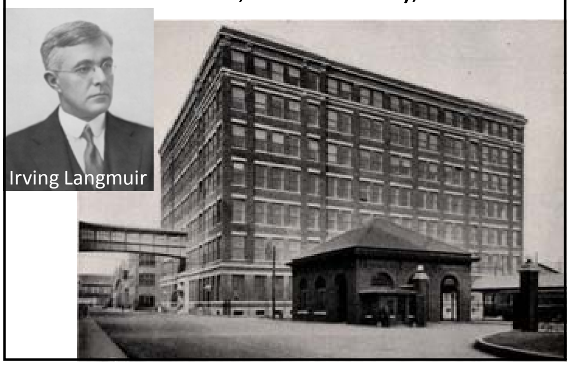
Negative Ion Sources: Magnetron and Penning

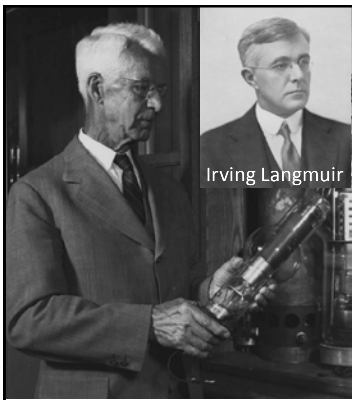
Dan Faircloth
Ion Source Section Leader
Rutherford Appleton Laboratory

Overview

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

GE Research Lab, Schenectady, NY 1916





Albert Hull

Using magnetism to find alternatives to patented electrostatic control of valves

E x B

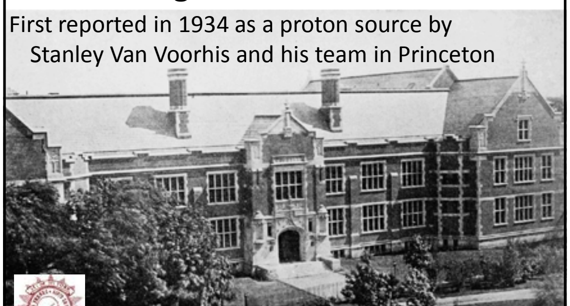
1920 Comet valves? Boomerang valves? Ballistic valves? MAGNETRON VALVES

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

Langmuir talks to his fellow New England scientists

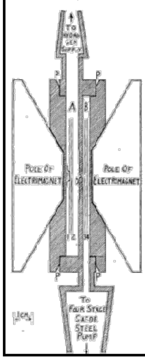
Magnetron Ion Source

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

Louis Maxwell
The Franklin Institute
Philadelphia 1930

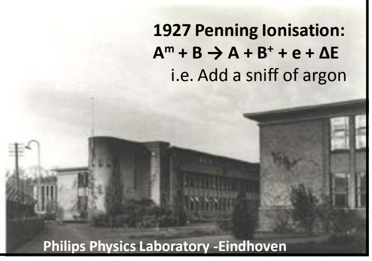


Penning Ion Source

1937 Penning Ionisation Gauge or Philips Ionisation Gauge (PIG)

Frans Penning

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

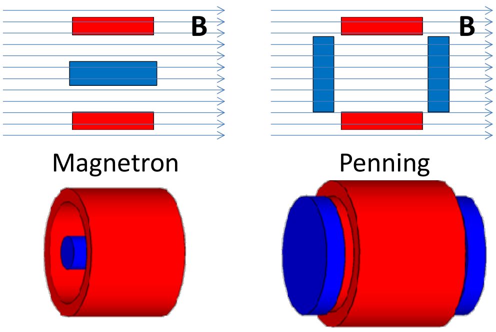


Spawn a series of variations

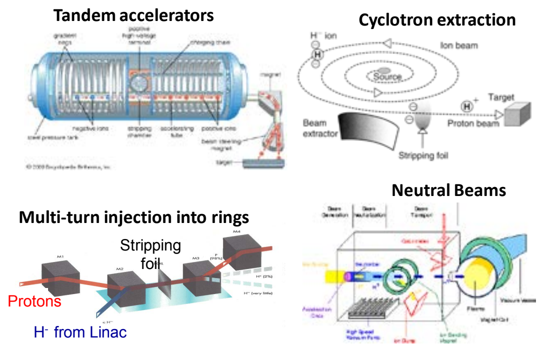
- Penning Source - Calutron source
  - Bernas source
  - Nielson source
- Magnetron Source - Freeman source

The Penning style source (Calutron) starts the Cold War

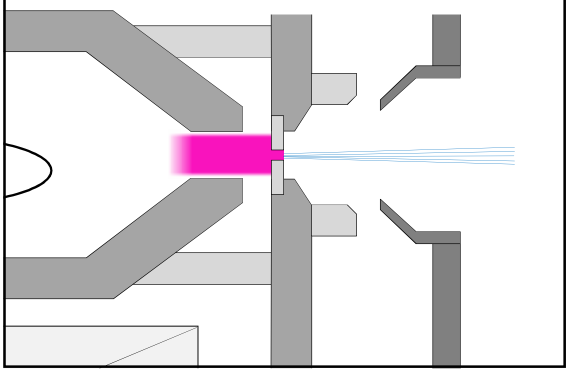
Fundamental Geometry



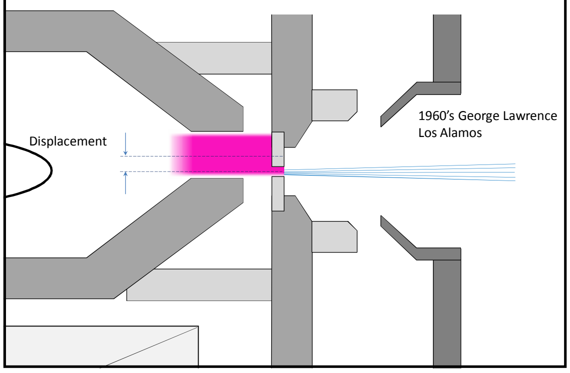
Increasing Need for Negative Ion Beams



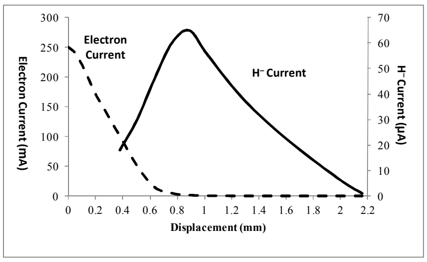
Off Axis Duoplasmatron Extraction



Off Axis Duoplasmatron Extraction

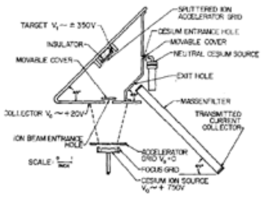


Off Axis Duoplasmatron Extraction



1962 Victor Krohn

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



Space Technology Laboratories inc.
Redondo Beach, California

Early 1970s Budker Institute of Nuclear Physics Novosibirsk

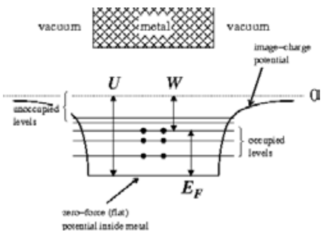
Surface Plasma Sources (SPS)

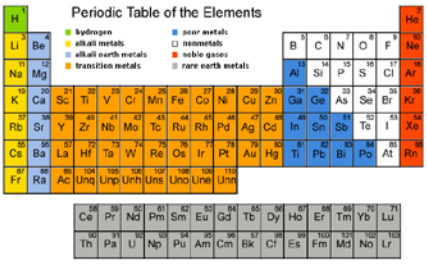
Gennady Dimov, Yuri Belchenko , Vadim Dudnikov

Production of H⁻ ions by surface ionisation with the addition of ceasium

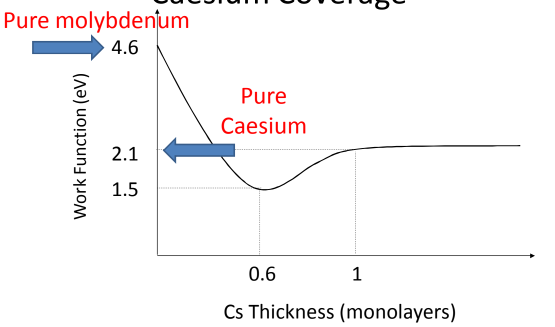
Electrodes...

...have work functions

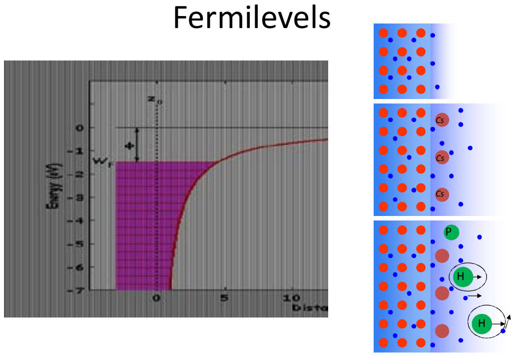




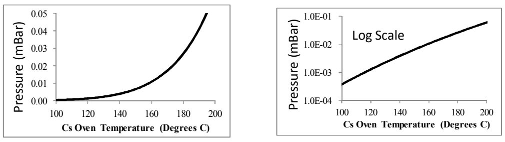
Caesium Coverage



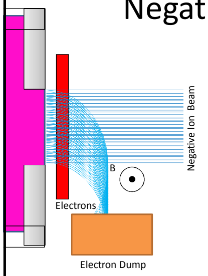
Fermilevels



Vary Caesium Vapour Pressure to Control Caesium Coverage



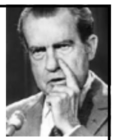
Negative Ion Extraction



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

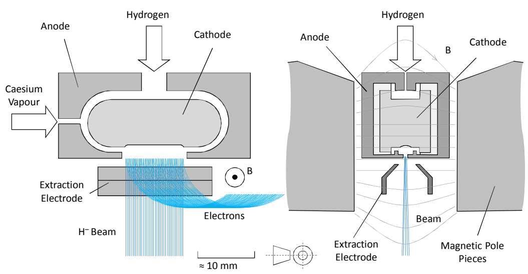
SPS sources:
only 0.5 to 10 times H⁻ current

1970s Caesium Revolution!

