H^- Ion Source Research and Development at the Oak Ridge National Laboratory

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The 7th International Symposium on Negative Ions, Beams and Sources

- The Spallation Neutron Source (SNS)
- A brief history of ion source development at the SNS and our current goals
- Experimental resources for ion source testing
- A snapshot of ongoing experimental R&D efforts

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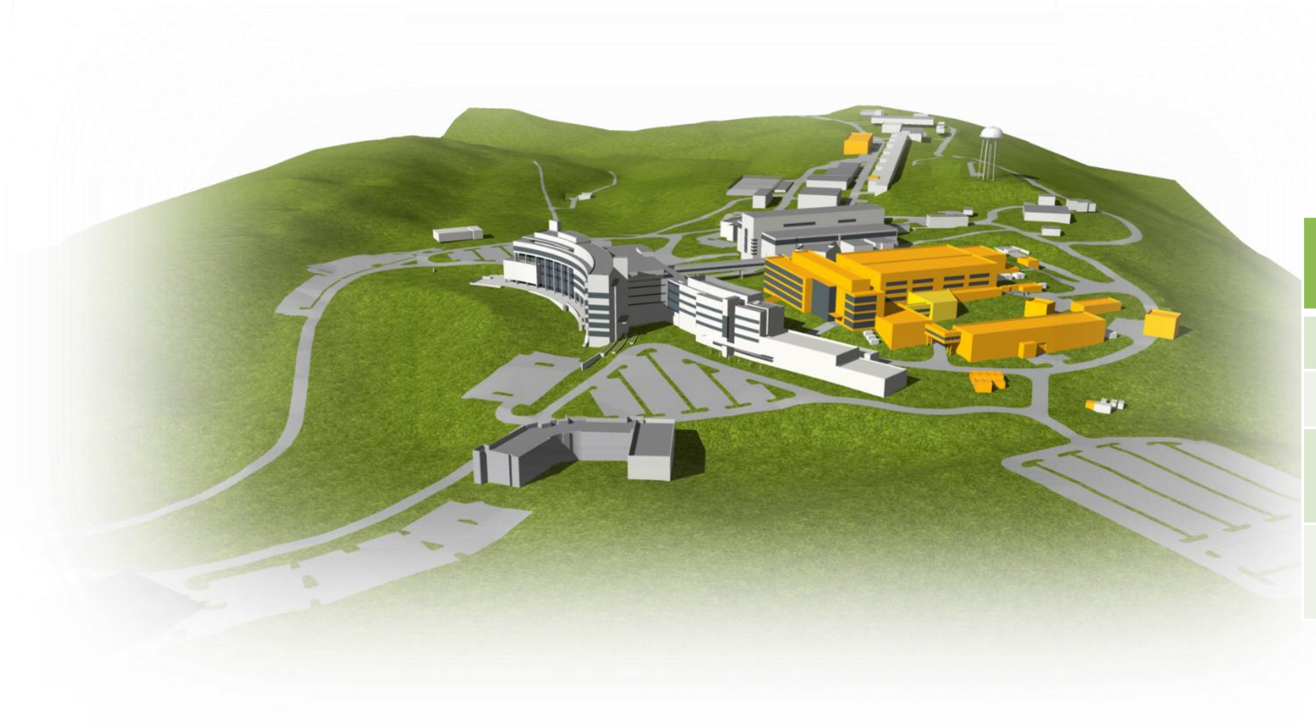
The Spallation Neutron Source

ORNL hosts the worlds most powerful accelerator-based neutron source. More than 1000 users per year conduct experiments in physics, chemistry, biology, material science and engineering.



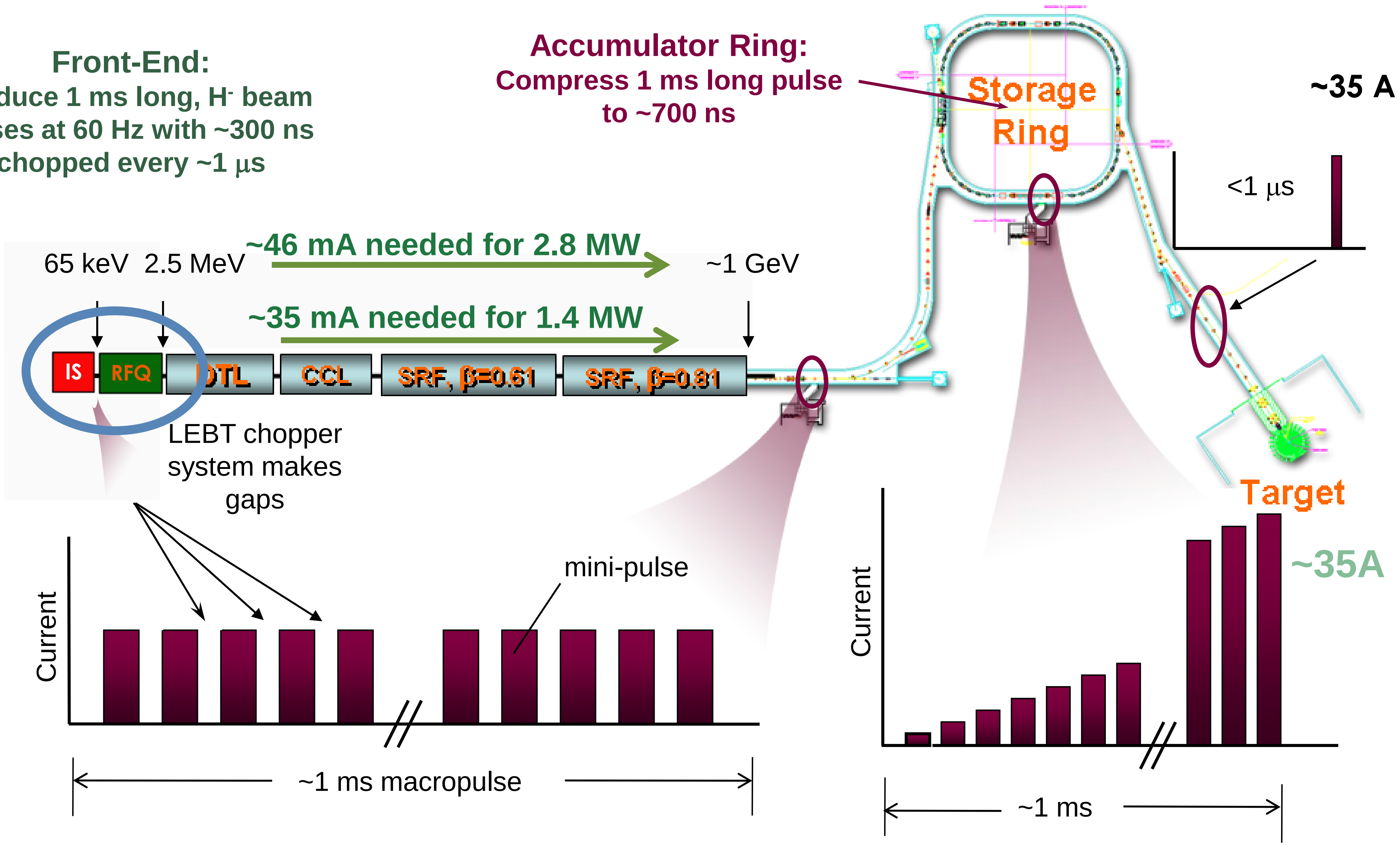
Currently the SNS operates near 1.4 MW with future plans to run at 2.8 MW to support a second target station.

