# Volume and Surface-Enhanced Negative Ion Sources

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*A Lecture of the*
*CERN Accelerator School on*
*"Ion Sources"*

*in collaboration with*

SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
Faculty of Electrical Engineering and Information Technology

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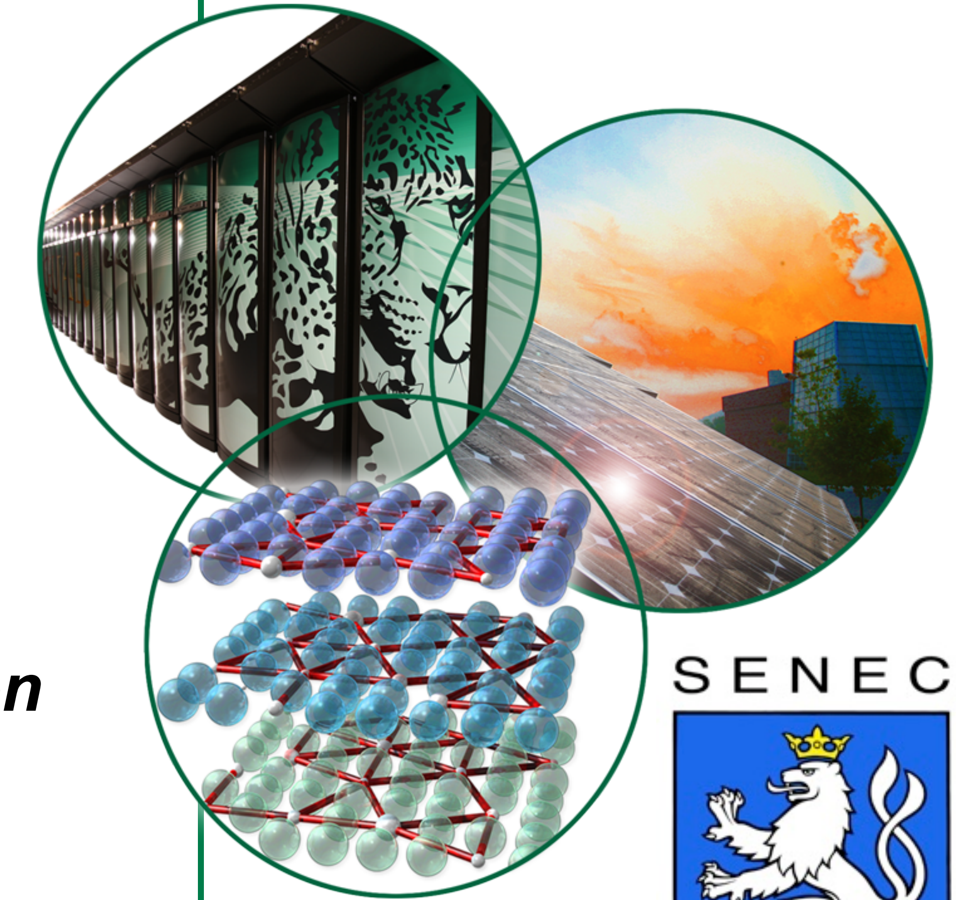

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- Cs and its Thermal Management
- Producing Persistent Beams and its Limitations
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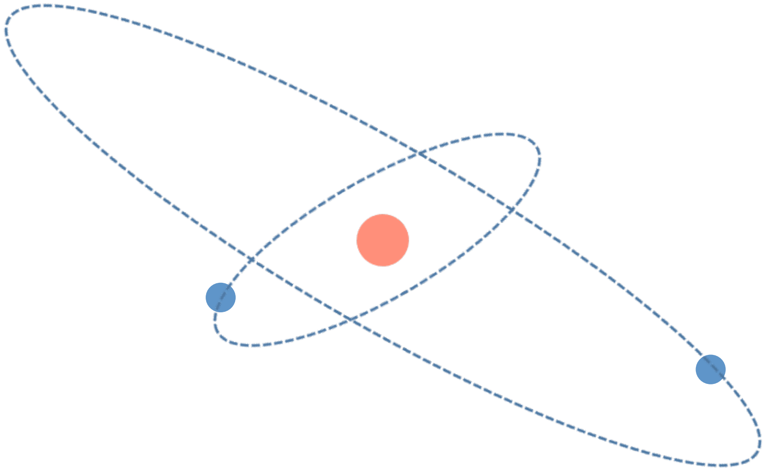
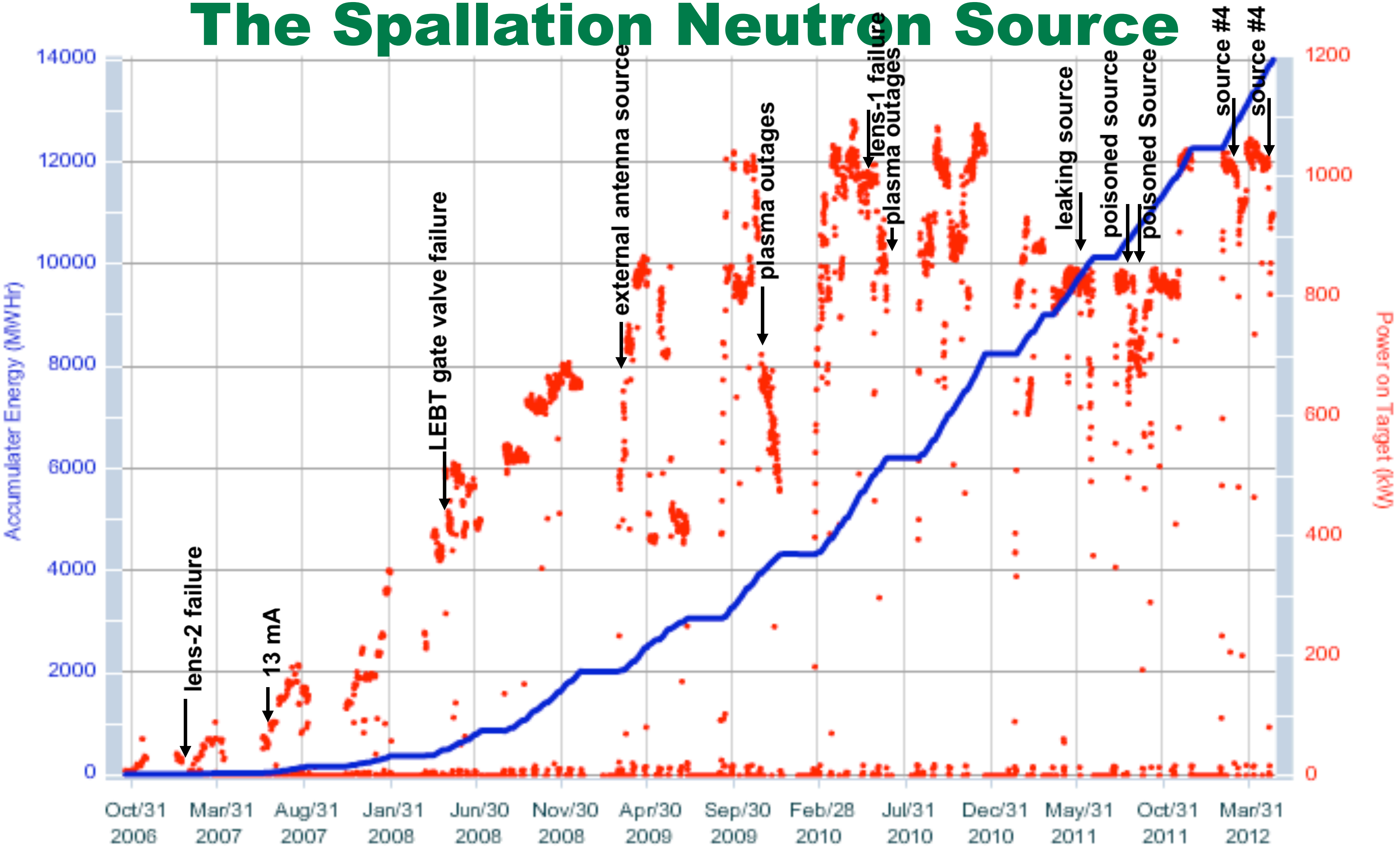


***It is all about extracting more H$^-$ ions!***

The Spallation Neutron Source is running ~1 MW since the fall of 2009

# The Spallation Neutron Source



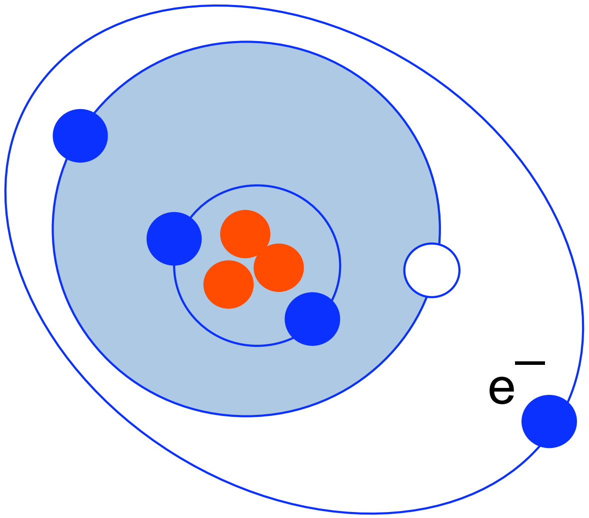
**Most of 2011 the power was reduced to 800 kW due to budget uncertainty.**

**Since Dec 2011 SNS is back at 1 MW with an availability of ~93%.**

**This requires ~50 mA of $H^-$ for 0.88 ms at 60 Hz for up to 6 weeks.**

# Negative Ions – There is one too many!

- Especially atoms with an open shell attract an extra electron and can form a stable ion with a net charge of –e.

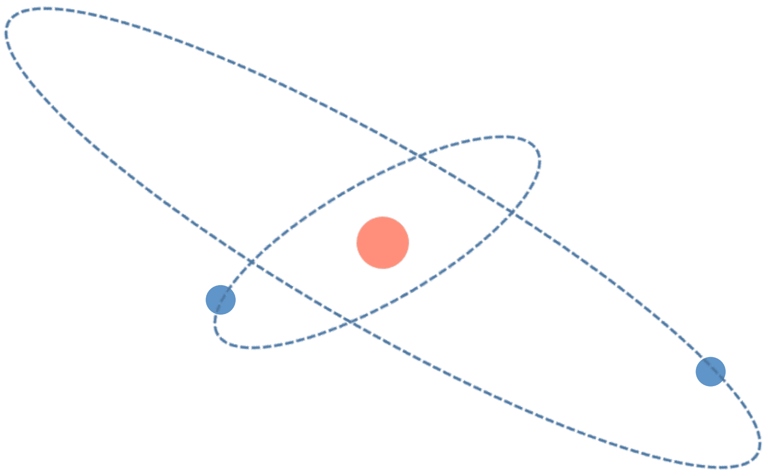


- The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron.
- The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for $Ti^-$ and 3.6 eV for $Cl^-$, e.g. 0.75 eV for $H^-$.
- For electron energies above 10 eV, the $H^-$ ionization cross section is ~$30 \cdot 10^{-16}$ cm², ~30 times larger than for a typical neutral atom!!
- For $H^+$ energies below 1 keV, the recombination cross section is larger than $100 \cdot 10^{-16}$ cm².

*Negative ions are fragile !*

***Charged particle collisions destroy negative ions easily!!***

# Content



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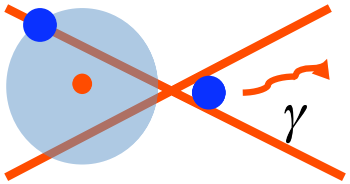
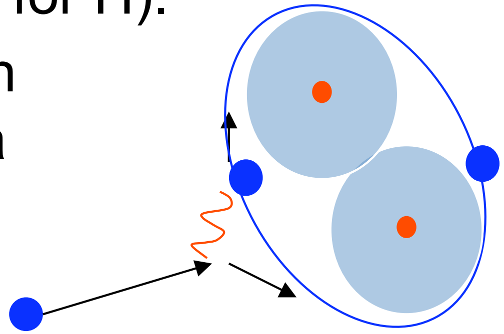
***It is all about extracting more $H^-$ ions!***

# So how are $H^-$ ions produced?



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

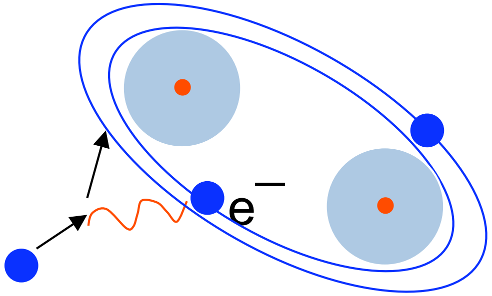
But Radiative Capture is rare ($5 \cdot 10^{-22}$ $cm^2$ for H).



- More likely are processes where the excess energy can be transferred to a third particle, e.g. when dissociating a molecule (4.5 eV for $H_2$): $H_2 + e = H + H + e$

and sometimes $= H + H^-$

($\sim 10^{-20}$ $cm^2$ for $H_2$ and $E_e > 10$ eV)



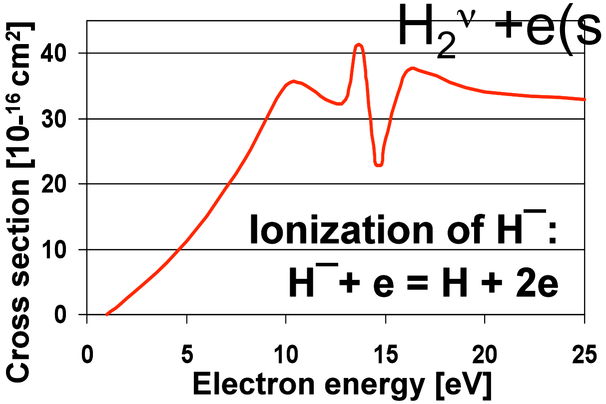
- Most likely are processes which excite a molecule to the edge of breakup (rovibrationally excited $4 < \nu < 12$)

$$H_2 + e(\text{fast}) = H_2^{\nu} + e$$

($\sim 5 \cdot 10^{-18}$ $cm^2$ for $4 \le \nu \le 9$ and $E_e > 15$ eV)

and then dissociated by a slow electron

$$H_2^{\nu} + e(\text{slow}) = H + H^-$$ ($\sim 3 \cdot 10^{-20}$ $cm^2$ for $4 \le \nu \le 9$ & $E_e < 1$ eV)



- However, the fast electron needed to excite the molecules, destroy ($\sim 3 \cdot 10^{-15}$ $cm^2$) the $H^-$ faster than they are produced!

**A catch 22!**

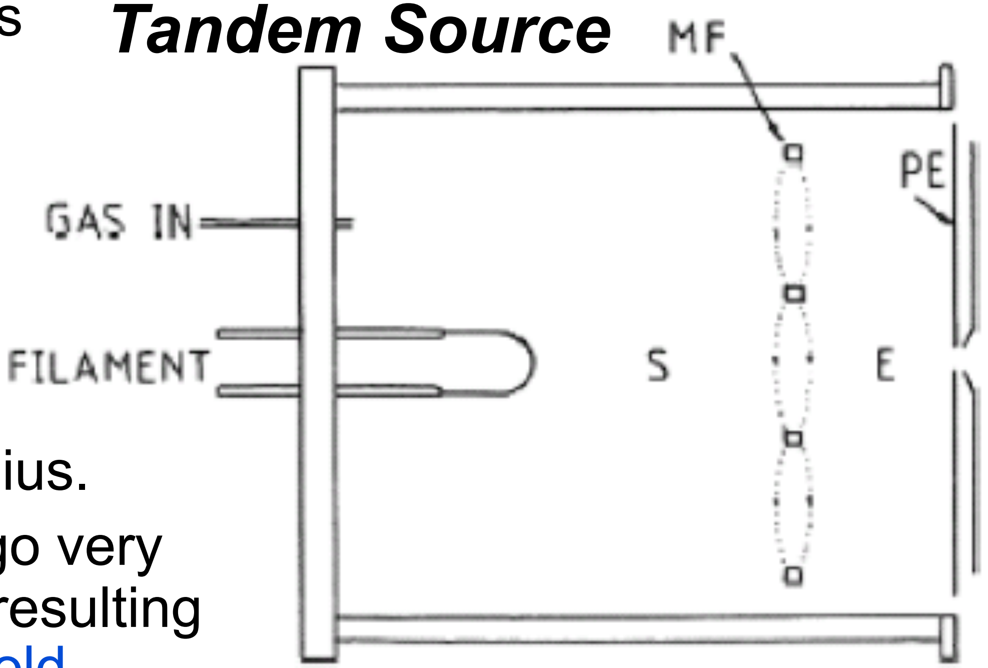
# The Magnetic Filter Field in Volume H$^-$ Sources

- The generation of intense ion beams requires powerful plasma where a myriad of energetic electrons excite and ionize atoms and molecules.
- In a Tandem source, a magnetic field reflects energetic electrons, e.g. in a 200 Gauss field 35-eV electrons turn around on a 1 mm radius.
- Cold electrons and cold ions undergo very many collisions with other particles, resulting in a diffusion process which favors cold charged particles ($v_{diff} \sim T^{-½}$). Therefore the electron temperature decreases exponentially through  the filter field.
- Excited neutral molecules migrate freely through the filter field.

The cold electron colliding with exited molecules near the outlet produce the extractable H$^-$ ions!

***Excellent! Lots of H$^-$ ions!***

***Tandem Source***



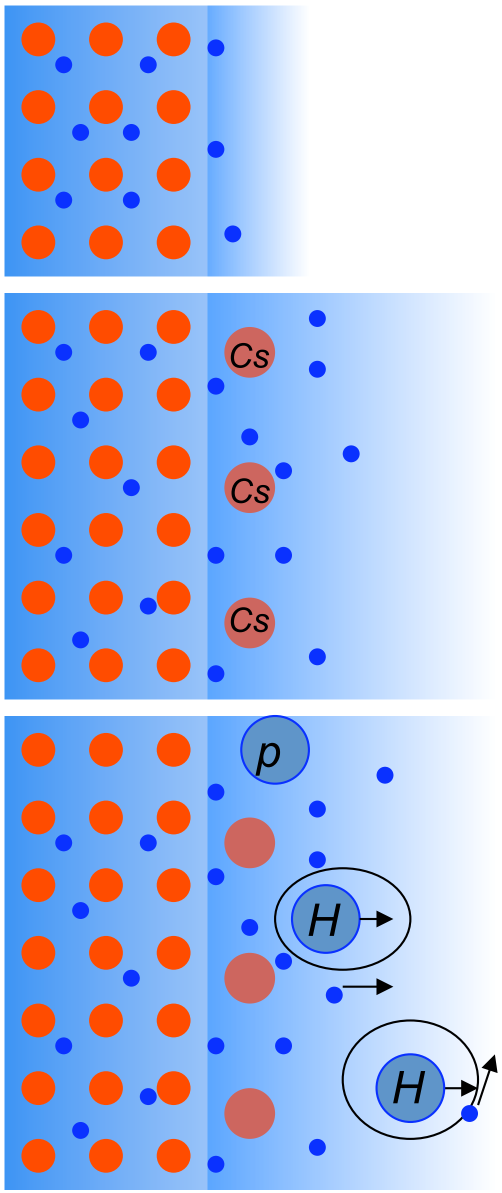
*From M. Bacal, NIM **B37/38** (1989) 28*

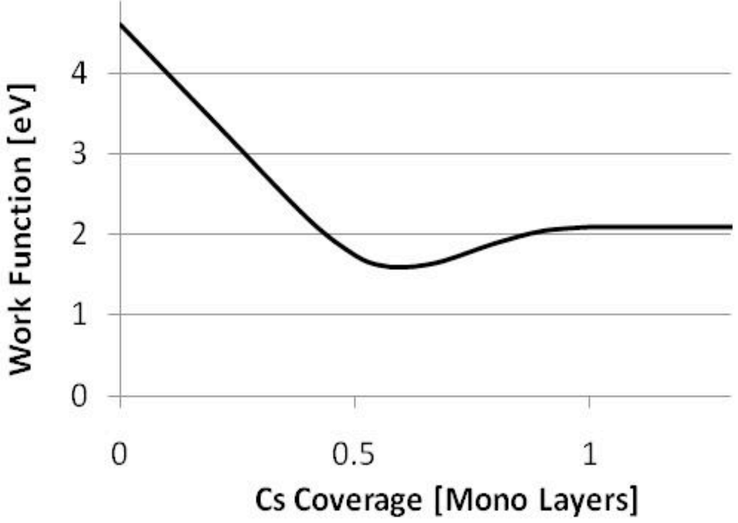
***But we need more!***

***Let's look for a supplement!***

# Surface Production of $H^-$ Ions

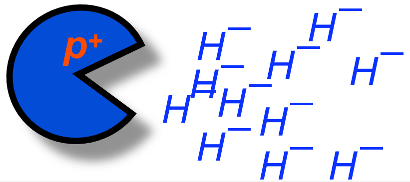
- *Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface.*
- *Alkali metals have lower work functions (2-3 eV). When adsorbed on a metal surface as a partial monolayer, alkali atoms can lower the surface work function to values even below their bulk work function, e.g. ~1.6 eV for Cs on Mo.*
- *Lowering the work function increases the probability that hydrogen atoms leaving the surface capture a second electron.*
- *The dominant process is protons capturing an electron when hitting the surface, and capturing a 2nd electron when bouncing back into the plasma.*





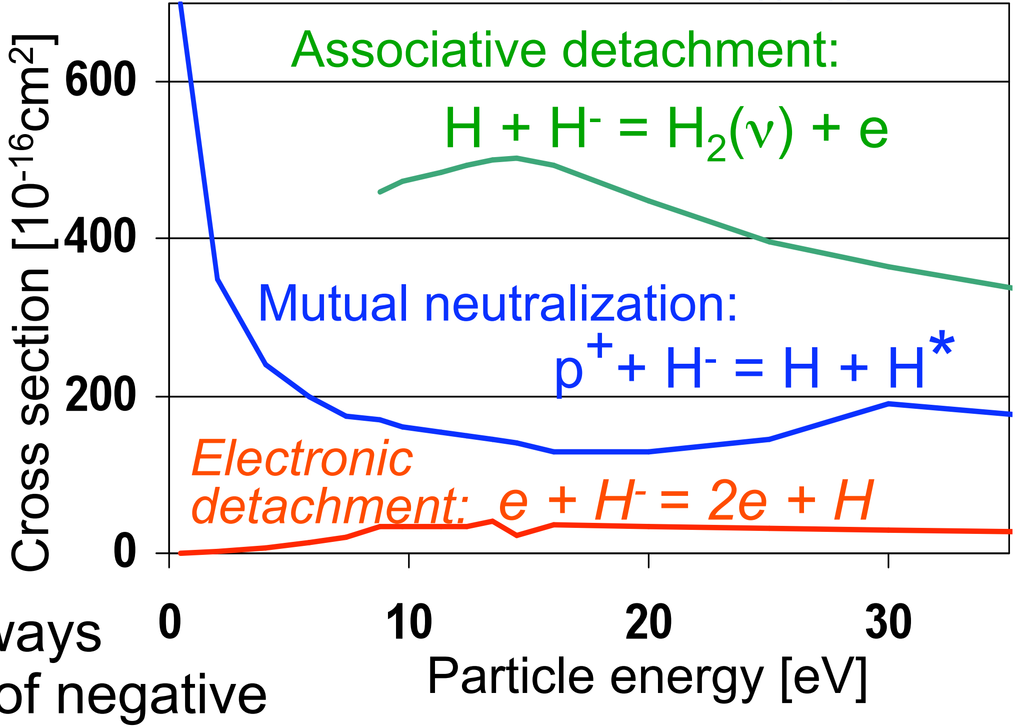
In the absence of Cs, residues on the surface ($H_2O$) and/or sputtered atoms (especially alkali from ceramics) can also lower the work function!