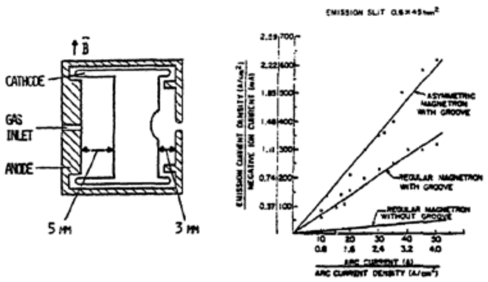


- Soviets spread the word and develop sources
- BNL Krsto Prelec et al. develop the magnetron for NBI
- LANL Paul Allison et al. develop the Penning
- Berkley Ehlers+Leung develop Surface Converter sources
- Fermilab Chuck Schmidt et al. develop the BNL magnetron for accelerators

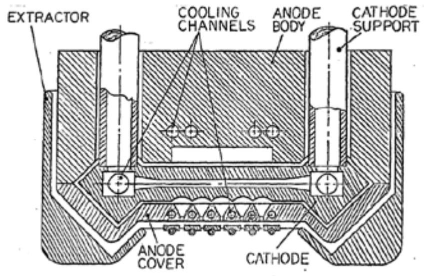
Magnetron Source



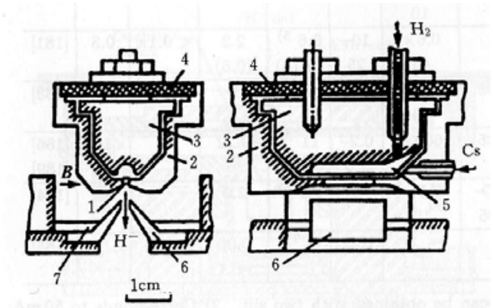
1980 BNL Developments



BNL 2 A Beam H^- Magnetron for NBI

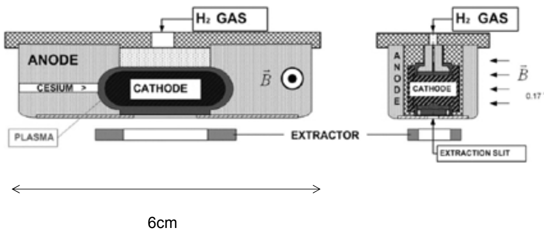


11 A Budker Semiplanotron



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

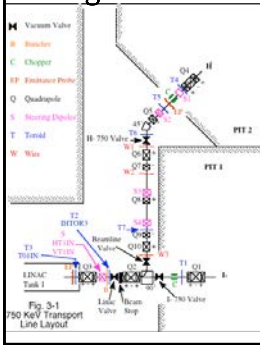
Fermilab Magnetron



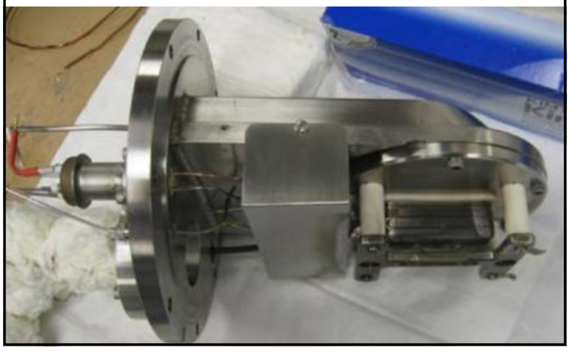
Fermilab Magnetron

Fermilab Magnetron

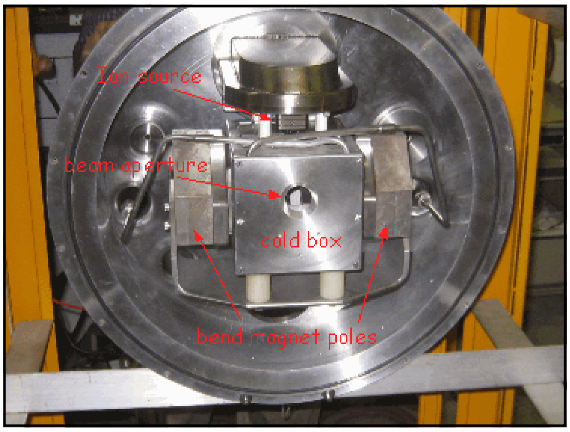

Fermilab Magnetron

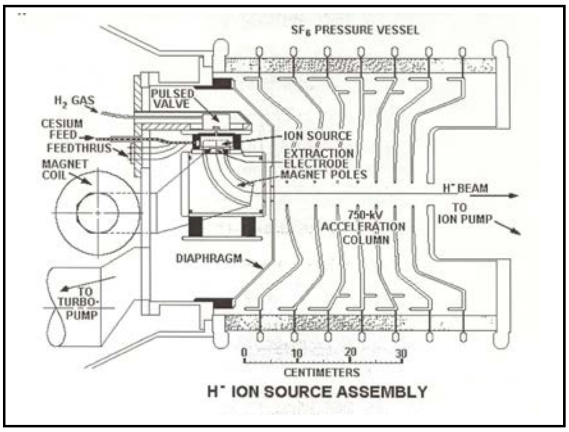


Fermilab Magnetron

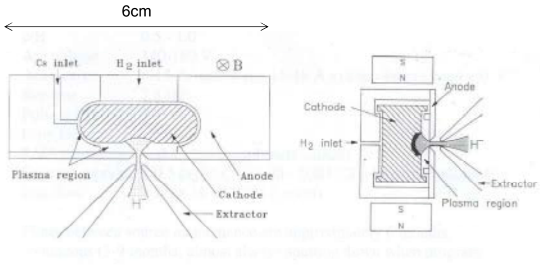


Caesium:
Friend of H^-
but
mortal enemy
of high voltage





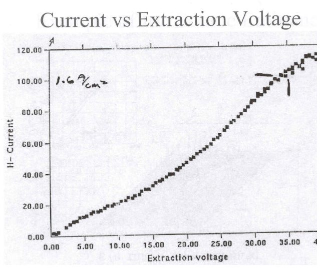
BNL Magnetron



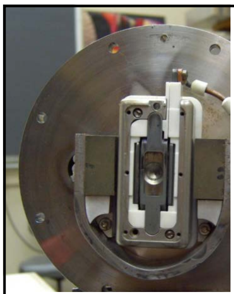
1989 BNL Magnetron

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

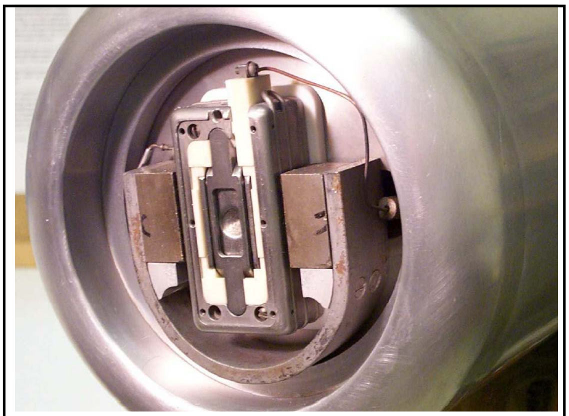
H- current	90-100mA
Extraction Voltage	35kV
Arc Voltage	140-160V
Arc Current	8-18A
Rep Rate	7.5Hz
Pulse width	700μs
Duty Factor	0.5%
Cs consumption	0.5mg/hr
Gas Flow	3sccm
RMS emittance	0.4 πmm.mrad (normalized)

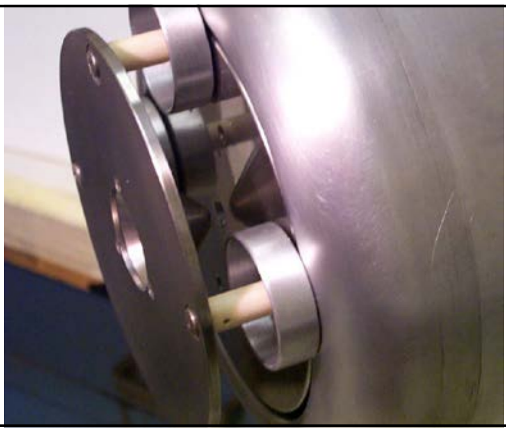


BNL Magnetron

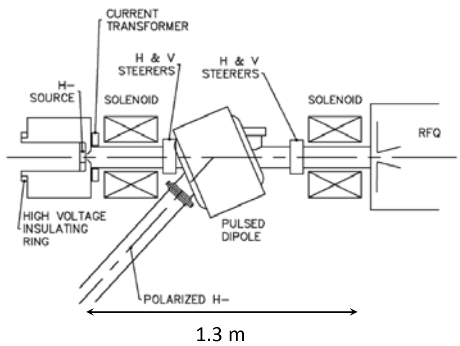


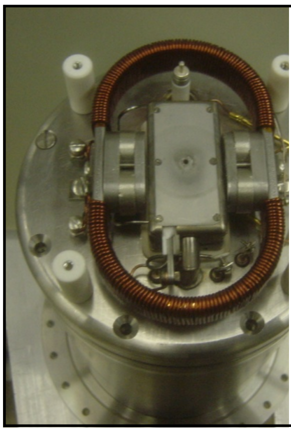
Extraction cone:
45deg angle
3.2 mm aperture





