IPP Ion Sources for Fusion

Large RF-driven sources for H^- and D^- are developed for the NBI of the fusion experiment ITER.

Max-Planck-Institut für Plasmaphysik

	BUG	ELISE	ITER
P_{RF}	100 kW	300 kW	800 kW
A_{source} $A_{extract.}$ apert.#	0.3×0.6 m² 0.01 m² 70	1.0×1.0 m² 0.1 m² 640	1.0×2.0 m² 0.2 m² 1280
I_{acc} U_{tot}	2 A 50 kV	20 A 60 kV	40 A 1 MeV
All H^- and D^-, BUG & ELISE currently pulsed (10 s every 3 min), upgrade to cw extraction			

RF-driven Sources

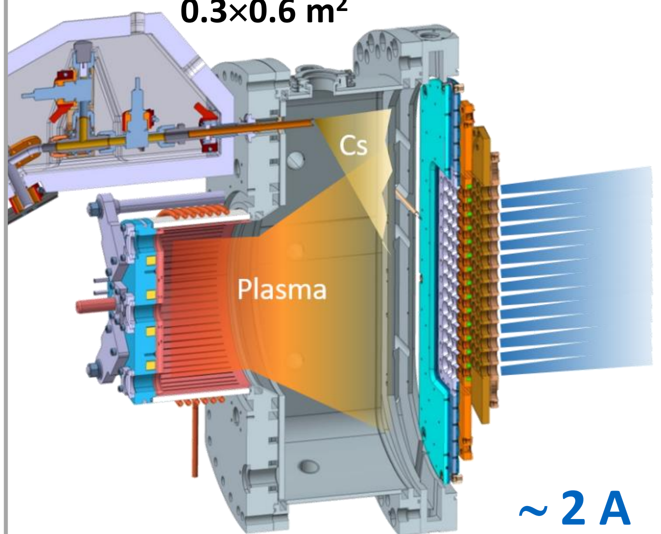
Modular concept – RF driver for plasma generation and one large expansion chamber.

Operation at 0.3 Pa with Cs for sufficient negative ions and for reduction of co-extracted electrons.

Multi-aperture extraction system with three grids:
PG plasma grid, EG extraction grid, GG grounded grid

BATMAN Upgrade, prototype source

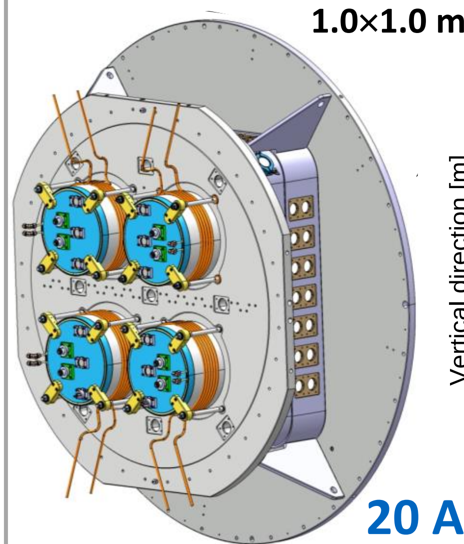
0.3×0.6 m²



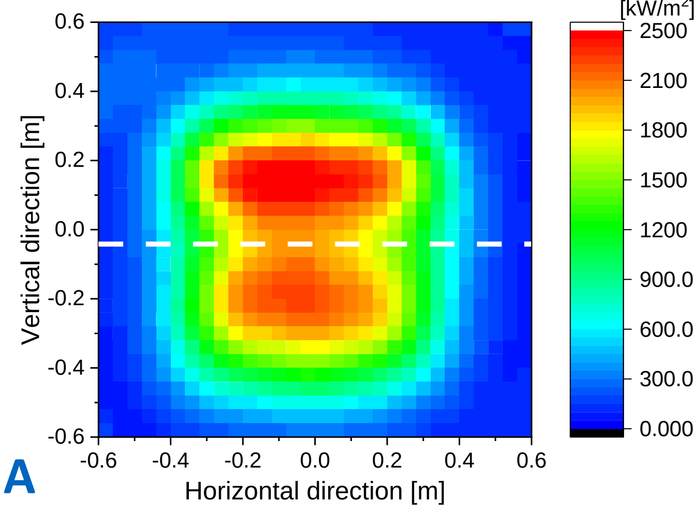
× 4

ELISE, ½ size ITER source

1.0×1.0 m²



Beam at the calorimeter



Diagnostics and Modelling

Plasma diagnostics: OES (n_e, T_e, T_{gas}, T_H), Langmuir probes (n_e, T_e, ϕ), TDLAS (n_{Cs}), CRDS (n_{H-})

Beam diagnostics: electrical current measurement, BES (divergence, stripping, uniformity), calorimeter (divergence, power density, uniformity)

Modelling: RF coupling (fluid code), collisional-radiative model (Yacora), meniscus (PIC code ONIX), beam transport (particle tracking codes IBSimu, BBCNI, ABC3D)

Glossary

NBI	neutral beam injection
P_{RF}	RF generator power
A_{source}	source area
$A_{extract.}$	extraction area
apert. #	number of apertures
I_{acc}, U_{tot}	accelerated current, total voltage
j_{ex}, j_e	extracted current density, co-extracted electrons
OES	optical emission spectroscopy
TDLAS	tunable diode laser absorption spectroscopy
CRDS	cavity ringdown spectroscopy
BES	beam emission spectroscopy

People attending the NIBS 2020

Dirk Wünderlich (ELISE test facility)
Andrew Hurlbatt (beam diagnostics)
Adrian Heiler (work function C12A7:e)
Ursel Fantz (division head)

Further reading

IPP overviews

Overview of the RF source development programme at IPP Garching, Speth et al. (2006)

Towards large and powerful radio frequency driven negative ion sources for fusion, Heinemann et al. (2017)

Recent status: BUG and ELISE

Advanced NBI beam characterization capabilities at the recently improved test facility BATMAN Upgrade, Fantz et al. (2019)

Achievement of ITER-relevant accelerated negative hydrogen ion current densities over 1000 s at the ELISE test facility, Wünderlich et al. (2019)

Modelling

Review of particle-in-cell modeling for the extraction region of large negative hydrogen ion sources for fusion, Wünderlich et al. (2018)

Yacora on the Web, Wünderlich et al. (2020)

The particle tracking code BBCNI for large negative ion beams and their diagnostics, Hurlbatt et al. (2019)

