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U.S. DEPARTMENT OF ENERGY

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

Daniela Leitner (LBNL, MSU),
Damon Todd (LBNL),
Daniel Winklehner (MIT)

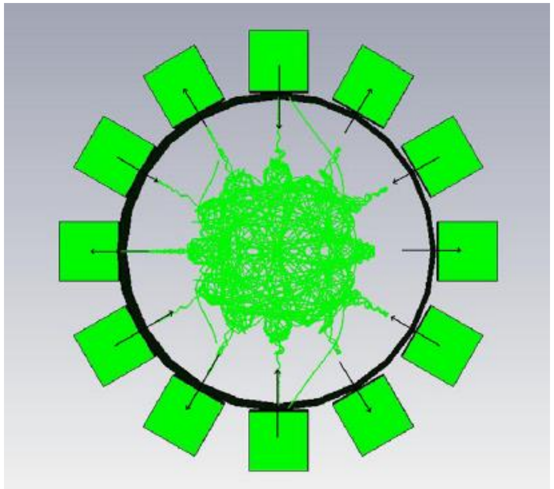
Massachusetts Institute of Technology

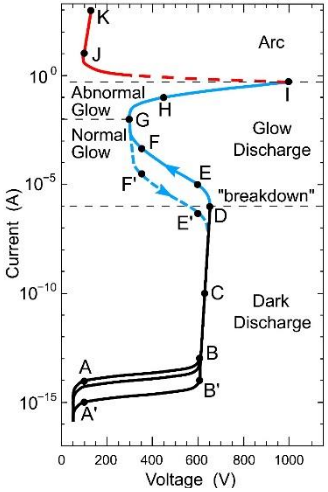
Outline

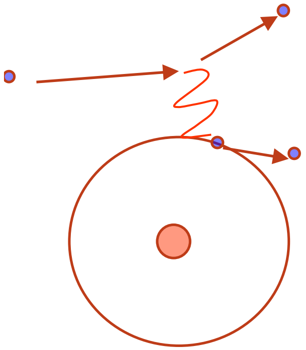
- Introduction – basic principles of multicusp ion sources
- Different heating methods (filament, RF antenna, ECR?)
- Usages: H+, H-, He+, H2+, …
- Positive (H+, H2+, He+, …) multicusp ion sources
  - Optimization
- Negative (H-, …) multicusp ion sources
  - Volume production
  - Surface-enhanced volume production (Cs)
  - Extraction of negative ions
  - Optimization
- Other types of negative ion sources

Quick Recap of Multicusp so far

- Ions and Electrons are confined in a multicusp magnetic field
- Electrons are given energy through an electric field (either by DC voltage or RF)
- Ionization through electron impact
- Many parameters that depend on the application

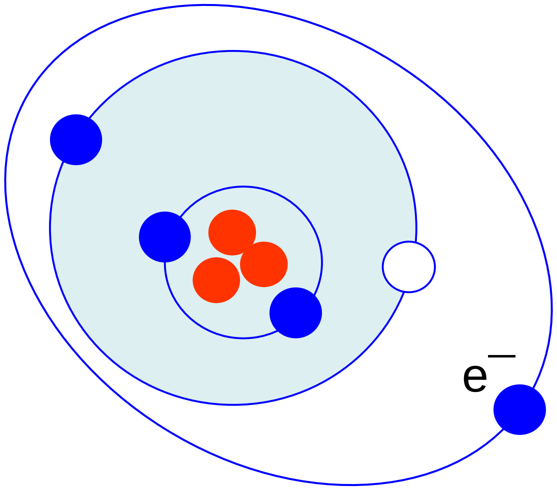






Parameter	Typical Values	Tuning	Comment
Permanent Magnet Multicusp Magnetic Field	0.8 – 1.4 T 8 – 16-Pole Front/Sides/ Back	No	Most likely need cooling. NdFe has higher field SmCo better Tc
Filament Heating			Many Parameters
Heating Current	O(10A)	Yes	
Discharge Current	O(1A)	Yes	
Discharge Voltage	O(100V)	Yes	
Filament Position	O(10cm)	Somewhat	Depends on Ion
Filament Material	W, Ta, LaB_6	Somewhat	Filament Shape? Lifetime
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!

Negative Ions

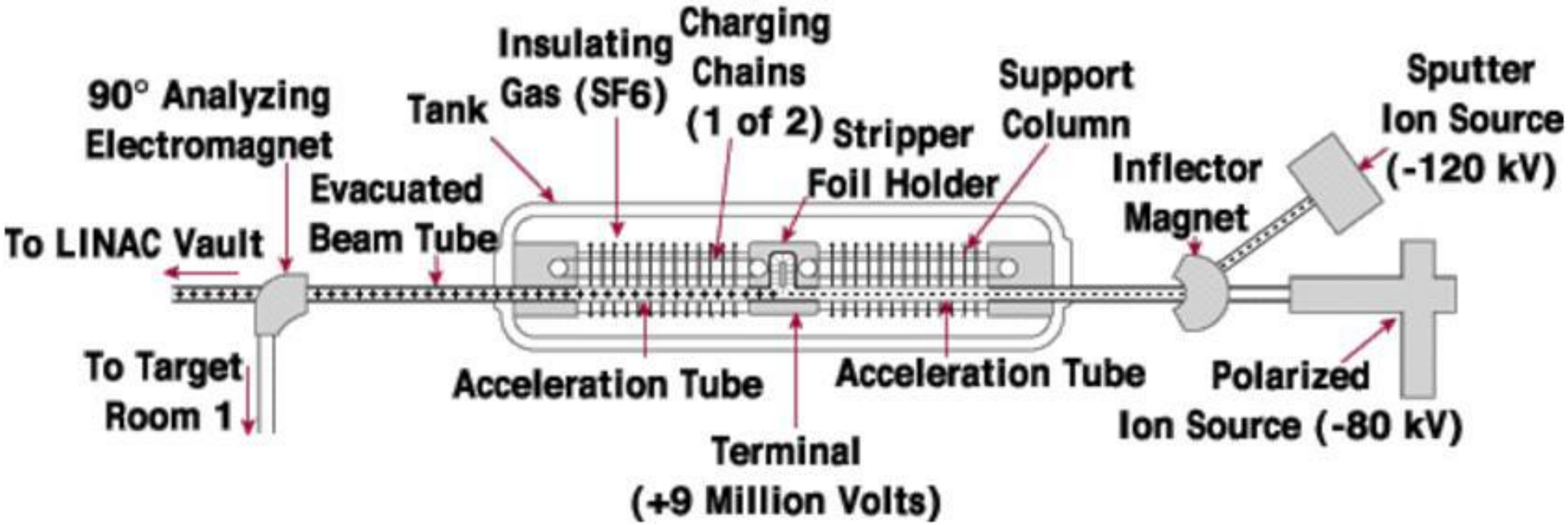


- Especially atoms with an open shell attract an extra electron and can form a stable ion with a net charge of –e.
- The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron.
- The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for Ti^- and 3.6 eV for Cl^-, e.g. 0.75 eV for H^-.
- For electron energies above 10 eV, the H^- ionization cross section is ~$30 \cdot 10^{-16}$ cm^2, ~30 times larger than for a typical neutral atom!!
- For H^+ energies below 1 keV, the recombination cross section is larger than $100 \cdot 10^{-16}$ cm^2.
- Charged particle collisions destroy negative ions easily!!

(Adapted from M. Stöckli, ORNL)

Why Negative Ions?

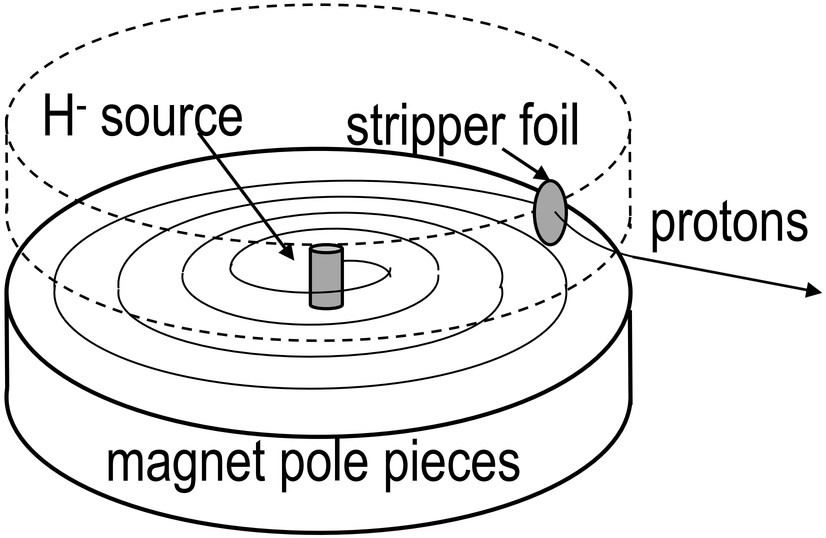
Historically: Tandem Accelerators



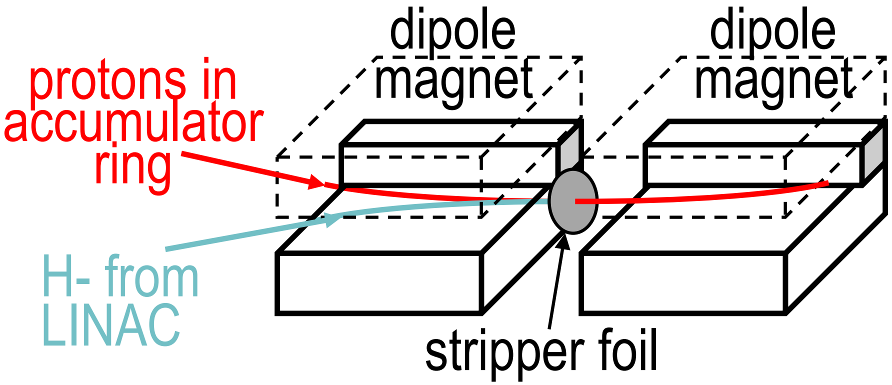
(Adapted from M. Stöckli, ORNL)

Why Negative Ions?

