OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Advancing H^- Injector Beam Intensity Frontier at High Duty-Factor for Multi-Megawatt Proton Accelerators

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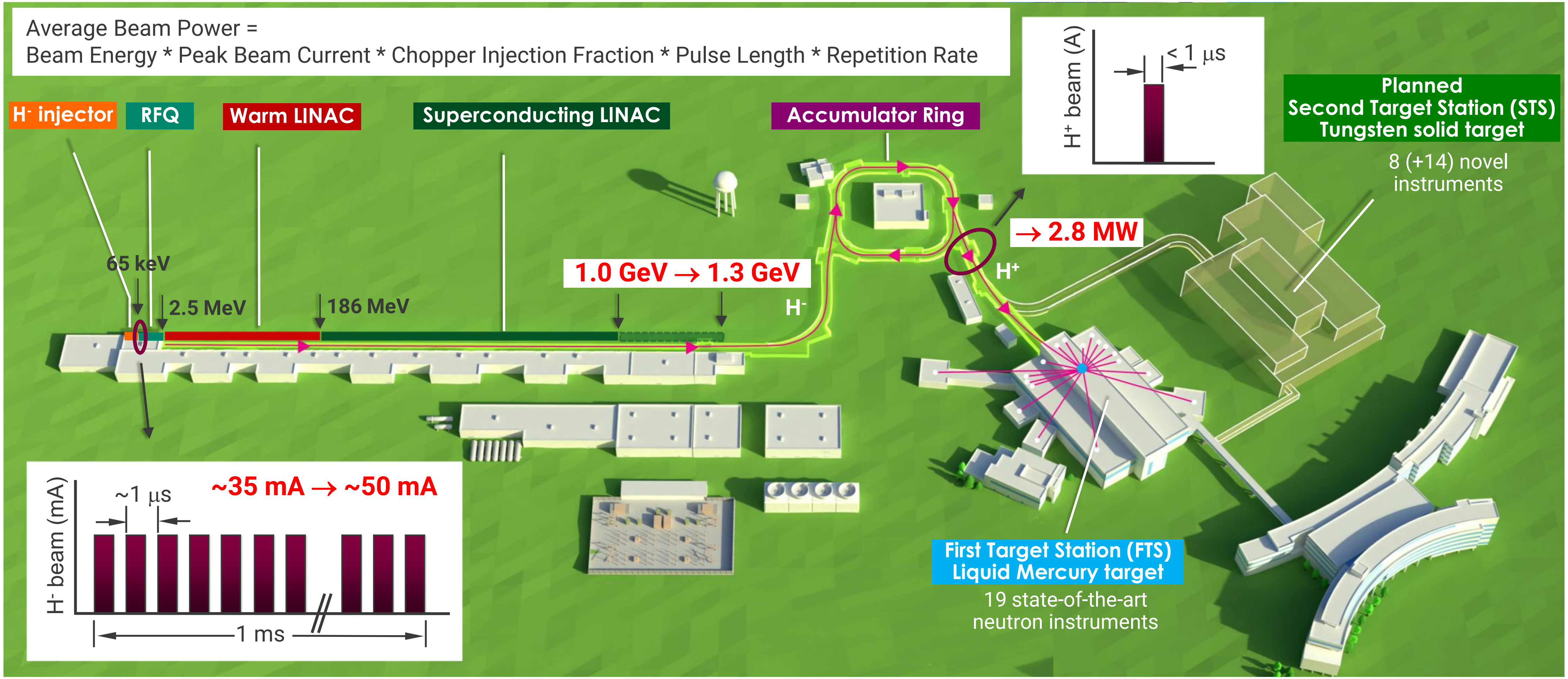
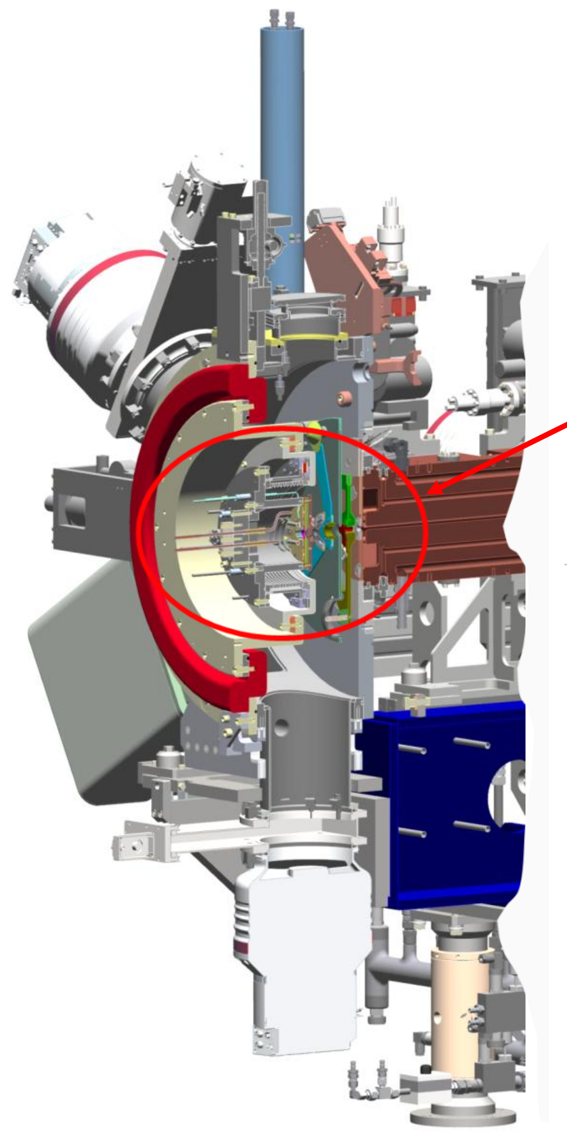
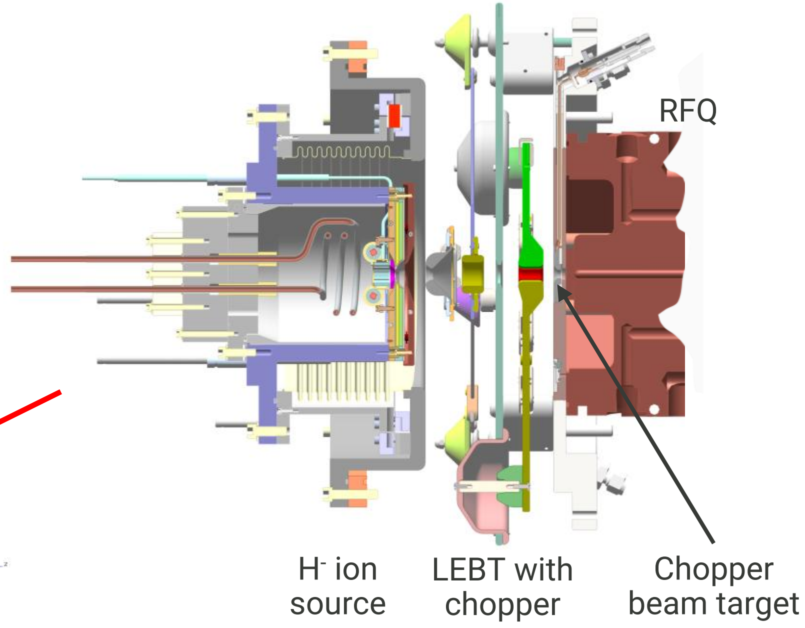
Spallation Neutron Source (SNS) – ramping up towards a multi-megawatt facility

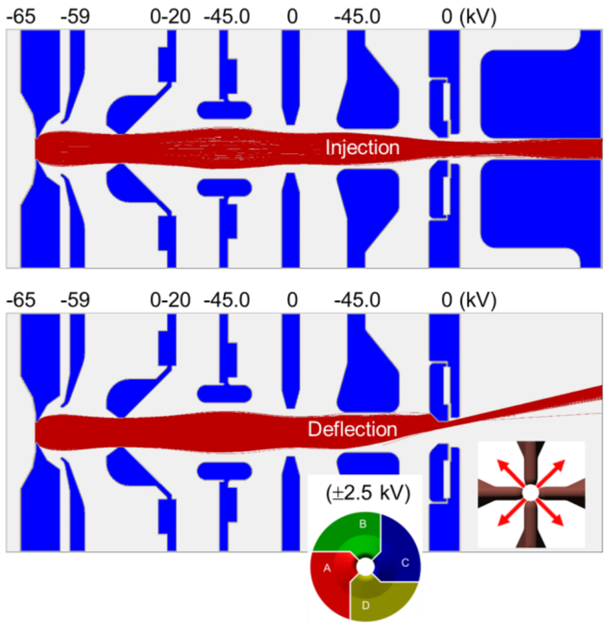


- SNS is a large-scale accelerator-based pulsed neutron facility
- Includes a 65 keV H^- injector, a 2.5 MeV RFQ, a Linac chain, a proton storage Ring, and neutron production target(s)
- Linac beam energy has recently been upgraded from 1.0 GeV to 1.3 GeV as part of the Proton Power Upgrade project
- Beam power ramp-up is progressing towards the PPU goal of 2.8 MW to support the future STS in addition to the FTS

The SNS Front End H^- Injector

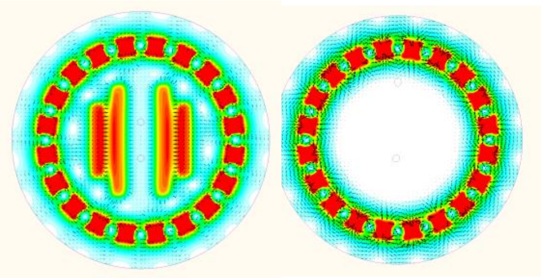




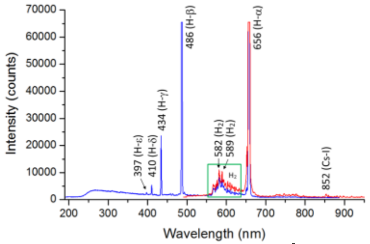


- An RF-driven, Cs-enhanced H^- ion source and a compact, 2-lens electrostatic LEBT with beam chopper
- Operates at 65 keV, 1.0 ms pulse length, 60 Hz rep rate, and ~1 MHz chopping
- By ~2012, achieved routine beam current 50-60 mA with 50-60 kW
- Since 2016, multiple-month long run cycles (up to 6 months) with >99.5% availability
- Since 2022, significant progress in boosting the ion source output capability
  - To ensure a sufficient bema current margin for the SNS new requirements
  - To advance the frontier of H^- injector beam current worldwide.

