Operation and Research Activities on the Three H^- Injector Systems at the Spallation Neutron Source

Baoxi Han, Robert Welton, Chris Stinson, Terry Pennisi, Syd Murray Jr., Vic Andzulis, Greg Terszakowec, Martin Stockli, and Sang-Ho Kim

Spallation Neutron Source
Oak Ridge National Laboratory
Oak Ridge, TN 37831, USA

The 8th International Symposium on Negative Ions, Beams and Sources (NIBS'22)

October 2-7, 2022, Padova, Italy

Outline of the talk

- The SNS accelerator Front-End H^- injector and its recent operational performance
- Operational experience with the Beam Test Facility H^- injector
- Highlights from development activities on the Ion Source Test Stand H^- injector
- Summary and outlook

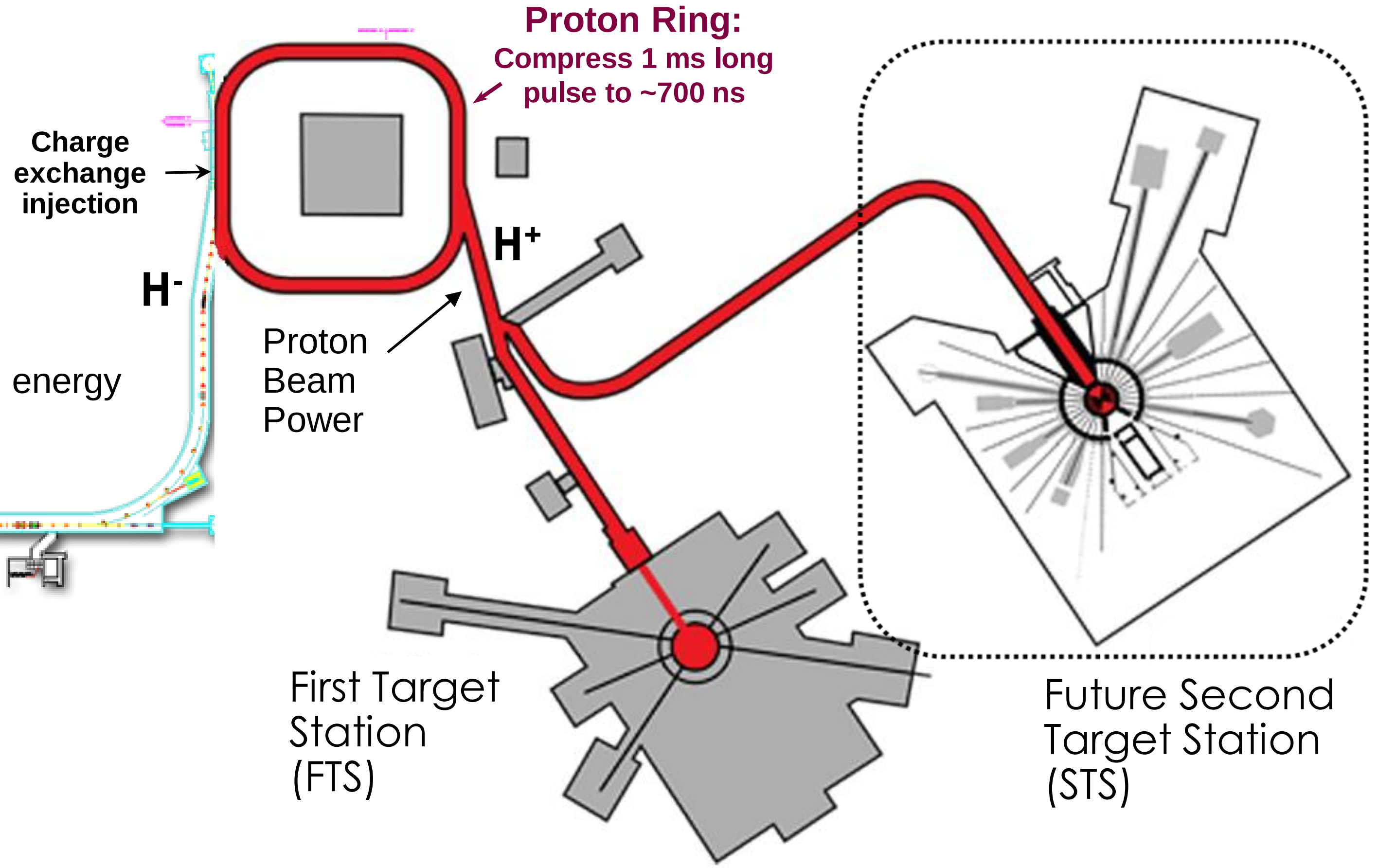
Overview of the SNS accelerator systems

H^- injector:
H^- ion source + LEBT

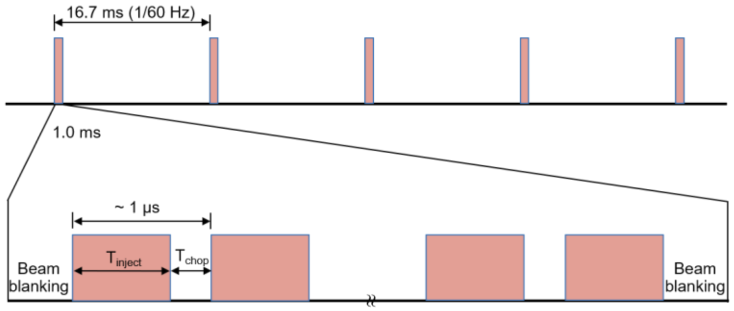
Ion source provides 1-ms long H^- beams pulsed at 60 Hz

Average Beam Power is the product of:

– Beam Energy
– Pulse Length
– Peak Current
– Repetition Rate
– Injected (un-chopped) Beam Fraction



LEBT transports and injects the 1.0 ms beam pulses to the RFQ with ~300 ns chopped every ~1 μs

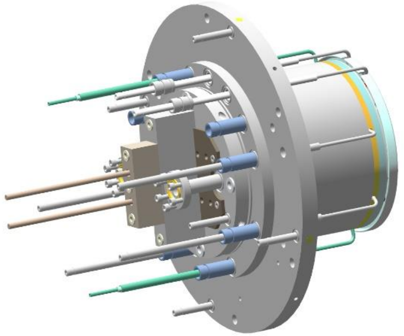


	Proton beam power	Linac beam energy	LEBT chopper chopping fraction	Required RFQ output peak beam current	Required H^- injector beam current *
SNS present operation	1.4 MW	1.0 GeV	down to 22%	~35 mA	40 - 55 mA
SNS Proton Beam Power Upgrade (PPU) project goals	2.8 MW 2.0 MW on FTS 0.8 MW on STS	1.3 GeV	down to18%	~46 mA	50 - 75 mA

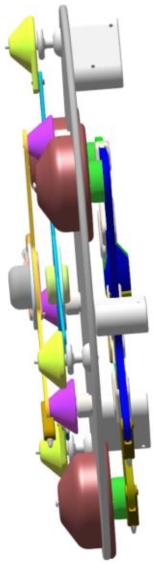
* Required beam current delivered from the H^- injector varies depending on the RFQ operation power level

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

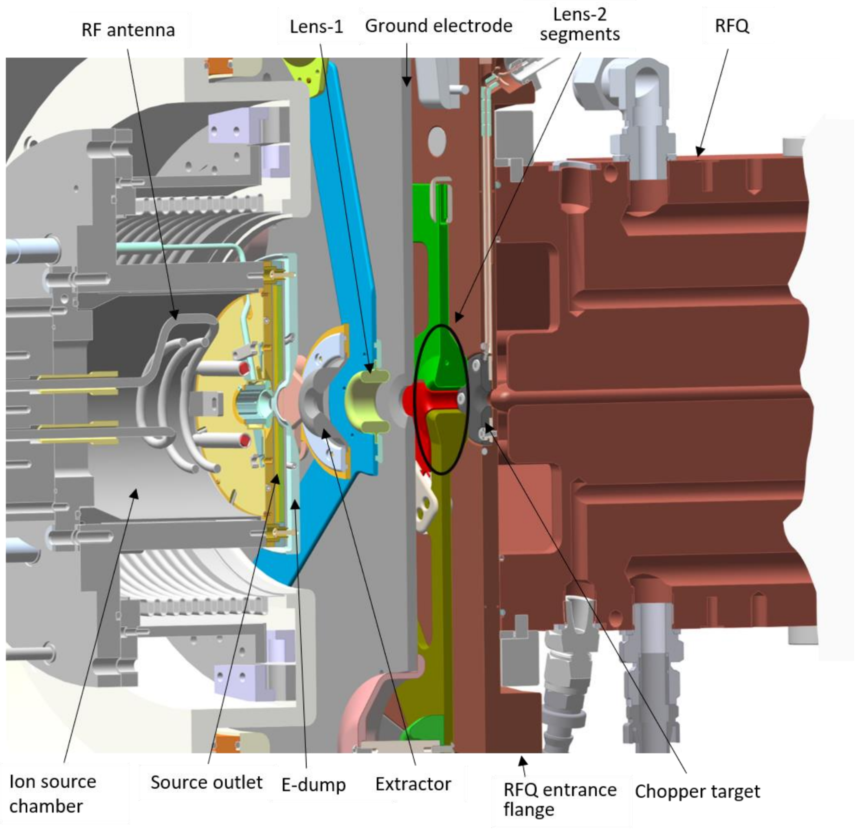
The SNS accelerator Front-End H^- injector

