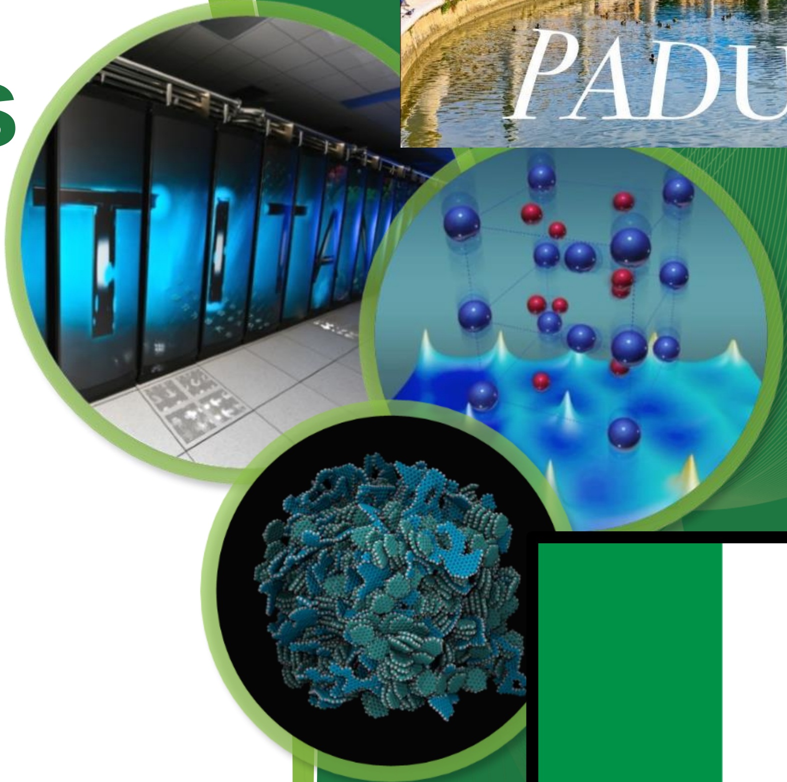
RF (Light) Negative Ion Sources for Non-Fusion Applications

Martin P. Stockli

Spallation Neutron Source, ORNL



8th International Symposium on Negative Ions, Beams and Sources

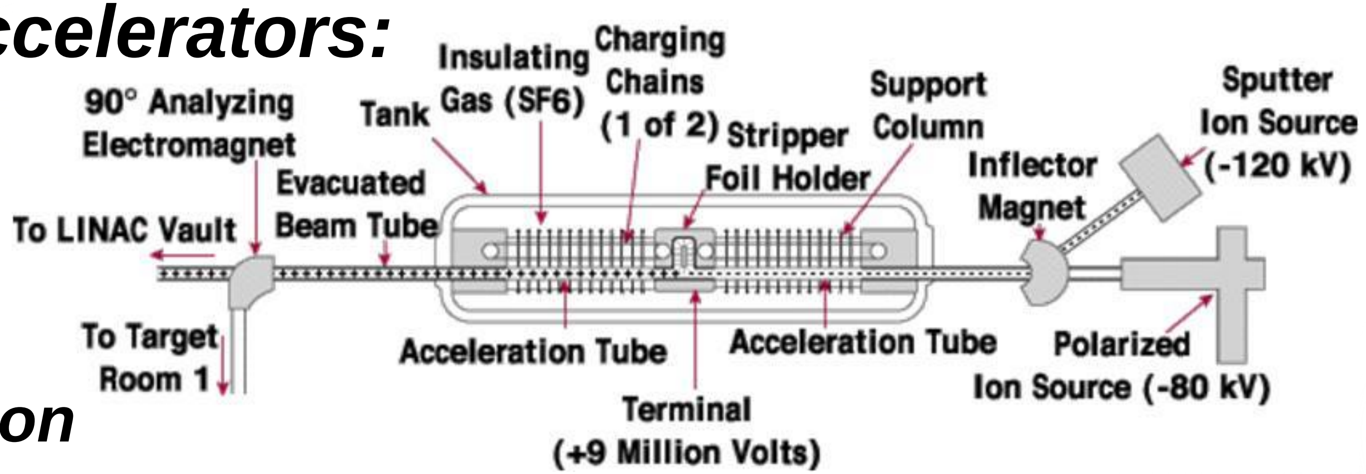
Orto Botanico di Padova, Bella Italia

October 3, 2022

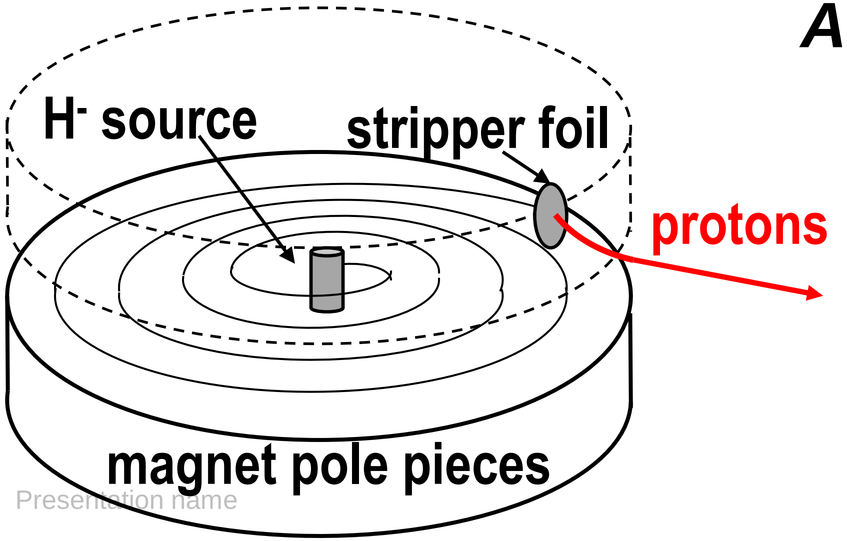
Negative⁻ Ions are very unique:

Negative ions can be made positive.
This radical change has very unique applications:

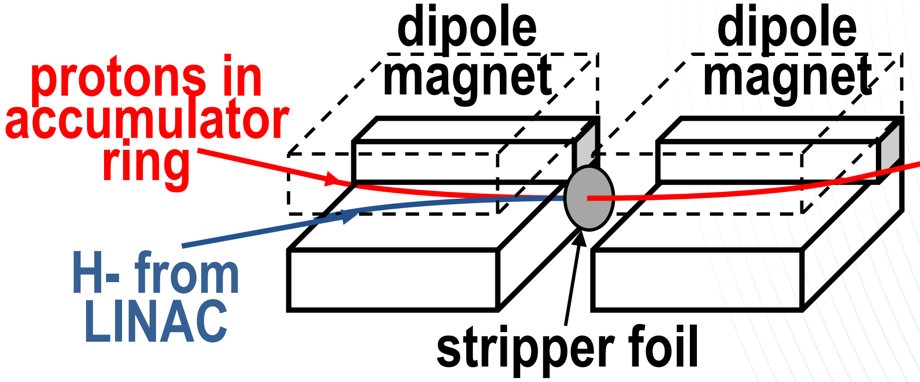
Tandem Accelerators:

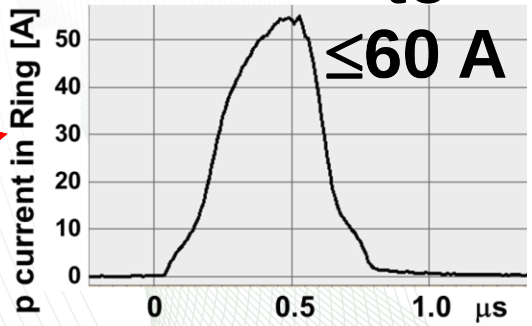


Efficient Extraction from Cyclotrons:



Accumulating Ions in a limited Phase Space:





50 mA to ≤60 A

e.g. the Spallation Neutron Source

OAK RIDGE National Laboratory

Introduction: The 2002 Status of High Current H- Sources

Source type	Laboratory-Facility	Beam current [mA]	Rep rate [Hz]	Beam pulse length [ms]	Beam duty factor [%]	Duty factor Upsale factor	Service cycle		Lifetime@ 50 mA & 6% d. f.
							weeks	A·h	days
Magnetron	BNL-AGS	95	7.5	0.63	0.47	13	26	2.0	27.1
	FNAL	75	15	0.07	0.1	60	16	0.20	2.8
	DESY-HERA	60	5	0.1	0.05	120	52	0.26	3.6
	ANL-IPNS	48	30	0.07	0.21	29	16	0.27	3.8
Penning	RAL-ISIS	35	50	0.2	1.0	6	4	0.24	3.3
	INR-MMF	50	100	0.2	2.0	3	Intermittent use		
Multicusp Converter	LANL-LANCE	<20	120	0.815	9.8	0.6	4	1.3	18.3
	KEK-KENS	18	20	0.2	0.4	15	14	0.17	2.4
Multicusp RF	SSC	60	10	0.1	0.1	60	1	0.01	0.14
	DESY-test HERA	40	8	0.15	0.12	50	150	1.2	16.8
Required	***ORNL-SNS***	***50***	***60***	***1.0***	***6.0***	***1***	***3***	***1.5***	***21***

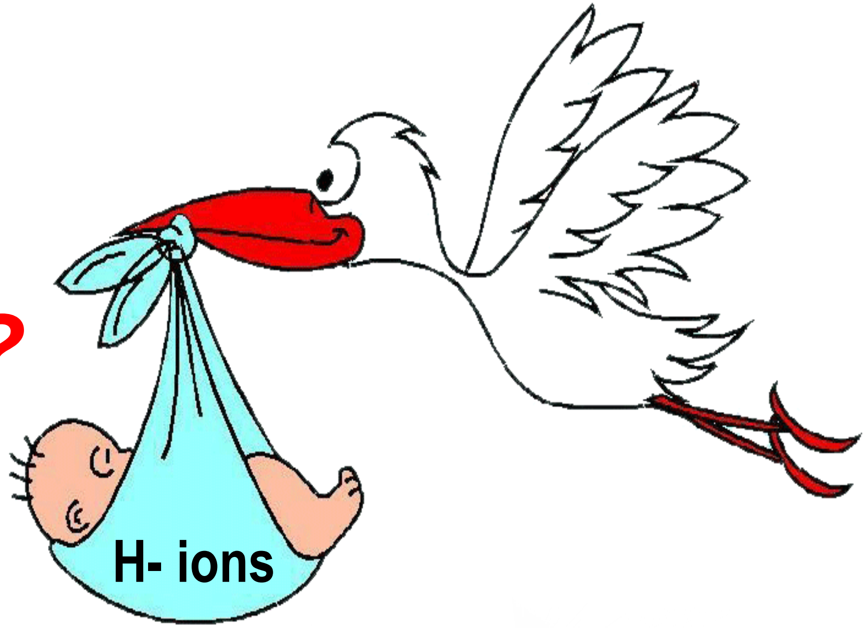
- Only the BNL sources matches the beam-current and the lifetime, but the duty-factor needs to be upscaled by 13!
- Only the LANL source is close to the duty-factor and lifetime, but its current needs to be increased by 3!
- ISIS with 35mA and 1% is the closest, but insufficient!

The unprecedented SNS Requirements required a new H- Source!

Abstract

- Twenty years ago, there was no ion source that could provide high-currents (>20 mA) of H^- beams at high duty factors (>>1%).
- In addition, the lifetime of H^- sources was limited to 2 Amp-hours.
- Accordingly, high-duty-factor H^- sources had to be replaced every few weeks!
- The H^- ion sources limited the power of the accelerators!
- **The development of RF H^- sources has reversed the situation:**
- **Now accelerators limit the applicable performance of RF H^- sources.**
- **RF H^- sources yield >100 mA of H^- with duty factors up to 10% and lifetimes up to 10 Amp-hours using as little as 5 mg Cs.**

Content



Where are the H- Ions coming from?

- The Physics of Discharges
- Lifetime Issues
- The Physics of Negative Ions
- The Development of RF H^- Sources
- Conclusions

It is all about producing

more light Negative Ions for longer times!

