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U.S. DEPARTMENT OF ENERGY

USPAS - Fundamentals of Ion Sources
7. Multicusp Ion Sources I

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Massachusetts Institute of Technology

Outline

- Introduction – basic principles of multicusp ion sources
- Different heating methods (filament, RF antenna, ECR?)
- Usages: H^+, H^-, He^+, H_2^+, …
- Positive (H^+, H_2^+, He^+, …) multicusp ion sources
  - Optimization
- Negative (H^-, …) multicusp ion sources
  - Volume production
  - Surface-enhanced volume production (Cs)
  - Extraction of negative ions
  - Optimization
- Other types of negative ion sources

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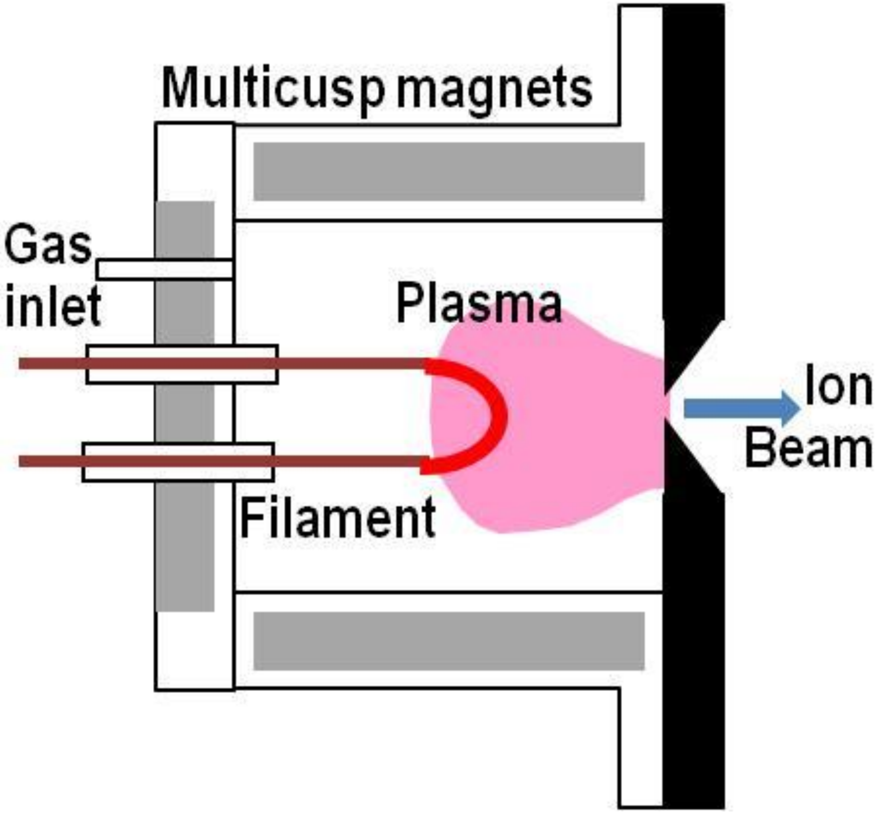
Basics

Basic Building Blocks:

- Confinement
- Raw Material (Gas)
- Energy for Electrons (Heating)
- Extraction



- *1973 Limpaecher & MacKenzie at UCLA build a 86 liter plasma vessel with 1252 alternating Alnico bar magnets lining the walls. Plasma is very quiescent; RSI 44, 1973, 726*
- *1979 Ehlers and Leung at LBNL start to develop multicusp ion sources for hydrogen and later for negative ions.*

Design Parameters

Parameter	Typical Values	Tuning	Comment
Magnetic Field	?	?	
Heating	?	?	
Material	?	?	
Extraction	?	?	

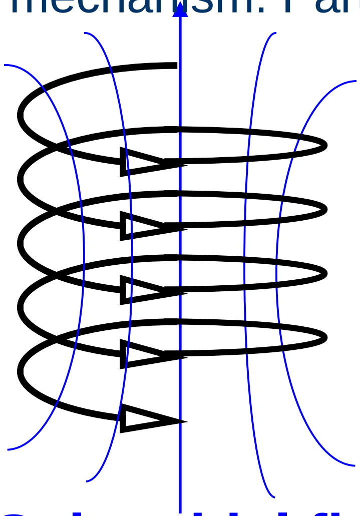
Design Parameters

Parameter	Typical Values	Tuning	Comment
Magnetic Field	?	?	
Heating	?	?	
Material/Gas	?	?	
Extraction	?	?	

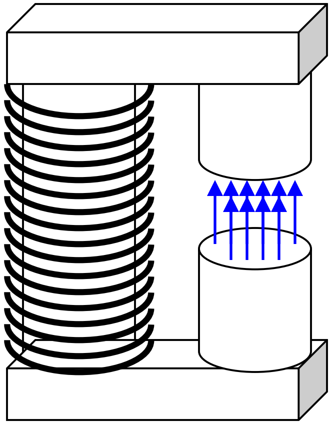
Start with magnetic field…

Magnetic Confinement

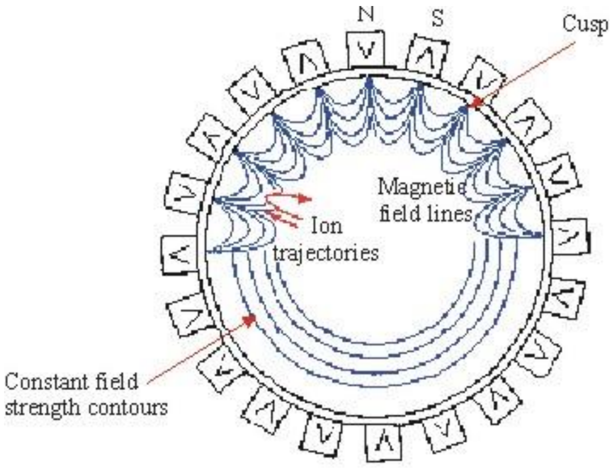
- In the direction of the fields there is no force, transverse the particles are bend into the circular motion $F = q(\vec{E} + \vec{v} \times \vec{B})$
- Helical motion increases the time the electron send in the discharge chamber- field lines can only be crossed through collisions – wall losses are reduced
- Add strongly increasing magnetic field as the confinement mechanism: Particles get reflected by an increasing magnetic field



