35 years of H- ions at Fermilab

NIBS 2012

3rd International Symposium on Negat

3-7 September 2012, Jyv

Outline:

- How we got here
- Where we are
- Where we are headed

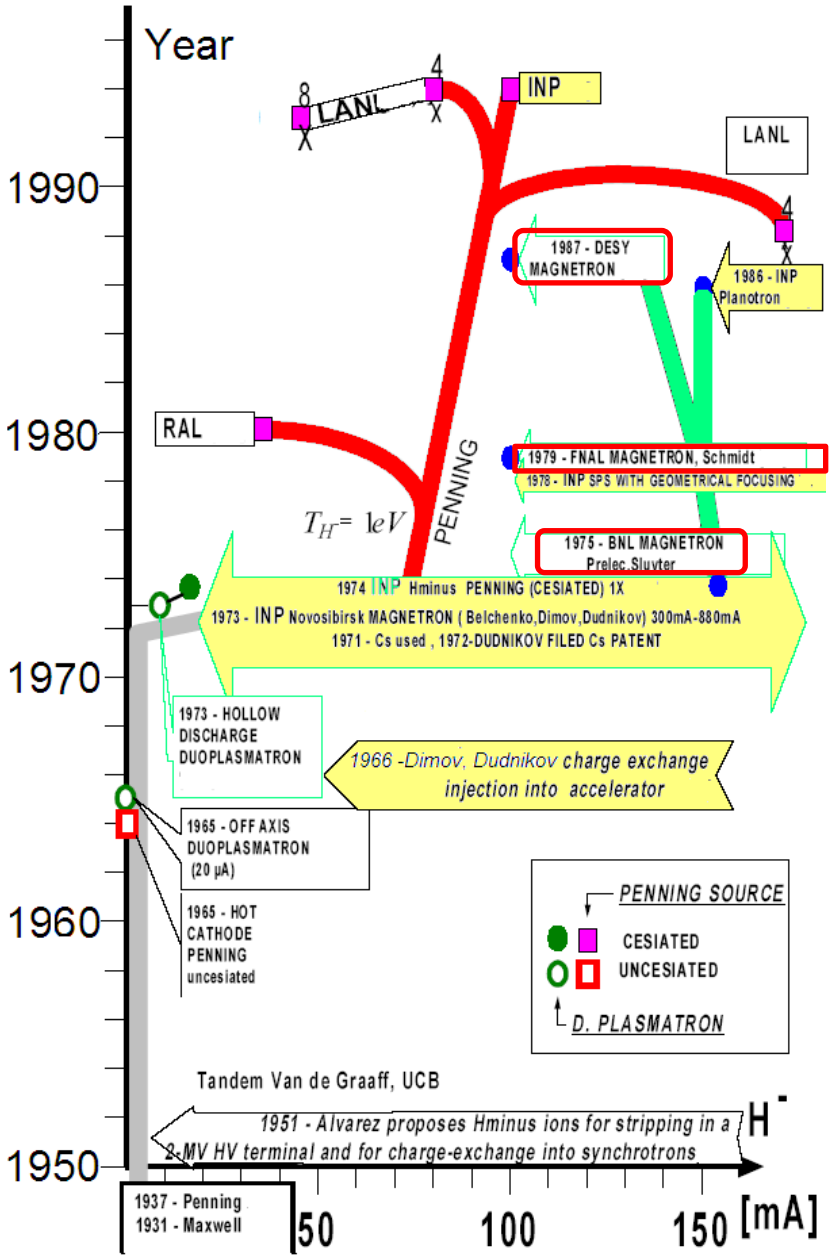
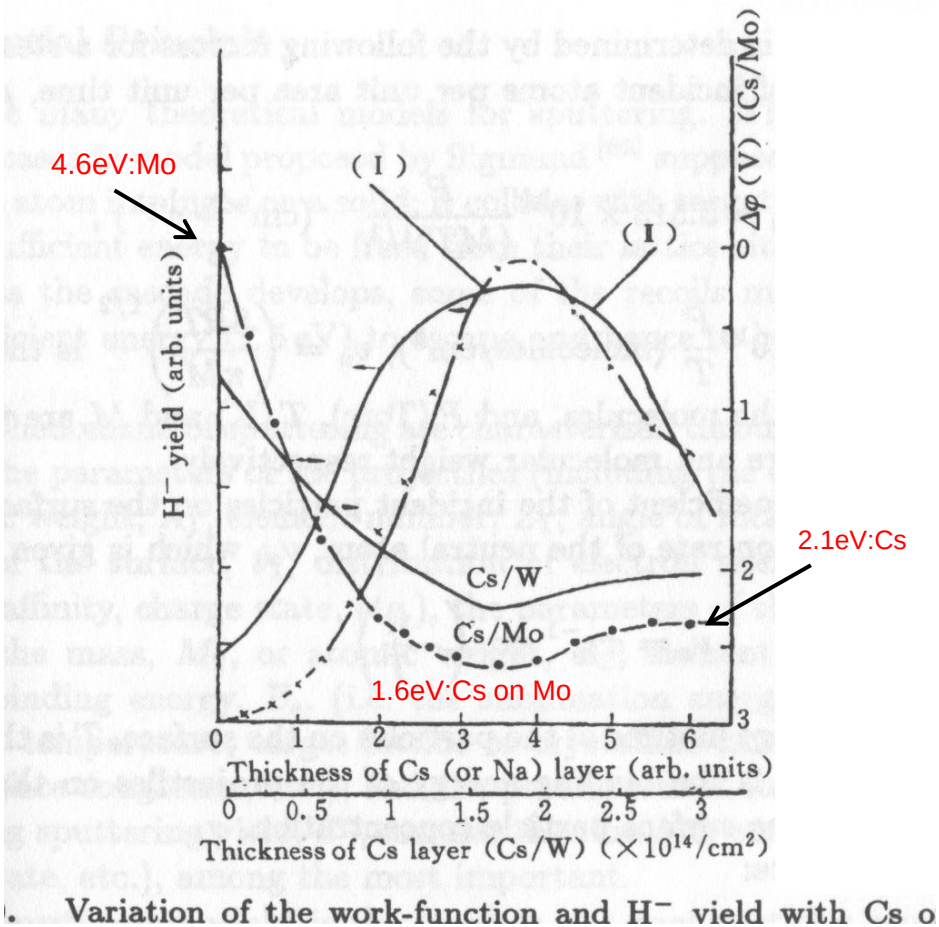


Figure: V.Dudnikov

Surface production of ions



Variation of the work-function and H^- yield with Cs o

- Metals have an abundance of loosely bound electrons, for molybdenum it takes 4.6eV to removed an electron.
- Cesium has a work function of 2.1eV, but can lower the surface work function of molybdenum to 1.6eV with a 0.6 monolayer.
- Since the work function exceeds the electron affinity of hydrogen atoms, a majority of hydrogen particles leave the surface as neutrals. However a few will pick up an excess electron when leaving the surface.
- Some of these H- ions will make their way though the plasma to the anode and be extracted.

Zhang: Ion Sources

Magnetron sources

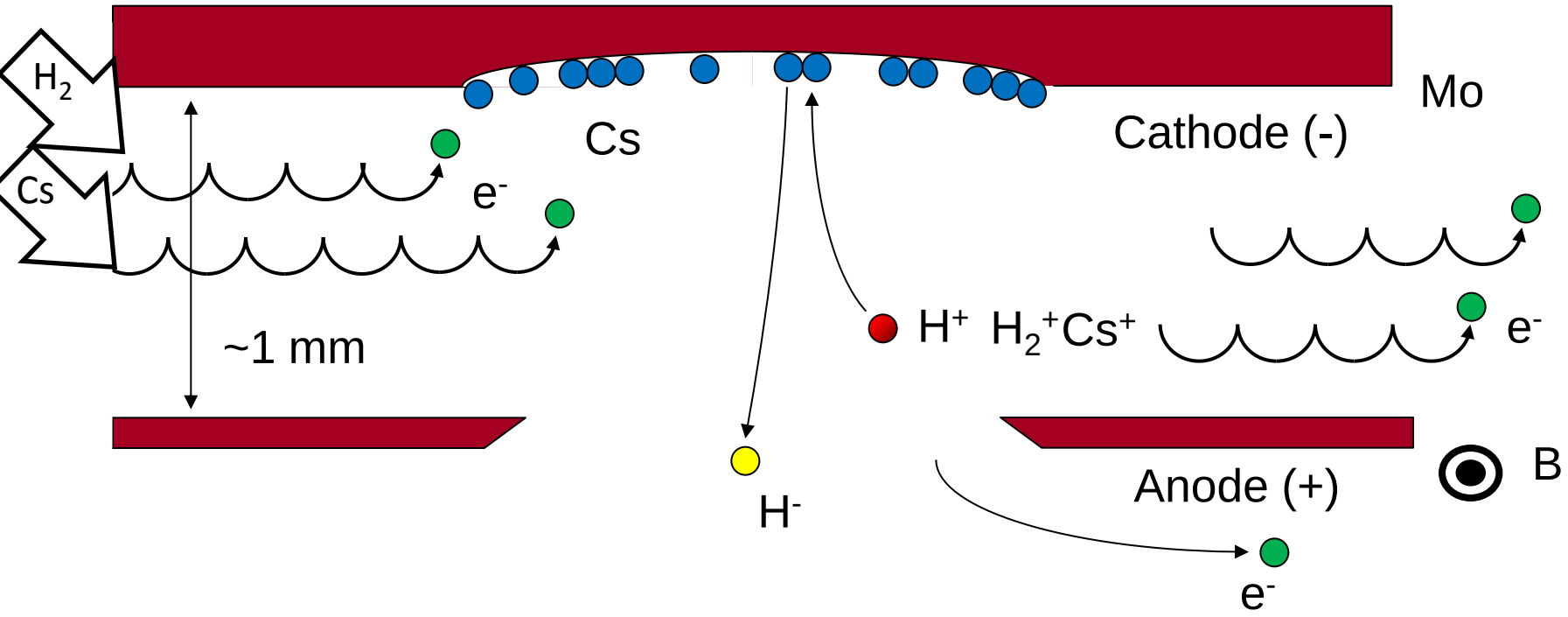


Figure: Martin Stockli

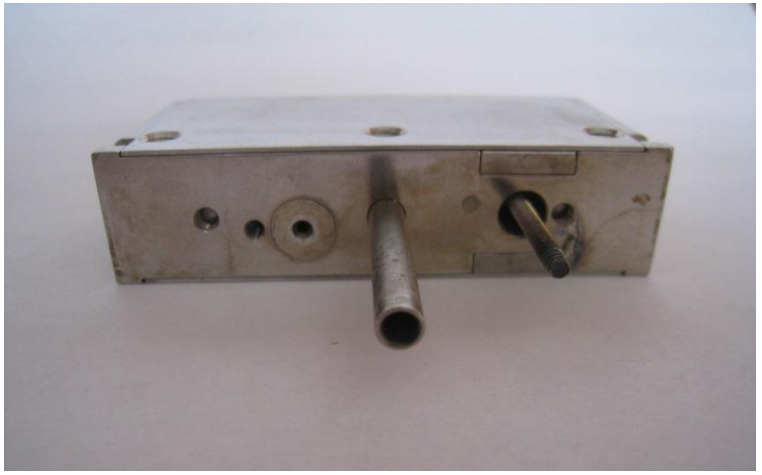
- In gas discharge plasma positive hydrogen and cesium ions are formed
- These ions are accelerated toward the cathode
- Some of the ions that strike the surface have enough energy to "bounce" off the surface, and some small number of those leave the surface as H- ions.

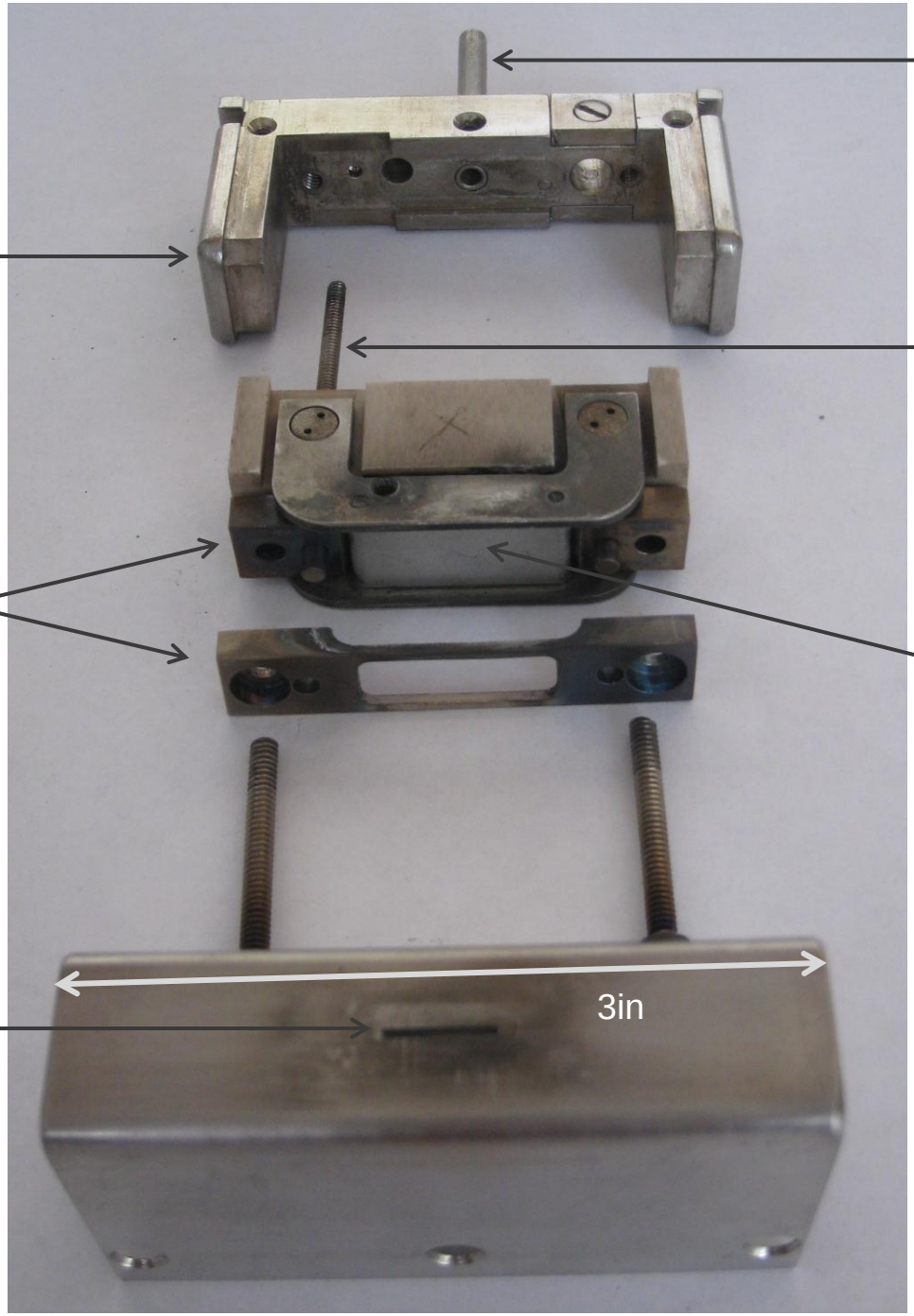
Plasma parameters

$n_{H2} \sim 10^{16}$ cm^{-3}
$n_e \sim 10^{13}$-10^{14} cm^{-3}
Te ~ 1eV / 15 eV

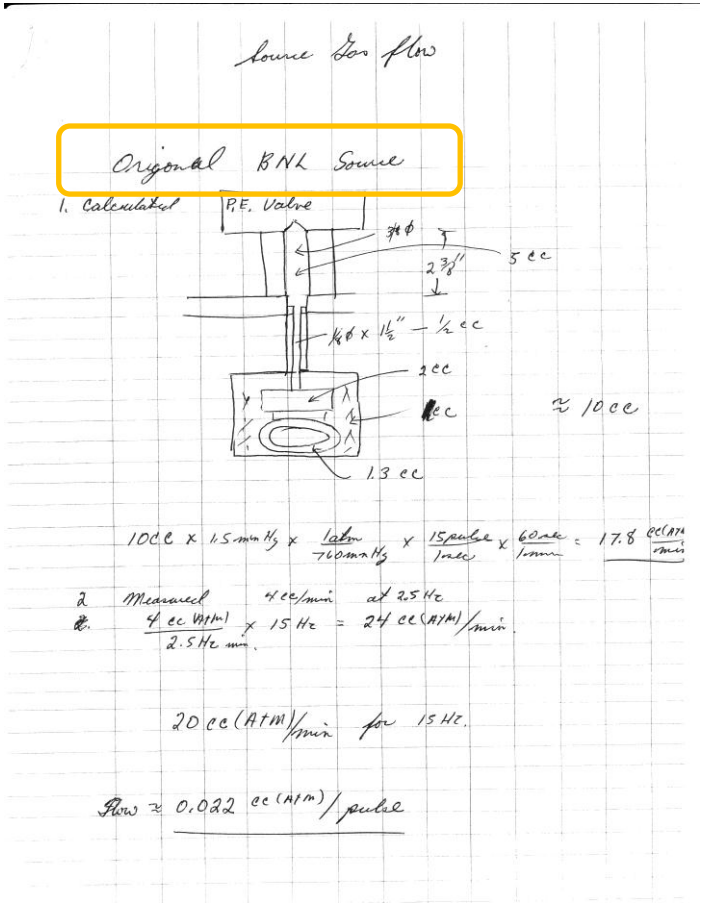
Prototype magnetron H- ion source bought by FNAL for $40k from Brookhaven in the late 70's

- This source was designed for fusion research
- Low current DC source
- Large gas volume (important later on)
- Used Cs pellets to enhance H- production



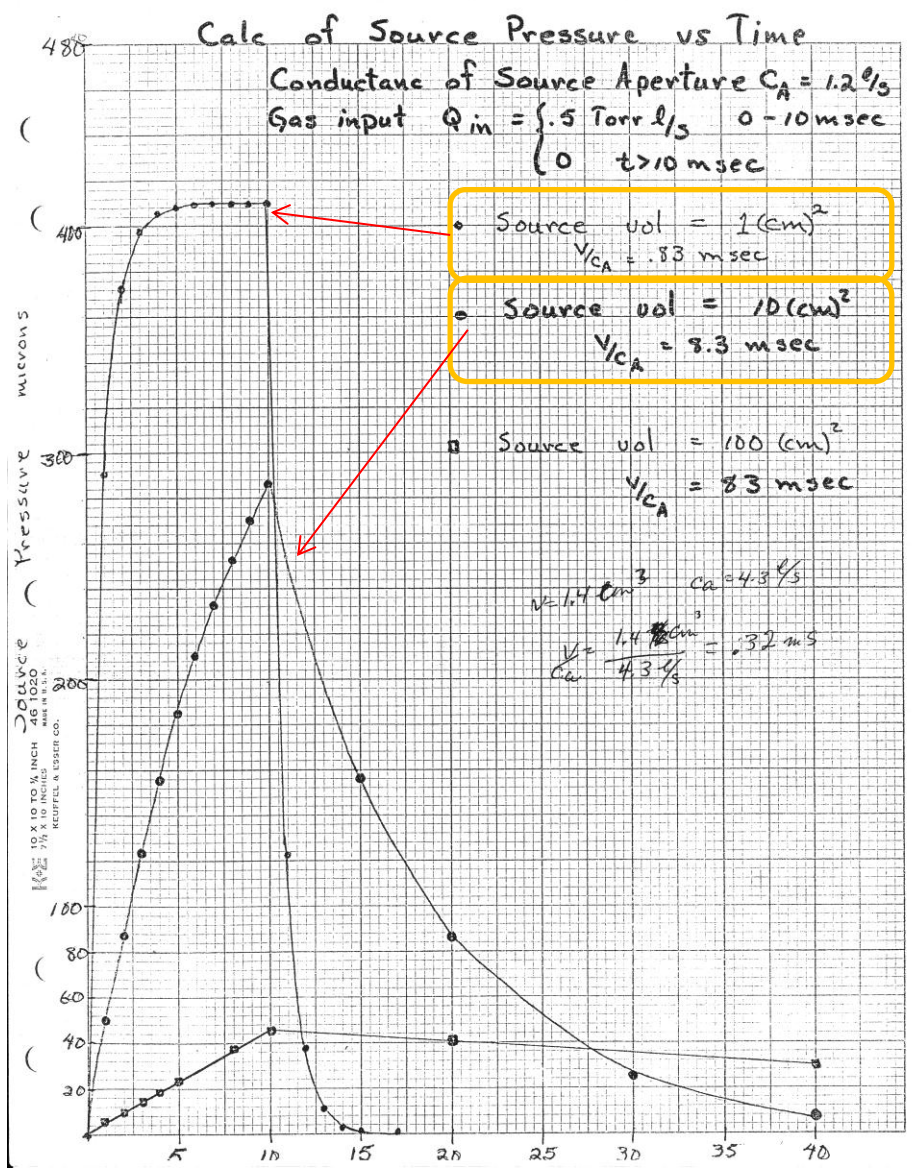

Hydrogen inlet
Source Body
Cathode connection
Anode
Cathode
Anode cover plate (extraction aperture)
3in

BNL source was installed in bell jar and tested at 15Hz



Interesting side note early test were done using cesium chromate and titanium powder to make cesium tablets that were inserted into the cathode

Chuck Schmidt chose the new source volume based on source pressure.



