Ion Source and LEBT Performance, Limitations, and Challenges

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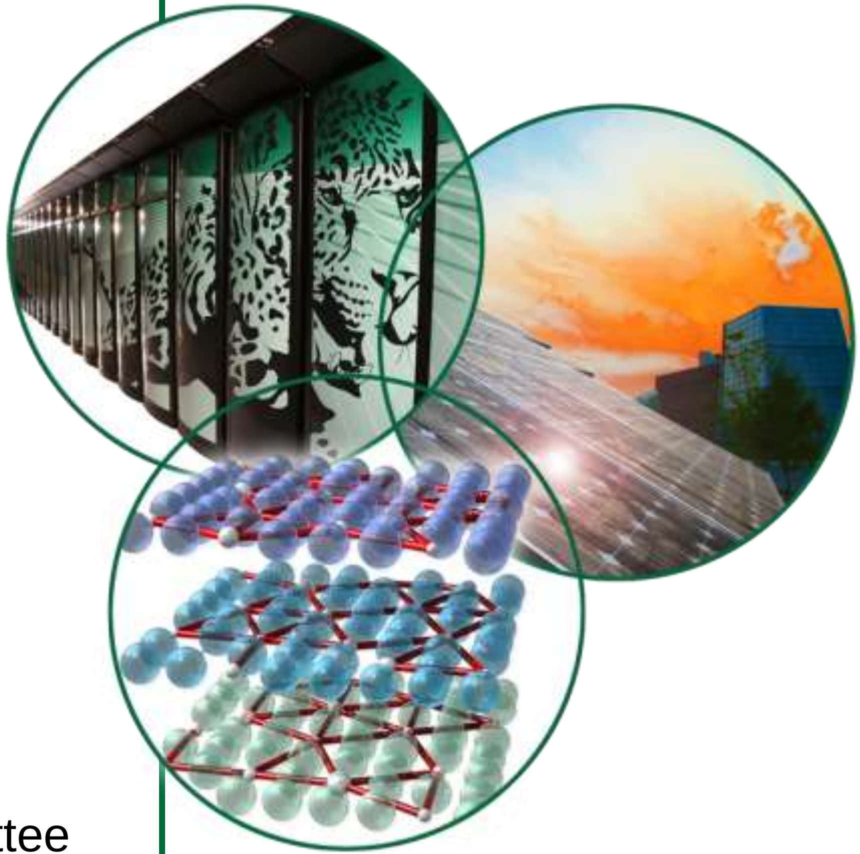

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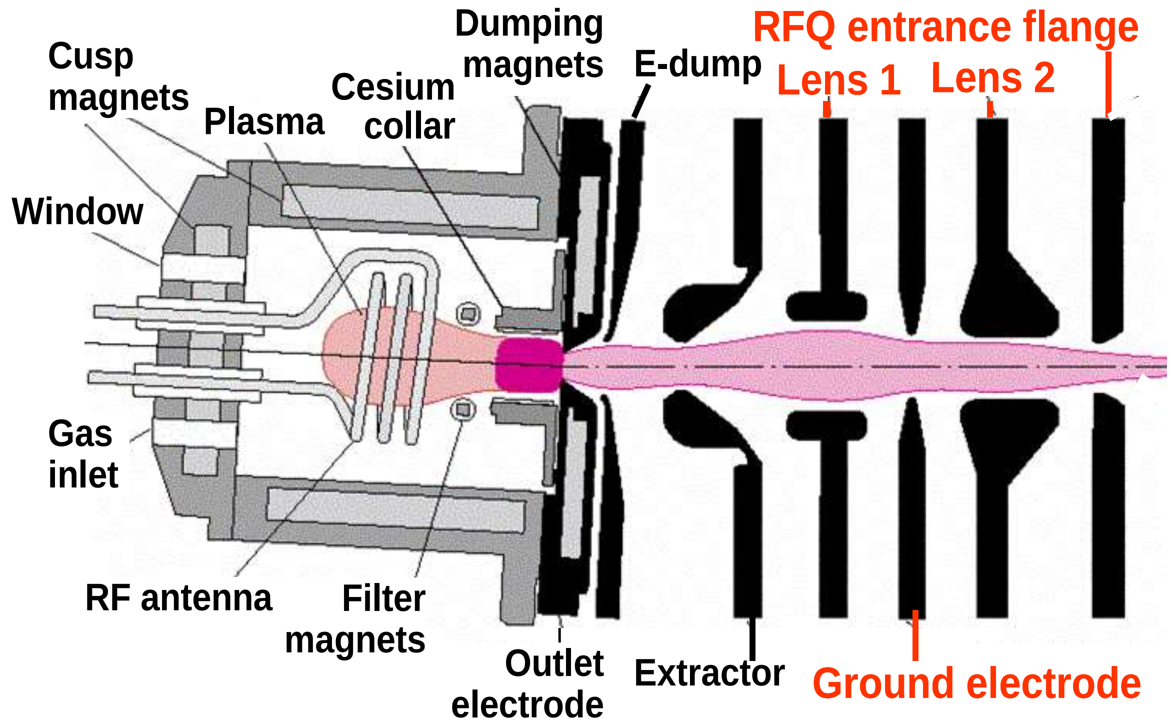

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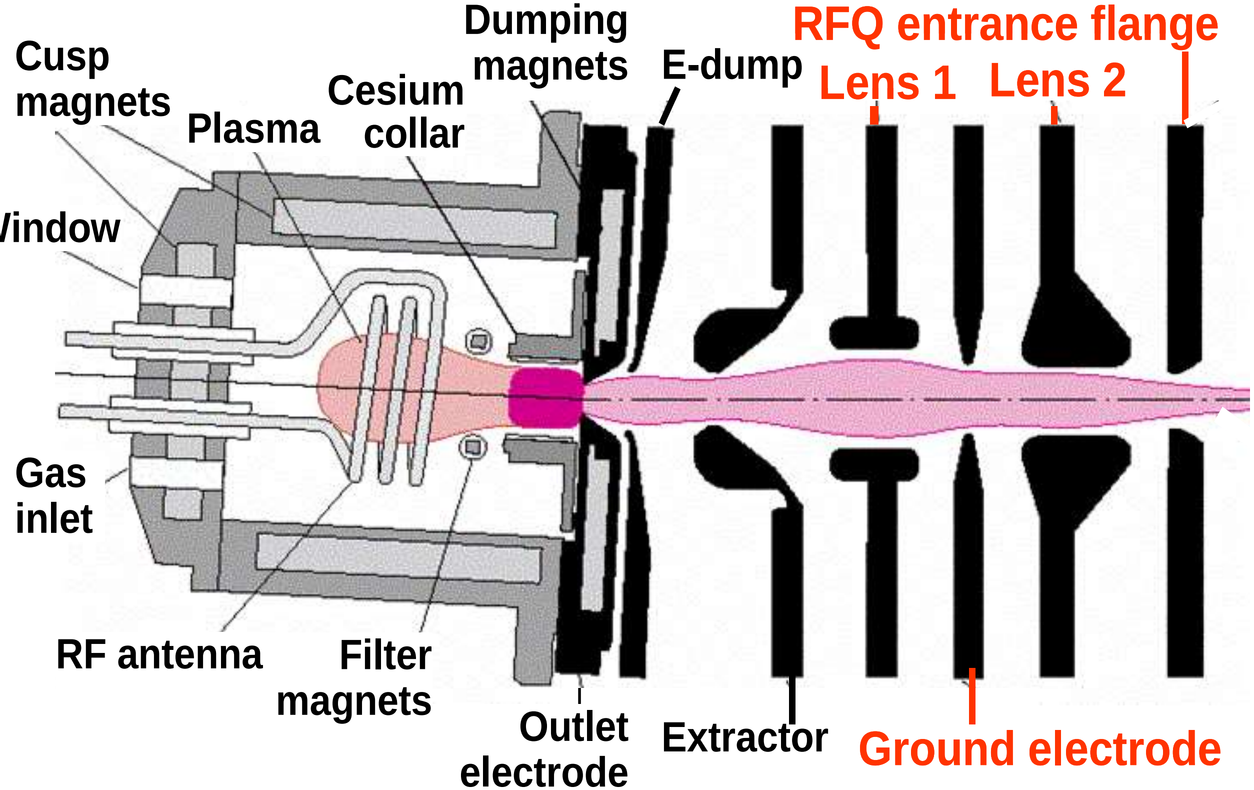
- Overview
- LEBT Performance and Issue Mitigation
- Ion Source Performance and Issue Mitigation
- The Cs Discrepancy
- The Cs Collar Temperature Story II, a Sequel
- Long-Range R&D
- Summary and Conclusions

The SNS Baseline Ion Source and LEBT

- LBNL developed the SNS H^- ion source, a cesium-enhanced, multicusp ion source.
- Typically 250 W from a 600-W, 13-MHz amplifier generates a continuous low-power plasma.
- The high current beam pulses are generated by superimposing 30-70 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 does not allow for any beam characterization in front of the RFQ. The beam current is measured after emerging from the RFQ and practically equals the LINAC beam current.
- This is significantly less beam current than typically emerges from the test stand LEBT when the source is operated with similar parameters.

We may inject 50-80 mA into the RFQ!

SNS Ion Source & LEBT Plan and Performance

Production Run	Duty factor	Pulse length	mA required	mA in MEBT	RF [kW]	%Availability	Comments
FY06-1		~.1 ms	20	28-20	~70	99.9	1 ion source, 1 cesiation, raise collar temp
FY07-1	0.2%	~.25ms	20	30-16	~70	99.98	1 ion source, 1 cesiation + 24h @115°C
FY07-2	0.8%	~0.4ms	20	20-10	60-80	70.6	Arcing LEBT; antenna puncture after 37 days, start 2-week source cycles
FY07-3	1.8%	~0.5ms	20	13-20	80	97.2	Modified lens-2; e-target failures; tune for long pulses
FY08-1	3.0%	~0.6ms	25	25-30	35-50	99.65	Implement Mo Cs collar outlet
FY08-2	3.6%	~0.6ms	25/30	20-37	uncal.	94.9	Restore matching network; new tube; Beam on LEBT gate valve
FY08-3 FY09-1	4.0%	0.69ms	32	32-38	48-55	99.22	Start 3-week source cycles; Ramp up e-dump
FY09-2	5.0%	0.8 ms	35	36-38	~50	97.52	Start "Perfect Tune";remove external antenna source after 8 weeks
FY09-3 FY10-1	5.6%	0.9 ms	38	42-26	50-42	98.84	Pre-align LEBT; start 4-week cycles; slim extractor; RF system deteriorates
FY10-2	6.2%	1.0 ms	38				

The SNS Power Ramp Up Plan is simple:
1) With every run, ramp up pulse length and duty factor - up to 1 ms and 6%.
2) Start with accelerating 20 mA, then ramp by ~4 mA with every run up to 38 mA.
3) Simultaneously ramp up Source & LEBT availability from 95% to 99.54%.

So far the plan has mostly worked, except for a few things that went wrong.

However, all major failures are well understood; mitigations were implemented to make recurrences unlikely.

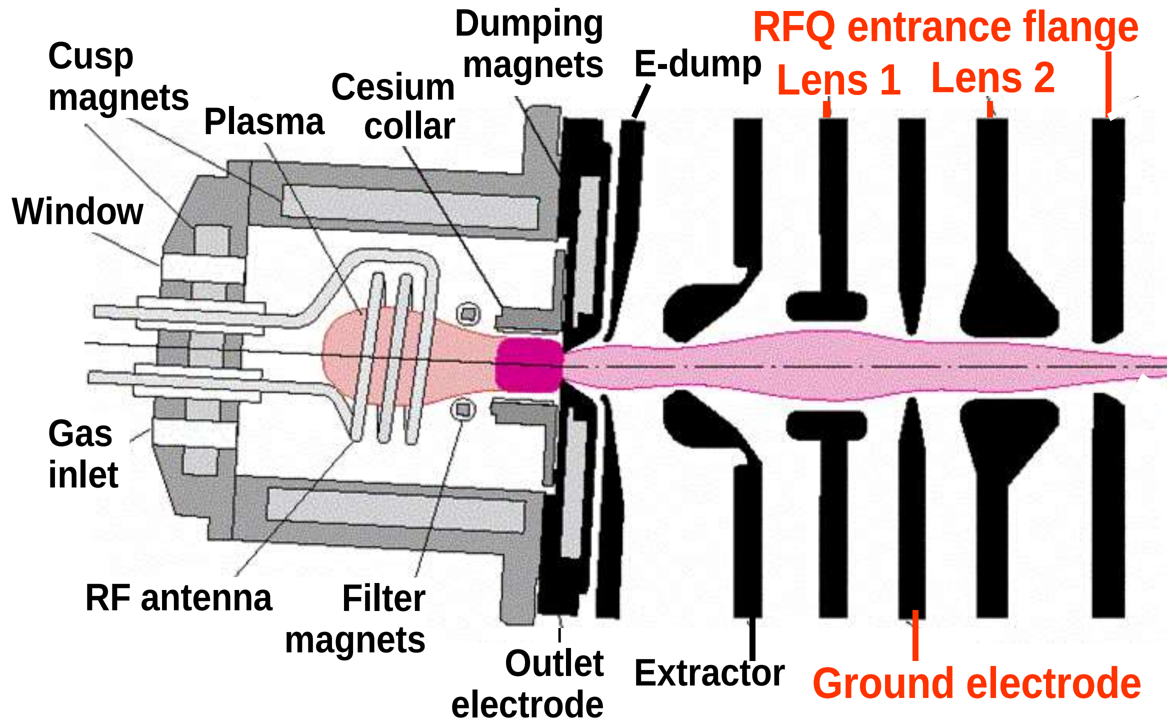
Ion Source and LEBT Improvements since the 2009 AAC review

Availability Upgrades

- Implemented external antenna source (3-3-09)
- Replaced 15 kV tuning capacitor with 18 kV tuning capacitor (3-24-09)
- Replace 1 kV-1 kW P-gun supply with 3 kV-100W supply (3-31-09)
- Install RF power meter (4-6-09)
- Re-implemented modified LBNL source (4-27-09)
- The LEBT feedthroughs were rebuilt with more robust resistor support rods. This reduces the likelihood of bad connections, especially after service or inspections.
- LEBT chopper mixer boxes were reconfigured with “Isolation Products” feedthroughs. This has eliminated the “Dielectric Sciences” feedthroughs, which were prone to breaking and caused significant downtime in summer of 2008.
- All LEBT cables have been replaced with cables featuring terminations for “Isolation Products” feedthroughs. Theses cables are much easier to handle. In addition we have again a configuration, which allows trouble shooting by removing the chopper mixer box out of the circuit.
- Removed horizontal ion source positioning system and produced drawings as built for spare fabrication. Replaced acme screw jacks with new ones, which have less play, especially horizontally.
- Rebuilt test stand 2 MHz transformer to be identical to Frontend. Acquired parts for 3rd transformer.
- 3 different extractors were tested. All LEBTs conditioned to <1 arc/hour in a very few days. Constraints did not allow us to obtain accurate data. The Cu extractor stays the coolest but desires the largest deflection angle, making it most sensitive to changes in the meniscus.
- The baseline 430 SS knob extractor gets warm, with the extractor locally recrystallizing. Melted in the past, but there is overwhelming evidence of abuse. No melting on the Frontend under highly disciplined conditions up to 5.4% duty factor. The slim 430 SS extractor was installed because unidentified LEBT problems were suspected.
- Replaced Frontend OPI control station.

Performance Upgrades

•Install new OPI near Front end for aligning source with extractor.
•Start to run with 0 tilt angle, which yields more beam than 2 or 3°tilt angle (8-28-09)
•No pressure change with 2 vs. 1 scroll pump (No beam gain because of pumping speed limit)



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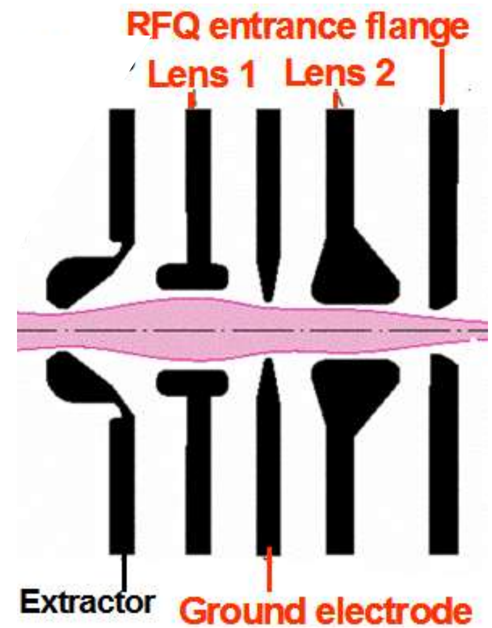
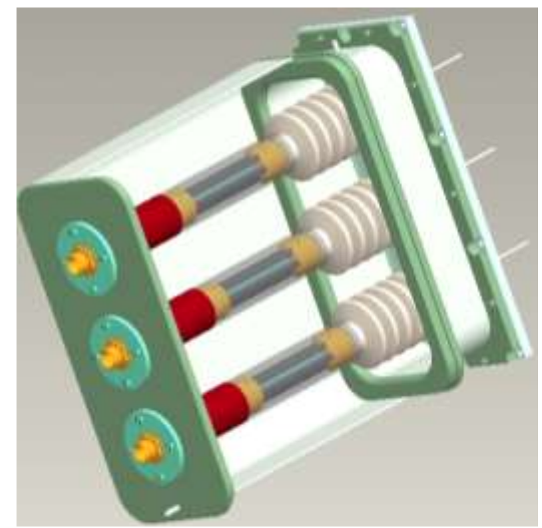
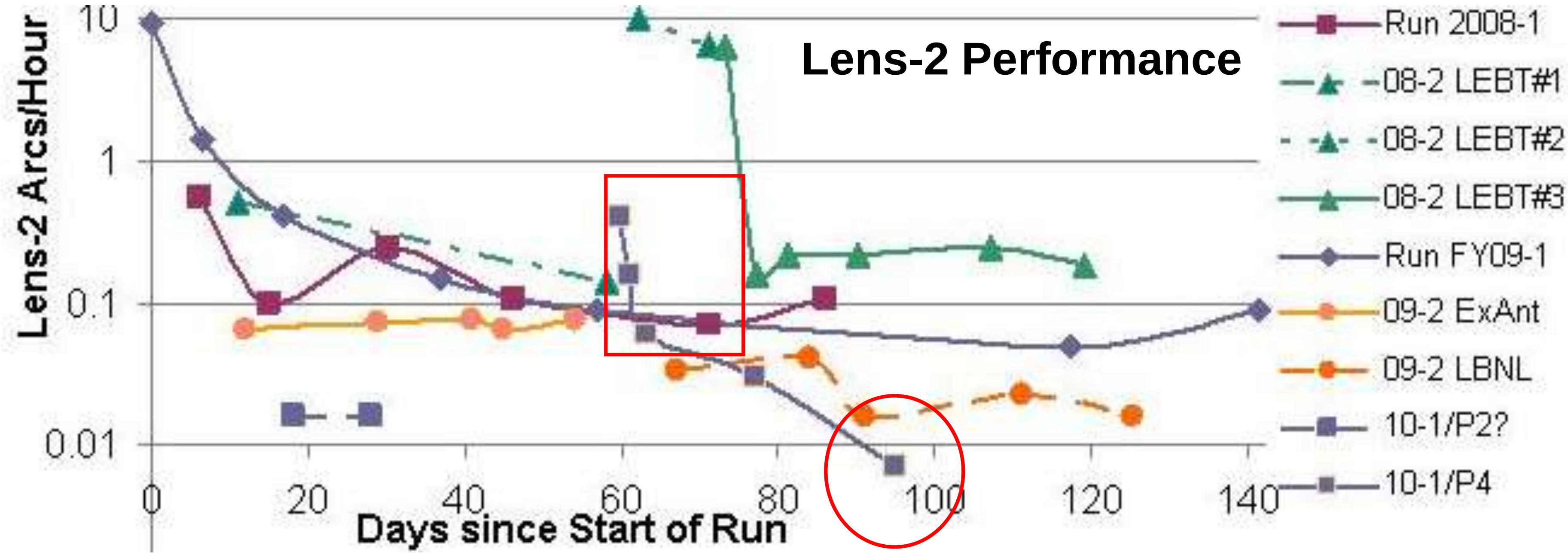
The State of the e-LEBT:

- We continue to control the partial pressure of water with “dry” installations of “dried” spare sources.
- We reduced the cesiation time to 20 minutes.
- Revised procedures eliminated lens-2 arcs during source startups and restarts.
- Optimized pumping and tighter source assemblies lowered the LEBT pressure by ~40%.
- Lens-2 arcs continue to become less frequent.
- The new LEBT feedthroughs work well. Inspections have found NO signs of discharges in the resistor vault.
- All fragile “Dielectric Science” feedthroughs have been replaced with robust “Isolation Products” feedthroughs and more flexible cabels.
- A “slim” extractor has apparently resolved the extractor heating problem.
- We have developed a LEBT maintenance program.
- One spare LEBT is used in the test stand. A ready spare LEBT has been assembled and is stored in the vacuum oven.
- Spare LEBT feedthroughs have been installed on the test stand.





Recent Lens-2 Arcing Issues:



- After running beam into the LEBT gate valve, emergency cleaning and rebuilding lens-2 yielded a poor assembly, causing ~9 arcs/h (Run08-2/#2).
- At the start of run 09-1, it took 10 days for lens-2 to condition to <1 arc/h.
- During run 09-2 the arc rate was always <0.1 arcs/hour.
- Towards end of run 09-2, LEBT was found to be significantly misaligned.
- During run 10-1 raising lens-2 voltage by 1 kV briefly caused 0.4 arcs/hour.
- Run 10-1 ended with 3 arcs during a 18-day period.

Despite a 6-fold duty factor increase, lens-2 arcing improved from ~1 arc per minute in 2007 to ~1 arc per week in 2009.

The new biannual LEBT Maintenance Program:

Our biannual LEBT maintenance is designed to prevent the reoccurrence of all past issues:

1. A refurbished, pre-aligned LEBT is installed early in the maintenance period, which limits the accumulation of alignment errors caused by thermal cycling.

2.The newly installed lens-2 is tested for ~10 kV holding capability between the 4 segments, which checks the precision assembly and assures trouble-free chopping performance.

3.Before the start of the run Lens-2 (at least) **is conditioned to ~60 kV**, which reduces the risk of arcing when lenses have to be pushed to higher voltages. This activity occurs on weekends because during the week the lenses are used to test sources in the MEBT beam stop mode.

This should yield less than 1 arc/day
for all neutron production periods!

Extractor Problem Solved:

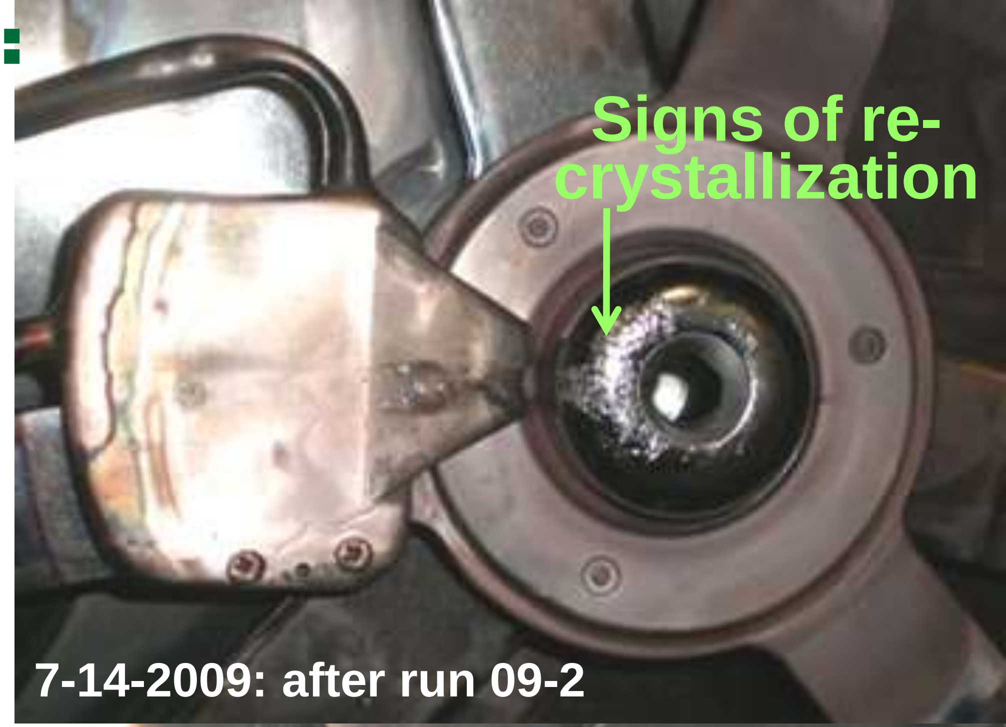
- As discovered in 2001, some of the co-extracted electrons miss the e-dump and hit the extractor or the water-cooled e-target.
- Increasing the duty factor caused the 430 SS extractor to start to overheat and re-crystallize.

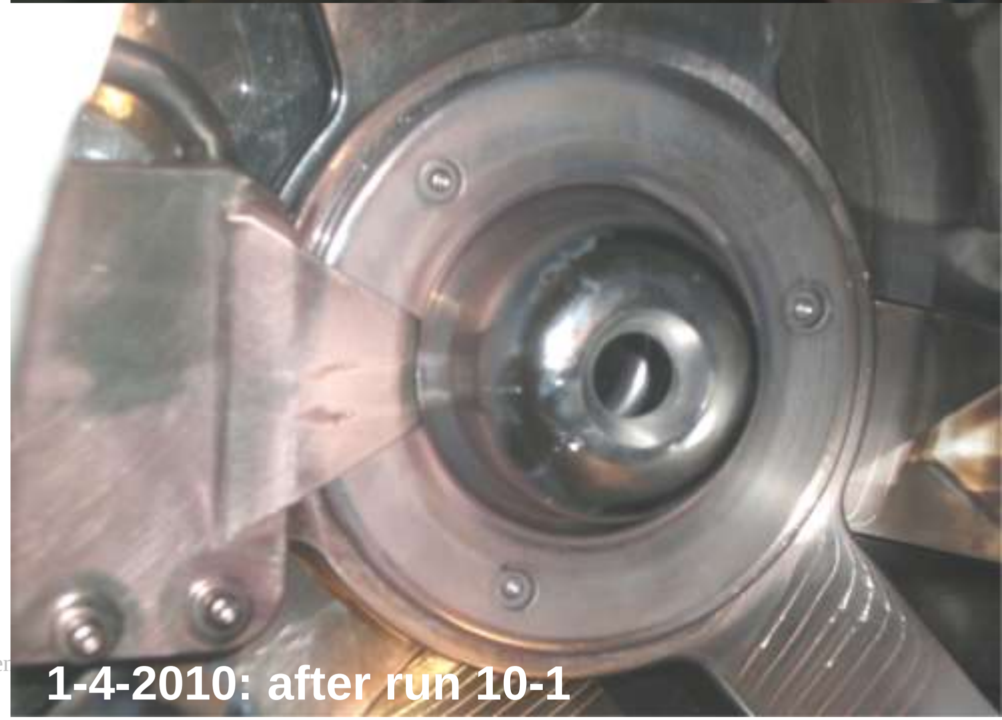
We tested 3 extractors after run 9-02:

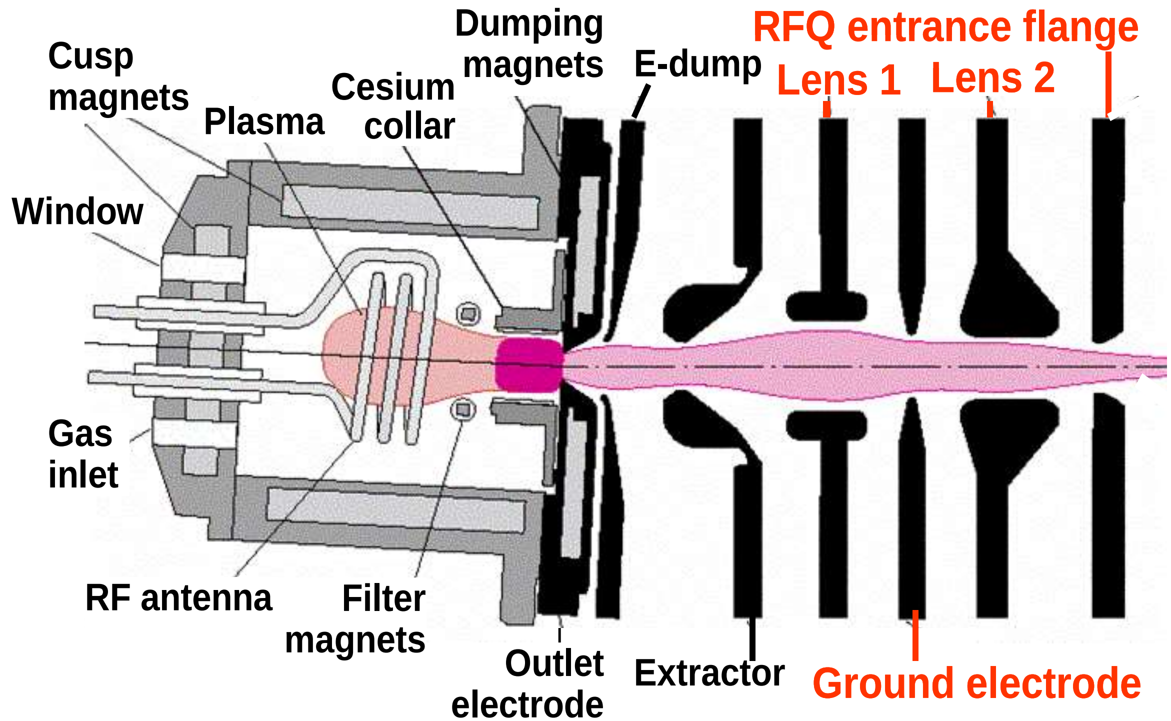
1. Original 430-SS knob extractor
2. A fancy water-cooled Cu extractor
3. A slim 430-SS knob extractor, where a larger radius gave 2 mm more clearance for electrons.

- All worked well for the few-day tests. Concerns about the lack of field clamping let us select the slim extractor, which survived run 10-1 with minimal wear.

Lesson learned: Mitigating discovered problems with minimal solutions minimizes the risk of introducing new problems.







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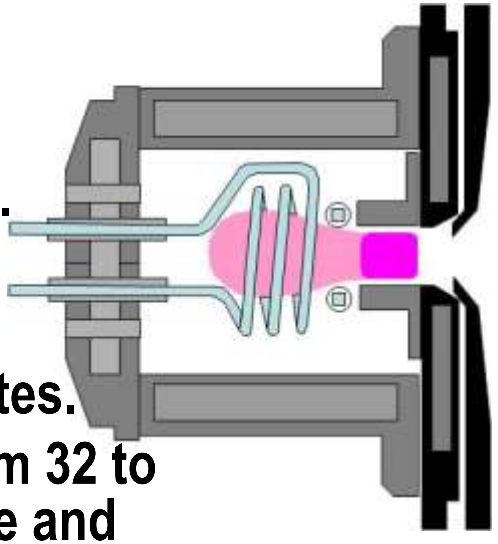
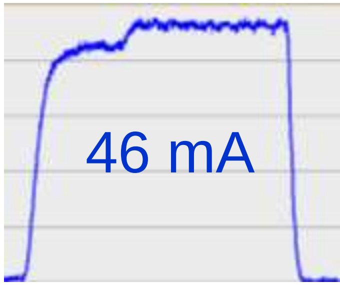
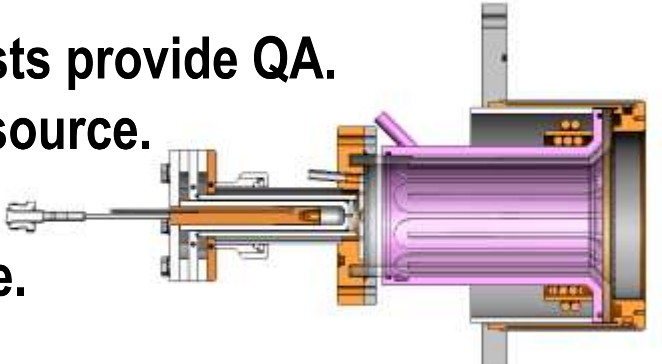
The State of the Ion Source:



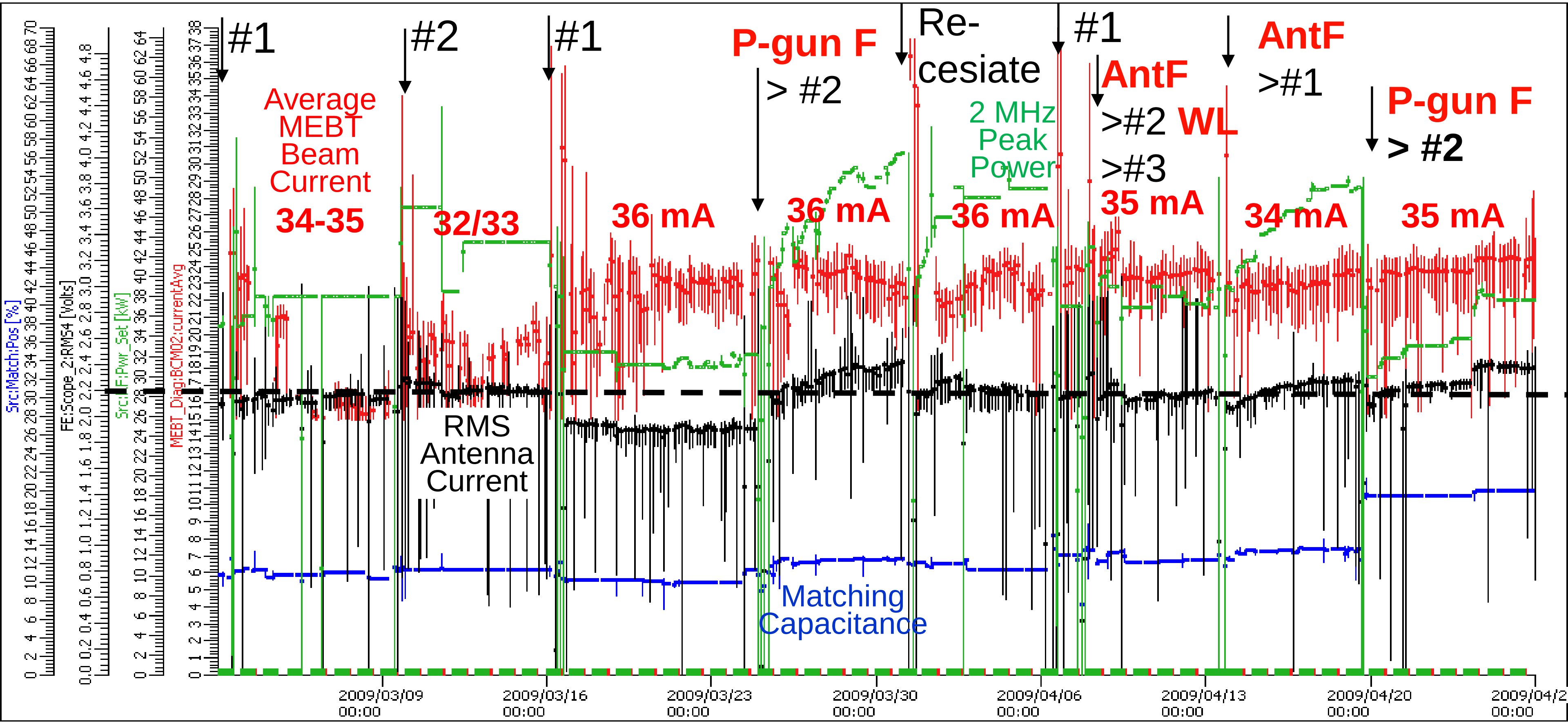
- The source duty factor has been increased from 4 to 5.4%.
- The source lifecycle has been increased from 3 to 4 weeks.
- The source availability remains >99.5% due to one antenna failure per ~20 week run.
- The cesiation period has been reduced from 30 to 20 minutes.
- The "routine" LINAC beam current has been increased from 32 to 38 mA, mainly by capitalizing on the higher e-dump voltage and improved alignments. We have reached the 1.4 MW requirement.
- Tighter source assemblies have lowered H_2 consumption.
- Optimized pumping has reduced the LEBT beam losses by ~30%.
- One 4-week run was executed with 42 mA MEBT beam current.
- 46 mA were demonstrated for 32 hours in the MEBT beam stop.