Solenoidal field

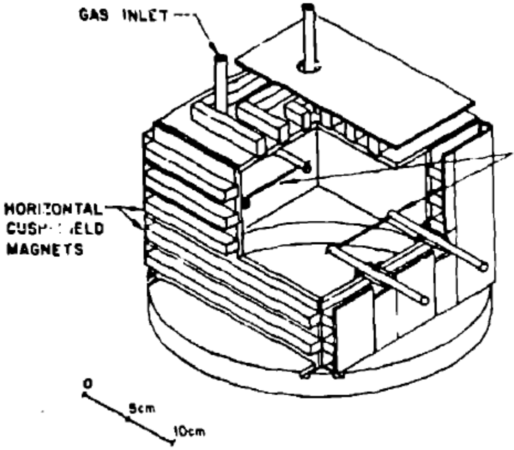


Dipole field

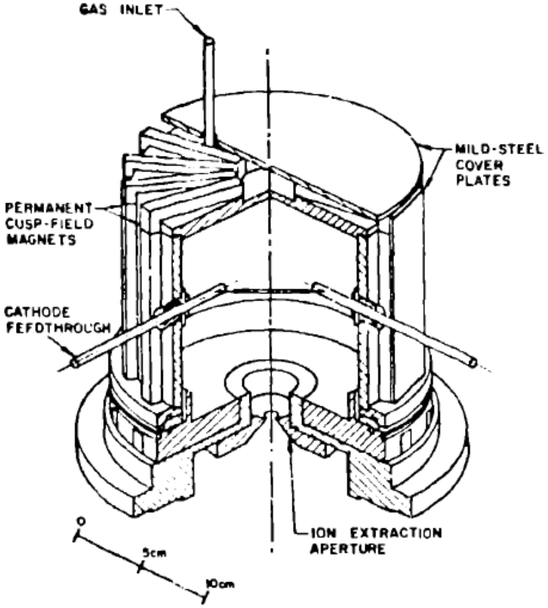


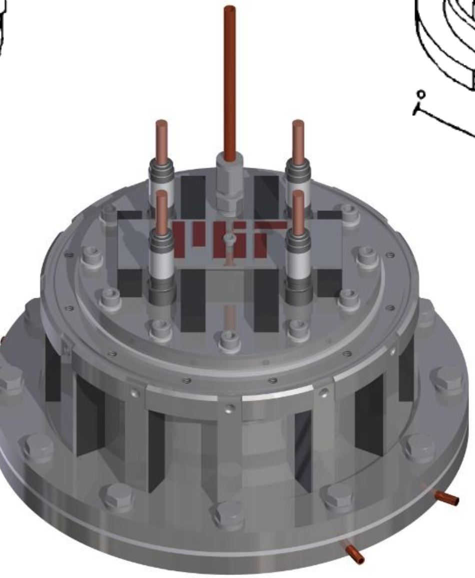
Multicusp field

Multicusp Configurations



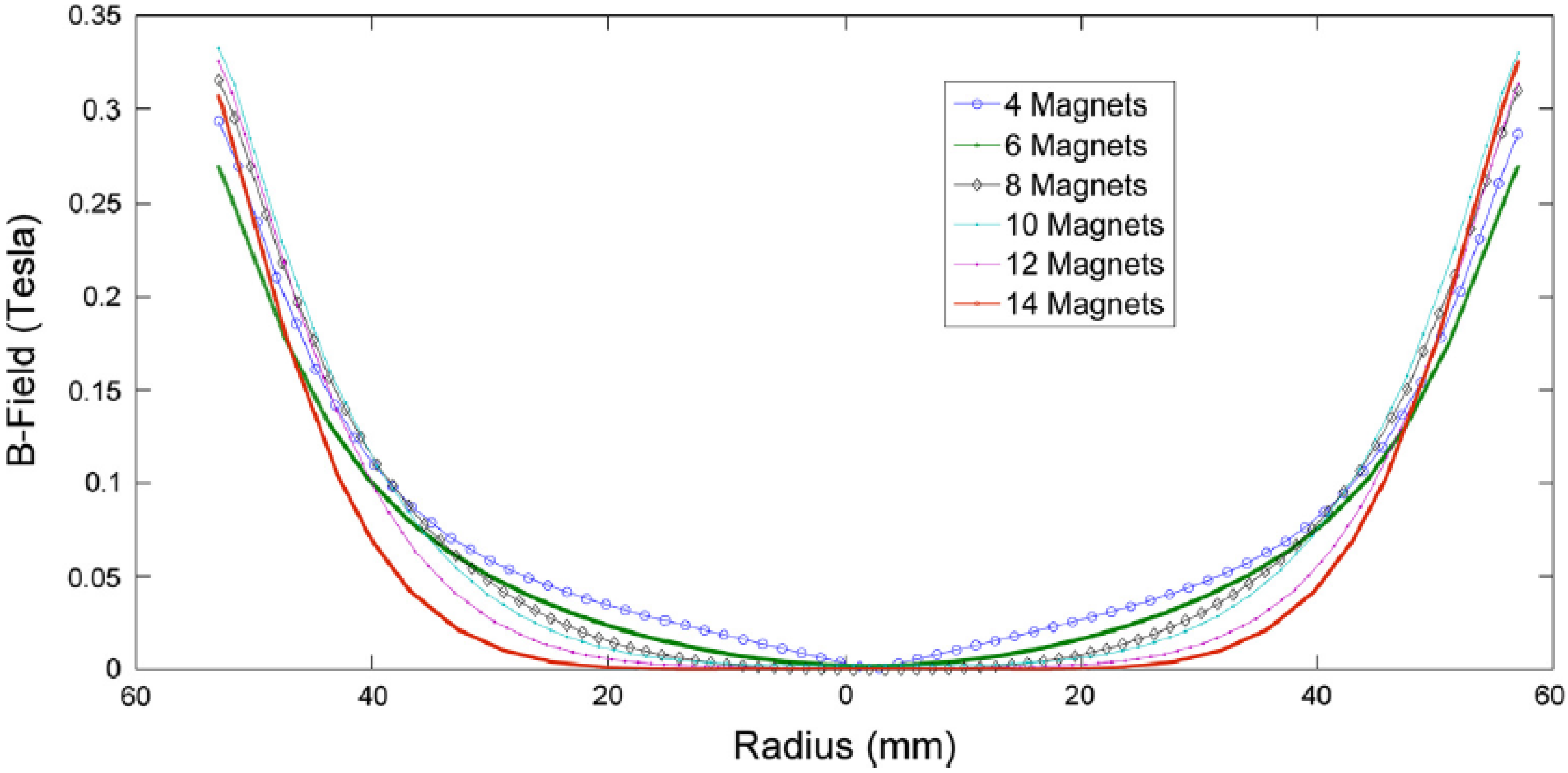
D. Boonyawan et al., RSI 71, 2000





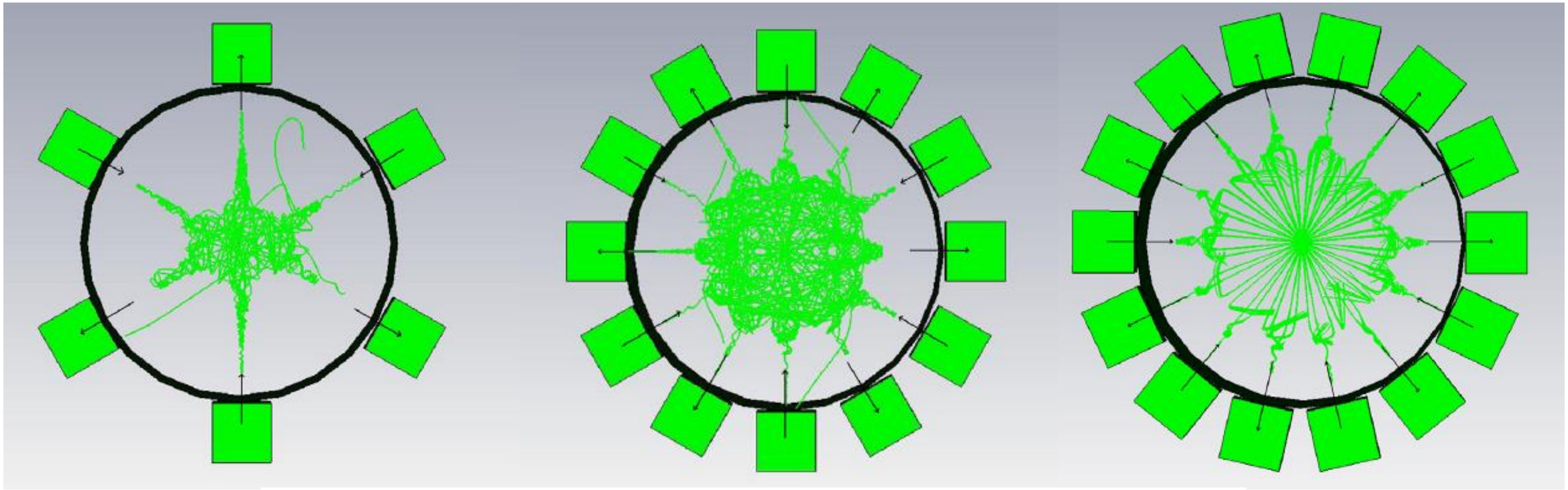
S. Axani, D. Winklehner, MIT 2015-2016

Number of Magnets I



M. Hosseinzadeh et al., NIMA 2013

Number of Magnets II

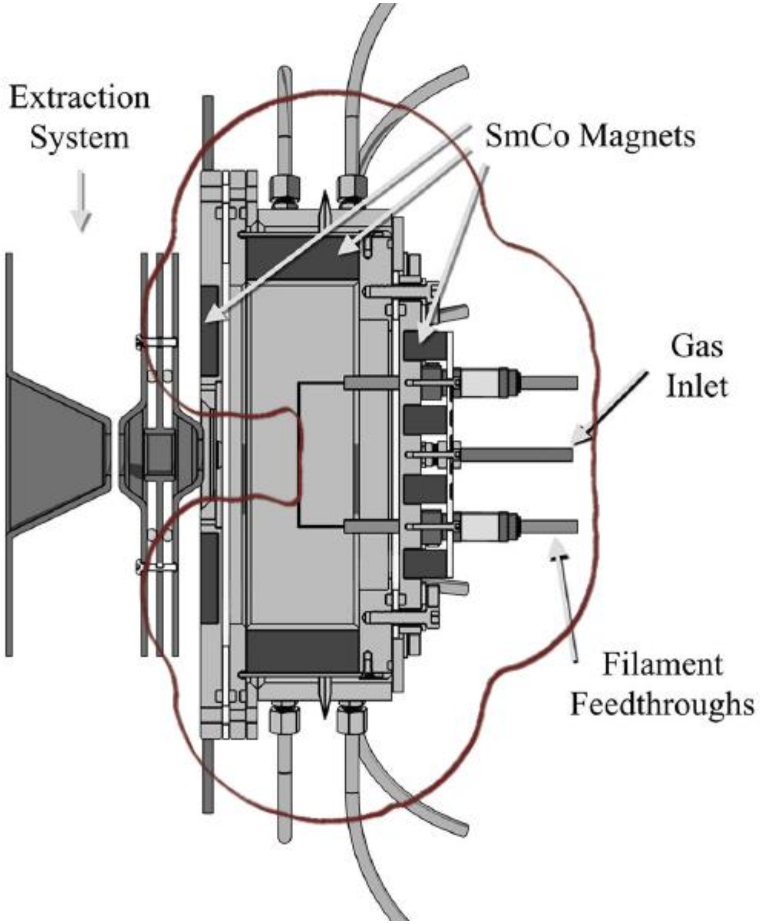


Mean life of electrons(s)	Sum of electron trajectory (m)	Number of magnets
7.06e – 7	29,453	4
1.47e – 6	61,641	6
5.51e – 6	231,440	8
7.8e – 6	328,062	10
8.79e – 6	368,032	12
7.01e – 6	294,260	14

M. Hosseinzadeh et al., NIMA 2013

Field Free at Extraction

- We typically use the 10 Gauss contour to define a field-free region (< 10 Gauss).
- Arrange magnets such that there is a field-free region around extraction.
- Should be able to achieve very low emittances. Now only depends on T_i, extraction system and I_{beam}



Permanent Magnets

Magnet	B_r (T)	H_{ci} (kA/m)	$(BH)_{max}$ (kJ/m^3)	T_c (°C)
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000	200–440	310–400
$Nd_2Fe_{14}B$ (bonded)	0.6–0.7	600–1200	60–100	310–400
$SmCo_5$ (sintered)	0.8–1.1	600–2000	120–200	720
$Sm(Co,Fe,Cu,Zr)_7$ (sintered)	0.9–1.15	450–1300	150–240	800

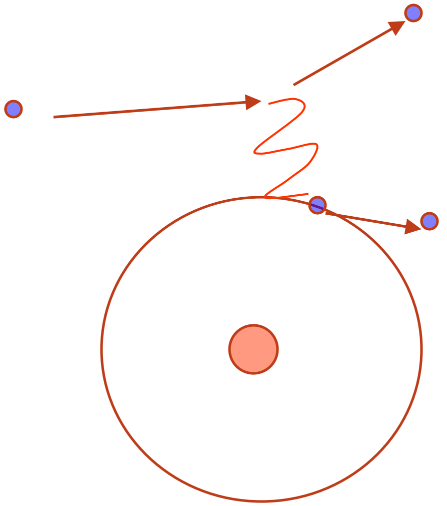
Source: Wikipedia

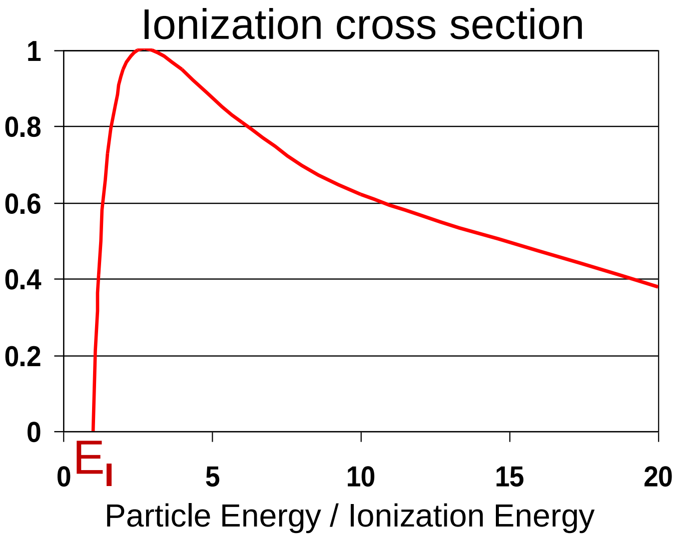
Design Parameters

Parameter	Typical Values	Tuning	Comment
Permanent Magnet Multicusp Magnetic Field	0.8 – 1.4 T 8 – 16-Pole Front/Sides/ Back	No	Most likely need cooling NdFe has higher field SmCo better Tc
Heating	?	?	
Material/Gas	?	?	
Extraction	?	?	

Electron Impact Ionization

- The removal of an electron from gaseous atoms or molecules requires electric fields in excess of 10^{10} V/m, only possible with atomic distances typically reached in collisions with charged particles.
- The conservation of energy and momentum favors electrons as the most efficient ionizing particles, and therefore most ion sources use electron impact ionization.
- The conservation of energy is responsible for an absolute threshold, the ionization energy E_I, the minimum energy which needs to be transferred for successful ionization.
- Gases have ionization energies between 12 eV for O_2 and 25 eV for He, e.g. 15 eV for H_2 molecules and 14 eV for H atoms.
- The ionization cross section has a maximum close to 3 times the ionization energy E_I and therefore electrons with an energy between 50 and 100 eV ionize all gases efficiently.





Adapted from: M. Stöckli, US-CERN-Japan Accelerator School 2013

Heating Methods

How can we give the electrons the necessary energy to ionize?