BNL Magnetron

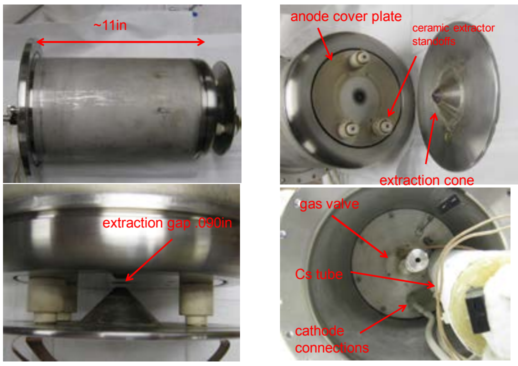




2012 New Fermilab Magnetron

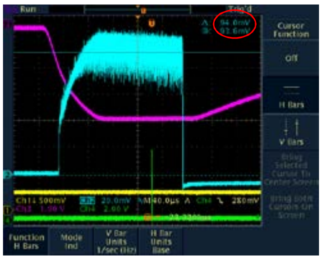
(Based on BNL design)

New Fermilab Magnetron

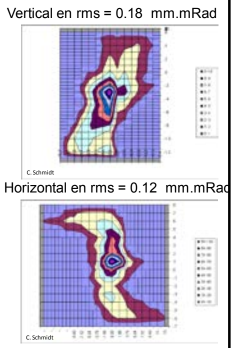


Fermilab HINS Magnetron

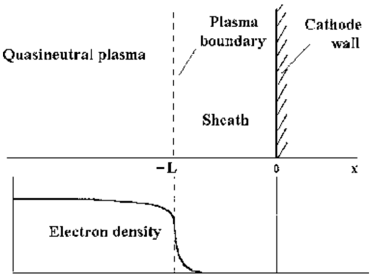
94 mA

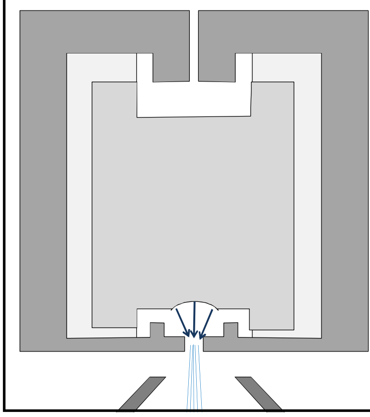


Magnetrons are noisy!



Plasma Sheath





Magnetron Source

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

Resonant Charge Exchange

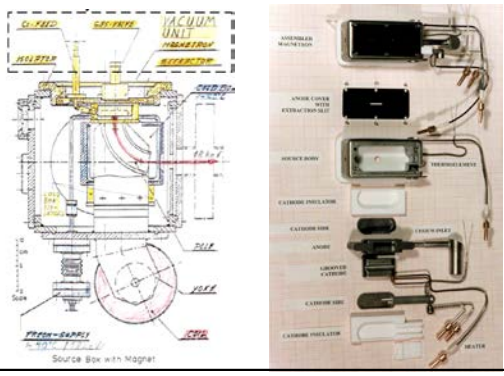
Leaving slow H^-

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

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

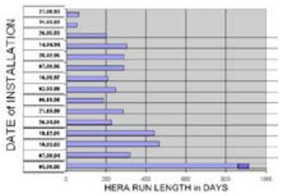
Can undergo resonant charge exchange with fast H^- (≈ 80 eV) produced at the cathode surfaces

DESY HERA Magnetron Source



DESY HERA Magnetron Source

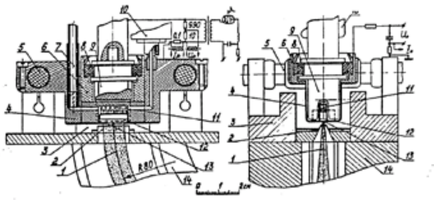
beam energy	18 keV	arc voltage	140 V
H^- beam current	60 mA	arc current	47 A
emittance		arc pulse width	75 μsec
$\varepsilon_{x\,rms,norm}$ ($\varepsilon_{x\,90\%,norm}$) (35mA beam)	0.28(1.35) π mm mrad	extraction repetition rate	1/4 Hz -1Hz
$\varepsilon_{y\,rms,norm}$ ($\varepsilon_{y\,90\%,norm}$)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



Almost Three Years!

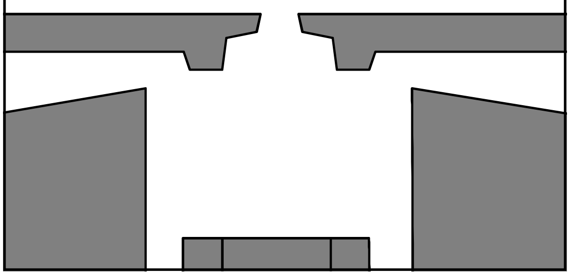
Penning Ion Sources

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



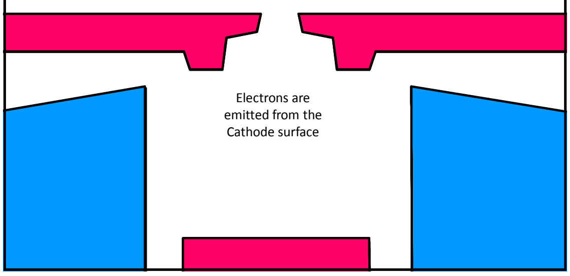
Key Design Points for H^- Production:

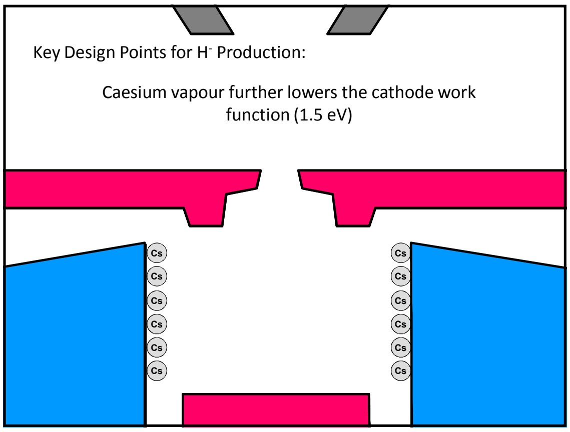
1. Electrodes are made of Molybdenum 4.5 eV work function and a high melting point

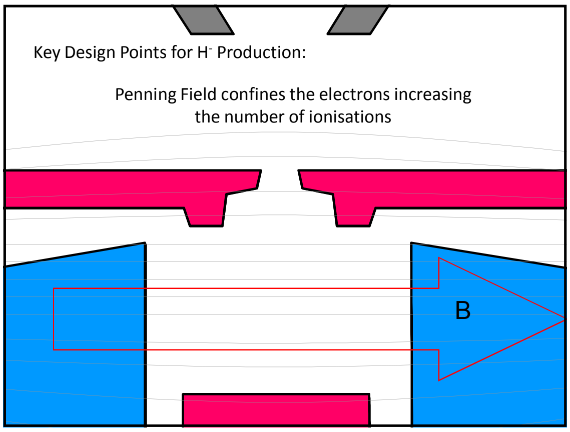


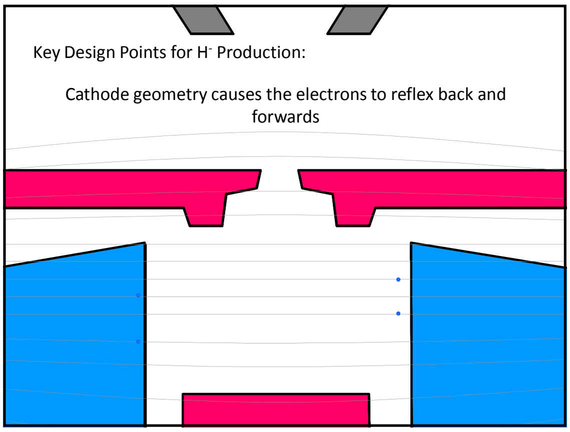
Key Design Points for H^- Production:

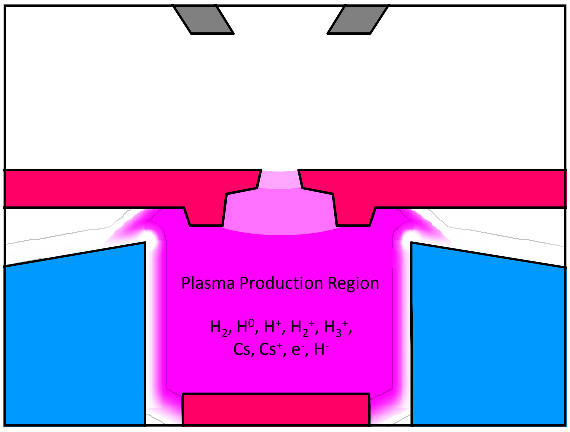
Electrodes are made of Molybdenum (4.5 eV work function) and a high melting point

