Why BNL's magnetron ?

Circular aperture magnetron operated at BNL since 1989

Linac4	Typical Running Parameters	
80 mA	H- current	90 - 100 mA (1.5 A/cm^2)
45 kV	Extraction	35 kV
	e/H	0.5 - 1.0
	Arc voltage	140-160 V
	Arc current	8-18 A (often run 15-18 A to keep source temp up)
0.8-2.0 Hz	Rep rate	7.5 Hz
700 µs	Pulse width	700 µs
0.07-0.14 %	Duty factor	0.5%
0.25 π *mm·mrad*	RMS emittance	~ 0.4 π mm mrad (normalized)
5-10 g/year	Cs consumption	< 0.5 mg/hr (T_{Cs} = 90 - 100 C 5 gm lasts >6-9 months)
	Gas flow	~ 2.5 x 10^{-2} T-l/s (2 sccm)

> 6 month — Times between source maintenance are approximately 6 months continuous (3-9 months; almost always shutting down when program ends, rather than due to failure).

Ok — We can shut the source down, change it out, restart, and be running well again in 8 hours.

J. Alessi 4/9/02

BROOKHAVEN NATIONAL LABORATORY

CP642, *High Intensity and High Brightness Hadron Beams: 20th ICFA Advanced Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams*, edited by W. Chou, Y. Mori, D. Neuffer, and J.-F. Ostiguy

BNL's Magnetron: Linac4 IS-03

June 2010, L4IS-review: BNL' magnetron is the option for nominal current

To be addressed:	
1) Import technology	4) Operation at low duty factor
2) Impact of higher beam energy,	5) Cs-handling
3) Dumping of co-extracted electron	6) Emittance

September 2011, ICIS: Investigation of ISIS and BNL ion source electrodes after extended operation

April 2012: BNL's drawings received, short test of the gas-pulse at BNL

September 2012, NIBS: Estimation of sputtering damages on a Magnetron H^- ion source induced by Cs^+ and H^+ ions. Operation and thermal modelling of the ISIS H^- source from 50 to 2 Hz repetition rates

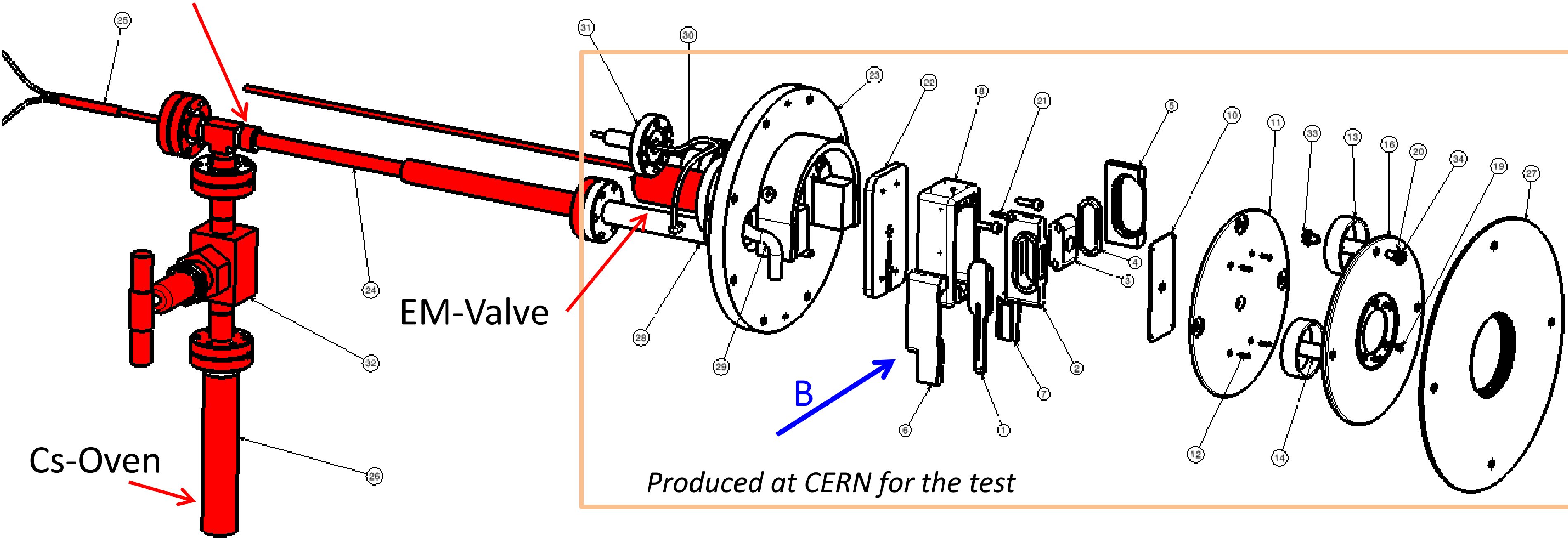
November 2012: 3D model and a set of components drawings available (metric and US), from them a Discharge chamber and Puller are produced at CERN.

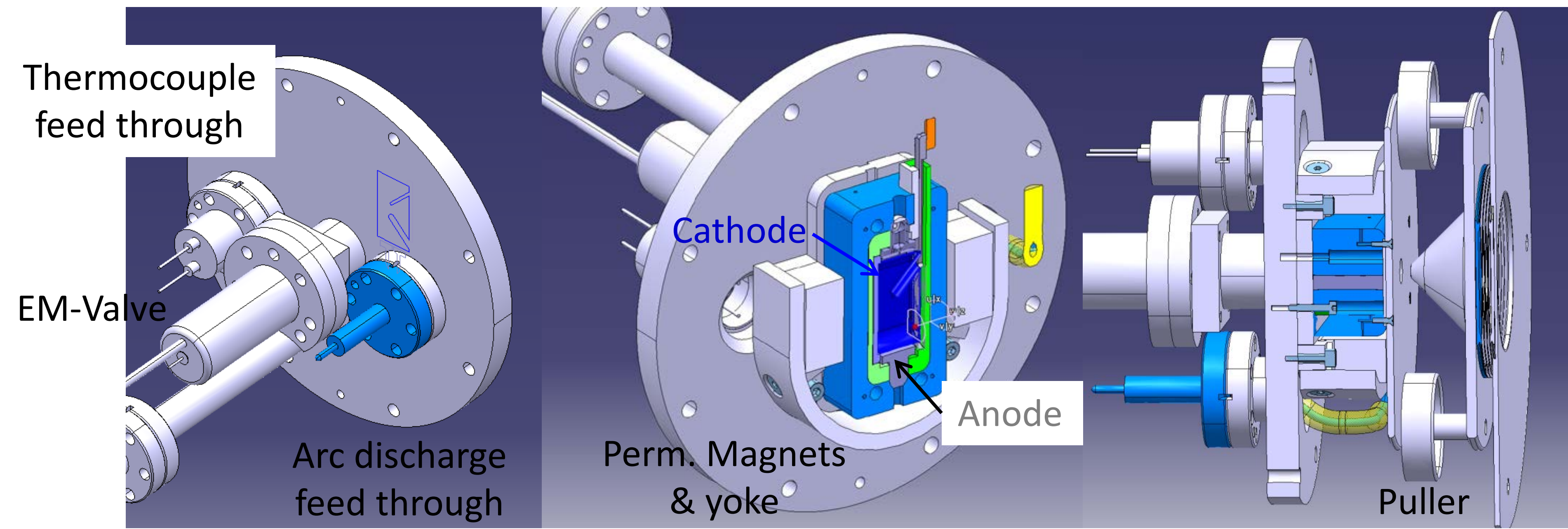
Oct. 2013 CERN's discharge chamber tested within BNL's ion source at the Linac injection line → O(120 mA H^-)

The major contribution of D. Steyeart, the support from J. Alessi, T. Lehn, A. Zelenski, J. Ritter and the BNL ion source development team is thankfully acknowledged

BNL's Magnetron 3D model

D. Steyaert





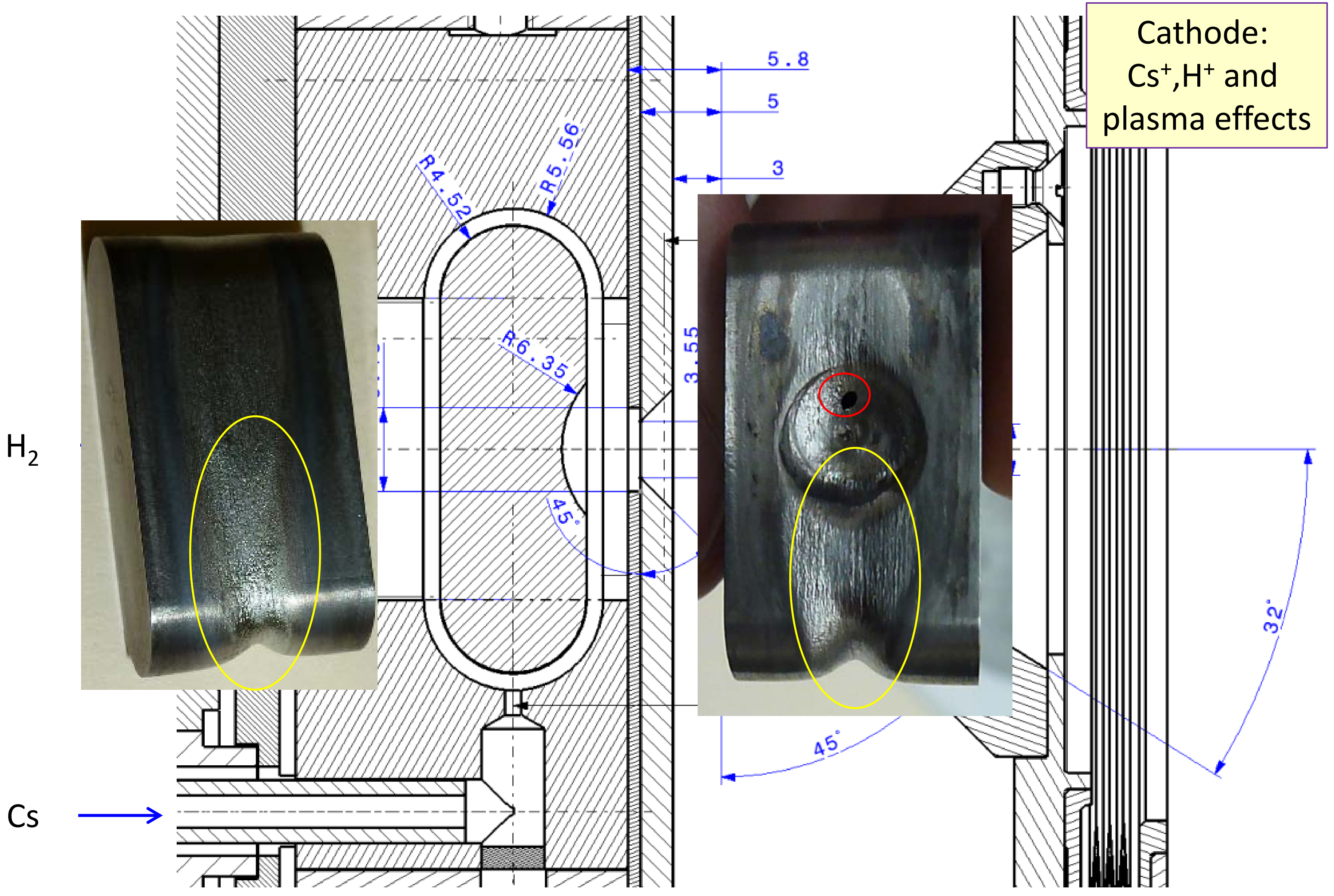
Typical observations following a long run:

The source is very clean inside (polished)

