Recent Advancements in the H^- Injector Performance for the Spallation Neutron Source Operation and Upgrade

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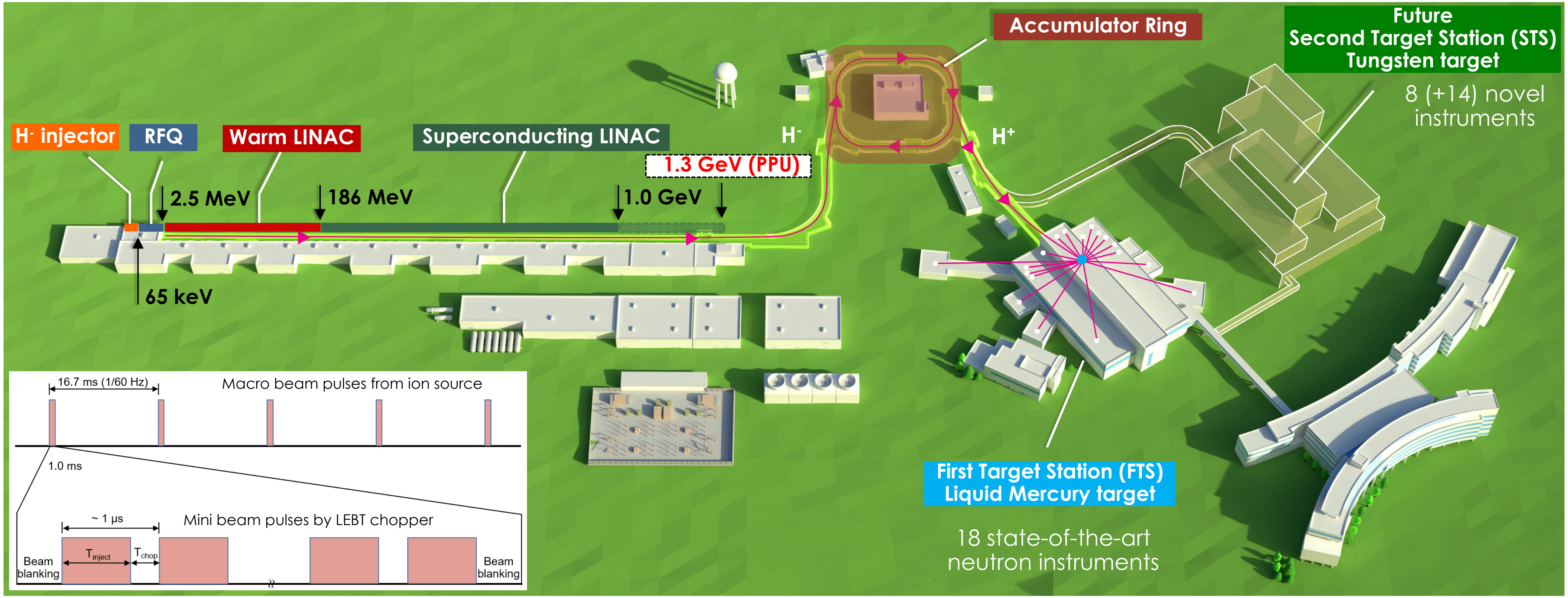
Outline of the talk

- ❑ Status of the SNS operation and upgrade
- ❑ The SNS H^- injector and operation performance
- ❑ Recent advancements on the H^- injector test stand
- ❑ Summary and outlook

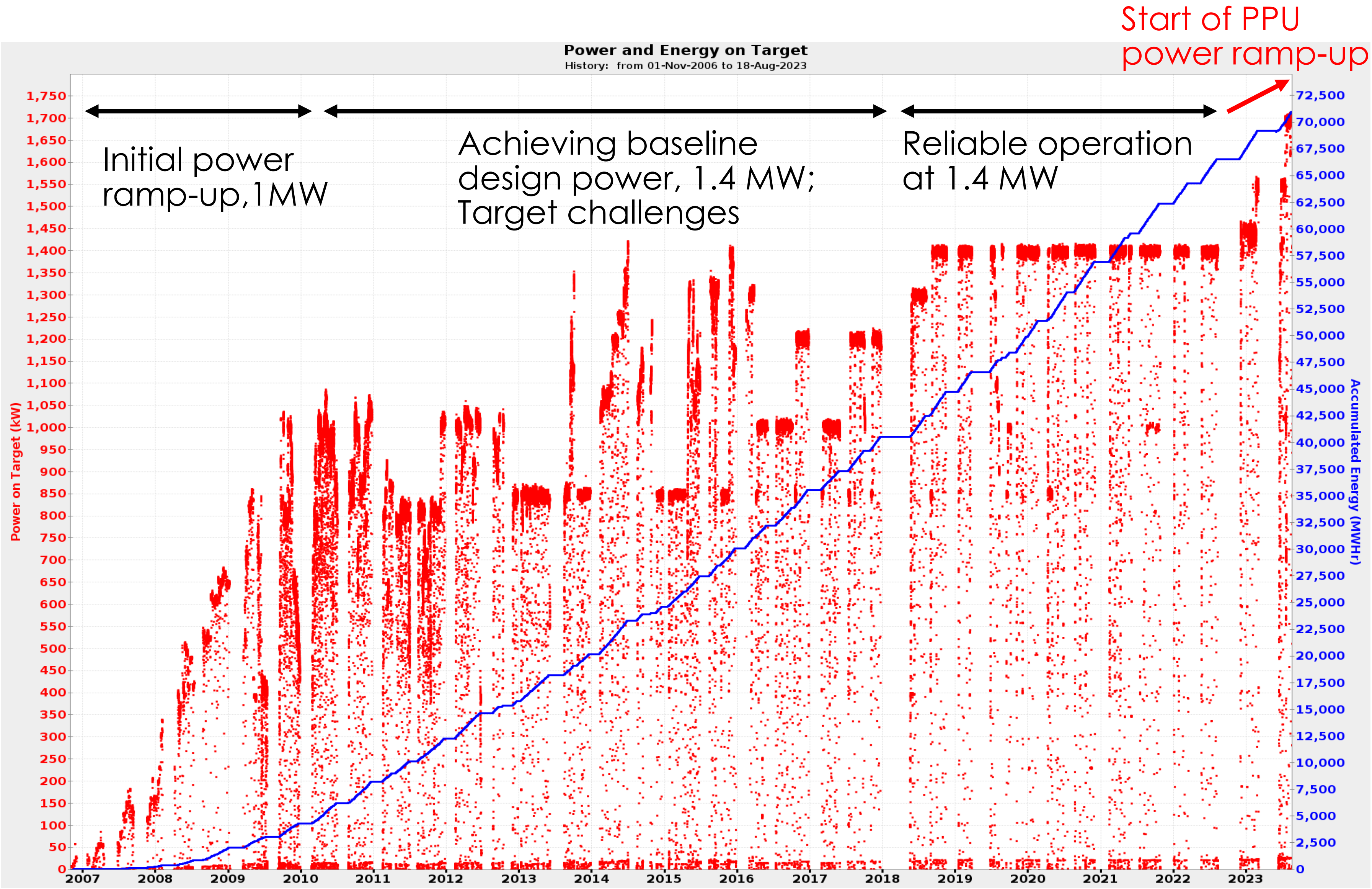
SNS overview and Proton Power Upgrade from 1.4 MW to 2.8 MW