- Stripping Extraction from Cyclotrons



- Accumulating Ions in a limited Phase Space:

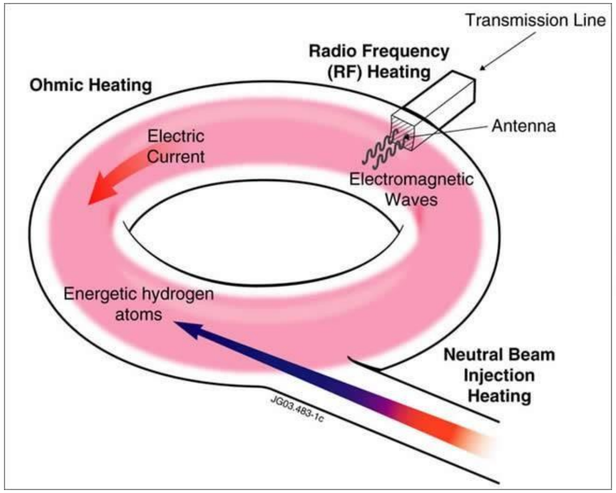


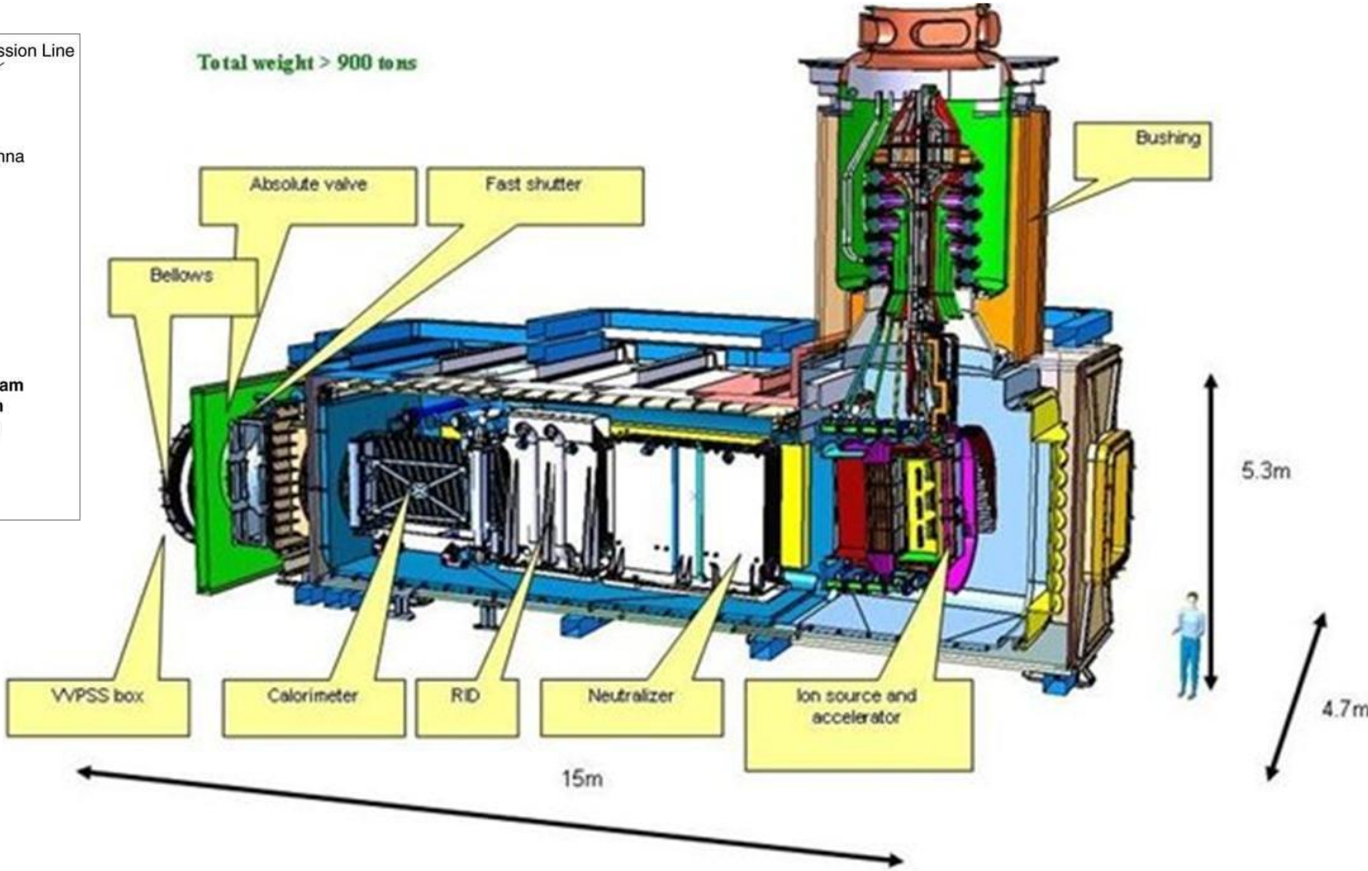
e.g. the Spallation Neutron Source

(Adapted from M. Stöckli, ORNL)

Why Negative Ions?

Neutral Beam Injection





From: http://www.iter.org/mach/heating

Brief History of H$^-$ sources

- 1977: M. Bacal finds large negative ion fraction in hydrogen plasma
- 1982: Ehlers, Leung & Bacal invent the “tandem source” at LBNL
- Several volume H$^-$ sources were developed, including the DESY RF source with an external antenna. It produced 0.1 ms long, 40 mA H$^-$ pulses at 5 Hz with a lifetime exceeding 1 year.
- Parallel, since 1960 the use of Cs in ion sources to increase negative ion currents is studied.


Marthe Bacal


Ka-Ngo Leung

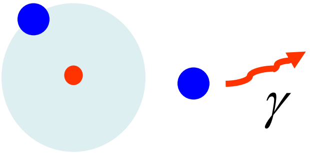

Jens Peters


Yuri Belchenko

(Adapted from M. Stöckli, ORNL)

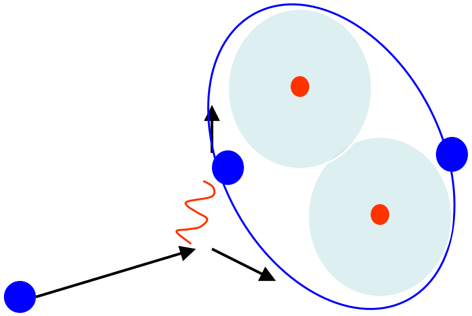
Volume Production of H^-

- Conserving energy & momentum when forming a negative ion through direct electron attachment, the excess energy has to be dissipated through a photon: $H + e = H^- + \gamma$

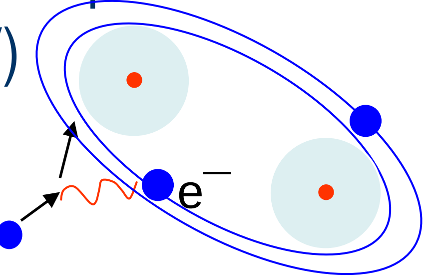


- But few H^0 allow for Radiative Capture (10^{-18} cm^2 for E_e~1eV)

- More likely are processes where excess energy can be transferred to a third particle, $H_2 + e = H + H + e$
  and sometimes $= H + H^-$
  (~10^{-20} cm^2 for H_2 and E_e >7 eV)

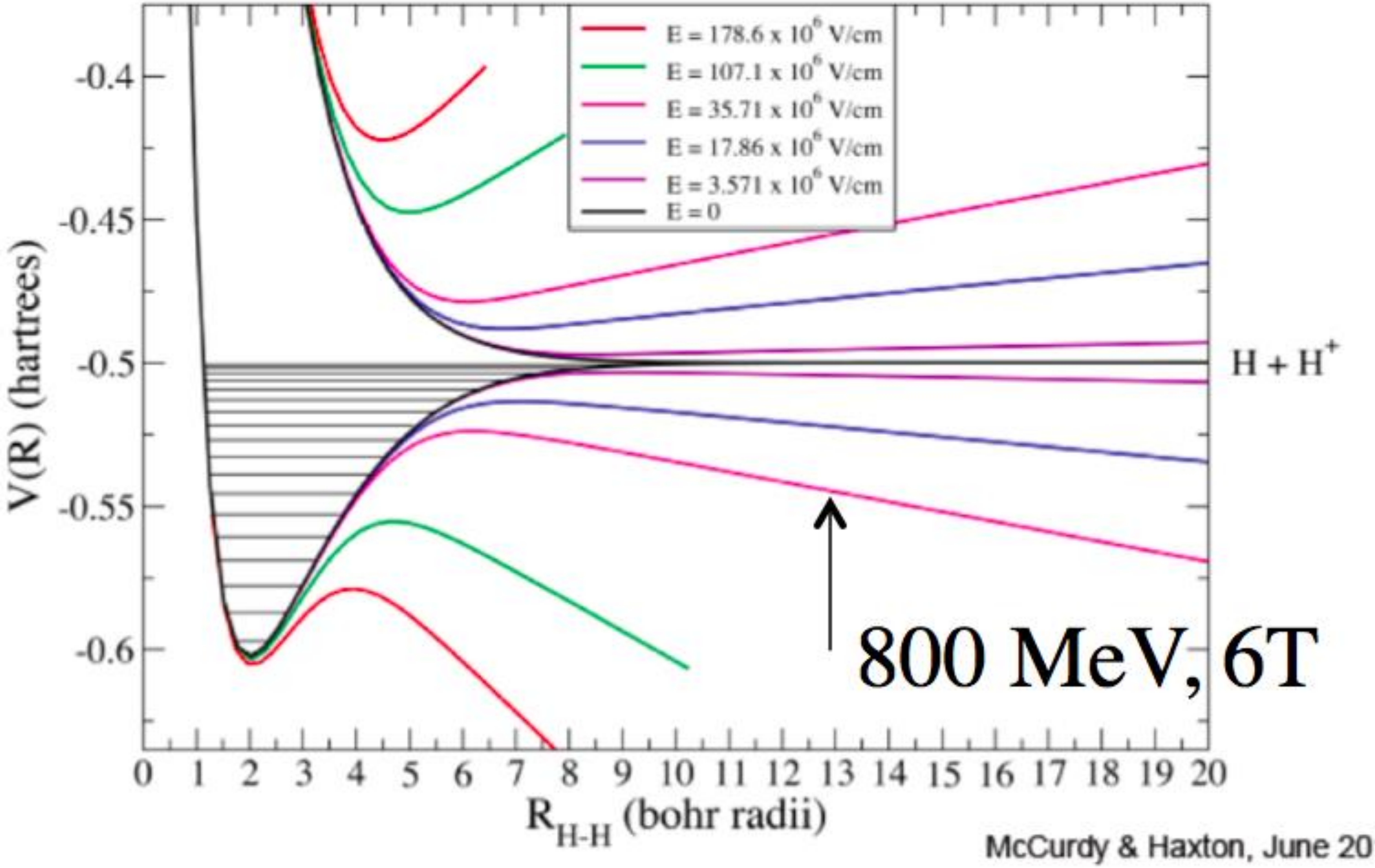


- Most likely is the excitation of a molecule to the edge of breakup:
  $H_2 + e(\text{fast}) = H_2^{\nu} + e$ (~$5{\cdot}10^{-18}$cm^2 for $4 \leq \nu \leq 9$ & E_e >20 eV)
  and then dissociated by a slow electron:
  $H_2^{\nu} + e(\text{slow}) = H + H^-$ (<10^{-15} cm^2 for $4 \leq \nu \leq 9$ & E_e~1eV)



(Adapted from M. Stöckli, ORNL)

