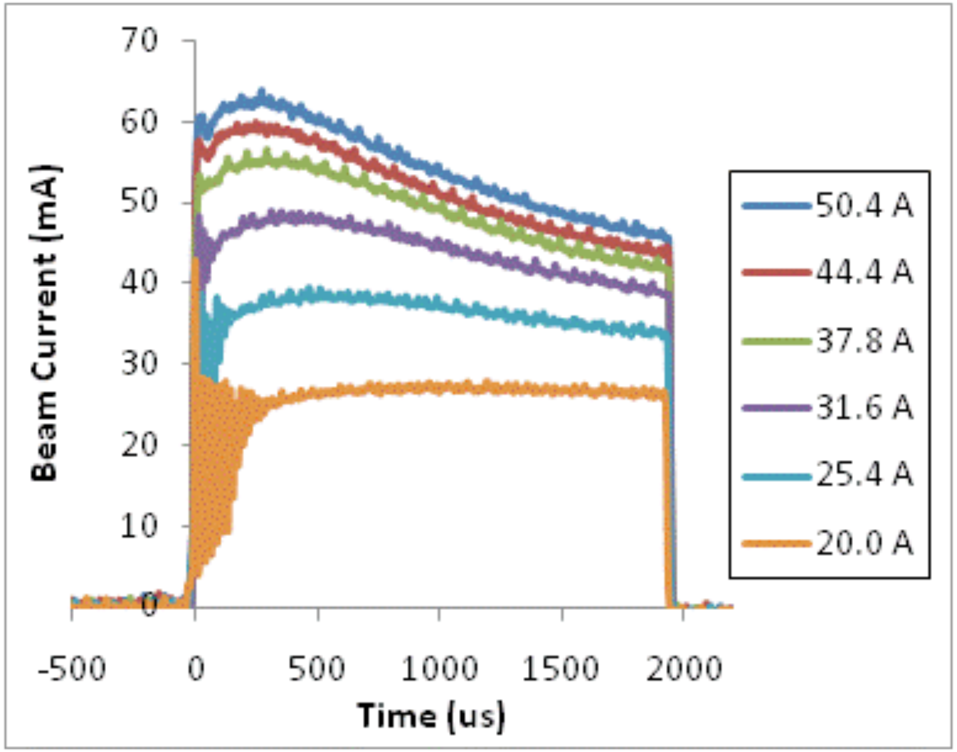
60 mA 2ms 25 Hz Operation



2.2 ms, 64 A discharge, 19.6 kV extraction voltage, 65 keV beam, 190°C caesium oven, 16 $mLmin^{-1}$ H_2