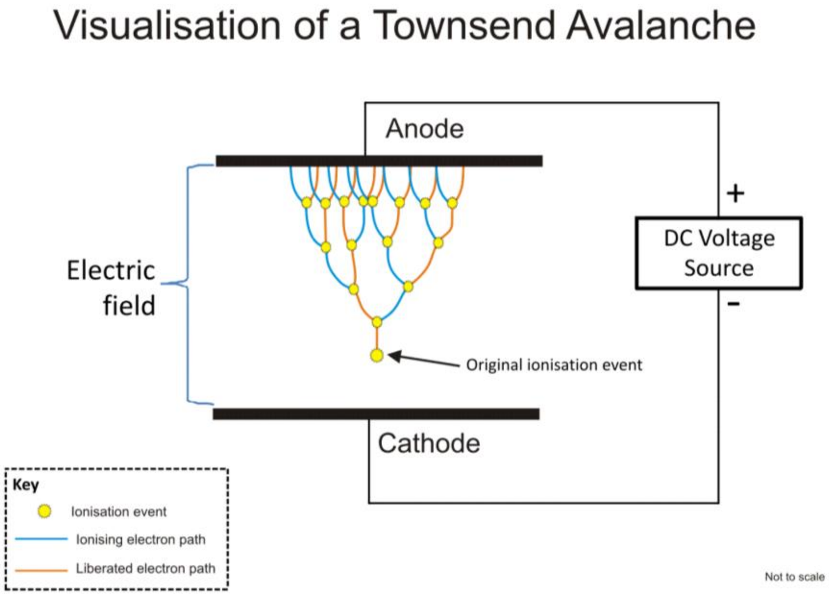
- Filament: Create through heat and accelerate in low static electric field.
- RF: Use electrons from collisions and accelerate with electric field
- Electron Cyclotron Resonance (ECR). 2.45 GHz corresponds to ~875 Gauss.

Townsend Discharge

- Around 1900 John Sealy Townsend studied discharges below the breakdown voltage (dark discharges).
- UV light illuminating the cathode produces photo electrons.
- Applying sufficient voltage, the discharge current *I* grows exponentially with the distance *d* between the electrodes:

  $$I = I_0 \cdot \mathrm{e}^{\alpha \cdot d}$$

  where I_0 is the photoelectric current and α is the 1st Townsend coefficient



- Increasing the gap d increases the number of electron multiplications, causing an avalanche, i.e. exponential growth.
- Keeping *d* constant and increasing the voltage *V* shortens the distance between ionizing collisions, which increases the discharge current *I* exponentially.

(Adapted from M. Stöckli, ORNL)

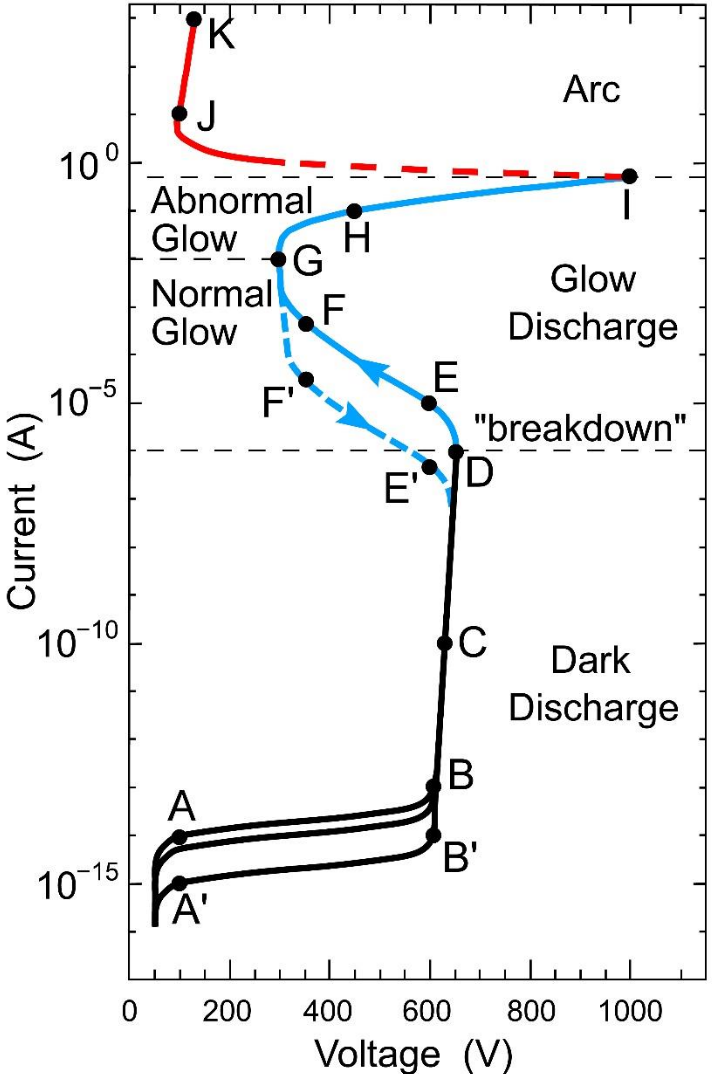
Image: https://en.wikipedia.org "Electron avalanche" by Dougsim

Discharge Regimes

- Small voltages yield nA currents by collecting electron–ion pairs produced by radiation.
- Raising the voltage starts the Townsend multiplication, yielding many µA (corona).
- Suddenly the gas starts to glow and the current grows to many mA at a much reduced voltage.
- Discharge current diverges when the ions impacting on the cathode generate enough secondary electrons to replace all seed electrons:

$$I = I_0 \cdot \frac{e^{\alpha \cdot d}}{1 - \gamma \cdot (e^{\alpha \cdot d} - 1)}$$

- Increasing the reduced voltage increases the glowing plasma volume and the current.



(Adapted from M. Stöckli, ORNL)

Image: https://en.wikipedia.org
"Glow discharge" by Chetvorno

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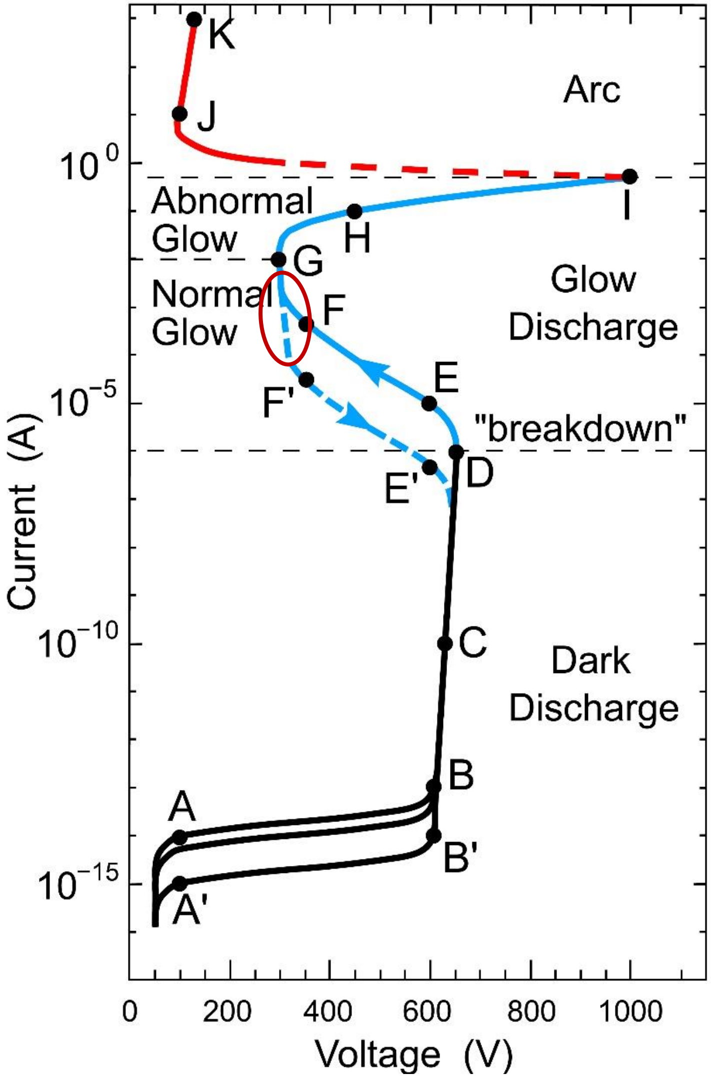
Discharge ion sources typically operate at the low current end of glow discharges.



(Adapted from M. Stöckli, ORNL)

Image: https://en.wikipedia.org
"Glow discharge" by Chetvorno

Discharge Regimes

A. random pulses by cosmic radiation
B. saturation current
C. avalanche Townsend discharge
D. self-sustained Townsend discharge
E. unstable region: corona discharge
F. sub-normal glow discharge
G. normal glow discharge
H. abnormal glow discharge
I. unstable region: glow-arc transition
J. electric arc
K. electric arc