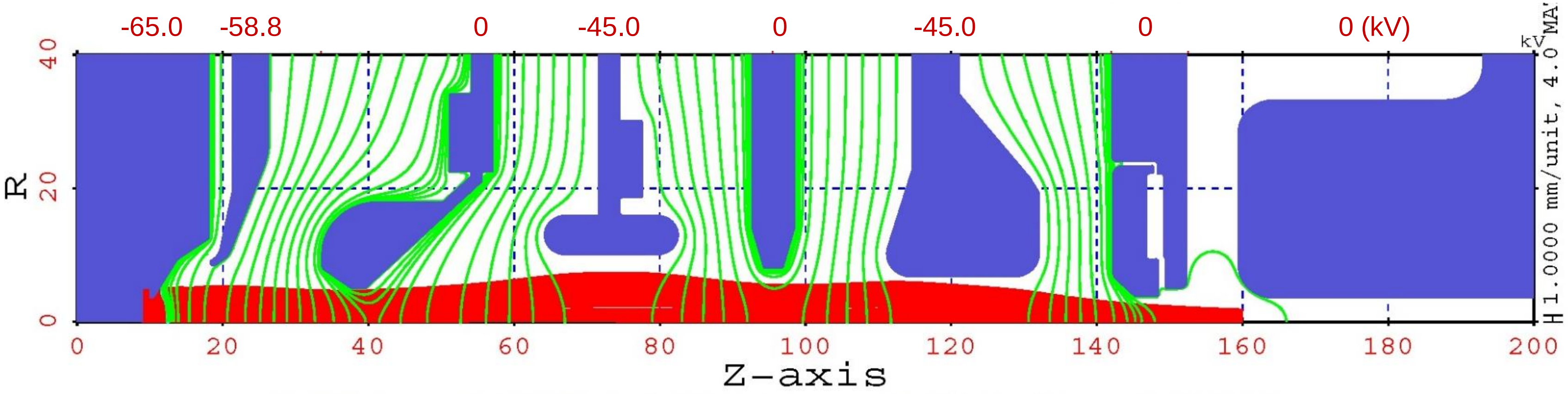


An RF-driven, Cs-enhanced, multi-cusp H^- ion source

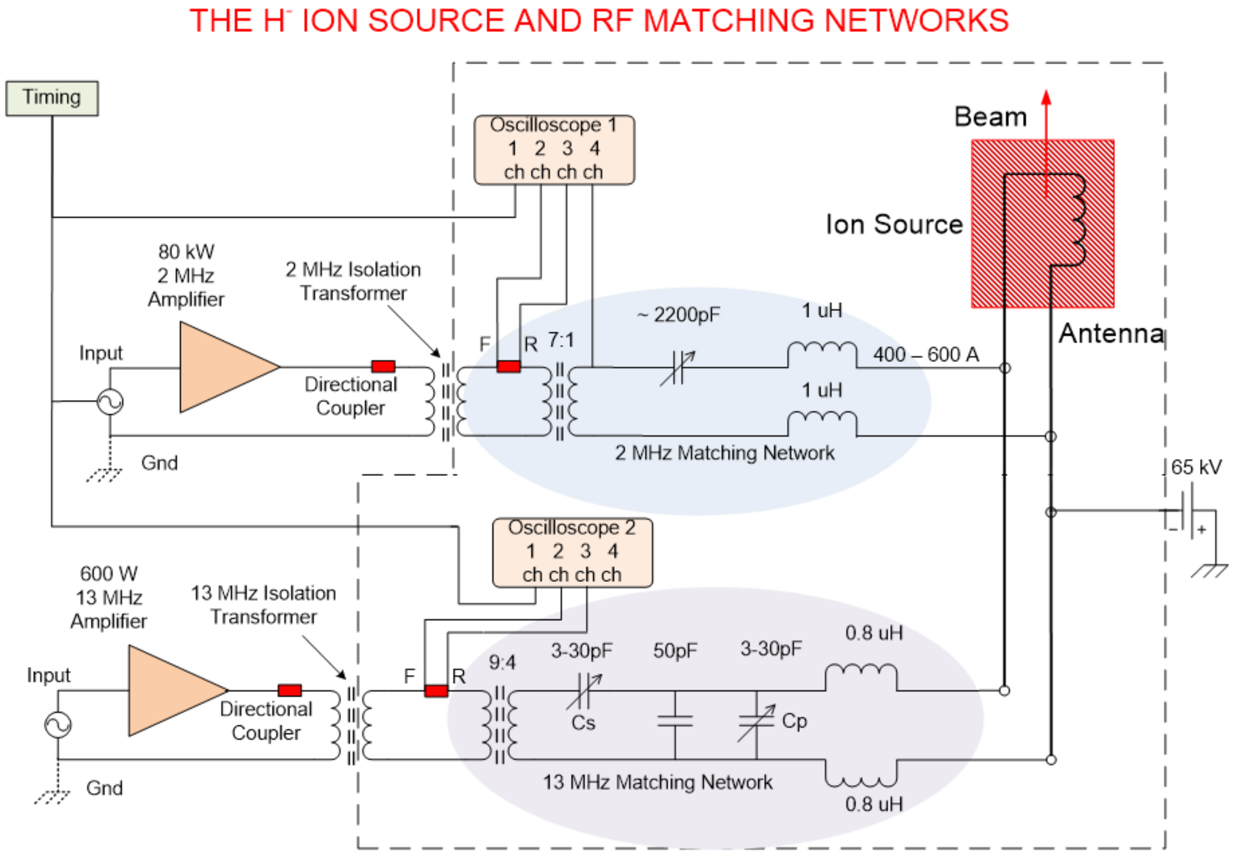


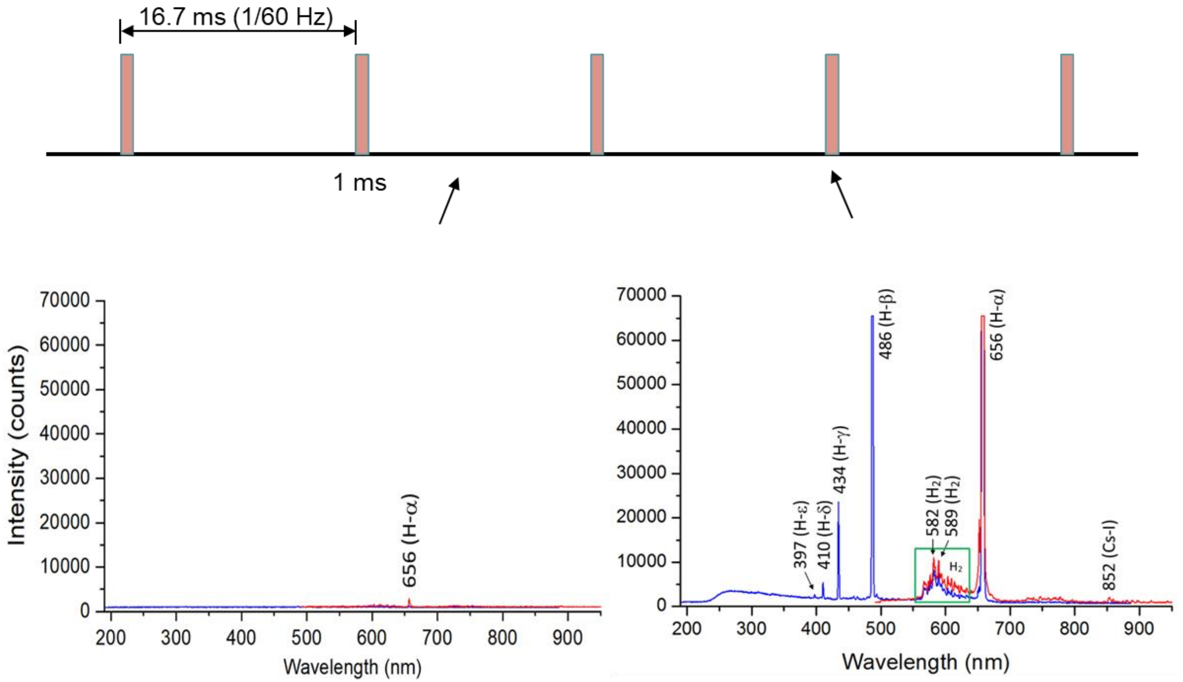
A compact 2-lens electrostatic low energy beam transport system (LEBT)





The SNS H⁻ ion source RF systems and timing structure





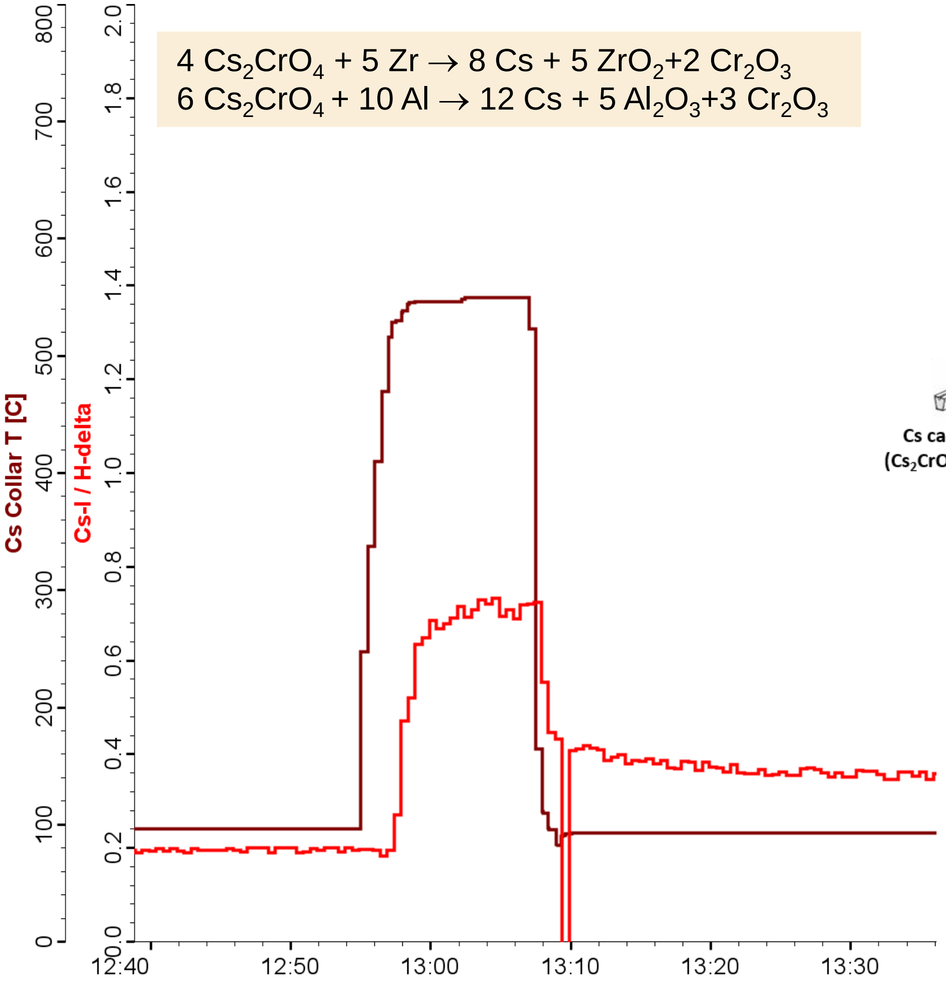
Continuous, low power (typically ~300 W) 13.56-MHz RF maintains a low-density background plasma to facilitate fast turn-on of the main pulsed plasma

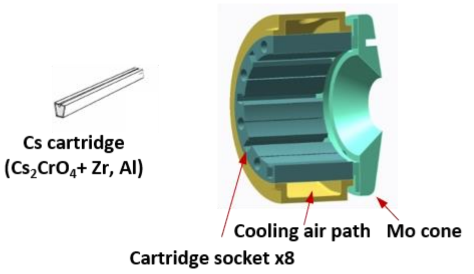
High power (typically ~55 kW) 2-MHz RF pulsed at 60 Hz with 1.0 ms pulse length drives the main plasma for beam production

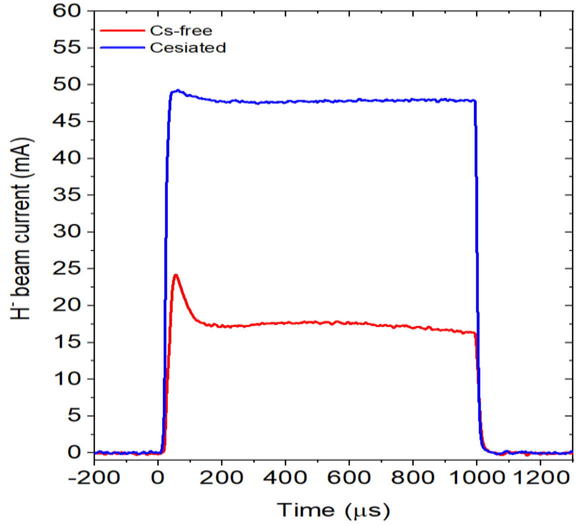
Cesium enhances the H⁻ current by 2-3 times