OAK RIDGE National Laboratory

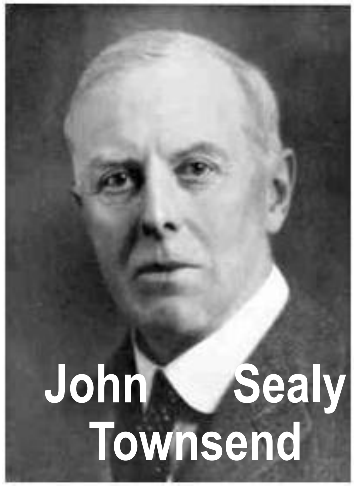
The Townsend Discharge

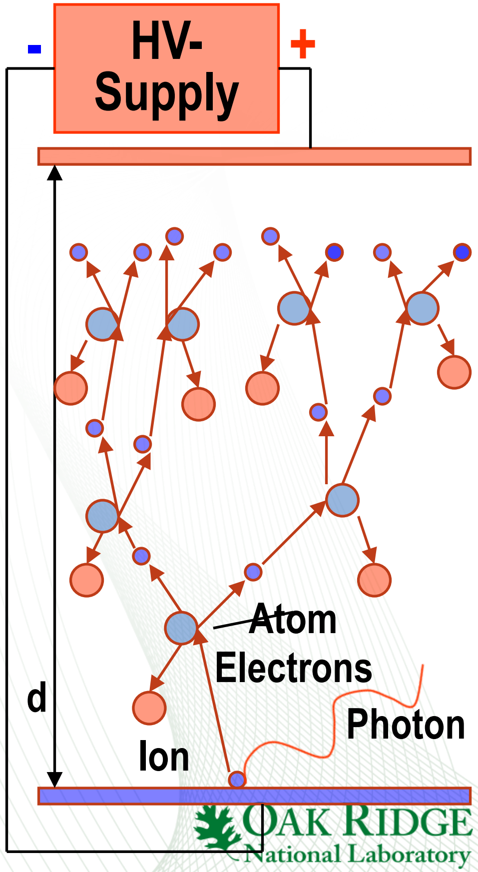
- Around 1900 John Sealy Townsend studied discharges below the breakdown voltage (dark discharges).
- UV light illuminating the cathode produces photo electrons.
- Applying sufficient voltage, the discharge current *I* grows exponentially with the distance *d* between the electrodes:

$$I = I_0 \cdot \exp(\alpha \cdot d)$$

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

- Modern-day explanation: After gaining enough energy, the photo electrons ionize atoms, doubling the number of free electrons.
- 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.





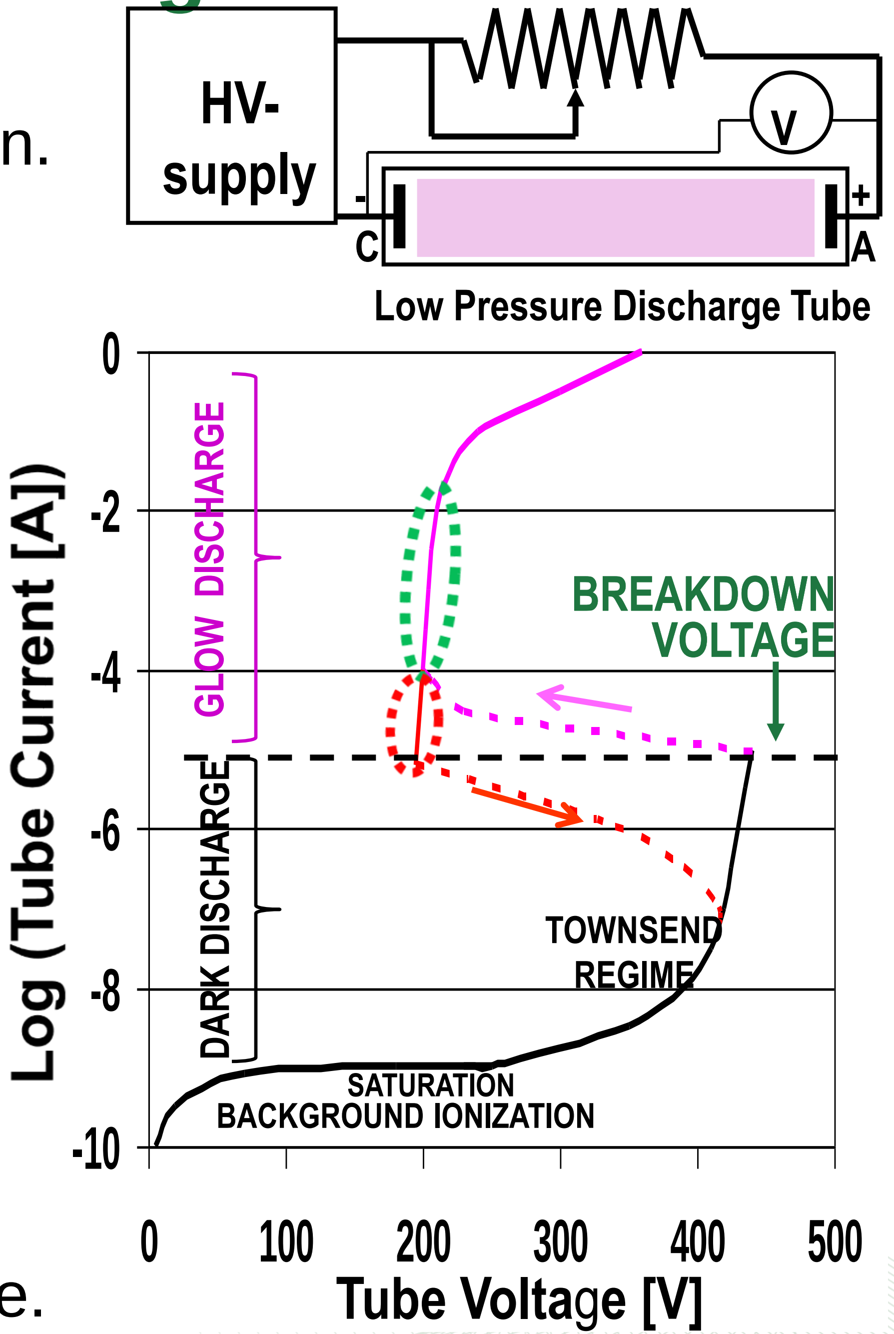
Exponential growth!!

The Evolution of Low Pressure Gas Discharges

- Small voltages yields nA currents by collecting electron–ion pairs produced by background radiation.
- Raising the voltage starts the Townsend multiplication, yielding many µA (corona).
- Increasing the voltage, suddenly the gas starts to glow and the current grows up to many mA at a much reduced voltage.

Electron multiplication at anode — Ions at cathode per initial electron

- Discharge current $I = I_0 \cdot e^{\alpha \cdot d} / (1 - \gamma \cdot (e^{\alpha \cdot d} - 1))$ diverges when the ions impacting on the cathode generate enough secondary electrons to replace all seed electrons.
- Increasing the reduced voltage increases the glowing plasma volume and the current.
- Discharge ion sources typically operate at the low current end of glow discharges to minimize losses.
  - Dropping below a current/voltage threshold extinguishes the glow, restoring the dark state.

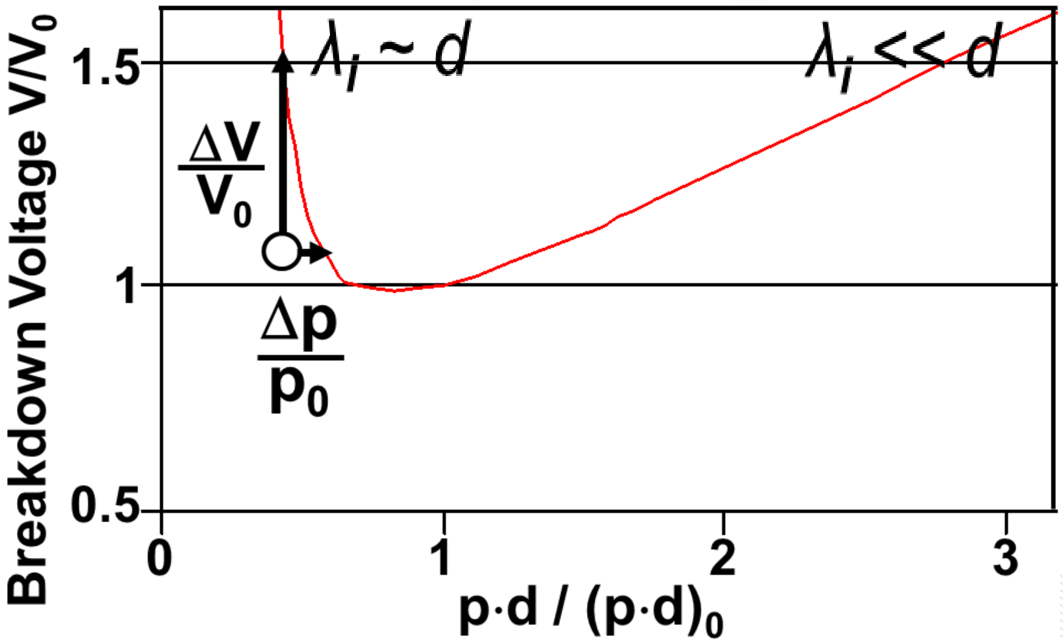


The Breakdown Voltage (Paschen's Law)

- In 1889, Friedrich Paschen describes the breakdown voltage ***V***: $V = a \cdot p \cdot d / (\ln(p \cdot d) + b)$ with pressure ***p***, electrode gap ***d***, and ***a*** & ***b***, *which* depend on the gas and the electrodes.
- Normalization with the minimum voltage V_{min} and corresponding $(p \cdot d)_{min}$ creates an universal curve.

Gas	Cathode	V_{min} (V)	$(p \cdot d)_{min}$ (Torr•mm)
Air		360	15
H_2	Pt	295	12.5
He	Fe	150	25

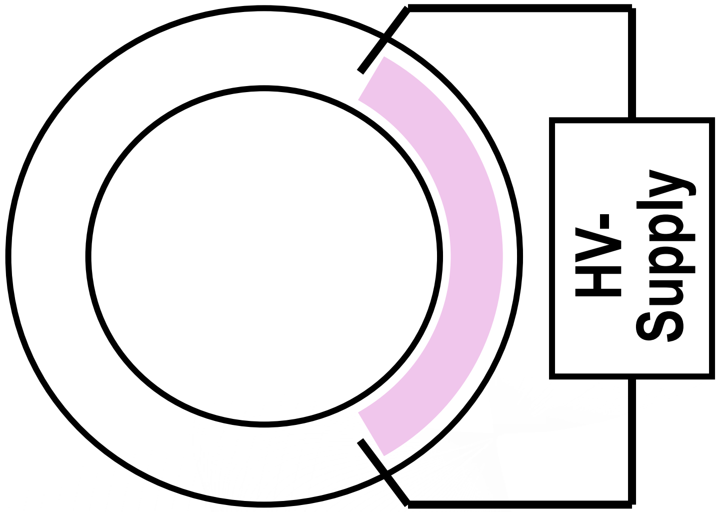
- Gases are good insulators at very low– and very high pressures.
  - Free electrons have to gain enough energy to ionize an atom or molecule in the next collision (λ_i).
  - Decreasing the pressure increases the mean path between collisions (λ_i), which can compensated by proportionally increasing *d*.
  - The minimum represents the minimum energy spent on producing enough ions for one secondary electron from the cathode.
  - At high $p \cdot d$, the voltage increases linearly with the gap between the electrodes.
  - At low $p \cdot d$, the electrons need more energy to liberate more than one electron.



Paschen Experiment

- Take a glass toroid with 2 electrodes forming a 125 mm and a 250 mm gap.
- Fill it with 0.1 Torr Hydrogen
- Raise the voltage …….. 290V, 300V: *short gap lights up*

  …….390V, 400V: *long gap lights up*



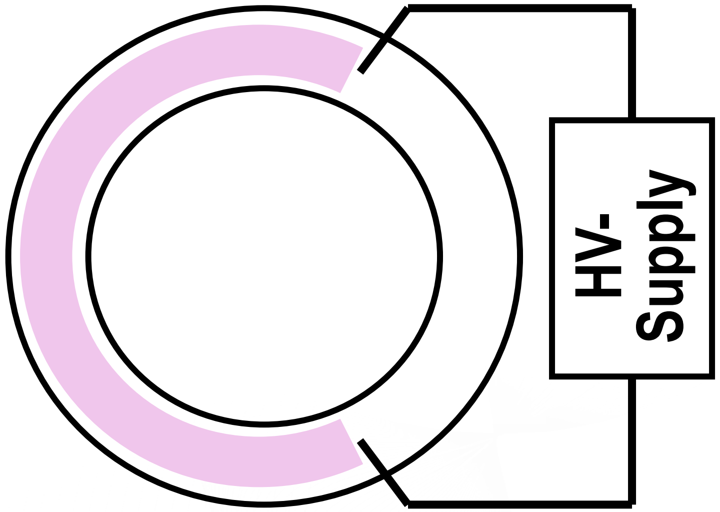
$$V = a \cdot p \cdot d/(\ln(p \cdot d)+b)$$