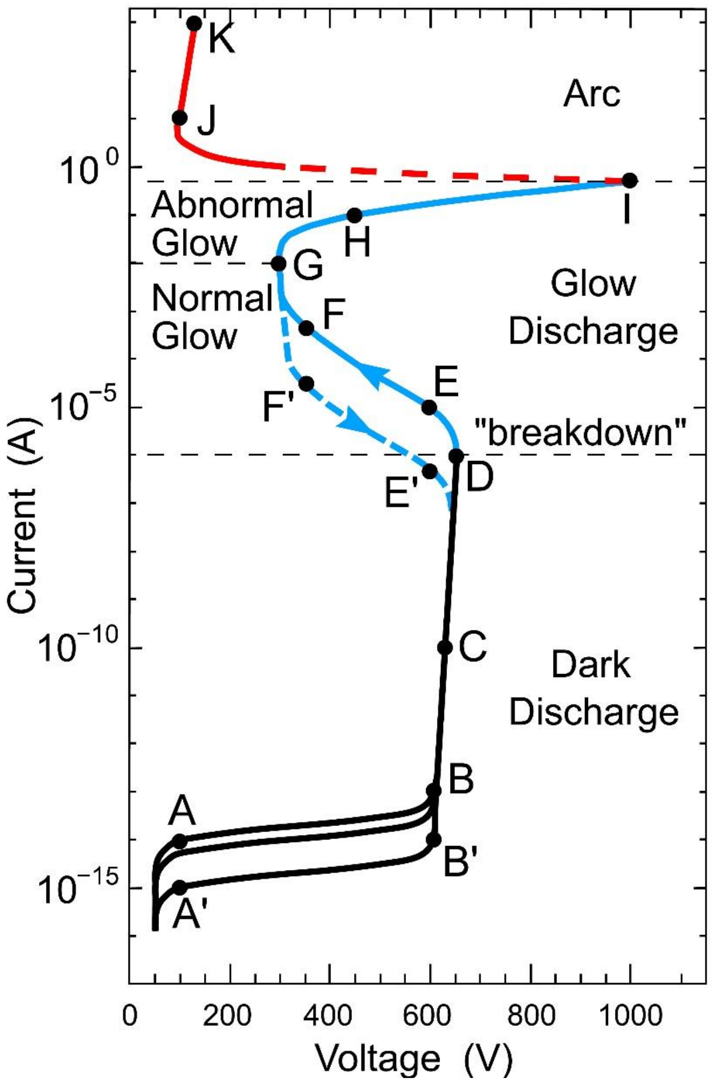


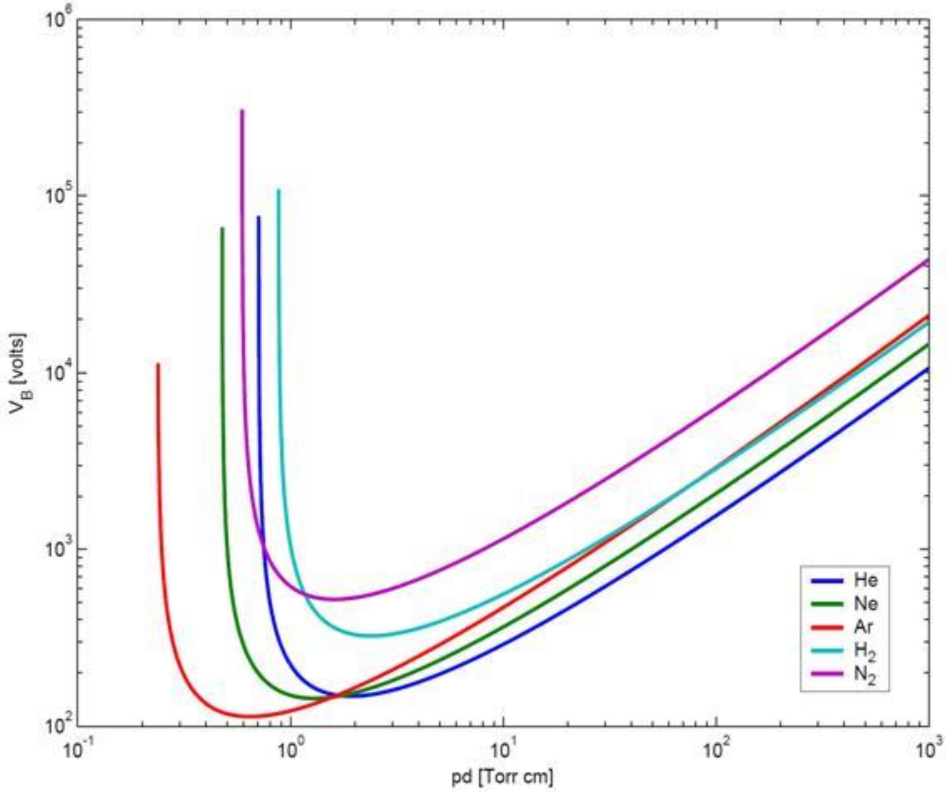
Image: https://en.wikipedia.org
“Glow discharge” by Chetvorno

Breakdown Voltage (Paschen's Law)

- In 1889, Friedrich Paschen describes the breakdown voltage *V*:

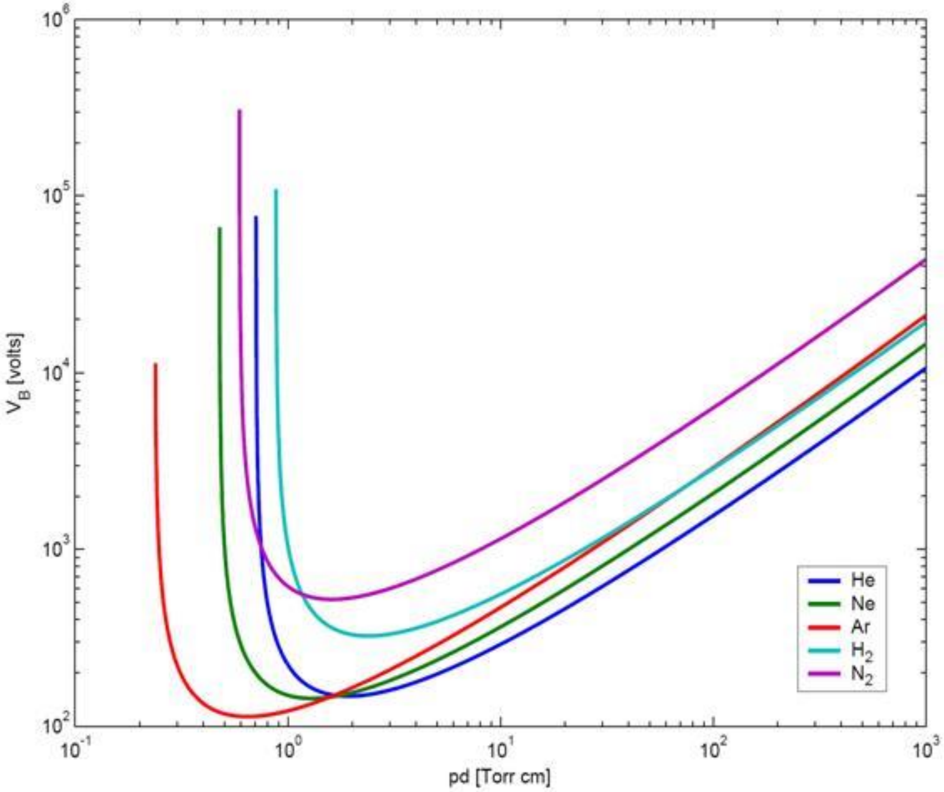
$$V = \frac{a \cdot p \cdot d}{\ln\left(p \cdot d\right) + b}$$

  with pressure *p*, electrode gap *d*, and parameters *a* & *b*, which depend on the gas and the electrodes.
- Normalization with the minimum voltage V_{min} and corresponding $(p \cdot d)_{min}$ creates a universal curve.
- Gases are good insulators at very low and very high pressures.

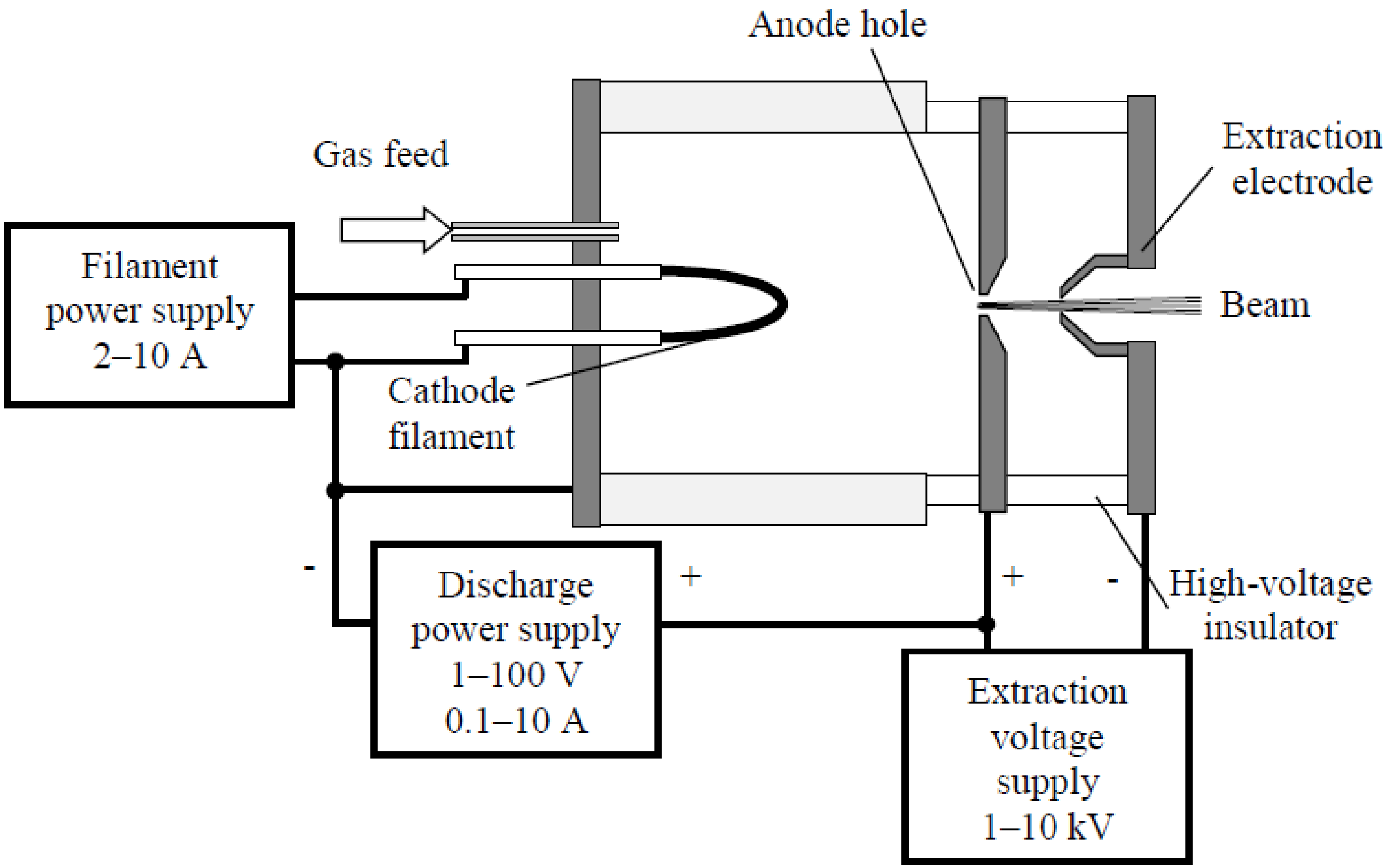


Breakdown Voltage (Paschen's Law)

- Free electrons have to gain enough energy to ionize an atom in the next collision (λ_i).
- Decreasing the pressure increases the mean path between collisions (λ_i), which is compensated by proportionally increasing d.
- The minimum represents the minimum energy spent on producing enough ions for one secondary electron from the cathode.
- At high p · d, the voltage increases linearly with the gap between the electrodes.
- At low p · d, the electrons need more energy to liberate more than one electron.



Filament Wiring



Design Parameters

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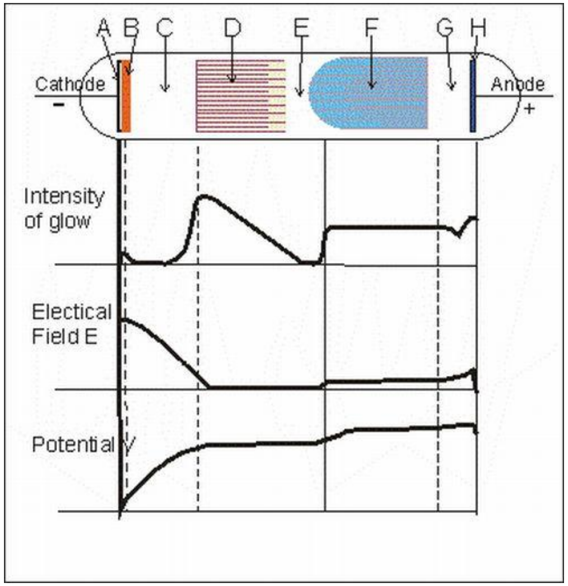
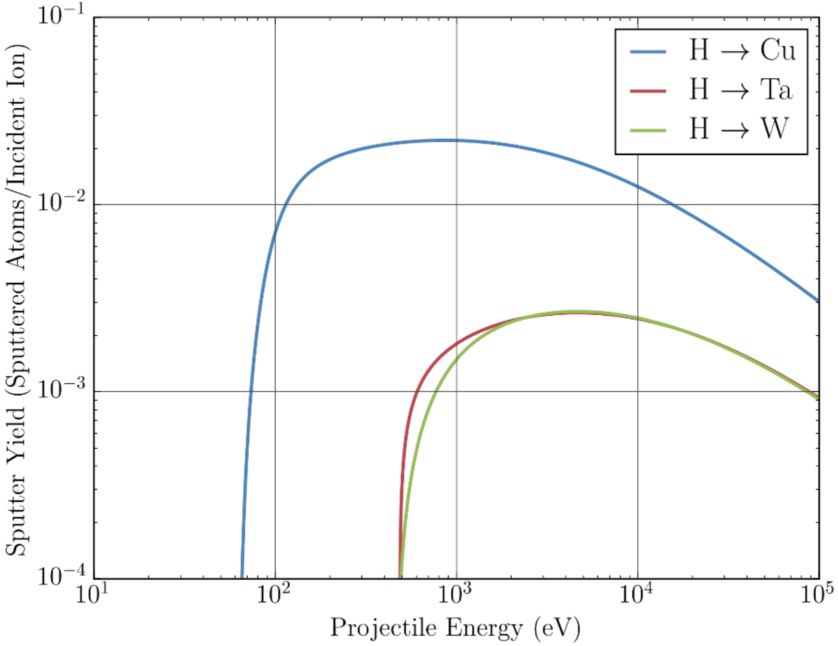
Permanent Magnet Multicusp Magnetic Field	0.8 – 1.4 T 8 – 16-Pole Front/Sides/ Back	No	Most likely need cooling. NdFe has higher field SmCo better Tc
<u>Filament Heating</u>			
Heating Current	O(10A)	Yes	
Discharge Current	O(1A)	Yes	
Discharge Voltage	O(100V)	Yes	
Filament Position	O(10cm)	Maybe	Depends on Ion
Material/Gas	1e-5 to 1e-3 Torr	Yes	
Extraction	?	?	