University of Augsburg – AG Experimentelle Plasmaphysik

Fundamental investigations supporting NNBI development at IPP

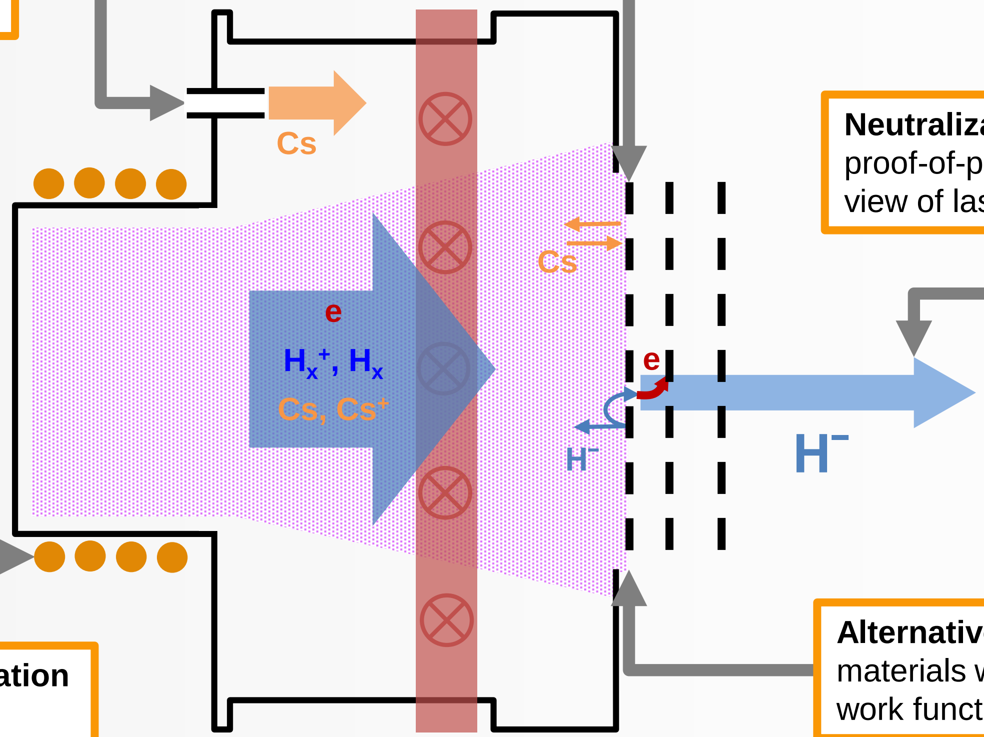
People at NIBS 2020
Adrian Heiler (WF C12A7:e)
Ursel Fantz (Prof.)

Fundamental plasma physics
atomic and molecular low-temperature plasmas

Diagnostics
development or adaption of diagnostic methods

Cs dynamics
work function of caesiated surfaces in vacuum and plasma

RF ion sources for fusion



Neutralization
proof-of-principle studies in view of laser neutralization

Efficiency of RF plasma generation
studies regarding power transfer efficiency, alternative RF concepts

Alternatives to Cs
materials with low surface work function

University of Augsburg – AG Experimentelle Plasmaphysik

Fundamental investigations supporting NNBI development at IPP

	ACCesS	HOMER	CHARLIE	PlanICE	Laser neutralizer cavity
Discharge type	planar ICP (27.12 MHz)	ECR (2.45 GHz)	ICP, Helicon (1-30 MHz)	planar ICP (2 MHz)	-
max. Power	600 W	1 kW	2 kW	2 kW	8 W
Pressure range	2-20 Pa	0.3-10 Pa	0.2-10 Pa	1-10 Pa	cavity: < 1mbar – 1 bar
Purpose in view of NNBI sources	studies on caesiated surfaces, work function of Cs alternatives	Cs alternatives, low power extraction system	RF power transfer efficiency, Helicon concepts	RF power transfer efficiency	stable coupling of cw laser into high-finesse cavity
Sample holder	yes	yes	no	no	-
Diagnostics	OES, Langmuir probe, (WABS), TDLAS Cs, (CRDS), SID, (QMB), RGA, WF	OES, Langmuir probe, (laser photo detach-ment), (CRDS)	OES, probes (Langmuir/ double/Mach), TDLAS H_α, VUV	OES, Langmuir probe, AC probe, TDLAS H_α, VUV, EMS	power meters, photodiode, CMOS camera, beam profiler
Modelling	CR modelling (Yacora), molecular band simulations				-

ICP: inductively coupled plasma
ECR: electron cyclotron heating
OES: optical emission spectrosc.
WABS: white light absorption spectroscopy
TDLAS: tunable diode laser absorption spectroscopy
CRDS: cavity ring-down spectroscopy
SID: surface ionization detector
QMB: quartz micro balance
RGA: residual gas analyzer
WF: work function meas. system
VUV: VUV spectroscopy
EMS: energy resolved mass spectrometer
CR: collisional-radiative

Further reading

Cs: Enhancing the accuracy of the Fowler method for…, Friedl (2016)
Correlation of Cs flux and work function of a converter surface…, Cristofaro et al. (2020)

Cs-free: Investigations on Cs-free alternatives for negative ion formation in..., Kurutz et al. (2017)
Work Function of Cs-Free Materials for…, Friedl et al. (2018)

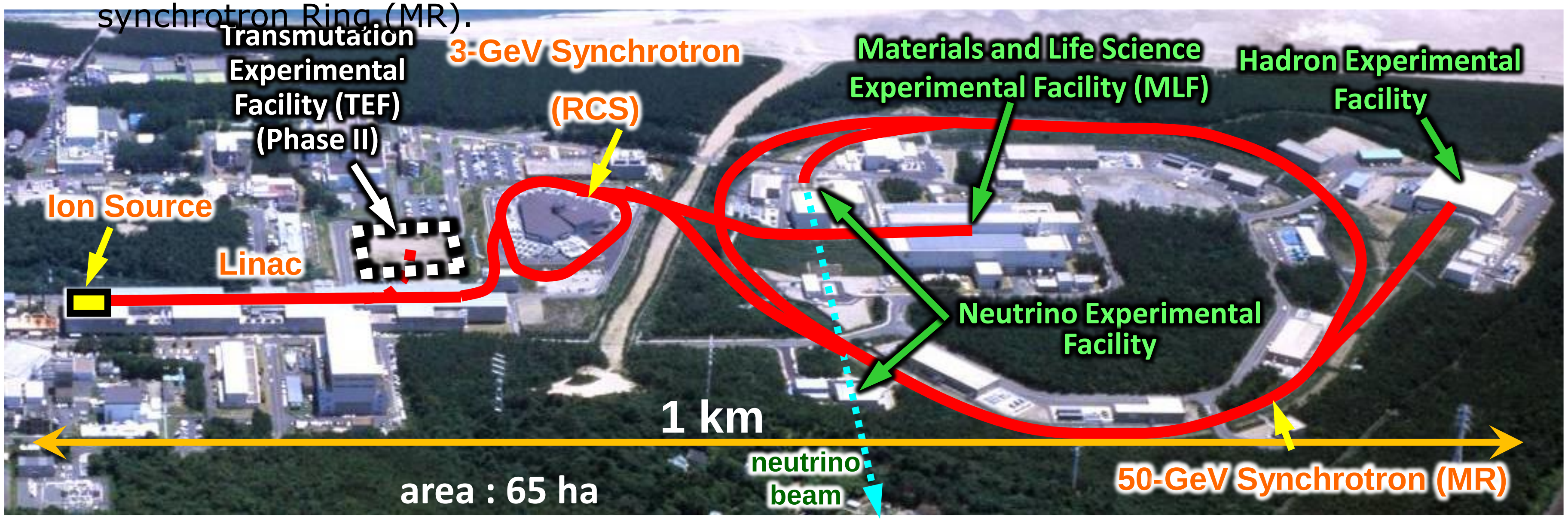
RF: RF power transfer efficiency of inductively coupled…, Rauner et al. (2017)
Influence of the excitation frequency on the RF power transfer…, Rauner et al. (2019)

Laser: Laboratory Experiment for the Development of a Laser Neutralizer…, Friedl et al. (2018)

Diagnostics: Application of a Langmuir probe AC technique for [EEDFs]…, Heiler et al. (2020)

Overview of the J-PARC
(Japan Proton Accelerator Research Complex)

- J-PARC comprises a high-intensity proton accelerator and the experimental facilities that utilize the proton beam.
- The J-PARC accelerator consists of a linear accelerator (Linac), a Rapid Cycling Synchrotron (RCS) and a Main synchrotron Ring (MR).



