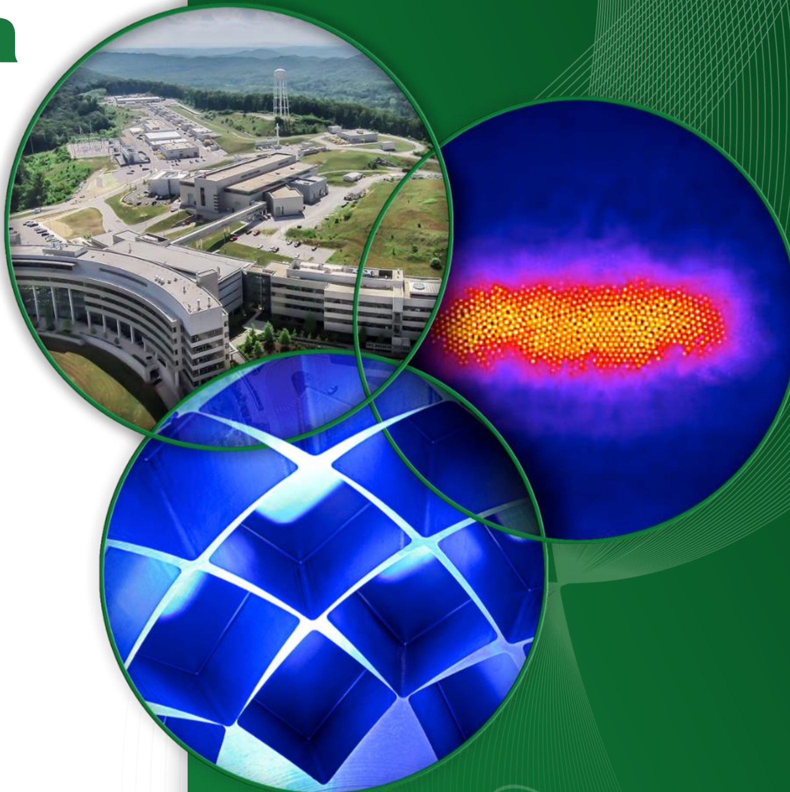
Recent Performance of the SNS H^- Ion Source with a Record Long Run



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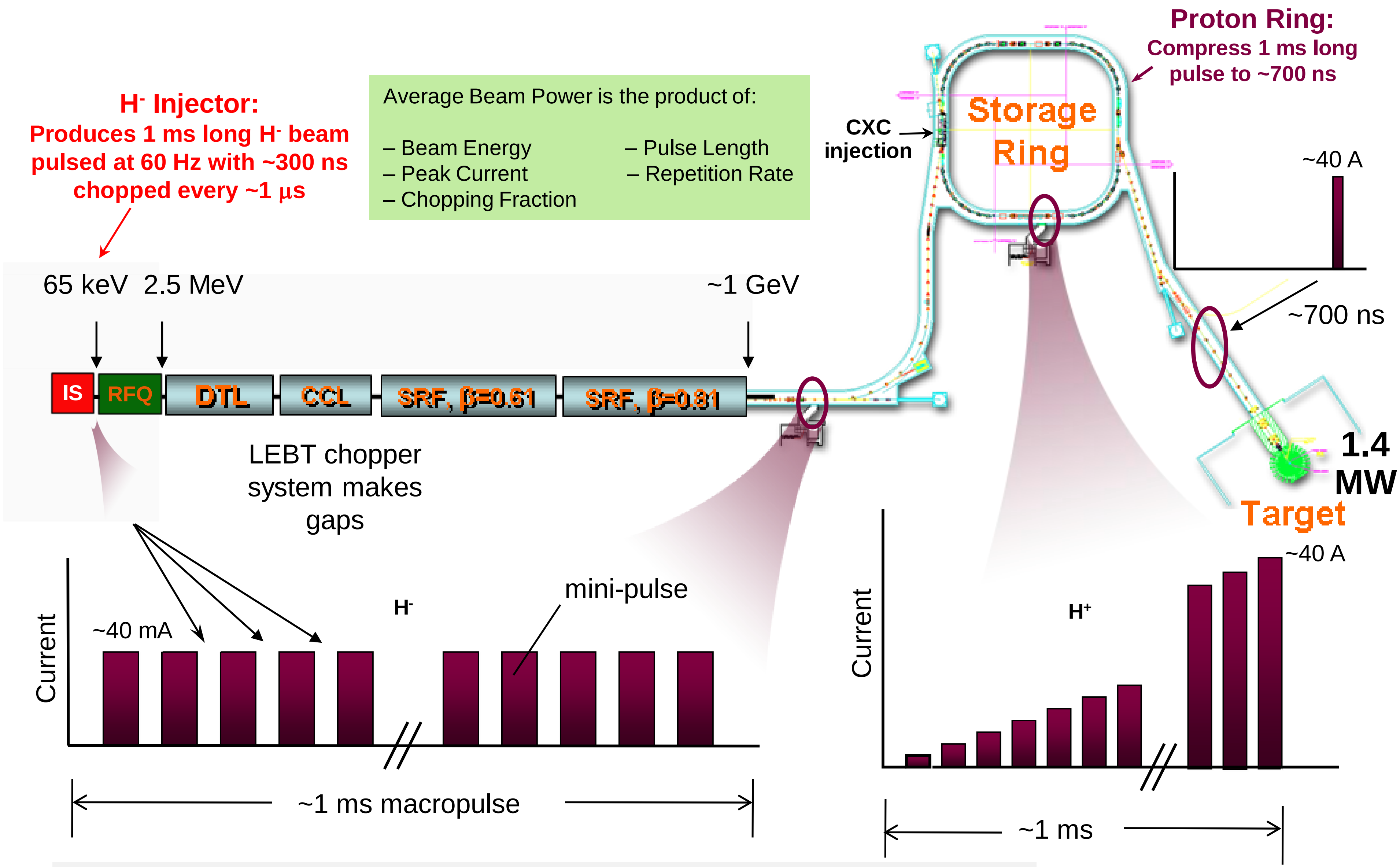
The 7th International Symposium on Negative Ions, Beams and Sources (NIBS'20)
(September 1-11, 2020)

Outline of the talk

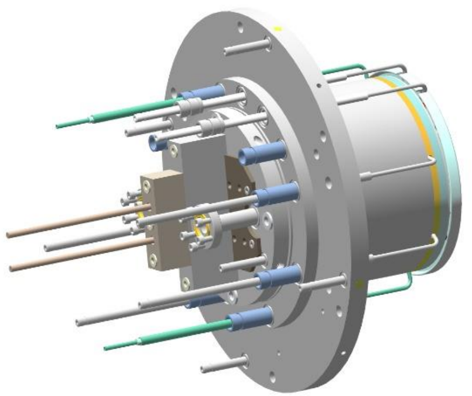
- The SNS accelerator complex and its H^- injector
- A new RFQ and an upgraded ion source support infrastructure
- Recent performance of the ion source and LEBT operation
- Summary and outlook

The SNS accelerator system overview

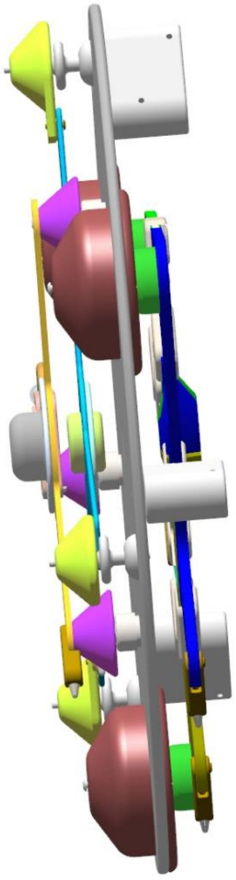


The multi-turn charge exchange injection and low loss beam extraction from the storage ring requires chopped H^- beam from the linac.

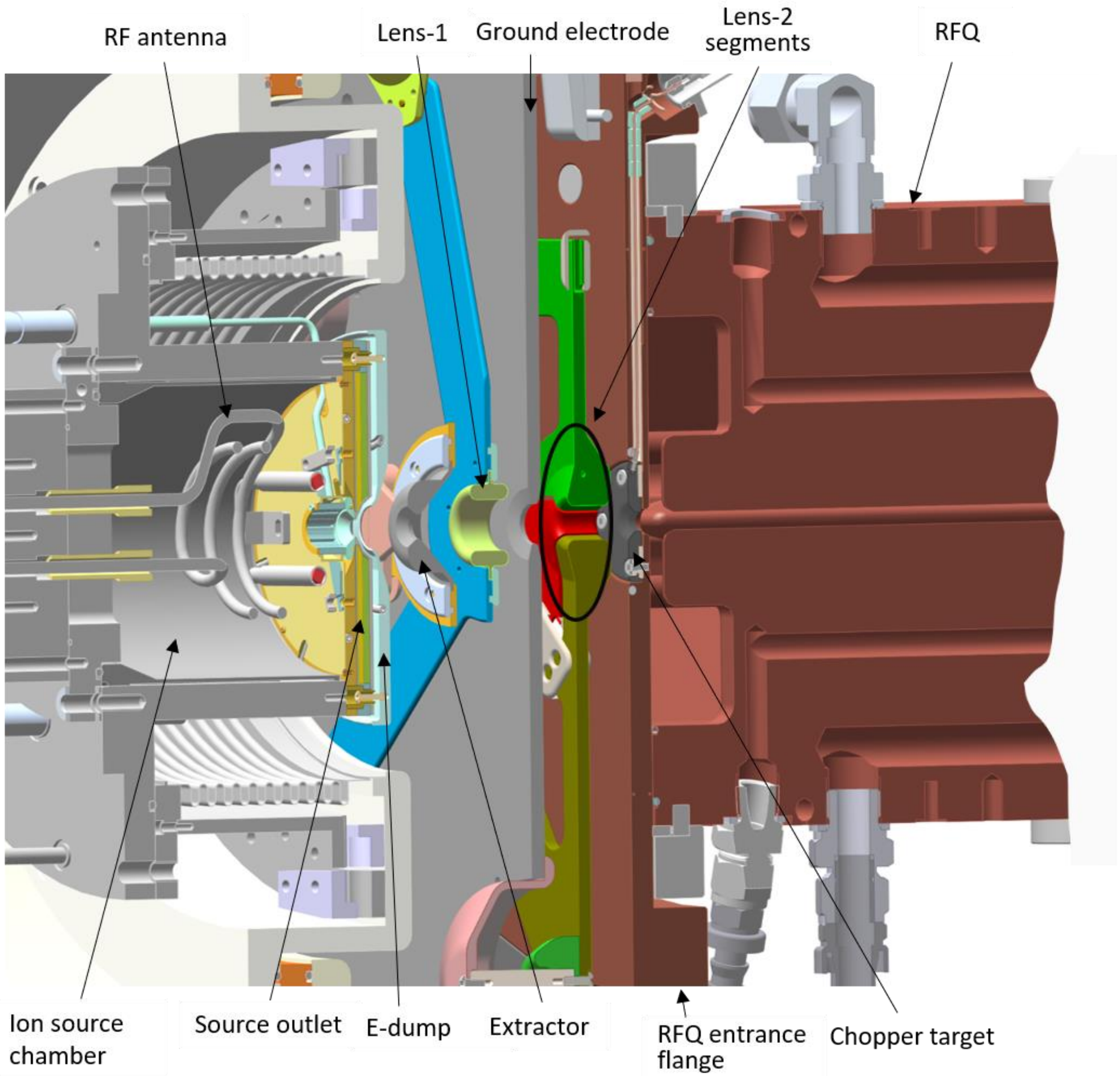
The SNS H$^-$ injector



Ion source assembly

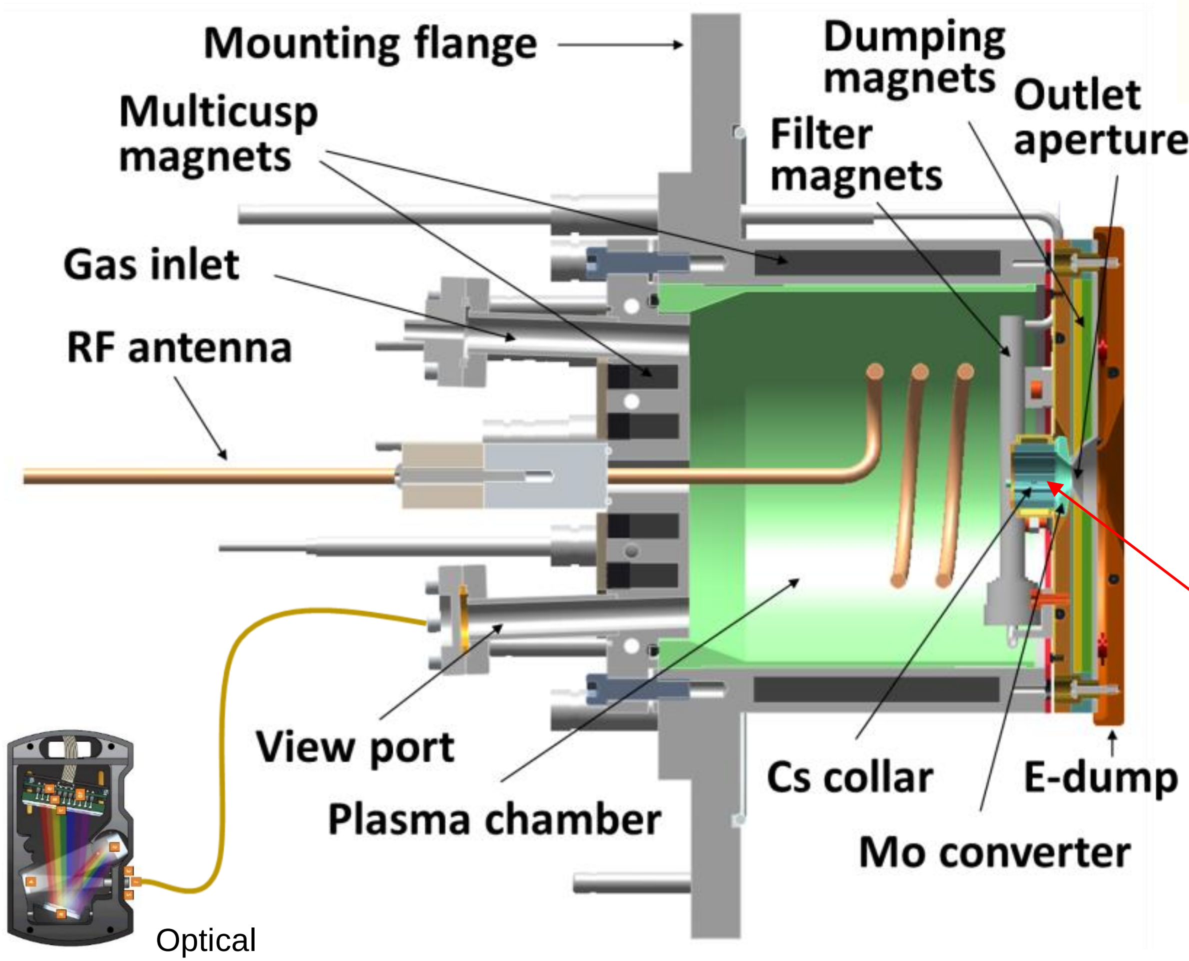


LEBT assembly



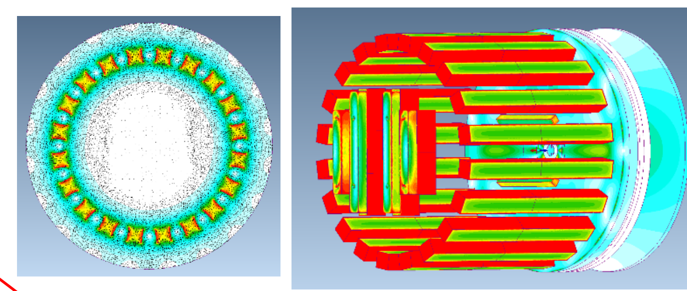
- The SNS H$^-$ injector was originally designed and built at LBNL and further developed at ORNL.
- An RF-driven, Cs-enhanced, multi-cusp H$^-$ ion source
- A compact 2-lens electrostatic low energy beam transport (LEBT)