Filament Lifetime?

- An electric field is required to accelerate the electrons to an energy sufficient to ionize the neutral particles.
- The electric field, however, also accelerates the ions in the plasma sheath at the cathode. These accelerated ions impact on the electrode
- Sputtering reduces the filaments thickness until they break.
- Sputtered metal atoms coat insulators until they break down.

Sputtering reduces the lifetime of the source and needs to be minimized!





Data from: Behrisch, Eckstein, Sputtering by Particle Bombardment, Springer 2007

Improve the Situation

- The low sputter rates of heavy, refractory metals yield longer lifetimes!

Material	Sputter Rate @ 1 keV (atoms/ion)	Sputter Threshold (eV)
Cu	0.03	O(60)
W	0.0015	O(450)
Ta	0.0018	O(450)

LaB_6 Cathodes:

- Insulator lifetimes can be extended with recessed areas providing partial shadows. This extends the lifetime until the growing metal films flake and peel away from non-shadowed areas and short out an insulator. (not only a problem with filaments!)
- What if we don't need a filament? → RF antennas (but come with other problems)

Image: https://en.wikipedia.org
"Lab6cathodes" by Doreen L. Wynja

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Filament Heating			
Heating Current	O(10A)	Yes	
Discharge Current	O(1A)	Yes	
Discharge Voltage	O(100V)	Yes	
Filament Position	O(10cm)	No-ish	Depends on Ion
Filament Material	W, Ta, LaB_6	No-ish	Filament Shape? Lifetime
Material/Gas	1e-5 to 1e-3 Torr	Yes	
Extraction	?	?	

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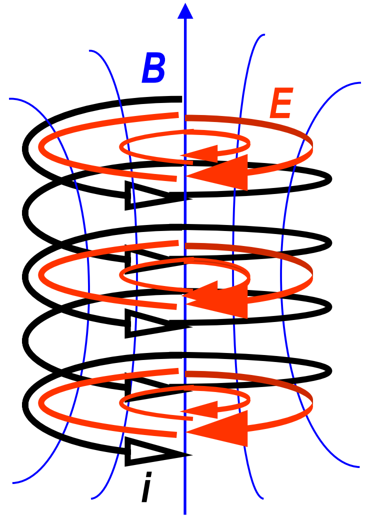
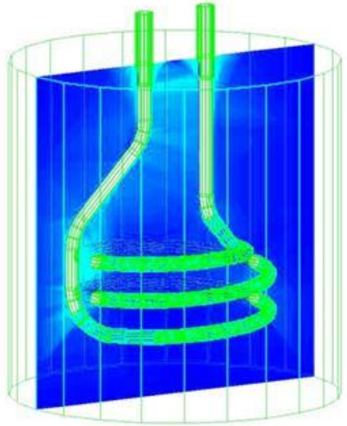
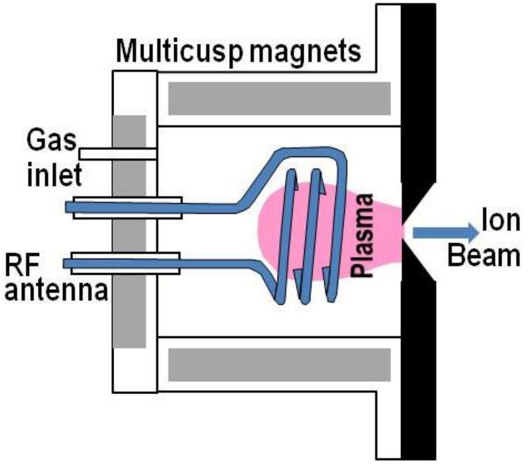
RF Driven Multicusp Ion Sources

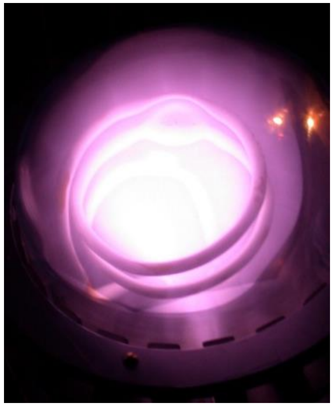
- The 2nd Maxwell Equation describes a curling *E* field generated by a changing magnetic field in absence of any charges! $\Delta \times E = -\frac{\partial B}{\partial t}$
- A changing magnetic field *B* can be produced with an alternating current $i = i_0 \cdot \cos(\omega t)$ in N windings with radius r_0: $B = \frac{1}{2}\mu_0 \frac{N \cdot i}{r_0}$
- Now integrate Maxwell's equation to get Faraday's law and solve for *E:*

$$\int E \cdot ds = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\int B \cdot dS \rightarrow E(r,t) = \frac{1}{4}\frac{r}{r_0} \cdot \mu_0 \omega N i_0 \cdot \sin(\omega t)$$





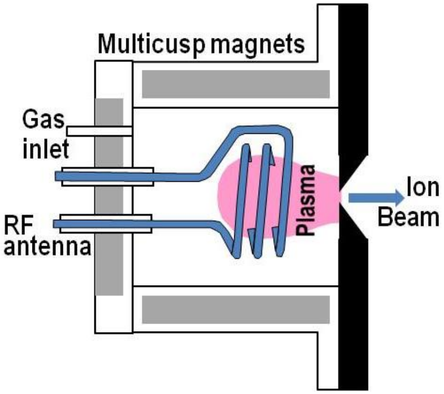




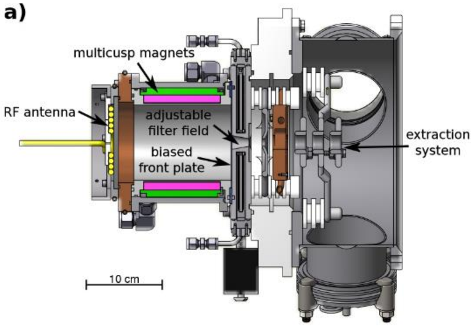
Adapted from: M. Stöckli, US-CERN-Japan Accelerator School 2013

Types of RF drives

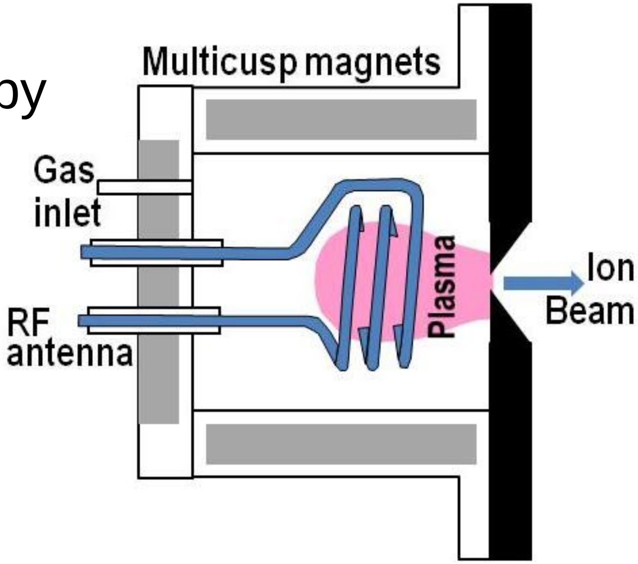
- Capacitively coupled (not typically used for ion sources)
- Inductively coupled with Internal Antenna.



- Inductively coupled with external Antenna.



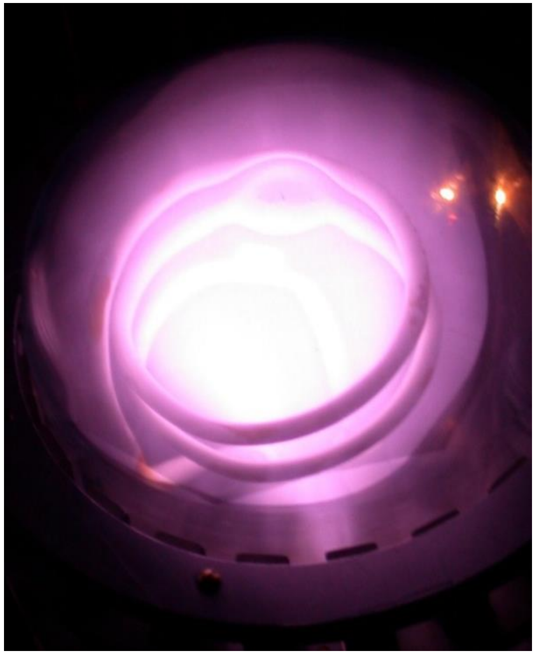
- In 1990 LBNL replaced the filament in their multicusp ion source with a 3-turn antenna, driven by 2 MHz.
- In 1992-1994 this source was tested for SSC yielding up to 100 mA (?) for 0.1 ms at 10 Hz.
- 1999-2001 LBNL developed this source for SNS, hoping to eventually reach the 7% duty factor.



In 2001 the plasma was visualized by replacing the stainless steel source chamber with a glass dome surrounded by identical cusp magnets.

- The inductively induced plasma is bright inside the antenna, driven by the high induced fields near the antenna. The magnetic bucket causes the plasma to drift to the center, compensating for the smaller electric fields.
- Less plasma drifts into the confining cusp fields.

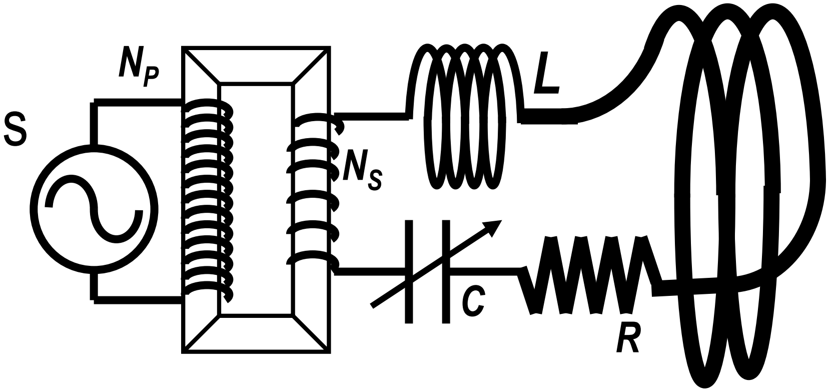
Multicusp confinement is well suited for an inductively driven ion source!

