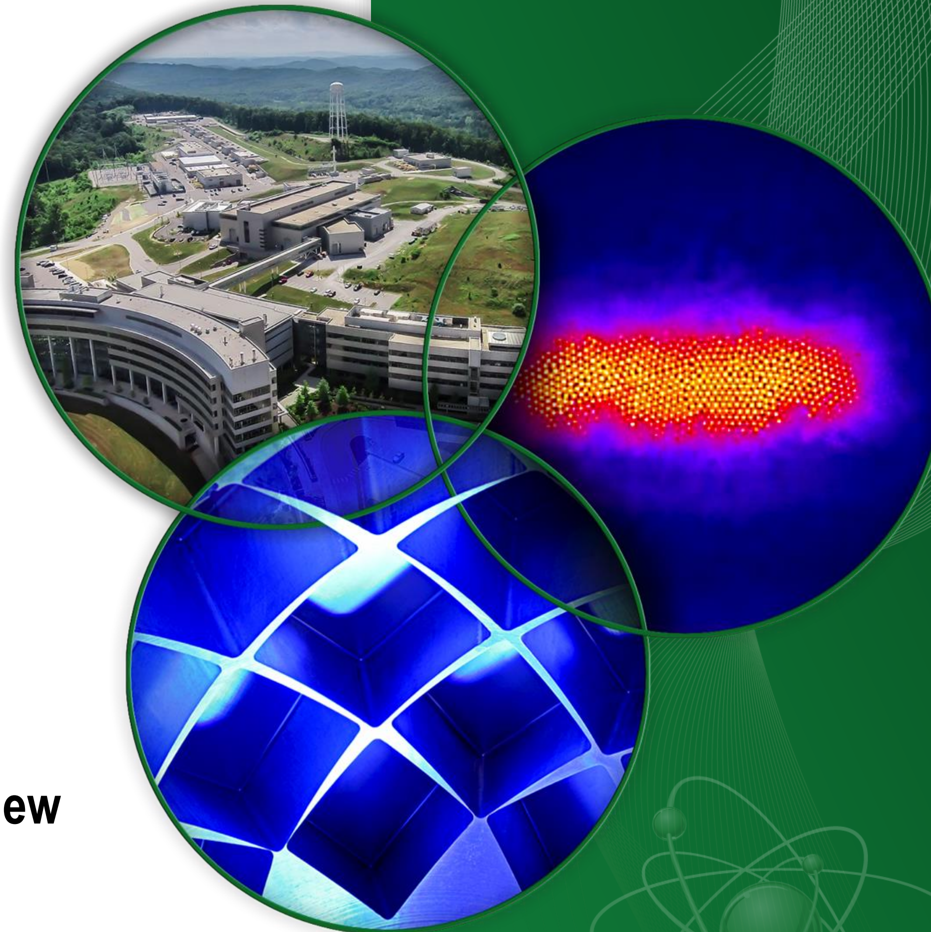
Ion Source Development, Plans, and Test Stand



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Ion Source Team Lead

Accelerator Advisory Committee Review
Oak Ridge, TN
March 25, 2015

ORNL is managed by UT-Battelle
for the US Department of Energy

From the 2013 AAC Report: 1.2 Ion Source

AAC 2012 recommendation – "In the short term we recommend focusing on the more limited program of thoroughly understanding the issues with the present sources"

This has been taken seriously by the source group, and there has been very good improvement in the performance of the ion sources. Three sources now predictably support 1MW operation for up to 6 week periods.

Commended for these improvements in reliability and reproducibility (antenna QA, well defined procedures for source turn-on and conditioning, better monitoring of LEBT temperatures, etc.)

At this stage, best path forward to further improvements in reliability and stability of the final H- beam is to increase the margin from the source over the requirements.

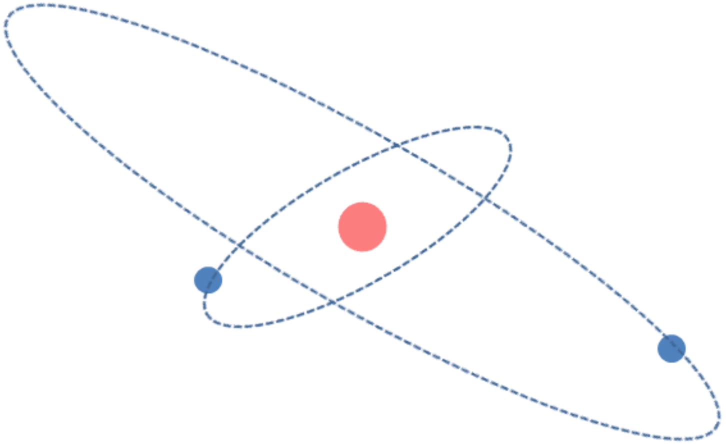
Should resume source R&D, to test ideas for possible intensity improvements to gain margin (external antenna, internal antenna legs out of plasma, biased converter electrode, etc.). The Integrated Test Stand will be heavily booked, so this needs to be a parallel effort in the ion source test stand.

Investigate the possibility of antenna conditioning on a separate, more modest test bench that is independent from the ion source test stand.

Recommendations

- Ion source R&D should resume in the source test stand (this should then continue, separate and independent of the source required for the Integrated Test Stand)

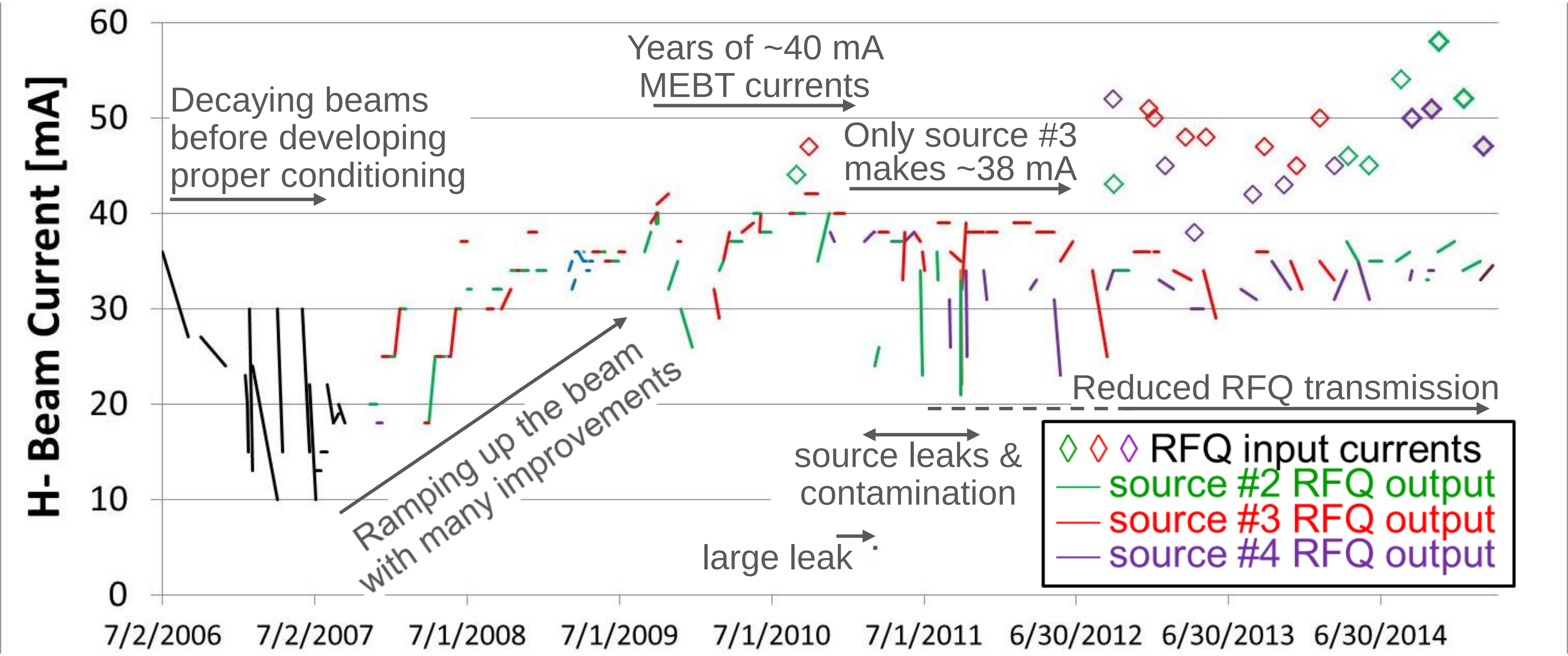
Content



- Brief Performance History
- Recent Performance
- Recent issues and failures
  - The LEBT gate valve
  - Plasma outages
  - The external antenna source
- Conclusions

It is all about delivering more H^- ions!

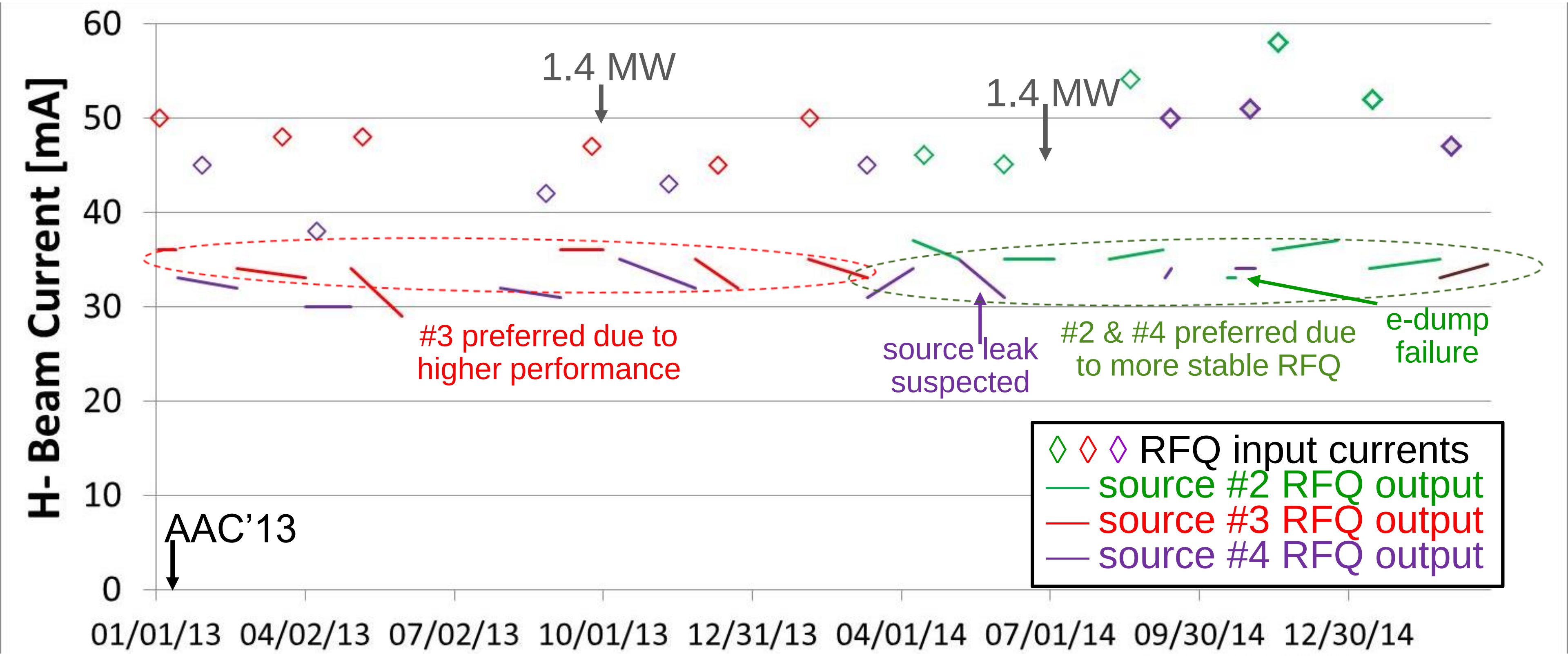
Ion Source and LEBT Performance History



127 production source cycles provided as many opportunities to learn, improve and perfect the operation of our H^- ion source and drive up its performance to unprecedented levels.