# The $p^+$ac-Man Problem!



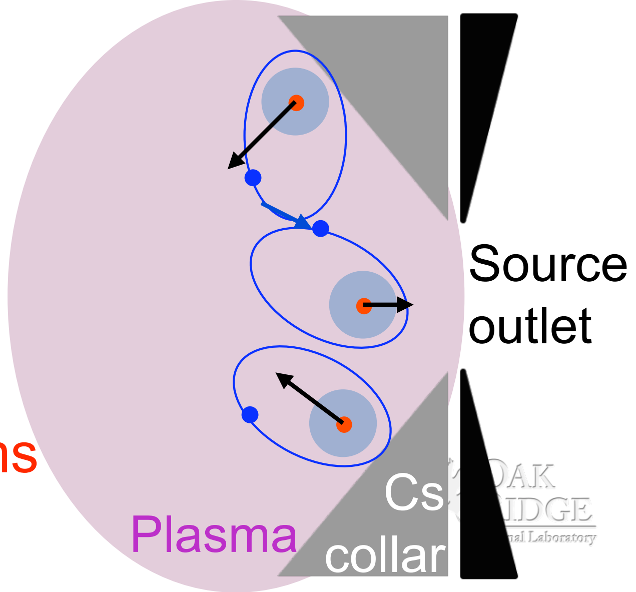
*$H^-$ ions are mainly destroyed by 3 mechanisms:*

- *In cold plasma losses are dominated by mutual neutralization ($\sigma = 7\cdot10^{-14}$ cm$^2$ for $T_{p+} \approx 0.5$eV). After a path length x through a proton density $n_{p+}$, the number of surviving $H^-$ ions is : $N_{H^-} = N_0 \cdot e^{-n \cdot x \cdot \sigma}$, or for $n_{p+}$= ~$10^{13}$ cm$^{-3}$, only about ⅓ survive a path length of $x=(n_{p+}\cdot\sigma)^{-1} \approx 1.4$ cm ≈ $^9/_{16}$"!*



- Plasma are neutral and therefore always contain protons and therefore losses of negative ions are unavoidable. It is therefore important to produce the negative ions as close as possible to the source outlet: the ion converter or Cs collar!
- Protons bouncing from the converter surface and capturing two electrons are accelerated twice by the plasma potential and head away from the outlet.
- However, the resonant charge exchange allow the loosely bound electrons to transfer easily to cold atoms

$H^- + H = H + H^-$ ~$10^{-14}$cm$^2$ for $E_{H^-}$<100 eV



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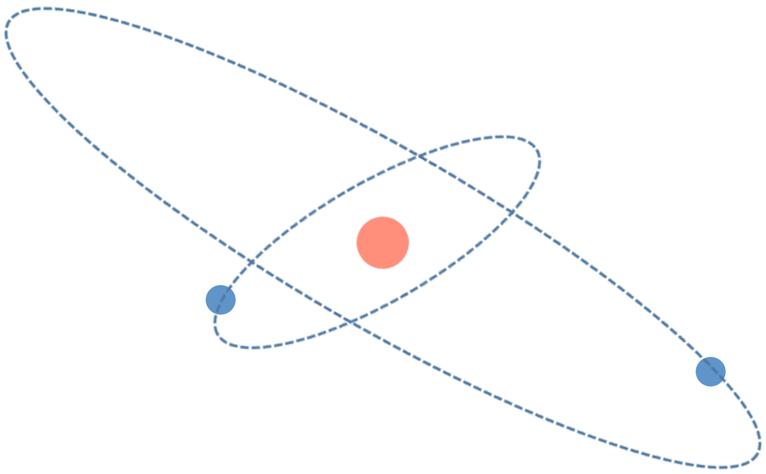

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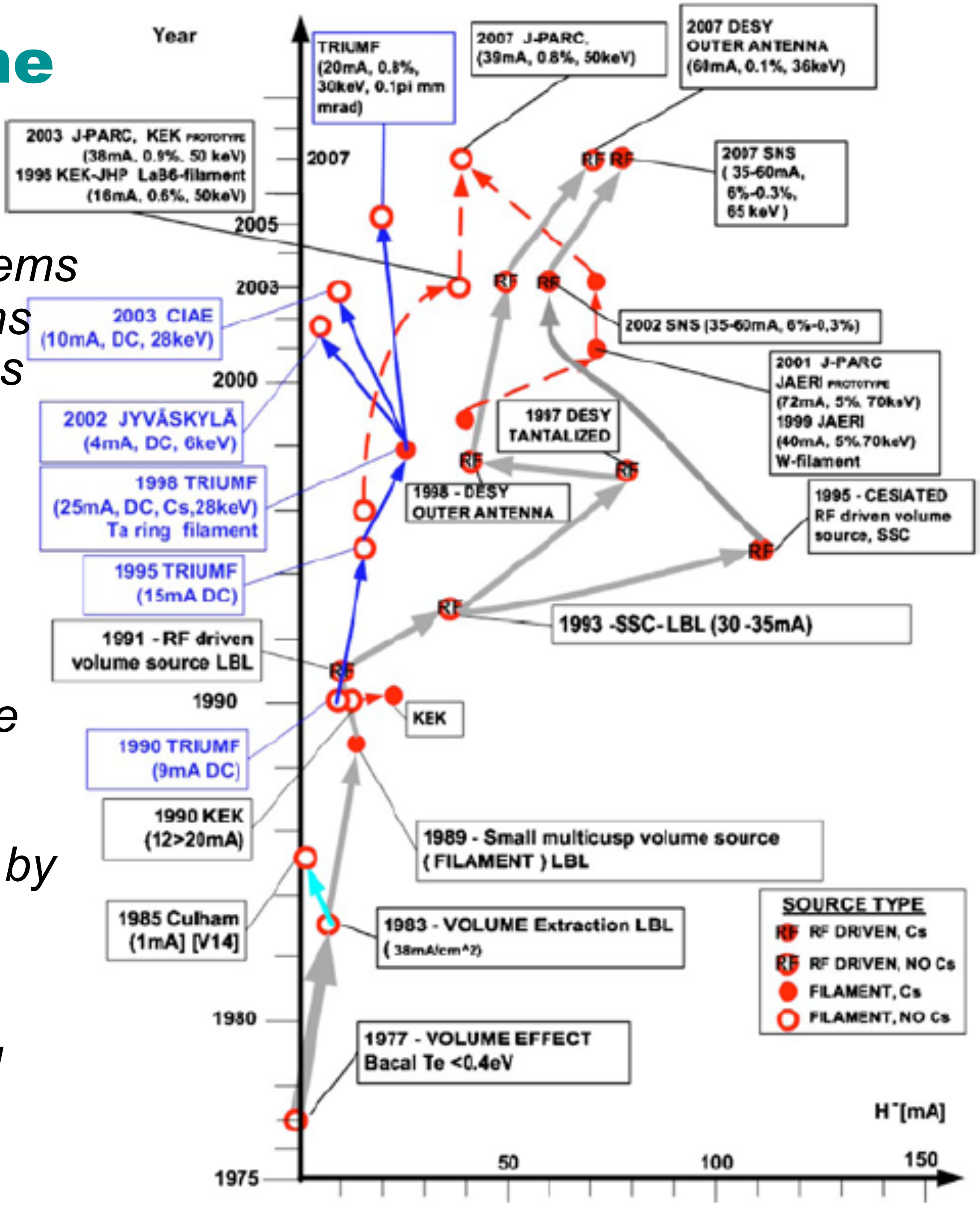
***It is all about extracting more $H^-$ ions!***

# Brief History of Negative and Volume $H^-$ Sources

- *Negative ion sources were developed to strip electrons for*
  - *1) multiplying the energy in Tandems*
  - *2) extracting beam from cyclotrons*
  - *3) stacking beams in synchrotrons*
- *~1965 more negative ions were found near surfaces.*
- *~1970 Dimov, Belchenko & Dudnikov added Cs to their magnetron: see lecture on CSPS*

- *In 1977 Bacal discovered volume produced $H^-$ ions;*
- *In the 80ties, LBNL developed multicusp volume sources driven by a filament and later by RF.*
- *This evolved in to the low duty factor SSC and DESY sources.*
- *In the 90ties TRIUMF developed their DC H- volume source.*
- *~2000 LBNL developed the high duty-factor SNS source.*

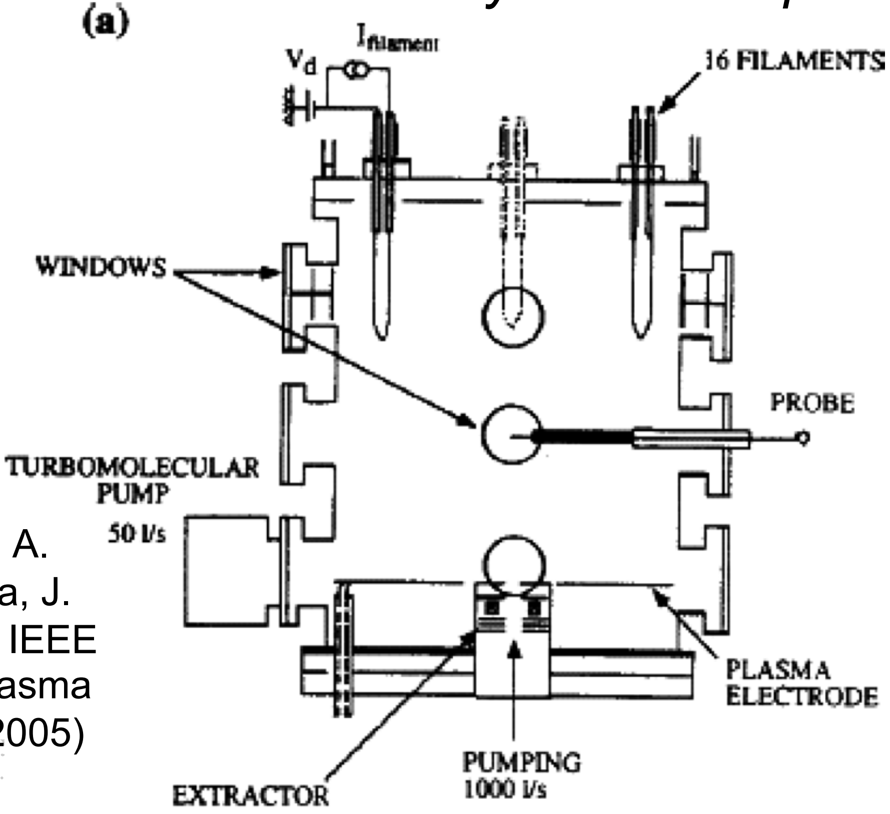


From J. Peters, RSI 79 (2008) 02A515

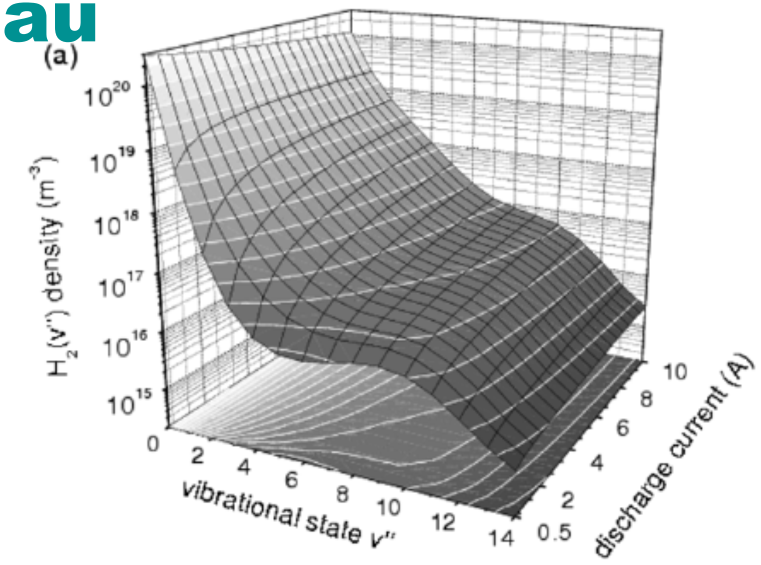
# Mme. Bacal’s Camembert, Ecole Polytechnique, Palaiseau

T. Mossbach, Plasma Sources S&T **14** (2005) 610.

- *In 1977 Bacal found a very large population of negative ions using a Langmuir probe.*
- *In 1997 photo-detachment showed a ~1/3 ratio of $H^-$ ions and electrons.*
- *Camembert is a large filament driven R&D ion source, that is extensively used to study the volume production of $H^-$.*
- *The plasma is confined by a multicusp field.*



M. Bacal, A. Hatayama, J. Peters, IEEE Trans. Plasma Sci. **33** (2005) 1845



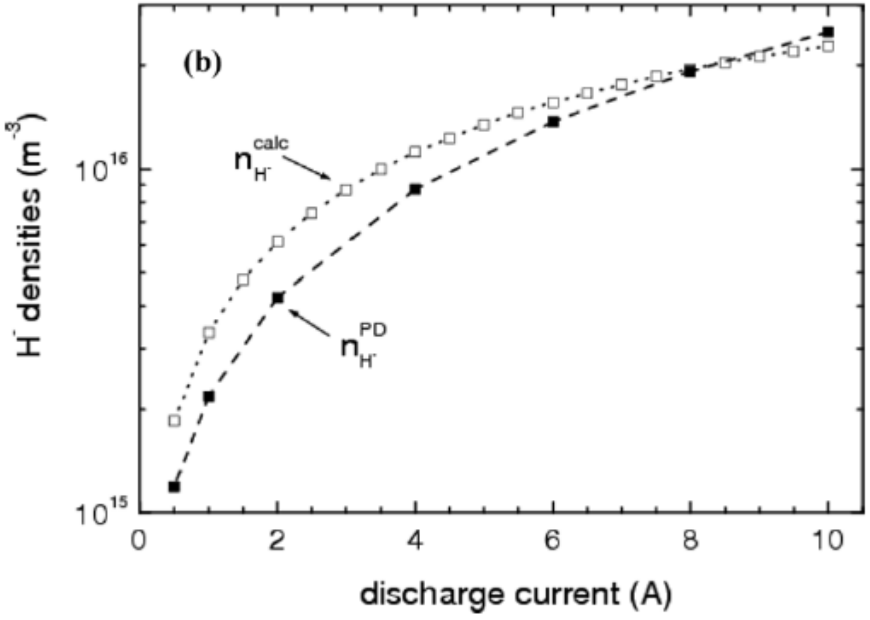
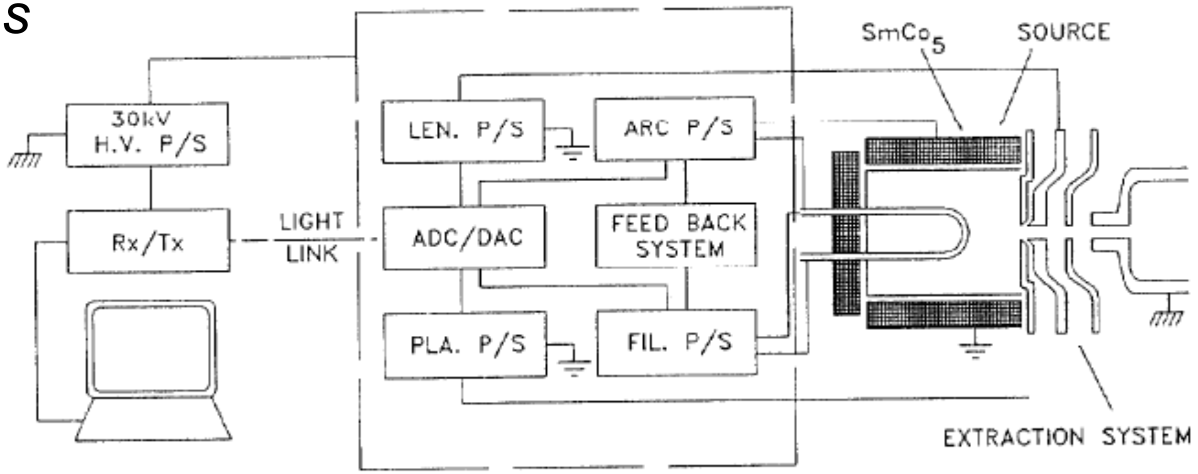


Fig. 1. Experimental verification of the volume production mechanism. (a) Population of vibrational states versus discharge current. (b) Comparison of $H^-$ densities measured by photodetachment (full squares) and calculated from vibrational populations. (Used with permission from [17].)

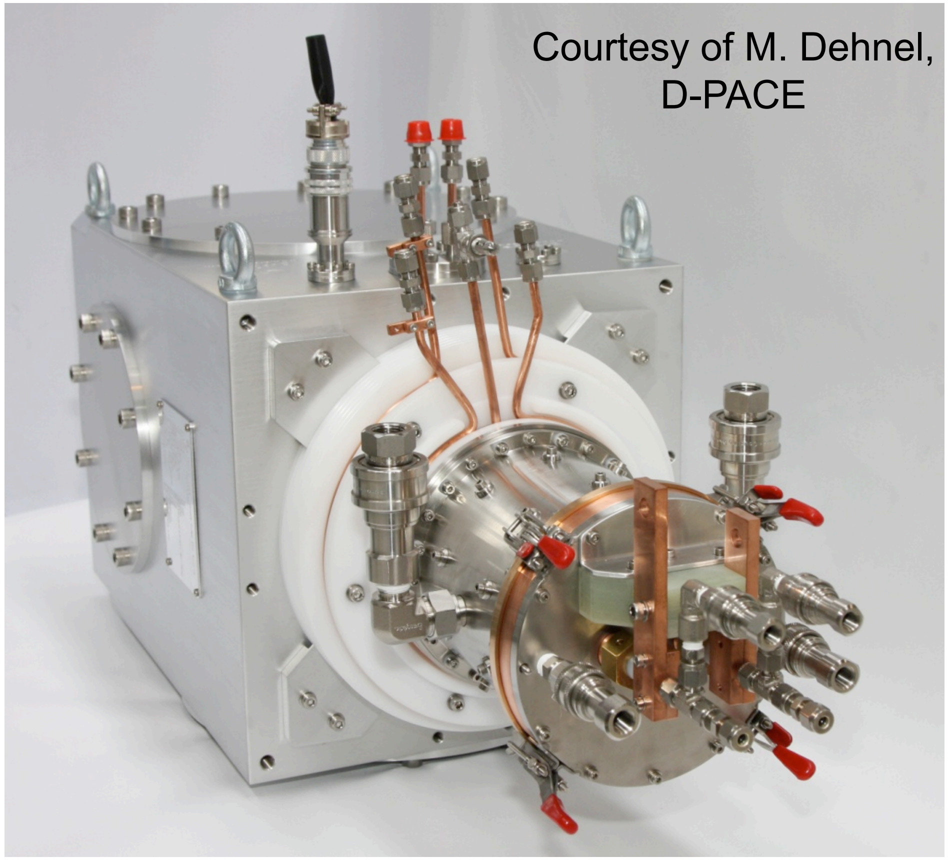
# The TRIUMF $H^-$ Source

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*
- *Filter field generated by two inverted cusp magnets near the outlet.*
- *A 6 mA, 5.8 keV copy was developed for Jyvaskyla.*
- *Licensed to and sold by D-PACE at www.d-pace.com*



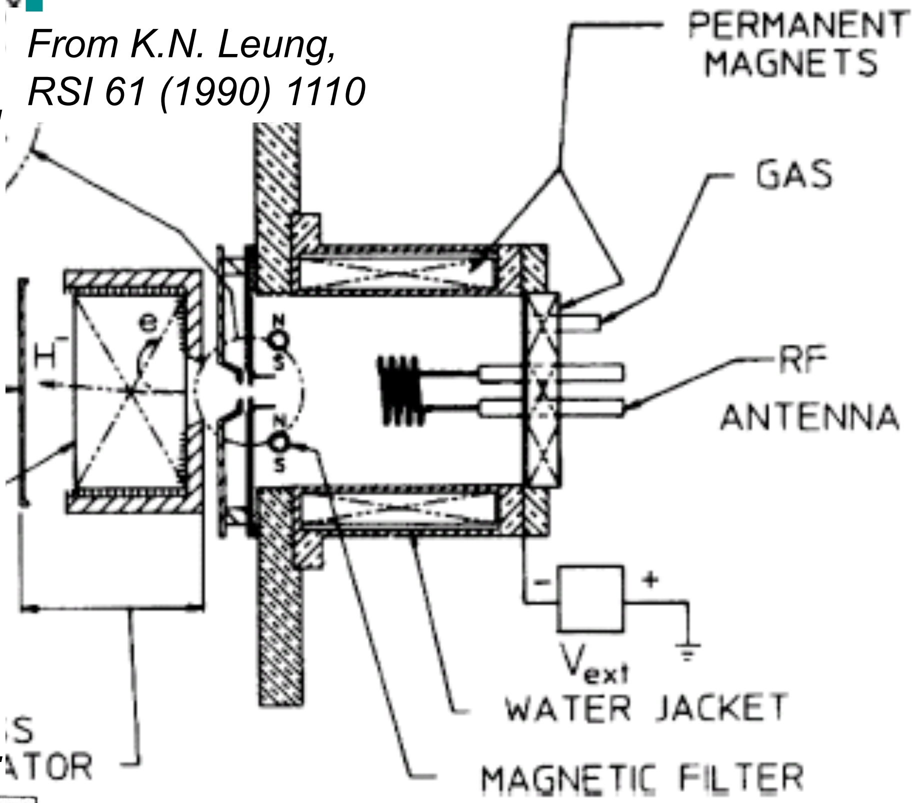
| | |
|---|---|
| Beam Current: | 15 mA continuous |
| Ion Energy: | 20-30 kV |
| Filament: | 340 A, 3.5 V; 1.2 kW |
| Arc supply: | 29 A, 120 V; 3.5 kW |
| Normalized rms emittance | ~0.22 π·mm·mrad |
| Plasma lens | 30 A, 10 V; 0.3 kW |
| Efficiency: | ~ 3 mA / kW |
| Filament lifetime: | ≥14 days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


Courtesy of M. Dehnel,
D-PACE

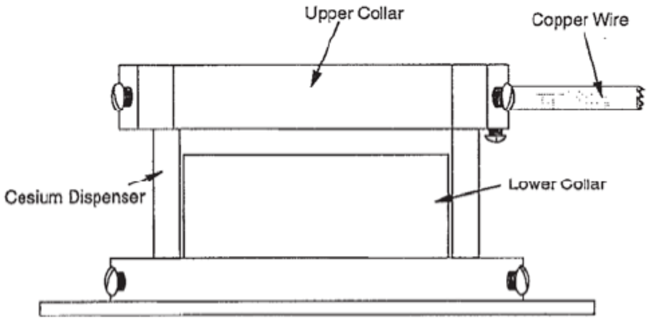
# The Berkeley $H^-$ developments

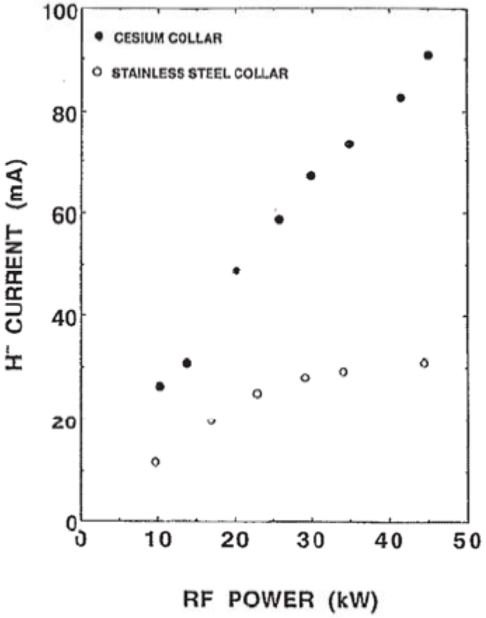
- In 1990 Leung et al. report the use of inductively generated plasma for producing $H^-$ beams "**with almost no lifetime limitation**". The efficiency is higher than their filament source.
- In 1993 Leung et al report a 3 fold gain in $H^-$ beam using a collar with SAES Cs dispenser.
- In 1996, Saadatmand et al. report 70-100 mA running at 10 Hz 0.1 ms with the SSC source modeled after the LBNL source. H- beam appeared to be stable for up to 8 hrs.