$4\ Cs_2CrO_4 + 5\ Zr \rightarrow 8\ Cs + 5\ ZrO_2 + 2\ Cr_2O_3$

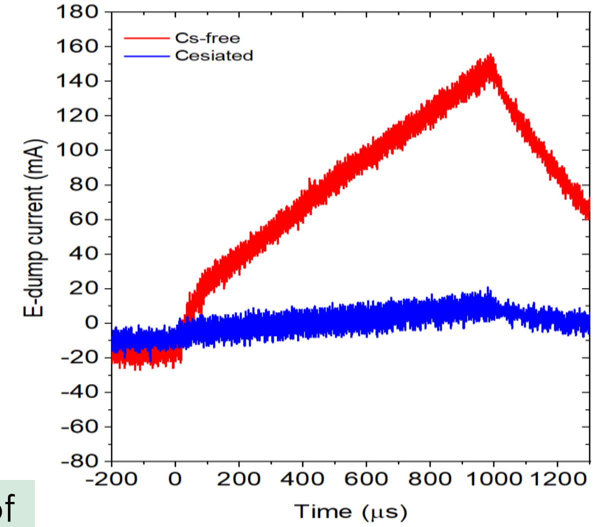
$6\ Cs_2CrO_4 + 10\ Al \rightarrow 12\ Cs + 5\ Al_2O_3 + 3\ Cr_2O_3$







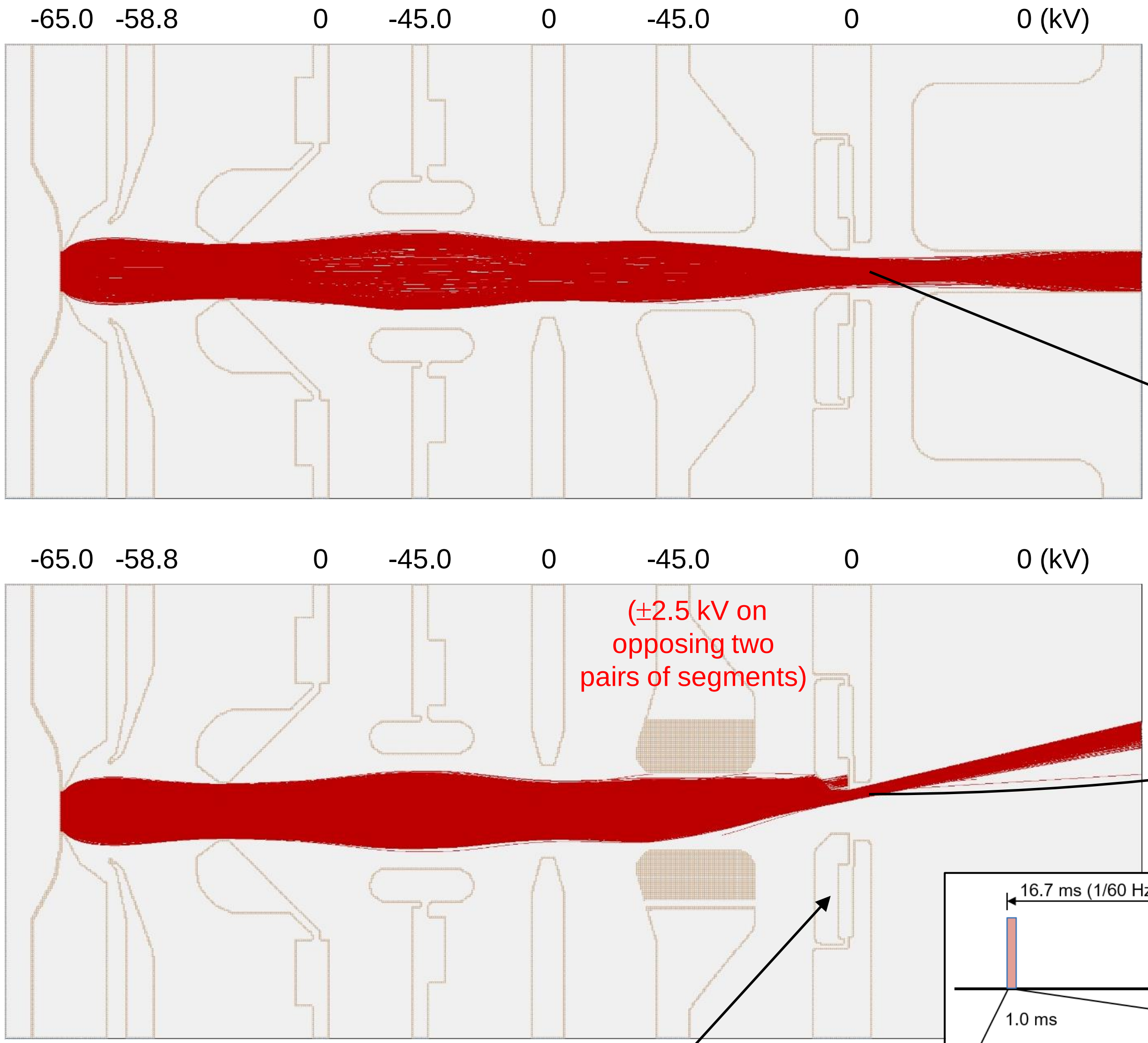
H⁻ current

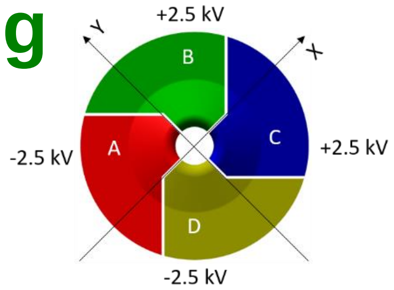


E-dump load current (after a RC filter)

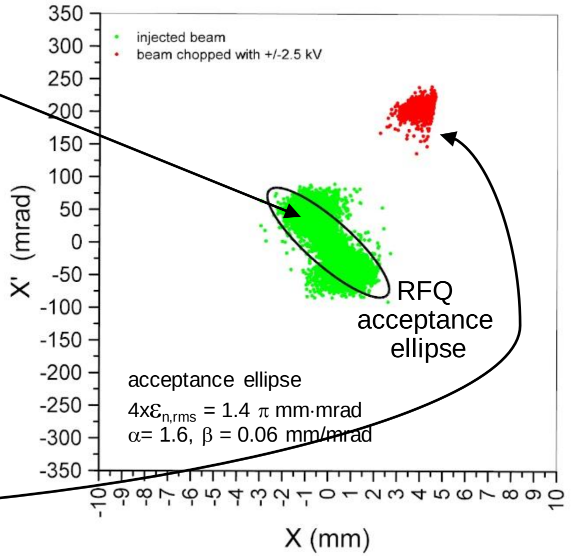
Illustration of a typical cesiation process and an example showing the effects of a cesiation on the extracted H⁻ beam current and the load on the e-dump electrode for the SNS ion sources

The LEBT: beam transport, injection and chopping

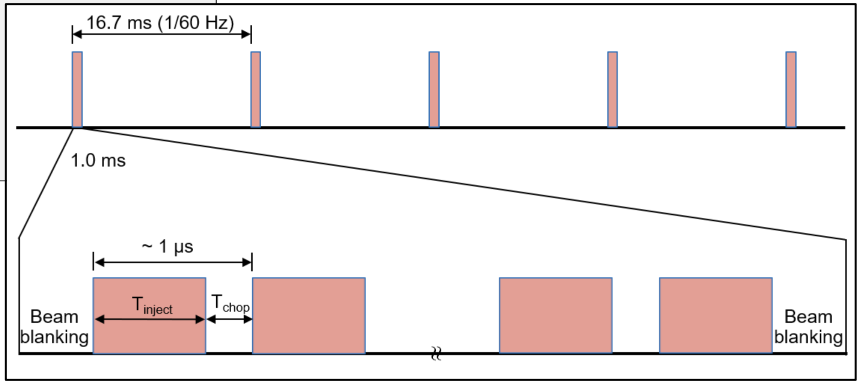




injected or chopped beam vs. the RFQ acceptance ellipse at the RFQ injection reference plane. The X axis is aligned to the direction of beam deflection



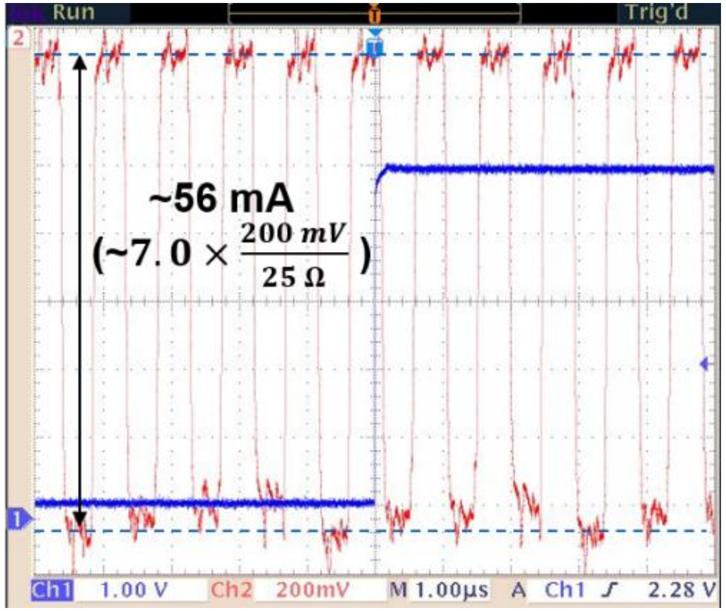
The chopper target is electrically isolated from the RFQ flange. It receives the chopped beam and drains it to ground through a resistor circuit.