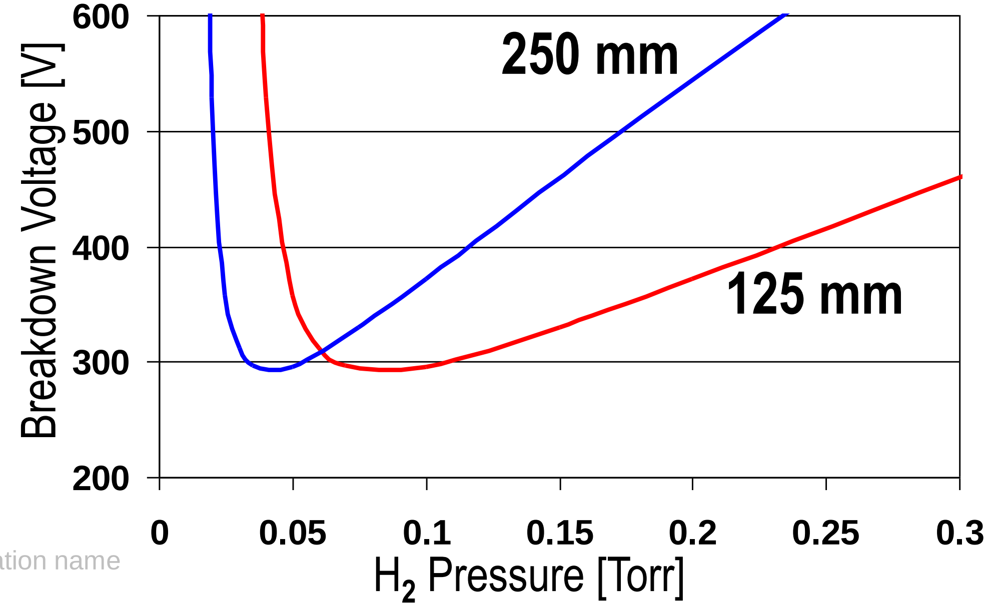
Paschen Follies

- Take a glass toroid with 2 electrodes forming a 125 mm and a 250 mm gap.
- Fill it with 0.1 Torr Hydrogen
- Raise the voltage …….. 290V, 300V: *short gap lights up*

  …….390V, 400V: *long gap lights up*
- Now reduce pressure to 0.05 Torr.
- Raise the voltage ……. 290V, 300V: *long gap lights up*

  …….390V, 400V: *short gap lights up*



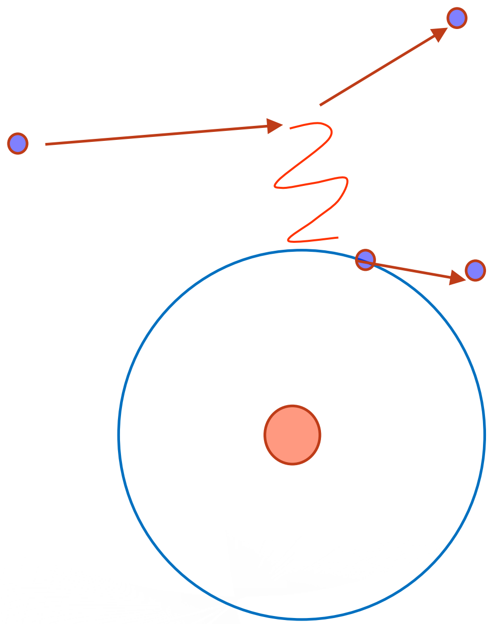


$$V = a \cdot p \cdot d/(\ln(p \cdot d)+b)$$

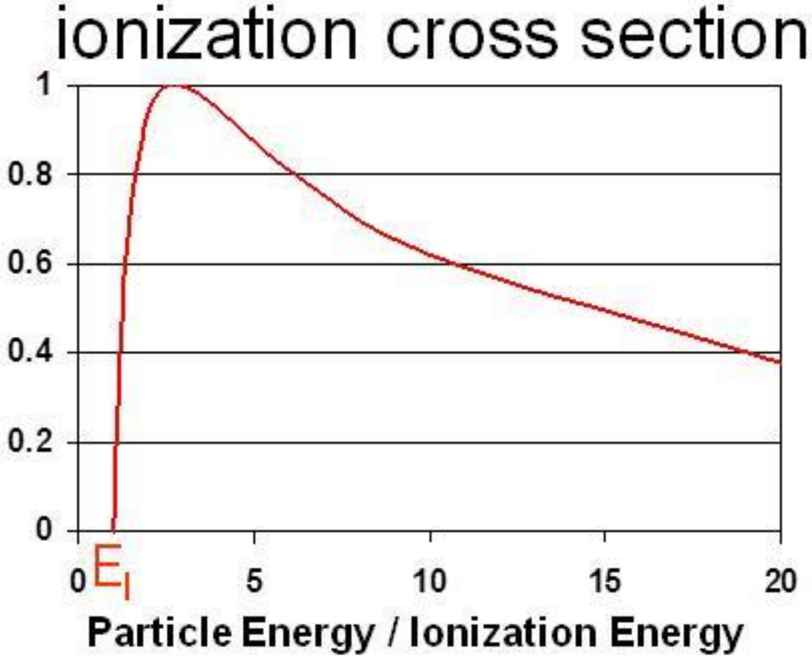
At pressures below the Paschen minimum discharges between more distant electrodes are more likely because they benefit from a higher electron multiplicity!!!

Ionization of Atoms and Molecules in Gases

- 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 [$F_C = (4\pi\epsilon_o)^{-1} \cdot q_1 \cdot q_2 / r_{12}^2$].



- 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.

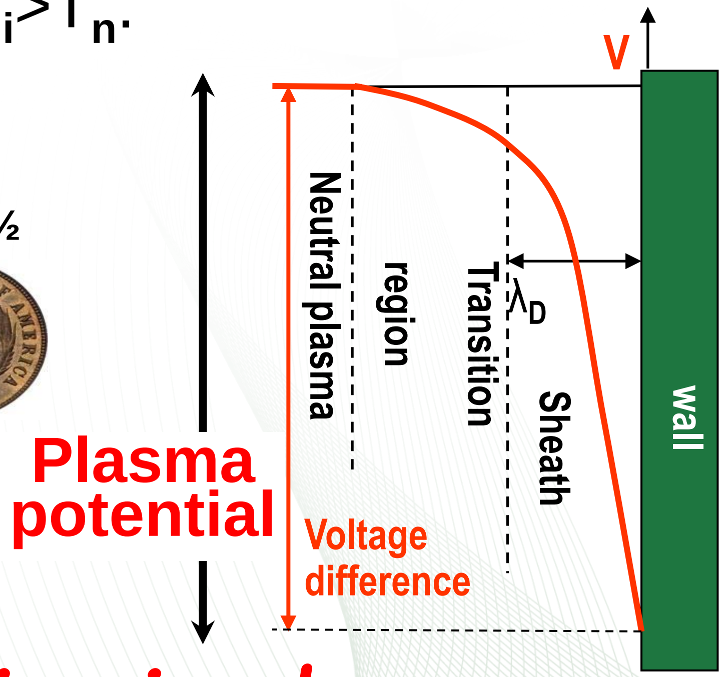


- Gases have ionization energies between 12 eV for O_2 and 25 eV for He, e.g. 15 eV for H_2 molecules and 14 eV for H atoms.
- The ionization cross section has a maximum close to 3 times the ionization energy E_I and therefore electrons with an energy between 50 and 100 eV ionize all gases efficiently.

My  of Plasma Physics for Ion Sources

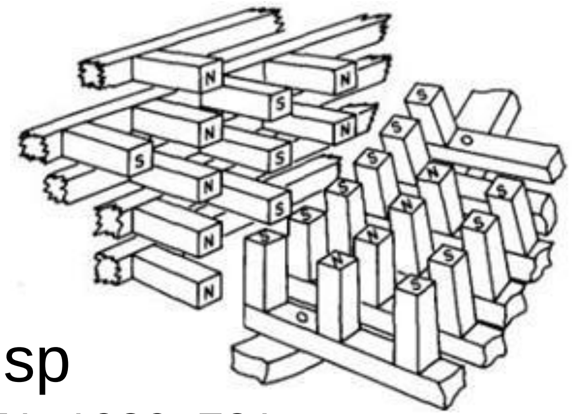
- Plasma is partly ionized gas or vapor, containing neutrals, electrons and ions with densities n_n, n_e, and n_i, typically in the range of 10^{10} to 10^{16} particles per cm^3, roughly 10^{-6} and 0.1 Torr.
- The repulsive nature of equal charges requires that plasmas are practically neutral (quasi-neutral): $e \cdot \Sigma Q_i \cdot n_i = e \cdot n_e$
- Plasma physics dominates if roughly 10% of the gas is ionized.
- The average particle speed is $v_p = (8kT_p/\pi \cdot m_P)^{½}$ with $T_e \geq T_i > T_n$.
- Electrons are fast: $v_e \geq 43 \cdot v_i$.
- Charges interact only within a distance λ_D, the Debye length: $\lambda_D^2 = \epsilon_o kT_e / e^2 n_e$ or $\lambda_D\,[cm] = 743 \cdot (T_e[eV]/n_e[cm^{-3}])^{½}$
- This is a few μm for the SNS ion source.

- Some of the rapidly moving electrons escape to the wall. The space charge of the slowly following ion creates an electric field, resulting in the plasma potential several Debye lengths away from the wall.



The plasma potential accelerates escaping ions!

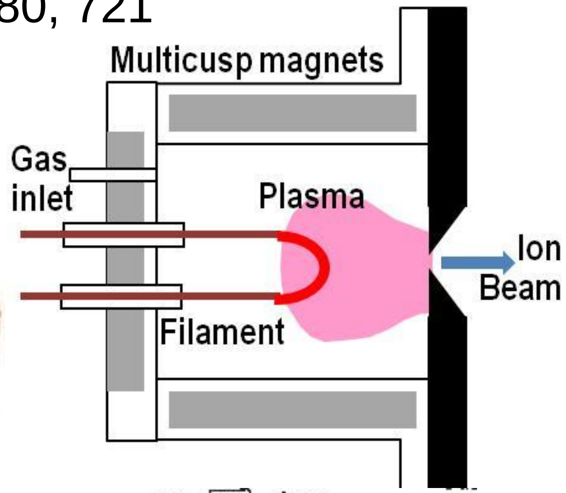
The Multicusp or Bucket Ion source



- 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

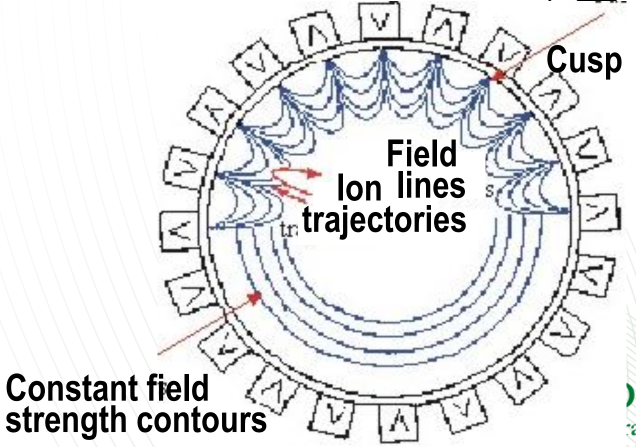
- 1979 Ehlers and Leung at LBNL start to develop multicusp ion sources for hydrogen and later for negative ions. RSI 51, 1980, 721

- Strong permanent magnets (Sm-Co, Nd-Fe, or NdFeB) mounted close to the vacuum yield high fields.
- The magnetic field decreases with the distance from the wall, and is zero on the axis, a minimum field configuration, forming a magnetic bucket.

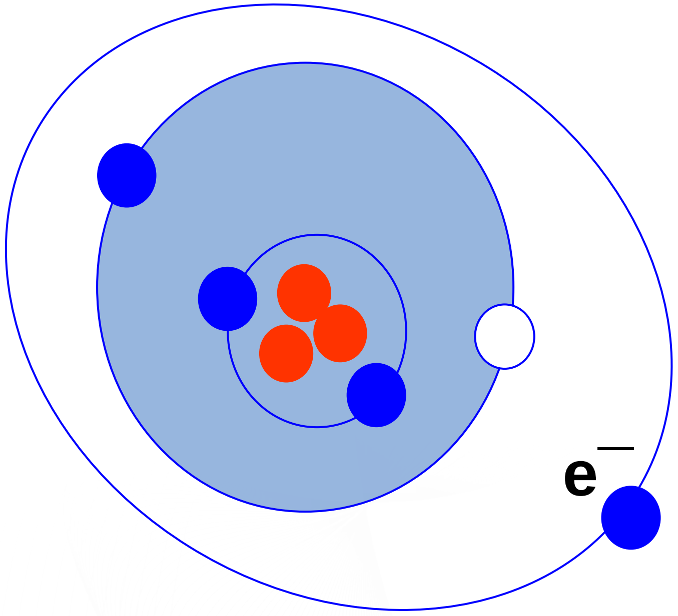


- The strong magnetic field at the wall acts as a magnetic mirror, returning most ions back to the center.
- The discharge is driven by heavy duty filament(s) or a RF antenna with the chamber wall being the anode.

- Filament lifetime limited by **sputtering**, especially for heavy gases and/or at higher pressures.



Negative^{-} Ions – There is one too many!



