Ion Source and LEBT Performance, Limitations and Challenges

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AAC Review

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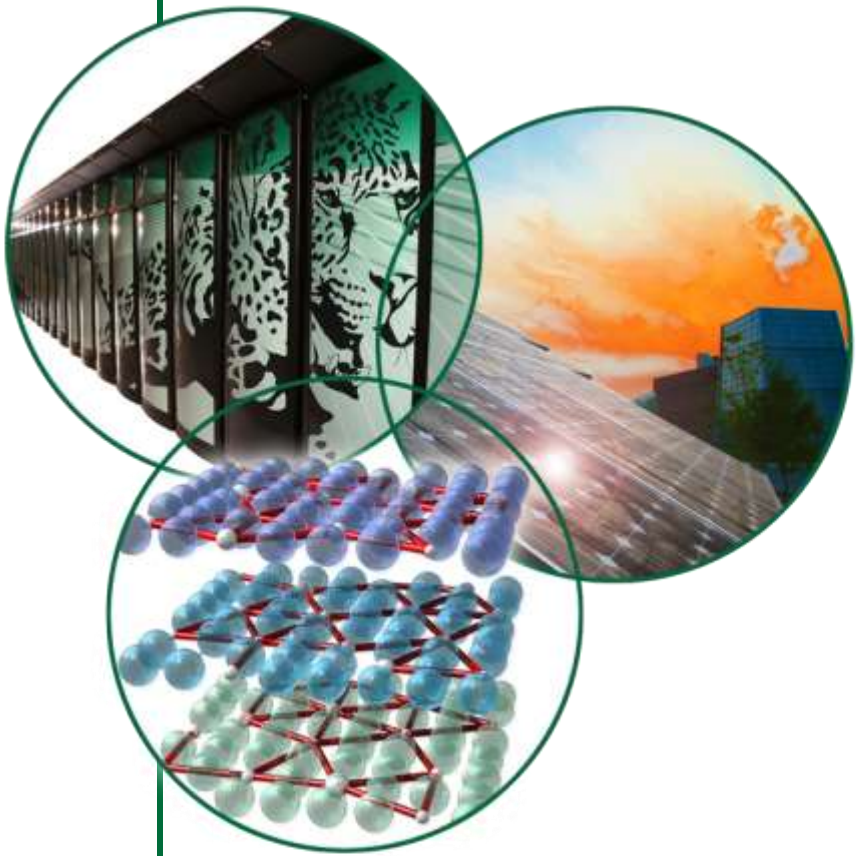

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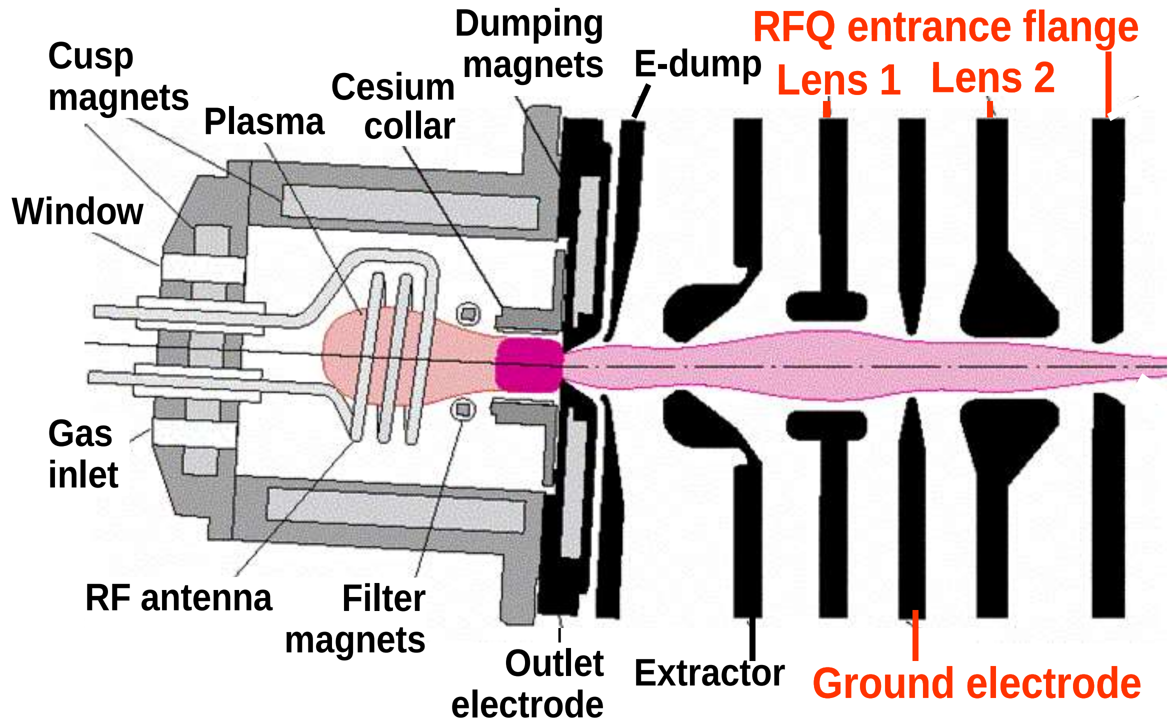

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- Extending the Source Service Cycle
- Antenna Issues
- Source Leak Issues
- Source Contamination Issues
- LEBT Issues
- Future Plans

Ion Source and LEBT Action Items from the 2010 AAC Review:

1) Investigate whether O-rings in the discharge chamber can be exposed to excessive power loads and if so, devise and implement a mitigation strategy.

- *The baseline sources have delivered persistent beams for more than 4 years. No O-rings with significant heat-damage have ever been found. The O-rings are conditioned with the rest of the source and their emission apparently drops to an acceptable level by the time of cesiation.*
- *Prebaked O-rings and modified Ultra-torr fittings for the filter magnet housing are being used in the external antenna source. The beam output continues to decay.*
- *After establishing a source contamination monitor, it may be used to judge the benefits of prebaked O-rings and fitting modifications.*

2) Continue the development of the external-antenna RF ion source, employing short pulsed plasma gun.

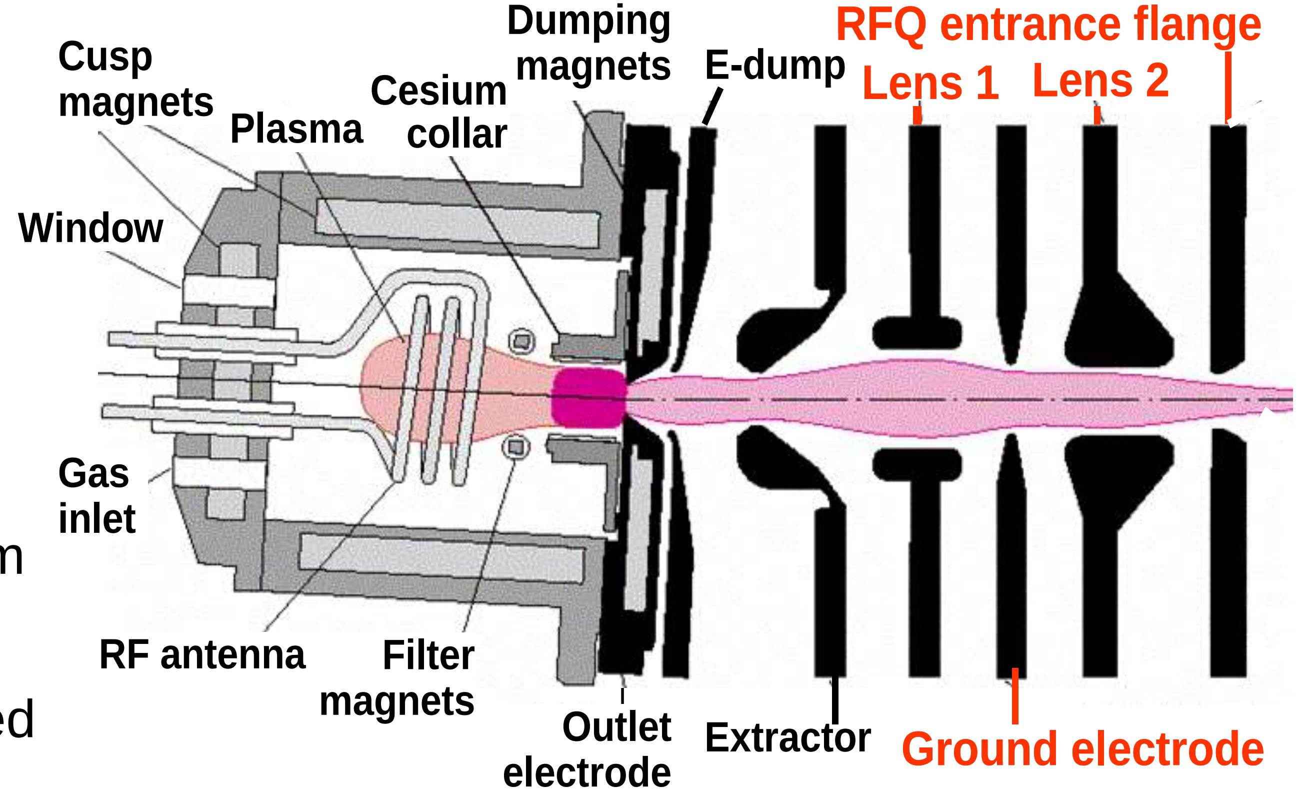
- *A practically sputter-free 13 MHz plasma gun was developed, however the beam degradation continues!*

3) Pursue a collaboration with the National Science Academy in Sumy, Ukraine, to develop and test a cesiated reverse magnetron at their facility:

- *Shrinking budgets did not allow for this effort!*

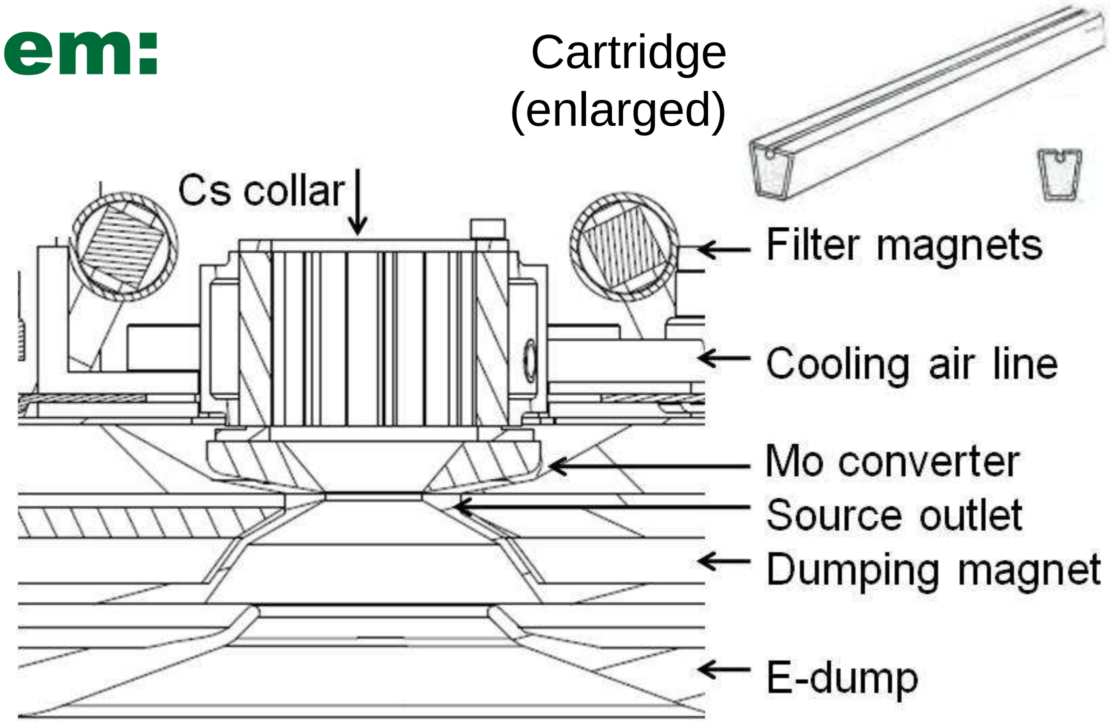
The SNS Baseline Ion Source and LEBT

- 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 and practically 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!***

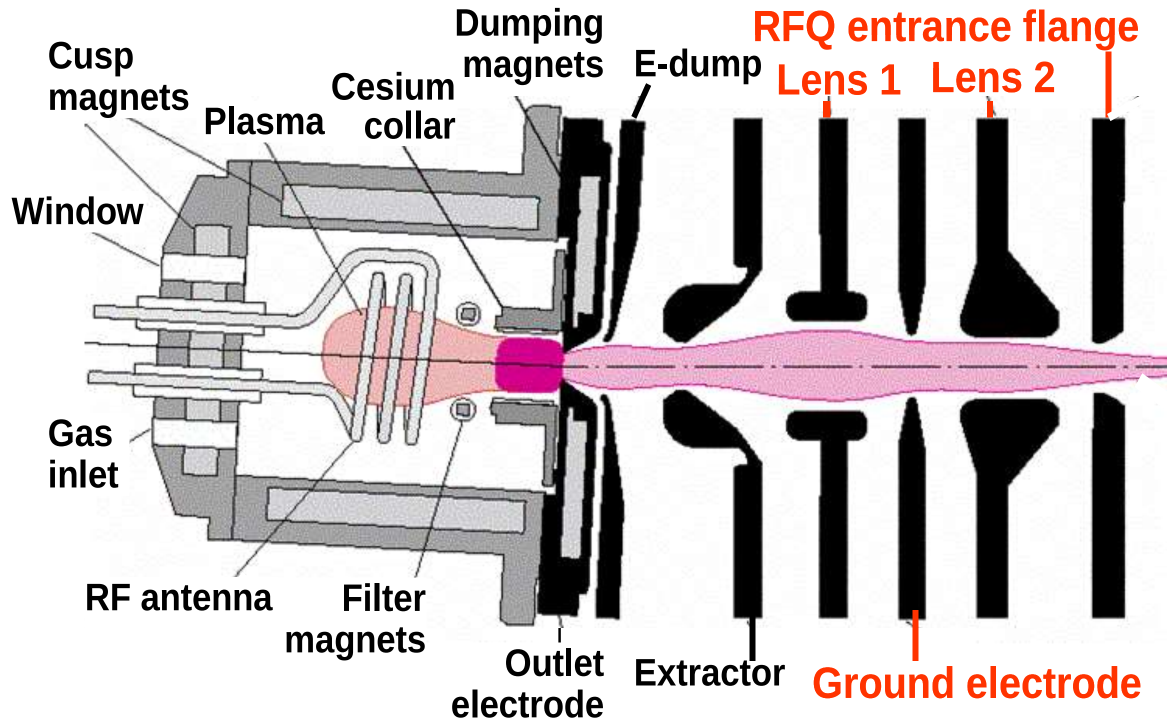
The Cs_2CrO_4 System:



- 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 and the Mo converter is sputter-cleaned for ~3 hours. Then the collar is heated for 10 minutes to 550°C to release ~3 mg of Cs. Then the temperature is lowered to ~180°C. This appears to produce an optimal monolayer of Cs, which appears to become persistent.
- After a few days the H^- beam becomes persistent.
- No beam decay or signs of age are normally noticed.