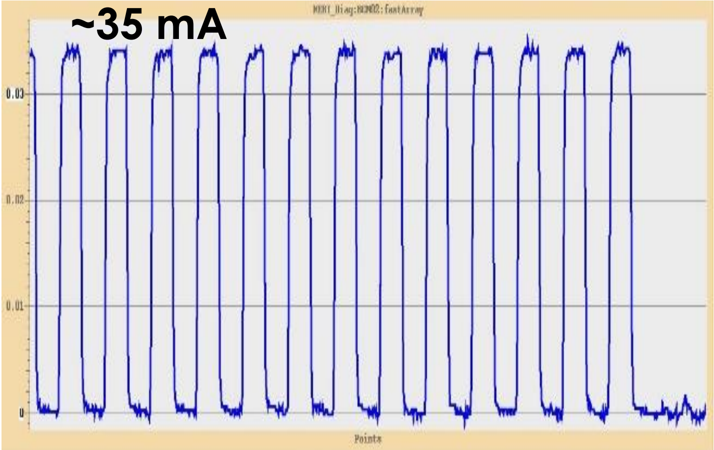


OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

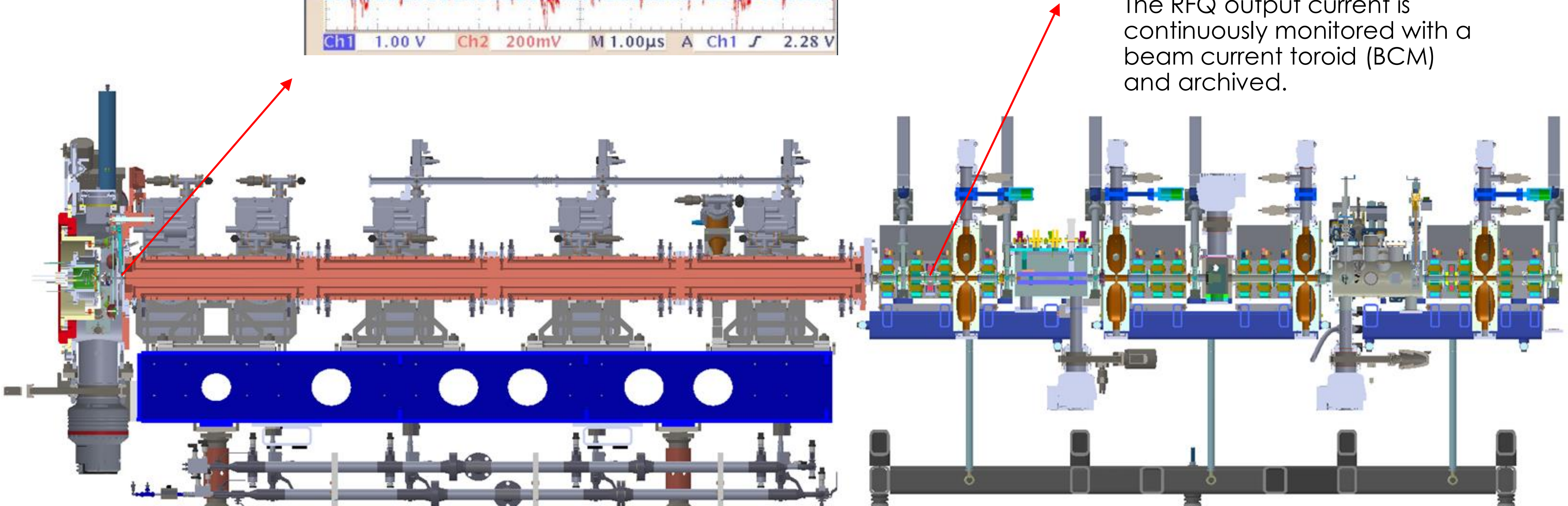
Measurements of beam currents delivered from the H^- injector and out of the RFQ

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

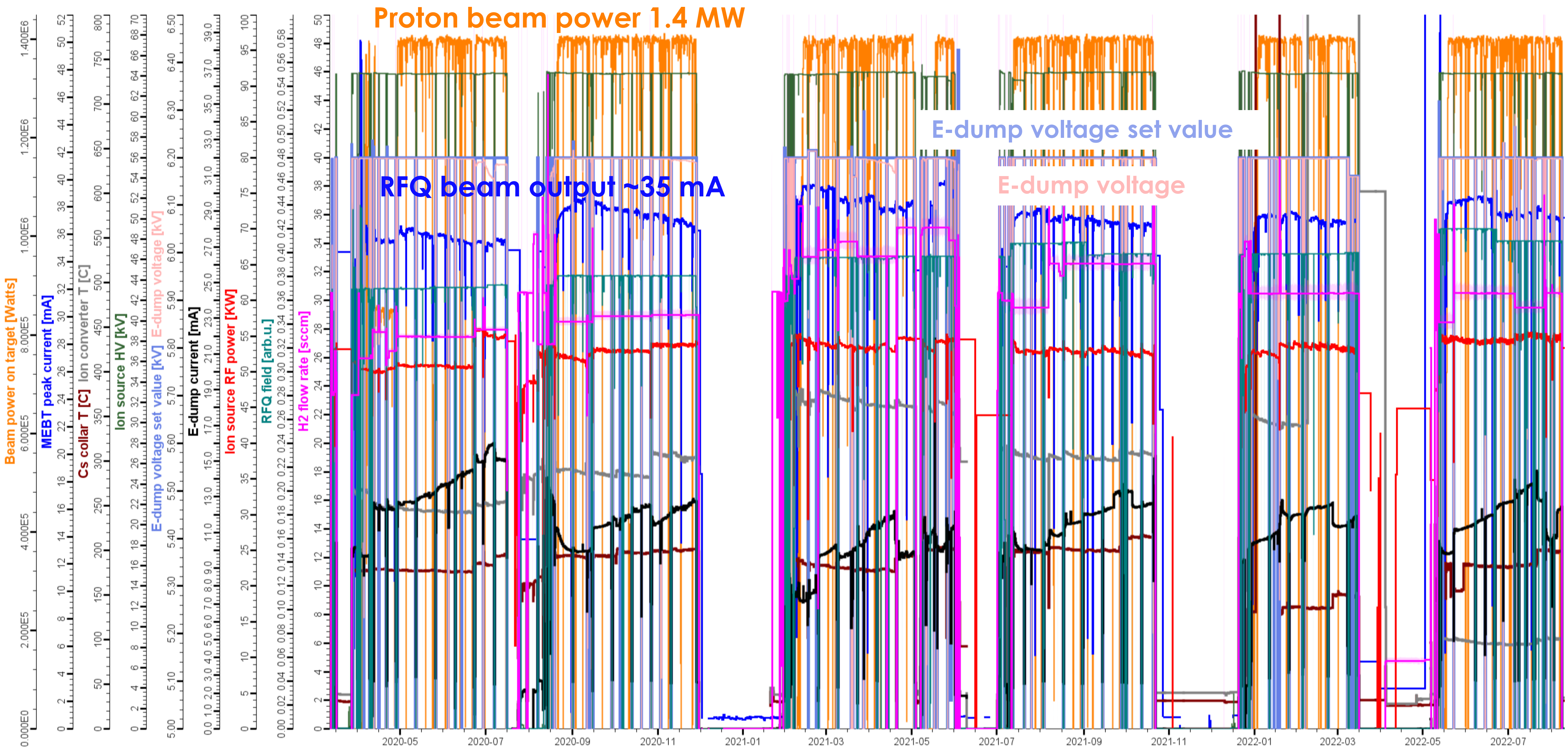




The RFQ output current is continuously monitored with a beam current toroid (BCM) and archived.



Recent operational performance of the Front-End H^- injector



Since 2020, we have extended the ions source service duration to cover an entire production run cycle of SNS with a single ion source serving 3 - 4 months as scheduled.

Recent operational performance of the Front-End H^- injector

- some key metrics

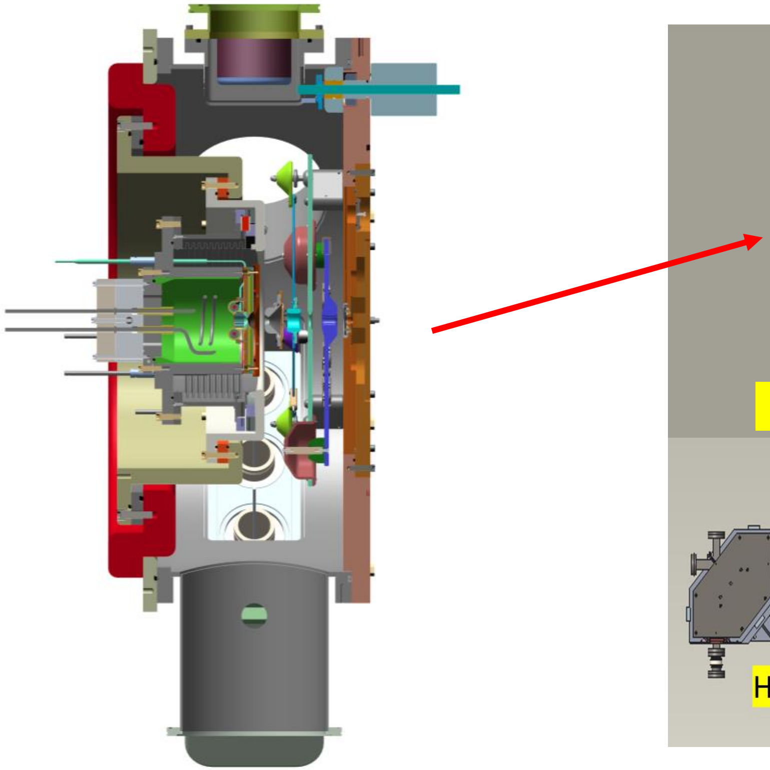
Start date	End date	IS ID#	Days of operation	Injector availability	Date of beam measurement	RFQ input current	RFQ output current	remarks
3/12/2020	7/16/2020	#2	116	99.9%	3/16/2020	~54 mA	34 mA	3/16-3/27, ion source was turned off awaiting other systems to be ready from maintenance activities
7/24/2020	11/30/2020	#2	129	99.9%	8/7/2020	~55 mA	34 mA	
1/29/2021	6/1/2021	#2	120	99.9%	2/1/2021	~54 mA	34 mA	(5/4-5/7, ion source was turned off awaiting target issues to be resolved)
7/2/2021	10/23/2021	#2	113	99.8%	7/4/2021	~54 mA	34 mA	
12/20/2021	3/16/2022	#2	86	99.8%	12/27/2021	~56 mA	35 mA	
5/9/2022	8/9/2022	#2	92	99.0%	6/20/2022	~57 mA	35.5 mA	

