Recent H⁻ ion source research and development at the Oak Ridge National Laboratory

The 8th International Symposium on Negative Ions, Beams and Sources

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- The Spallation Neutron Source (SNS): ion sources, test facilities and the accelerator
- Goals of the ion source R&D program
- R&D efforts since last NIBs:
  - Explore larger extraction apertures
  - Improve plasma ignition in the external antenna source
  - RF coupling efficiency measurents
  - Improve electron dumping

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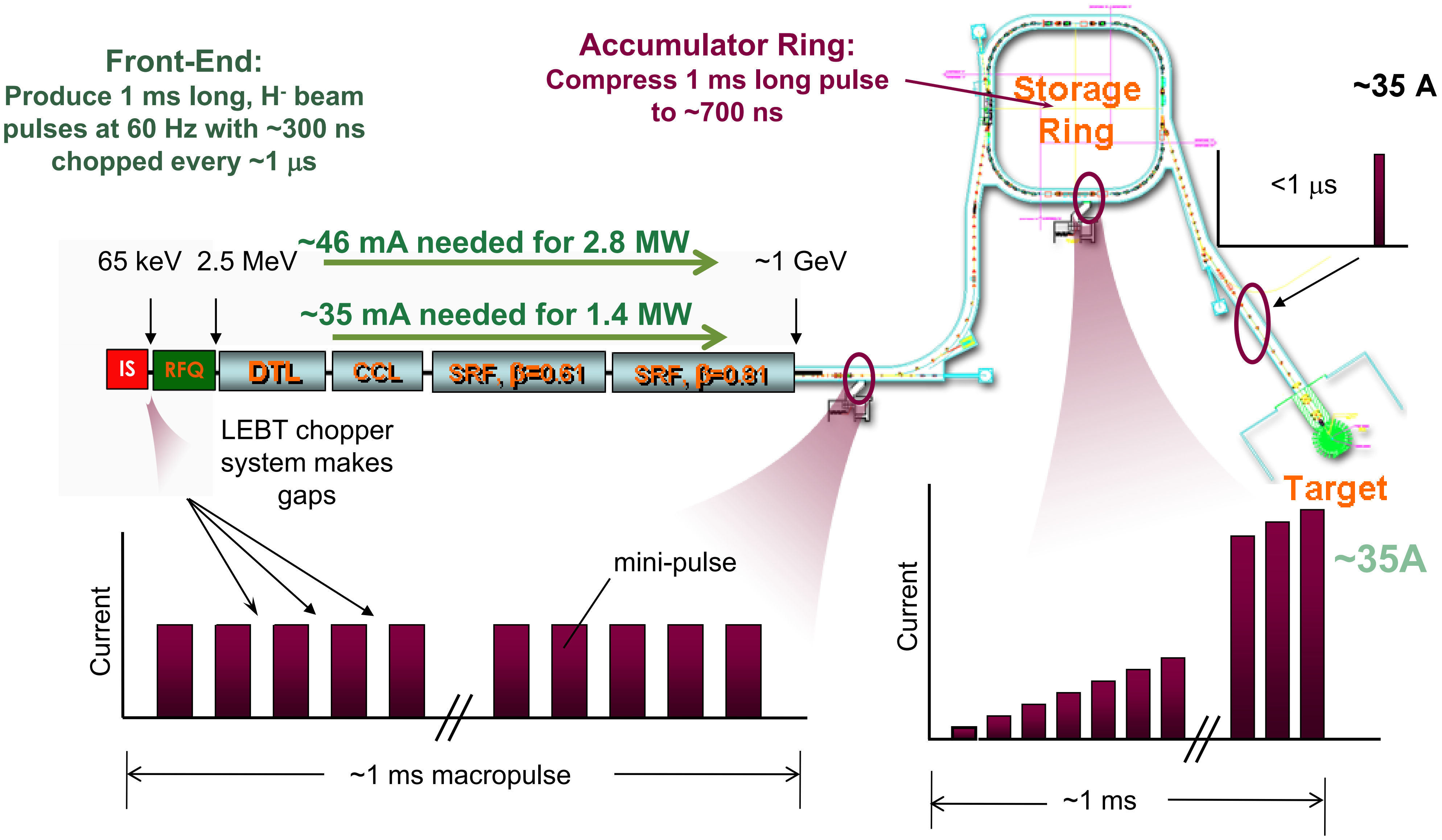
The SNS Accelerator System Overview

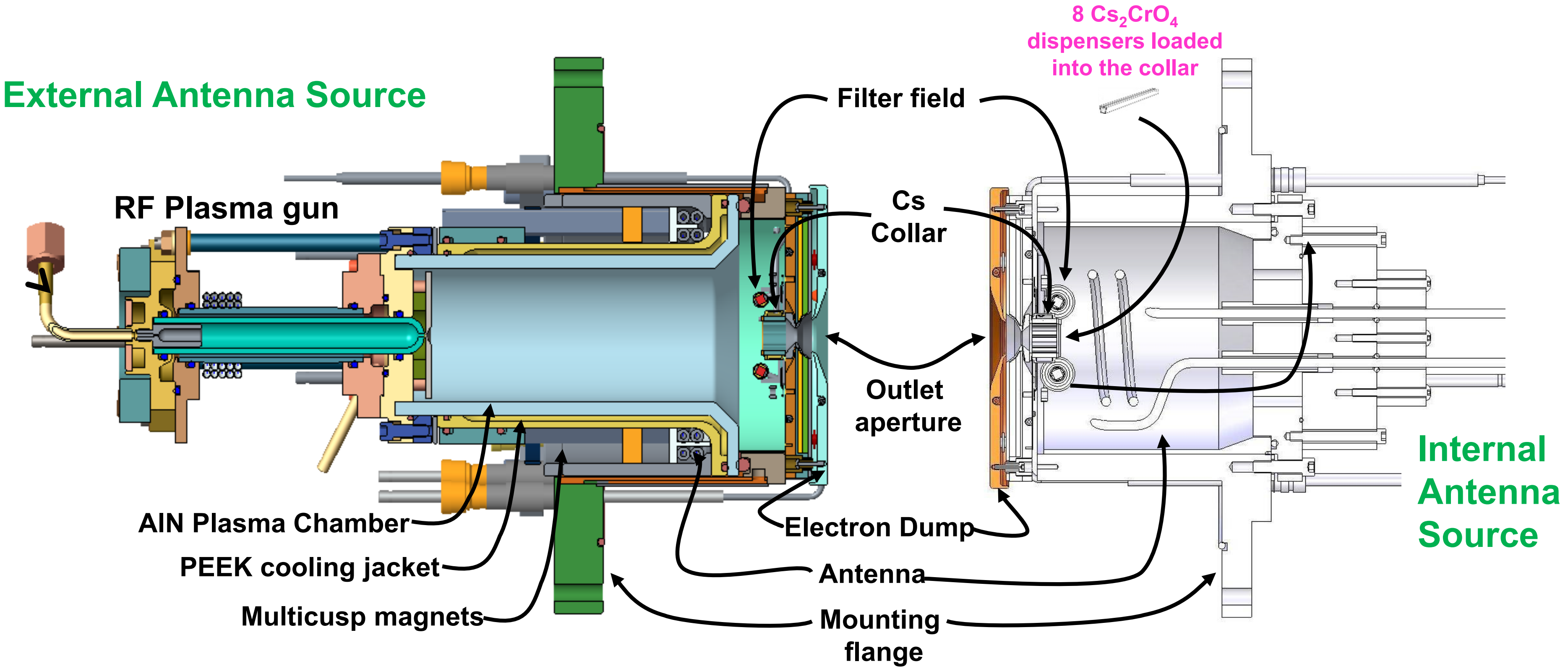


~LEBT currents: 40-75mA

Goals of the Ion Source R&D Program

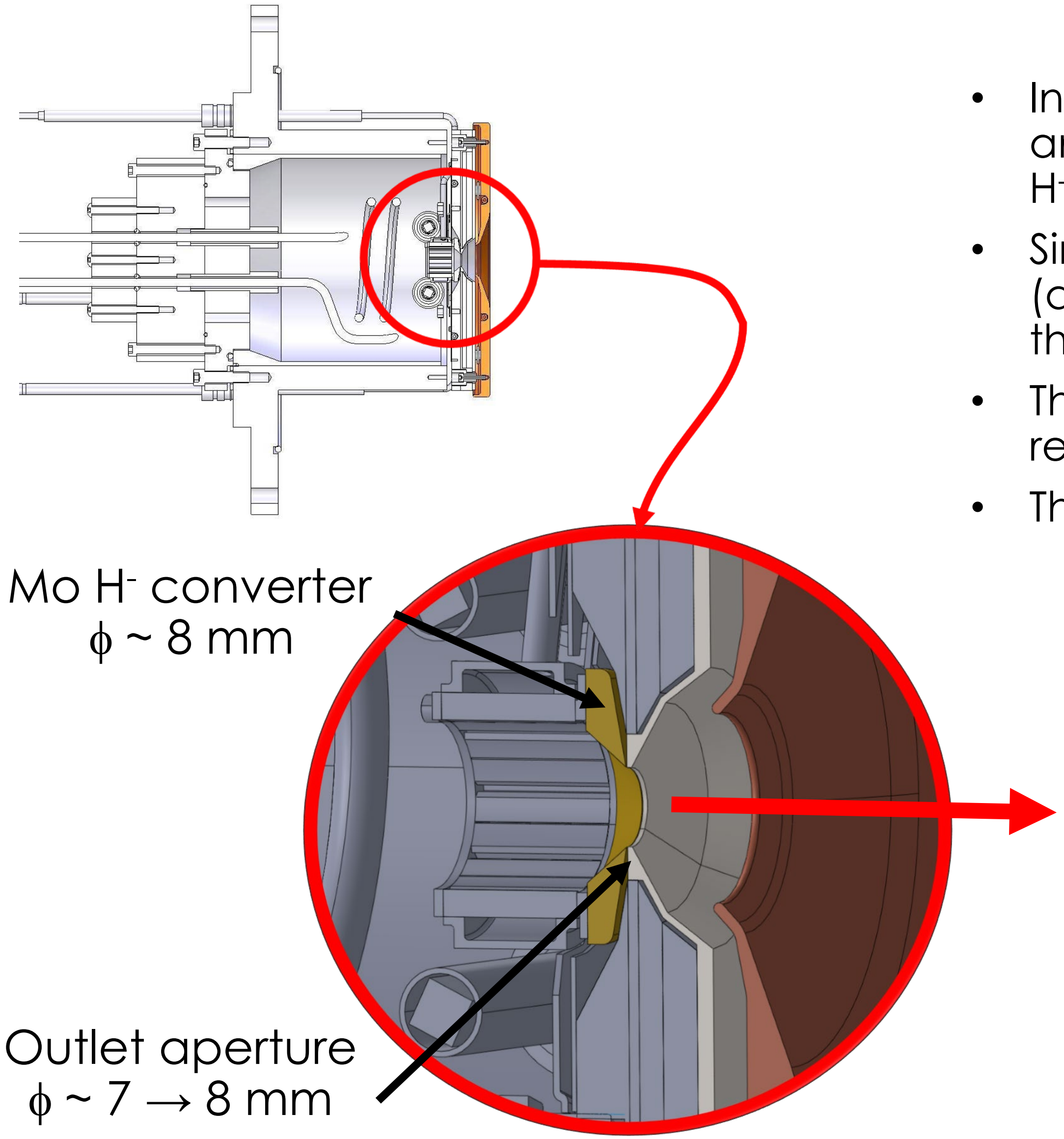
- **Support 1.4 MW SNS operations**
  - ~35 mA from RFQ
  - Continuous improvements to the source, LEBT and infrastructure
- **Support future 2.8 MW SNS operations**
  - ~46 mA from RFQ
  - 1st STS experiments ~2028
  - Will require LEBT beam current near the upper limit of its historical operating range and a healthy RFQ
  - Needs increased beam current margin
- **Fully develop the external antenna source**
  - Eliminates the risk of the internal antennas (single vender using a proprietary process)
  - Needs to have equal or better reliability and performance than the internal antenna source
  - Needs reliable plasma ignition
- **Continue to contribute to the H^- ion source intensity frontier**
  - Collaborations and consultations with other laboratories – LANL, ISIS, CERN, J-Parc, SIPRC-ONRL, NanoSIMs-ORNL
  - Improved modelling of SNS and similar ion sources and LEBTs