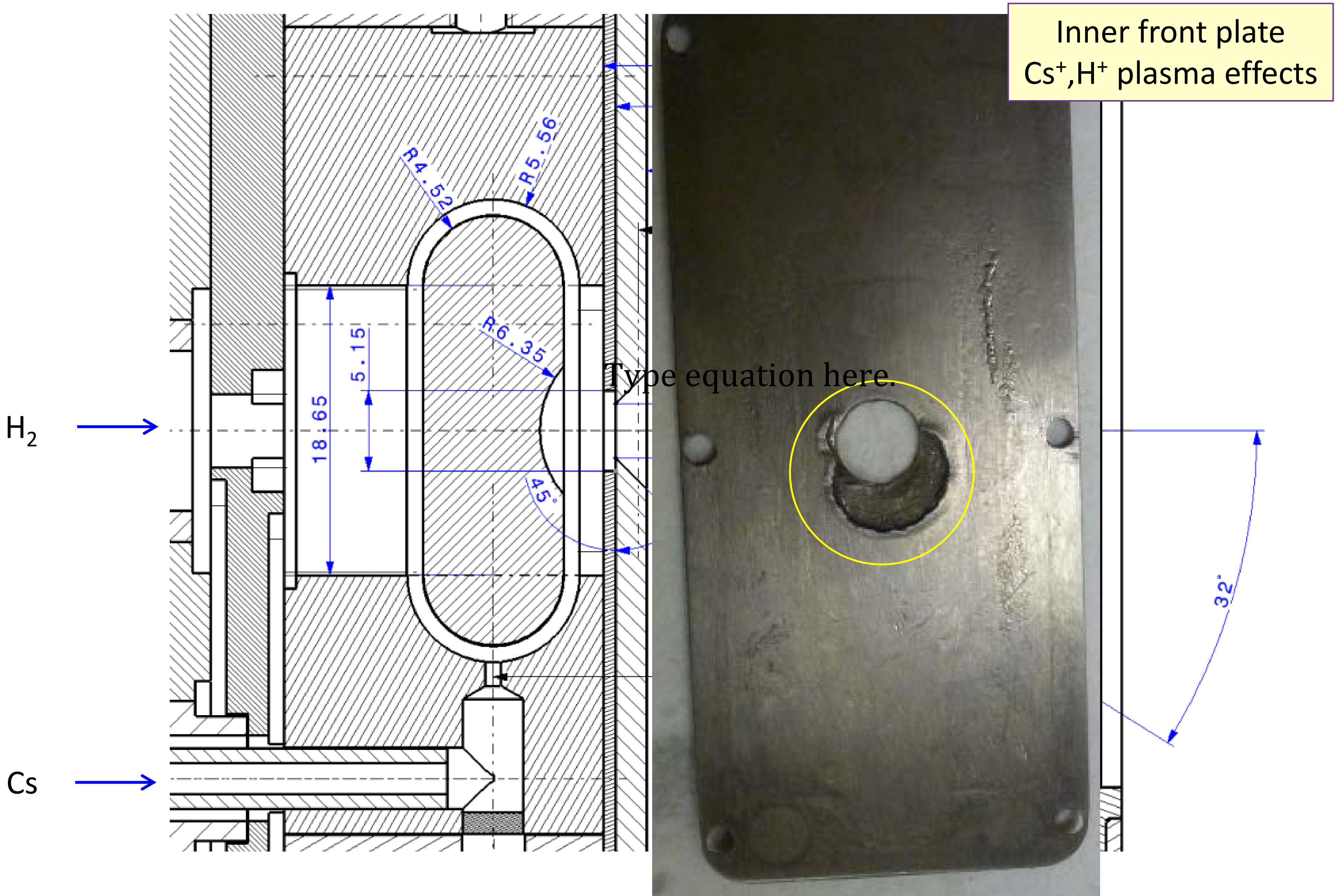
There is erosion of the extraction tip (ions, electrons), anode aperture (electrons), cathode dimple (backstreaming ions), cathode opposite Cs feed (discharge). In spite of these very significant changes in dimensions for the extraction geometry and cathode focusing, the performance remains very constant (output from linac). We often clean parts and reinstall, even with the heavy erosion.

Cs never seen beyond the extractor electrode.

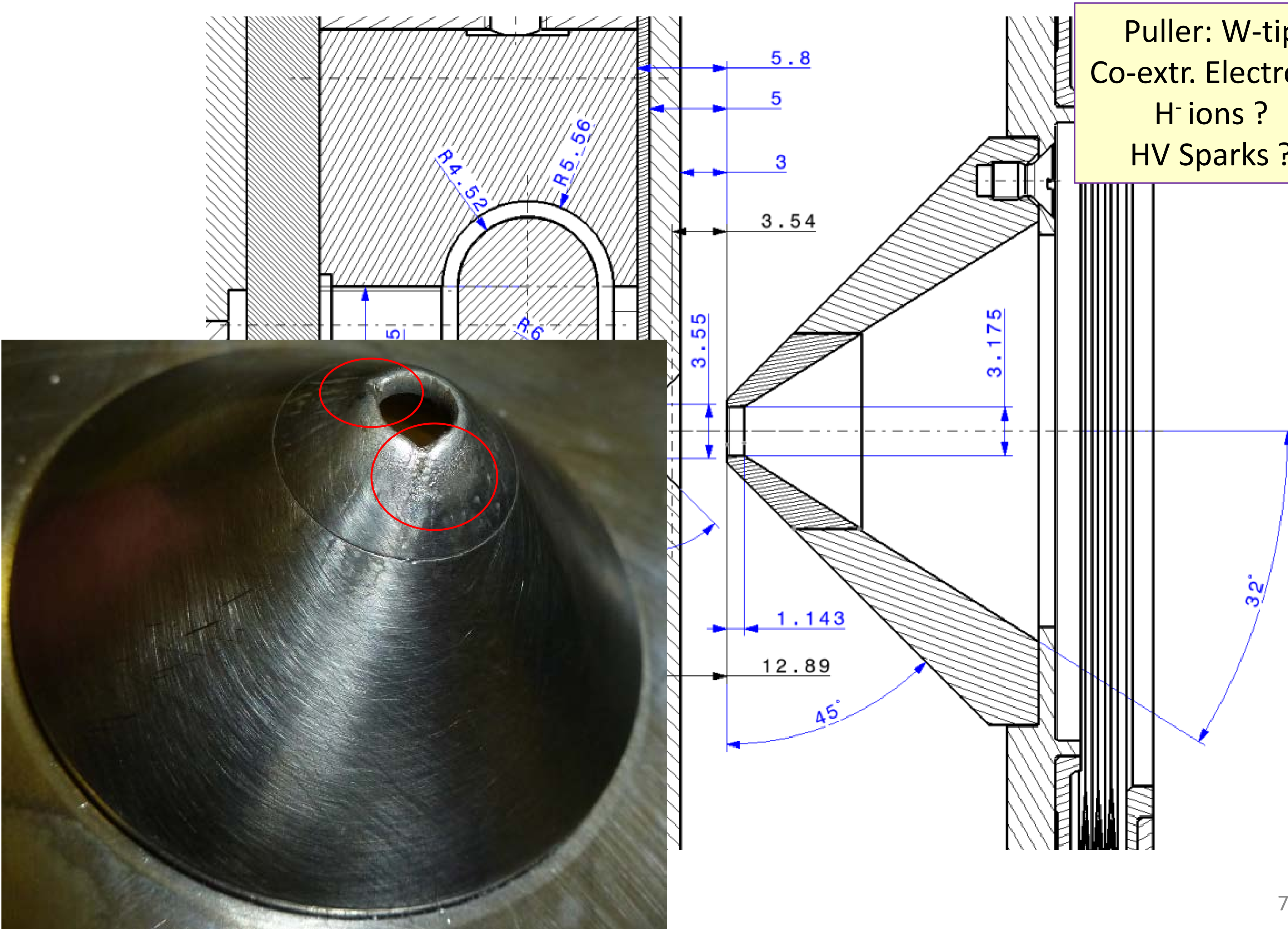
Ageing and Wear after 2 years operation



Ageing and Wear after 2 years operation

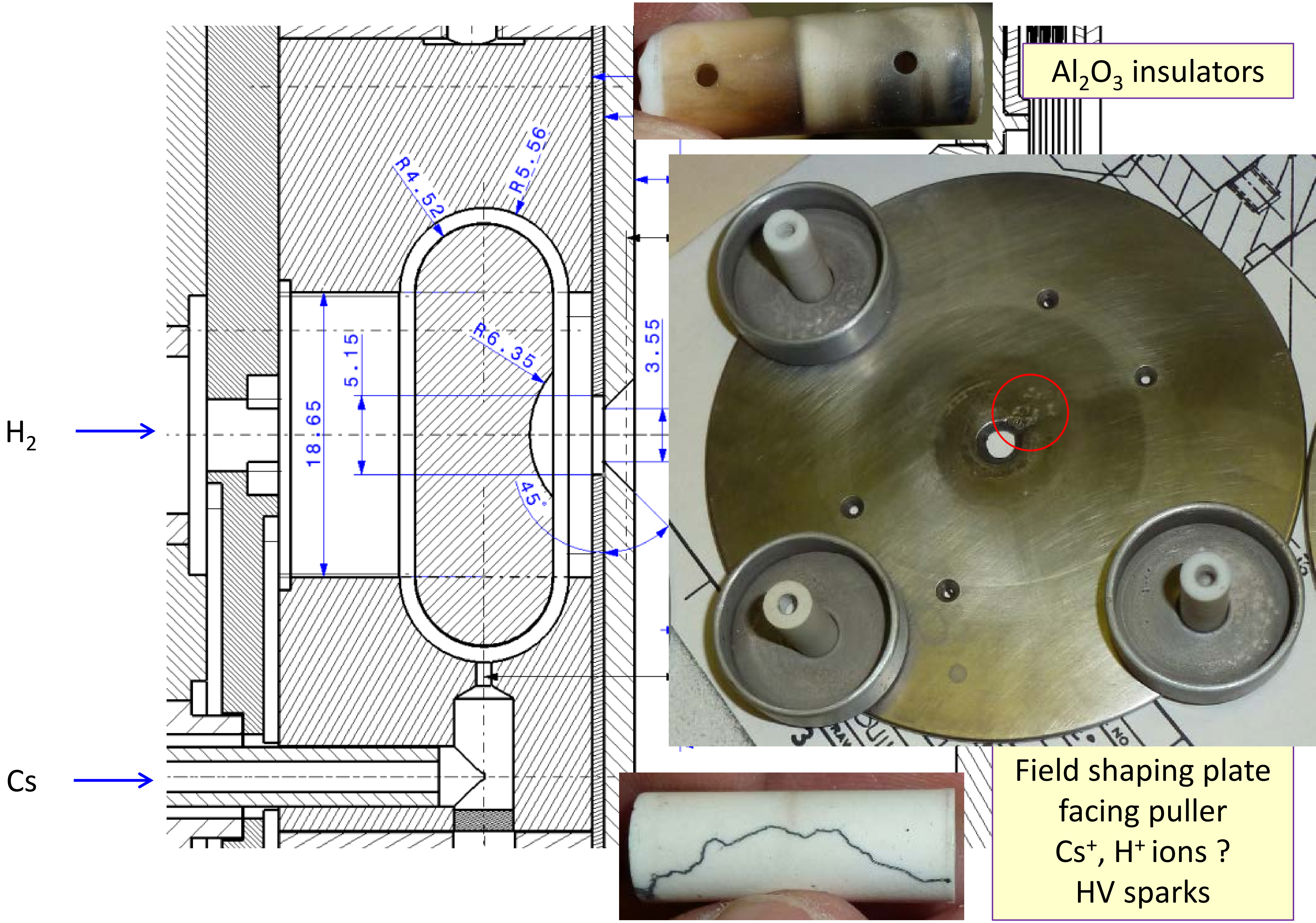


Ageing and Wear after 2 years operation

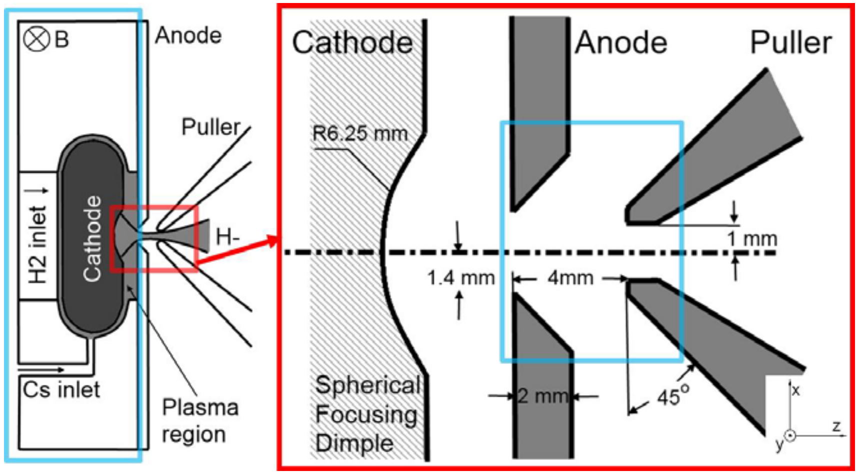


Puller: W-tip
Co-extr. Electrons
H^- ions ?
HV Sparks ?

Ageing and Wear after 2 years operation



Simulation of BNL's Magnetron with IBSimu



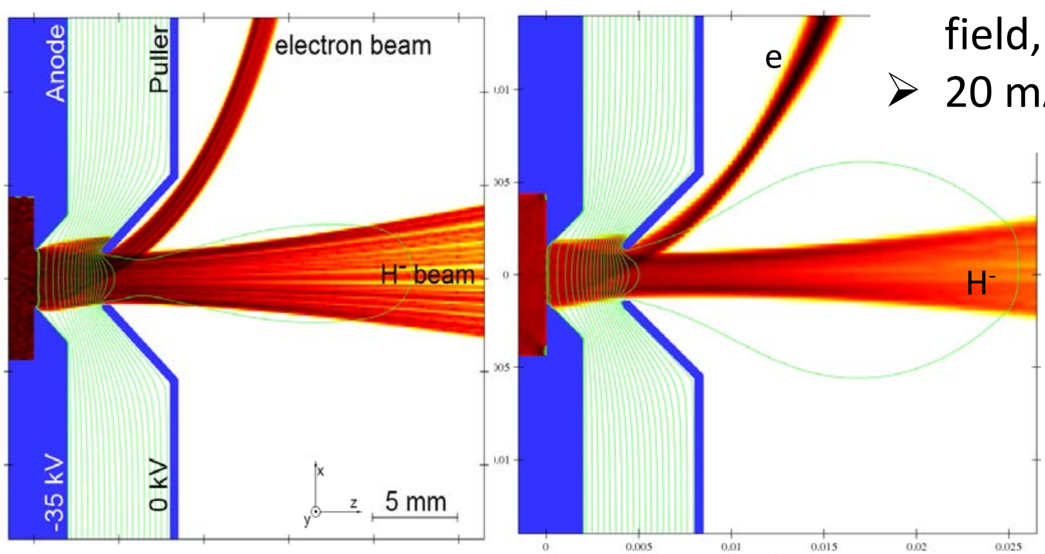
IBSimu settings:

- H^- beam current density is set to 1.6 A/cm2, resulting in a current of 100 mA.
- Electron to H^- ratio = ½ (50 mA)
- A 3-D magnetic field map created in OPERA from the known magnet geometry and adjusting the field to a peak of 900 G.