The ion source

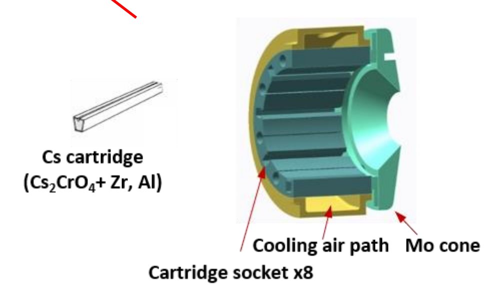


Optical spectrometer

2.5-turn, porcelain-coated, water-cooled, copper tube antenna

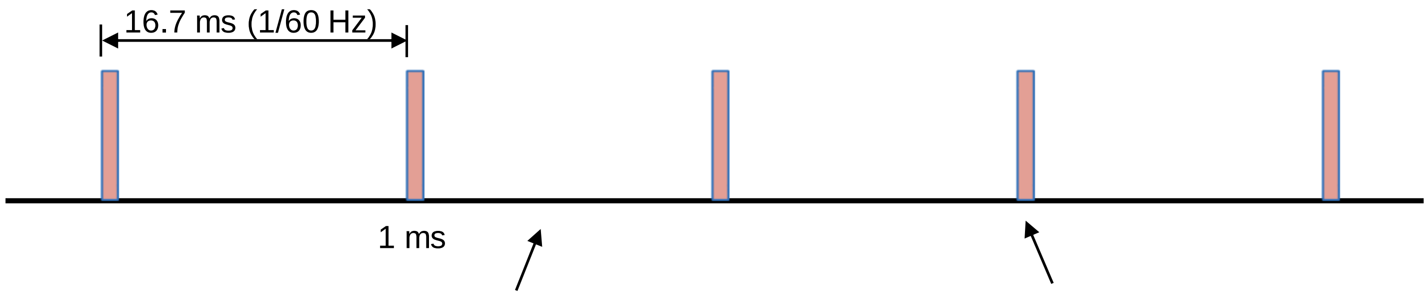


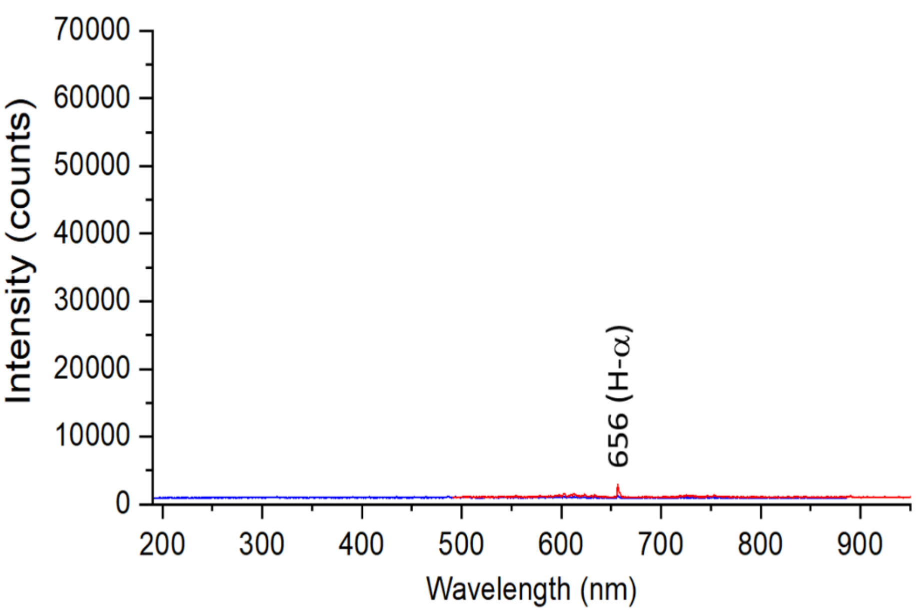
Plasma confinement cusp fields

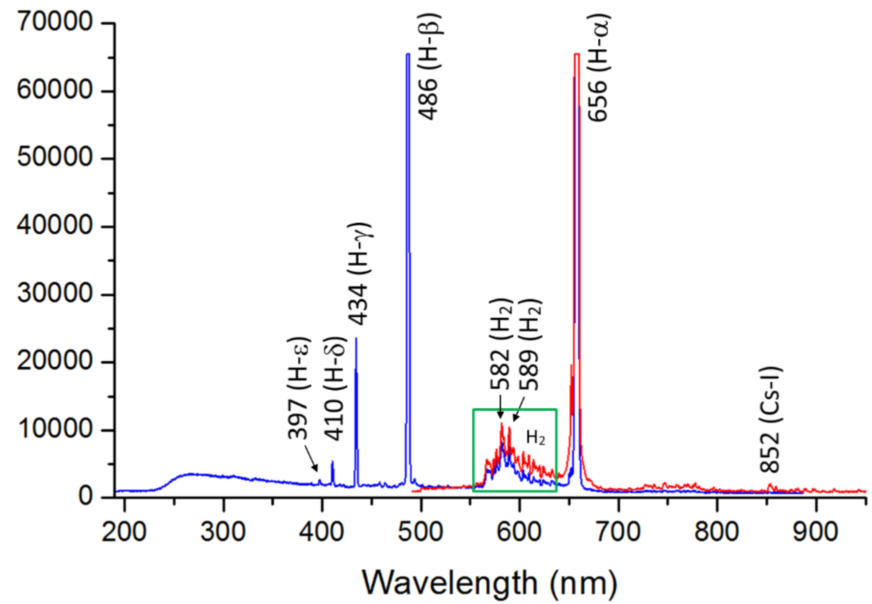


Cesium dispenser system

SNS ion source RF timing structure





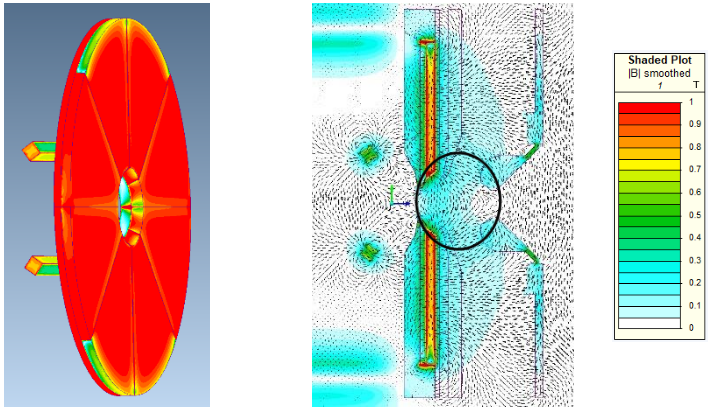


Continuous, low power (typically ~300 W) 13.56-MHz RF maintains a low density plasma in the chamber to facilitate fast turn-on of the main plasma

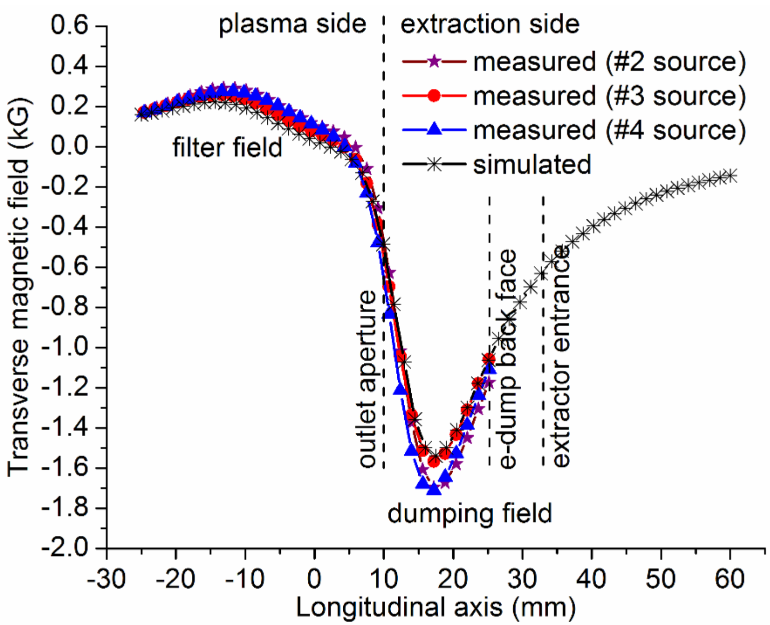
High power (typically ~50 kW) 2-MHz RF pulsed at 60 Hz with 1 ms pulse length drives the main plasma for beam production

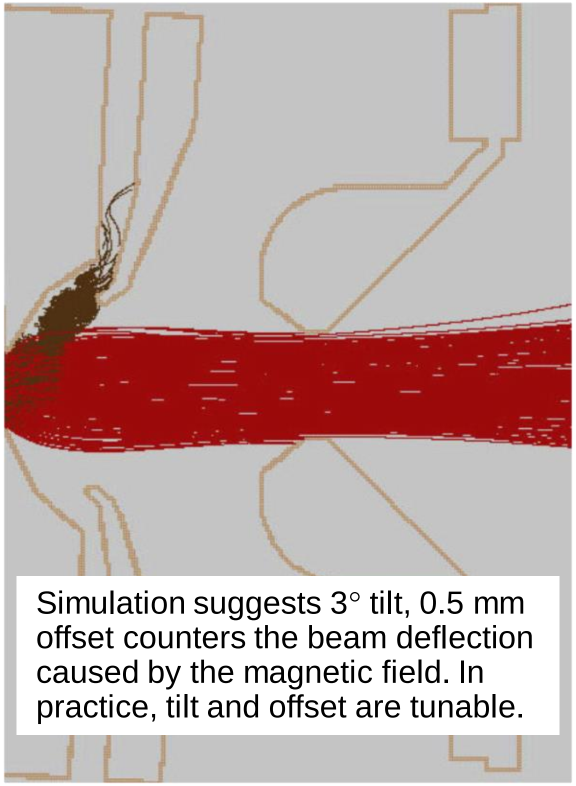
Separation of the co-extracted electrons, and the ion source tilt and offset mechanism

- Transverse dipole magnetic field in the outlet region deflects the co-extracted electrons towards the e-dump electrode
- The ion source together with the e-dump electrode can be tilted and offset against the LEBT axis to compensate the effect of electron dumping field on the ion beam



Co-extracted e^- dumping field



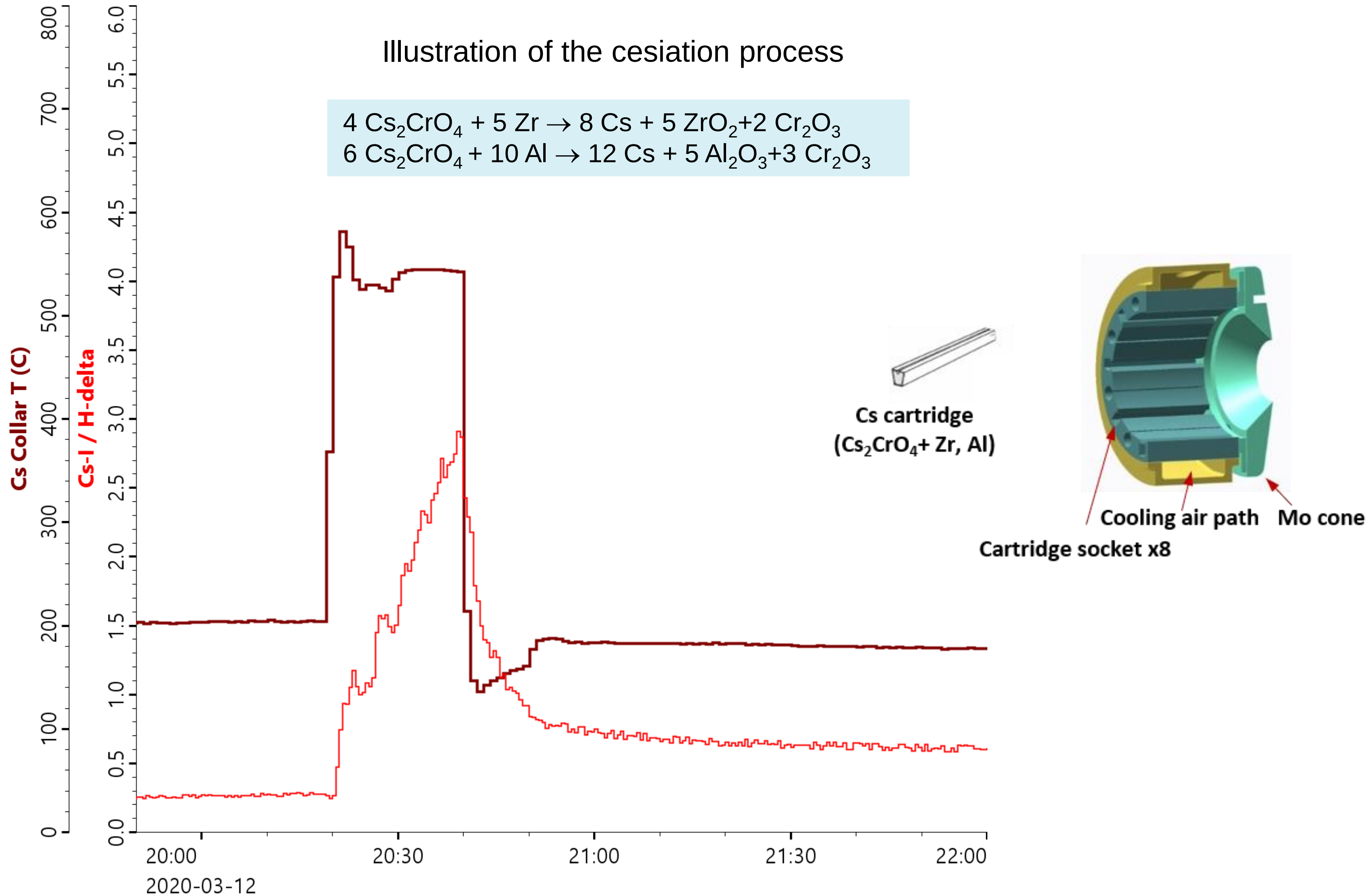


Simulation suggests 3° tilt, 0.5 mm offset counters the beam deflection caused by the magnetic field. In practice, tilt and offset are tunable.