- The focus was on availability and therefore no attempt was made to break the 56 mA record of 11-2008.
- We have completely proceduralized the ion source refurbishments, replacements and startup. Checklists provide QA.
- We thank LBNL for developing a highly capable H^- source.
- We continue to develop better RF power systems.
- We continue to develop the external antenna source.



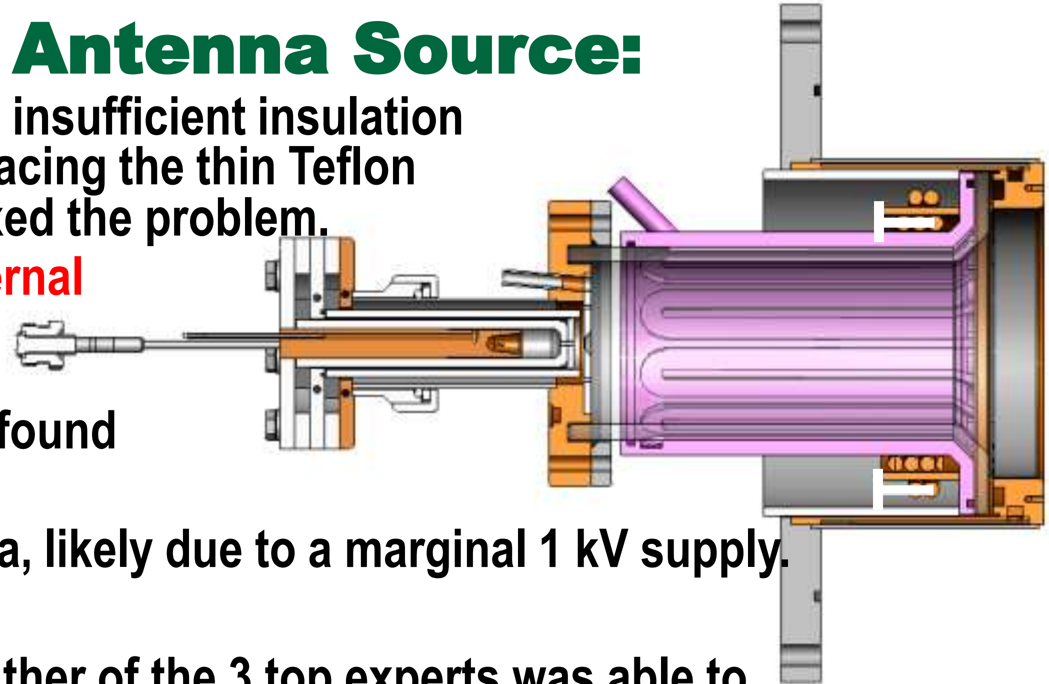
External Antenna Performance: (1st 8 weeks of run 09-2)



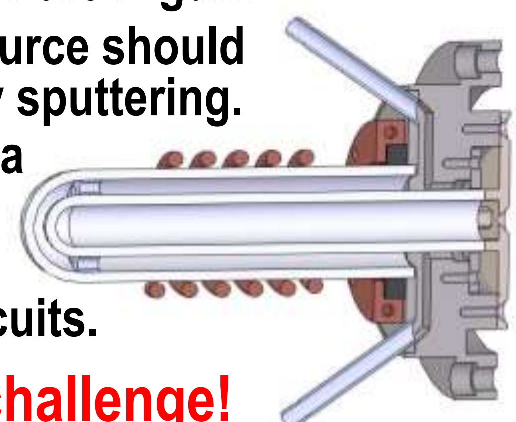
- ➢Run 09-2 started with the external antenna source to improve availability.
- ➢Initially the source was replaced weekly to hone our maintenance skills.
- ➢We learned producing the required 35 mA with minimal antenna current (2.2)
- ➢After trying to increase the service cycle, 2 plasma gun failures, 2 antenna failures and 1 water-leak made us abandoning the effort **(96.6% availability)**.

However, a big concern is the apparent poisoning, which often required a continuous increase of the antenna current.

State of the External Antenna Source:

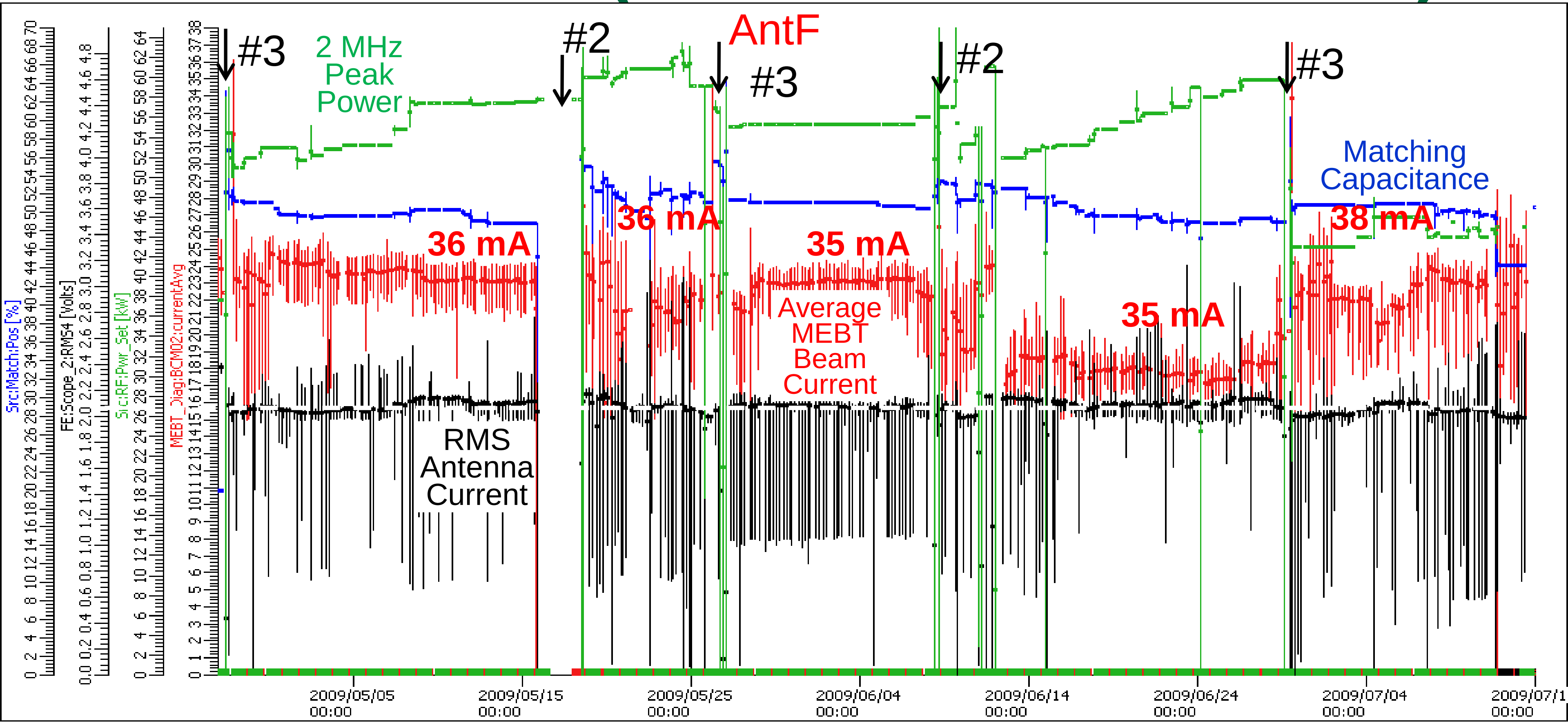


- The antenna failures occurred due to insufficient insulation between the in- and out-tubes. Replacing the thin Teflon sleeve with a T-shaped Teflon ring fixed the problem.
- Shortly before implementing the external antenna source on the Frontend, the cathode of the P-gun was changed from Cu to Mo to reduce the coating found on the plasma chamber wall.
- 3-25-09: P-gun fails to reignite plasma, likely due to a marginal 1 kV supply.
- 3-31-09: Install 3 kV supply.
- 4-19-09: P-gun fails suddenly and neither of the 3 top experts was able to restart it. Source replacement was required. It became clear that we had no data, experience, or understanding of how to run the P-gun for longevity and reliability. Accordingly we re-implemented the modified LBNL source.
- The occasionally observed poisoning is a significant concern because it may require frequent cesiations. The problem may originate from the AlN or the P-gun.
- In any case, the expected longevity of the external antenna source should NOT be compromised by a plasma starter with a life limited by sputtering.
- Driving a continuous 13 MHz plasma through the large antenna requires up to 1 kW power, which raised several issues.
- The ideal solution appears to be an RF plasma gun, which reduces issues due to a complete separation of the two RF circuits.



Proving >99.7% availability will be a challenge!

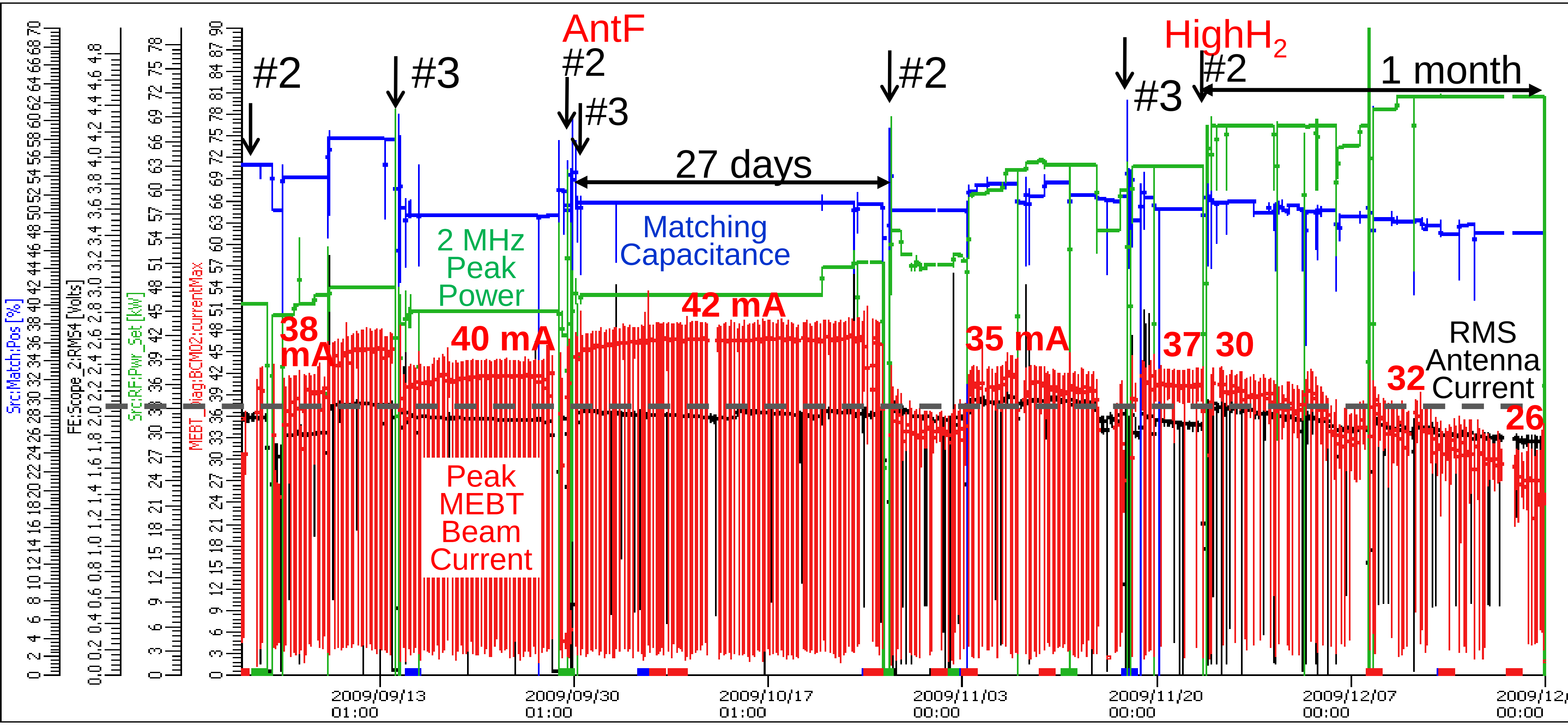
The LBNL source: (last 11 weeks of run 09-2):



- Run 09-2 was finished with the LBNL H- source, which provided the same beam currents with less antenna current, but slightly higher RF power.
- The required antenna was very consistently near 2.1 (~540 A pk-pk).
- The LBNL H- source had one antenna failure, yielding **~99.5% availability**.
- The ion source and LEBT system availability was 98.08%, mainly due to RF amplifier problems. This is below the desired availability of 99% to 99.5%.

We need to improve our RF systems!

The 38mA Challenge of Run 10-1



- ➢Run 10-1 started with finding 0° tilt angles yield more beam than 2.5° or 3°.
- ➢38, 40, and 42 mA met the 38 mA requirement with moderate RF power.
- ➢An antenna failure required the replacement of a source on its 2nd day.
- ➢High H_2 and confusion let to another emergency source replacement!
- ➢On 11-27, 2 MHz trips restricted the beam ~30 mA, and 35 mA a week later.
- ➢Focusing on availability, several limited efforts were undertaken to correct the RF problems. None succeeded. ***We need to improve our RF systems!***

RF System is being fixed and tested.

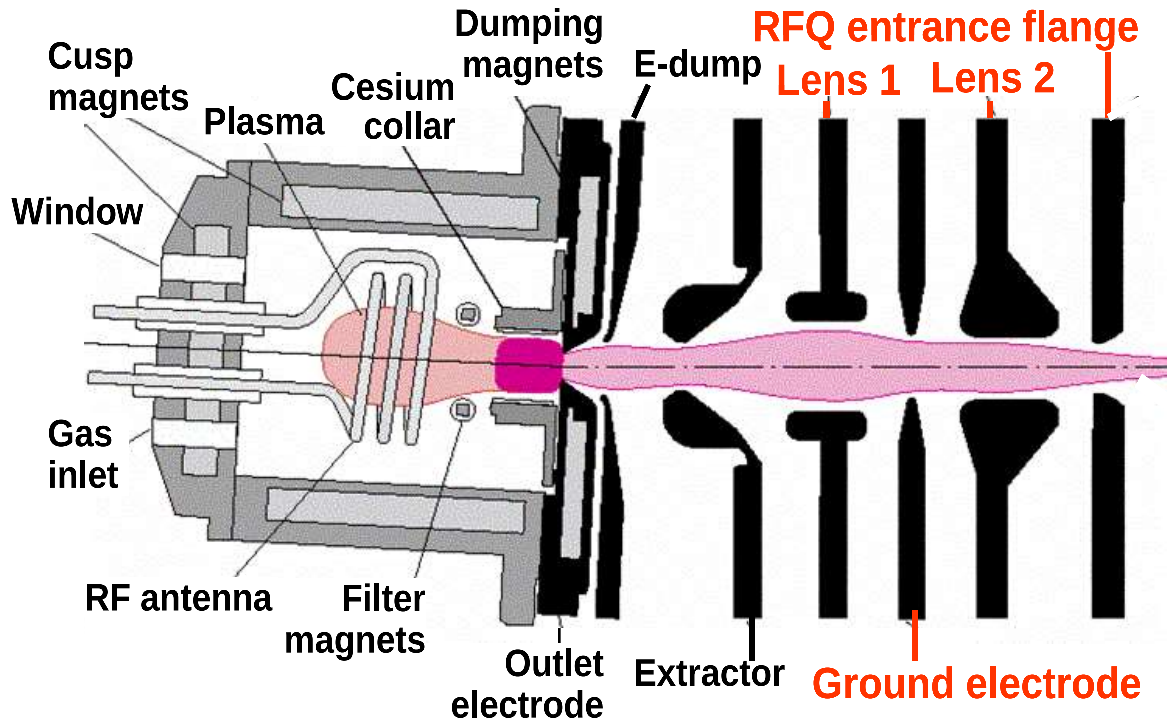
- The secondary loop of the 2 MHz matching network, including its transformer, is owned by the ion source group, advised by the RF group.
- The 2 MHz amplifier system and the primary 2 MHz loop is owned by the RF group, assisted by the ion source group.
- The QEI 2-MHz system is unreliable, cumbersome to access, and difficult to repair. Tuning, testing, and repairing are time consuming and can rarely be guaranteed within an 8 hour maintenance shift.

Focusing on availability, the 2 MHz performance was compromised during run 10-1 until the maintenance period:

- A shorted backup blocking capacitor was replaced.
- A new RF power meter has restricted the airflow to the RF driver since the beginning of the run.
- The tube was marginal and was replaced.
- The amp was tested with matched loads and source plasma.
- We expect that we soon can install a new source and start up the Frontend to show that we can make 38 mA with ~50 kW.

RF System will be improved

- The 2 MHz power level is a critical source diagnostic. Initially we had to rely on scopes on the 65 kV platform, which are difficult to control and read.
- ~1 year ago, Controls gave us an "rms" value of the antenna current. Being archived, it is invaluable. However, the scope's transmission utility has issues.
- The availability of the new 2 MHz power meter has improved, but it may need a better trigger. It will be benchmarked against the antenna current during run 10-2.
- The QEI driver is unreliable and not matched. The plan is for it to be replaced by a properly-matched Ophir driver. Ophir drivers are being used for the Ring RF. The test stand is ready for testing.
- Being on the 65 kV platform, the 2 MHz system is difficult to tune, test, and repair. The RF group has developed a 65 kV 2 MHz transformer. It was successfully tested with plasma without HV. Electrical has prepared the test stand for beam testing with a QEI system on ground. If successful, 2 spares need to be built and we can start planning the implementation of 2 RF systems near the Frontend.
- 2x60-kW, solid-state Tomco amplifiers will be tested after the QEI tests.
- Frequency shifting between breakdown and beam production will be addressed after 2 MHz system is on ground.