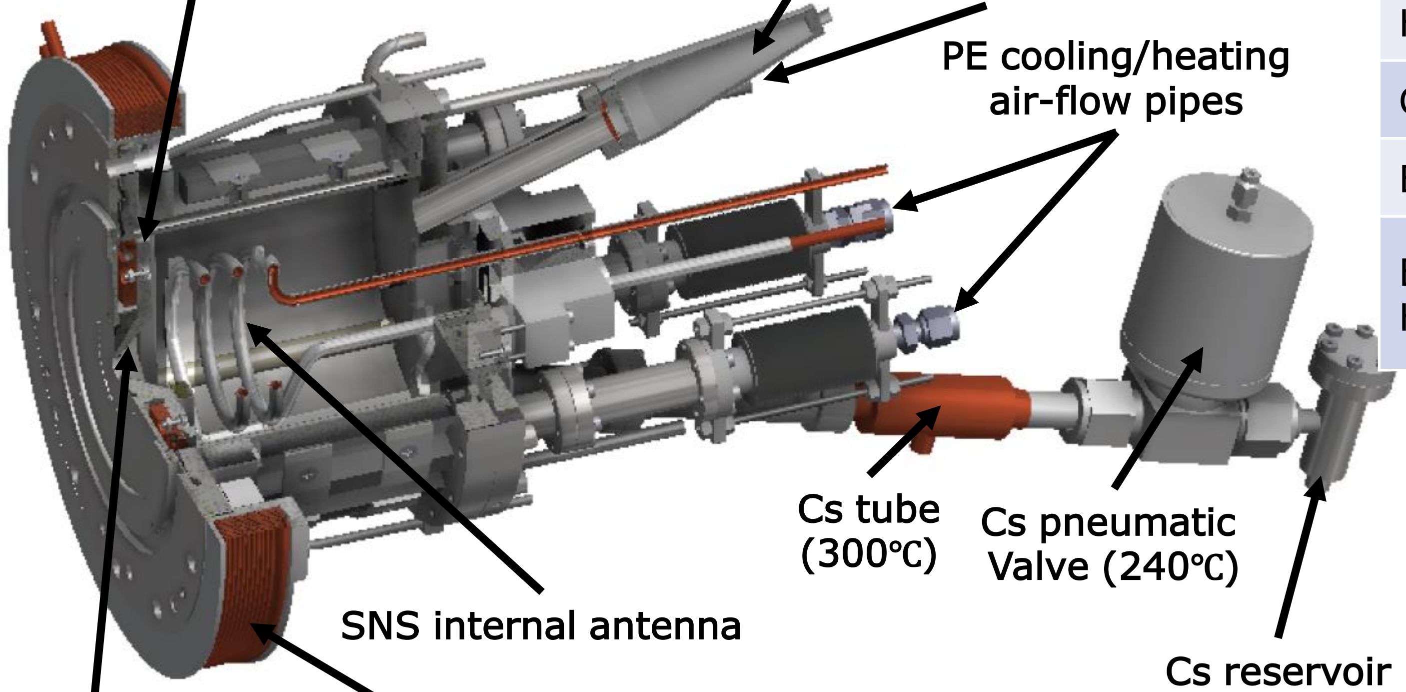
- The proton beams accelerated at the RCS are delivered to the Materials and Life Science Experimental Facility (MLF) and injected into the MR.
- After the proton beams accelerated at the MR, they are delivered to the Neutron Production Facility (NU) or to the Hadron beam Facility (HD).

Linac
- H^- **beam** acceleration
- Beam energy : **400 MeV**
- Beam current:
  50 mA for user operation
  60 mA for beam study
  (peak current at Linac exit)
- Pulse length : < 0.5 ms
- Repetition: 25 Hz

Rapid Cycling Synchrotron(RCS)
- Charge-exchange injection $H^- \rightarrow H^+$
- Beam energy :**3 GeV**
- Injection into MR
- Delivery to MLF
- Beam supply to MLF with the beam power of **600 kW** (in 2020)

Main Ring (MR)
- Beam energy :**30 GeV**
- Beam power
  - **500 kW** (in 2020) to NU
  - **50 kW** (in 2020) to HD