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

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 + 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) +1(>4) +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) +1(3) +2(0)	~98.5	three 5+-week cycles; inductance increased; grounded 2 MHz
2011-1	5.4% 4.4%	0.9 ms 0.73 ms	38	38-30	~60	1(22) +1(6) +1(2)	98.2%	Start frequency hopping; lower duty factor after 2nd failure; 2 source leaks
2011-2	4.4% 5.3%	0.73 ms 0.88 ms	38	38-30	~55	1*(1) 1 (9)	98.7%	*1 antenna fails at beginning of run; contamination of #2 & #4; 6 week run
^(lifetime of failed antenna)								



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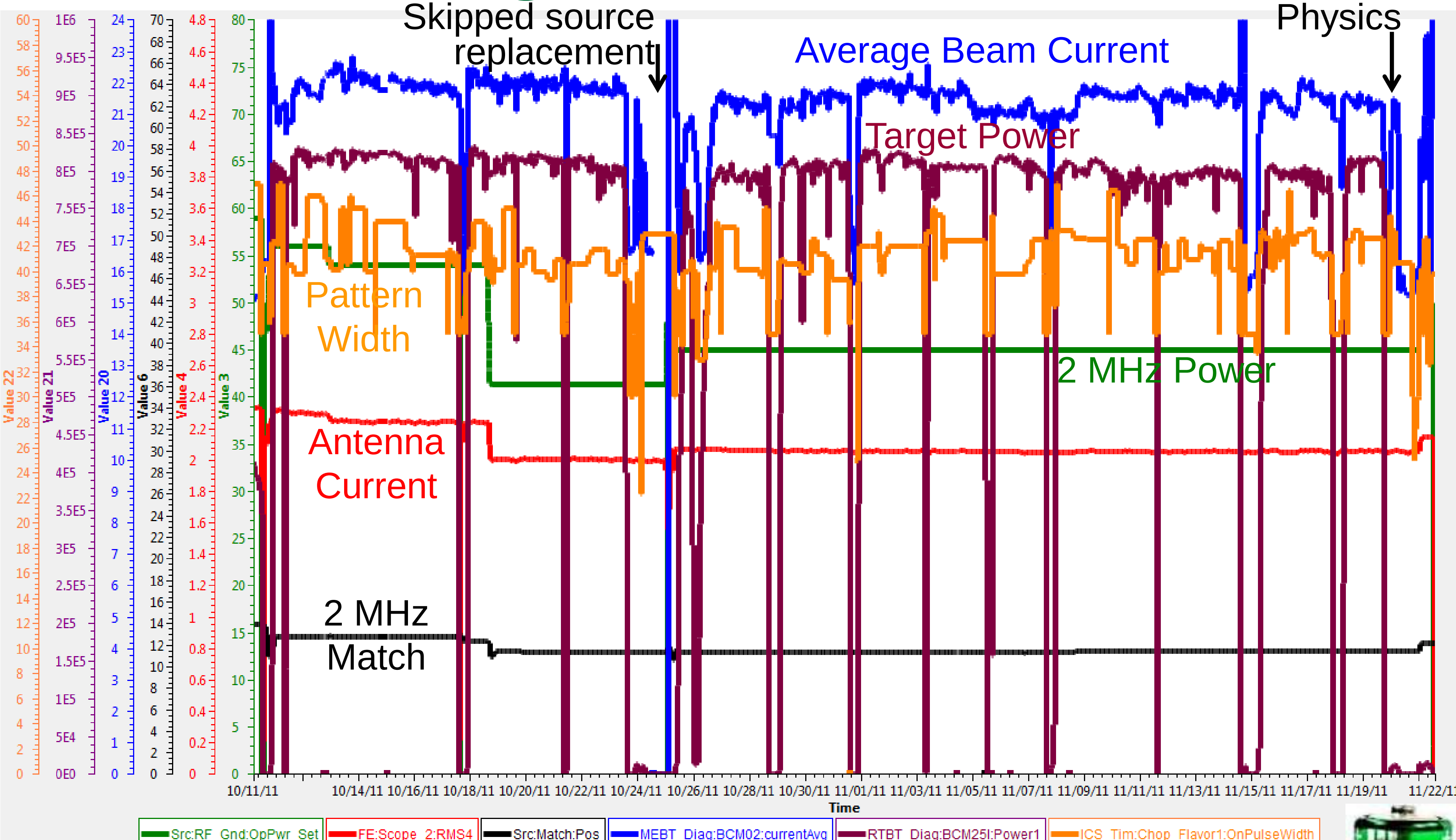
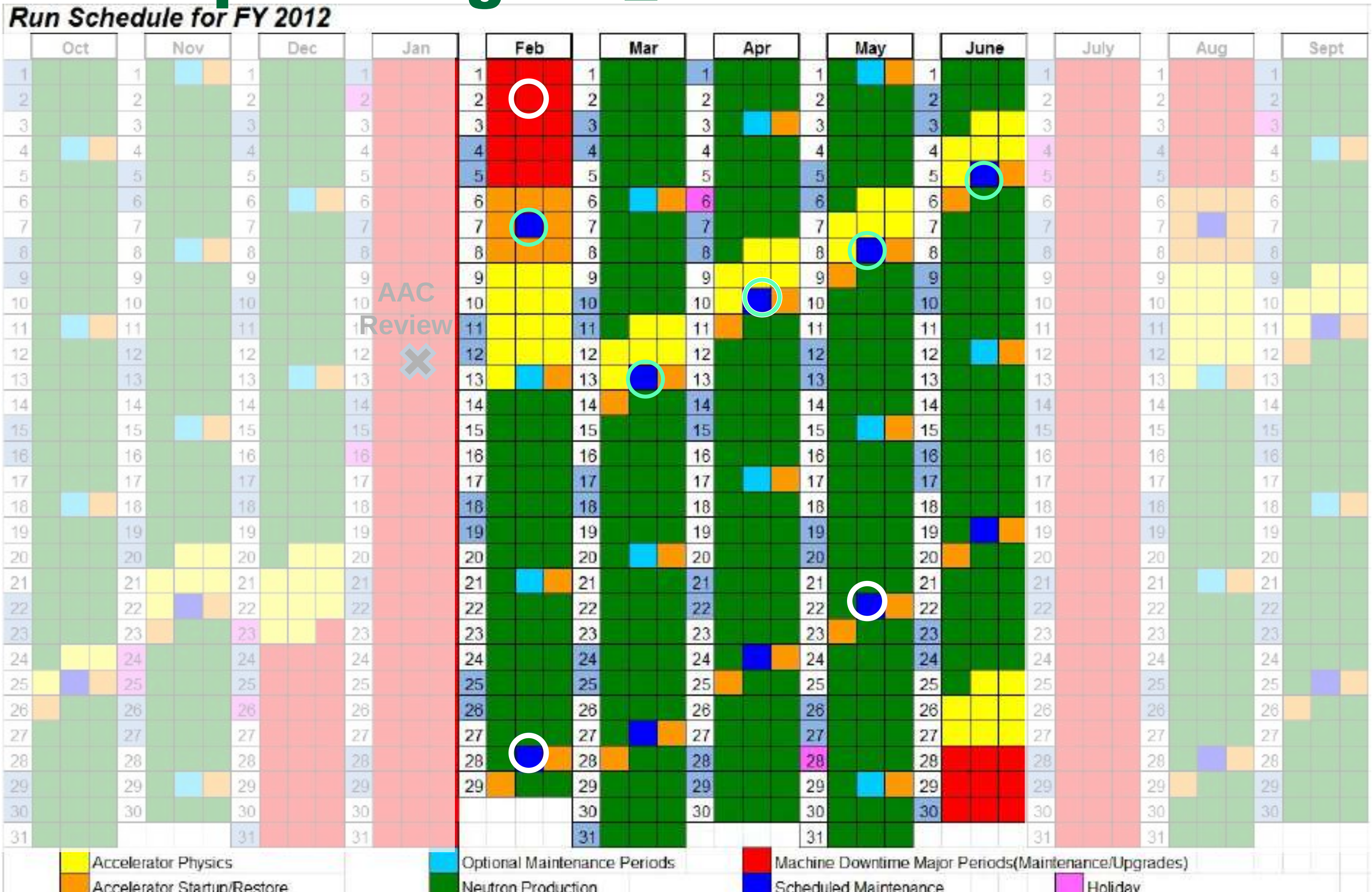
6 weeks of degradation-free 38 mA Beam



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

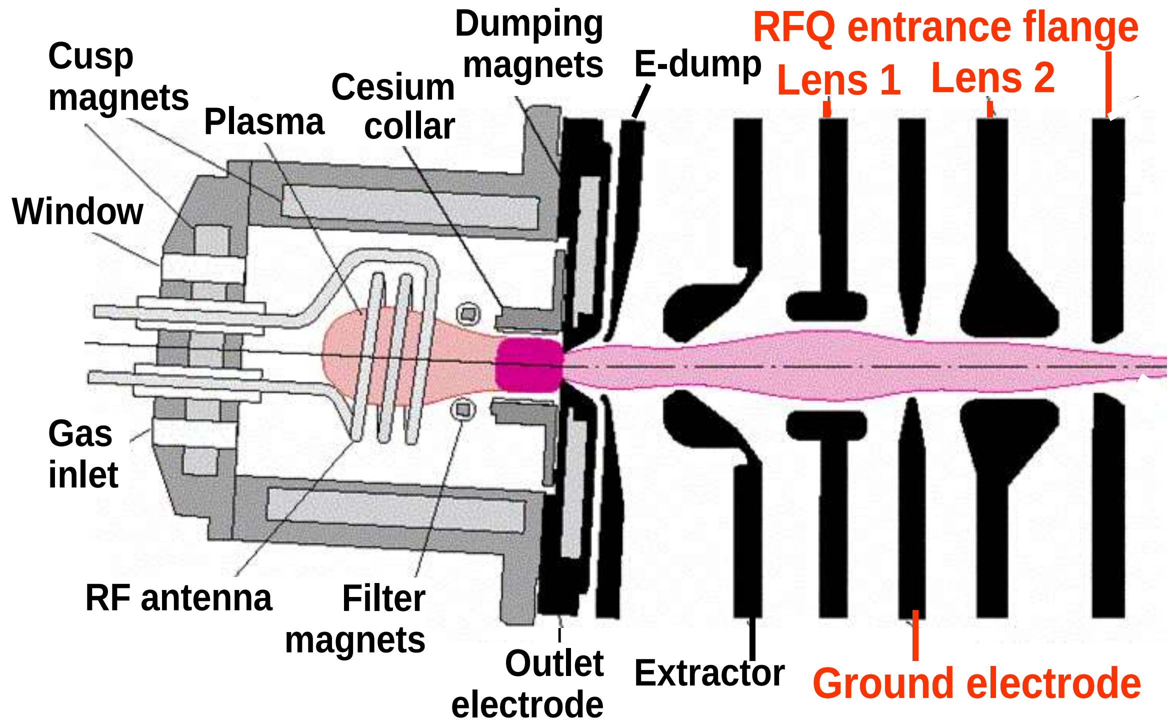
Finally, RF technology is extending the life times of ion sources!

Capitalizing on ≥6 weeks life time



Implementing a ~6-week source service cycle eliminates 1source change.

This frees up >10 hours for AP studies or Neutron Production!



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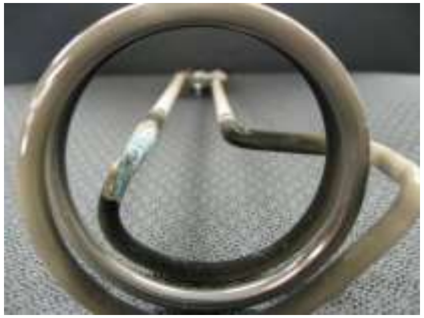
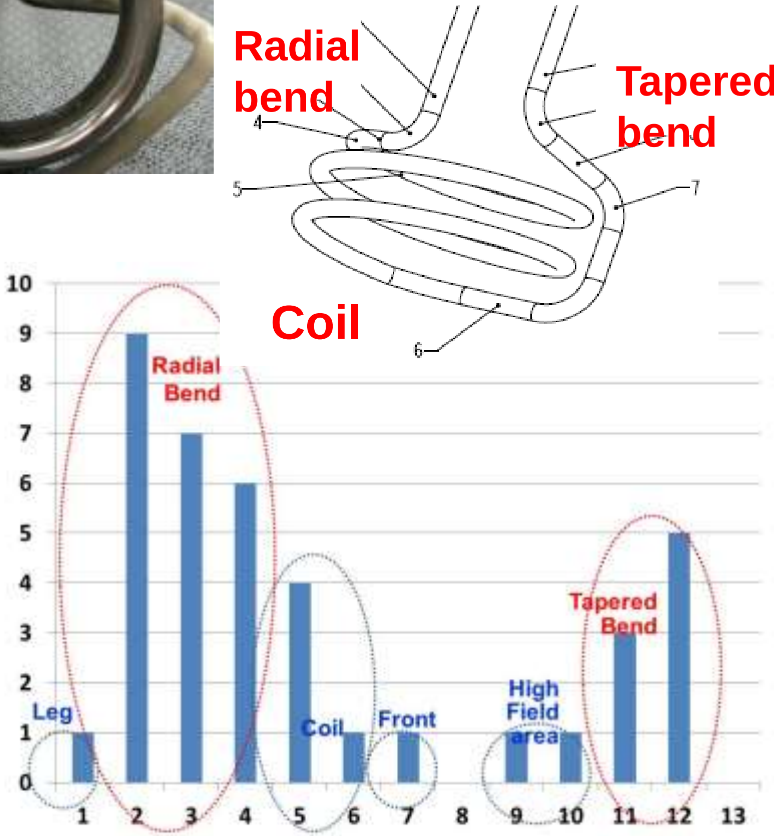
The SNS Antenna Problem

•Since raising the RF power to ~60 kW and the source pulse length to 0.9 ms in 2010, the antenna failure rate increased from ~1 per run to ~4 per run.