Results:

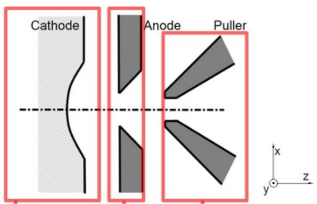
- The H^- beam is transported through the puller at close to 100% efficiency.
- 60 % of the co-extracted electrons (30mA), which trajectories are bent by the magnetic field, are dumped on the puller electrode tip.
- 20 mA e-beam passes the puller electrode.

-35 kV -45 kV



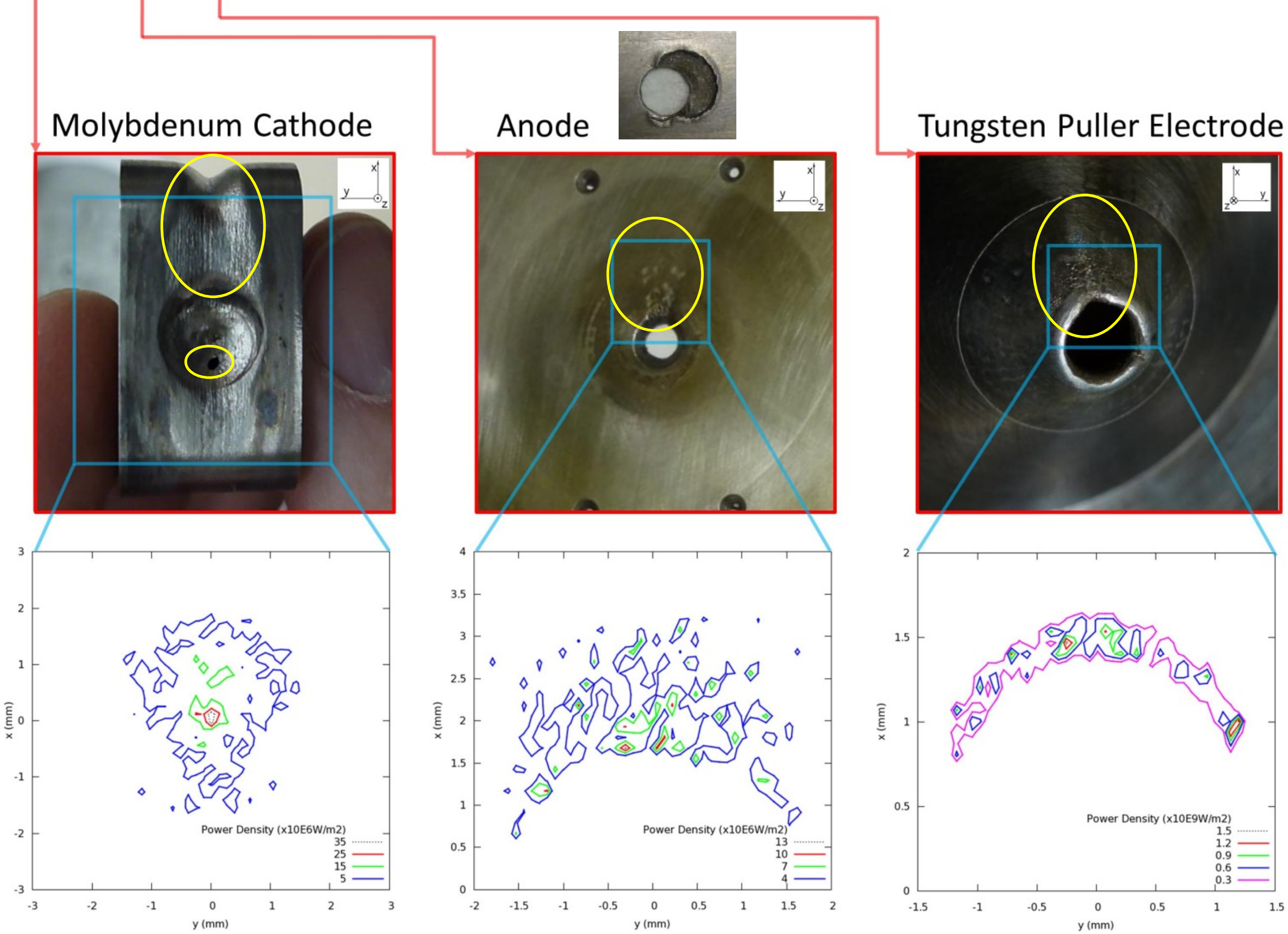
1) J. Lettry, J. Alessi, D. Faircloth, A. Gerardin, T. Kalvas, H. Pereira, and S. Sgobba, Investigation of ISIS and BNL ion source electrodes after extended operation, Review of Scientific Instruments 83, 02A728 (2012).
2) H. Pereira, J. Lettry, J. Alessi and T. Kalvas, *Estimation of Sputtering Damages on a Magnetron H^- Ion Source Induced by Cs^+ and H^+ Ions*, *AIP Conf. Proc.* 1515 (2013) pp.81-88.

Ageing/wear mechanisms



Observation of erosion/damages on:

- Mo-cathode: 1mm hole
  1-2 mm wear on circumference.
- Anode plate facing puller
- W-tip of the puller electrode.

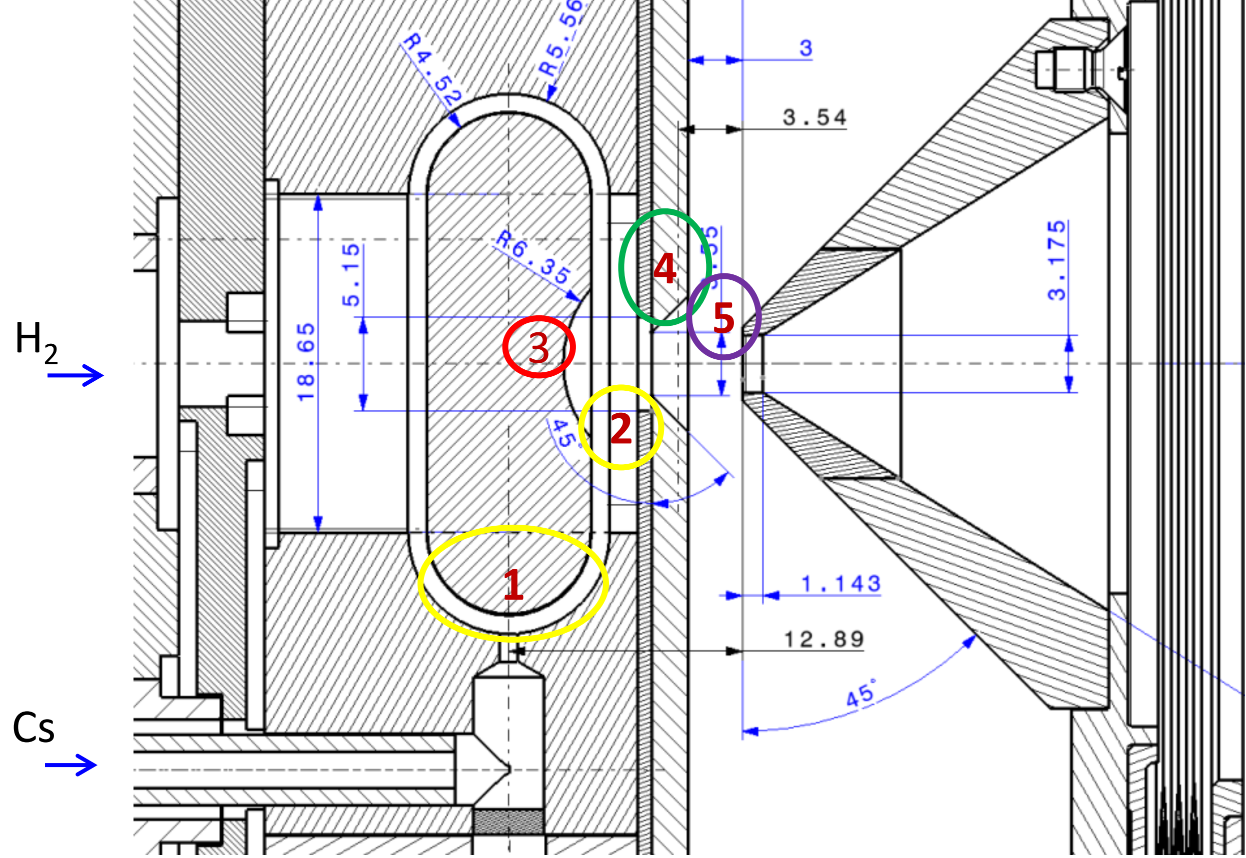


***IBSimu*: creation & tracking of positive ions within the extraction region** (electron and H^- beam induced ionization of Hydrogen gas and Cs vapor). The positive ions travel backwards in direction of the anode and Mo-cathode

***IBSimu*: H^-,e-beams → power density on surface**

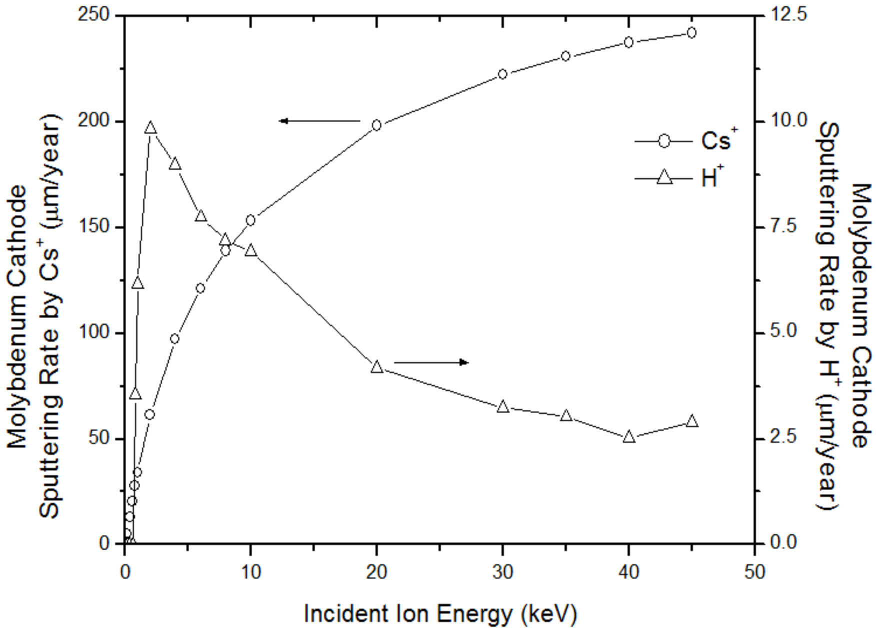
- Mo-sputtering via positive ions (H^+ or Cs^+) on cathode and anode.
- 30 mA of 35 keV electrons deposit a peak power above 1 kW/mm^2 on the W-tip of the puller electrode

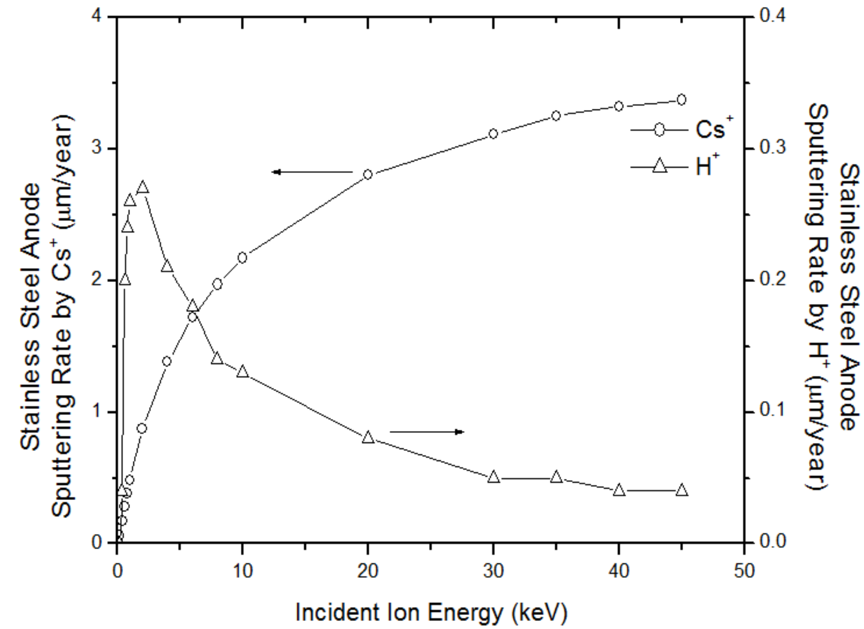
Ageing / wear summary

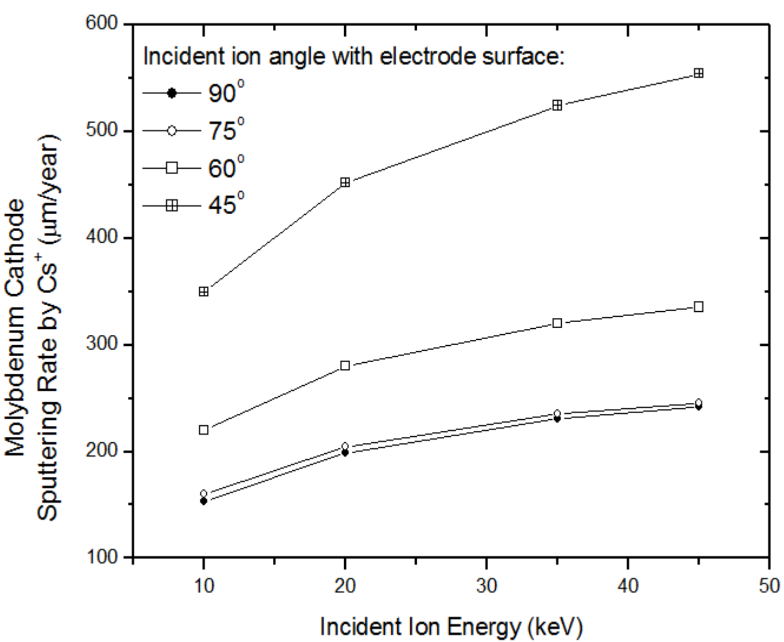


	Operation Parameters / *IS-component*	Arc voltage	Arc current	H_2-pressure	Cs-pressure	Duty factor	Extraction HV	e/H^-	Sparking	*Erosion Process*
1	Mo-cathode surface	×	×	×	×	×				e-H_2-Cs Plasma > Flakes ?
2	SS inner anode plate	×	×	×	×	×				e-H2-Cs Plasma
3	Mo-cathode dimple			×	×	×	×	×		Backward accel. p, Cs^+ ions
4	SS outer anode plate			×	×	×	×	×	×	Backward accel. p, Cs^+ ions
5	W-tip puller					×	×	×	×	e-beam overheating, H^- ions