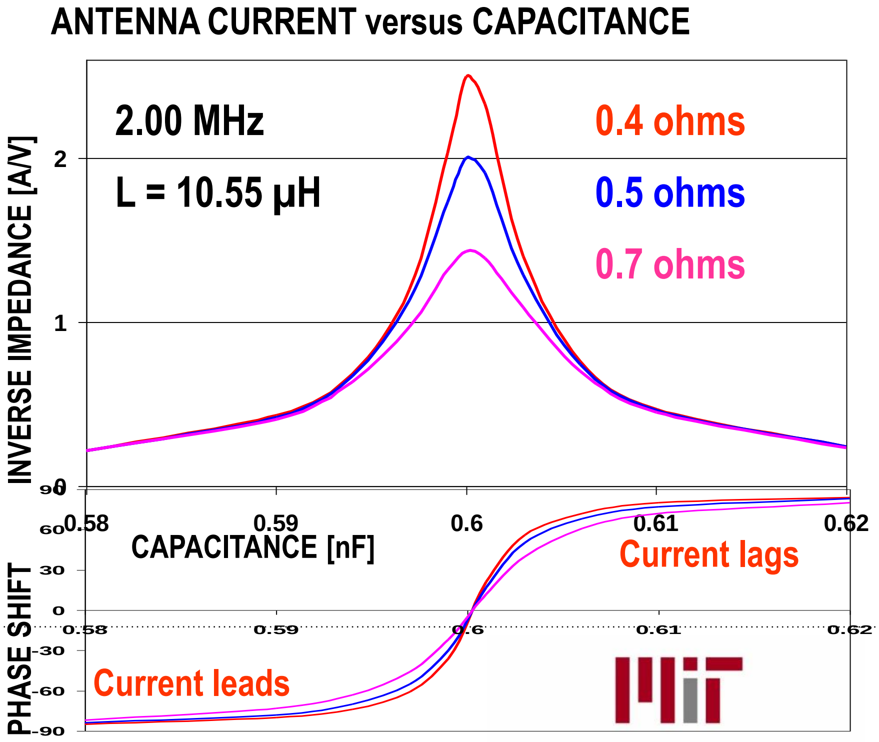


Adapted from: M. Stöckli, US-CERN-Japan Accelerator School 2013

Making more Ions with a RF-driven Ion Source

- More ions ⇐ denser plasma ⇐ higher electric fields ⇐ higher antenna current!
- The RF amplifier output impedance needs to be matched to the impedance of the ion source to get the system in resonance!
- The ion source RLC circuit has a resonant frequency of $\omega^2 = (LC)^{-1}$ and an impedance $Z = \mathcal{E}_o / i_o = (R^2 + (\omega L - (\omega C)^{-1})^2)^{1/2}$
- $L \approx 10\ \mu H$ and $\omega \approx 2 \cdot \pi \cdot 2\ MHz$ requires tuning C around 0.6 nF to obtain the maximum current $i_o = \mathcal{E}_o / R$.
- Adjusting the transformer ratio N_S/N_P matches the RF amplifier power to the impedance of the ion source.
- The resonance can be located with the phase shift.




ANTENNA CURRENT versus CAPACITANCE

Adapted from: M. Stöckli, US-CERN-Japan Accelerator School 2013

Design Parameters

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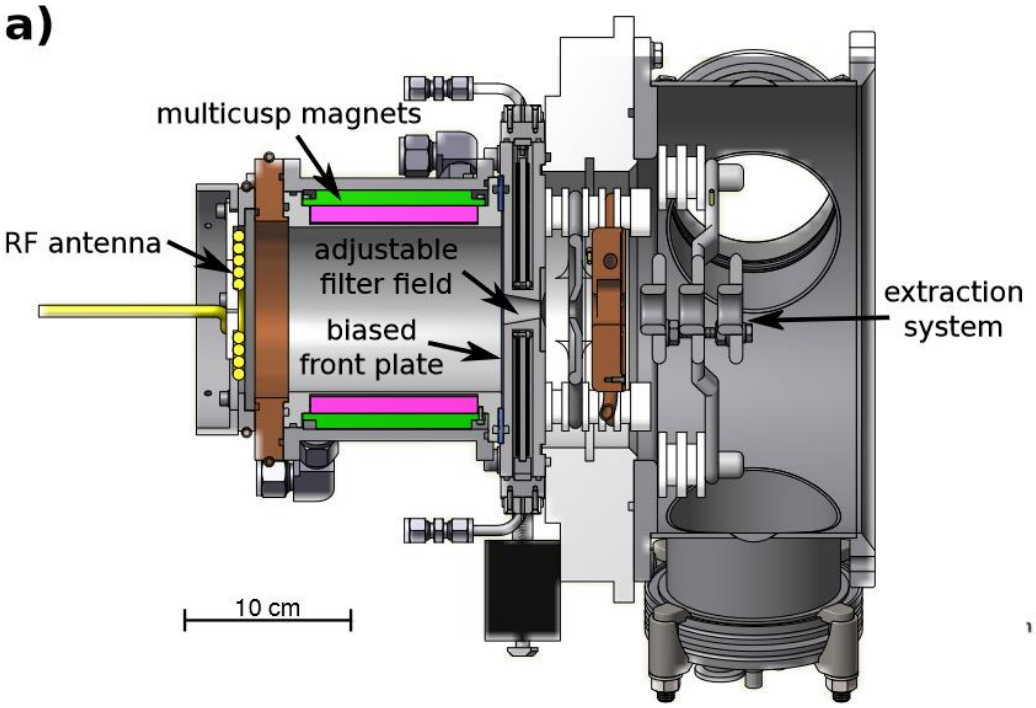
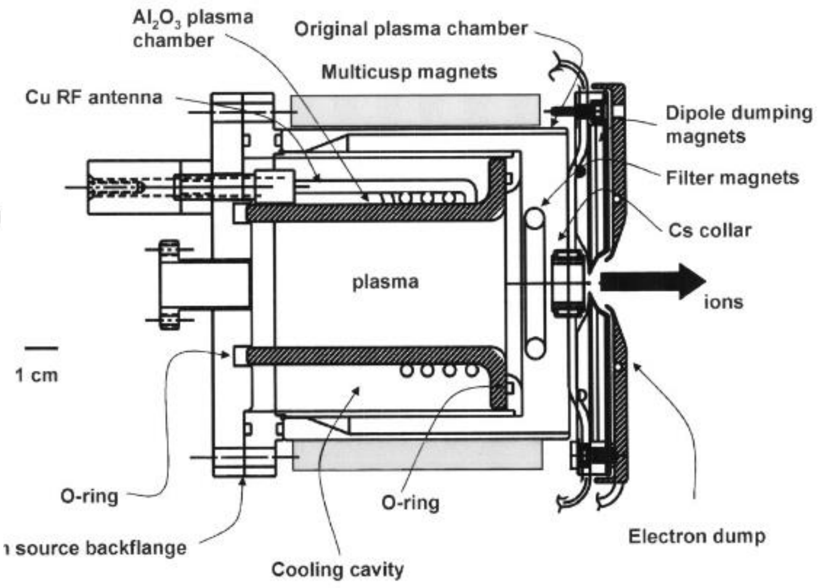
<u>Filament Heating</u>			Many Parameters
… or …			
<u>RF Heating</u>			
Frequency	5~13 MHz	Somewhat	
Power	few – 100 kW	Yes	
Material/Gas	1e-5 to 1e-3 Torr	Yes	
Extraction	?	?	

External RF Antennas

In the back:



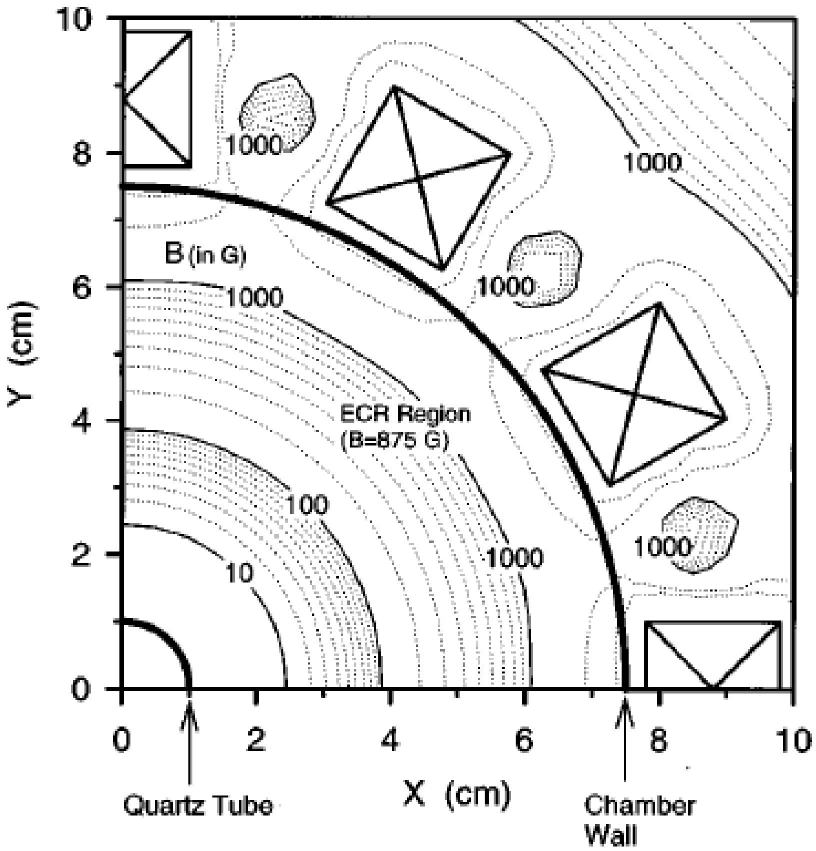
Around the chamber:



J. Komppula, arXiv:1503.08061v1, 2015
Welton et al. RSI 2004

Hybrid ECR-Multicusp Ion Sources?