The SNS ion sources



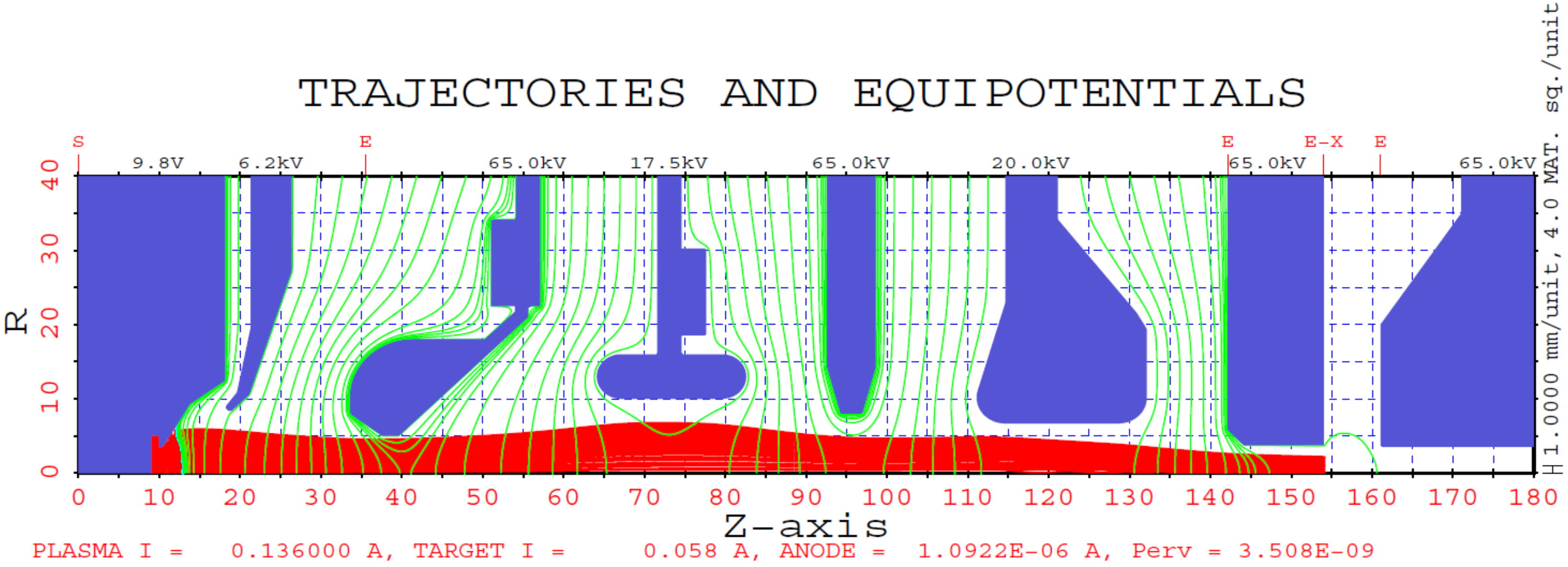
- **Internal antenna source** – Neutron production ion source for the SNS. Features an internal porcelain coated antenna. Delivers 50-60 mA through the Low Energy Beam Transport (LEBT). Designed at LBNL and extensively developed at ORNL.
- **External antenna source** – Alternative ion source for the SNS. Features a AlN plasma chamber, external antenna and uses an **RF-assisted, DC plasma ignition gun.**

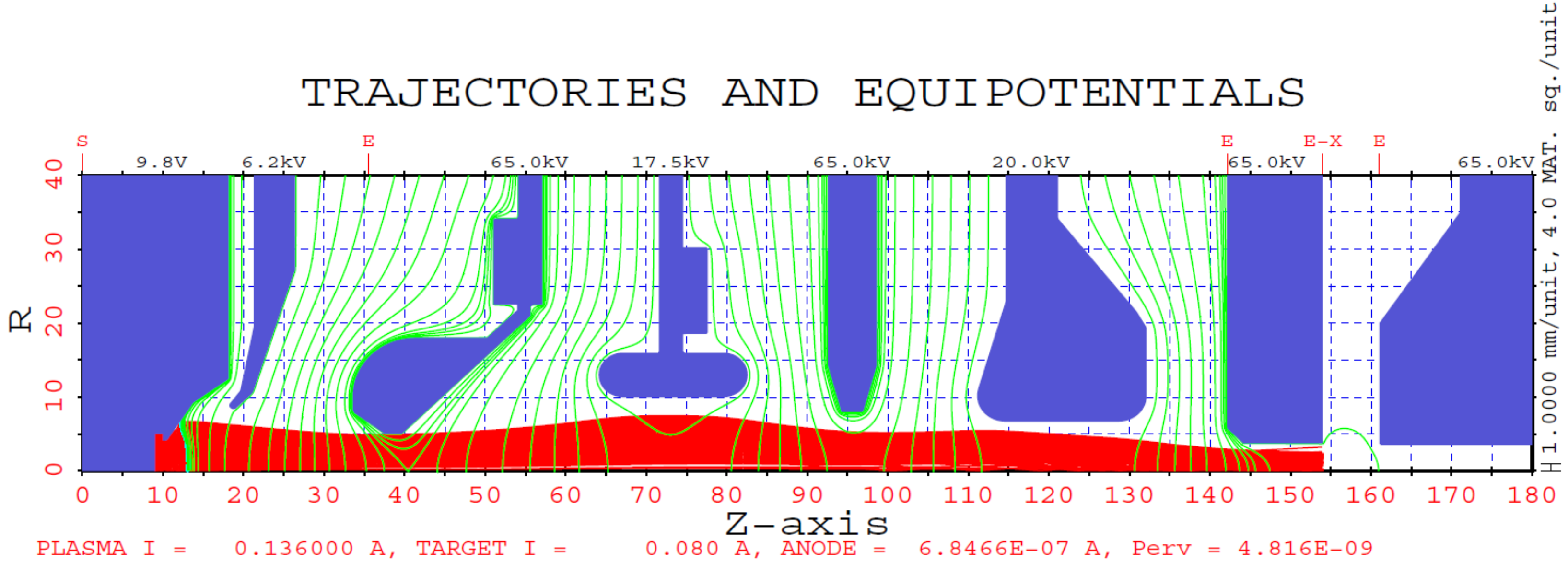
Recent R&D efforts: Explore larger extraction aperture



- In 2012 we studied variations in H^- converter aperture diameters and found that larger ones seemed to contribute to increased H^- beam current.
- Since then, we standardized this structure to have ϕ ~8.2 mm (design = 7mm) apertures in our production ion sources. We left the **outlet aperture diameter fixed ~7mm**.
- This year, due to the desire for higher beam current margins, we reconsidered **increasing the outlet aperture diameter by ~1 mm**.
- This work was motivated by the following factors:
  - **Increased beam current** due to accessing ~30% more plasma emission surface
  - **H_2 flow out of source is restricted** by conductance through 2 apertures (one fixed). Simple vacuum calculations suggest that a manageable flow increase of ~15% will be needed to maintain pressure.
  - **Manageable increase of beam emittance** - Experience at J-Parc and beam simulations suggest emittance growth should not significantly impact beam accepted into the RFQ

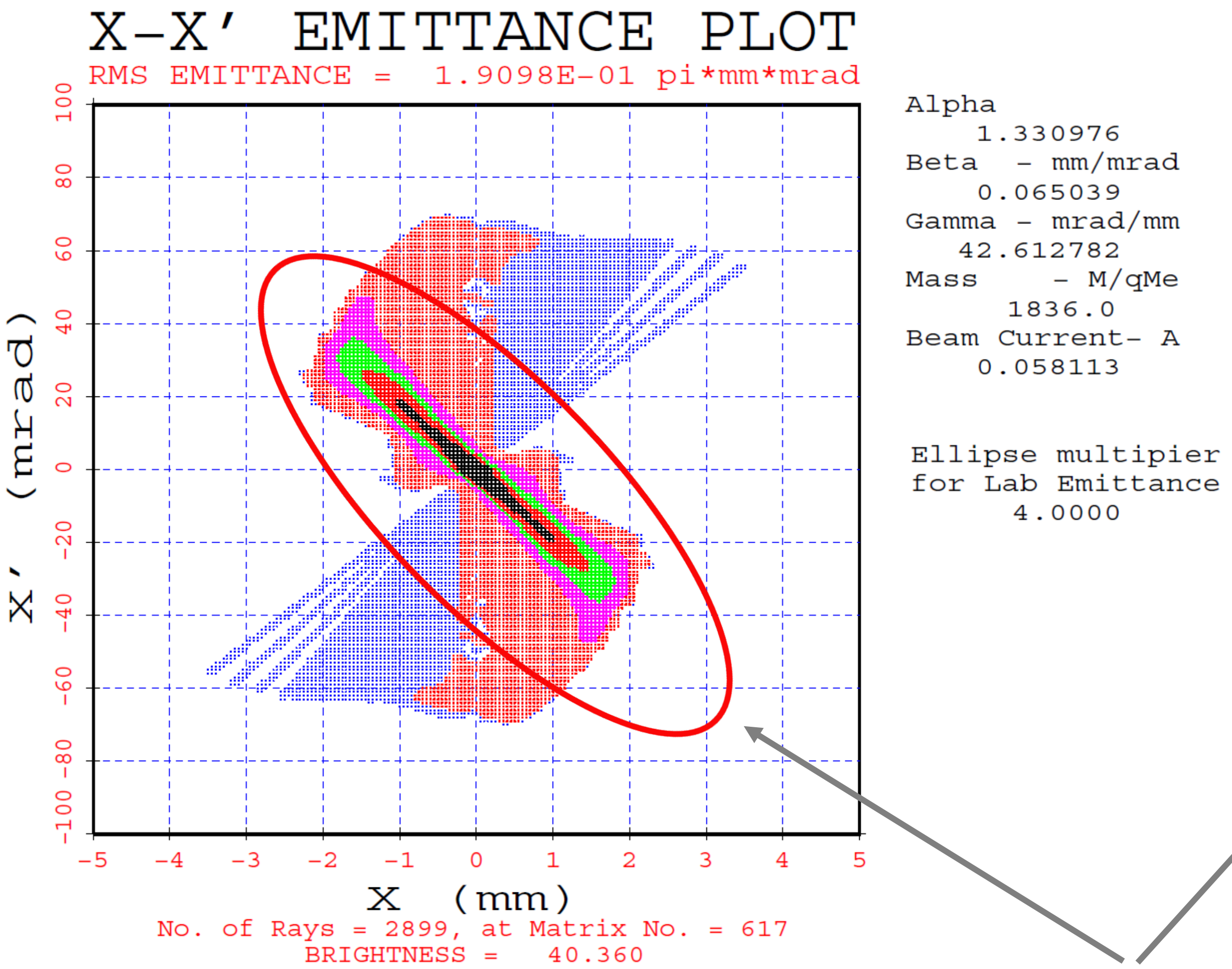
Larger extraction aperture: Beam simulations