SNS ion source cesiation

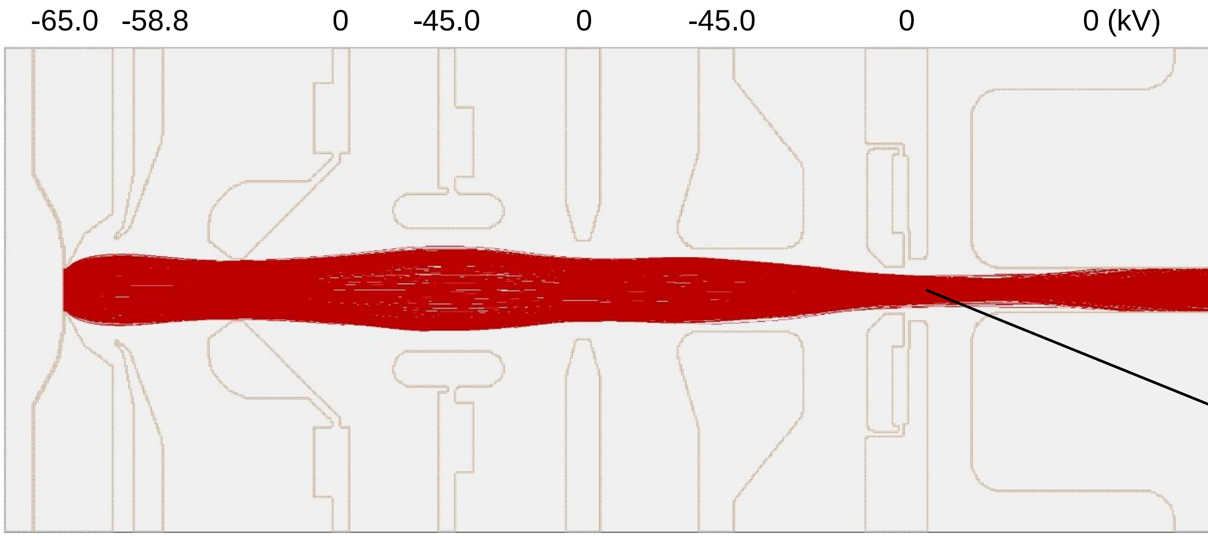
Illustration of the cesiation process

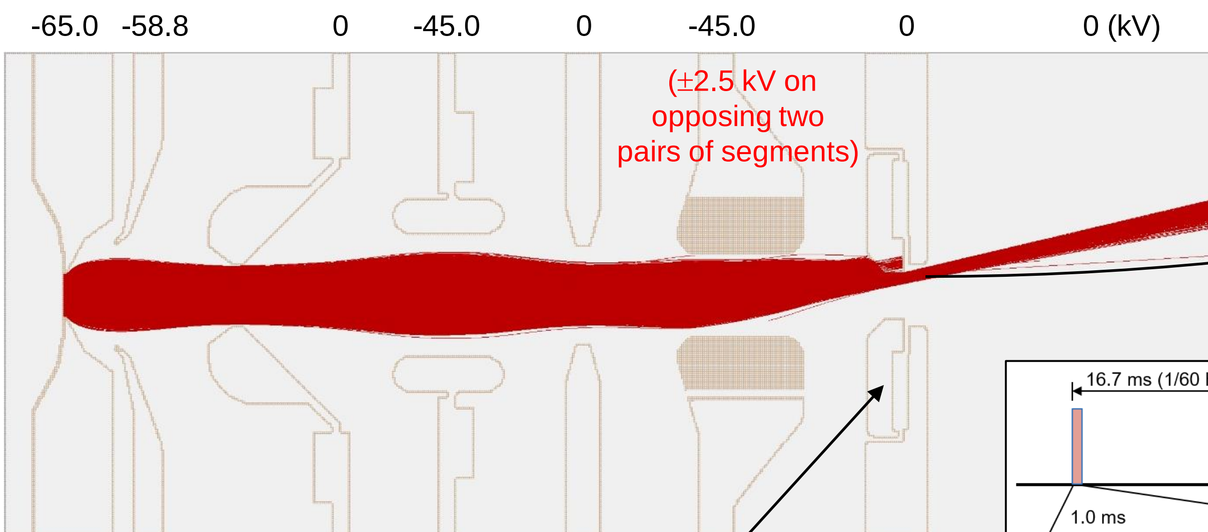
$4\ Cs_2CrO_4 + 5\ Zr \rightarrow 8\ Cs + 5\ ZrO_2 + 2\ Cr_2O_3$
$6\ Cs_2CrO_4 + 10\ Al \rightarrow 12\ Cs + 5\ Al_2O_3 + 3\ Cr_2O_3$

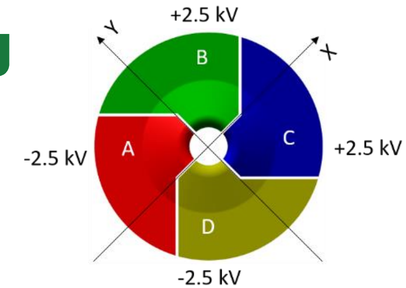


For the SNS ion sources, typically a dose of cesiation enables high current ion source operation covering several months.

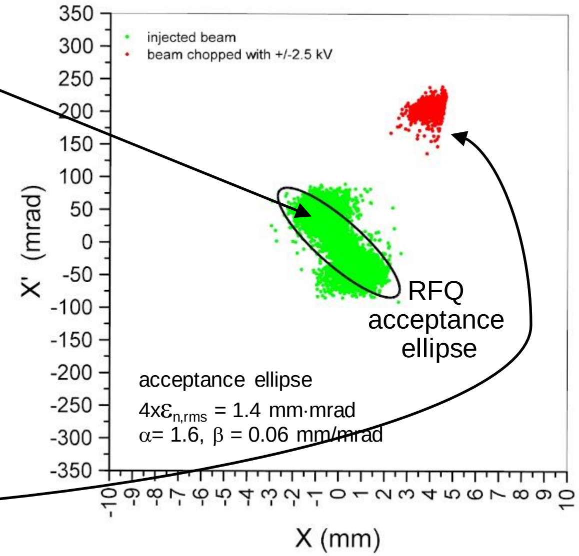
Beam injection vs. beam chopping



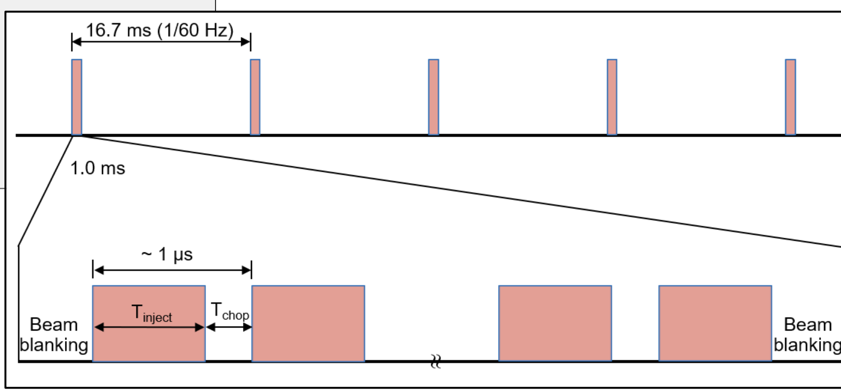




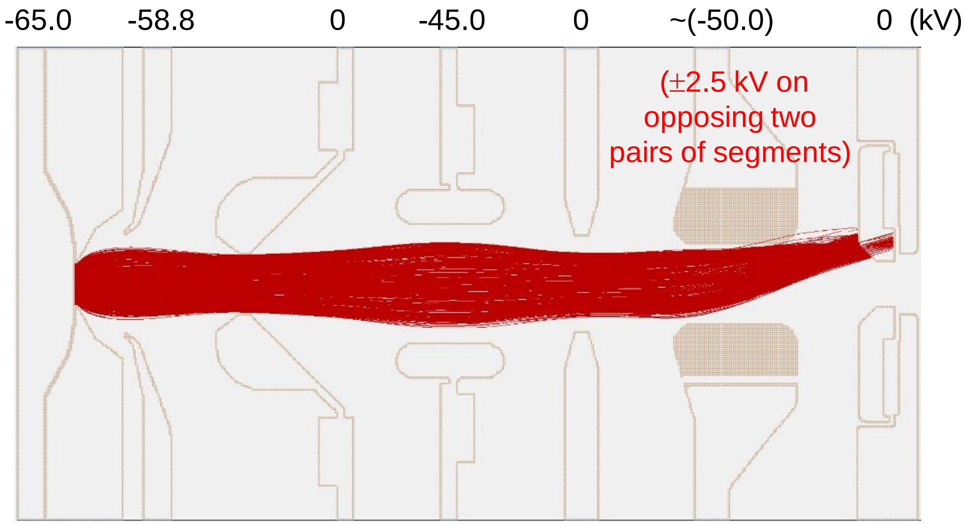
injected or chopped beam vs. the RFQ acceptance ellipse at the RFQ injection reference plane. The X axis is aligned to the direction of beam deflection

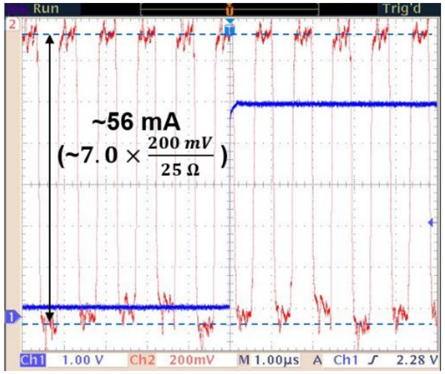


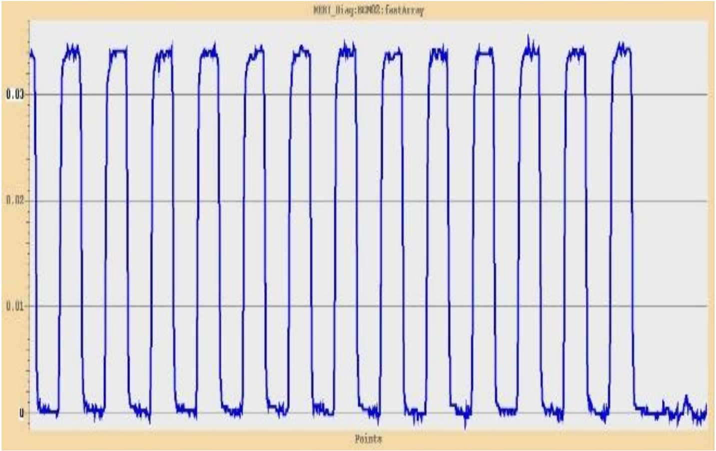
The chopper target is electrically isolated from the RFQ flange. It receives the chopped beam and drains to ground through a resistor circuit.



Measurements of beam currents

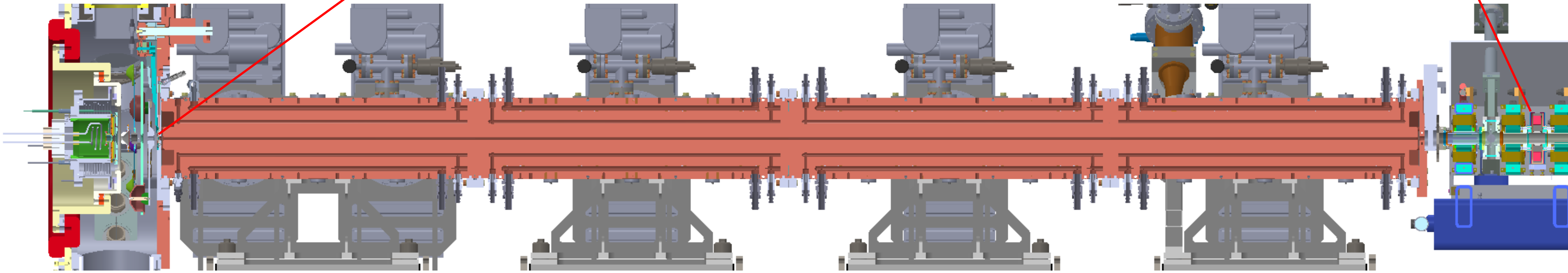






The input to the RFQ from the IS-LEBT can be measured on the chopper target by fully deflecting and collecting the beam onto the chopper target.