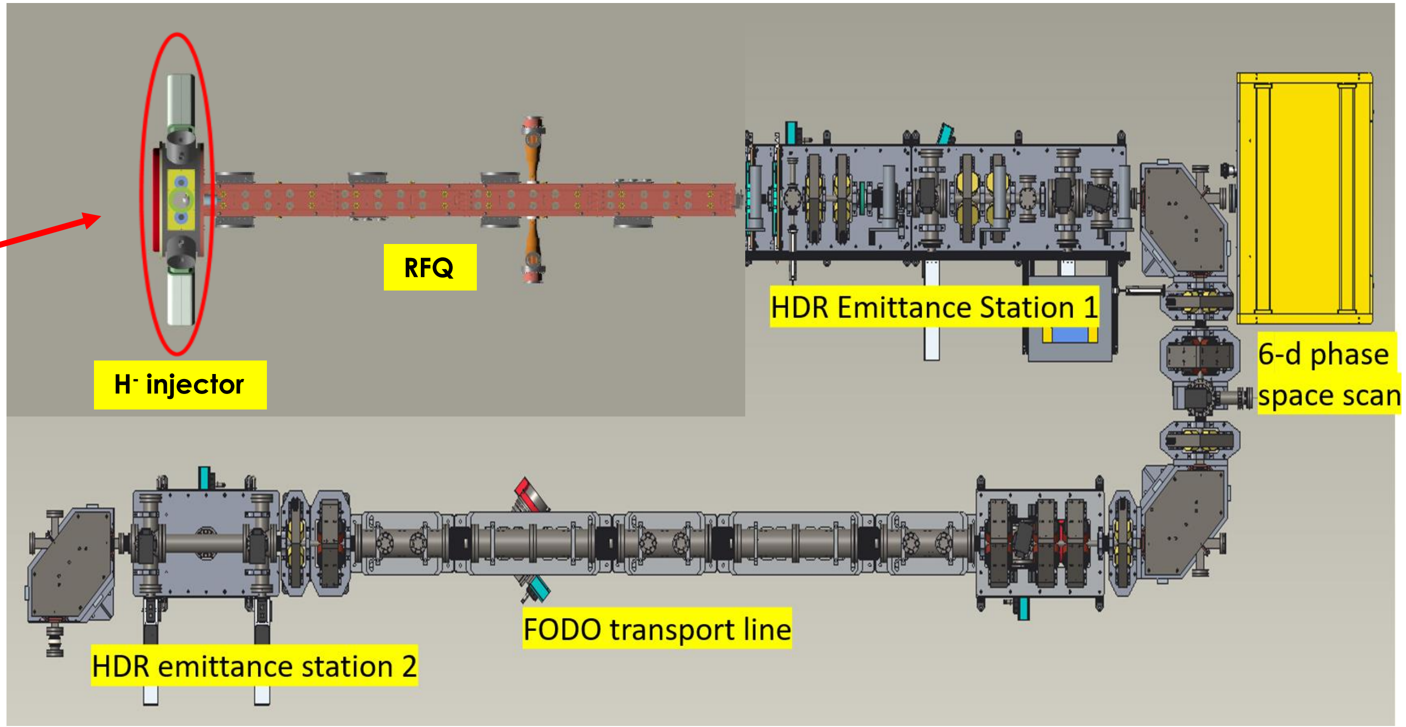
- Ion source was operated 3-4 months for each of the past 6 production run cycles of SNS.
- The H^- injector availability was mostly ≥99.8% except for the run May-August 2022 in which the second lens of the LEBT experienced inter-segmental arcs causing ~19 hours of downtime.
- Beam current with ~55 mA was delivered from the injector allowing the RFQ be operated at minimal power level for required output current of ~35 mA.

Outline of the talk

- The SNS accelerator Front-End H^- injector and its recent operational performance
- Operational experience with the Beam Test Facility H^- injector
- Highlights from development activities on the Ion Source Test Stand H^- injector
- Summary and outlook

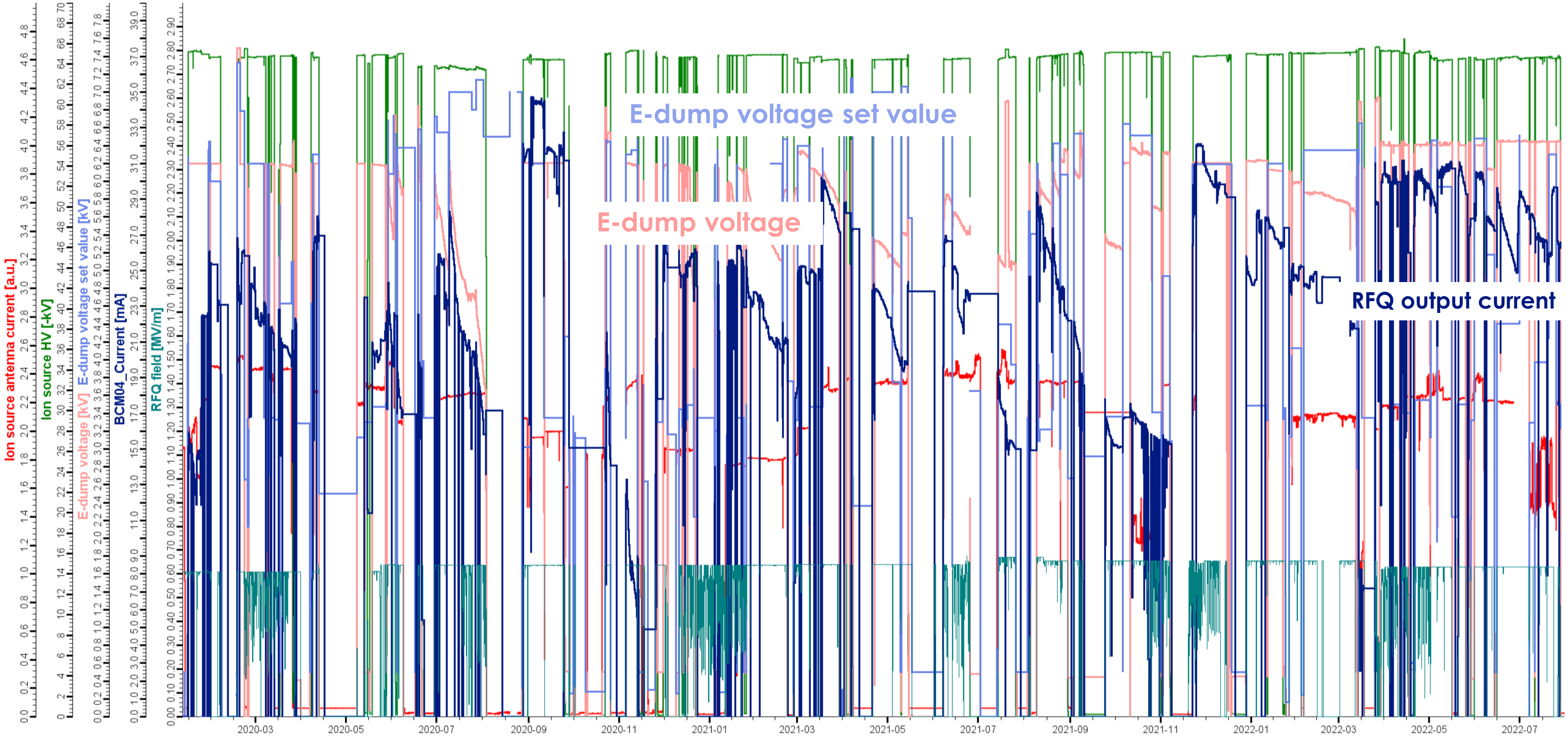
The 2.5 MeV Beam Test Facility (BTF) at SNS





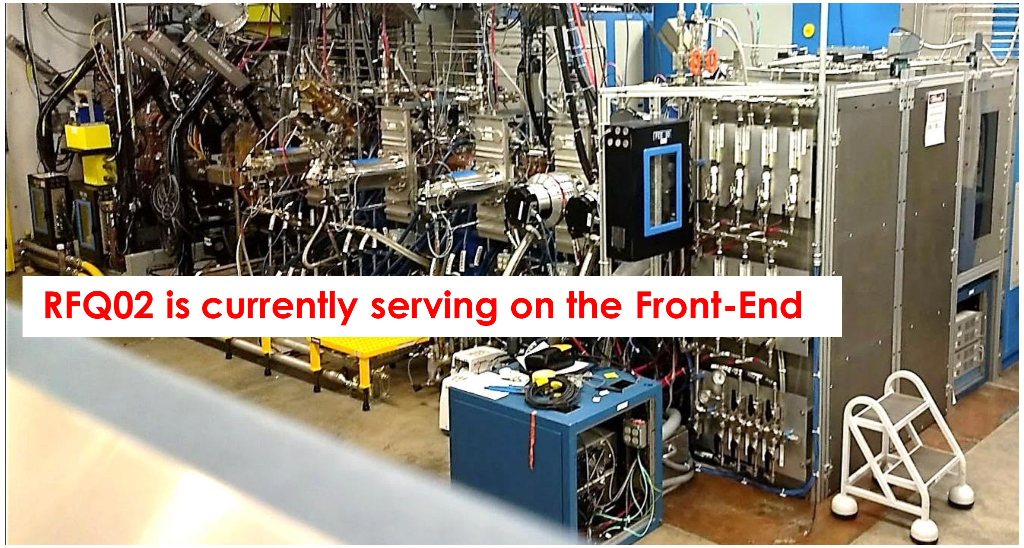
- A 2.5 MeV test facility that was originally setup for commissioning a new RFQ (RFQ02) acquired to replace the SNS old RFQ (RFQ01)on the accelerator Front-End.
- After the RFQ02 was installed on the Front-End in May 2018, the RFQ01 was moved to the BTF.
- Beam line was extended, and many beam diagnostics instruments were added for beam studies.
- The H^- injector on the BTF is essentially the same design as the SNS Front-End injector with some differences in implementation.

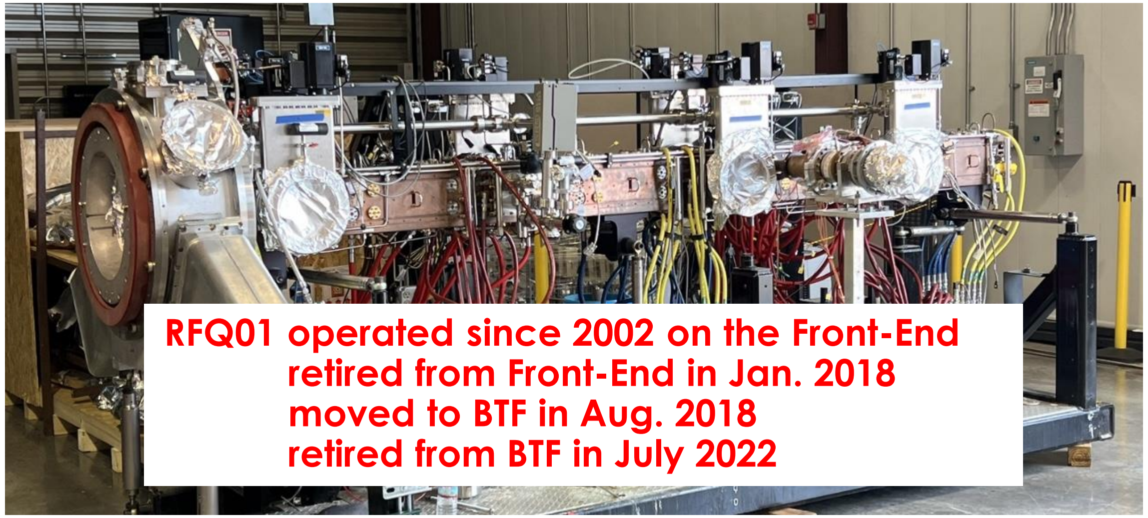
Recent operational experience with the BTF H^- injector



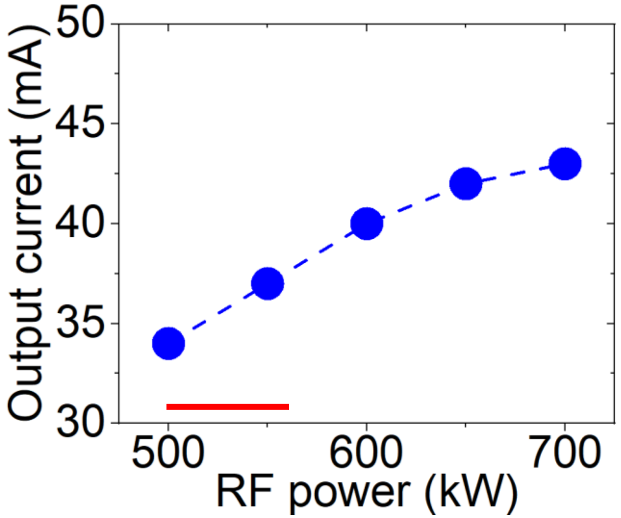
- Similar to the Front-End, each ion source 3~4 months of operation with reasonable availability according to the priority level.
- Ion source testing leading to improvement in beam persistency and electron dumping voltage stability.
- The beam current was not as good as on the Front-End, only up to 32 mA out of RFQ and often decayed, owing to:
  ∗ No top tier ion sources deployed, ∗ Degraded RFQ, ∗ Lower capacity pumps (3x910 l/s) vs. Front-End pumps (3x1450 l/s)
- There was an antenna failure incident on 3/18/2022 with tier-2 antenna after ~112 days of operation mostly at ~65 kW.