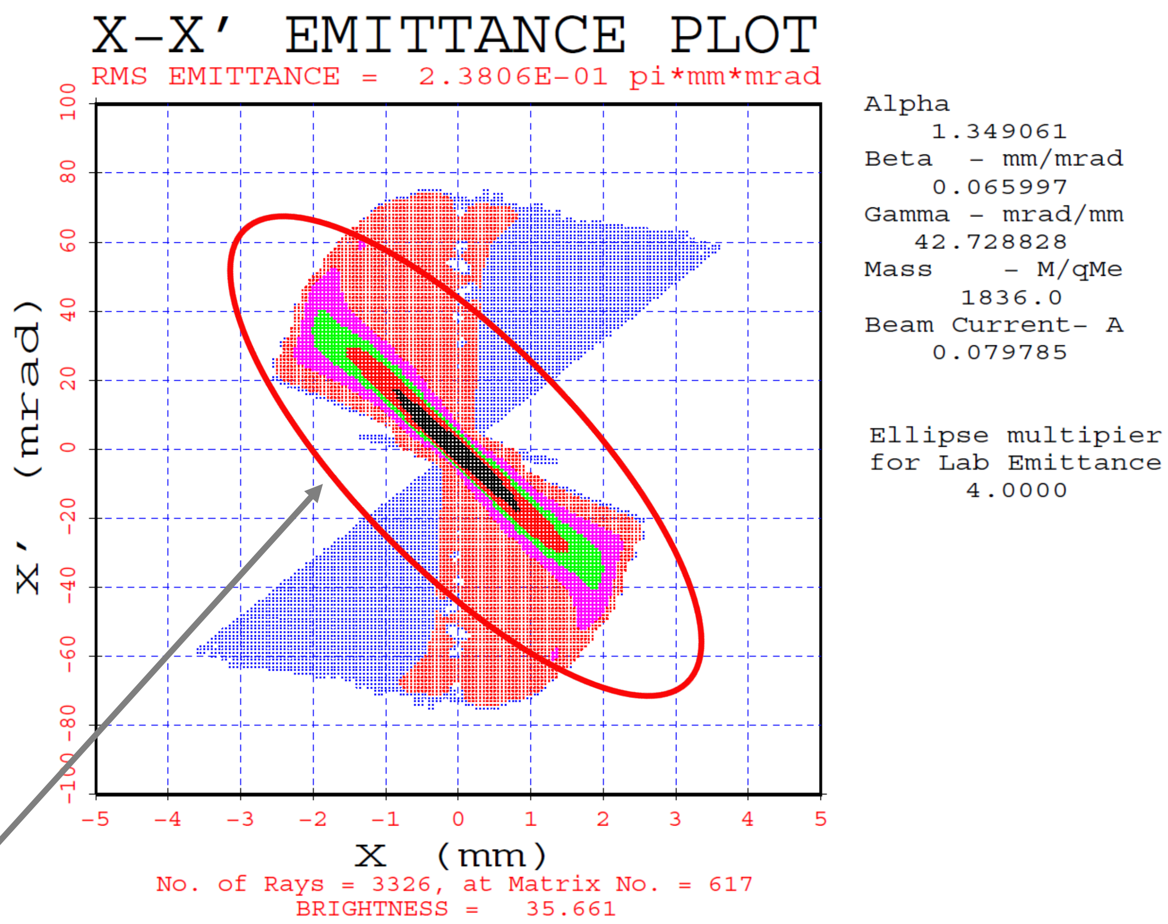




- PBGUNS simulations were first performed to match our experimental source output with nominal ϕ~7mm outlet.
- Simulations were then run under the same conditions expect with a larger ~8 mm outlet aperture
- As expected, significantly more beam current was extracted for the same plasma current densities
- Emittance growth after the LEBT was also found to be only moderately larger with similar beam current injected into the RFQ

Larger extraction aperture: Beam simulations

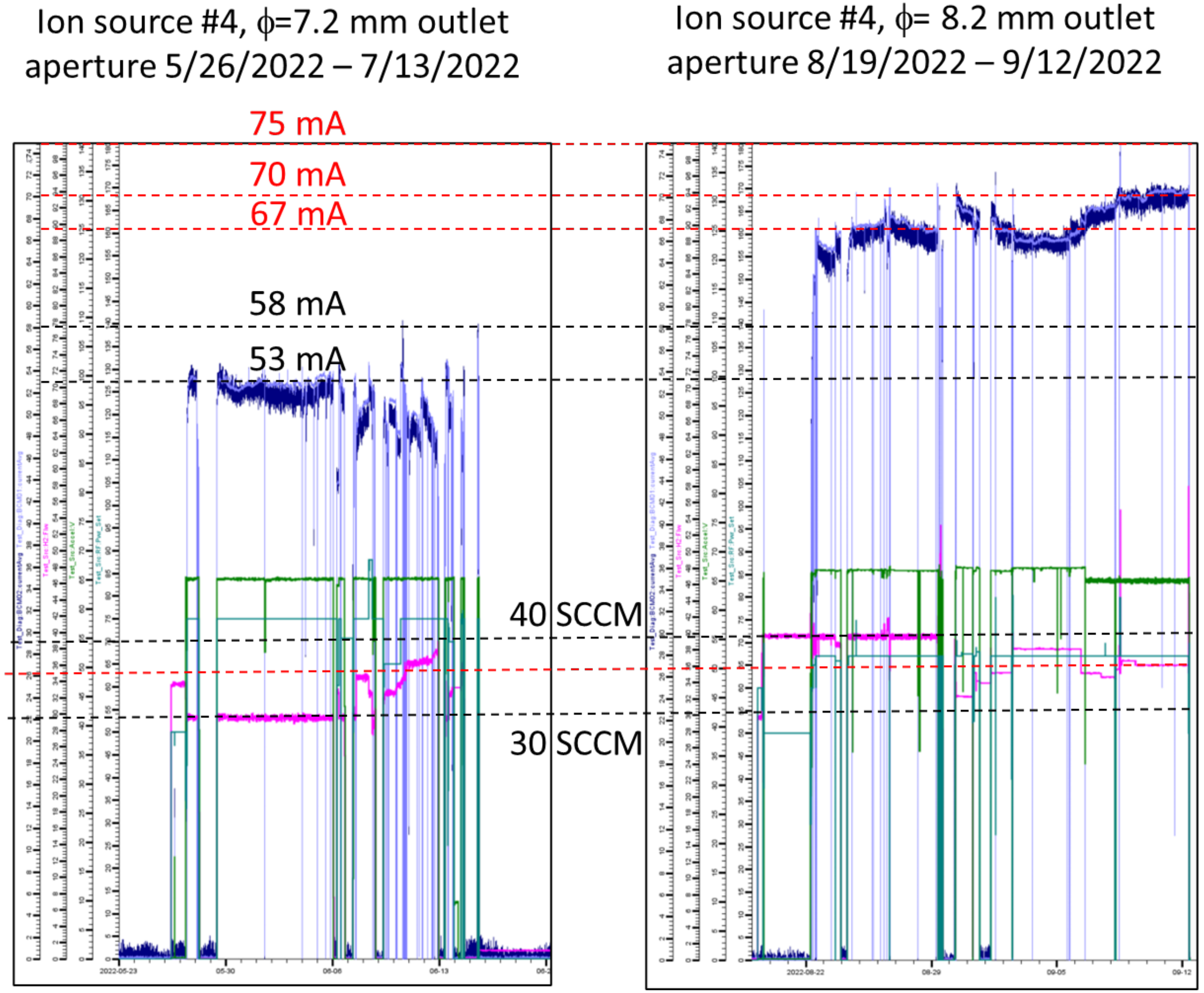




~ RFQ
acceptance

Larger extraction aperture: Testing in ISTS

- Production source #4 was tested on the ISTS with both the nominal ~7 mm outlet aperture and then with the ~8 mm aperture
- ~25-30% increase in beam current was recorded with comparable power and higher H2 flow
- Currently measuring emittance on ISTS



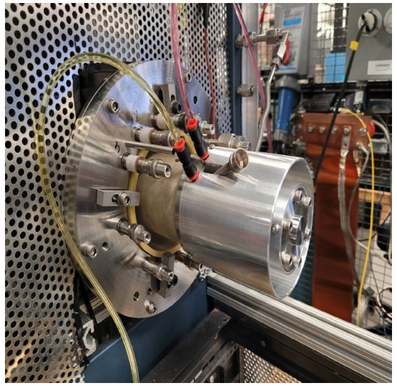
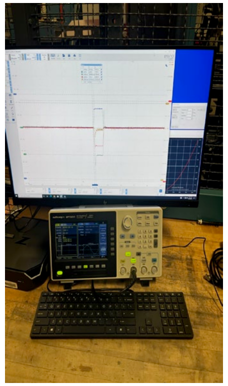
Recent R&D efforts: External antenna source

- Effort was reduced in priority due to years of reliable internal antenna operation on the SNS accelerator and large inventory of Tier-1 antennas (last failure ~9 years ago)
- Recently we did have 2 x Tier-2 antenna failures on #4 at the ISTS (7-11-22) and BTF (3-19-22).
- Testing on the external antenna source on the BTF 2016-2020 revealed **plasma ignition gun** was the **primary issue** with the source.

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!

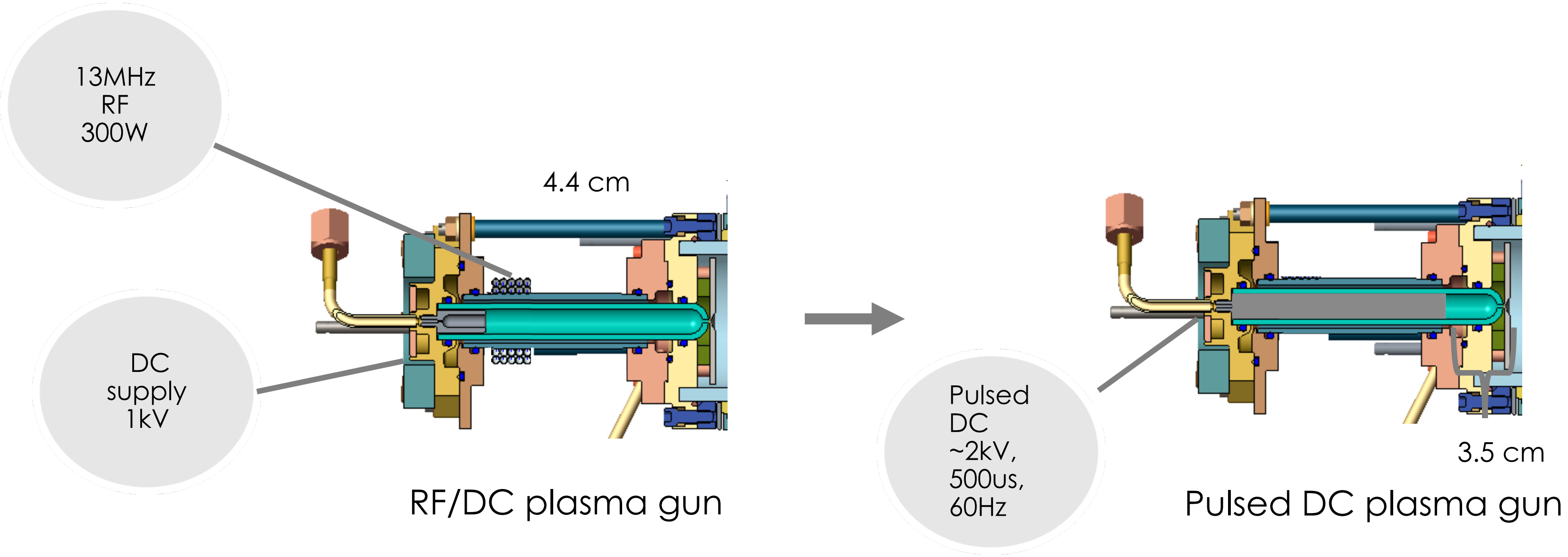
- Built dedicated plasma gun test bench to study plasma gun directly

- Vacuum chamber, 700l/s
- DC, pulsed and RF power supplies
- Probe to measure emitted plasma flux
- Pico scope and signal generator

The Plasma Gun Test Bench (TB)

External antenna source ignition: pulsed DC p-gun



- We learned that if we extended the cathode of the RF/DC plasma gun and replaced the RF system with a pulsed DC cathode power supply we could obtain comparable emission currents to the original RF/DC gun
- On the Test Bench we then ran the pulsed gun for **~4 months** with ~1mA collector current (0.5 ms, 2600V, ~6mA discharge current @ 60Hz)
- We then attached this gun to an ion source and ignited the source reliably for ~**2 months** on the ISTS (1 ms, 3000V, 6mA, 60Hz) with no loss of discharge current.
- Results encouraged us to design a dedicated pulsed DC gun for use with a production external antenna ion source….