However, due to the nature of ion sources, especially H^- ion sources, many things are not fully understood and not exactly reproducible, and remain challenges!

Recent Ion Source and LEBT Performance



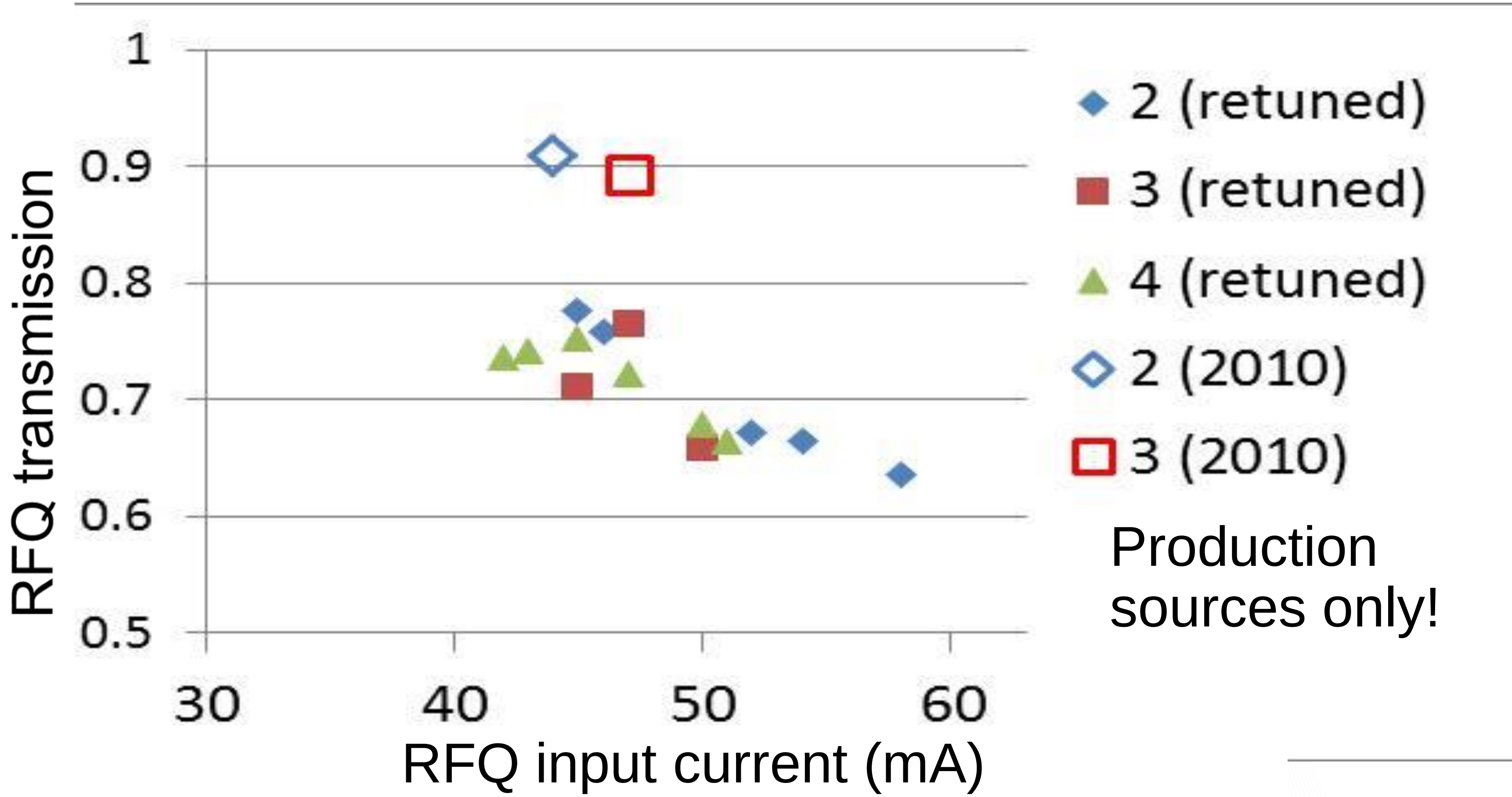
Source #3 was the favored workhorse until spring 2014, when it became disliked due to its thermally loading of the RFQ and limiting its power.

Source #2 was benched in 2011 after a severe contamination. After being tuned up in 2014, it became the favored workhorse.

Source #4 serves as the alternate for the last 4 years. While its LEBT output lacks several mA, in the MEBT it is only ~1mA less than #2.

At least 2 sources are capable of 1.4 MW!

RFQ Transmission



- In 2012 RFQ transmission measurements showed a large scatter.
- The 2013 RFQ retune improved transmission and reduced the scatter.
- More carefully LEBT tuning further reduced the scatter since 2014 (see #2).

The 1.4 MW challenge has helped us to increase the MEBT current to a consistent ~35 mA.

Production Run *(CY)*	Duty cycle %	Pulse length *ms*	mA required	mA in MEBT	RF *[kW]*	tilt *deg*	Antenna Failures (days)	%Availability#	Comments
2006-1		~.1	20	28-20	~70	3	0	99.9	1 ion source, 1 cesiation, raise collar temp
2006-2	0.2	~.25	20	30-16	~70	3	0	99.98	1 ion source, 1 cesiation + 24h @115°C
2007-1	0.8	~0.4	20	20-10	60-80	3	1(37)	70.6	Lens-2 arcing; 2-week source cycles after ant fails
2007-2	1.8	~0.5	20	13-20	80	3	0	97.2	Modified lens2; e-target failures; long pulse tuning
2007-3	3.0	~0.6	25	25-30	35-50	3	0	99.65	modified Cs collar (Mo converter); new LEBT
2008-1	3.6	~0.6	25/30	20-37	uncal	3	1 (6)	94.9	Restore matching network; new tube; Beam on LEBT gate valve
2008-2	4.0	0.69	32	32-38	48-55	3	1 (9)	99.22	Start 3-week source cycles; Ramp up e-dump & collar temperature
2009-1	5.0	0.8	35	34-38	~50	3	2 ExAn + 1 (8)	97.52	Start "Perfect Tune"; use external antenna$ source for 1st 8 weeks; start 7.2% conditioning
2009-2	5.1	0.85	38	42-26	~55	0	1 (1)	98.84	Start replacing LEBT, slim extractor; start 4-week cycles; 2 MHz degrades; plasma outages at end
2010-1	5.4	0.9	38	39-30	~60	0	1*(11) +1(>4)+ 1(0)	96.80	Repair & tune-up RF; punctured antenna* to beam back in ~6 hours; lens1 & e-dump breakdowns;
2010-2	5.4	0.9	38	46-36	<55	0	2(10) +1(3) +2(0)	~98.5	Replace 1.6 µH with two 1 µH inductors; start 2 MHz on ground
2011-1	5.4 4.4	0.9 0.73	38	38-30	~60	1.5	1(22) +1(6) +1(2)	98.2	Double LEBT pumping; start frequency hopping; source leaks by electric arc & by plasma heating; start 6% conditioning
2011-2	4.4 5.3	0.73 0.88	38	38-30	~55	0	1*(>5) 1 (9)	98.7	*start of run; contamination of #2 & 4; 6 week #3 run; start rigorous antenna selection & Dc% conditioning
2012-1	5.3	0.88	38	38/34	~60	3	0	99.3	6/2 week cycles with source 3 & 4
2012-2	5.3	0.88	30-34	30-35	~60	3	0	99.7	LEBT & converter TCs; 2 targets fail
2013-1	5.3	0.88	30-34	30-35	~60	0/1.5	1 (11)	99.5	37 day run with #4; mostly 850 kW
2013-2	5.3	0.88	30-36	34-36	~55	0	0	99.4	46 days #4; then 26 days #3 for ≥ 850 kW
2014-1	≤6	≤1.0	30-35	30-35	~55	0	0	99.7	1-1.4 MW; start ½-hour HV delay after cesiations; ignition frequency increased from 1.96 to 1.985 MHz
2014-2	≤6	≤1.0	34	34-36	~55	0	0	98.2	12h 2-MHz repair; e-dump, target & MEBT fail; plasma outages
2015-1	≤6	≤1.0	34	34-35	~55	0	1*(41)		*resistor failure; DI-water

Due to the reduced RFQ transmission the ion source and LEBT expectations were lowered to ~35 mA with a ~99.5% availability!

Recent Ion Source and LEBT Downtimes

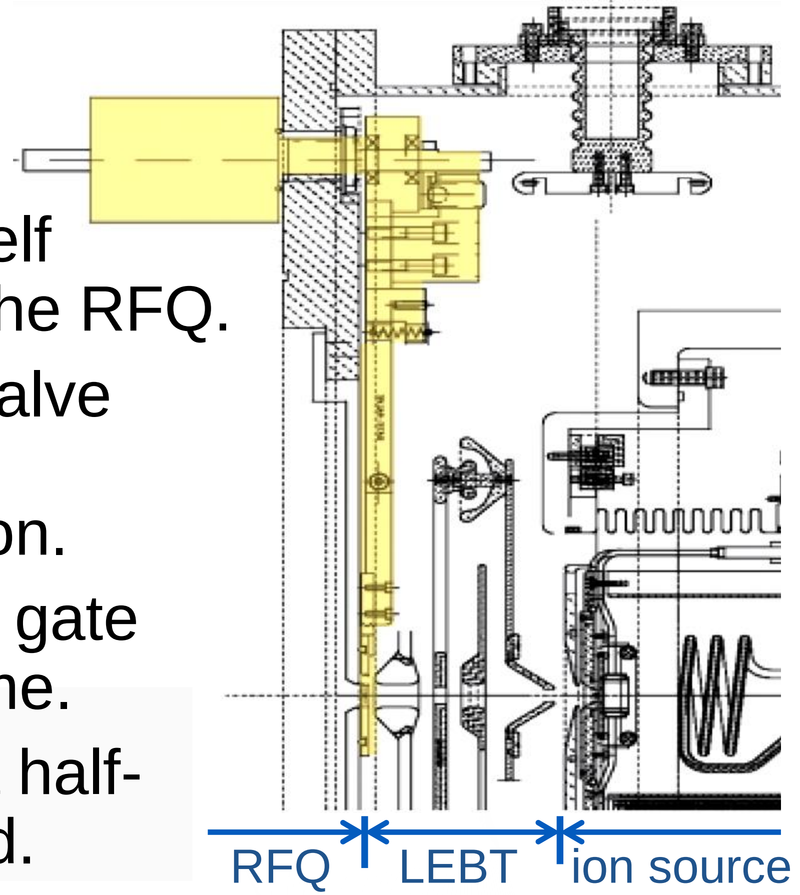
Date	Shift	Downtime	%	Notes
11-Aug-14	N	0.1		Plasma extinguished x2
12-Aug-14	N	0.5		2 MHz Amplifier Output Circuit Failure
12-Aug-14	D	11.5		2 MHz Amplifier Output Circuit Failure
14-Aug-14	N	0.1		LEBT chopper interlocks with sparks/voltage dips x2
16-Aug-14	N	0.2		Source's 65 KV voltage dip
18-Aug-14	N	0.2		Source's 65 KV voltage dip
20-Aug-14	D	1		Ion Source Plasma Extinguished
21-Aug-14	D	0.1		Voltage dips/sparks x3
24-Aug-14	N	0.1		Source plasma went out
10-Sep-14	D	0.5		Ion Source Tuning/Alignment
11-Sep-14	N	0.2		Ion Source Plasma Extinguish
17-Oct-14	N	0.8		Ion Source; 13MHz problem causing Ion Source outages
22-Oct-14	D	1.3		Ion Source plasma extinguished
22-Oct-14	D	7		Ion Source changeout and startup
22-Oct-14	N	1.8		Ion Source repair / replacement
26-Oct-14	D	0.1		Ion Source Plasma Extinguished
16-Dec-14	D	1		Ion Source 65kv repair
16-Dec-14	D	1.1		Ion Source 65kv repair
19-Jan-15	N	0.1		Ion source spark detector latched beam off
23-Jan-15	N	0.1		Source's plasma went out
23-Jan-15	N	0.2		Source's 65 KV voltage dip
1-Feb-15	N	0.9		Ion Source 65 kV Arcing-estimated cumulative times for multiple trips
5-Feb-15	N	2.7		13 MHz amplifier failure
11-Feb-15	D	0.1		Ion Source Plasma Extinguished 3 Times
22-Feb-15	N	2.1		Ion source cooling flow restriction causing source issues
23-Feb-15	D	0.9		Ion Source Cooling Hose Replacement
24-Feb-15	N	0.1		LEBT sparks due to Lens 2 voltage dips
27-Feb-15	D	2.5		Ion Source Antenna Cooling Hose Replacement
Total		37.3	%	
2 MHz		12	32	Lack of fitting spare parts; IS RF team now readied a complete spare unit
e-dump		8.8	24	marginal design was improved, but implementation stopped in 2011
plasma outages &13 MHz		6.5	17	An old problem resurfacing due to effort to reduce H2 pressure
65 kV		3.7	10	Recurring problem due to marginal desig and humidity
Others		6	16	mostly water issue adressed by water team
LEBT		0.3	1	doing great!!