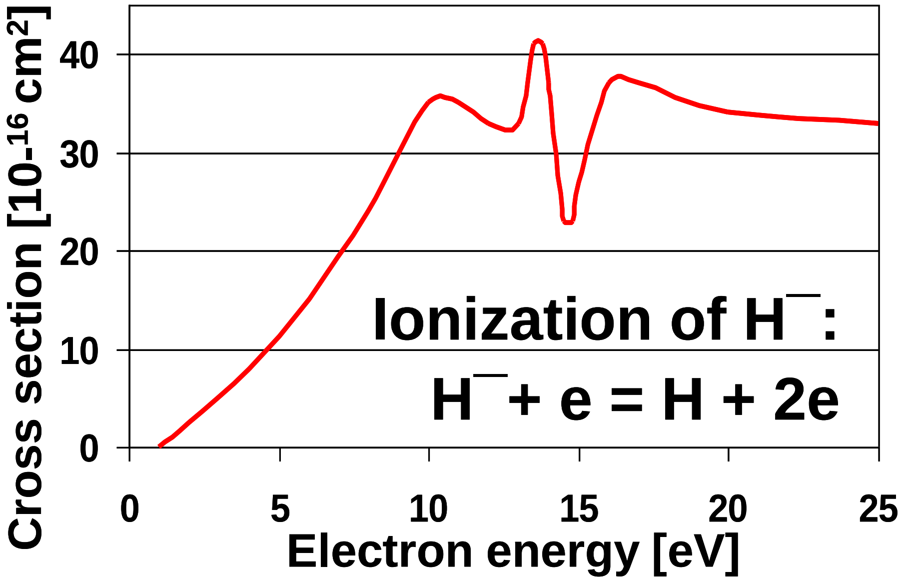
Vibrational States (+Lorentz Stripping)



McCurdy & Haxton, June 2011

Problem is…

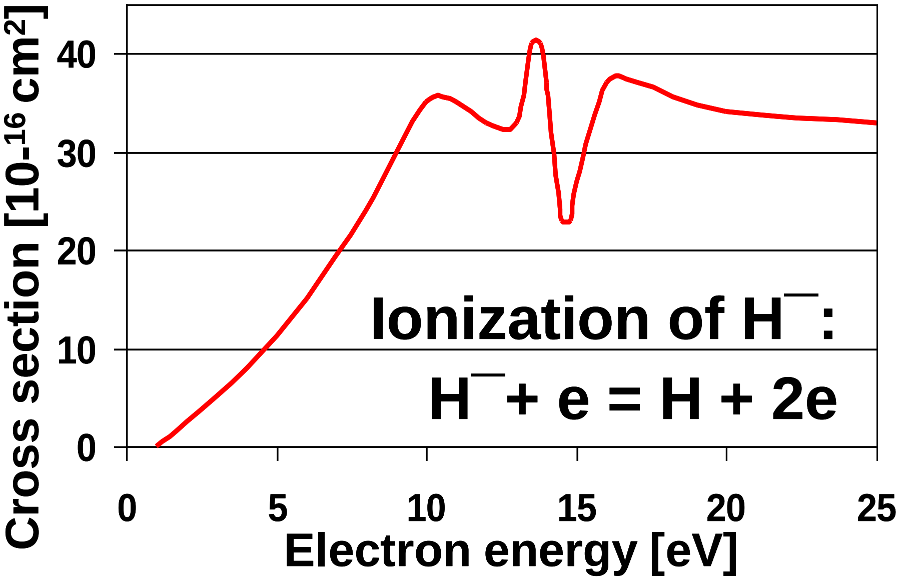
- Fast electrons needed to excite the molecules destroy (~3·10^{-15}cm^2) the H$^-$!



(Adapted from M. Stöckli, ORNL)

Problem is…

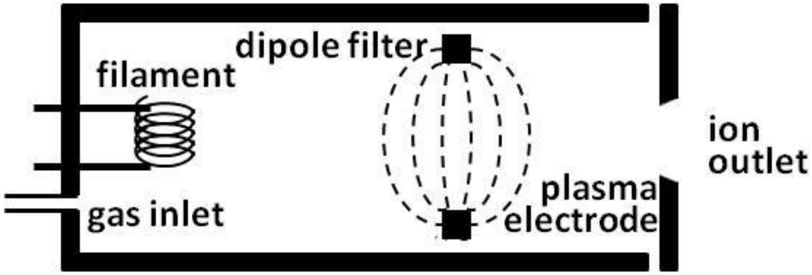
- Fast electrons needed to excite the molecules destroy (~$3 \cdot 10^{-15}$cm^2) the H^-!
- Solution: “Tandem Source”



Ionization of H^-:

$H^- + e = H + 2e$

Tandem Source

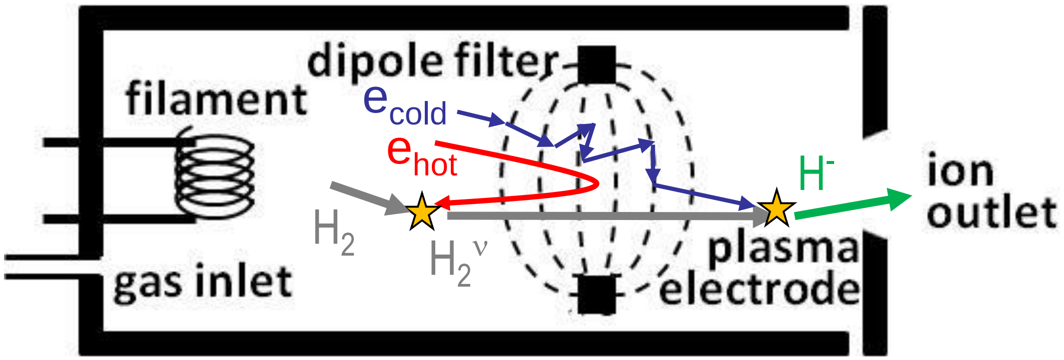


(Adapted from M. Stöckli, ORNL)

Magnetic Filter

- The magnetic filter reflects energetic electrons, e.g. 200 Gauss turn around 35-eV electrons on a 1 mm radius.
- Cold electrons and ions undergo many collisions with other particles, resulting in a diffusion process that favors cold charged particles ($v_{diff} \sim T^{-½}$).
- Excited neutral molecules migrate freely through the filter field & can break up near the outlet.

Tandem Source

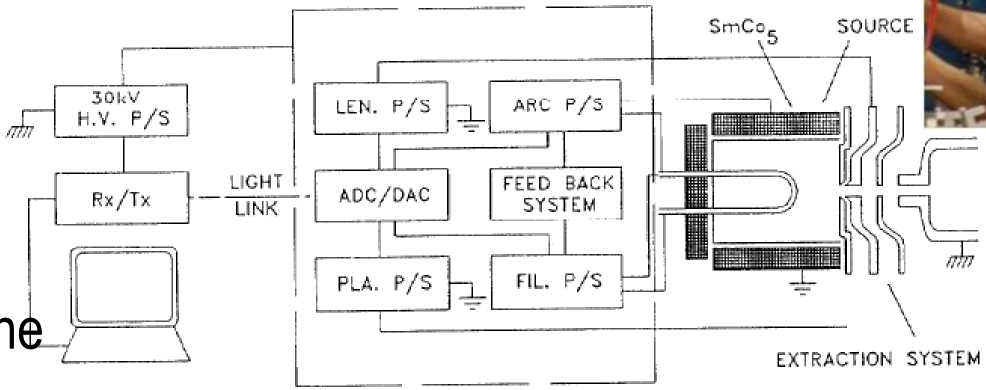


(Adapted from M. Stöckli, ORNL)

The TRIUMF H$^-$ Source

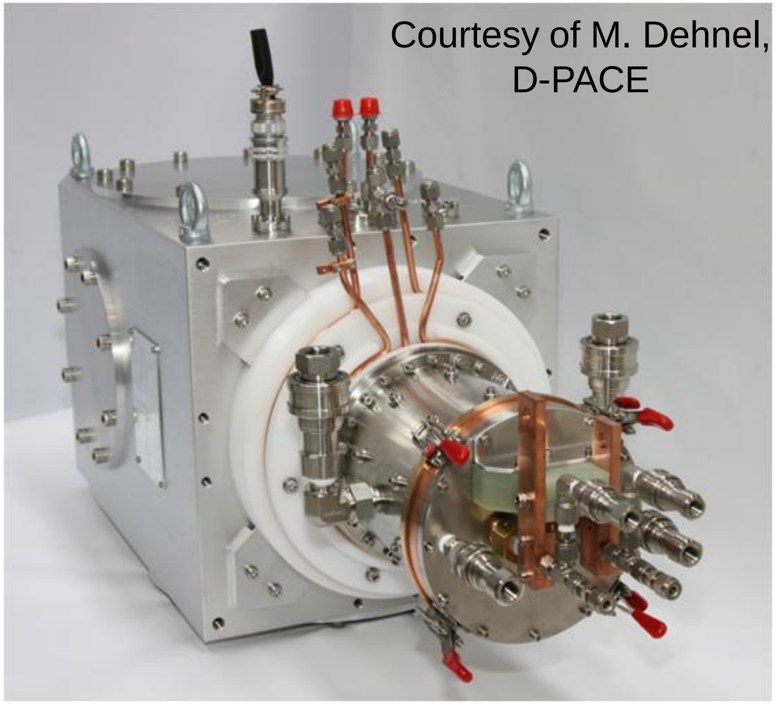
K. Jayamanna, M. McDonald, D.H. Yuan, P.W. Schmor, EPAC (1990) 647

- The TRIUMF H$^-$ source was developed ~1990 to inject H$^-$ into the TRIUMF Cyclotron.
- A filament driven plasma is confined by a multicusp field.
- 2 inverted cusp magnets near the outlet produce the filter field.
- A 6 mA, 5.8 keV copy was developed for Jyväskylä.