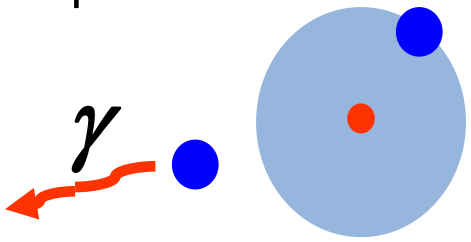
- Atoms with an open shell can attract an extra electron and form stable ions with a net charge of -e.
- The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron.
- The electron affinities are substantially smaller than ionization energies, covering 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 ~$30\cdot10^{-16}$ cm^2, ~30 times larger than for a typical neutral atom!!
- For H^{+} energies below 1 keV, the recombination cross section is larger than $100\cdot10^{-16}$ cm^2.
- Charged particle collisions destroy negative ions easily!!

Negative ions are fragile and accordingly rare!!

So how are H^- ions produced?

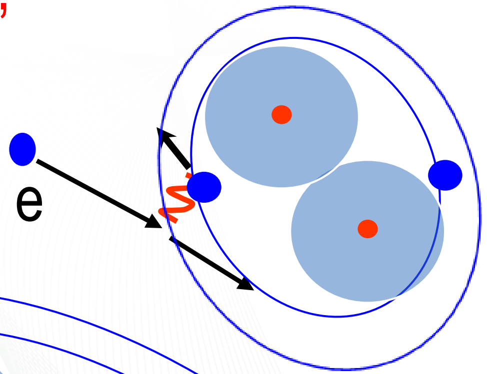
In 1977 **Martha Bacal** found very large signals from negative ions in low-power hydrogen plasmas. She continues to study this production process.

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



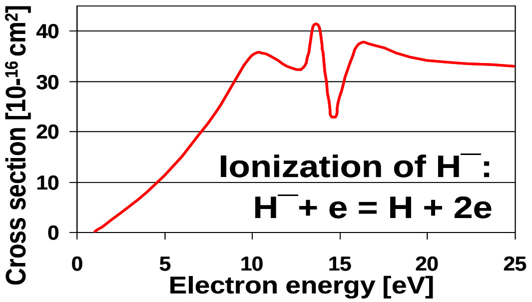
But few of the few H^0 atoms allow for Radiative Capture (10^{-18} cm^2 for E_e~1eV)

- More likely are processes where excess energy can be transferred to a third particle, e.g. when dissociating molecules (>4.5 eV for H_2): $H_2 + e = H + H + e$ and sometimes: $H_2 + e = H + H^-$ (~10^{-20} cm^2 for H_2 and E_e >7 eV)



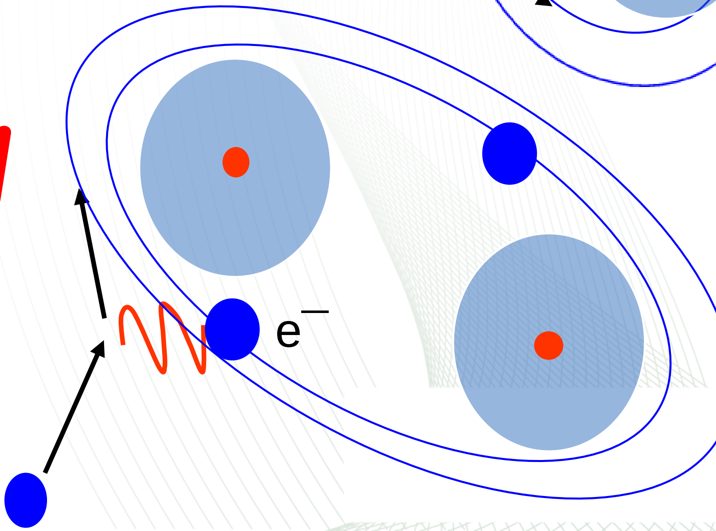
- Most likely is the excitation of molecules to the edge of breakup: $H_2 + e(\text{fast}) = H_2^{\nu} + e$ (~$5{\cdot}10^{-18}$cm^2 for $4 \leq \nu \leq 9$ & E_e >20 eV) and then being dissociated by a slow electron: $H_2^{\nu} + e(\text{slow}) = H + H^-$ (<10^{-15} cm^2 for $4 \leq \nu \leq 9$ &E_e~1eV)

This is the ***Volume production!***



- But the fast electrons needed to excite the molecules destroy (~$3{\cdot}10^{-15}$cm^2) the H^- ions!

Incompatible conditions!

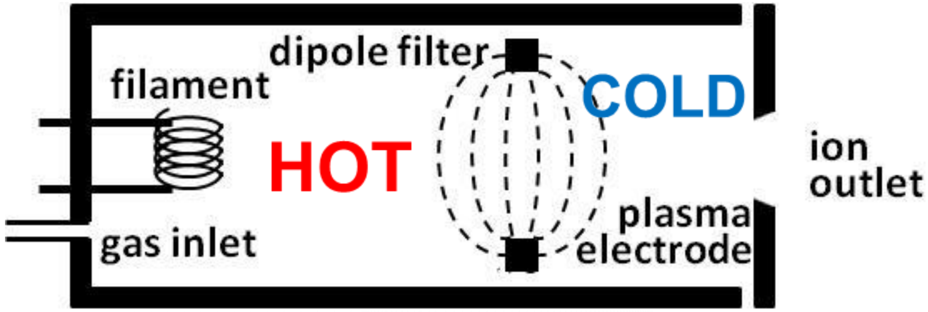


The Magnetic Filter Field in Volume H^- Sources

- The generation of intense H^- beams requires powerful plasma where a myriad of energetic electrons ionize and excite molecules, but also rapidly destroy H^- ions.

- In 1982 Leung, Ehlers & Bacal invented the Tandem source containing a magnetic dipole filter. RSI 54 (1983)56

Tandem Source

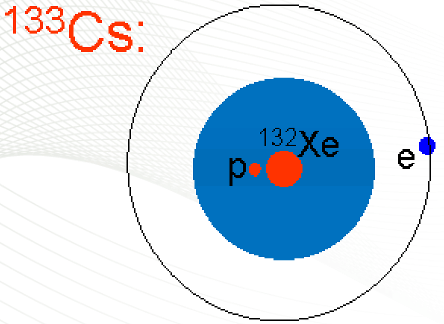


- The magnetic filter reflects energetic electrons, e.g. 200 Gauss turn around 35-eV electrons on a 1 mm radius.

- Cold electrons and ions undergo many collisions with other particles, resulting in a diffusion process that favors **cold** charged particles (v_{diff} ~$T^{-½}$). Excited neutral molecules migrate freely through the filter field & can break up near the outlet.

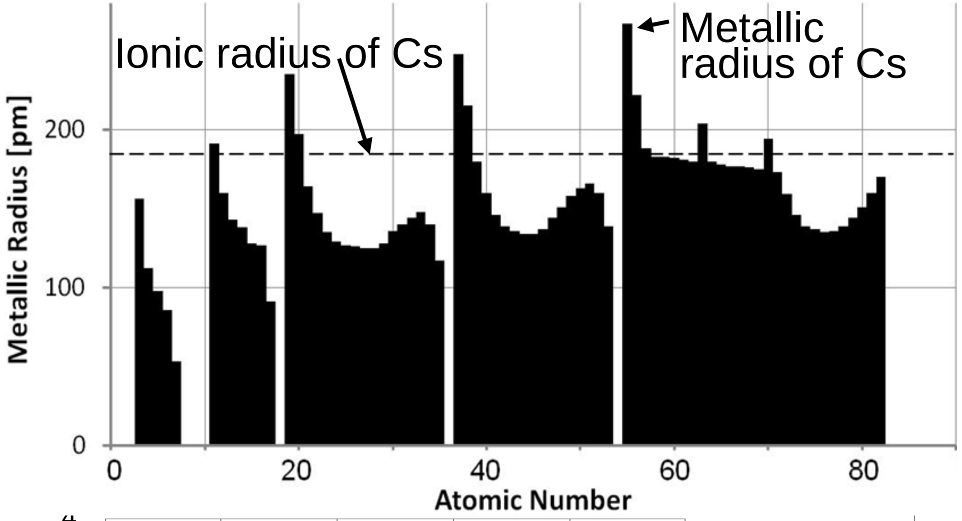
Incompatible conditions separated in space !

Cesium on Metal Surfaces

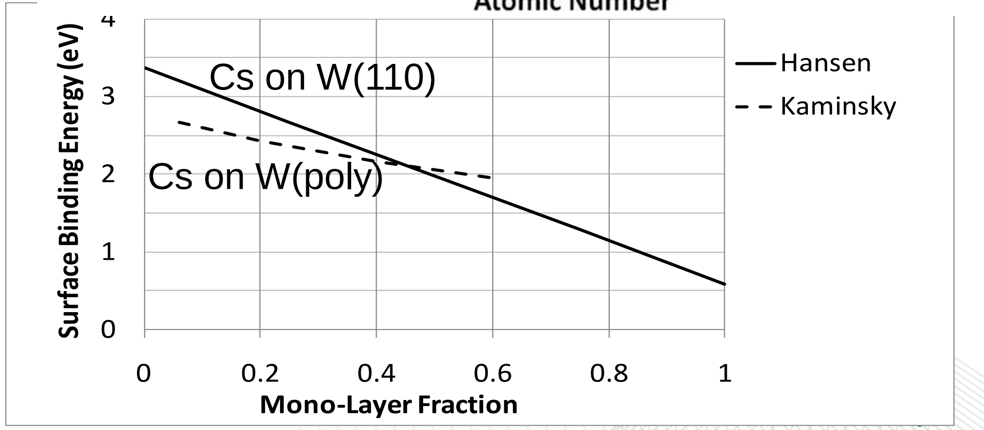


- Cs is ^{132}Xe +1 proton +1 electron.
- Is the largest atom (5.3 Å ∅).
- Has the smallest ionization energy 3.9eV
- Has a small density: 1.9 g/cm^3
- Has a low melting point: 28°C or 83°F

- Cs atoms on clean metal surfaces form metallic bonds as their outer electrons mix with the conduction electrons. Metallic 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.



- This allows for controlling the surface coverage with the surface temperature.

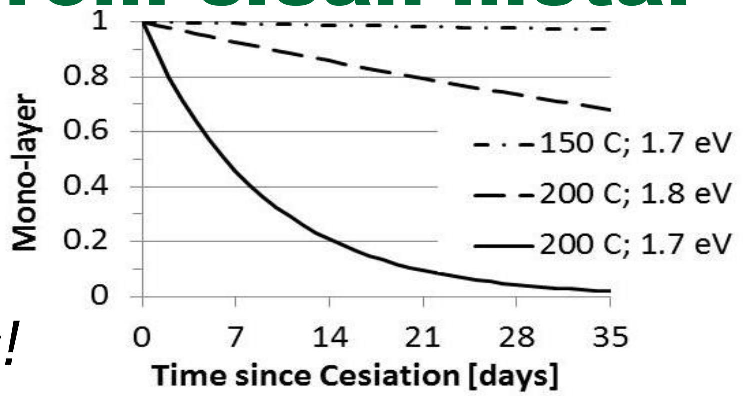
Thermal desorption of Cs from clean metal

The mean dwell time τ characterizes the thermal desorption:

$\tau = \tau_0 \cdot \exp(E_{Cs}/k \cdot T) = 6 \cdot 10^{-13} \cdot \exp(E_{Cs}/k \cdot T)$

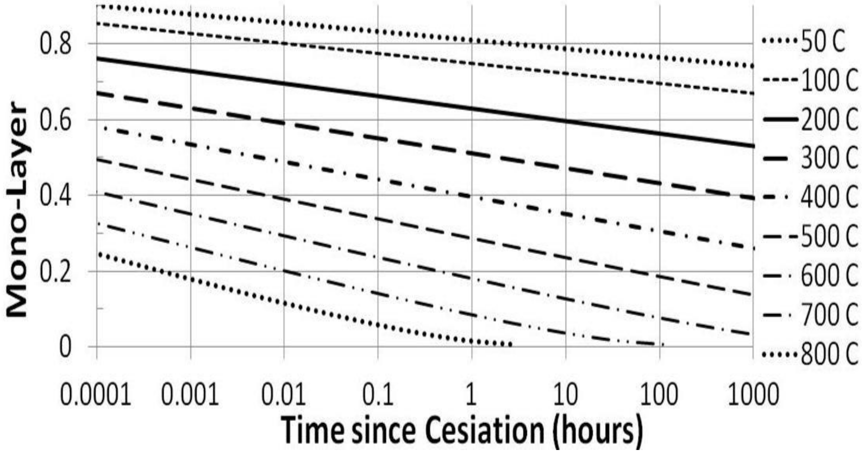
(Cs on clean W: Lee & Sickney,72)

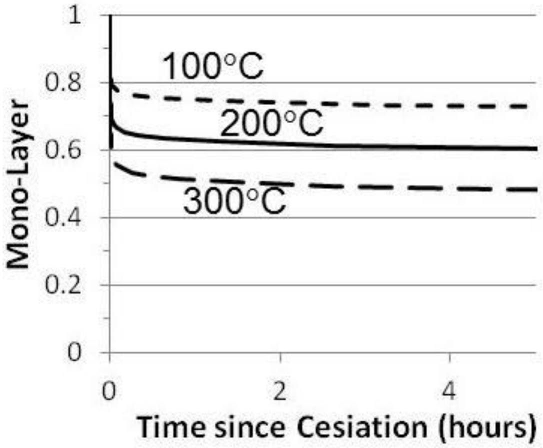
Minimize losses with low temperatures!