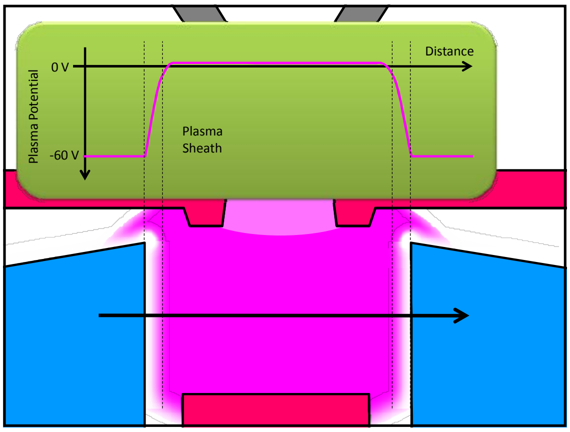


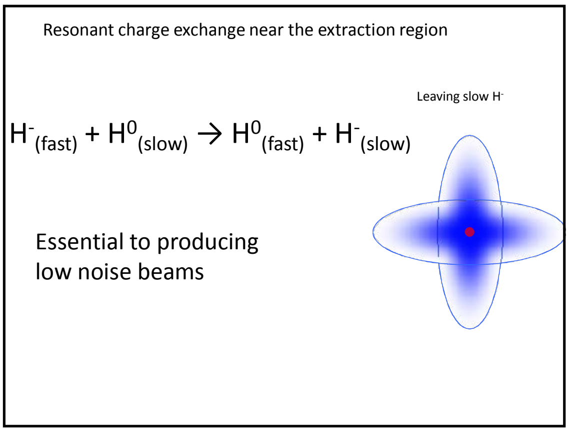

Key Design Points for H^- Production:
Caesium vapour further lowers the cathode work function (1.5 eV)
Cs

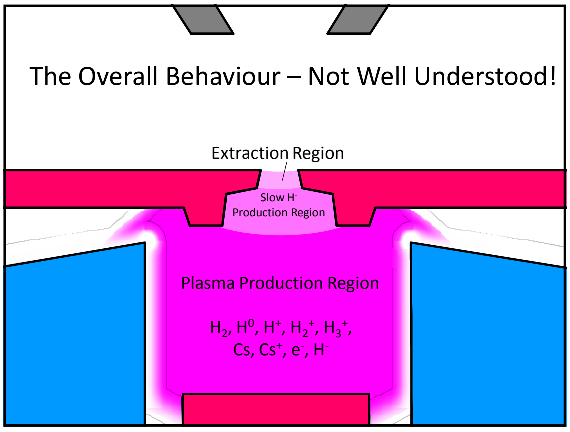

Key Design Points for H^- Production:
Penning Field confines the electrons increasing the number of ionisations
B

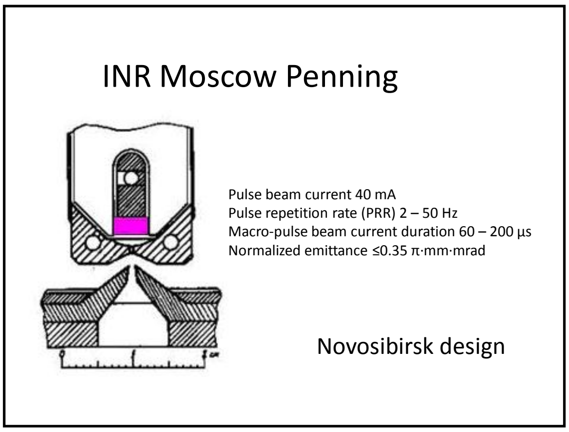

Key Design Points for H^- Production:
Cathode geometry causes the electrons to reflex back and forwards


Plasma Production Region
H_2, H^0, H^+, H_2^+, H_3^+,
Cs, Cs^+, e^-, H^-

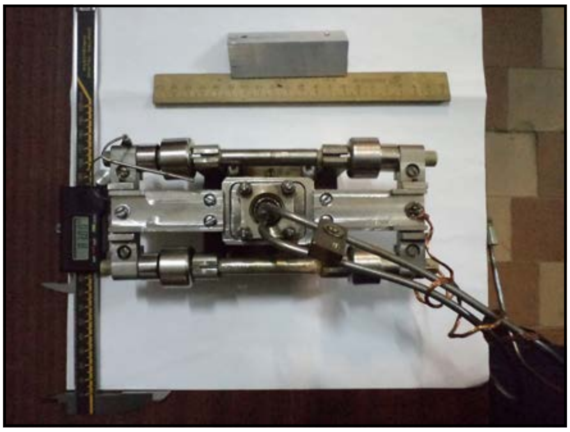

Plasma Potential
0 V
-60 V
Distance
Plasma Sheath

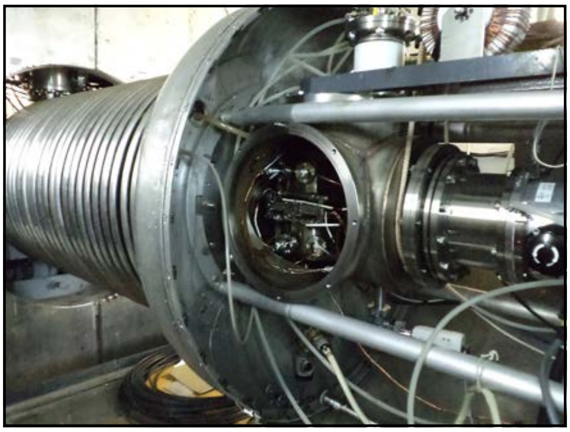

Resonant charge exchange near the extraction region
$H^-_{(fast)} + H^0_{(slow)} \rightarrow H^0_{(fast)} + H^-_{(slow)}$
Leaving slow H^-
Essential to producing low noise beams

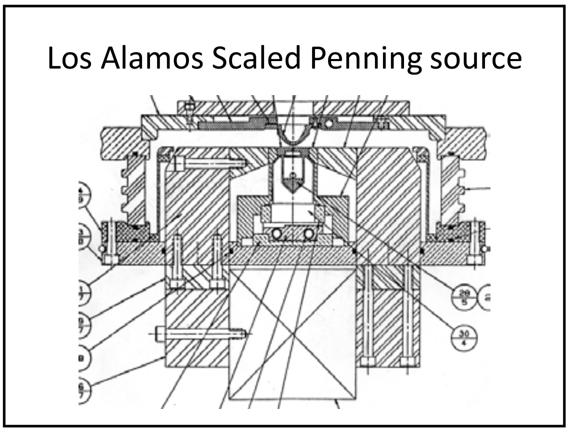

The Overall Behaviour – Not Well Understood!
Extraction Region
Slow H⁻ Production Region
Plasma Production Region
H_2, H^0, H^+, H_2^+, H_3^+,
Cs, Cs^+, e^-, H^-

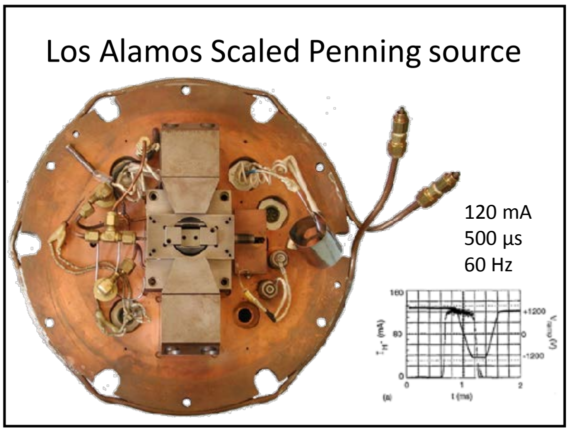

INR Moscow Penning
Pulse beam current 40 mA
Pulse repetition rate (PRR) 2 – 50 Hz
Macro-pulse beam current duration 60 – 200 μs
Normalized emittance ≤0.35 π·mm·mrad
Novosibirsk design