Ion Source Issues and Potential Solutions

2014 Issues	Potential 2015 Studies & Solutions
Loading the RFQ with H2/N2	Implement LEBT gate valve *SM*
Variations of the H2 flow	Characterize source conductance
Inadequate plasma diagnostics	Implement fast light sensors *BH*
Plasma outages	Investigate plasma outages *MS+BH*
13 MHz inconsistencies	Characterize 13 MHz plasma *MS+SM*
E-dump failures	Collect E-dump current data *BH*
QEI repair time	Implement e-dump upgrades *RW*
Performance variations	Acquire ready spare parts *CP*
Occasional beam decay	Adjust source usage cycle *MS*
Arcing at the start of a run	Improve HV insulation
Cs variations during startup	Lower conditioning temperature
converter temperature variations	Redesign collar/converter
Source, LEBT, RFQ alignment	Design alignment experiments
Operational optimizations	Improve optimization routines
Teststand lockout and usage	Test modifications on TS & ITF *SM+RW*
ExAnt source inconsistencies	Characterize ExAnt Cs systems *RW*
E-dump stability	Test E-dump HV filter *MS+SM*
Unreliable emittance data	Design water-cooled entrance slits

In 2015 we focus on the LEBT gate valve, plasma outages, and the ExAnt source!

LEBT Gate Valve



- The short electrostatic LEBT does not allow for installing an off-the-shelf gate valve between the LEBT and the RFQ.
- LBNL designed a slim swing gate valve with a limited sealing force. Lack of maintenance made leakage common.
- In 2008 beam was delivered on the gate valve causing ~50 hours of downtime.
- Early 2009 the lever was found in a half-way position and therefore removed.
- Venting the RFQ with N_2 for every source change became an issue in 2014 when raising the power level above 1MW.
- The LEBT valve lever mount was beefed up and secured.
- On the test stand no leaks were found in all of >10 closures.
- Interlocked Frontend redeployment as soon as possible!

It will be serviced as a part of the biannual LEBT maintenance to reduce the risk of future leaks.

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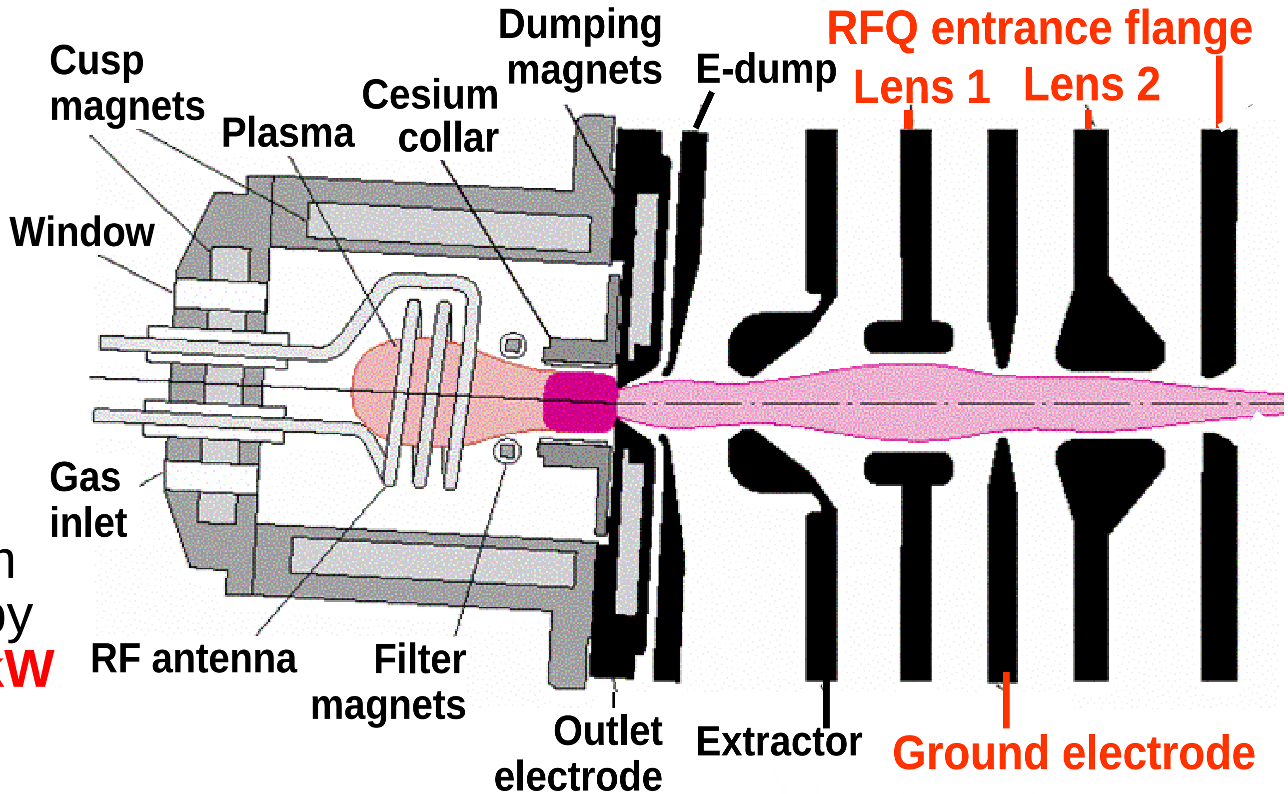
The SNS Baseline Ion Source and LEBT

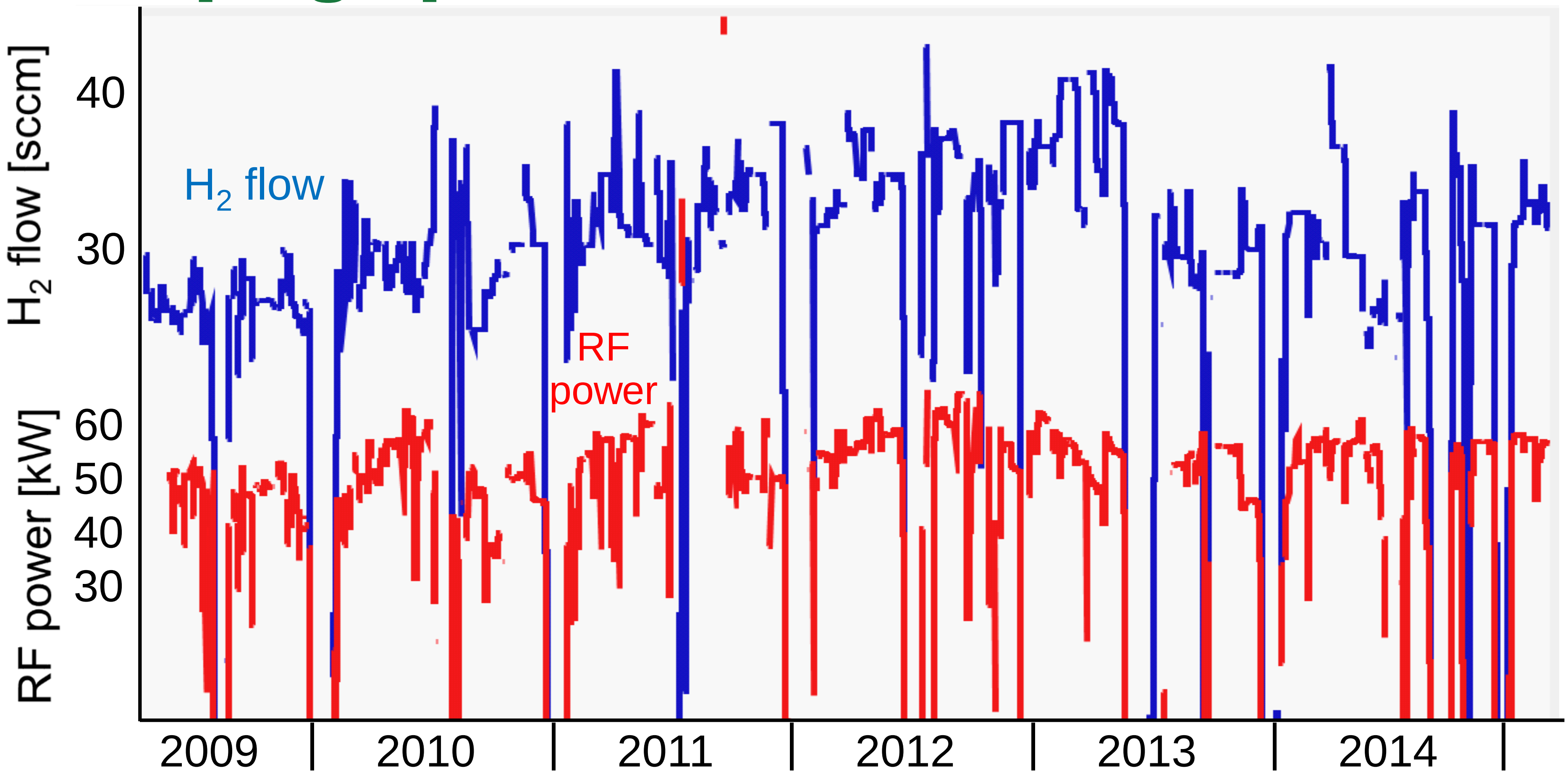
- LBNL developed the SNS H^- ion source, a cesium-enhanced, multicusp ion source.
- Typically 300 W from a 600-W, **13-MHz supply generates a continuous low-power plasma**.
- The high current beam pulses are generated by superimposing **50-70 kW from a pulsed 80-kW, 2-MHz** amplifier.



- 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.

While there remain issues, this is a record-breaking Injector!

Ramping up the Ion Source



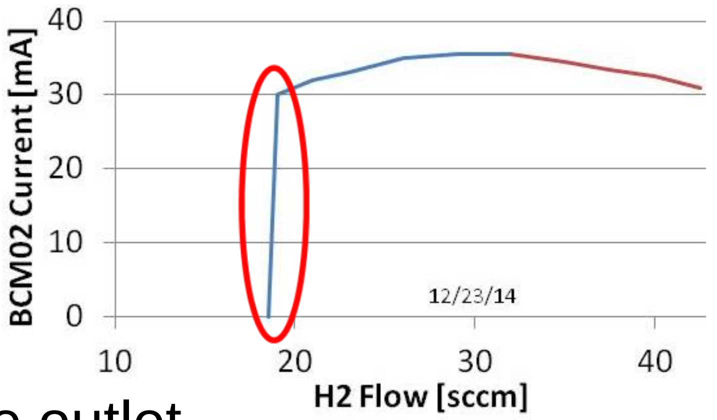
- After 2009 the H_2 was increased from 25 to 30 sccm to avoid plasma outages.
- In 2011 we started to increase the H_2 up to 40 sccm and the RF power up to 60 kW to compensate for the decreasing H- beam current in the MEBT.
- Since the RFQ retune, we use mostly ~30 sccm and ~55 kW.

However, less H_2 should allow for higher RFQ powers and higher transmissions!