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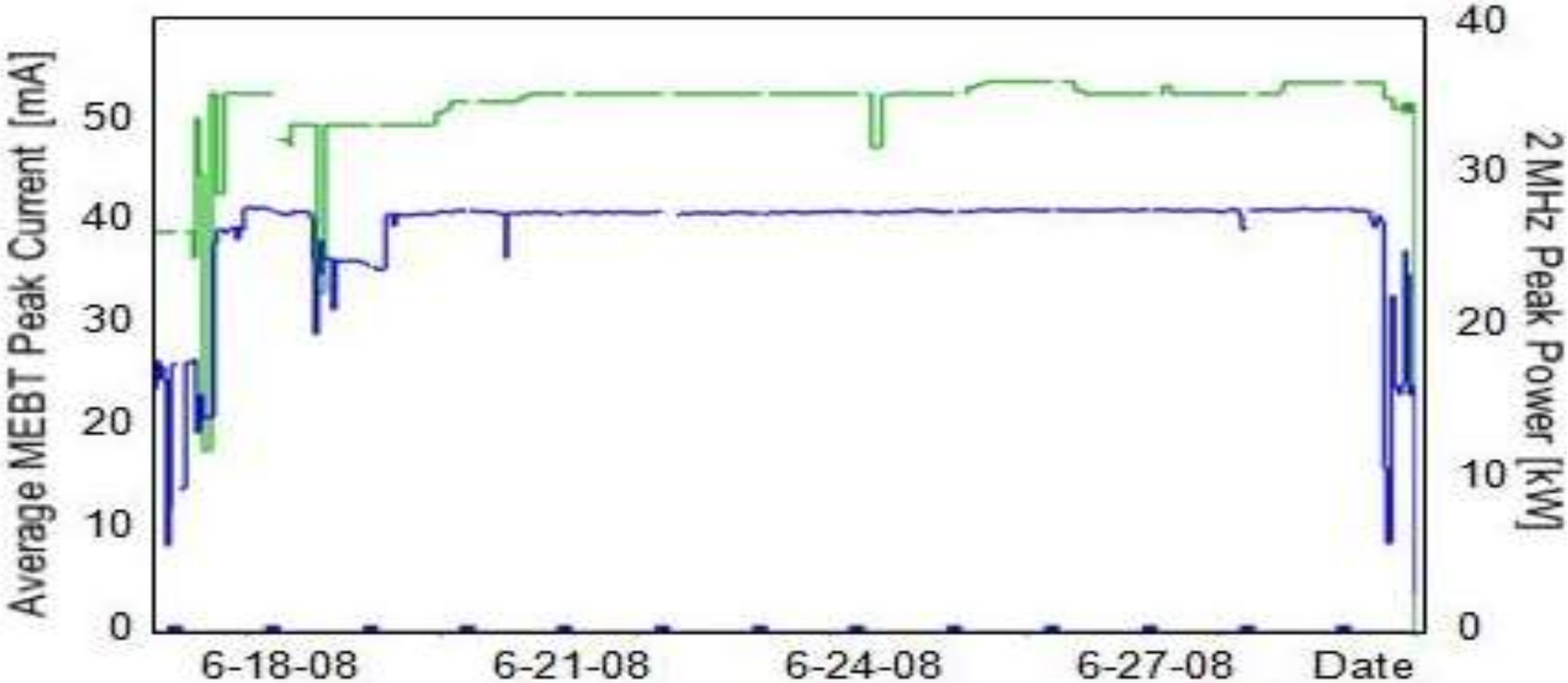
The Cs Discrepancy

- To maintain the H$^-$ beam current H- sources require a steady flux of Cs (~1 mg/h for magnetrons, ~10 mg/h for Penning).



- With the modified LBNL source we normally observe nearly perfect beam persistence, meaning the beam current remains approximately constant without drastically increasing the RF power and without adding Cs.

Why do we NOT need a steady flux of Cs?

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.

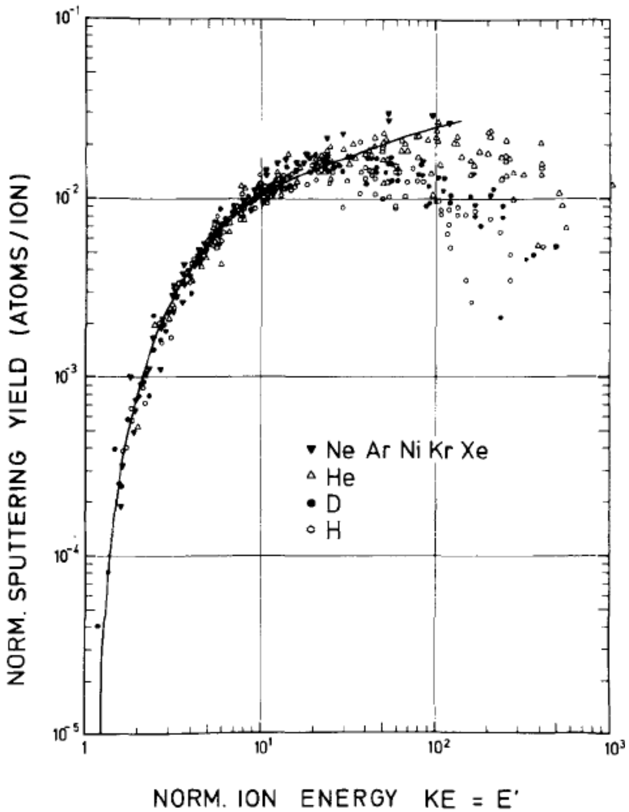


FIG. 1. Normalized yield data as a function of $E' = K E$. The solid line represents Eq. (4).

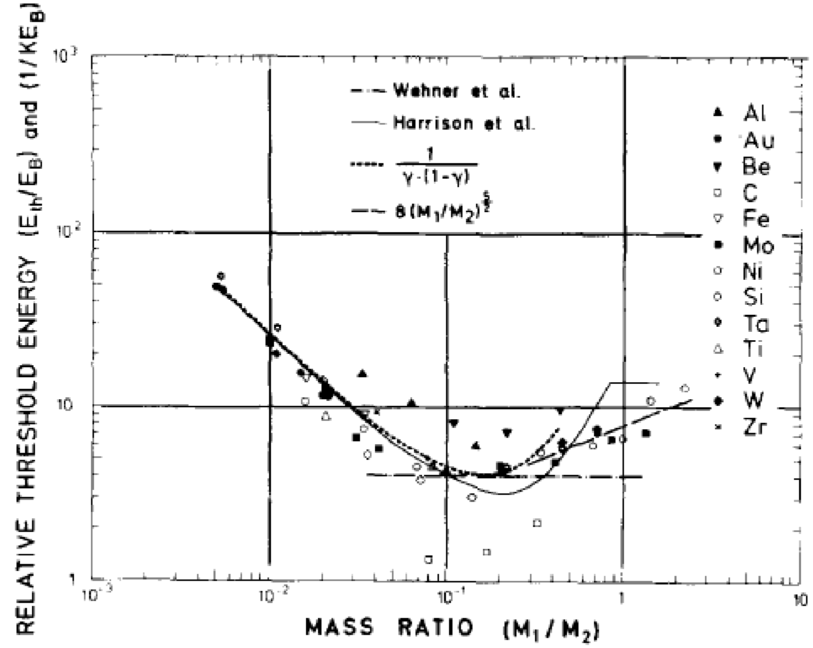


FIG. 2. Comparison of different relative threshold energies with the experimental data (----,— — — analytical fit, this work;— Ref. 10; – · – · – Ref. 14).

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

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

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

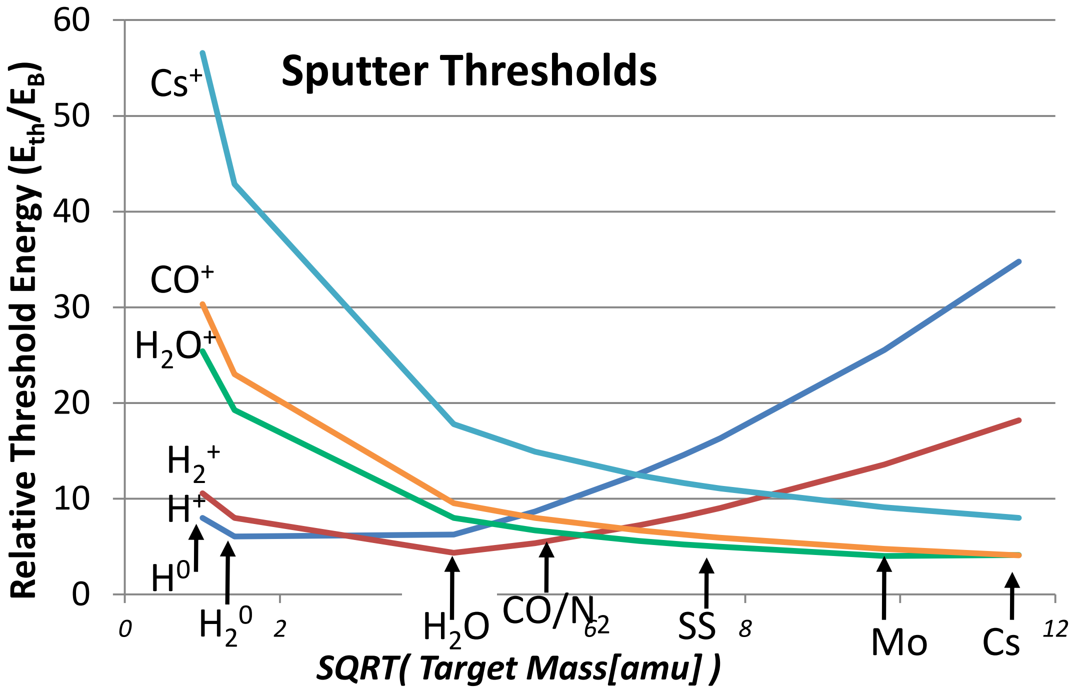
$$\text{with } \gamma = 4 \cdot m_i \cdot m_a/(m_i+m_a)^2$$

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

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

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 $m_i \approx m_a/10$.
- Typical bond energies of a few eV require ions with tens of eV for sputtering. More definite answers will be obtained after measuring the plasma potential.



Therefore, in cesiated hydrogen plasma

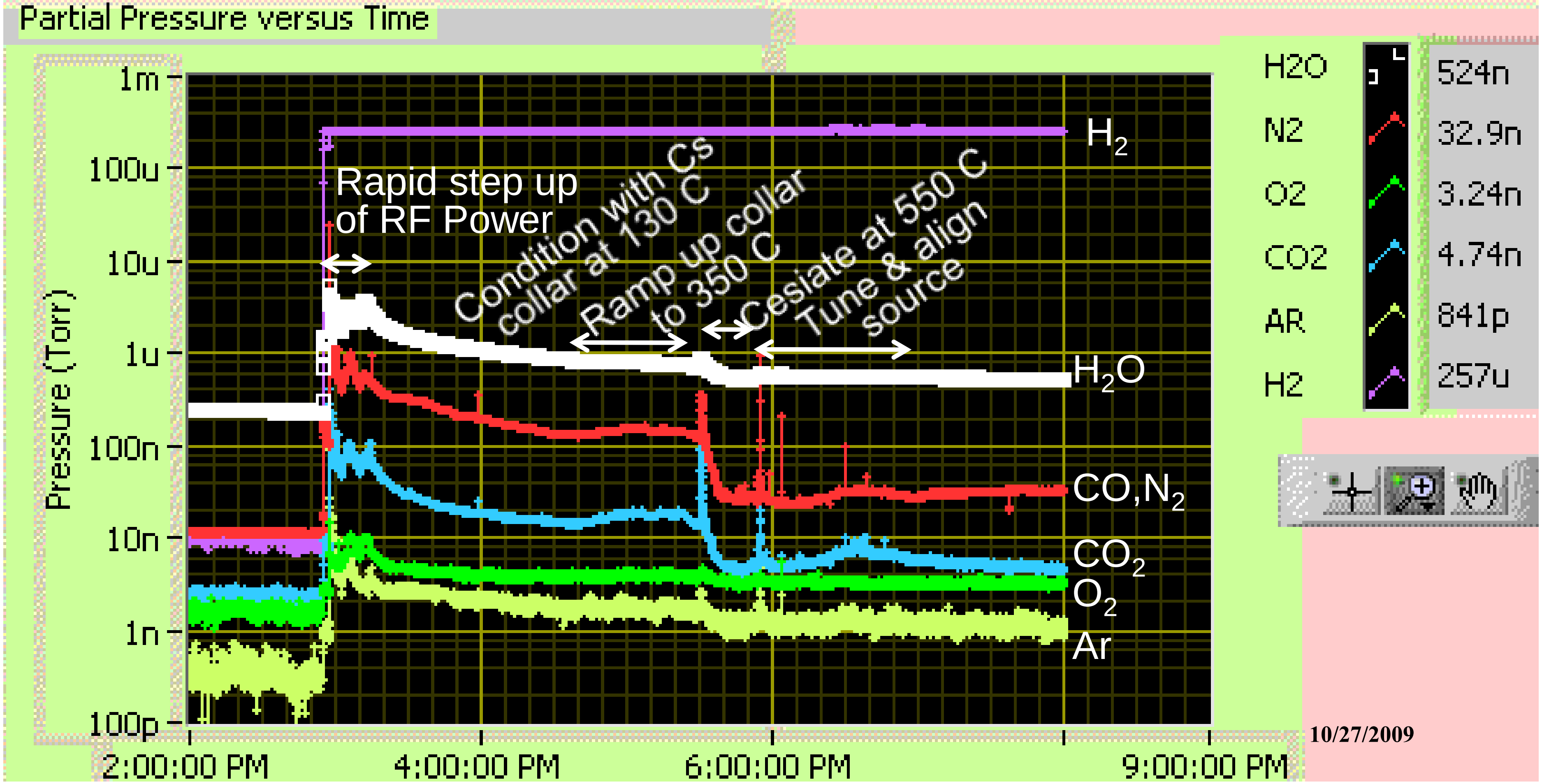
- Hydrogen ions sputter hydrogen atoms and molecules
- Hydrogen ions efficiently sputter water and typical residual gas molecules
- Hydrogen ions are unlikely to sputter adsorbed Cs
- Cs ions sputter adsorbed Cs (in surface plasma sources (SPS))
- When present, moderately heavy ions (air, water) sputter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

Minimizing heavy (Cs) and moderately heavy plasma impurities minimizes the sputtering of the Cs!

To reduce the Cs sputtering we:

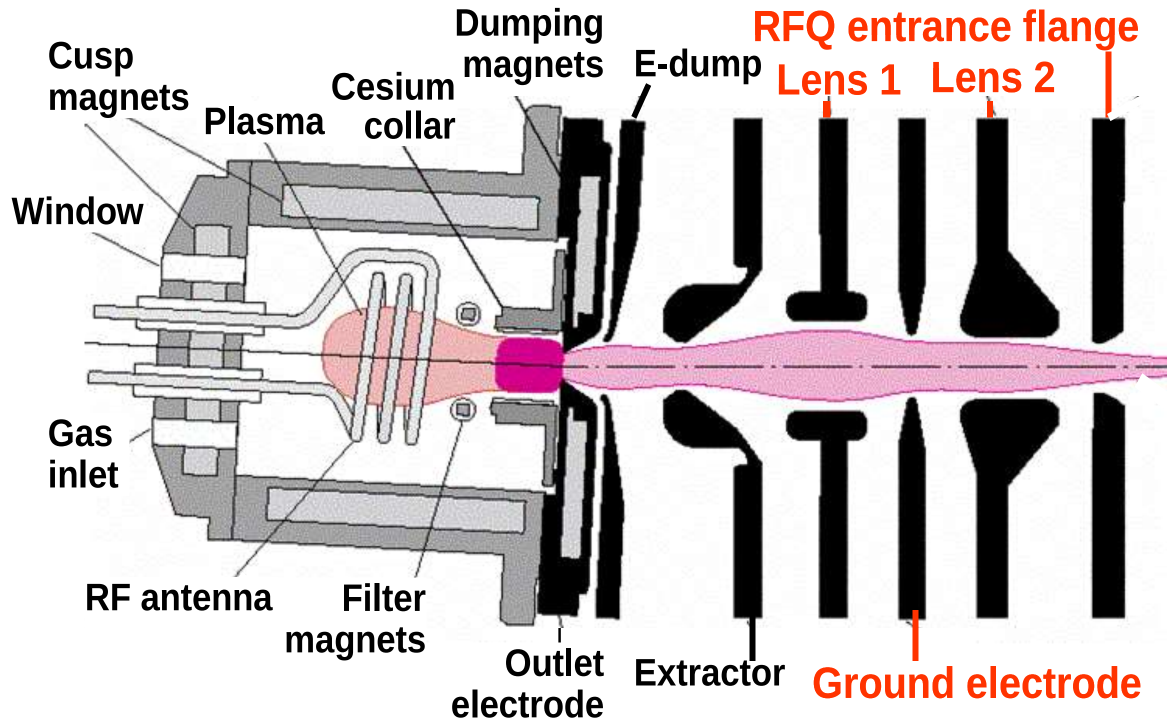
- ✓ Dry the sources with dry air
- ✓ Install with minimum moist air exposure
- ✓ Eliminate all air and water leaks
- ✓ Condition to low residual gas pressures
- ✓ Avoid excessive temperatures

Opportunities for Improving the Startup!



The rapid pressure drop at the beginning of the cesiation is the remaining surface contaminants being gettered by the activated getter. Increasing the conditioning temperature may further shorten the required cesiation time.

The excellent beam persistence suggests minimal Cs sputtering. This suggests that 0.5 μT H_2O partial pressure in the LEBT is sufficient to minimize the Cs sputtering!