	Proton beam power (average)	Linac beam energy	Linac beam current	Macro pulse length	Macro pulse repetition rate	Mini pulse injection fraction	Desired beam current from the H- injector *
SNS Baseline operation	1.4 MW	1.0 GeV	~35 mA	1.0 ms	60 Hz	up to 78%	40 - 55 mA
SNS ongoing Proton Power Upgrade (PPU) goals	2.8 MW (2.0 MW on FTS) (0.8 MW on STS)	1.3 GeV	~46 mA	1.0 ms	60 Hz	Up to 82%	50 - 75 mA

* To allow substantial operating margin for the machine for required beam power

SNS started PPU power ramp-up after 5 years of reliable operation at 1.4 MW



- 2.8 MW beam power capability by 2026
- Long outage from August 2023 through June 2024 for PPU major upgrade work:
  - RF systems
  - Superconducting Linac
  - Accumulator ring
  - Controls and Diagnostics
  - Conventional systems
- FTS mercury target upgrade: jet flow and gas injection
- **Improvements in the H^- injector performance**
  - **For additional operating margin with beam current**
  - **To support high reliability**

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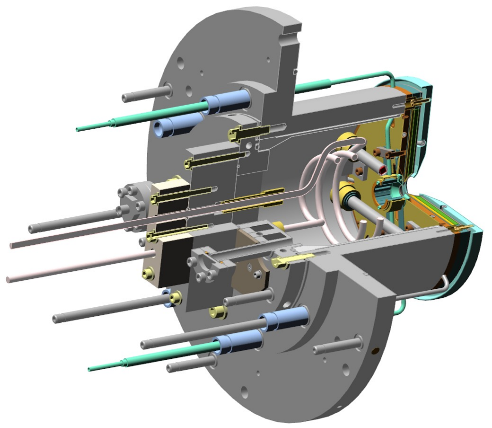
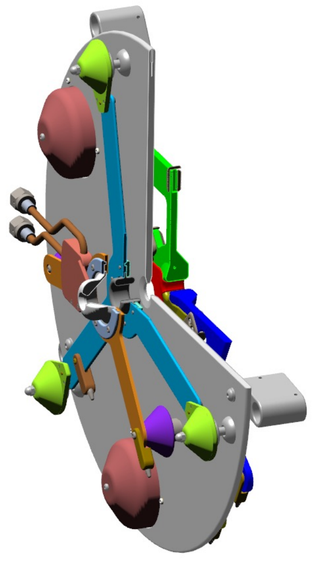
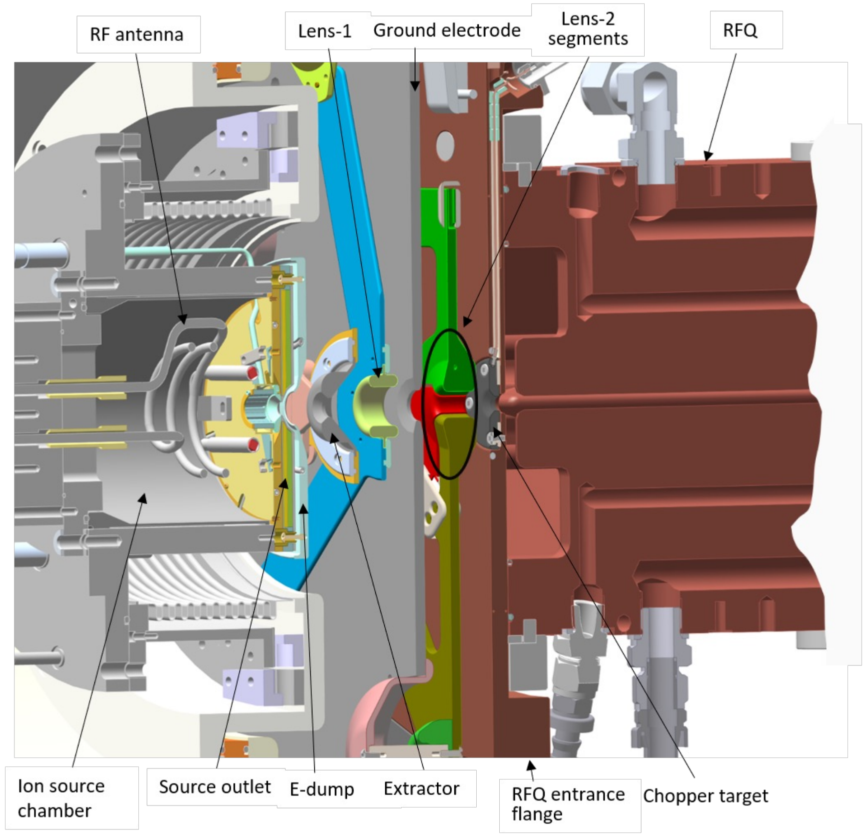
The SNS accelerator Front-End H^- injector system