The Driver of the H_2 flow

The H^- MEBT current has to be maximized

- Increasing the H^- beam $\Leftarrow$ denser plasma $\Leftarrow$ more H_2 AND higher electric fields $\Leftarrow$ higher antenna current.
- Increasing the H^- beam $\Leftarrow$ minimize H^- losses $\Leftarrow$ reduce plasma & H_2 near source outlet.

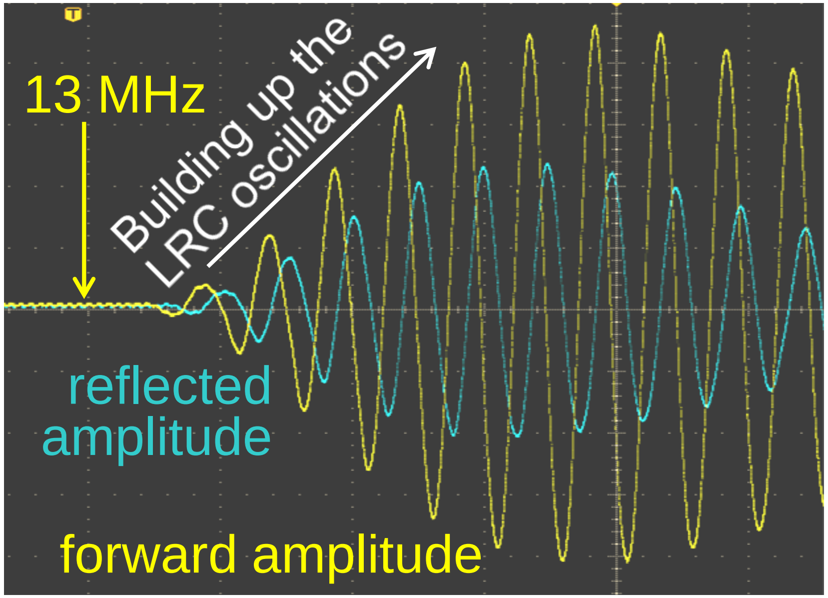


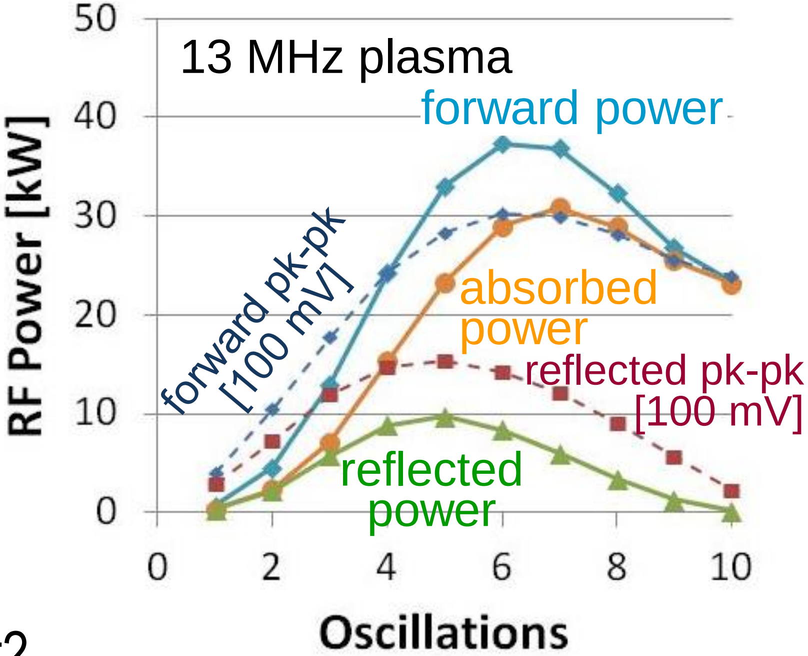
➢ There is an optimum H_2 flow that maximizes the H- beam output!

- Each source is started with 30 sccm of H_2. It is increased by 1 or 2 sccm every time the plasma goes out. After tuning up the source, the H_2 is lowered until the plasma goes out. Then H_2 is increased by 1-2 sccm and the plasma reignited.
- Some times during the night Operations has to further increase the H_2 flow to avoid recurring plasma outages.
- One day/week later the source is retuned and the H_2 is lowered until the plasma goes out. Then H_2 is increased by 1-2 sccm and the plasma reignited.
- The source is conditioned, cesiated and tuned up with ~50 kW. Only then, and only if needed, is the RF increased to increase the BCM02 current.
  In the unlikely event that the beam current does not increase the RF is lowered to the maximum BCM02 current.

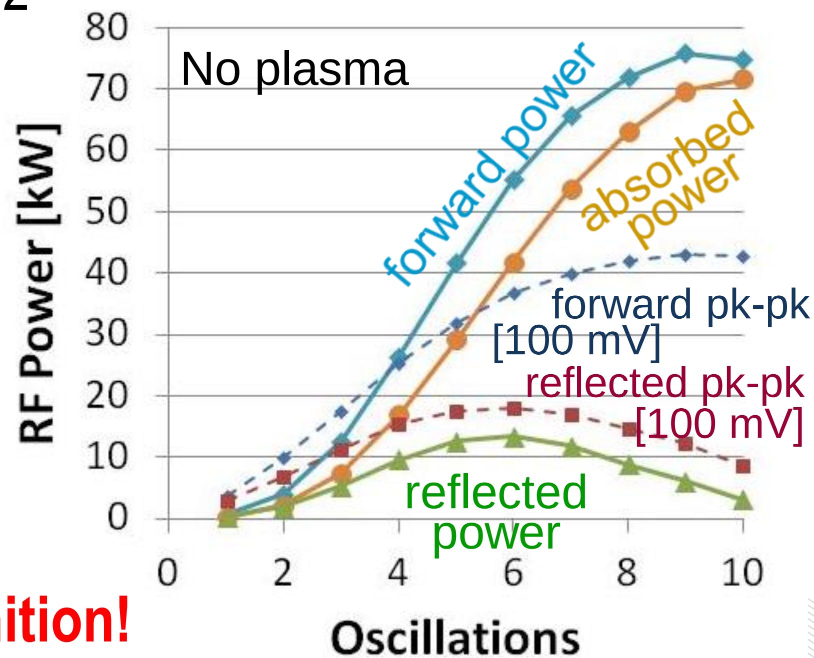
Low H_2 pressures cause Plasma Outages which need to be understood!

Ramping the 2 MHz with 1.96 MHz





•RF build-up was studied with 4-week-old source #2 using a 2 MHz directional coupler on ground.
•With 13 MHz plasma the LRC circuit rapidly builds up oscillations before drifting off resonance due the evolving plasma inductance.
•Only little RF power is reflected because the plasma absorbs the RF readily.
•However, without plasma the LRC circuit builds up to 76 kW, absorbing up to 71 kW. The electric fields generated by the very large antenna current are unable to break down the pure H_2 gas.



The 80 kW QEI cannot provide reliable ignition!

How to reliably ignite the Pulsed SNS Source?

Unable to reliably ignite a clean H2 source with the 2 MHz RF, the only option is to

1. Ignite continuous 13 MHz plasma with a pressure bump (PUFF).
2. Use the 13 MHz plasma to absorb the 2 MHz plasma.
3. After a plasma outage go back to 1).

It is that simple! And we do for >7 years!

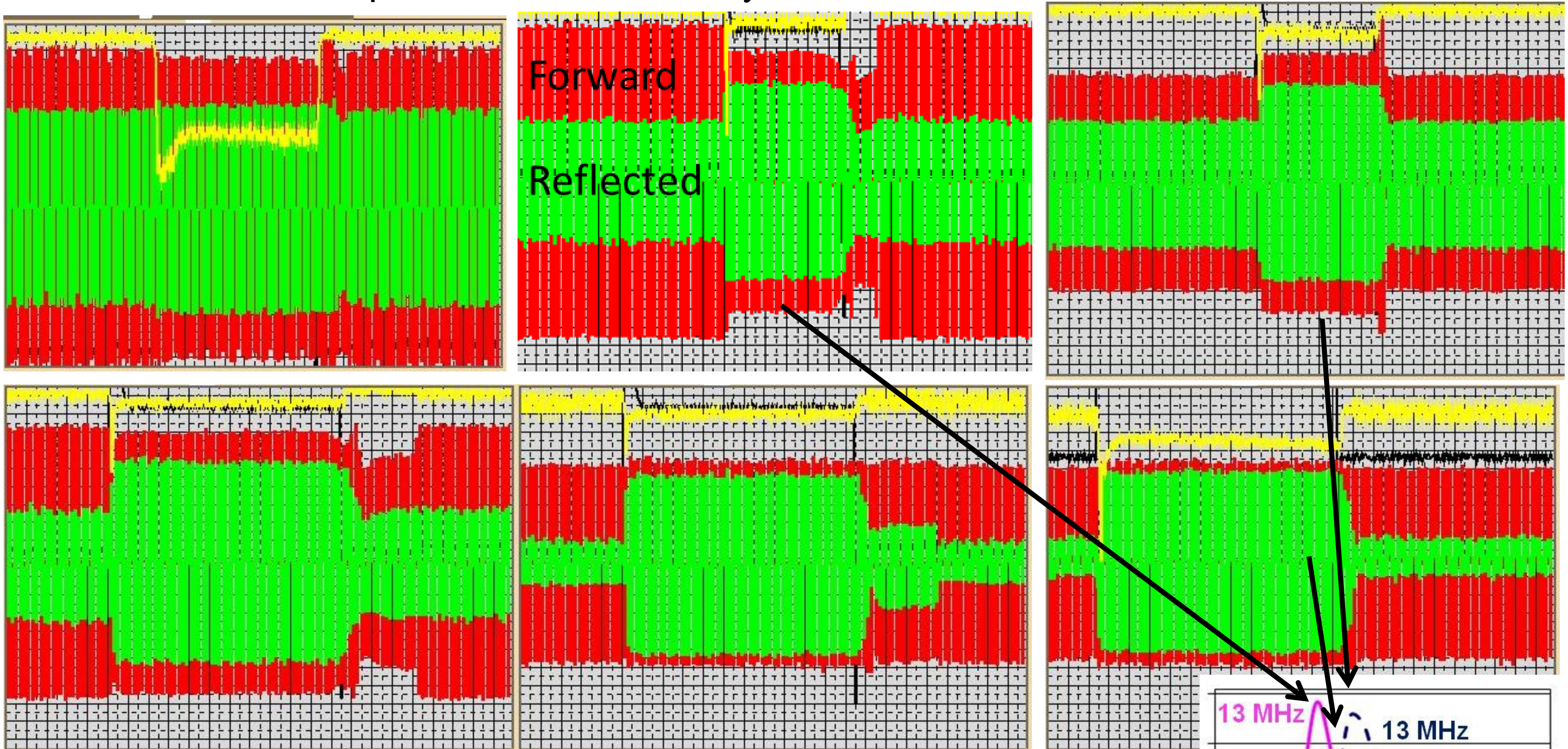
However, until July 2007 we operated without 13 MHz because the 2 MHz ignited the plasma of the poorly-conditioned, dirty sources which delivered decaying beams.

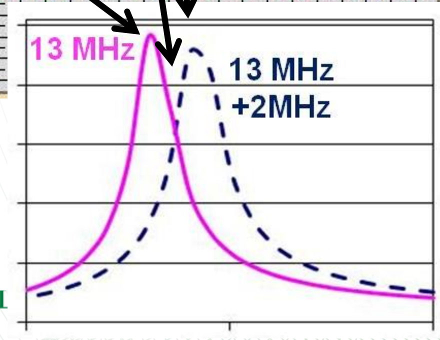
We need to focus on always maintaining some of the 13 MHz plasma for very clean, old sources!

13 MHz COMDEL CX600

Description	Specifications
Mismatch Protection:	Continuous operation into any impedance mismatch condition without damage or malfunction; forward power foldback shall occur within 500us if reflected power exceeds 100 Watts.