The H^- Ion Source

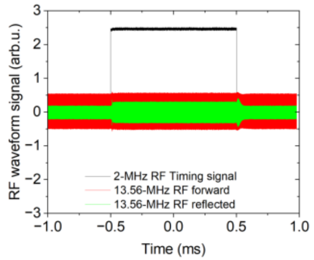


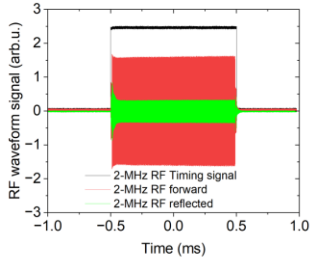
multicusp fields



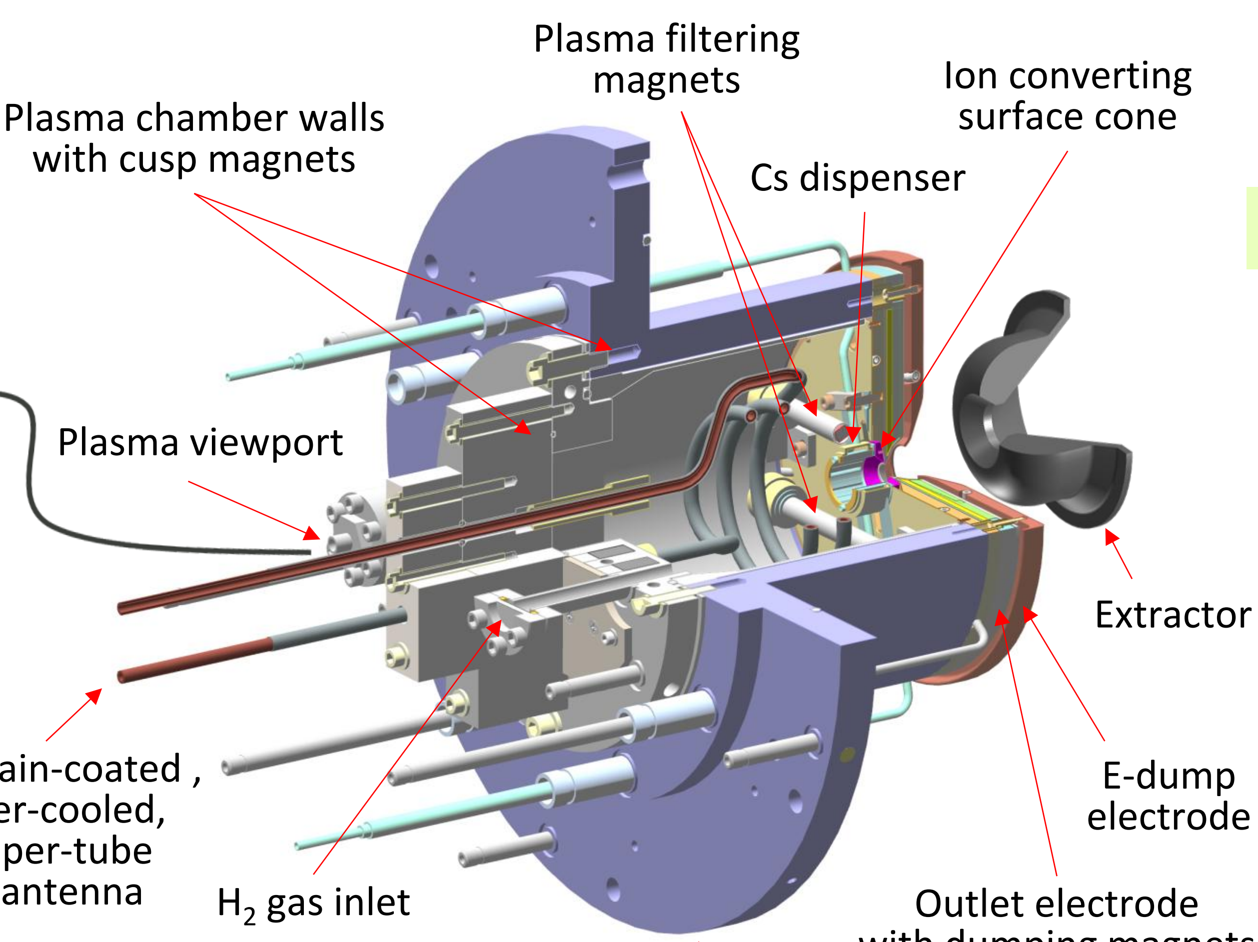
Plasma spectroscopy

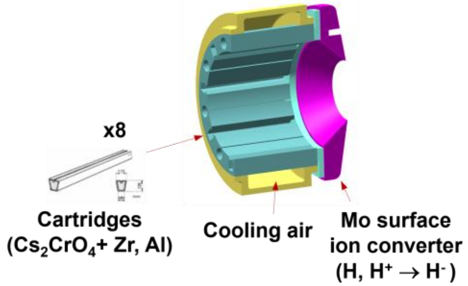
13.56 MHz CW RF for low density background plasma with ~300 W





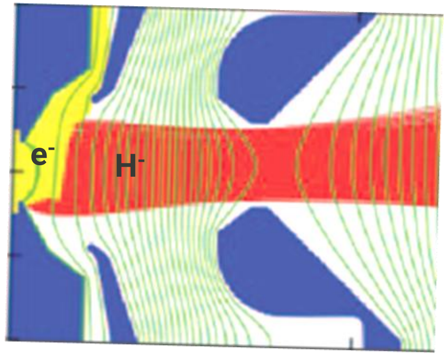
2 MHz RF for 1.0 ms, 60 Hz high density plasma, with ~50 kW

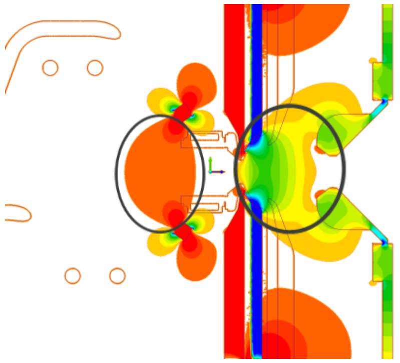




$4\ Cs_2CrO_4 + 5\ Zr \rightarrow 8\ Cs + 5\ ZrO_2 + 2\ Cr_2O_3$

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





filter field

Electron dumping field

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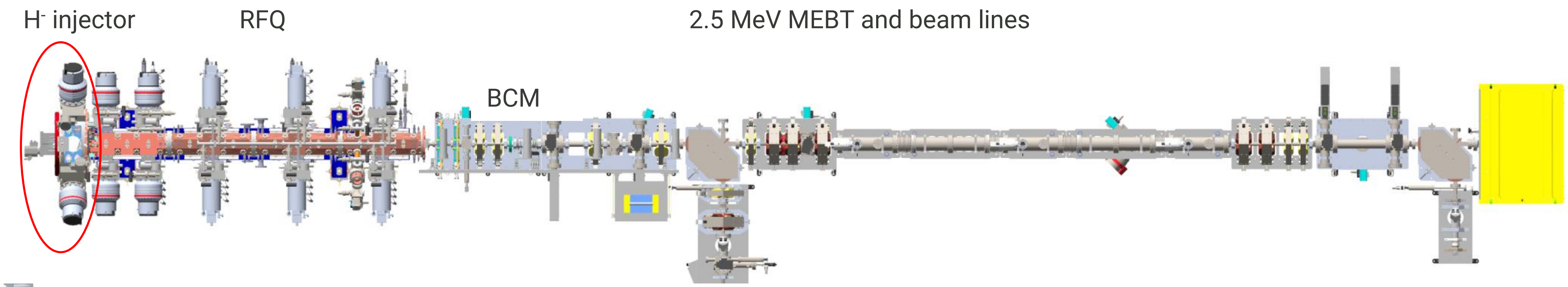
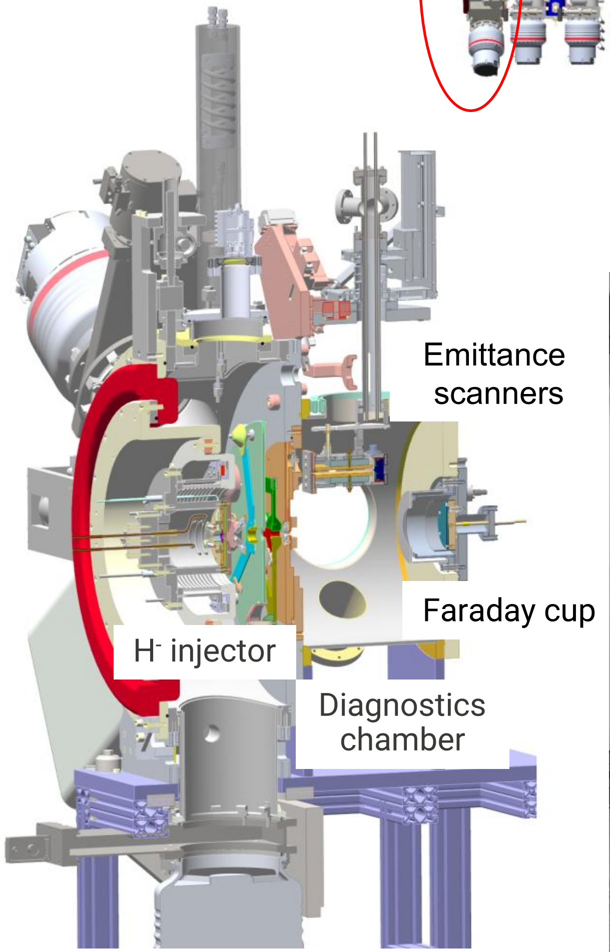
H^- Injector Test Facilities at SNS



2.5 MeV Beam Test Facility (BTF)



- ISTS is a R&D platform for ion source and LEBT, which is equipped with advanced diagnostics tools for equipment, plasma, and beam
- BTF is mostly used for RFQ testing and beam studies at 2.5 MeV, which utilizes a H^- injector almost identical to the SNS Front End injector
- New developments in the ion source and LEBT can be validated on the BTF for usability on the SNS accelerator in advance, particularly when beam time on the main accelerator is unavailable.