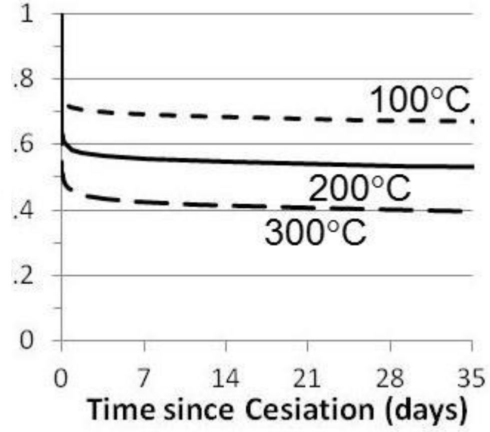


However, E_{Cs} is a function of the coverage θ, which can be derived from the loss = $d\theta/dt$ = flux = θ/τ so: $\theta(t) = \int(d\theta/dt) \cdot dt = \theta_0 - \int(\theta(t)/\tau(T(t),E_{Cs}(\theta)) \cdot dt$

Starting at θ_0=0.995, the times it takes to shed 0.01 mono-layers are added to obtain $t(\theta)$

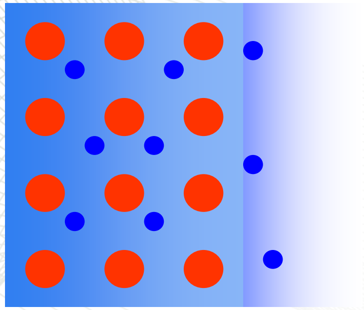




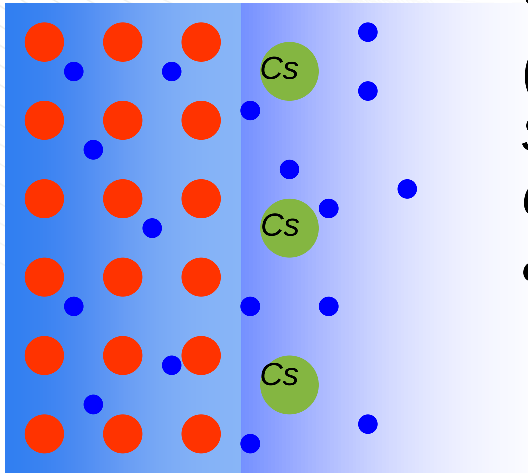


The increasing binding energy assymtotically eliminates thermal emission.

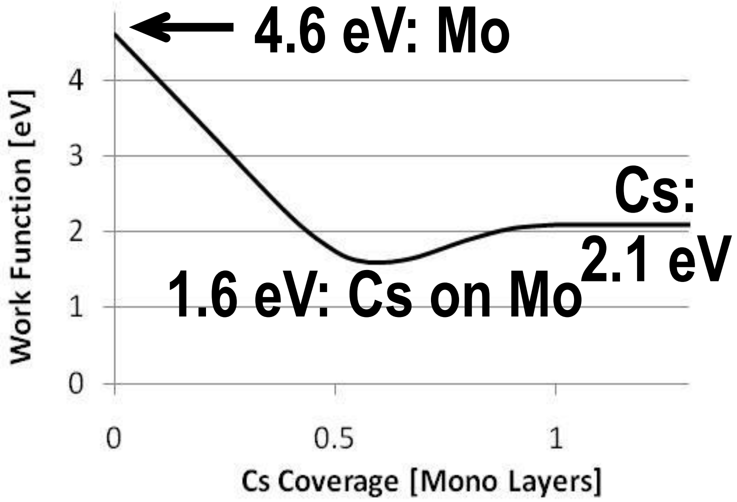
Surface Production of H⁻ Ions



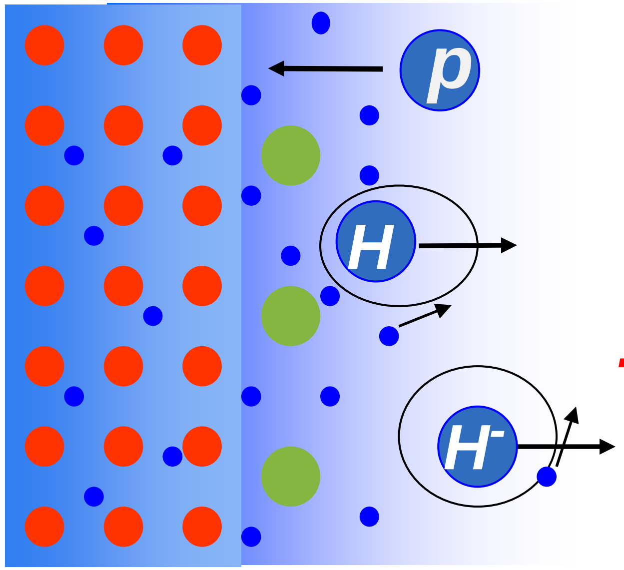
- *Metals host an abundance of conduction electrons bound with ~4.5 to 6 eV to the matrix.*



- *Alkali metals have low work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, alkali atoms extend the electron cloud above the surface and so lower the surface work function.*



- *A partial layer of Cesium on a metal surface lowers the workfunction below the workfunction of bulk Cs!*



- *Protons capturing an electron when hitting the surface and hyper-thermal atoms can capture a 2nd electron when bouncing back into the plasma.*

This is the Surface Production of H^-!

Kinetic Surface Ionization by Rasser

Sur. Sci. 118 (1982) 697

While at FOM in Amsterdam, U. of Nancy's B. Rasser calculates H^- ions produced from H ions and atoms being elastically reflected from W(110), Cs, and cesiated W surfaces. Rasser's He calculates probabilities that are very similar to the probabilities calculated by Bladin and by Norskov.

$$\beta^-(v_z) = P_i(\infty) = \frac{1}{v_z}\int_{z_0}^{\infty}\Delta(z)\cdot n^-(z)\exp\left[-\frac{1}{v_z}\int_{z}^{\infty}\Delta(z')dz'\right]dz + P_i(0)\exp\left[-\frac{1}{v_z}\int_{z}^{\infty}\Delta(z')dz'\right]$$

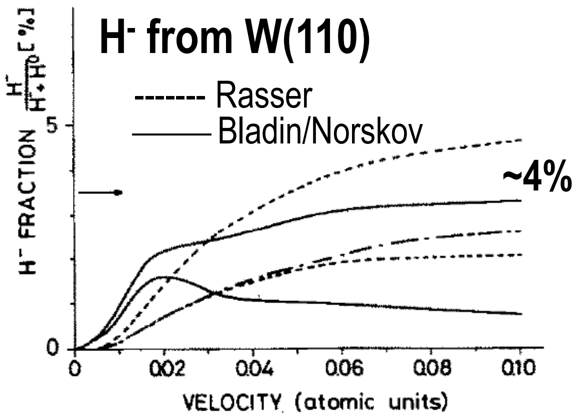
β^- final H^- yield

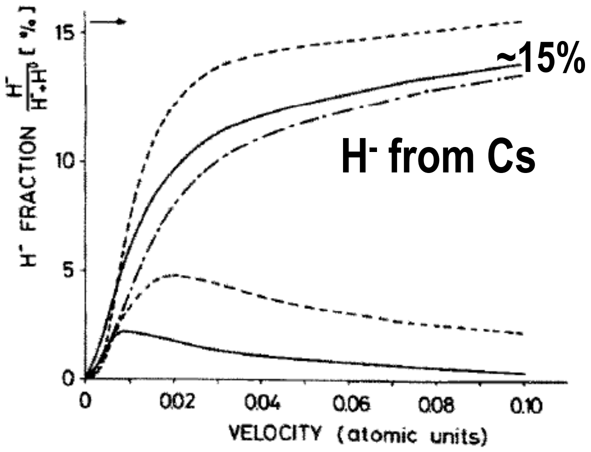
$P_i(z)$ H^- probability at position z

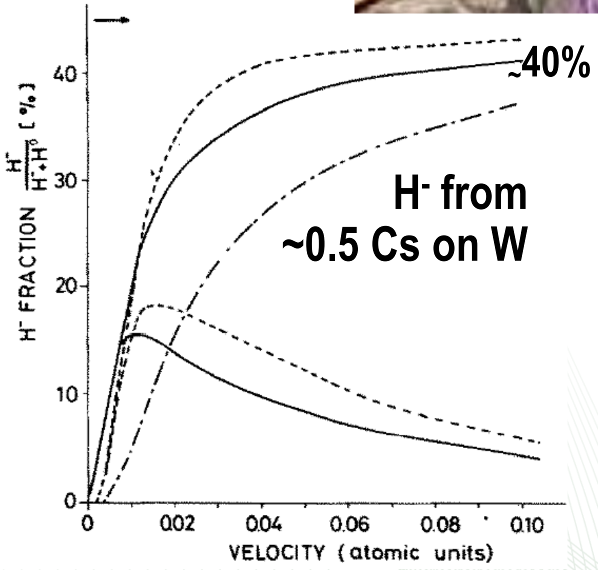
Δ width of H^- level

n- instantaneous H^- yield

v_z projectile velocity normal to surface







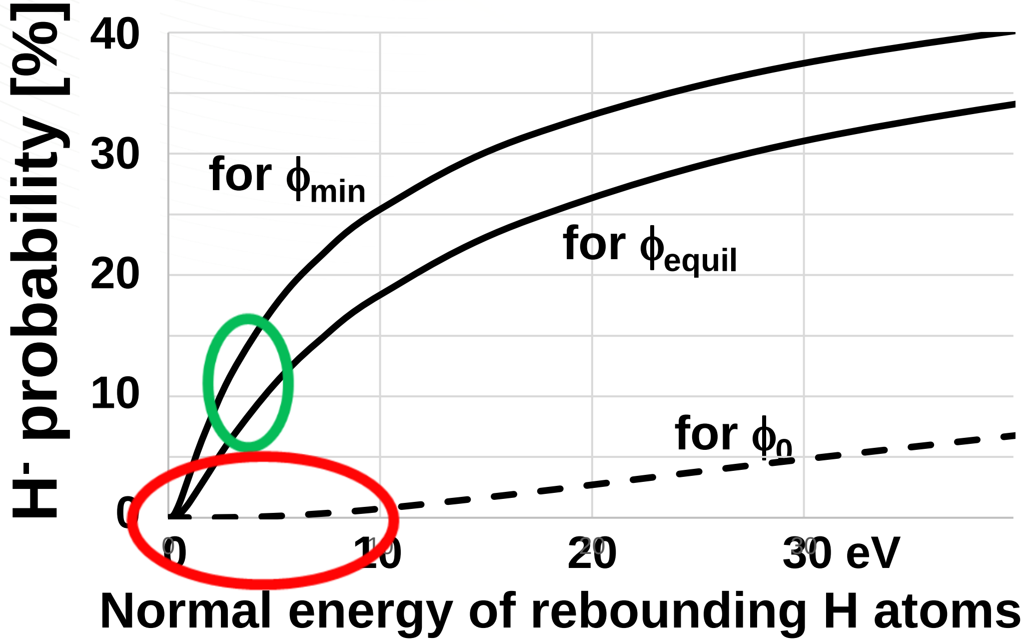
Partially cesiating a surface can increase the H^- yield 10 fold and more!