	1.4 MW Operation	PPU & STS Upgrade
Energy (GeV)	1.0	1.3
Beam duty factor	6%	6%
Ion source output beam current (mA)	~45	~60
RFQ output beam current (mA)	~35	~46

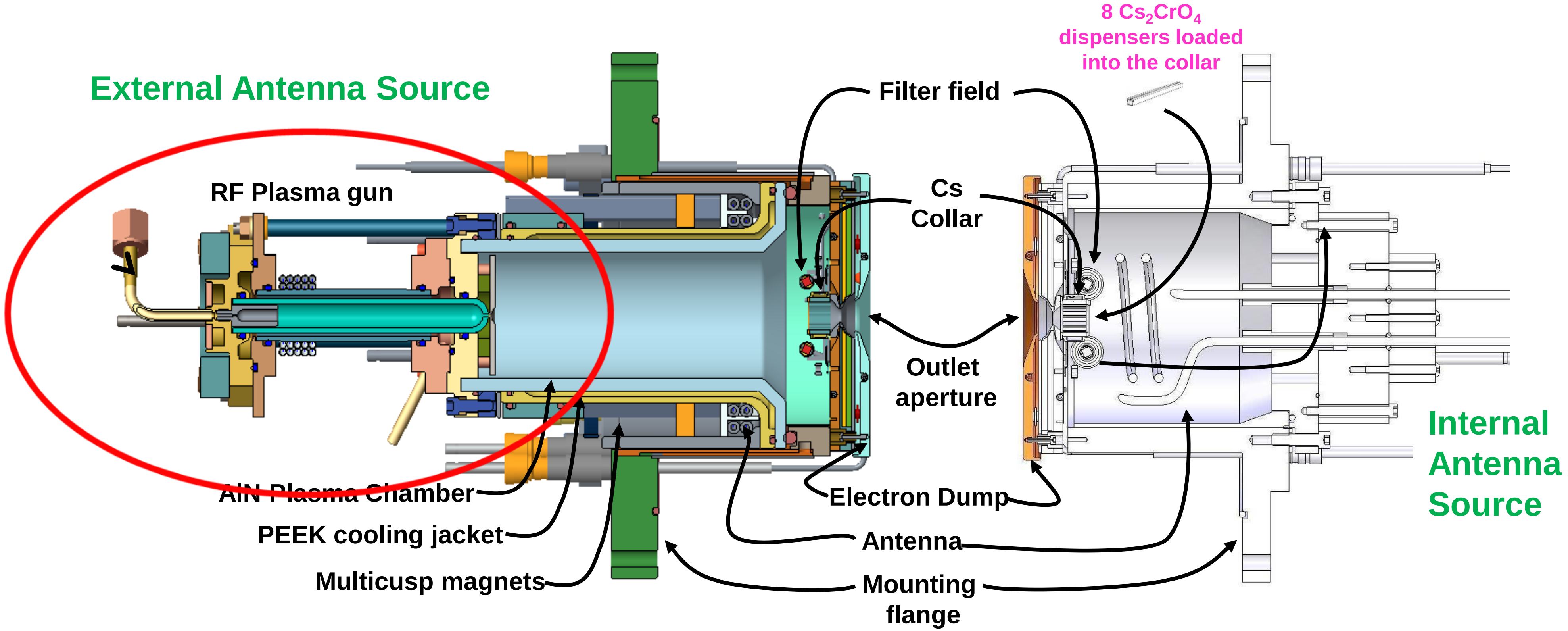
The SNS Accelerator System Overview

Front-End:
Produce 1 ms long, H$^-$ beam pulses at 60 Hz with ~300 ns chopped every ~1 μs

Accumulator Ring:
Compress 1 ms long pulse to ~700 ns



The SNS Ion Sources



- **Internal antenna source** – Delivers 50-60 mA through the Low Energy Beam Transport (LEBT). The workhorse of the SNS accelerator (#**2**,3,**4**,5,**6**,7), originally designed and built at LBNL and developed at ORNL. It uses a difficult-to-fabricate internal antenna.

- **External antenna source** – Also delivers 50-60 mA through the LEBT. The workhorse of the BTF and alternative source for the SNS (x2, x3, x4). We continue to refine assembly and operating procedures. It requires a plasma ignition gun which is still under development.

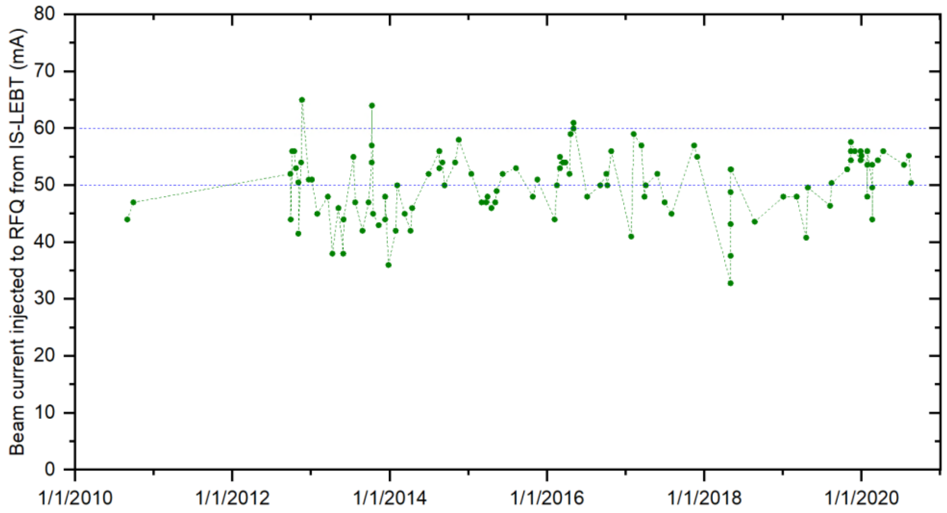
Brief History of Ion Source R&D at the SNS

Key research and development accomplishments of the SNS ion source group

- Increased **average beam current** from the RFQ by more than an order of magnitude since the beginning of the SNS.

  ~20mA at <1% duty-factor, 2 weeks → ~35mA at 6%, 4 months, >99.5% reliability
- Redesigned the SNS **internal antenna** and developed a highly optimized coating and selection process with Cherokee Porcelain essentially eliminating frequent antenna failures
- Redesigned the **mechanical structure** of the operational **LEBT** greatly improving reliability
- Designed, built and currently testing an **external antenna ion source** which has demonstrated several >100 days runs on the BTF
- Implemented significant upgrades to the SNS front end ion source systems in 2018 and moved RF generators to ground
- Developed a LEBT beam current measurement technique allowing RFQ transmission measurement
- Designed, developed, and deployed all ion source infrastructure for the Beam Test Facility (BTF)
- Today the SNS ion source delivers ~**9 A·hours per run** - significantly more than other comparable H^- facilities (**ICIS Brightness award in 2017)**

Current Ion Source R&D Goals



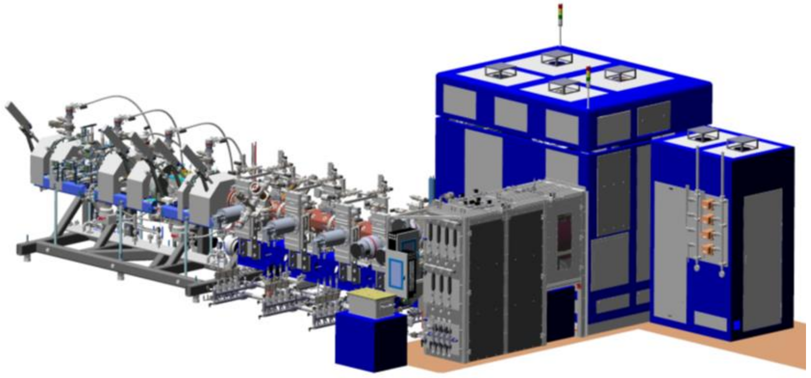
- **Support 1.4 MW SNS operations at ~35 mA from RFQ**
  - Continuous improvements to the source, LEBT and infrastructure
  - Refine cesiation and startup processes
  - Mitigate e-dump voltage decay
  - Refine Cs collar and filter field structures
  - Increase operational margin during times of degraded RFQ performance
- **Support 2.8 MW SNS operations at ~46mA from RFQ**

  (Requires LEBT beam current near the upper limit of its historical operating range and a healthy RFQ)
  - Continuous improvements to the internal and external antenna sources, LEBT and infrastructure
  - Modelling and eventual testing of a J-Parc-type extraction system
  - Conduct sustained high beam current tests at our test facilities
- **Fully develop the external antenna source**

  (Alternative SNS ion source – eliminates the risk of the internal antennas which are fabricated by a single vender using a proprietary process)
  - Equal or better reliability and performance than the internal antenna source
  - Success depends critically on developing reliable plasma ignition
- **Continue to contribute to the H$^-$ ion source intensity frontier**
  - Collaborations with other laboratories – LANL, ISIS, ESS, CERN, J-Parc, etc.
  - Modelling of source extraction and LEBT transport at high intensity