Brief update on the SNS RFQ accelerators





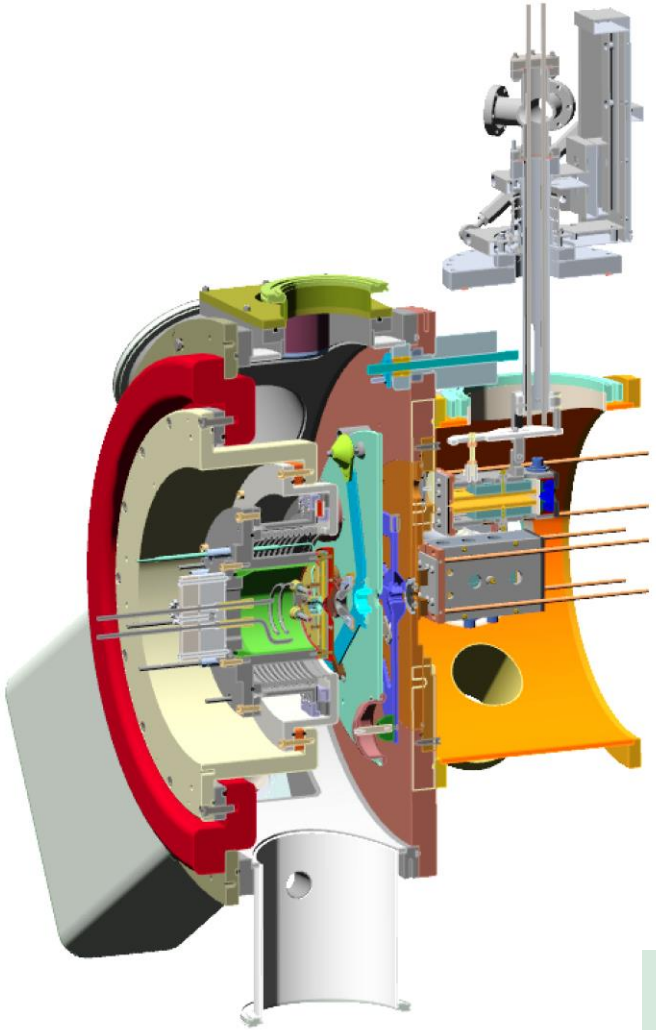
Since the RFQ02 experienced RF C-seal failure in Nov. 2018, it has been operated at minimal necessary power level (70-80% of power) to support ~35 mA output beam current.



Outline of the talk

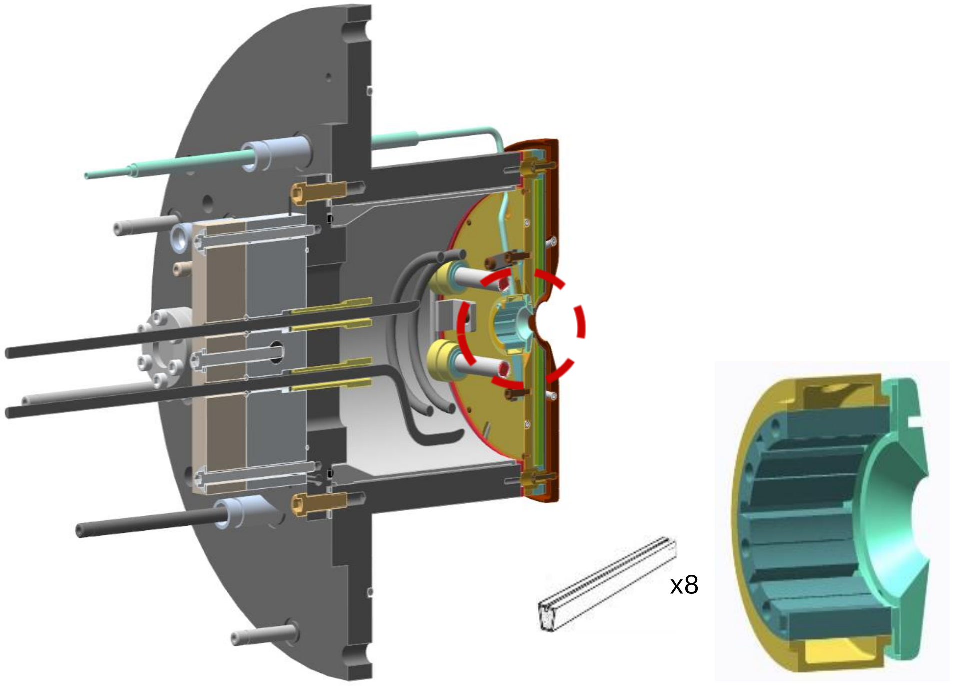
- The SNS accelerator Front-End H^- injector and its recent operational performance
- Operational experience with the Beam Test Facility H^- injector
- Highlights from development activities on the Ion Source Test Stand H^- injector
- Summary and outlook

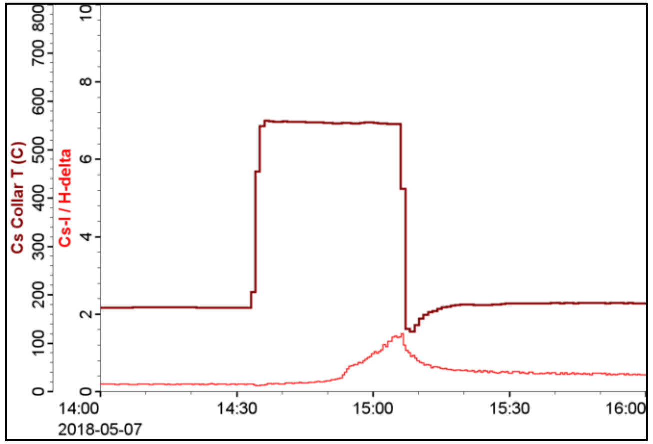
The Ion Source Test Stand (ISTS) at SNS



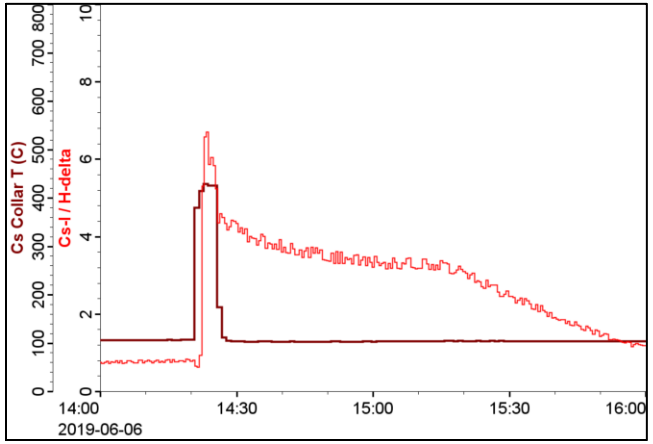
- The ISTS does not have an RFQ, but it is equipped with a beam diagnostic chamber allowing measurements of LEBT output beam current and emittance.
- The ISTS is used for R&D for injector improvement/upgrade, and it also serves as a source of validated spares.

Improved thermal control for ion source cesiation

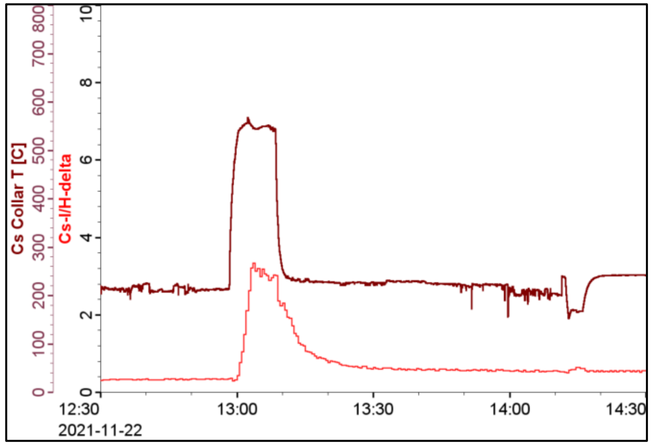




Cesiation chart of the ion source #2, which features the best beam performance



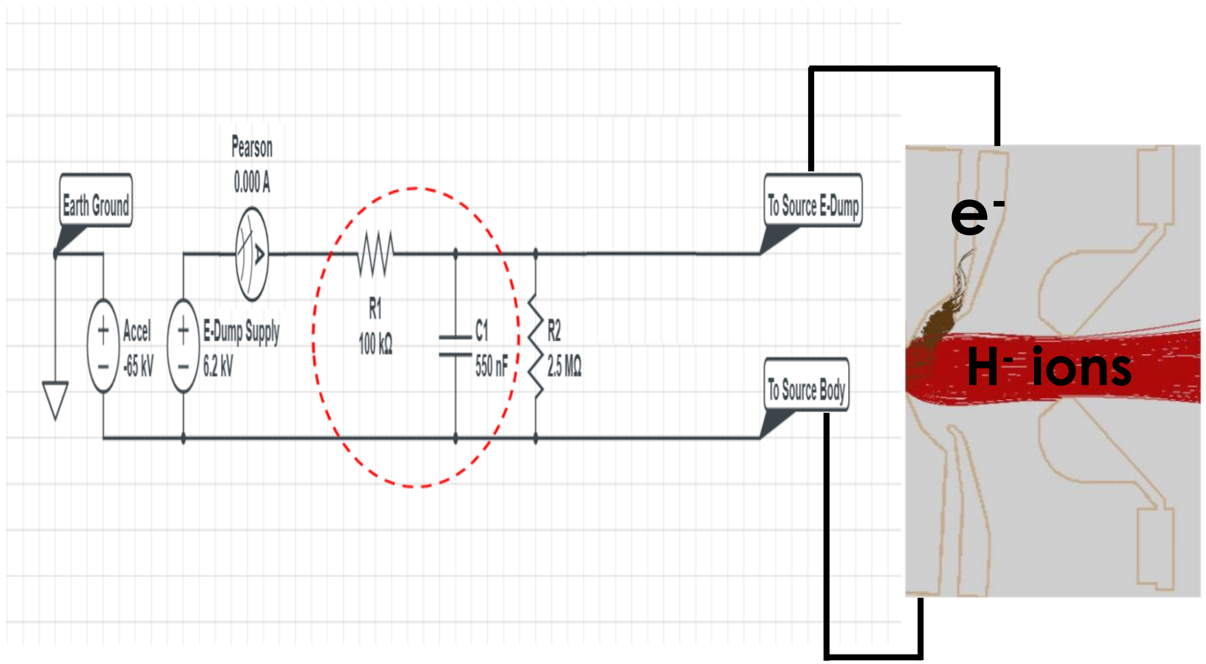
Cesiation chart of ion source #4 before the change showing excessive release of cesium