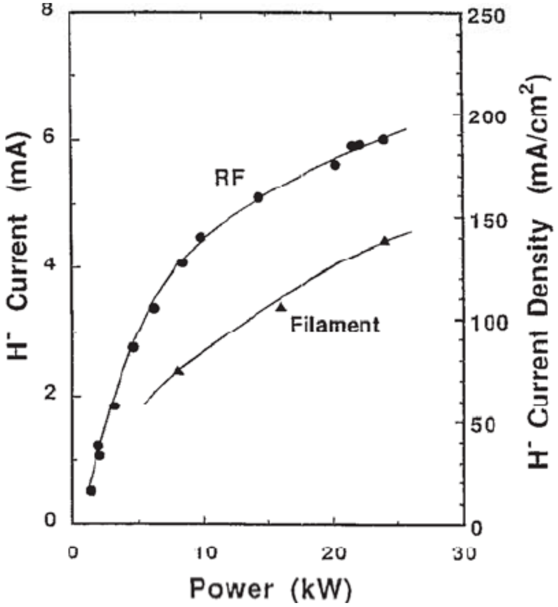
*From K.N. Leung, RSI 61 (1990) 1110*



*From K.N. Leung, RSI 64 (1993) 970*





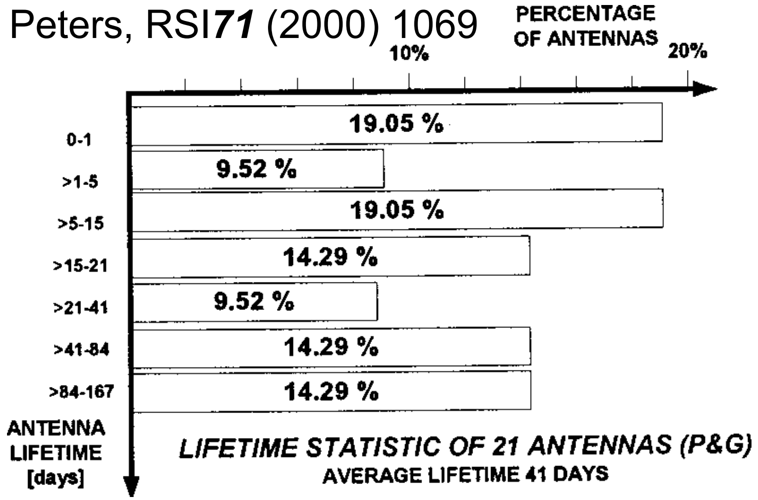


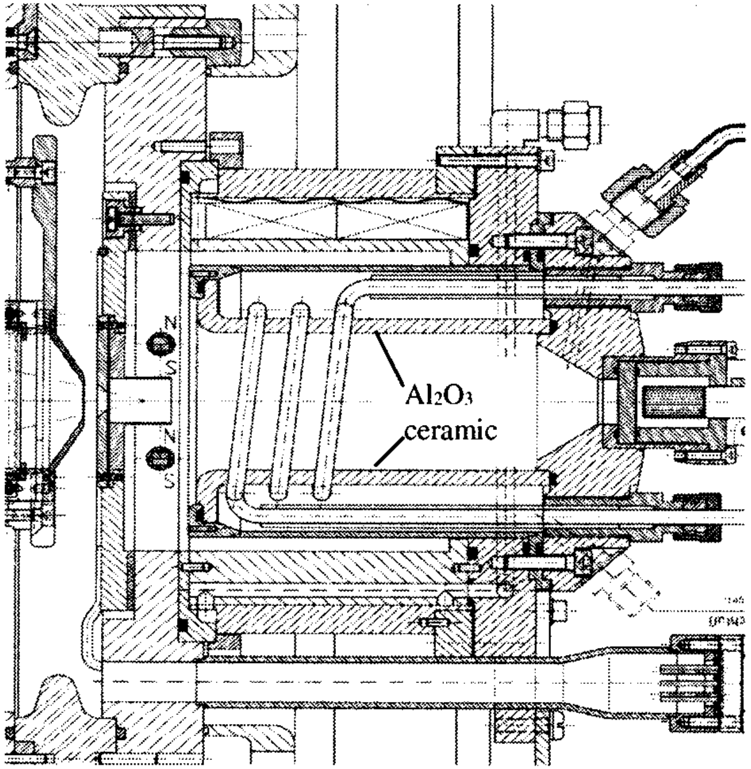
# The DESY source

- *Jens Peters from DESY purchased a LBNL RF H$^-$ source and 30 antennas and reported lifetimes with a median of ~2 weeks, with ~30% failing within the first few days.*

- *In response, DESY develops the Cs-free DESY source with an antenna wound around an alumina plasma chamber.*
- *Running at 5 Hz, 0.1 ms, the ~40 mA beam persists for at least 1 year.*

J. Peters, RSI*71* (2000) 1069





- *The source is highly optimized for the H$^-$ output.*
- *Numerous collars are developed to increase and study the H$^-$ production and the plasma.*
- *The DESY program stops when HERA is shut down.*

- *CERN is trying to adapt this source for the LINAC-4 requirements:*
*1) 45 kV up from 35 kV*
*2) 0.7 ms up from 0.2ms*

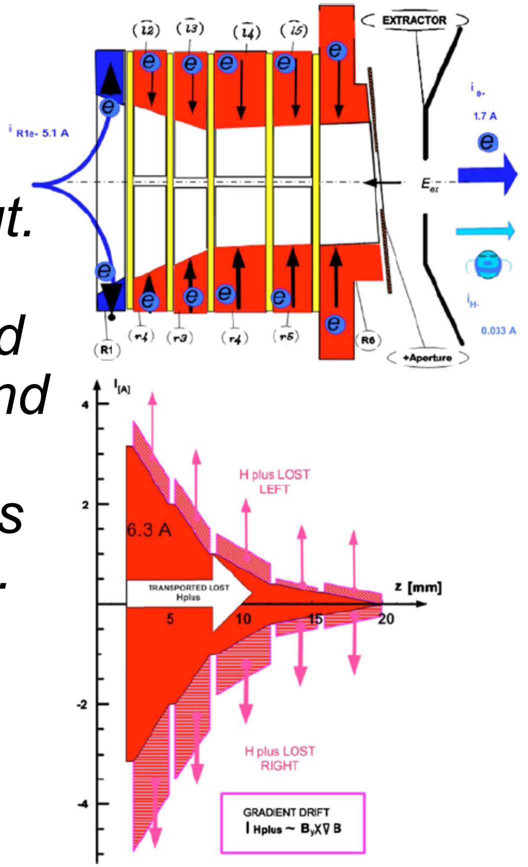


FIG. 4. (Color online) Currents of the cone-cylinder collar which is split longitudinally in six layers and in left and right parts (see text).

J. Peters, RSI*79* (2008) 02A515

# Identifying Negative Volume Sources

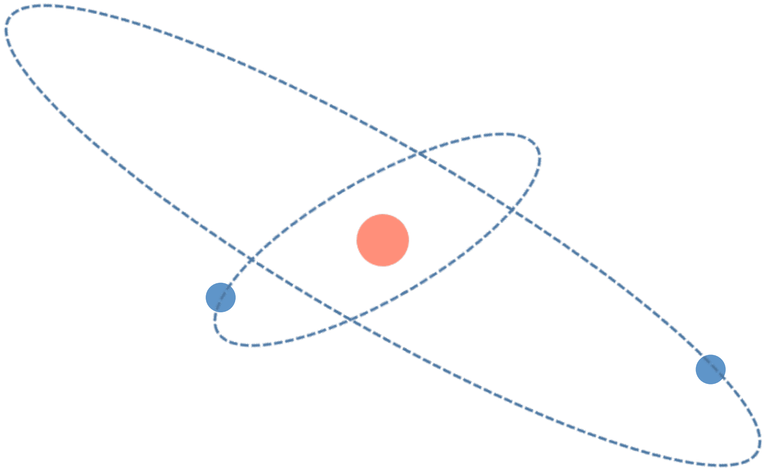
## Volume Sources for Negative Ions

- Feature a filter field near the source outlet (~70-300 Gauss)
- Feature a large outlet, typically 7-10 mm∅, to extract many volume produced negative ions. (This contrasts the typical ~1mm wide extraction slots of the CSPS (magnetron & Penning; but 2 mm holes have been used on CSPS and the LBNL volume).
- Typically feature a plasma electrode to enhance the extraction of negative ions (except the SNS source).
- Some feature a collar surrounding the outlet, which reduces the neutral flux and can redirect particles towards the outlet. It could also add excited molecules (DESY source).

## In addition Surface-enhanced Volume Sources for Negative Ions

- Feature typically an Mo outlet collar with a surface optimized to produce extractable negative ions. The surface is typically ~45° to intercept a lot of plasma and hopefully reflect the surface produced ions towards the outlet.
- Some surface-enhanced volume sources use heat (JPARC) or Cs (SNS) to enhance the surface production of $H^-$ ions.

# Content



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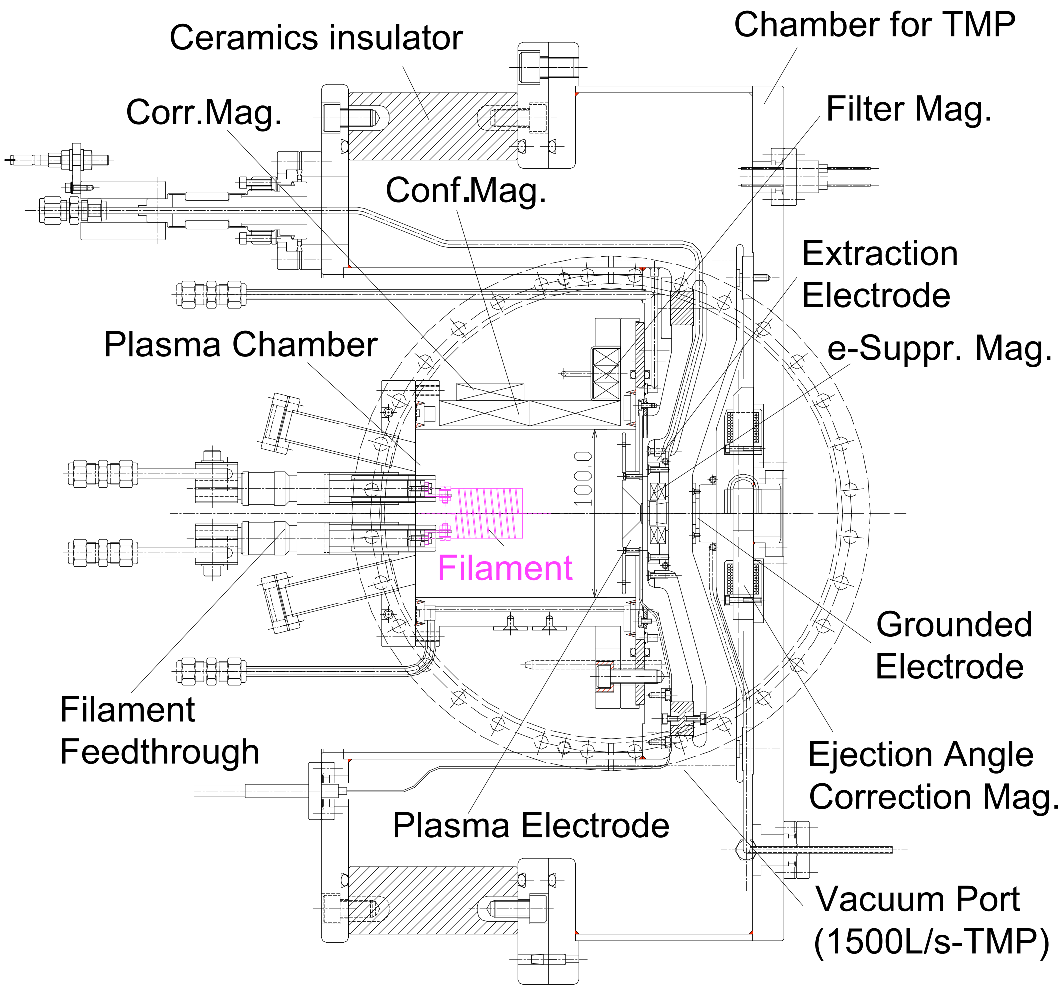
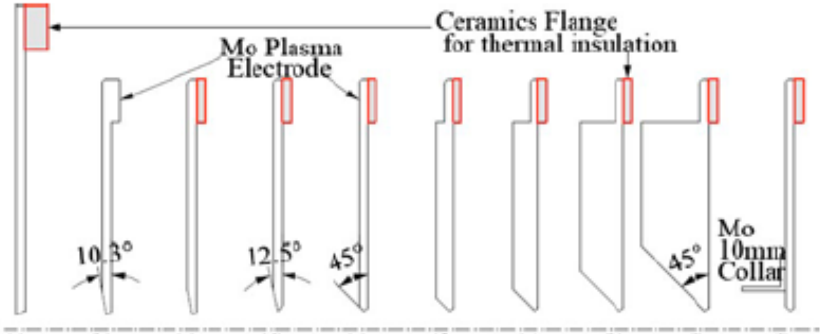
***It is all about extracting more $H^-$ ions!***

# J-PARC $H^-$ source

- J-PARC developed a Cs-free, $LaB_6$ filament driven $H^-$ source to inject into their RCS.
- 17 mA $H^-$ with 1.2 kW filament and 21 kW arc power at 0.5 ms 25 Hz, 50 days lifetime.
- Much R&D on filaments and plasma electrode, which needs to be ~500°C.
- 38 mA have been demonstrated 0.3 ms 25 Hz.
- Plasma electrode gets coated with Boron and some La. Cs does not enhance the $H^-$ current.
- Cs enhancement observed with W filament, but large Cs consumption and very short life.
- A steady flow of Cs is needed apparently to continuously cover deposits from the filament.

***Sputtering limits lifetime!***





| | (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) |
|---|---|---|---|---|---|---|---|---|---|---|
| Taper Angle [°] | 0(JHP) | 10.3 | 10.3 | 12.5 | 45 | 45 | 45 | 45 | 45 | 45 |
| Thickness [mm] | T2 | T2 | T2 | T2 | T2 | T4 | T6 | T10 | T16 | T2 |
| Diameter of Beam Hole [mm] | D7 | D7 | D7 | D9 | D9 | D9 | D9 | D9 | D9 | D9 |
| Iarc [A] | 220 | 290 | 290 | 290 | 290 | 290 | 290 | 290 | 290 | 290 |
| I H [mA] | 16 | 16 | 20 | 25 | 26 | 30.6 | 34.4 | 38 | 38 | 30 |

A. Ueno et al, RSI 81 (2010) 02A720

# Back to the Basics: The Maxwell Equations

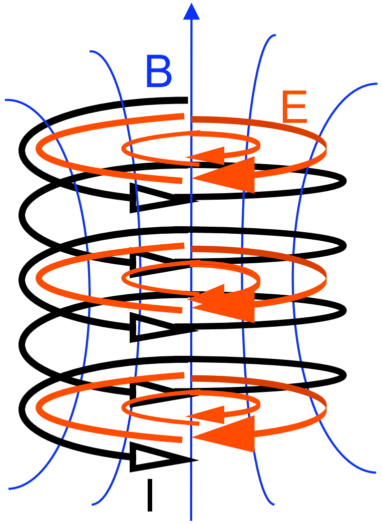
- The 1st Maxwell equation describes the sputtering due to ions accelerated by the cathode surface charges.
- The 3rd Maxwell Equation, $\nabla \times E = -\partial B/\partial t$ describes a curling E field generated by a changing magnetic field in absence of any surface charge!
- A changing magnetic 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 3rd equation for Faraday's law: $\int E \cdot ds = -d\Phi_B/dt = -d/dt \int B \cdot dA$
- and solve for E: $E(r,t) = ¼ \cdot r/r_o \cdot \mu_o \cdot \omega \cdot N \cdot i_o \cdot \sin(\omega t)$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

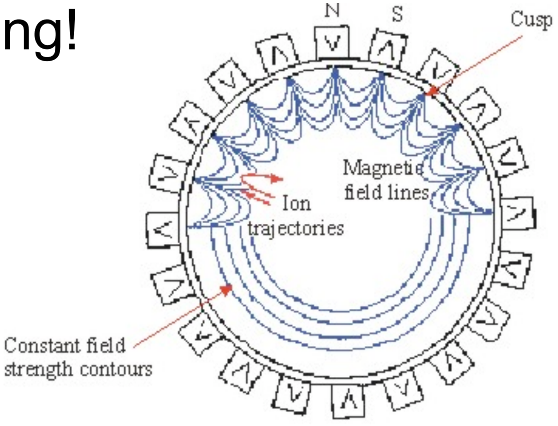
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

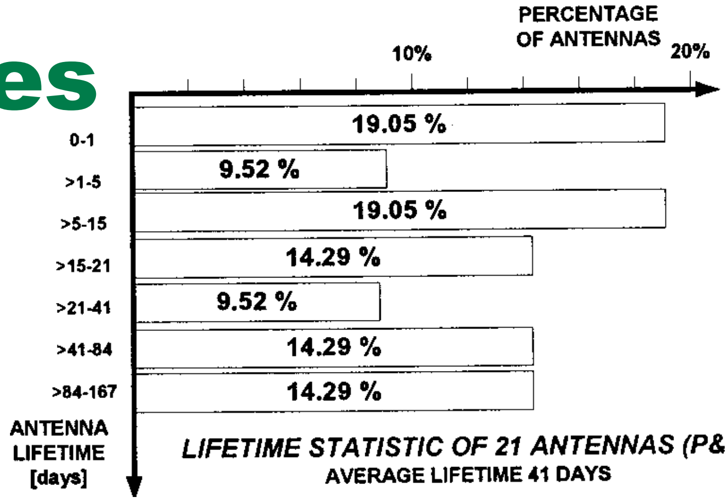


- The field in the center is ~zero
- The field outside the winding is ~zero
- The strongest field is on the inside of the coils and parallel to the windings, which should greatly reduce sputtering!
- The plasma is mostly generated near the inside of the windings.
- The RF causes the plasma to drift in circular direction.
- The multicups field guides the drifting plasma towards the center.