Estimation of Cs^+ and H^+ sputtering rates



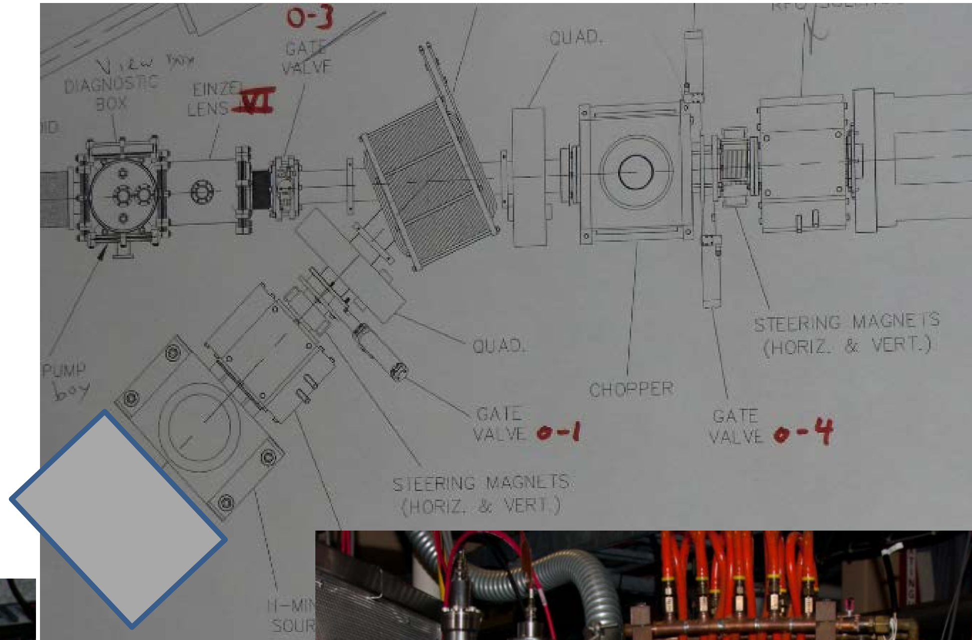




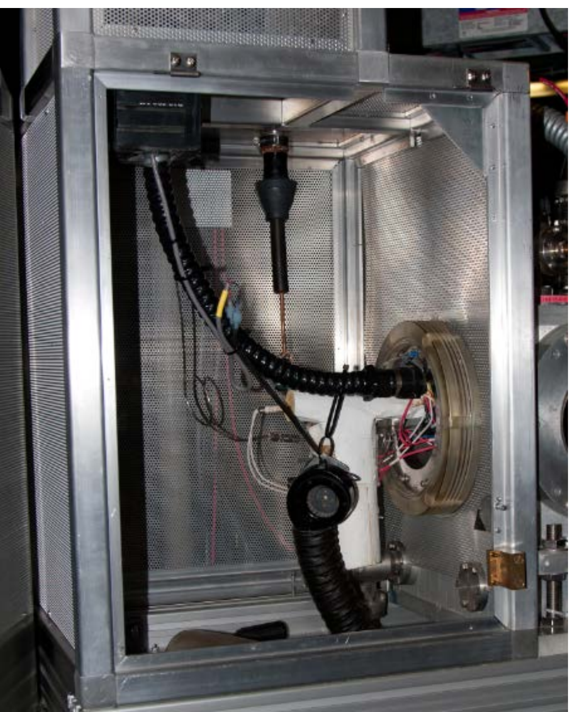
Within a few simplified assumptions (no sparking) & BNL's duty factor of 0.5%:

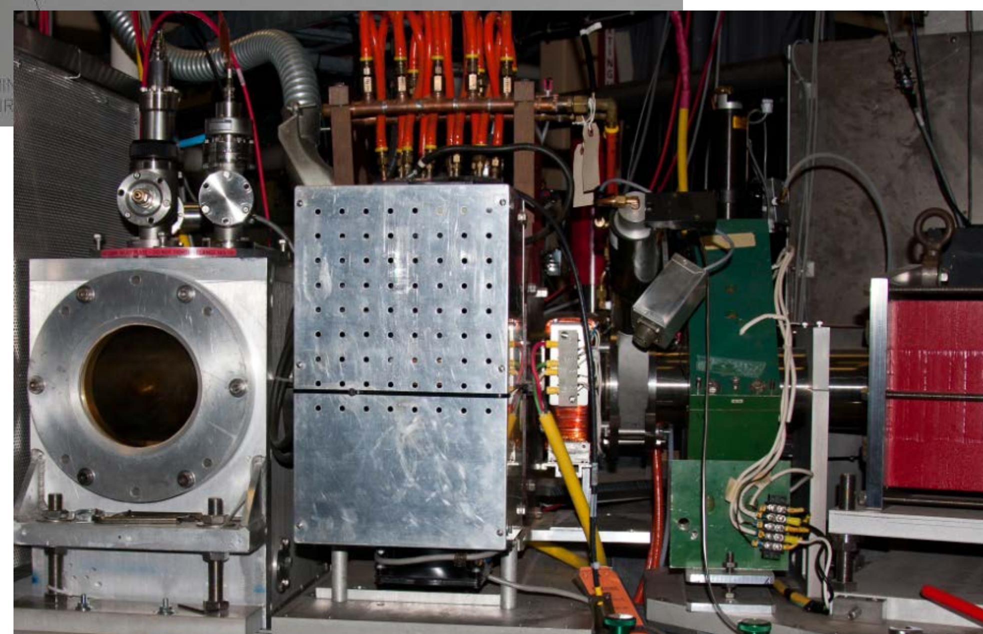
- Mo-cathode dominated by Cs-sputtering rate of O(200) μm/year.
- SS-anode plate O(3) μm/year
- Scales down with Linac4 duty factor (0.2%)
- Effect of increased extraction voltage from BNL 35 → *Linac4 45 kV:*
  - *O(10%) Increased sputtering rate*
  - *O(25%) increased energy density tbc. via IBSimu modeling of e,H^-,p,Cs^+ beams*

2013-10 *Test location at BNL: Linac injector*



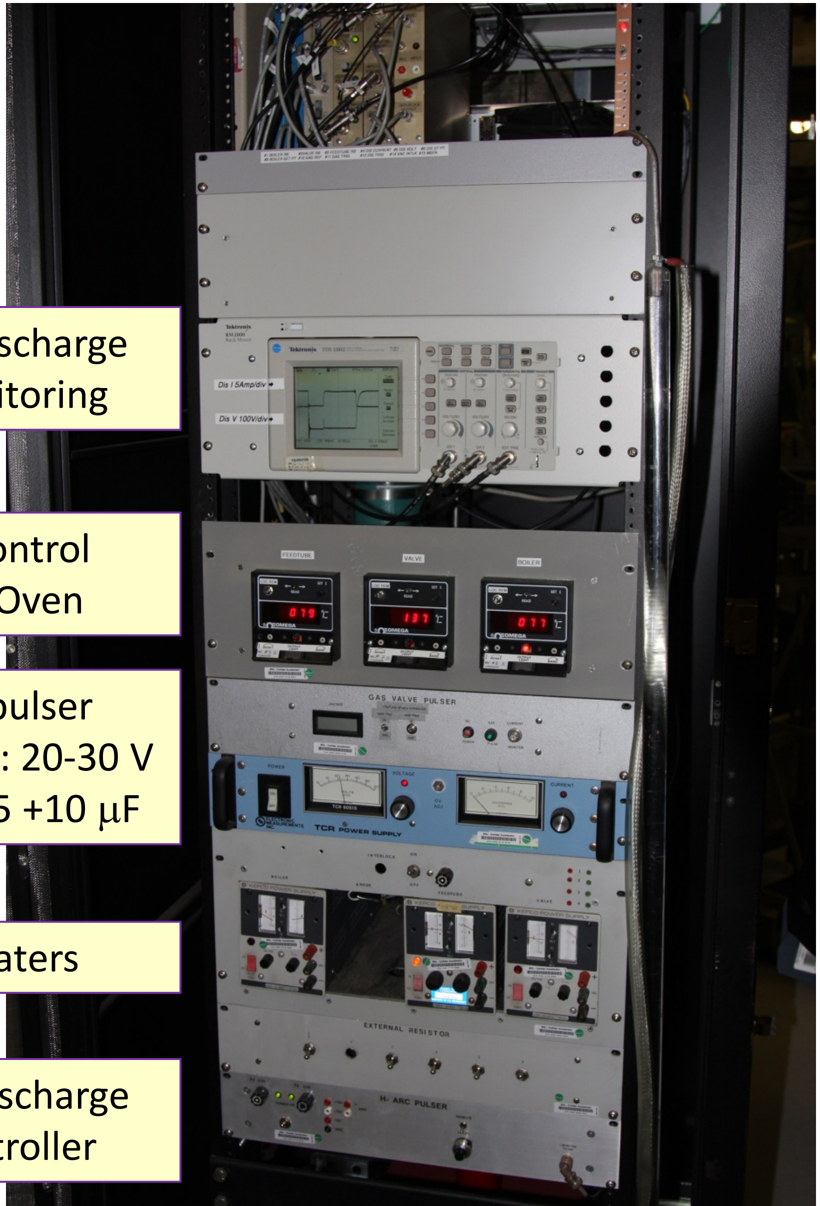
Faraday cage
- Cs-Oven
- H2-feed line





H^- source housing, solenoid & steering magnet

HV-rack



Arc discharge monitoring

T-control Cs-Oven

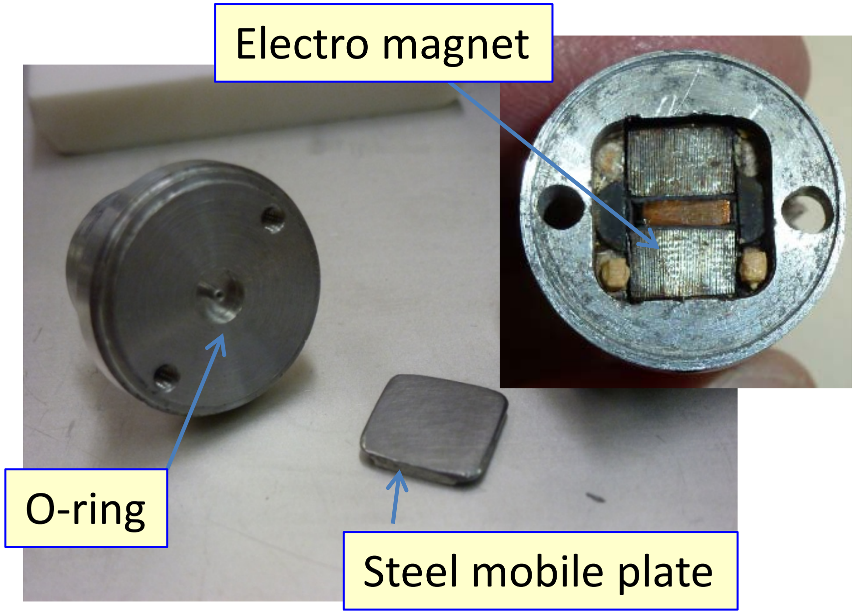
H_2-pulser Control: 20-30 V 15, +75 +10 μF