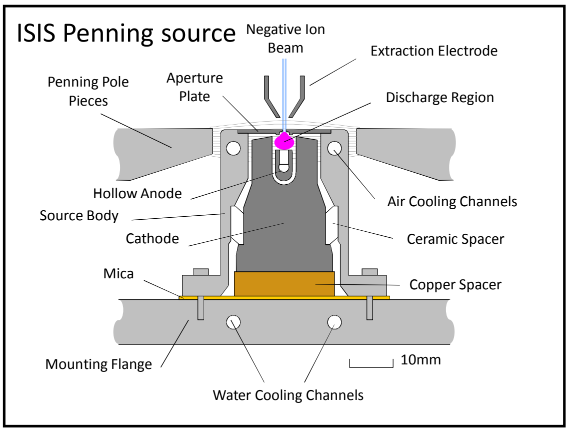

INR Moscow Penning

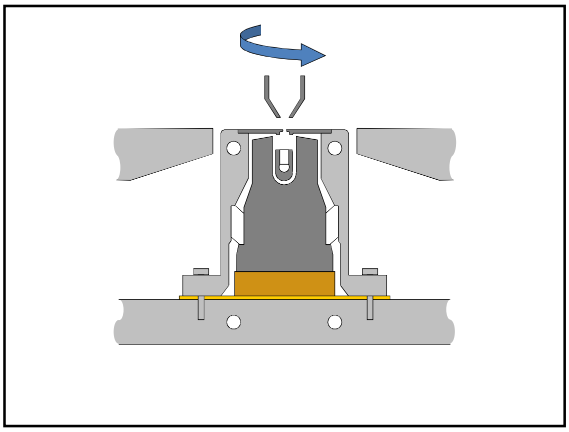


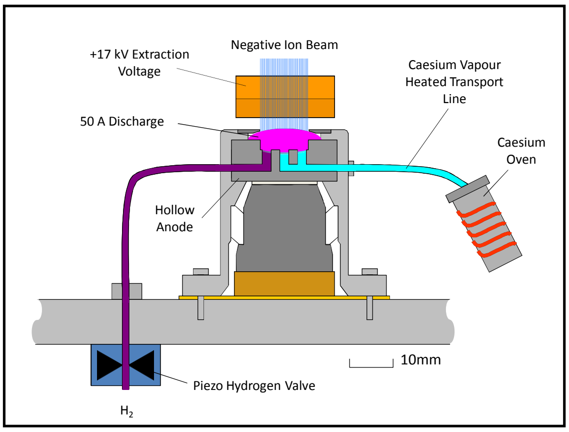


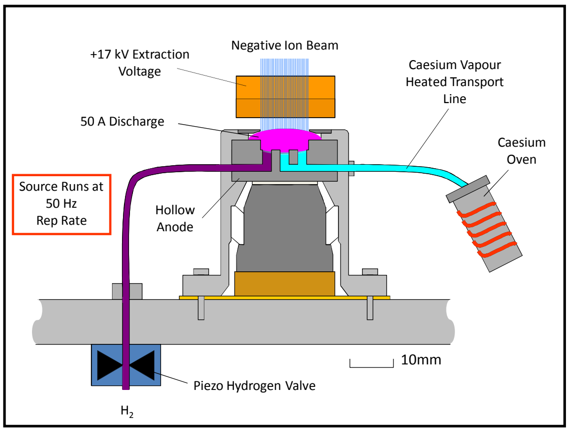

Los Alamos Scaled Penning source

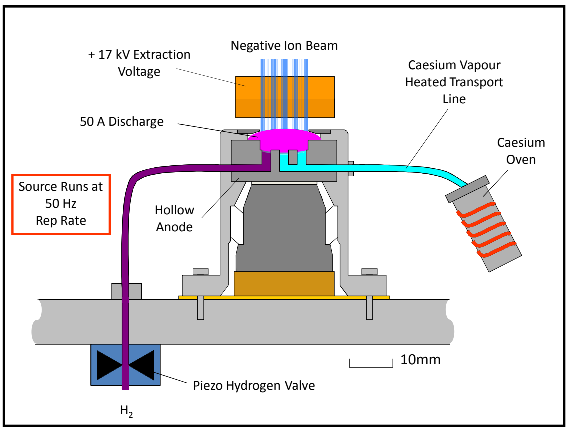

Los Alamos Scaled Penning source
120 mA
500 µs
60 Hz

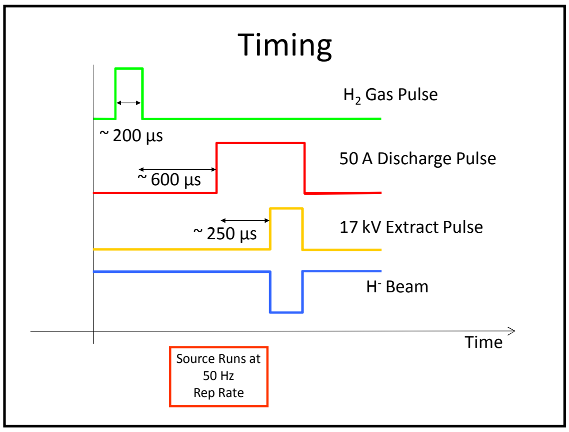

ISIS Penning source
Negative Ion Beam
Extraction Electrode
Penning Pole Pieces
Aperture Plate
Discharge Region
Hollow Anode
Source Body
Cathode
Air Cooling Channels
Ceramic Spacer
Mica
Copper Spacer
Mounting Flange
10mm
Water Cooling Channels

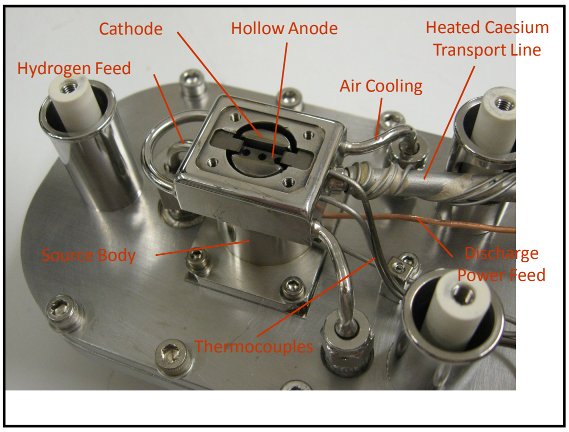


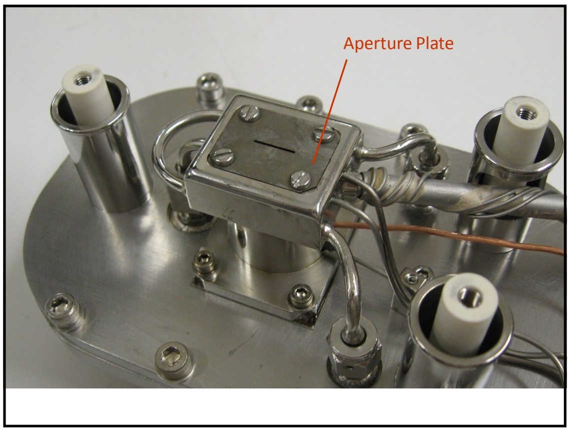

+17 kV Extraction Voltage
Negative Ion Beam
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Hollow Anode
10mm
Piezo Hydrogen Valve
H2

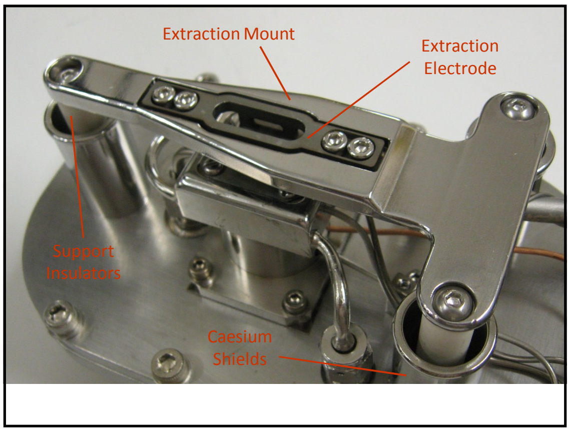

+17 kV Extraction Voltage
Negative Ion Beam
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Source Runs at 50 Hz Rep Rate
Hollow Anode
10mm
Piezo Hydrogen Valve
H2

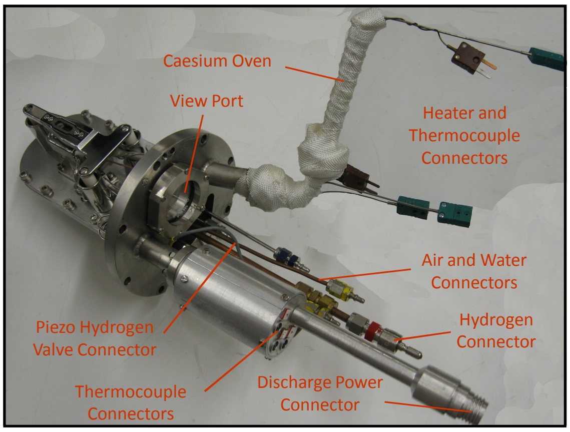

+ 17 kV Extraction Voltage
Negative Ion Beam
Caesium Vapour Heated Transport Line
50 A Discharge
Caesium Oven
Source Runs at 50 Hz Rep Rate
Hollow Anode
10mm
Piezo Hydrogen Valve
H2


Timing
H2 Gas Pulse
~ 200 µs
50 A Discharge Pulse
~ 600 µs
17 kV Extract Pulse
~ 250 µs
H- Beam
Time
Source Runs at
50 Hz
Rep Rate

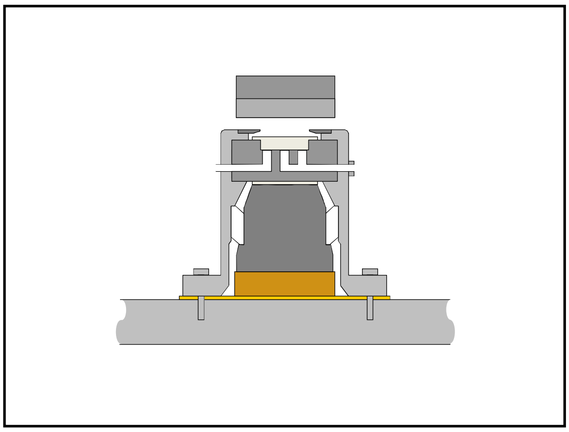

Cathode
Hollow Anode
Heated Caesium
Transport Line
Hydrogen Feed
Air Cooling
Source Body
Discharge
Power Feed
Thermocouples