Design considerations for an optimal pulsed DC plasma gun

- **Design criteria for an optimal plasma gun:**
  - High electric field throughout the cathode-anode gap **>7200 V/m** with maximal axial uniformity
  - Outlet aperture dimensions: ϕ=2 mm x L=2.5-3.2 mm which was shown to provide sufficient discharge pressure at nominal H_2 flow
  - Anode cathode gap: ~4 cm based on Paschen optimum for pressures of ~0.4 Torr (measured and calculated)
  - Ceramic constriction of anode current (hollow anode)
  - Utilize gas injection at source potential – no ceramic break
  - Minimize use of elastomer seals (UHV)
  - Gun bakable 200-400 C

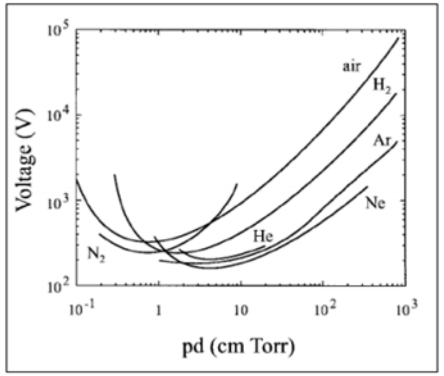
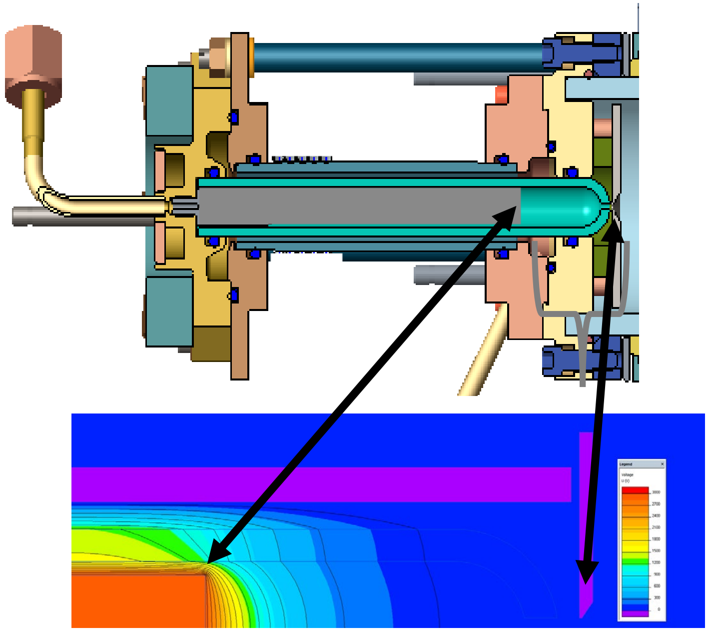
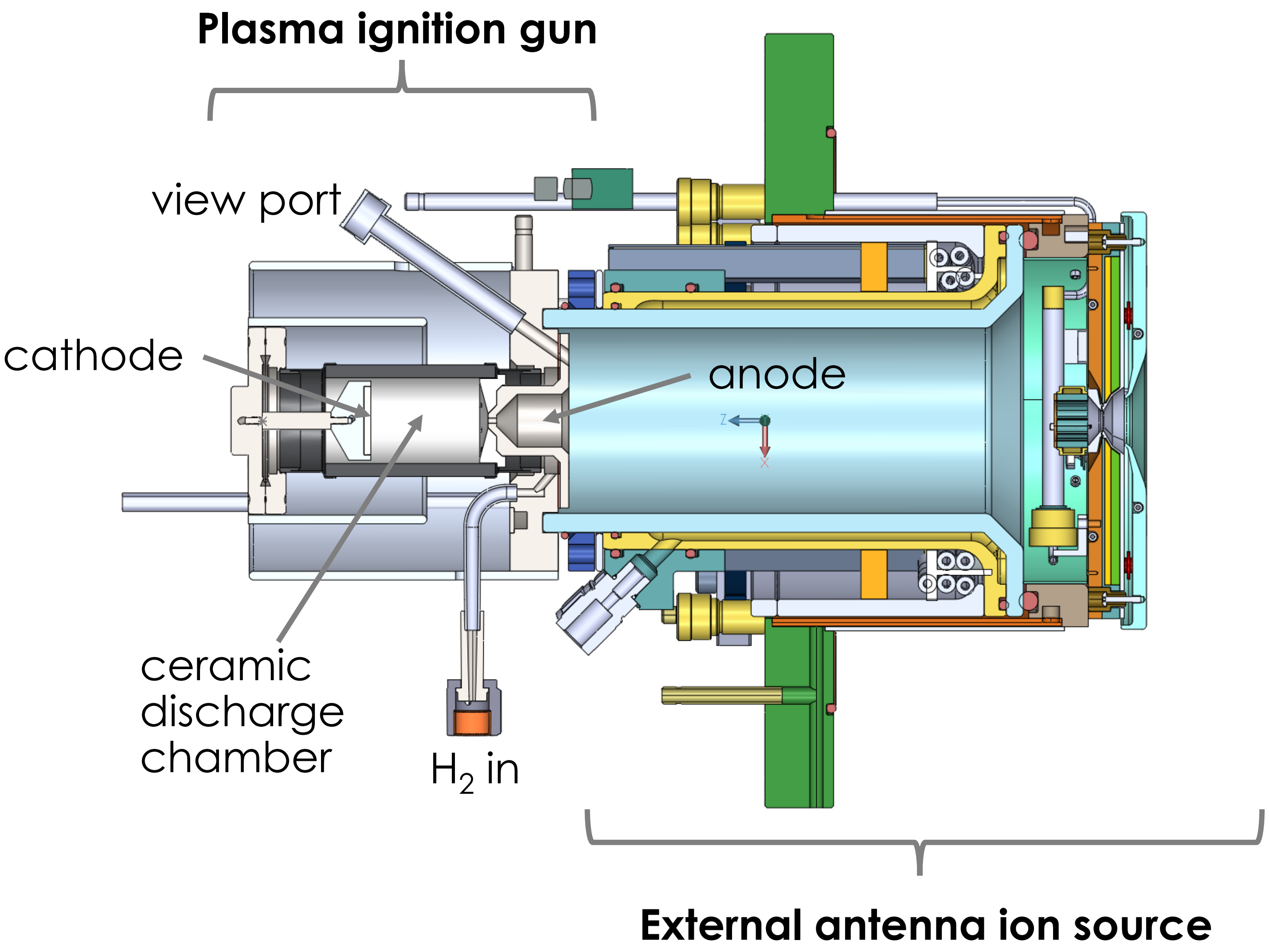


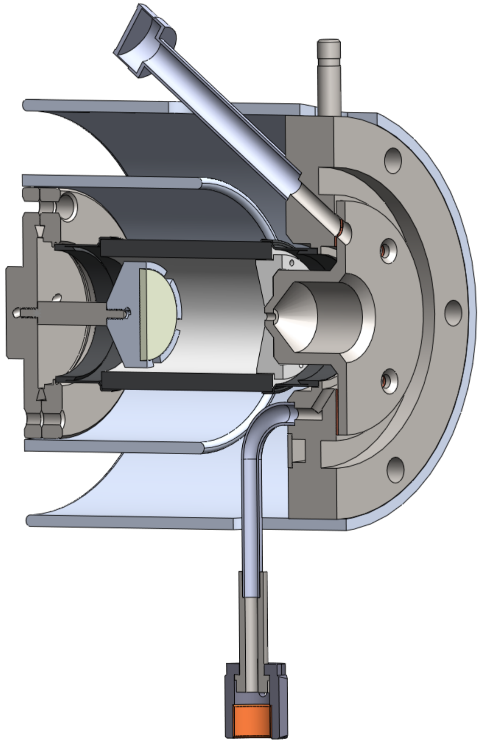
Figure 2.3: Paschen Curve for parallel plate arrangement in various gases (Raizer, 1991. Appeared in Schütze *et al.*, 1998)