The fill time of the BNL source was 8.3ms and it did not reach high enough pressure for plasma to form at 15Hz reprate.

FNAL Source
Operating at 15 Hz

1. Ion pump pressure 6×10^{-6} mmHg) 5000 ℓ/sec

$5000\,\ell/sec \times 6\times10^{-6}\,mmHg \times \frac{1\,atm}{760\,mmHg} \times \frac{60\,sec}{1\,min} \times \frac{10^3\,cc}{1\,\ell}$

$= 2.4$ cc (ATM)/min

2. Observed on bell jar stand
Flow of ≈ 3 cc (ATM)/min ± at 15 Hz

3. Calculated. Vol = 1.4 cm³ at 15 Hz.

$1.4\,cc \times 1.5\,mmHg \times \frac{1\,atm}{760\,mmHg} \times \frac{15\,pulse}{1\,sec} \times \frac{60\,sec}{1\,min} = 2.5\,cc^{(ATM)}/min$

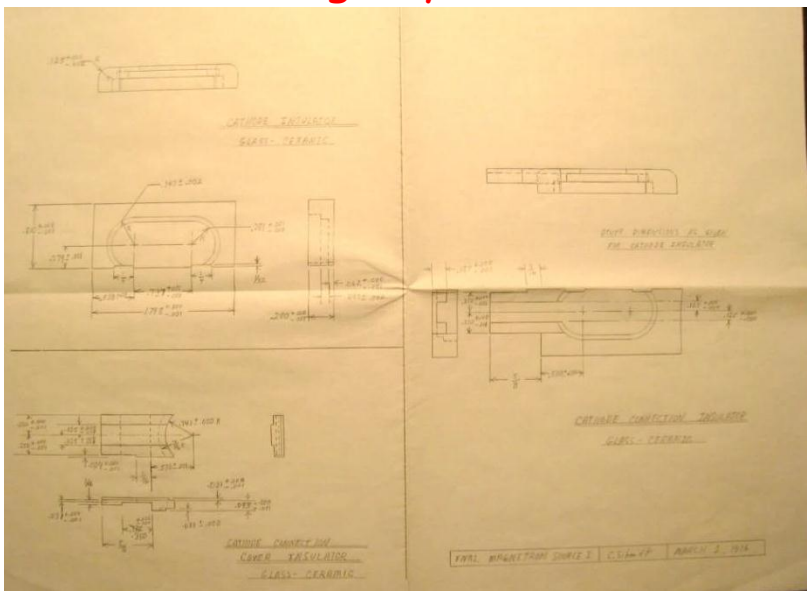
Flow ≈ 0.0028 cc(ATM)/pulse

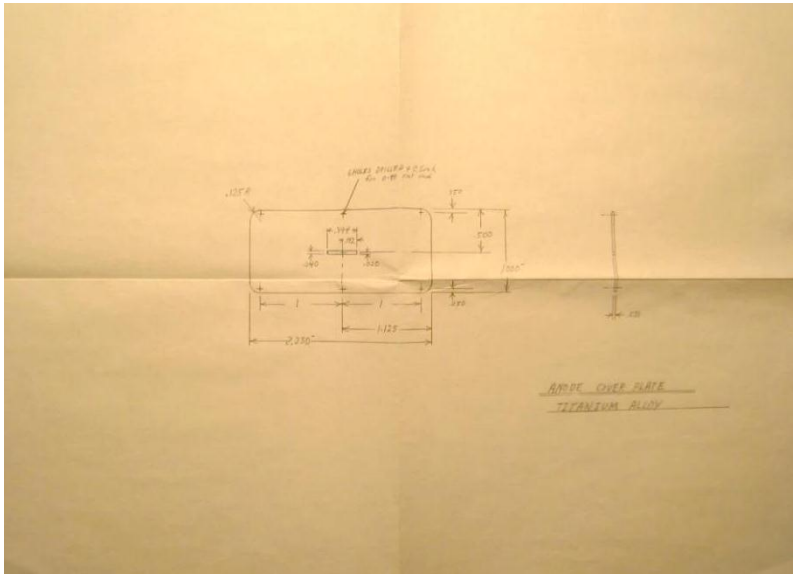
2.5 cc ATM/min = .0317 Tℓ/sec

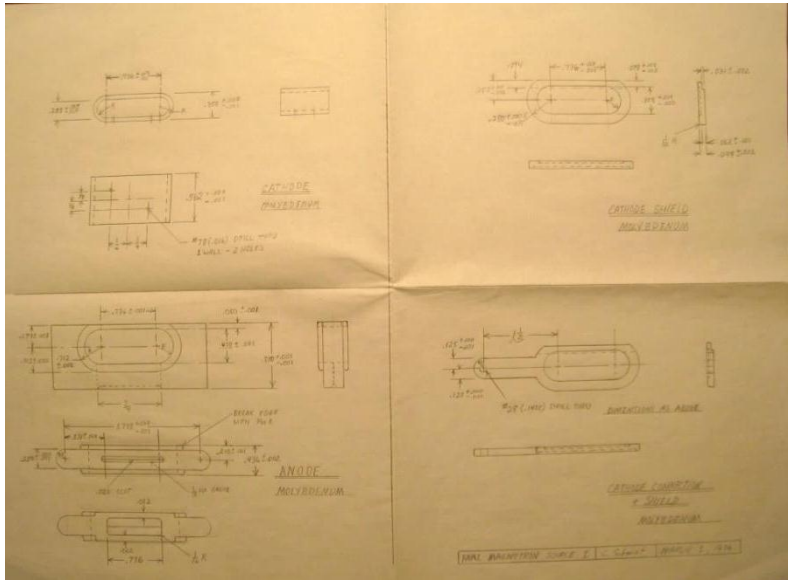
3 cc ATM/min = 0.038 Tℓ/sec

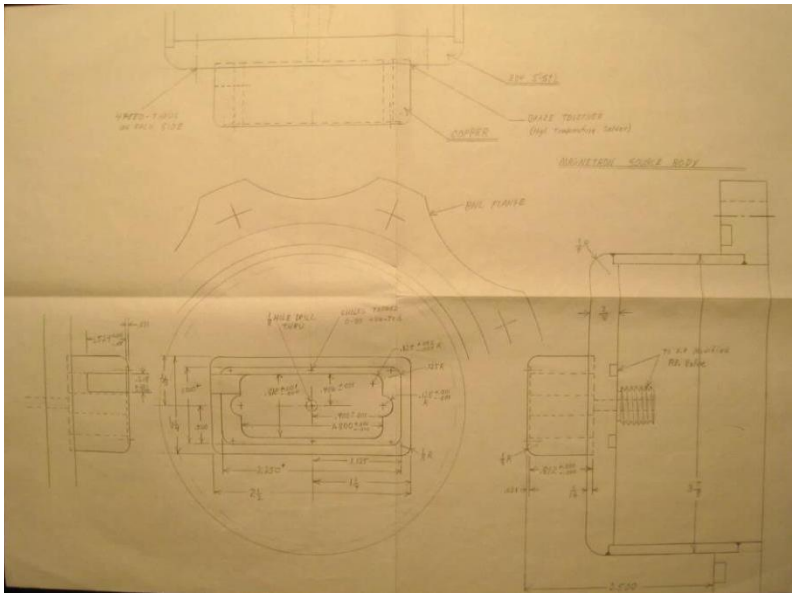
Original source drawings done on CW Schmidt's kitchen table in 1976

Clever design by Chuck Schmidt reduced internal volume by a factor of 10 !



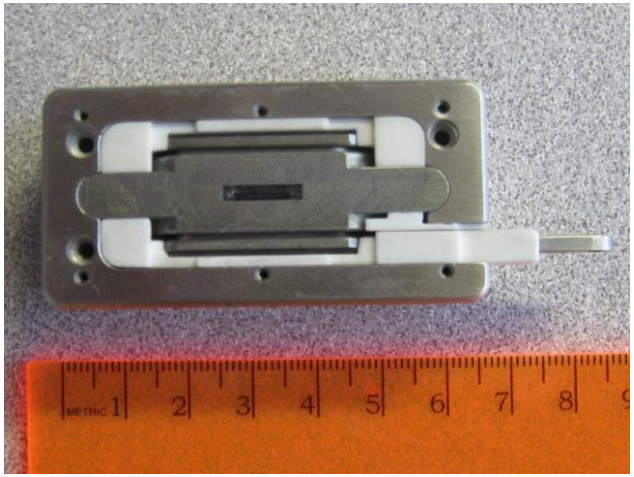


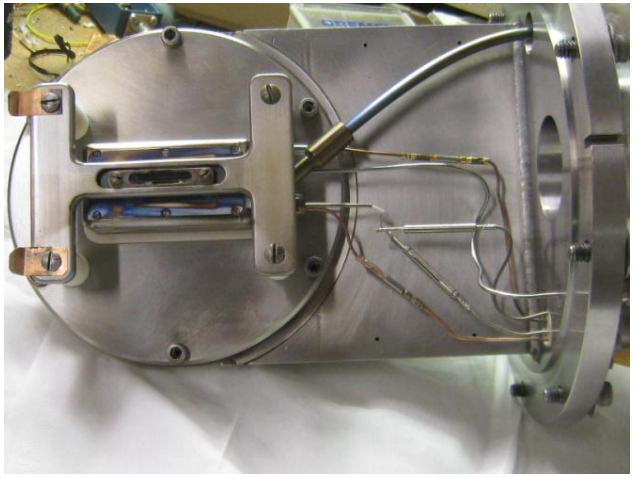


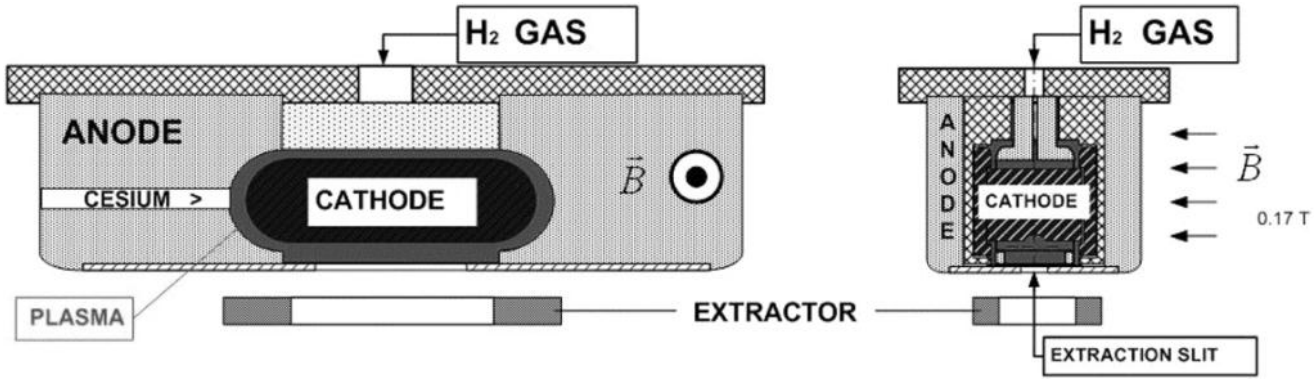


Chuck's source that was used in the Cockcroft-Walton accelerators:

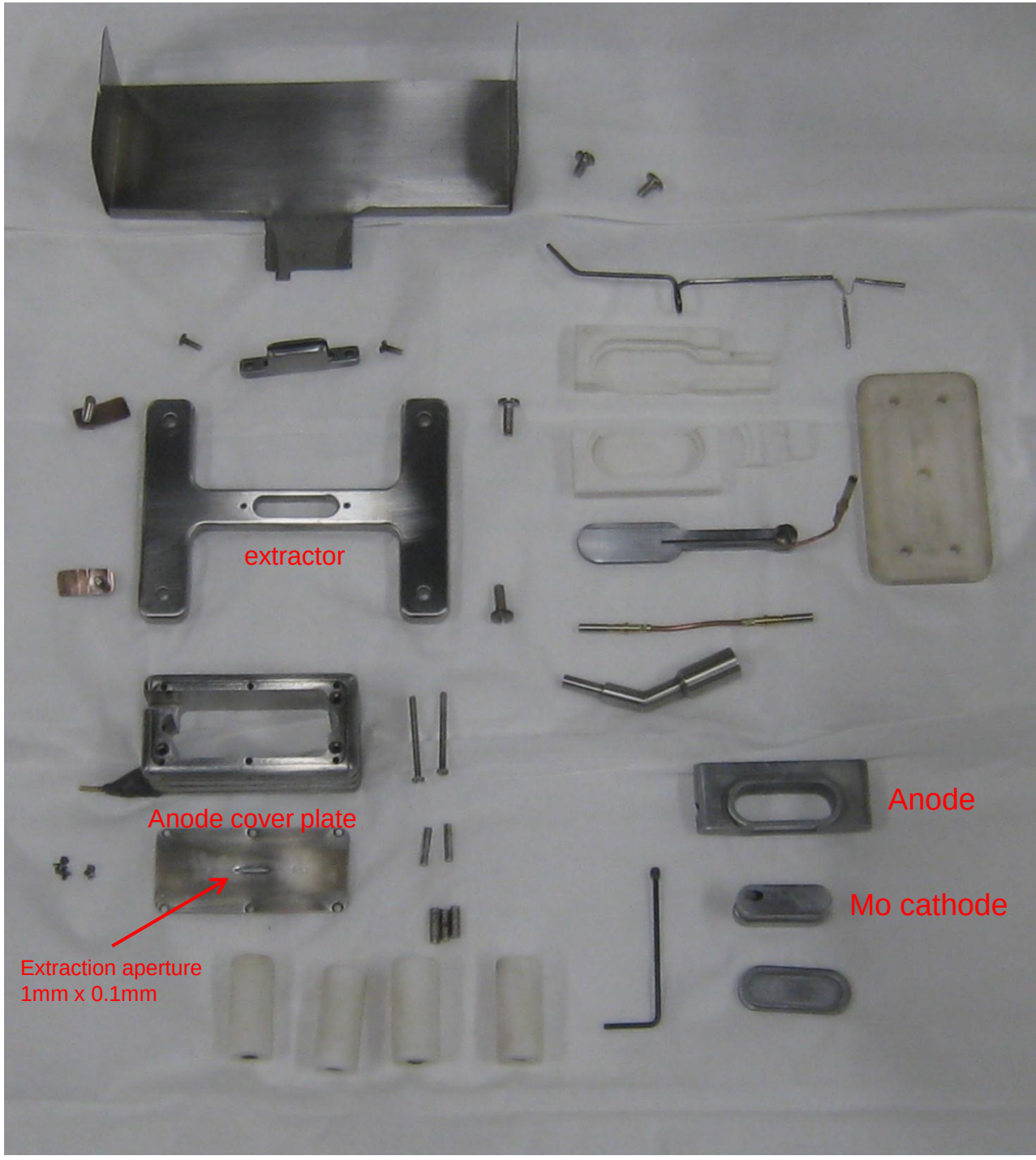
Compact size



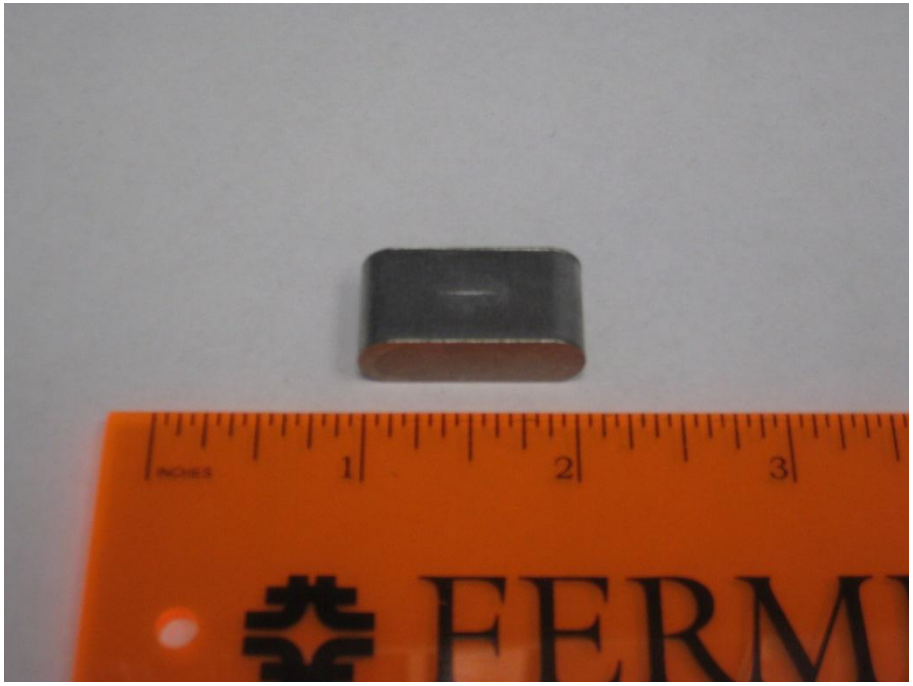




- Chuck Schmidt's original design.
- Based on the BNL source
- Appropriate for pulsed operation.

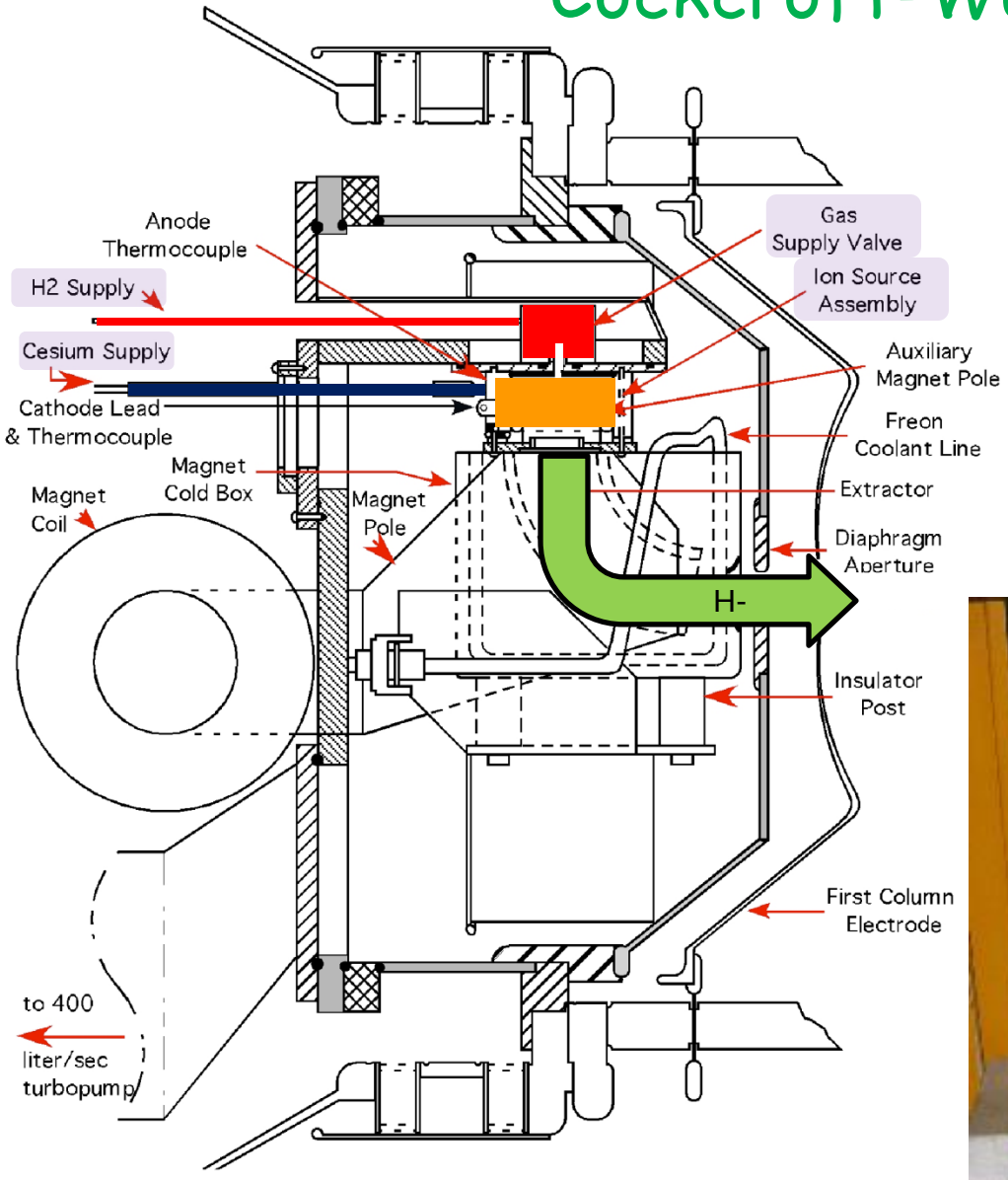


The original magnetron used a flat cathode which will become very important later on !