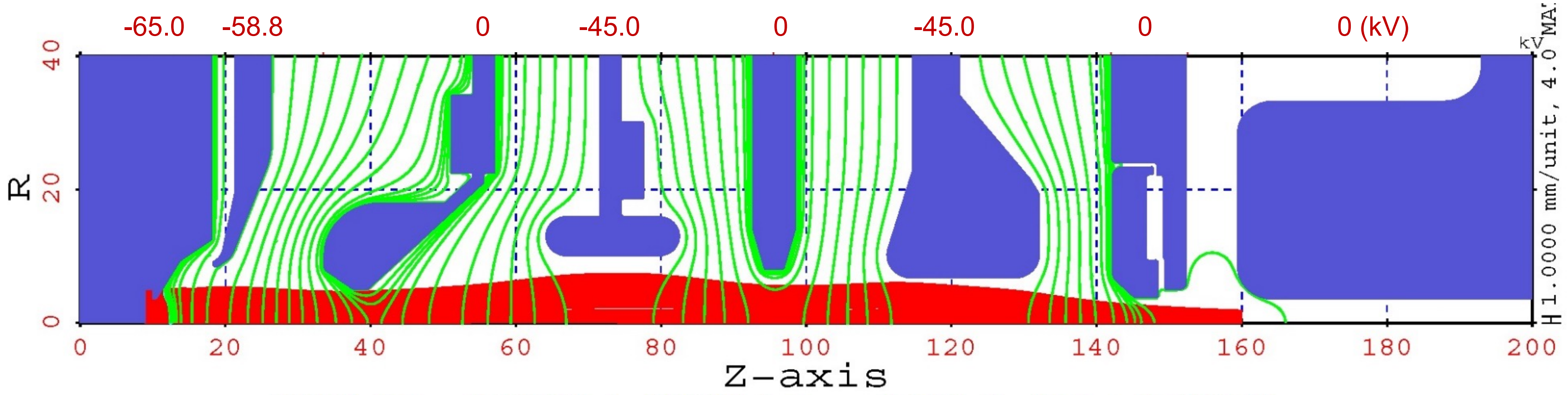


An RF-driven, Cs-enhanced, multi-cusp H^- ion source



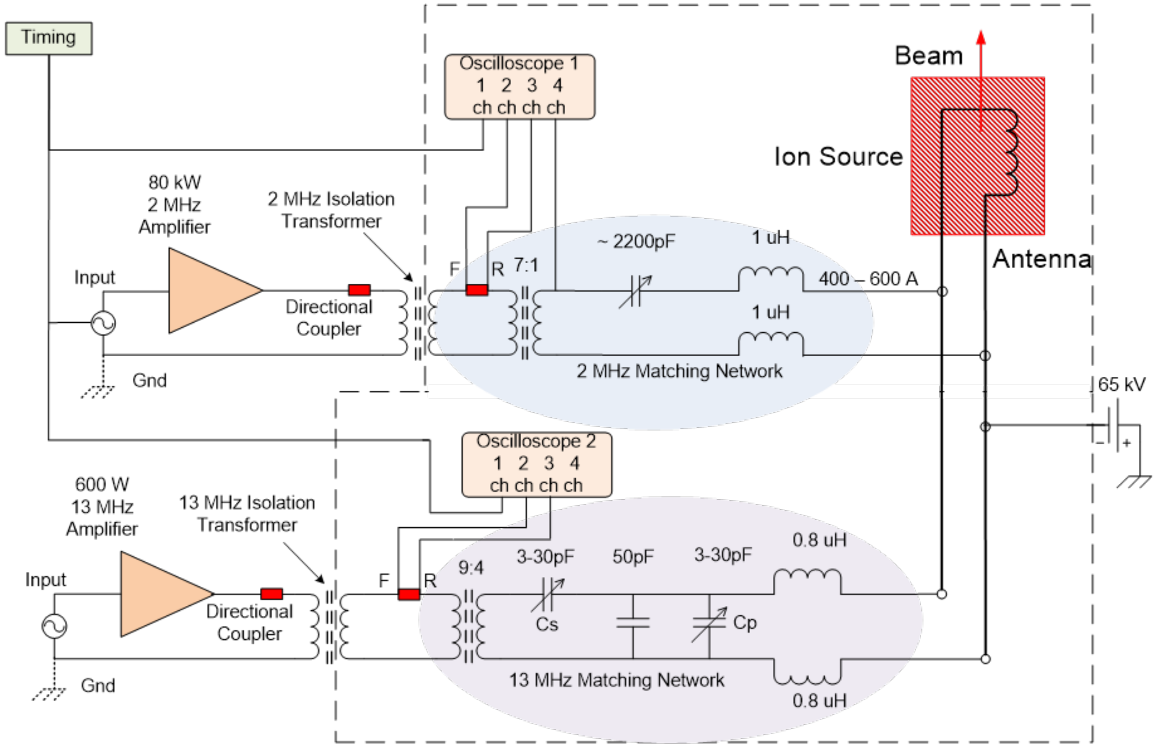
A compact 2-lens electrostatic low energy beam transport system (LEBT)