•Most antennas fail within the first week of operation, long before the end of the typical 4-week service cycle, which suggests infant mortality.



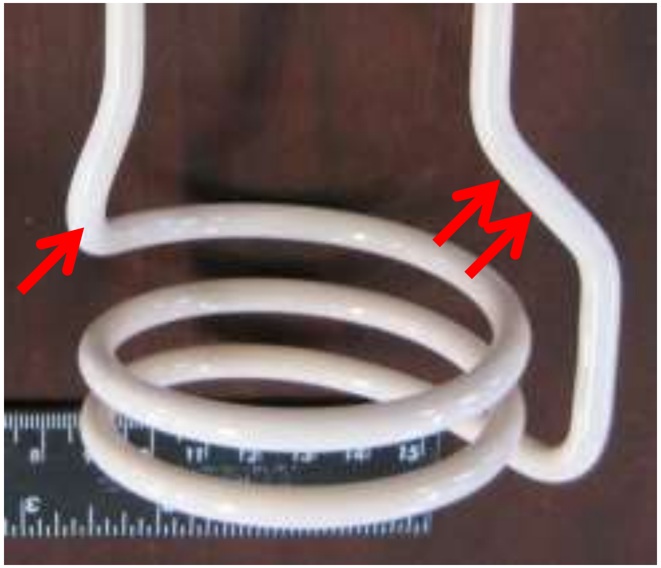
•Failure analysis shows that ~77% of antennas fail in the leg bends, which penetrate into the core of the plasma. Apparently intense heating combined with high porosity can drive the porcelain surface above the melting point, which destroys the insulation.

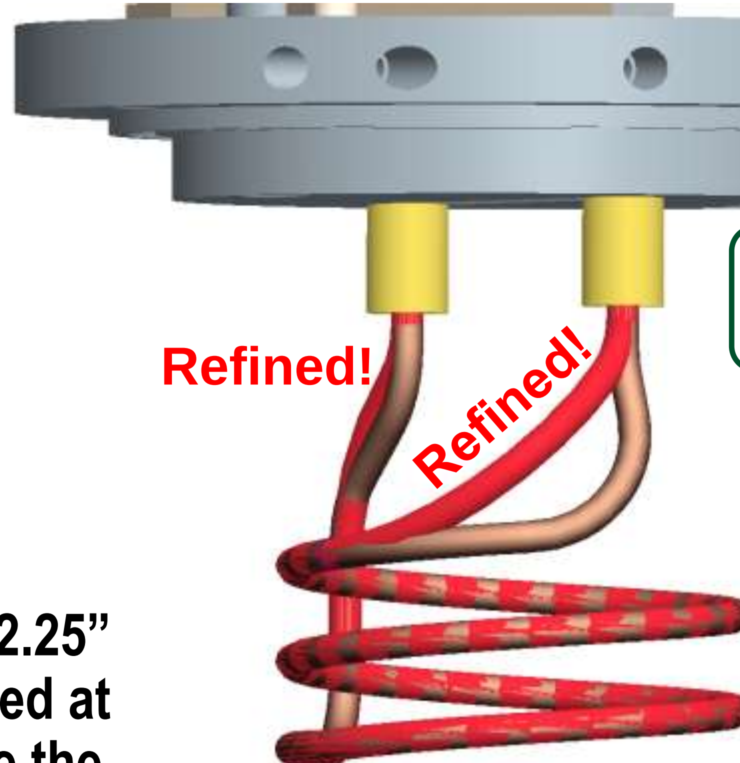


To reduce the number of antenna failures we

1. are extending the source service cycle
2. are testing thinner porcelain coatings
3. use tighter acceptance criteria in the leg bends and exclude any tangible surface imperfections
4. develop a relaxed radii antenna where the legs do not penetrate the plasma core
5. develop an external antenna source

Our Top Priority: Relaxed Radii Antennas

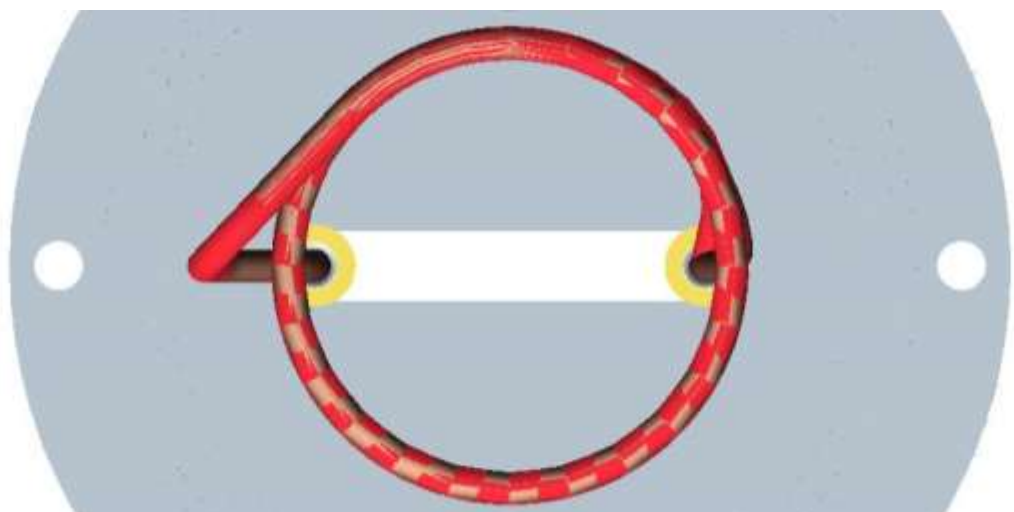


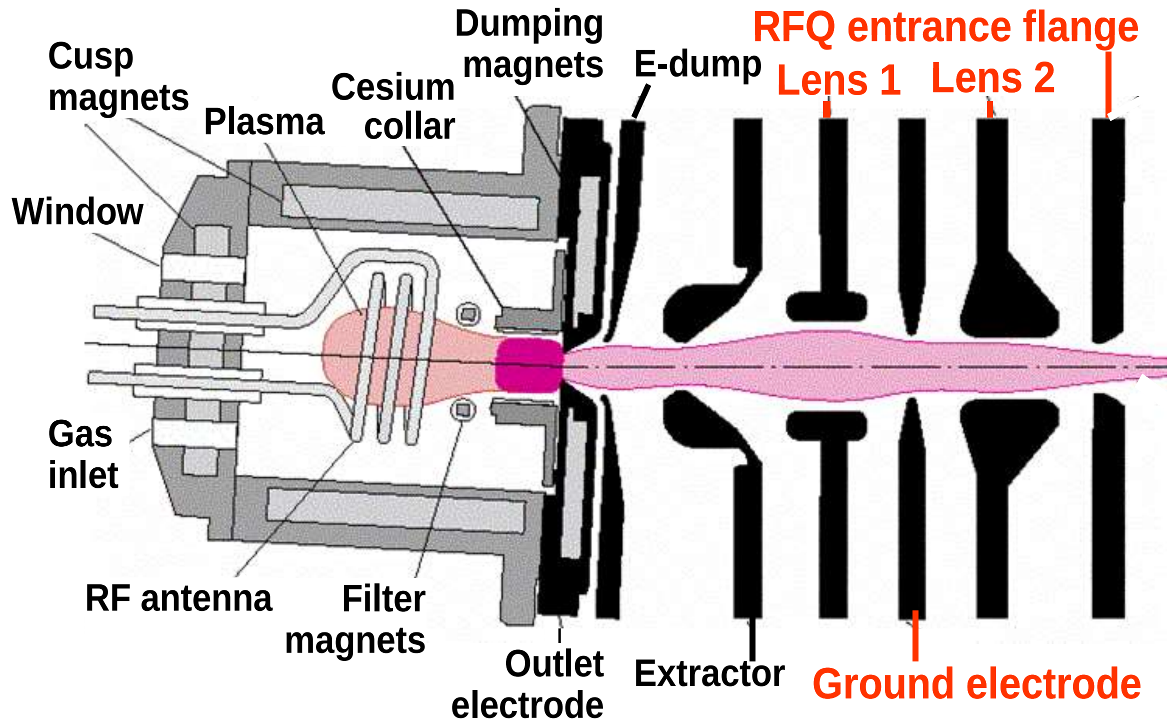


The antenna was redesigned with 2.25" between the legs. When being tested at high duty factor, some failed where the legs were closest to the plasma!

The design is being fine tuned by increasing the leg spacing to 2.50" and relaxing the radii to move the antenna legs as far as possible from the plasma core.

We expect testing in early 2012.





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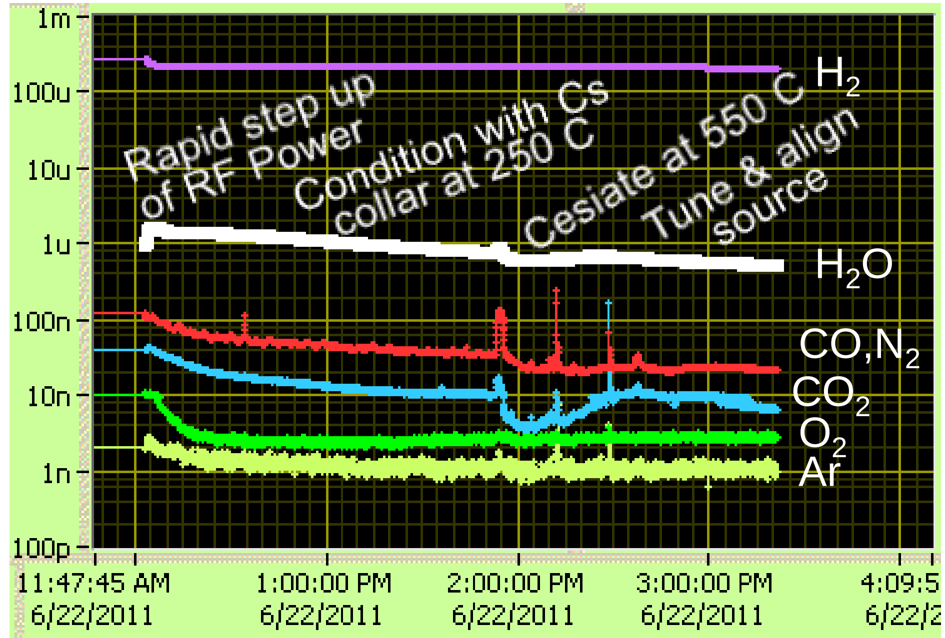
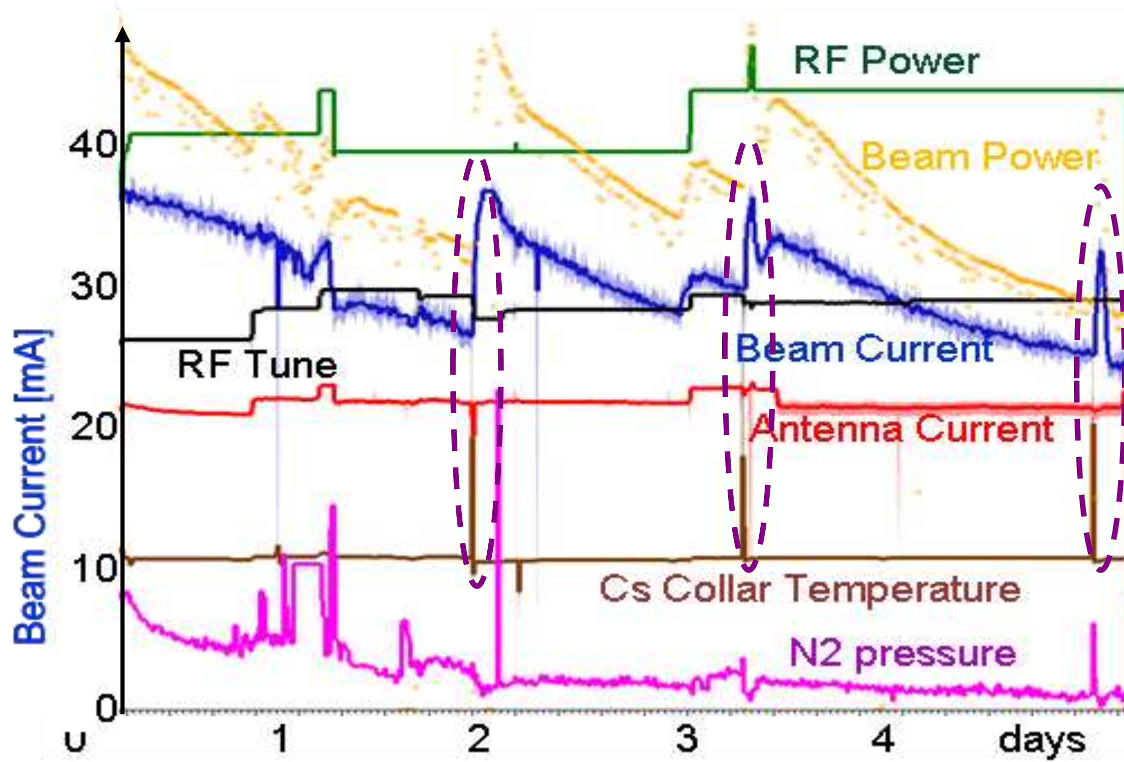
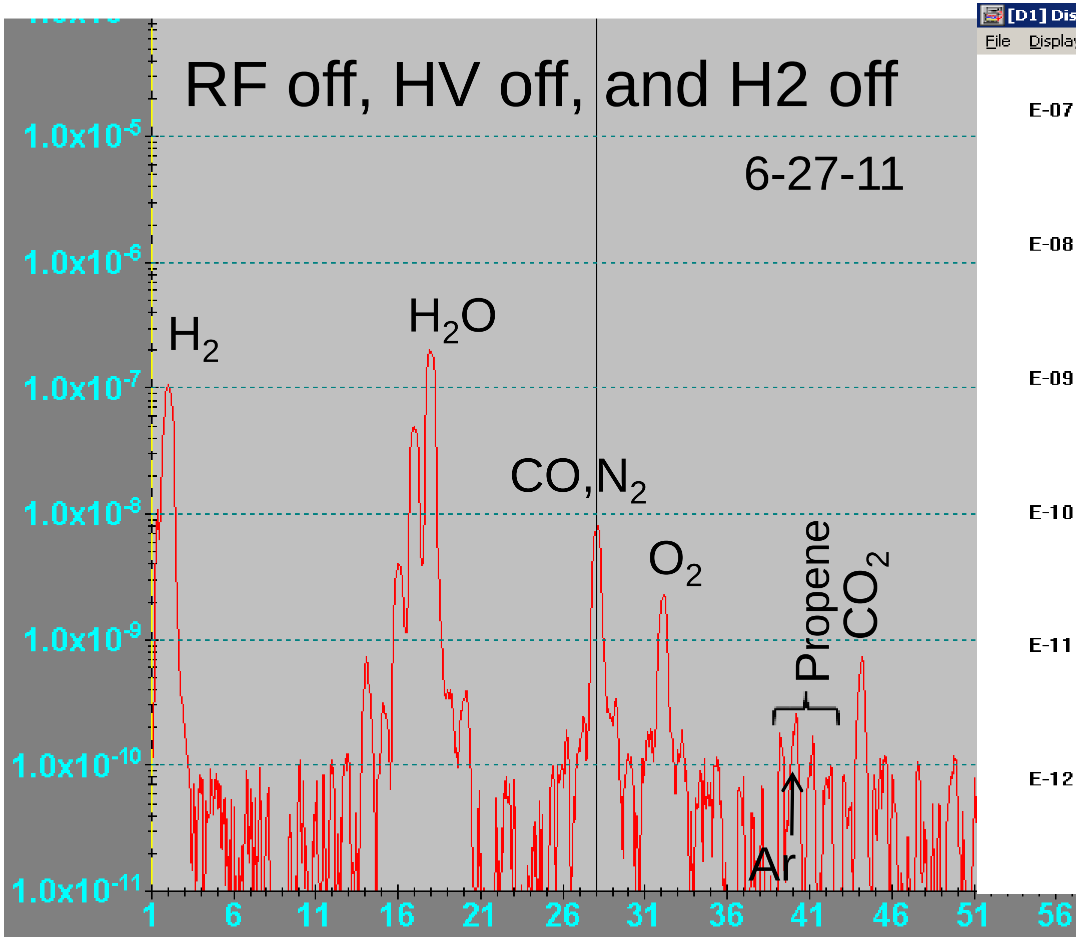
A Leaky Source