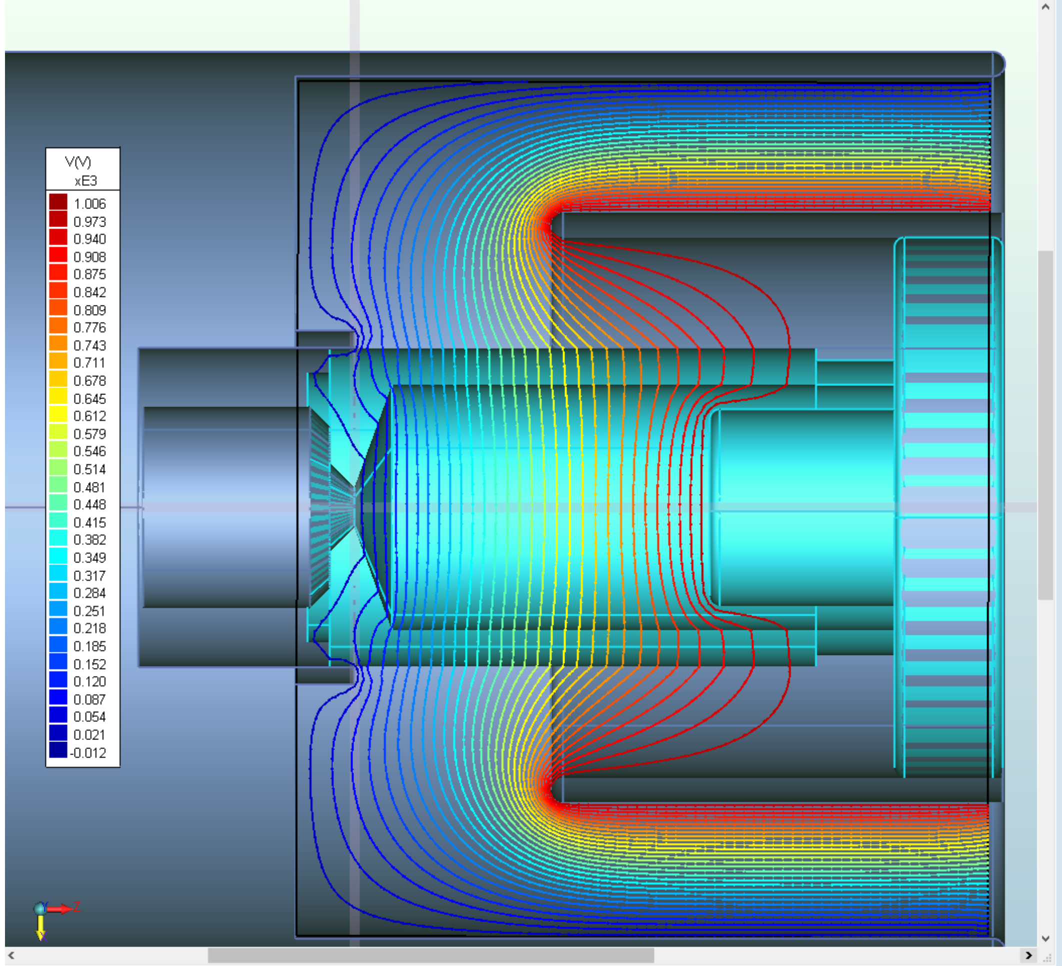
4.75x10^5 V/m   2x10^3 V/m

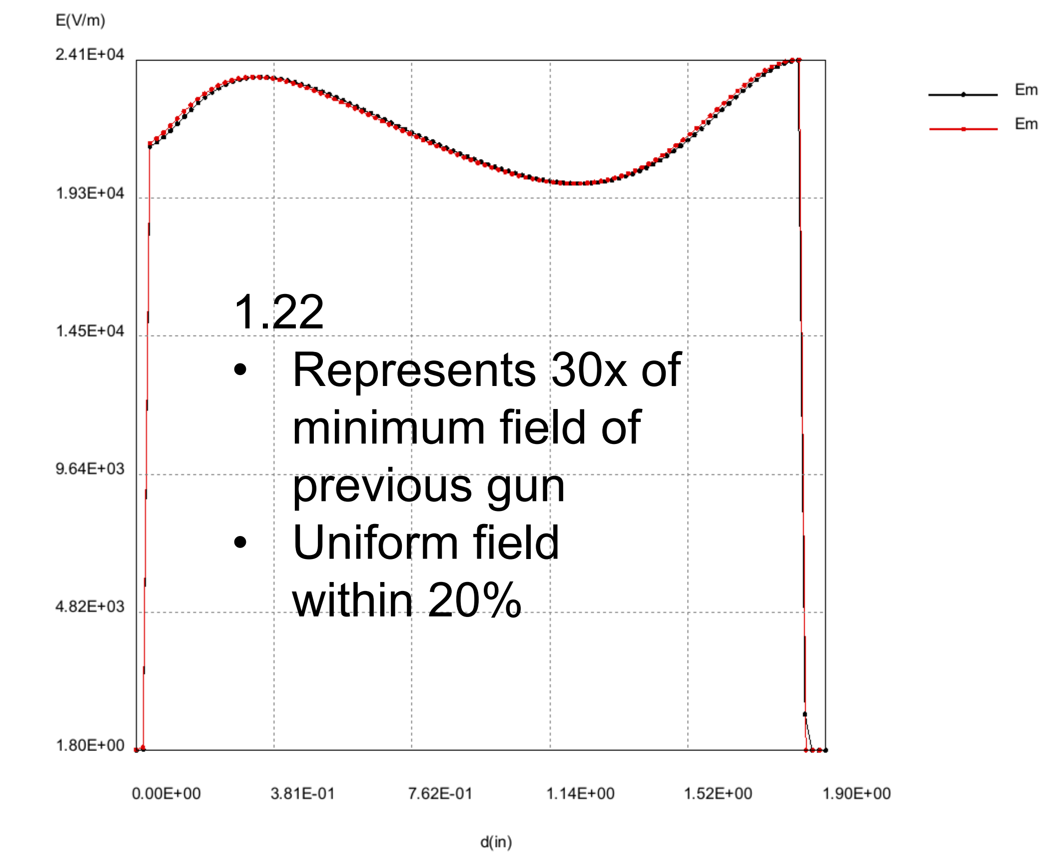
Mechanical design of the pulsed plasma gun





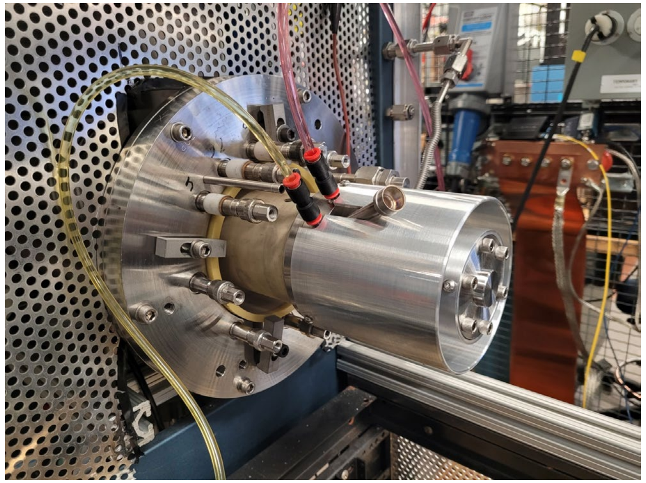
Electrostatic modelling of the new Pulsed DC P-gun

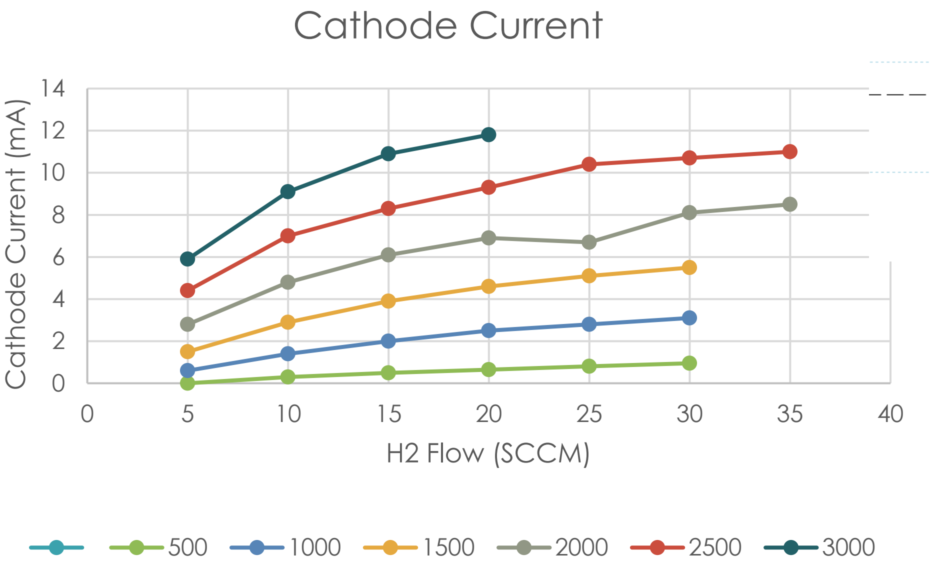




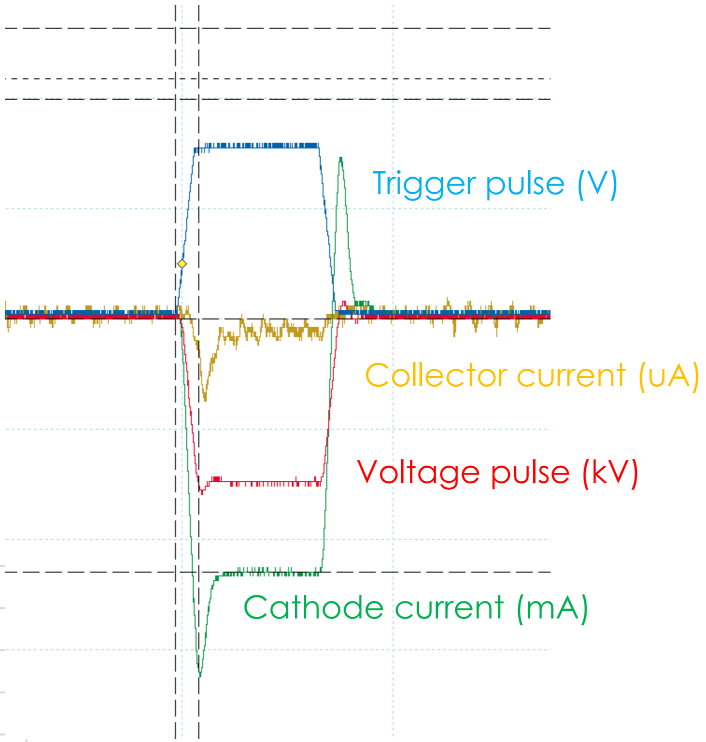
Experimental characterization of Pulsed DC P-gun on TB

- Gun tested on P-gun on Test bench with pulsed Trek supply (0.5-4kV, up to 20 mA, 0.5 ms, 60 Hz, 5-50 SCCM)
- Gun produced much more discharge current and required a series resistor, typically, 150 kΩ to operate within the power supply limit.
- Emitted plasma flux collected by a probe ~3.5 cm away from outlet versus <1cm for pervious tests (arb units)

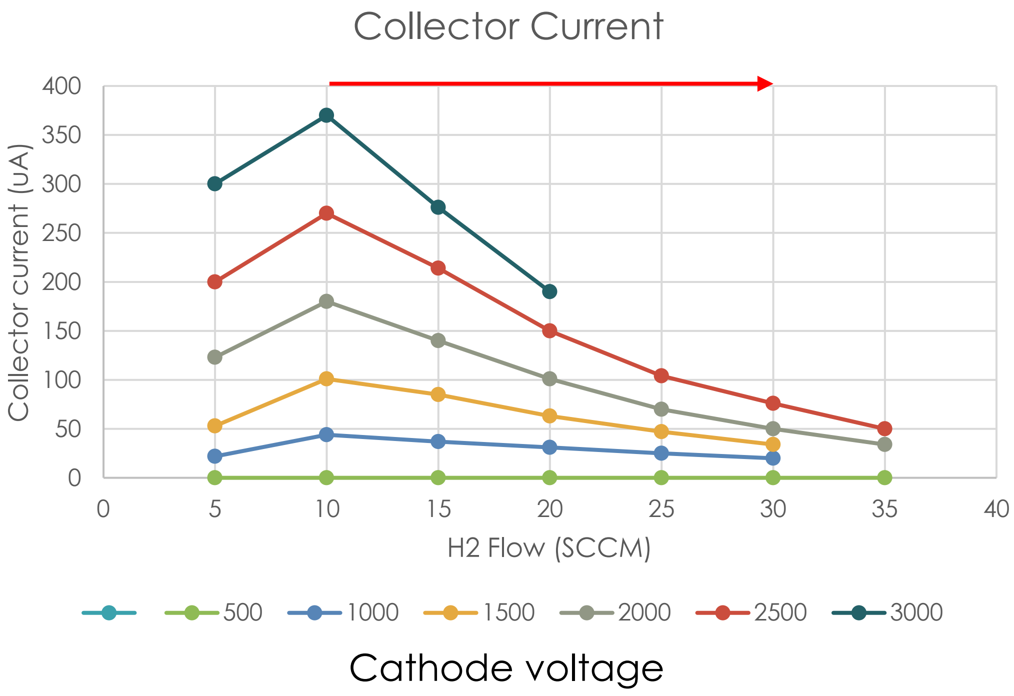




Cathode voltage



Experimental characterization of Pulsed DC P-gun on TB

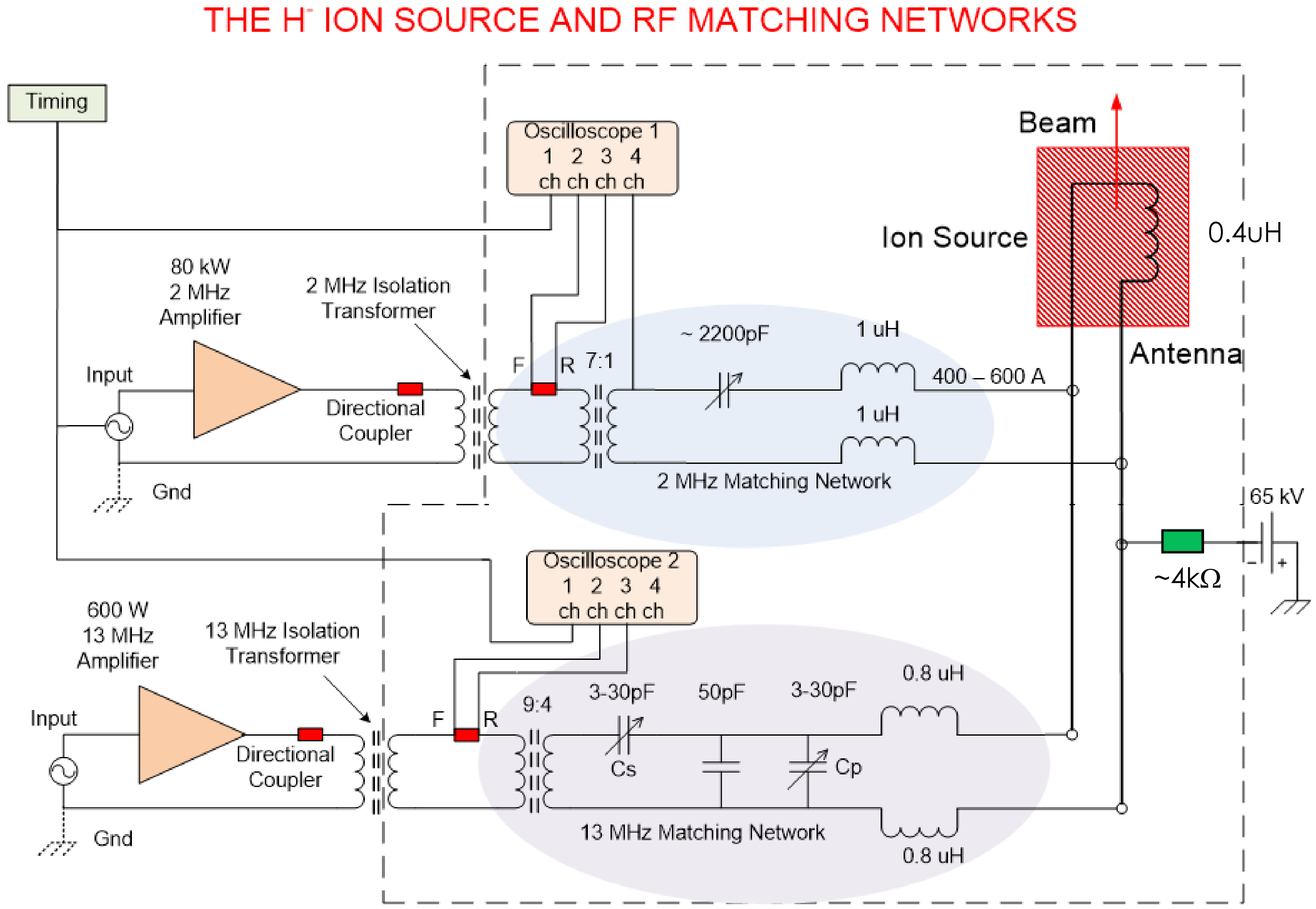


- Probe data shows optimum output at 10 SCCM indicating operation there near the Stoltow point of the Paschen discharge.