The RFQ output current is continuously monitored with a beam current toroid (BCM02) and achieved



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- The SNS accelerator complex and its H^- injector
- A new RFQ and an upgraded ion source support infrastructure
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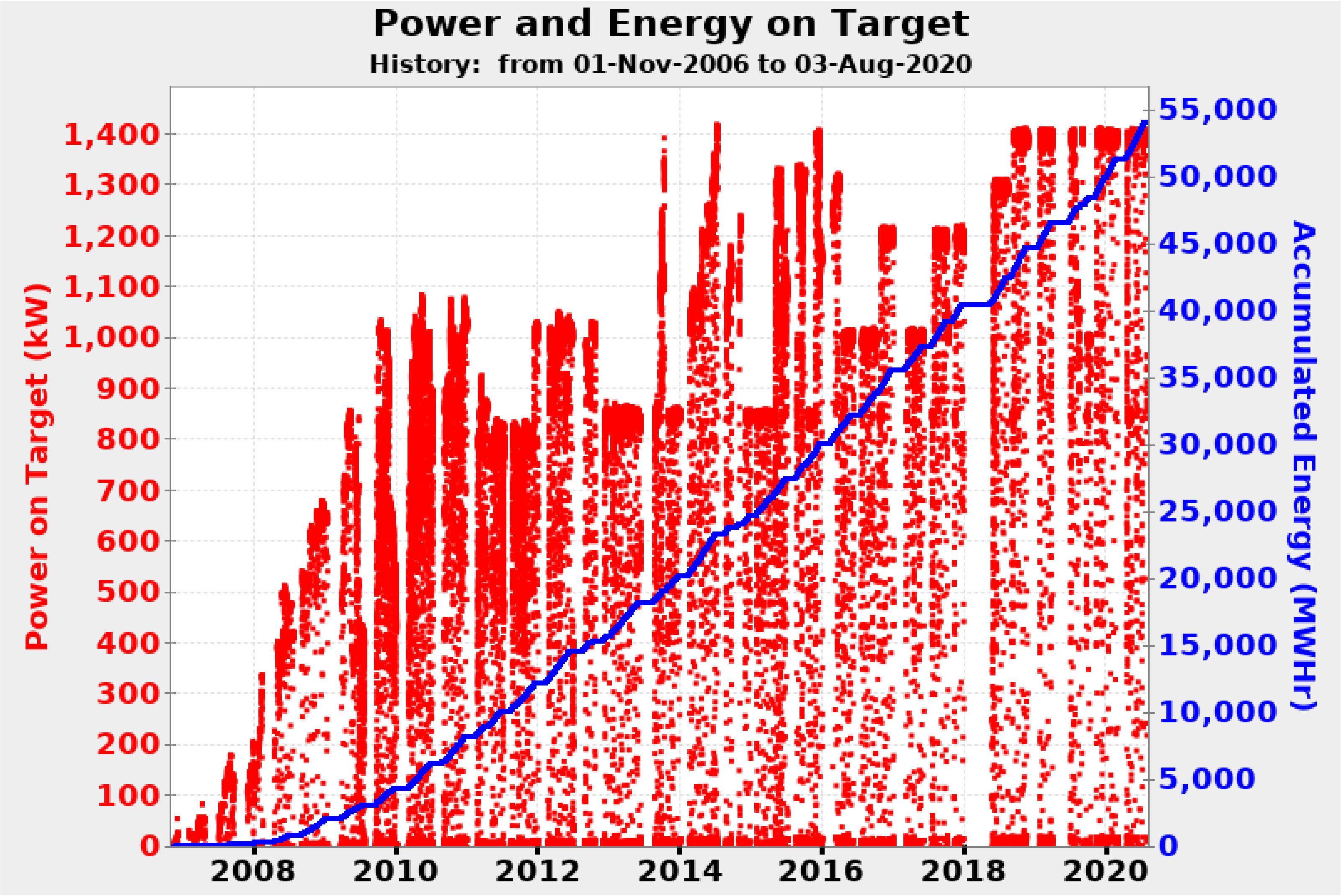
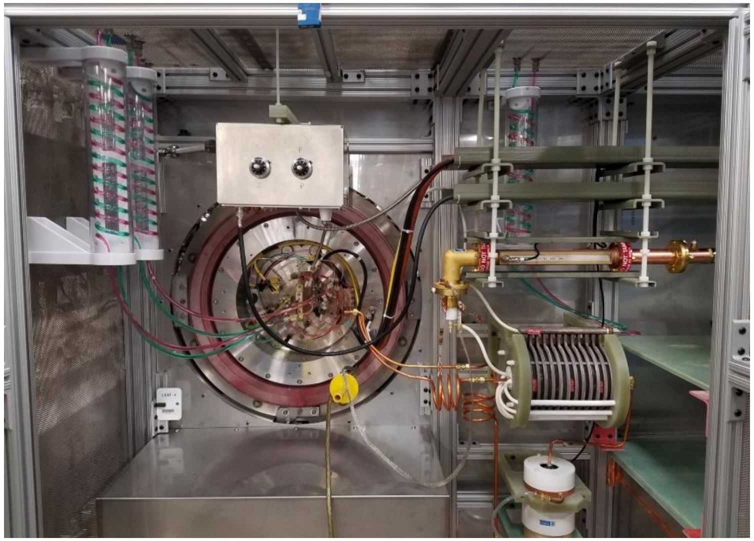
The SNS beam operation since its commencing in 2006



In April 2018, the original SNS RFQ was replaced with a new RFQ, and the ion source support infrastructure was also upgraded

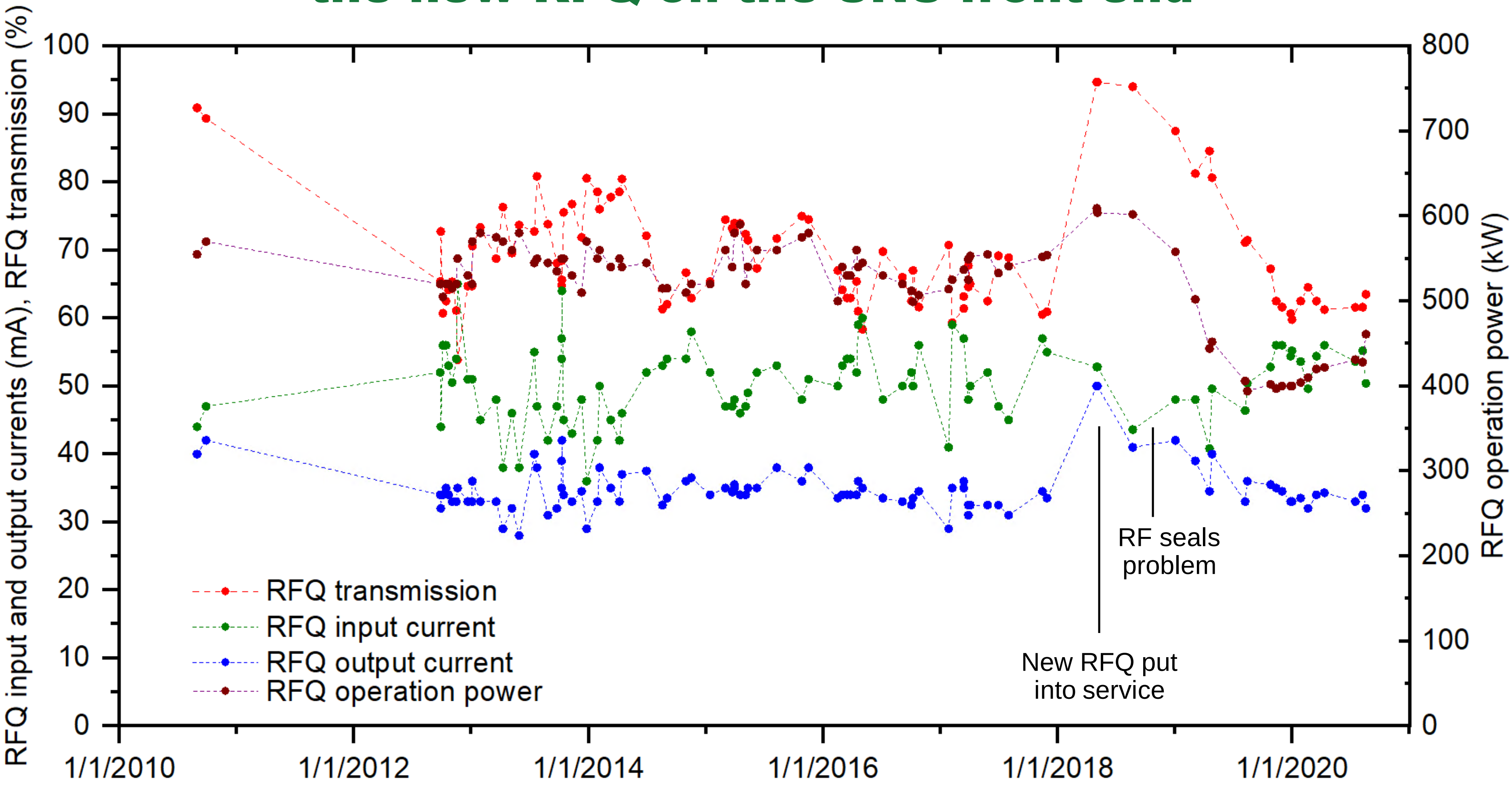
A new RFQ and an upgraded ion source support infrastructure on the SNS front end



- New HV enclosure (cage) and improved routing of HV cables and water lines
- Increased all HV gaps to >6 inches, external sparks are rarely observed
- New integrated configuration of 2-MHz RF matching network (RF circuit is essentially identical to the original)
- H_2 gas is fed to source from a bottle on ground through a ceramic break

Reference: R.F. Welton et al, Installation and commissioning of the ion source systems for the new spallation neutron source 2.5 MeV injector, Rev. Sci. Instrum. 91, 013334 (2020); https://doi.org/10.1063/1.5128508

The beam transmission performance of the new RFQ on the SNS front end



- In May 2018, the beam transmission performance with the new RFQ reached ~90% restoring it to the initial good performance of the original Berkeley RFQ
- Due to failure of RF seals on the end walls of the new RFQ in November 2018, the RFQ has been operated since then with reduced power to mitigate the risk of RF seal failure

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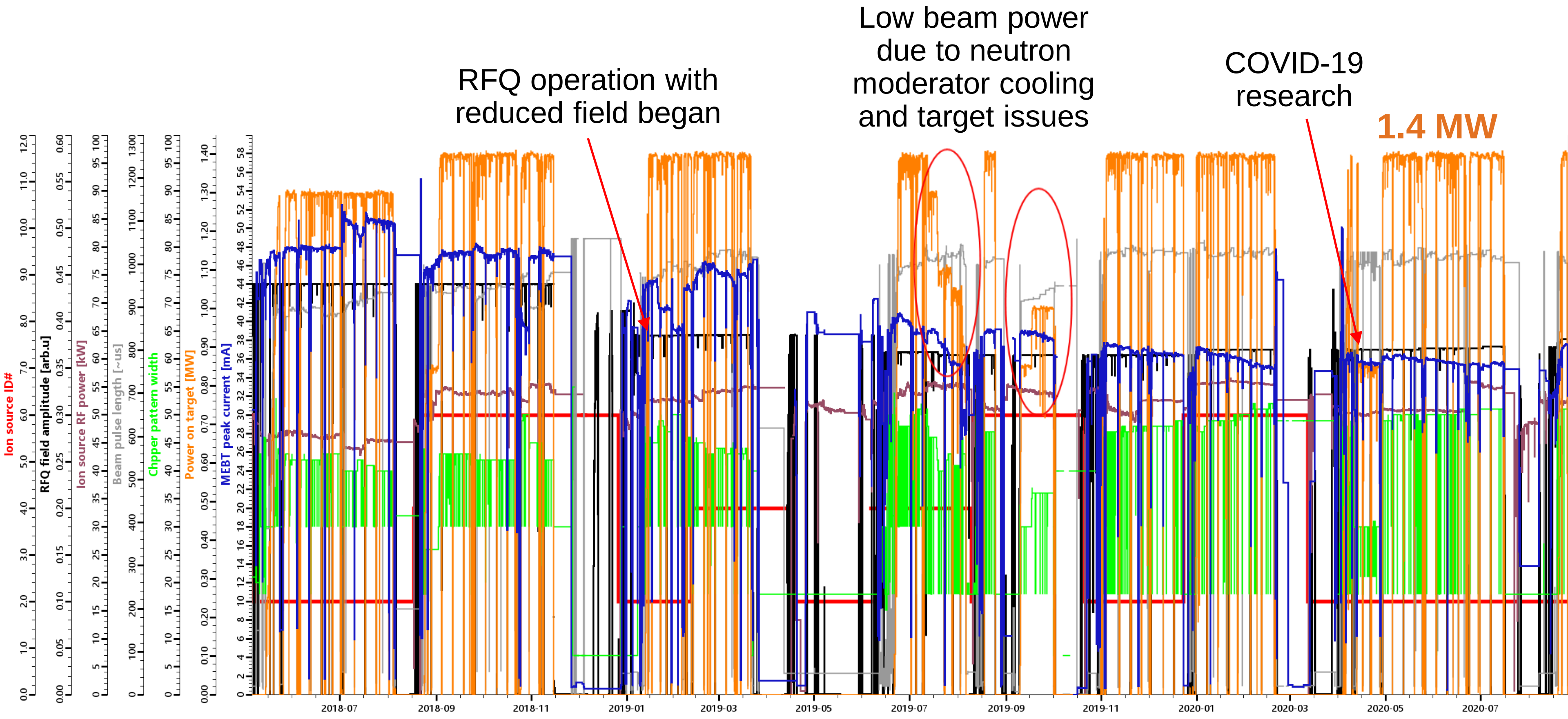
Ion source operation since the new RFQ installation