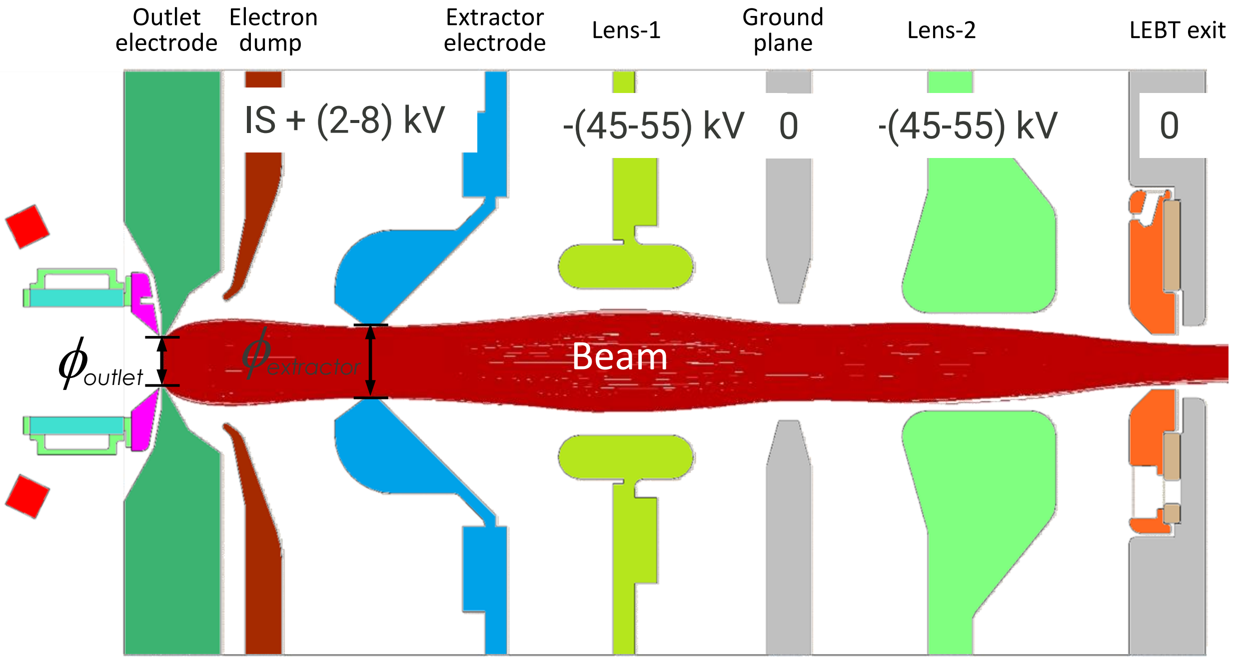
Ion Source Test Stand (ISTS)