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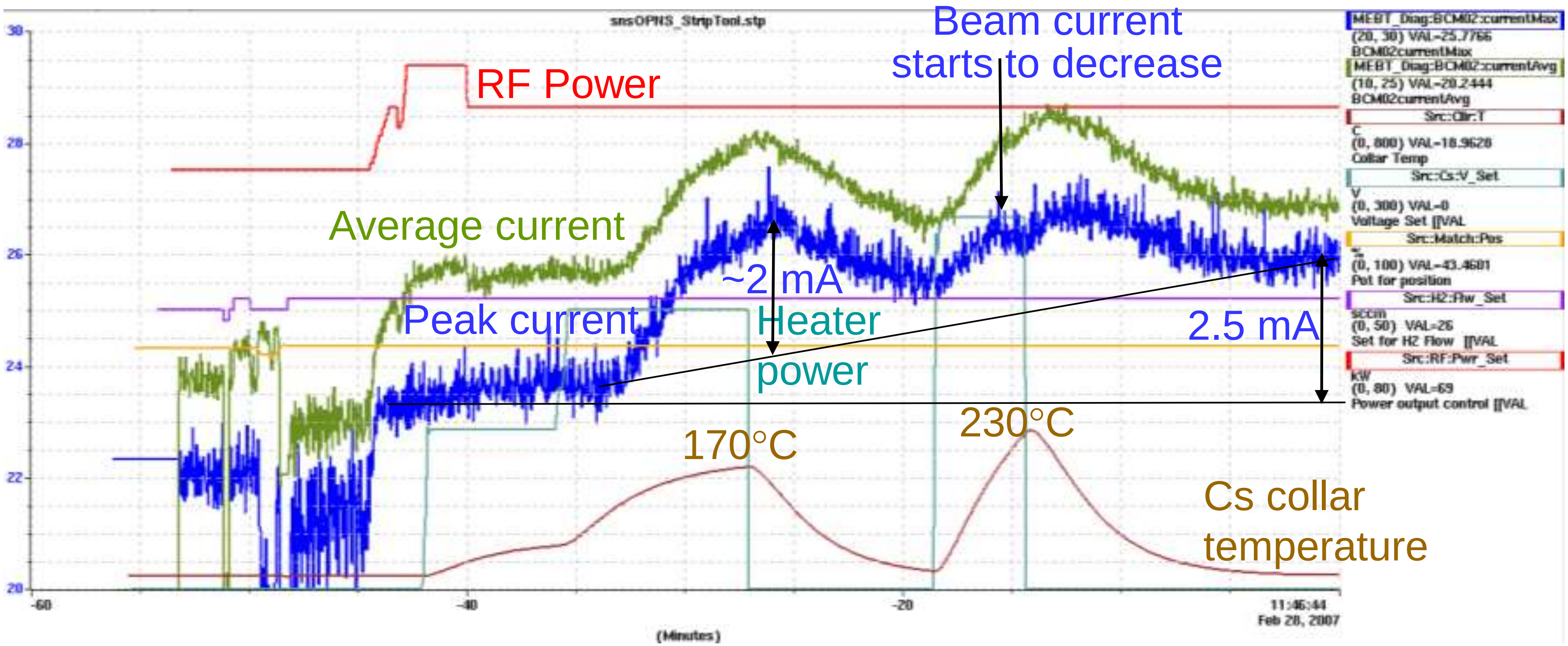
The Cs Collar Temperature Saga of the Past



•When the Cs collar is heated, the beam current normally increases. When the heater is switched off, the beam current normally decreases.

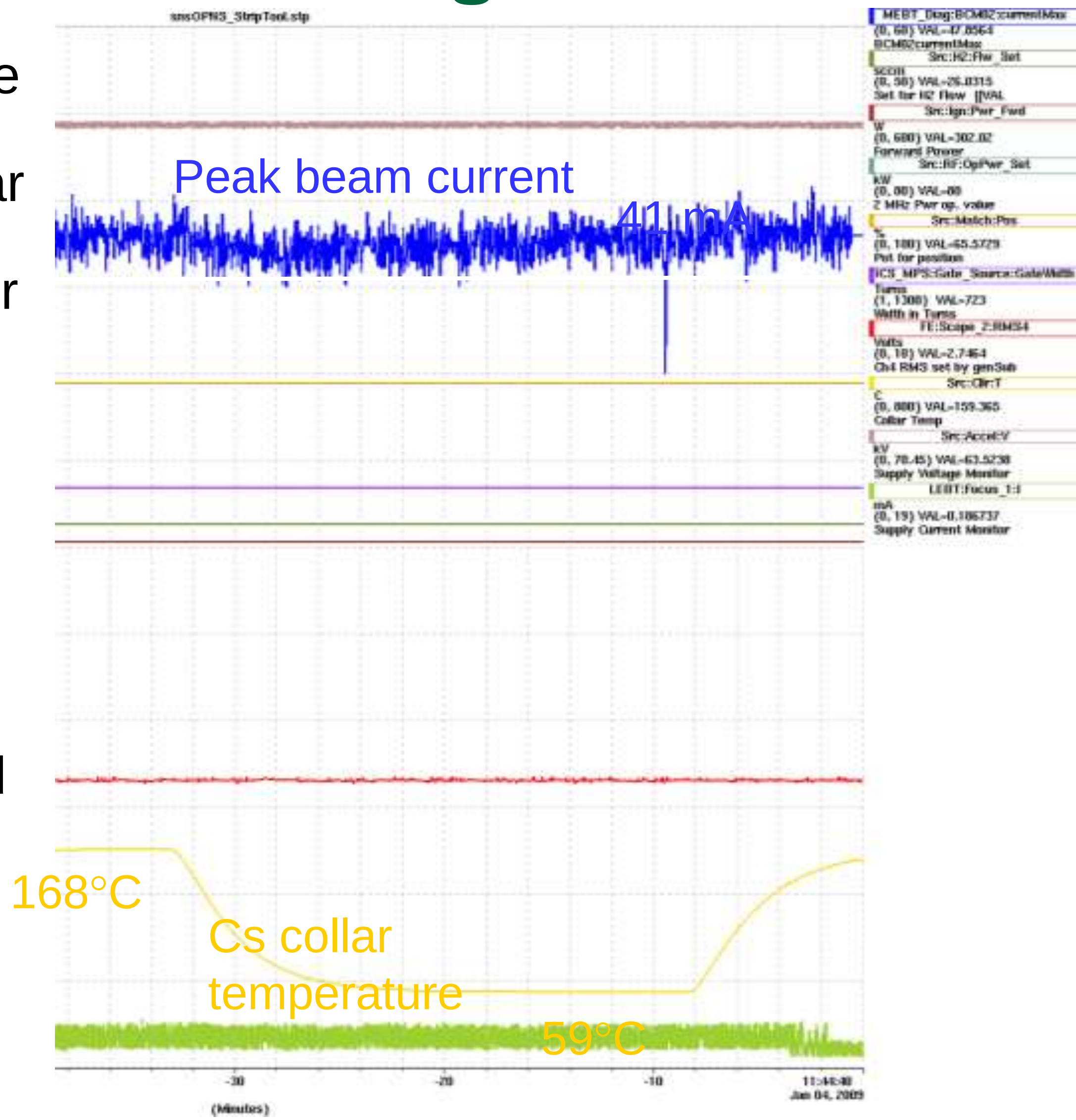
•Even if the temperature returns to the same value, the remaining current can be higher (2.5 mA), likely caused by a redistribution of Cs. We used this method many times before we proceduralized conditioning and cesiation.

•In addition, the beam current appears to track with the Cs collar temperature, adding ~8% when at 170°C. However, the current starts to decrease when reaching 180°C, possibly due to a loss of Cs.

At what temperature can we operate for long periods without encountering a significant performance loss?

The Cs Collar Temperature Saga of the Past

- To assure beam degradation-free production periods with warm Cs collars, we increased the Cs collar temperature by 20°C with every new source, watching carefully for performance degradation. No performance degradation was observed for 160°.
- After 3 weeks at 160°C, the heater was switched off for 20 minutes, which dropped the temperature to 59°C. The beam current did not significantly change during this period, nor did it significantly increase after turning the heater back on.
- In the past we concluded the observed current changes may have been caused by thermally induced motions of the Cs collar.



Last year I concluded that there seems to be NO temperature effect!

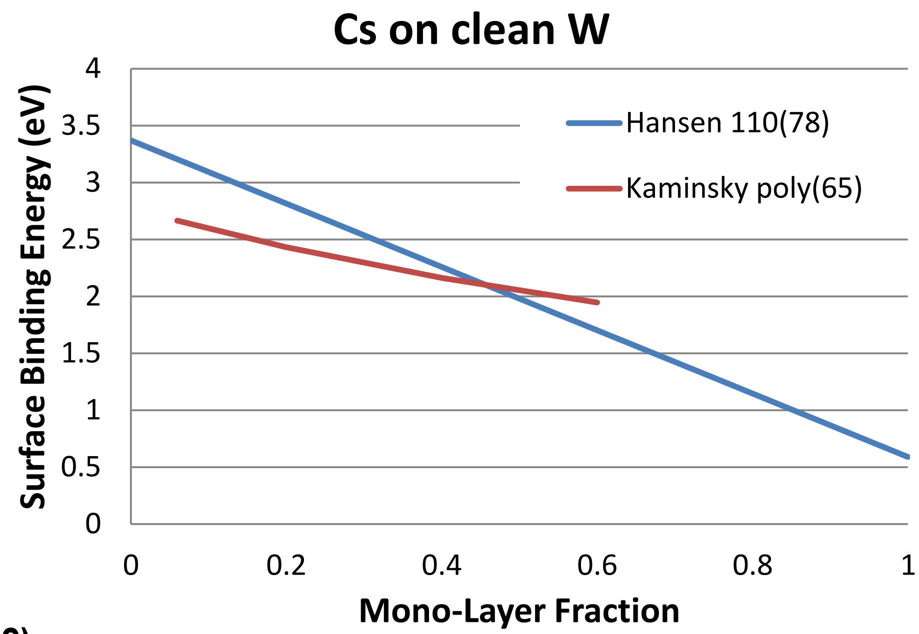
However, this only indicates no reversible temperature effect!

There may be an irreversible temperature effect!

Thermal desorption of Cs

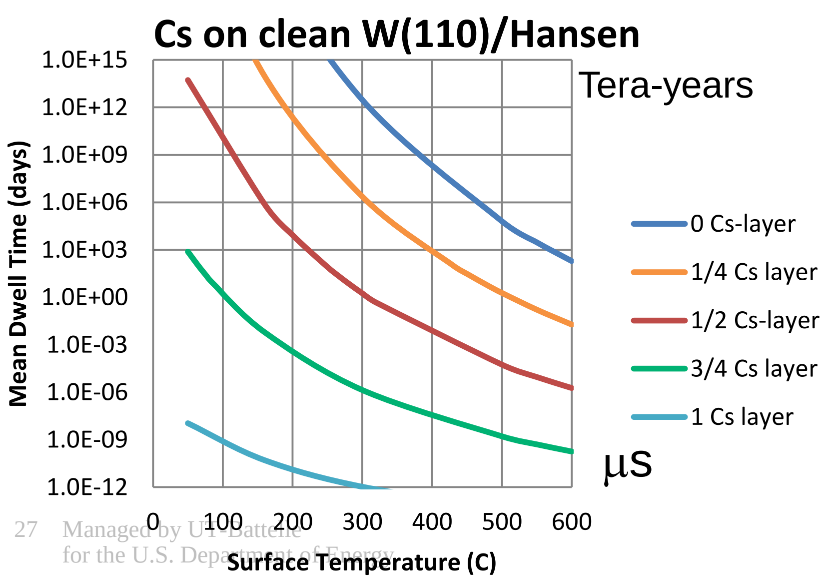
The Cs binding energy E_{Cs} depends on the surface coverage:

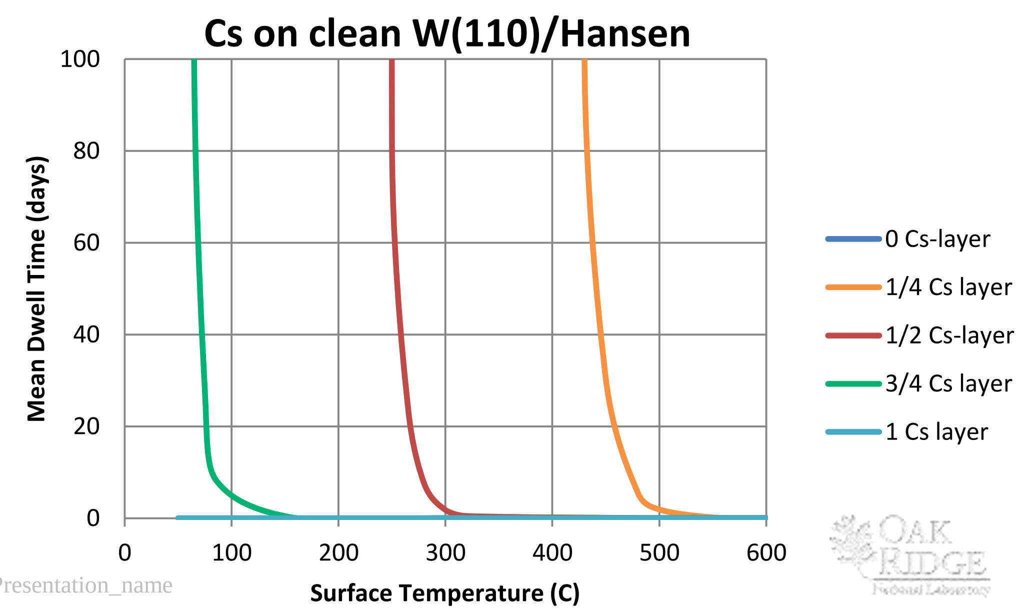
- $E_{Cs} = 3.37 - 2.78\cdot\theta$ (Hansen,78)
- $E_{Cs} = 2.78/(1+0.714\cdot\theta)$ (Kaminsky, 65)



Thermal desorption is characterized as Mean Dwell Time τ:

- $\tau(\theta) = \tau_0\cdot\exp(E_{Cs}(\theta)/k\cdot T)$
- $\tau = 6\cdot10^{-13}\cdot\exp(E_{Cs}/k\cdot T)$ (Lee & Sickney,72)





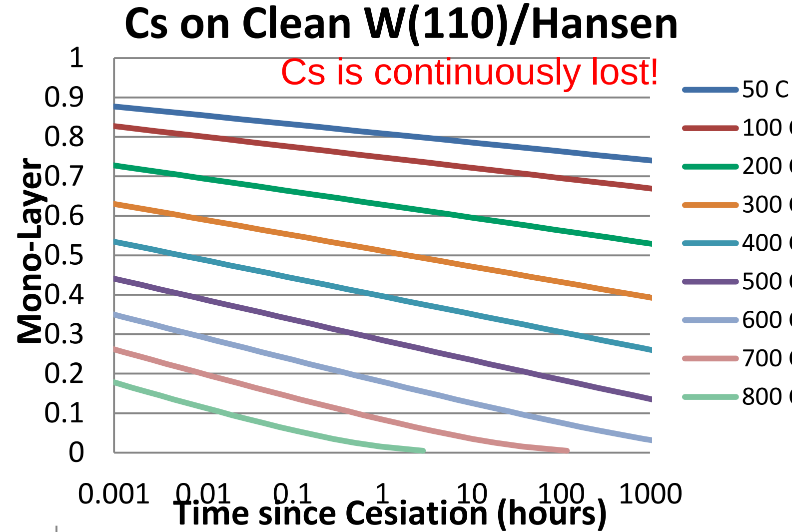
Optimizing the Cs layer

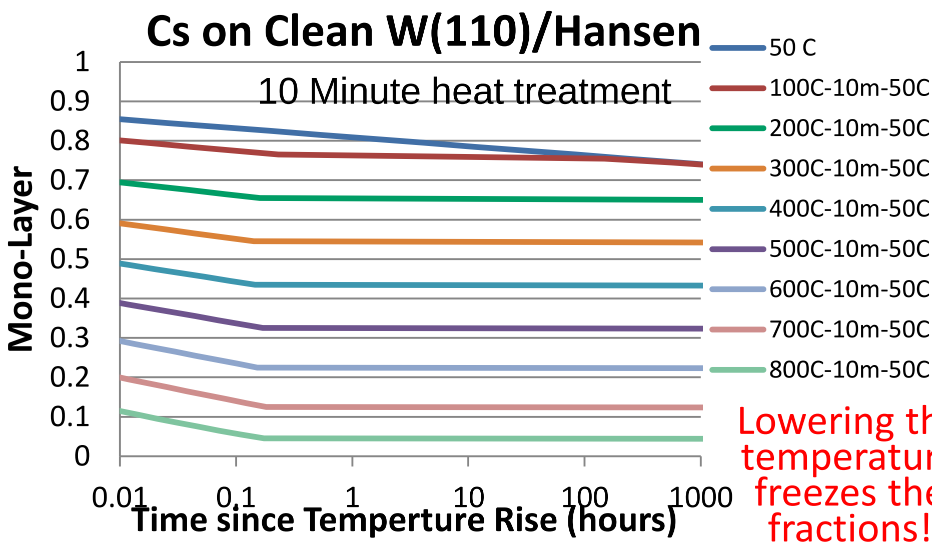
However, as Cs desorbs, the binding energy of the remaining Cs increases, which helps to stabilize the mono-layer fraction!

$$\text{loss} = d\theta/dt = \text{flux} = \theta/\tau$$

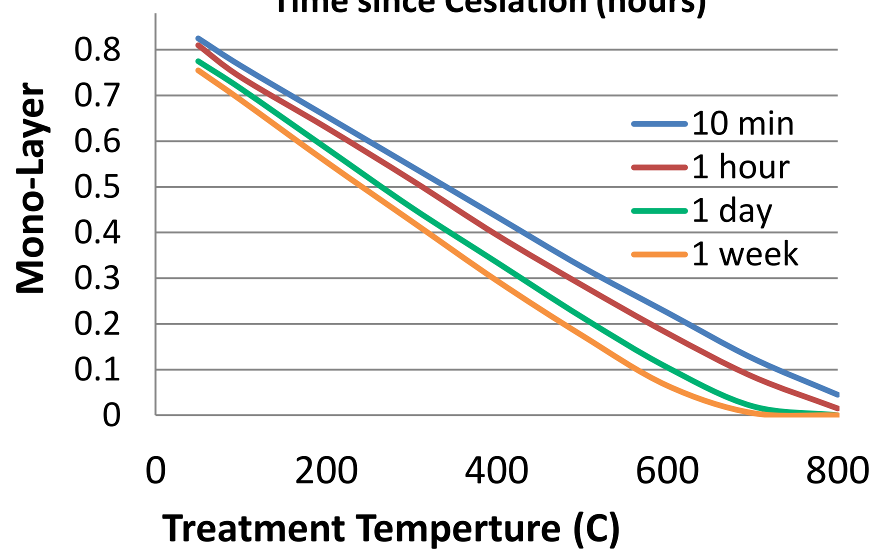
$$\theta(t) = \int (d\theta/dt)\cdot dt = \theta_0 - \int(\theta(t)/\tau(T(t),E_{Cs}(\theta))\cdot dt$$