Last summer FE scope#1 was successfully restored to show forward & reflected 13 MHz





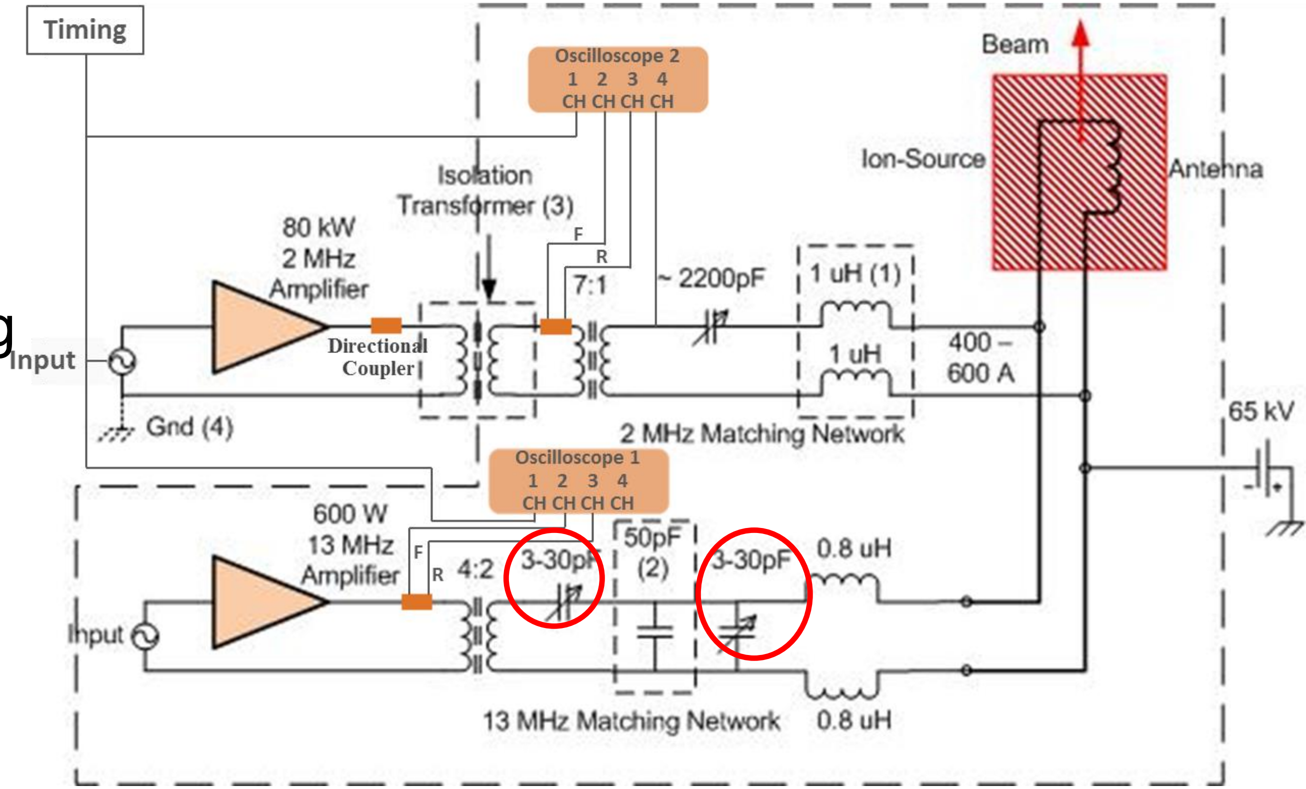
Sometimes the forward power barely changes and sometimes it gains!
Sometimes the reflected power has after-burns, sometimes it is normal

The 13 MHz matching network tunes are inconsistent!

The 2 MHz plasma reflects most of the 13 MHz!

13 MHz matching network

- The 13 MHz matching network is tuned with 2 variable capacitors, until the reflected 13 MHz is minimized.
- The dial-free, 65-kV-bridging, plastic screwdrivers limit the tuning accuracy.

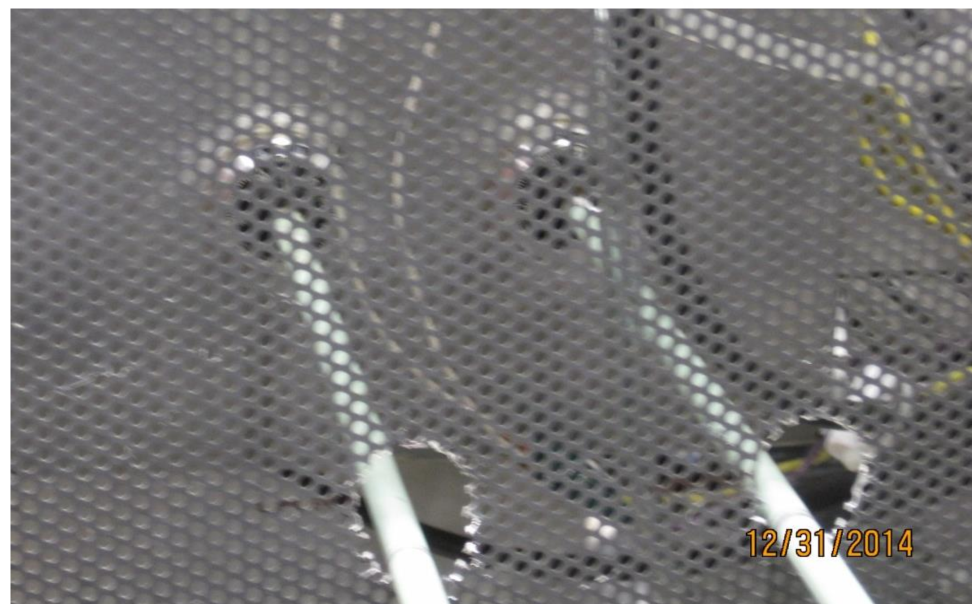


More consistent tunes require

1.) many-turn dials

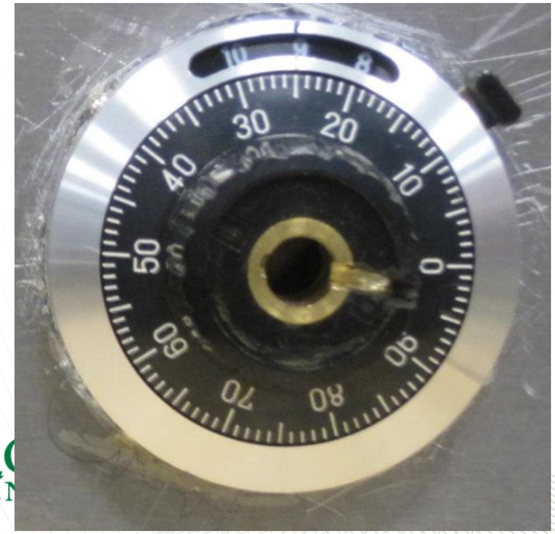
2.) more sensitive and fast feedback signals

This should eventually lead to more robust tunes!



13 MHz matching network

- Plasma robustness is better judged by its light emission.
- Fast, high-gain Si photo detectors were acquired with fiber-optics that can be connected to the source. Their 350-1000 nm sensitivity detects all visible light emitted from the source. With up to 80-ns rise times they can instantaneously measure the light between beam pulses as well as during the pulses.
- Very recently 15-turn dials were implemented on the ion source test stand. After installing source #5 the time-resolved light emission, the time resolved forward & reflected power as indicated by the Comdel (& maybe by a directional coupler) will be mapped versus the values of the 2 capacitor.
- Then the plasma-outage H_2 flow will be established for a few selected combinations.
- Consistency will be established ~1 week later.

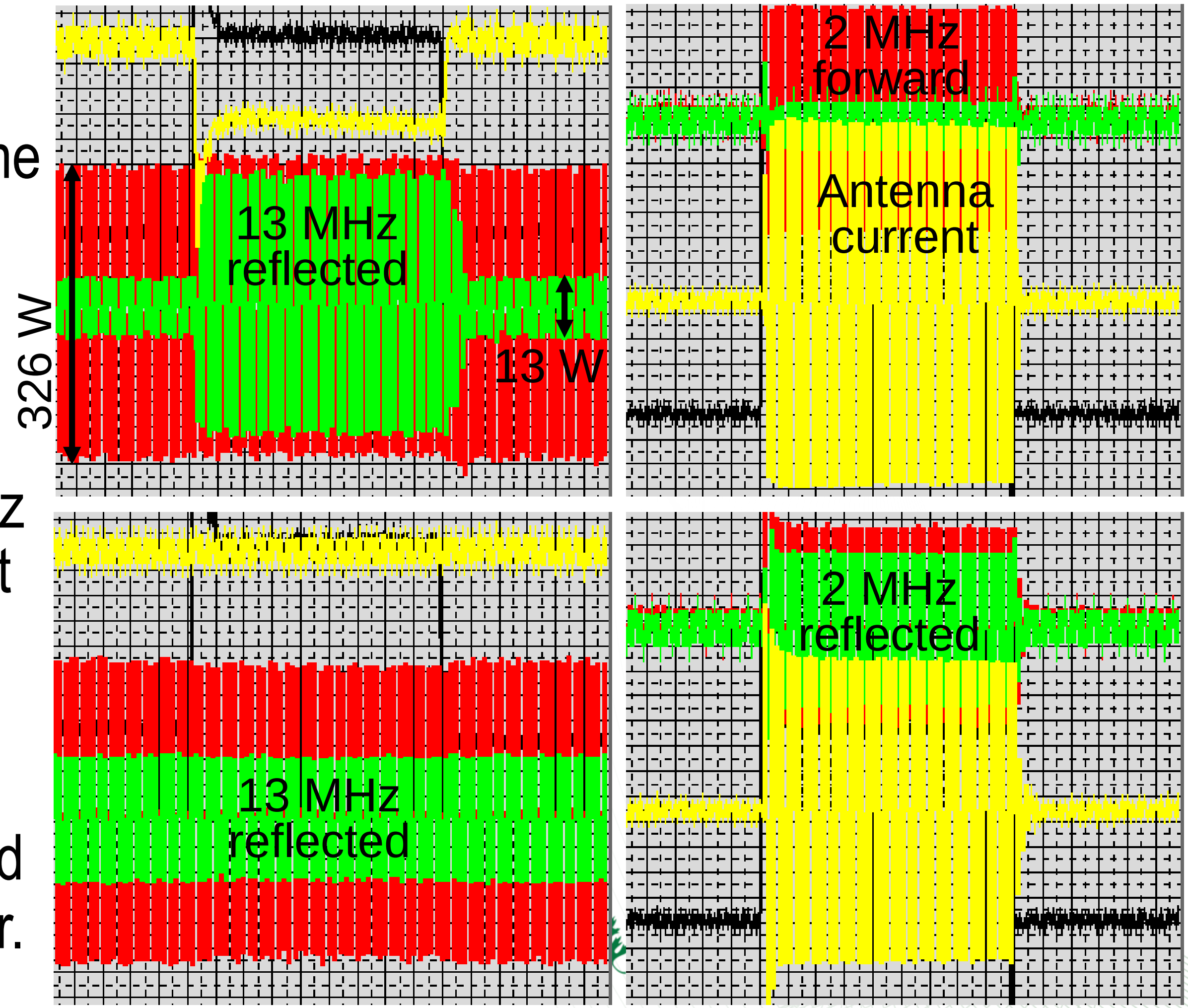


Promising results will be presented to the CCC with a request for FE installation during a source change!