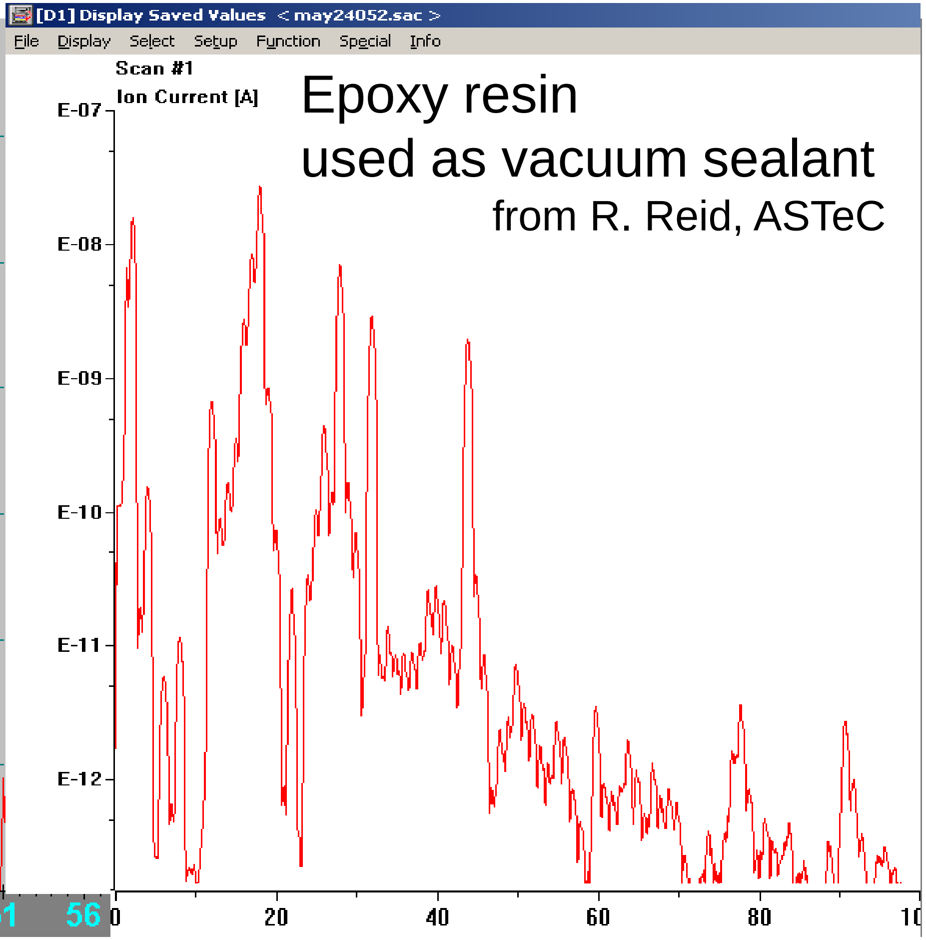
- June 22, 2011: Source #2 is installed and no leak is found with a He leak check.
- A smooth startup lowers all relevant partial pressures rapidly.
- Cesiation yields ~36 mA.
- However, the beam current decays at a rate between 1 and 2% per hour.
- Two recesiations restore temporarily most of the beam, but the decay continues.
- 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!





The LEBT Vacuum 101



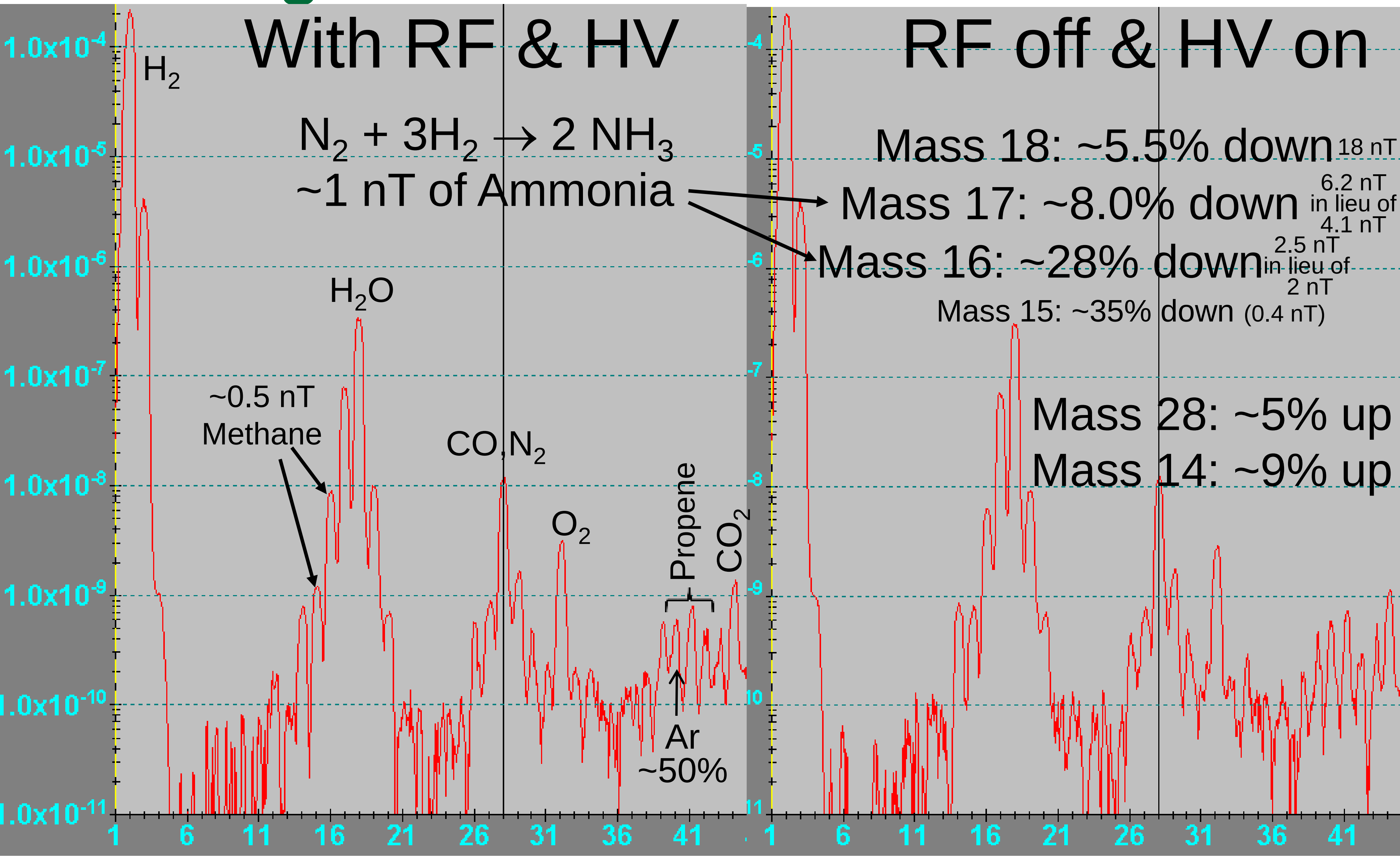


Looking at the LEBT RGA, air leaks are often suspected due to the high pp of mass 28 and 32.

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

The Staged Shutdown of Source #2!



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

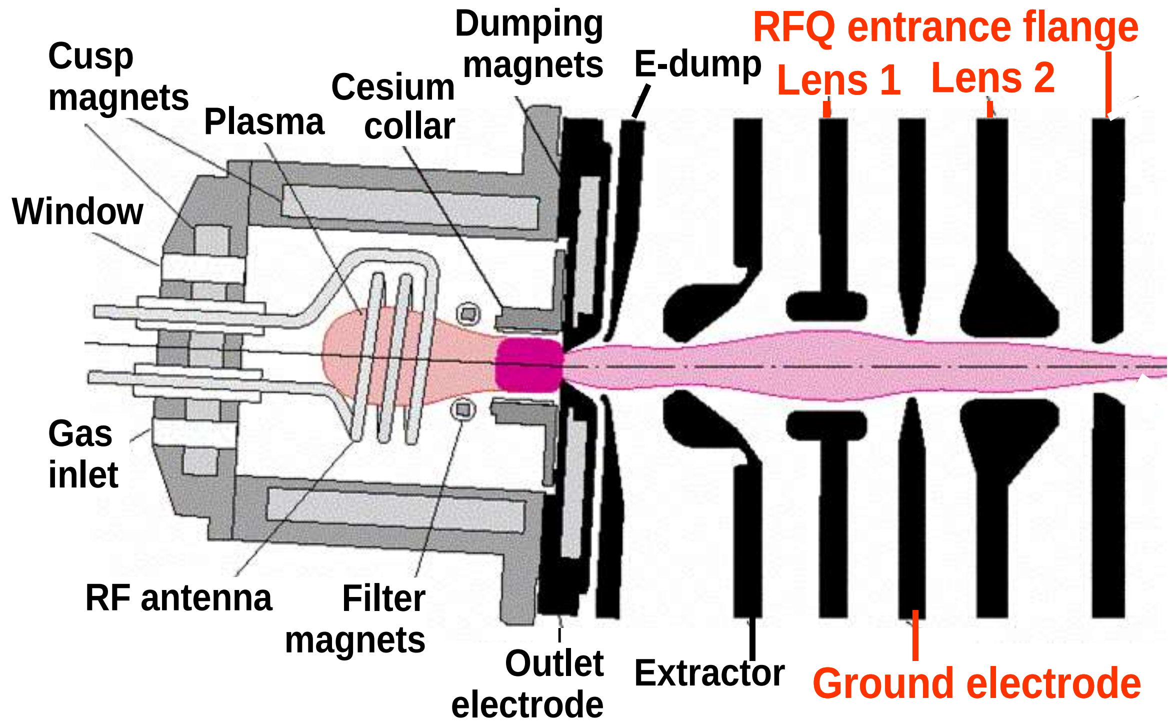
A ~10^{-10} leak in a window increased to ~10^{-6} when being heated by plasma!

Lessons from past Vacuum Issues

- The leaking window was an old style brazed mini-CF window.
  All windows have been replaced with new style brazed windows.
- Large leaks limit beams to a few mA, an immediate attention getter!
  The LEBT RGA will show a large increase of mass 40 (air) or 18 (water).
  We check the LEBT RGA for signs of large leaks every time before starting to condition and before starting to cesiate a new source!
- Small leaks are difficult to identify due to
  1. The large LEBT pumping speed
  2. The large emission of air-like components by the epoxy insulator
  3. The possible chemical conversion of the major components of air
  4. The interference of the major Ar peaks with propene (m=40) and water (m=20), both of which vary for several reasons.

  A constant beam decay is currently the most sensitive leak indicator!
  However, this becomes only obvious after ~ a day when expecting a persistent beam!

We continue to explore lowering our sensitivity thresholds through improved analysis of the RGA spectra and maybe optical spectra.