Ion Source Outlet Aperture and Extraction Voltage Scaling

Net extraction voltage scaling

IS
-65 kV
Up to -68 kV

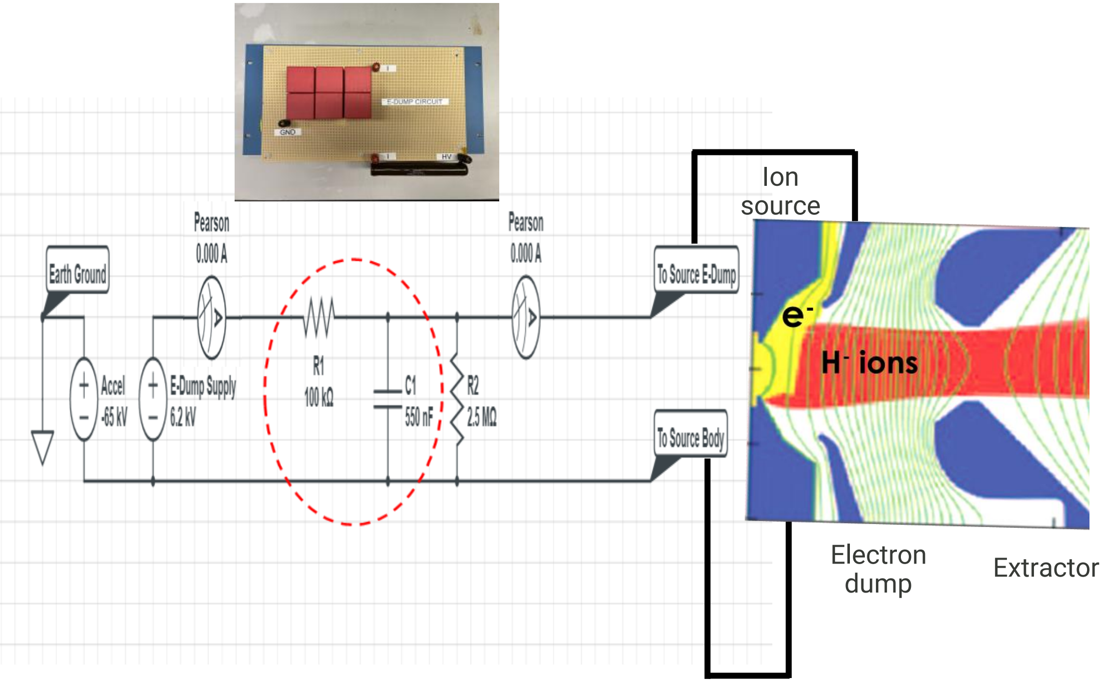
Extr
0-18 kV



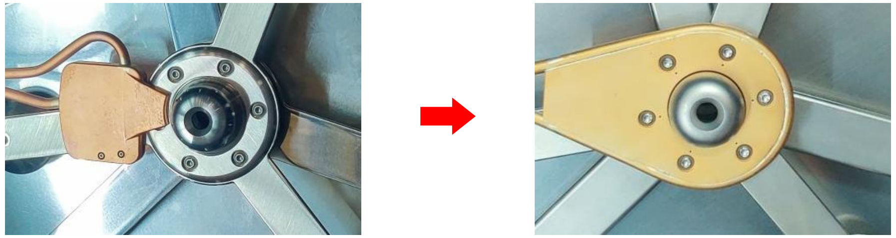
ϕ_{outlet} 7 mm → 8 mm → 9 mm → 10 mm

$\phi_{extractor}$ 10 mm → 12 mm for ϕ_{outlet} 10 mm

Ion source outlet aperture scaling

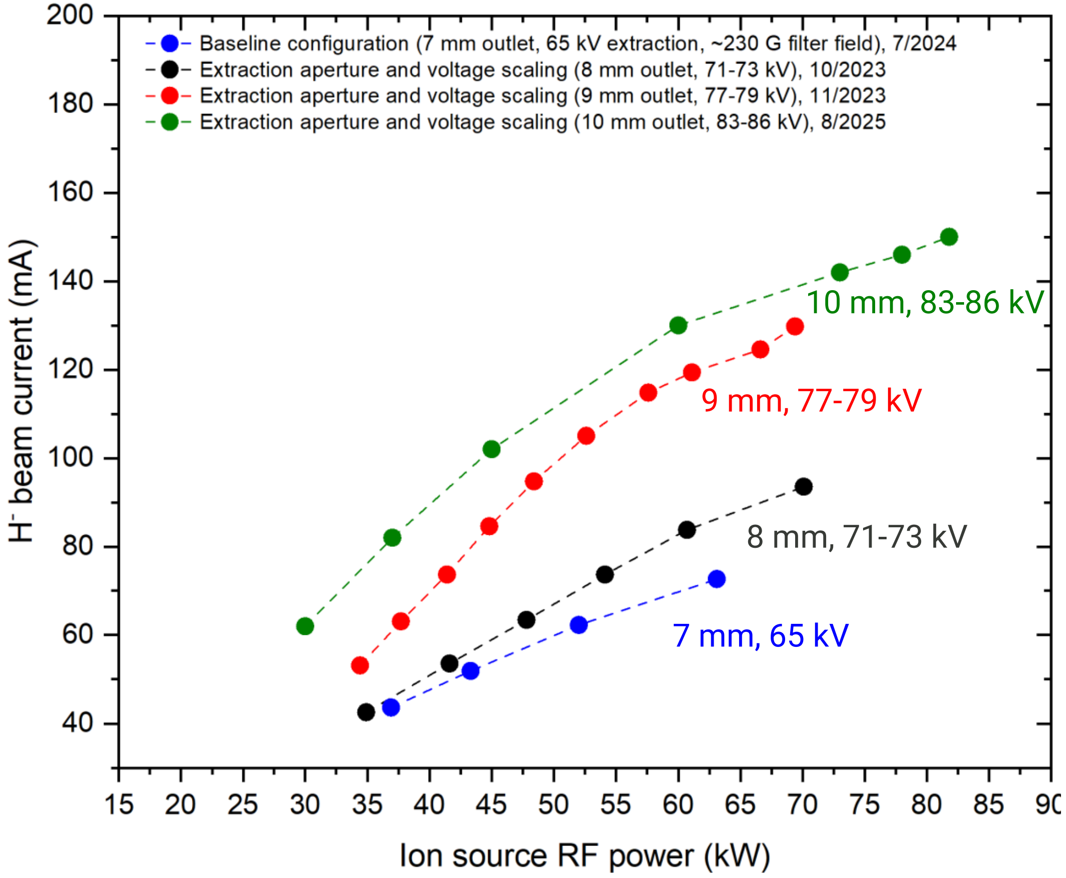


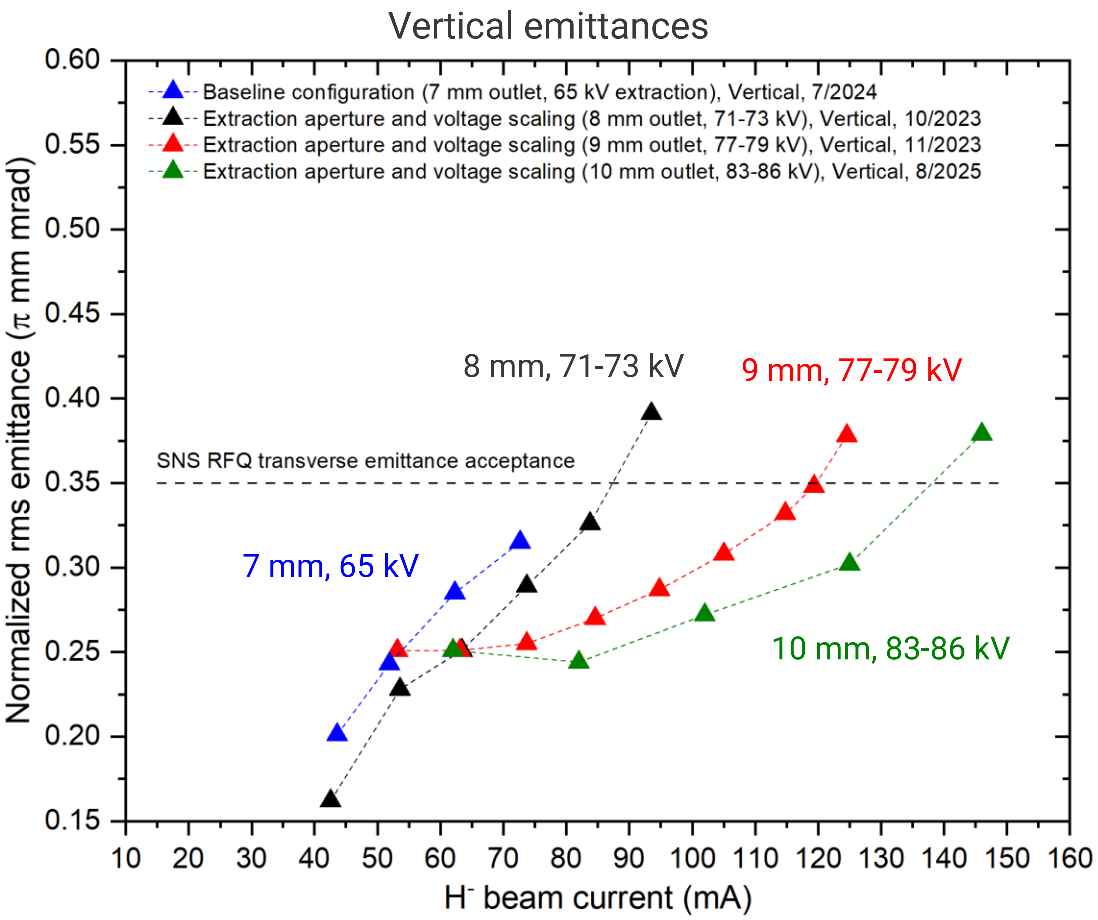
Enhanced RC circuit for the e-dump electrode



Improved cooling for extractor electrode

Ion Source Outlet Aperture and Extraction Voltage Scaling





- Increasing the outlet aperture along with tuned up extraction voltage boosted the beam current vs. RF power while reducing the emittance vs. beam current
- Doubled the beam output capability from ~60 mA to ~120 mA beam at routine operational RF power of 50-60 kW
- >150 mA beam current was demonstrated with a 10 mm outlet aperture source @~80 kW with (68+18) kV extraction
- High voltage arcing becomes serious when the ion source potential beyond 68 kV with our current setup

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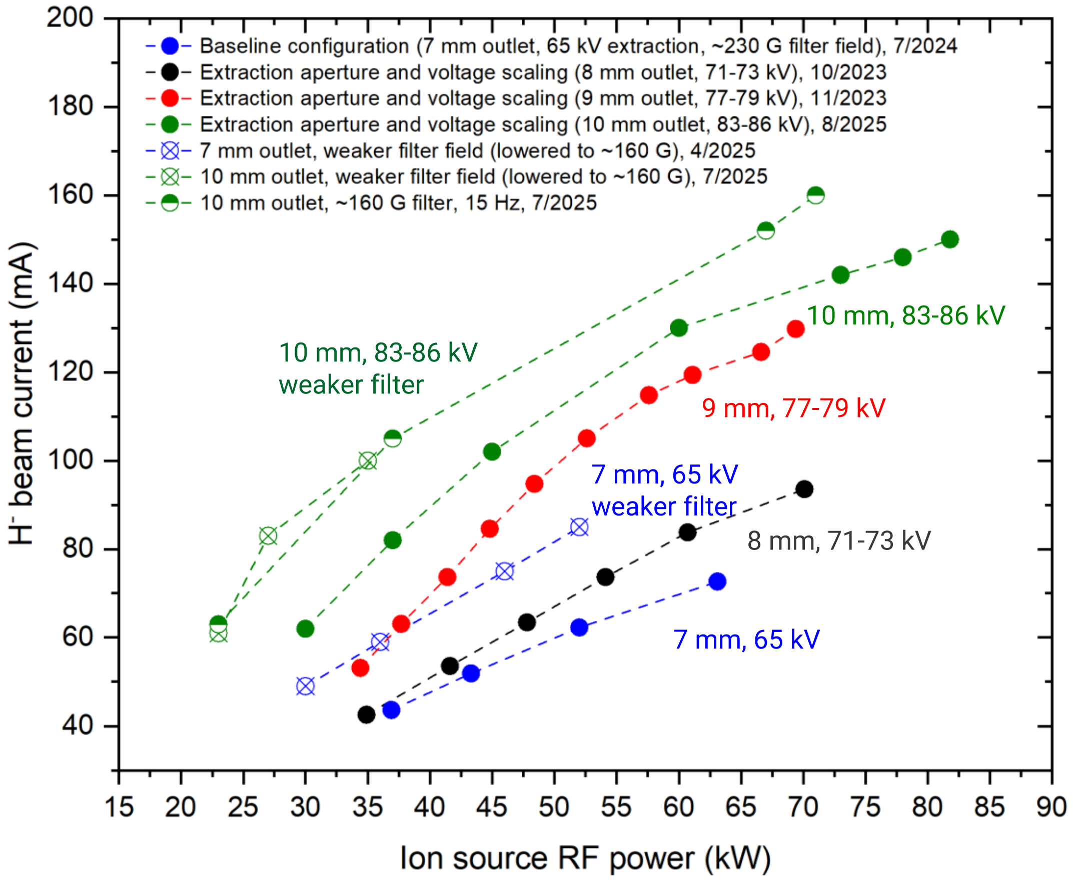
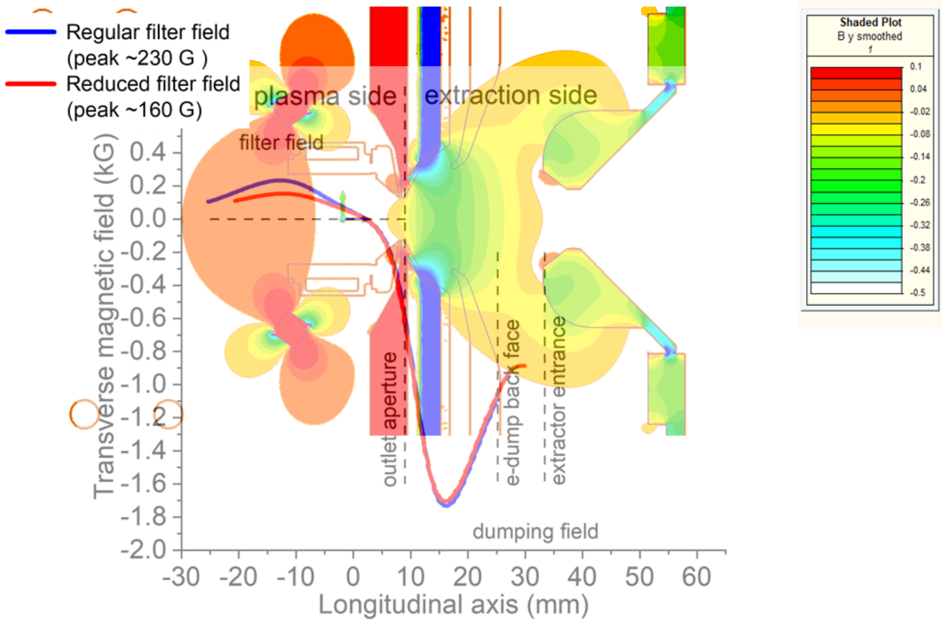
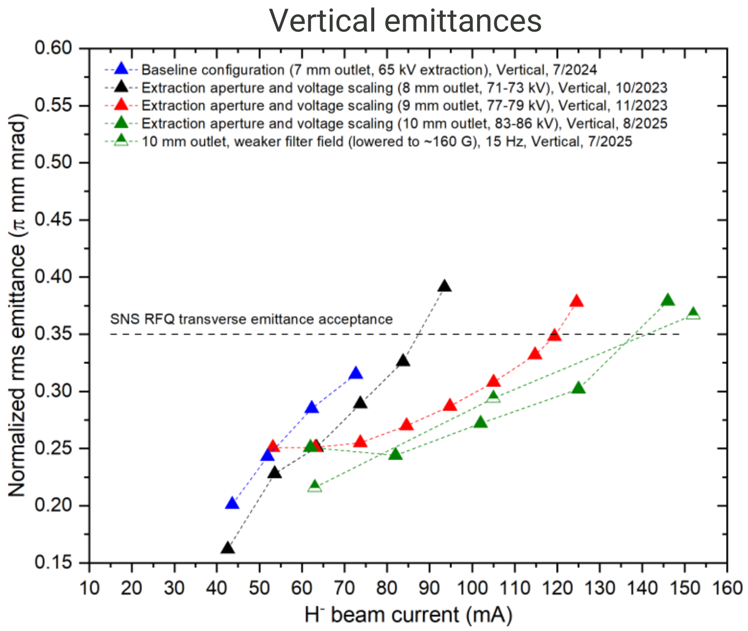
Ion Source Outlet Aperture and Extraction Voltage Scaling, and filter field adjustment (~230 G to ~160 G)