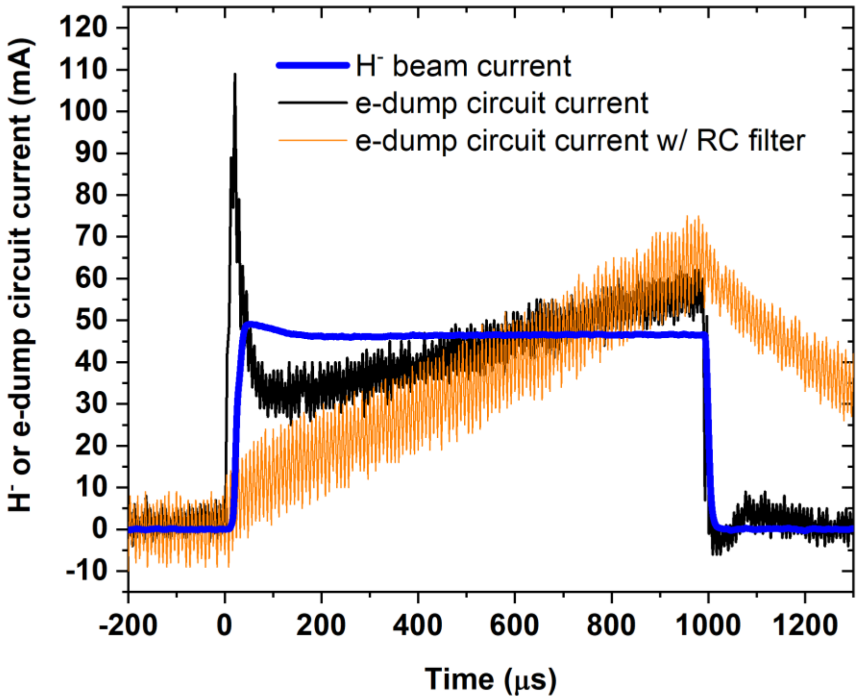


Cesiation chart of ion source #4 after the change

- We have a fleet of ion sources of same design, #2, #3, #4, #5, #6 and #7.
- Performance variations among ion sources are often observed.
- With better thermal control of cesium, the ion source #2 is the best performing source in terms of beam output, persistency and reliability.
- Installing a cesium collar with tight fitting sockets mimicking the source #2 improved the thermal control of cesiation significantly for the source #4.

Electron dumping circuit optimization

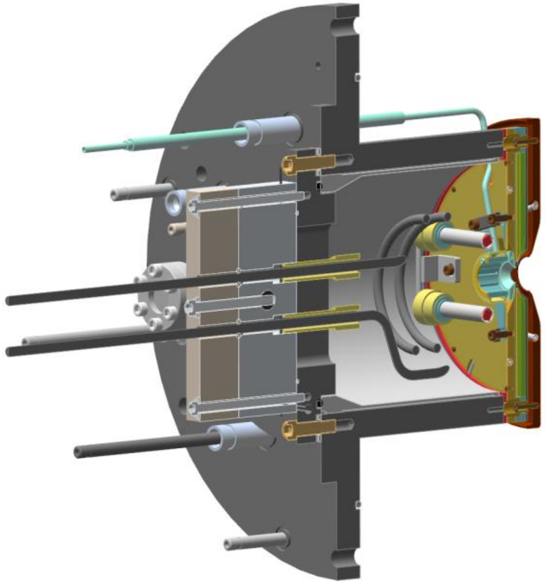


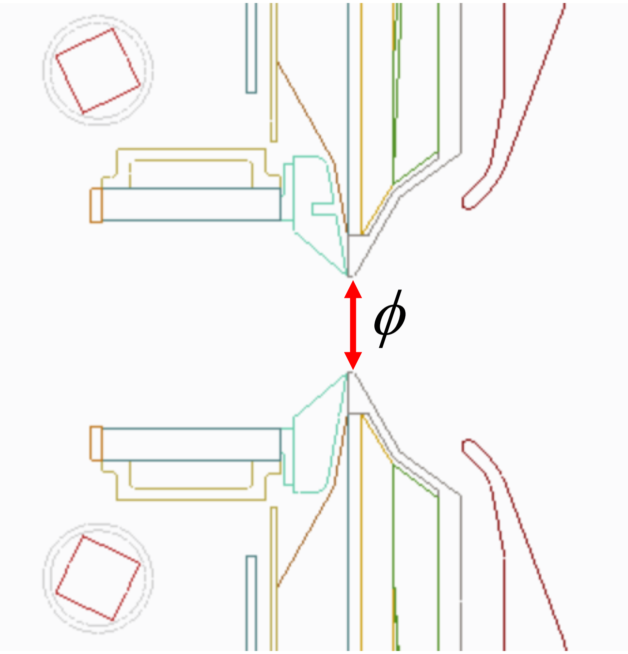


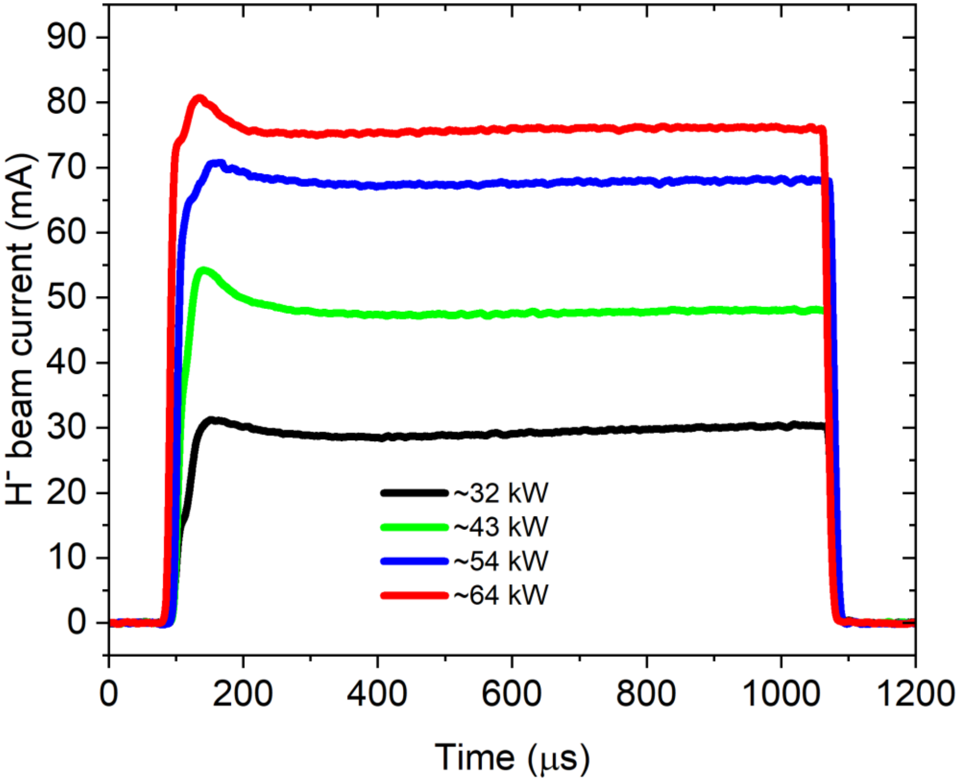
Note: in this demonstration, the orange trace was with R=1 KΩ, C=0.1 μF (in May 2019)

- During a long service duration of ion source, the co-extracted electron current typically grows over time (likely) due to degrading cesium coverage on the ion converter surface.
- When the electron current load exceeds the power supply capability, the voltage on the electron dumping electrode starts to droop.
- RF noise in the e-dump circuit cables and/or control loops can aggravate the voltage drooping problem.
- This issue is generally manageable with our best performing ion sources under well controlled environment.
- An RC charging circuit helps the DC power supply tolerate the excessive pulsed current load.
- An optimized set of parameters, R=100 kΩ and C=0.55μF, has recently demonstrated very stable e-dump voltage on both the ISTS and BTF for about 3-4 months.