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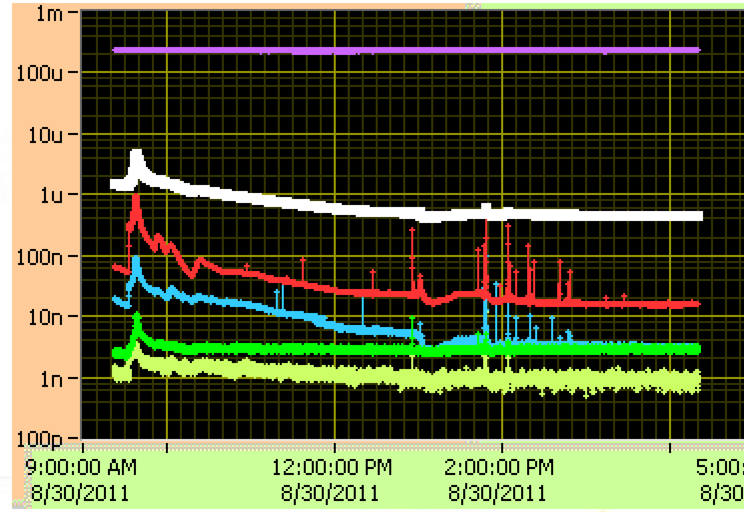
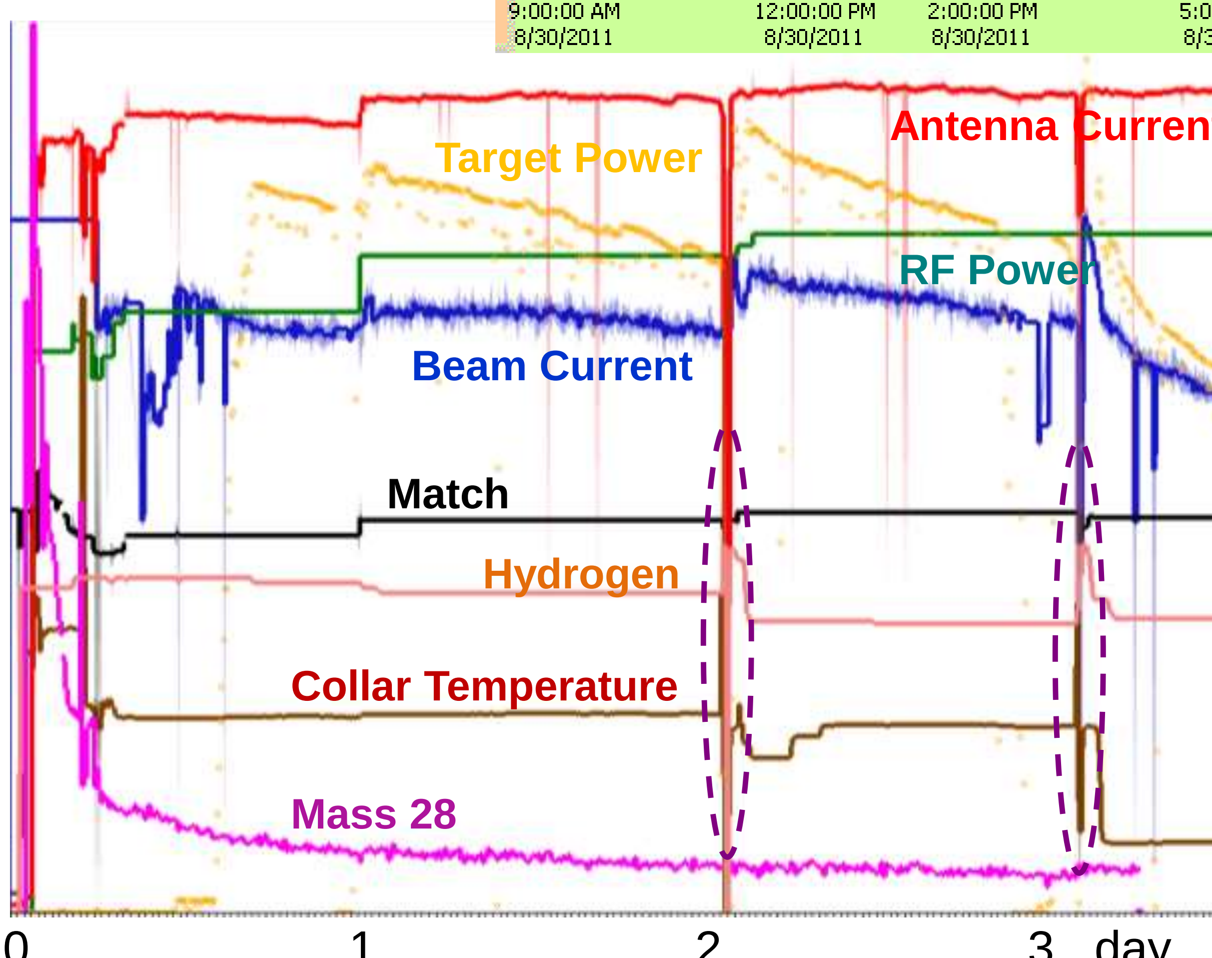
The First Poisoned Source

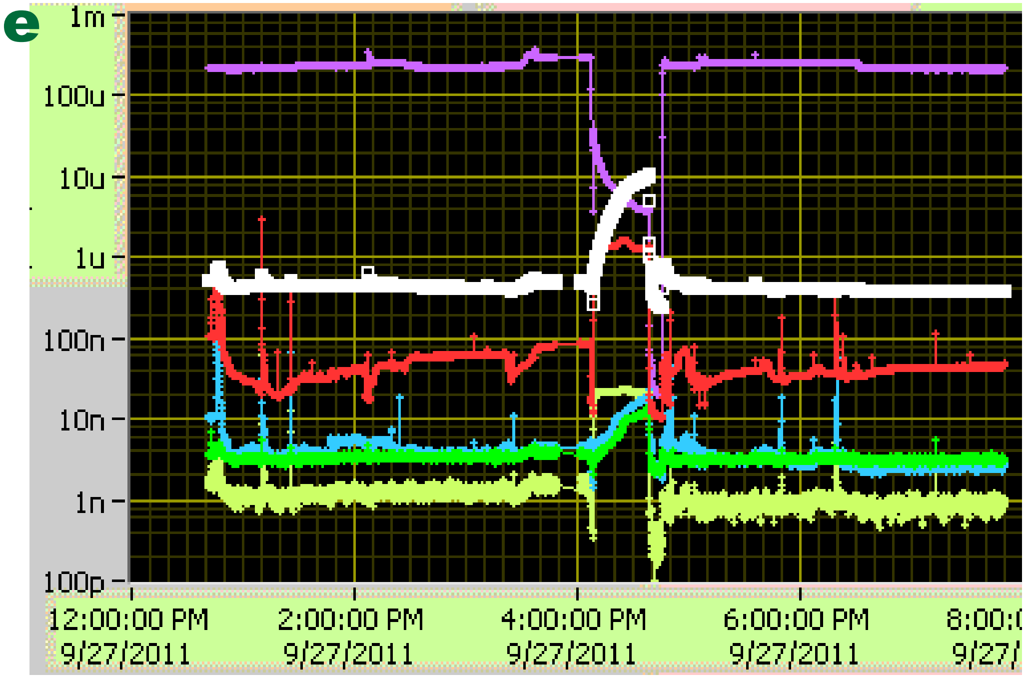


- August 30, 2011: Source #4 is installed and no leak is found with a He leak check.
- A smooth startup lowers all relevant partial pressures rapidly.
- Cesiation yields ~31 mA.
- The beam current decays by 11%/day.
- A 3rd day recesiation raises the beam current by ~15%, and the beam loss to 15%.
- 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 initially runs normal.

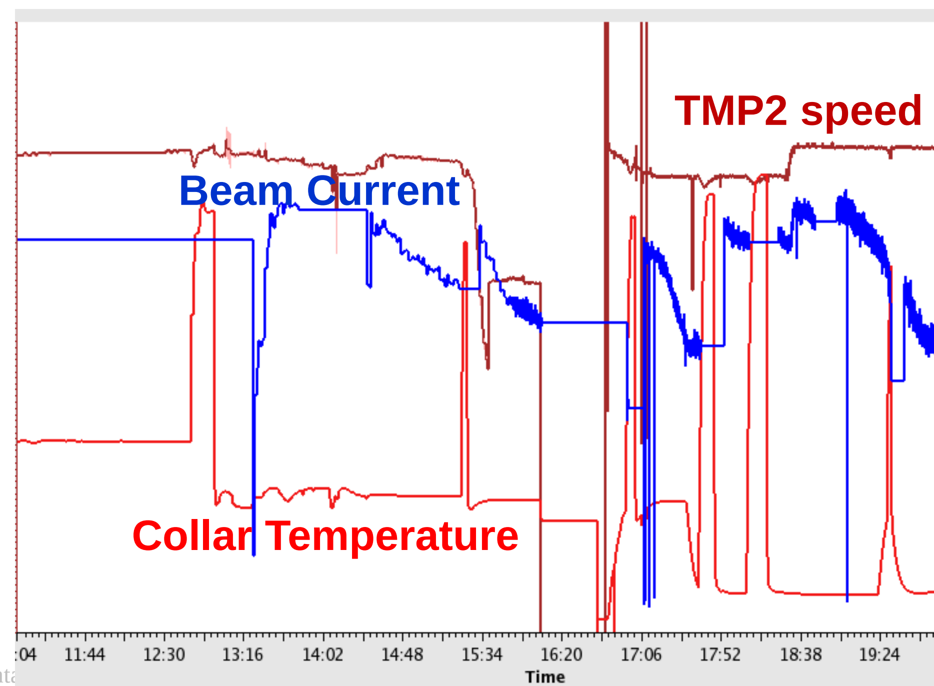


A gravely Poisoned Source

- September 27, 2011: Source #2 is installed and no leak is found with a He leak check.
- The startup is smooth, but excess of mass 28 and 32 are noted.
- Cesiation yields ~33 mA.
- The beam current decays by ~18%/hour, while mass 28 & 44 rise.
- A recesiation increases the beam current, but accelerates the decay.
- The RGA shows large amounts of CO, CH_4, and C_3H_6.
- TMP2 fails due to lack of cooling water. Water blockage found, removed, and restarted.

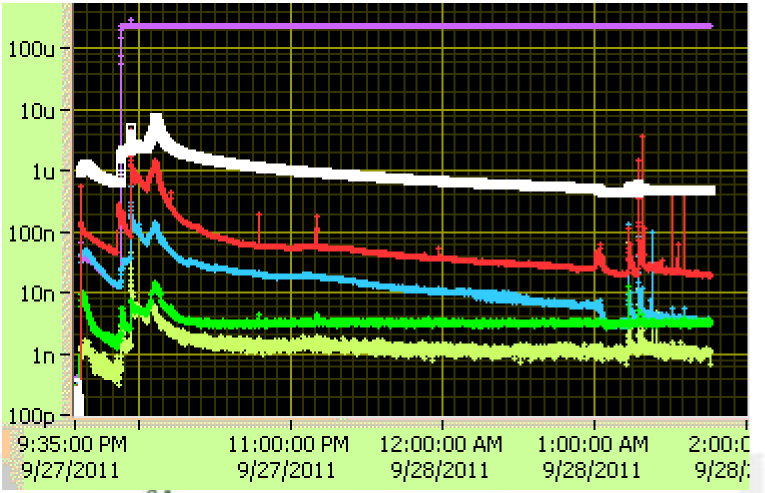


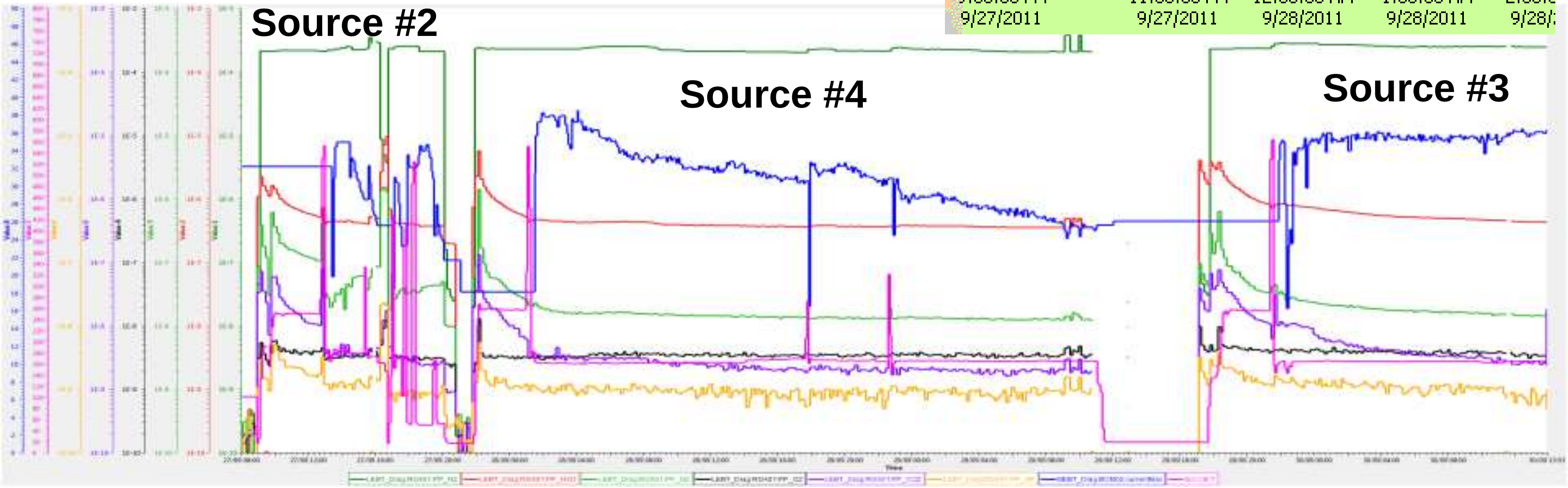
- Numerous recesiations can restore the beam but do not improve the beam decay
- Lowering the collar temperature slows the decay rate, but it remains near 20%/hour.
- **Beam rises show that Cs is delivered, but it does not stick!**
- **This is consistent with a severely poisoned Mo collar!**



Source #4 Poisoning confirmed

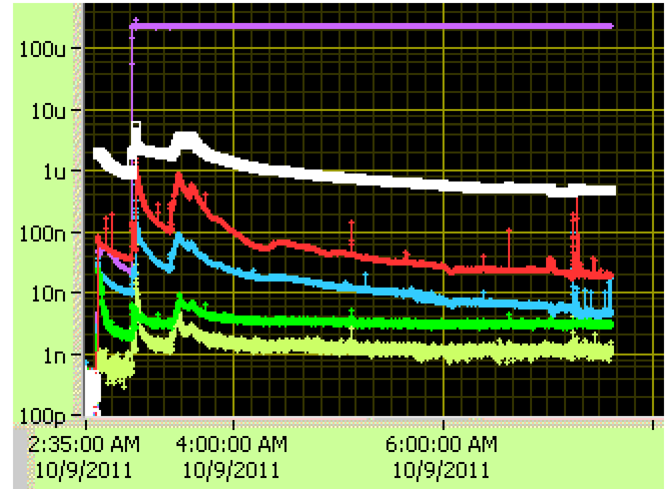
- The same evening, September 27, the severely poisoned source #2 is replaced with the refurbished source #4.
- Nothing unusual is noted during startup, which yields ~36 mA.
- However, the beam decays with ~1% per hour.