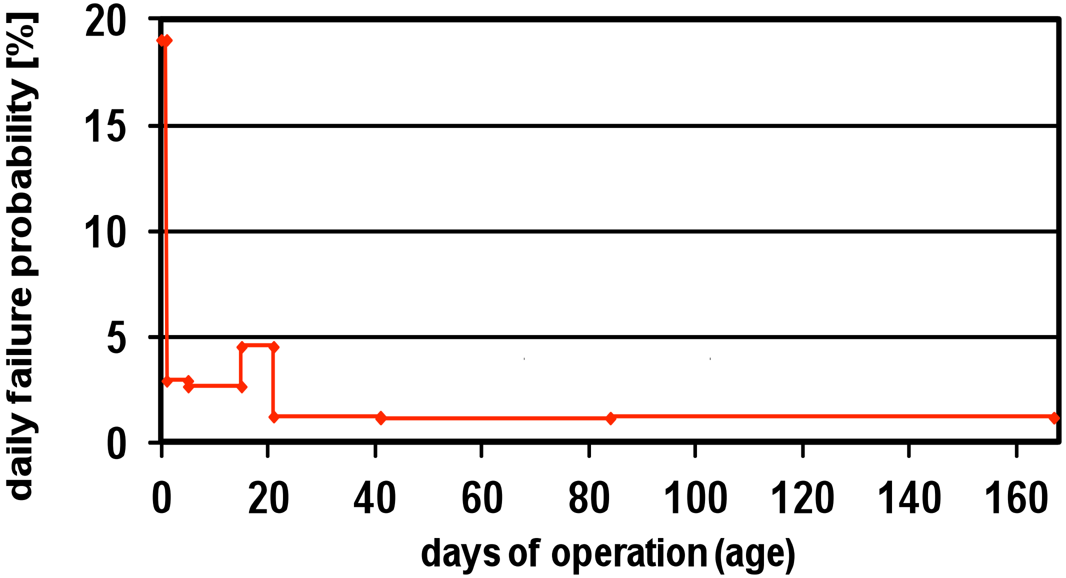
# P&G Antenna Lifetimes

As originally reported in
J. Peters, RSI**71** (2000) 1069:



*$T_\mu$ = 41 days;*
*$T_m$ = 16 days;*
*2.4 years operational data!*

**Plotted as daily failure probability:**



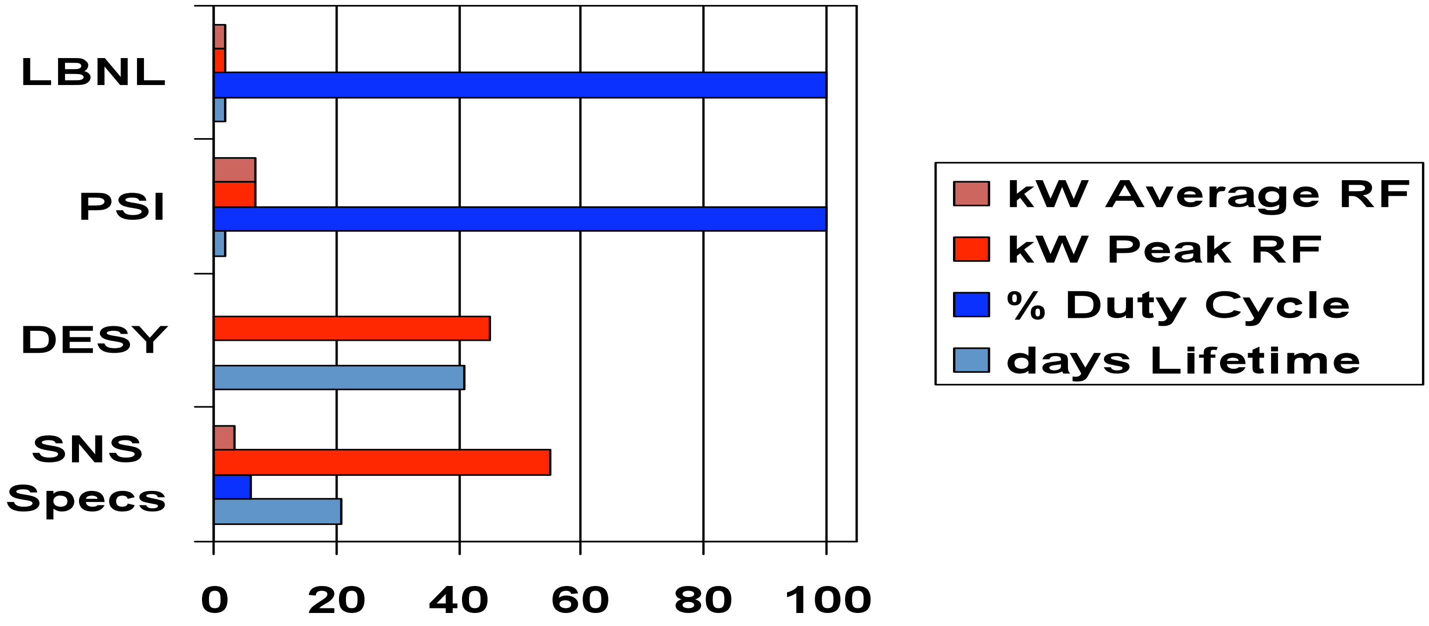
- The data show 37% of antennas fail in the first 21 days (infant mortality) superimposed on a 1.2% age-independent daily failure probability.
- Eliminating infant mortality could double average lifetime!
- **There is no sign of old-age failure as one would see with filaments!**

***These data were obtained with 2 Hz, 0.1 ms. How does the lifetime scale for 60 Hz, 1.0 ms, the SNS requirement?***

# RF Antenna Lifetimes known in Fall of 2001

| Lab | Antenna / Coating | MHz Frequency | kW RF-Power | % Duty Cycle | hours Life-time | Reference |
|---|---|---|---|---|---|---|
| Northrop Grumman | Cu tube/ Porcelain<br>SS / bare | 2 | 3.6 | 100 | >260 | S.T. Melnychuk, RSI 67(1996)1317. |
| LBNL | Cu tube / P&G Porcelain<br>Cu braid / Quartz | 13.56<br>13.56 | 2<br>2 | 100<br>100 | ~15<br>~20 | D. Wutte, AIP-CP# 473 (1999) 566. |
| LBNL | Cu tube / P&G Porcelain<br>Ag wire / Quartz<br>Ti tube / Quartz | 13.56<br>13.56<br>13.56 | 2<br>2<br>2 | 100<br>100<br>100 | < 50<br>>100<br>>500 | K.N. Leung, RSI 71(2000)1064.<br>J. Reijonen, RSI 71(2000)1134. |
| DESY | Cu tube / P&G Porcelain | 2 | 45 | 0.02 | 984 | J. Peters, RSI 71 (2000) 1069 |
| PSI | Cu tube / P&G Porcelain<br>Cu tube / Zug Porcelain<br>Cu tube / blue Porcelain<br>best / Quartz | 2<br>2<br>2<br>2 | 6-8<br>6-8<br>6-8<br>6-8 | 100<br>100<br>100<br>100 | ~50<br>~100<br>~200<br>~250 | H. Einenkel, private communications 2001. |
| Chiang Mai U. | Cu braid / Quartz | 13.56 | 0.3 | 100 | >>200 | D. Boonyawan, priv. comm.2001 |

# Scaling of P&G Antenna Lifetimes for SNS

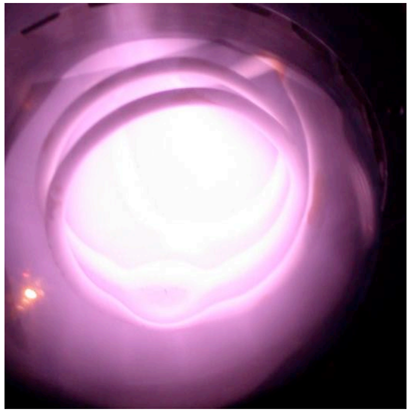


- If the average RF power is the limiting factor, then $T_\mu = 2$ days
  and if the lifetime can be duty cycle scaled, then $T_\mu = 35$ days ??
- If the peak RF power is the limiting factor, then $T_\mu < 41$ days ??
  and if life time should be repetition rate scaled, then $T_\mu < 0.7$days
  or if life time should be duty cycle scaled, then $T_\mu < 0.2$days

**The best justifiable scalings suggest: $T_\mu = 1 \pm 1$ day**

- *P&G antennas featured a single layer of ~0.15 mm porcelain, good for ~1 kV.*
- *However with 600A pk-pk, there are ~600V per turn or 1.5 kV over the antenna.*
- *Infant mortality likely due to hidden porcelain defects, such as excess porosity.*

# ORNL/Cherokee Antenna Developments



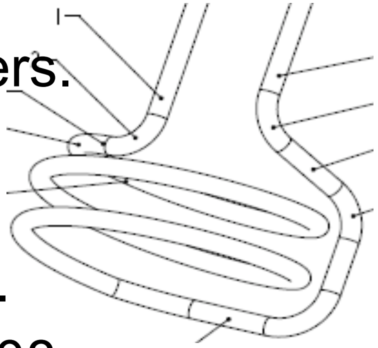
CHEROKEE PORCELAIN ENAMEL CORPORATION

The initial goals were to

1. reduce the infant mortality by applying multiple layers.
2. increase the standoff voltage by accumulating a thicker layer
3. reduce the sputtering with low dielectric porcelain ($TiO_2$ free)

Today the SNS source uses ~0.6 mm porcelain made of 5-7 layers.

-Thinner coatings tend to break down, thicker coating tend to chip, or melt where the legs penetrate into the plasma.



- 1 antenna failure during the low duty-factor runs in 2006/2007.
- Raising the duty-factor to >3% and RF power to ~50 kW in 2008, yielded ~1 antenna failure per ~20 week run.
- Increasing conditioning to 7% at 50 kW caused several early failures.
- All but 1 antenna failures were in the first 11 days.

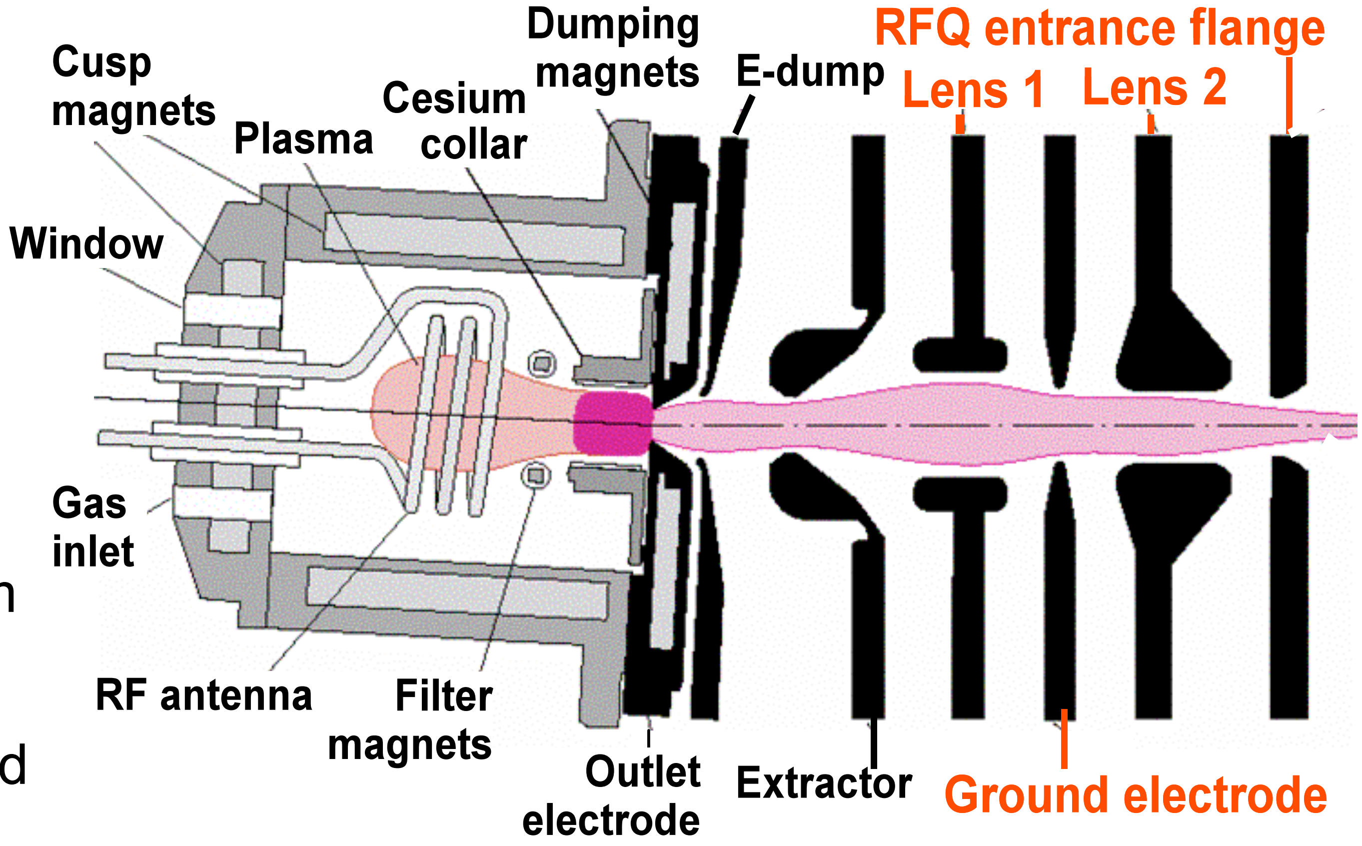
Since fall of 2011, we use antennas free of tangible surface imperfections.

With 5.3% duty-factor and 50/60 kW, no antenna failure so far in run 2012-1.

**We are working on distancing the legs from the plasma!**

# The SNS Baseline Ion Source and LEBT

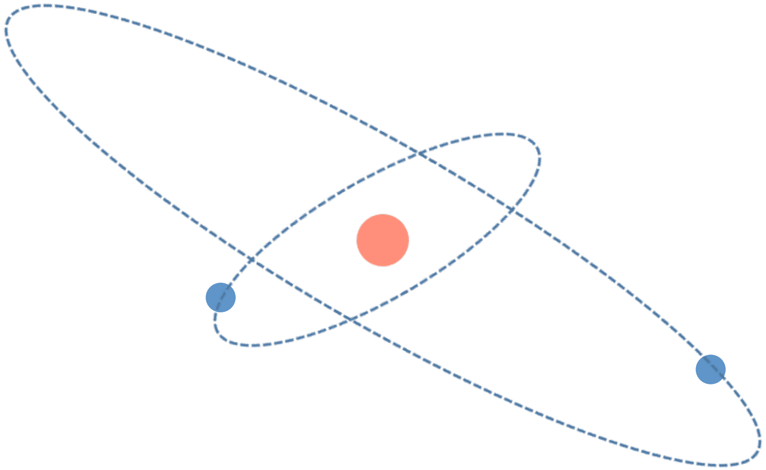
- LBNL developed the SNS $H^-$ ion source, a cesium-enhanced, multicusp ion source.
- Typically 300 W from a 600-W, 13-MHz amplifier generates a continuous low-power plasma.
- The high current beam pulses are generated by superimposing 50-60 kW from a pulsed 80-kW, 2-Mz amplifier.



- The two-lens, electro-static LEBT is 12-cm long. Lens-2 is split into four quadrants to steer, chop, and blank the beam.
- The compactness of the LEBT constrains beam characterizations in front of the RFQ. The beam current is measured after emerging from the RFQ, which equals the LINAC beam current.
- Measuring the chopped beam on the RFQ entrance flange shows ~50 mA being injected into the RFQ under nominal conditions (= ~38 mA LINAC peak current).

***This is ~230 C of $H^-$ ions per day!***

# Content



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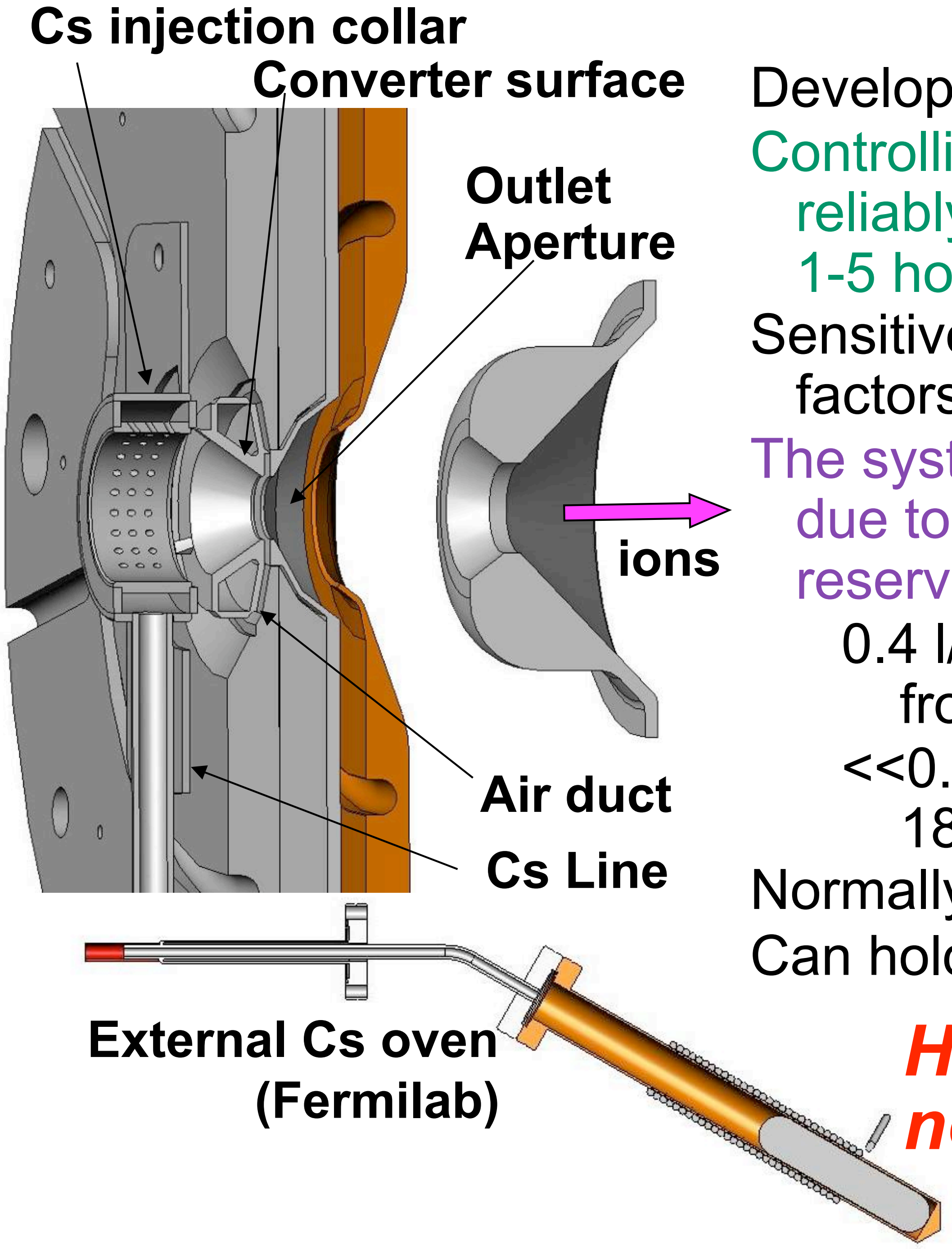
- Conclusions

***It is all about extracting more $H^-$ ions!***

# The External Cesium Reservoir

R. Welton et al, LINAC'06, 364



Developed from the Fermilab design.

Controlling the reservoir temperature reliably controls the Cs flux with an 1-5 hour delay for 185° to 110°C.

Sensitive to "cold" spots and low duty factors

The system conditions rather slowly due to the remoteness of the Cs reservoir:

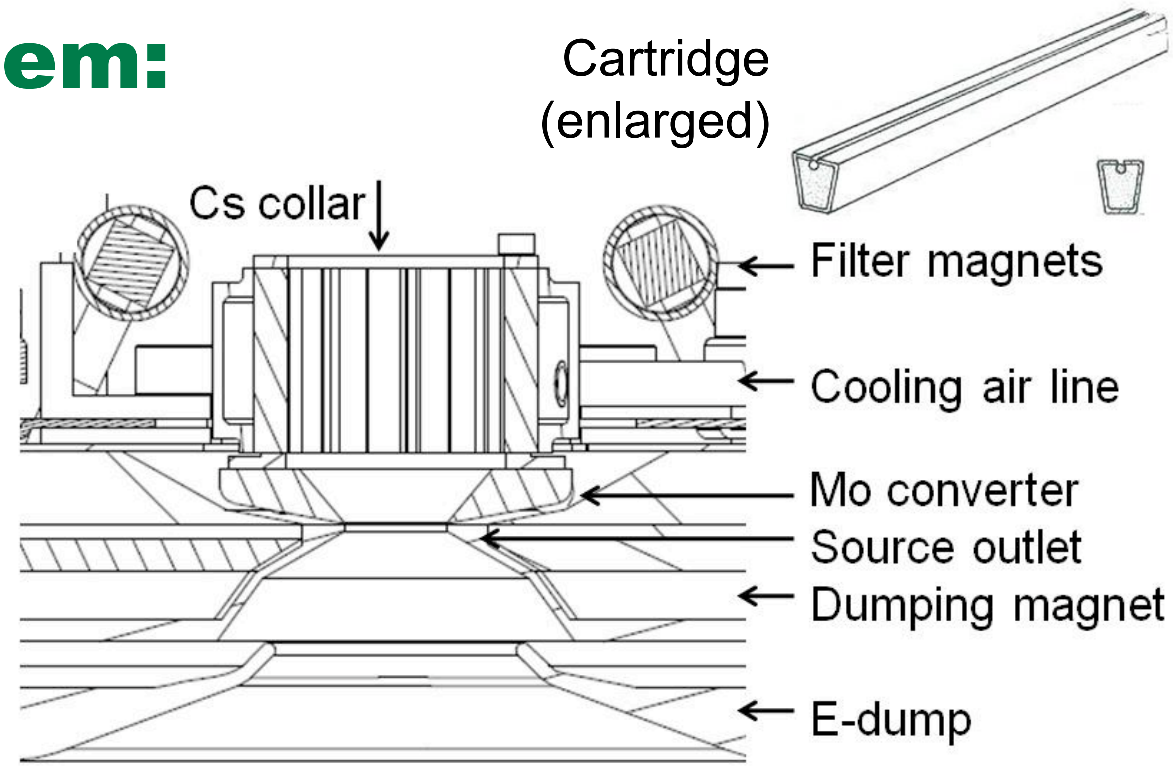
- 0.4 l/s pumping speed for mass 18 from the Cs line
- <<0.04 l/s pumping speed for mass 18 from the Cs reservoir

Normally degassed over night.

Can hold 0.2, 1, and 5g ampoules.