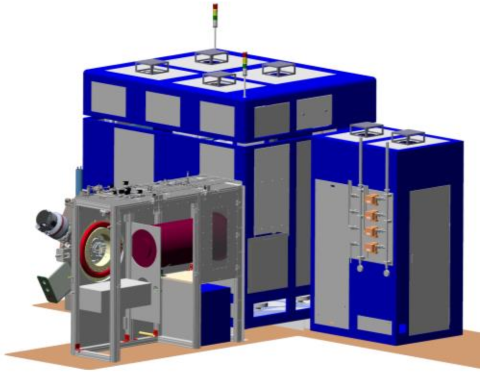
Ion Source Testing Resources at the SNS

- All ion sources can be used interchangeably between the 3 facilities



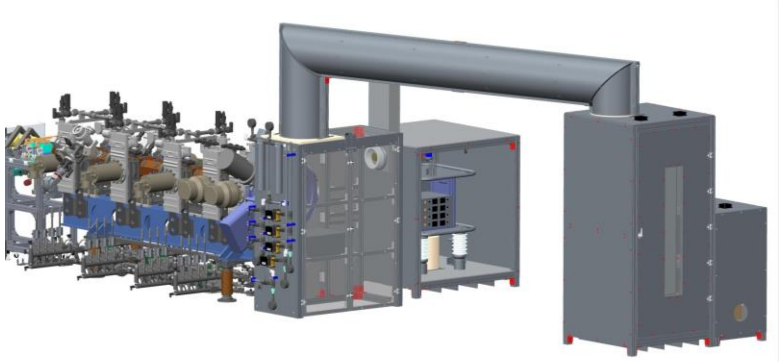
- Ion source
- LEBT
- RFQ
- Diag. in MEBT (beam current and emittance)

The SNS Front End System



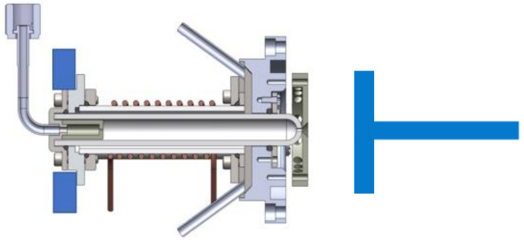
- Ion source
- LEBT
- BCM, FC, emittance

The Ion Source Test Stand (ISTS)



- Ion source
- LEBT
- RFQ
- Diag. in MEBT
- (beam current and emittance)

The Beam Test Facility (BTF)



- Plasma gun
- Electron collector

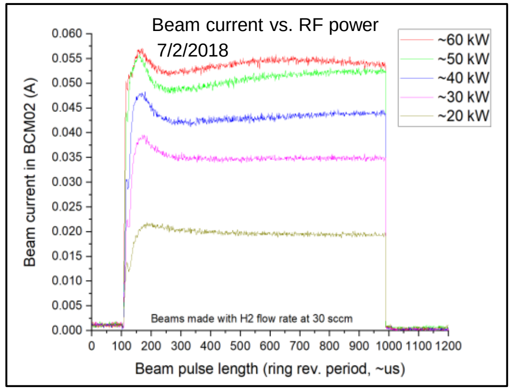
The Plasma Gun Test Bench

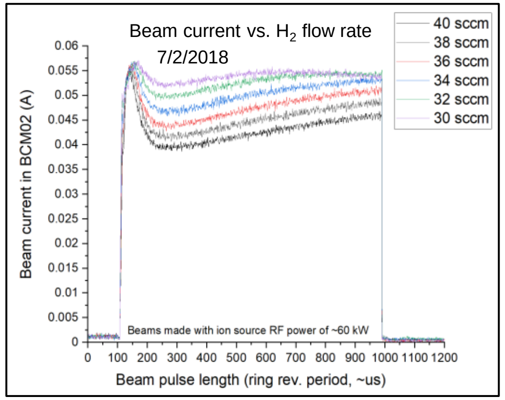
Robert Welton NIBS Sept 4, 2020

Current R&D Conducted on the SNS Front End

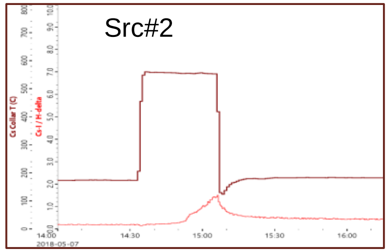
- During maintenance periods the SNS front end can be operated using a MEBT beam stop
- This allows source parametric source, LEBT and RFQ studies

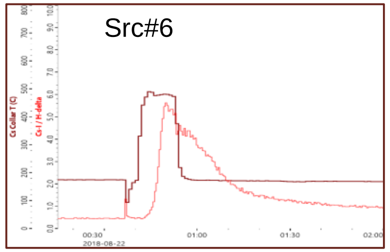
Beam current and pulse shape characterization

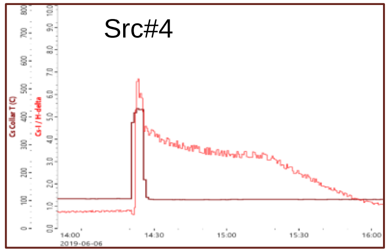




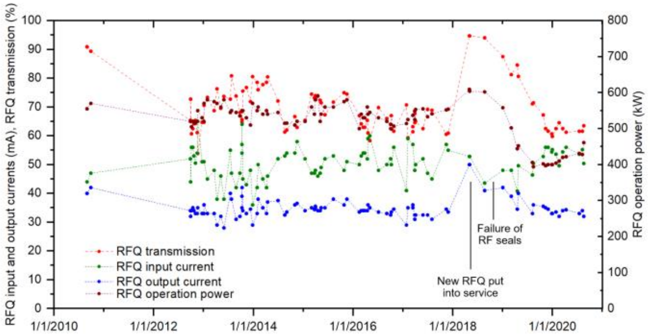
Effort of optimization and standardizing cesiation process