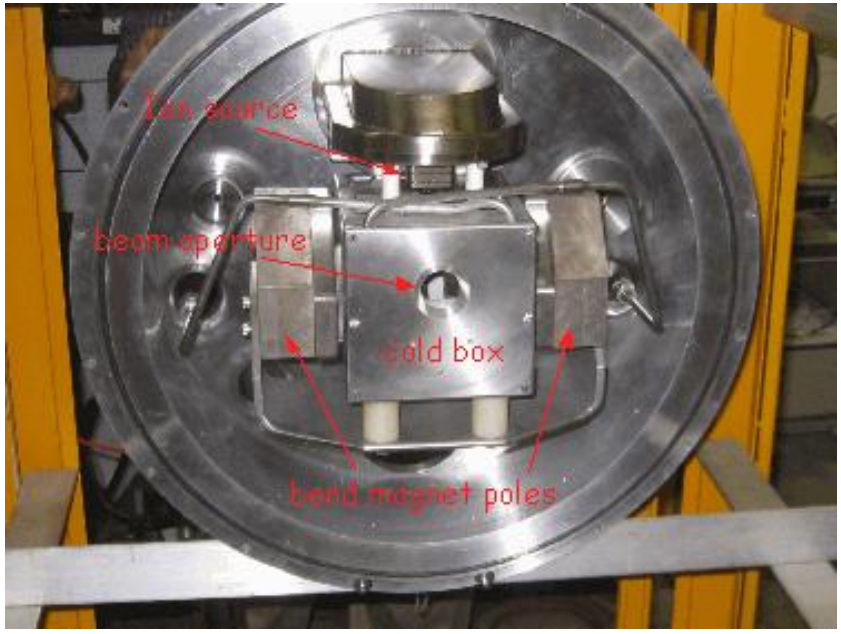


Parameter	Value
Arc current	180A
Arc Voltage	130V
Beam current	50mA
Power efficiency	2mA/kW
Source lifetime	3 months

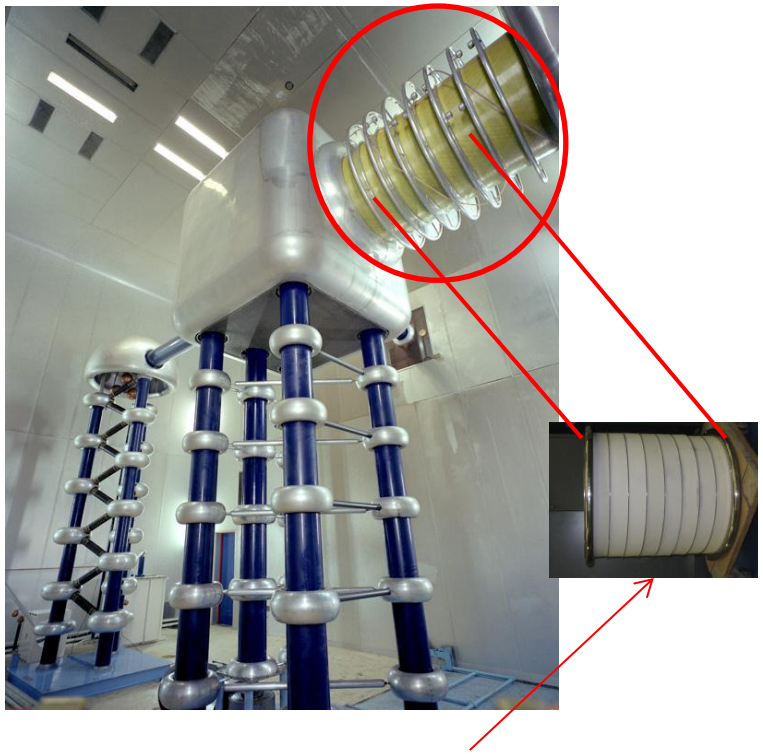
Cockcroft-Walton



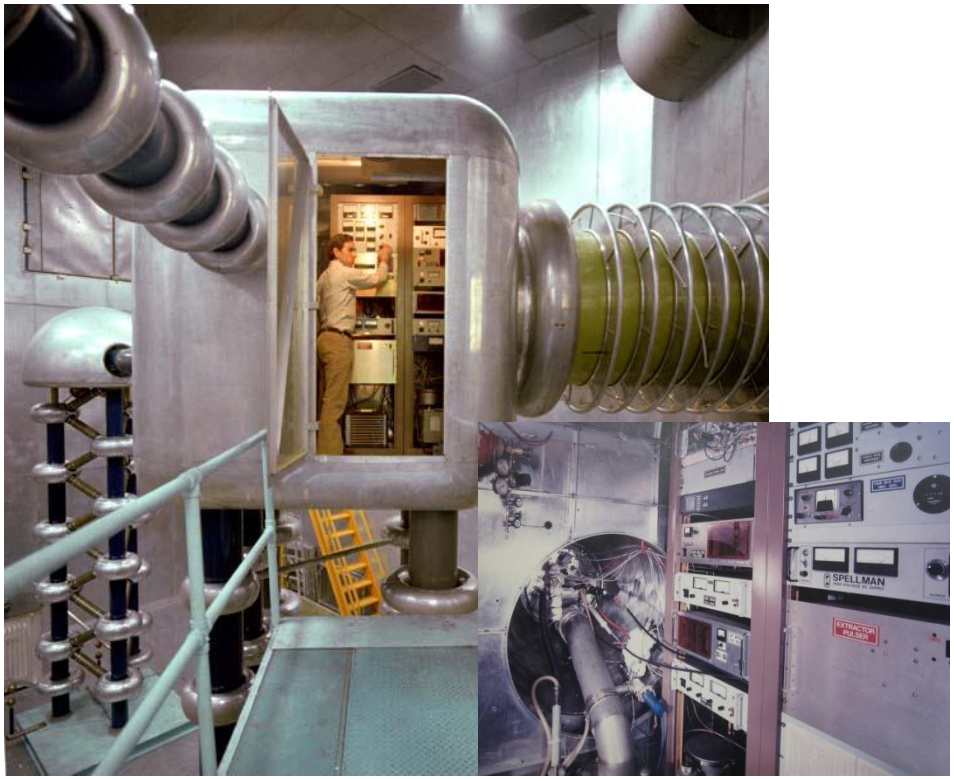
- The source was mounted pointing down with a 90deg bend magnet.
- There was a cold box that trapped Cs before it entered the accelerating column.
- Co-extracted electrons swept away by the bend magnet



Cockcroft- Walton continued

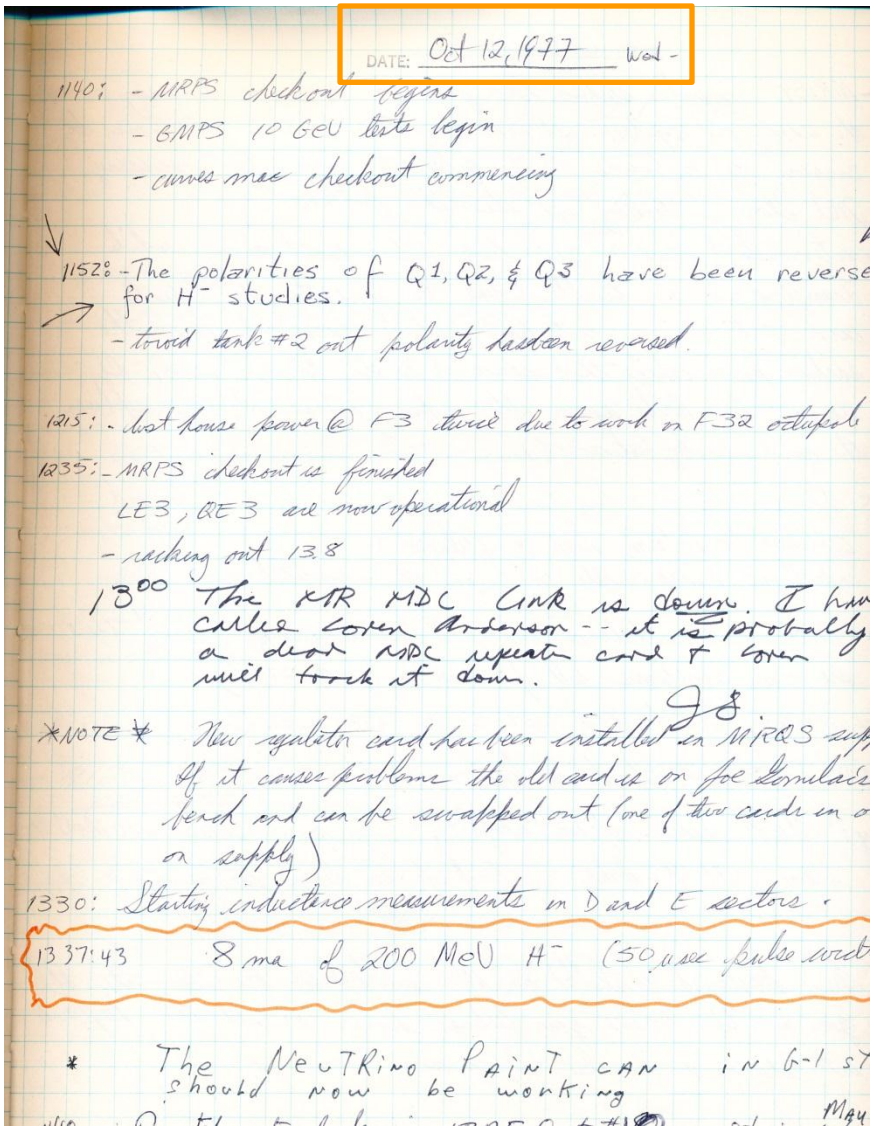


- 750keV accelerating column
- 100kV between each electrode



Dome contains ion source electronics and vacuum pumping

The 1st H- ions accelerated down Linac



DATE: Oct 12, 1977 Wed -

1140: - MRPS checkout begins
- GMPS 10 GeV tests begin
- curves mag checkout commencing

1152: - The polarities of Q1, Q2, & Q3 have been reverse for H⁻ studies.
- toroid tank #2 out polarity has been reversed.

1215: - lost house power @ F3 twice due to work on F32 ectupole

1235: - MRPS checkout is finished
LE3, QE3 are now operational
- racking out 13.8

1300 The MR MDC CAMAC is down. I have called Loren Anderson -- it is probably a dead MDC repeater card & Loren will look it down.
JS

NOTE New regulator card has been installed in MRQS supply. If it causes problems the old card is on the Booster bench and can be swapped out (one of the cards in the supply)

1330: Starting inductance measurements in D and E sectors.

1337:43 8 ma @ 200 MeV H⁻ (50 usec pulse width)

* The NEUTRINO PAINT CAN in 6-1 should now be working

M44

1710 @ 15 ma H- 200 mev

@ The magnet that read 40% high is still 40% high with no visual apparent reasons.

1725 NI Lobe Blower Needs To Be Changed. Est 5 hrs

1737 MR. Hipot

Bends 50 ma @ 1KV
Quads 60 ma @ 1KV

1750 13.8 QN Establishing a 200/300 ramp with cap tree and QE3 SLE3 in.

1755 Gerry Czop thinks the N-1 problem is in the valves.

1800 - There is a Problem with the Buncher Gradient, apparently caused By H⁻. The gradient intermittantly drops To zero, the LL changes from .5-.8 volts & the phase error changes. This is all believed To be caused By vacuum activity Kurt Owen is aware of the Problem. All should clean up when we return To normal opperation.

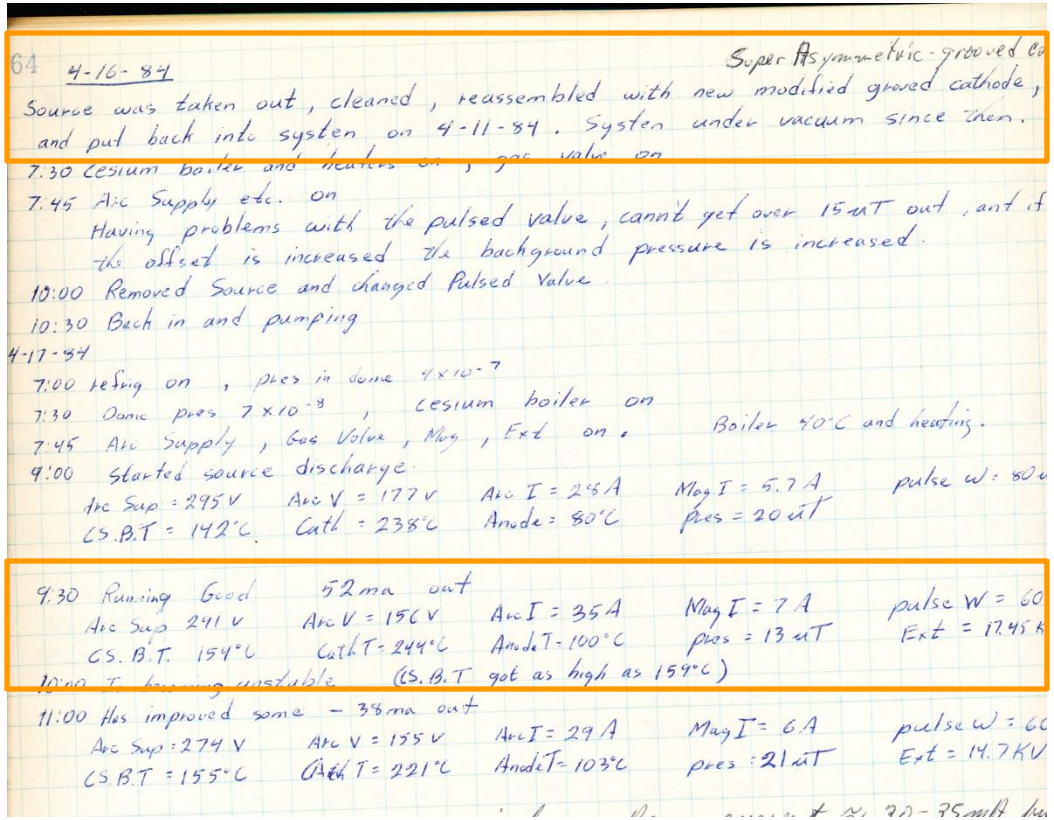
M. Olson as For W. Ca

1830 H- studies done switching back to H+ 17 ma

1915 Booster studies and instruction begin H+ 120 ma

Like all good accelerator experiments, it took less than 1 shift to prove that it works !

The original cathode was used for years. Then it was decided to grove the cathode on one side to help focus the beam at the anode extraction slit. This was a huge improvement. Later, the cathodes were grooved all the way around thinking that it would reduce "noise" in the extracted beam current which was thought to be the result of too low of a plasma volume.



64 4-16-84 Super Asymmetric - grooved ca

Source was taken out, cleaned, reassembled with new modified groved cathode, and put back into systen on 4-11-84. Systen under vacuum since then.

7.30 Cesium boiler and heaters on, gas valve on

7.45 Arc Supply etc. on

Having problems with the pulsed valve, cannt get over 15 uT out, ant if the offset is increased the background pressure is increased.

10:00 Removed Source and changed Pulsed Valve

10:30 Back in and pumping

4-17-84

7:00 Heting on, pres in dome 4x10-7

7:30 Ionic pres 7x10-8, Cesium boiler on

7:45 Arc Supply, Gas Valve, Mag, Ext on. Boiler 40°C and heating.

9:00 Started source discharge

Arc Sup = 295 V Arc V = 177 V Arc I = 25 A Mag I = 5.7 A pulse w = 80

CS.B.T = 142°C Cath = 238°C Anode = 80°C pres = 20 uT

9:30 Running Good 52 ma out

Arc Sup 241 V Arc V = 156 V Arc I = 35 A Mag I = 7 A pulse W = 60

CS. B.T. 154°C CathT = 244°C AnodeT = 100°C pres = 13 uT Ext = 17.45 K

10:00 T. burning unstable (CS.B.T got as high as 159°C)

11:00 Has improved some - 38 ma out

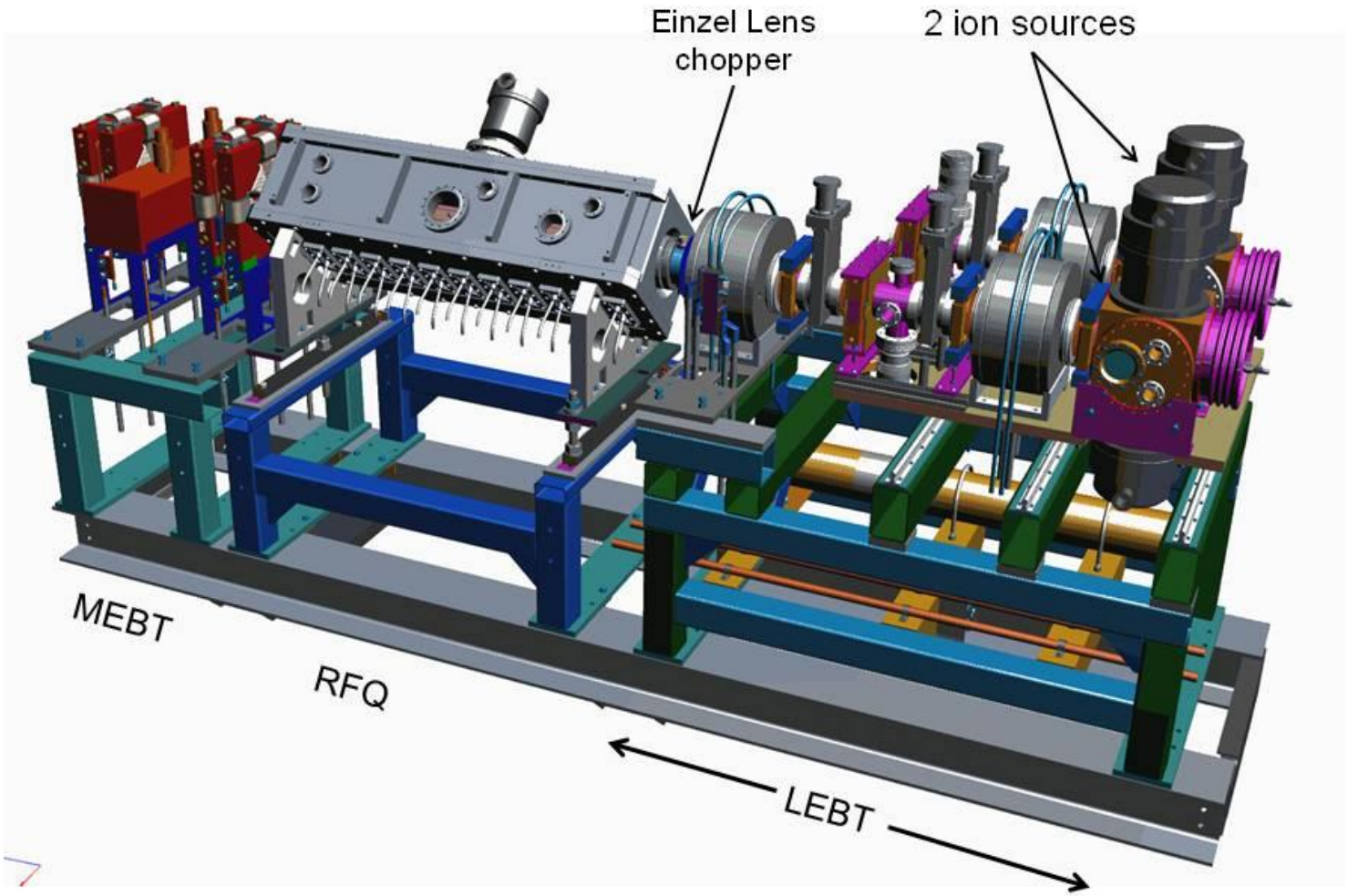
Arc Sup: 274 V Arc V = 155 V Arc I = 29 A Mag I = 6 A pulse w = 60