Droop is unavoidable at 50 Hz 2 ms

H^- Beam Current

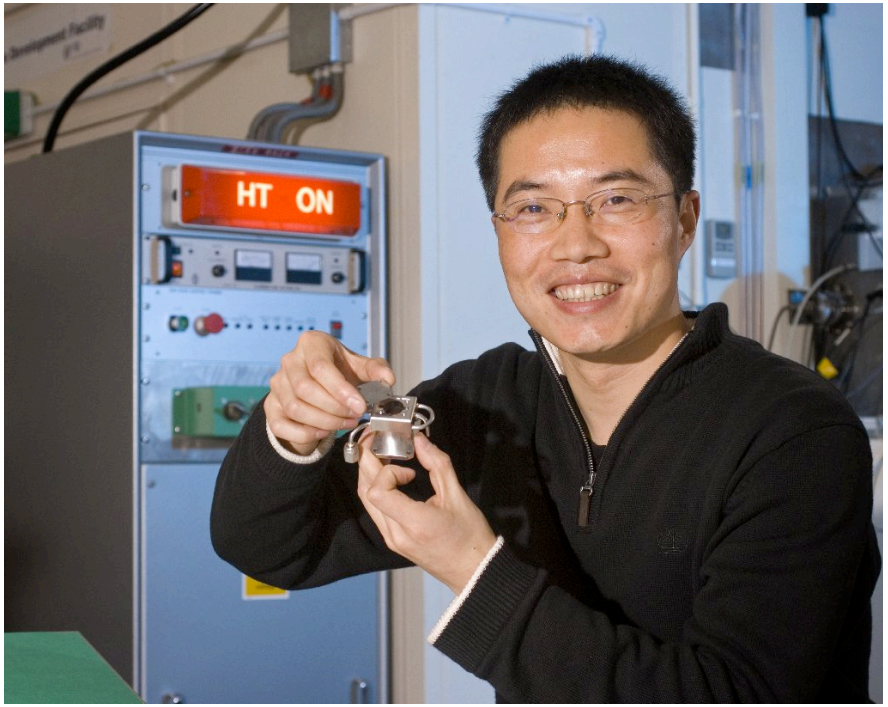


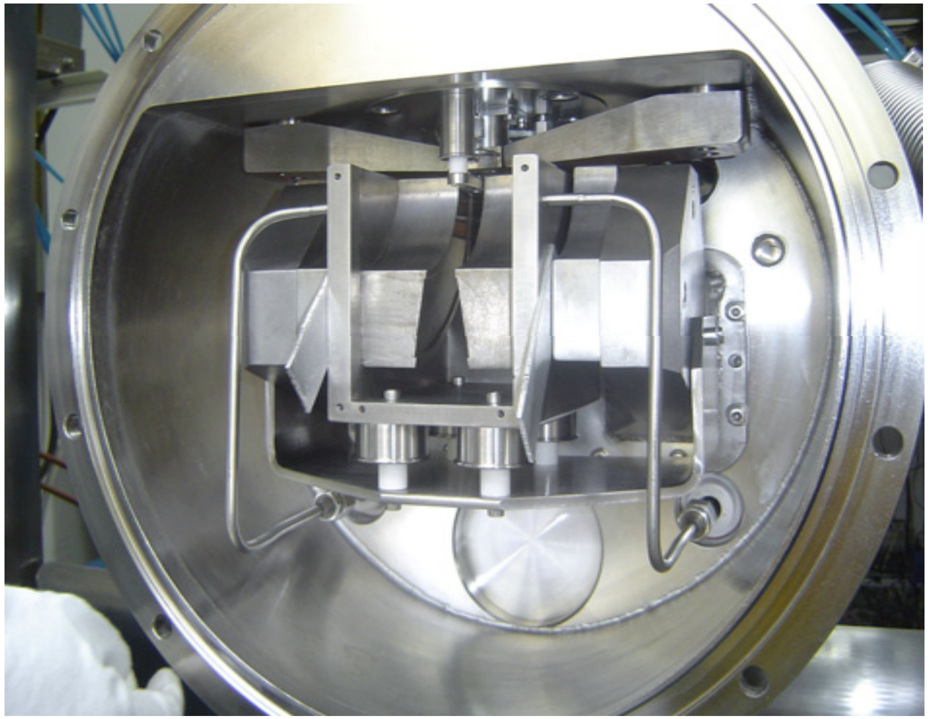
- Hydrogen timing has been fully investigated including double pulses
- Neither caesium or hydrogen settings can mitigate this droop

It is a fundamental problem with electrode surface temperature rise during the pulse