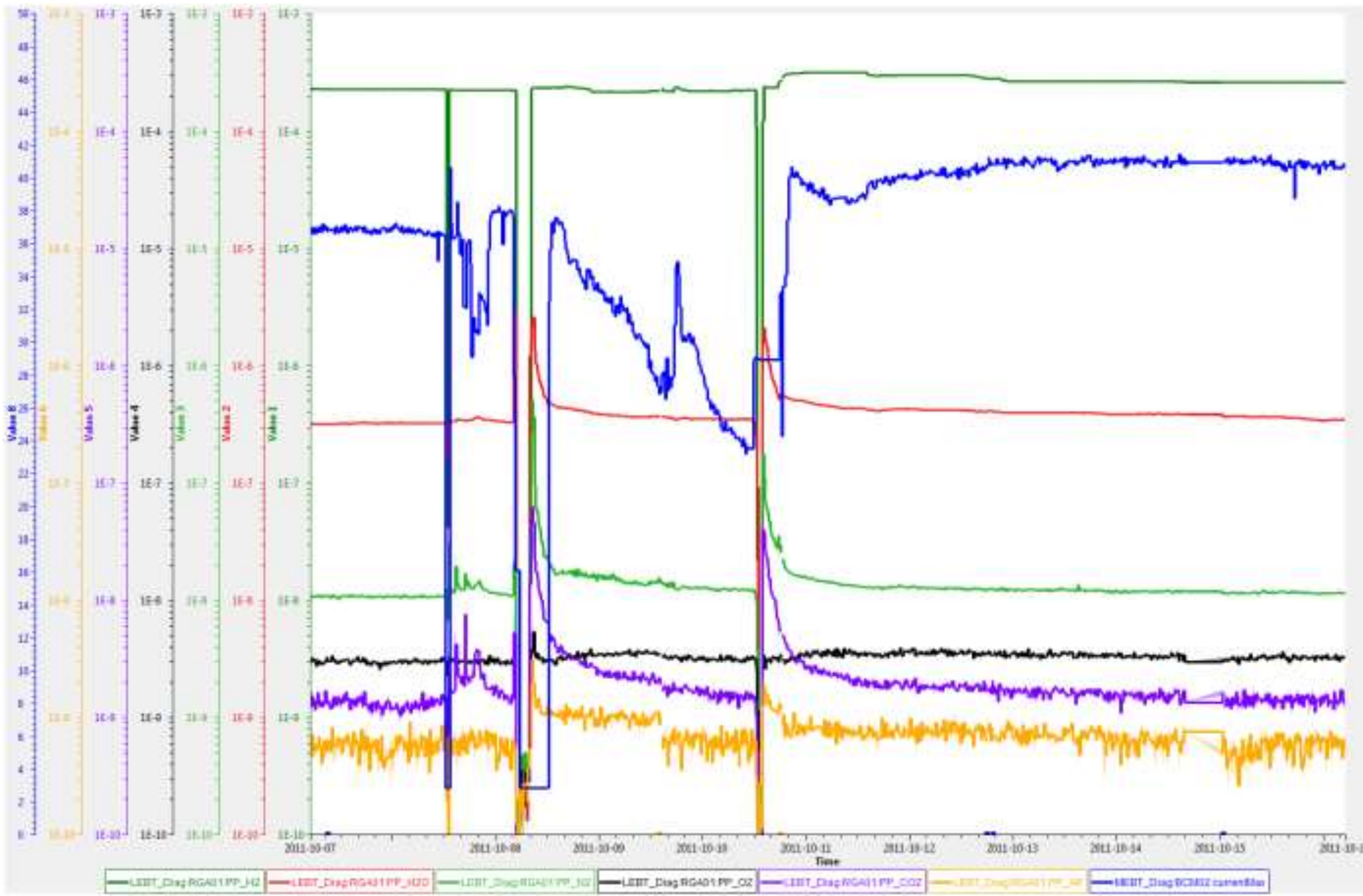


- Timid recesiations restore some of the beam but do not stop the decay.
- Extensive leak checking reveals no leak;
- Activating the rotary feedthrough of the LEBT gate valve raises the pressure.
- The rotary feedthrough of LEBT gate valve is replaced with a blank.
- Source #3 starts up under heavy LEBT arcing which continues for several days.
- The degraded LEBT vacuum requires a low lens-1 voltage, yielding ~34 mA.

Source #4 Poisoning reconfirmed

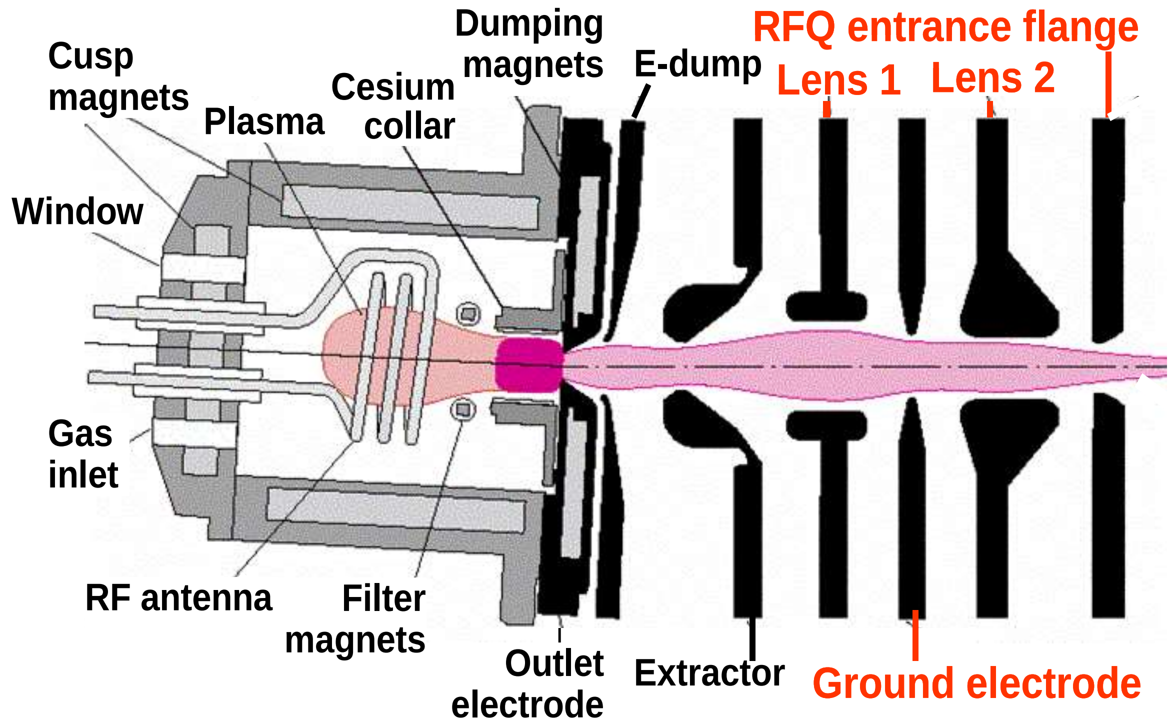


- 10-8-11: A lens-1 event requires lower lens-1 voltage.
- Beam hits lens-2 and becomes unstable.
- Retune restores 38 mA.
- 6 hours later the antenna fails.
- Source #4 starts up normally, yielding ~34 mA.
- It decays with ~1%/hour .
- Clearly, the rotary feedthrough was not the problem.
- A Monday cesiation briefly restores the beam, which rapidly decays back to the 1% slope.
- Source #3 is installed on maintenance day and starts up with ~36 mA.
- It decays for ~12 hours, but then starts growing.
- This source made more than 800 kW.



Discussion of Source Poisoning

- **Initially we suspected turbo pump oil, which now is seen by the RGA but not before. However, source #3 recovered easily from it.**
- **Beginning November we found a tear in the diaphragm of the drypump, which was used to pump down the sources for storage.**
- **Apparently microscopic rubber dust contaminated mostly source #2, to a lesser degree source #4. The dust produced the hydrocarbons, which are heavy enough to sputter away our persistent Cs layer. No traces of the rubber dust was found in either source nor the ion source storage cart.**
- **The two poisoned sources seem to gradually recover every time they are being used. Neither aggressive cleaning nor Ar sputter cleaning did appear to drastically improve their persistence.**
- **The ion source storage cart is being redesigned and rebuilt to prevent such occurrences in the future. In addition gauges are added to characterize the sources for their "dryness" before being installed in the front end. Such data should help to better understand and fine tune the drying and conditioning processes.**
- ***We are working towards assembling ion sources and LEBTs in a class 10,000 clean room.***
- ***We are working on a fitting routine for RGA data, which should lower the detection thresholds for impurities.***



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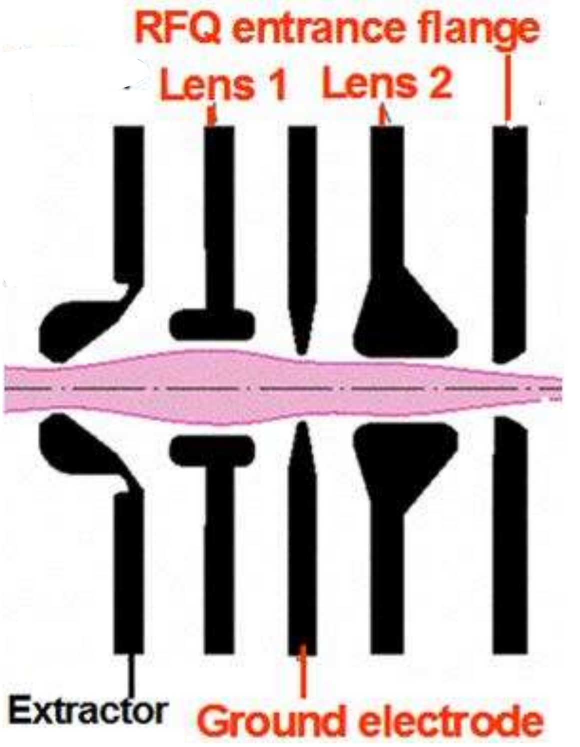
The State of the e-LEBT:

- We continue to control the partial pressure of water with “dry” installations of “dried” spare sources.
- Cesiation time was reduced to ~10 min. or ~3mg Cs.
- Revised procedures practically eliminated most LEBT arcing during source startups and restarts.
- Optimized pumping and tighter source assemblies lowered the LEBT pressure by ~40%.
- The Electric Group has eliminated the LEBT chopper failures by implementing smart protections.
- We started to monitor sputtering from the LEBT chopper target and from intersegment arcing, which coats the intersegment insulators of lens-2.
- Uncontrolled beam losses and corona discharges lead to a lens-1 failure, causing ~2 days downtime.
- A subsequent similar event was mitigated by venting the LEBT for 20 min. with N_2 and running with a reduced lens-1 voltage.
- Since then, the lens-1 voltage is lowered every time the load current exceeds a certain threshold.

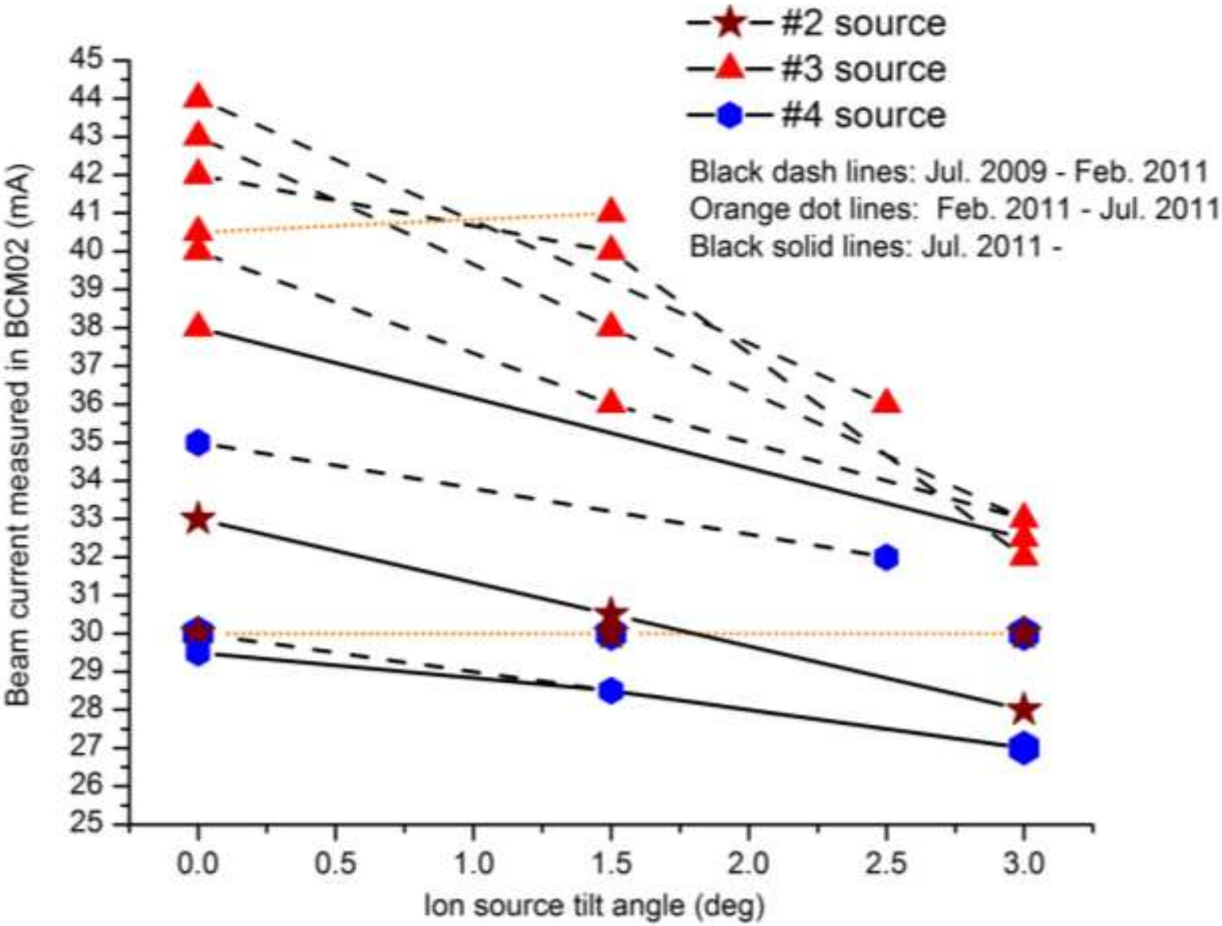
We work towards using the supply’s current limit to prevent the overheating of lens-1!