- Typical field contours in multicusp source.
- Stands to reason that a 2.45 GHz microwave generator could be coupled through a waveguide (as in an ECR)
- Some promising first results are out there…

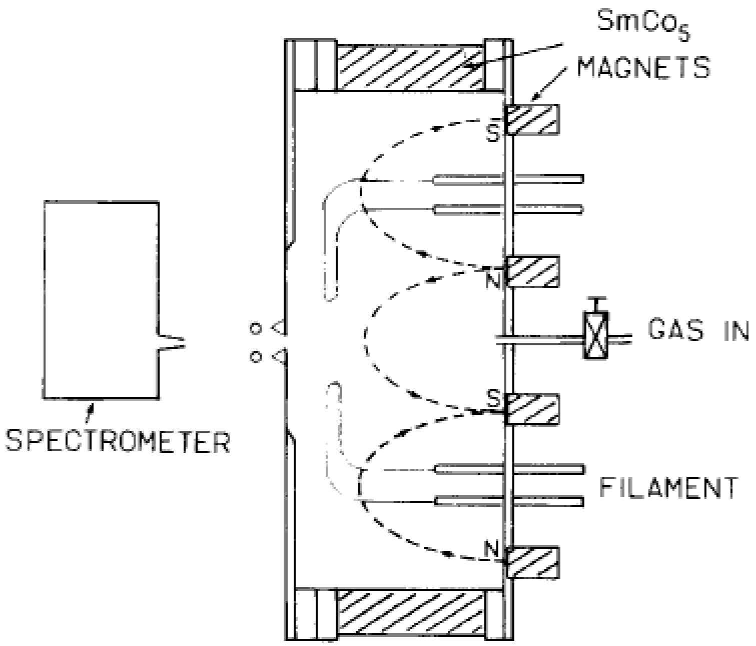


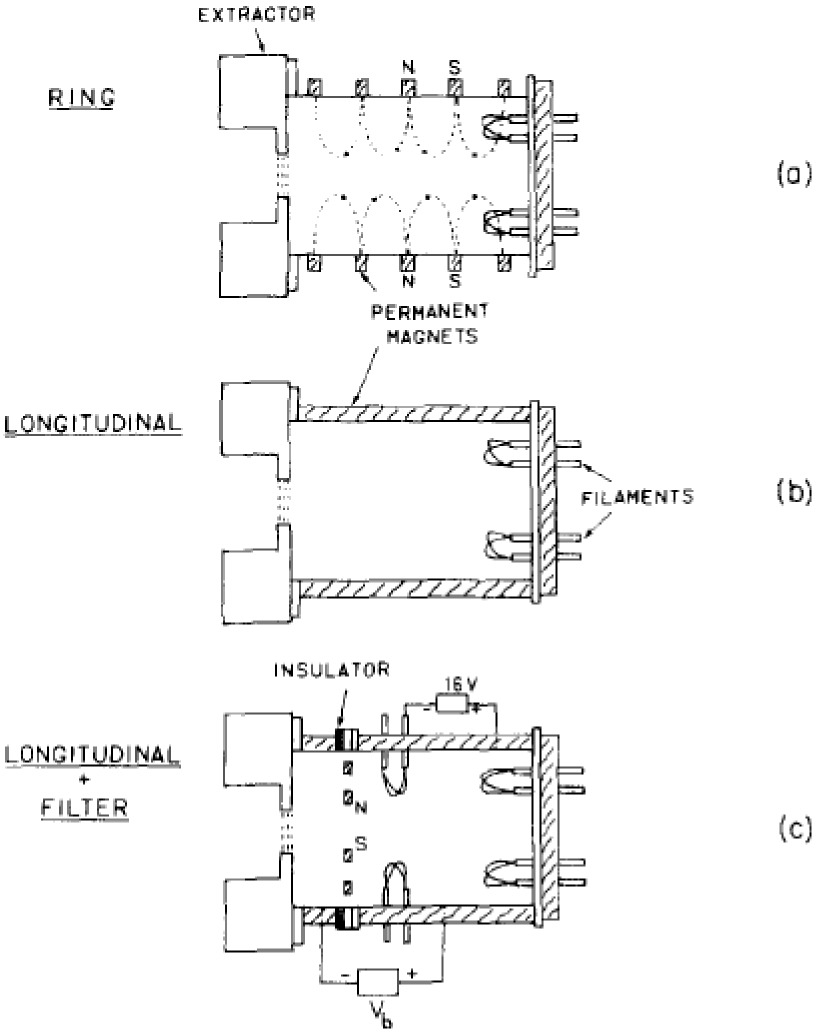
M. Tuda et al., Journal of Vacuum Science and Tech. A, 1998

Examples of Positive Ion Multicusp Sources

LBNL did a lot of development 1970ies – now.

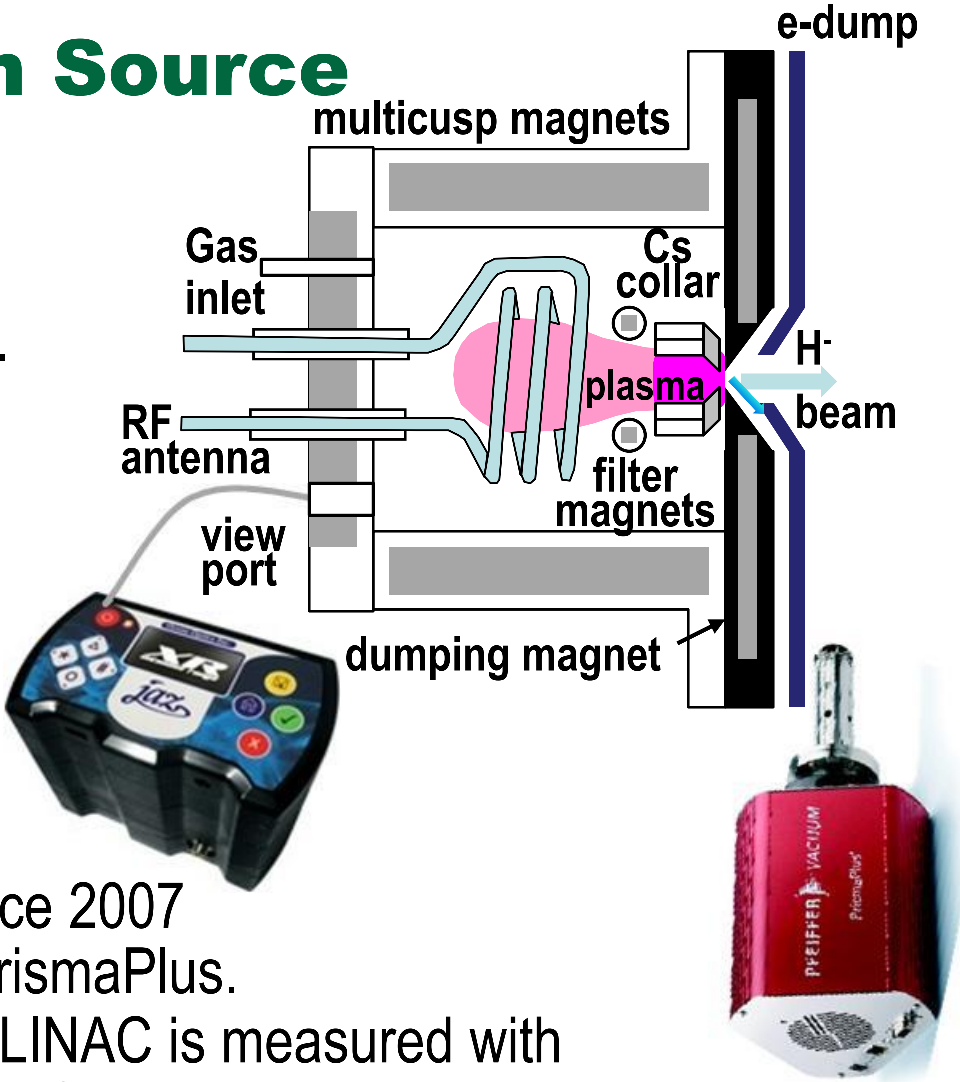
K. Leung, K. Ehlers



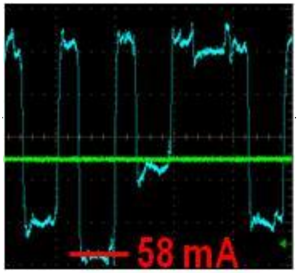


The SNS Baseline Ion Source

LBNL developed and SNS improved the cesium-enhanced, RF-driven multicusp ion source, which delivers ~1-ms long H^- current pulses at 60 Hz.

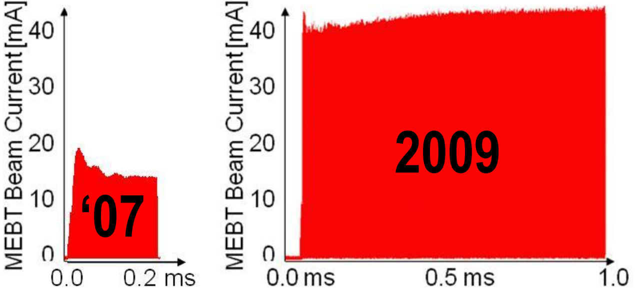


- About 300 W 13-MHz RF generate continuous low-power plasma.
- 50-60 kW of 2 MHz RF are added for ~1 ms at 60 Hz to produce the H^- beam pulses.
- A jaz spectrometer analyzes 220-1100 nm emissions since 2011.
- Gaseous emissions are monitored since 2007 and since 2013 with a more sensitive PrismaPlus.
- The H^- beam current injected into the LINAC is measured with a beam current torroid after the RFQ and 2 quadrupoles.

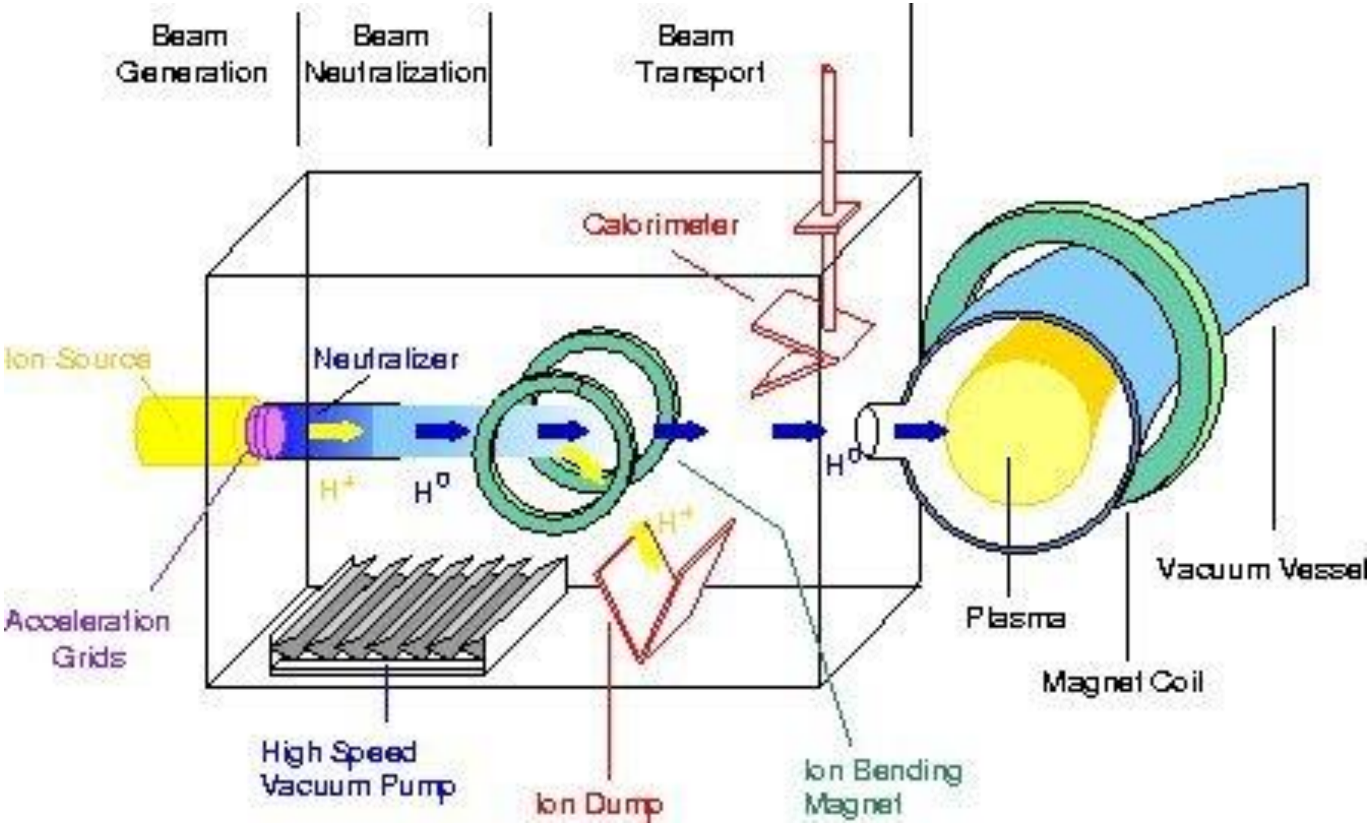


- The beam current injected into the RFQ is measured since 2012.