CS.B.T = 155°C CathT = 221°C AnodeT = 103°C pres = 21 uT Ext = 14.7 KV

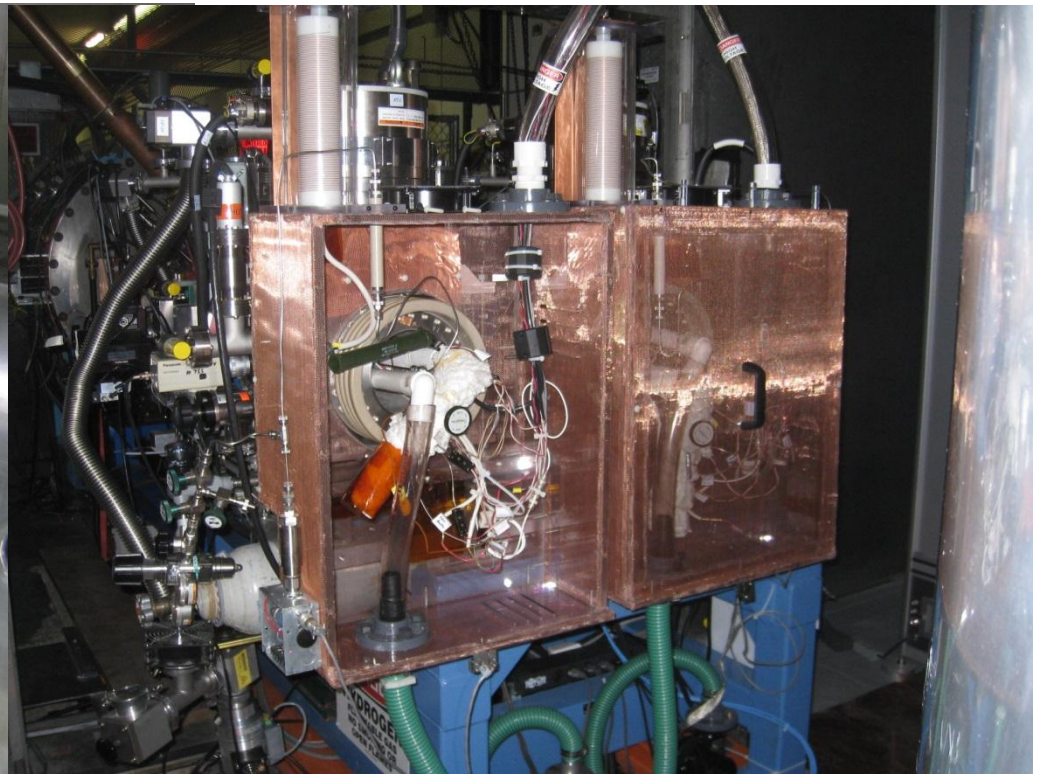
- Average power now: 156V x 35A x15 (1/s) x 60(μs) = 4.9W
- Arc current went from 180A to 35A with cathode focusing!

This is where things remained until the installation of the new ion source and RFQ……

Where we are now…

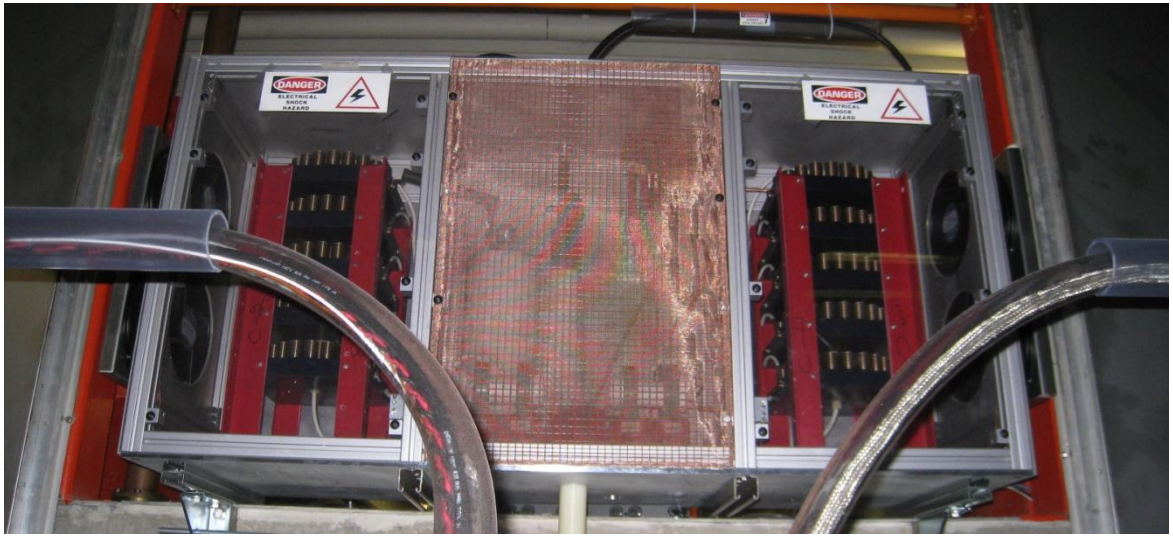


The ion source is based on a design by Jim Alessi of BNL

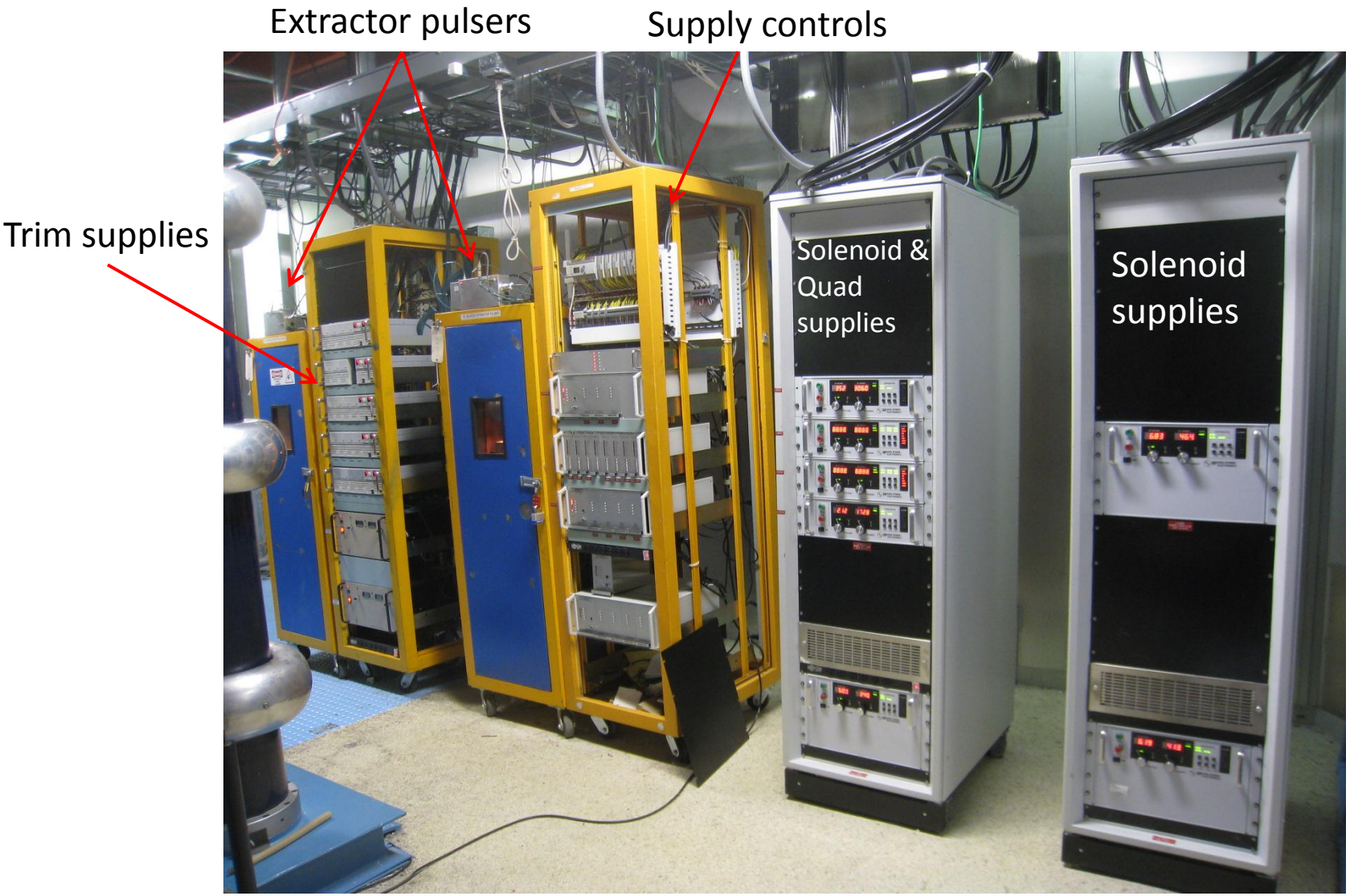


Ion source HV electronics

Einzel lens chopper

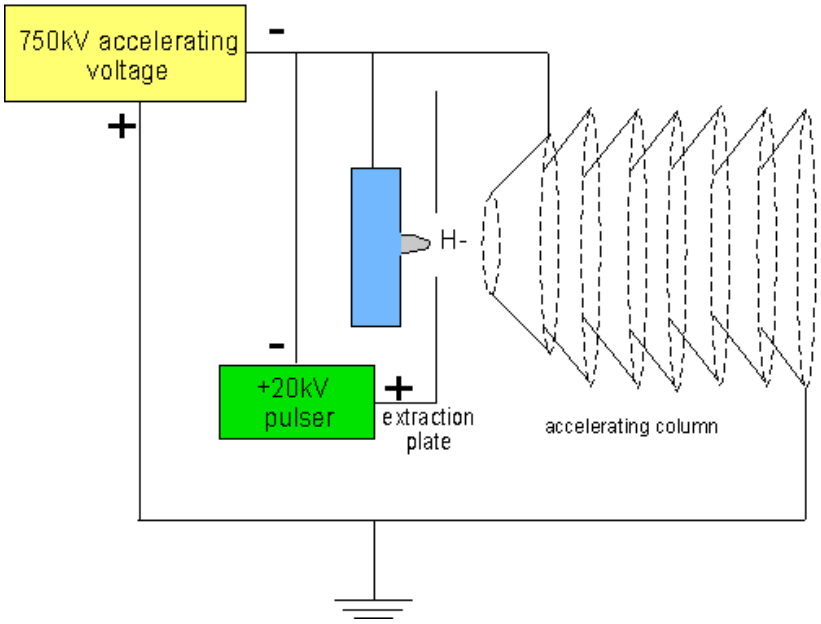


Equipment bellow deck



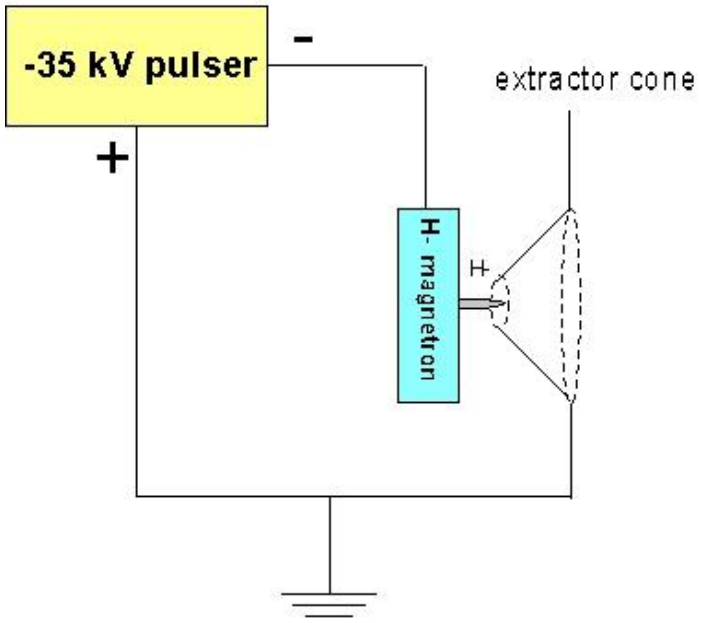
Different extraction scheme

Cockcroft-Walton



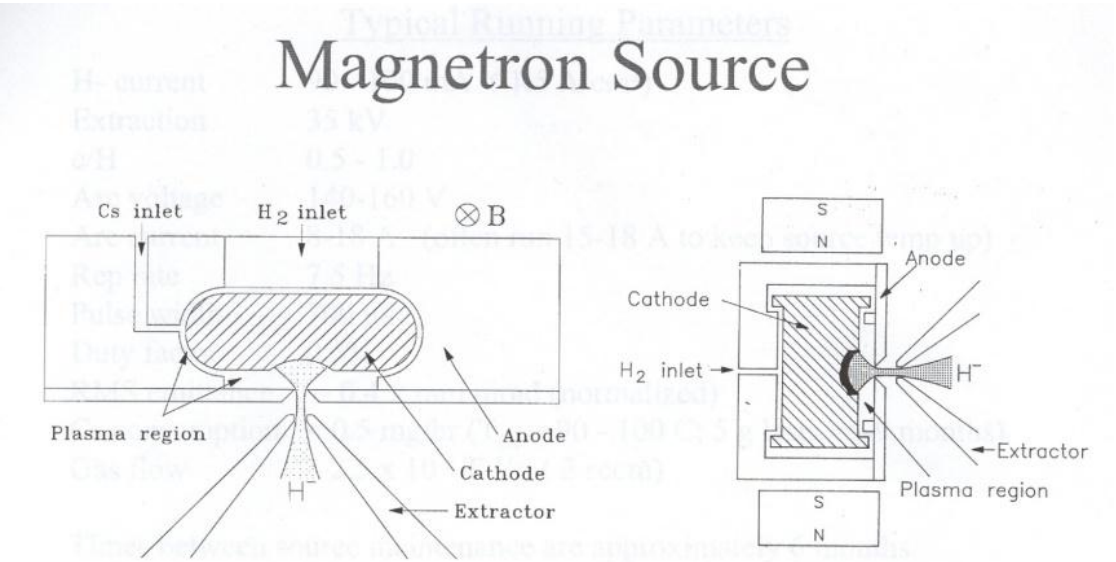
- DC accelerating voltage
- Extractor pulsed

New source with RFQ

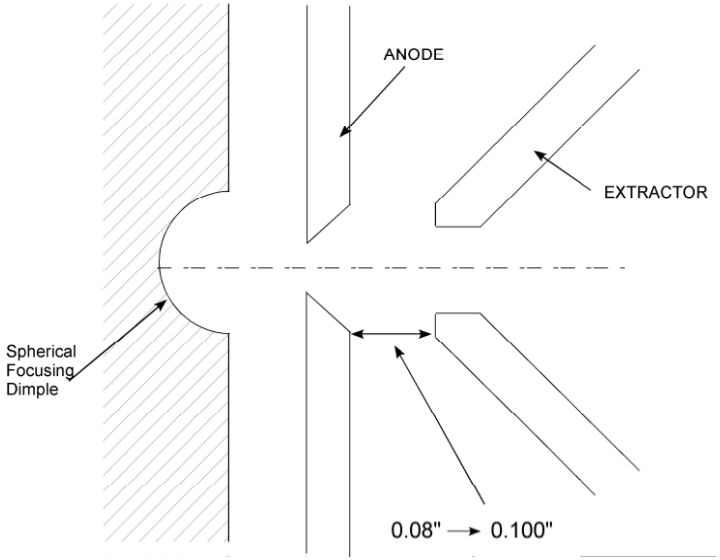


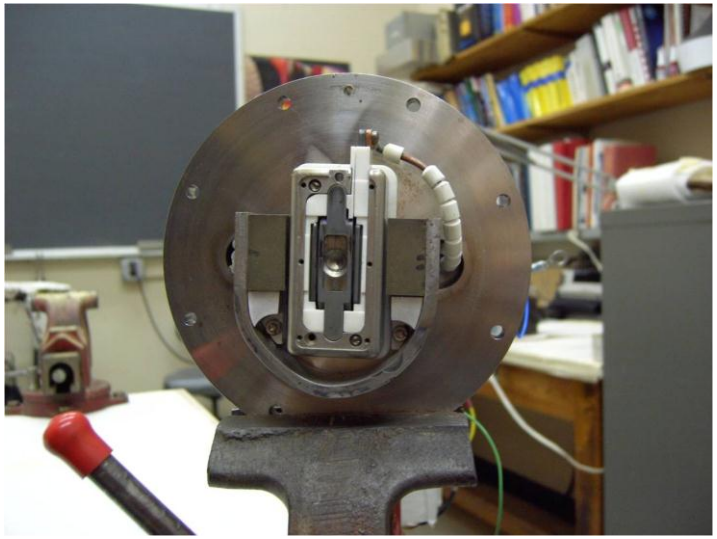
- Source pulsed to -35kV
- Extractor at ground
- Higher voltage across extraction gap ($I \propto V^{3/2}$)

BNL Style Source



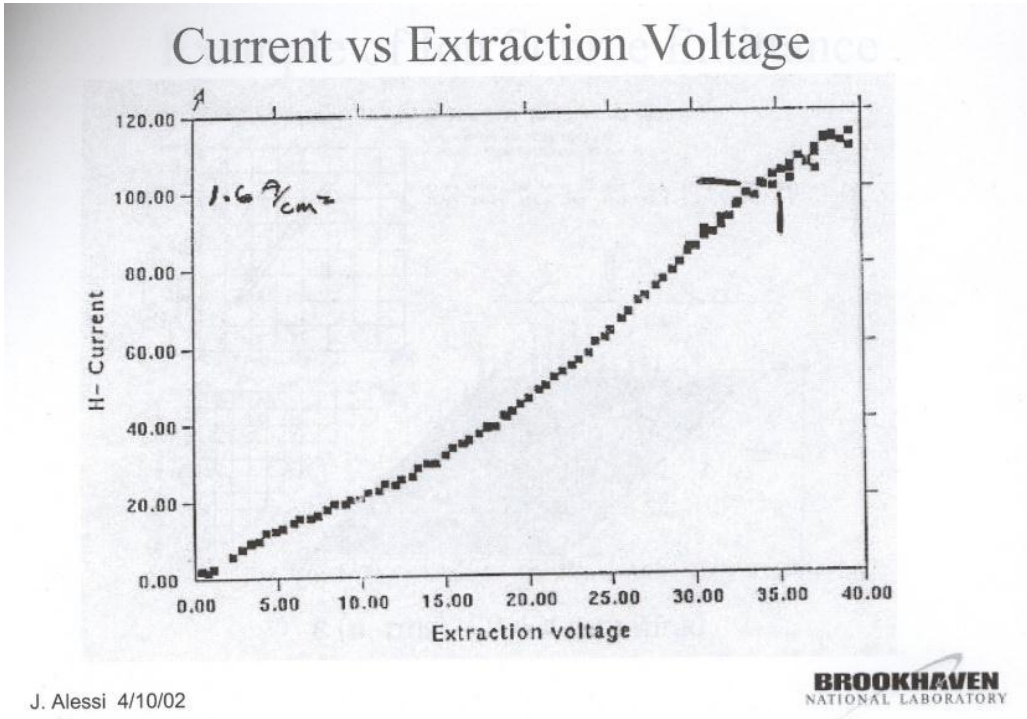
Figures: Jim Alessi BNL





Spherical focusing dimple cathode !