Keerthi Jayamanna

Beam Current:	**15 mA continuous**
Ion Energy:	**20-30 kV**
Filament:	**340 A, 3.5 V; 1.2 kW**
Arc supply:	**29 A, 120 V; 3.5 kW**
$\varepsilon_{rms, norm}$	**~0.22 π·mm·mrad**
Plasma lens	**30 A, 10 V; 0.3 kW**
Efficiency:	**~ 3 mA / kW**
Filament lifetime:	**≥14 days at peak current**

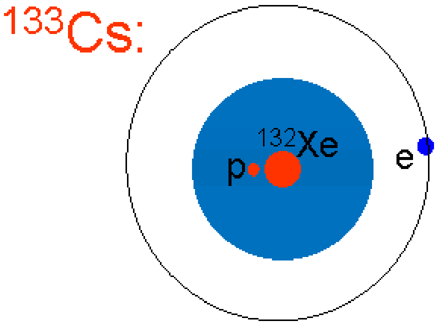


Courtesy of M. Dehnel, D-PACE

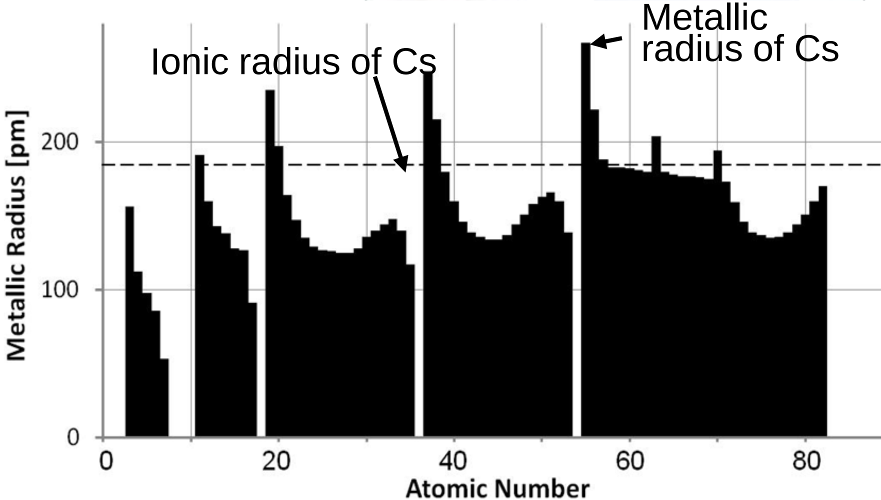
Parameter	Typical Values	Tuning	Comment
Permanent Magnet Multicusp Magnetic Field	0.8 – 1.4 T 8 – 16-Pole Front/Sides/ Back	No	Most likely need cooling. NdFe has higher field SmCo better Tc
Filament Heating	Many Parameters		
…	…		
RF Heating	Many Parameters		
…	…		
Filter Field	O(100 Gauss)	Somewhat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

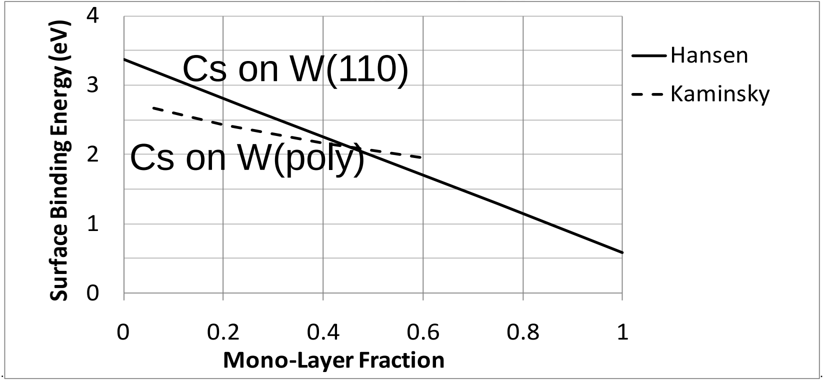
Sources can deliver ~15 mA DC, up to 50 mA pulsed.
Now improve extracted current with Cs…

Cesium on Metal Surfaces



- Cs is ^{132}Xe +1 proton +1 electron.
- The largest atom (2.65 A radius).
- The smallest ionization energy 3.9eV
- Small density: 1.9 g/cm^3
- Low melting point: 28.4°C.
- Cs atoms on clean metal surfaces form ionic-like bonds as their outer electrons mix with the conduction electrons.
- Ionic bonds are strong, resisting thermal emission as well as sputtering.
- Additional layers of Cs form covalent bonds with ~0.5 eV, which easily break.
- The Cs diameter being larger than the substrate matrix lattice causes the surface binding energy to decrease with increasing surface coverage.
- The increasing binding energy stabilizes the thermal emission.
- This allows for controlling the surface coverage with the surface temperature.

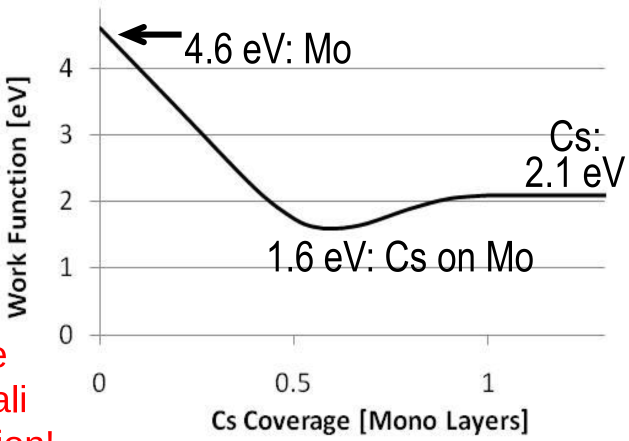




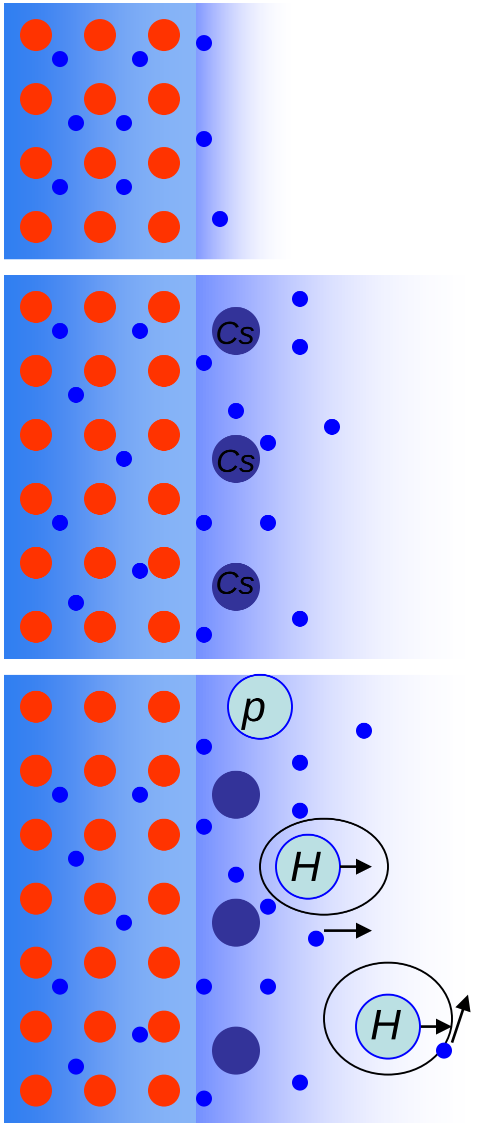
(Adapted from M. Stöckli, ORNL)

Surface Production of H^- Ions

- Metals host an abundance of loosely-bound conduction electrons, but it takes about 4.5 to 6 eV to remove an electron from the surface.
- Alkali metals have lower work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, alkali atoms can lower the surface work function below their bulk work function.
- Lowering the work function increases the probability that fast hydrogen atoms leaving the surface capture a second electron.
- Protons capturing an electron when hitting the surface and hyper-thermal atoms can capture a 2nd electron when bouncing back into the plasma.



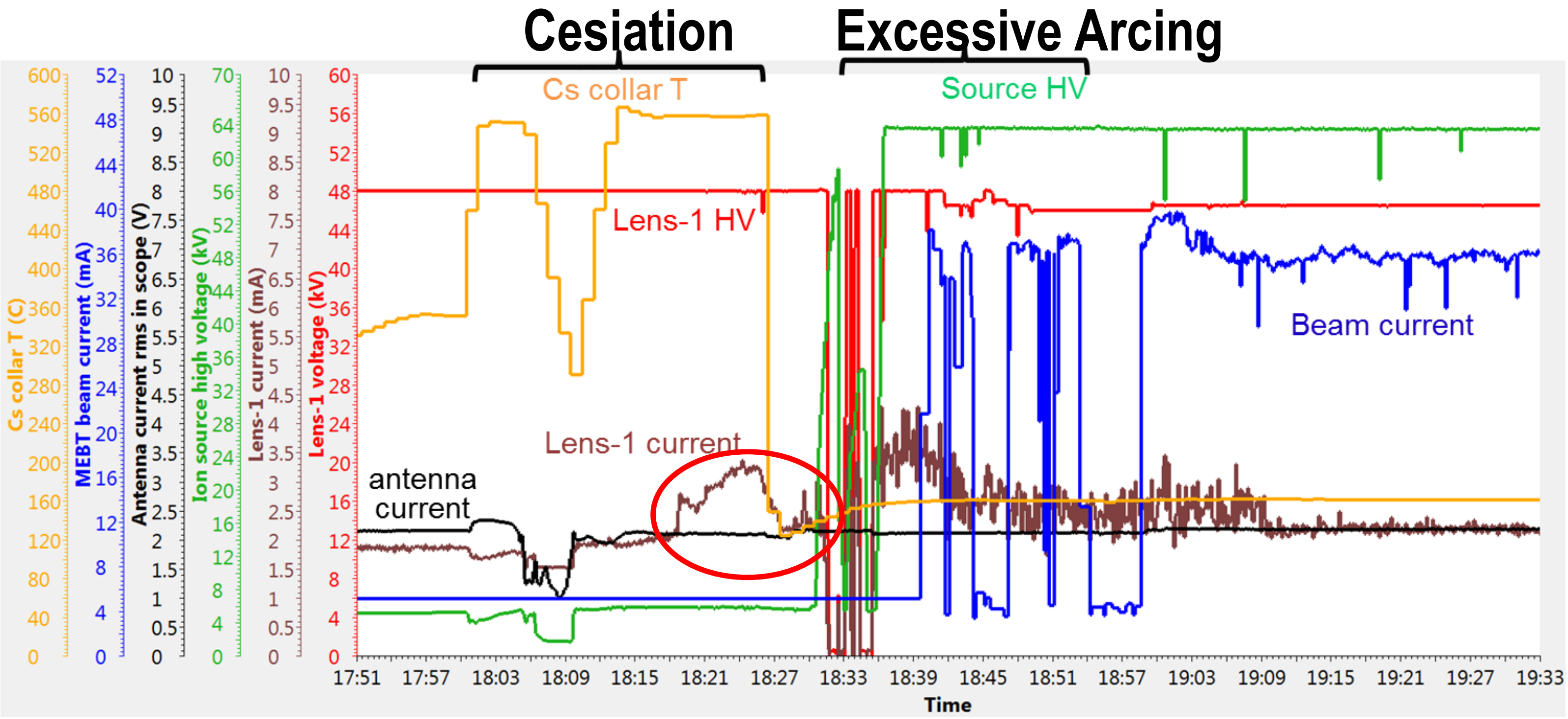
In the absence of Cs, residues on the surface (H_2O) and/or sputtered atoms (especially alkali from ceramics) can also lower the work function!