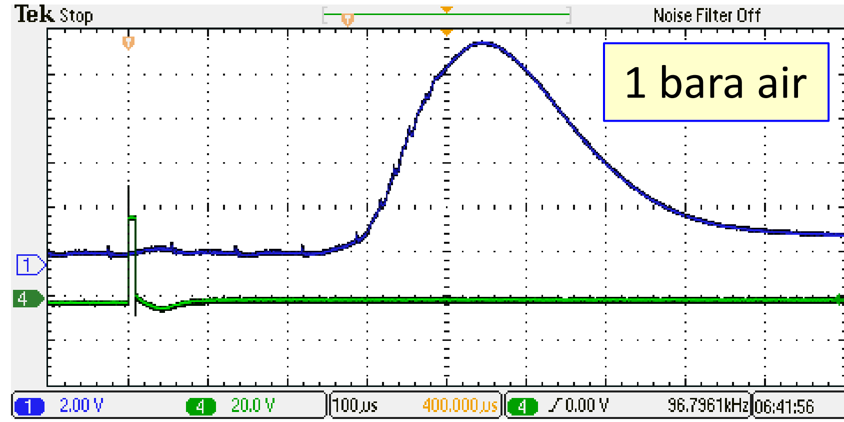
Heaters

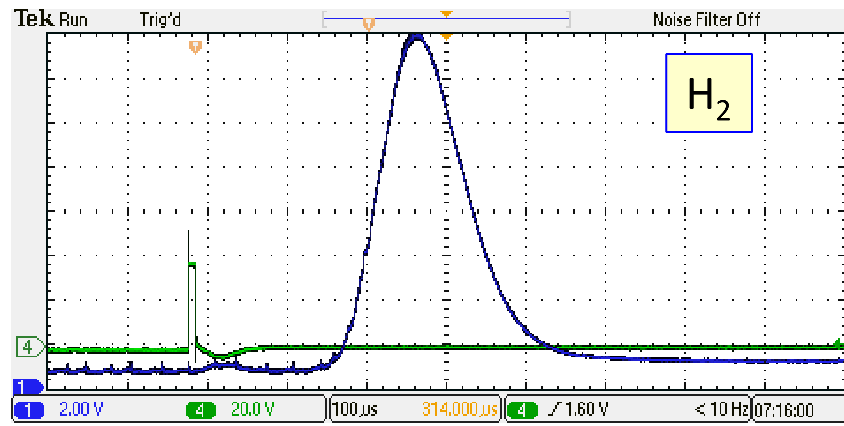
Arc-discharge controller

H_2 feed line pressure regulation

H_2 injection EM-valve Measurement *2011-04*



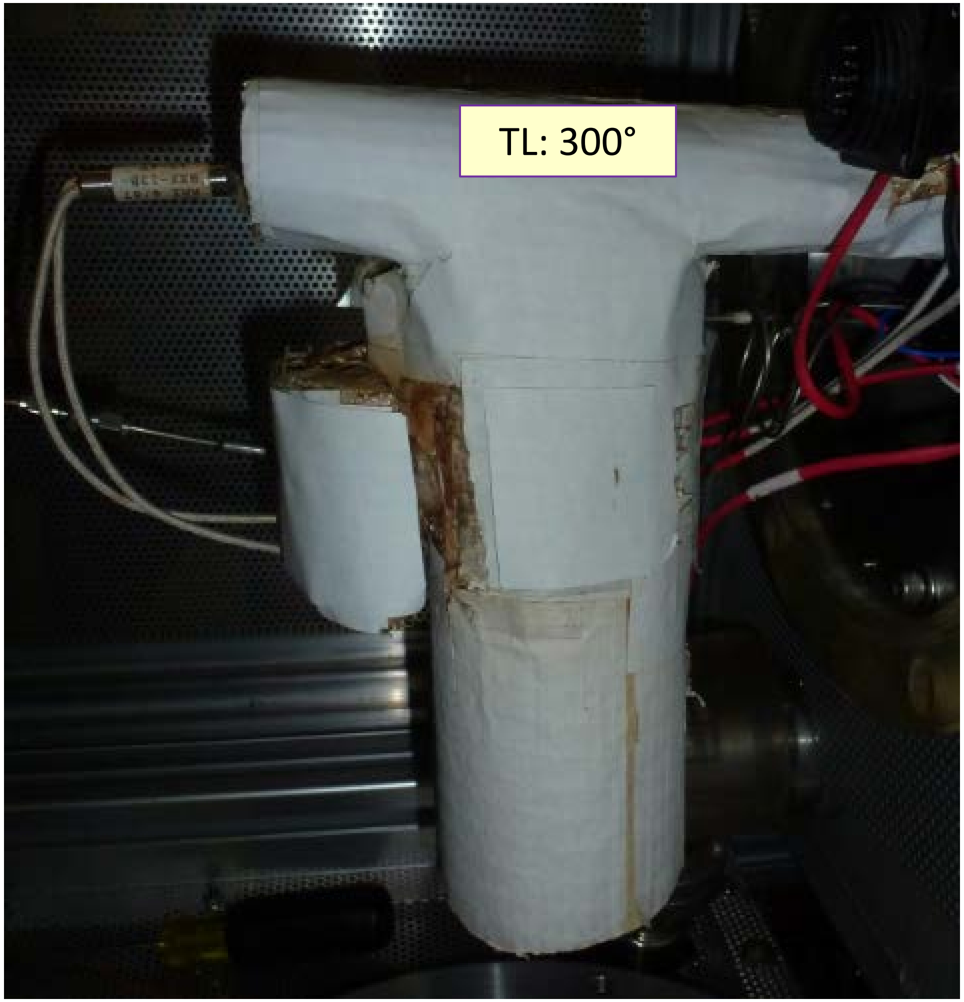


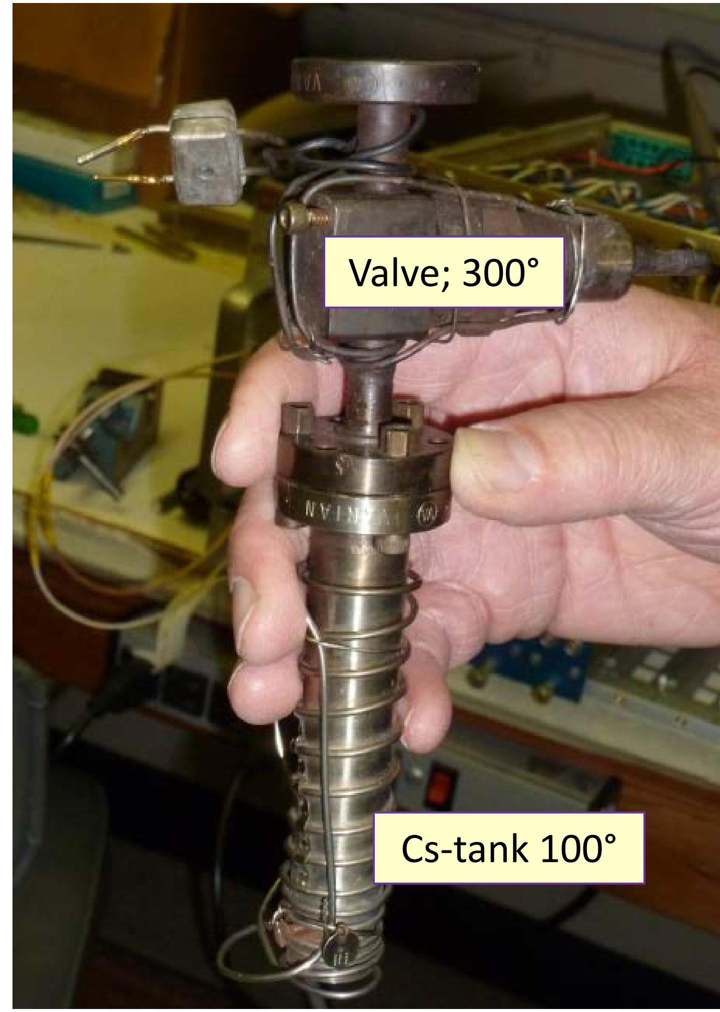


Gauge: **mks** , controller 937A, direct readout via a Tektronix oscilloscope
Control via pulse generator (square function)

Courtesy of J. Alessi, A. Zelensky and G. Aloian

Cs-Oven ^& transfer line



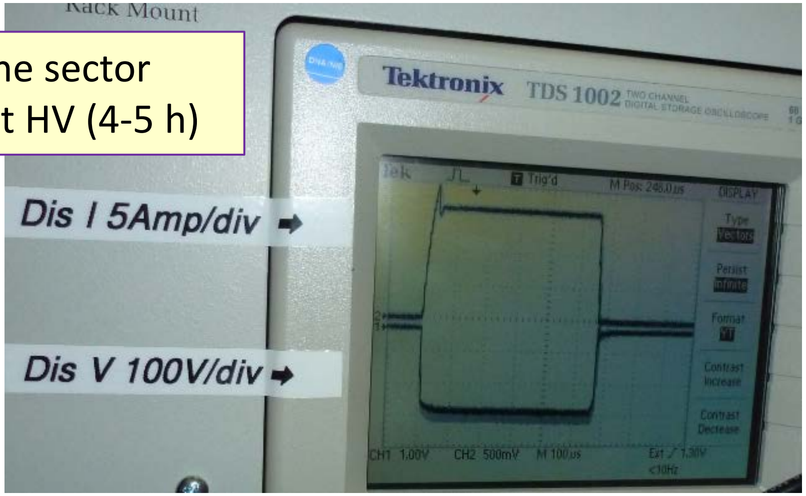


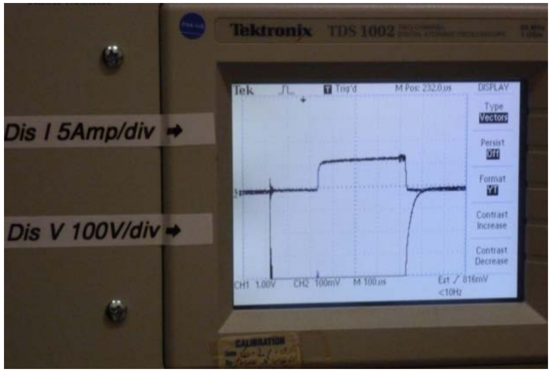
Transfer line Internal resistor heating

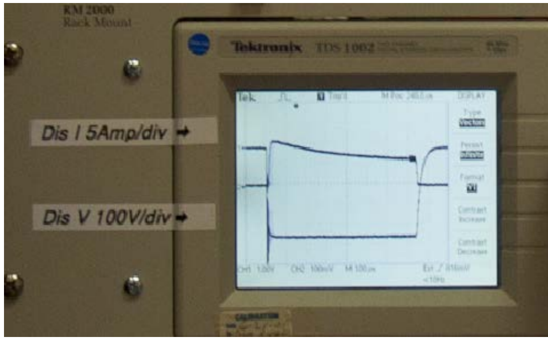
Commissioning of the cesiated Arc-discharge

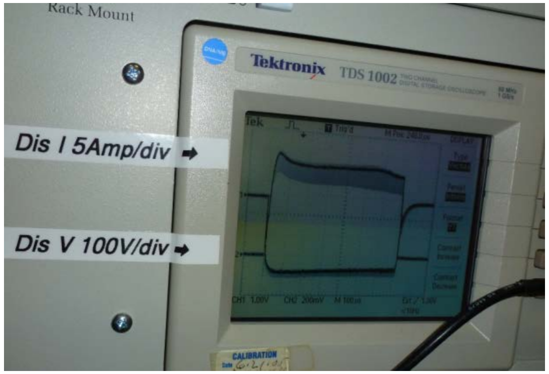
1) BNL team disassembly-reassembly of CERN's Magnetron, connection of BNL's set of permanent magnets, connection of EM H_2 pulser valve, adaptation of W-tip of the puller and e-beam welded bellow HV flange.
2) Pumping down (2200 l/s) source and feed line, heating of Cs-transfer line (300°), start the arc discharge H_2 pulser with excess pressure on gas feed line and enhance capacitive discharge (20-30 V, **15**, +75 +10 μF). Ramp up of the Cs-temperature to 100° then 120°.
3) Wait for cesiation tracked via a reduction of the Arc impedance from high resistance down to typically 10 Ohms (20 A for 200 V). Arc supply in current controlled mode.
4) Reduction of the H2 flow to 15+10 μF, tuning the H2 pulse timing. The arc current is by now only weakly depending on the voltage.