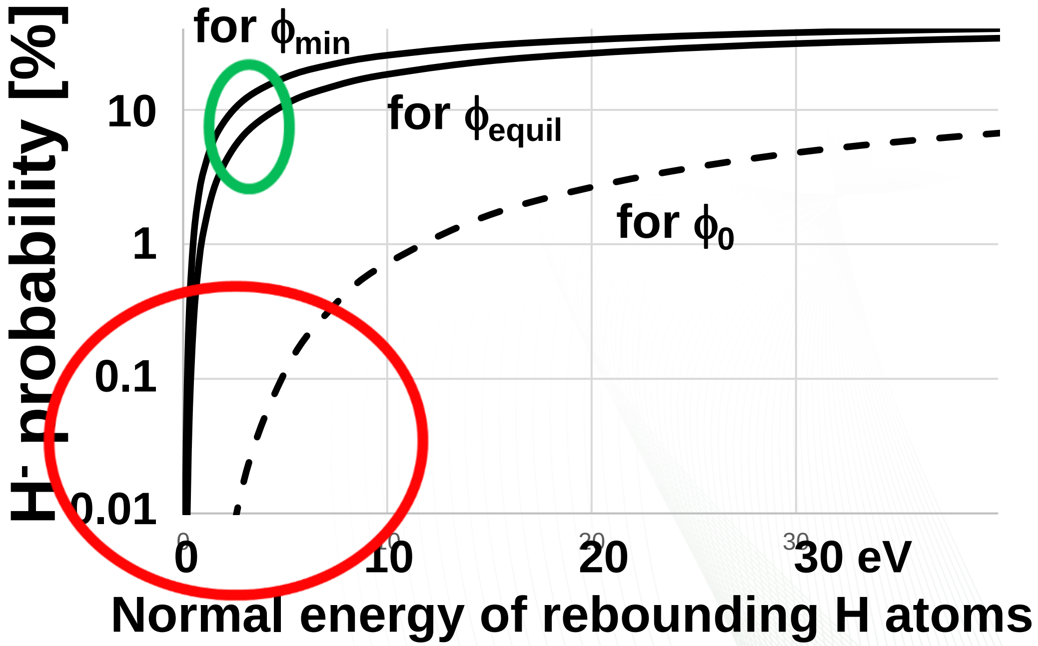
Kinetic Surface Ionization by Rasser

Sur. Sci. 118 (1982) 697

For low velocities ($v_\perp$<0.1 a.u.): $\beta^- = 2/\pi \cdot \exp(-\pi\,(\phi - Ea)/(2 \cdot a \cdot v_\perp))$

β^- : final H^- yield ϕ: Workfunction   Ea: Electron affinity $v_\perp$: projectile velocity normal to surface



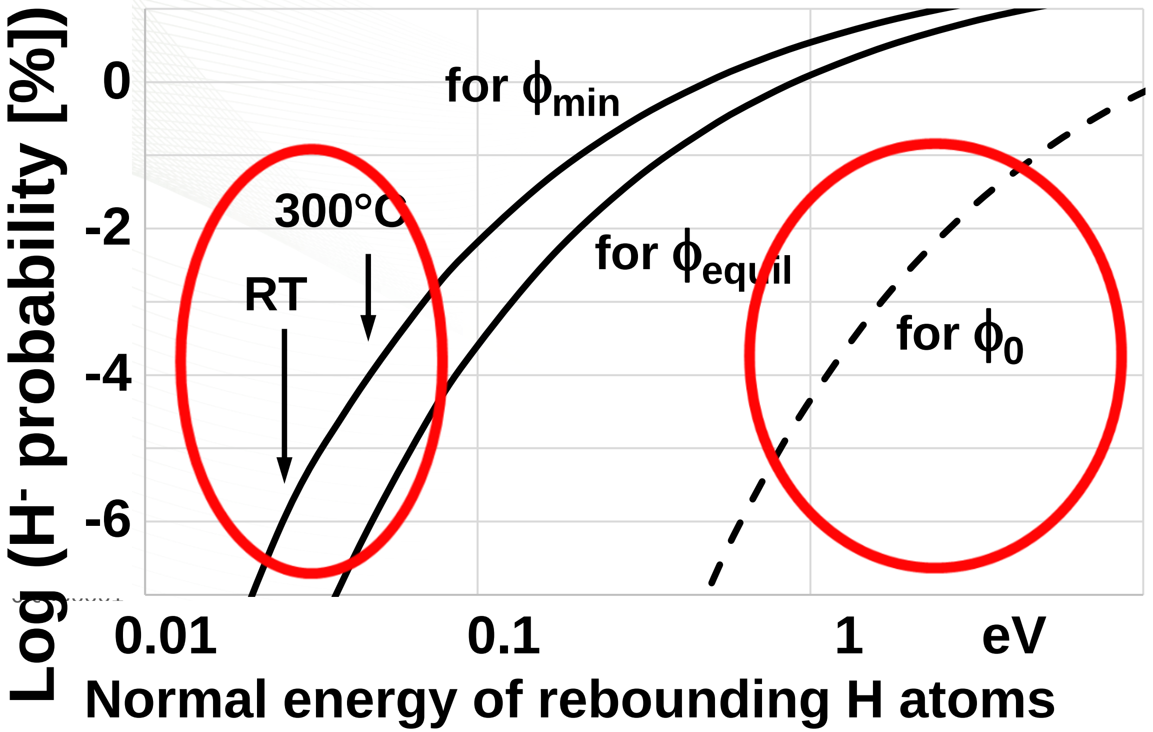


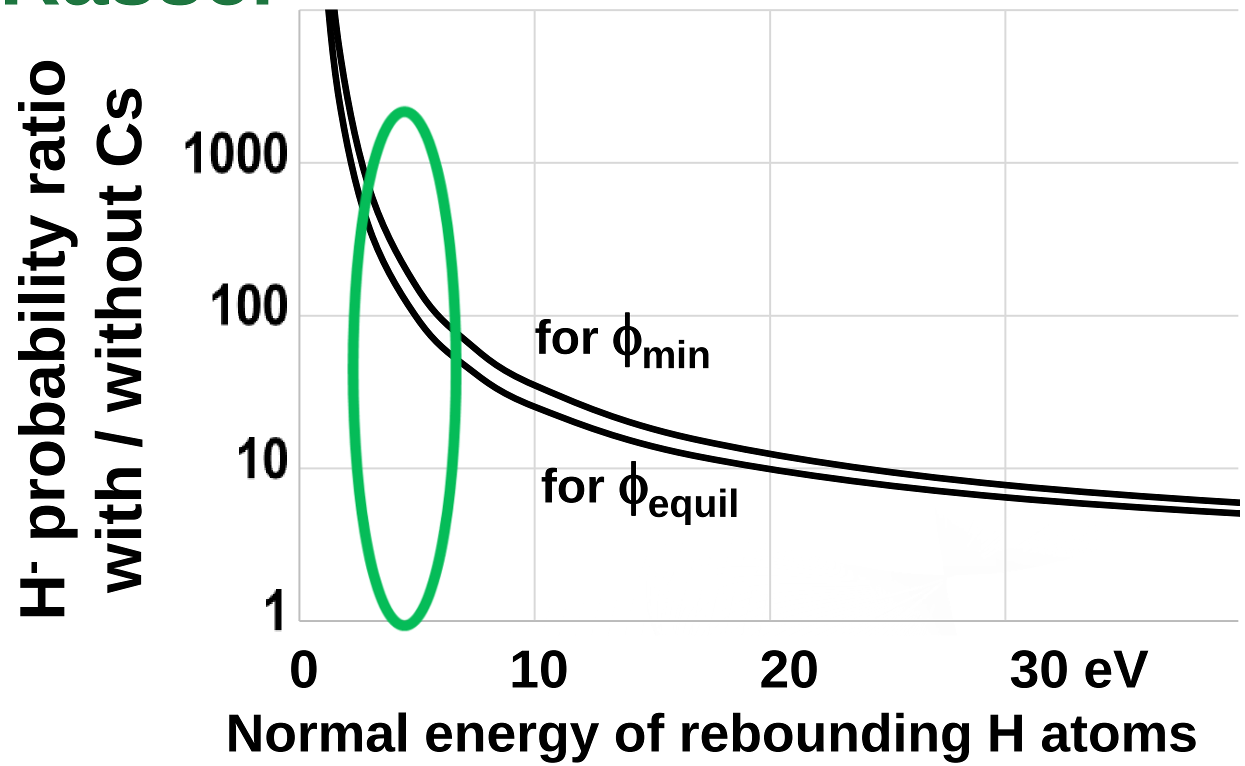
For the few eV plasma potentials the probability is ~10% !

However, without Cs and/or for low energies it is negligable!

Kinetic Surface Ionization by Rasser

Sur. Sci. 118 (1982) 697





Without Cs the H- surface production is negligible with or without plasma !

With Cs, but without plasma the H- surface production is negligable!

Desorption does NOT create negative ions!

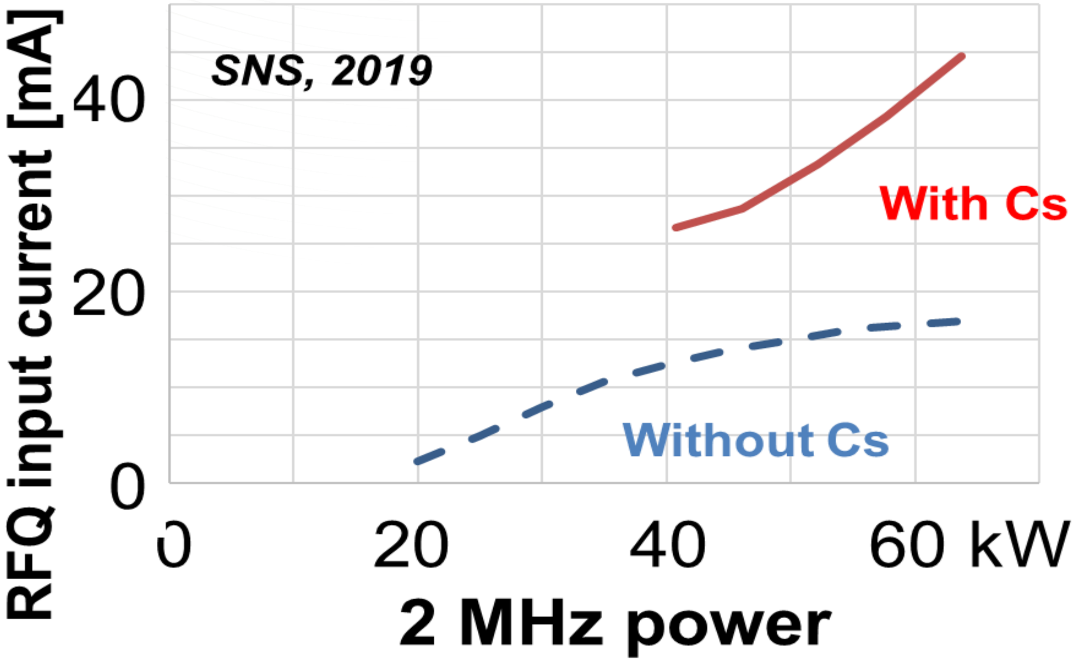
Without Cs the H^- surface production is negligible!

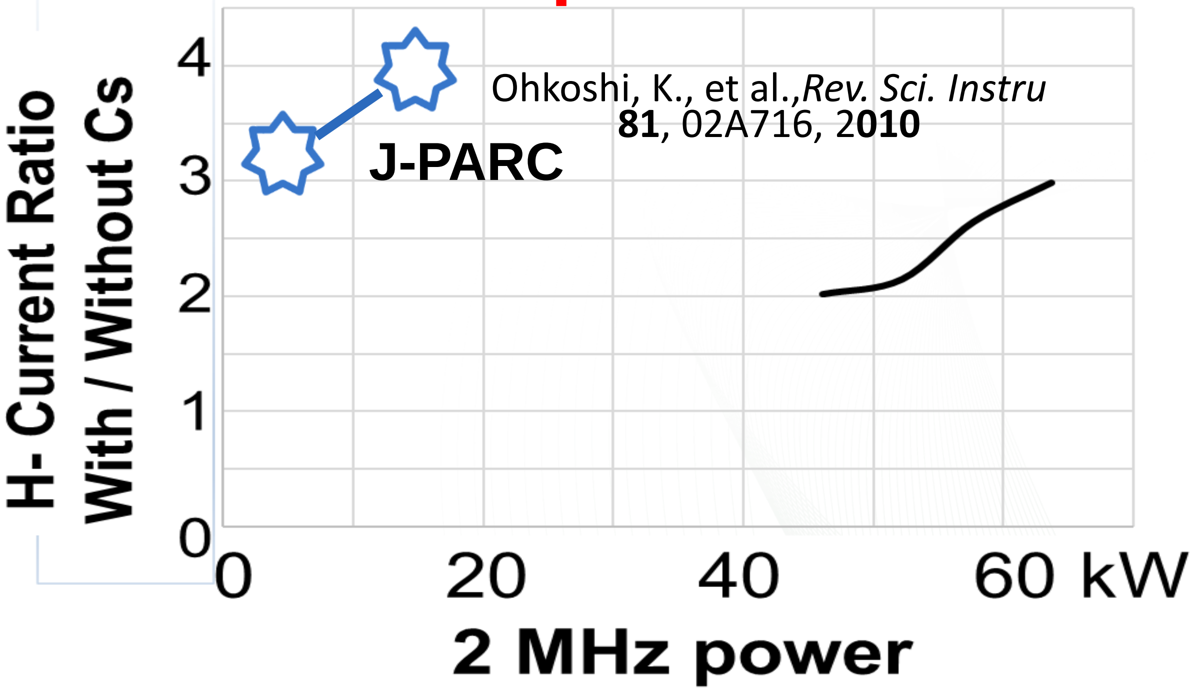
Without Cs the RF sources are pure Volume sources!

NOT Surface Plasma Sources!

Determining the Volume and the Surface produced fraction!