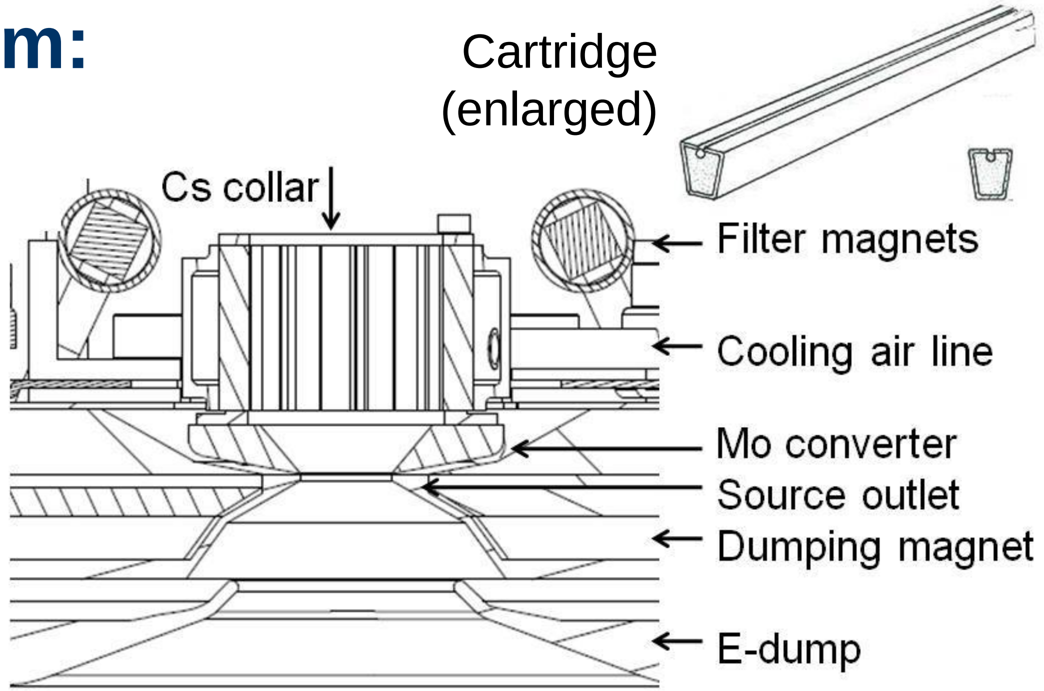
(Adapted from M. Stöckli, ORNL)

Problems with Cs (SNS Example)

- Cs lowers the work function, which increases the production of negative ions AND the emission of electrons from negatively charged ion source and associated electrodes (Lens-1).
- Uncontrolled discharges can damage or disable systems and cause extended down time.
- Cs needs to be minimized near HVs!



The SNS Cs_2CrO_4 System:



- To minimize Cs-induced arcing in the compact SNS LEBT, LBNL introduced 8 Cs_2CrO_4 cartridges (SAES Getters), which together contain <30 mg Cs. Integrated into the Cs collar, the compact system allows for rapid startups!

- The Mo ion converter is electrically and thermally attached the Cs collar. The temperature of the system is controlled with heated air.

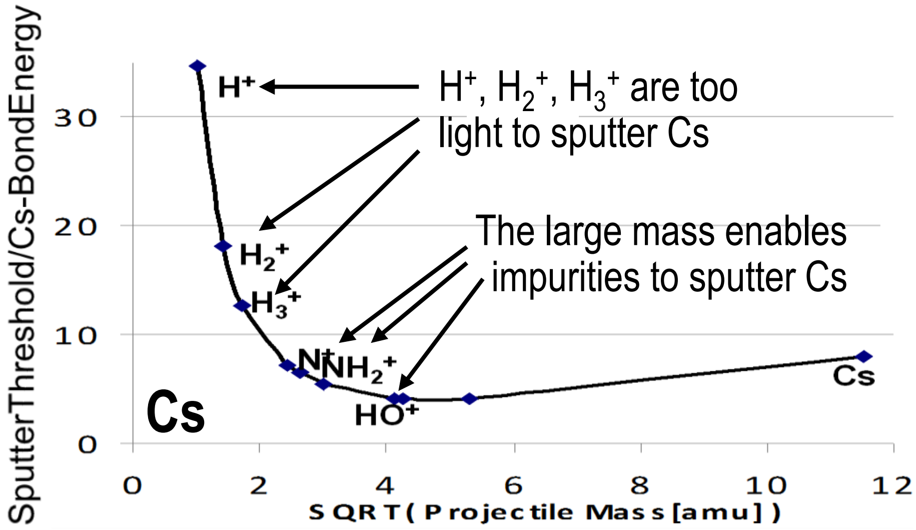
- Right after being evacuated, the system is outgassed at 250°C and the Mo converter is sputter-cleaned for ~3 hours. Then the collar is heated for 12 minutes to 550°C to release ~4 mg of Cs. Then the temperature is lowered to ~170°C. This appears to produce a nearly optimal monolayer of Cs, which becomes persistent.

- Some times a few mA are lost in the 1st few hours.
- Often the H^- beam grows a few mA for a few days.
- Then the beam becomes persistent, practically free of decay!

SNS produces >9 kC or >2.5 A·h of H^- ions without any maintenance!

Requirements for Persistent H^- Beams

- To obtain persistent beams with Cs-enhanced H^- sources, a stable fractional mono layer of Cs needs to be maintained.
- Cs can be lost through thermal emission and through sputtering.
- In Cs-enhanced H^- sources some Cs is lost and replaced through a small flux of Cs, which requires experience; e.g.; the Hera magnetron started with 6 mg/day in 1993 and ended with 0.7 mg/day in 2008.
- The LANCE source requires ~1 g/day, ~10^3 times more.
- However, when scaled with the plasma duty factor, LANCE requires ~8 g/plasma-day, whereas DESY required 37g/plasma-day in 2008.
- At such rates the SNS source would run out of Cs in ~1 hour!
- The ~4 mg Cs in the SNS H^- source yield ~50 mA H^- beam for up to 6 weeks.
- This corresponds to ~0.12 mg/day or ~2 mg/plasma-day, >4000 times less than other H^- sources.
- Apparently, the SNS H^- source is sputter-free due to its low plasma potential and its high purity of the hydrogen plasma!



H^+, H_2^+, H_3^+ are too light to sputter Cs

The large mass enables impurities to sputter Cs

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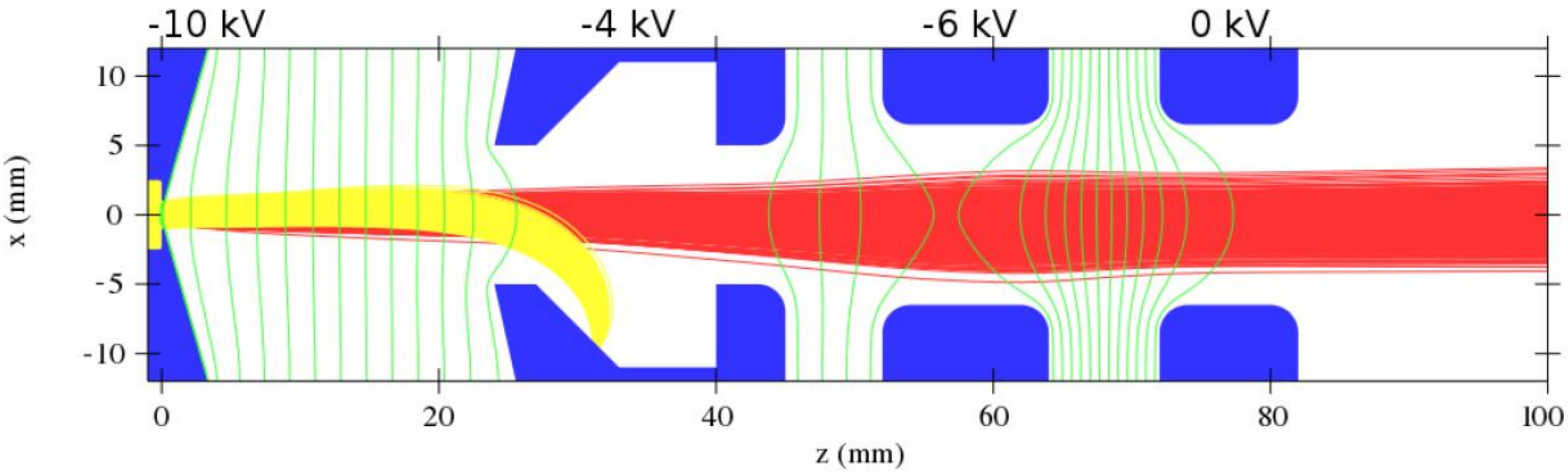
Filament Heating	Many Parameters		
…	…		
RF Heating	Many Parameters		
…	…		
Filter Field	O(100 Gauss)	Somewhat	
Cesium	> .12 mg/plasma-day	Somewhat	Can lead to sparking
Material/Gas	1e-5 to 1e-3 Torr	Yes	
Extraction	Up to 100 kV	Somewhat	Depends strongly on application!

Co-extracted Electrons

- Electron Current can be much higher than ion current.
- Poses a real problem for damaging parts of the beam line if not disposed of in a controlled fashion.
- Extraction system needs to include electron dump.
- Electrons can be diverted electrostatically or magnetically (typical).