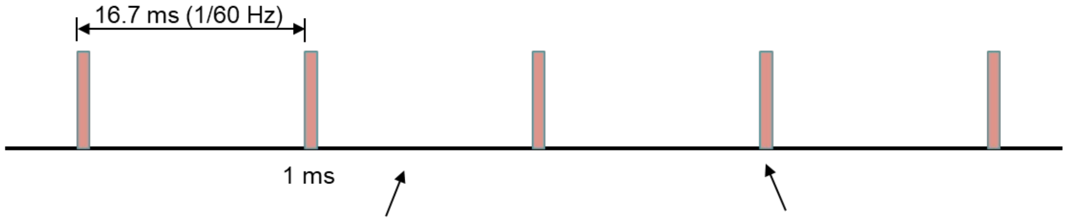


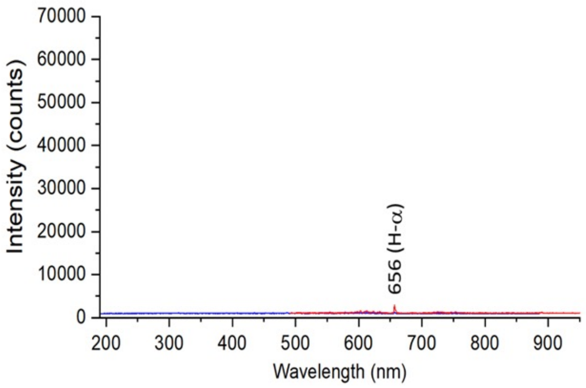


The SNS H$^-$ ion source RF systems and timing structure

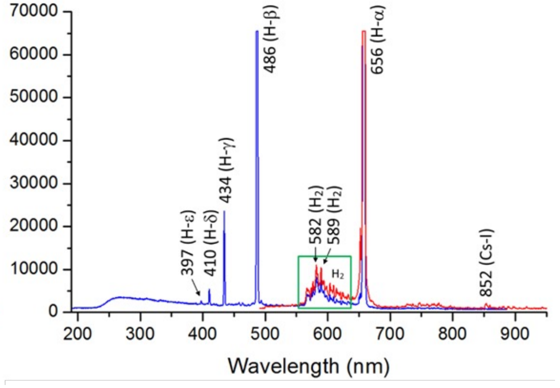
SNS H$^-$ ion source RF systems diagram



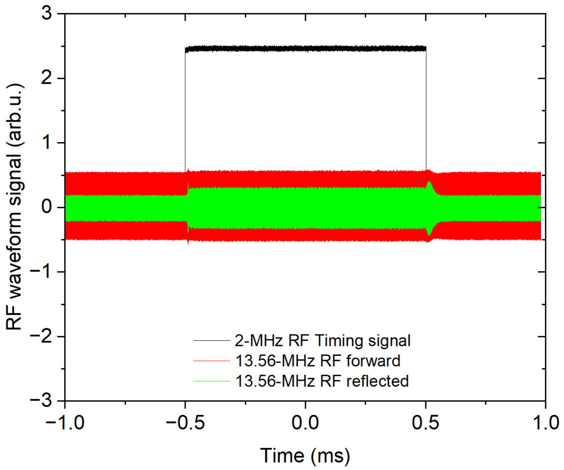




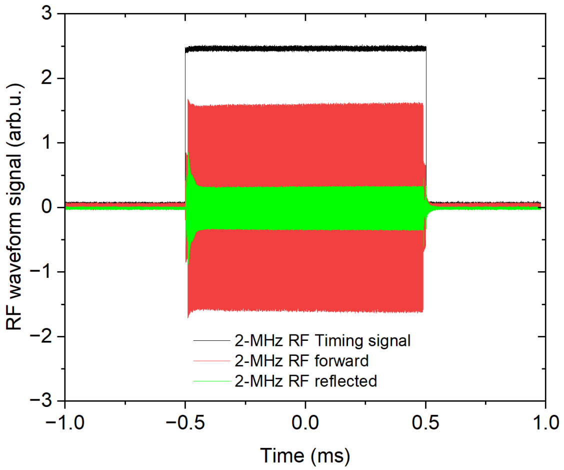
OES spectra of plasma in-between pulses



OES spectra of plasma during pulses



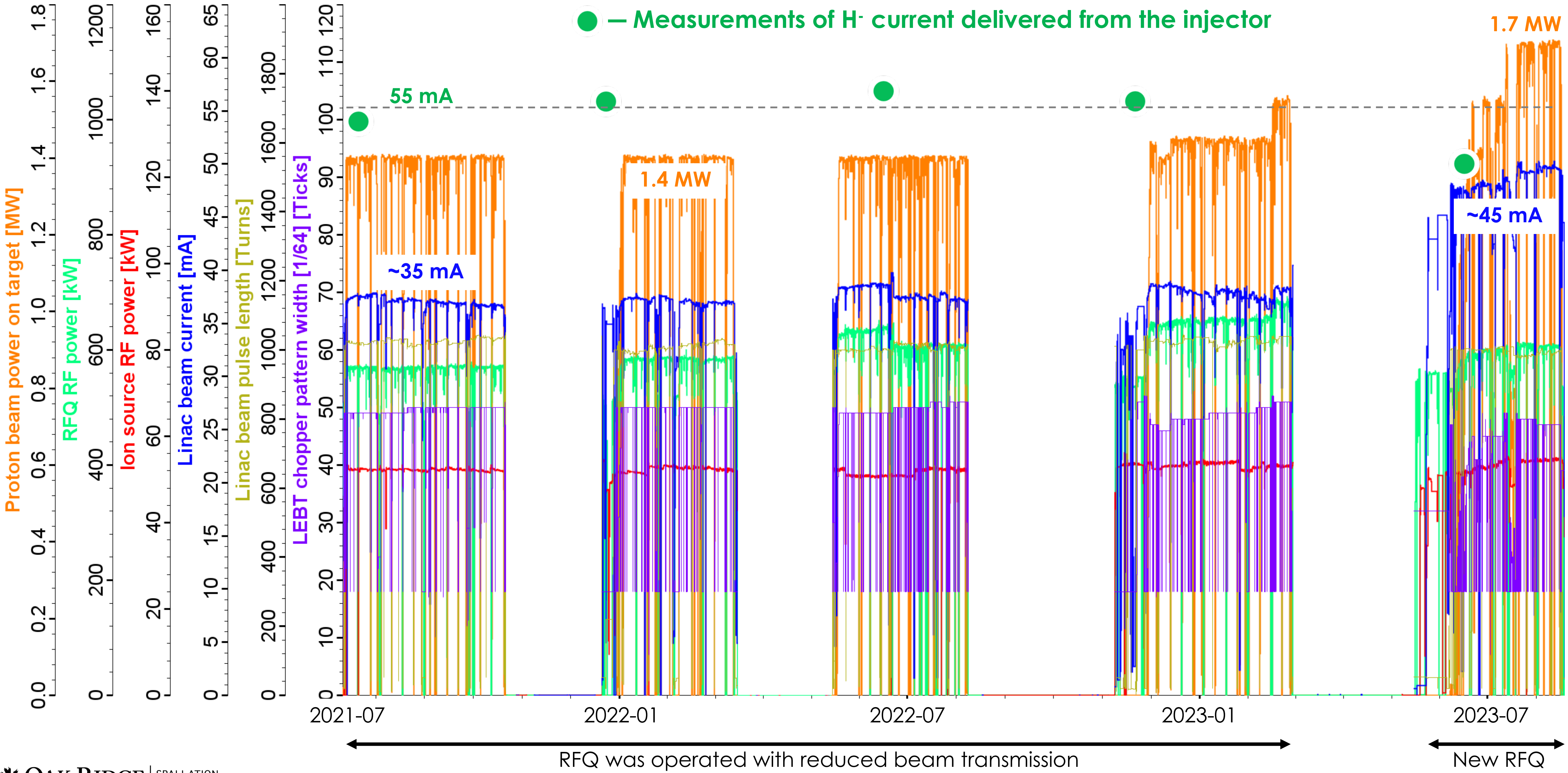
13.56-MHz RF waveforms



2-MHz RF waveforms

- A high-power (typically ~55 kW) 2-MHz RF system pulsed at 60 Hz with1.0 ms pulse length drives the high-density pulsed plasma for high current beam production
- A low-power (typically ~300 W) continuous, 13.56-MHz RF system maintains a low-density background plasma to facilitate fast and reliable turn-on of the high-density pulsed plasma

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



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
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	LEBT arcing
11/8/2022	2/28/2023	#3	112	99.3%	11/8/2022	~56 mA	~34 mA	LEBT arcing
5/19/2023	8/18/2023	#6	91	99.9%	6/5/2023	~50 mA	~45 mA	New RFQ

- The H^- injector supported the SNS production run cycles (3 - 4 months) providing 50-57 mA beam current without major maintenance.
- The H^- injector availability was excellent except for two occasions where the LEBT arcing needed conditioning which caused some hours of downtime, overall availability on average >99.5%

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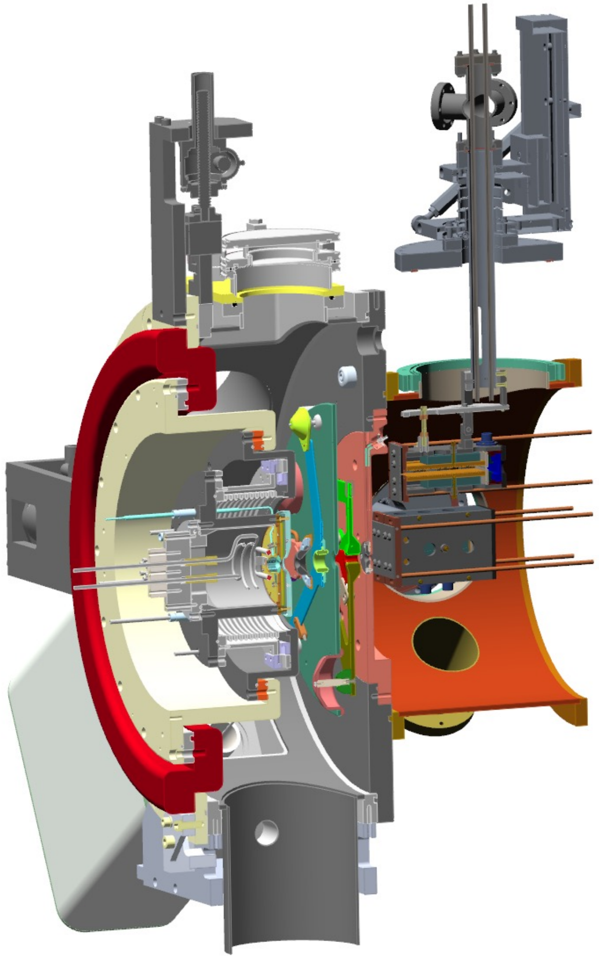
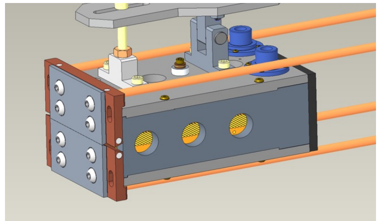
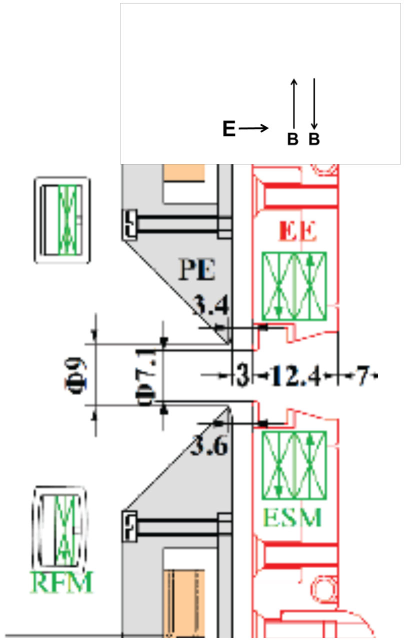
The Ion Source Test Stand (ISTS) at SNS as R&D platform



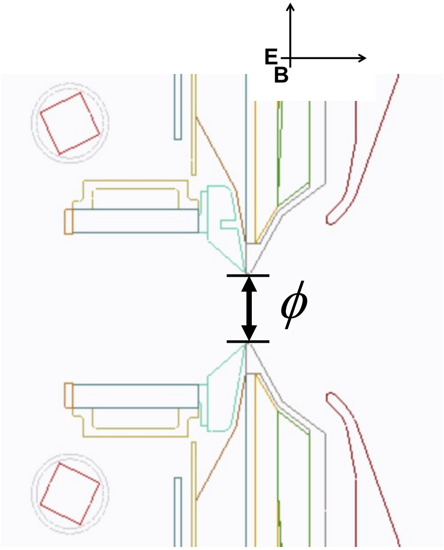


- The ISTS is almost identical to the SNS Front-End H^- injector
- A diagnostic chamber with a Faraday Cup and a set of newly upgraded full beam power capable Allison emittance scanners