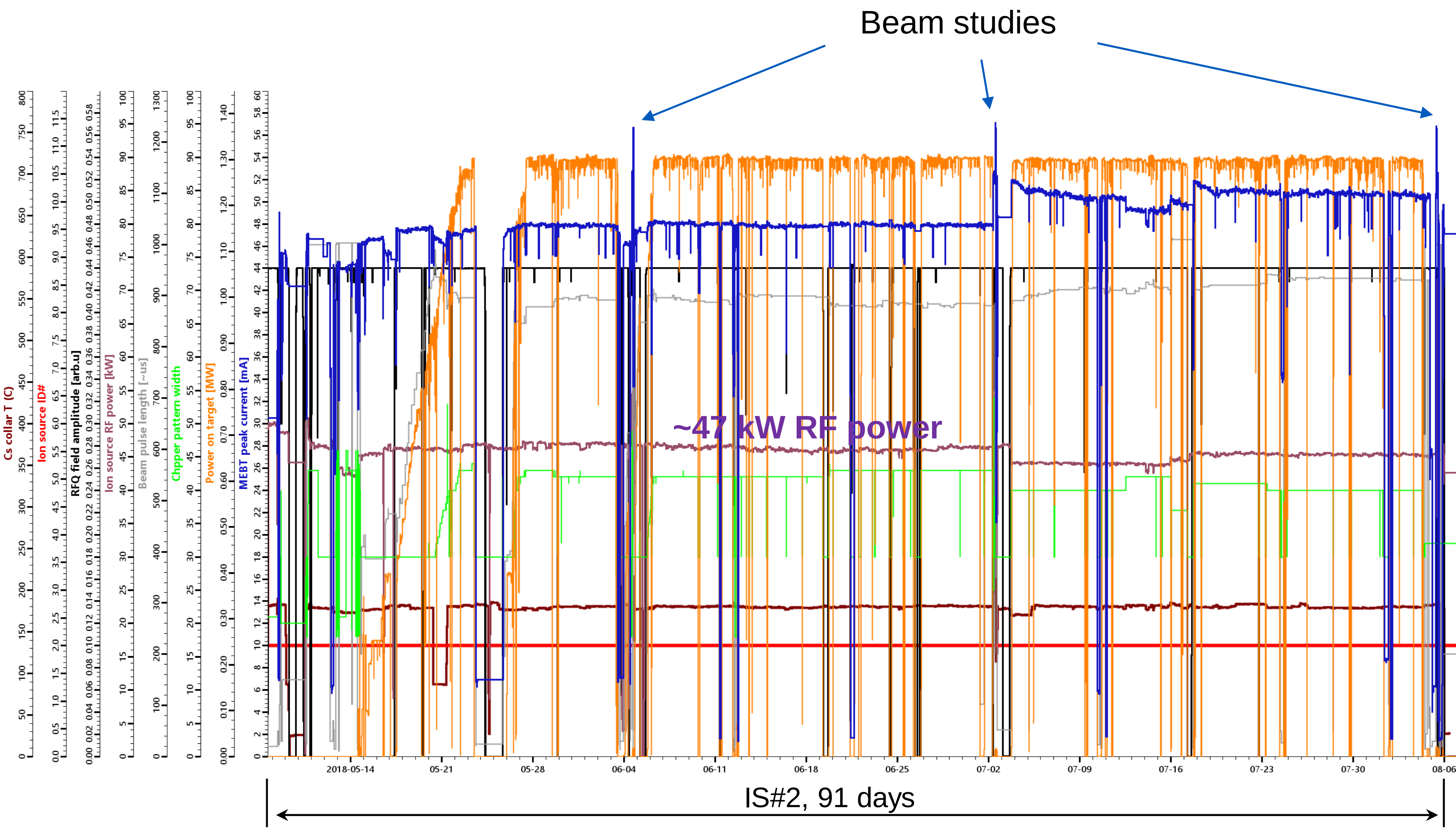


- Ion sources delivered >40 mA LINAC beam current for first two source cycles each operating for ~3 months with a moderate ion source output current owing to good beam transmission performance of the newly installed RFQ.
- Despite the conservative operation of the RFQ with reduced field, ion sources delivered adequate beam current supporting the SNS operation for required beam power, mostly 1.4 MW
- During the most recent run, the ion source operated record long 116 days with a single source

Ion source operation since the new RFQ installation

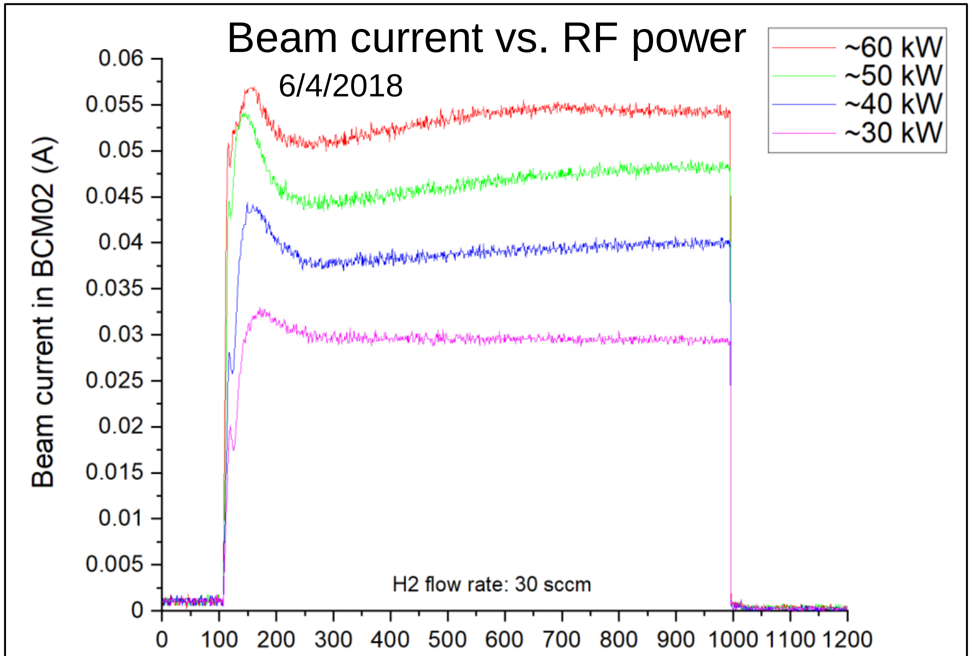
Start date	End date	IS ID#	Days of operation	Date of beam measurement	RFQ input current	RFQ output current	remarks
5/7/2018	8/6/2018	#2	91	6/4/2018		43 mA	
8/17/2018	8/21/2018	#4	4				LEBT thermocouple popped out and arced to ion source HV
8/21/2018	11/16/2018	#6	87	8/22/2018	~44 mA	41 mA	RFQ RF seal failure, run ended early
12/27/2018	2/11/2019	#2	46	1/2/2019	~48 mA	42 mA	E-dump insulator issue, source was changed in a convenient opportunity
2/11/2019	3/26/2019	#4	43	3/5/2019	~48 mA	39 mA	Target mercury loop issue, run ended early
4/17/2019	6/3/2019	#2	47	4/26/2019	~50 mA	40 mA	
6/6/2019	8/8/2019	#4	63	8/7/2019	~46 mA	33 mA	
8/9/2019	8/10/2019	#2	1				Filter magnet not locked in place, caused too high co-extracted electrons
8/10/2019	10/3/2019	#6	54	8/14/2019	~50 mA	36 mA	
10/21/2019	12/23/2019	#2	63	10/25/2019	~53 mA	35.5 mA	
12/23/2019	2/21/2020	#6	60	12/21/2019	~54 mA	33 mA	
3/12/2020	7/16/2020	#2	116	3/16/2020	~54 mA	34 mA	3/16-3/27 source was turned off awaiting other systems to be ready from maintenance activities
7/24/2020		#2		8/7/2020	~55 mA	34 mA	

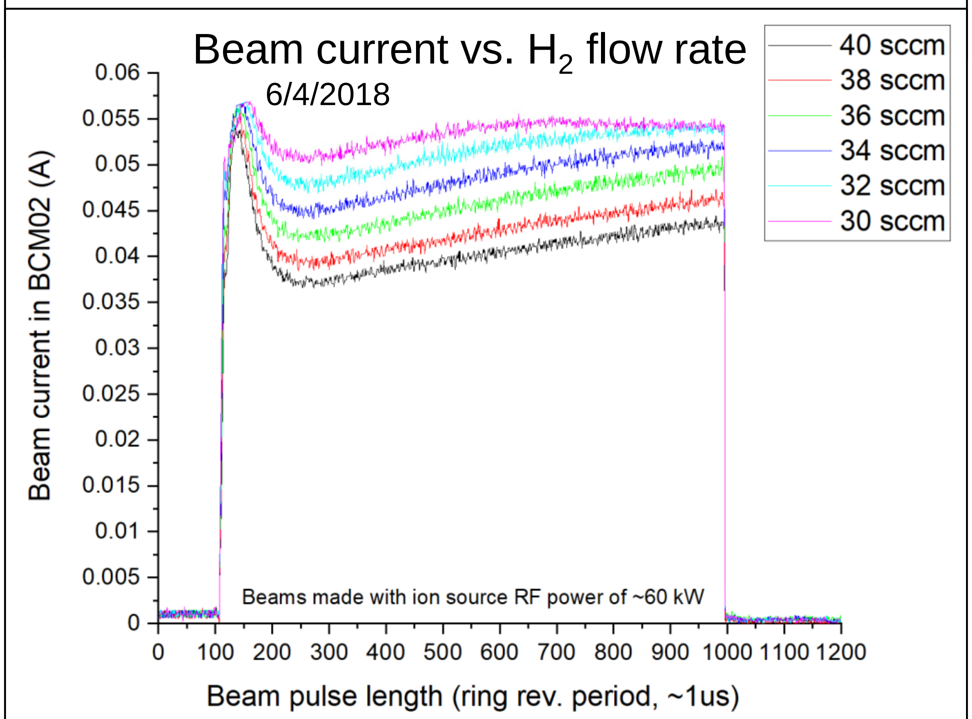
Ion source beam studies with the new RFQ

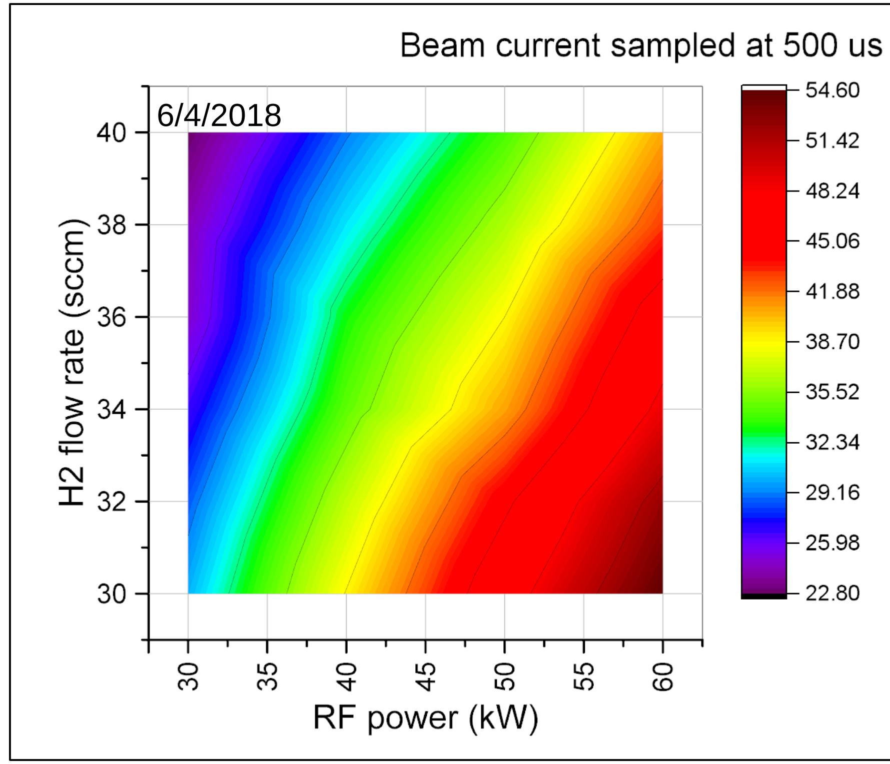


Ion source beam studies were carried out on 6/4, 7/2, and 8/5, 2018 during the machine time allocated for accelerator physics

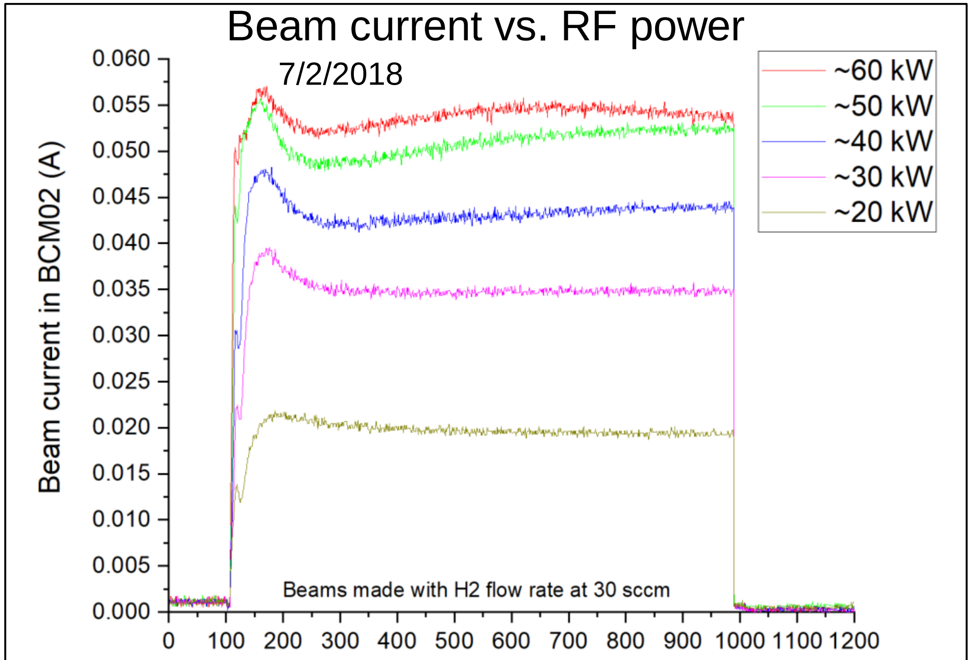
Tests of beam current vs. RF power and H_2 flow rate 6/4/2018