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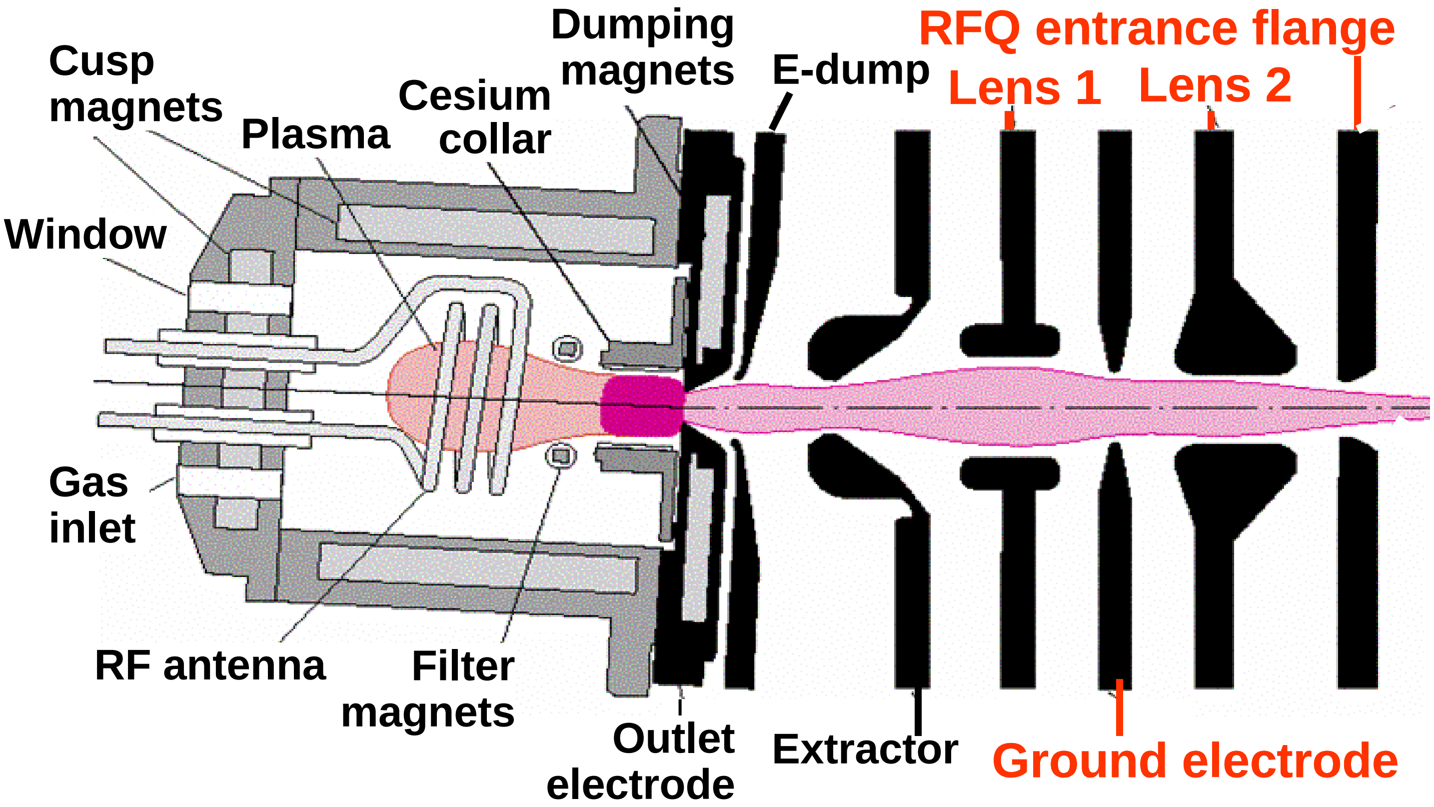
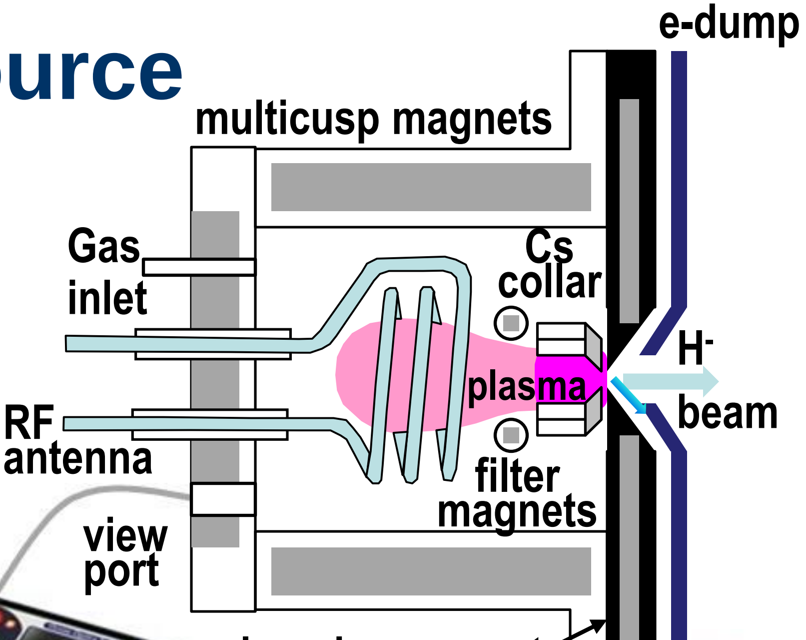
…	…		
Filter Field	O(100 Gauss)	Somewhat	
Cesium	> .12 mg/plasma-day	Somewhat	Can lead to sparking
Material/Gas	1e-5 to 1e-3 Torr	Yes	
Extraction	Depends strongly on application: Up to 100 kV for positive ions -10's of kV for negative ions	Somewhat	Depends strongly on application: Negative: Electron Dump!

Examples: SNS Ion Source



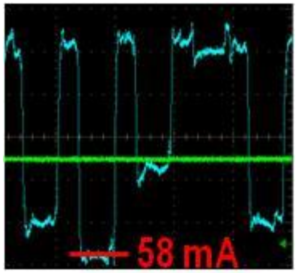
The SNS Baseline Ion Source

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



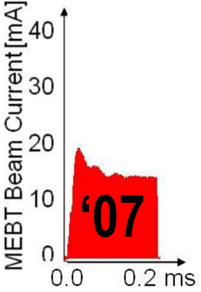
- About 300 W 13-MHz RF generate continuous low-power plasma.
- 50-60 kW of 2 MHz RF are added for ~1 ms at 60 Hz to produce the H^- beam pulses.
- A jaz spectrometer analyzes 220-1100 nm emissions since 2011.
- Gaseous emissions are monitored since 2007 and since 2013 with a more sensitive PrismaPlus.

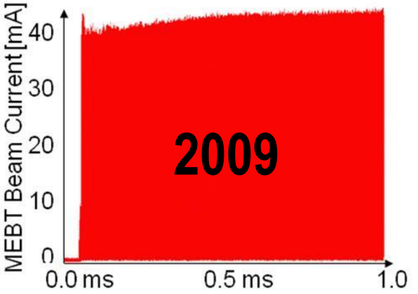
- The H^- beam current injected into the LINAC is measured with a beam current torroid after the RFQ and 2 quadrupoles.



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

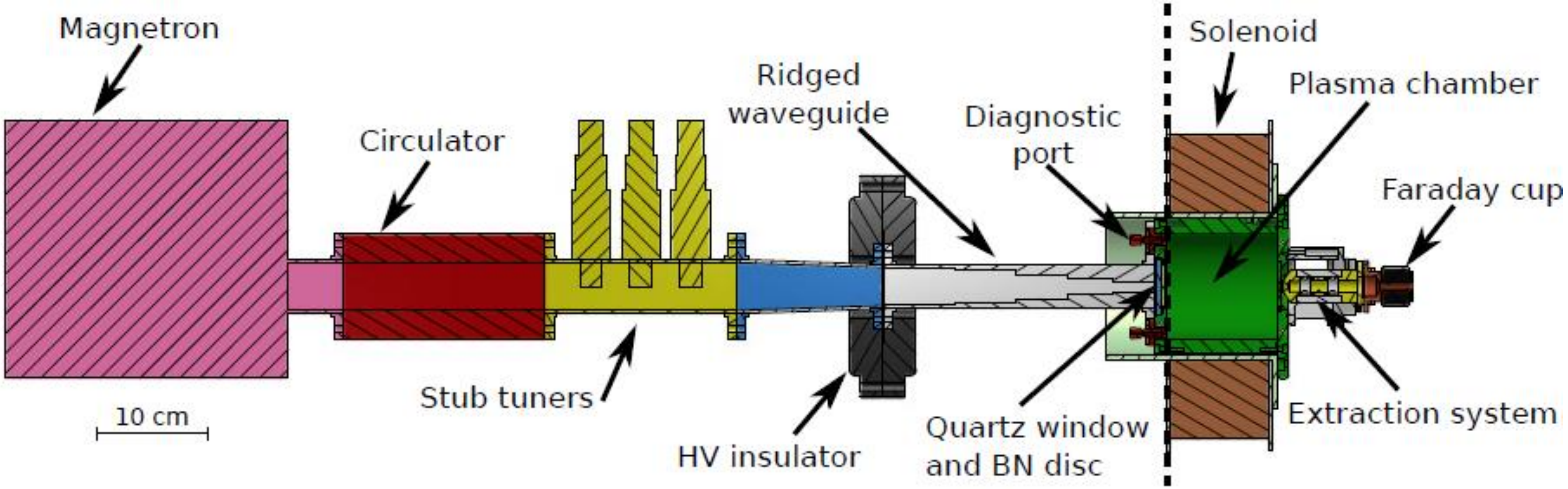
50-60 mA go into the RFQ!





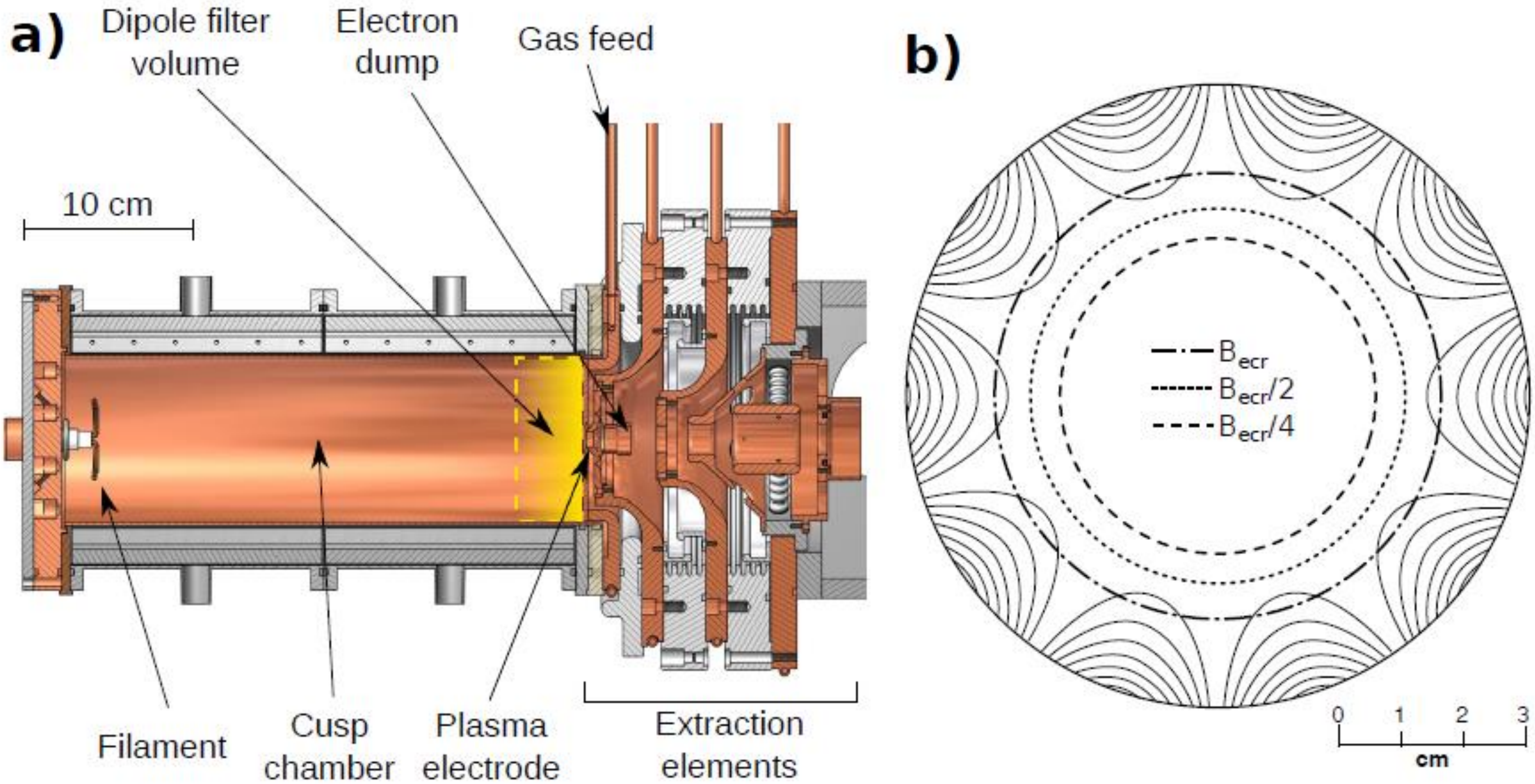
MW Waveguide Coupled Heating

- Microwave system from 2.45 GHz off-resonance ECR
- Ridged waveguide
- Quartz window