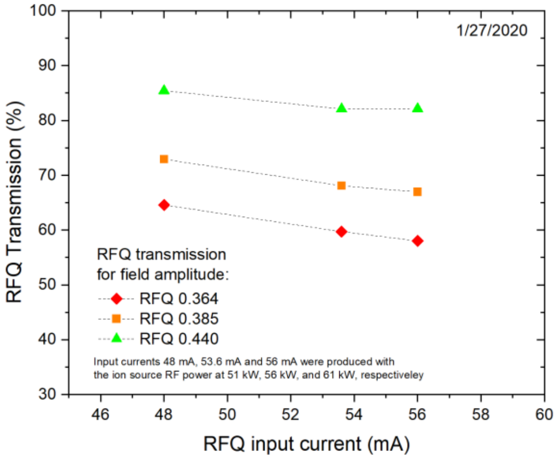






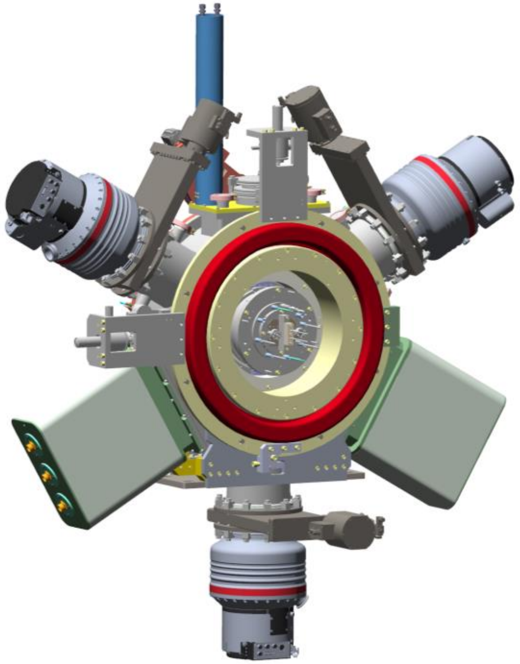
Characterization of RFQ transmission



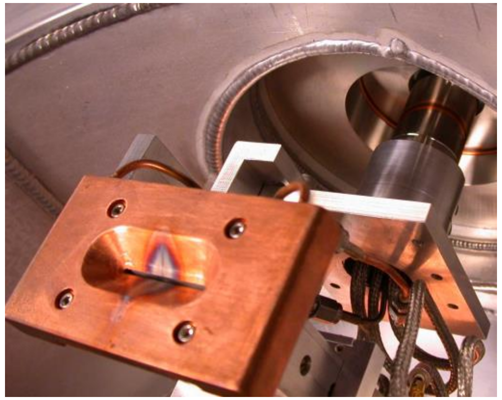


See B. Han, next talk

R&D Conducted on the Ion Source Test Stand

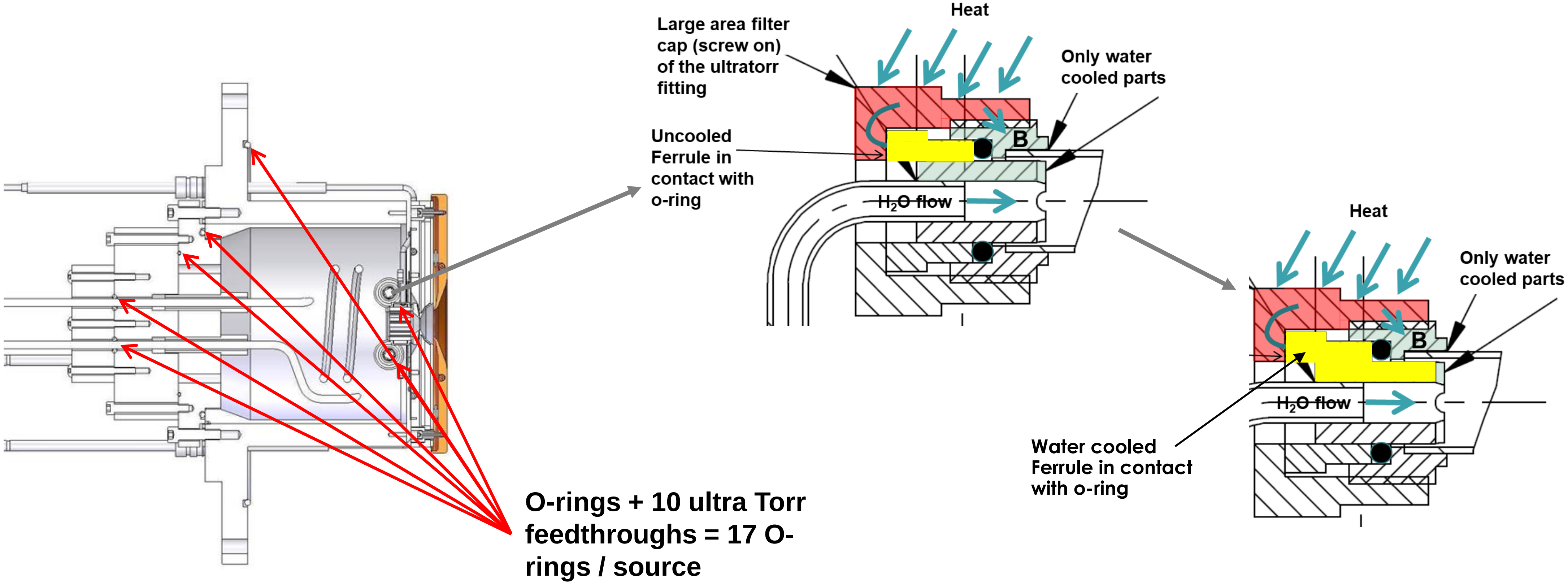


- Purpose of the ISTS
  - Measuring ion source / LEBT beam currents and emittance (no RFQ)
  - Validate newly fabricated spare source components
  - Initial testing platform for ion source and LEBT systems upgrades
  - Ready source of functional spare parts for the SNS front end
- Current studies
  - Validation of new outlet apertures and external antenna source bodies
  - Explore o-ring heating issues
  - Detailed emittance studies for each source needed for better accelerator simulations



O-ring Temperature Measurements on Test Stand

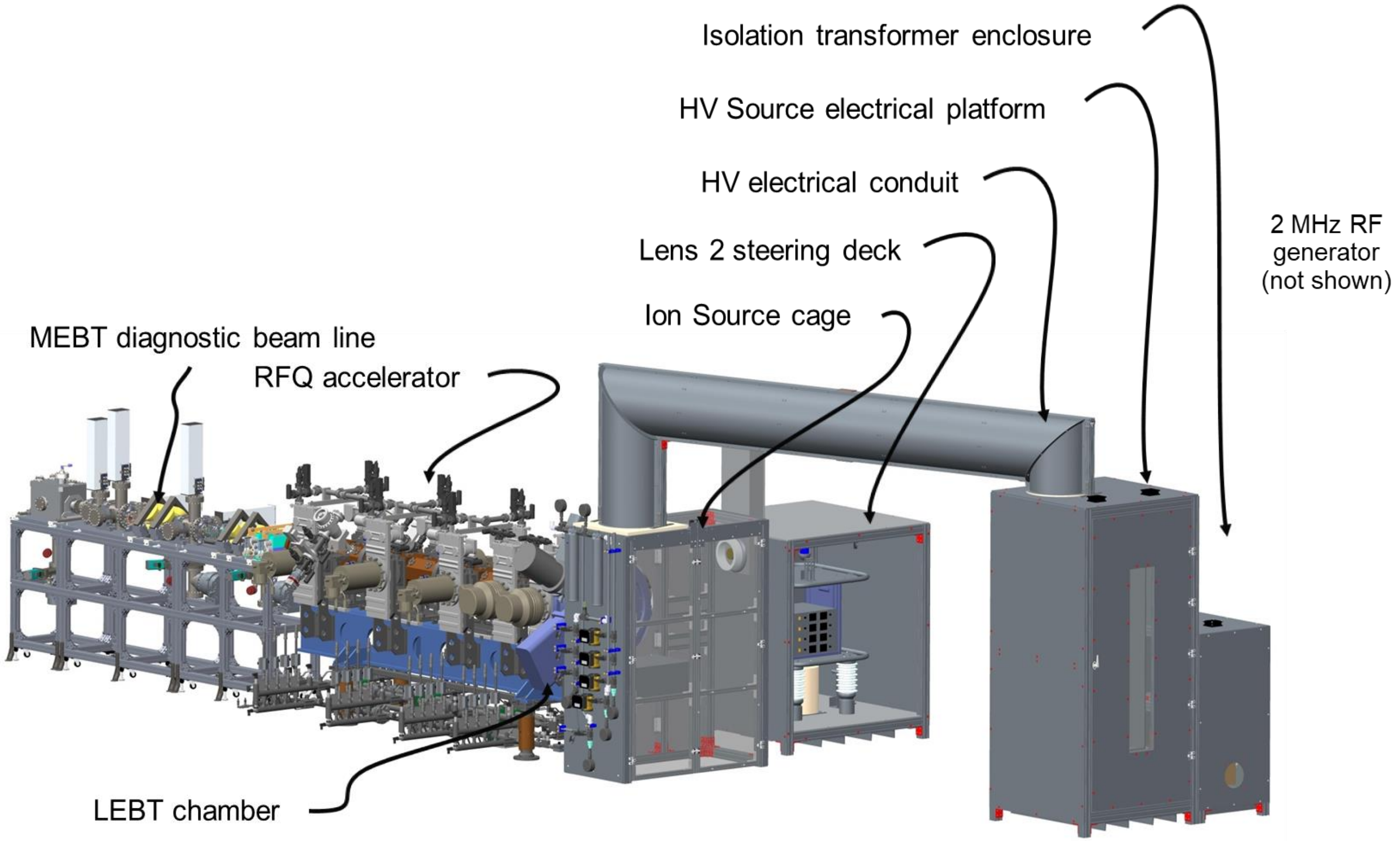
- O-rings in our source are an obvious non-UHV component which could outgas and release contaminates into the system if the operating temperatures are exceeded.
- Test stand studies using thermocouples found that the filter field o-ring could be heated to 220C which is outside its designed operating range.
- We designed and are testing a water-cooled ferrule



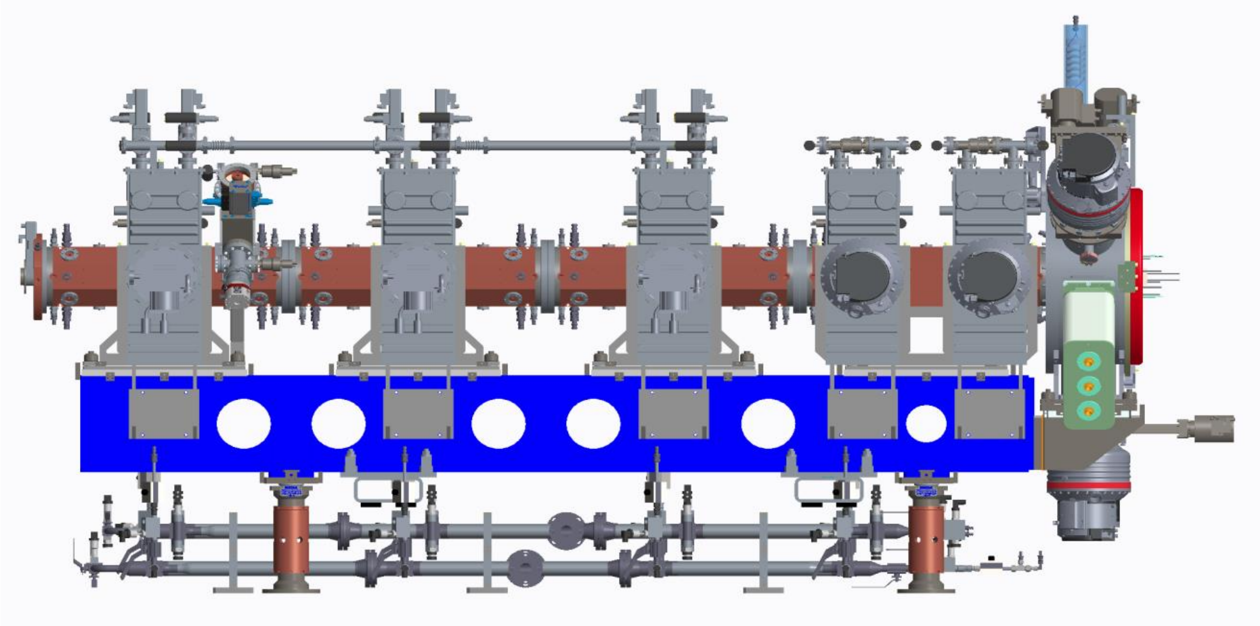
O-rings + 10 ultra Torr feedthroughs = 17 O-rings / source