ISIS Source Around the World

IHEP China are using the
ISIS source on CSNS

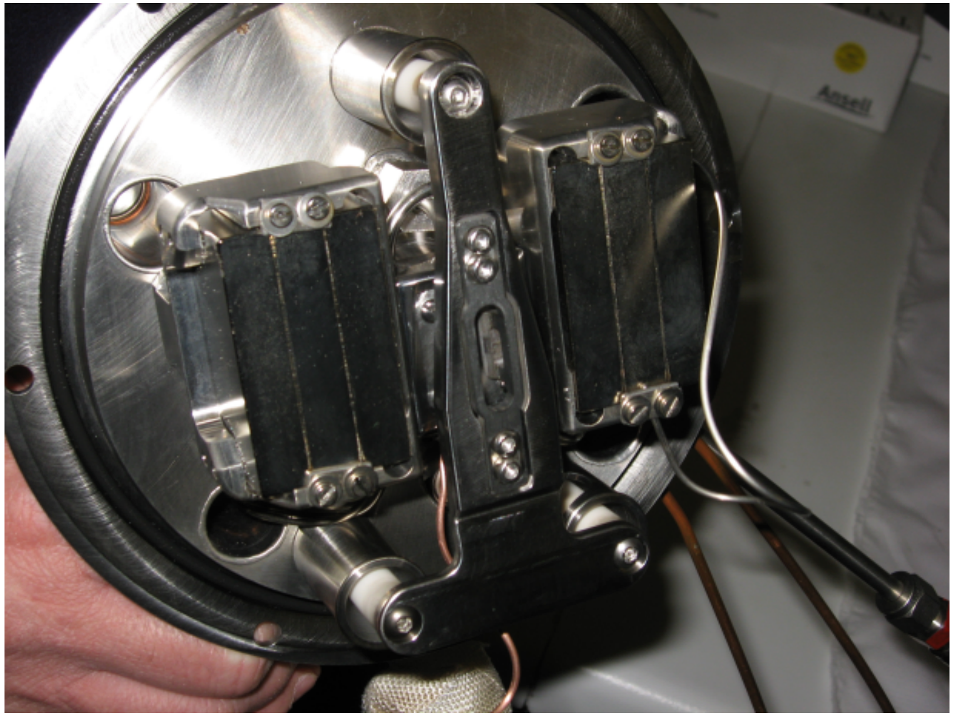




Chinese Spallation Neutron Source

ISIS Source Around the World

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



ESS Bilbao

Future

Plasma and Extraction Test Stand:

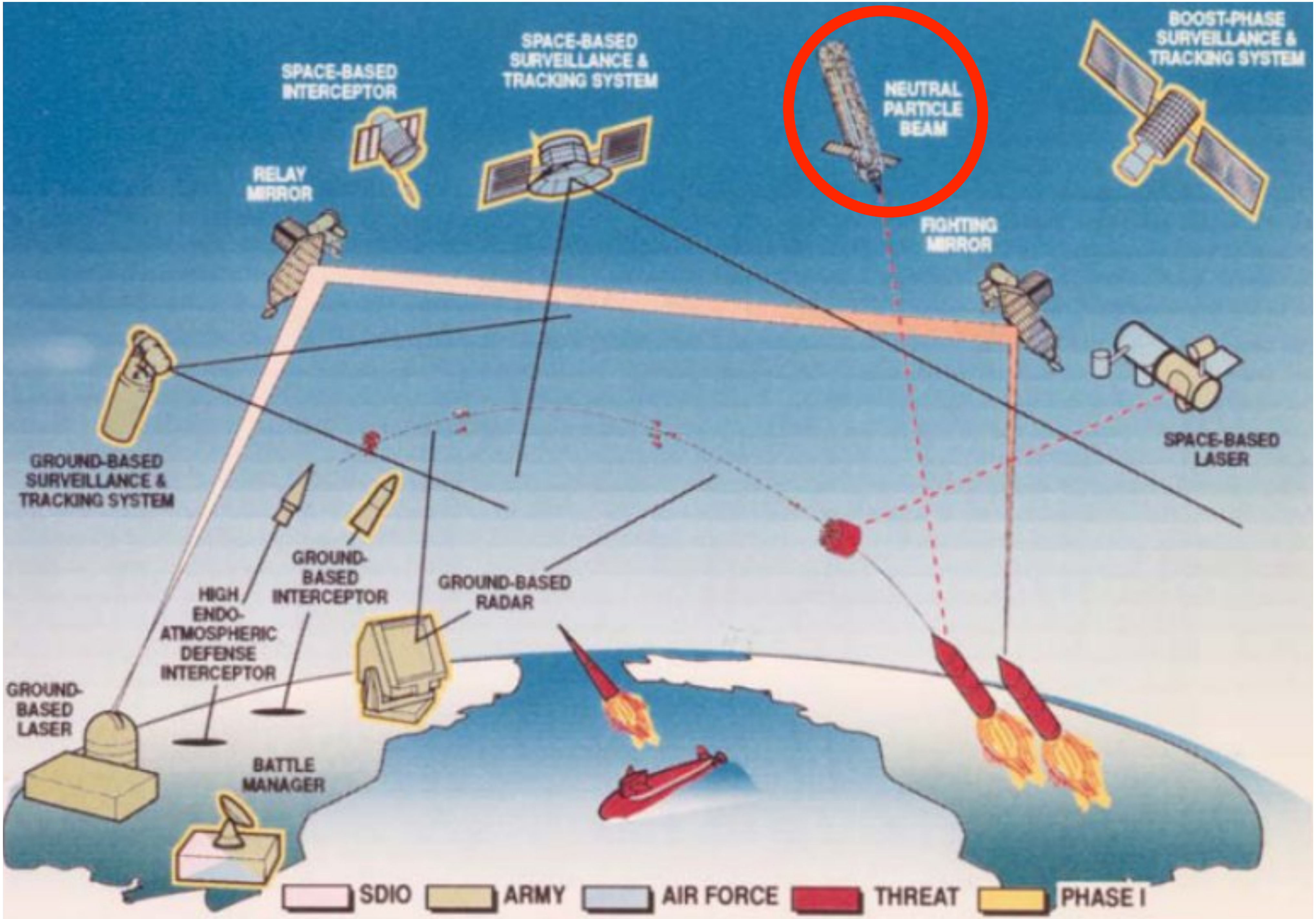
- Detailed understanding of plasma
- Detailed understanding of extraction
- Scaled source