$\theta(t)$ is calculated by summing the times it takes for 0.01 mono-layer losses, starting from θ_0 =0.995



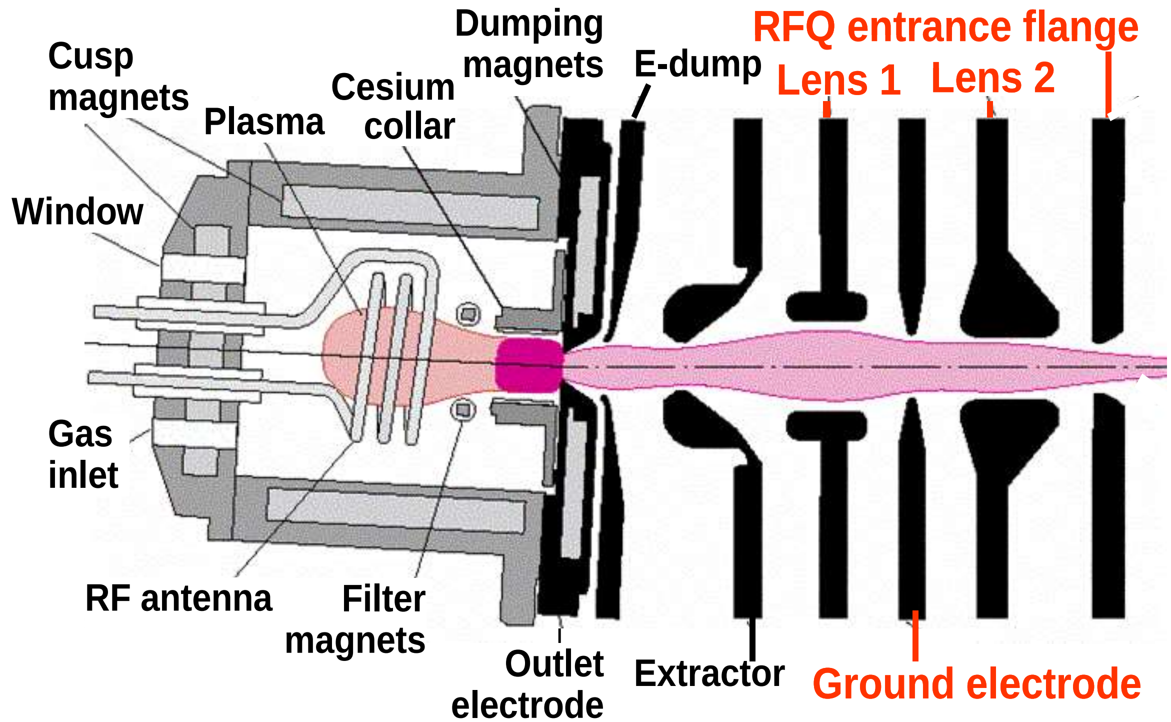


Lowering the temperature freezes the fractions!



Converter temperature profiles allow for creating the Cs fraction that yields the most beam and then freezing it!

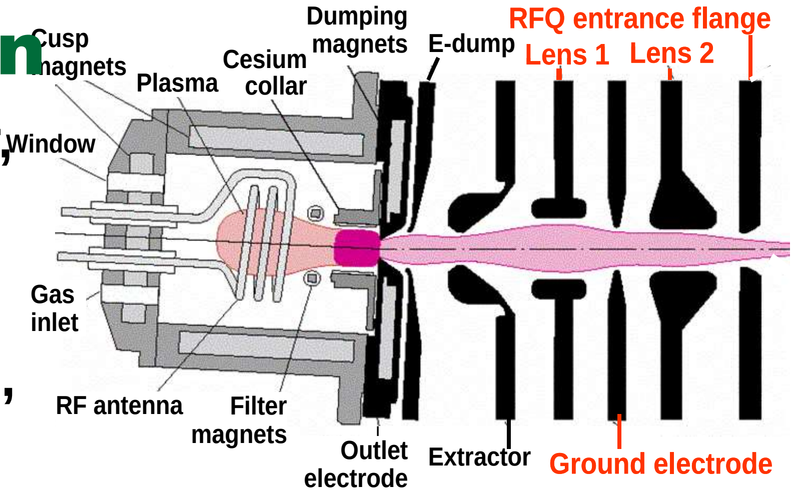
We have started a program to find the best temperature profile, which we expect to implement for producing more beam more consistently!



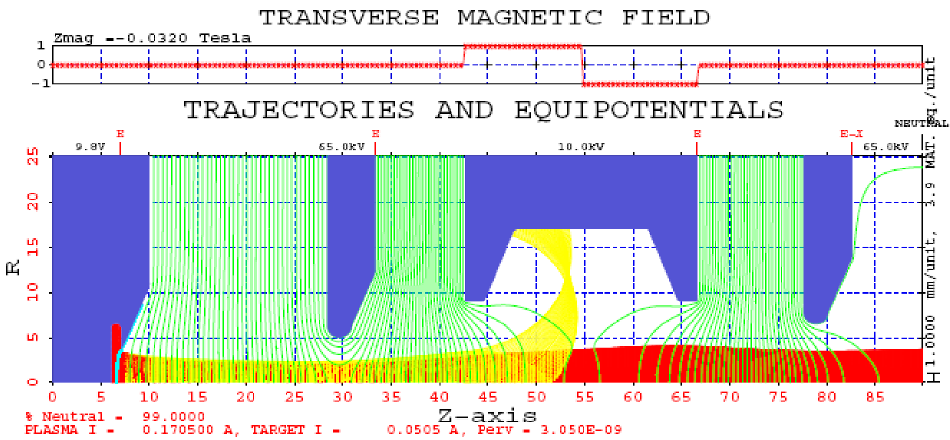
Content

- Overview
- LEBT Performance and Issue Mitigation
- Ion Source Performance and Issue Mitigation
- The Cs Discrepancy
- The Cs Collar Temperature Story II, a Sequel
- Long-Range R&D
- Summary and Conclusions

The State of the Extraction



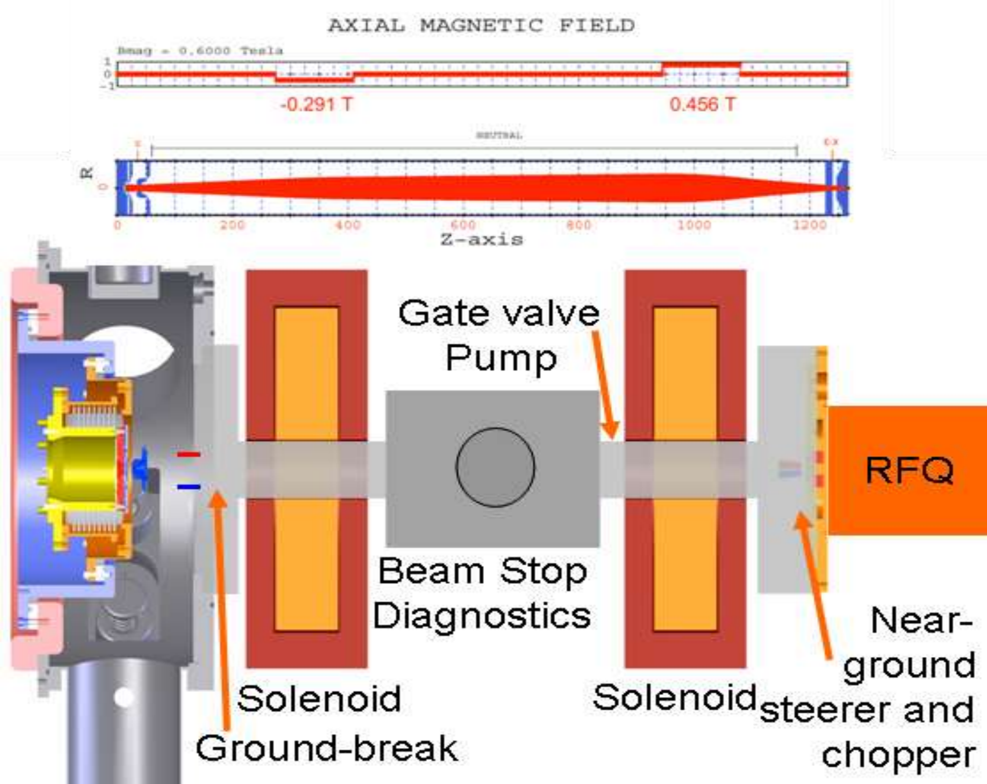
- As discussed, the e-dump, the extractor, and the 2 lenses are strongly coupled.
- The highest MEBT beam current is found with the e-dump ~7 kV. However running with 7 kV overheats the e-dump, likely due to the beam-edge hitting the extractor as predicted by PBGUN.
- The positive extractor can increase the extraction field by ~30%. The highest beam current is obtained without extractor voltage. Few kV make no big difference, but the beam is reduced by voltages >5 kV.
- This is consistent with the meniscus near the outlet.
- This is consistent with extracting all extractable ions.
- Most beam was found with 0 tilt angle. We will continue to explore the issue, which may be simply an artifact of the alignment.
- *The low B-field extraction system has been redesigned to avoid Glidcop and to restore the ion trajectories. If the prototype demonstrates a superior emittance, a production model will be developed.*



The State of the cool, arc-free 2-Solenoid LEBT

- 2-solenoid LEBTs stay cool because they are cooled by ambient air.
- Near-ground chopper is at RFQ entrance, far from the arcing source.
- It combines a working chopper with a proven high-power LEBT design.
- Differential pumping and a gate valve help the RFQ.
- Diagnostics allows for full power source testing.

A prototype 2-solenoid LEBT is being assembled to demonstrate that the beam at the LEBT exit 1) is stable, 2) meets the RFQ input Twiss parameters, 3) produces beam rise and fall times as least as fast as the baseline e-LEBT.

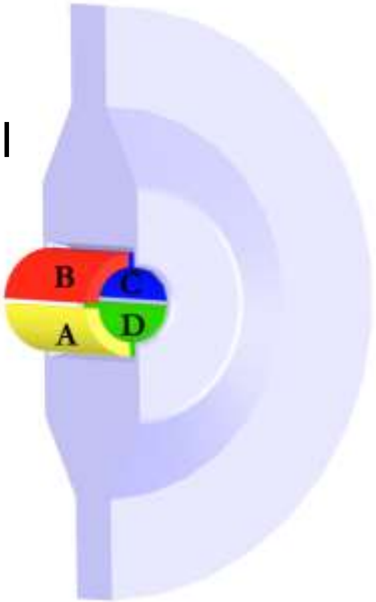


Alternative: Better availability with a shielded, near-ground chopper for the e-LEBT

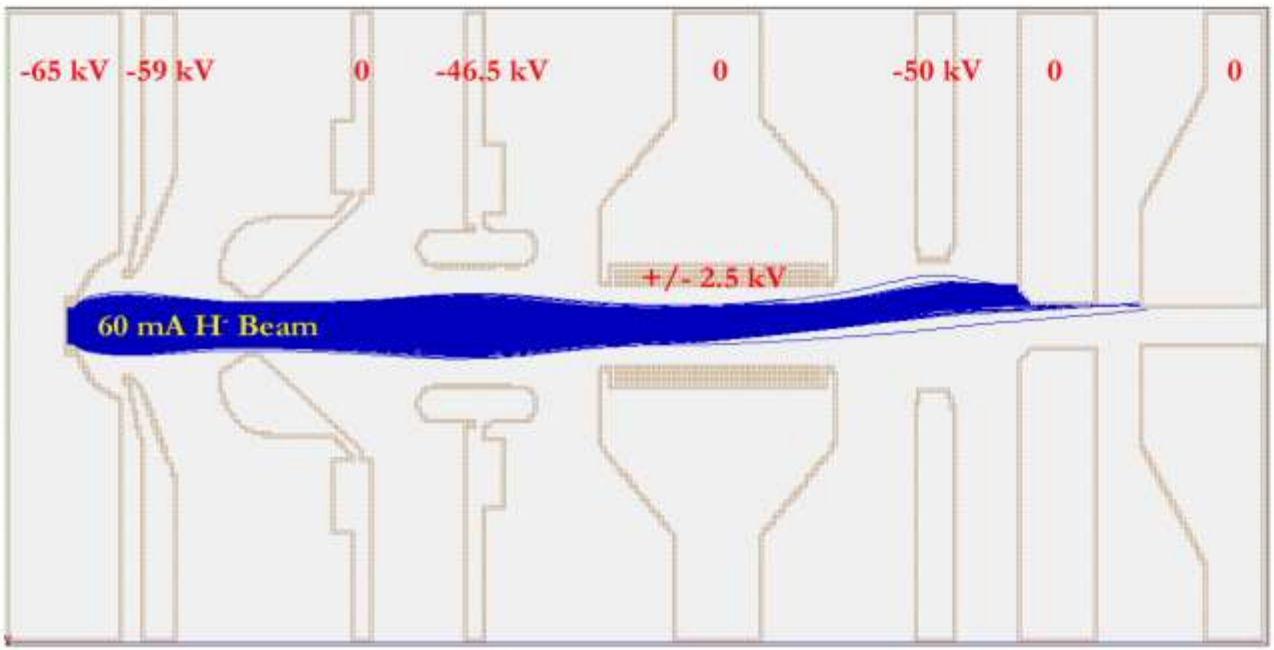
If LEBT arcs again start to create significant downtime, or the prototype 2-solenoid LEBT fails to meet the 3 requirements, we will develop a near-ground chopper for the e-LEBT.

When the chopper is placed between the lenses, the 2nd lens re-straightens the beam. Successful chopping requires displacing the beam sufficiently before it enters the second lens.

Model calculations have shown that lengthening the chopper and increasing the aperture of the 2nd lens allow for complete chopping of the beam.



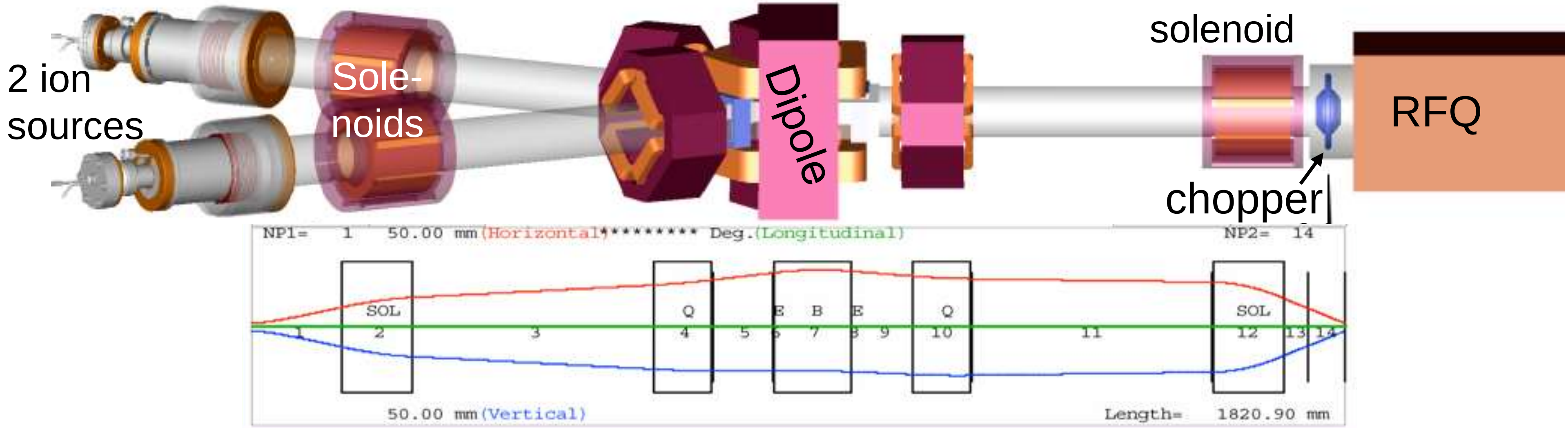
A prototype will be built for the test stand. We will demonstrate that the beam at the LEBT exit
1) is stable
2) meets the required Twiss parameters
3) produces beam rise and fall times as least as fast as the baseline e-LEBT



A 2-source LEBT for High Current and High Availability!

When ion sources are pushed to high performance levels, the risk of premature failures increases. This is mitigated with a 2-source LEBT: when one source fails, Operations switches sources in less than 1 hour.

- ➢Symmetry minimizes tuning: Reverse the dipole and fine tune!
- ➢Both ion source beam lines feature full-power beam stops, emittance scanners, pumps, and vacuum gate valves: While the new source is in production, the failed source is replaced with a spare. The spare is conditioned, tuned, and checked before being turned over to Operations.
- ➢Such source switching magnets are common, but they are normally not built to stringent requirements. A prototype is needed to prove that a low emittance beam can be bent with minimal emittance growth!



After successfully proofing the 2-solenoid LEBT, a 30° Y-magnet will be inserted between the solenoids!

Long Range Source R&D:

- 56 mA in the MEBT have been demonstrated, which is close to the 59 mA, ≤0.35 π·mm·mrad LINAC beam current required for 3 MW operations. The beam current was limited by the available 60 kW RF power.
- We have shown that availability greatly improves when the RF power is reduced.
- Therefore we desire to develop low-emittance ion sources which can deliver 59 mA in the MEBT with a minimum of power, parts, and components.

The ion source R&D will include:

- Continue the development of the SNS RF ion sources
- Continue to develop a SNS Helicon H^- source
- Test a Helicon saddle antenna developed by Muons, Inc.

} Our focus!