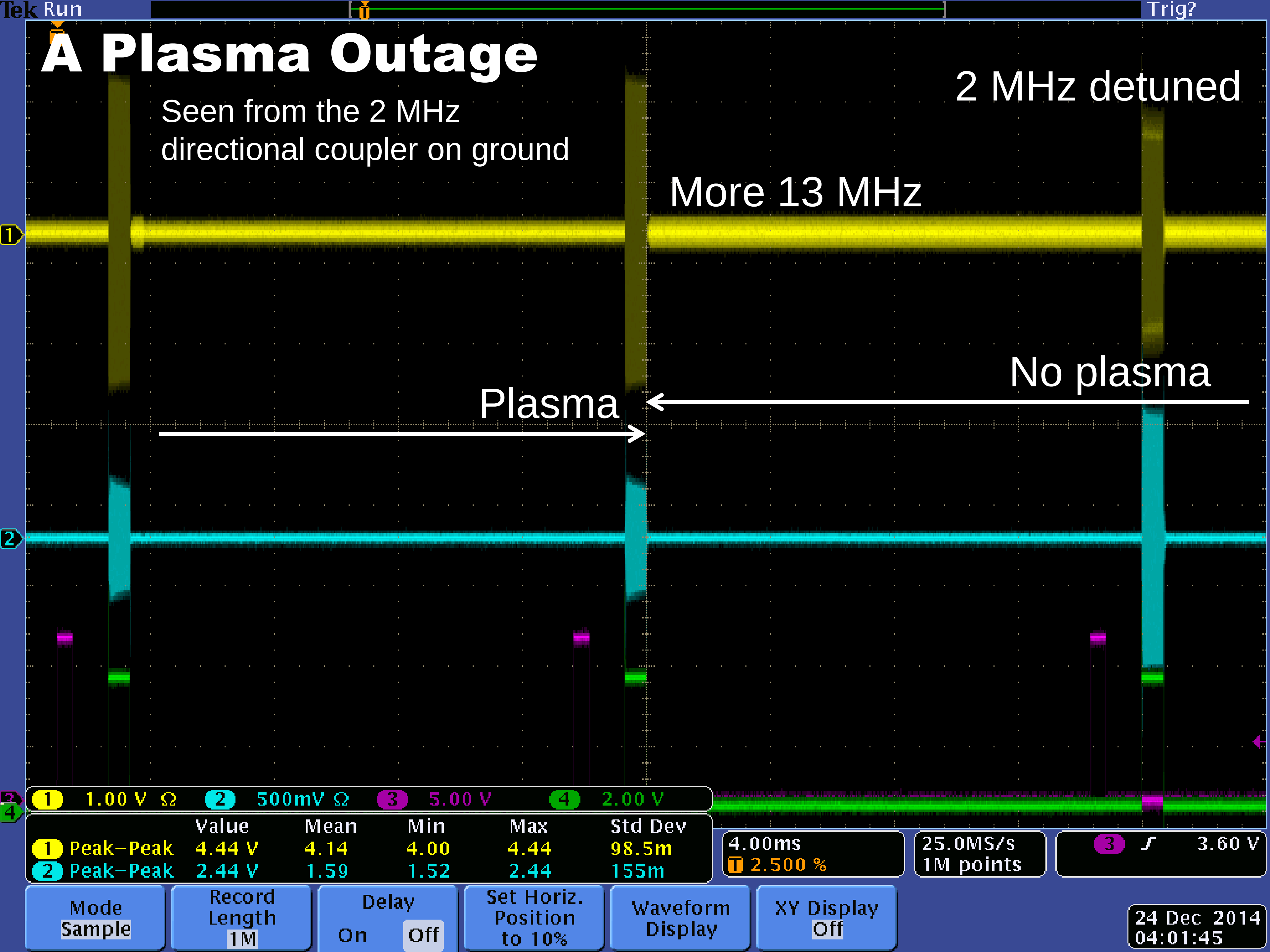
On the FE it will improve studies of sources at the end of their usage cycle and should allow for robuster tunes that may allow for lower H2 flow!

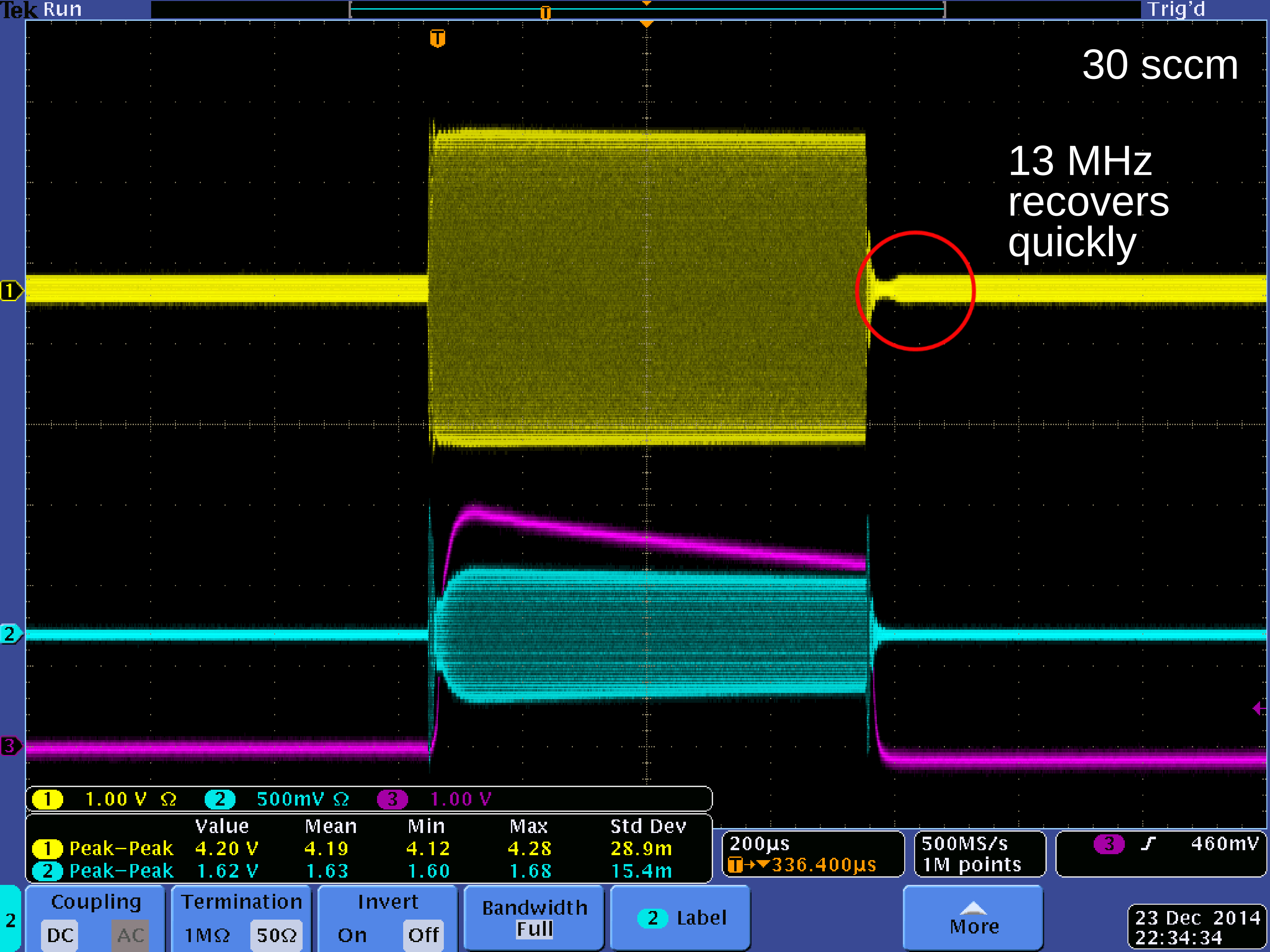
What causes Plasma Outages?

- Despite slightly inconsistent tunes, the observed 13 MHz signals appear robust with a minimum clampdown if any.
- No excessive power spikes have yet been observed, maybe due to the 60 Hz trigger rate and the ~1 Hz update rate of the scopes.
- Triggering the scopes with the intense plasma light allows for capturing the time around the last pulse to study each outage.
- This was tried with 39-day old source #2.
- The 2 MHz kept the 13 MHz forward power ~uniform but quadrupled the reflected amplitude without clampdown.
- Plasma outages quadrupled the 13 MHz reflected power.