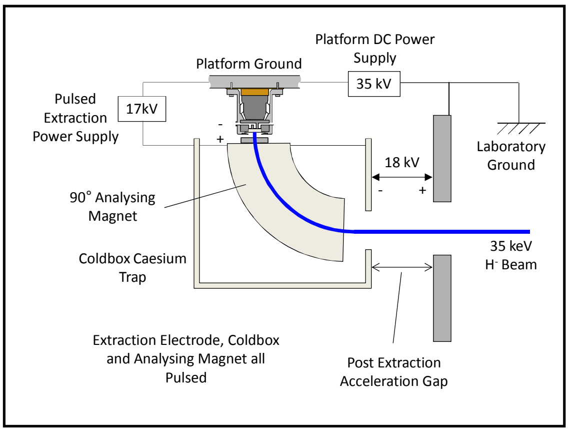

Aperture Plate

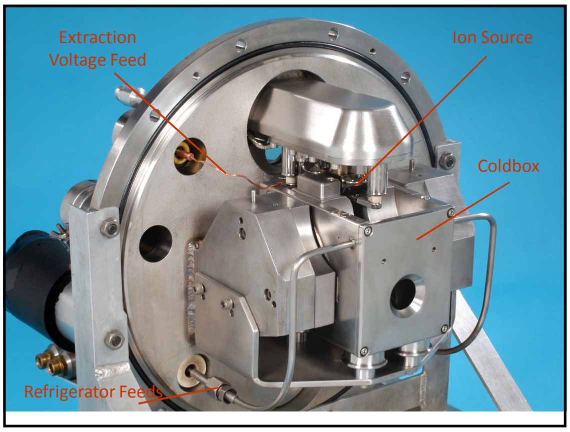

Extraction Mount
Extraction
Electrode
Support
Insulators
Caesium
Shields

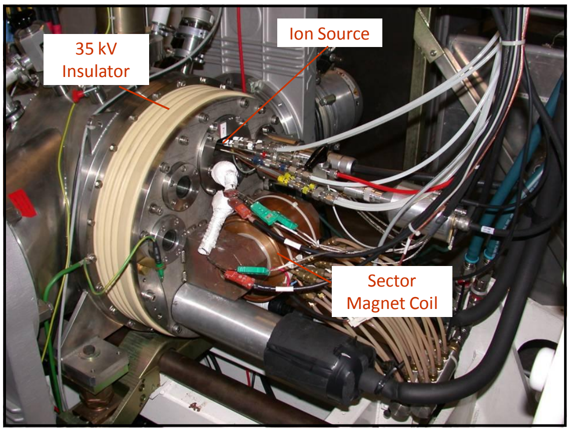

Caesium Oven
View Port
Heater and
Thermocouple
Connectors
Air and Water
Connectors
Hydrogen
Connector
Piezo Hydrogen
Valve Connector
Thermocouple
Connectors
Discharge Power
Connector

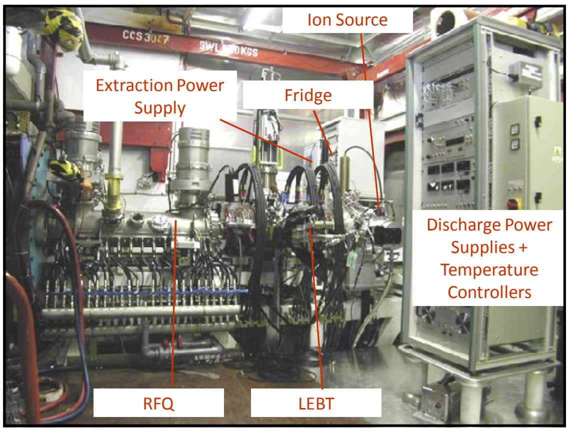

Caesium Oven

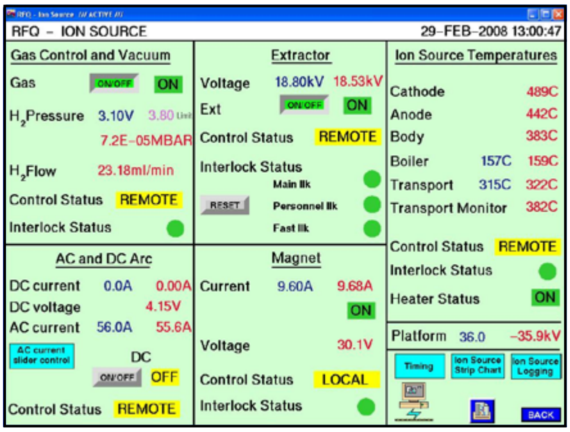



Platform DC Power Supply
Platform Ground
35 kV
Pulsed Extraction Power Supply
17kV
18 kV
Laboratory Ground
90° Analysing Magnet
Coldbox Caesium Trap
35 keV H- Beam
Extraction Electrode, Coldbox and Analysing Magnet all Pulsed
Post Extraction Acceleration Gap


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


RFQ – ION SOURCE
29-FEB-2008 13:00:47
Gas Control and Vacuum
Gas ON/OFF ON
H2Pressure 3.10V 3.80
7.2E-05MBAR
H2Flow 23.18ml/min
Control Status REMOTE
Interlock Status
Extractor
Voltage 18.80kV 18.53kV
Ext ON/OFF ON
Control Status REMOTE
Interlock Status
Main Ilk
RESET
Personnel Ilk
Fast Ilk
Ion Source Temperatures
Cathode 489C
Anode 442C
Body 383C
Boiler 157C 159C
Transport 315C 322C
Transport Monitor 382C
Control Status REMOTE
Interlock Status
Heater Status ON
AC and DC Arc
DC current 0.0A 0.00A
DC voltage 4.15V
AC current 56.0A 55.6A
AC current slider control
DC
ON/OFF OFF
Control Status REMOTE
Magnet
Current 9.60A 9.68A
ON
Voltage 30.1V
Control Status LOCAL
Interlock Status
Platform 36.0 -35.9kV
Timing
Ion Source Strip Chart
Ion Source Logging
BACK

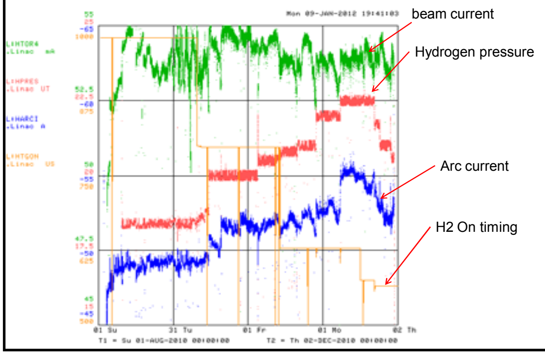
SPS Failure Modes

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

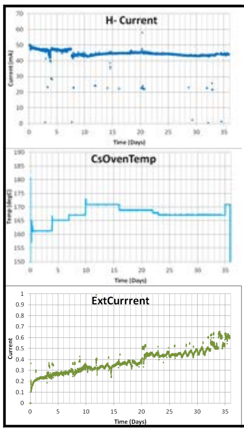
Compare SPS Lifetimes

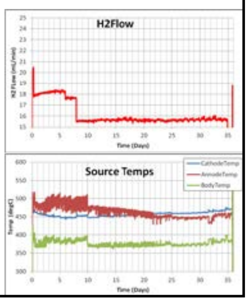
	DESY	FNAL	BNL	ISIS
Discharge Current (A)	47	50	18	55
Pulse length (us)	75	80	700	800
Rep rate (Hz)	6.25	15	7.5	50
Duty Factor (%)	0.047	0.12	0.525	4
Lifetime (Days)	900	200	270	30
Lifetime (Plasma Days)	0.42	0.24	1.42	1.2