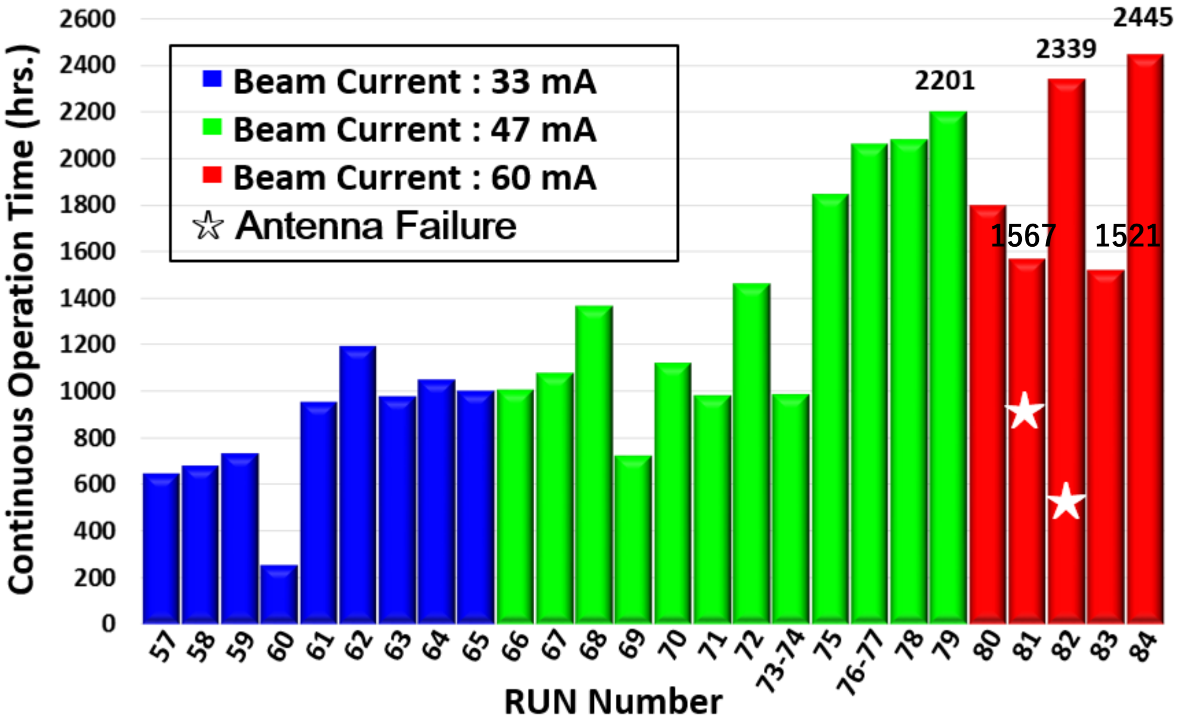
J-PARC Cesiated RF H^- ion source

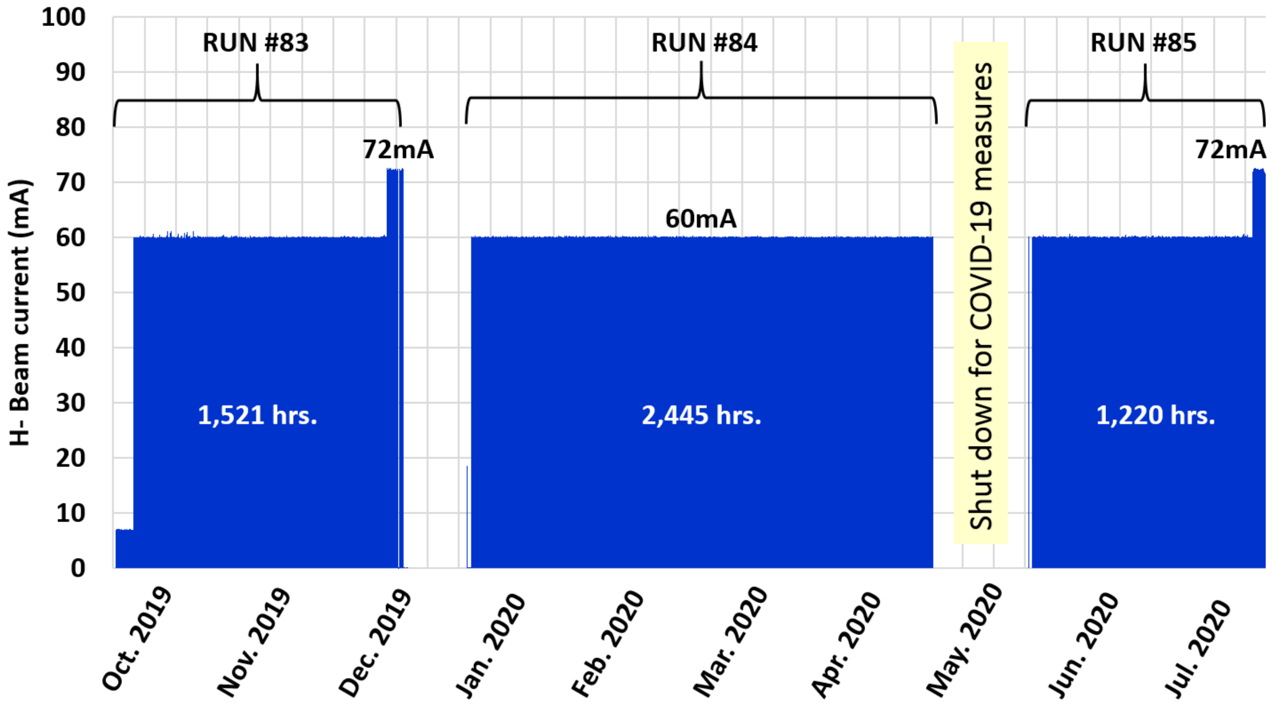


Specifications	
Discharge type	Internal antenna RF discharge
Repetition rate	25 Hz
RF frequency	30 MHz (cw, ~ 50 W) 2 MHz (0.8 ms pulsed, ~ 35 kW)
H_2 gas flow rate	21 sccm
Cs consumption	0.28 g in 1,567 hrs (in 2019)
Beam energy	50 keV
Extracted H^- beam current	60 mA (for user operation) 72 mA (for accelerator beam study)

- The inner volume of the plasma chamber is 100 mm in diameter and 120 mm in length.
- H_2 plasmas are confined by 18-pole cusp magnetic field.
- The aperture of the PE is 9 mm in diameter.

Progress of J-PARC RF H$^-$ ion source





<u>Continuous operation time prolonged :</u>

~1.5 months →2.5 months (Run#75)

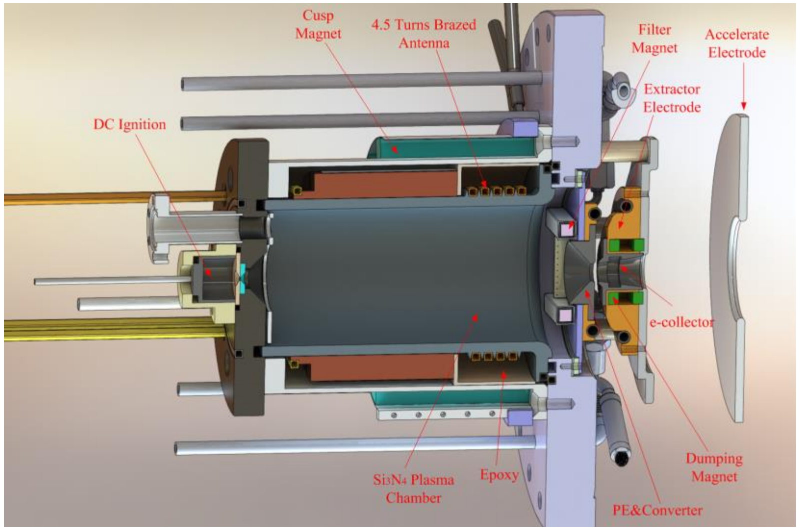
→3 months (2017 Autumn~) → 3.5 months (2020 Jan.- Apr.)

Ion Sources at China Spallation Neutron Source (CSNS)

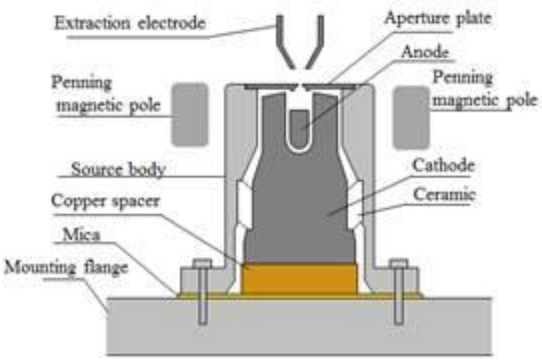
Negative Hydrogen ion sources

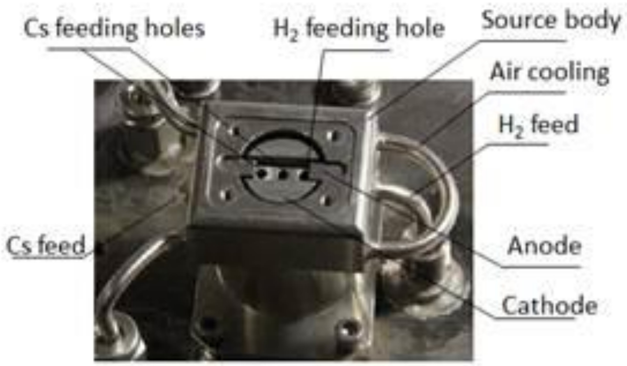
H-sources	Penning H- ion source*	RF-External Antenna
Status	Operation	Commissioning
Max Current	Up to 40mA	22mA-Uncesiated
Rep. Rate	25Hz	25Hz
Pul. Width	500us	Up to 1000us
Cesium Use	Cesiated	Uncesiated/Cesiated
Life time	4 weeks	>1 months

* A copy of ISIS ion source



CSNS RF ion source (commissioning)



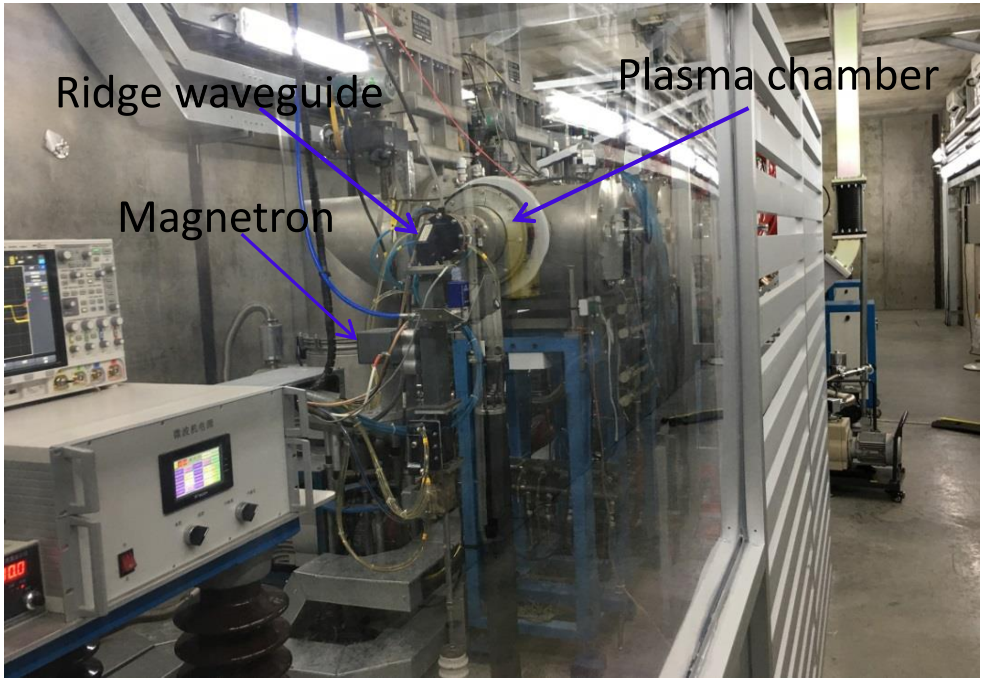


This ion source is designed referring to ISIS ion source. It is used at 25Hz-500us, with 40mA H-. Ce is required to improve H^- yield.