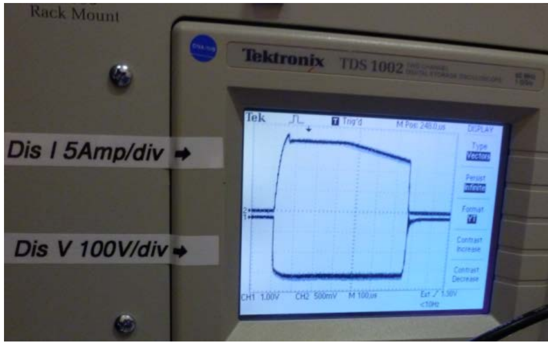
➢ Ready to open the sector valve and to start HV (4-5 h)



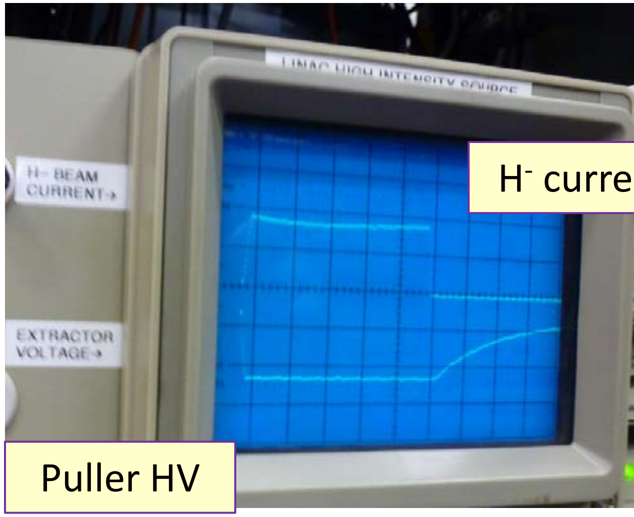


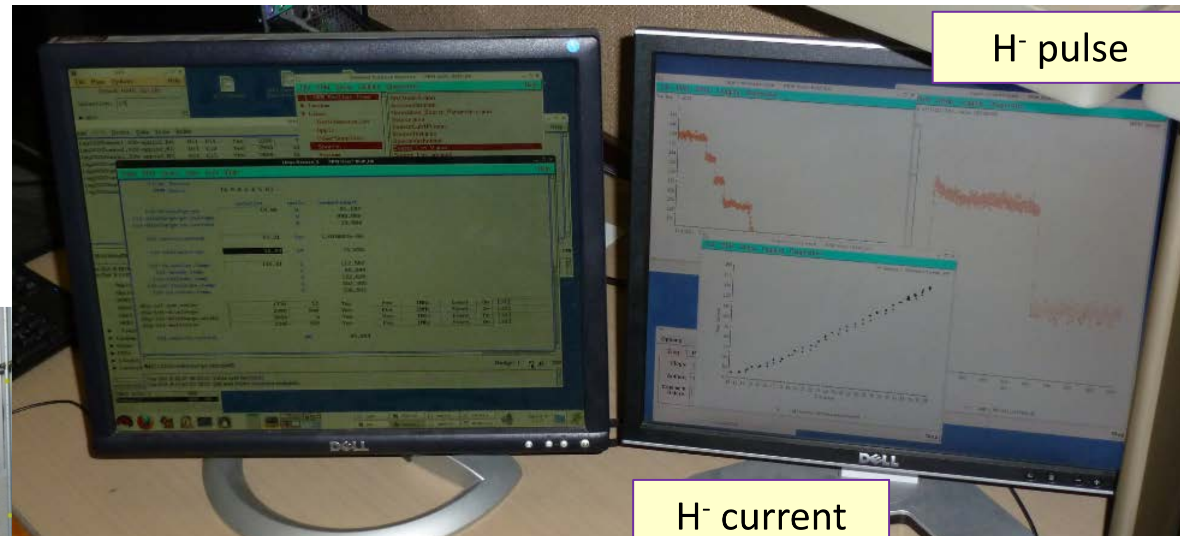






BNL's IS local control room



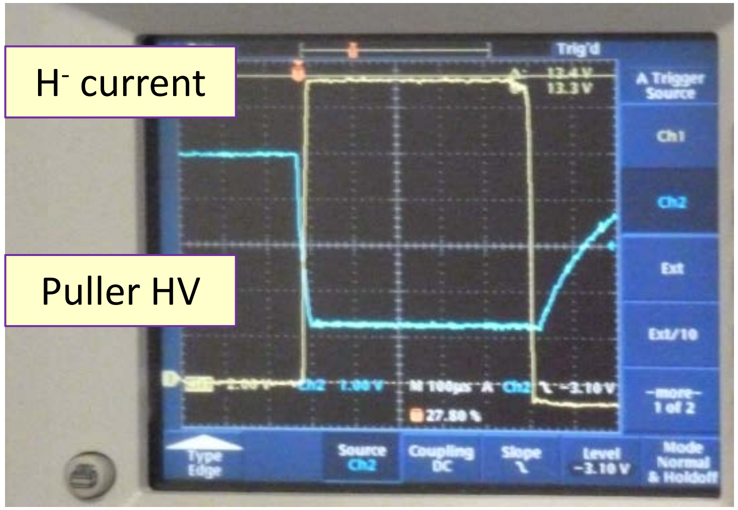


System operational @ 6.6 Hz ☺

Operating at 2 Hz rep. rate

H⁻ current

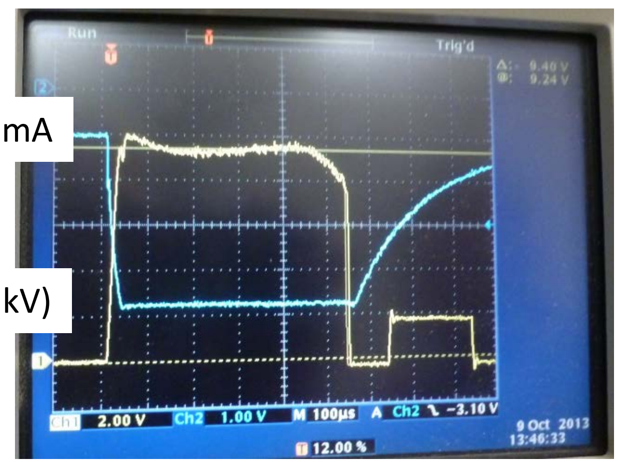
Puller HV



Saturation of the H^- current acquisition ☺

H^- = 145 mA

HV = -38 kV)

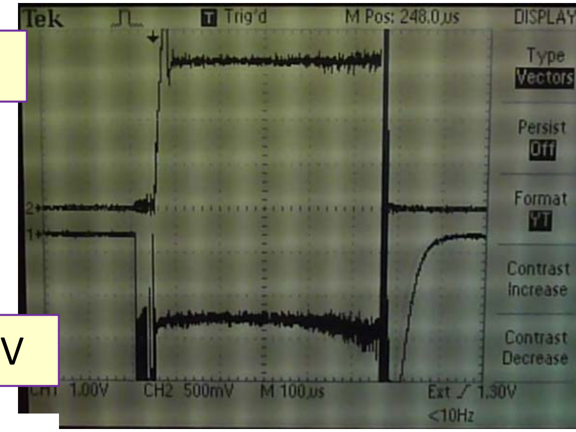


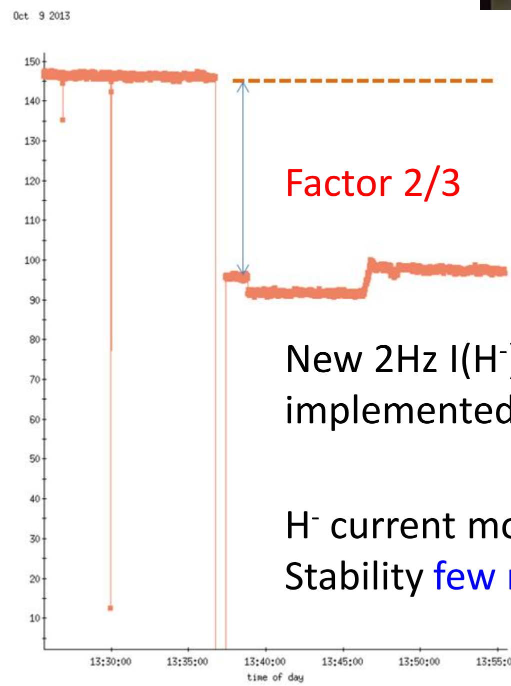
After modification of the H^- current acquisition
from 20 mA/V to 30 mA /V

Arc current 18 A

Z_{Arc} = 10.5 Ω

Arc voltage 190 V





Factor 2/3

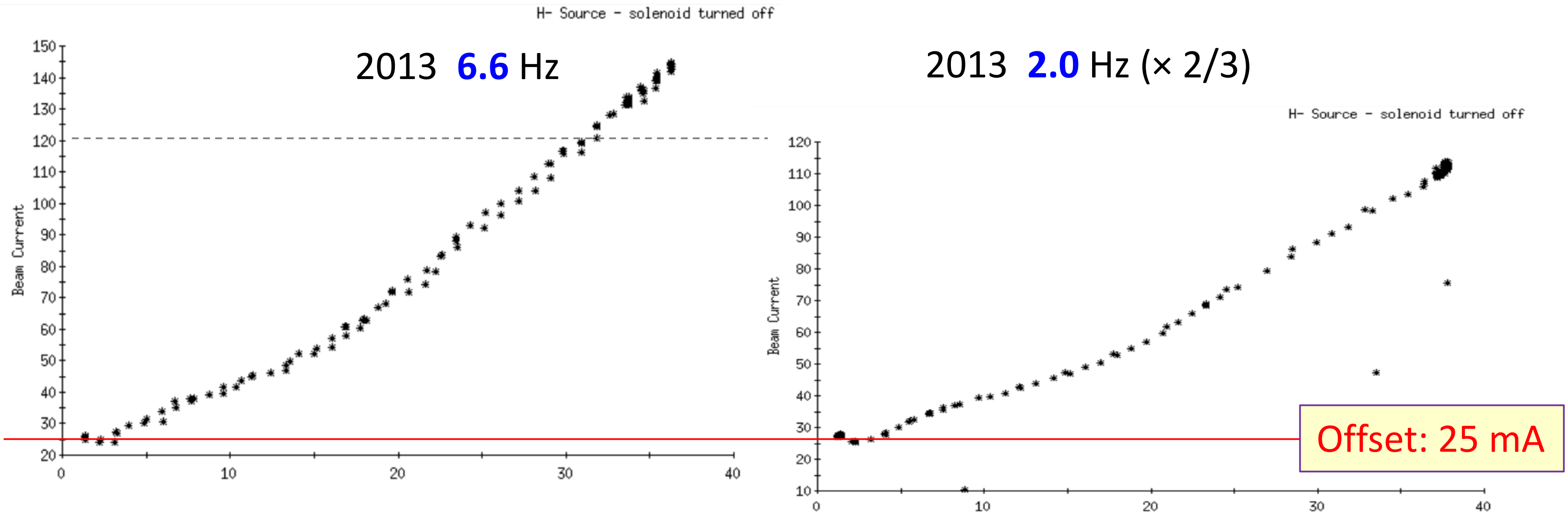
New 2Hz $I(H^-)$ calibration was not implemented in the monitoring log.

H^- current monitoring pulse by pulse
Stability few mA/h (no stabilization time)

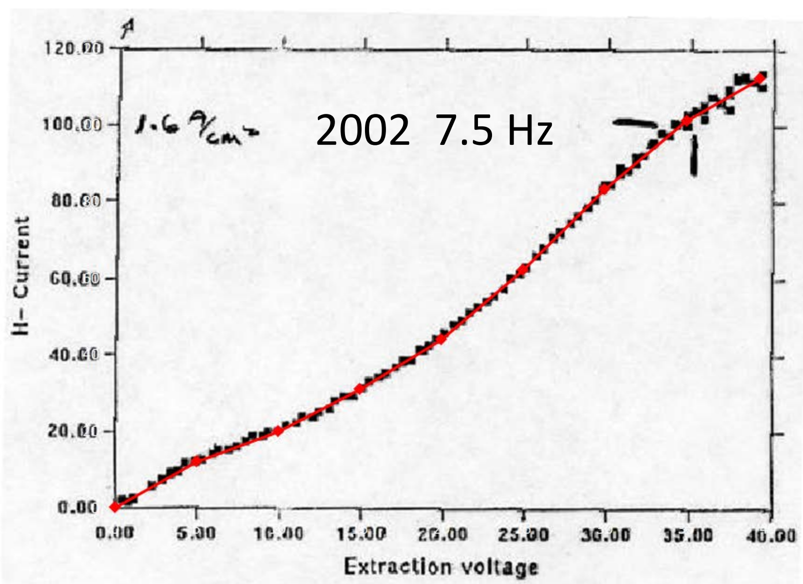
- ✓ T-Oven = 104°
- ✓ $dI(H^-)/dt = O(1)$ mA/h
- ✓ Very responsive to H_2 pressure variation
- ✓ Increase of T-Oven to 130° induces HV sparks
- ✓ Peak H^- current 135mA @ 39.5 kV

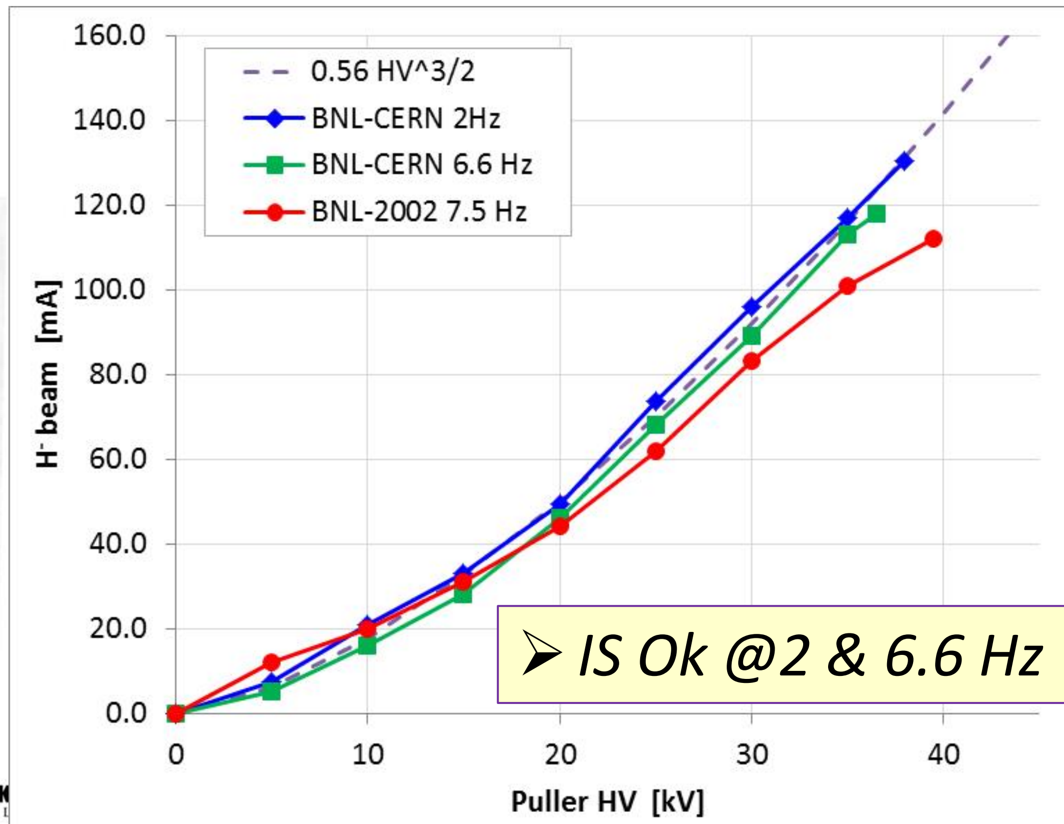
2013 **6.6** Hz

2013 **2.0** Hz (× 2/3)