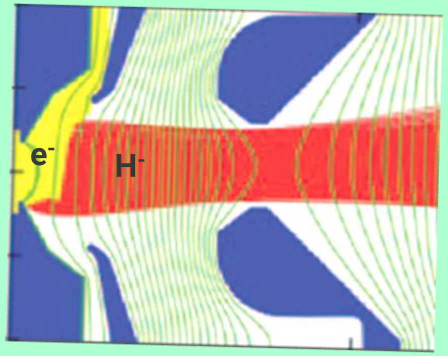




- Reducing the filter field from ~230 G peak to ~160 G peak further enhanced the beam current vs. RF power efficiency
- Due to excessive electron loading, the RF duty-factor had to be tuned down to 15 Hz for power >35 kW for 10 mm aperture source
- Up to 165 mA beam current was demonstrated with a 10 mm outlet aperture source @~70 kW with (68+18) kV extraction

Elevated Co-extracted Electrons Due to Weaker Filter Field

Outlet E-dump Extractor



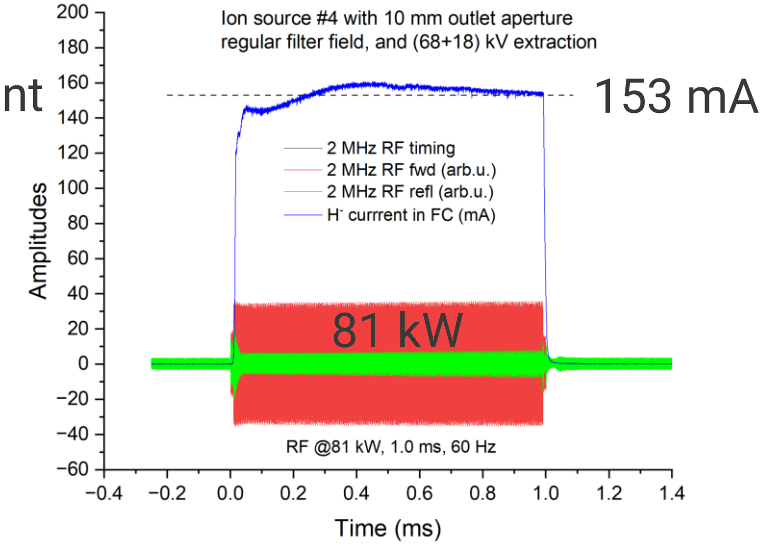
Co-extracted electrons

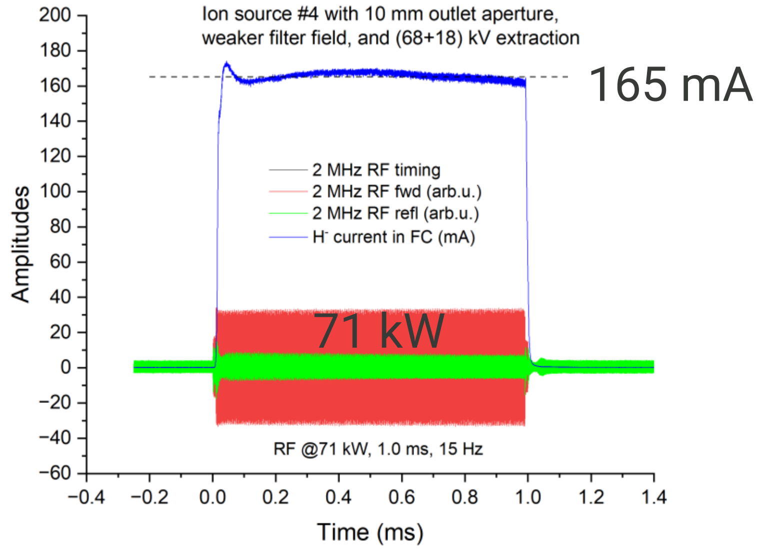
- Recycled to outlet
- Collected at e-dump
- A very small fraction misses e-dump and reaches extractor