Boosting the ion source beam output capability



J-PARC ion source extraction, ϕ9 mm, larger ion converter surface, E, B field separated, >100 mA*

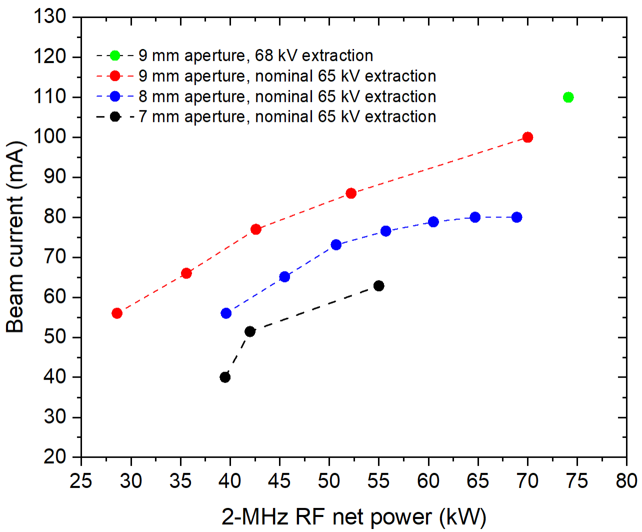


SNS ion source extraction

Optimization started with simple changes

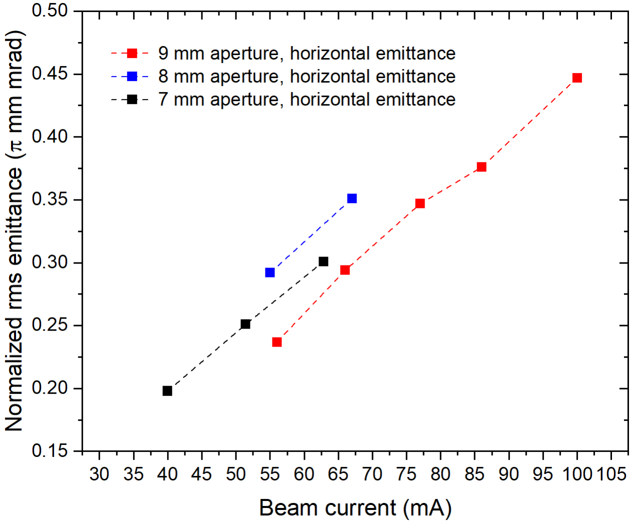
ϕ 7 mm → 8 mm → 9 mm

Beam current

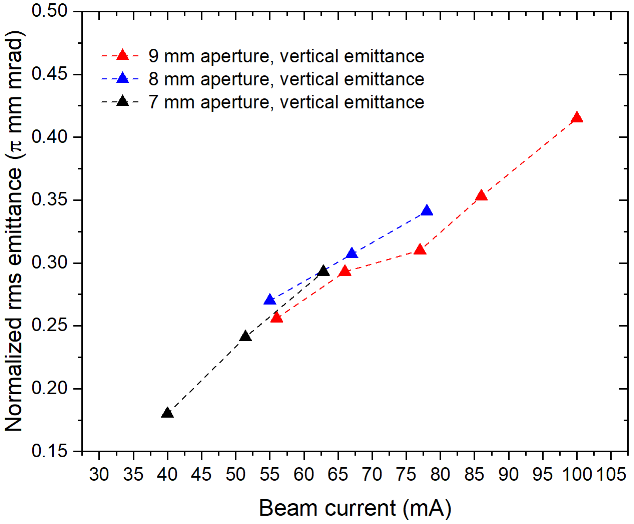


Beam emittance

Horizontal



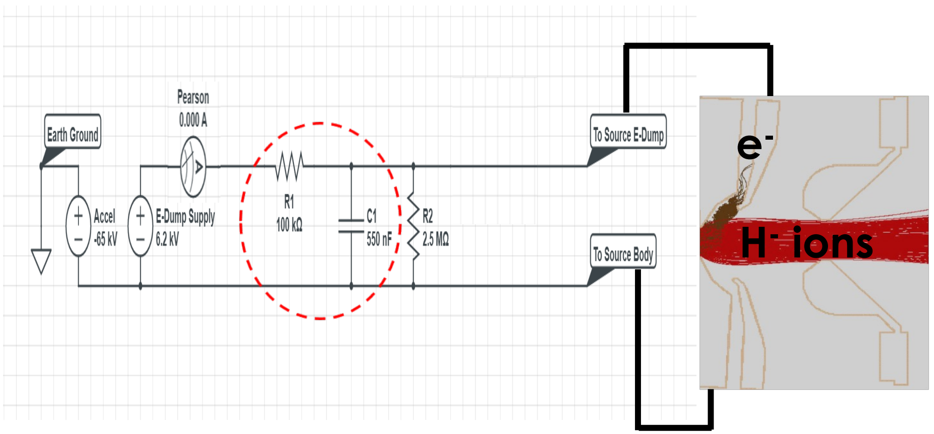
Vertical



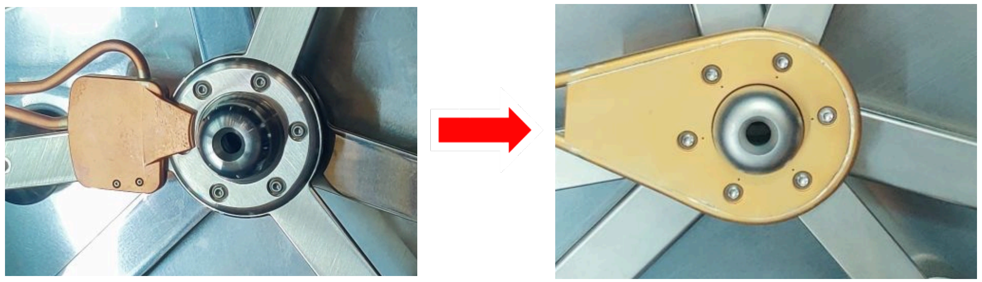
- Up to ~110 mA beam current was demonstrated with ϕ9 mm
- 80-90 mA at routine operational RF power range of 50-60 kW
- About 50% increase in ion source beam current output with a ϕ9 mm outlet aperture vs. the current ϕ7 mm aperture
- Beam emittances of larger apertures are within proximity of the ϕ7 mm aperture (horizontal measurements had larger scatter)

* Courtesy of A. Ueno et al, AIP Conference Proceedings 2052, 050003 (2018)