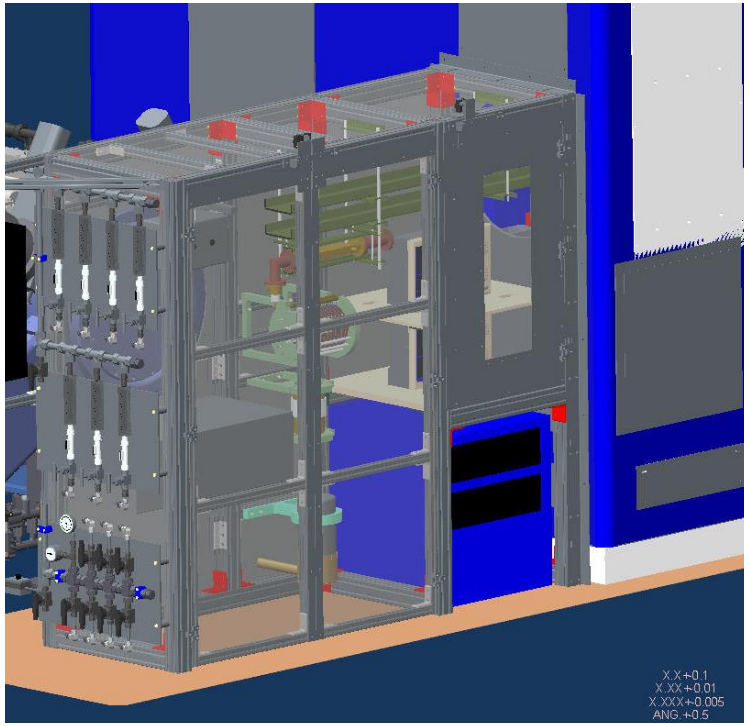
Ion Source R&D Conducted on the Beam Test Facility

- The BTF is a stand-alone research 2.5 MeV accelerator used to validate new RFQs and conduct beam physics and ion source research.
- The facility has been used to test infrastructure upgrades to the ion source systems of the SNS.
- Latest versions of the external antenna source are currently being tested in long beam production runs.



The BTF and ISTS were used to Develop the Components for the 2018 SNS 2.5 MeV Injector

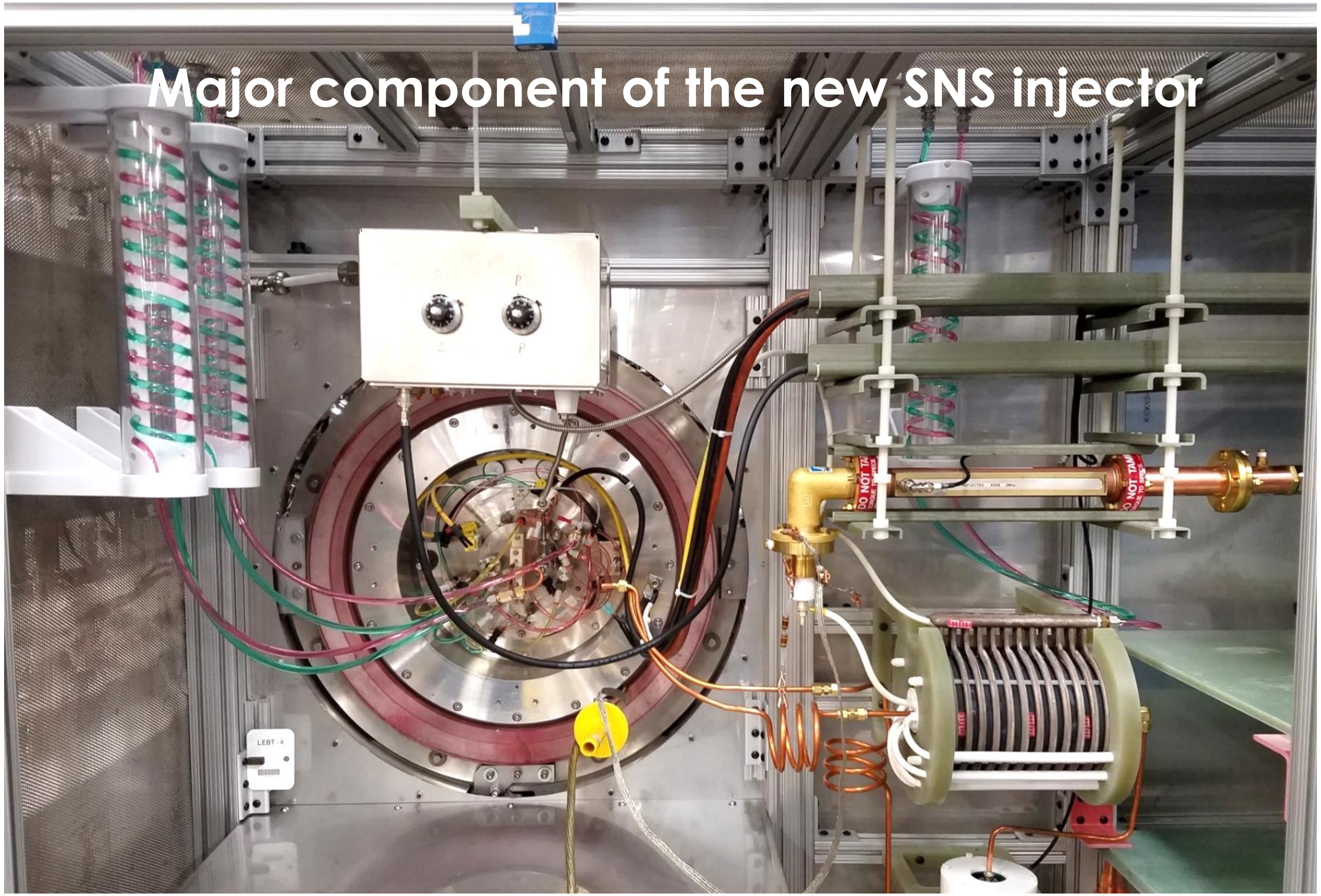




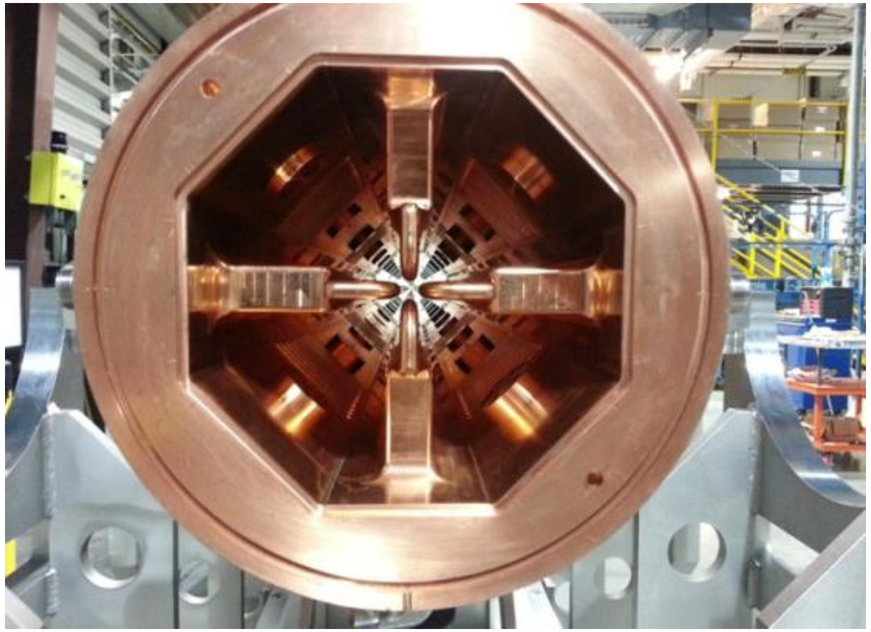
- New on-ground H_2 gas system
- New open architecture 2 MHz matching network
- New serviceable chopper target
- New ultra-thin LEBT/RFQ gate valve
- New larger-clearance HV enclosure

The New 2.5 MeV SNS Injector

- Greatly improved routing of HV source cables and water lines
- Increased all HV gaps to > 15 cm
- Uses helical HV water breaks (long path length, compact form factor)
- Integrated, open geometry, 2 MHz matching network
- On-ground H_2 gas system installed, feeding the source through a 12 cm ceramic break.
- New serviceable chopper target installed


Major component of the new SNS injector

In 2018 the New SNS 2.5 MeV SNS Injector was Installed !