Fermilab Magnetron Ageing

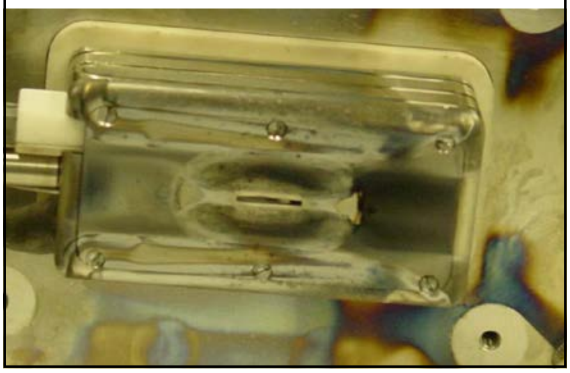


ISIS Penning Ageing

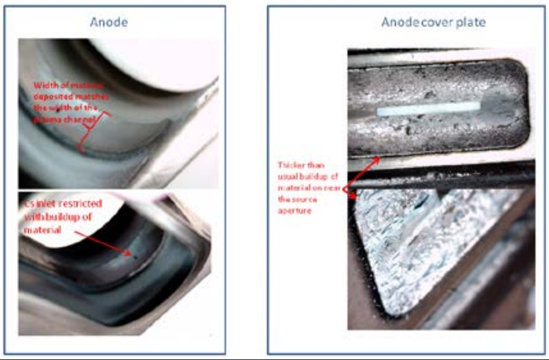




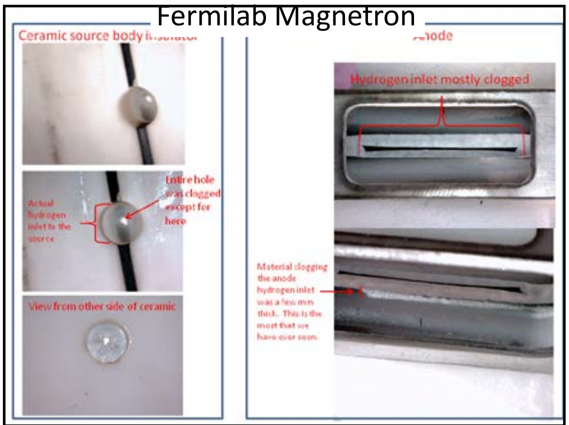
Fermilab Magnetron



Fermilab Magnetron



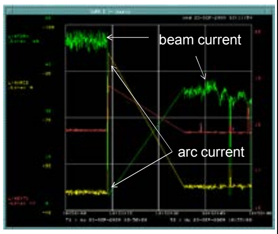
Fermilab Magnetron



Fermilab Magnetron

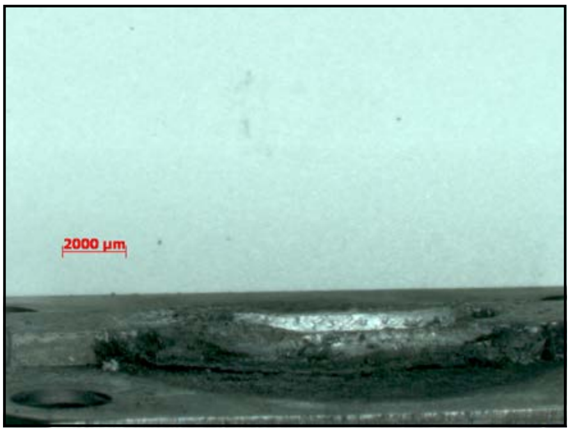
Typical Source Failures

Cathode material flakes blocking source extraction aperture

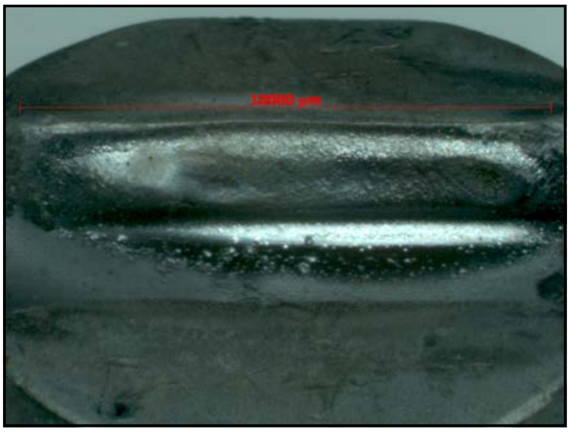


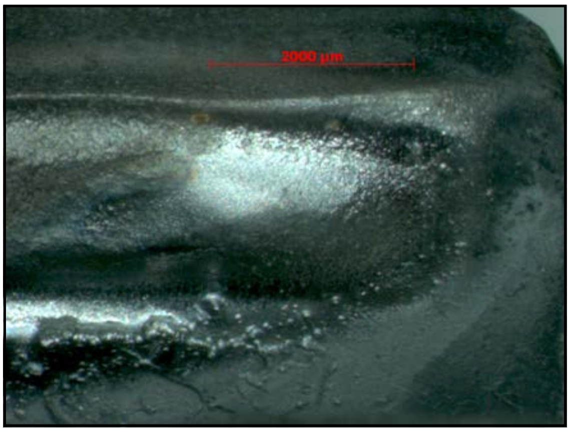
Cathode material flakes off and causes cathode/anode shorts

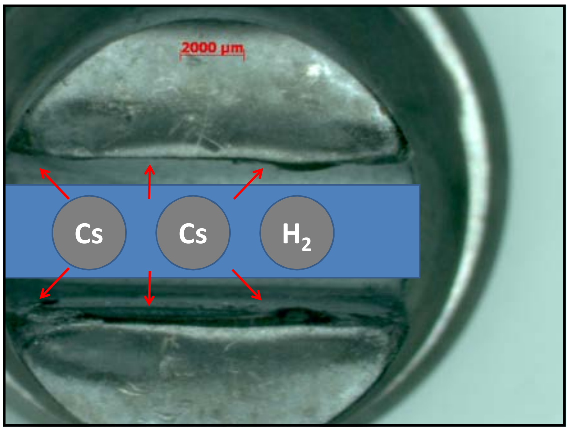
ISIS Penning 26 Day Electrode Wear

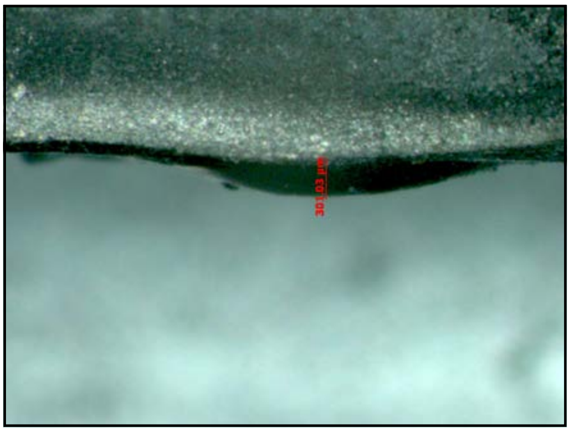

2000 µm


2000 µm


10000 µm


2000 µm


2000 µm
Cs
Cs
H2


301.03 µm

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

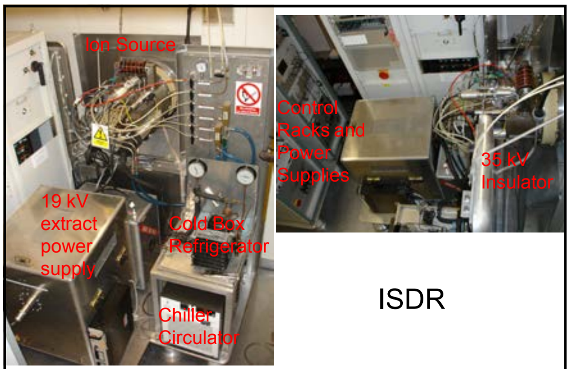
FETS Source

Experimental sources

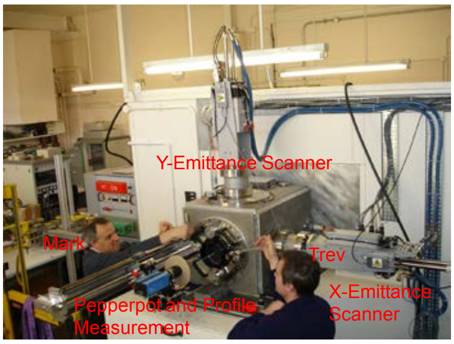
High current

Long pulse

65 keV



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

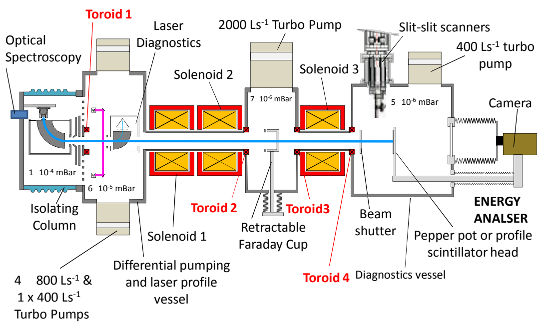
Experimental sources

High current

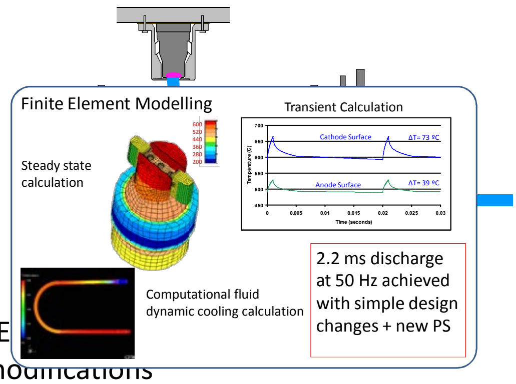
Long pulse

65 keV

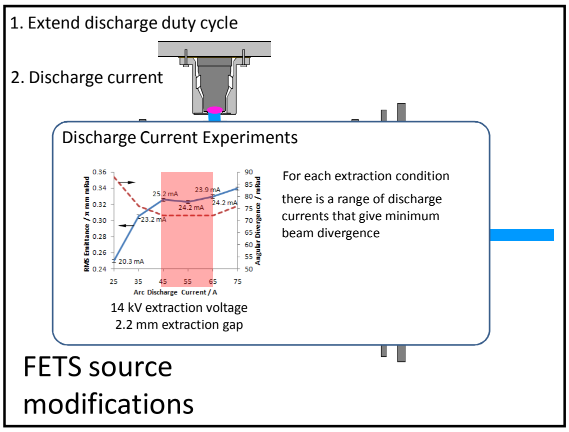
Diagnostics and a LEBT are critical to Ion Source Development