***However, more Cs does not yield more $H^-$ beam!***

# The $Cs_2CrO_4$ System:

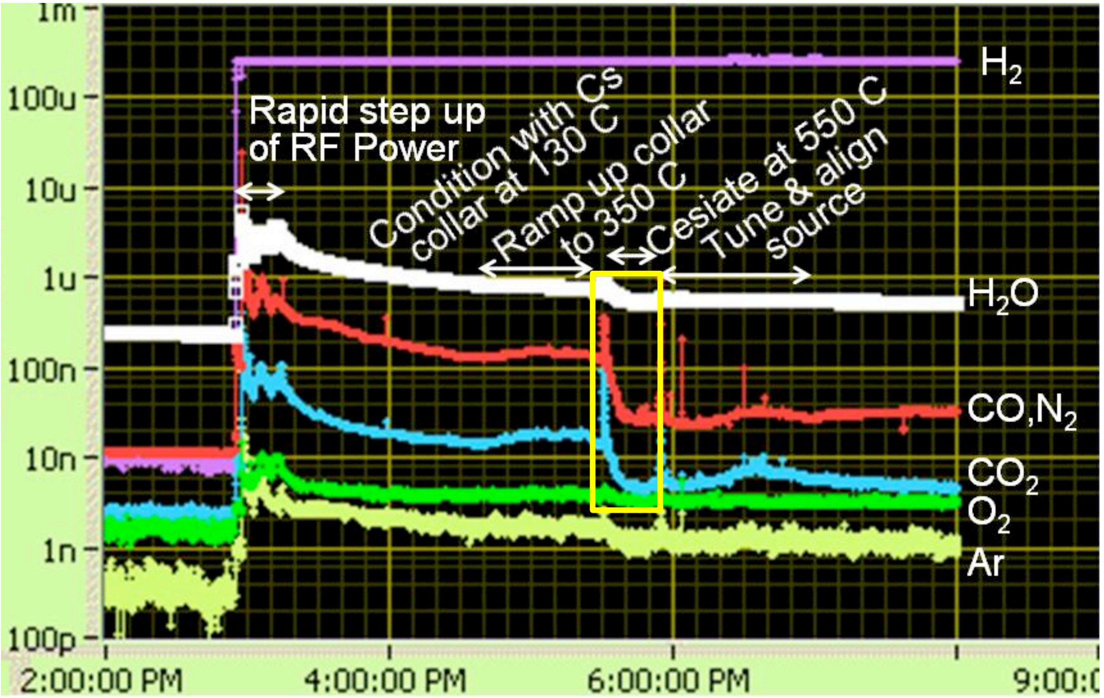


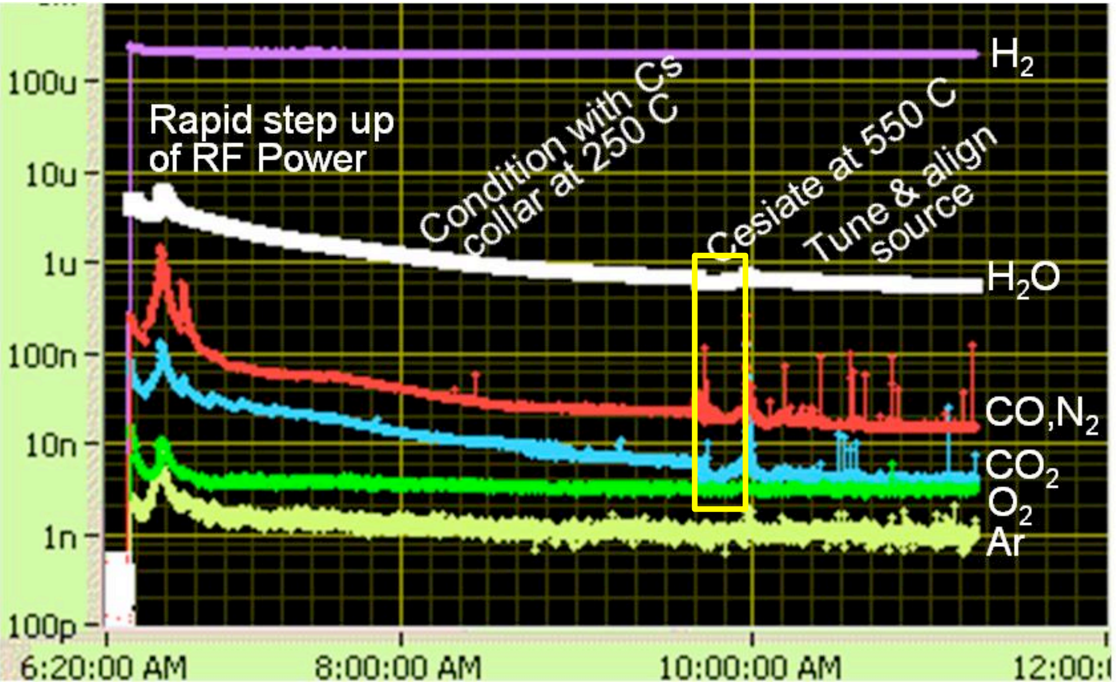
- To minimize Cs-induced arcing in our ultra-compact LEBT and the nearby RFQ, LBNL introduced 8 $Cs_2CrO_4$ cartridges (SAES Getters), which together contain <30 mg Cs. They are integrated into the Cs collar. The system compactness allows for rapid startups!
- The Mo ion converter is electrically and thermally attached to 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 appears to become persistent.
- Often the $H^-$ beam grows a little for a few days.
- Then the beam becomes persistent, free of decay!

***We have produced >9 kC or >2.5 A·h of $H^-$ ions without any maintenance!***

# Conditioning the Cs cartridges

- Without degassing, the Zr-Al getter first absorbs the gasses sorbed on the surfaces of the powdery chromate/getter mixture, which can take hours. Only then will it start to reduce the $Cs_2CrO_4$. Degassing is accelerated with heat.
- Complete degassing is confirmed when the collar temperature can be raised to ~550 C, and the partial pressure of residual gases barely change.
- This is normally achieved with ~3 hours at 250 C, well below the maximum 500 C degassing temperature recommended by SAES.





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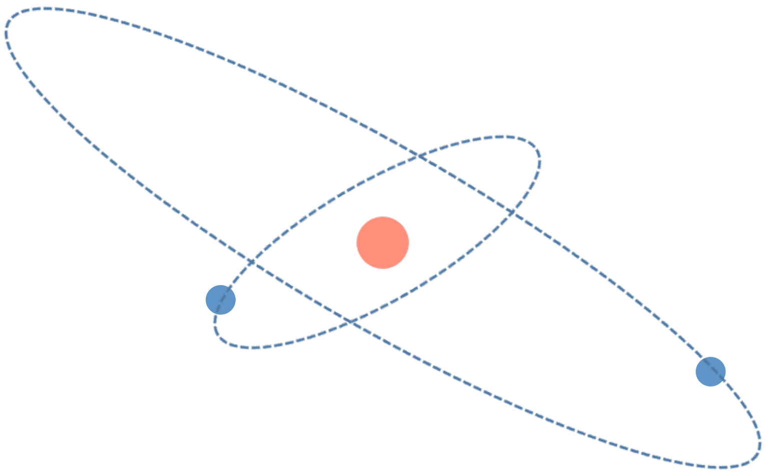

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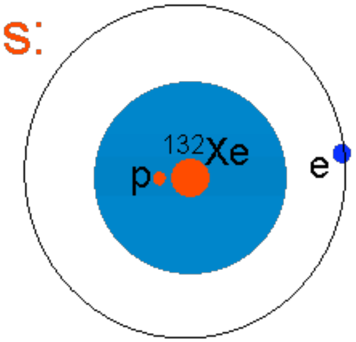
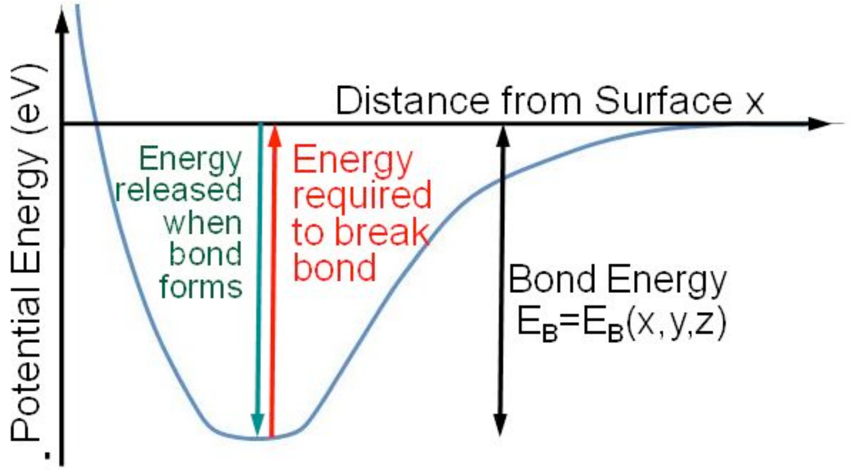
# Cesium on Metal Surfaces

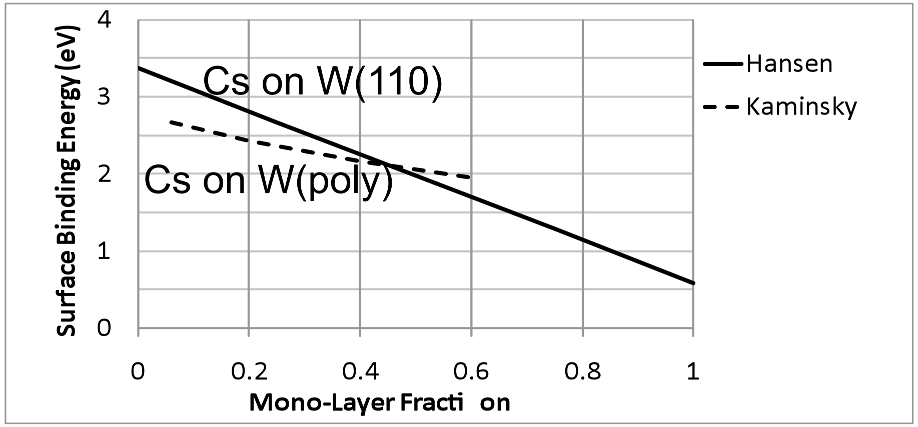
$^{133}$Cs:

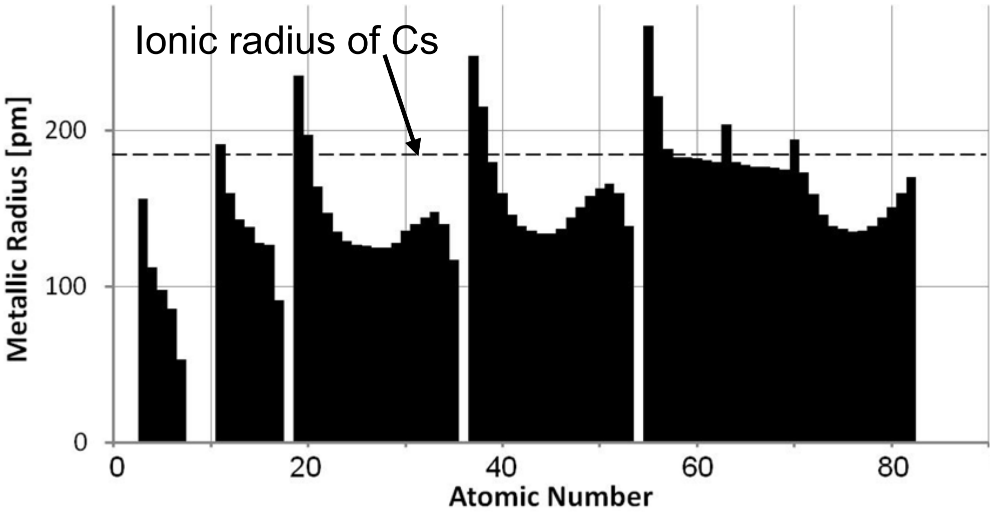


- Cs is $^{132}$Xe atoms with one additional proton and electron.
- It is the largest atom with only 3.9 eV ionization energy!



- Cs atoms on clean metal surfaces form an ionic-like bond as their outer electron mixes with conduction electrons.
- Ionic bonds are strong, resisting thermal emission as well as sputtering.
- However, additional layers of Cs will form covalent bonds with energies of ~0.4 eV, which easily break in thermal emission and sputtering.
- Data show the binding energy to decrease with increasing surface coverage.
- This appears to be a consequence of the mismatch between the lattice constant of the substrate metal and the ionic diameter of Cs.



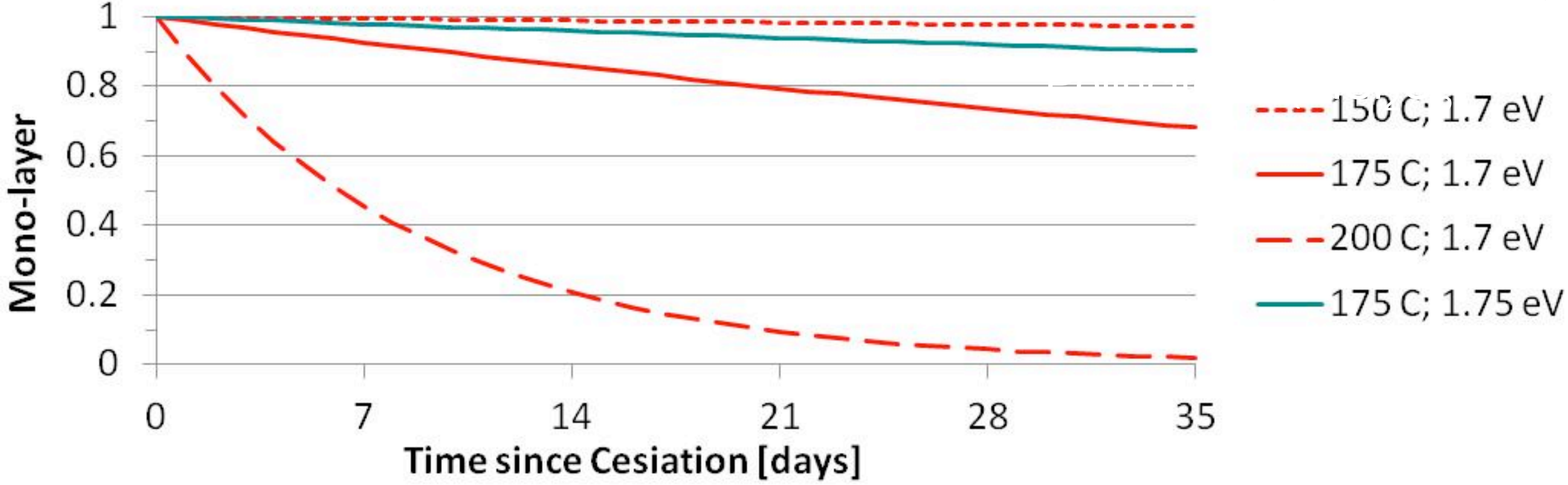


# Thermal Desorption from a Surface

Thermal desorption is characterized as Mean Dwell Time $\tau$:

$$\tau_a = \tau_0 \cdot \exp(E_{Cs}/k \cdot T) = 6 \cdot 10^{-13} \cdot \exp(E_{Cs}/k \cdot T)$$ (Cs on clean W: Lee & Sickney,72)

•For a constant binding energy $E_{Cs}$ and coefficient $\tau_0$, the thermal emission exponentially depopulates the Cs from the surface: $\theta(t) = \theta_0 \cdot \exp(-t/\tau_a(E_{Cs},T))$



•To minimize the Cs loss, we cooled the collar to ~60°C from 2006 – 2008.

•In 2009 we found that increasing the Cs collar temperature increases the $H^-$ output. Since then, the Cs collar is operated near 170°C.

•This is not surprising because the cesiations likely produce a mono-layer that is denser than optimal (>0.6).

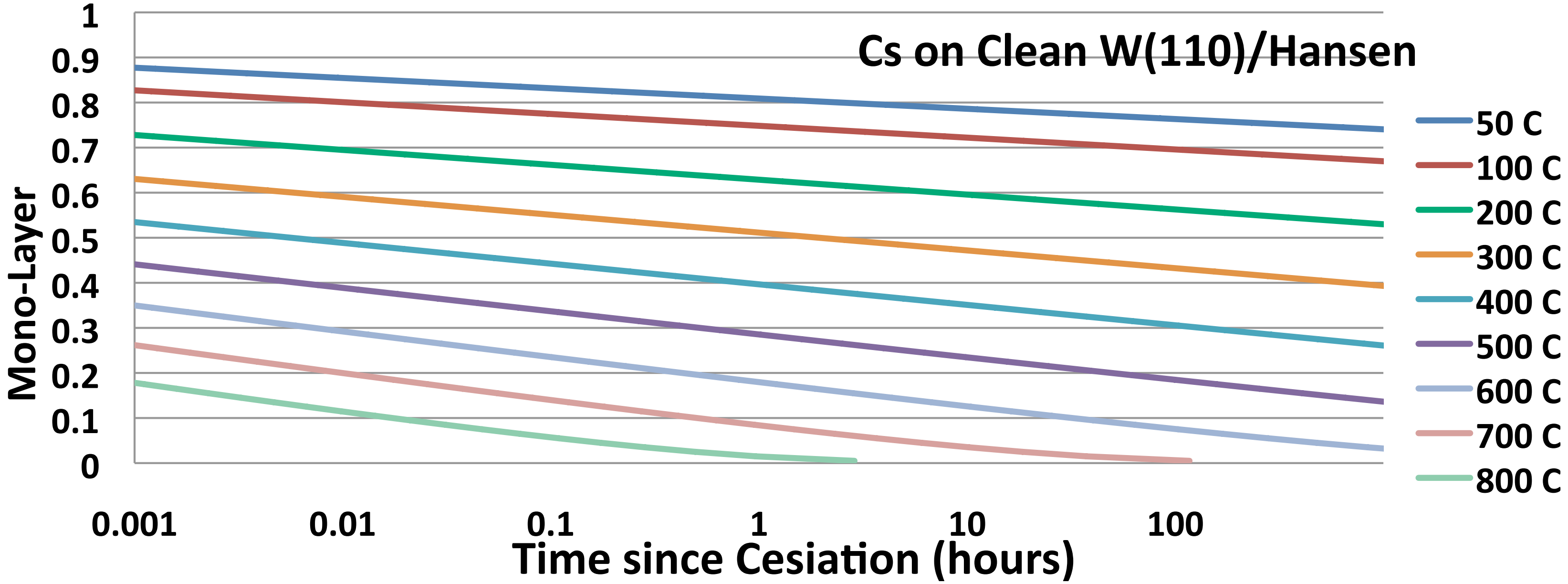
•Apparently, the 170°C temperature desorbs the excess Cs.

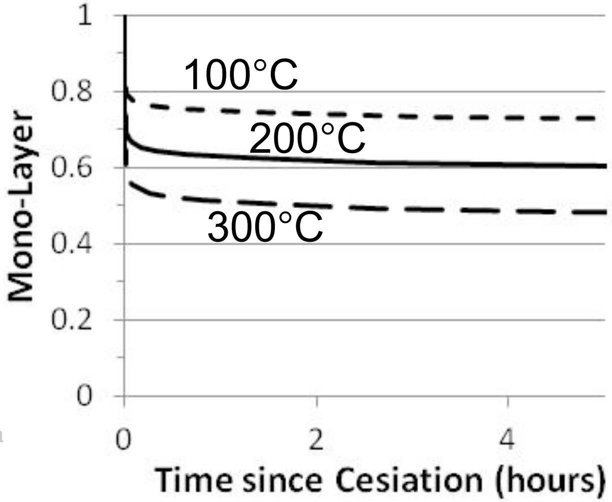
*However, remaining at 170°C, the beam does not continue to decay!*

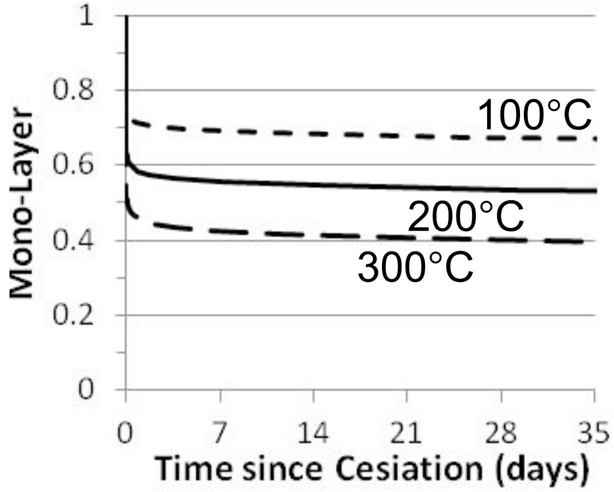
# Thermal desorption of Cs on clean metal

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

**Starting at $\theta_0=0.995$, the times it takes to shed 0.01 mono-layers are added to obtain $t(\theta)$**

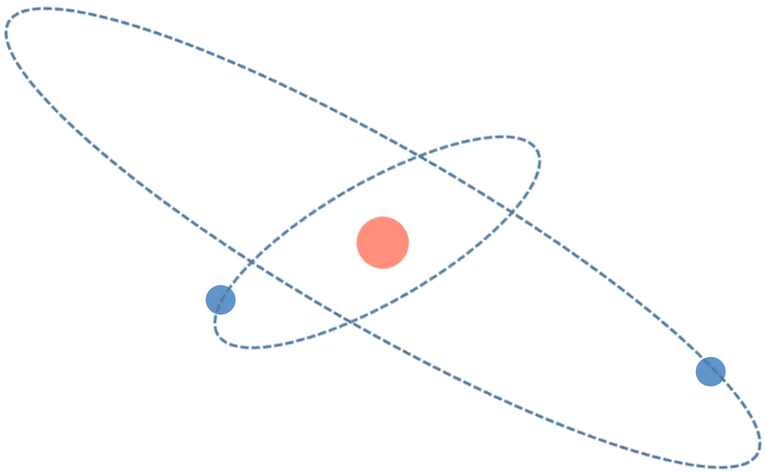






**The desorption increases the bond energy, which stabilizes the Cs layer.**

# Content



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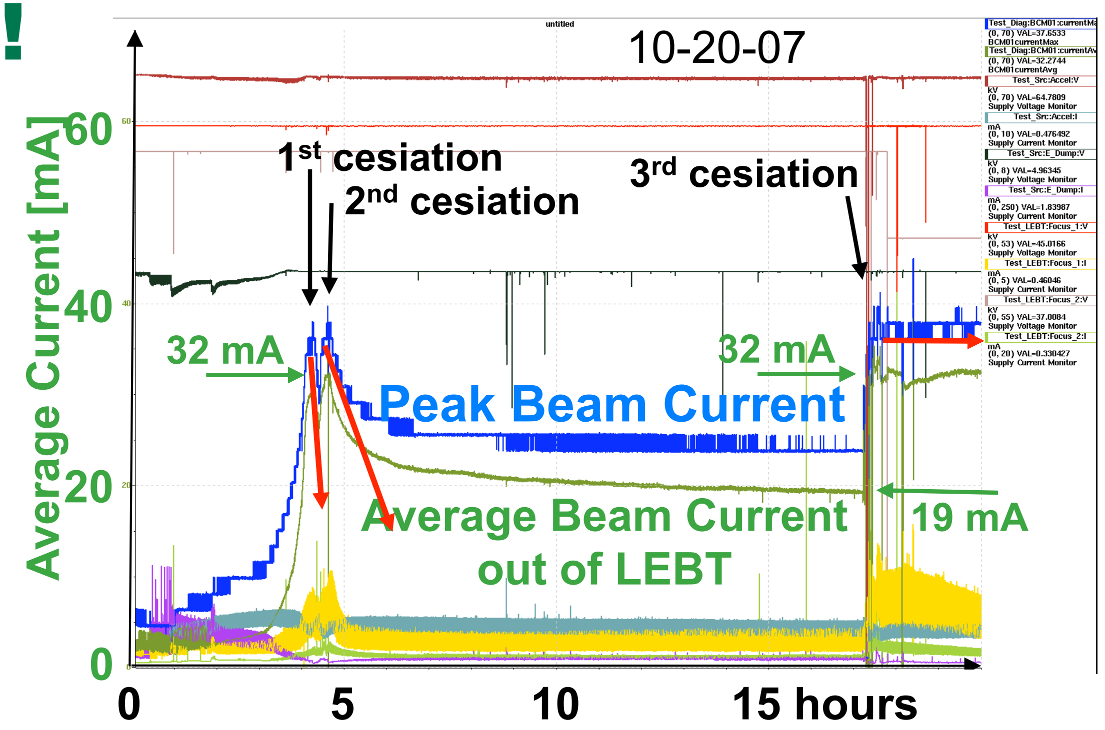
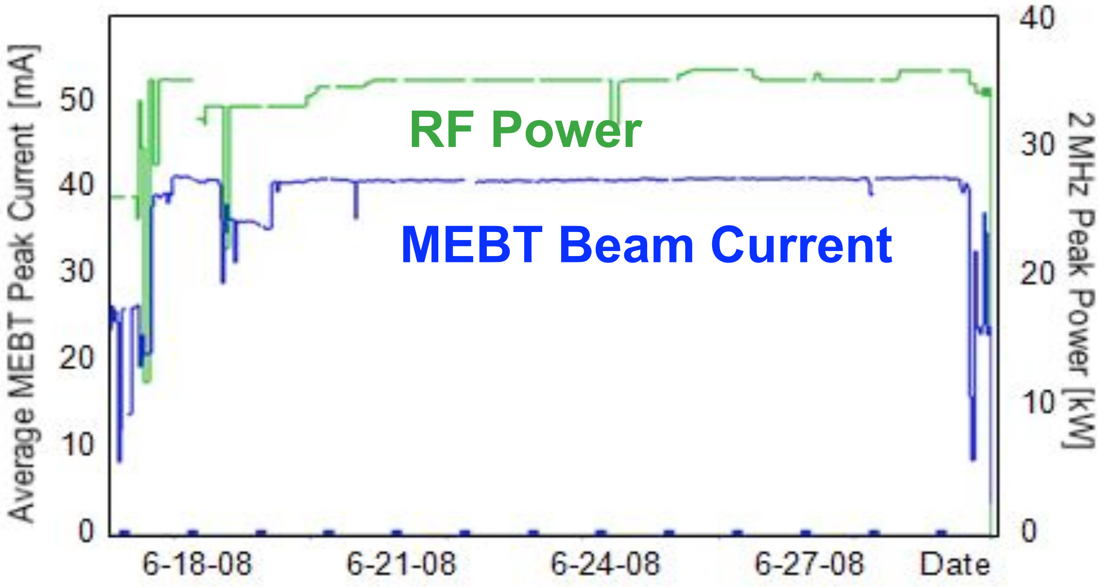
# Making the Cs stick!