Ion Source Tilt and Offset Experiments

Courtesy of B. Han

- Design estimation and the first few years' operation experience showed 2.5-3.0° tilt angle be the optimal for maximizing the beam in the BCM02
- Starting in July 2009, we found more BCM02 beam currents with the ion source at smaller tilt angles. The beam always peaked at a 0° tilt angle for the next three ~0.5 year LEBT service cycles, using different LEBTs and all three different ion sources.
- However, in the first half of 2011, the BCM02 beam current showed no significant dependence on the tilt angle. The angle was set to 1.5°.
- Starting in July 2011, with a newly refurbished LEBT, the BCM02 beam current peaks again at 0° tilt.
- It is unclear why the BCM02 beam current peaks near 0° tilt, and not at the design angle of 3°.



To get consistently high LINAC beam currents, we need to understand the LEBT beam transport and alignment issues.

The Evolving LEBT Maintenance Program:

- Sometimes during run CY11-1, the LEBT dropped by ~0.5 mm with respect to the RFQ. Evaluating the optimized steerer voltages suggest that the typical LEBT alignment is normally within 0.2 mm, a small fraction of the 10 mm extractor I.D. and the 7.5 mm RFQ entrance.
- It was also found that the extractor shifted from the LEBT axis ~0.3 mm.
- During run CY11-2, the LEBT stayed in place, the extractor shifted ~0.7 mm.

Our biannual LEBT maintenance is designed to prevent downtime and more recently to document the alignment of each LEBT:

1. The post-service lens-2 intersegment leakage currents and voltage holding capability are being measured.

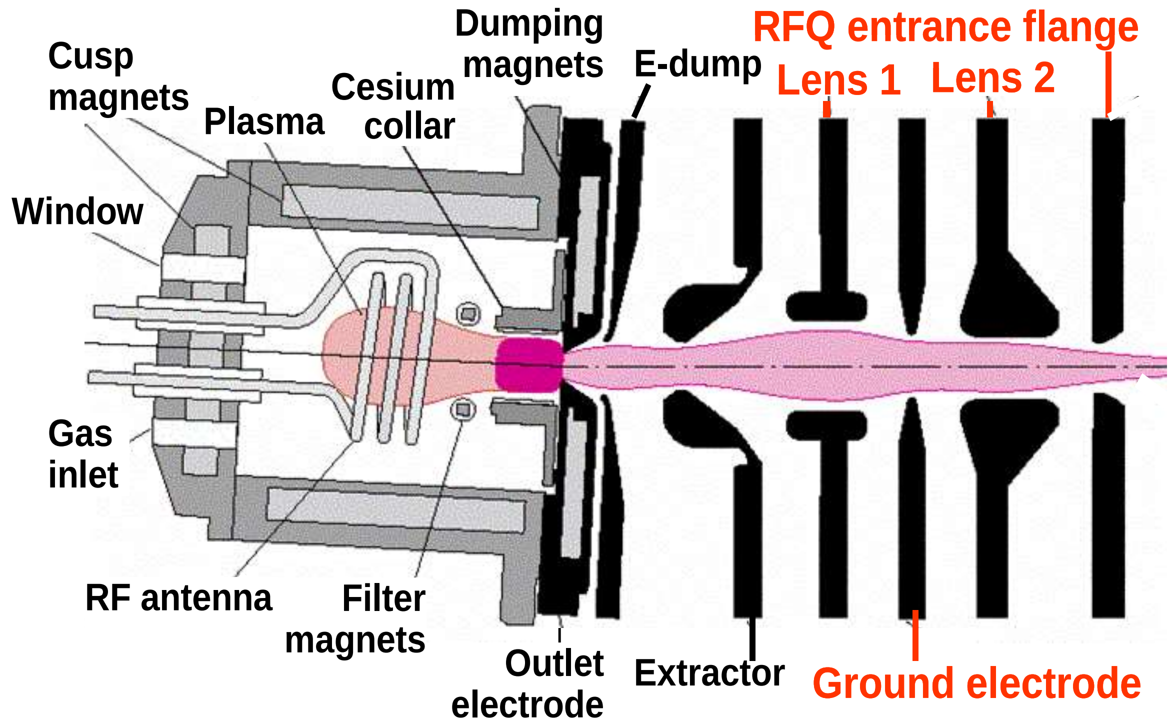
2. The post-service LEBT versus the RFQ alignment is evaluated.

3. The LEBT is replaced with a refurbished, pre-aligned LEBT, which is aligned against the RFQ.

4. The transverse voltage holding capability is then measured for each of the four 4-segments of the refurbished lens-2.

5. The new LEBT is conditioned and tested with different sources for 2-3 weeks.

6. The post-service LEBT is gradually disassembled, while evaluating and documenting any inter-LEBT misalignments.



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Long Term Priority: Developing a robust LEBT, which meets or exceeds the performance of the baseline LEBT

Electrostatic LEBTs are very cost-effective.

The strong electric fields prevent any sizeable beam neutralization.

Their compactness limits space-charge driven emittance growth.

However, the electrically (and thermally) isolated electrodes can heat up due to uncontrolled beam losses and discharges, which caused ~ 2 days of downtime in 2010. However, a smart current control appears to keep this issue under control.

To meet or exceed the performance of the baseline LEBT, a new LEBT has to demonstrate that it can achieve or surpass

1. The stability of all beam parameters during most of the 1 ms long pulses
2. The actual beam size measured near the entrance of the RFQ
3. The actual beam convergence near the entrance of the RFQ despite being compressed over an up to 7 times longer distance

While the physics models predict success, incompleteness of the models require a proof of principal that those requirements can be met.

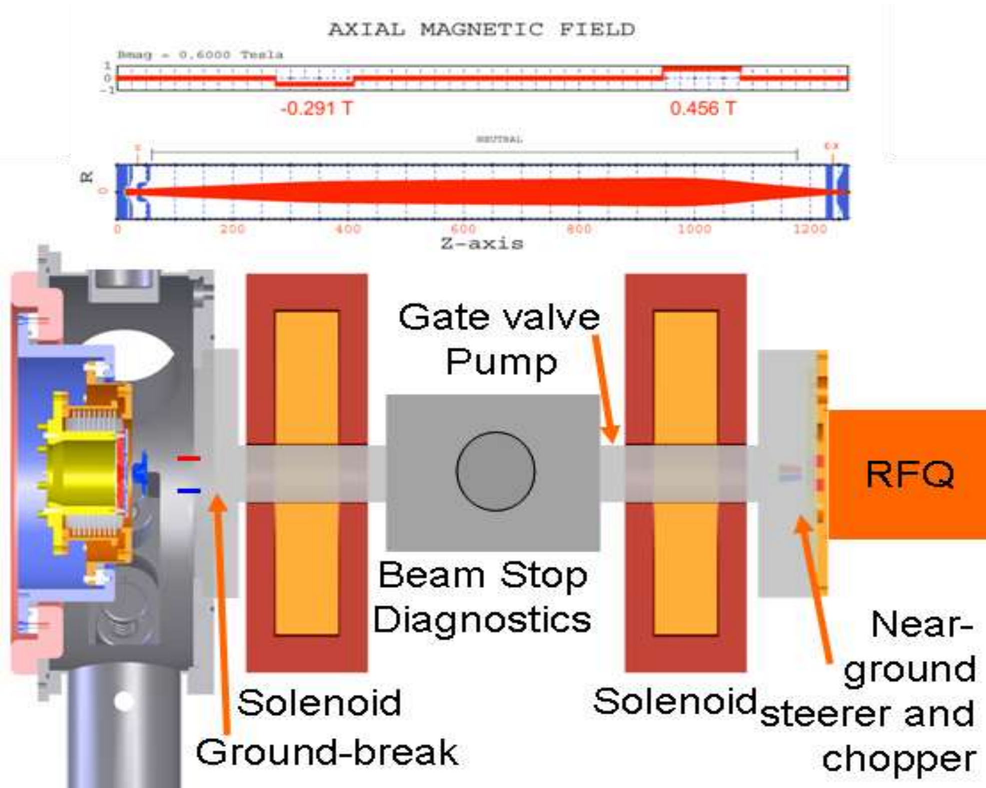
The emittance measurements will be executed with Allison scanners

One emittance scanner will be modified to measure the beam rise times

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 may 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.

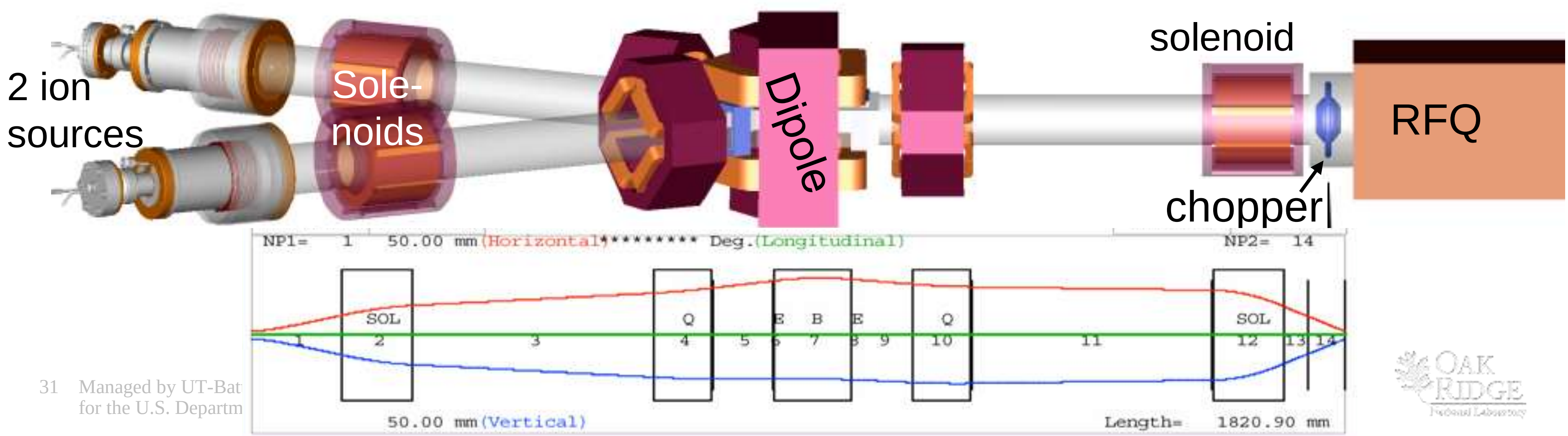


Superior availability with a 2-source LEBT

Far superior availability can be obtained with a 2-source LEBT: when one source fails, Operations can switch to the other source in less than one hour. This mitigates the risks of lifetime limits and premature failures, which surface when ion sources are pushed to very high performance levels.

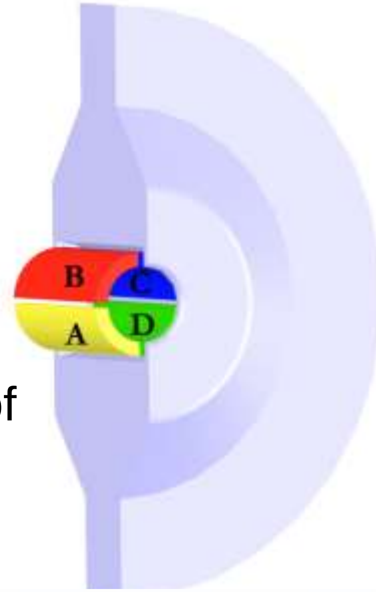
- Symmetry minimizes tuning: Reverse the dipole and fine tune!
- Both ion source beam lines feature a full-power beam stop, emittance scanners, pumps, and a vacuum gate valve: While the new source is in production, the failed source is replaced with a spare. The spare is conditioned, tuned, and completely checked out before being turned over to Operations.

Such source switching magnets are common, but they are normally not built to stringent requirements. After demonstrating requirements with the 2-solenoid LEBT, a 2/3 prototype will be built to 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



Alternative: Eliminate arc-induced chopper failures with a shielded, near-ground chopper for the e-LEBT

- If the prototype 2-solenoid LEBT fails to meet the 3 requirements, and chopper failures cause again significant downtime, 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 show that lengthening the chopper and increasing the aperture of the 2nd lens allow for complete chopping of the beam. However, the load on the LEBT chopper target is higher!