- Next steps for **Plasma gun**
  - Modify collector probe to allow normal measurements 3.5 → 1 cm from outlet
  - Open aperture to shift Stoltow point to 30 SCCM the nominal operating flow of the ion source and increase charge flux
  - Conduct lifetime test on Test Bench
  - Test with ion source on ISTS

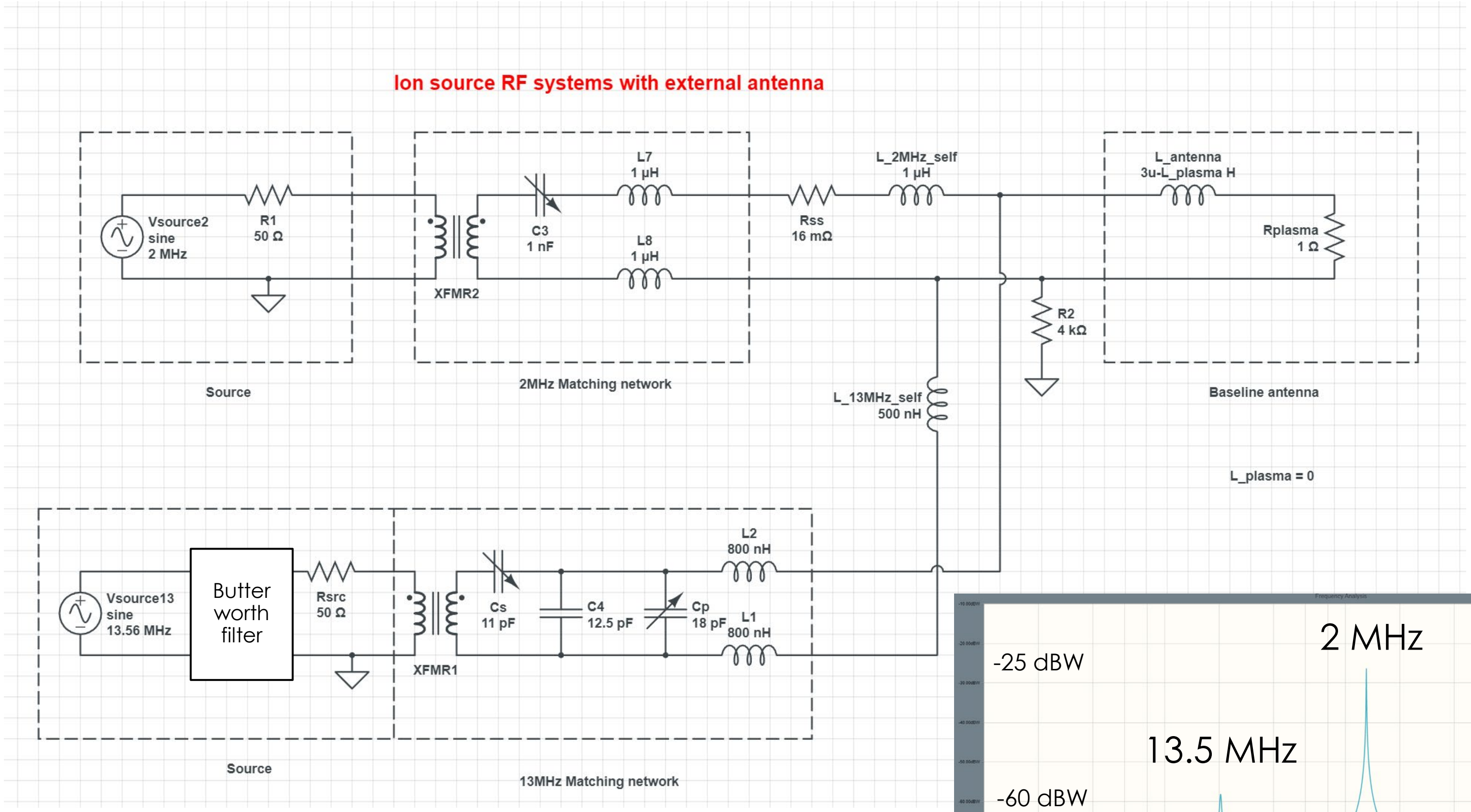
- Next steps for **External antenna source**
  - Bring refurbishment practice to the quality level as SNS production ion sources: use written and complete build and teardown sheets
  - Address DI water corrosion of the AlN chamber
    - Parylene coatings after baking
    - Oxidizing AlN surface 1300 C

External antenna source ignition: Dual Frequency excitation



- Alternative plasma ignition scheme to using plasma ignition guns
- Uses existing SNS internal antenna ion source RF ignition system (2 +13MHz)
- In May of 2021 a brief proof-of-principle test was performed using external antenna source. Two 13MHz generators were damaged

External antenna source ignition: Reconfigured matching network



- Butterworth filter added to protect 13MHz generator from 2 MHz
- C4 reduced to allow Cp to tune from center of range to capture resonance
- Frequency domain simulation shows power dissipated in the plasma max for both 2 and 13 MHz
- Network analyzer was then used to dial in initial variable capacitor settings prior to operation

- New system ran well for several weeks of operation in Jan 2022
- H_2 flow: ~33-42 SCCM
- 13 MHz power: 500W
- 2 MHz power: 45kW

- In January of 2022 several weeks of ignition were demonstrated with the modified matching network.
- We plan to continue to explore this option

Recent R&D efforts: RF power efficiency measurements

- Quantifies RF power delivered to the plasma not ion creation efficiency
- Collaborative effort with RAL-ISIS
- Conducted at the end of the dual frequency excitation experiments in February 2022
- Follows methodology of Dominikus Zielke J. Phys D 54 155202 (2021)
- P_{plasma}: power absorbed by the plasma
- $P_{generator}$: power transferred from the generator
- P_{loss}: total power lost in the transmission line, transformer, matching circuit, RF antenna, ohmic heating of surrounding metal structures, …
- These losses are quantified by the (effective) network resistance $R_{network}$
- RMS values used

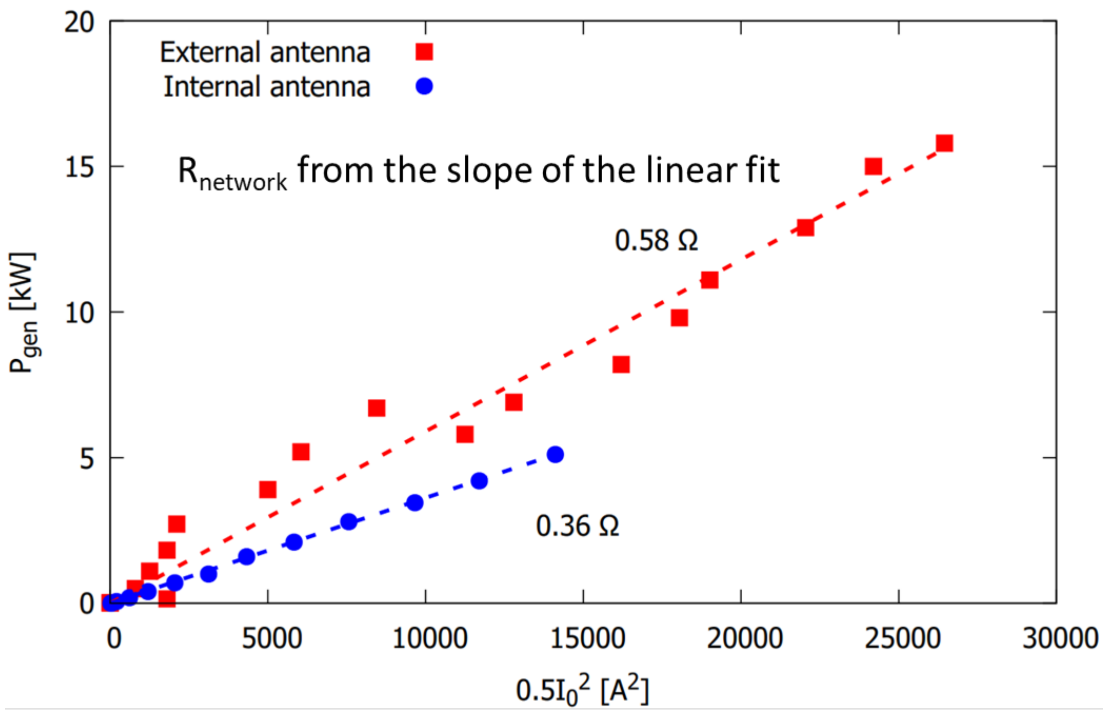
$$\eta = \frac{P_{plasma}}{P_{generator}} = \frac{P_{generator} - P_{loss}}{P_{generator}}$$

$$P_{generator} = P_{forward} - P_{reflected}$$

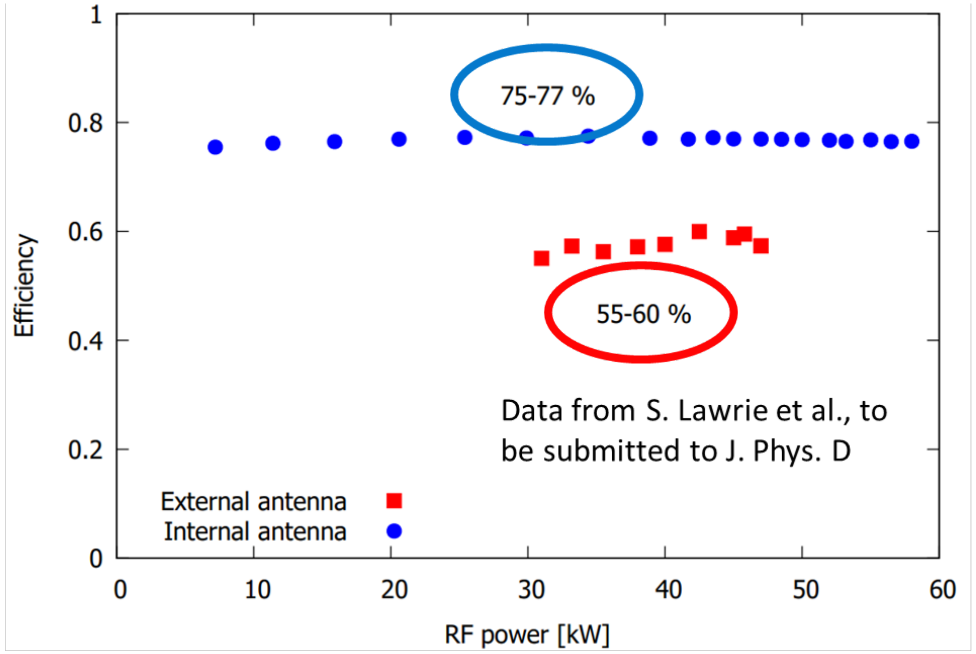
$$P_{loss} = \frac{1}{2} R_{network} I_0^2$$