BNL style source, huge improvement!



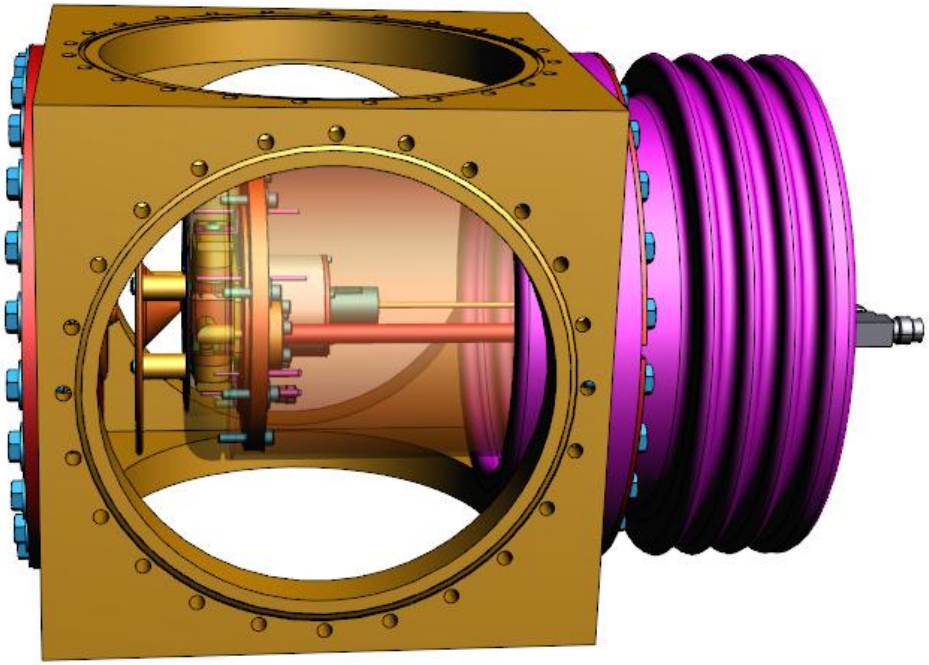
Parameter	Value
Arc current	15A
Arc Voltage	150V
Beam current	100mA
Power efficiency	67mA/kW
Source lifetime	9 months!

Increase in power efficiency comes from:

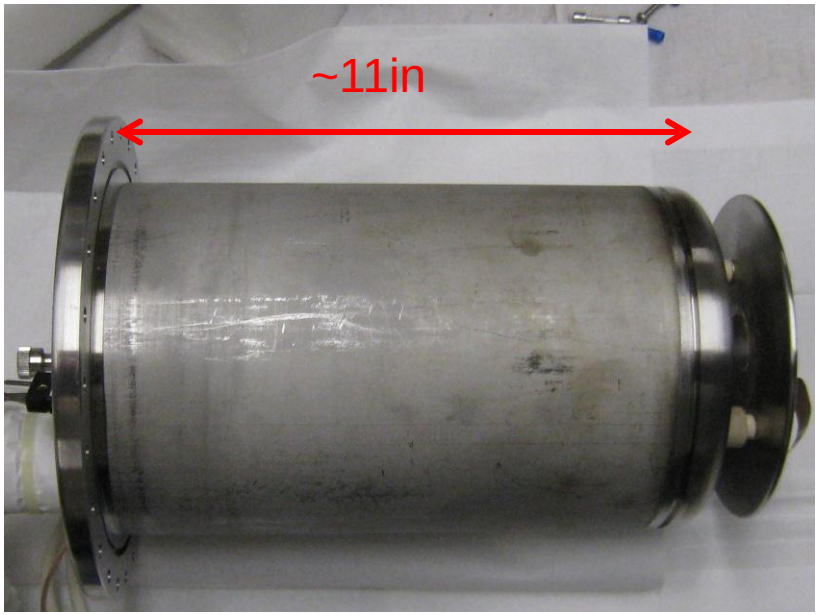
- Spherical dimpled cathode
- 35kV extraction

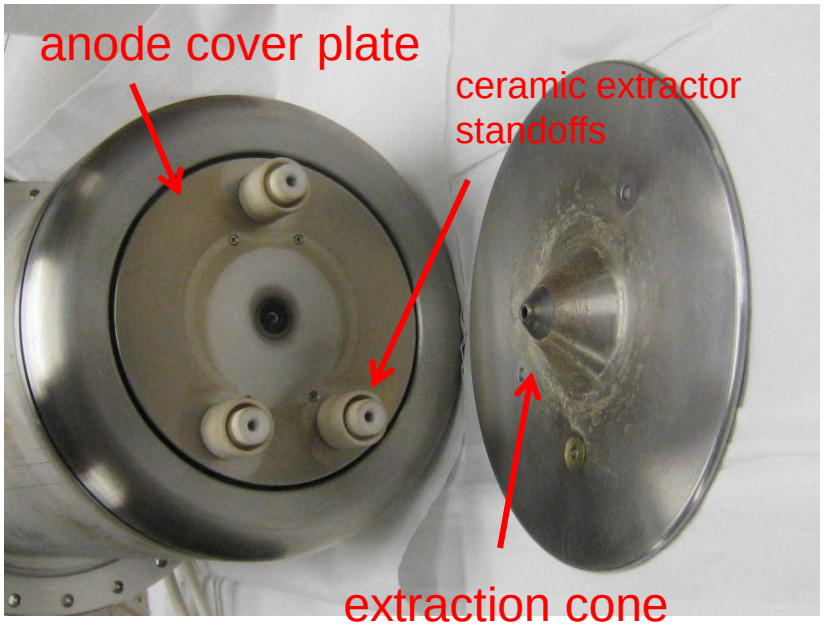
New FNAL magnetron

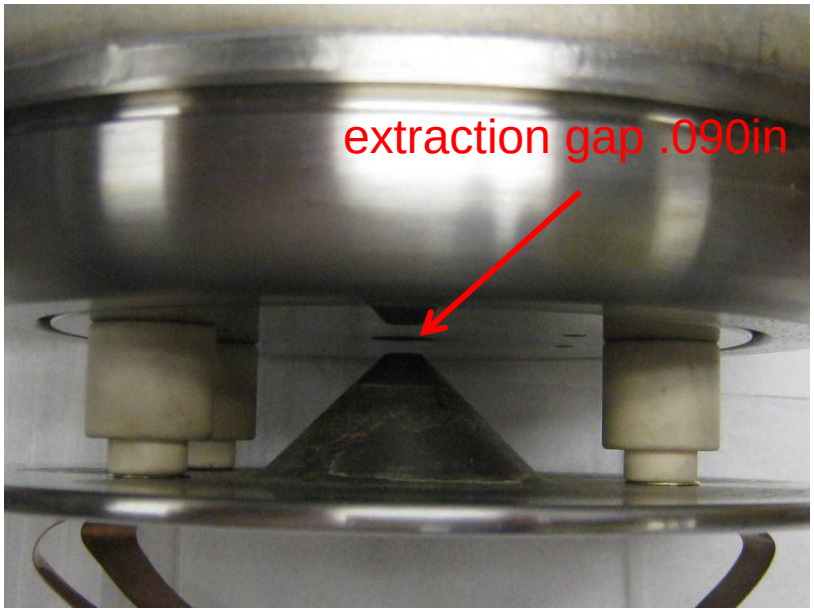
- 10 inch source cube
- Technicians involved with design
- Round aperture

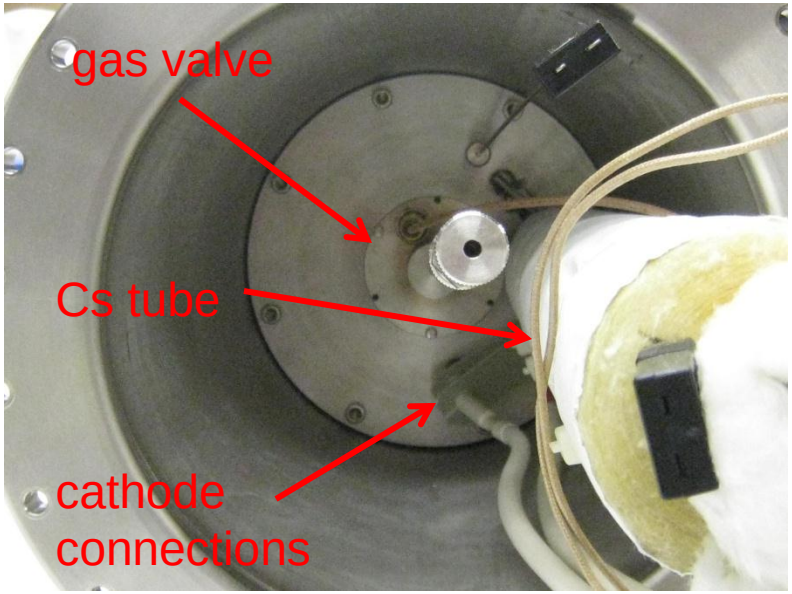


New FNAL source design



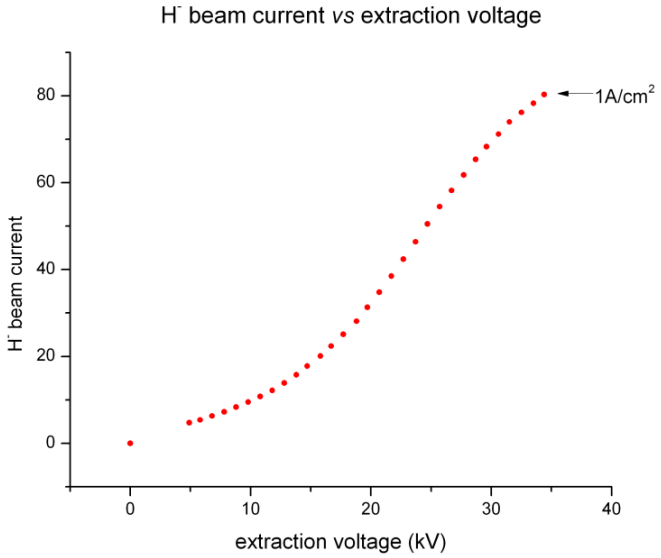


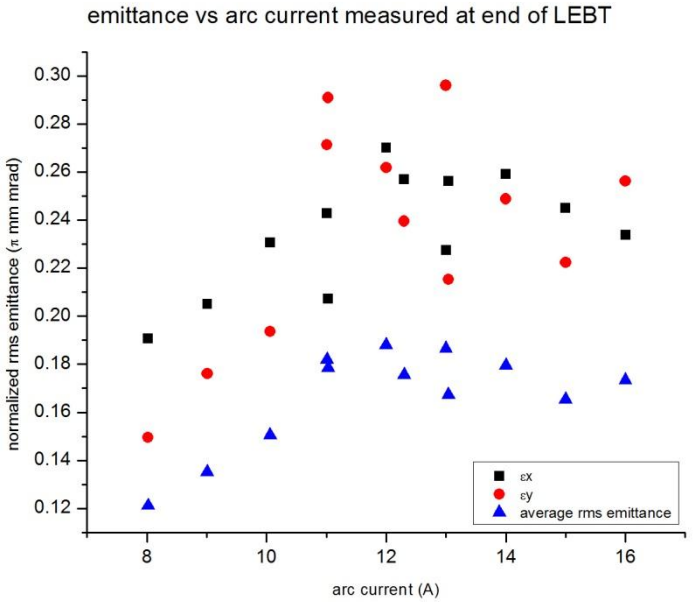




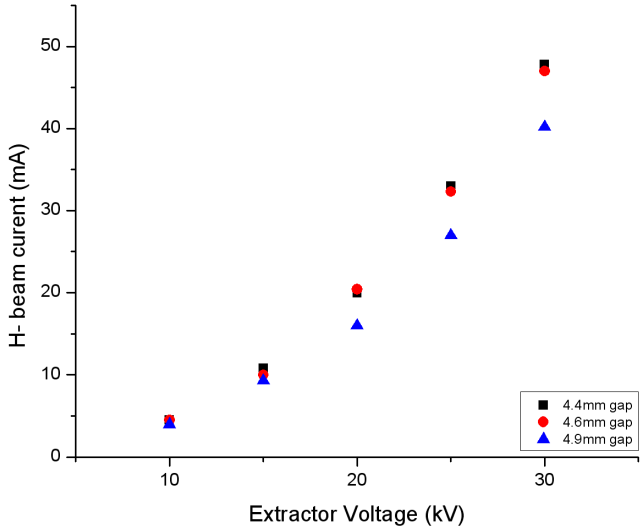
Some studies done on new magnetron

Perveance, able to achieve 1A/cm^2 @35kV





extracted beam current vs extractor voltage for various extraction gap sizes



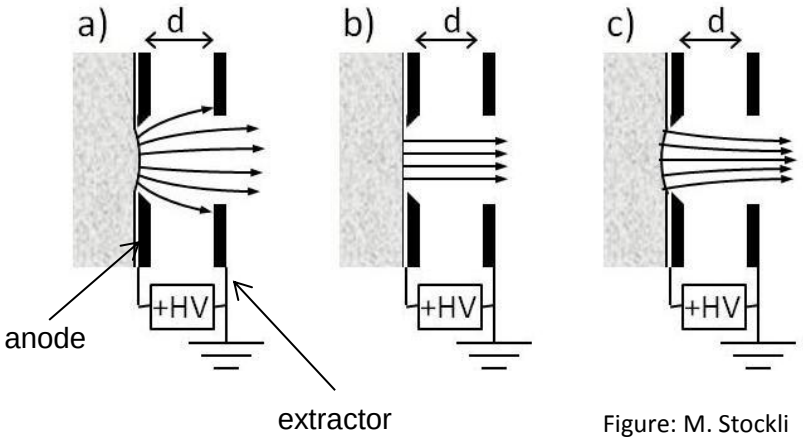
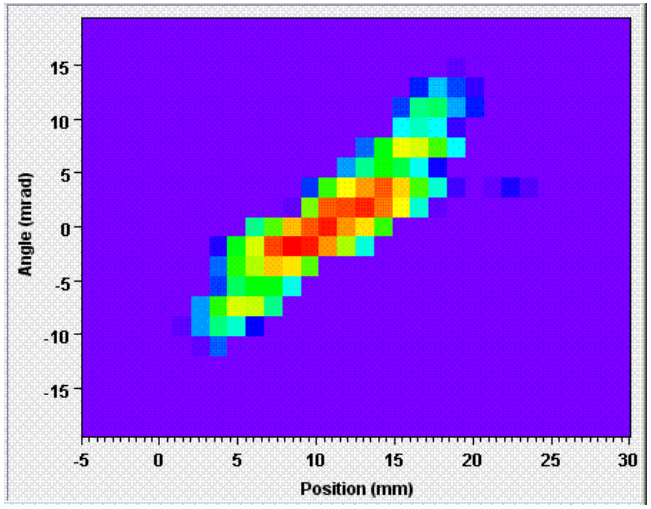
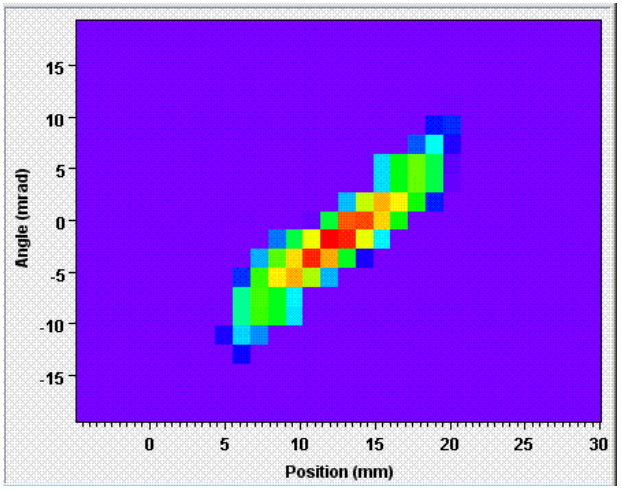


Figure: M. Stockli

LEBT emittance with nominal RFQ settings

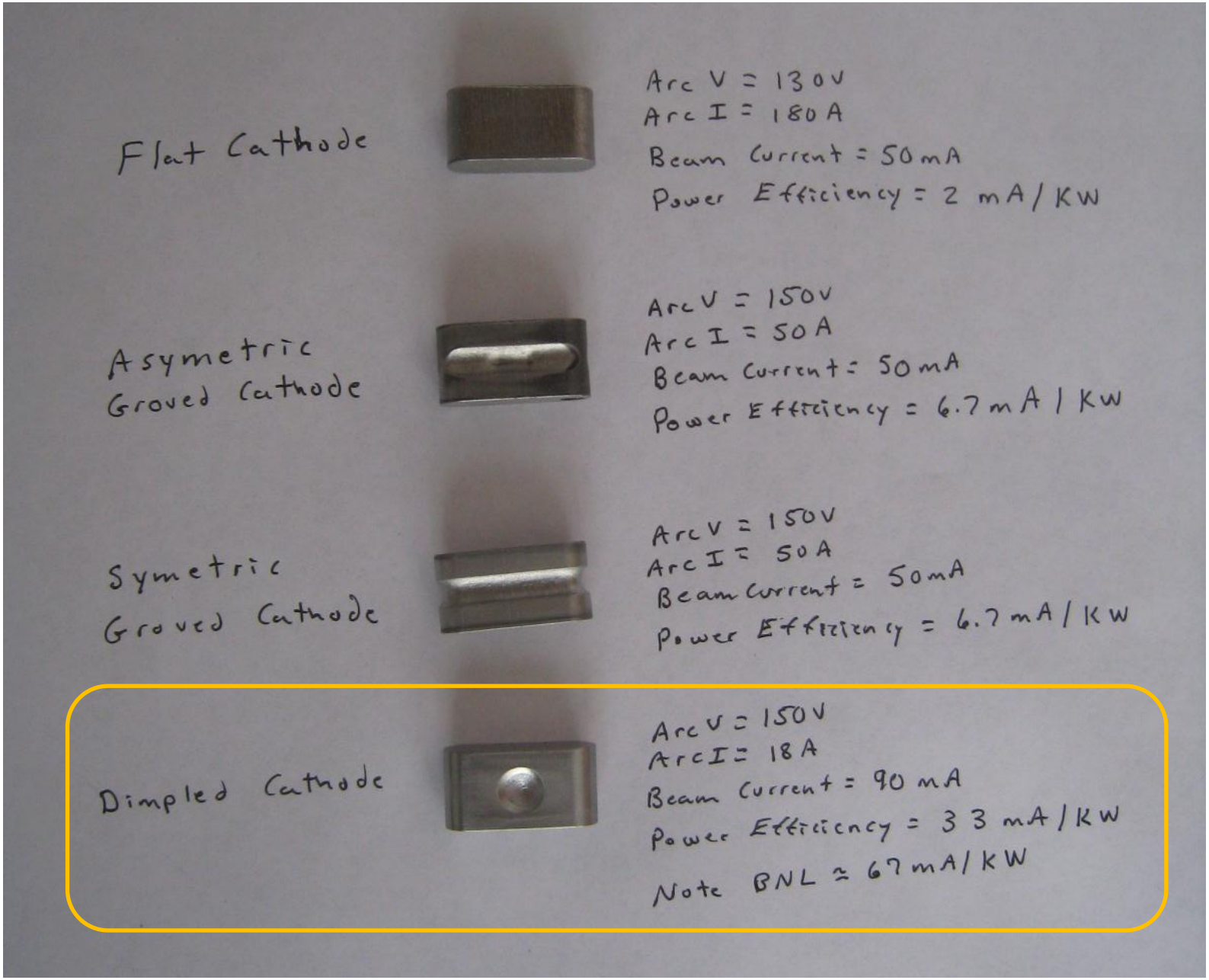


Vertical 0.25 π mm mrad normalized 1σ



Horizontal 0.15 π mm mrad normalized 1σ

Evolution of magnetron cathodes



Extractor sparking, one of our greatest challenges !