- Before 2008 we limited full-power plasma conditioning to 30 minutes to minimize the risk of antenna failures.
- Cesiations increased the beam currents, but it would rapidly decay. Recesiation yielded the same current, which would decay less rapidly. However, next-morning cesiations produced persistent beams.

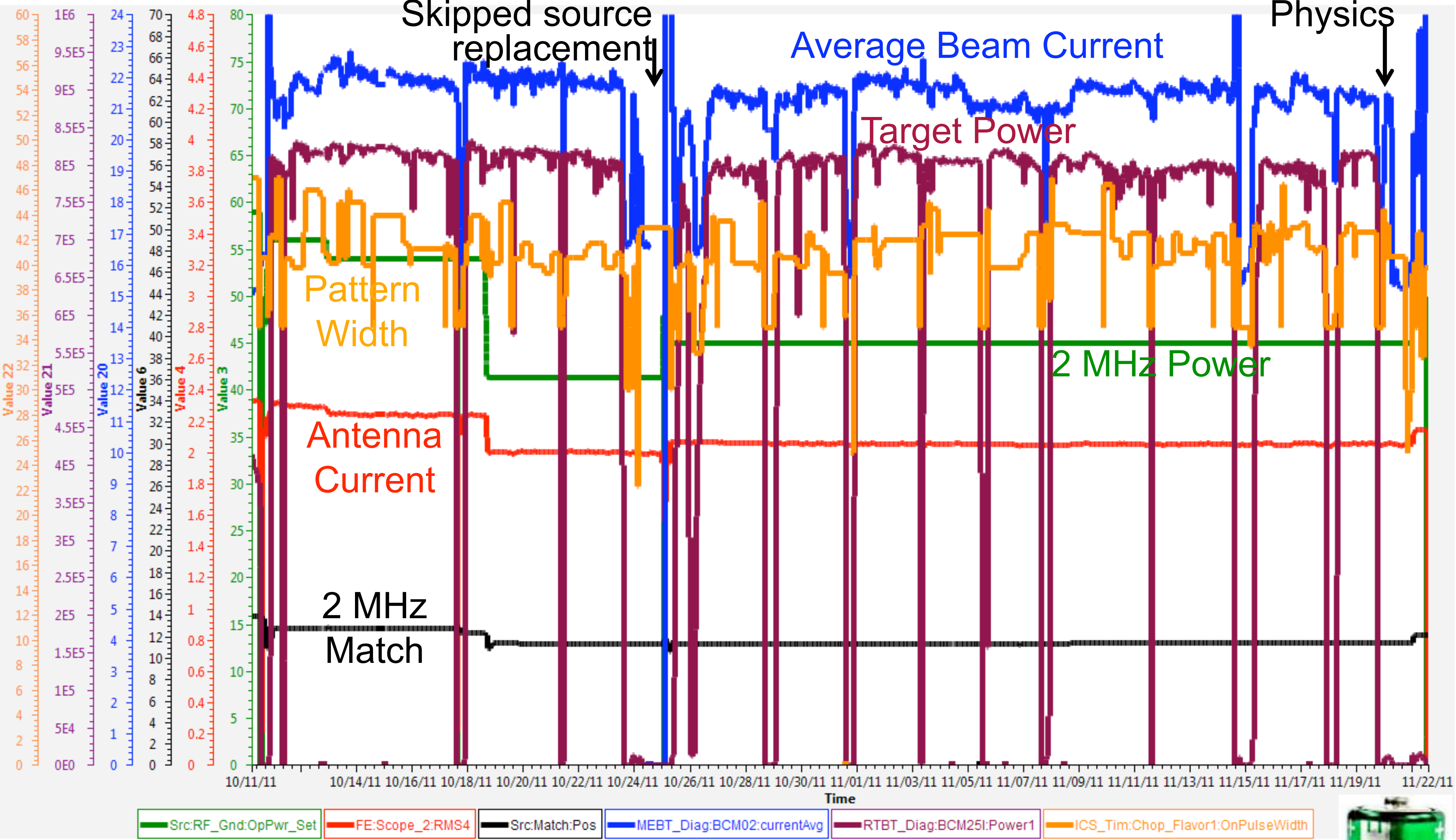


- When we increased the full-power plasma conditioning to 2.5 hours, the first cesiation normally produced a persistent beam, lasting many weeks!
- Apparently, the plasma conditioning scrubs the metal surface atomically clean, replacing the covalent bonds with surface sorbates with ionic bonds with the metal surface!



**Beam decay rate = $f$(Cs loss rate) = $f$(average bond strength)**

# 6 weeks of persistent 38 mA LINAC Beam



On 11-22-11, source #3 was removed after running degradation-fre
for 6 weeks producing ~38 mA LINAC beam current.

*Finally, RF technology is extending the life times of ion sources!*

# Requirements for Persistent H$^-$ Beams

- To obtain persistent beams with Cs-enhanced H$^-$ sources, one needs to maintain a stable fractional mono layer of Cs.
- Cs can be lost through thermal emission and through sputtering.
- In most Cs-enhanced H$^-$ sources, the lost Cs is 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.
- With the SNS baseline H$^-$ source, ~4 mg of Cs is released after ~3 hours of conditioning with ~50 kW at 5.3% duty-factor. After that the Cs collar temperature is lowered to ~170°C.
- Sometimes the beam decays by a few mA over the next few hours, a feature that is not understood.
- Most frequently the beam grows a few mA over the next few days, a feature that is attributed to being slightly beyond the optimal fraction of the Cs layer.
- After a few days the beam is persistent for up to 6 weeks, having used ~0.12 mg/day or ~2 mg/plasma-day, >4000 times less than other H$^-$ sources.

**Is the SNS H- source free of sputter losses?**

# Ion-Induced Sputtering

**Sputtering of surfaces and adsorbates play an important role in plasma ion sources. It is governed by the adsorbate mass $m_a$ and bond-energy $E_a$, and the ion mass $m_i$ and energy $E_i$, which is normally dominated by the plasma potential.**

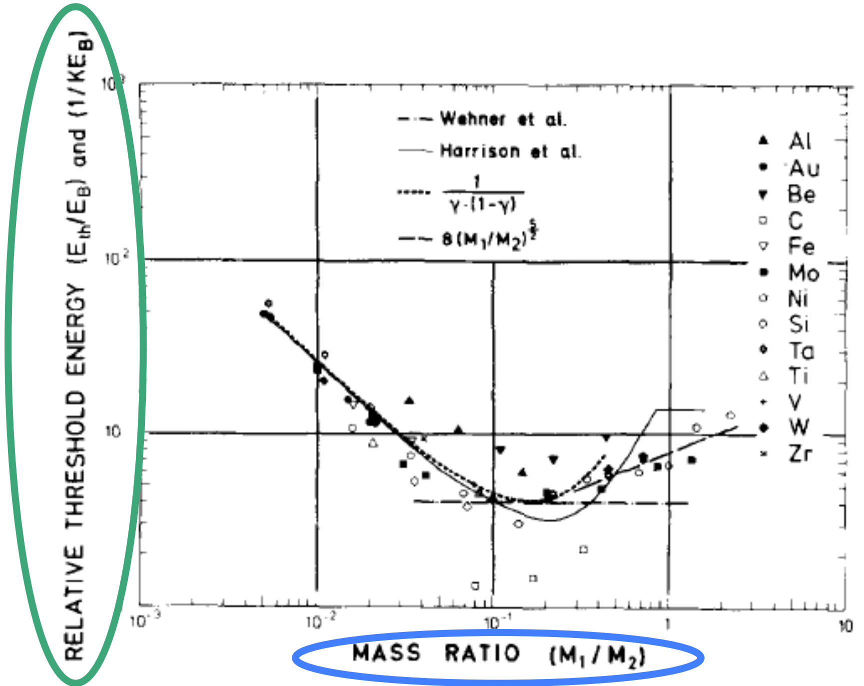


FIG. 2. Comparison of different relative threshold energies with the experimental data (----,— — — analytical fit, this work;— Ref. 10; – · – · – Ref. 14).

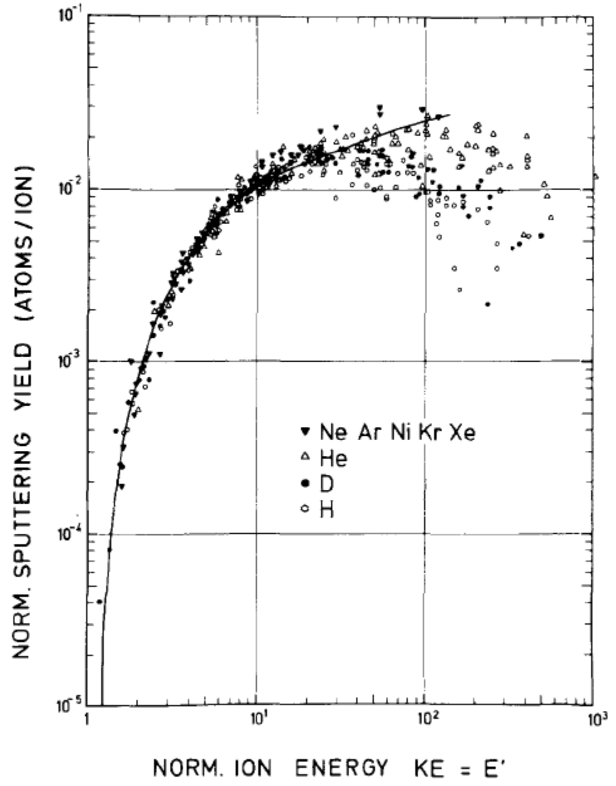


FIG. 1. Normalized yield data as a function of $E' = K\,E$. The solid line represents Eq. (4).

Bohdansky and Roth (JAP51,2861,1980) give the threshold as

**$E_{th} \approx 8\cdot E_a\cdot(m_i/m_a)^{2/5}$ for $m_i > 0.3\cdot m_a$**

**$E_{th} \approx E_a/(\gamma\cdot(1-\gamma))$ for $m_i \leq 0.3\cdot m_a$**

**with $\gamma = 4\cdot m_i\cdot m_a/(m_i+m_a)^2$**

**For $m_i/m_a<1$ the atom per ion yield is**

**$Y \approx 0.006\cdot m_a\cdot\gamma^{5/3}\cdot E_i^{1/4}\cdot(1-E_{th}/E_i)^{7/2}$**

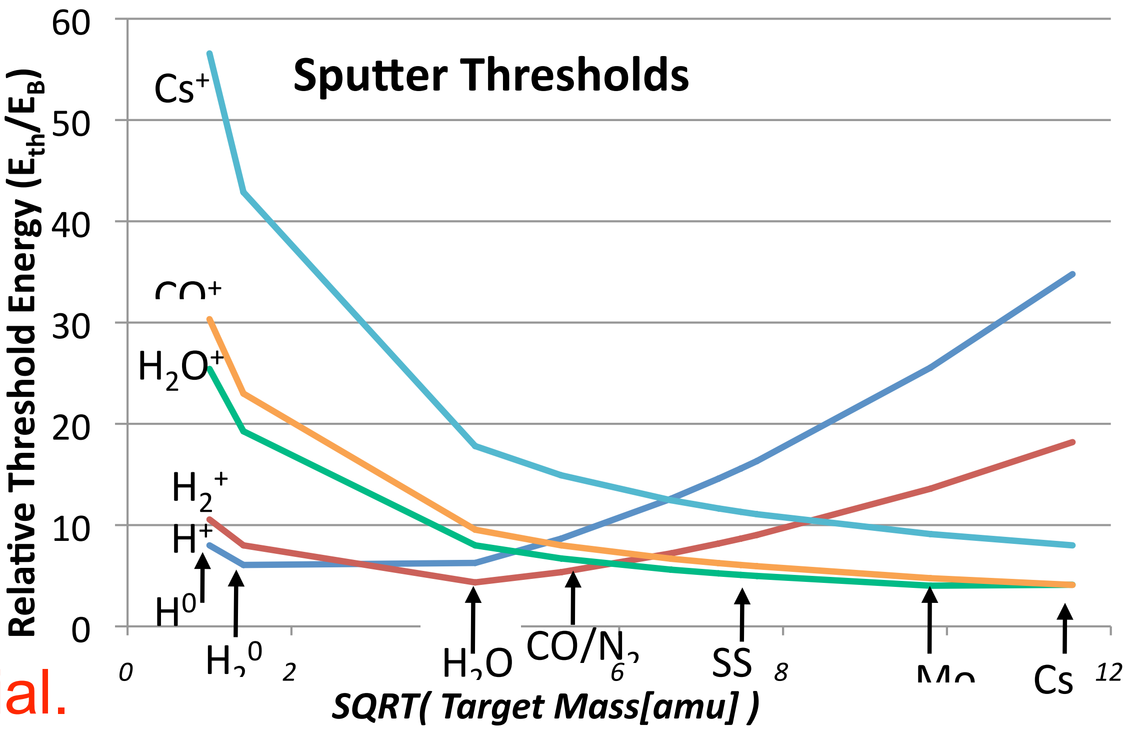
**Sputter rate = $f$((mass ratio $m_i/m_a$) & (ion energy/adsorbate bond strength))**

**Bond strengths are critical in sputtering & thermal emission!**

# Ion-induced Sputtering in cesiated $H^-$ sources

- Highly asymmetric systems have prohibitively high thresholds.
- The smallest threshold of $E_i \approx 4 \cdot E_B$ is found for $m_i \approx m_a/5$.
- Typical bond energies of a few eV require ions with tens of eV for sputtering.

More definite answers shall be obtained by measuring the plasma potential.



Therefore, in cesiated hydrogen plasma

- Hydrogen ions sputter hydrogen atoms and molecules
- Hydrogen ions efficiently sputter water and typical residual gas molecules
- Hydrogen ions are unlikely to sputter adsorbed Cs
- Cs ions sputter adsorbed Cs (in surface plasma sources (SPS))
- When present, moderately heavy ions (air, water) sputter Cs efficiently

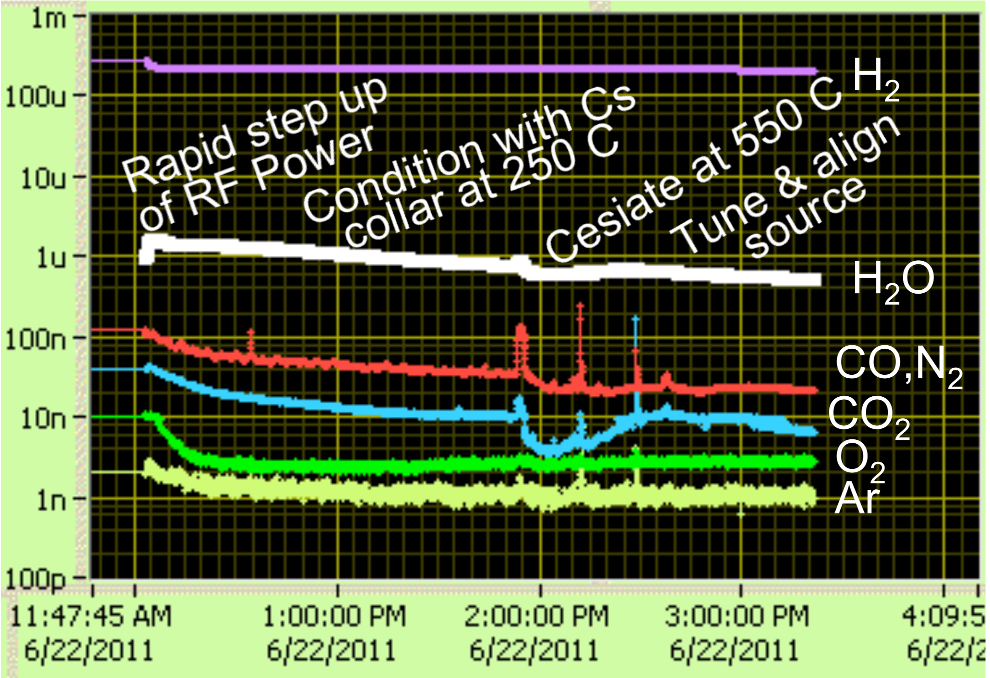
To reduce the Cs sputtering we:

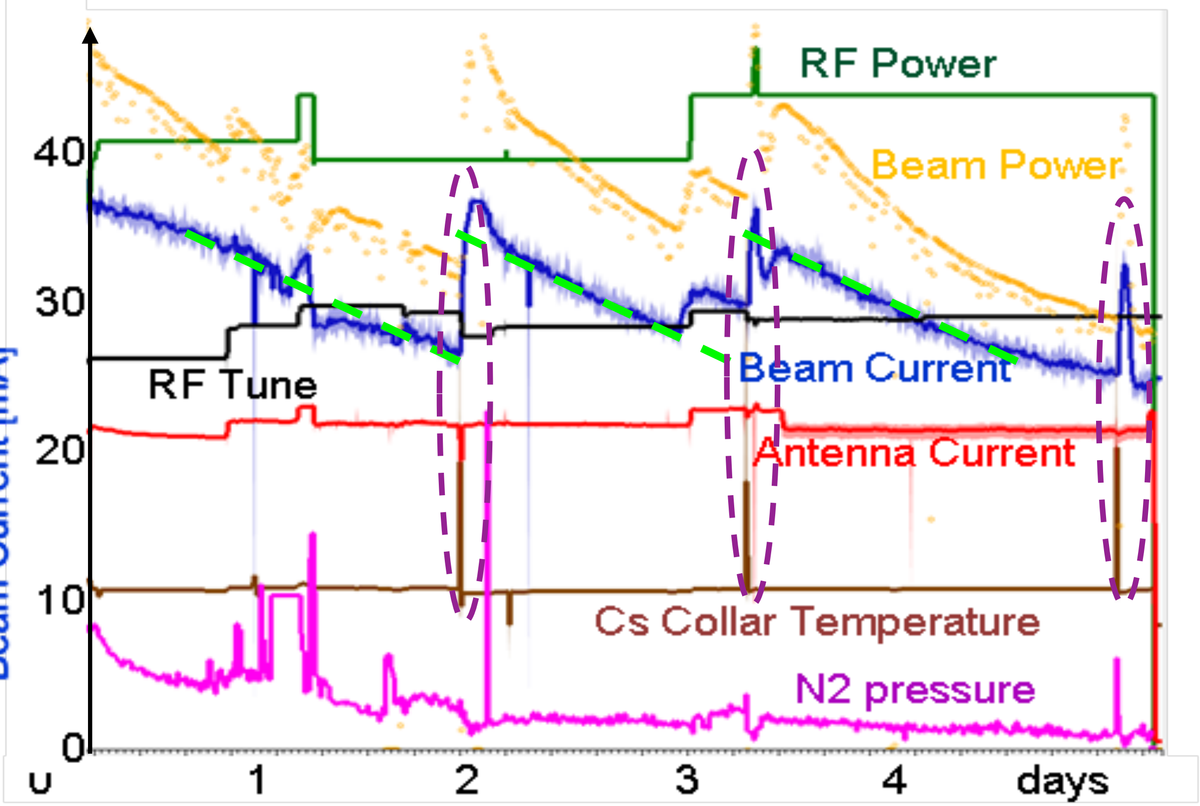
✓Dry the sources with dry air or $N_2$
✓Install with minimum moist air exposure
✓Eliminate all air and water leaks
✓Condition to low residual gas pressures

*The combination of a low plasma potential and high plasma purity can greatly reduce the sputtering of Cs!*