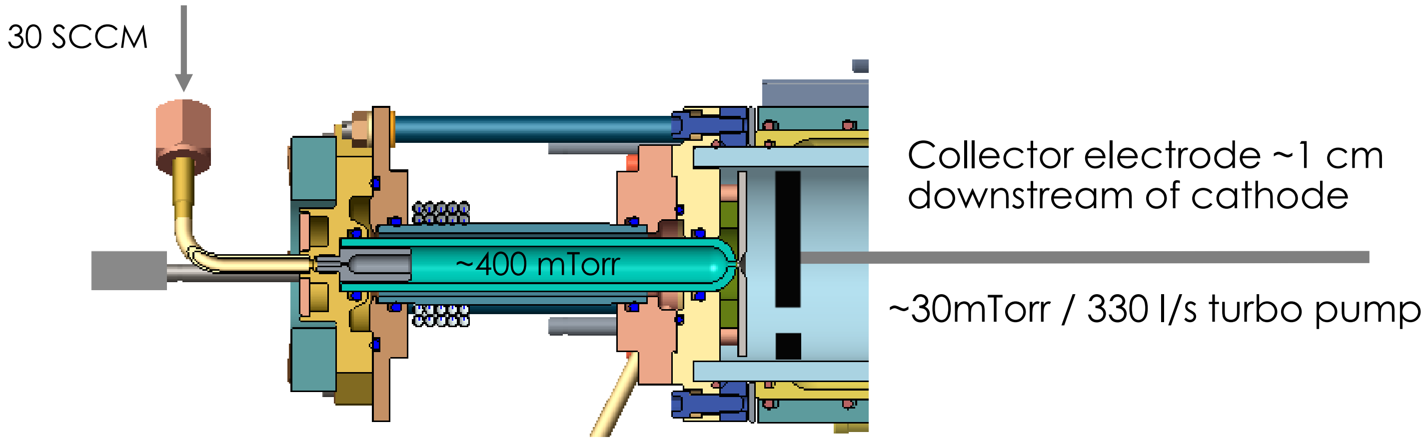
- New injector immediately increased the available SNS beam current by ~20% due to improved RFQ transmission. Beam current is presently limited by RFQ end wall issues – being resolved
- External spark rate has dramatically decreased – less beam interruptions
- Easy on ground bottle exchange is now possible
- RFQ now remains under vacuum during source changes
- Chopper target can now be replaced with the LEBT electrode if needed
- Overall ion source / LEBT availability remains >99.5%
- All installed ion source upgrades have performed very well during operations since the 2018 SNS installation.

Summary of External Antenna Ion Sources Tested on the BTF

Source	RFQ	installed	removed	Days tested	RF set point	LEBT beam current	MEBT beam current	Issues
x3	RI	Nov 28, 2016	Dec 9, 2016	~11 days	~36 kW ~35 kW ~43 kW		~40 mA ~44 mA ~50 mA	5D measurements no explicit Cesiation!, source removed to test production source
x4	RI	Jan 25, 2017	Feb 17	~18 days	~32 kW	~45 mA	~40mA	Lens 2 conditioning, plasma ignition, Cs collar inlet air leak caused replacement a QA issue (scratch on tube)
x3	RI	May 1, 2017	June 16	~29 days	~38 kW	NA	40-45mA	Extractor feedthrough resistors failed, arcing in sagging isolation transformer cable, 13 MHz supply swap, source replaced due to antenna loop bleed resistor failure
x4	RI	Jun 16, 2017	Oct 29	~70 days	~35 kW	NA	40 mA	P-gun cable failure, used for low intensity beam studies, high gas, spikes on p-gun current, run terminated to move injector to SNS
x4	LBNL	Aug 13, 2018	June 14, 2018	~125 days	~35kW	~45 mA	~25-30 mA	Run terminated due to plasma ignition failure, had to increase p-gun voltage >300V
x3	LBNL	June 24, 2019	June 27, 2019	~2 days	~25kW	NA	~12 mA	Water leaks in/out of vacuum-ceramic chamber likely not polished (update, polishing has completely fixed these leaks on all subsequent installations (4-2020))
x4	LBNL	Nov 15, 2019	March 21, 2020	~110 days	~30kW	~45 mA	20-25mA	Source pulled due to p-gun ignition issues
x4	LBNL	June 16, 2020	August 3, 2020	~40 days	~30kW	~45 mA	15-25mA	H2 gas mis calibrated flow much greater than readback, short gun ok

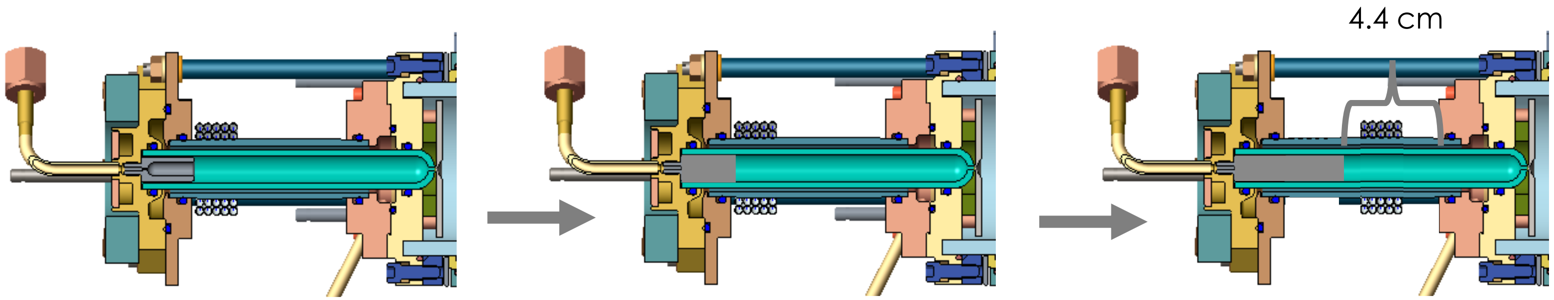
Plasma ignition gun remains problematic!

R&D Conducted on the Plasma Gun Test Bench



- The plasma ignition gun for the external antenna source is a hollow anode, RF/DC glow discharge feeding electrons into the main 2 MHz ion source plasma chamber
- The plasma gun test bench is a vacuum chamber that directly measures output of the gun under nominal H_2 flow conditions
- The bench has a 13 MHz 600W RF supply, a DC 3000V and a pulsed 4000V supply
- The stand allow us to rapidly explore different configurations and do lifetime tests without tying up other testing resources.
- Two promising gun configurations were developed on the test bench ….

Paschen-optimized Plasma Gun Configuration



Original hollow W cathode

Solid W cathode

Shifted cathode

- First, we focused on improving the DC discharge alone, since it is essential for ignition of the main plasma.
- Next, direct measurement of the plasma current from the gun allowed us to optimize cathode shape – we found a solid W cathode outperformed the hollow W cathode
- Analysis using Paschen breakdown theory suggests the Stoletow point will occur at cathode – anode gap ~3.2 cm. We, therefore, closed the gap as much as possible to 7 → 4.4 cm while still fitting the RF antenna.
- This configuration ran very well on the test bench and was used in the summer 2020 BTF campaign without issue. During the cathode voltage did not need to be raised above 200V, keeping below the sputter threshold for H_2^+ on W!