Recent effort in boosting the ion source beam output

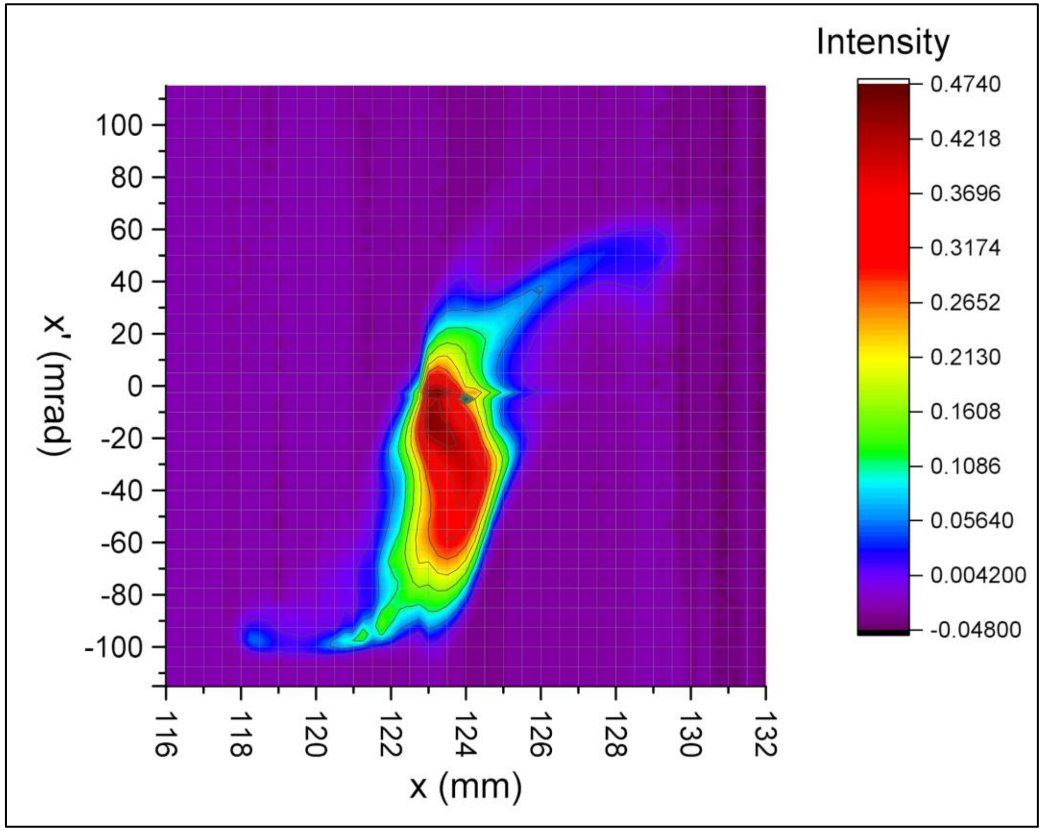


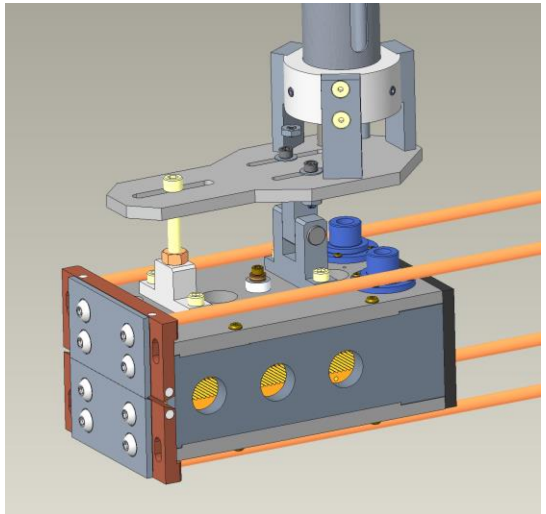


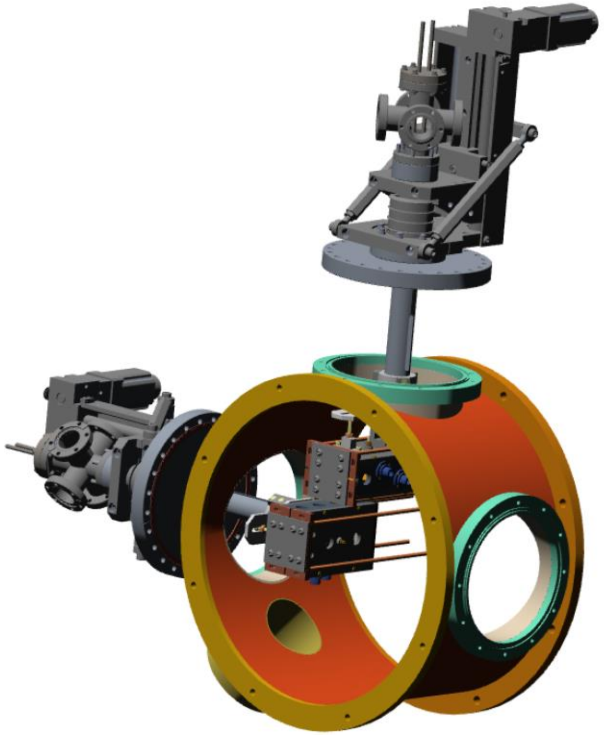


- Ion source #4 was tested with an increased outlet aperture ϕ8.2 mm
- ~70 mA within the normal operation RF power range, ~75 mA at higher power
- This is >20% boost of beam output produced with a typical outlet aperture ϕ7.0 mm for the same ion source at same RF power range
- The boosted beam output capability is expected to provide enhanced margin for the SNS present operation at 1.4 MW and relax the stress on RFQ for the PPU with STS

Emittance scanner upgrade





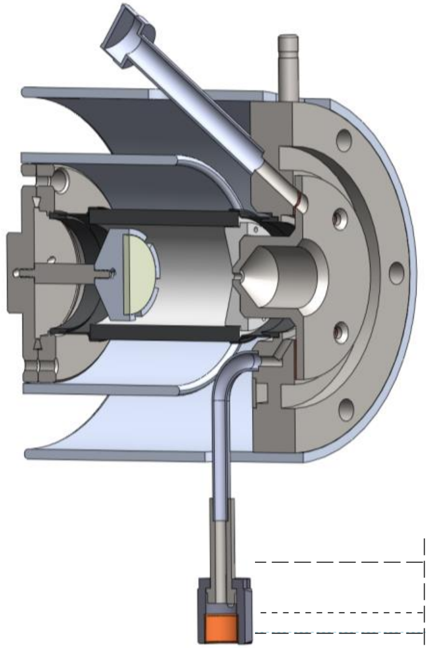


A preliminary emittance measurement

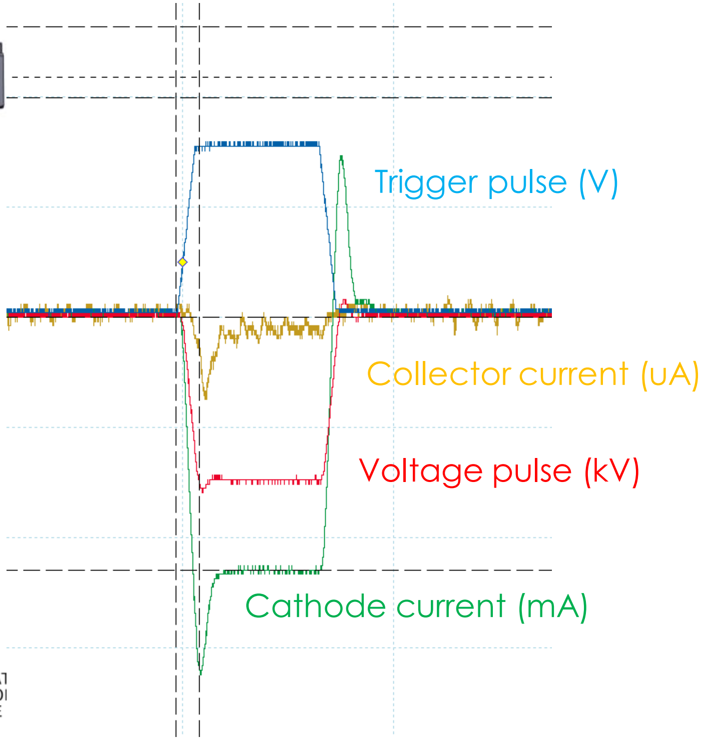
Normalized rms emittance for a ~55 mA beam
0.333 π mm·mrad for 0.5% threshold
0.326 π mm·mrad for 2.0% threshold

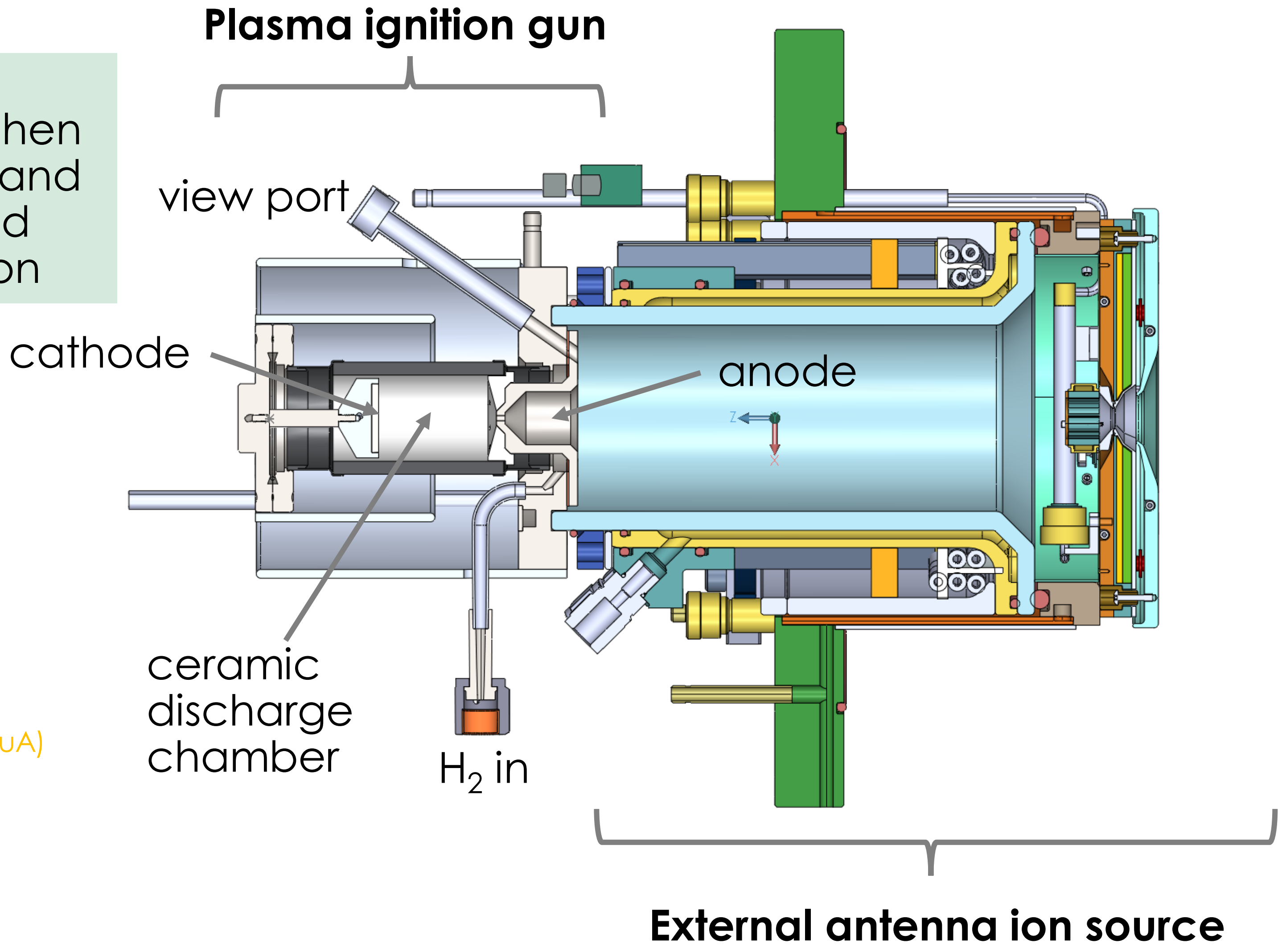
- A set of emittance scanners with water-cooled front-slits have been installed and are being tested on the ion source test stand.
- With actively cooled scanners we will be able to measure beam emittance at our ion source nominal rep rate 60 Hz.

A new plasma gun for the R&D external-antenna ion source



Electric field is optimized for Paschen discharge regime and designed for pulsed DC mode operation





Summary and outlook

- The H^- injector on the SNS accelerator Front-End consists of an RF-driven, Cs-enhanced H^- ion source and a compact 2-lens electrostatic LEBT. The ion source operates at 6% duty-factor (60 Hz, 1 ms) delivering 65 keV beam to the RFQ.
- Ion source was operated for 3~4 months with high current (>50 mA)and high availability (average 99.7%) covering entire period for each of the past 6 production run cycles of SNS.
- A H^- injector similar to the Front-End injector delivers beam on the BTF for 2.5 MeV beam physics studies, and a H^- injector system equipped with low energy beam diagnostics serves as our ion source and LEBT development platform.
- Latest development activities on the ion source test stand and the BTF include improved thermal control on ion source cesiation, optimized parameters for electron dumping circuit, boosted beam output capability of ion source, upgraded low energy emittance scanners, and a newly optimized plasma gun for the R&D external-antenna ion source.
- Next steps, solidification of the boosted ion source output capability and systematic emittance characterization are expected.

Thank you for your attention!