# A Tiny Source Leak!

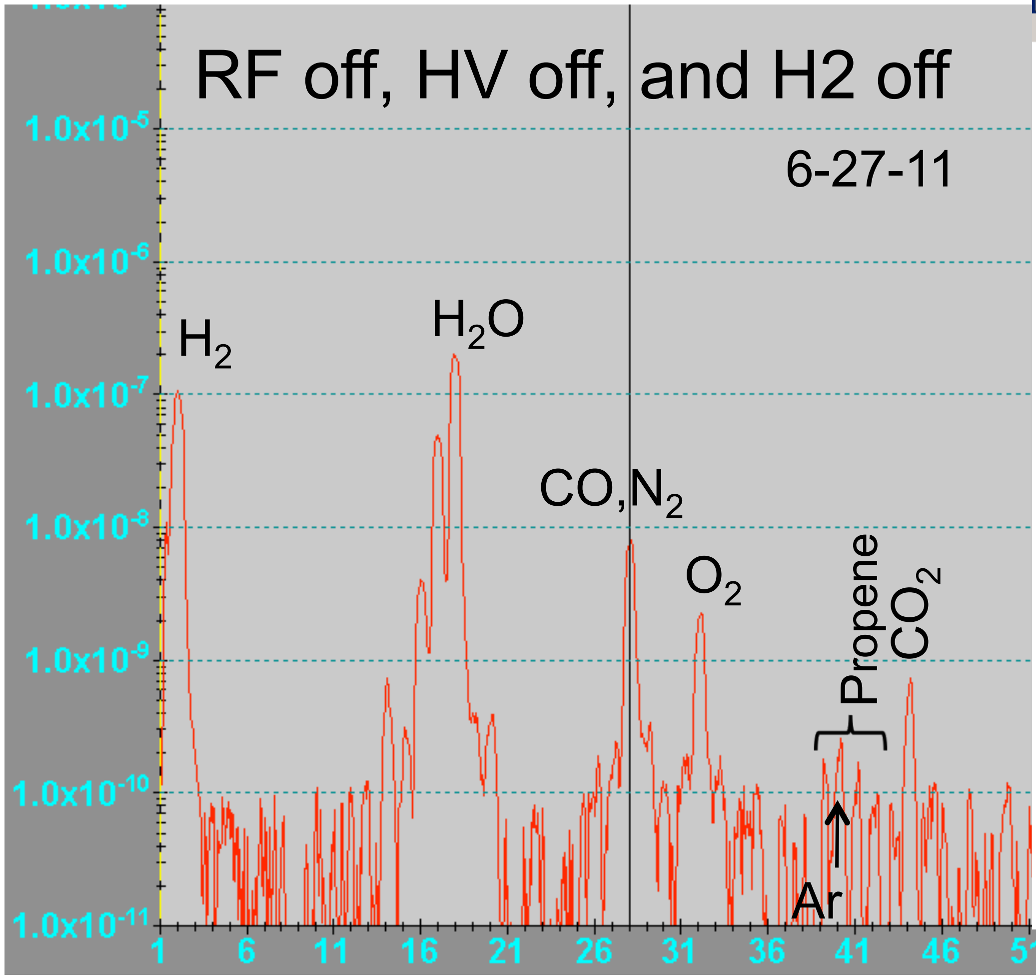
- **June 22, 2011: Source #2 is installed and no leak is found with a He leak check.**
- **A smooth startup lowers all relevant partial pressures rapidly.**
- **Cesiation yields ~36 mA.**
- **However, the beam current decays at a rate between 1-2% per hour.**
- **Two recesiations restore temporarily most of the beam, but the decay continues at a constant rate.**
- **A 3rd recesiation restores some beam within an hour but decays within the next hour to the previous level.**
- **The source has to be replaced on day 5!**

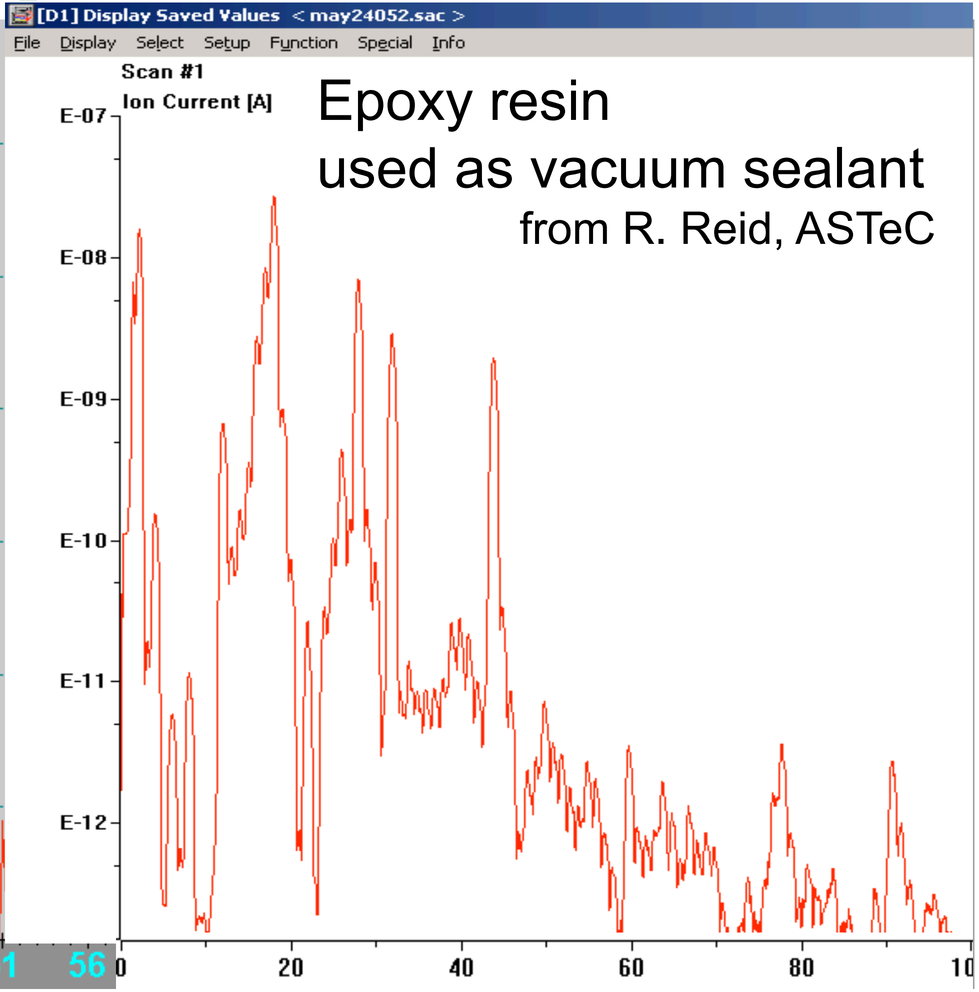




***Let us look at the RGA!***

# The LEBT Vacuum 101





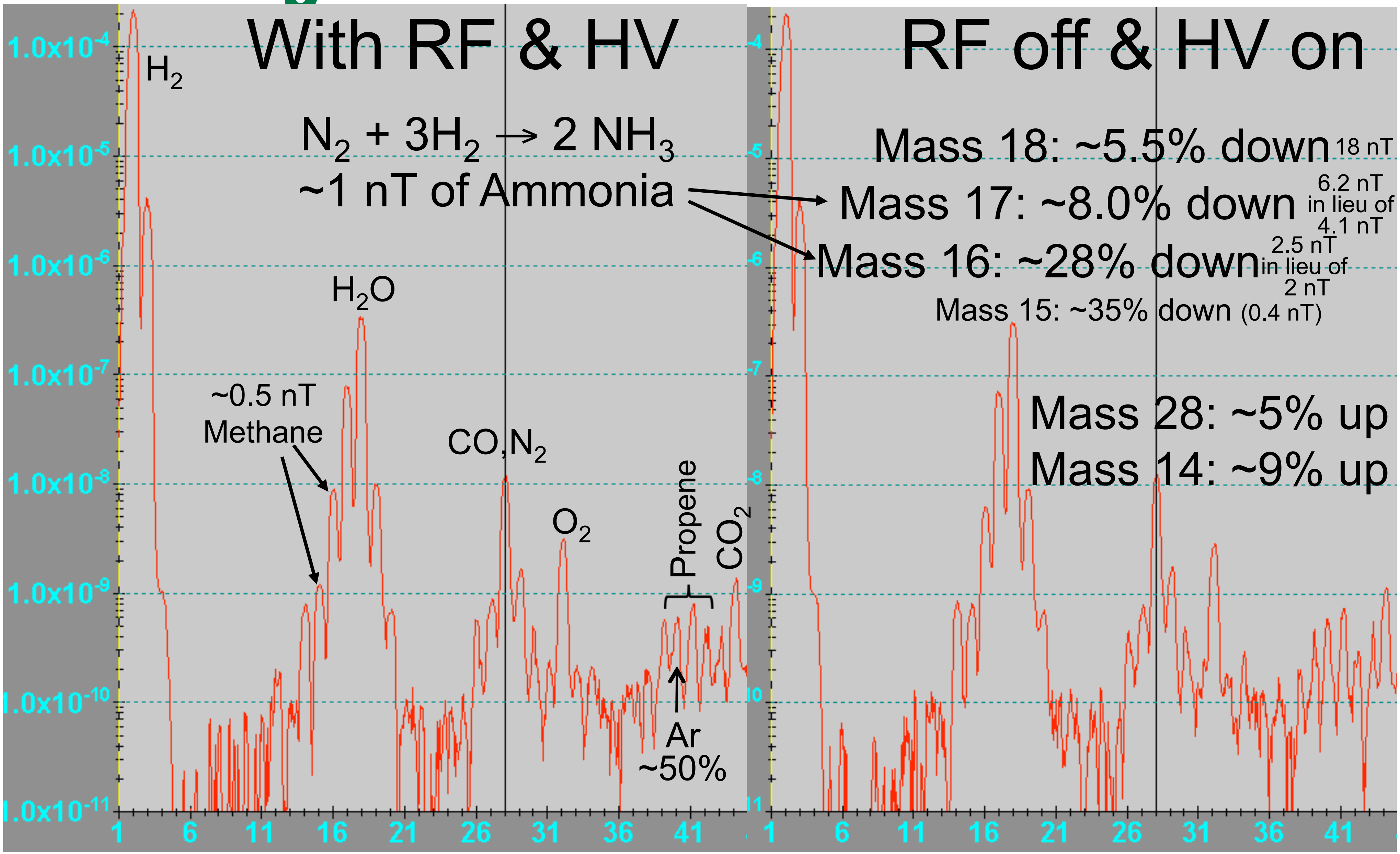
Epoxy resin
used as vacuum sealant
from R. Reid, ASTeC

Looking at the LEBT RGA, air leaks are often suspected due to the high pp of mass 28 and 32.

- However, the LEBT and ion source are thoroughly leak checked before the start of every run.
- Every ion source is leak checked as the 2nd last step in the refurbishment process.
- In addition the ion source and LEBT are leak checked after every ion source installation.

**The SNS 65-kV insulator is made of epoxy, which has a very similar fingerprint!**

# The Staged Shutdown of Source #2!



With RF & HV

RF off & HV on

$H_2$

$N_2 + 3H_2 \rightarrow 2\ NH_3$

~1 nT of Ammonia

$H_2O$

~0.5 nT Methane

CO,$N_2$

$O_2$

Propene

$CO_2$

Ar ~50%

Mass 18: ~5.5% down 18 nT

Mass 17: ~8.0% down 6.2 nT in lieu of 4.1 nT

Mass 16: ~28% down 2.5 nT in lieu of 2 nT

Mass 15: ~35% down (0.4 nT)

Mass 28: ~5% up

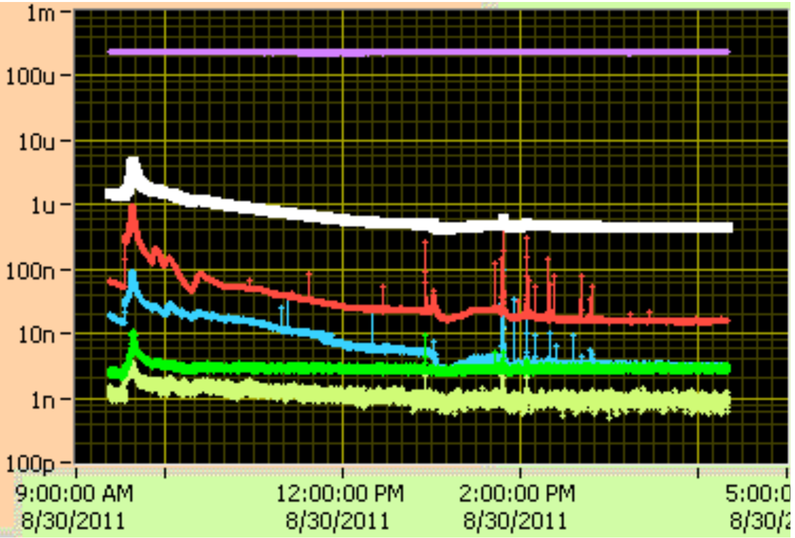
Mass 14: ~9% up

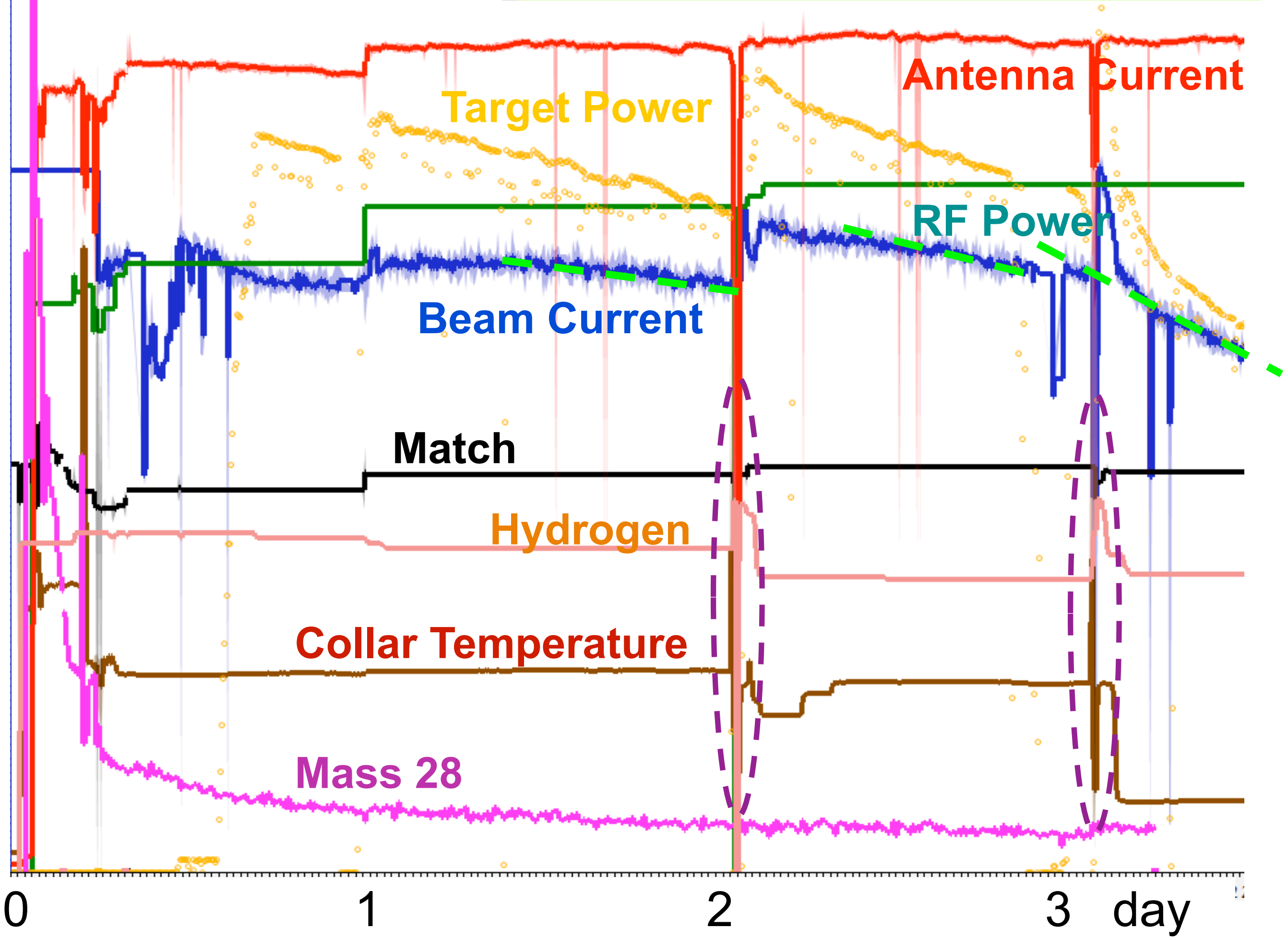
**Barely noticeable, the hydrogen plasma converted a ~$10^{-6}$ air leak into $NH_3$ and $H_2O$!**

**A ~$10^{-10}$ leak in a window increased to ~$10^{-6}$ when being heated by plasma!**

# The first Poisoned Source

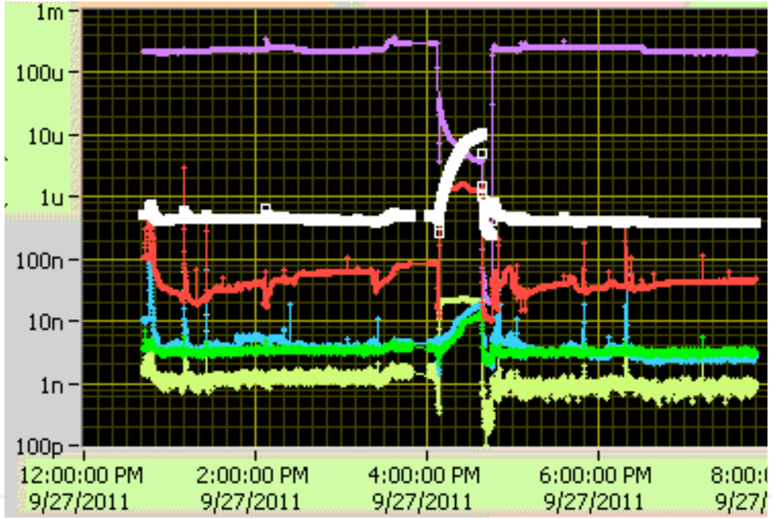
- August 30, 2011: Source #4 is installed and no leak is found with a He leak check.
- A smooth startup lowers all relevant partial pressures rapidly.
- Cesiation yields ~31 mA.
- The beam current decays by 11%/day.
- A 3rd day recesiation raises the beam current by ~15%, and the beam loss to 15%.
- A 4th day recesiation raises the beam current by ~30%, which rapidly decays to the previous level, and then decays with ~45%/day.
- A staged shut down shows RF to produce 2 nT methane
- An extensive leak check finds no relevant leaks.
- The beam loss increasing with each cesiation suggests a poisoned source!
- The source is replaced with source #3, which ran normal.

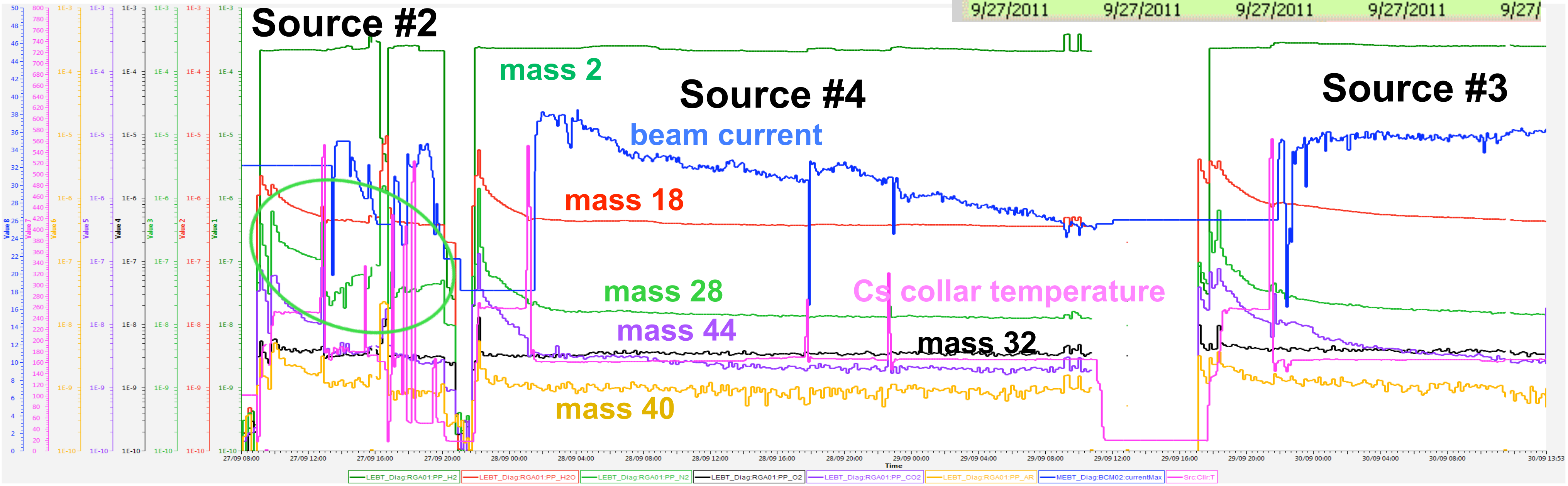




# More Poisoned Sources

- On 9/27/11 source #4 is started up.
- Beam decays with ~20%/hour, while mass 28 & 32 raise. RGA shows CO, $CH_4$ and $C_3H_6$. Recesiations restore the beam, but do not stop the 20%/hour decay.
- In the evening it is replaced with source #4, which repeats its 1%/hour decay performance.





- Two days later source #4 is replaced with source #3, which shows normal persistence.
- Neither aggressive cleaning, nor Ar sputter cleaning eliminates the poison. It gradually fades away over multiple test runs on the test stand. Source #3 is never affected.
- Later, a tear was found in the diaphragm of the fore pump used to evacuate sources for storage. The poisoning was likely caused by microscopic rubber dust.