H^- beam yield





J. Alessi 4/9/02

Cs-Atomic Oven: bright wall collimation model

Magnetron's anode plate

Puller

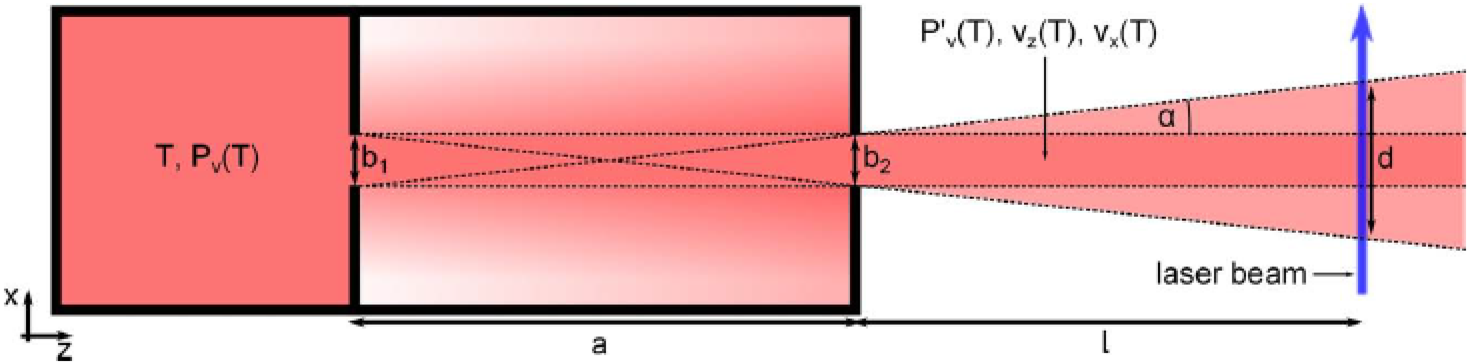


Figure 1.2: Scheme of an effusive oven with aperture 1 of diameter b_1 and aperture 2 at a distance a with diameter b_2. Inside the box, the atoms have temperature T and velocity distribution $P_v(T)$. Only atoms inside the dotted lines contribute to the atomic beam. The beam emerges into a solid angle $\omega = 2\pi(1 - \cos\alpha)$ and has diameter d at a distance l from aperture 2. The atoms in the beam have velocity distribution $P'_v(T)$ and longitudinal and transversal velocity components $v_z(T)$ and $v_x(T, f)$. A laser beam crosses the atomic beam transversal at distance l from aperture 2.

$$f = \left(\frac{b_1/2 + b_2/2}{a}\right)$$

$$d = 2\left((a + l)\,f - \frac{b_1}{2}\right)$$

Assumption 20% of all Cesium travels through the puller

- O(1) g/y through the puller (and into the LEBT)
- O(25) mg/y into the RFQ (20 mm diam.at 2.3m dist.)

Master thesis J. Schindler Uni. Innsbruck, July 2011

Cs Vapour pressure

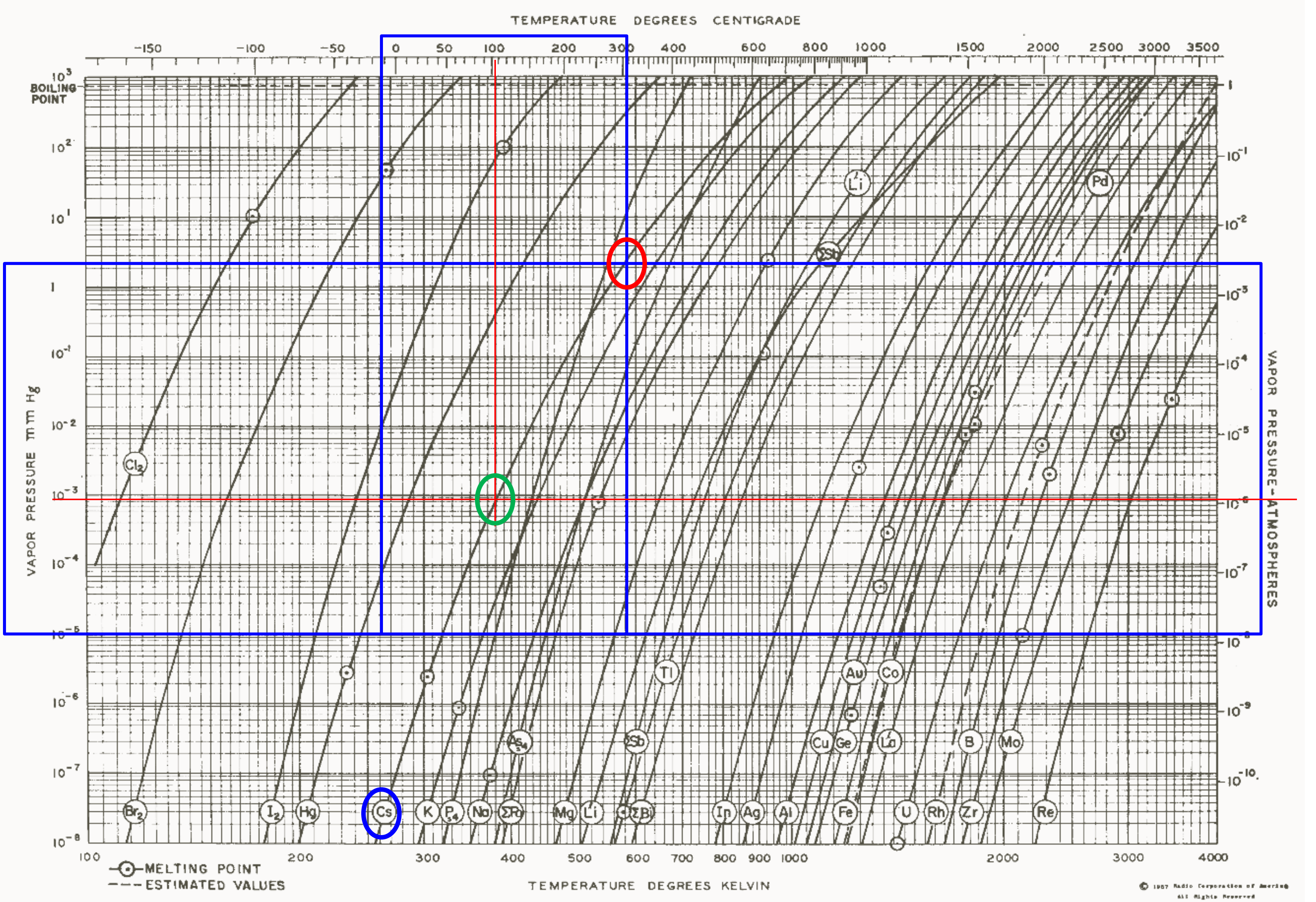


Figure A1(a). Vapor pressure curves for the more common elements. After Honig (Ref. 5:14). (*Courtesy RCA*

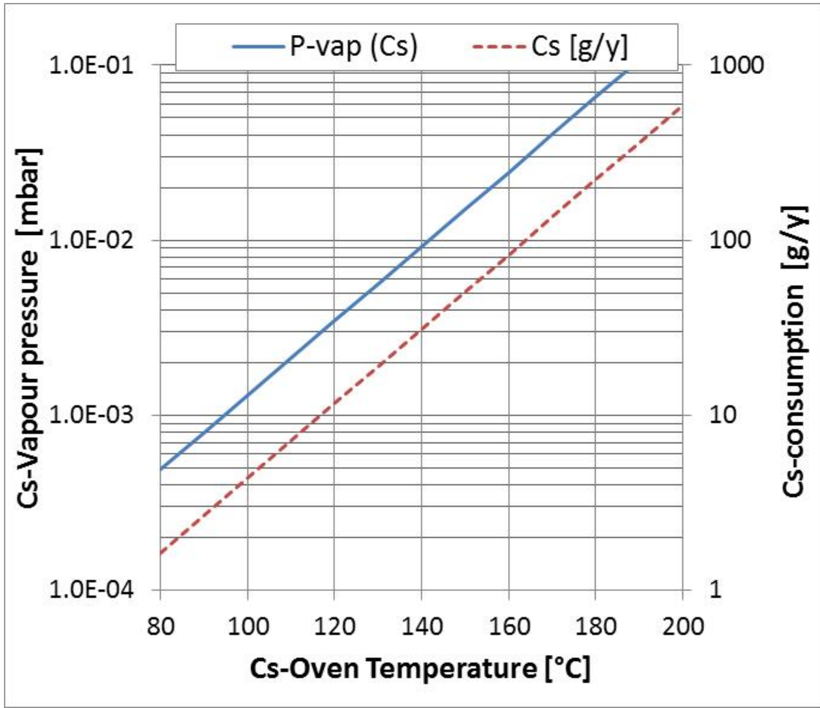
Cesium

- Yearly consumption for a Cs-oven temperature of 100 °C: 4.5 g/year
- Vapour pressure gradient at T_0 = 100° : $dp/p_0/dT$= 1 decade / 47°
- Emission form an atomic oven → O(25) mg/year in the RFQ & 1g/y into LEBT
- Negligible interaction of ^{133}Cs-atoms $_{(T\text{-cathode})}$, r_{Cs}=2.60 Å with the $H_{2\ (room\ temp.)}$, d_{H_2}=0.74 Å
  – Rest gas in the LEBT: mean free path (p_0) ~100 m at 1e-6 mbar

But: "*Cs never seen beyond the extraction electrode*" *at BNL*
→ BNL's magnetron does not behave as a Cs-atomic Oven

Cs-related Risk scenarios:

- Impact of steady state Cs-flux on RFQ operation not fully clarified; likely increase of e-emission due to lowering of cesiated surface work function
- Maintenance of cesiated inner-surface of vacuum components
- Operation of cesiated beam diagnostics (grids)
- Cs-Oven overheating (*Worst case 300°* → Cs×1000)
  - → Conditioning of the source with closed LEBT valve
  - → Limitation of Cs-Oven heating to 130°
  - → Single bending or dog legged bend in the LEBT or tilted source (> increased emittance)
  - → Condensation of Cs-vapour



BNL Test of CERN's Magnetron: Summary

		Typ. BNL 2002		CERN-BNL test	
		min	max		
H- current	mA	90	100	120	130
current density	A/cm^2	1.6		1.52	1.64
Extraction	kV	35		38	39
RMS emittance	π mm·mrad	0.4			
e/H		0.5	1	*0.75*	*0.75*
e-current	mA	45	100	*90*	*98*
Puller current:	mA	135	200	*210*	*228*
Arc voltage	V	140	160	190	190
Arc current	A	8	18	18	18
Plasma impedence	Ω	17.5	8.9	10.6	10.6
Arc power	kW	1.1	2.5	3.42	3.42
Rep. rate	Hz	7.5		6.6	2
Pulse width	μs	700		700	700
Duty factor		0.53%		0.46%	0.14%
Av. Arc-power	W	5.8	13.1	15.8	4.8
T(Cs-Oven)	°C	90	100		110-120
Cs-Vapour pressure	mbar	8.0E-04	1.0E-03		*2.1-35 E-3*
Cs consumption	mg/hr	0.5			
	g/y	4.38			*7.1-11.7*
Gas flow	sccm	2		*2*	*0.7*
Pressure				1.50E-06	7.00E-07

Linac4 specification:

80 mA within 0.25 π mm·mrad

- Meas. of emittance @45 kV
- Beam intensity tuning via extraction voltage

- 45 kV pulsed transformer designed for 200 mA. Low energy e-dumping not realistic ?
- Measurement of e/H

- T-controlled cathode ?