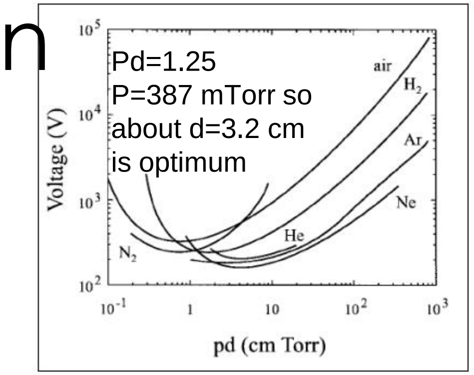

Pd=1.25
P=387 mTorr so
about d=3.2 cm
is optimum

Figure 2.3: Paschen Curve for parallel plate arrangement in various gases (Raizer, 1991. Appeared in Schütze *et al.*, 1998)

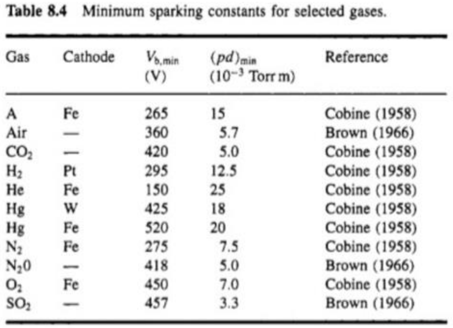
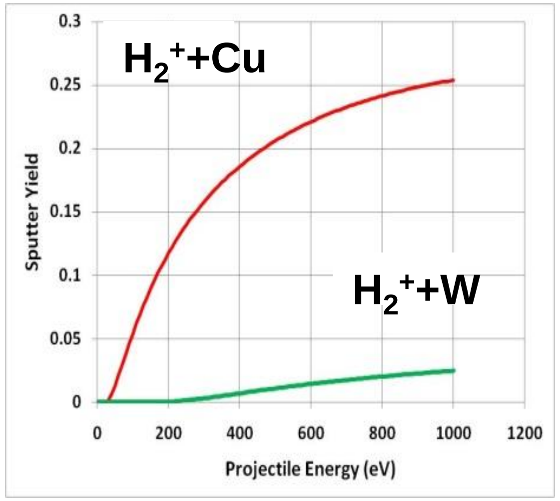


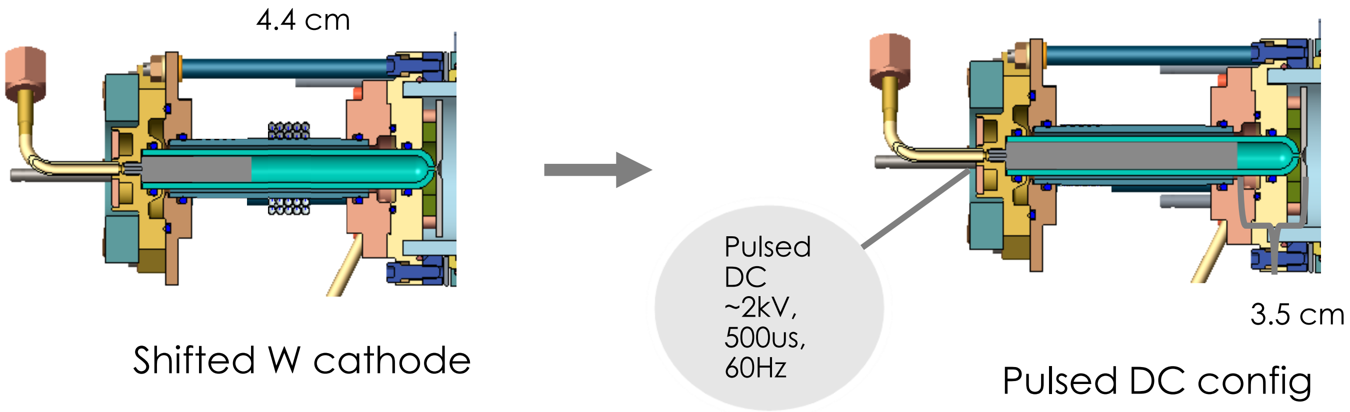
Table 8.4 Minimum sparking constants for selected gases.

Gas	Cathode	$V_{b,min}$ (V)	$(pd)_{min}$ (10^{-3} Torr m)	Reference
A	Fe	265	15	Cobine (1958)
Air	—	360	5.7	Brown (1966)
CO_2	—	420	5.0	Cobine (1958)
H_2	Pt	295	12.5	Cobine (1958)
He	Fe	150	25	Cobine (1958)
Hg	W	425	18	Cobine (1958)
Hg	Fe	520	20	Cobine (1958)
N_2	Fe	275	7.5	Cobine (1958)
N_20	—	418	5.0	Brown (1966)
O_2	Fe	450	7.0	Cobine (1958)
SO_2	—	457	3.3	Brown (1966)

Sputter yields

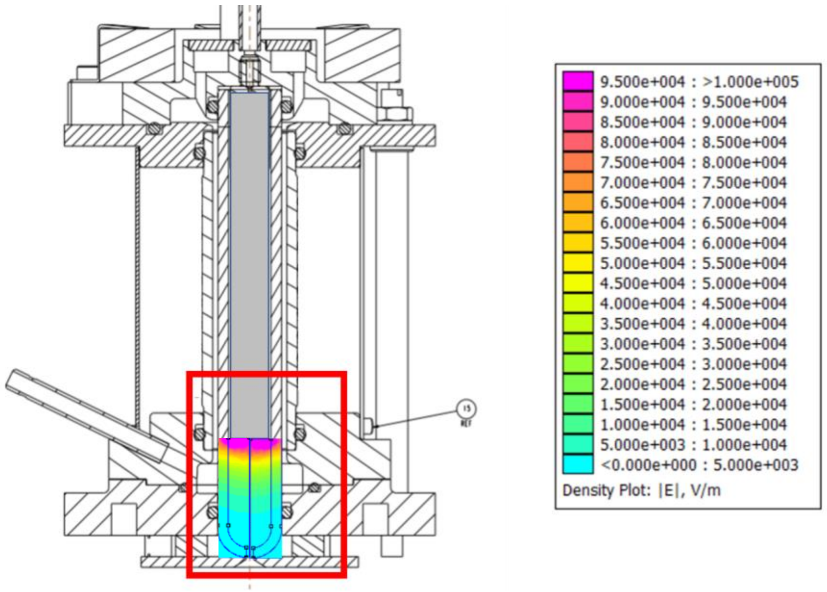


Pulsed DC (no RF) Plasma Gun Configuration

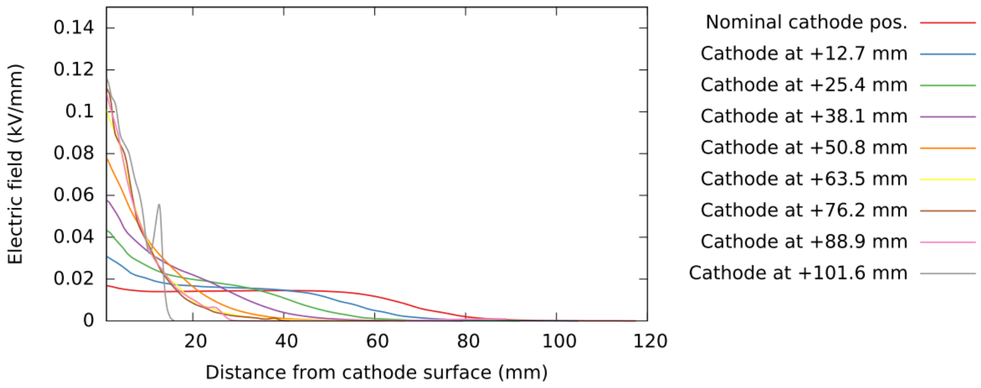


Shifted W cathode

Pulsed DC config

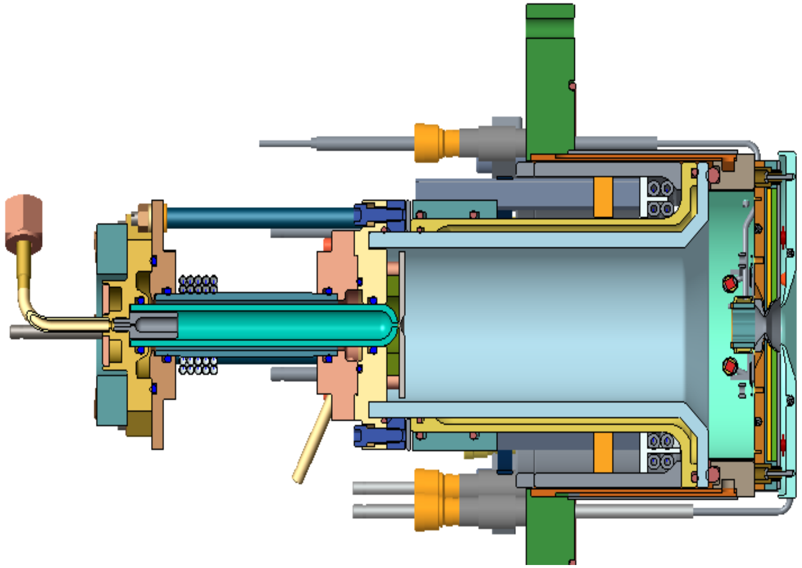


- If we could operate the gun without RF and achieve similar current output while reducing sputtering aging using a pulsed DC supply operating at low duty factor, this configuration could be a viable alternative.
- So far, we demonstrated DC operation (no RF) at ~2kV with a 4 cm gap delivering an output of ~1mA of collector current for ~3 weeks. This suggests that if the power supply was pulsed, an equivalent sputter lifetime of 1.9 years could be possible with a 3% duty factor!
- We have just begun testing this configuration in pulsed mode (~2kV, ~500us, 60Hz) with an anode-cathode gap of 3.5 cm. It ran continuously for 12 days. Tests are ongoing.