**Apparently the absence of poison and air enable sputter-free plasma!**

# The Duty Factor and the Scaling of Sources

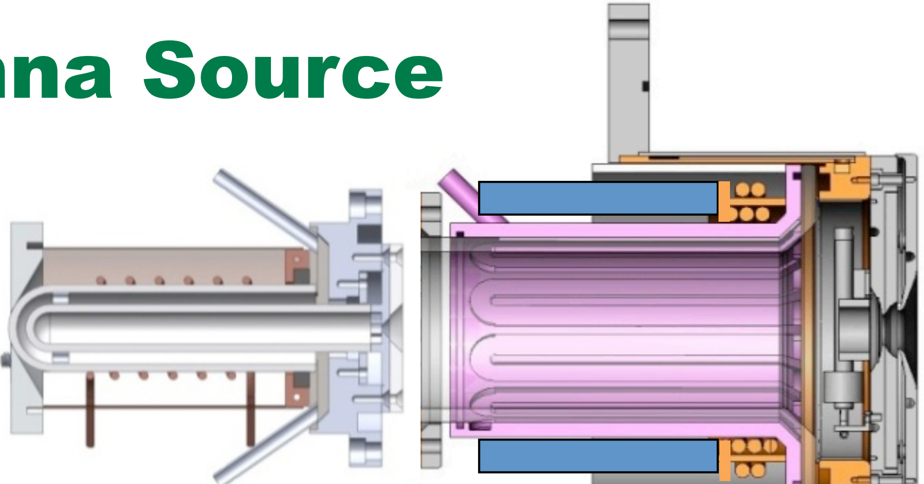
Ion sources are complex and the scaling depends on the process, e.g.:

- Thermal emission depends predominantly on the average temperature, which depends on the average heat load and cooling. However, hard driven, pulsed systems may require modeling because the surface temperature can spike.
- At low power RF antennas are robust. Duty factor is irrelevant for infinite lifetimes.
- For antenna failures, the lifetime should scale with the
  - plasma duty factor when the problem is plasma related
  - rep rate when the problem is caused by turn-on transients
  - source high-voltage duty-factor when the problem is the high-voltage
- For plasma related problems, such as sputtering, scaling with the duty factor can make or break the chances of success. For example
  - Without Cs, the SNS source starts out with ~15 mA. However the beam decays over the next many hours, likely due to the converter being sputter cleaned. At 1 Hz, the beam would persist for days before some loss would be noted!
  - At 60-Hz 1-ms, a 1% loss/hour is evident within a few hours. At 1 Hz it would take more than a week, and at 1Hz & 0.2 ms more than a month before the equivalent loss becomes evident.
  - Consuming 8 or 37 gCs/plasma-day, the SNS source would run out of Cs after 1.7 or 0.4 hours.

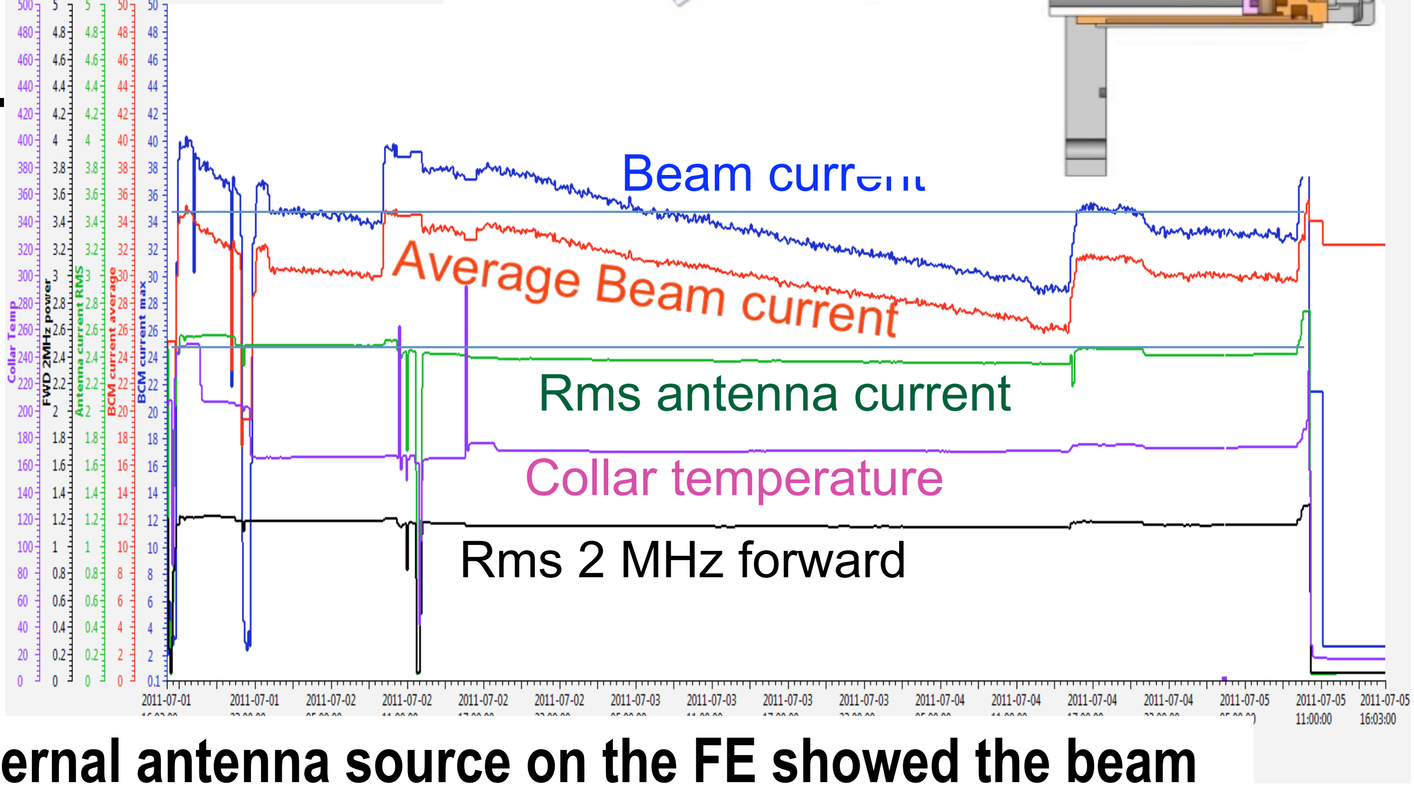
**The Duty-Factor matters!**

# The SNS External Antenna Source

- In 2003 SNS starts developing an external antenna source using the baseline reentrant flange and source outlet.
  In 2006 the $Al_2O_3$ plasma chamber fails twice below the required 6% duty factor.



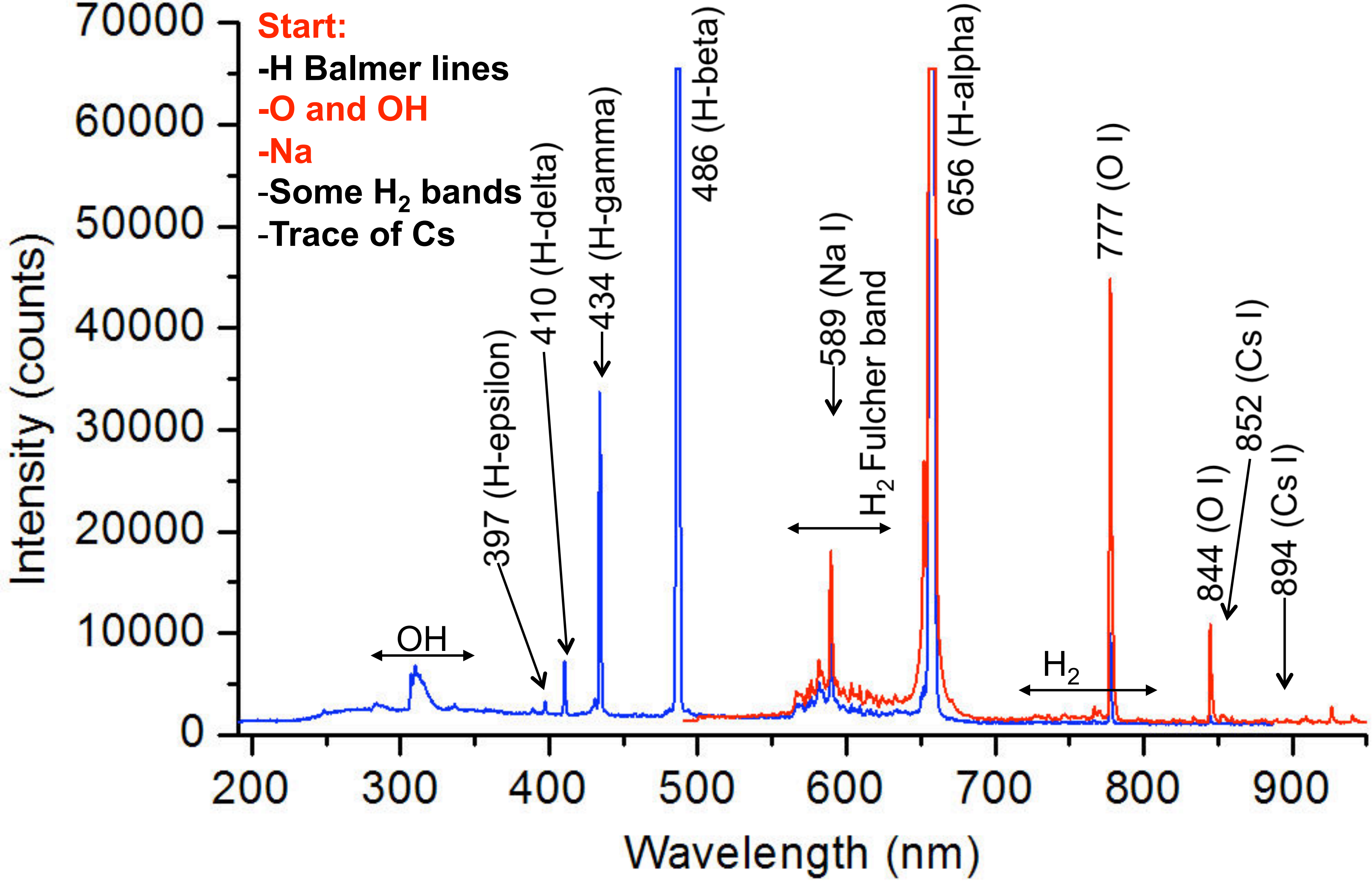
- In 2007 the AlN plasma chamber is introduced.
- In 2008 implemented as production source. This was stopped after 8 weeks due to infant problems and beam decay of ~10%/week.
- Replacing DC plasma gun with a RF gun did not stop beam decay.



- A recent test of our external antenna source on the FE showed the beam to decay, partly due to change in tune, some maybe due to a loss of Cs. The impurities appear to originate from the AlN plasma chamber.

***At 1 Hz, ~10% loss per 60 weeks would not be an issue!***

# Jaz Spectrometer Monitoring the Plasma Purity



**Start:**

**-H Balmer lines**

**-O and OH**

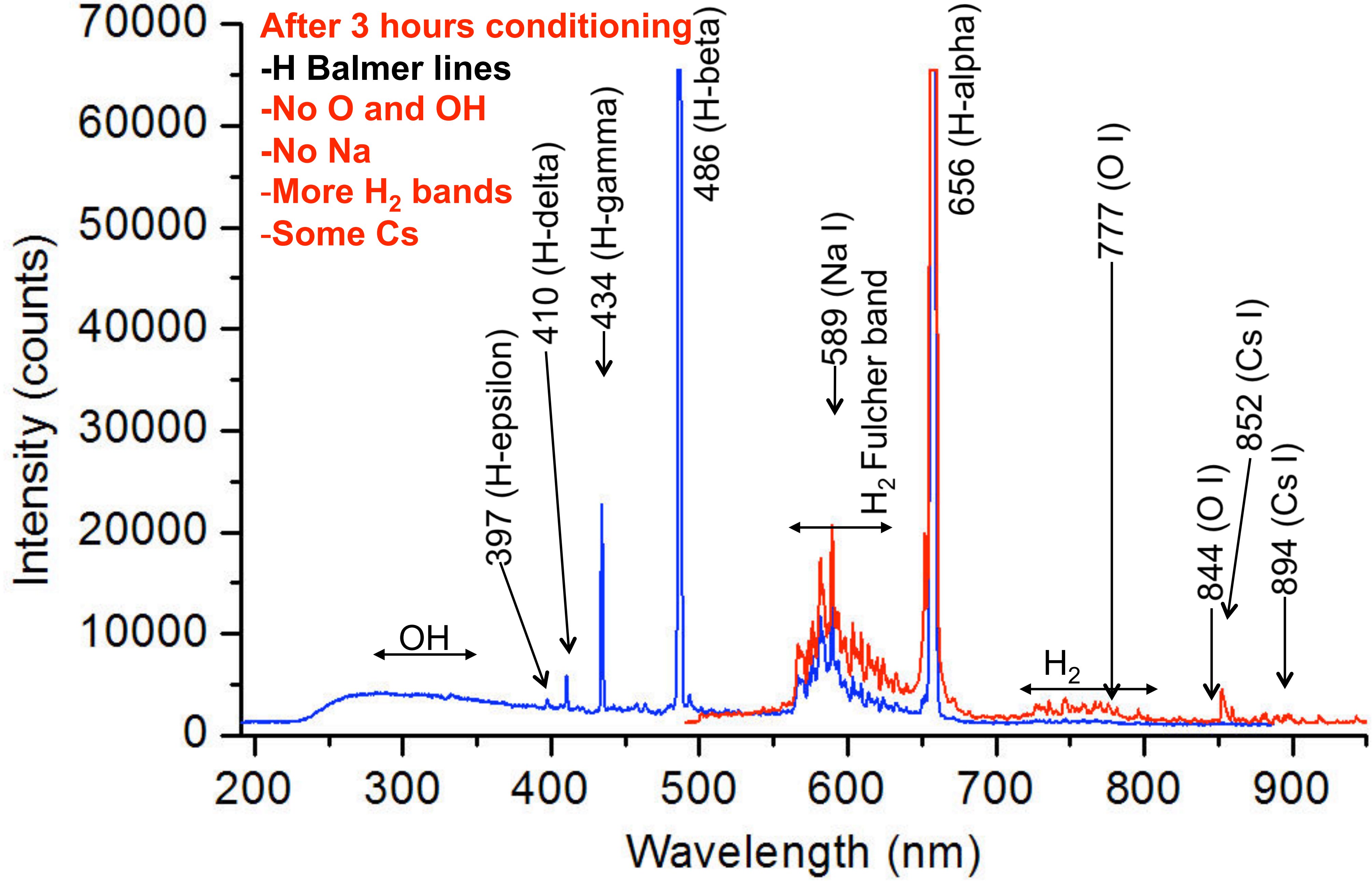
**-Na**

**-Some $H_2$ bands**

**-Trace of Cs**

*The impurities are consistent with $H_2O$ and some antenna sputtering.*

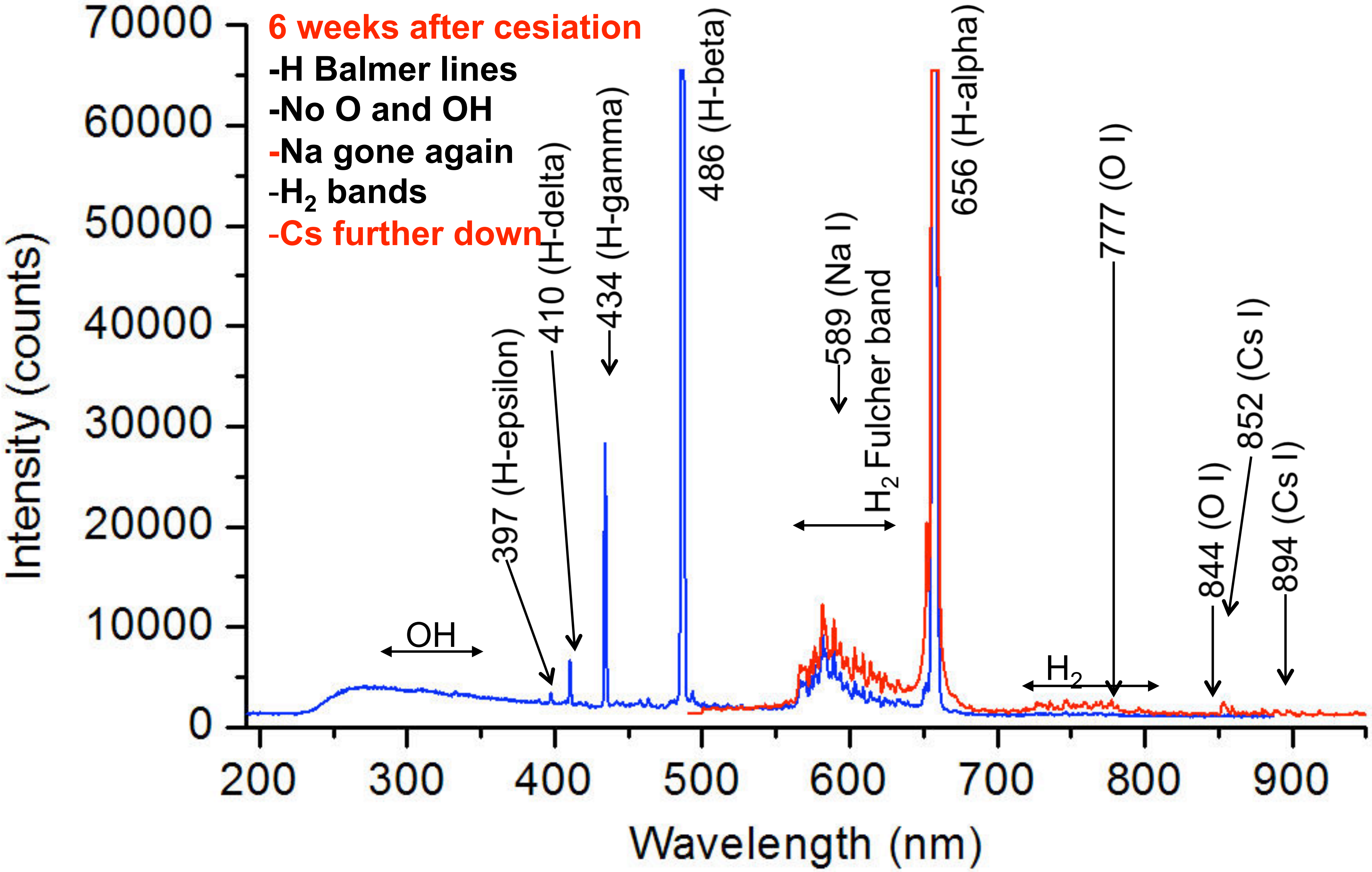
# Jaz Spectrometer Monitoring the Plasma Purity



After 3 hours conditioning
- -H Balmer lines
- -No O and OH
- -No Na
- -More $H_2$ bands
- -Some Cs

*All obvious impurities have disappeared!*

# Jaz Spectrometer Monitoring the Plasma Purity



*Consistent with a high purity hydrogen plasma!*

# Summary and Conclusions

- Mme. Bacal's discovery of volume produced $H^-$ ions 35 years ago started the very successful development of volume sources for negative ions, especially after the introduction of the filter field and multi-cusp confinement.
- Leung's introduction of RF plasma for $H^-$ production was initially very successful at low power. Challenges had be overcome to operate at high power and high duty factor with high availability.
- The external antenna source developed at DESY was very successful at low duty factor, making 40 mA without Cs for years!
- The introduction of Cs 50 years ago by Gennady Dimov, Vadim Dudnikov, and Yury Belchenko had a dramatic impact on the production of negative ions. Leung's introduction of the Cs cartridges was successful at low duty factor.
- Increasing the duty factor frequently poses large challenges!
- Operating the SNS source with a high purity hydrogen plasma has drastically reduced the Cs consumption. This allows for cesiated $H^-$ production at high duty factor without limiting the lifetime.
- The SNS source produces ~10 kC or 2.7 A·hrs of $H^-$ with a single source with the 6-week source cycles without beam decay.

**THANK YOU!** *for your attention!*

# Ion Source Ramp Up for Neutron Production

| Production Run (CY) | Duty factor | Pulse length | mA required | mA in MEBT | RF [kW] | Random Antenna Failures^ | %Availability# | Comments |
|---|---|---|---|---|---|---|---|---|
| 2006-1 | | ~.1 ms | 20 | 28-20 | ~70 | 0 | 99.9 | 1 ion source, 1 cesiation, raise collar temp |
| 2006-2 | 0.2% | ~.25ms | 20 | 30-16 | ~70 | 0 | 99.98 | 1 ion source, 1 cesiation + 24h @115°C |
| 2007-1 | 0.8% | ~0.4ms | 20 | 20-10 | 60-80 | 1*(37) | 70.6 | Arcing LEBT; punctured antenna* after 37 days, start 2-week source cycles |
| 2007-2 | 1.8% | ~0.5ms | 20 | 13-20 | 80 | 0 | 97.2 | Modified lens-2; e-target failures; tune for long pulses |
| 2007-3 | 3.0% | ~0.6ms | 25 | 25-30 | 35-50 | 0 | 99.65 | **modified Cs collar (Mo outlet)** |
| 2008-1 | 3.6% | ~0.6ms | 25/30 | 20-37 | uncal | 1 (6) | 94.9 | Restore matching network; new tube; Beam on LEBT gate valve |
| 2008-2 | 4.0% | 0.69ms | 32 | 32-38 | 48-55 | 1 (9) | 99.22 | Start 3-week source cycles; Ramp up e-dump & collar temperature |
| 2009-1 | 5.0% | 0.8 ms | 35 | 34-38 | ~50 | 2 ExAn<br>+ 1 (8) | 97.52 | Start “Perfect Tune”; use external antenna\$ source for 1st 8 weeks |
| 2009-2 | 5.1% | 0.85ms | 38 | 42-26 | ~55 | 1 (1) | 98.84 | Start replacing LEBT, slim extractor; start 4-week cycles; 2 MHz degrades |
| 2010-1 | 5.4% | 0.9 ms | 38 | 39-30 | ~60 | 1*(11)<br>+1(>4)<br>+1(0) | 96.80 | Repair and tune-up RF; punctured antenna* to beam back in ~6 hours; lens-1 & e-dump breakdowns; |
| 2010-2 | 5.4% | 0.9 ms | 38 | 46-36 | <55 | 2(10)<br>+1(3)<br>+2(0) | ~98.5 | **Replace 1.6 µH with two 1 µH inductors; start 2 MHz on ground** |
| 2011-1 | 5.4%<br>4.4% | 0.9 ms<br>0.73 ms | 38 | 38-30 | ~60 | 1(22)<br>+1(6)<br>+1(2) | 98.2% | Double LEBT pumping; start frequency hopping; 2 source leaks |
| 2011-2 | 4.4%<br>5.3% | 0.73 ms<br>0.88 ms | 38 | 38-30 | ~55 | 1*(>5)<br>1 (9) | 98.7% | *1 antenna fails at beginning of run; contamination of #2 & #4; 6 week run |

^(lifetime of failed antenna)

***Reaching ~50 mA and ~5% duty factor challenged the SNS ion source and LEBT!***