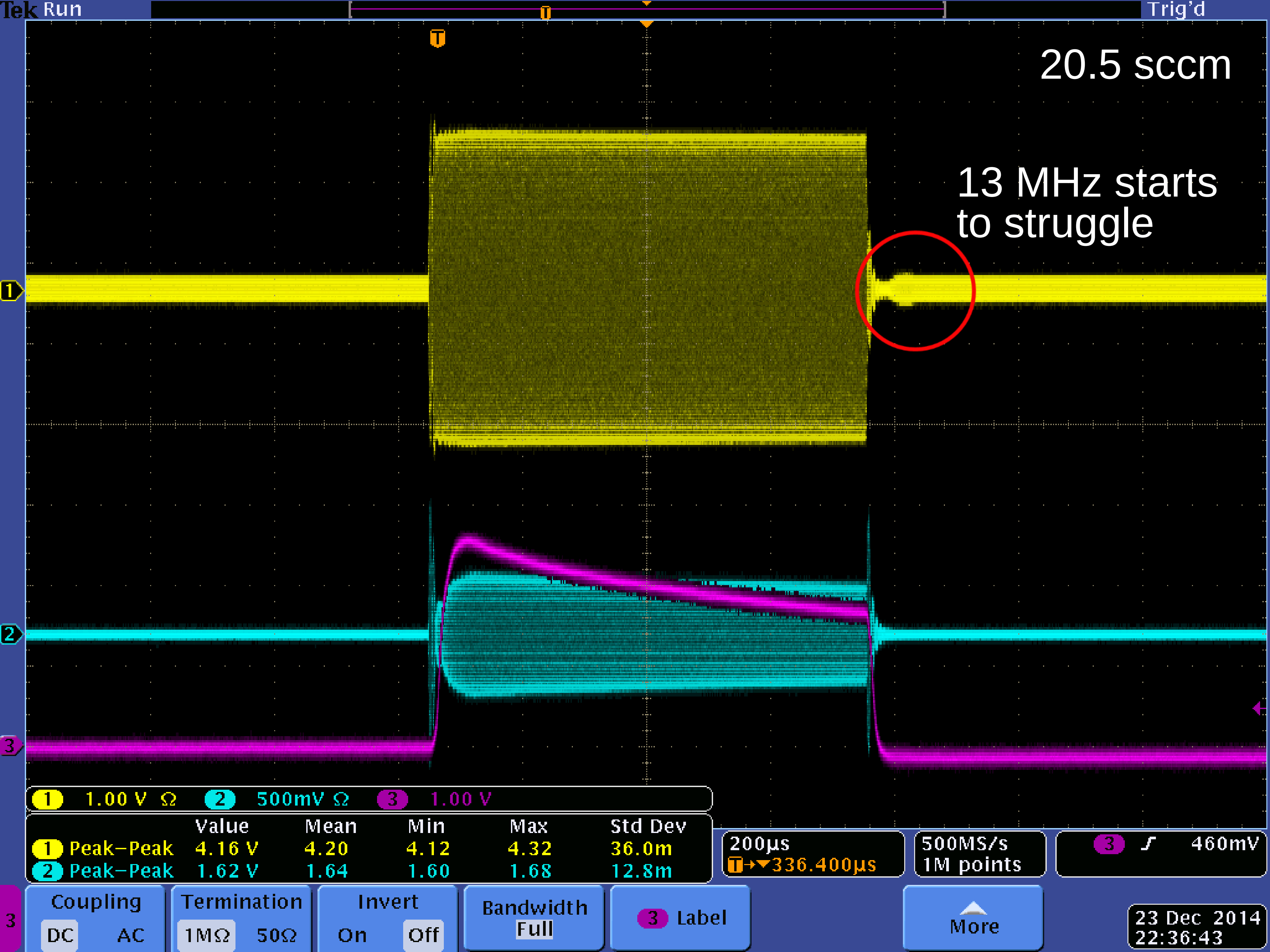


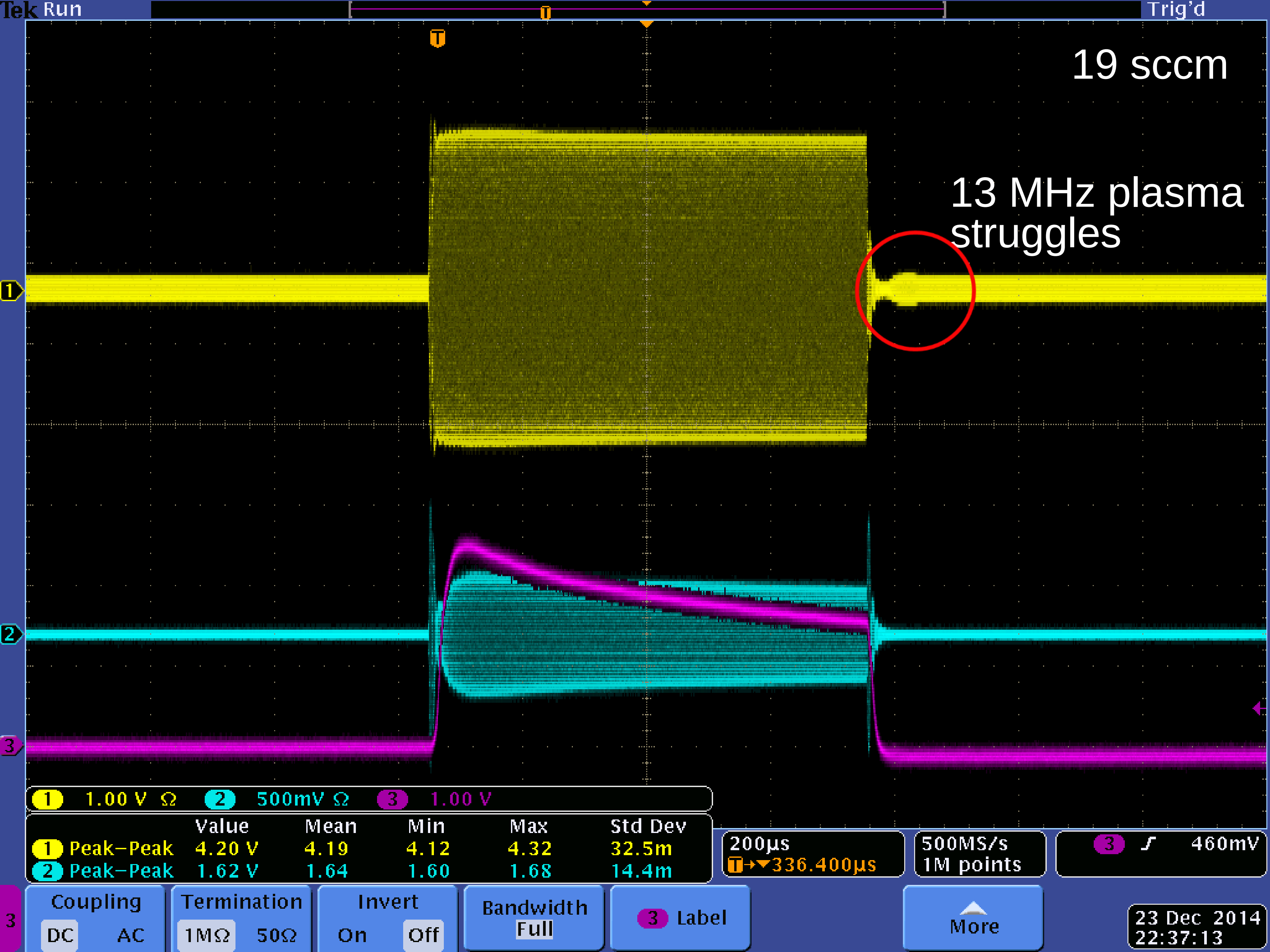
A Plasma Outage

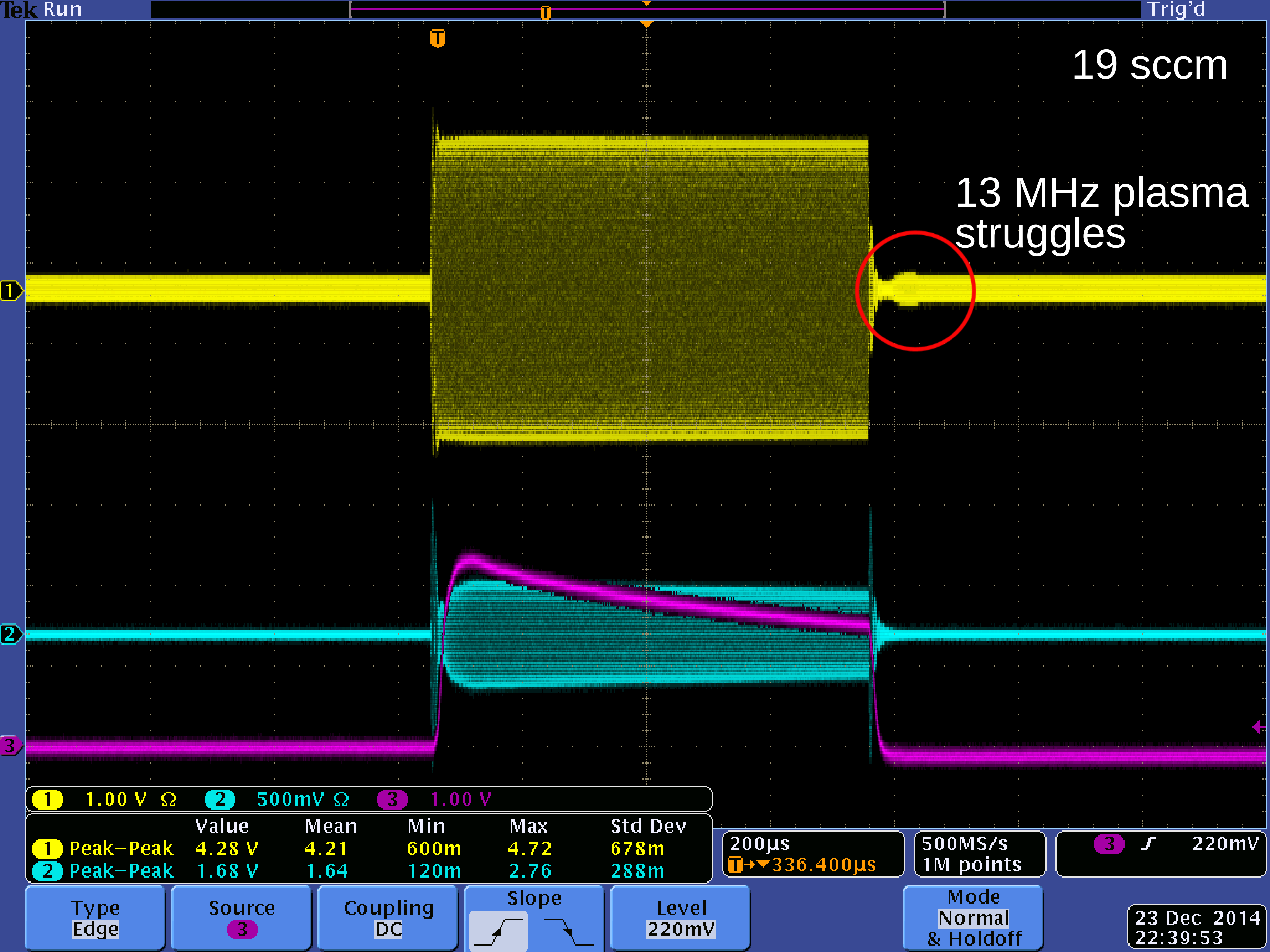


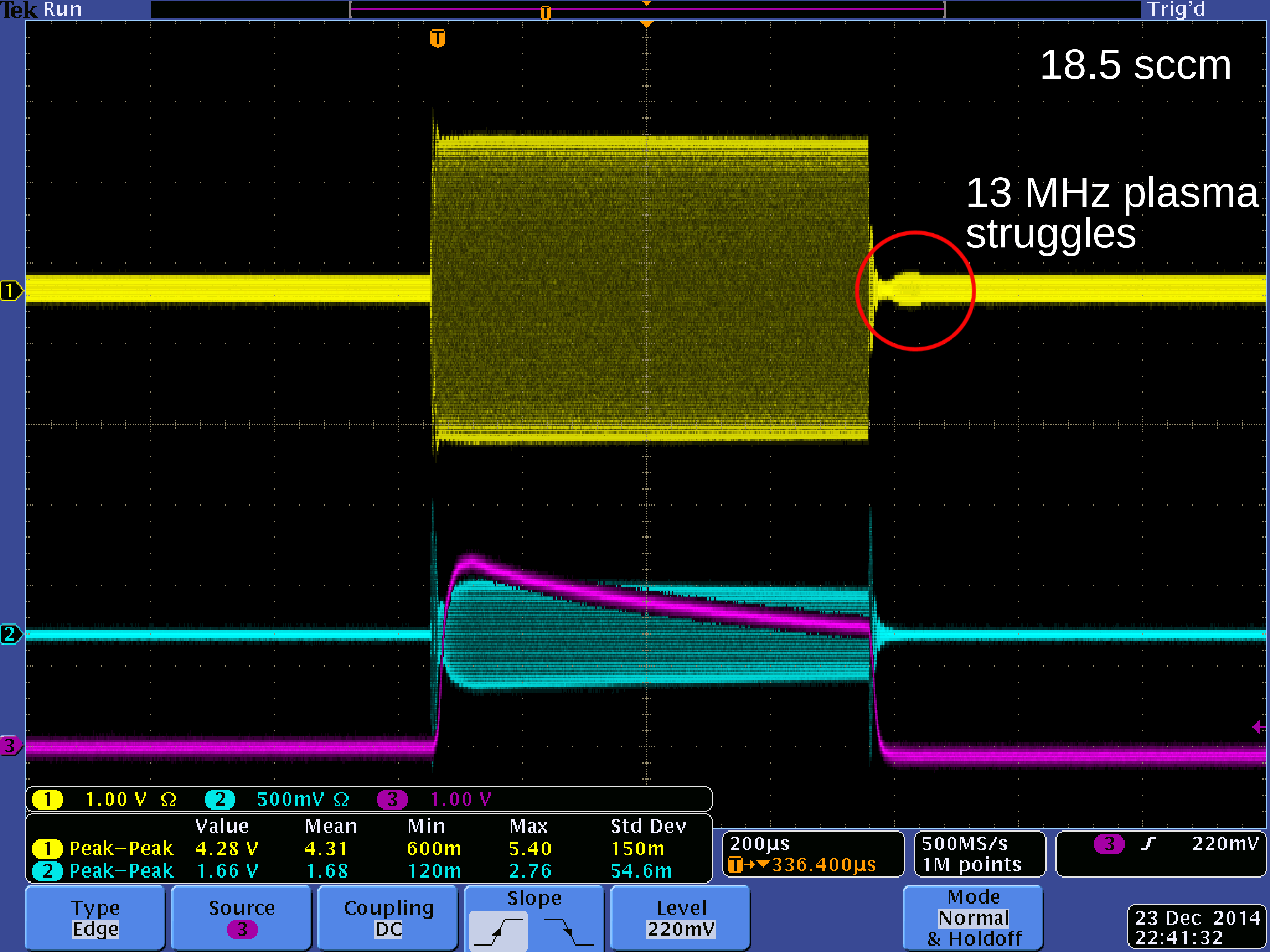


Tek Run
Trig'd
30 sccm
13 MHz recovers quickly
1
2
3
1.00 V Ω
500mV Ω
1.00 V
Value Mean Min Max Std Dev
Peak−Peak 4.20 V 4.19 4.12 4.28 28.9m
Peak−Peak 1.62 V 1.63 1.60 1.68 15.4m
200µs
336.400µs
500MS/s
1M points
460mV
Coupling DC AC
Termination 1MΩ 50Ω
Invert On Off
Bandwidth Full
Label
More
23 Dec 2014
22:34:34