How the Penning Source Ended the Cold War

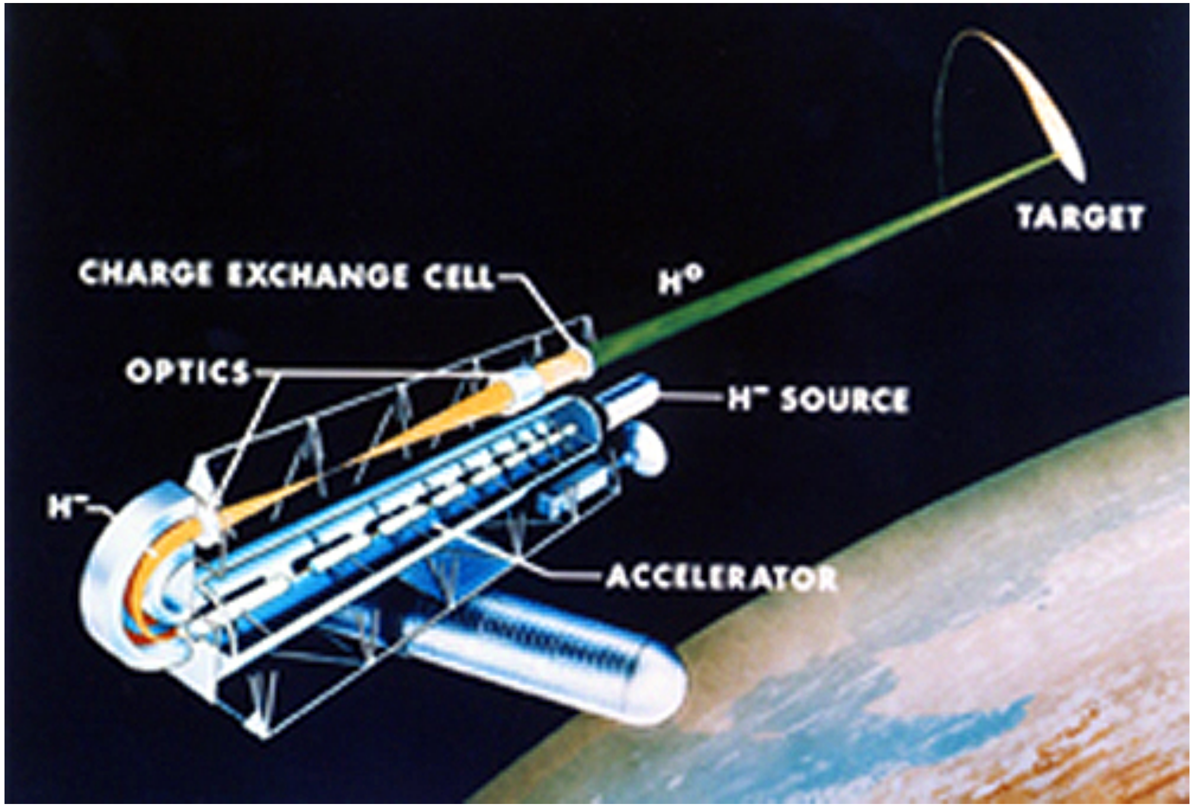
MAD Strategy:
Mutually
Assured
Destruction

Star Wars

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

Thanks to:

Dan Bollinger for magnetron slides

Viktor Klenov for INR Penning photographs