Proton Sources

This source is used for linear accelerator on Boron Neutron Capture Cancer Therapy (BNCT) facility.
ECR ion source is applied as a proton source. Protons are accelerated up to 3.0MeV by RFQ and bombard the Li target.

H2 flux	8.0sccm
Total beam current	70mA
Suppression Voltage	2.2kV
Beam Energy	75KeV
Discharge Power at 2.45GHz	1.5kW
Proton fraction	85%



FNAL Beam

A Magnetron H- source feeds a magnetic LEBT, RFQ, MEBT, and DTL which accelerates the ions to 400 MeV where the electrons are stripped off at injection into a Booster ring which accelerates the protons to 8 GeV prior to injection into the Main Injector for their final energy of 120 GeV. Protons are used for a wide range experiments ranging from fixed-target to neutrino production.

Sources

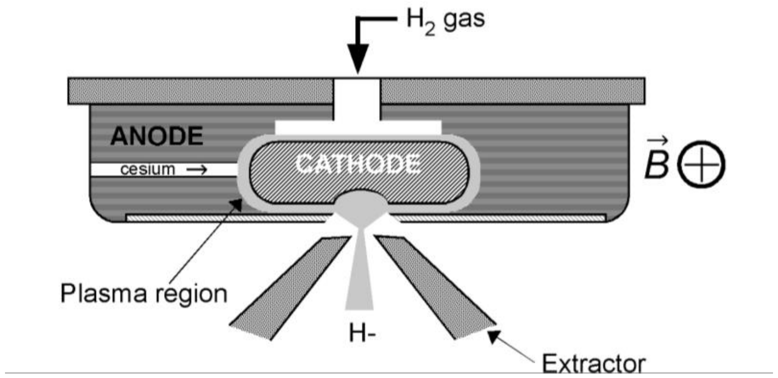
Operational- Cesiated magnetron, ions directly extracted at 35 keV (shown bellow). The source pulses at 15 Hz continuously for at least 9 months/year. High extraction voltage and low arc current have made for a long lifetime reliable source.

PIXIE- D-Pace CW ion source produces 10 mA of H- ions which are extracted at 30 kV into a magnetic LEBT and RFQ. This is a prototype front end for the future PIPII accelerator at FNAL.

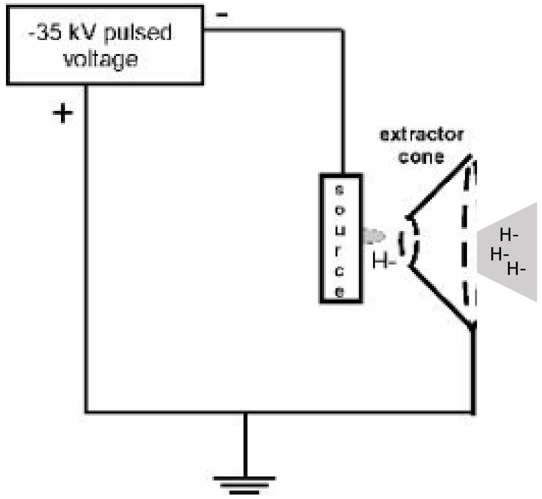
IOTA/FAST- Duoplasmatron proton source will produce 15 mA of H+ extracted at 30 kV. IOTA is a small R&D accelerator.

Operational	PIXIE (PIPII)	IOTA/FAST
Magnetron	D-Pace Volume-Cusp	Duoplasmatron
60 mA (H- ions)	10 mA (H- ions)	100 mA Protons
200 μs	DC	1.77 μs
35 keV	30 keV	30 keV
15 Hz	CW	Single turn

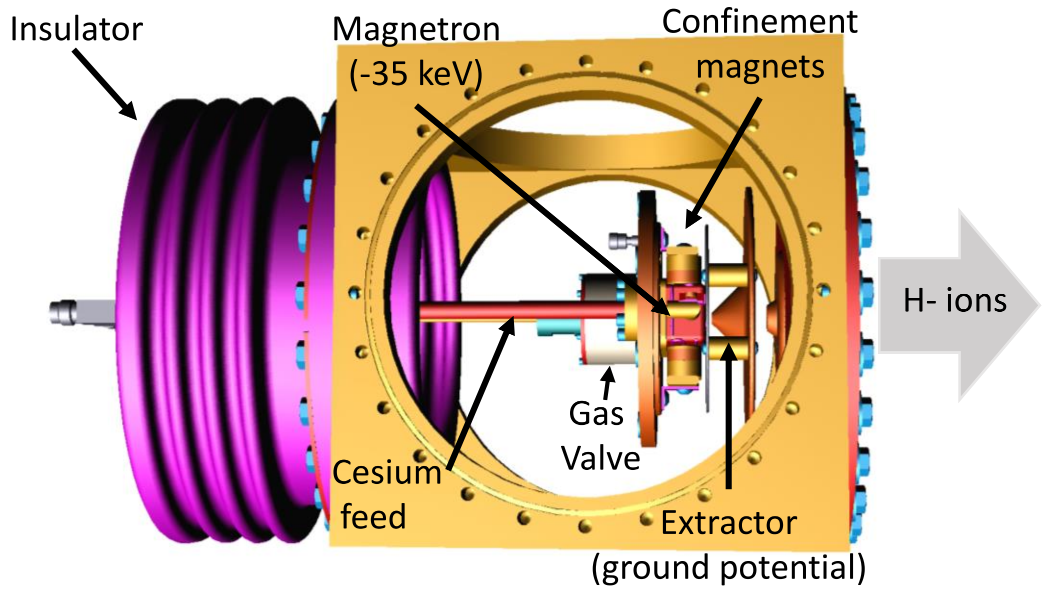
Magnetron



Extraction scheme



Operational Ion source



Operational Source Details:

Cathode-molybdenium with a spherical dimple that provides focusing of the ions towards the circular opening in the anode cover plate.

Cesium- 5g of metallic cesium in the “boiler” provide cesium vapor which lowers the work function of the molybdenum cathode for enhanced H- production.

Anode- as well as the anode cover plate made of molybdenium for reduced erosion

Extractor- 45 deg cone made of tungsten to reduce erosion from co-extracted electrons. Electrode is at ground protential.

Confinement magnets- 1 kG provide ExB field for plasma production as well as confinement. Stray magnetic field in the extraction region bend co-extracted electrons away from the extractor cone.

Gas Valve- Parker Series 9 solenoid pulsed valve operating at 160 V and varying PW.

Extractor Pulser- 35 kV DTI solid state pulser which rated for 50 kV and 50 A. Source and all electronics are pulsed to –35 kV.