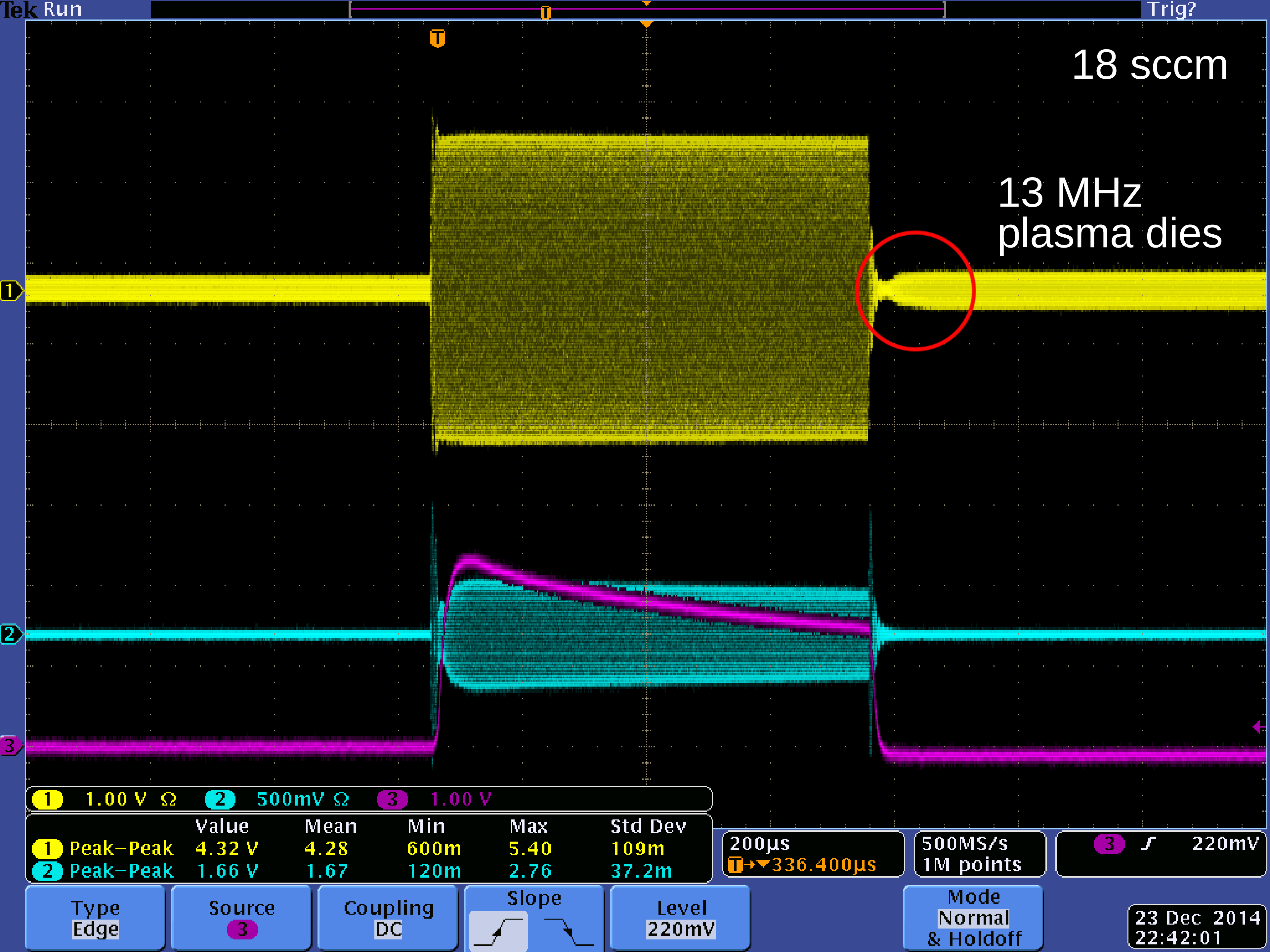

Tek Run
Trig'd
20.5 sccm
13 MHz starts
to struggle
1 1.00 V Ω 2 500mV Ω 3 1.00 V
Value Mean Min Max Std Dev
1 Peak–Peak 4.16 V 4.20 4.12 4.32 36.0m
2 Peak–Peak 1.62 V 1.64 1.60 1.68 12.8m
200µs
336.400µs
500MS/s
1M points
3 460mV
Coupling DC AC
Termination 1MΩ 50Ω
Invert On Off
Bandwidth Full
3 Label
More
23 Dec 2014
22:36:43


Tek Run
Trig'd
19 sccm
13 MHz plasma
struggles
1.00 V Ω
500mV Ω
1.00 V
Value Mean Min Max Std Dev
1 Peak−Peak 4.20 V 4.19 4.12 4.32 32.5m
2 Peak−Peak 1.62 V 1.64 1.60 1.68 14.4m
200µs
336.400µs
500MS/s
1M points
460mV
Coupling
DC AC
Termination
1MΩ 50Ω
Invert
On Off
Bandwidth
Full
Label
More
23 Dec 2014
22:37:13


Tek Run
Trig'd
19 sccm
13 MHz plasma struggles
1 1.00 V Ω 2 500mV Ω 3 1.00 V
Value Mean Min Max Std Dev
1 Peak−Peak 4.28 V 4.21 600m 4.72 678m
2 Peak−Peak 1.68 V 1.64 120m 2.76 288m
200µs
→▼336.400µs
500MS/s
1M points
3 220mV
Type Edge
Source 3
Coupling DC
Slope
Level 220mV
Mode Normal & Holdoff
23 Dec 2014
22:39:53

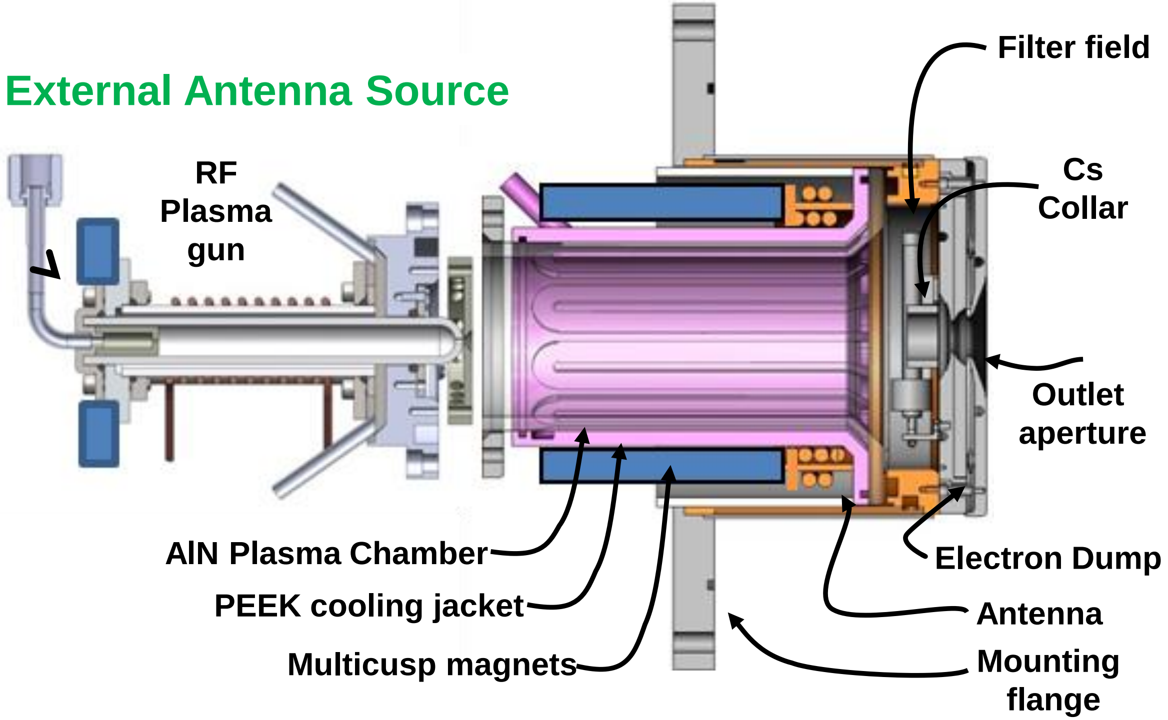


Tek Run
Trig'd
18.5 sccm
13 MHz plasma
struggles
1 1.00 V Ω
2 500mV Ω
3 1.00 V
Value Mean Min Max Std Dev
1 Peak-Peak 4.28 V 4.31 600m 5.40 150m
2 Peak-Peak 1.66 V 1.68 120m 2.76 54.6m
200µs
→336.400µs
500MS/s
1M points
3 220mV
Type
Edge
Source
3
Coupling
DC
Slope
Level
220mV
Mode
Normal
& Holdoff
23 Dec 2014
22:41:32



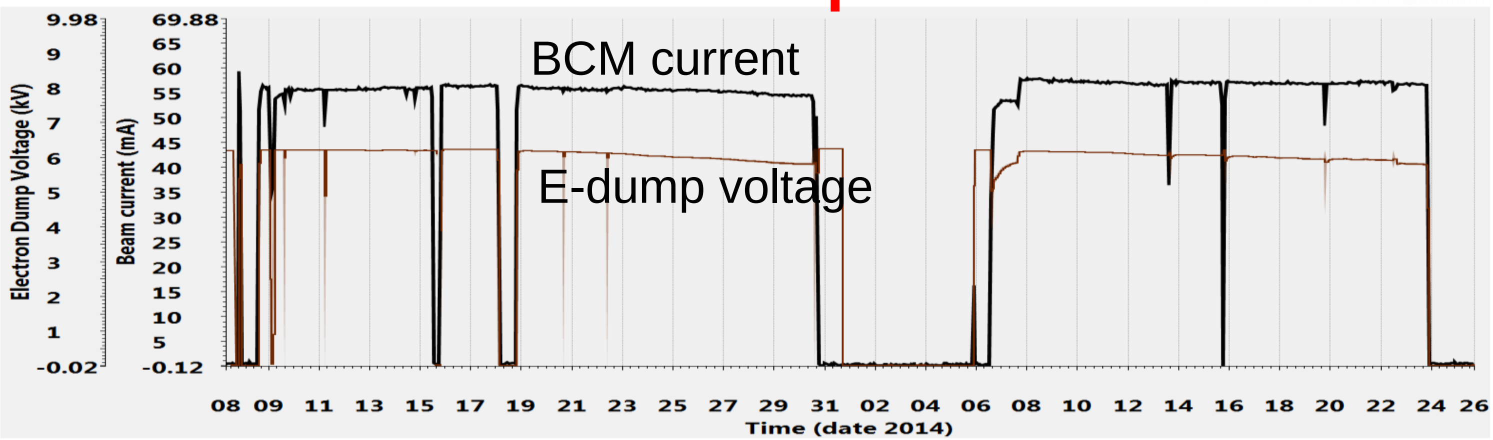
Tek Run
Trig?
18 sccm
13 MHz
plasma dies
1.00 V Ω
500mV Ω
1.00 V
Value
Mean
Min
Max
Std Dev
Peak−Peak 4.32 V 4.28 600m 5.40 109m
Peak−Peak 1.66 V 1.67 120m 2.76 37.2m
200µs
336.400µs
500MS/s
1M points
220mV
Type
Edge
Source
3
Coupling
DC
Slope
Level
220mV
Mode
Normal
& Holdoff
23 Dec 2014
22:42:01

SNS External antenna source



- RF-driven (pulsed 2 MHz, 30-50 kW), Cs-enhanced, multicusp H^- sources capable of delivering ~50 mA.
- Similar to baseline source except for a water cooled AlN plasma chamber, antenna external to the vacuum and a plasma gun for ignition.

While there remain issues a 40-day run with stable beam and e-dump has been demonstrated.



40 day run

Summary and Conclusions

- We have shifted to ion source #2 and #4 which yield a lower thermal load to the RFQ.
- Paying more attention and spending more time tuning the source and LEBT has increased the current output.
- However, the compromised RFQ transmission reduces this gain to 1-2 mA.
- We have made progress in reducing the H_2 pressure without having frequent plasma outages.
- As time allowed we have redirected our efforts to the ion source test stand, testing a new RF amp, wide-leg antennas, a new H_2 supply configuration, etc. Excellent progress was achieved with the external antenna source
- The LEBT gate valve is being successfully tested on the test stand in preparation for Frontend installation.

Thank you for your attention!

Ion Source RF

- The 2 MHz QEI amplifier continues to operate on ground outside of the 65 kV enclosure.
  - Only downtime was attributed to a failed connection on the output circuit
- The 2 MHz isolation transformer has required minimal maintenance since installation in July 2010
- The Tektronix generator/control system has been trouble-free
  - Implemented a frequency shift mode to better support plasma ignition
- Use of the Tomco 2 MHz, 120 kW solid-state amplifier has been successful on the test stand
  - The VSWR circuit was modified to improve reflected power operation
  - A second Tomco solid-state amplifier is installed on the ITSF