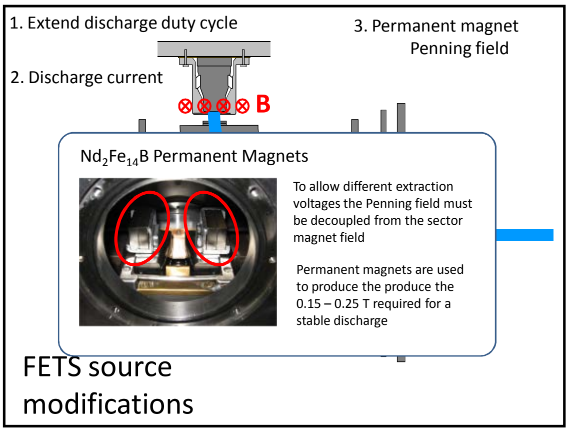


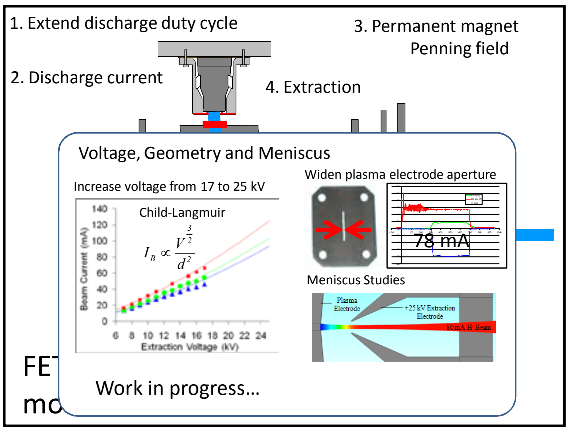
1. Extend discharge duty cycle

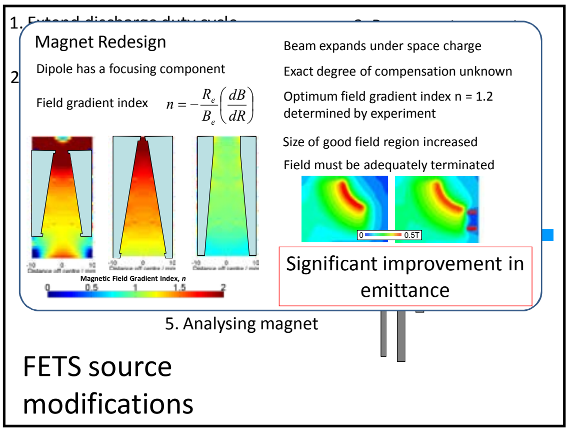


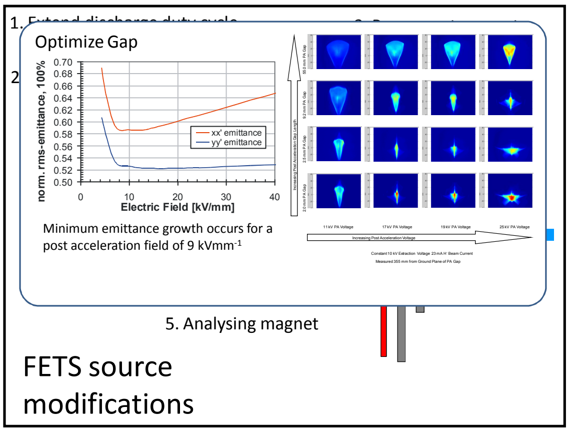
FE modifications

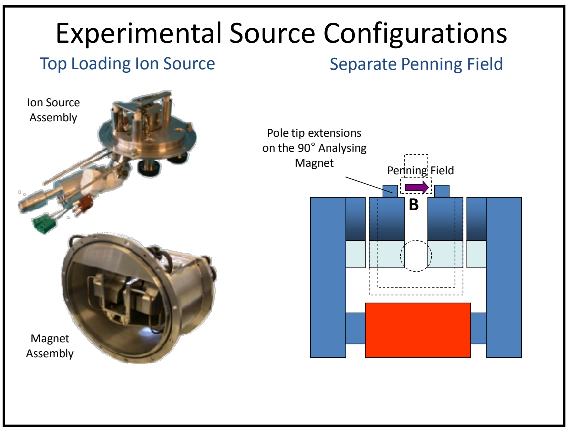

1. Extend discharge duty cycle
2. Discharge current
Discharge Current Experiments
For each extraction condition there is a range of discharge currents that give minimum beam divergence
Arc Discharge Current / A
14 kV extraction voltage
2.2 mm extraction gap
FETS source modifications

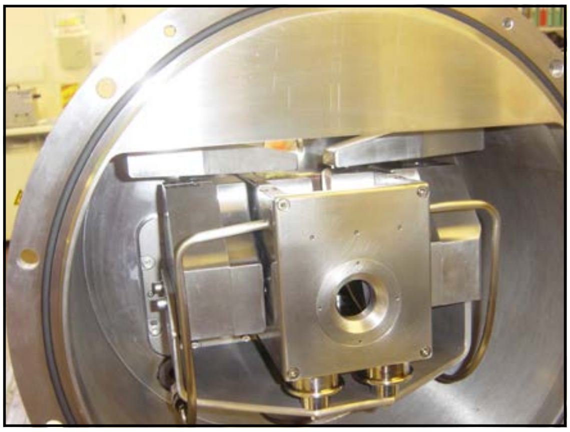

1. Extend discharge duty cycle
2. Discharge current
3. Permanent magnet Penning field
B
Nd2Fe14B Permanent Magnets
To allow different extraction voltages the Penning field must be decoupled from the sector magnet field
Permanent magnets are used to produce the produce the 0.15 – 0.25 T required for a stable discharge
FETS source modifications


1. Extend discharge duty cycle
2. Discharge current
3. Permanent magnet Penning field
4. Extraction
Voltage, Geometry and Meniscus
Increase voltage from 17 to 25 kV
Child-Langmuir
Beam Current (mA)
Extraction Voltage (kV)
Widen plasma electrode aperture
78 mA
Meniscus Studies
Work in progress…


Magnet Redesign
Dipole has a focusing component
Field gradient index
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
Magnetic Field Gradient Index, n
Significant improvement in emittance
5. Analysing magnet
FETS source modifications


Optimize Gap
norm. rms-emittance, 100%
Electric Field [kV/mm]
xx' emittance
yy' emittance
Minimum emittance growth occurs for a post acceleration field of 9 kVmm-1
5. Analysing magnet
FETS source modifications

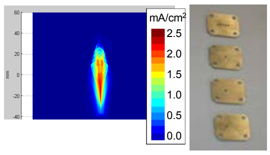

Experimental Source Configurations
Top Loading Ion Source
Separate Penning Field
Ion Source Assembly
Magnet Assembly
Pole tip extensions on the 90° Analysing Magnet
Penning Field
B

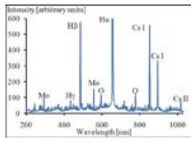


Many Experiments

- Energy Spread
- Extraction Voltage
- Extraction Geometry
- Post Acceleration Gap
- Post Acceleration Voltage
- Anode Geometry
- Operating Conditions

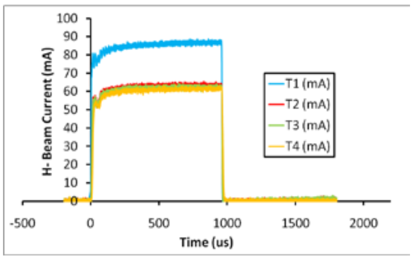
Multi Beamlett Extraction





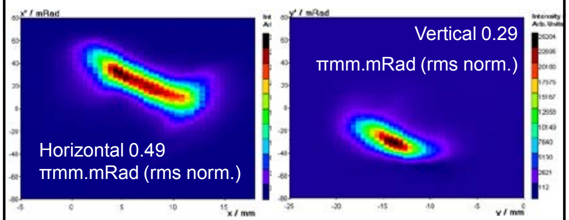
Optical Spectroscopy

62 mA 1ms 50 Hz Operation

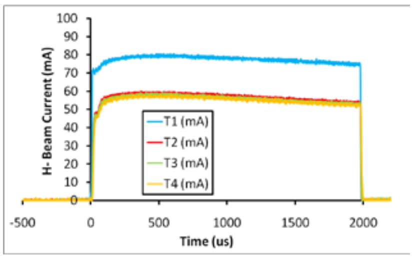


1.2 ms 60 A discharge, 19.6 kV extraction voltage, 65 keV beam, 180°C caesium oven, 16 mLmin^{-1} H_2

Emittances



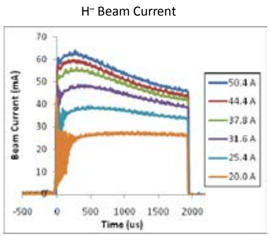
60 mA 2ms 25 Hz Operation



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

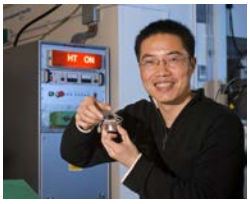


- Hydrogen timing has been fully investigated including double pulses
- Neither caesium or hydrogen settings can mitigate this droop

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:

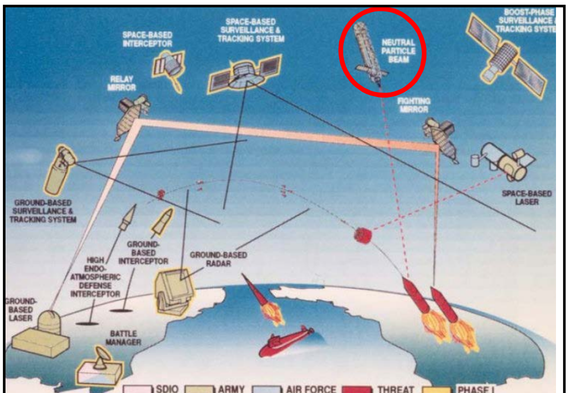
- Detailed understanding of plasma
- Detailed understanding of extraction
- Scaled source

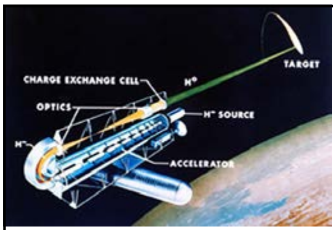
How the Penning Source Ended the Cold War

MAD Strategy:
Mutually
Assured
Destruction

Star Wars

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





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