Filter field ~230 G

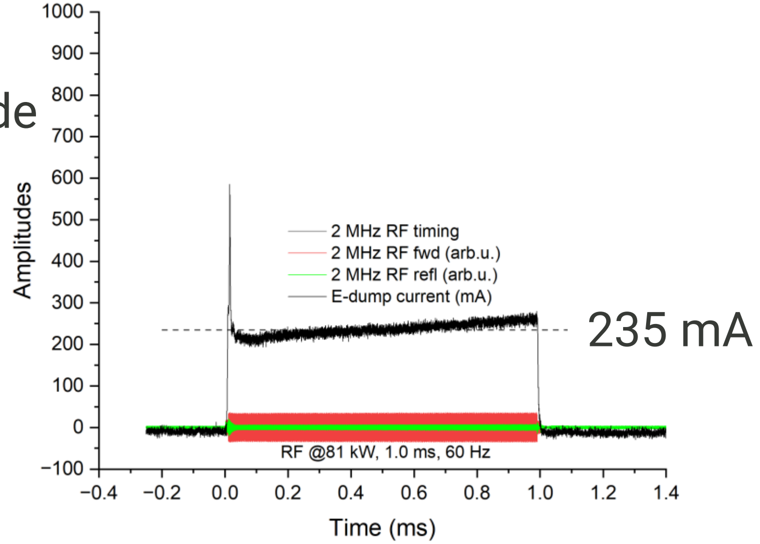
Filter field ~160 G

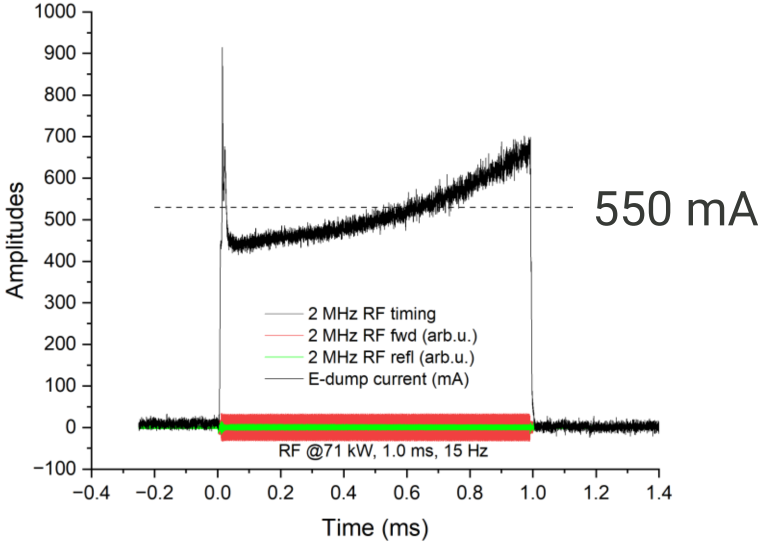
H^- current





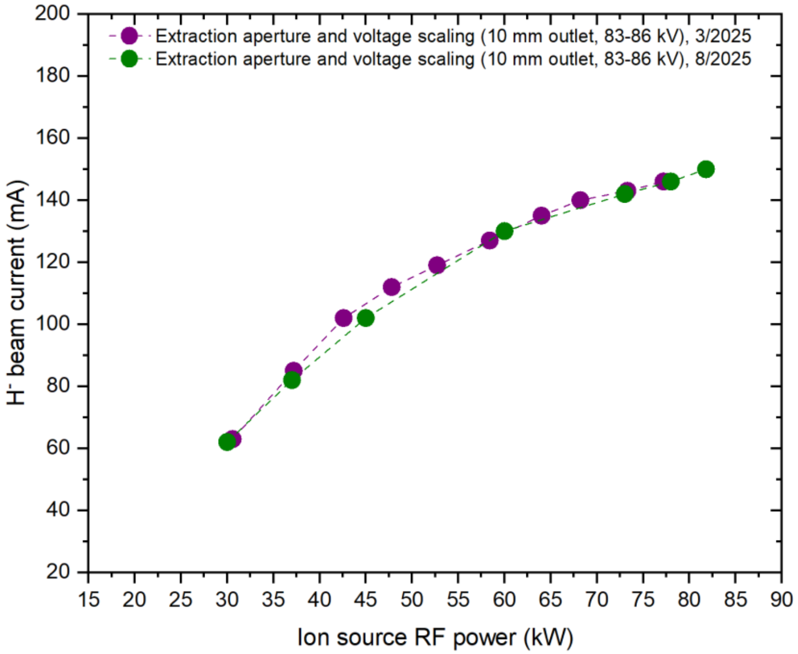
E-dump electrode current



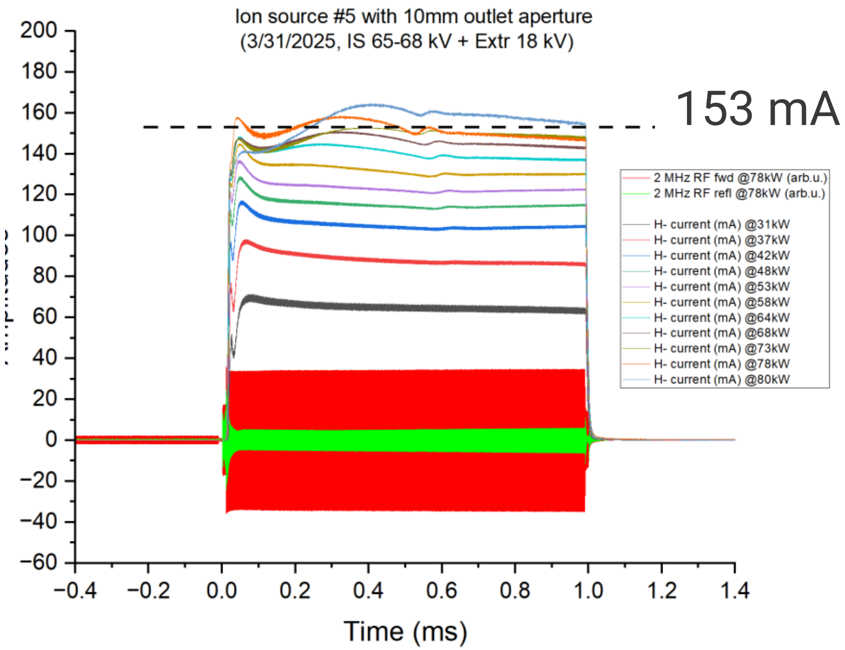


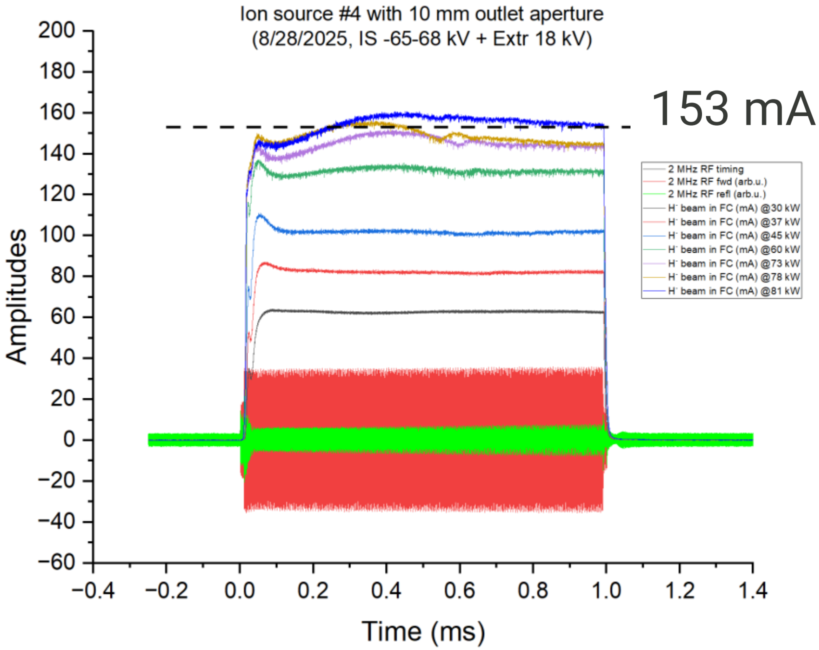
Test Results Repeatability

Performance repeatability, an example with the 10 mm outlet and enhanced extraction



Beam current (averaged over pulse length) vs. RF power in experiments in March and August 2025





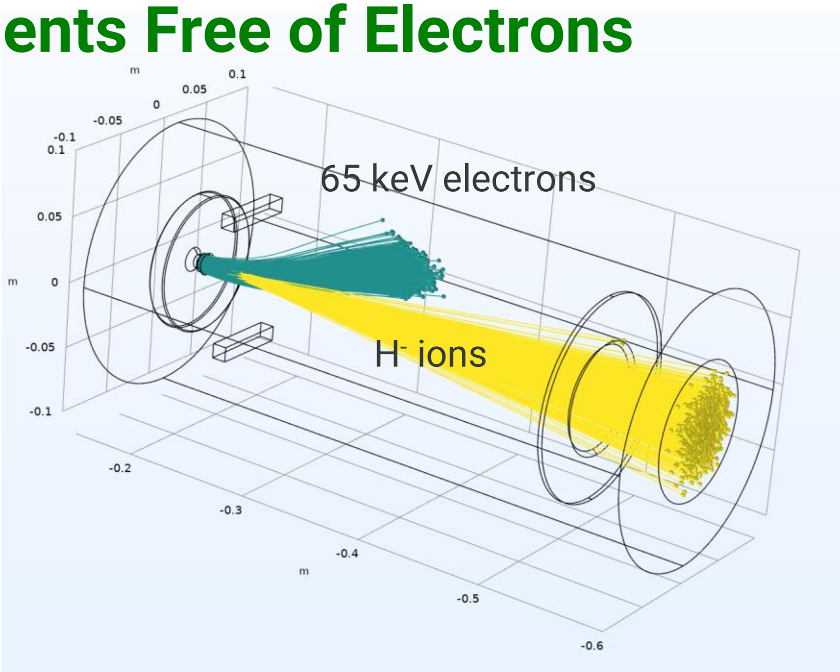
Beam pulse waveforms vs. RF power

In March 2025, source #5

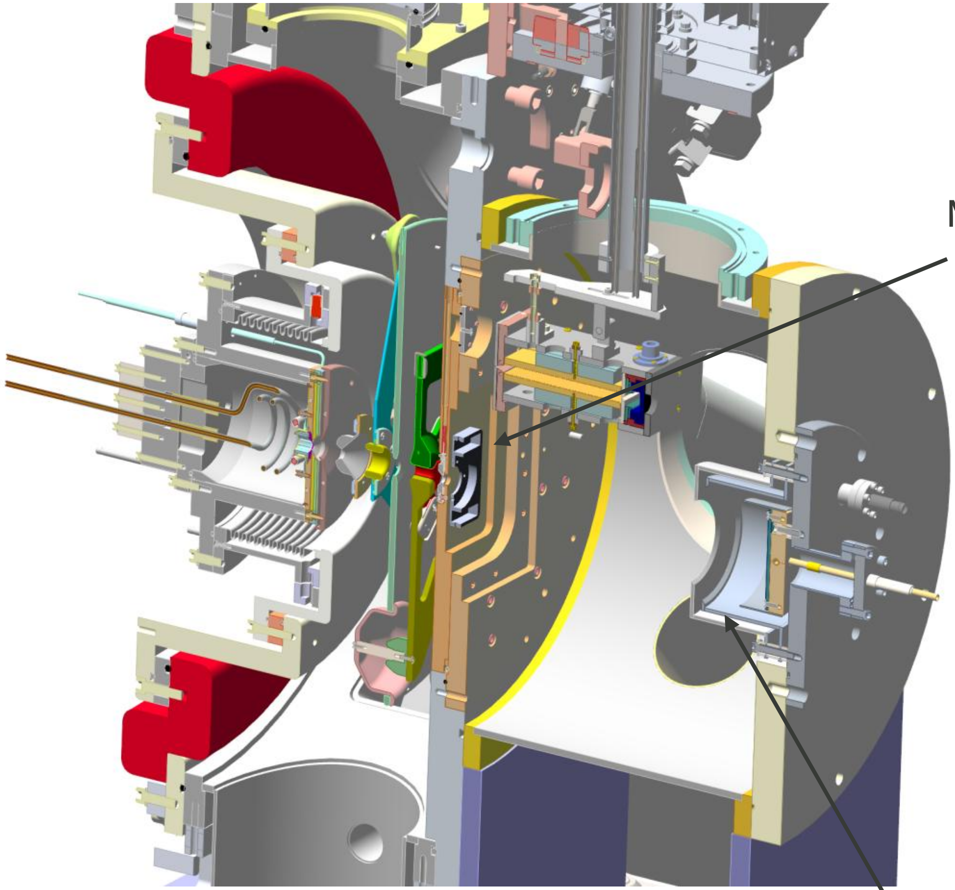
In March 2025, source #4

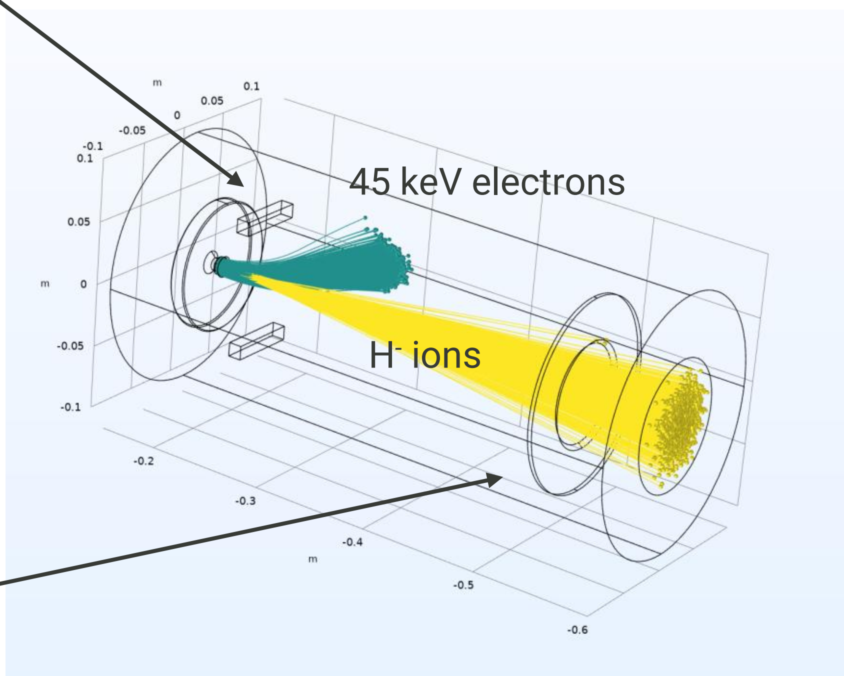
Verifying the ISTS H$^-$ Current Measurements Free of Electrons

- A pair of magnets at the LEBT exit creating transverse field
- Slight deflection of the 65 keV H$^-$ ions entering the FC
- Prevention of potential 45 keV and 65 keV electrons from entering the FC