J. Komppula, NIBS 2014

LIISA Source



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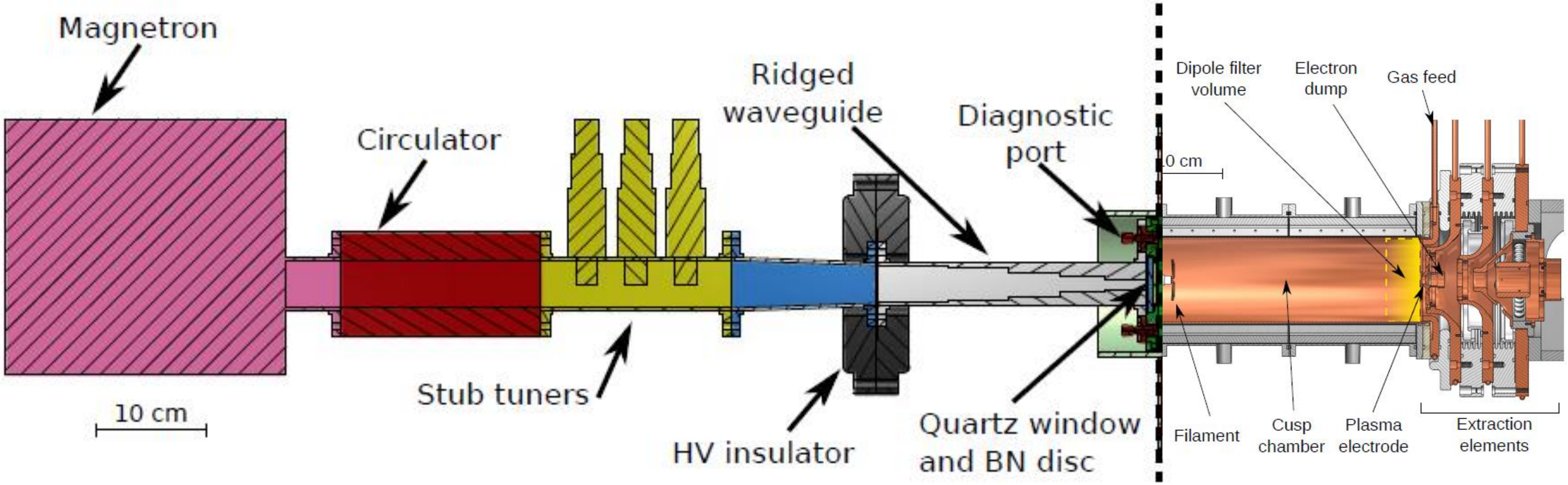
LIISA Source

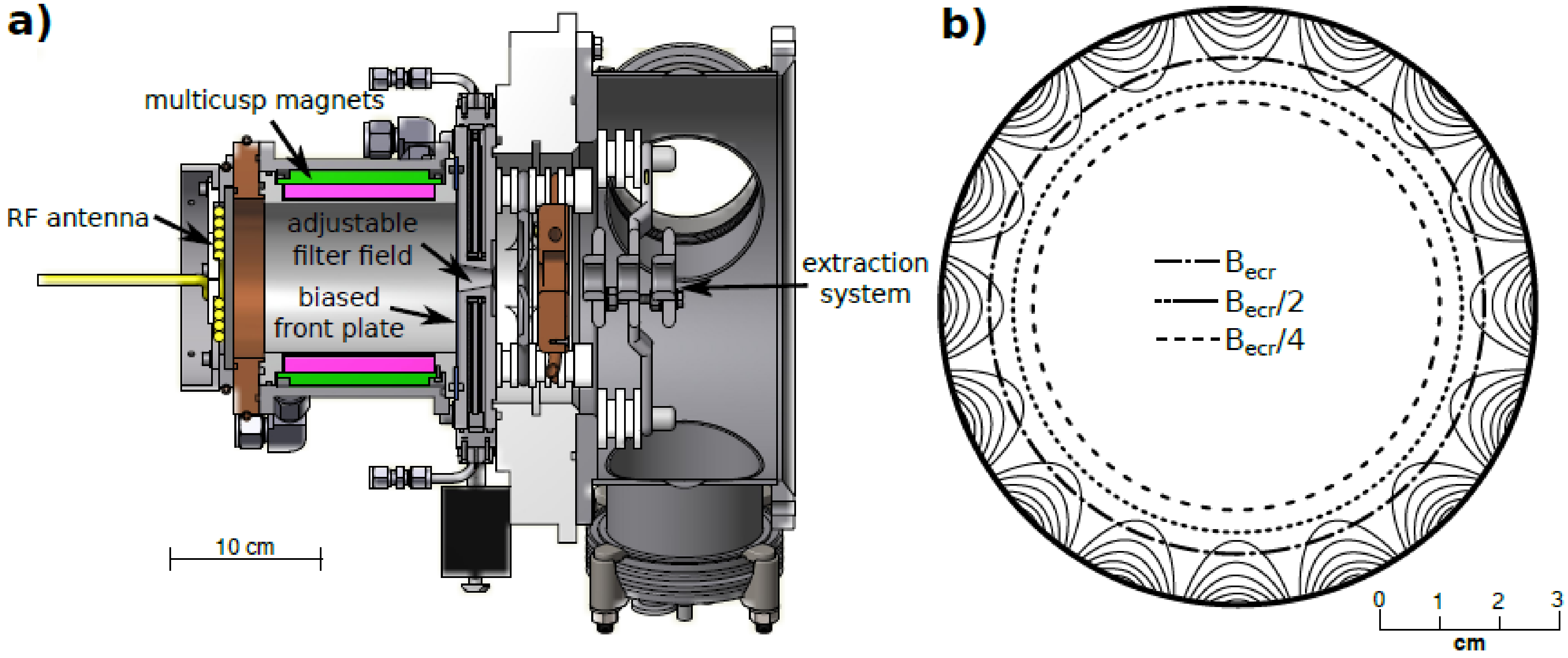
- Originally: Filament driven discharge H- source
- Now coupled with Magnetron for ECR heating



J. Komppula, NIBS 2014

RADIS Source

RF-driven discharge RADIS



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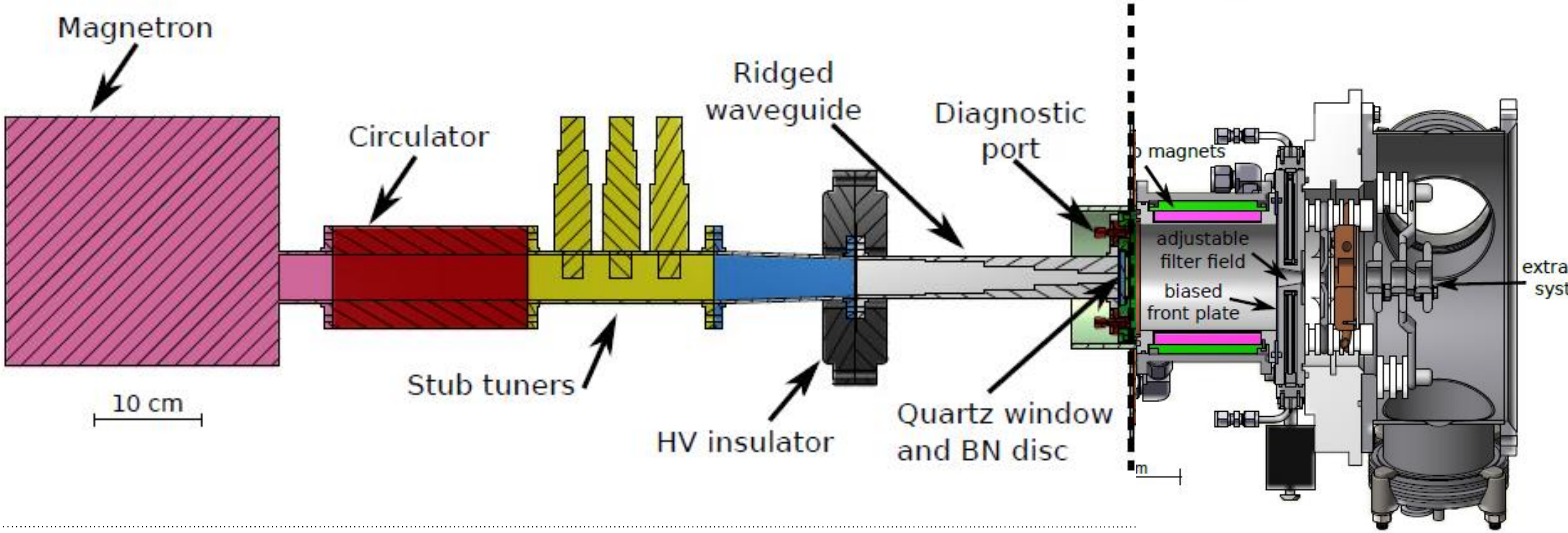
RADIS Source