Electrical and mechanical improvements for higher beam current source

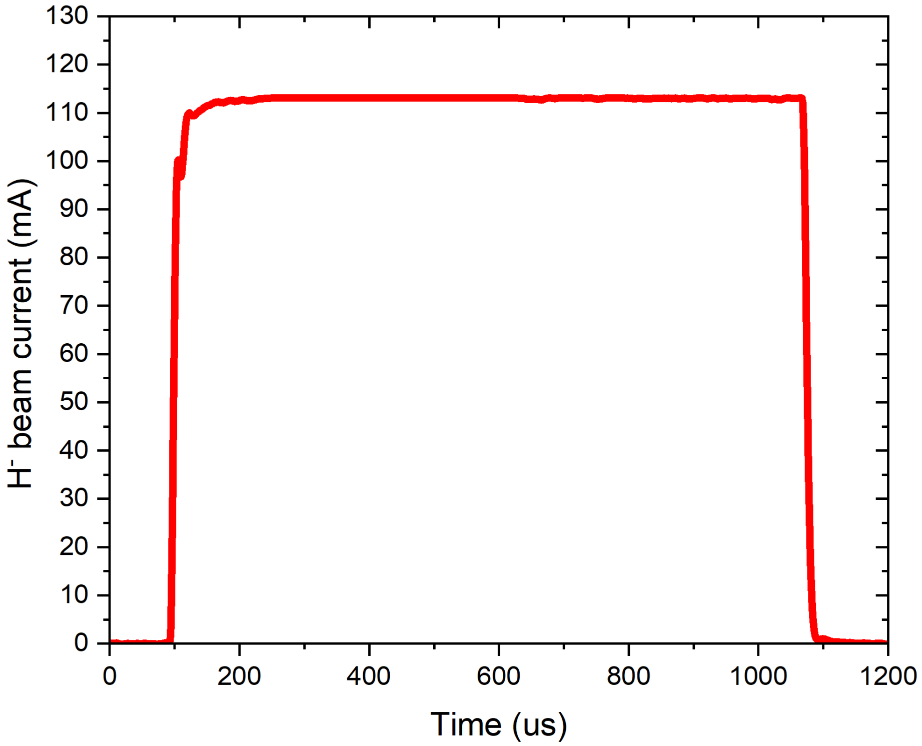


A voltage stabilizer circuit for electron-dump electrode



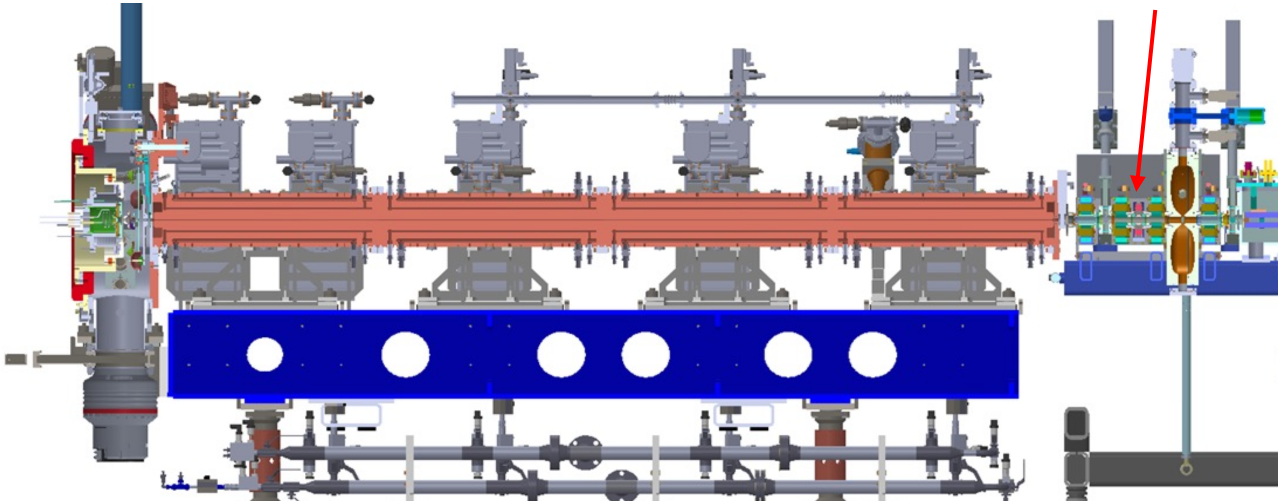
Improved cooling for the extractor electrode

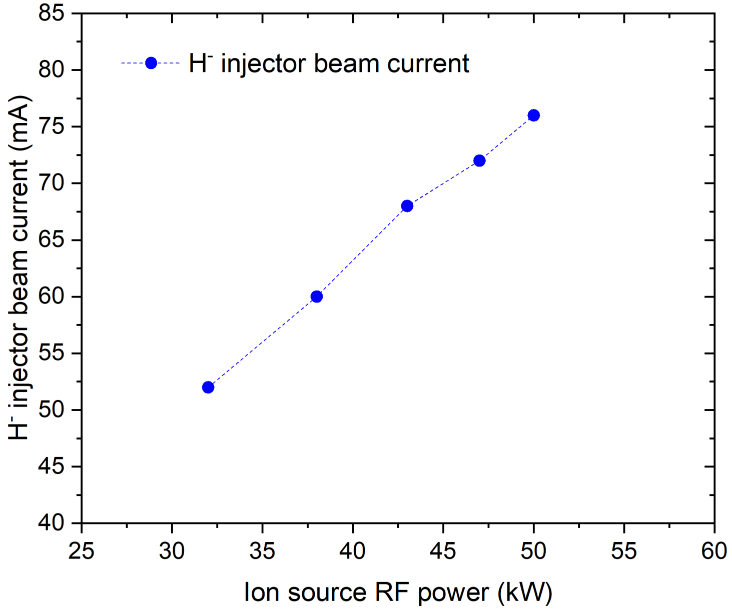
These improvements help the ion source and LEBT better cope with the increased loading from the electrons and scraped ions



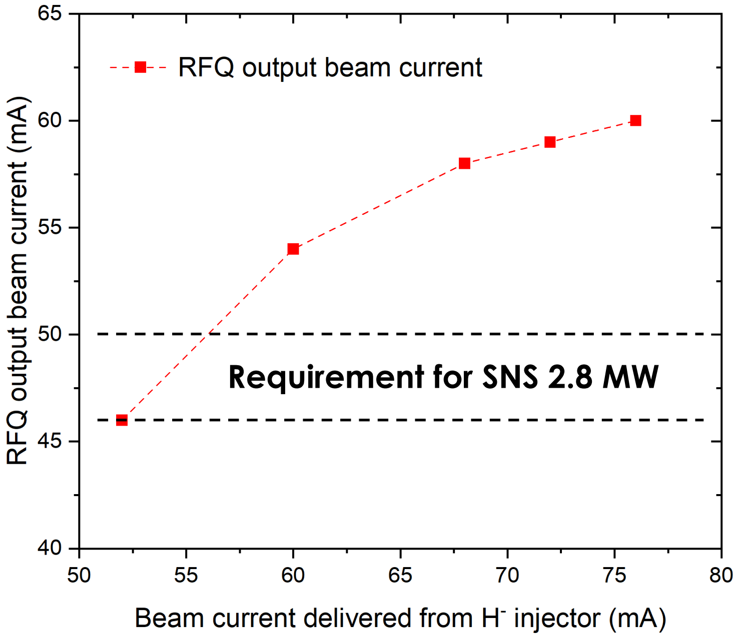
A nearly square beam pulse of ~110 mA with the ion source at -65 kV, electron-dump at -62 kV, and +15 kV voltage applied on the extractor electrode which is usually at ground potential