Magnets location

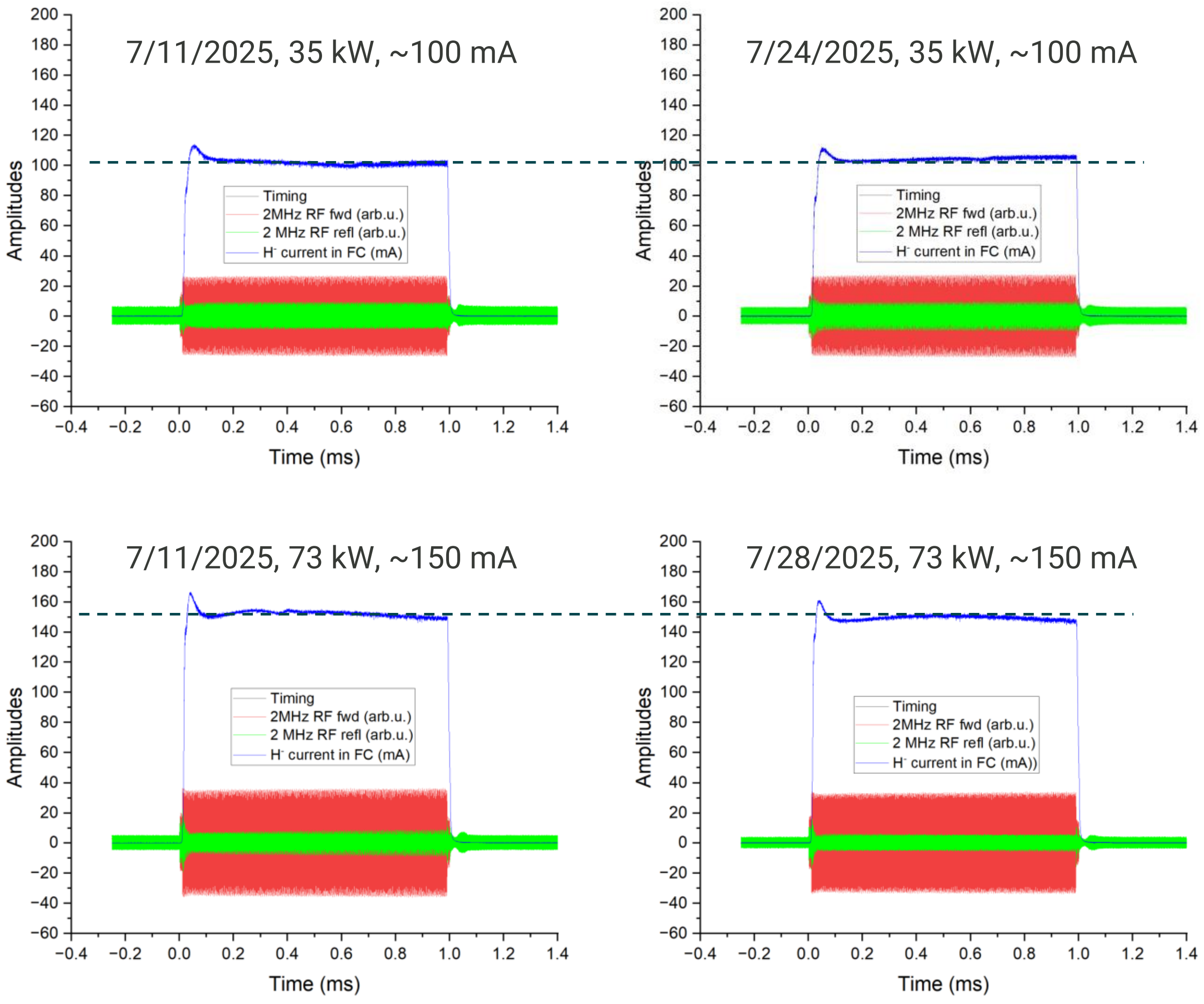


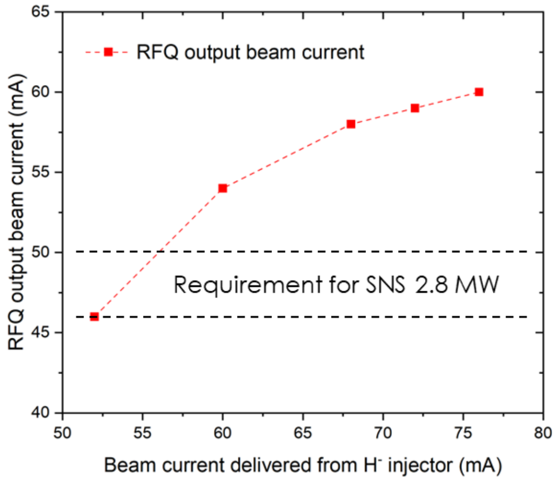


Faraday cup

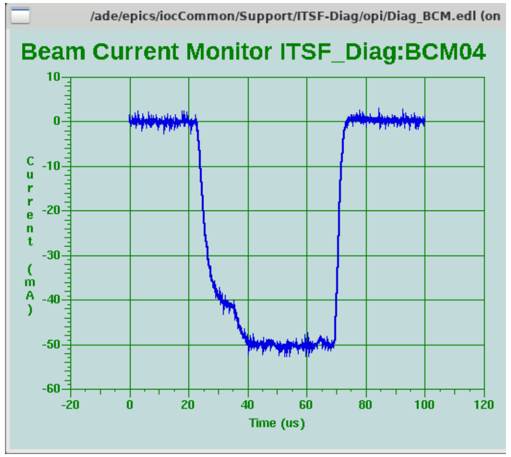
Validation of the ISTS H^- Current Measurements

Before magnets installed | With magnets





SNS Front End new RFQ output vs. input beam currents delivered with a 9 mm outlet aperture enhanced extraction ion source



BTF old RFQ routine output current of 50 mA with ~80 mA input current delivered with a 7 mm outlet aperture, reduced filter field ion source

- No significant difference in measured H^- beam currents on the ISTS before and after installing a pair of electron separation magnets at the LEBT exit.
- Beam test/operation results on the SNS Front End or BTF are in accordance with the respective characterized beam transmission rates of the RFQs.

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Beam Current Frontiers of H^- Ion Sources for Accelerators

List of top 15 by peak beam current*

List	Facility / Source	Type	Peak I (mA)	Comments
1	**SNS test stand (USA)**	RF multicusp	**165** **153**	1 ms, 15 Hz (1.5% DF) 1 ms, 60 Hz (6.0% DF)
2	**BNL magnetron (USA)**	Magnetron	**150**	600–1000 µs, 7 Hz (Zelenski et al.)
2	**BINP / INR (Moscow)**	Penning	**150**	Historical record (Dudnikov et al.)
3	**J-PARC test stand (Japan)**	RF multicusp	**145**	1 ms, 34 Hz (3.4% DF)
5	**LANL scaled Penning (USA)**	Penning	**120**	Test stand
6	**ISIS VESPA (UK)**	Penning	**100**	1.65 ms, 25 Hz (test stand)
7	**Fermilab (USA)**	Magnetron	**~80**	PIP R&D
8	**J-PARC operational (Japan)**	RF multicusp	**72**	Routine ops, 0.6 ms, 25 Hz
9	**SNS operational (USA)**	RF multicusp	**~60**	Routine ops, 1 ms, 60 Hz
10	**ISIS operational (UK)**	Penning	**55–60**	Routine ops, 200–250 µs, 50 Hz
11	**DESY HERA (Germany)**	Magnetron	**~60**	Historical ops
12	**CSNS (China)**	Penning	**50**	Routine ops, 0.5 ms, 25 Hz
13	**D-Pace (commercial, Canada)**	DC multicusp	**Up to 15**	100% (CW)
14	**TRIUMF (Canada, DC)**	Multicusp	**9**	100% (CW)
15	**PSI Injector II (Switzerland)**	DC Penning	**2.2**	100% (CW)

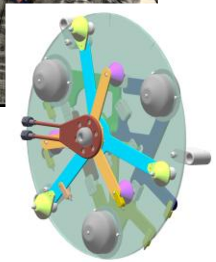
List of top 15 by duty-factor weighted average beam current*

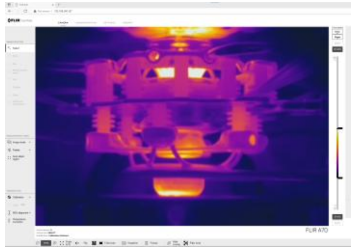
List	Facility / Source	Type	Peak I (mA)	Duty factor	Average I (mA)
1	**D-Pace (commercial, Canada)**	DC multicusp	Up to 15	100% (CW)	**Up to 15**
2	**SNS test stand (USA)**	RF multicusp	153	6.0% (1.0 ms × 60 Hz)	**9.3**
3	**TRIUMF (Canada)**	DC multicusp	9	100% (CW)	**9.0**
4	**J-PARC test stand (Japan)**	RF multicusp	145	3.4% (1.0 ms × 34 Hz)	**4.9**
5	**ISIS VESPA (UK)**	Penning	100	4.125% (1.65 ms × 25 Hz)	**4.1**
6	**SNS operational (USA)**	RF multicusp	~60	6.0% (1.0 ms × 60 Hz)	**3.6**
7	**RAL Penning test (UK)**	Penning	60	5.0% (1.0 ms × 50 Hz)	**3.0**
8	**PSI Injector II (Switzerland)**	DC Penning	2.2	100% (CW)	**2.2**
9	**J-PARC operational (Japan)**	RF multicusp	72	1.5% (0.6 ms × 25 Hz)	**1.1**
10	**BNL magnetron (USA)**	Magnetron	150	0.7% (1.0 ms × 7 Hz)	**1.05**
11	**ISIS operational (UK)**	Penning	55	1.25% (0.25 ms × 50 Hz)	**0.69**
12	**CSNS (China)**	Penning	50	1.25% (0.5 ms × 25 Hz)	**0.63**
13	**LANL scaled Penning (USA)**	Penning	120	*(not published)*	***(n/a)***
14	**BINP / INR (Moscow)**	Penning (historical)	150	*(not published)*	***(n/a)***
15	**DESY HERA (Germany)**	Magnetron	~60	*(not published)*	***(n/a)***

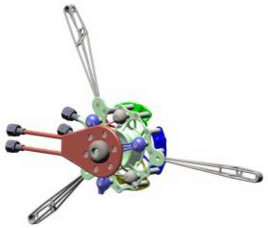
* These listings are compiled and organized solely based on online information.