Recent R&D efforts: RF power efficiency measurements

- The network resistance was measured for the SNS internal and external antenna sources by applying < 18 kW power without hydrogen flow (no plasma) and measuring the antenna current.
- The RF efficiency was then determined at different RF powers using the network resistance and fwd/refl powers at the amplifier



Data from S. Lawrie et al., to be submitted to J. Phys. D

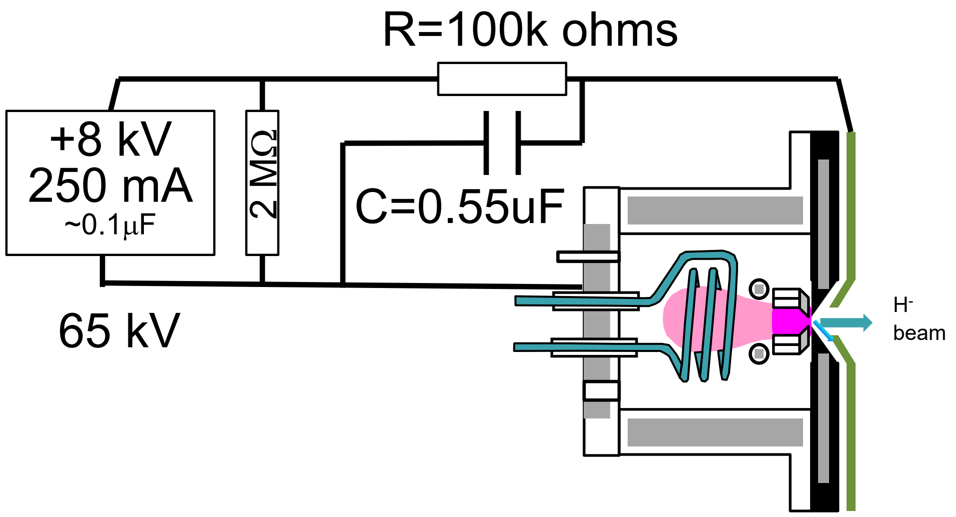


The internal antenna source has higher RF efficiency, almost 80%

This can provide some insight into why it is more difficult to implement dual frequency excitation in an external versus an internal antenna source

Recent R&D efforts: Stabilizing electron dump voltage decay

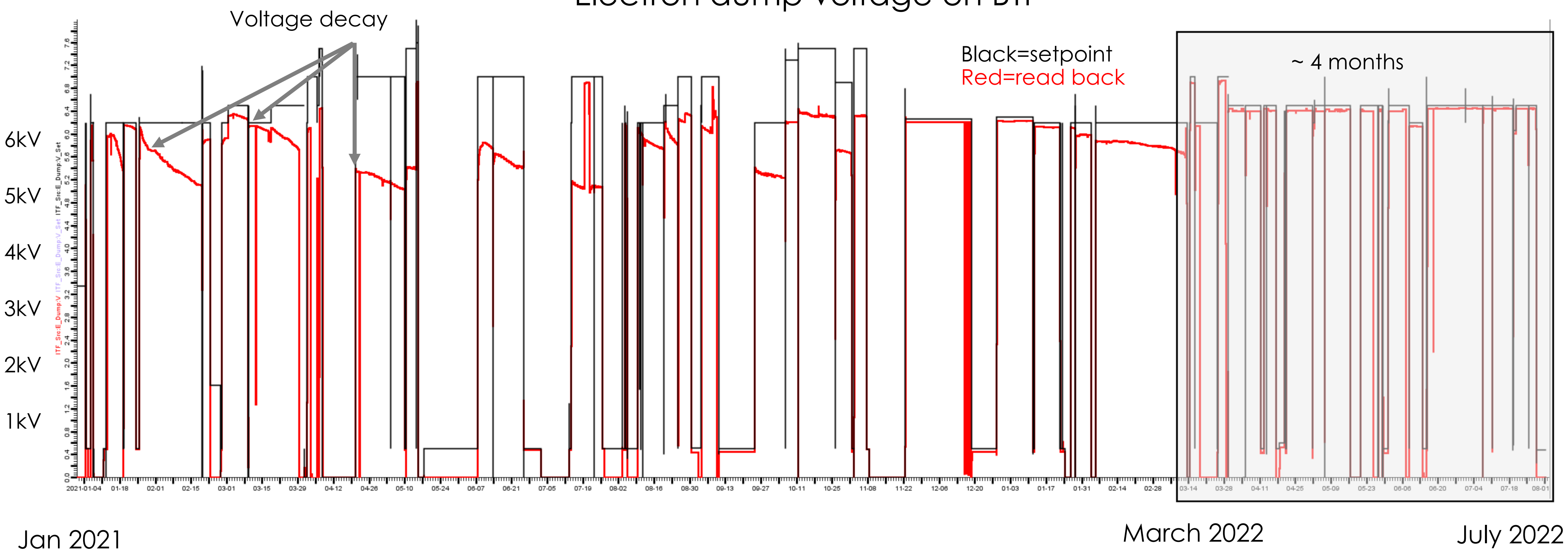
- SNS operations had long contended with a gradual sag of edump voltage over a 3-4 month run period.
- On the ISTS and BTF we implemented several candidate isolation circuits, gradually increasing capacitance until finally setting on this one



- The initial spike of electrons released from the plasma during the H^- pulse and periodic arcing events both to the source and to ground have likely caused the electron dumping supply (+8kV, 250mA) to struggle to maintain voltage over time.
- For example, we have observed ΔI~300 mA, Δt ~100 μs electron spikes from the beam pulse and know this can be much higher during arcing events
- Adding the RC circuit shown utilizes charge from C to source/sink this current while R will isolate and limit the current draw from the power supply.
- The charge needed from the capacitor during the spike is $\Delta Q = \Delta I\ \Delta t$ = 30uC; when this charge is consumed it will drop the voltage on the edump $\Delta V=\Delta Q/C$~54V and will thus require an additional current of $\Delta I = \Delta V/R$ = 0.5 mA from the power supply, well within range of the PS
- We recognize stored energy increases from 2 → 10 J representing a risk but also note that the Ion source high voltage supply operates with ~30J.

Electron dump stabilization circuit: electron dump voltage

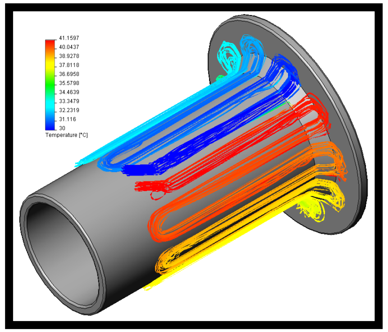
Electron dump voltage on BTF

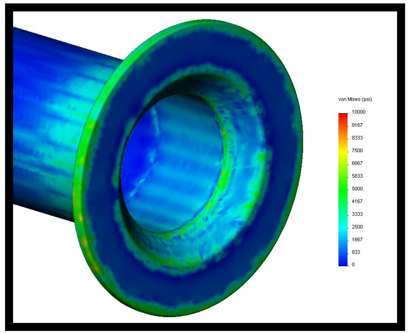


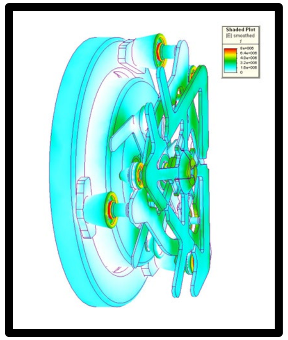
- Archieved electron dump voltage history on the BTF for 2021-2022.
- Electron dump voltage decay can be seen throughout the plot until March 21, 2022 when the electron dump circuit was installed
- Similar benefit was realized with an identical circuit on the ISTS also for ~4 months

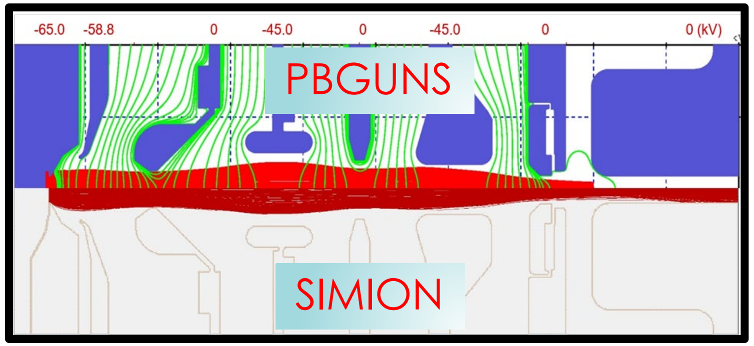
Computer Modeling and Inter-laboratory Collaborations

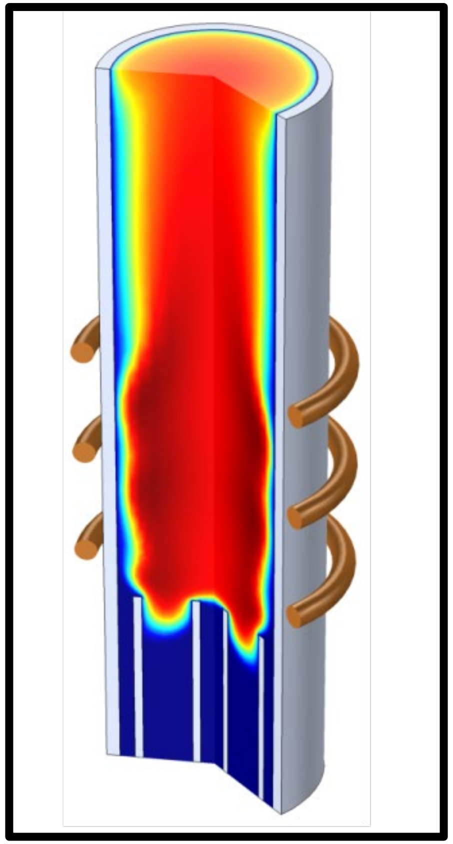
- Computer modeling has been a valuable tool in conducting ion source R&D and improving our ion sources and LEBTs. We have employed PBGUNS, SIMION, IBSIMU, ANSYS, SOLIDWORKS, Infolytica, LORENTZ and CST Studio. Recently we have expanded our tools to include **COMSOL, SIMSCALE and Circuit lab**



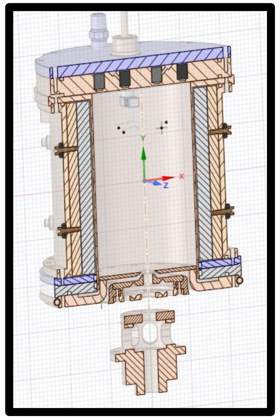


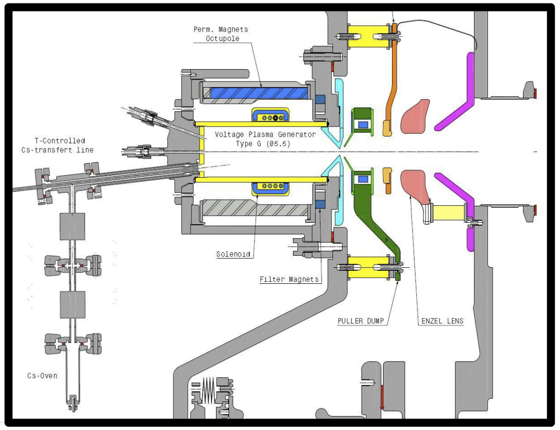






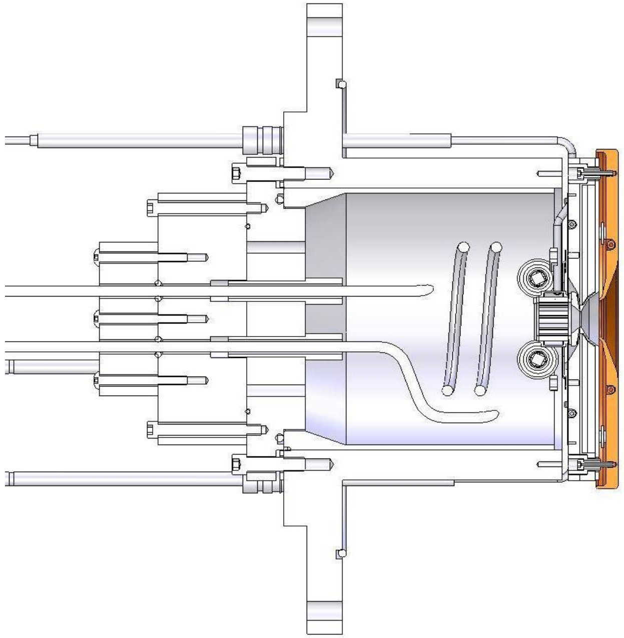
- The SNS ion source group participate in reviews and collaborations with many other laboratories: LANL, J-PARC, MIT, ISIS, CERN, D-Pace, SIPRC-ORNL and NanoSIMS-ORNL.