- Originally: RF driven H- source
- Now coupled with Magnetron for ECR heating



J. Komppula, NIBS 2014

ECR Heating Results

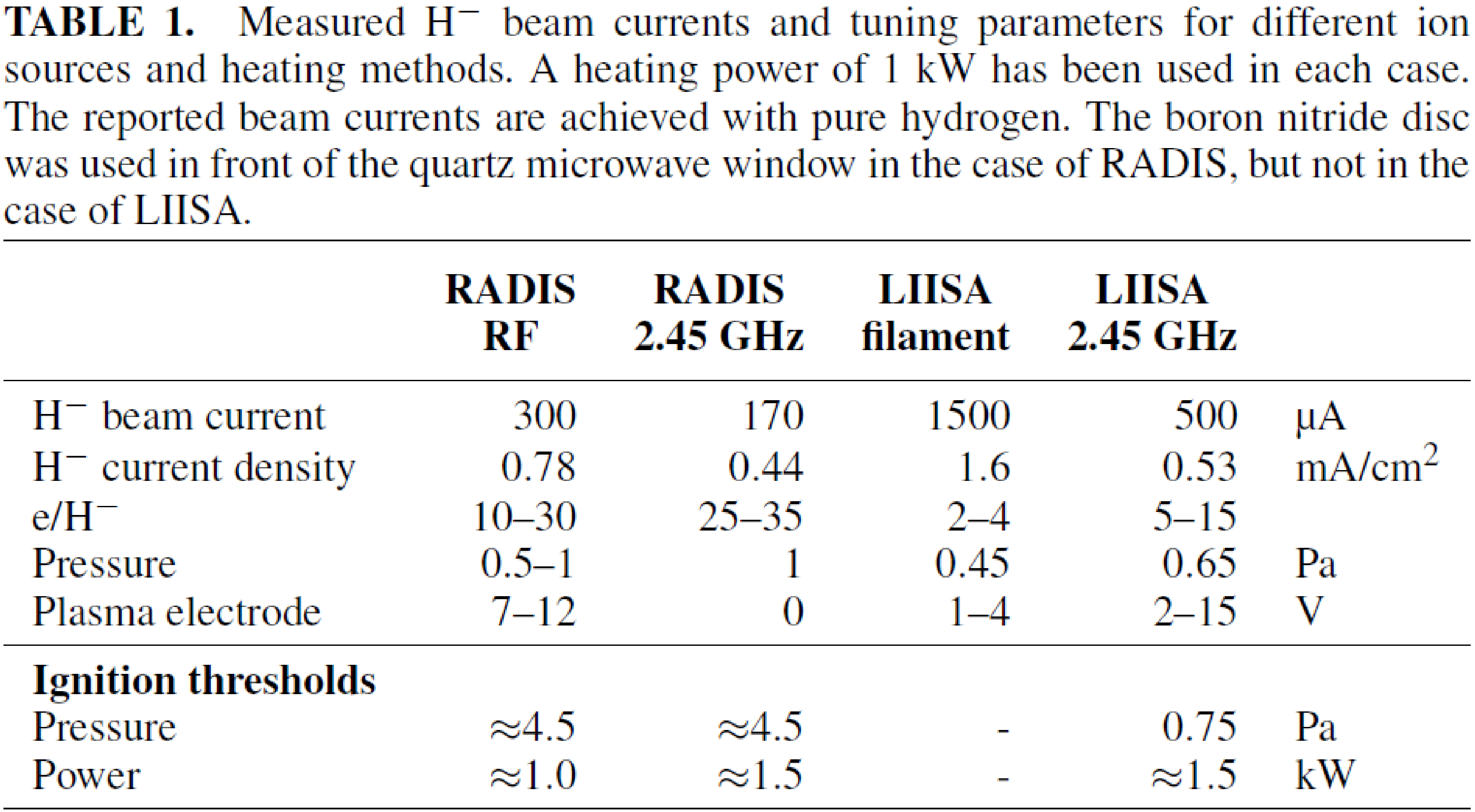


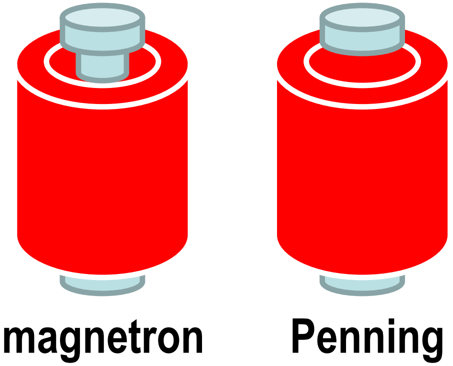
TABLE 1. Measured H^- beam currents and tuning parameters for different ion sources and heating methods. A heating power of 1 kW has been used in each case. The reported beam currents are achieved with pure hydrogen. The boron nitride disc was used in front of the quartz microwave window in the case of RADIS, but not in the case of LIISA.

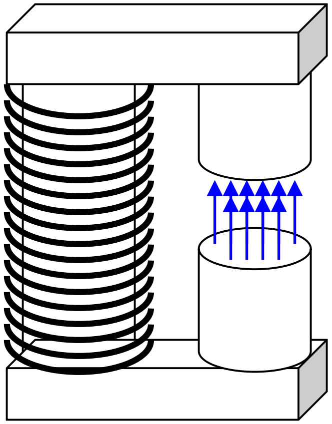
	RADIS RF	**RADIS 2.45 GHz**	**LIISA filament**	**LIISA 2.45 GHz**	
H^- beam current	300	170	1500	500	µA
H^- current density	0.78	0.44	1.6	0.53	mA/cm^2
e/H^-	10–30	25–35	2–4	5–15	
Pressure	0.5–1	1	0.45	0.65	Pa
Plasma electrode	7–12	0	1–4	2–15	V
Ignition thresholds					
Pressure	≈4.5	≈4.5	-	0.75	Pa
Power	≈1.0	≈1.5	-	≈1.5	kW

J. Komppula, NIBS 2014

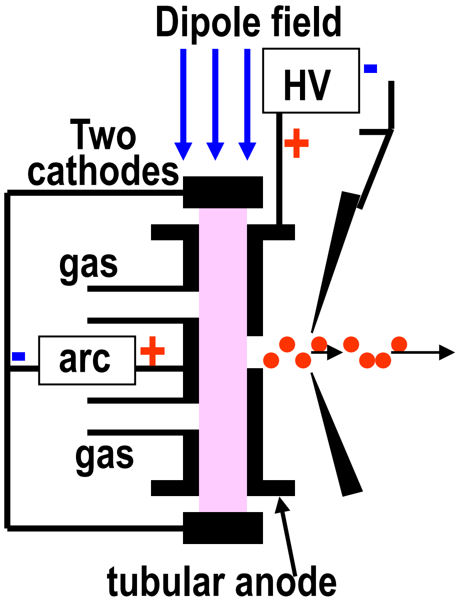
Other Types of Negative Ion Sources

- Magnetron
- Penning
- Compact Surface Plasma Sources (CSPS)
- Penning ion beams tend to be noisy and drift during operation.
- The ion induced sputtering of the cathode enables metal beams, but also limits the ion source lifetime!

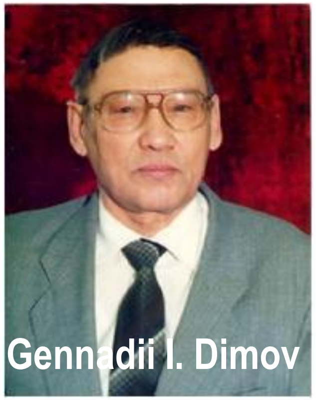




Dipole field

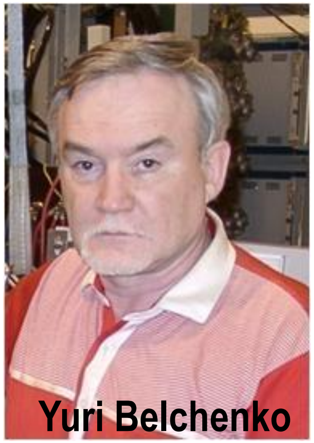


Cs in Negative Ion Sources



In the early 1970s, before the Cs physics was understood, G. Dimov, Y. Belchenko, and V. Dudnikov added Cs to their magnetron source increasing the H$^-$ current to 150 mA for up to 0.5% duty factors.

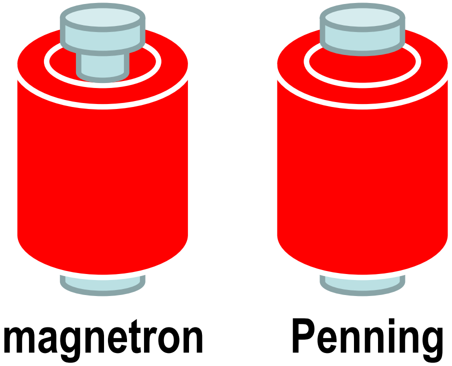
V.G. Dudnikov, *Russian Patent No. 411542 (1973)*
Y. Belchenko, G. Dimov, V. Dudnikov, *Nucl. Fusion, 14, 113 (1974)*



Then Vadim Dudnikov developed a Penning H$^-$ source that delivers 150 mA with a 1% duty factor.

With the Siberian “Know How”,

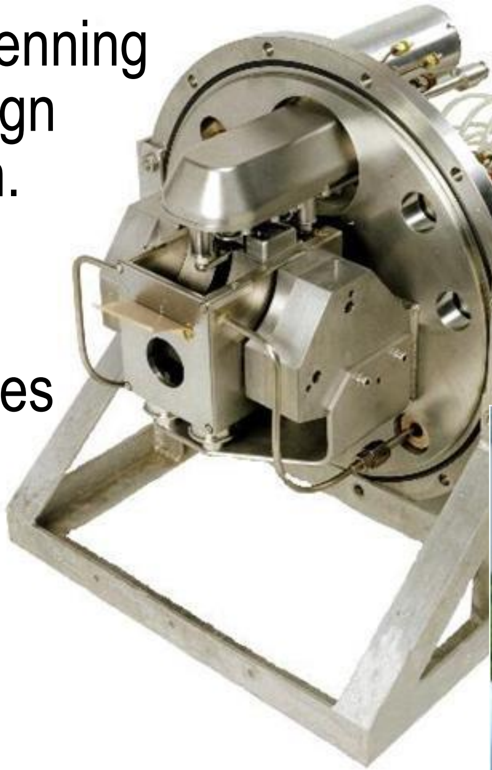
- BNL Krsto Prelec et al. developed magnetrons for NBI.
- LANL Paul Allison et al. developed Penning H$^-$ sources.
- LBNL Ehlers and Leung developed Surface Converter H$^-$ sources for LANL.
- FNAL Chuck Schmidt et al. developed the BNL magnetron for accelerators.



Compact Surface Plasma Sources (CSPS)

Recently, Yuri Belchenko developed a hollow cathode Penning source delivering 25 mA H- DC!

The RAL ISIS Penning H- Source



- In the early 1980s RAL develops the ISIS Penning H^- source by combining a LANL Penning design with some features from the FNAL magnetron.
- The design evolved over the years.
- Since 2002 Dan Faircloth leads the effort.
- It currently produces 35 mA H^- 0.25 ms pulses at 50 Hz for the 160 kW ISIS neutron source.
- It consumes 3 mg Cs per hour or ~2 g in its ~25 days lifetime. The Cs is trapped by the 90° dipole magnet inside a cold box.
- Using 0.8 ms plasma pulses, the lifetime is ~1 plasma day or 1 kC ≈ ¼ A·h of H^-, which appears to be typical for CSPS.
- In 2009 the development shifted to the FETS test stand, now reaching 50 Hz ~60 mA H^- beam at 3 MeV with 10% d.f.
- The Chinese Spallation Source has adopted this source, meeting their initial 20 mA and later 40 mA requirements.

100/200 kW
require 20/40 mA