ISTS results checked out on the Front-End through the RFQ



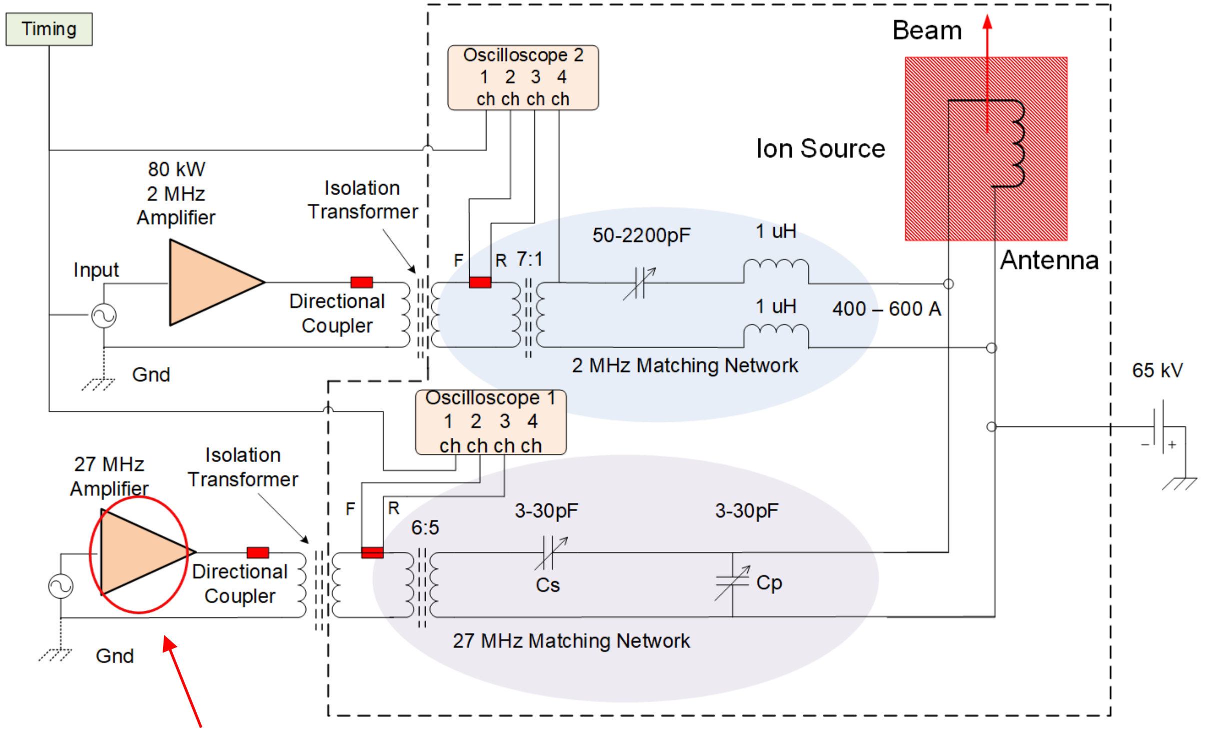


- A ϕ9 mm outlet aperture ion source was tested with the RFQ on the SNS accelerator Front-End
- 60 mA RFQ output beam current was demonstrated
  - The beam current delivered from the H^- injector was administratively restricted to <80 mA per the SNS Operation Envelope Limit.
  - The ion source was operated only up to 50 kW, which is within its routine operational RF power level
  - The RFQ was operated at its nominal power level

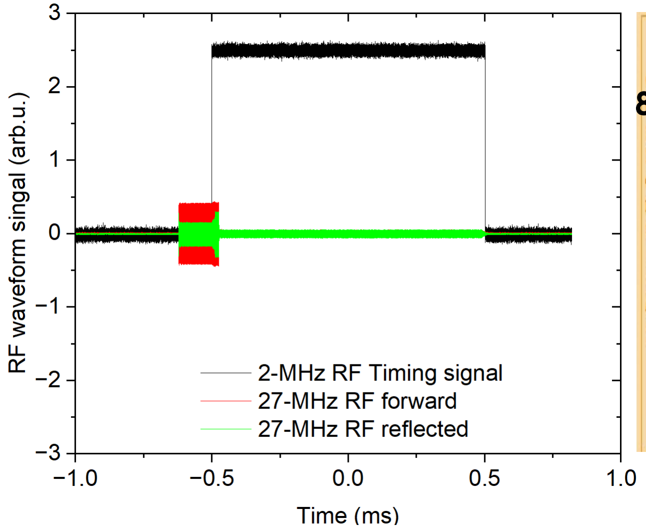


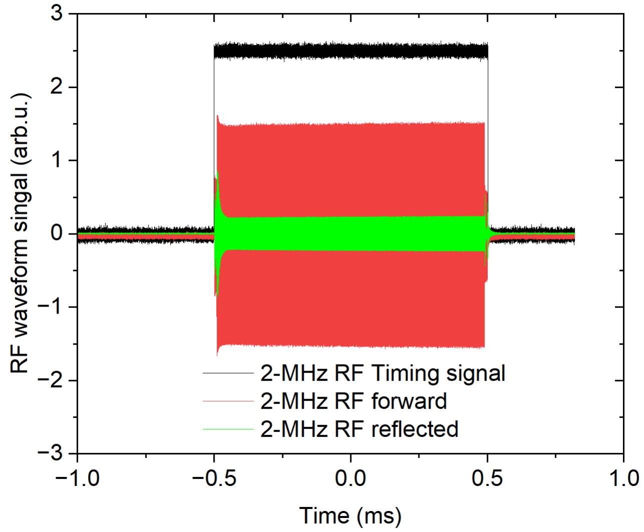
Improving the plasma ignition at low pressure: 27-MHz RF in place of 13-MHz RF for starter background plasma

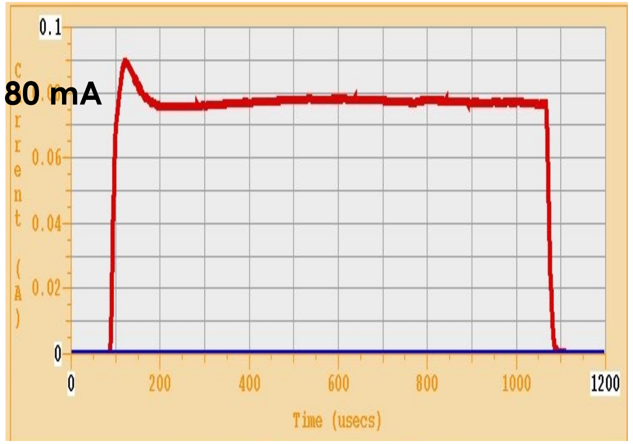
SNS H^- ion source RF systems diagram with modifications for 27-MHz testing

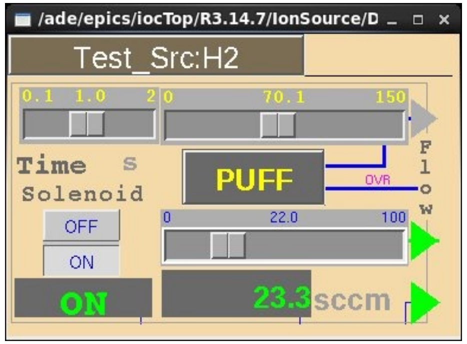


27-MHz OPHIR RF amplifier in place of COMDEL 13-MHz RF generator







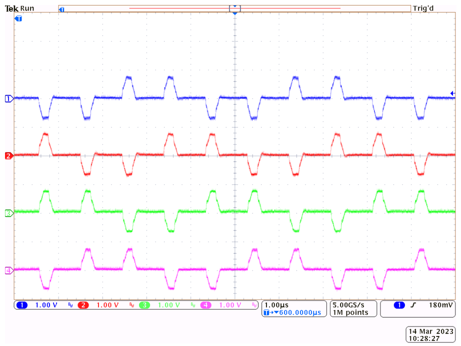


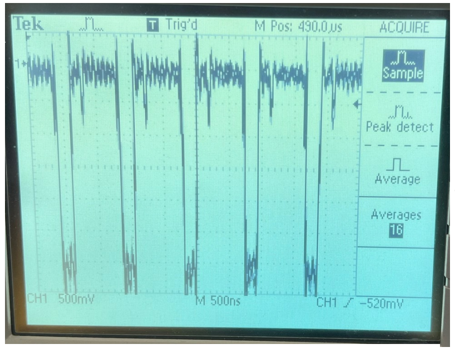
H2 gas flow rate optimized for beam current, seen here are 22 sccm, ~77 mA with a ϕ8 mm aperture ion source, plasma stayed on at 15 sccm