Summary and Conclusion

- This talk provided a brief snapshot of the past, present, and future of H^- ion source research at ORNL. Current R&D efforts conducted in each of our experimental facilities were discussed.
- Years of H^- ion source research and development has enabled the SNS to dramatically increase the total beam delivered to target during a run by a factor > 100 with reliability >99.5%.
- In 2018, the new 2.5 MeV injector developed on the BTF and ISTS, was installed on the SNS greatly improving our operating margin and ability to meet facility upgrade goals. All upgraded ion source systems performed very well.
- Specifically, significant progress was shown towards the development of a reliable ignition system for the external antenna source.



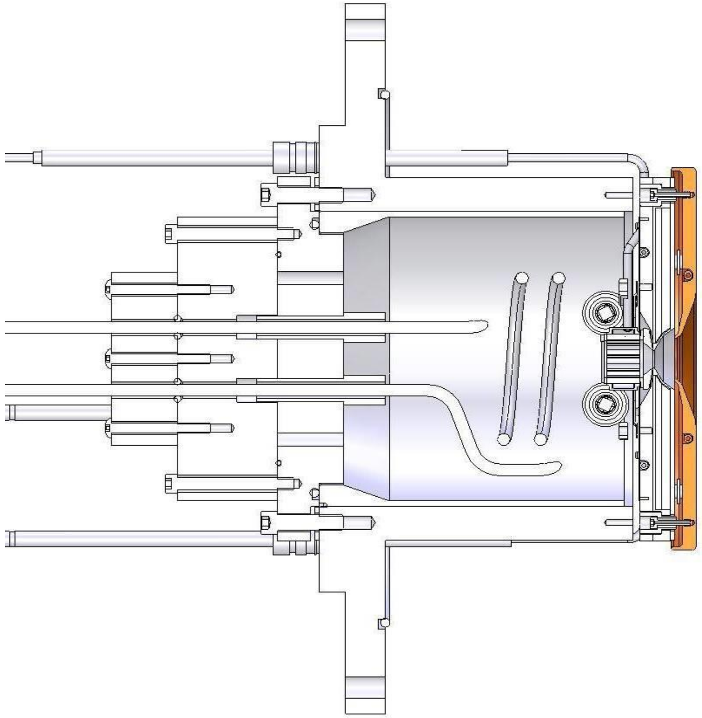


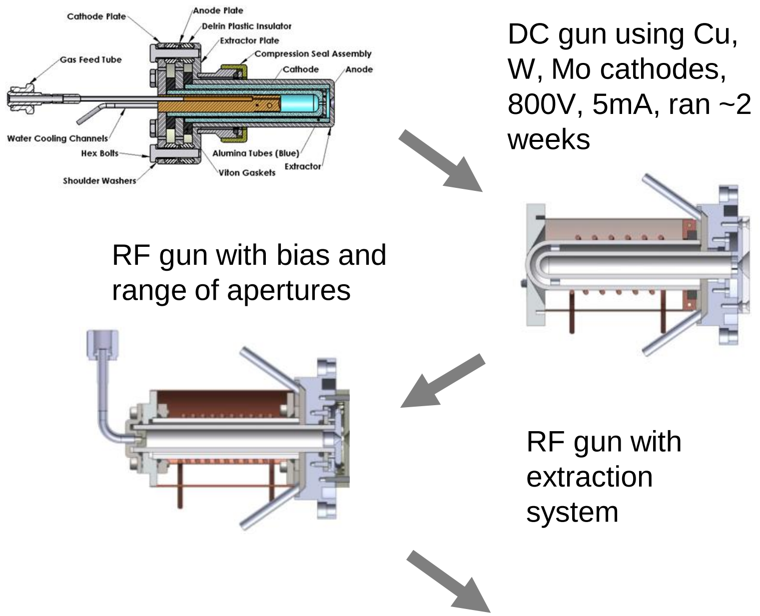
Photo credits: RF Welton

Supplemental slides

The Plasma Ignition Gun for the External Antenna Source

Background

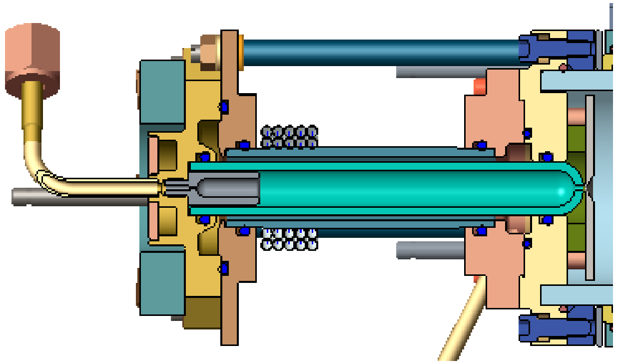
- Pulsed 2 MHz is not able ignite the plasma at 60 Hz, even with RF pulse shaping and frequency hopping.
- Applying cw13 MHz directly to the external antenna source did not provide reliable ignition.
- Various gun configurations have been tested with best performance from a hybrid DC/RF gun.
- However, after 80-120 days of operation, the gun often fails.
- Inconsistent performance across builds is also problematic.
- Often, the gun ignition requires increasing the cathode voltage >250V (above W sputter threshold) which limits lifetime due to deposition in the ceramic.



DC gun using Cu, W, Mo cathodes, 800V, 5mA, ran ~2 weeks

RF gun with bias and range of apertures

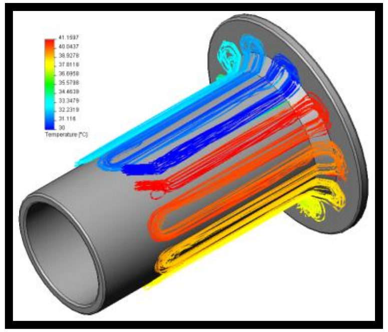
RF gun with extraction system

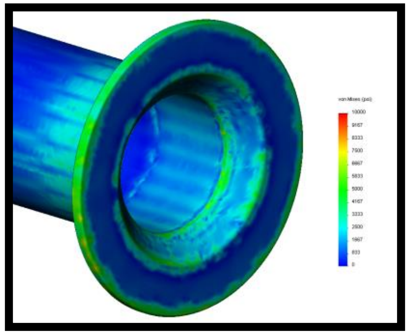


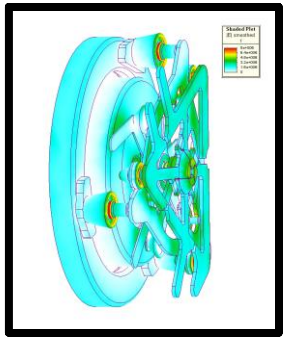
Current version: hollow anode DC gun with RF assist

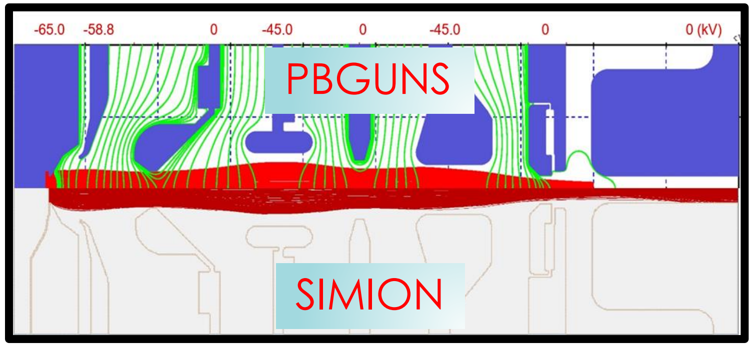
Computer Modeling and Inter-laboratory Collaborations

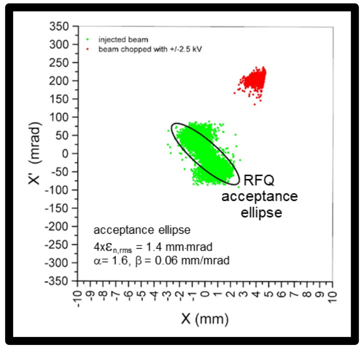
- Computer modeling has been a valuable tool in conducting ion source R&D and improving our ion sources and LEBTs. We have employed PBGUNS, SIMION, IBSIMU, ANSYS, SOLIDWORKS/COSMOS, Infolytica, LORENTZ and CST Studio











- The SNS ion source group participate in reviews and collaborations with many other laboratories: LANL injector upgrade, LANL R&D projects, MIT IsoDar, ISIS, CERN, ESS, D-Pace, and NSIF.