50-60 mA go into the RFQ!



Giant Ion Sources for Neutral Beams I

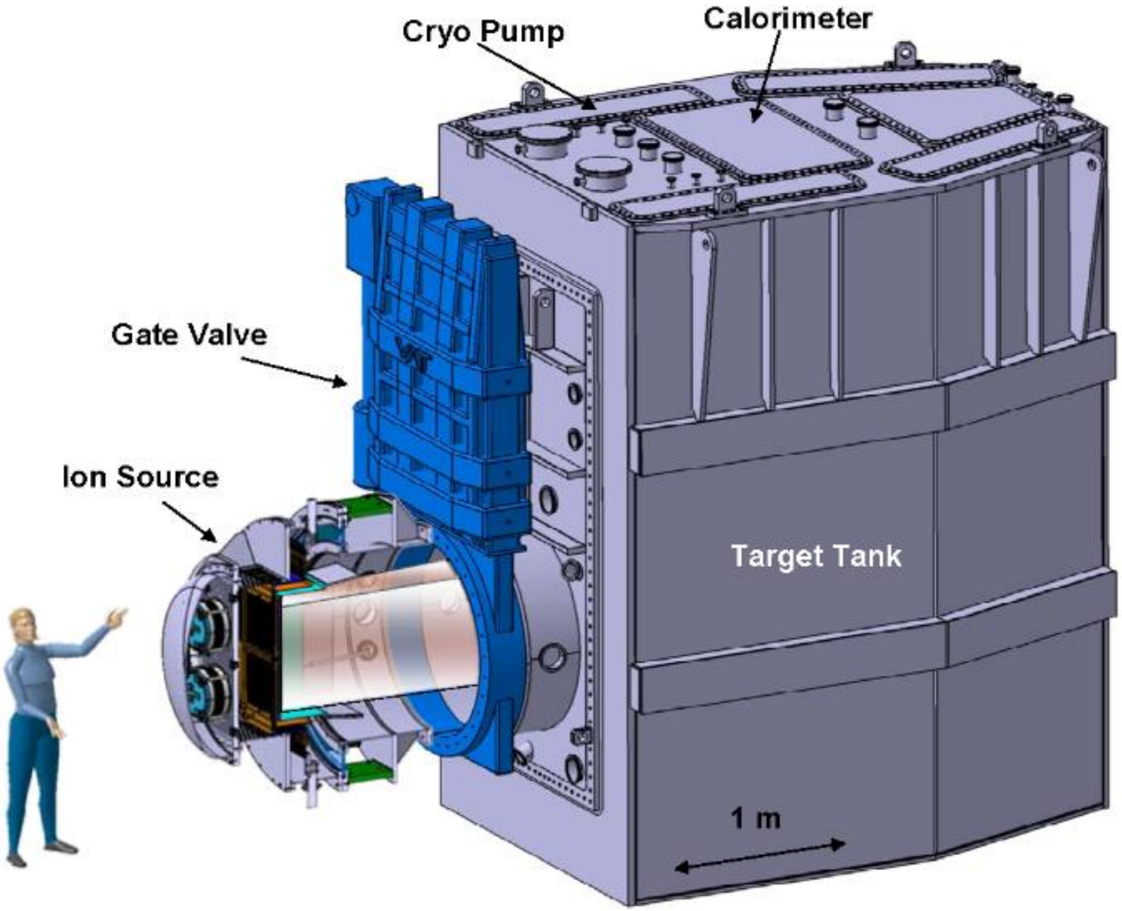


From: www.ipp.mpg.de

Comments

- Large volume plasma production
- Extraction over large area
- Currents in the 10’s of A range
- Positive Ion Beams: Sources can produce more current, but neutralization is worse above ~100 keV/amu
- Negative Ions: Typical nowadays
- Will talk more about negative ones tomorrow…

ELISE Test Facility for ITER ion source



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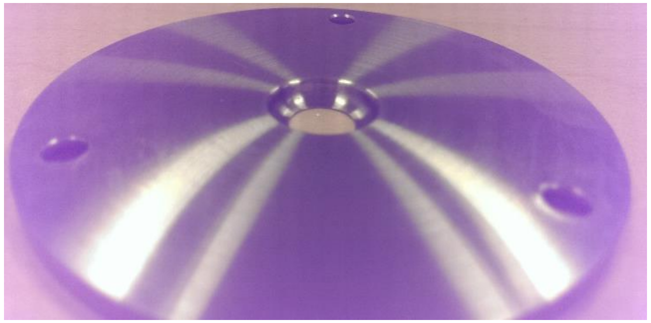
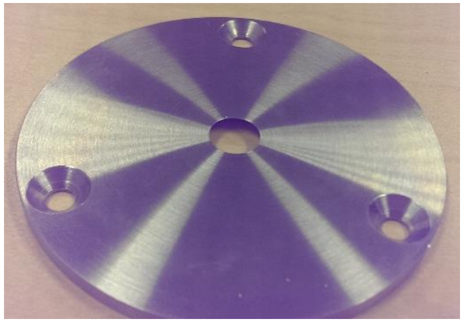
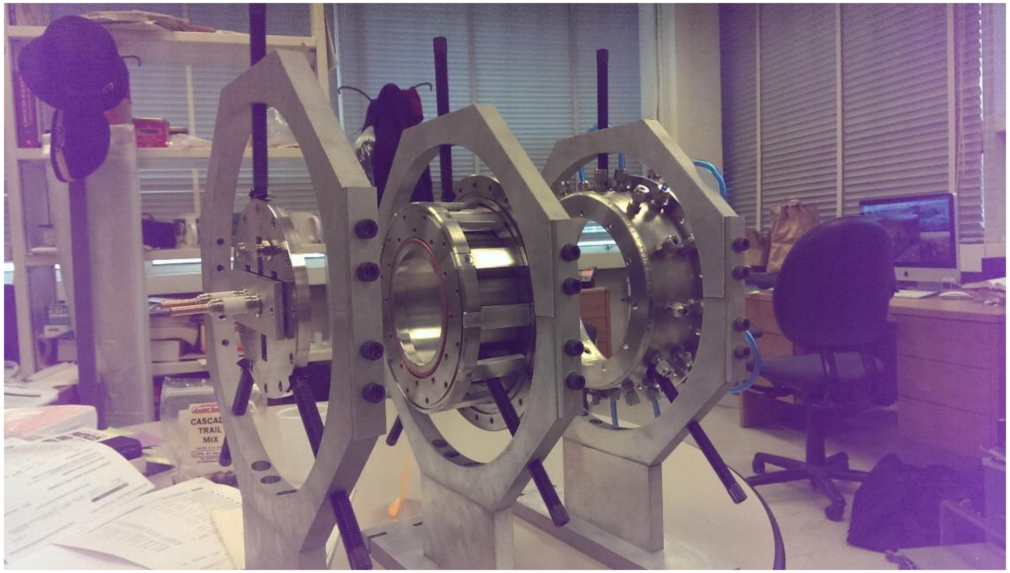
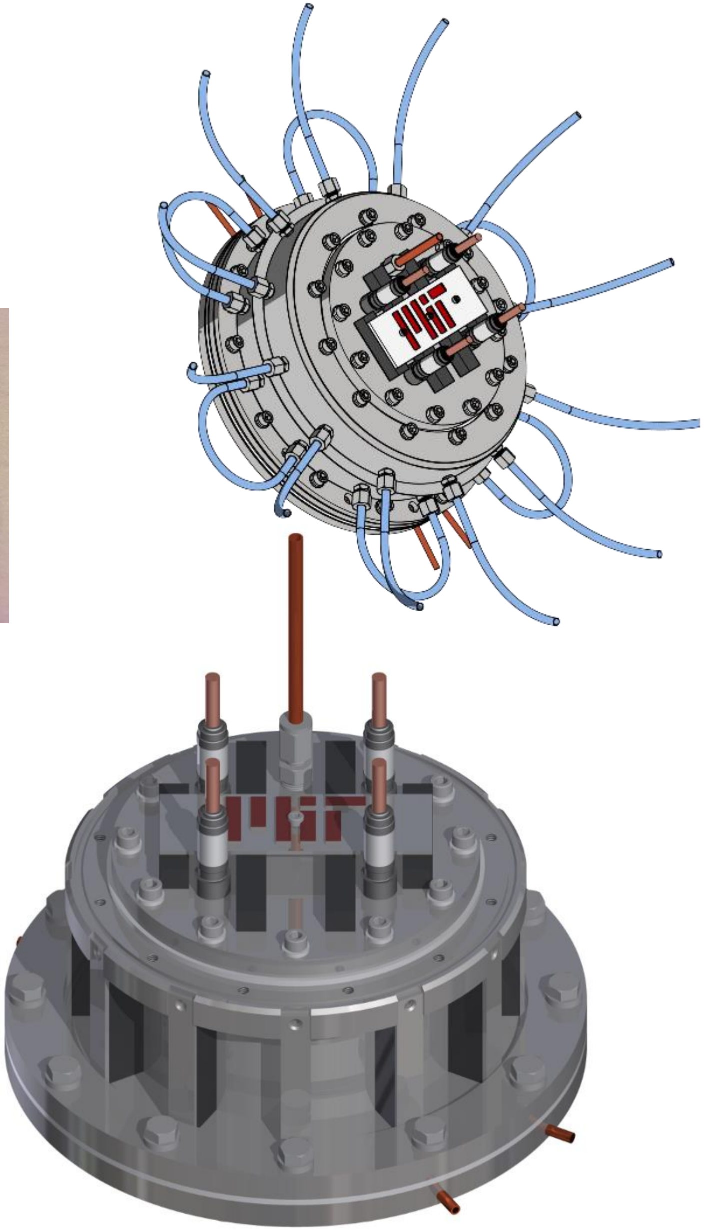
See other presentation









Design Parameters

Parameter	Typical Values	Tuning	Comment
Permanent Magnet Multicusp Magnetic Field	0.8 – 1.4 T 8 – 16-Pole Front/Sides/ Back	No	Most likely need cooling. NdFe has higher field SmCo better Tc
Filament Heating			Many Parameters
… or …			
RF Heating			
Frequency	5~13 MHz	Somewhat	
Power	few – 100 kW	Yes	
Material/Gas	1e-5 to 1e-3 Torr	Yes	
Extraction	Up to 100 kV	Somewhat	Depends strongly on application!