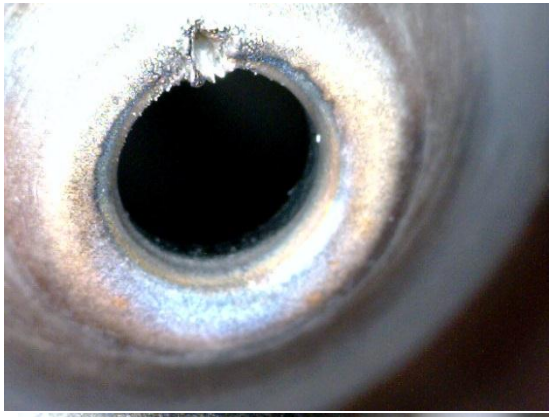
There have been 6 main issues that have lead to high spark rates:

1. Materials used
2. Magnetic Field
3. Source pressure
4. Extraction gap pressure
5. Cs control
6. Source electronics

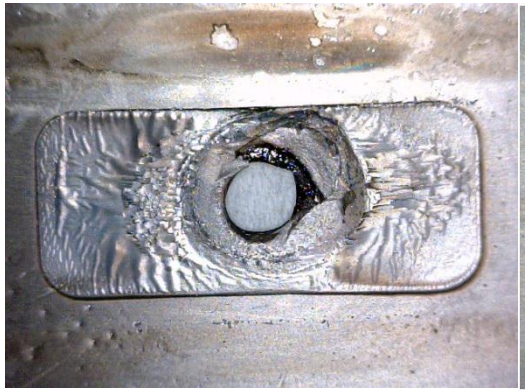
Materials

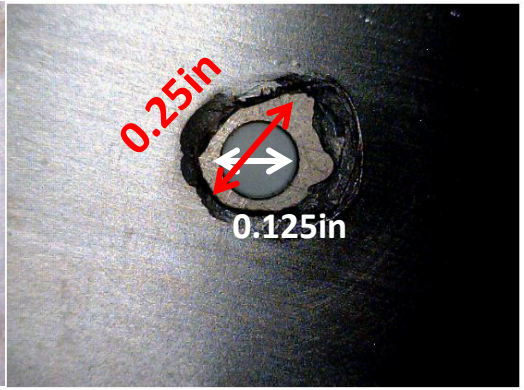
Materials play a big role, once the damage is done there is nothing left to do other than pull the source and fix it.

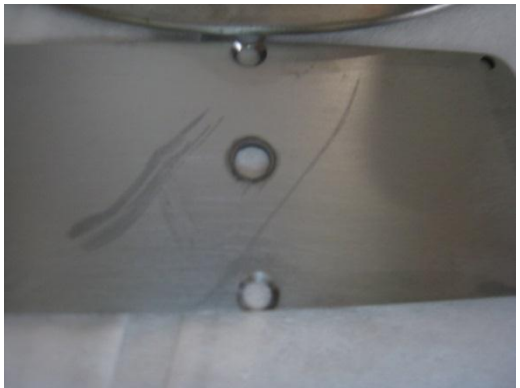
- Original extractor cone tip made out of molybdenum
- Energy of spark would cause damage that would lead to the need to pull the source and fix
- BNL uses tungsten for cone tips. They sent us one to try out. Big improvement in eliminating the damage from sparking



- Original inner anode cover plate made out of titanium
- Severe case of erosion increased the aperture from 0.125in to 0.25in !
- Once again BNL (“ahead of the curve”) sent us a molybdenum cover plate which has clearly solved the erosion problem

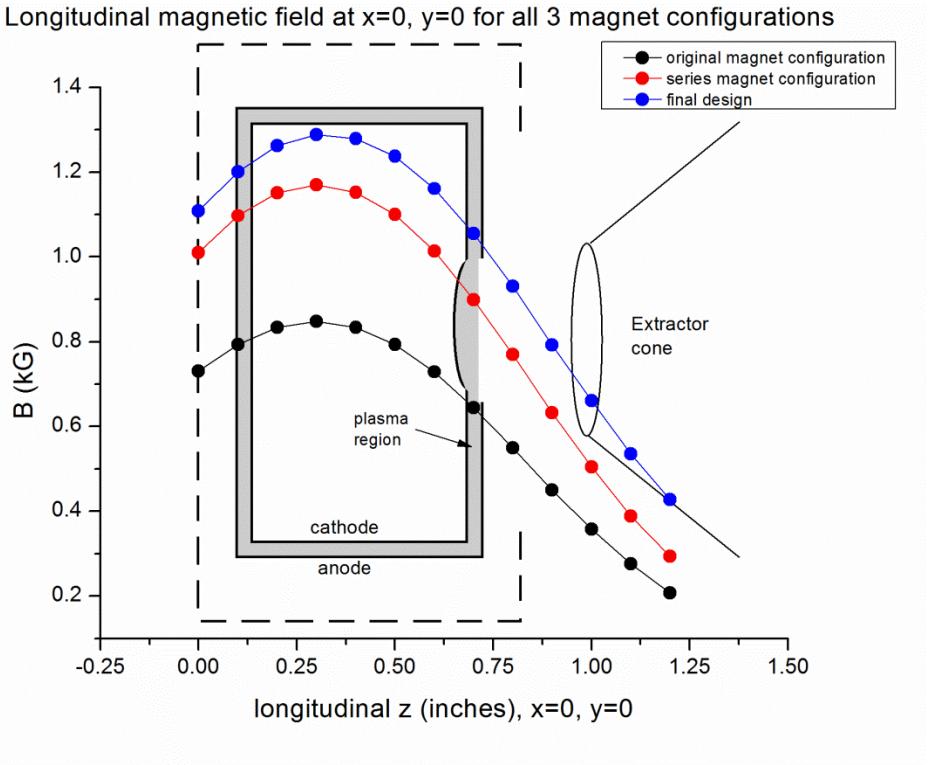




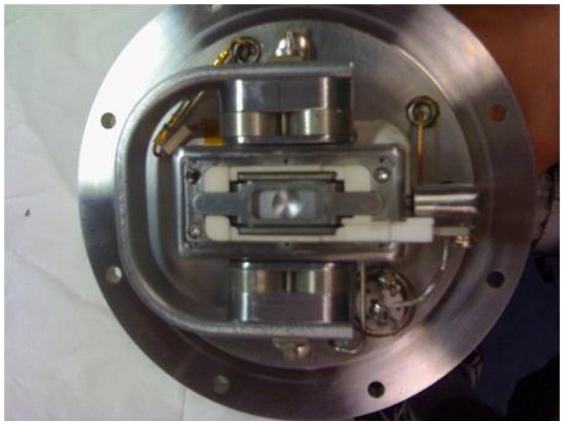


Magnetic field

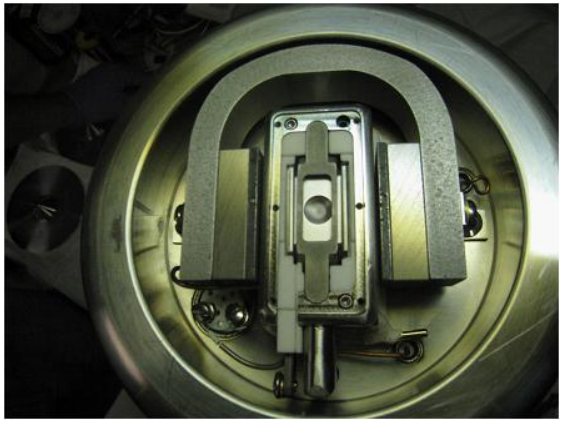
- Magnetic field plays a big role in both confinement and sweeping away co-extracted electrons
- Magnetrons prefer 1kG in the plasma region for proper confinement.
- Original magnets were marginal to start with and ended up too low (~700G) when warmed up.
- Redesigned the magnets and yoke with the help of Jim Volk



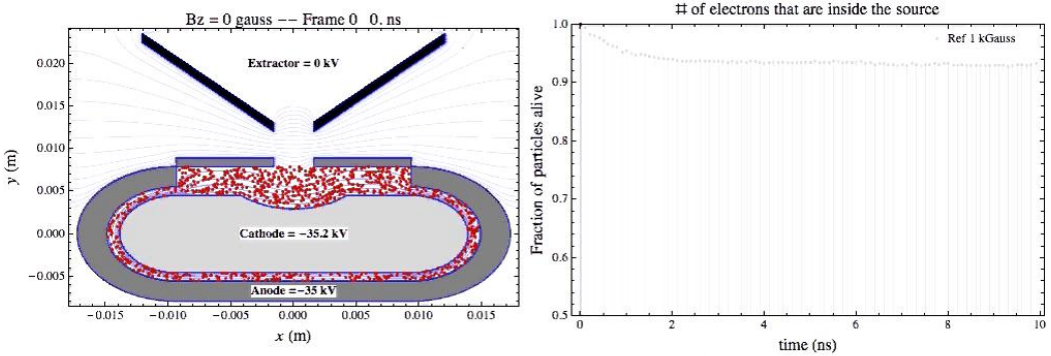
Original design: 4 SmCo disks



Final design: 2 SmCo rectangular magnets with higher field, thicker yoke



0 Gauss

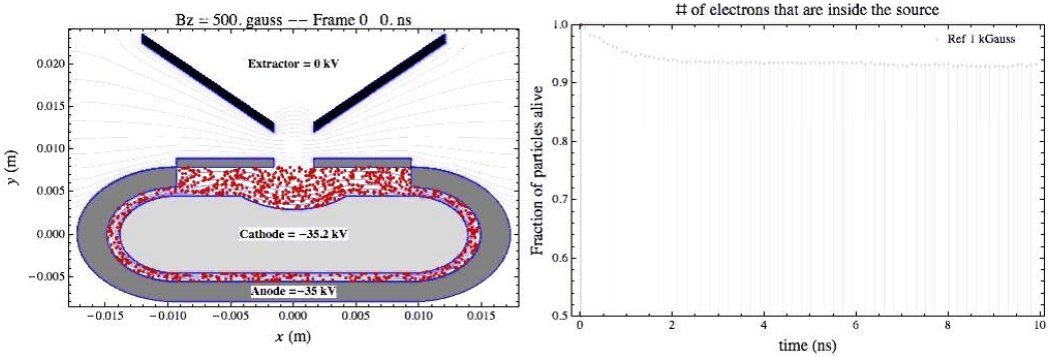


# of electrons inside source

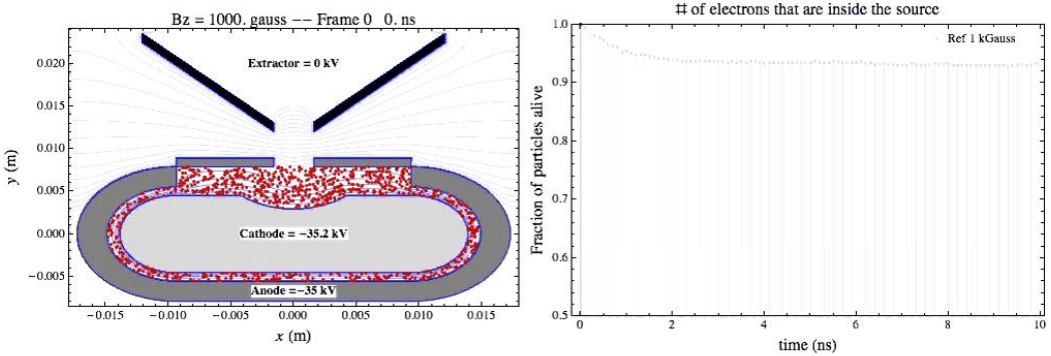
For all simulations:

- Extractor cone = 0V
- Cathode = -35.2kV

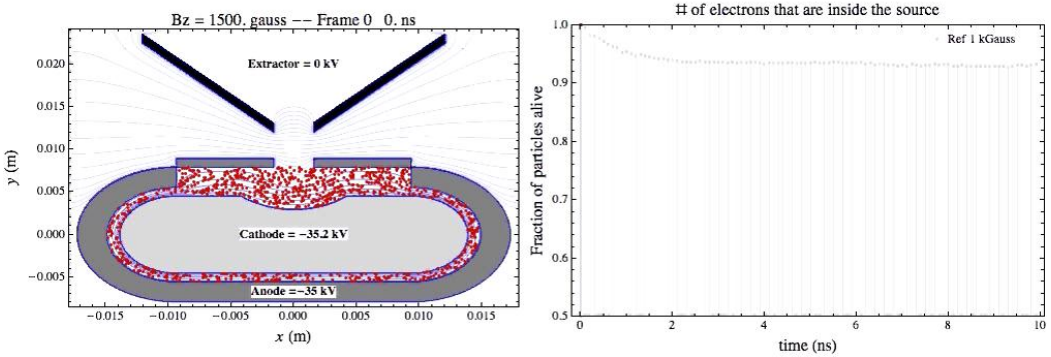
500 Gauss



1k Gauss

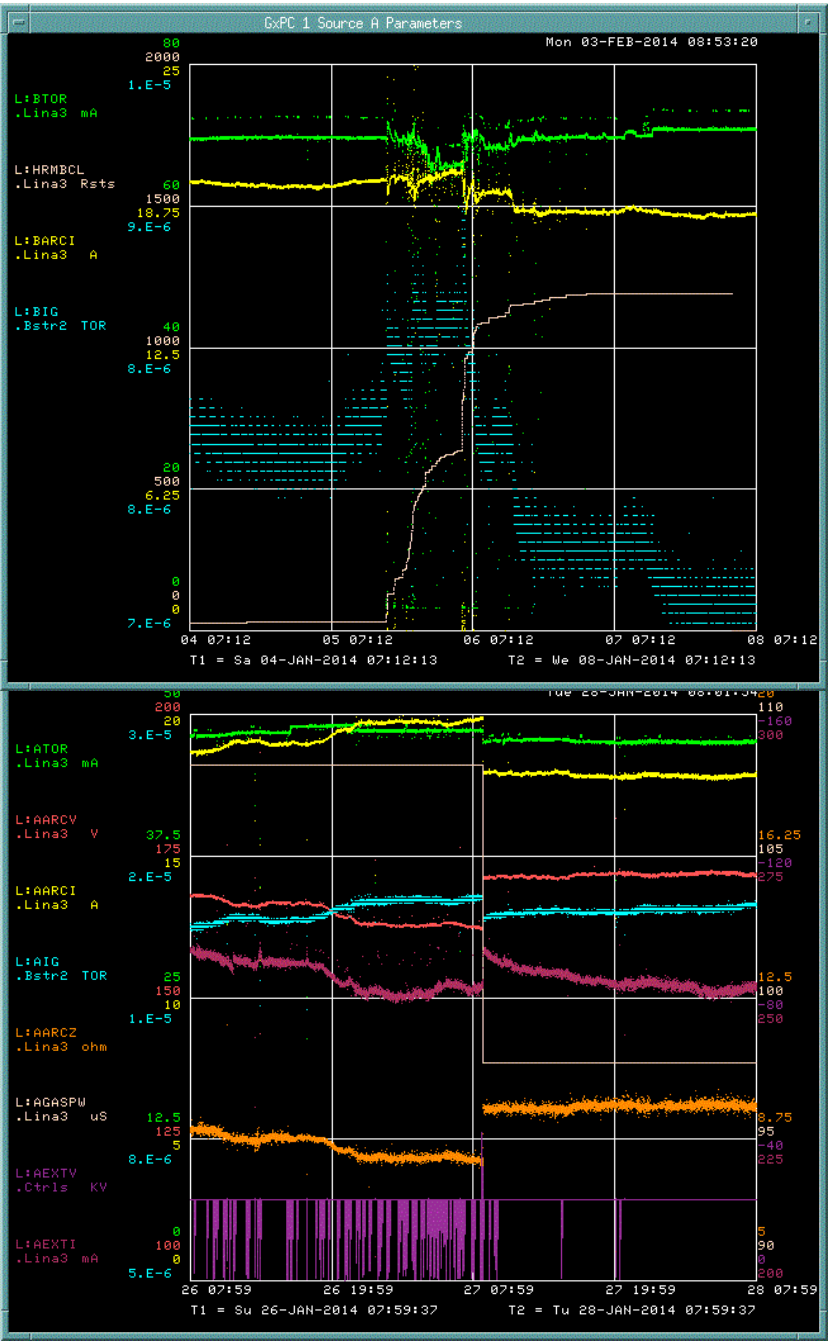


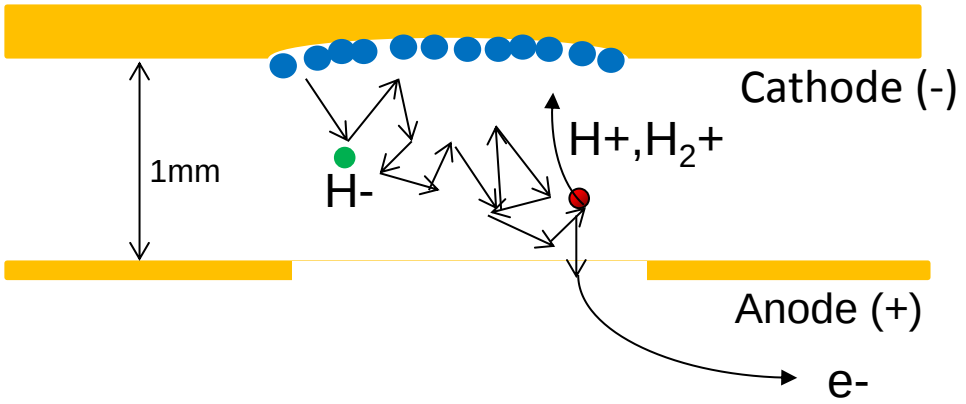
1.5k Gauss



Simulation by CY Tan

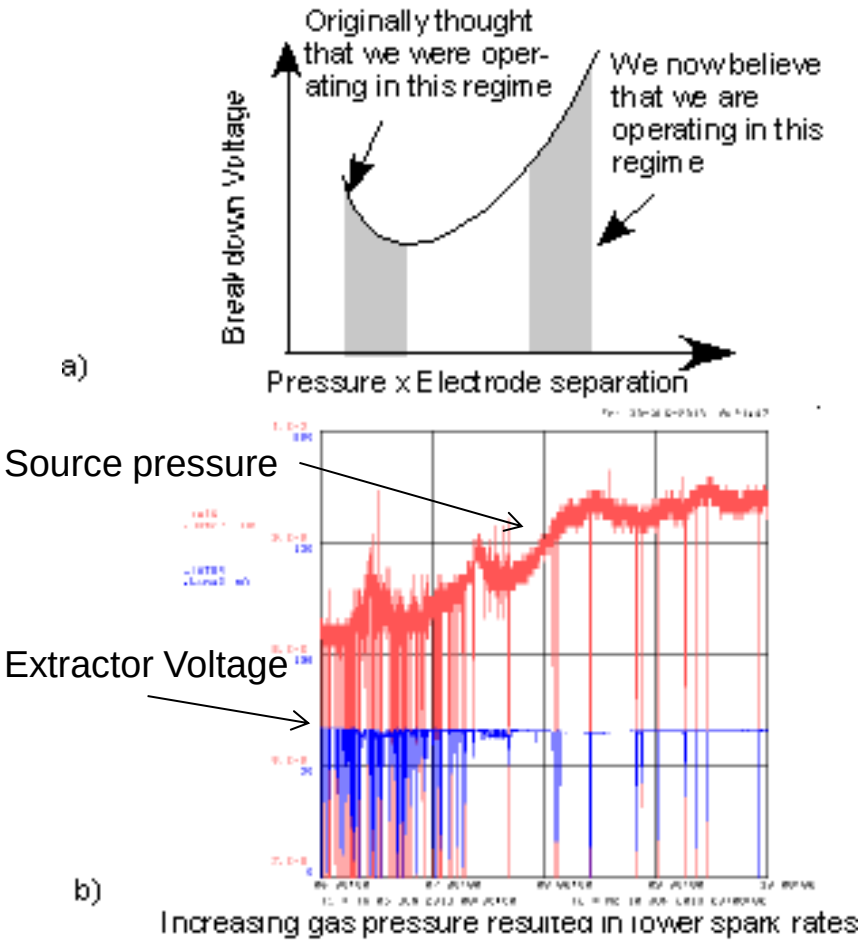
Source Pressure



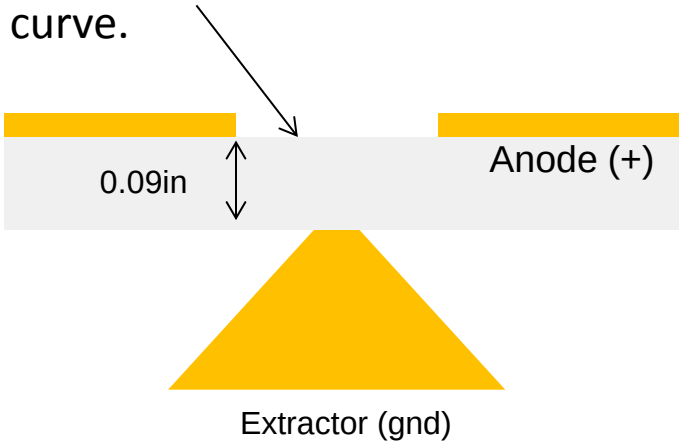


If source pressure is too high, one possibility is that the path length for the fragile H- ions is so long that the probability is high that some number of them will loose their electron on the way to the extraction aperture, leaving an excess of electrons to be extracted. Leading to sparking.