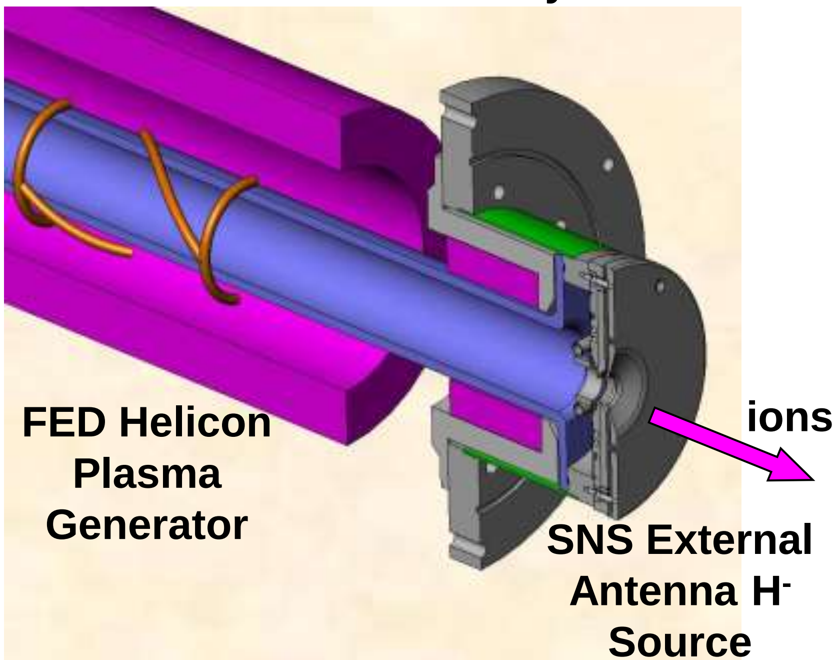
- Test a magnetron H- source proposed by Muons, Inc.
- Develop cesiation for the Sumy source in Sumy, Ukraine
- Monitor and collaborate with other facilities developing high-current, low-emittance H^- sources.

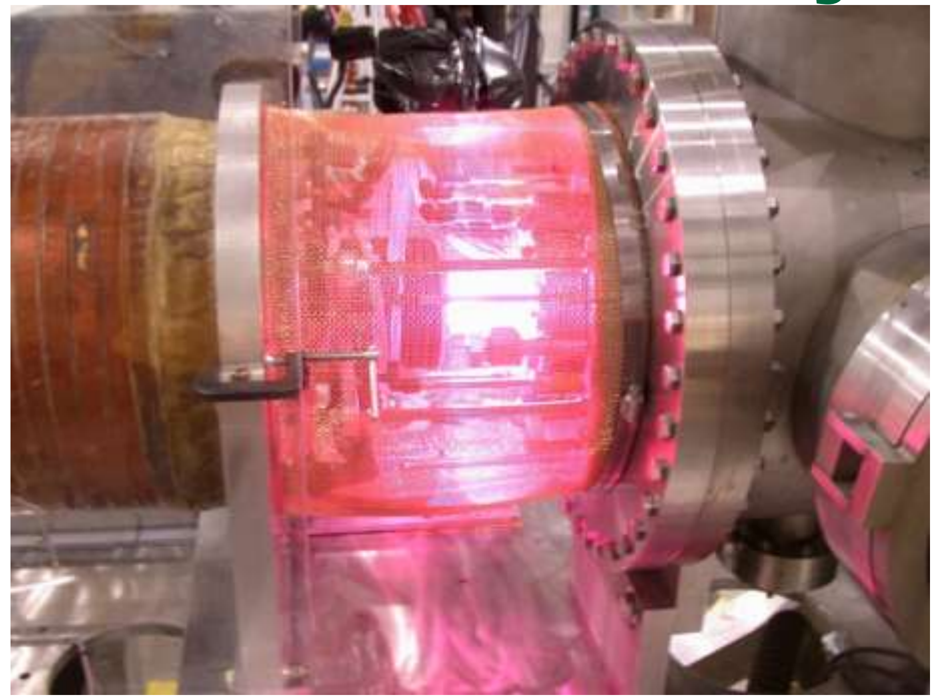
} Technology diversification!

- When a source yields promising results on the test stand, it will be tested on the Frontend at the beginning of a maintenance period.

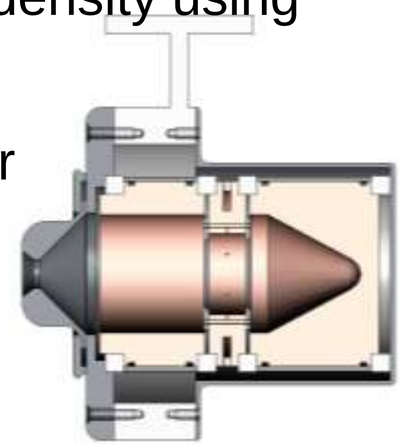
The Helicon H^- Ion Source and Test Facility

Courtesy of R. Welton



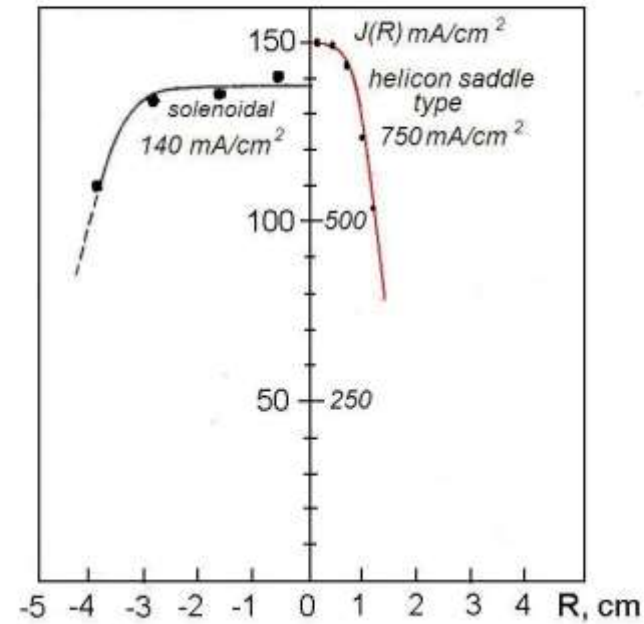


- Combines the highly developed VASMIR helicon plasma generator (FED) and ORNL-LBNL H^- ion source – initially funded by ORNL-LDRD.
- Plasma generator proven to produce ~10x higher plasma density using ~10x lower RF power.
- Restarted helicon test facility in the FED: On 7/28/07 produced a plasma ~10^{13} e/cm^3 near the peak of the mirror coil using 2.8 kW of RF (130 ms, 0.5 Hz ≈ 6%)
- A extraction module at +65 kV measured 13 mA ion beam before cesiation.

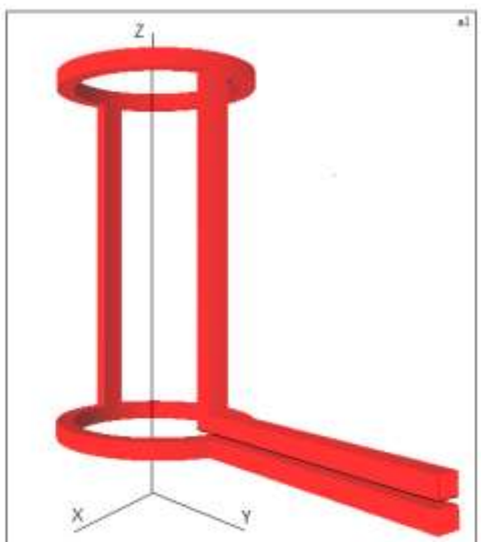


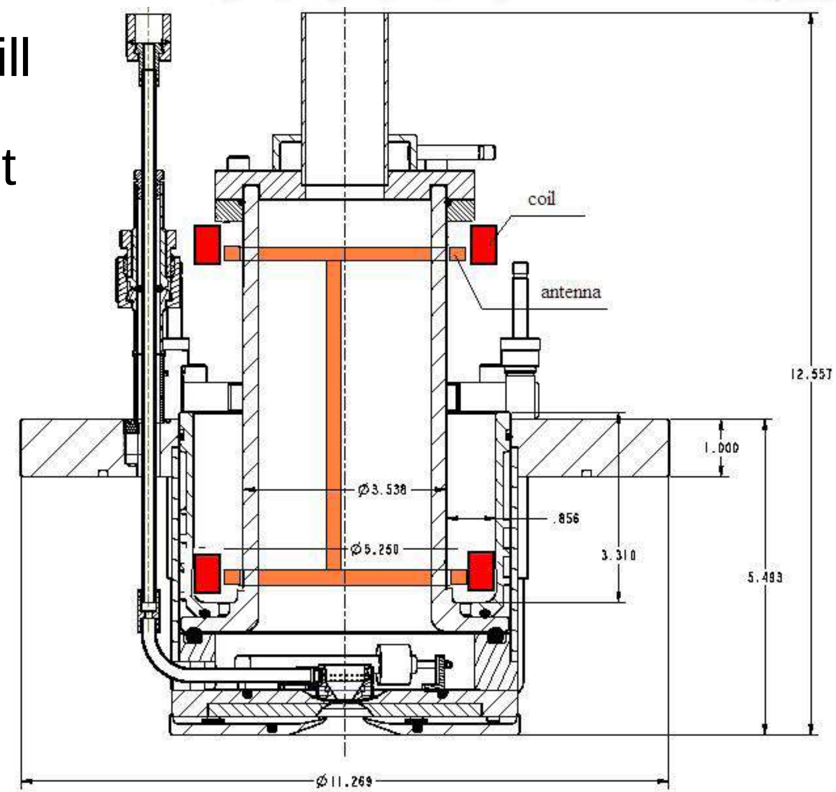
A Helicon Saddle Antenna for the SNS H- source

- Vadim Dudnikov, collaborating with Muons, Inc., is developing a Helicon saddle coil for the SNS external antenna source. This is expected to increase the plasma density near the outlet aperture by a factor of 5.
- Vadim is in the process of building a low-power prototype antenna and coil, which will be tested initially with plasma only. After successful plasma testing beam will be extracted and measured on the test stand. If very successful, a Frontend test is likely to follow.



If this yields more beam current, it would be relatively simple to implement!



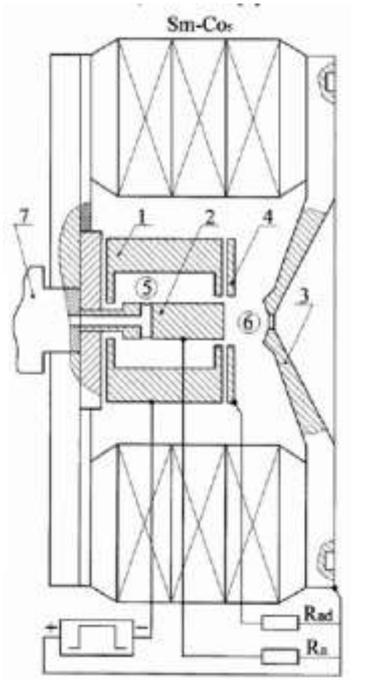


The Sumy H- source

The National Science Academy in Sumy, Ukraine, has a cesium-free, reverse gas magnetron source:

- 50 mA H^- ; 1ms pulses; 10 Hz
- 5.4 mm aperture outlet
- $1\text{-}2\cdot10^6$ pulses limited by gas valve (not needed at 60 Hz)
- > 0.2 $\pi\cdot$mm$\cdot$mrad

Adding Cesium should increase the current output and decrease the emittance**!**



1: cathode
2: anode
3: emission electrode
4: puller electrode
5: discharge chamber
6: outlet aperture
7: pulsed gas valve

We want to collaborate with Sumy to

- Introduce Cs
- Confirm previous performance and compare it with the cesiated performance.
- Optimize outlet aperture
- Water-cool the source for 60 Hz ops
- Every step will have to show expected improvements in current and emittance!

Most of the effort will be done in Sumy.

If successful, the source will be transferred to ORNL with Sumy support!

This alternate plasma technology mitigates the risk of encountering limits with RF-driven sources.

Summary and Conclusions

- We have learned to operate the LBNL ion source in a responsible, efficient, and reliable manner. We normally meet or exceed the power ramp-up requirements.
- 1 antenna failure per ~20-week run yields an **ion source availability of 99.7%.**
- **A 27-day neutron production run has utilized 42 mA, which exceeds the 1.4 MW requirements by 10%. We have delivered 46 mA for 32 hours to the MEBT beam stop. And we have demonstrated 56 mA in the MEBT beam stop.**
- We have confirmed the RF power system to be a serious reliability issue. We are working towards a ground-based RF system with improved availability.
- We continue to learn how to minimize Cs consumption. An initial **Cs dose of <10 mg is sufficient for ~4 weeks** of beam production. We expect to thermally optimize and stabilize the Cs layer in the near future.
- We will continue our efforts to produce more beam with less RF power.
- **LEBT arcing** has been drastically reduced, and a new maintenance program should limit arcing to **less than 1 arc per day**. The extractor heating has been controlled.
- A prototype 2-solenoid LEBT is being assembled and will be tested for suitability.
- The external antenna sources exhibited insurmountable infancy problems. We are in the process of developing a RF plasma gun, which should be able to support the desired long lifetimes with an availability >99.9 %.

Thank you for listening to our progress story!

Backup Slides

From the 2009 AAC report :

5. Ion Source and LEBT

5.1 Findings

The ion source is now supporting three uninterrupted weeks of operation at 4% duty factor and routinely delivering 38 mA beam through the MEBT. A multitude of technical and operational modifications has resulted in this significant improvement in performance. The internal rf antennas still fail about 1 out of 7 times on average, with no warning in terms of reduced performance. Spectroscopic diagnostics do not give any useful sign for impending failure either, indicating that failure occurs quite rapidly (possibly within seconds) once the porcelain coating is perforated. At this point, the 2-MHz rf system appears to be the largest risk for achieving high availability, and the procurement of a solid-state amplifier is being pursued.

The development of an ion source with external rf antenna has resulted in excellent test performance, and one such source was being made ready for beam production after the end of the review. 35 mA at 5% duty factor has been achieved at the end of the MEBT with such a source being administratively restricted in peak power. The Ion Source Group also intends to test a helicon-style saddle antenna with the same discharge chamber.

Further lines of development aim at directly utilizing a helicon discharge (now under development, intended to replace the present main discharge chamber) and examination of the performance of a Penning-style source developed at SUMY, Ukraine, but modified for cesiation.

With the extraction system, the importance of a fairly high electron-dump voltage was demonstrated; the main effect is the creation of a wider beam that is easier to focus by the second LEBT lens. An alternative extraction layout is being considered that provides electron dumping at a modest energy downstream of the extractor electrode; this system promises to yield lower emittances.

Continued from the 2009 AAC report :

After conditioning, the LEBT only experiences about one arc per day which, again, is a remarkable improvement. To further reduce the danger of sparking and also in view of developing an injector with two sources, a magnetic LEBT configuration with two solenoids has been modeled. For this option, the LEBT chopper would be placed downstream of the second solenoid, close to the RFQ entrance. This type of LEBT has been proven in many similar installations around the world, but the loss of space-charge compensation by the rf fields in the RFQ structure needs to be carefully simulated. Another option, an electrostatic two-lens LEBT with the chopper placed between the lenses, is being modeled as well. This design eliminates the need for splitting the second lens into four quadrants and allows applying the chopper waveforms from ground potential, with an expected major increase in reliability. It could be a short-term solution before a full magnetic LEBT has been assembled and beam-tested.

To ease the scheduling conflicts between source development and qualification for production runs, a second ion source test stand is being assembled.

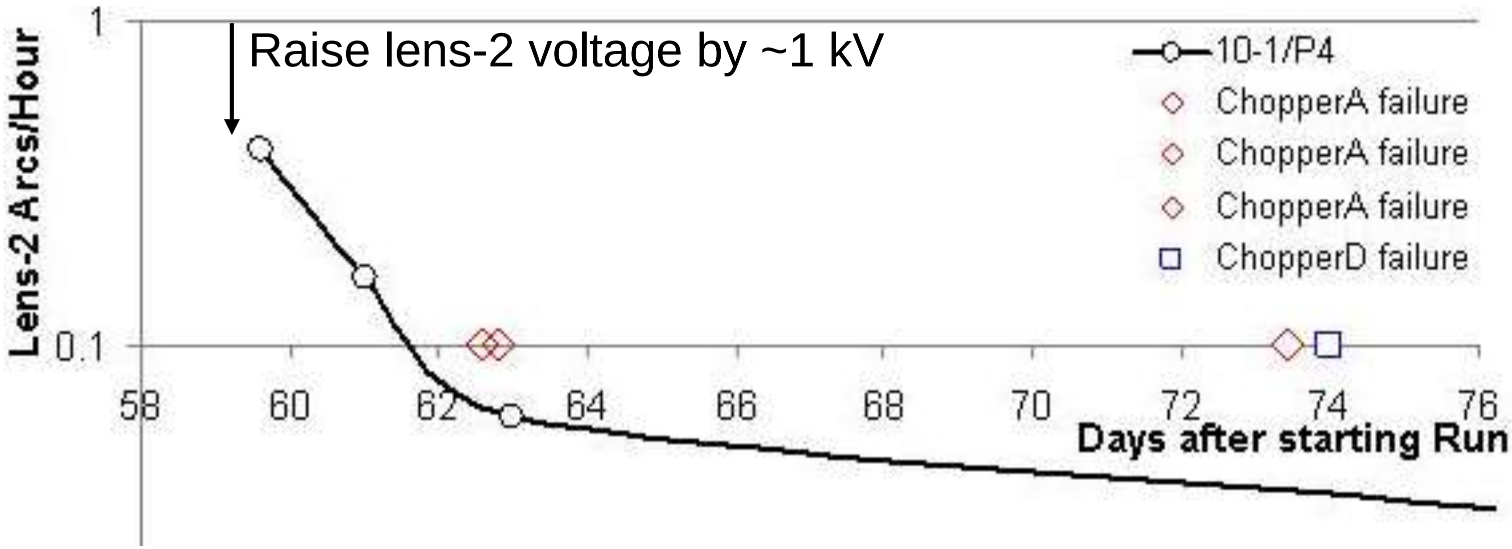
Issues with the presently used LEBT chopper are addressed in Section 6.

5.1.1 Comments and recommendations

Long-term, the reliability of the internal rf antenna type is insufficient for nominal SNS operations. At present, the development line of the standard multi-cusp source with external rf antenna appears most attractive and should be pursued as the main development activity.