- A short pulse, ~100 W of 27-MHz RF starting just before the 2-MHz high-power RF with only ~15 us overlap was enough to facilitate reliable turn-on of the high-density 2-MHz RF plasma
- 27 MHz RF allowed optimization of beam current at significantly reduced hydrogen flow rates without compromising plasma stability compared to what is possible with the current 13 MHz RF setup

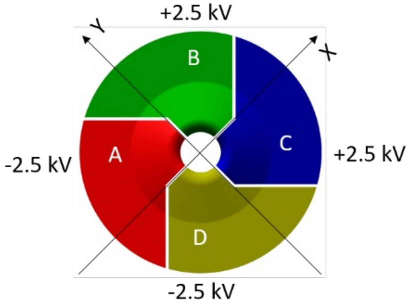
LEBT chopper system upgrade

Voltage waveforms for typical chopping



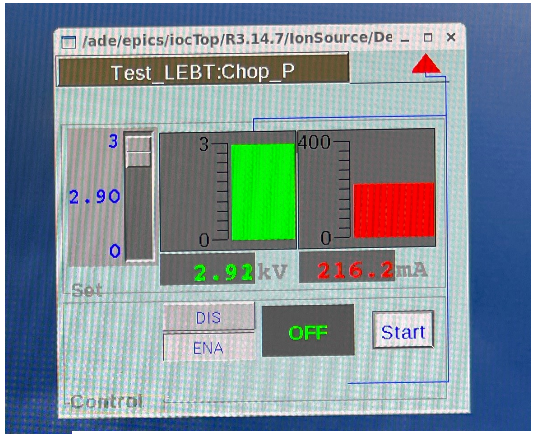


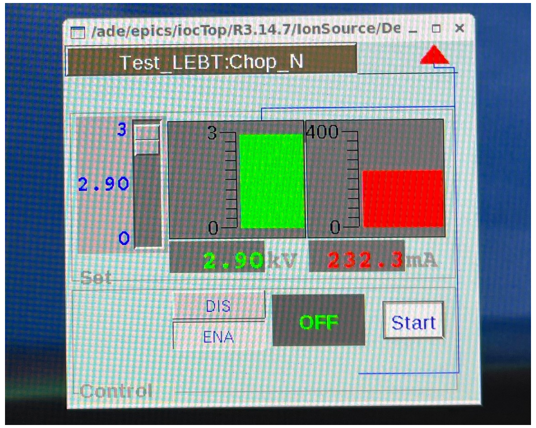
22% beam of every mini pulse was deflected on the chopper target



New design chopper pulsers

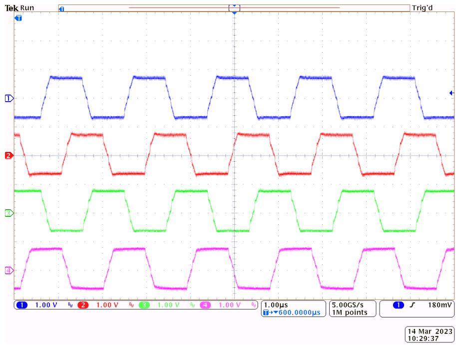
- Obsolescence mitigation
- Higher voltage for cleaner beam chopping in front of the RFQ
- Higher duty-factor for blanking nearly full length 1.0 ms beam at 60 Hz (for scenarios where only very short pulse beam at very low rep rate is desired to be injected into the RFQ, but without disturbing the ion source operation conditions)

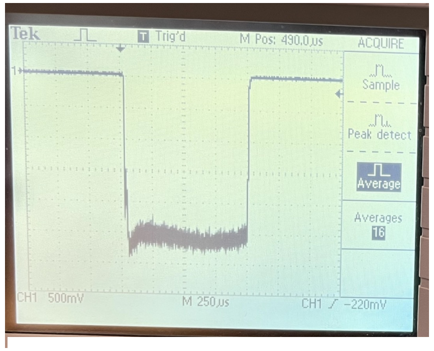




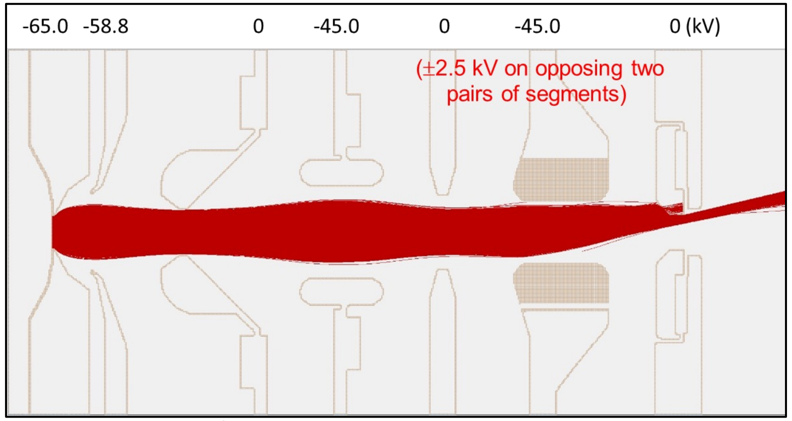
New pulsers were reliably operated up to 3 kV vs. 2.5 kV for the old pulsers

Voltage waveforms for beam blanking



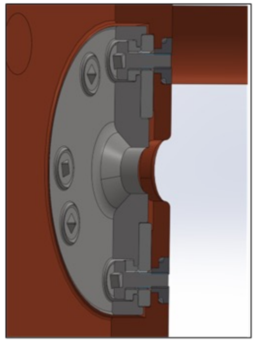


Full 1.0 ms beam at 60 Hz was deflected on the chopper target



Chopper target thermal tolerance

- Stopping high current, full 1.0 ms long beam at 60 Hz is thermally challenging for the chopper target
- Substantial improvement was made for thermal contact between the TZM beam target and the water-cooled RFQ flange with peak temperature dropping from ~600 C to below 200 C
- A new design is in conception



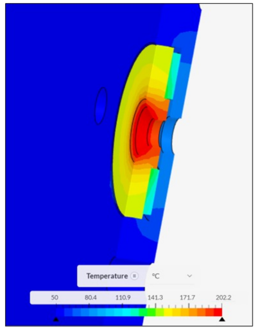


Illustration of the chopper target mount and thermal simulation

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Summary and outlook

- The SNS is on track to upgrade the proton beam power from 1.4 MW to 2.8 MW following successful operation at 1.4 MW in the past 5 years.
- The H^- injector supported the SNS production run cycles (3 - 4 months) providing 50-57 mA beam current with high availability, >99.5% on average over the recent two years.
- Latest advancements in the H^- injector performance to gain additional operating margin and reliability for the SNS operation and upgrade includes:
  - Boost of ion source beam output capability by ~50% and up to 110 mA, with larger outlet aperture size along with improved electron-dump circuit and better cooling for extractor electrode
  - Improved ignition reliability at lower pressures with 27-MHz RF for starter plasma allowing increased flexibility for beam optimization
  - LEBT chopper upgrades for cleaner chopping, full beam blanking and obsolescence mitigation
  - Diagnostics improvements: upgraded emittance scanner
- Next steps, solidification of the above-mentioned improvements to be ready for implementation on the SNS production accelerator system.

Thank you for your attention!