People attending NIBS 2020:

Dan Bollinger- Group Leader
Pat Karns- Assistant Group Leader

Further Reading:

Installation and commissioning of the new Fermi National Accelerator Laboratory H- Magnetron
https://aip.scitation.org/doi/10.1063/1.4833023

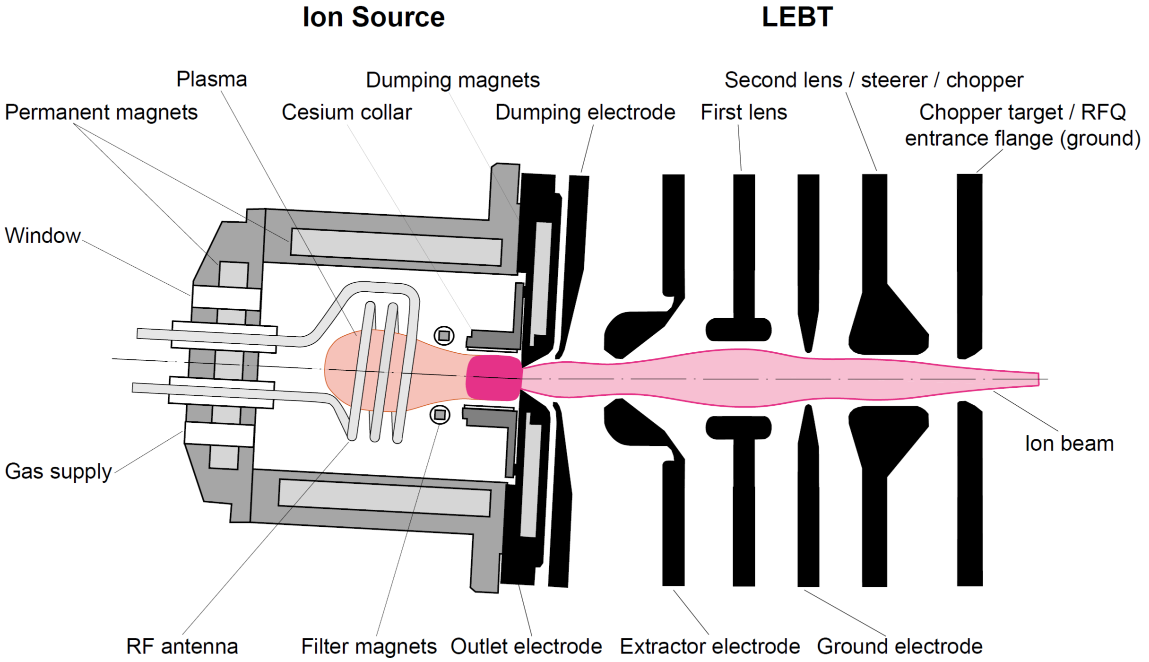
D. S. Bollinger, P. R. Karns and C. Tan, "A Cookbook for Building a High-Current Dimpled H− Magnetron Source for Accelerators," in IEEE Transactions on Plasma Science, vol. 43, no. 12, pp. 4110-4122, Dec. 2015, doi: 10.1109/TPS.2015.2491266.

A new solid state extractor pulser for the FNAL magnetron ion source
https://aip.scitation.org/doi/10.1063/1.4932121

Implementation of Design Changes Towards a More Reliable, Hands-off Magnetron Ion Source
https://arxiv.org/abs/1805.03049

The US Spallation Neutron Source

The Spallation Neutron Source (SNS) is the highest power pulsed neutron source currently operating worldwide and typically supports ~1000 users per year. The SNS accelerator system is sequentially comprised of an ion source, an electrostatic Low Energy Beam Transport system (LEBT), a 2.5 MeV Radio Frequency Quadrupole accelerator (RFQ), a series of higher-energy linear accelerators producing a 1 GeV beam injecting a proton accumulator ring which subsequently directs beam onto a liquid Hg target producing neutrons. The ion source produces pulses of H- ions with a current of 50-60 mA, pulse length of ~1 ms and repetition rate of 60 Hz. A LEBT chopping system divides the 1 ms pulse into ~1000 mini pulses for beam stacking into the ring and a fast kicker magnet then directs the stacked beam (~35 A at 1 GeV, ~1 us in duration) onto the Hg target at 60 Hz. Currently the SNS operates at 1.4 MW of proton beam power on target with plans to eventually reach 2.8 MW to simultaneously support a second target station. Approximately 35 and 46 mA, measured at the exit of the RFQ, are needed to achieve these target power levels, respectively.



The SNS Ion Sources

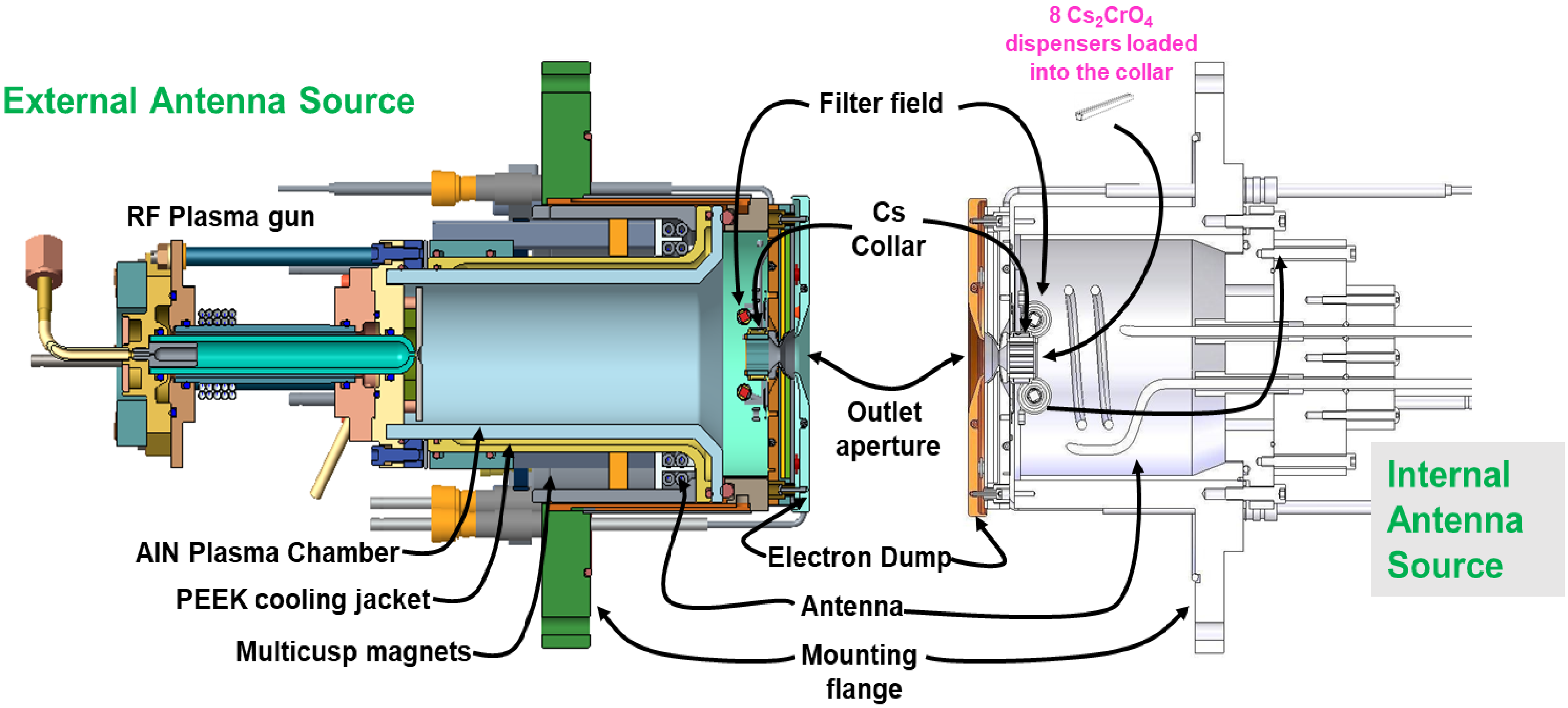
The Cs-enhanced, RF-driven, multicusp ion sources employed at the SNS deliver 50-60 mA of H^- current (pulse width: 1ms at a repetition rate of 60Hz) through an electrostatic LEBT with a normalized emittance of < 0.3 π mm mrad. The source can operate for periods up to 4 months without maintenance. The ion source plasma is confined by a multicusp magnet field created by a total of 20 rare earth magnets lining the cylindrical chamber wall (ϕ=10 cm, l=10 cm) and 4 magnets lining the back plate. RF power (2 MHz, 50-60 kW) is applied to a porcelain coated Cu antenna coiled to 2 1/2 turns and is immersed within the plasma chamber. A magnetic dipole (200-300 Gauss) filter separates the main plasma from a smaller H^- production region where low-energy electrons facilitate the production of large amounts of negative ions. An air heated/cooled collar surrounding this H^- production volume dispenses small quantities of Cs to enhance H^- production. A mixture of Cs_2CrO_4 with Zr and Al is heated to release mg quantities of Cs. The back plate of the source which holds the antenna can be seperated from the rest of the ion source to allow ease of maintenance. Once the negative ions are extracted a 1500-1700 G transverse magnetic field dumps the co-extracted electron beam on a dedicated dumping electrode maintained with a ~6 kV positive bias with respect to the extraction aperture. The SNS facility maintains 3 production internal antenna sources, 3 research-type internal antenna sources and 3 external antenna sources based on an AlN plasma chamber.