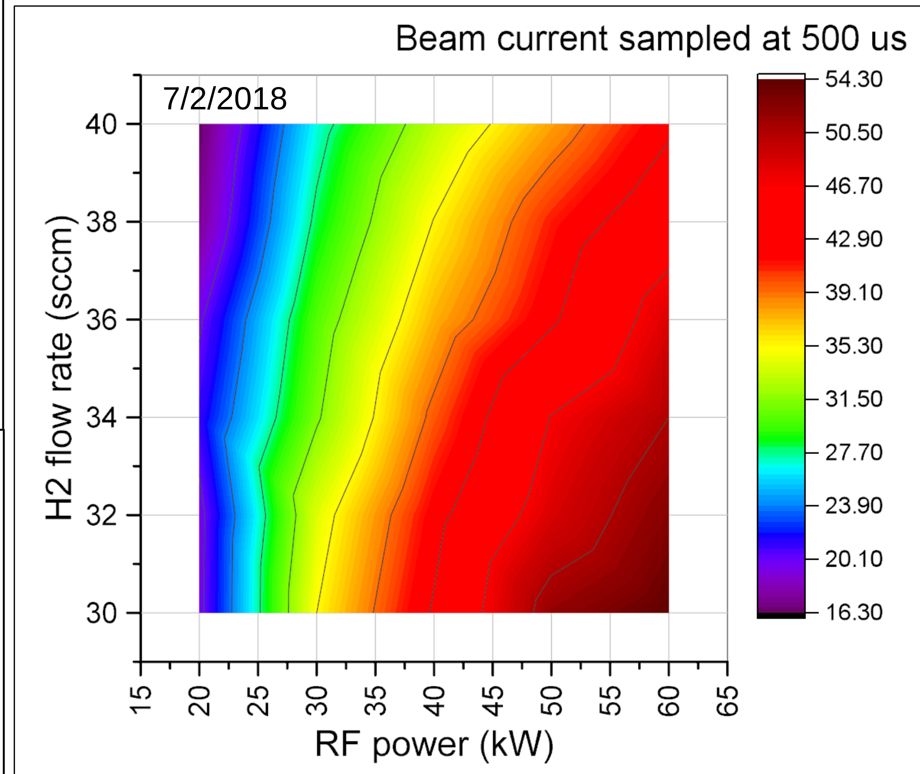


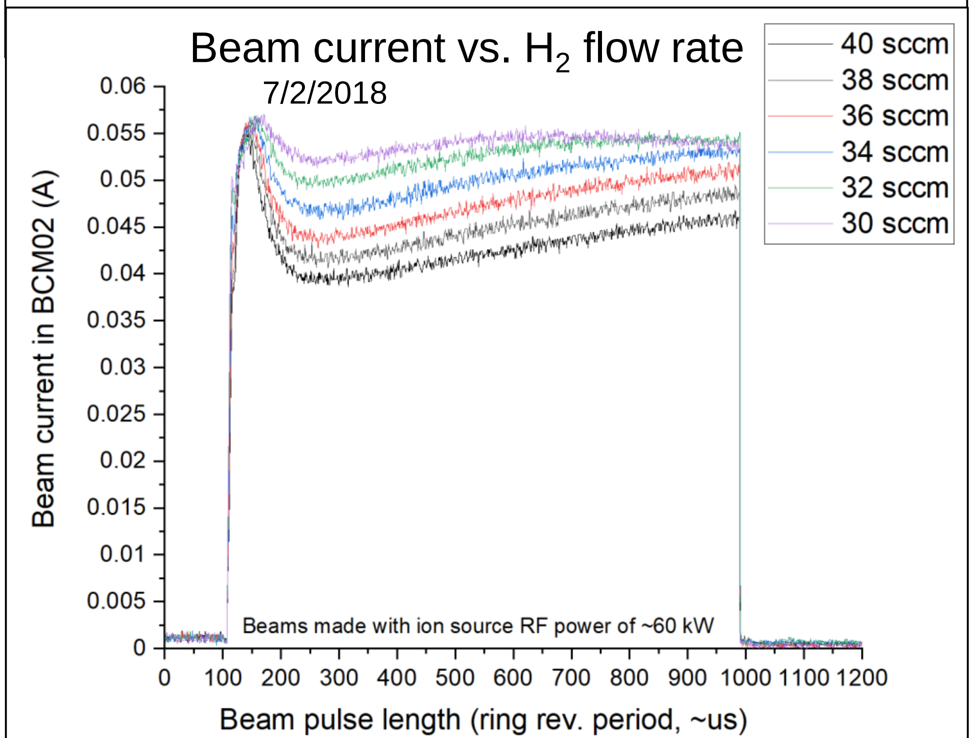


When H2 flow rate was varied for each power level of 30, 40, 50 and 60 kW, the corresponding beam pulse waveforms were recorded. The plot above is for the beam currents sampled at 500 us from the beginning of the pulses.



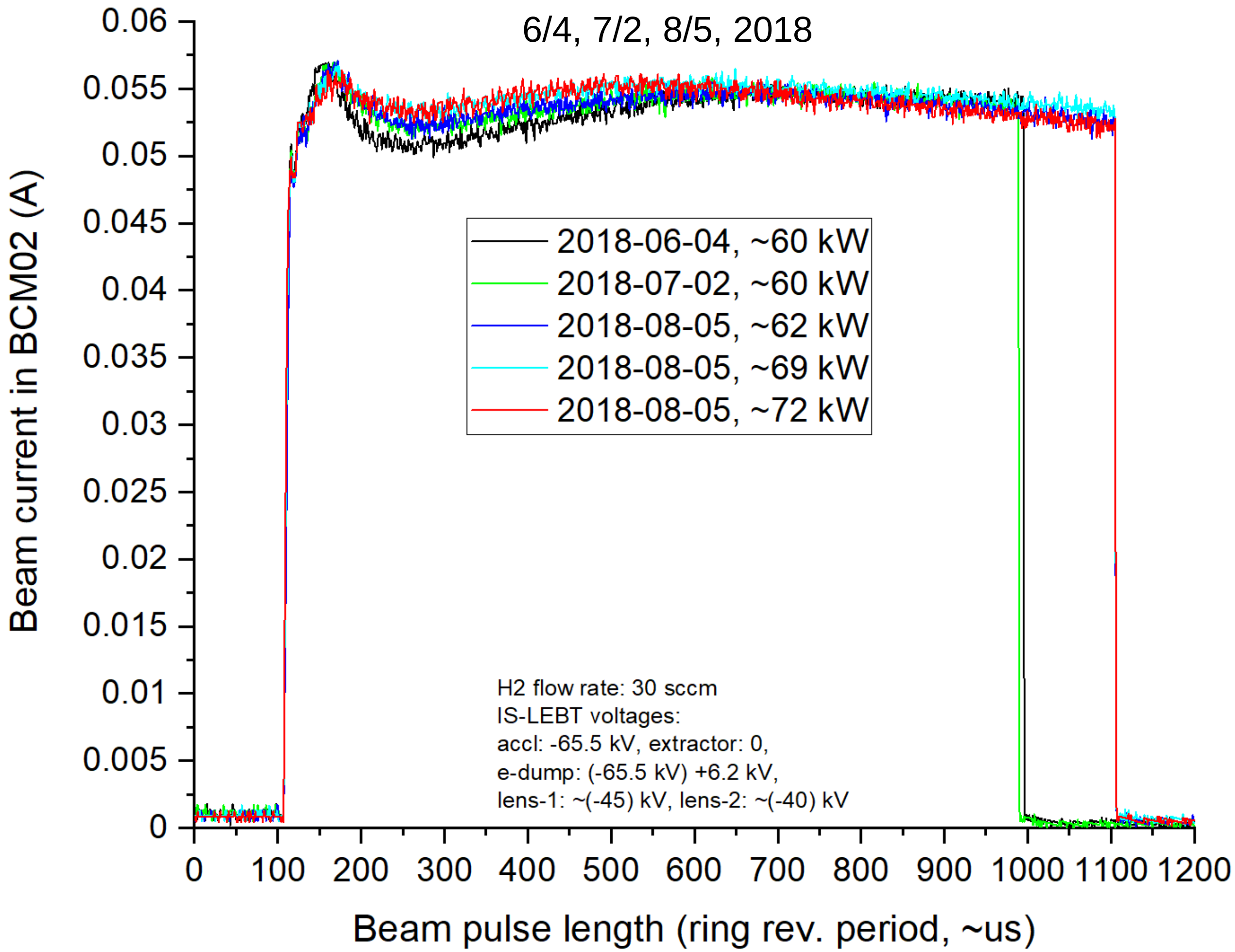
Tests of beam current vs. RF power and H_2 flow rate 7/2/2018





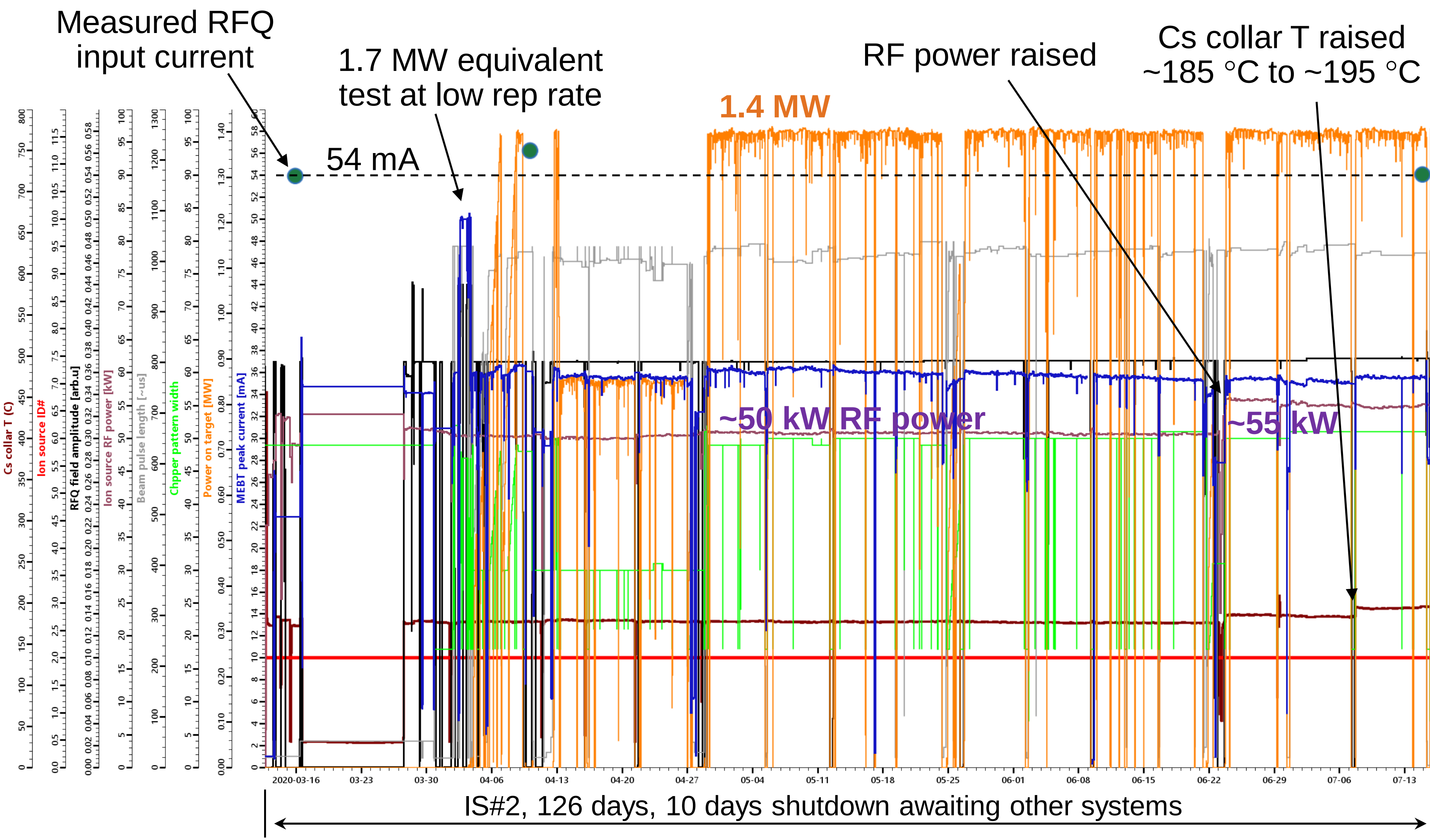
Similarly, the H2 flow rate was varied for each power level of 30, 40, 50 and 60 kW and the corresponding beam pulses were recorded. The plot above is for the current values sampled at 500 us from the beginning of the pulses.

High beam current tests on 6/4, 7/2, and 8/5/2018



- On three occasions, 6/4, 7/2, and 8/5 of 2018, the ion source consistently delivered ~53 mA LINAC beam current with a RF power of ~60 kW beyond which the beam current seemed to be saturated.
- These beam currents meets the SNS future Proton Power Upgrade and Second Target Station requirements.