- The only way to determine fractions of a beam is by measuring the output H- beam current without and with Cesium!
- Without Cs one obtains the **volume produced** fraction.
- The **current increase** after cesiation is the **surface produced** fraction





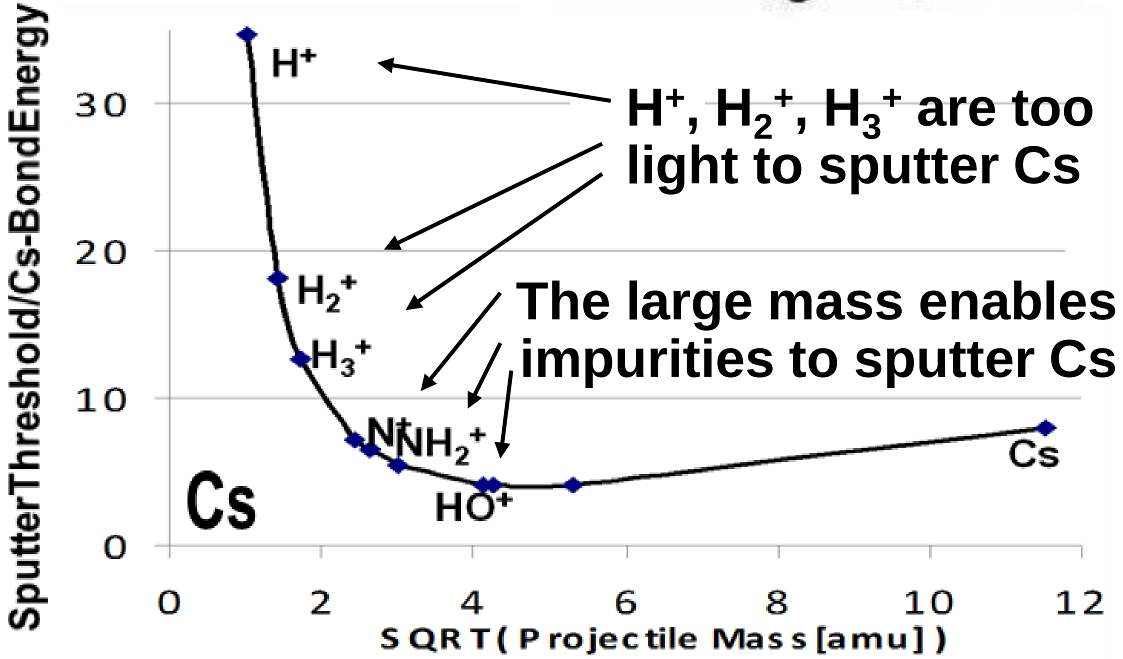
50-66 % are surface produced at SNS & 66-75% at J-PARC!

The surface produced fraction is NOT proportional the outlet diameter!

because H⁻ ions travel up to 10 mm before being extracted!

Sputtering, the silent ion source killer !!

- 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 and sputter atoms away from the electrode.
- The low sputter rates of heavy, refractory metals yield longer lifetimes, e.g. Mo!
- Sputtered metal atoms coat insulators until they break down.
- 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.
- Accelerated plasma ions sputter the Cs from metal substares!

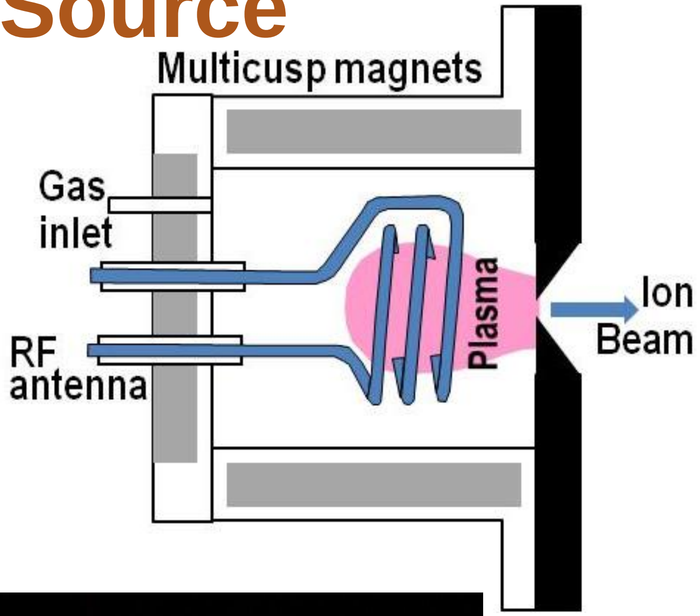


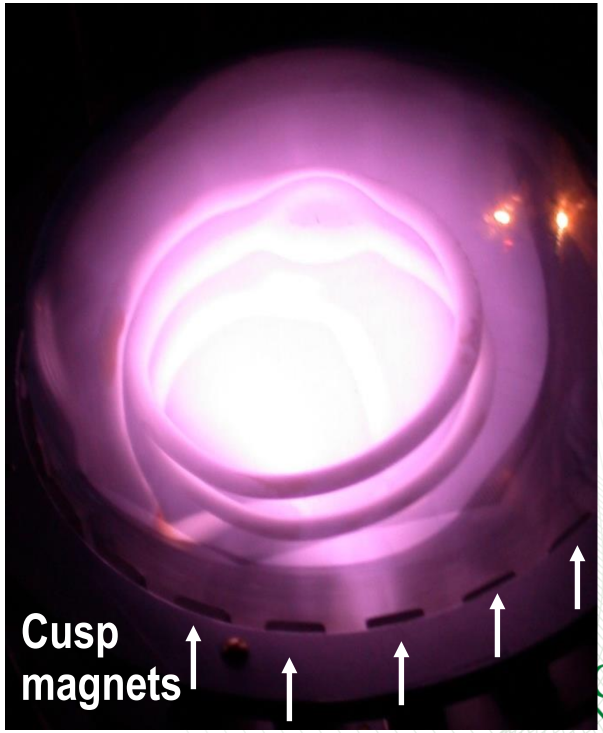
Sputtering limits the lifetime and hence **needs to be minimized!!**

The Inductive-coupled RF Multicusp Ion Source

- 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 induced high-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.

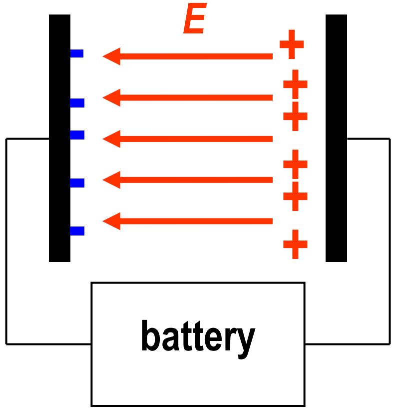
Multicusp confinement is well suited for an inductively driven ion source!





What did Maxwell tell us about Electric Fields?

- The 1st Maxwell Equation: $\nabla \cdot E = \rho / \varepsilon_o$ describes electric fields generated by any free net charges and the easy controllable surface charges ρ on electrodes. The negative surface charges attract the positive ions, **causing the sputtering!**



- The 2nd Maxwell Equation, however, $\nabla x E = - \partial B / \partial t$ describes a curling *E* field generated by a changing magnetic field in absence of any charges!

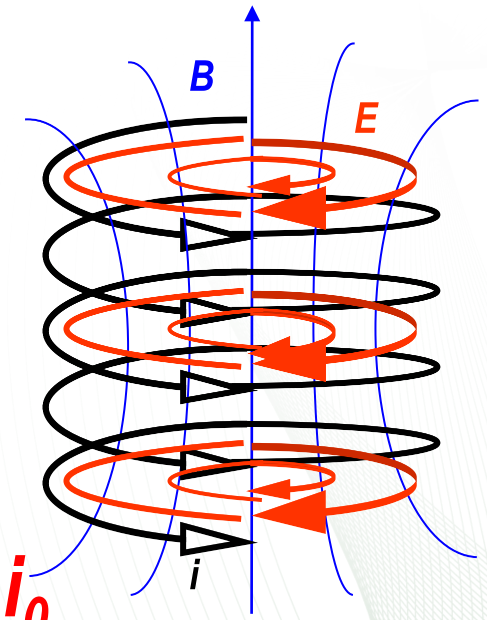
A changing magnetic field *B* can be produced with an alternating current $i = i_o \cdot cos(\omega t)$ in N windings with radius r_o : $B = ½ \cdot \mu_o \cdot N \cdot i / r_o$ (Biot-Savart).

Now integrate Maxwell's 2nd equation for Faraday's law:

$\int \mathbf{E} \cdot d\mathbf{s} = -d\Phi_B/dt = -d/dt \int \mathbf{B} \cdot d$ and solve

for *E*: $E(r,t)=¼ \cdot r/r_o \cdot \mu_o \omega \cdot N \cdot i_o \cdot sin(\omega\, t)$

$E \propto i_0$

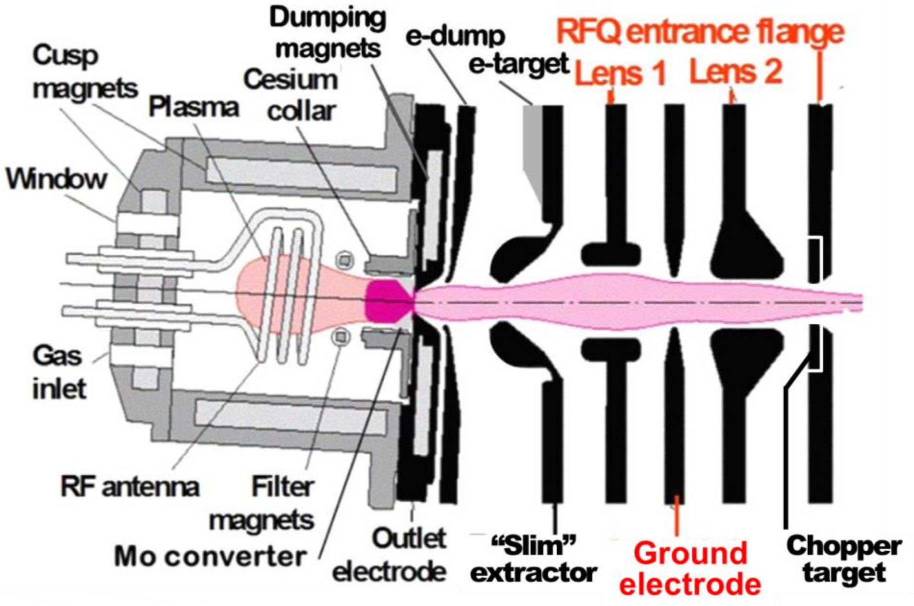


This are circular electric fields that bite their own tails rather than a poor electrode!

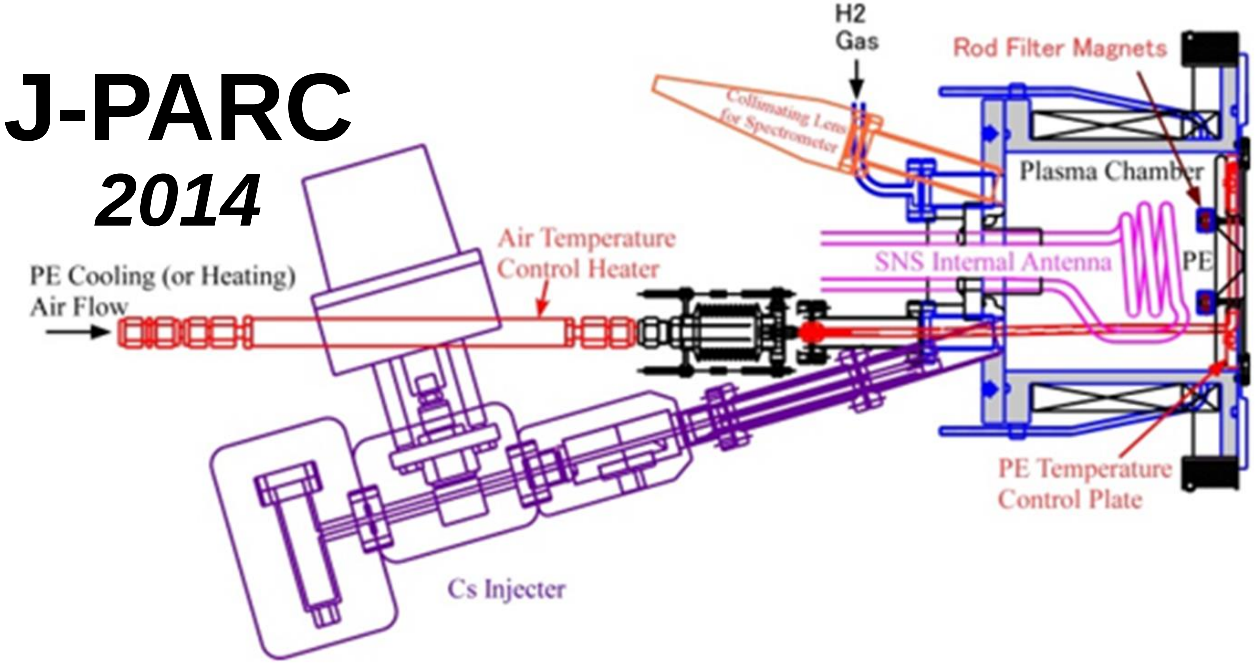
O.K., but does it work??