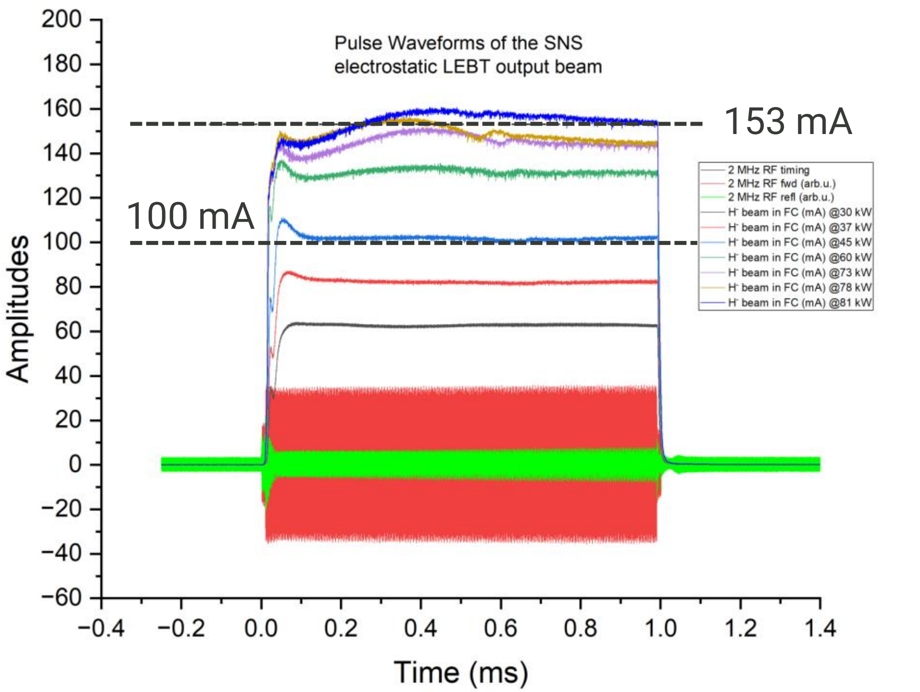
Progress with LEBT – Improvements to Electrostatic LEBT

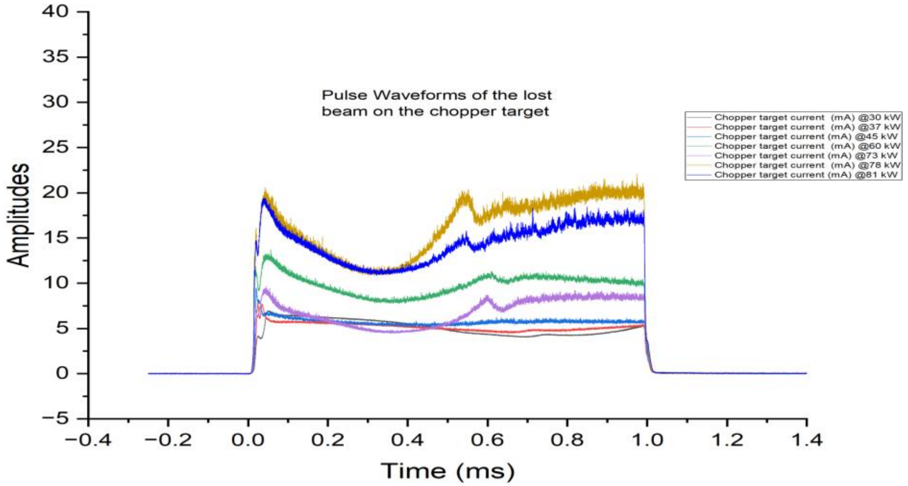
- The present electrostatic LEBT experiences beam pulse distortion and significant beam loss on the LEBT exit aperture (also known as the chopper target or the RFQ entrance aperture) at a beam current greater than ~100 mA.
- Optimization of aperture sizes and distances for the LEBT elements continues.
- An ultra compact realization of the existing electrostatic LEBT is tested for beam dynamics and operational robustness.
  - Lightweight, easier to assemble and install
  - Improved cooling for the assembly structure
  - Entire LEBT are observable with a thermal camera
  - Cost effective for experimenting and optimization





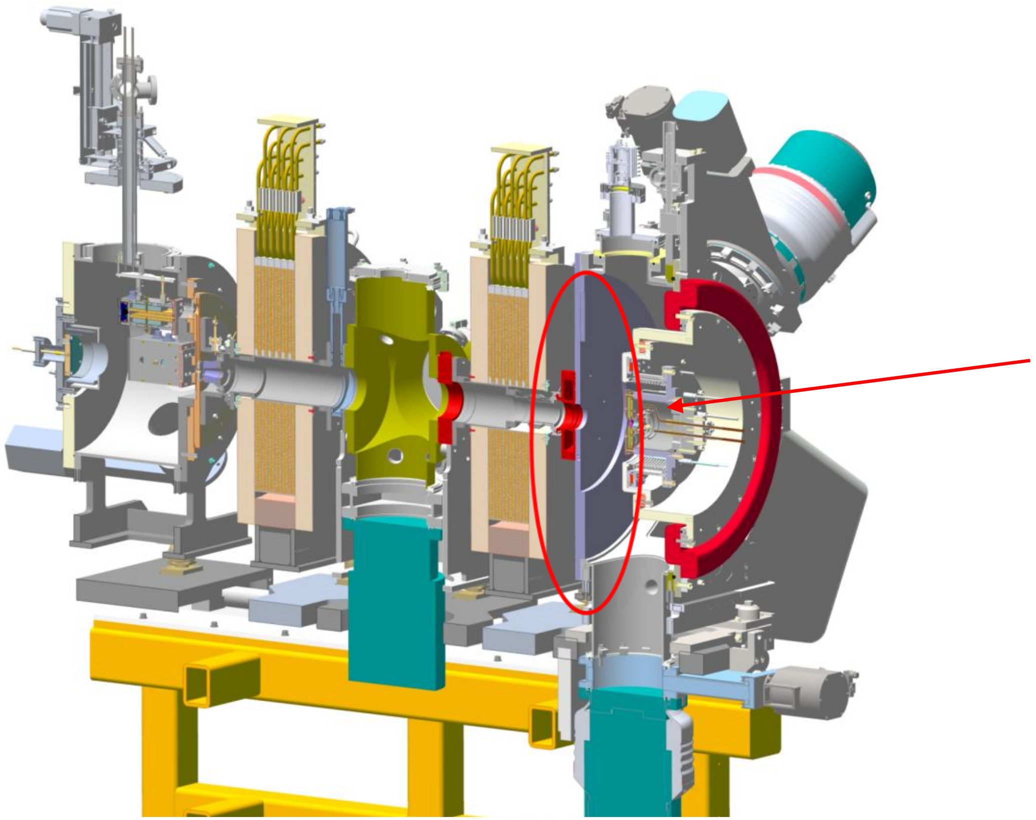


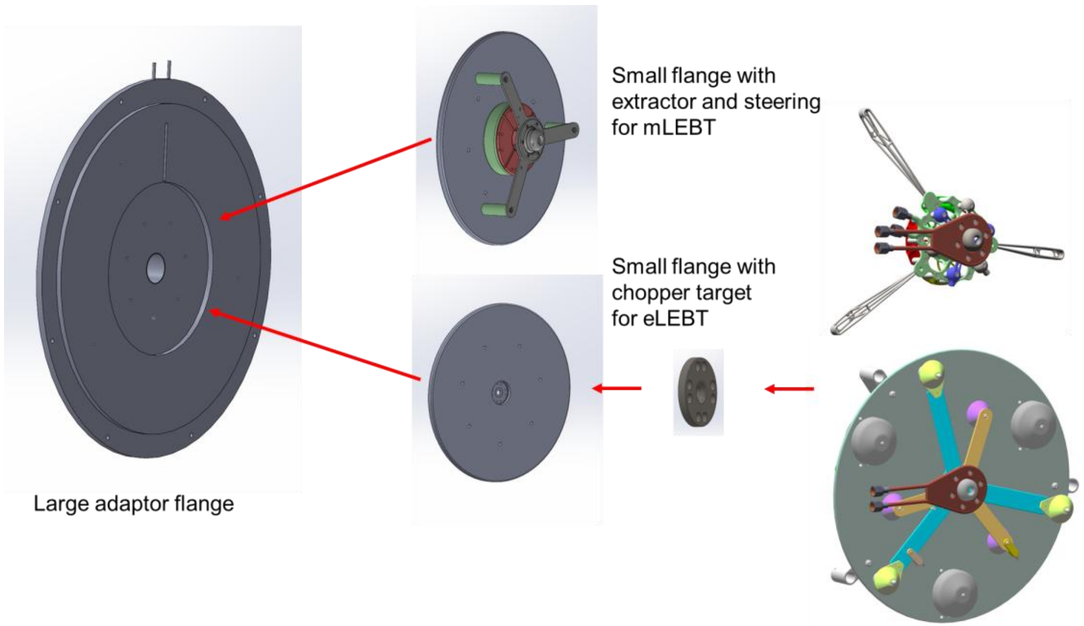




Progress with LEBT - 2-Solenoid Magnetic LEBT

- ISTS upgrade to include magnetic LEBT testing capability
- Switchable e/m dual-LEBT functionalities





- Operationally robust compared to arcing risks with eLEBT
- Capable for high current beams H^+ or H^- >100 mA
- Convenient beam diagnostics implementation
- Potential chopping and blanking within the LEBT away from the RFQ entrance

- A large adapter flange and two removable smaller flanges for switchable eLEBT or mLEBT
- An in-vacuum fast BCM for characterizing eLEBT output beam or mLEBT input beam

Summary and Outlook

- The SNS H^- injector supports the accelerator system power ramp-up towards the Proton Power Upgrade goal of 2.8 MW with 50-60 mA, 1.0 ms, 60 Hz beam with high availability (>99.5%).
- Recent progress has doubled the ion source output capability from ~60 mA to ~120 mA at a reliable routine operational RF power range 50-60 kW.
- >150 mA beam current at the SNS operational duty-factor of 6%, and up to 165 mA beam with 1.0 ms pulse length at 15 Hz were demonstrated.
- Outlook:
    - Optimize the ion source filter field and Cs system (dispenser and ion converter) for further improving the ion source power efficiency
    - Continue to improve the electrostatic LEBT for low distortion beam transport for higher beam current >100 mA
    - Test magnetic LEBT as an alternative H^- injector for very high currents

Thank you for your attention!