Longest run of the SNS H$^-$ ion source

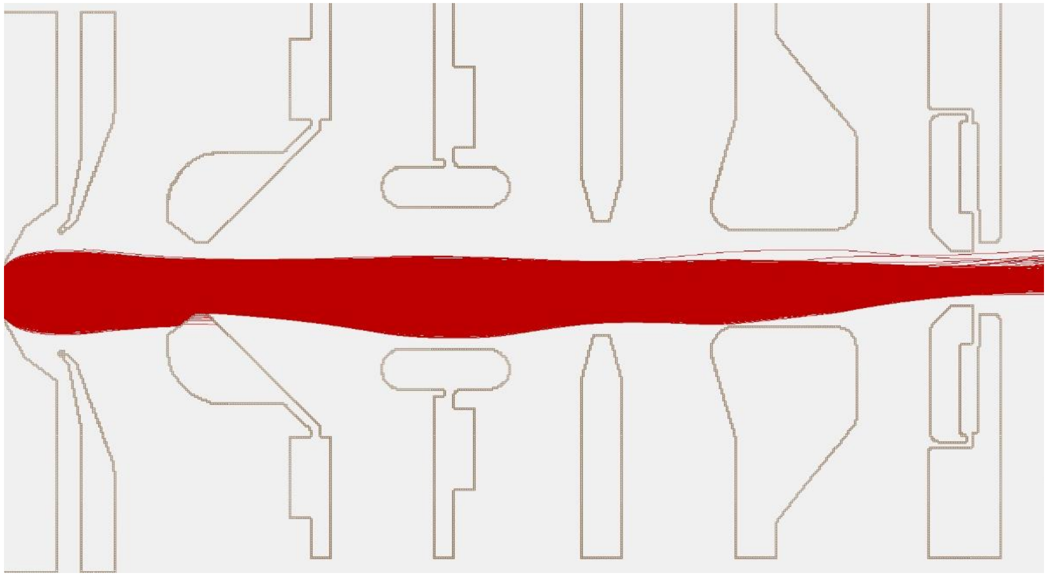


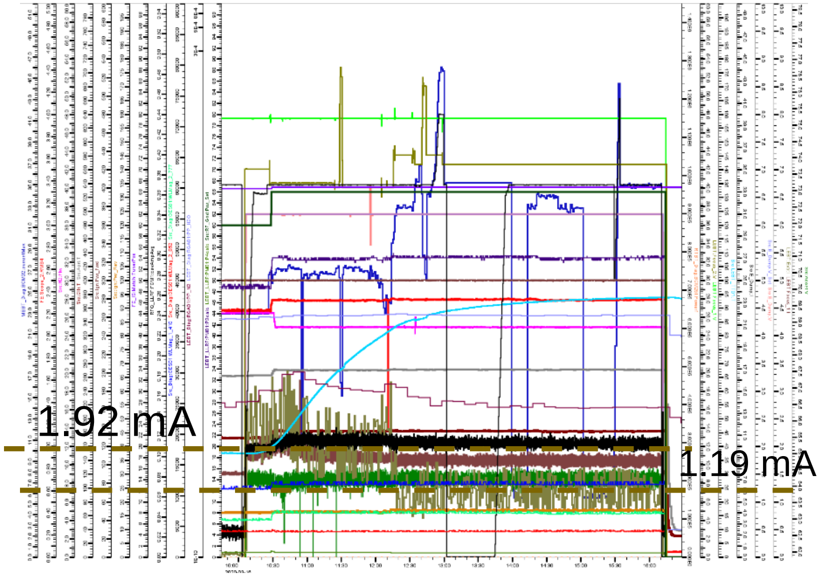
- IS#2 was operated for ~4 months with an availability of >99.5%
- A single dose of cesiation in the ion source startup yielded ~54 mA for the entire run
- After service inspections did not see significant wear or damage that would have limited further operation of the source.

Ion source initial misalignment and correction 3/16/2020

Due to disassembly/reassembly of the ion source mounting structure during the inspection of RF seal of the RFQ, the ion source alignment initially was quite off. Beam based alignment effort and LEBT tuning gained ~12 mA from the source and ~8 mA out of the RFQ.

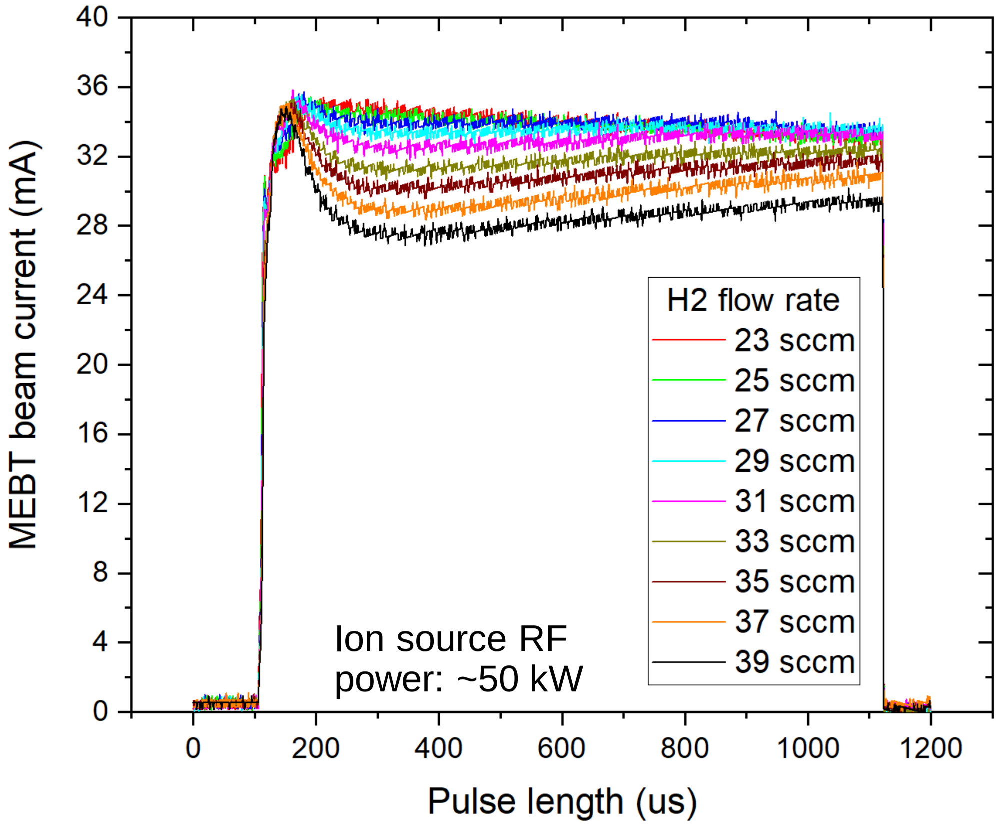
	Input to RFQ	Output from RFQ
Before alignment	42 mA	26 mA
After alignment	42+12 = 54 mA	26+8 = 34 mA

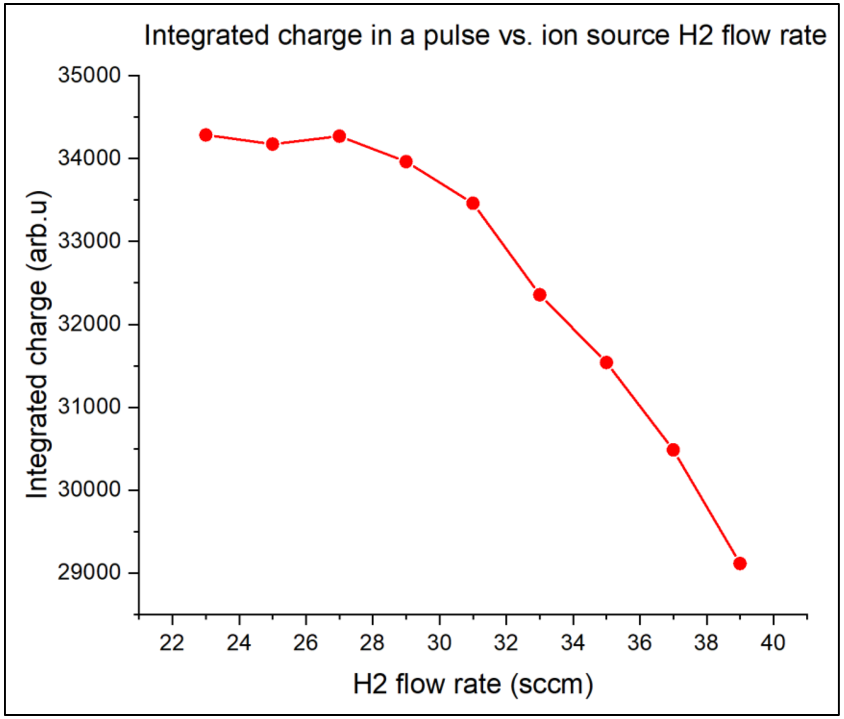




The change of average load current on the extractor electrode: 1.92 - 1.19 = 0.73 mA
The change of load current on extractor during ion source pulse: 0.73/0.06 = 12.2 mA

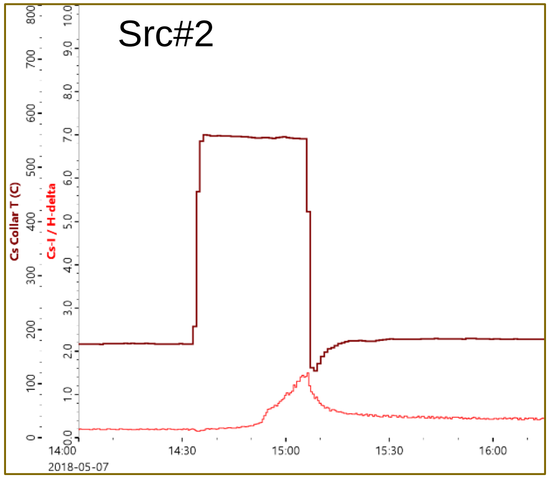
Beam current vs. ion source gas flow rate 4/10/2020

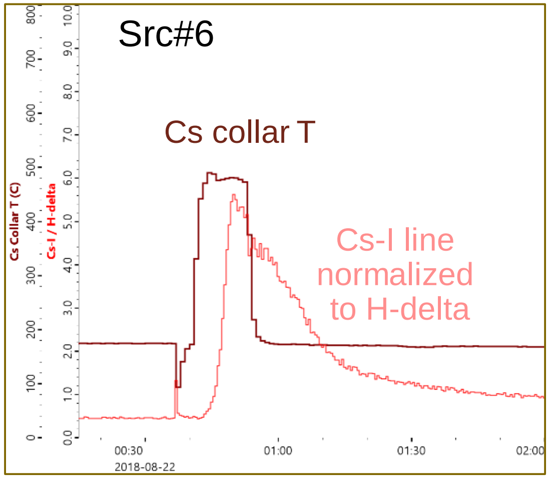


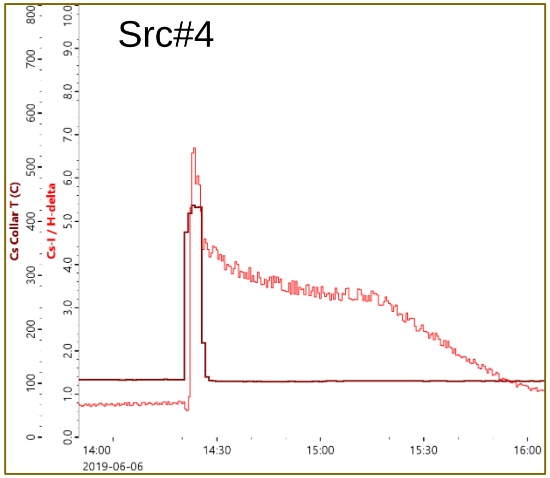


The beam pulse was flatter for the gas flow range of 23-27 sccm, and the integrated charge in a pulse was maximal

We continued to explore cesiation procedure for individual ion sources







- With better control of cesium, the ion source #2 is the best source in terms of beam output, persistency and reliability
- We continue to investigate the differences in mechanical tolerance of cesium collar assemblies of the individual ion sources to optimize and standardize the cesiation procedure

Summary and outlook

- The H^- injector on the SNS accelerator front-end consists of an RF-driven, Cs-enhanced, multi-cusp H^- ion source and a compact 2-lens electrostatic LEBT. The ion source operates at 6% duty-factor (60 Hz, 1 ms) with typical beam current of >50 mA injecting to the RFQ.
- With the beam transmission performance improved to ~90% by a new RFQ over the old RFQ's 60-70%, the ion source could maintain a significant margin for the operational beam power at 1.4 MW.
- Beam studies have demonstrated that the ion source is capable of delivering ~50 mA LINAC beam current for the future Proton Power Upgrade and Second Target Station project.
- We have completed a record long run with a single source operating ~4 months with high current (>50 mA) and excellent availability of over 99.5%.
- Optimizing and standardizing the cesiation process for ion sources are key to improving the consistency among sources and improving the beam current persistency.

Thank you for your attention!