People Attending NIBs

- Robert Welton
- Baoxi Han

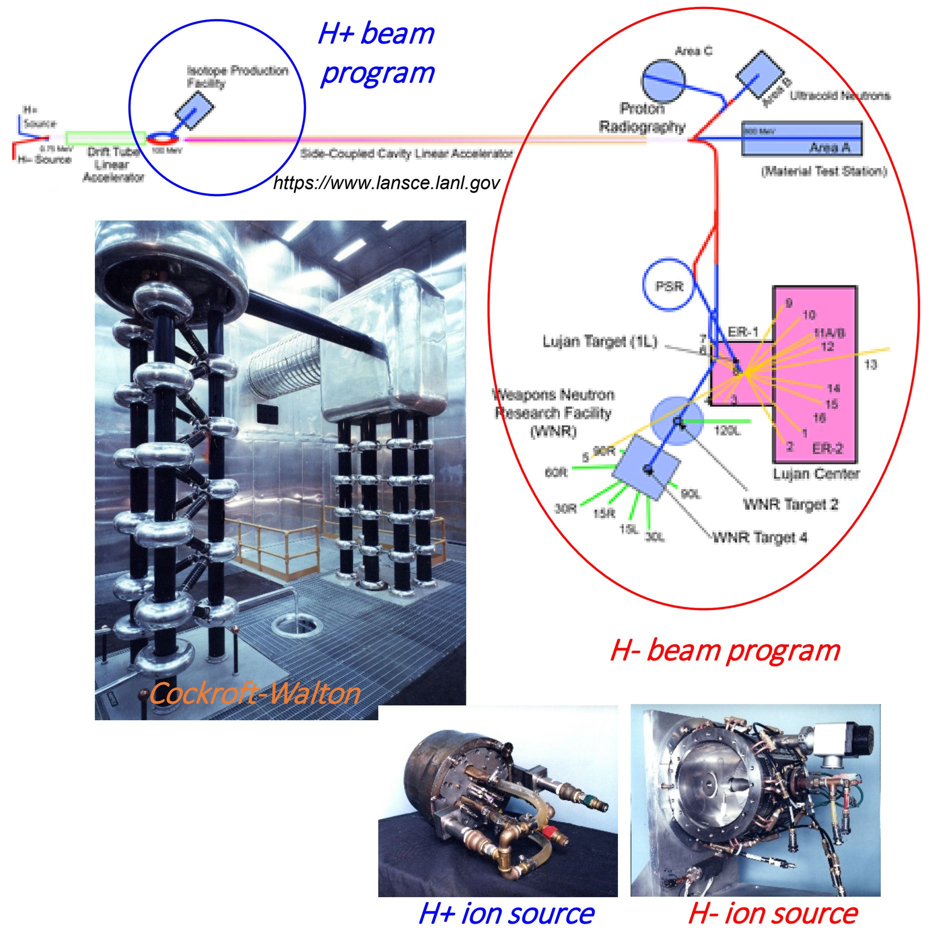
References

- R. Keller, et al, Sci. Instrum. 73 914 (2002)
- M.P. Stockli, et al, AIP Conf. Proc. 1869, 030010 (2017)
- B.Han, et al, AIP Conf. Proc. 1869, 30014 (2017)
- R.F. Welton, et al, Rev. Sci. Instrum. 91, 013334 (2020)
- R.F. Welton et al., Rev. Sci. Intrum. 73 1008 (2002)


External Antenna Source
RF Plasma gun
AIN Plasma Chamber
PEEK cooling jacket
Multicusp magnets
Filter field
8 Cs_2CrO_4 dispensers loaded into the collar
Cs Collar
Outlet aperture
Electron Dump
Antenna
Mounting flange
Internal Antenna Source

Los Alamos Neutron Science Center (LANSCE)

- H+ and H- beams
  - Injection to 750kV using Cockroft-Walton (C-W) Generators
    - H- beam has 80kV pre-extraction inside its C-W dome
  - H+ beam: 100 MeV, Supports one program.
  - H- beam: 800 MeV, supports multiple programs
- H- beam parameters
  - 120 Hz, 10% D.F. (833µs pulse)
  - 14-16 mA of H- current
  - Ion Source recycle every 4-5 weeks.