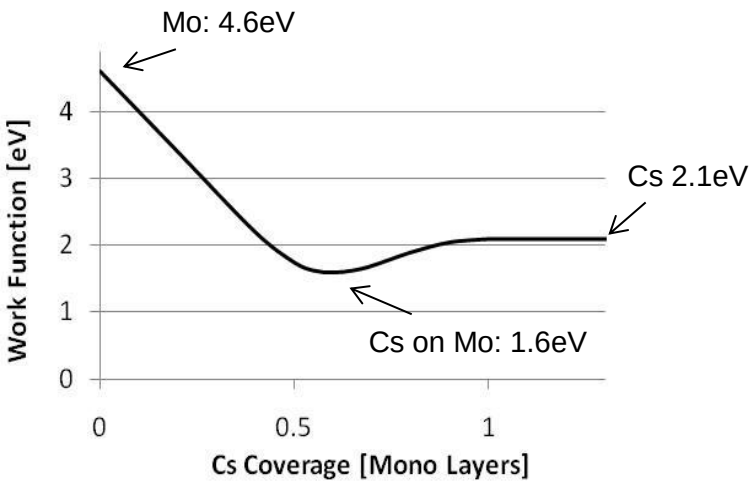
Source Pressure



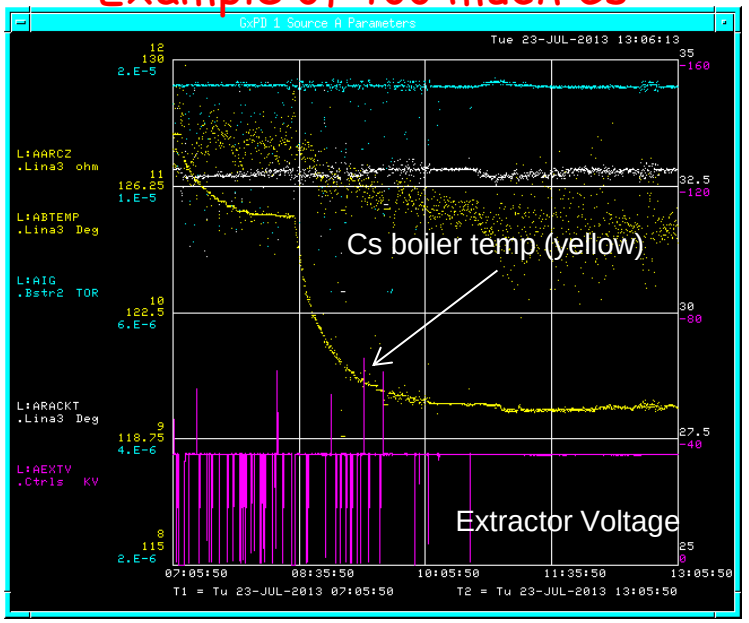
Another possibility is low average cube pressure. When the pressure is too low in the extraction gap and we are operating in a different regime of the Paschen curve.



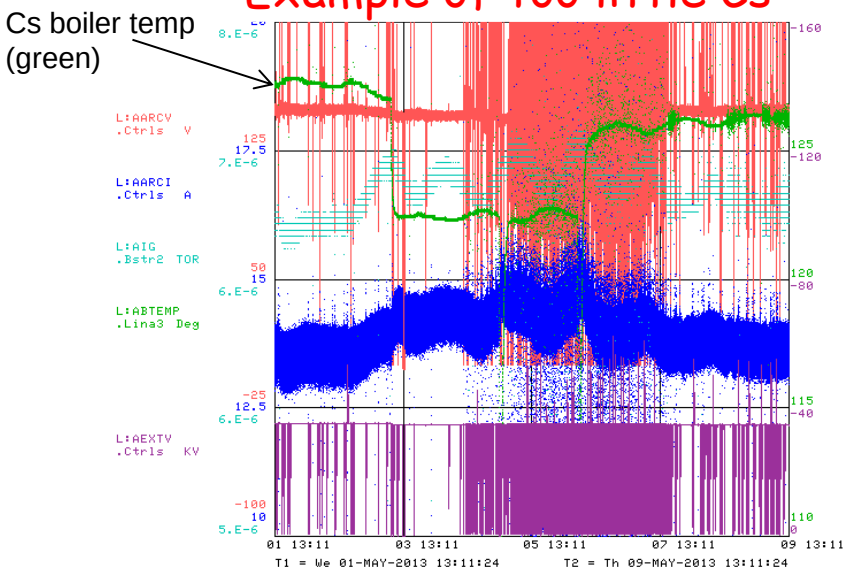
Cesium Control



Example of too much Cs



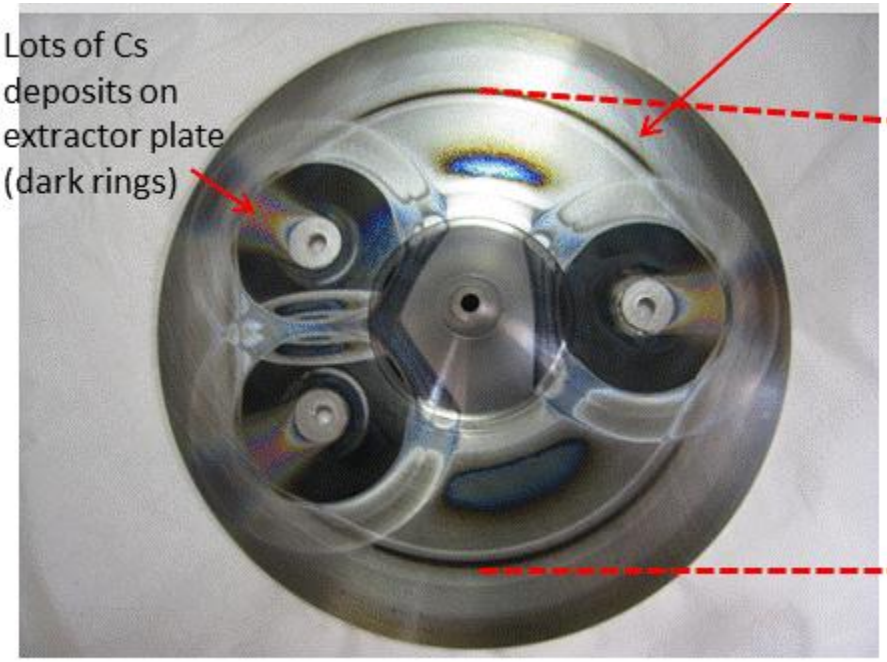
Example of too little Cs

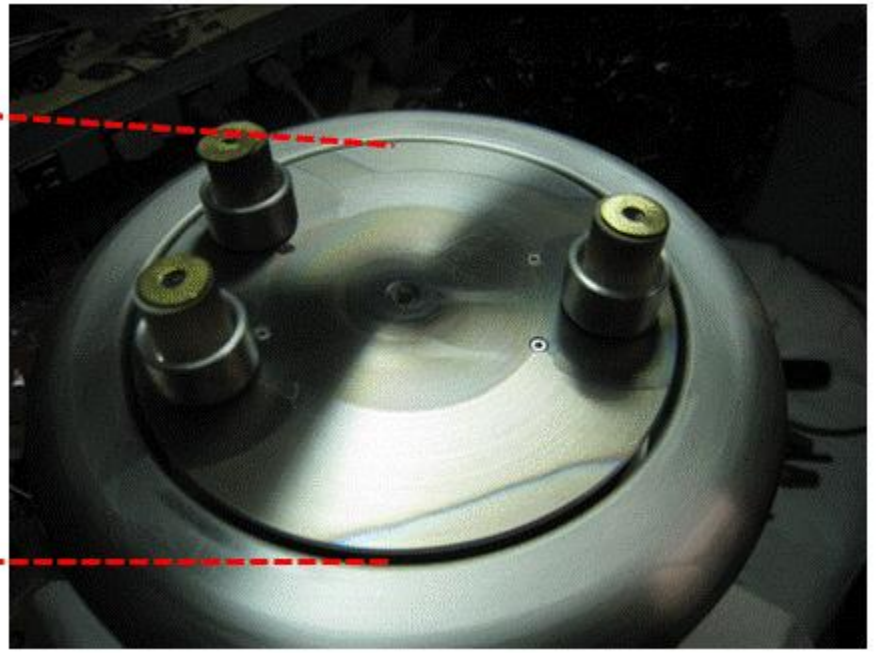


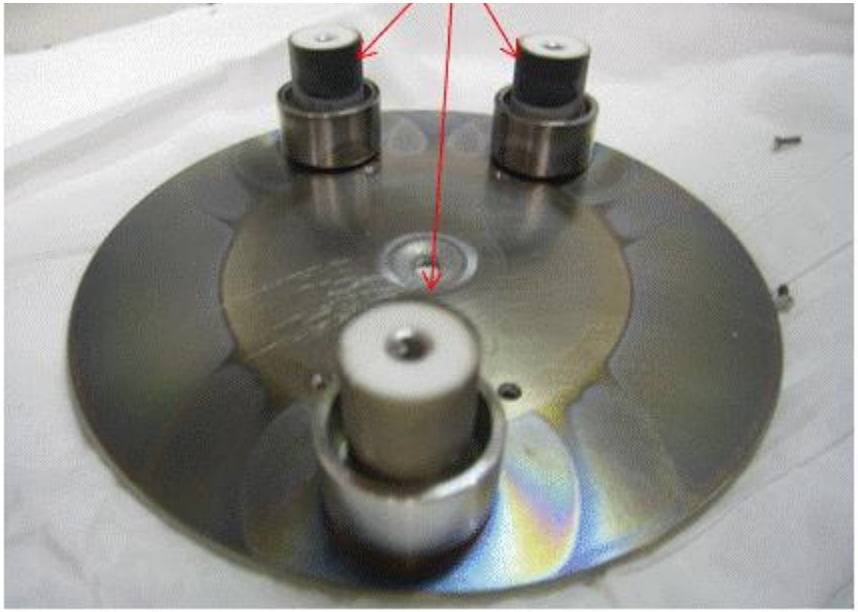
If the cesium layer is too thick/thin:

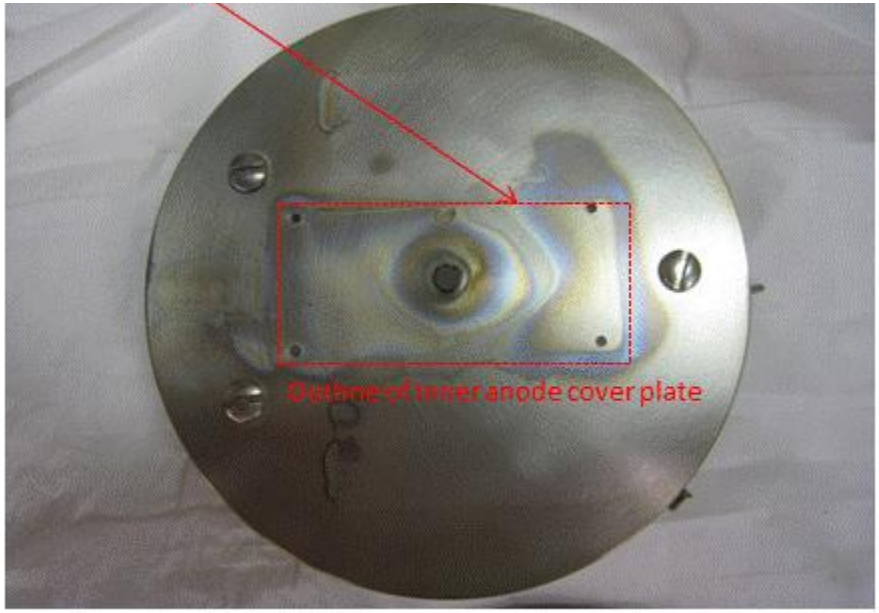
- Work function increases
- H- production decreases
- Number of free electrons increases

Examples of excess cesium in the source

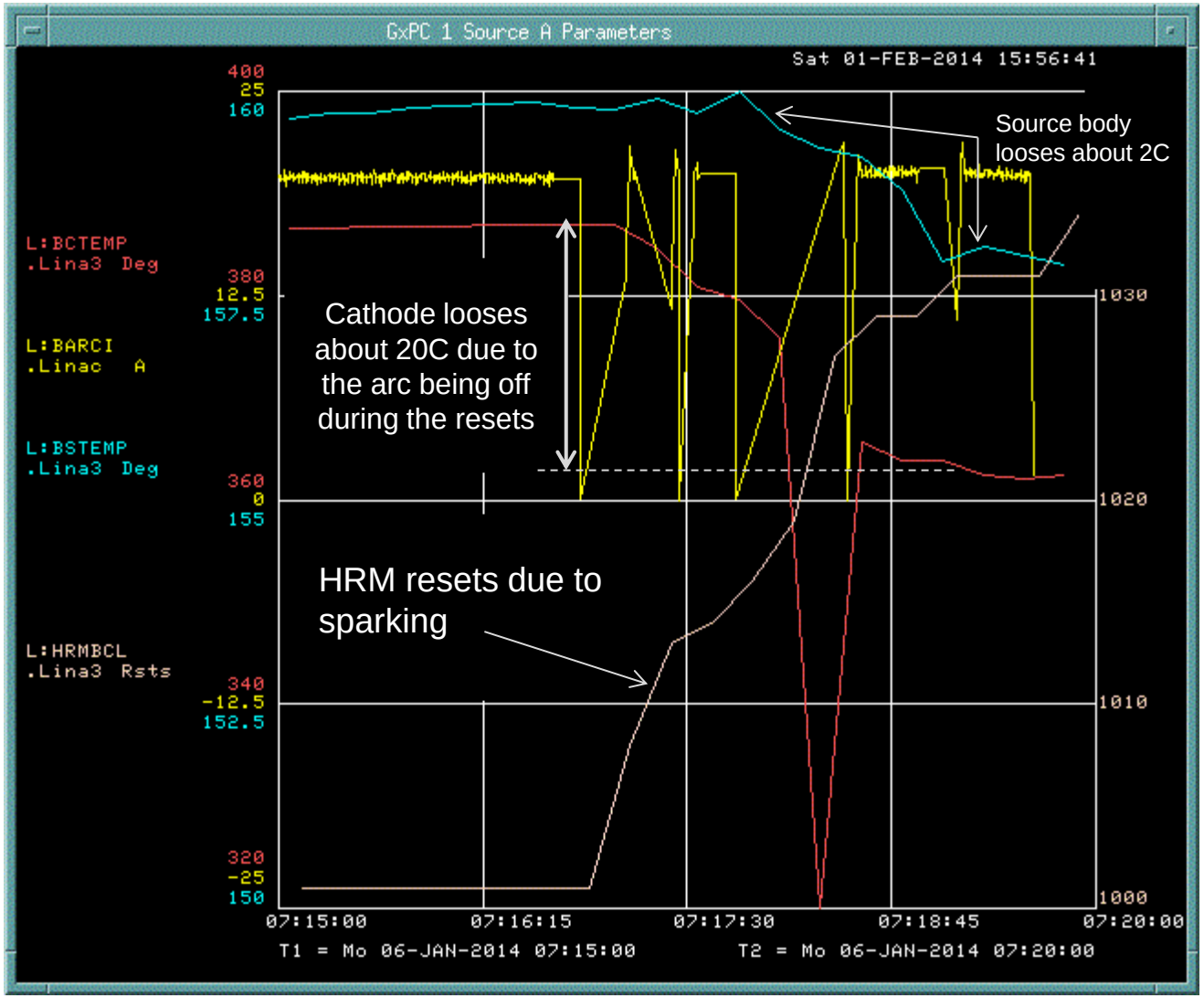








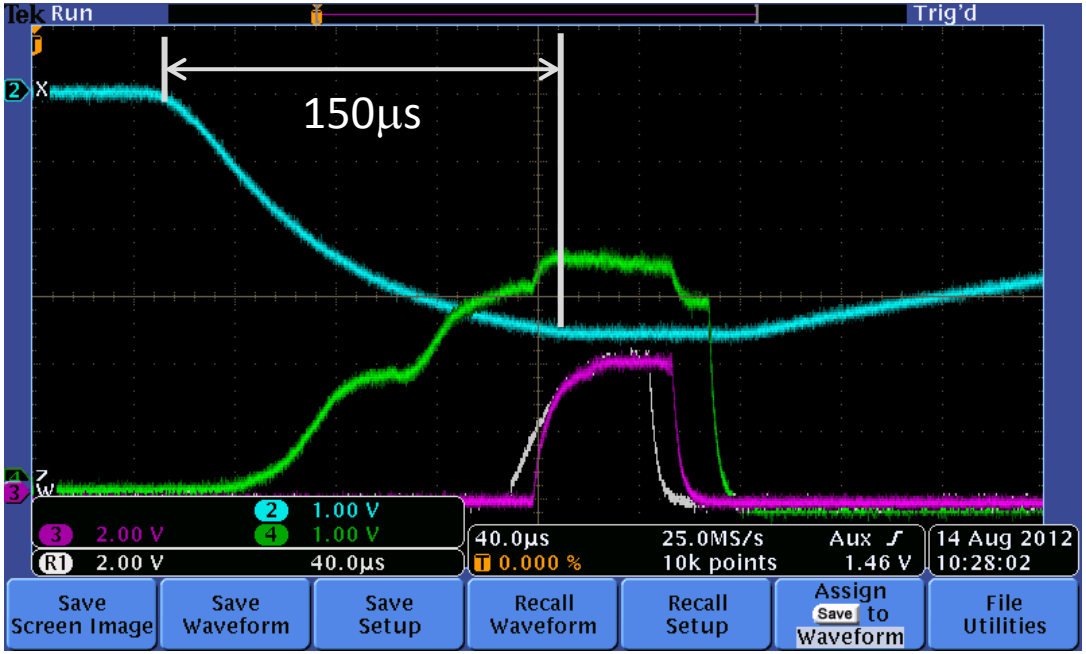
Source electronics



HRM in the HV rack hangs up during heavy sparking. During resets the HRM is off for a few seconds which means that the arc is not on during that time. This allows the cathode and source body to cool off since the only heating is from the arc power: (150V)(15A)(15Hz)(230μs) = 7.8W average power

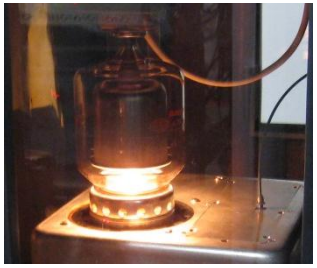
What we are working on:

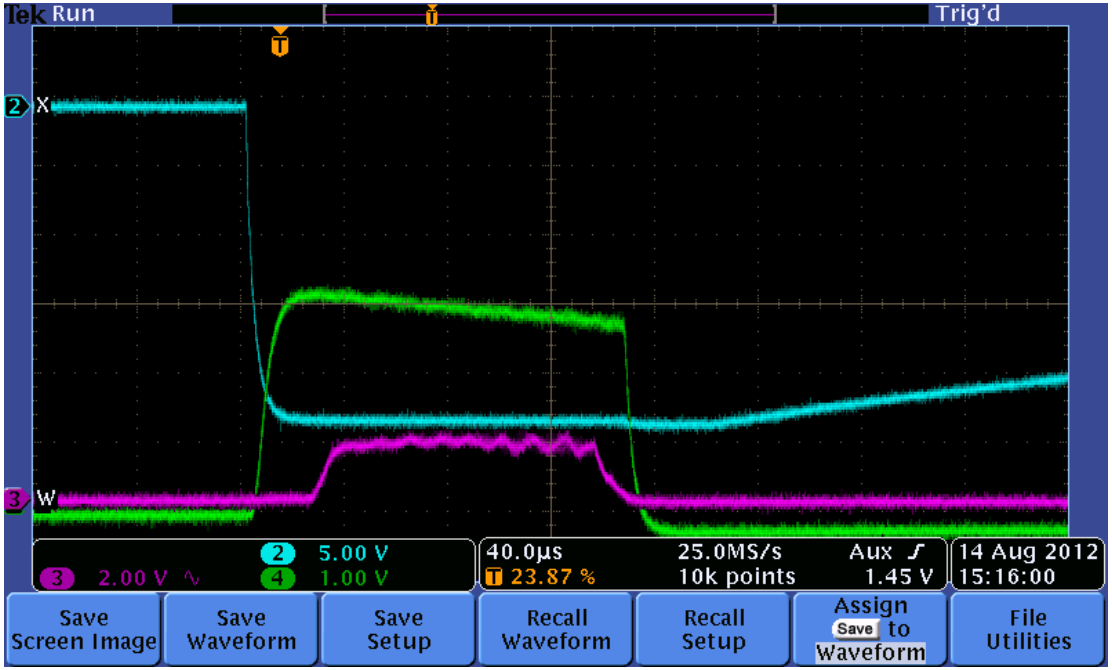
- Solid State extractor pulsers
- New gas valves
- 2 stage extraction
- Removing HRM from HV rack
- current regulated arc modulator
- Better Cs boiler (no glass, heat tape)
- Tungsten dimpled cathode



Current extractor pulser

- Vacuum tube based
- 150µs rise time
- Tube lifetime 3 months
- Long arc PW needed (230µs)
- Source duty factor 0.3%



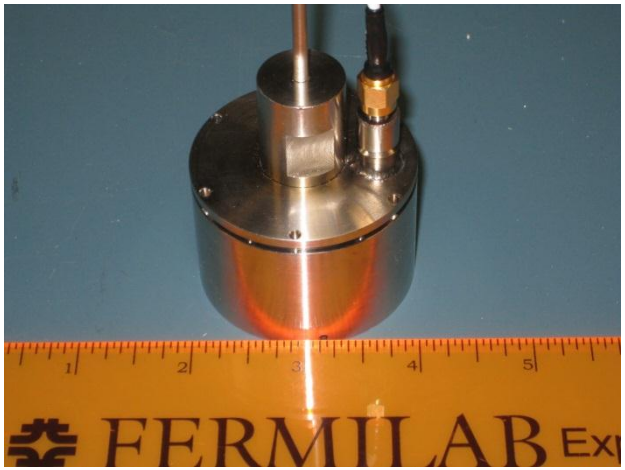


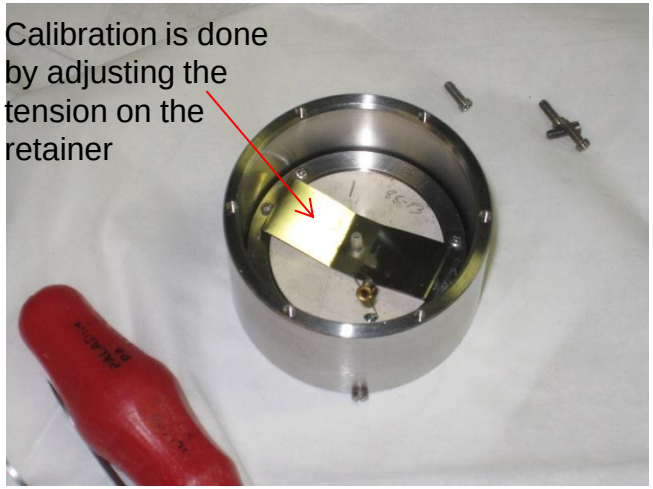
DTI Solid State Switches

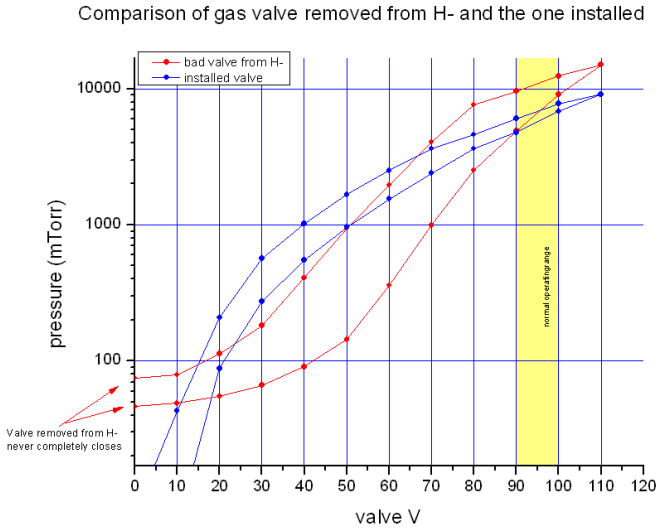
- 9.6µs rise time
- 50kV, 50A switches
- Source duty factor 0.12% a decrease of 40% !
- Should allow even longer lifetimes

Gas Valves

The current gas valves are Veco PV-10 piezoelectric valves. They are fast and reliable for the most part and have been in use since day one.







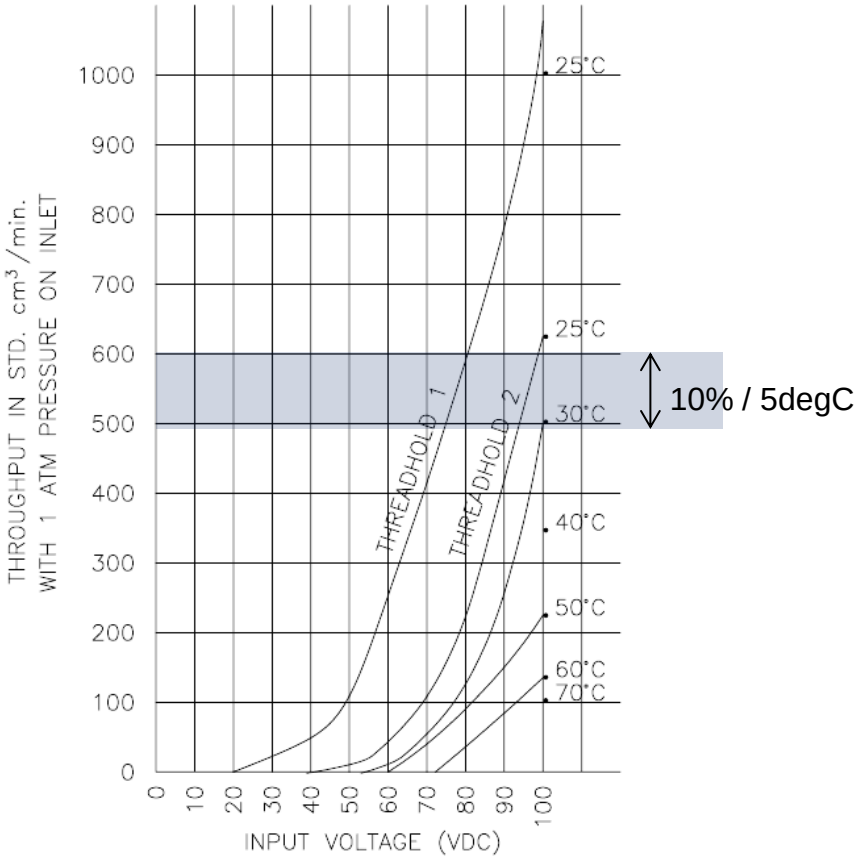
End up with a hysteresis curve like these. The valves start to open around 20V and are fully open by 100V

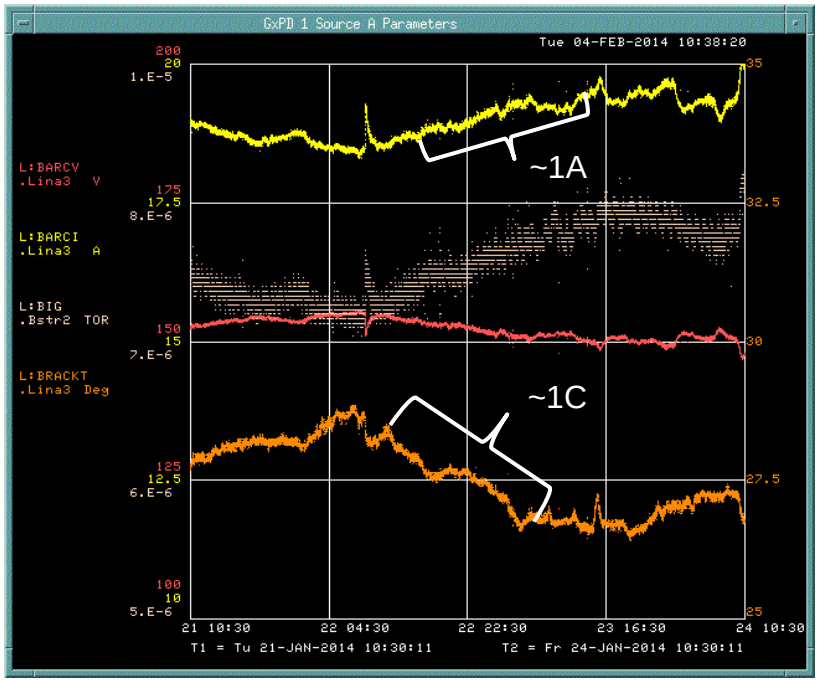
Gas Valves

However, these valves have a terrible temperature dependence !

- Even a change as small as 1C changes the arc current by about 1.5A and a change is source pressure of 1x 10^-6 Torr !
- This is a big change that can lead to sparking and big changes in beam current!

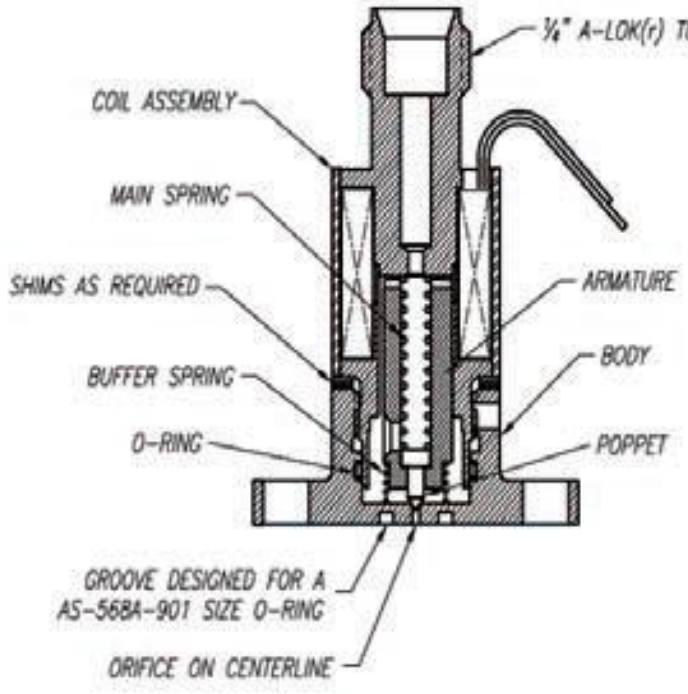
Veco PV-10 data sheet

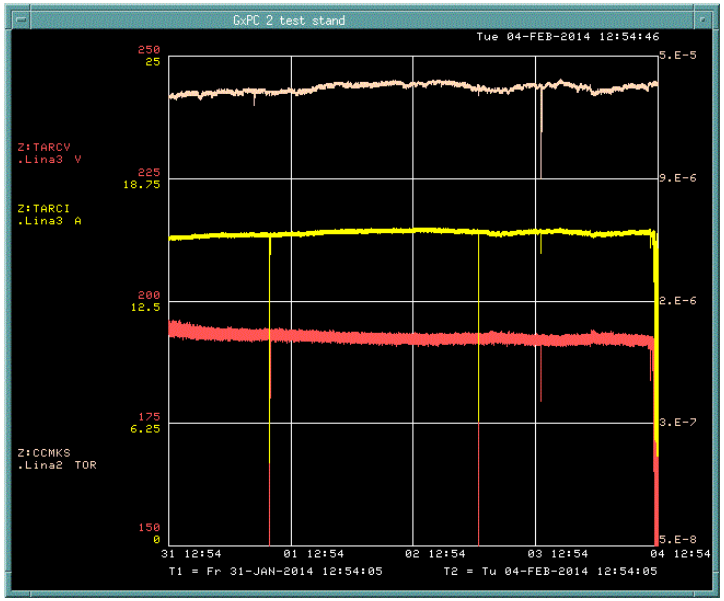




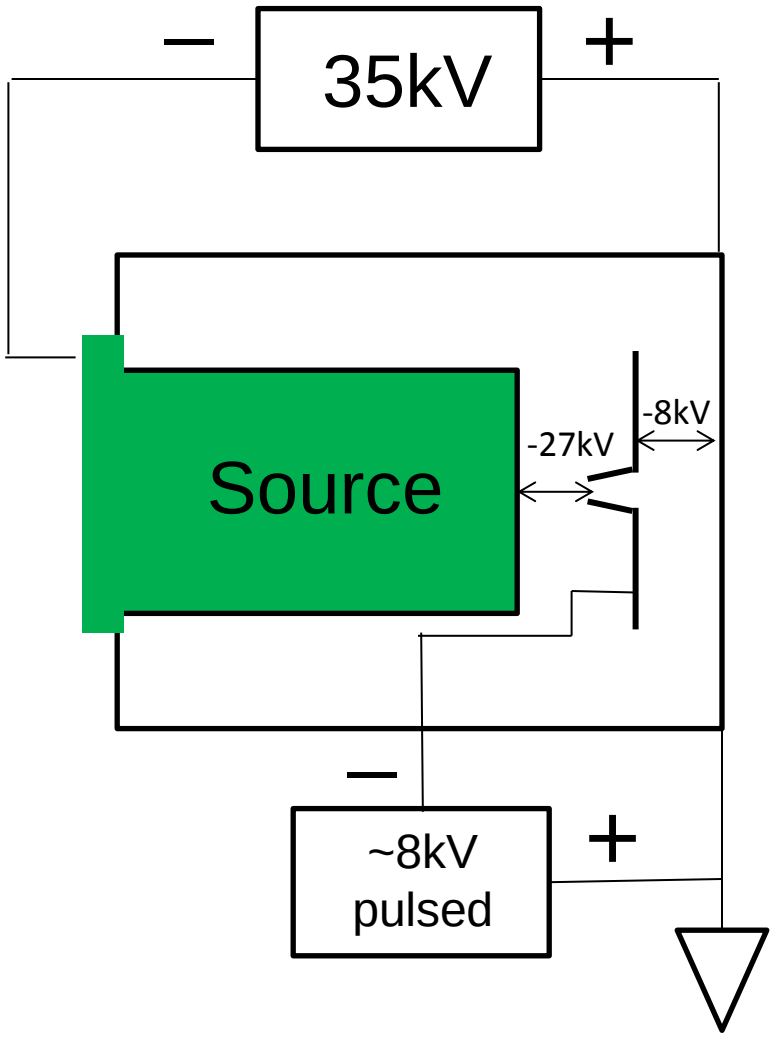
Gas Valves

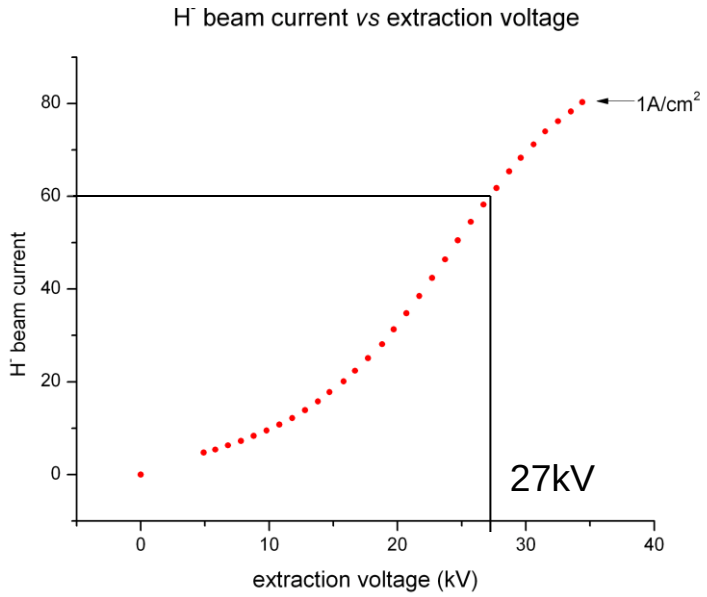
We are currently testing a solenoid type valve that should have not temperature dependence.





2 stage extraction scheme





- We only 27kV across extraction gap
- Less voltage should reduce sparking
- No need to pulse HV rack (it would set at 35kV DC)
- Currently testing on test stand

-35kV – (-27kV) – (-8kV) = 0

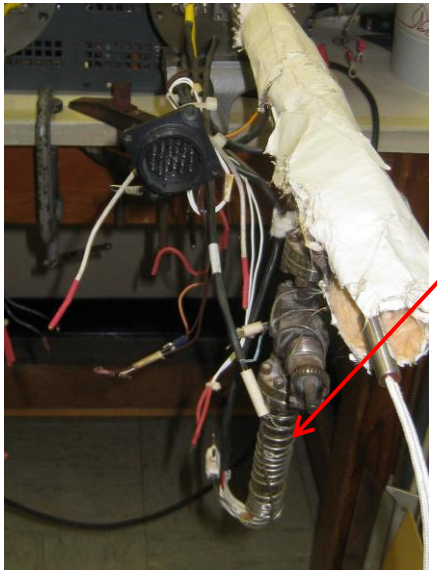
HRM removal

- Plan to remove HRM and install it in a ground controls rack.
- Communication via fiber transceivers will be installed
- Will be a big help in reducing the affect of sparking
- Will reduce overall spark rate due to asynchronous rebooting of HRM

Thanks to Mike Kucera for pursuing this option !

Cs boiler

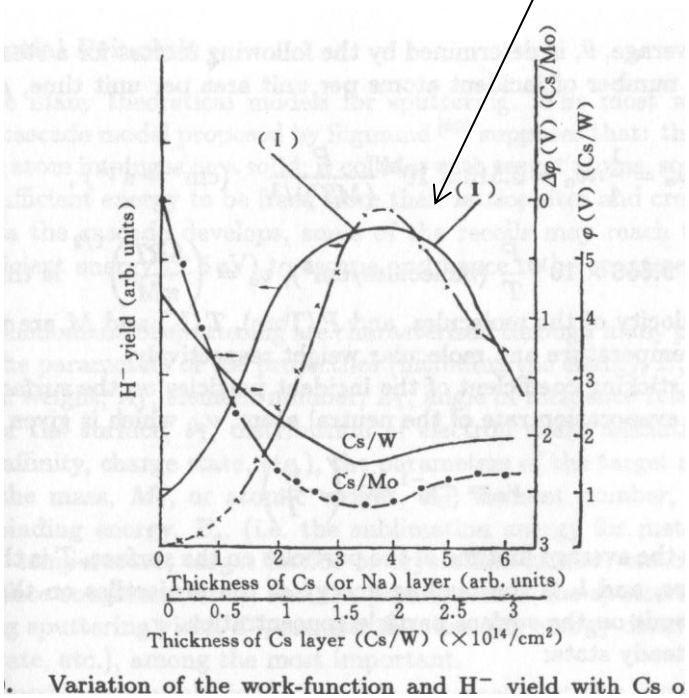
- We us 5g ampules of Cs.
- Sometimes Cs gets trapped in the broken glass



Need to get rid of heat tape and go to heater like BNL

W cathode dimple

Cs on W H- production peak is broader



Variation of the work-function and H⁻ yield with Cs o

All of this is cool, but the coolest thing about working on sources is: You don't have to commit a crime to be on the cover of the Chicago Tribune !

Thanks for your attention !