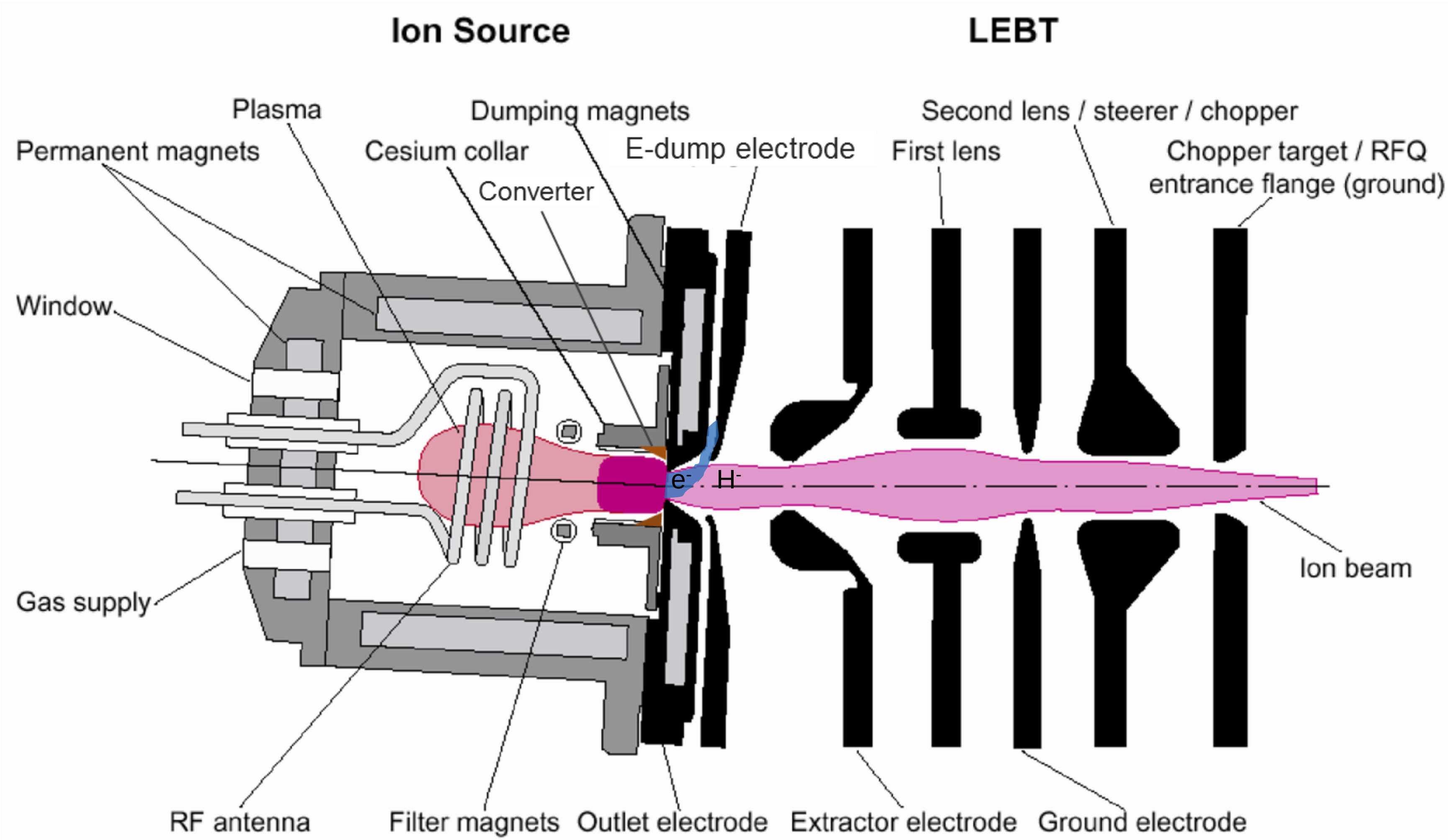
Backup slides

Beam current persistency over time

Date	IS RF power, Gas flow	RFQ input	RFQ FCM field	RFQ output	Transmission
3/16/2020	~54 kW, 24.5 sccm	~54 mA	0.370	34 mA	63%
4/10/2020	~50 kW, 25.5 sccm	~56 mA	0.370	34.3 mA	61%
7/15/2020	~55 kW 27.5 sccm	~54 mA	0.370	32.3 mA	60%

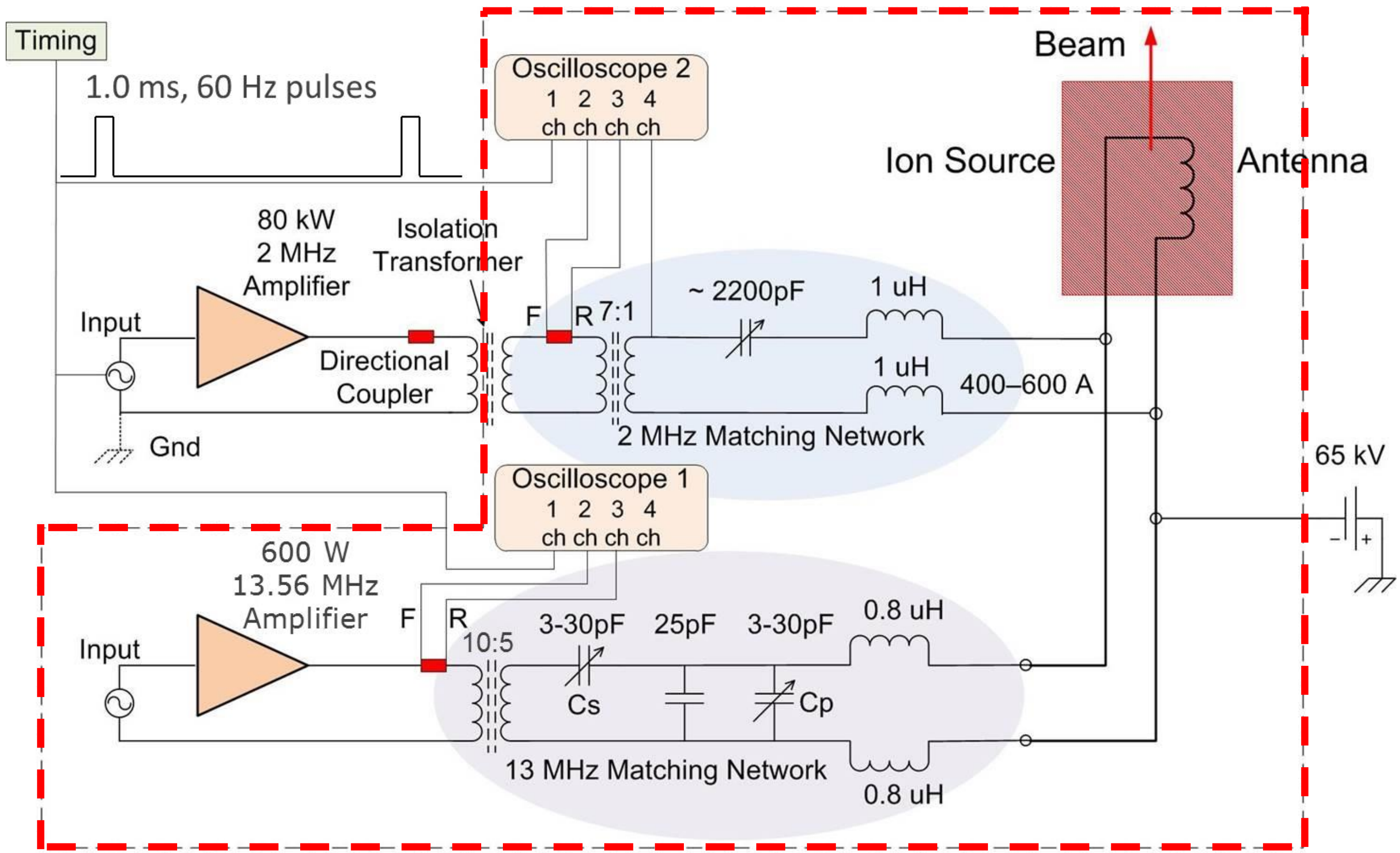
Date	IS RF power, Gas flow	RFQ input	RFQ FCM field	RFQ output	Transmission
3/16/2020	~54 kW, 24.5 sccm	~54 mA	0.440	44 mA	81%
4/10/2020	~50 kW, 25.5 sccm	~56 mA	0.440	45.8 mA	82%
7/15/2020	~55 kW, 27.5 sccm	~54 mA	0.440	43.5 mA	81%

The SNS H⁻ injector



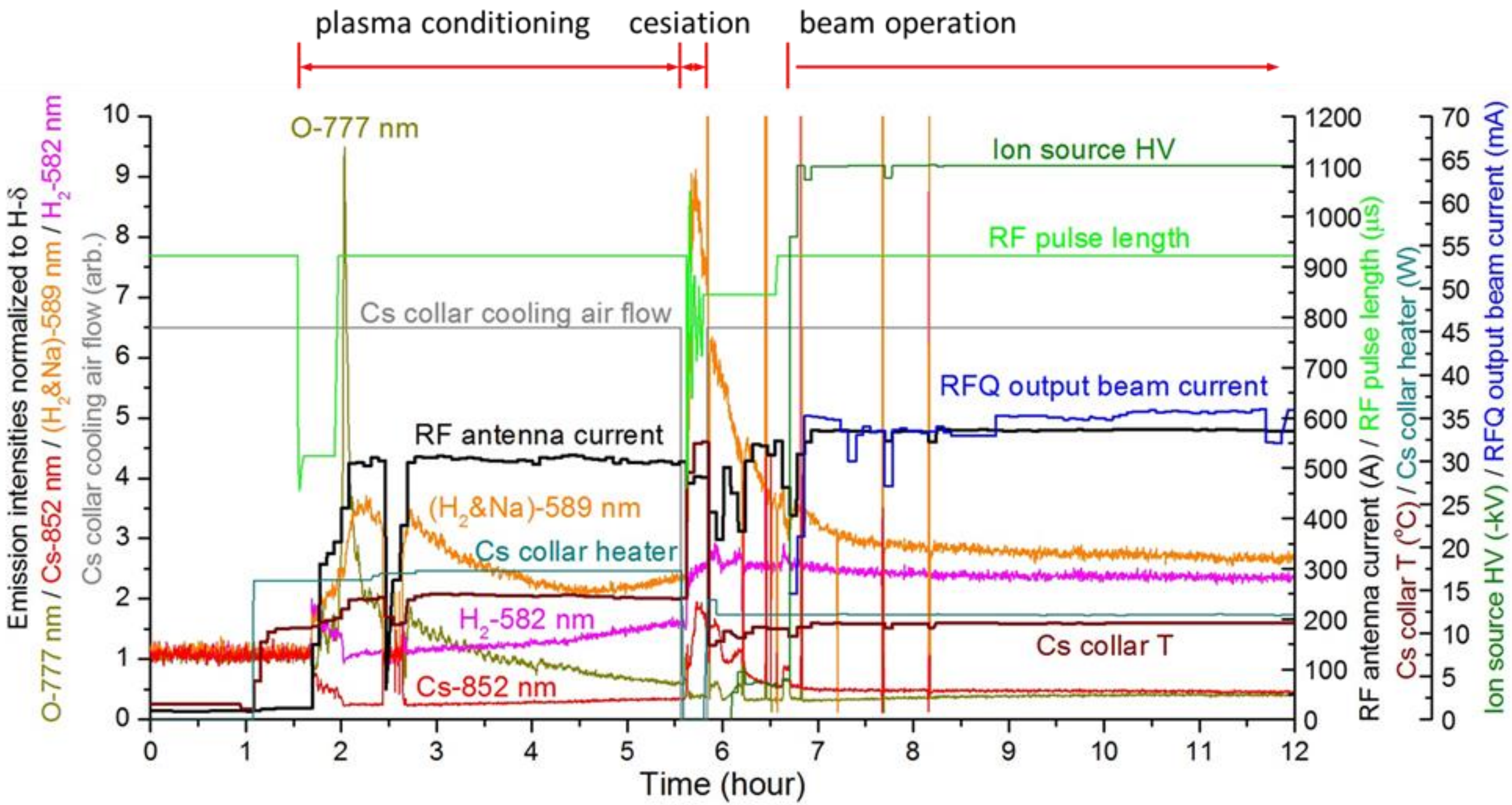
- The SNS H^- injector was originally designed and built at LBNL and further developed at ORNL.
- An RF-driven, Cs-enhanced, multi-cusp H^- ion source
- A compact 2-lens electrostatic low energy beam transport (LEBT)

Ion source RF circuit diagram



- 80-kW, pulsed, 2-MHz RF amplifier was moved from the ion source HV platform to ground in 2010. The RF is transmitted through an isolation transformer to the 2-MHz matching network which delivers impedance matched RF to the ion source antenna.
- 600-W, continuous, 13.56-MHz RF maintains a low-density continuous plasma to facilitate fast ignition of the pulsed, high-density 2-MHz RF plasma

Ion source startup process



1. The ion source is conditioned with plasma for ~3 hours, which outgases and sputter cleans the system. During the plasma conditioning, the Cs collar temperature is maintained at near 200 ^{0}C to help outgassing the Cs collar assembly completely. The Cs collar temperature is controlled by combined effects of RF power, cooling air flow rate and an external heating supplied to the air flow.
2. After 3 hours of conditioning, the Cs collar temperature is elevated to ~550 ^{0}C for ~12 minutes to cesiate the ion source.
3. The ion source high voltage is applied (no sooner than one hour from completion of cesiation) and the ion source and LEBT parameters are tuned to maximize the beam current out from the RFQ.

H^- Ion Sources for High Power Accelerators

*Martin P. Stockli, Robert F. Welton, and Baoxi Han, "Record productions establish RF-driven sources as the standard for generating high-duty-factor, high-current H^- beams for accelerators (Winner of the ICIS 2017 Brightness Award)", Review of Scientific Instruments **89**, 052202 (2018); doi: 10.1063/1.5025328*

TABLE III. Fall 2017 status of the injector of the worlds' nine H^- production facilities. **As of Fall 2017**

Source type	Laboratory-facility	Discharge and repetition rate	Plasma and beam duty factors (%)		Average beam pulse current (mA)	Extraction aperture	Service cycle /lifetime[a]	Extracted H^- charge (A h)
Magnetron surface	BNL-AGS	12-14 A; 130 V at 7.5 Hz	0.50 0.44	0.066 ms 0.058 ms	110-120	2.8 mm Ø	6-8 month	3.0
	FNAL-PSD	15 A; 180 V at 15 Hz	0.345 0.3	0.230 ms 0.200 ms	80	3.2 mm Ø	9 month	1.6 3.2[a]
Penning surface	RAL-ISIS	55 A; 70 V at 50 Hz	3.75 1.1	0.75 ms 0.22 ms	55	0.6×10 mm^2 slit	5 weeks[a]	0.51[a]
	CAS-CSNS	~50 A; ~100 V at 25 Hz	1.5 1.25	0.60 ms 0.50 ms	50	0.6×10 mm^2 slit	1 month[a]	0.46[a]
	INR RAS	100 A; 120 V at 50 Hz	1 1	0.40 ms 0.40 ms	20	1.0×10 mm^2 slit	Intermittent use	
Multicusp converter	LANL-LANCE	30-35 A; 180 V at 120 Hz	10 7.6	0.84 ms 0.63 ms	16-18	9.8 mm Ø	4 weeks	0.87
Internal RF antenna	ORNL-SNS	CW 300 W 13 MHz and 60 Hz 60 kW 2 MHz	6 5.94	1.00 ms 0.99 ms	>60	7 mm Ø	14 weeks	>7
	JAEA-J-PARC	CW 50 W 30 MHz and 25 Hz 22 kW 2 MHz	2 1.25	0.80 ms 0.50 ms	47	9 mm Ø	11 weeks	1.1
External RF antenna	CERN-Linac4	0.8 Hz 40 kW 2 MHz pulsed H_2	0.07 0.05	0.88 ms 0.63 ms	45	5.5 or 6.5 mm Ø	7 weeks	0.026

[a]Lifetimes (marked with a superscript a) are nowadays mostly replaced with shorter service cycles to avoid unplanned downtimes.