The four RF H- sources on Advanced Accelerators!

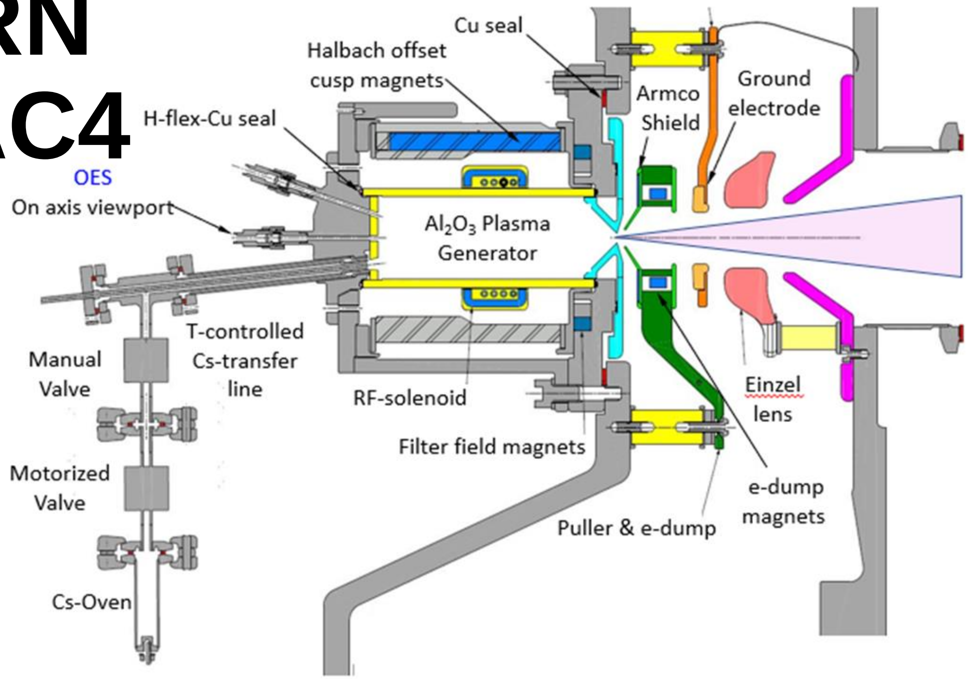
SNS
2006



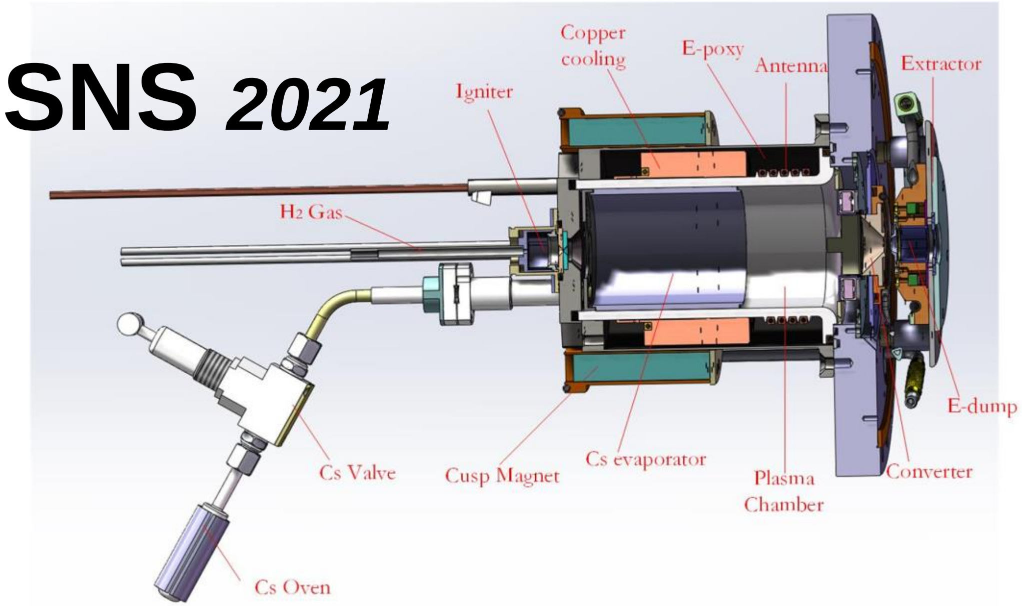
J-PARC
2014



CERN LINAC4
2020



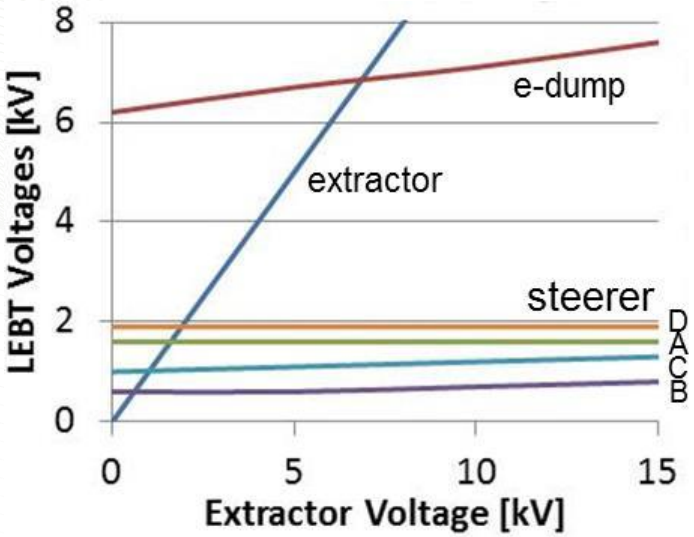
CSNS *2021*

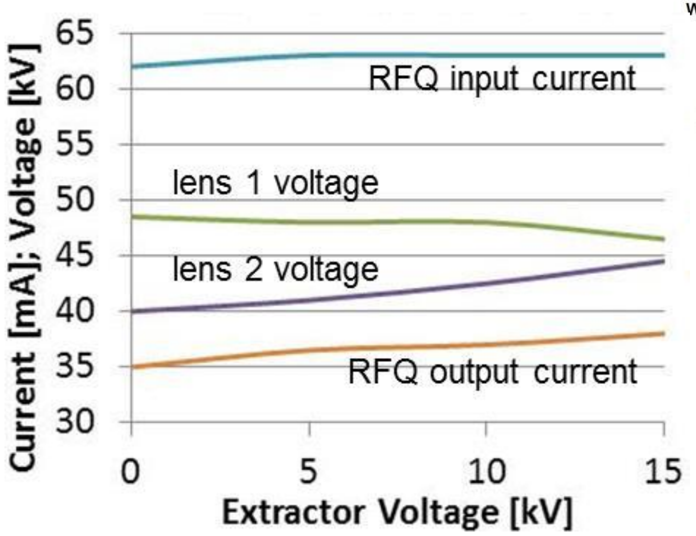


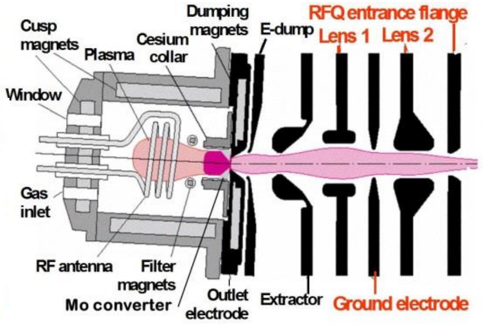
The four RF H- sources on Advanced Accelerators!

	UNITS	SNS	J-PARC	CERN	CSNS
Plasma chamber	material	304 SS	SS	Al_2O_3	Si_3N_4
continuous flow	sccm H_2	~30	~21	pulsed	~20
Antenna	location	internal	internal	external	external
RF frequency	MHz	2	2	2	2
RF Power	kW	~50	~21	~30	~30
RF pulse length	ms	1.0	0.8	0.9	0.7
Repetition Rate	Hz	60	25	0.83	25
Thermal load	kW	3.2	0.5	0.02	0.5
Outlet diameter	mm	7/8	9	7.5	8
Extraction Voltage	kV	65	50	45	50
LEBT output current	mA	50/-70	60	37	37
Longest usage cycle	weeks	19	22	61	45
Cs use per cycle	mg	~5	~90	~100	~150

Extraction Studies of 5/3/16



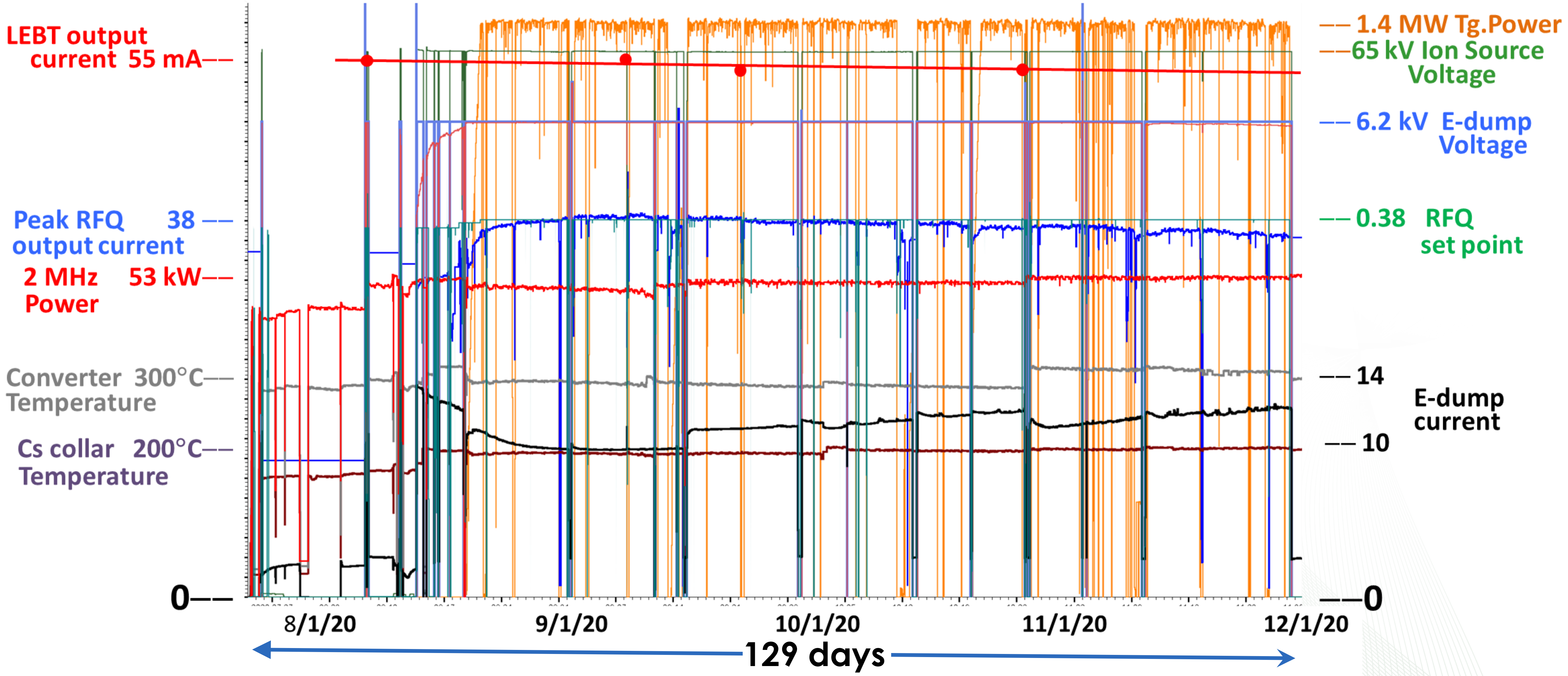




- E-dump was scaled to maintain an uniform extraction field.
- The LEBT chopper target current barely increased, consistent with an ion density limited extraction.
- Optimal RFQ output current required Lens 1 to be lowered and lens 2 to be increased to adjust the stronger lens 1 focus.
- Only steerers B & C needed slight increases.
- The RFQ output increased by ~10%, for another >100 kW.
- Results are consistent with lower LEBT beam emittances.

Lower beam emittances increase the RFQ transmission!

18.4 weeks of almost persistent 54 mA RFQ input Beam



- In the previous run, the ion source (#2) had ~129 days of plasma operation.
- ~54 mA beam was delivered to the RFQ for the run.
- Ion source and LEBT availability was 99.93% for the required periods.

Conclusions

- The RF H- sources have revolutionized the production of H- ions.
- They now deliver routinely up to 60 mA.
- They have increased the H- ion source lifetimes from 1 to 10 Amp-hrs!
- anniversay They have increased the duty factors from ~1 to 10%'
- NO antenna failed on the SNS main accelerator since 1-13-2013
- However, it was rediscoverd how to make antennas fail on the BTF and ISTS.
- No old age antenna failures have ever been identified!

Thank you for your attention!