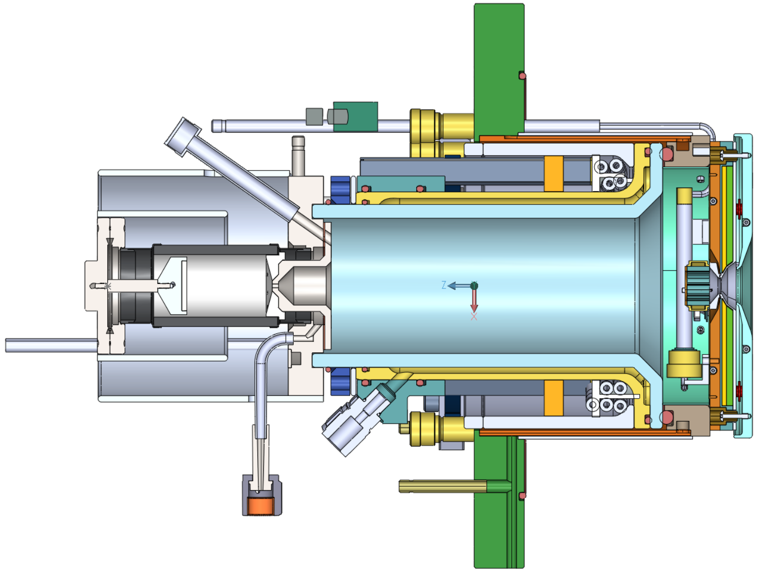




R&D highlights since the last NIBs

- The idea of simply opening the outlet aperture resulted in the extraction of significantly more beam current from the ion source. If emittance measurements are good this could be a significant step towards achieving the margin needed for future SNS facility upgrades.
- A production pulsed-plasma gun has been designed, built and tested on the Test bench. Performance greatly exceeds earlier versions; it now awaits testing with the SNS external antenna ion source
- A voltage stabilizing electron dump circuit has been incorporated into the BTF and ISTS eliminating voltage droop over time. It will be incorporated into the SNS production accelerator.
- Our group plans to significantly expand modelling capabilities and continues to foster many collaborations with other laboratories





In Loving Memory

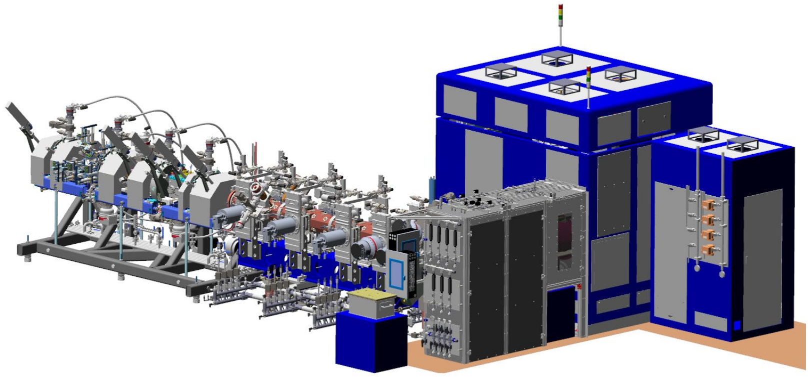
Aimee Andersen Dixon

1/12/1965 - 9/15/2022

Supplemental slides

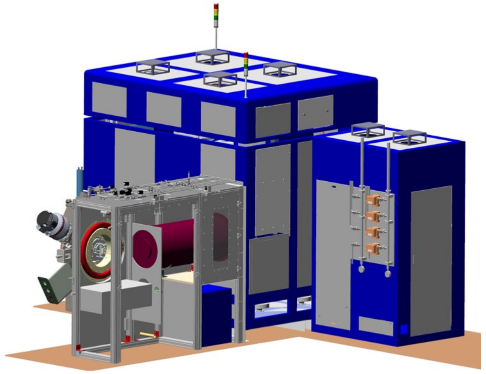
The SNS ion source test facilities

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



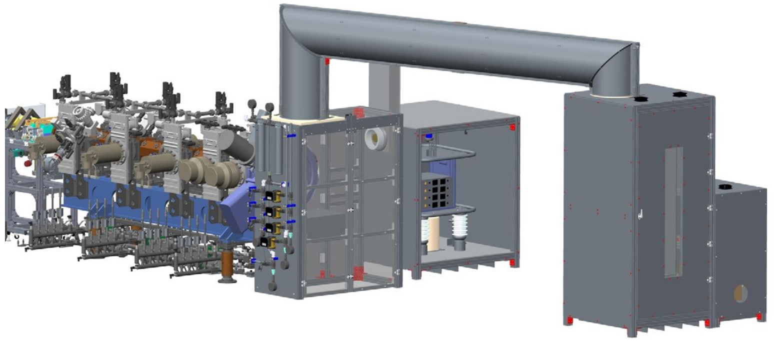
- Ion source
- LEBT
- RFQ
- Diag. in MEBT (beam current and emittance)

(a) The SNS Front End System



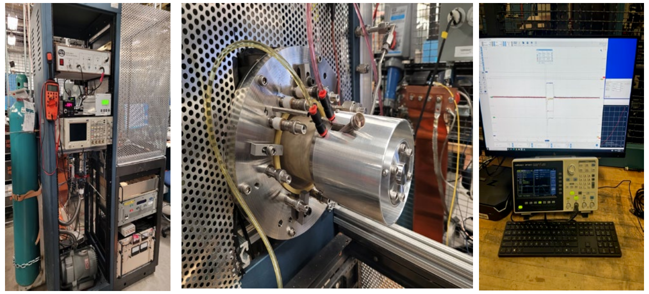
- Ion source
- LEBT
- BCM, FC, emittance

(b) The Ion Source Test Stand (ISTS)



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

(c) The Beam Test Facility (BTF)

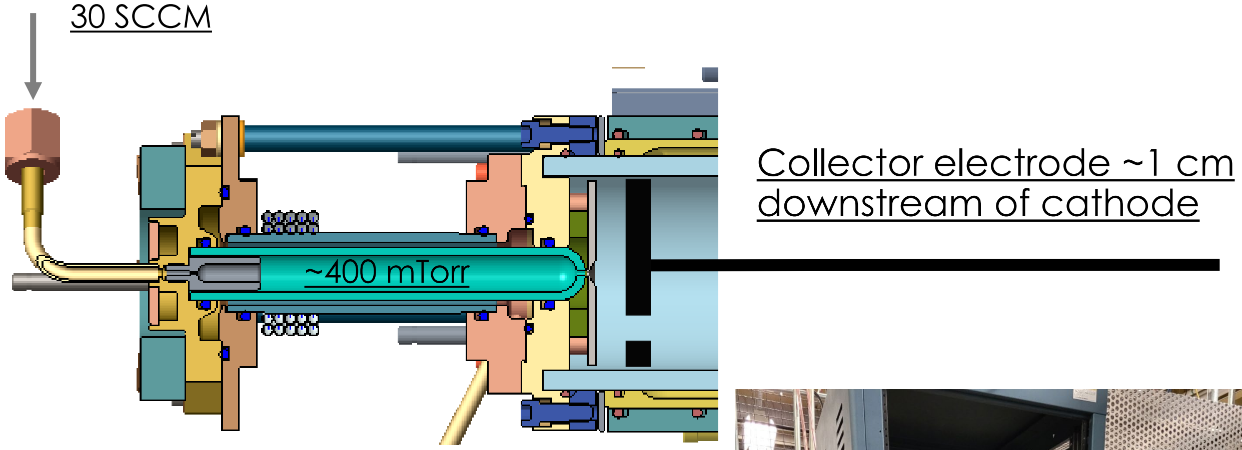


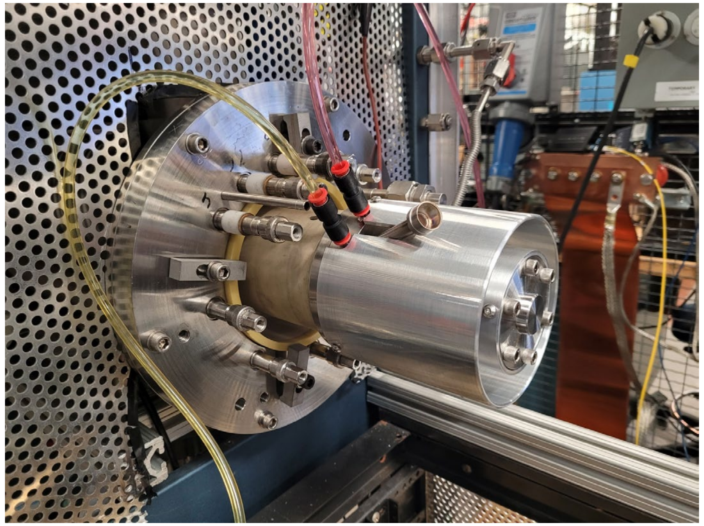
- Vacuum chamber
- DC, pulsed and RF power supplies
- Probe to measure emitted plasma flux
- Pico scope and signal generator

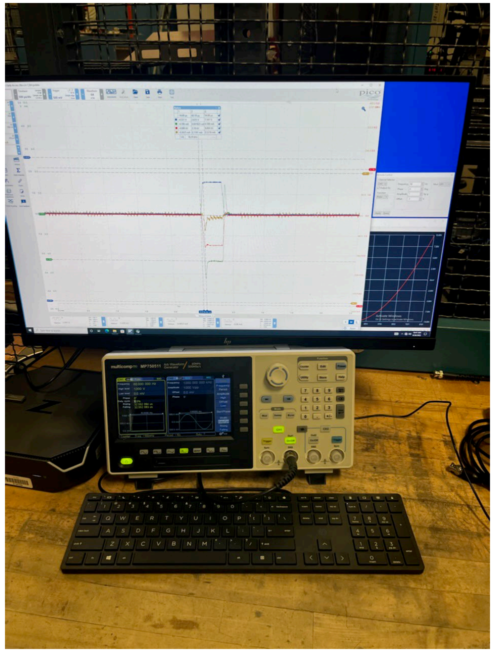
(d) The Plasma Gun Test Bench (TB)

External antenna source ignition: Plasma gun test bench

- In order to test and optimize plasma ignition guns we constructed a stand-alone, test bench capable of nominal gun operation in vacuum directly measuring output of the gun under nominal H_2 flow conditions
- 13 MHz 600W RF supply
- DC 3000V supply
- Pulsed 4kV, 20mA supply
- 700 l/s turbomolecular pump
- Signal generator & Pico scope







Recent internal antenna failure at the BTF and ISTS

- Overall, the SNS accelerator ion source continues to perform extremely well, see talk by B. Han
- These sources uses a top-tier porcelain enamel coated internal antennas essentially free of surface defects and coating thickness uniformity held to a tight tolerance. It usually runs for 3-4 months with minimal variations in source parameters, **no failures of these antennas in ~9 years on the SNS accelerator!**
- BTF and ISTS ion sources utilize near top-tier antennas, are replaced more frequently and often operated over a wide range of parameters
- Recently we had **2 antenna failures at these ancillary facilities** both from source #4. One failed on the ISTS very early in the run and the other after ~4 months of very higher power operation on the BTF
- These events and the risk of having a sole-source antenna vendor remind us of the **importance of continuing to develop the external antenna source**

Antenna failure:
Source #4, BTF, 3-19-22, earlier H2 bottle depletion   Source #4, ISTS, 7-11-22, near startup

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 **Cs collar** and **converter**
- 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)**