At this point it would be prudent to work towards viable final designs of two-solenoid and modified two-lens electrostatic LEBT's and also a modified extraction system with low-energy electron removal downstream of the extractor.

The Lens-2 Micro Spark Fest during Run FY10-01:



- During day 59 the lens-2 voltage was raised by ~1 kV, which briefly raised the arc rate to 0.4 arcs/hour (1 arc every 2.5 hours).
- Over the next 2 days the arc rate drops to <0.1 arc/hour.
- 3 days after raising the voltage, chopper channel A fails twice.
- 14 days after raising the voltage, chopper channel A fails again.
- 14.5 days after raising the voltage, chopper channel D fails.
- Either chopper has long-term memory or it is unreliable.

The ion source test stand is ready to test the SNS-designed chopper system!

Implementing R&D equipment, a case study:

- The External Antenna Source initially appeared very successful because its record peak performance was compared against the average performance of the (at the time) dysfunctional LBNL source.
- Accordingly, in 2007 Management strongly encouraged its implementation.
- 2-08: First Frondend test yielded poor performance due to an air-leak.
- 7-08: 2nd Frontend test was hampered by water-leaks & control issues, but the startup beam current exceeded the average LBNL beam by ~10%.
- 8-08: It was decided to improve the water system and start run 09-2 with the external antenna source to capitalize on the perceived higher availability.
- An in-depth, NFDD review was requested to get a prioritized improvement list
- The project physicist met with the responsible mechanical NFDD engineer, who endorsed the physicist's non-prioritized improvement plan.
- The improvements were implemented one by one, followed by short tests, which squeezed out the planned final 1-2 month of thorough lifetime tests.
- The focus was on water leaks. An antenna failure on the test stand was blamed on R&D, rather than investigated.
- Shortly before the implementation on the Frontend, the plasma gun cathode was changed from Cu to Mo without systematic or long-term tests.

Assessment: We need to follow through with a prioritizing improvement plan, then freeze it and test it to either identify the modes of failure or to demonstrate availability exceeding the baseline before presenting it to the Configuration Control Committee.

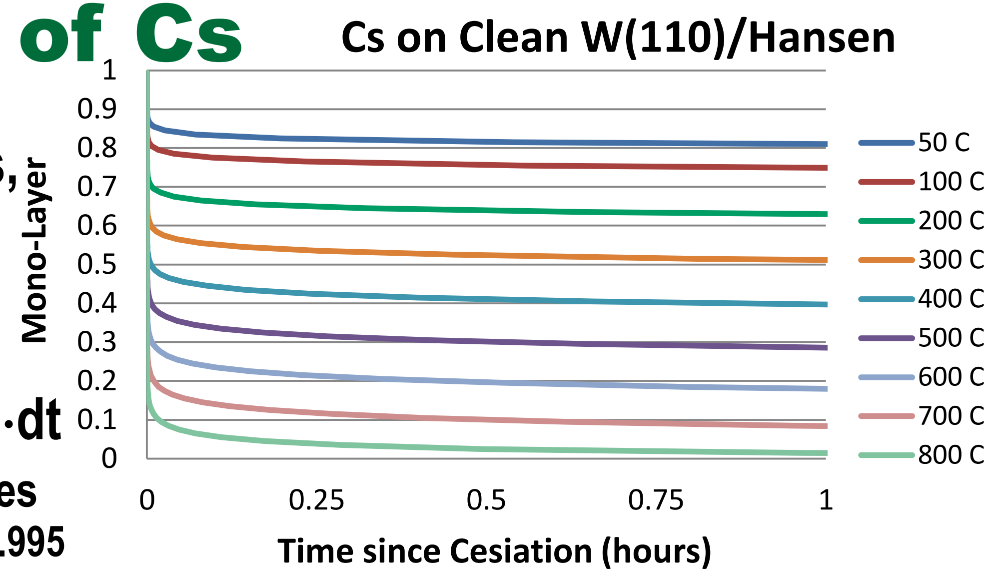
Thermal desorption of Cs

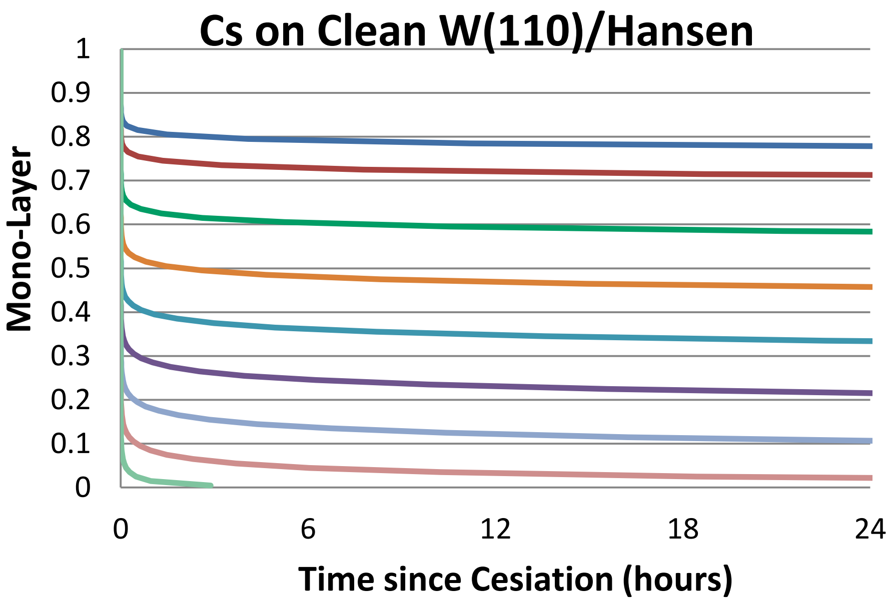
However, as Cs desorbs, the binding energy of the remaining Cs increases, which helps to stabilize the mono-layer fraction!

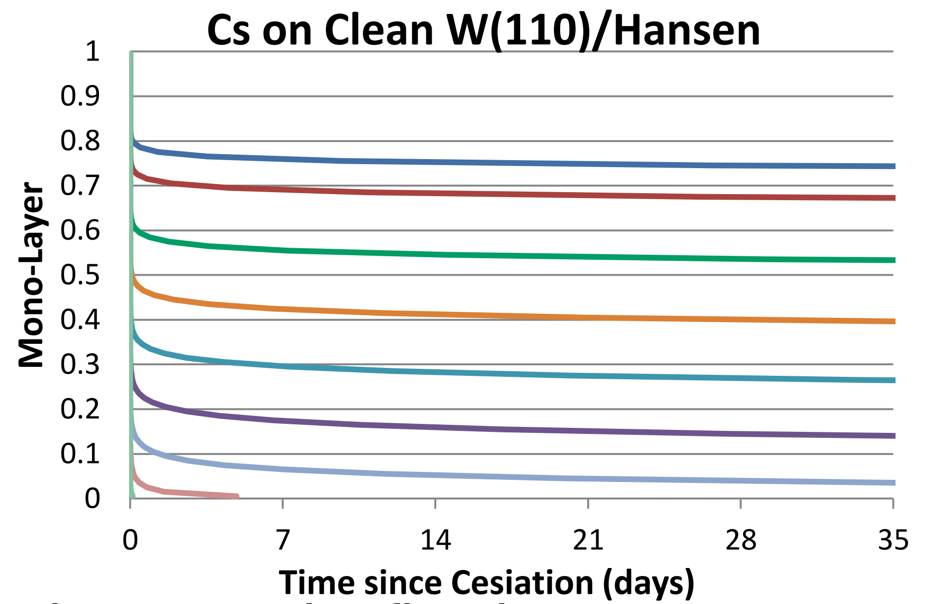
$$\text{loss} = \text{flux} = \theta/\tau$$

$$\theta(t) = \int (d\theta/dt)\cdot dt = \theta_0 - \int (\theta(t)/\tau(T, E_{Cs}(\theta)))\cdot dt$$

$\theta(t)$ is calculated by summing the times it takes for a 0.01 mono-layer loss, starting from θ_0 =0.995







About 0.1 mono-layer is lost over the first hour, another 0.1 mono-layer over the next month!

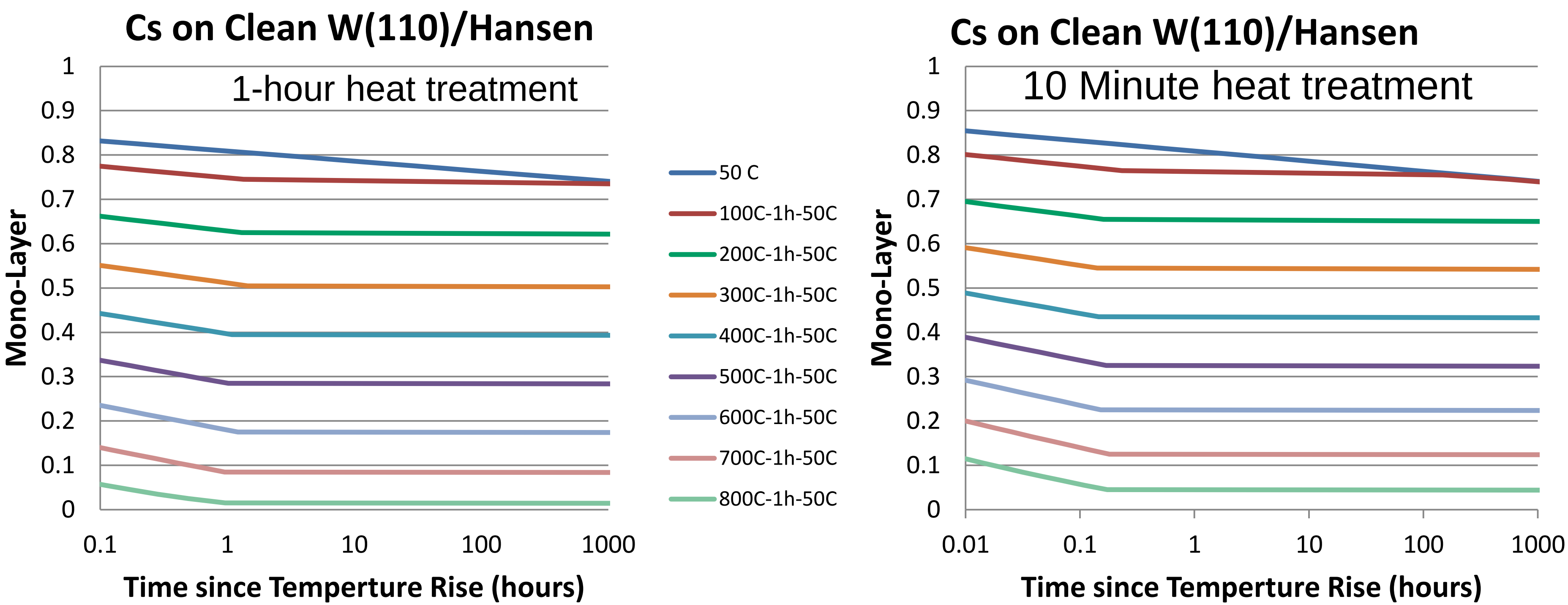
Can the exponential decay be stopped?

Control and Stabilization of the Cs layer

At constant temperature, the very gradual increase of the bond energy does not stabilize, it just gradually reduces the desorption rate. The system remains critical.

The temperature, however, can be drastically lowered, which drastically decreases the desorption rate, which stabilizes the mono-layer fraction, at least until the system becomes again critical.

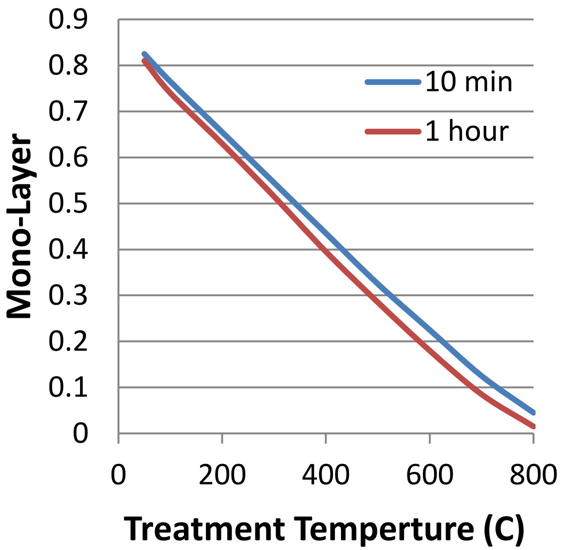
Different temperatures yield different mono-layer fractions, with a slight dependence on the treatment time.

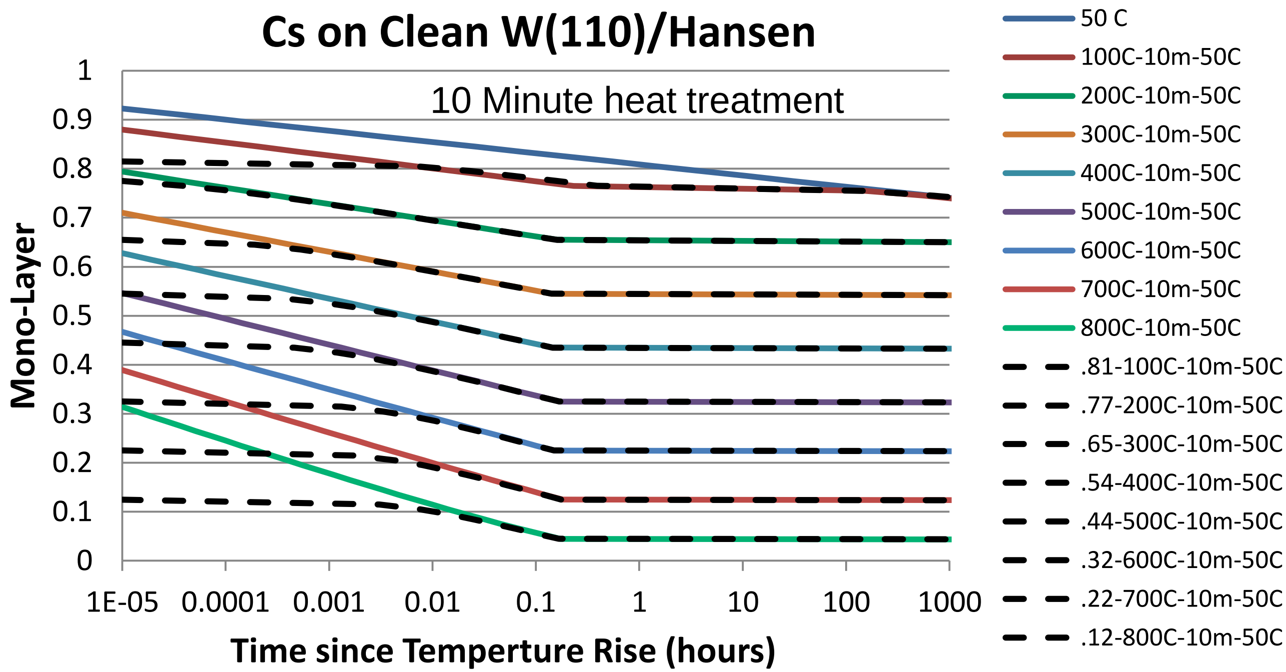


1. Cesiate with 50 C to obtain a dense layer of Cs.
2. Heat for ~10 minutes to X degrees to obtain desired fraction θ.
3. Stabilize by lowering temperature to ~50 C.

Control and Stabilization of the Cs layer

- **Given recipe yields reproducible fractions, although the absolute values may be shifted due to inaccurate binding energies.**
- **To increase the fraction requires a re-cesiation.**
- **For reproducibly lowering the fraction, is a re-cesiation required?**





When raising the temperature by 50 or 100 C, the system becomes critical within ≤1 minute, after which it desorbs following the law of desorption.

This allows measuring the beam current vs. the “relative” fraction θ!

Planned Experiments

1. Install LBNL source (no apparent beam degradation) with external Cs reservoir (Cs collar temperature independent of Cs supply flux).
2. Condition overnight with 7%-50-kW, with hot Cs reservoir, with hot Cs transport line, and with hot Cs collar.
3. Switch off Cs collar and reservoir heaters.
4. Break 1 g Cs ampoule.
5. Leave collar heater off while heating Cs transport line and raising Cs reservoir temperature to ~110 C. Record beam current vs. time. The beam current is expected to initially raise and then degrade, which would confirm a beam current maximum for a certain mono-layer fraction (~0.5 expected).
6. Switch off Cs reservoir and Cs transport heaters.
7. Heat Cs collar to ~100 C for ~10 minutes.
8. Switch Cs collar heater off and measure beam for ~50 minutes.
9. Repeat steps 7 and 8 while raising the collar temperature ~100 C above previous temperature.
10. Repeat steps 5 and 6 with a 10 C higher Cs reservoir temperature, which should cut the time in half for reaching the maximum beam current.
11. Repeat steps 7-9 with 50 C steps for the Cs collar
12. Repeat experiment with modified LBNL Cs collar to see the effect of the Cs flux from cartridges when simultaneously heating Cs collar and cartridges.

Capitalizing on the irreversible thermal Cs Effect

- **The temperatures of CSPS are typically adjusted to maintain a maximum H- beam, which is believed to occur when the converter surface has ~0.5 monolayer of Cs.**
- **Our past (somewhat random) tuning of the Cs collar temperature has not yielded consistent beam enhancements or losses.**
- **Our analysis suggests negligible Cs losses from sputtering. This conclusion could be strengthened by measuring the plasma potential.**
- **Our analysis suggests that the temperature history determines the Cs layer fraction. The thermal desorption appears allowing to select and stabilize the Cs layer fraction with specific temperature profiles.**
- **The ~equal-temperature Cs collar outlet and Cs cartridges convolute thermal losses with the Cs flux from cartridges.**
- **An experiment with the external Cs reservoir should yield the maximum beam current for a certain fractional mono-layer. If a maximum is confirmed, the experiment will identify the temperature profile that maximizes and stabilizes the beam current.**
- **If the Cs cartridges yield similar results, experiments can identify the temperature profile that maximizes and stabilizes beam current.**
- **At best we get more beam;**
- **likely we get more consistent beams or rule out a source of gradual beam current changes (conditioning);**
- **at least we get new data on the Cs collar temperatures that should be avoided.**