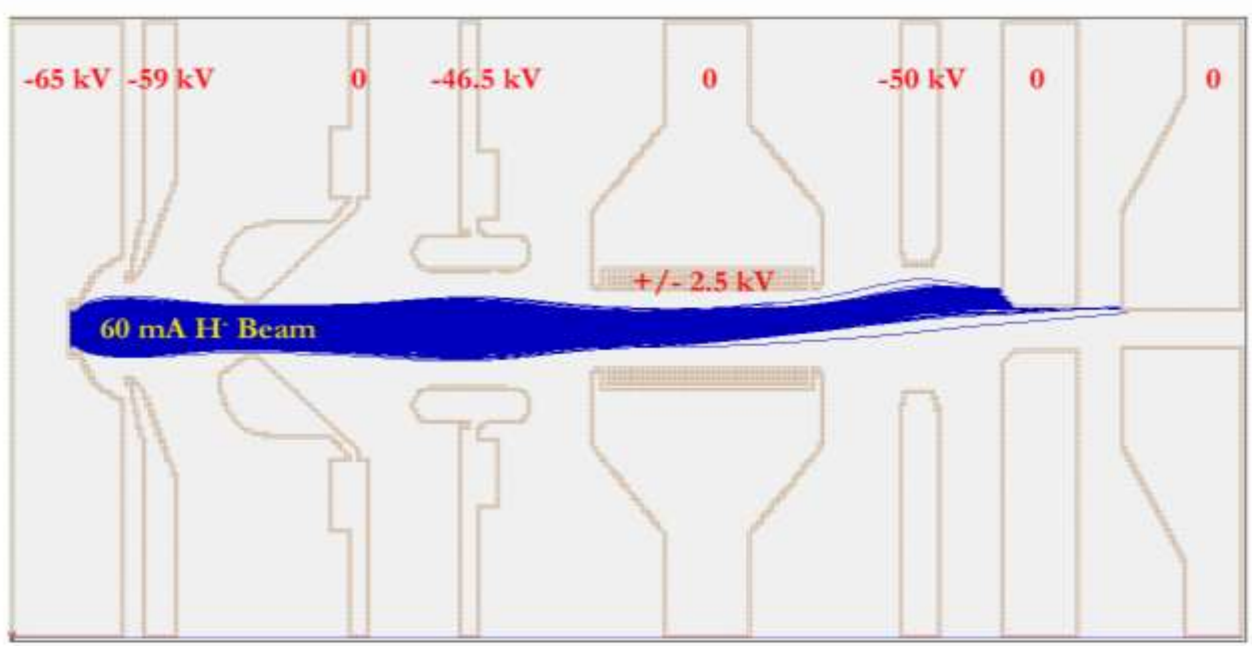
If the 2-solenoid LEBT cannot meet requirements, a prototype will be built for the test stand. We will demonstrate that the beam at the LEBT exit

1) is stable

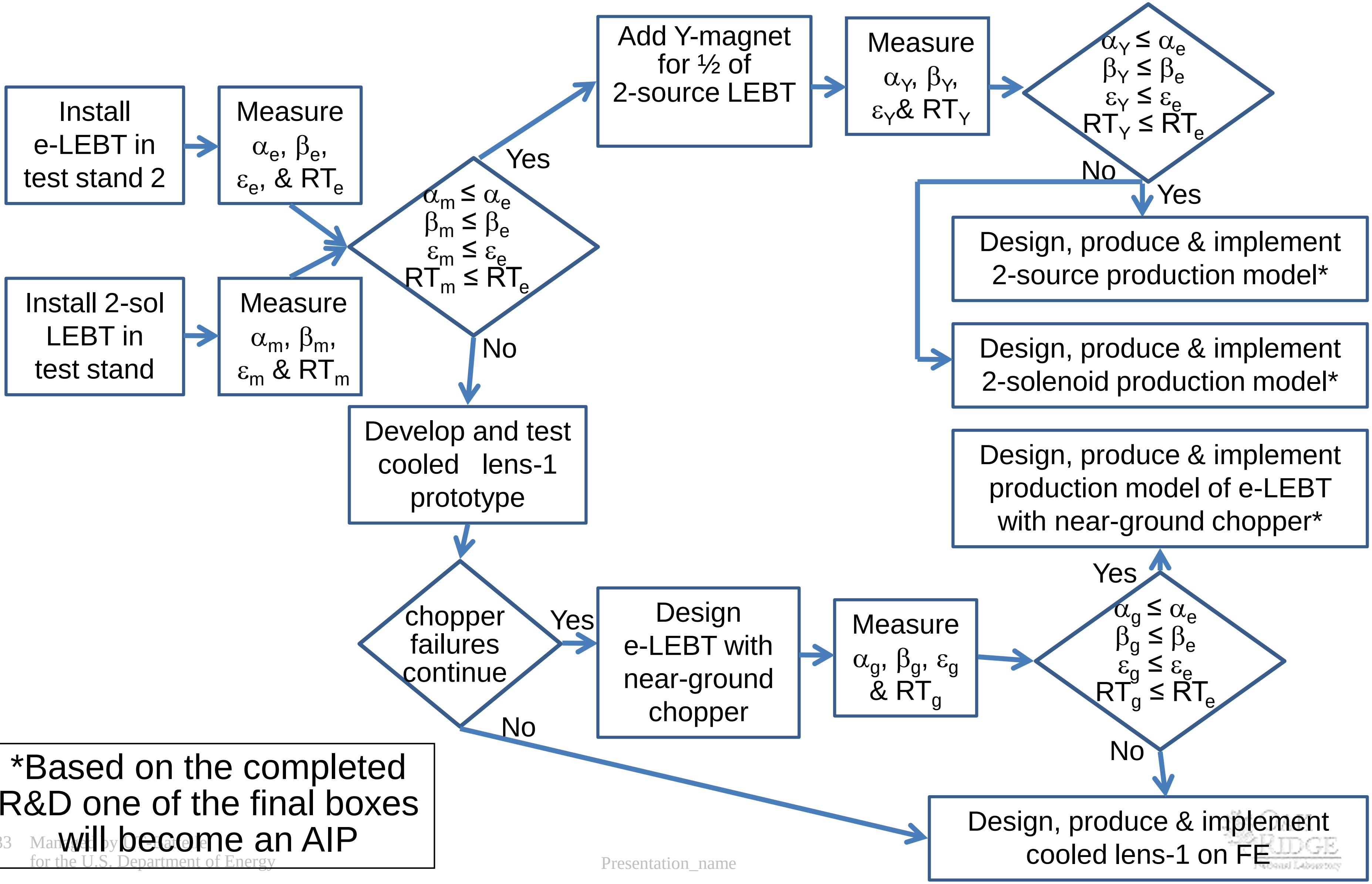
2) meets the required Twiss parameters

3) produces beam rise and fall times not slower than the baseline e-LEBT

4) Does not over heat the LEBT chopper target

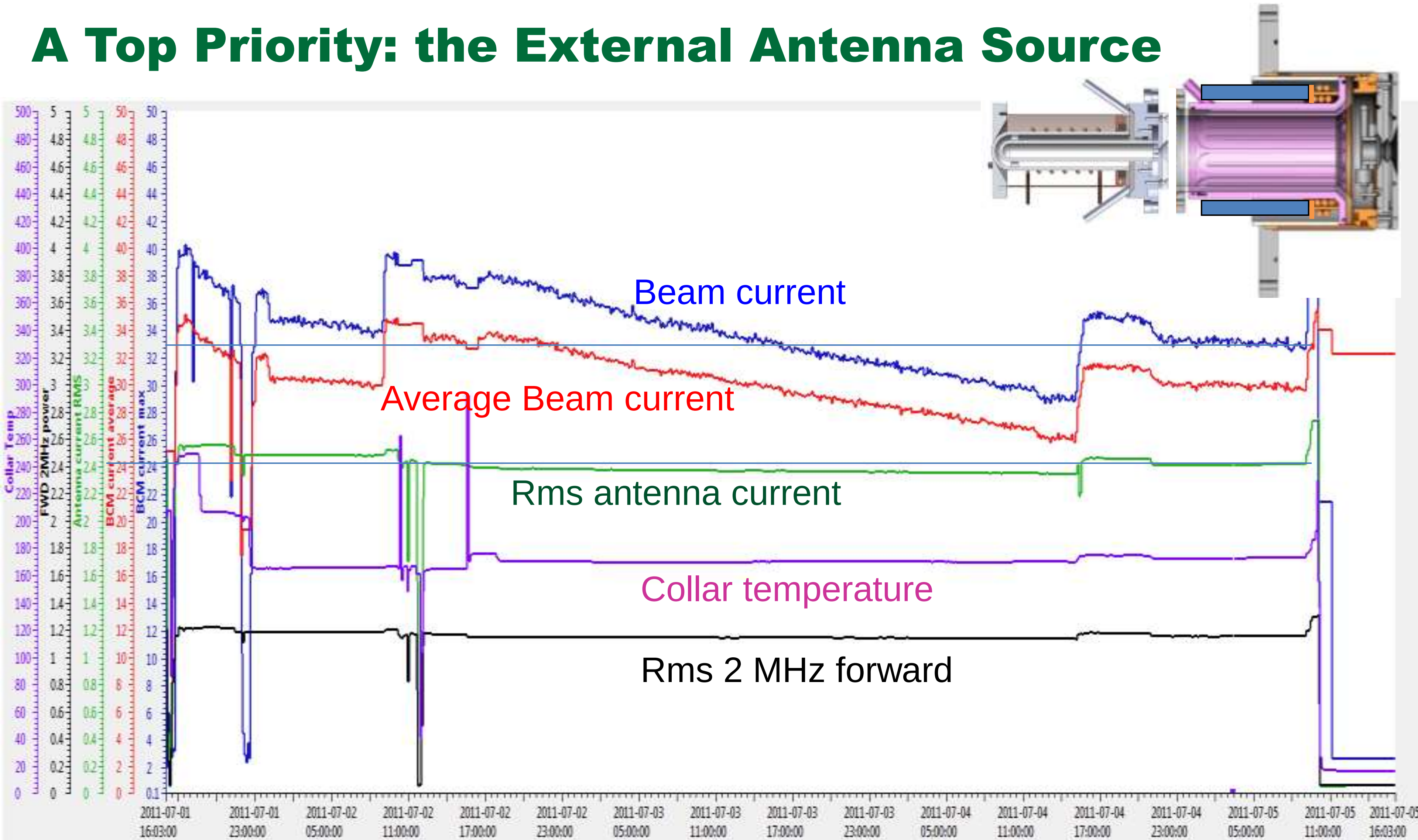


Implementing a robust LEBT, which meets or exceeds the performance of the baseline LEBT



*Based on the completed R&D one of the final boxes will become an AIP

A Top Priority: the External Antenna Source

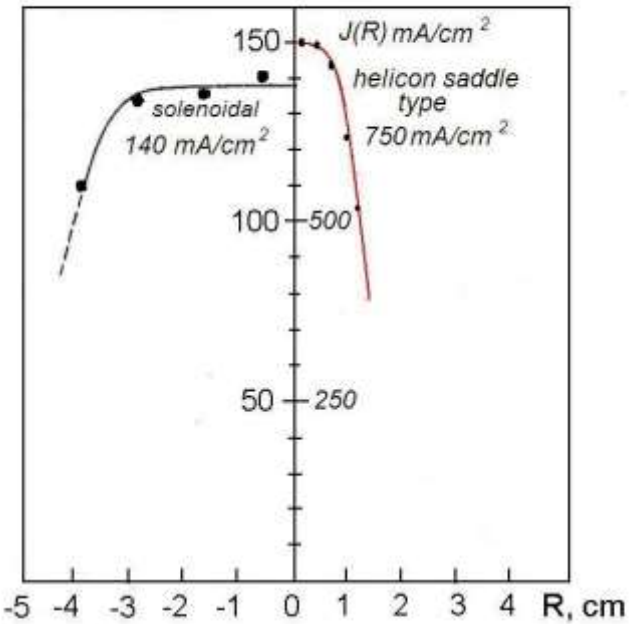


A recent test of our external antenna source on the FE showed the beam to decay, partly due to change in tune, partly due to a loss of Cs. The impurities appear to originate from the AlN plasma chamber.

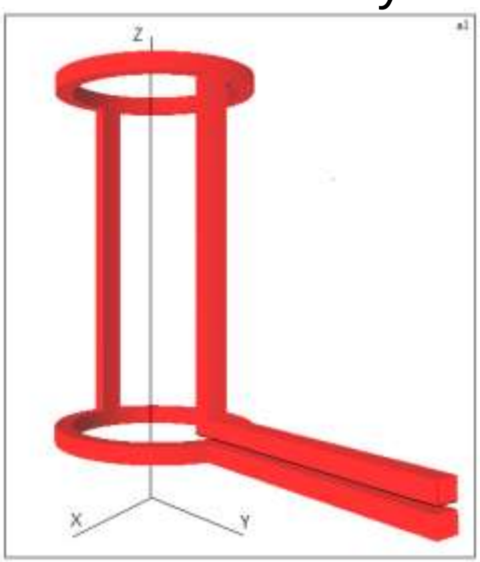
We focus on assessing and reducing the impurities that sputter the Cs.

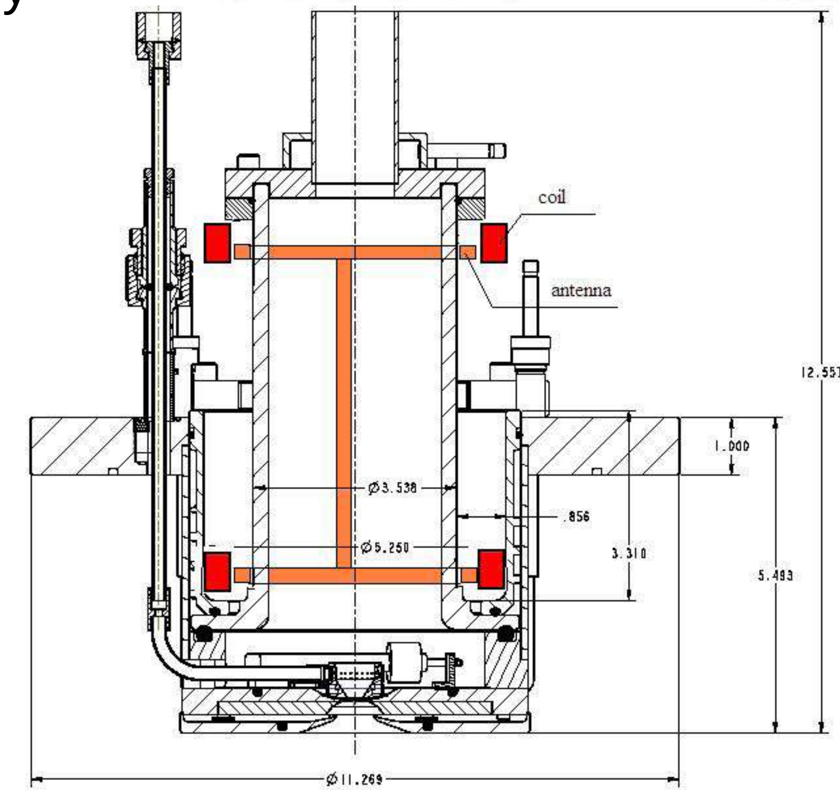
A Helicon Saddle Antenna for the SNS H- source

- Vadim Dudnikov, collaborating with Muons, Inc., and SNS, 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.
- The source has delivered ~50 mA with ~50 kW at low duty factor. Developments continue to further improve the efficiency and to develop a source that can withstand the rigors of 7.2% duty factor and long term operation. If very successful, a Frontend test is likely to follow.



More beam with less RF, that is the goal!





Summary and Conclusions

- The SNS ion source and LEBT normally work and produce record quantities of H^- ions in up to 6-week long service cycles.
- A ~3mg Cs dose yields normally persistent beam for up to 6 weeks.
- Source #3 normally meets the 38 mA requirement with <55 kW.
- Source #2 and #4 yield 34-36 mA with <60 kW and may still show slight poisoning, which may limit their service cycle to 1-2 weeks.
- We continue to explore causes for the different performances.
- After promising tests, the new source #6 will be tested on the FE.
- Increasing the RF power and duty factor have increased the infant mortality of the internal antennas. Several mitigations are being implemented and so far appear promising.
- The causes of beam decays have been identified and mitigated. We continue to try lowering relevant detection thresholds.
- A LEBT failure mode has been identified and appears to be successfully managed.
- As time permits, we continue our R&D program.

THANK YOU! *for your attention!*