Low temperature Cs-Oven operation would be an asset:

- Measurement of Cs-flow
- T-controlled magnetron's body
- Tilted source + Cs-condenser

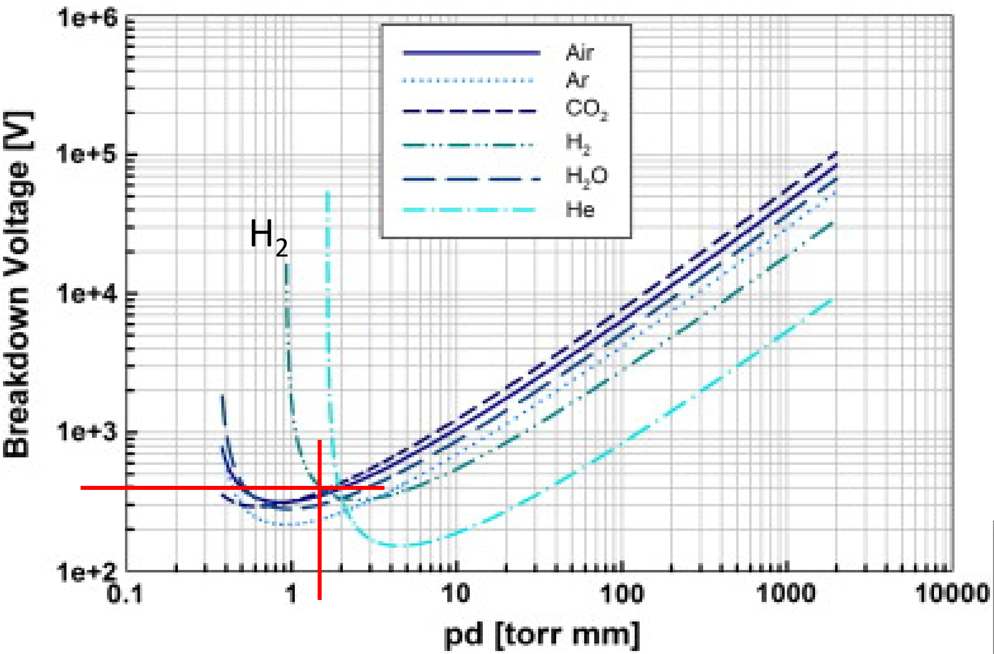
Magnetrons with heated anode body

- Avoiding a cold spot at the end of the Cs path: Improved start-up time
- Potential impact of the warm anode body to be assessed:
  - Reduction of overall Cs-consumption
  - Reduction of the necessary arc discharge current
  - Operation at 0.8 Hz

Mo-Cathode: Thermocouple location

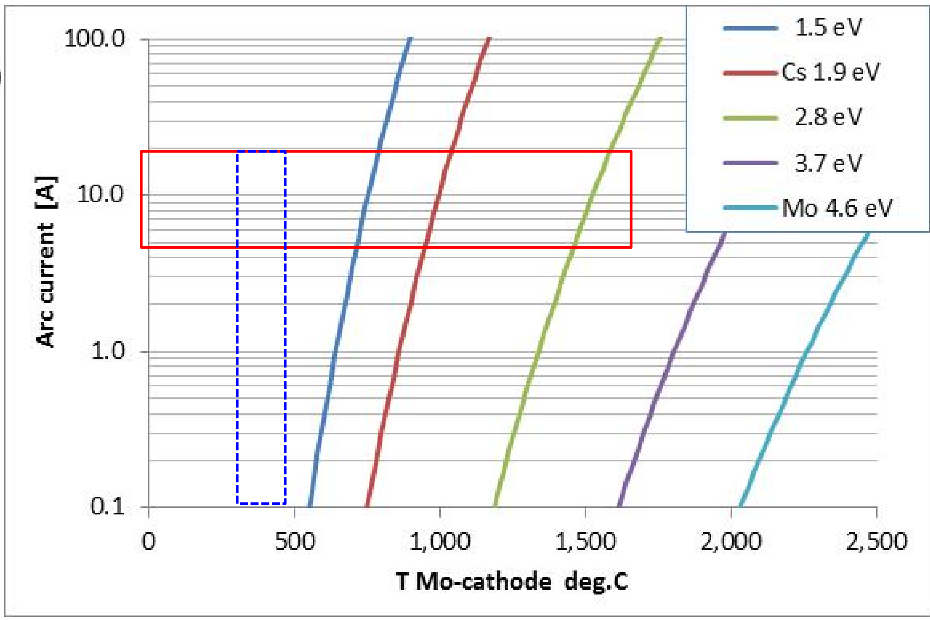
Direct cathode heating to compensate low rep rate heating ?

Paschen discharge, e-emission, arc impedance



Arc impedance min: 10.5 Ohm
Arc power 3.4 kW
Av. conductivity: 0.15 S/m
Arc electron density of 10^{18} m^{-3},

Richardson current (Temp., Work fct.) extracted from the cesiated Mo cathode:

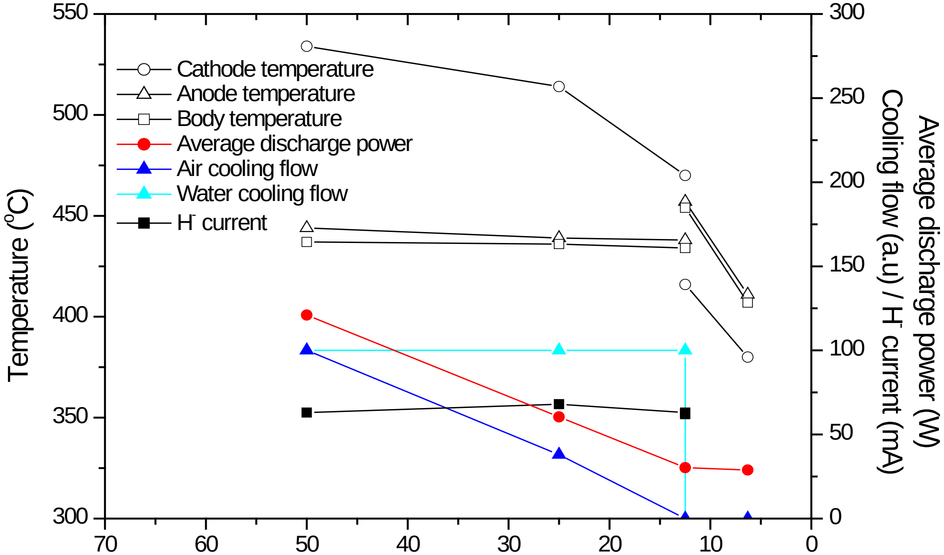


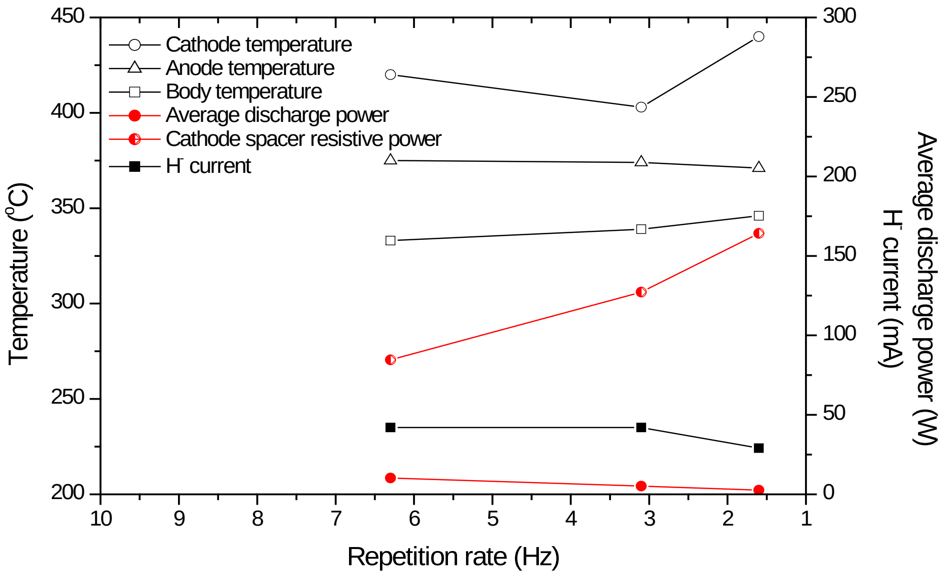
$U_{discharge}$ < 400V, d = 1 mm
→ $p(H_2)$ > 2 mbar, U_{min} = 320V
In clean H2, No Paschen discharge below 300 V

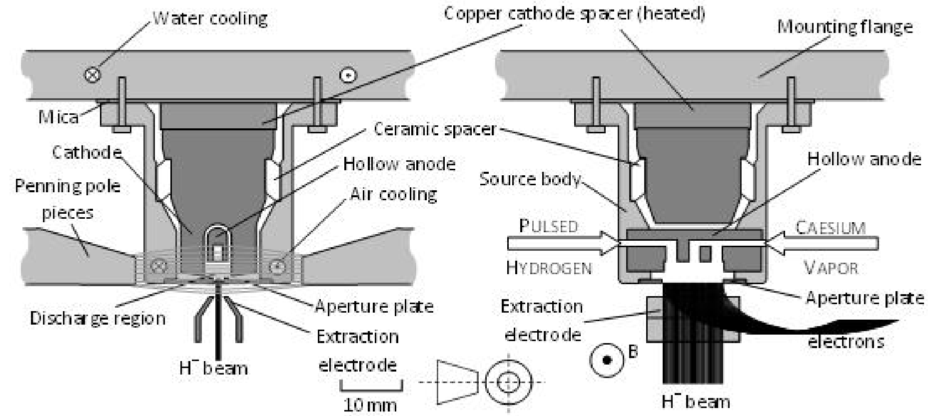
An estimation of the H_2 and Cs partial pressure and cesiated surface temperature in the arc region would be interesting.

AIP Conference Proceedings 111, 398 (1984); doi: 10.1063/1.34438
R. Witkover T-cathode bulk = ~**380 °**

ISIS Penning H^- IS, ageing and 2Hz operation

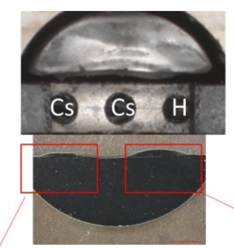




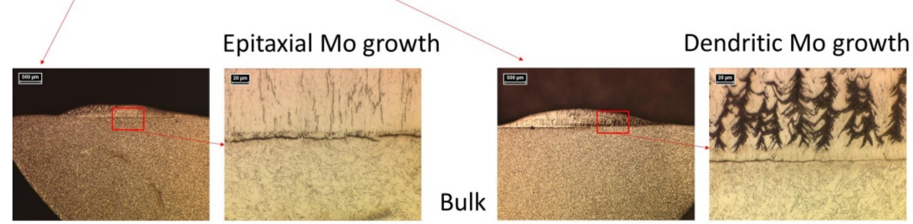


Results:

- Once equipped with and additional heating circuit (mandatory below 12 Hz) the ISIS penning IS operates at 2Hz.



- Cs^+,H^+ Sputtered Mo growth in a brittle layer on Mo-cathode.



1) J. Lettry, J. Alessi, D. Faircloth, A. Gerardin, T. Kalvas, H. Pereira, and S. Sgobba, Investigation of ISIS and BNL ion source electrodes after extended operation, Review of Scientific Instruments 83, 02A728 (2012).
2) H. Pereira, D. Faircloth and J. Lettry, *Operation and thermal modeling of the ISIS H- source from 50 to 2 Hz repetition rates, AIP Conf. Proc.* 1515 (2013) pp.114-120.

Conclusion, outlook: BNL's Magnetron as Linac4 IS-03

2Hz duty cycle : Operation at 2 Hz already demonstrated, discharge commissioning at higher repetition rate (6-10 Hz), additional heating is an asset to start the ion source, it may be beneficial to limit the Cs-flow

- 0.8 Hz operation via 1 pulse out of 3
- ISIS operation at 1.6 Hz demonstrated, R&D more in T-control less in Cs-handling

Operation at 45 kV: Beam optics mandatory for Electrons and H^-,

Ageing: Marginal increase of the sputtering anticipated for Cs^+ or H^+ ions. Tracking of e-beam-power surface density mandatory

Emittance: Measurement at 45 kV mandatory, ~0.5 π·mm·mrad expected

H^- intensity: O(100) mA anticipated with O(80%) transmission through the RFQ.

H_2 injection: New valve and comparative measurement mandatory,

Arc discharge power supply: Achievable by the TE-team, 2015 ?

Design and production: New flange and external ceramic insulator required.

Cs-flow: Direct view to the RFQ for atomic beam between pulses, measurement required to confirm estimation of O(25) mg/y or clarify suppression mechanism.

Magnetron at CERN: No show stopper but mandatory 6 month testing the magnetron at the IS-test-stand prior to decision of operation. Design of a Cs-trap + tilted source or dog legged LEBT mandatory.

BNL's Off-line test stand could be refurbished for Magnetron R&D

The support from J. Alessi, T. Lehn, A. Zelenski, J. Ritter, D, Faircloth and the BNL & ISIS ion source development teams is thankfully acknowledged

BNL: Nice place, Nice people, Thanks a lot to the ion source specialist team

IS03 WP summary

Remaining tasks towards testing the magnetron at the Linac4 IS –test stand

- Design an Arc discharge power supply and produce 3u + spare parts (TE)
- H_2 pulsed injection valve, (BE)
- Calculate Beam optics protecting the RFQ from IS's Cs-flux (BE)
- Design and produce support flange, Cs-condenser and tilted extraction, (EN)
- Design and produce Ceramics insulator (EN)
- Emittance measurement. (BE)
- Learning phase on operation + >6 month measurement at the test stand

Resources: 3 FTE + 100k CHF