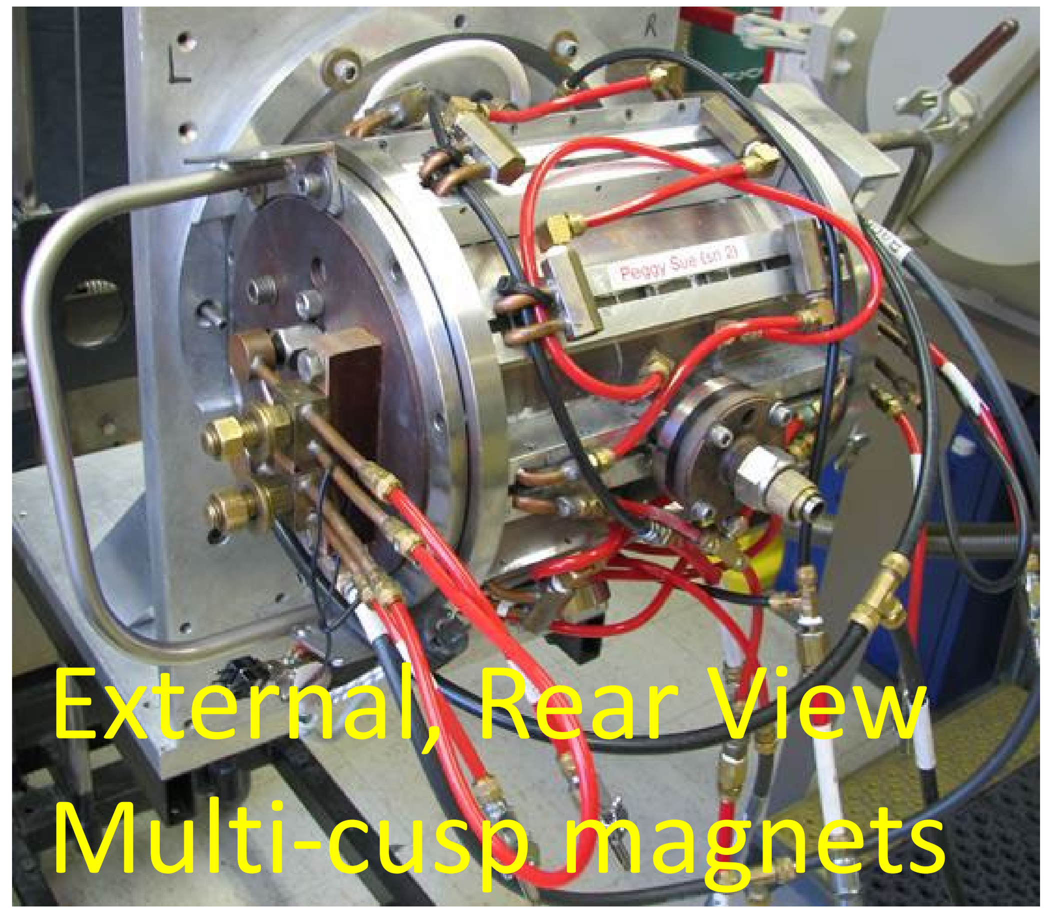
Further Information

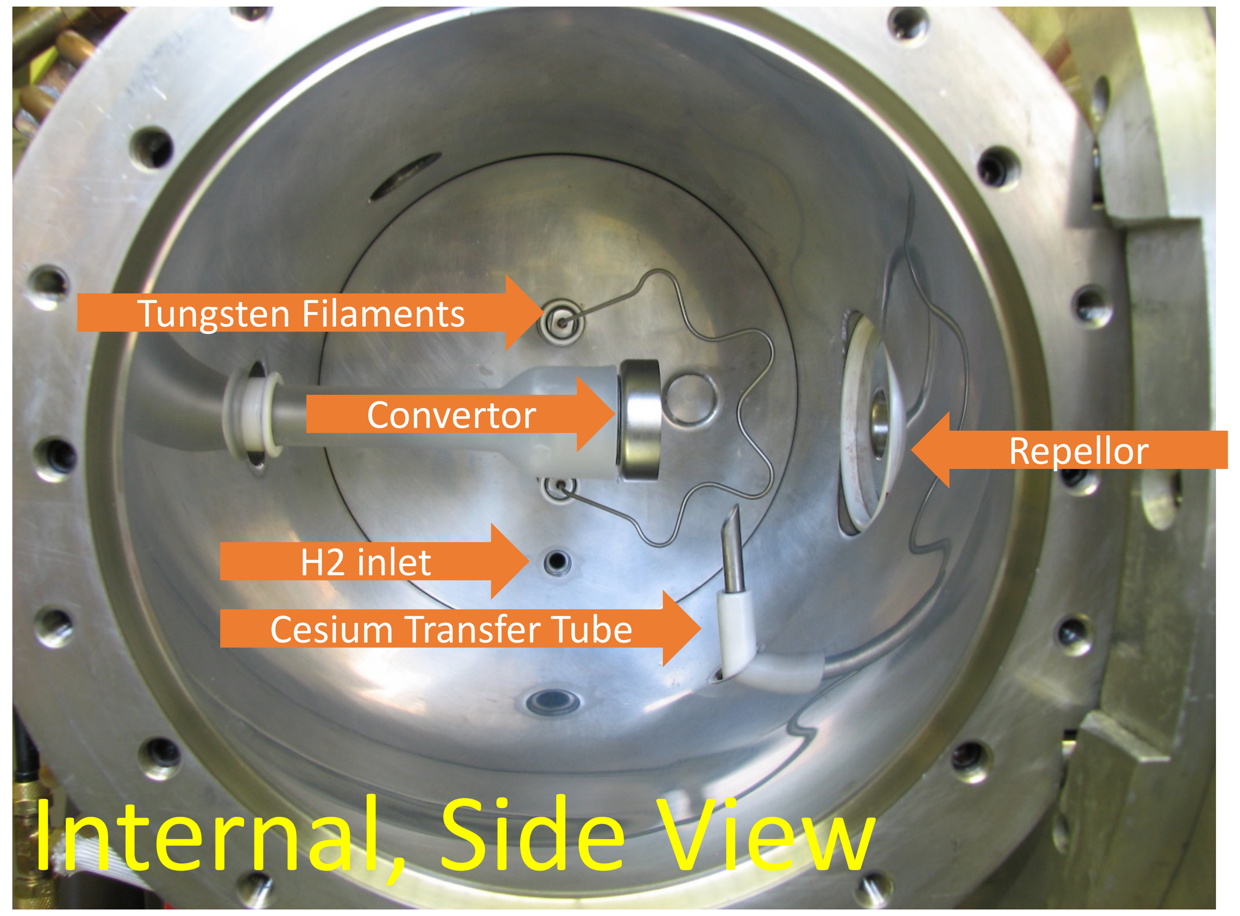
Website: https://lansce.lanl.gov/

NIBS 2020 Presentations
34. Modeling filaments in H- ion source from the first principles
36. Quantifying the Cesium and H- Densities Inside the LANSCE H- Ion Source with Laser Absorption Techniques
57. Transport of a negative ion beam through a hydrogen plasma

NIBS2020 attendees: Ilija Draganic, Enrique Henestroza, David Kleinjan, Nikolai Yampolsky

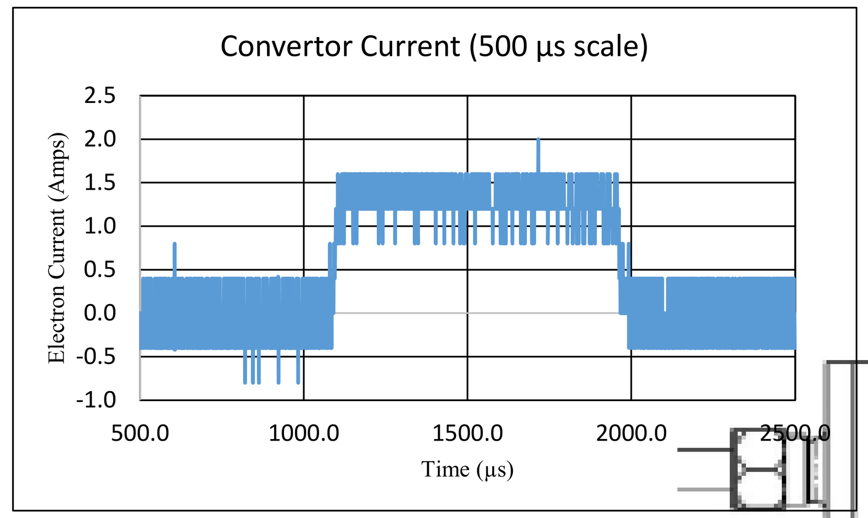
Multi-cusp Cesiated Surface Conversion H- Source



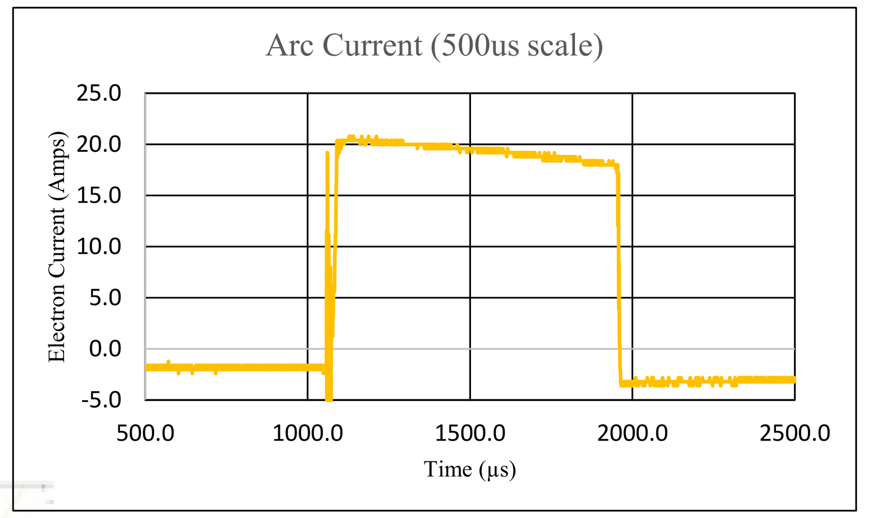


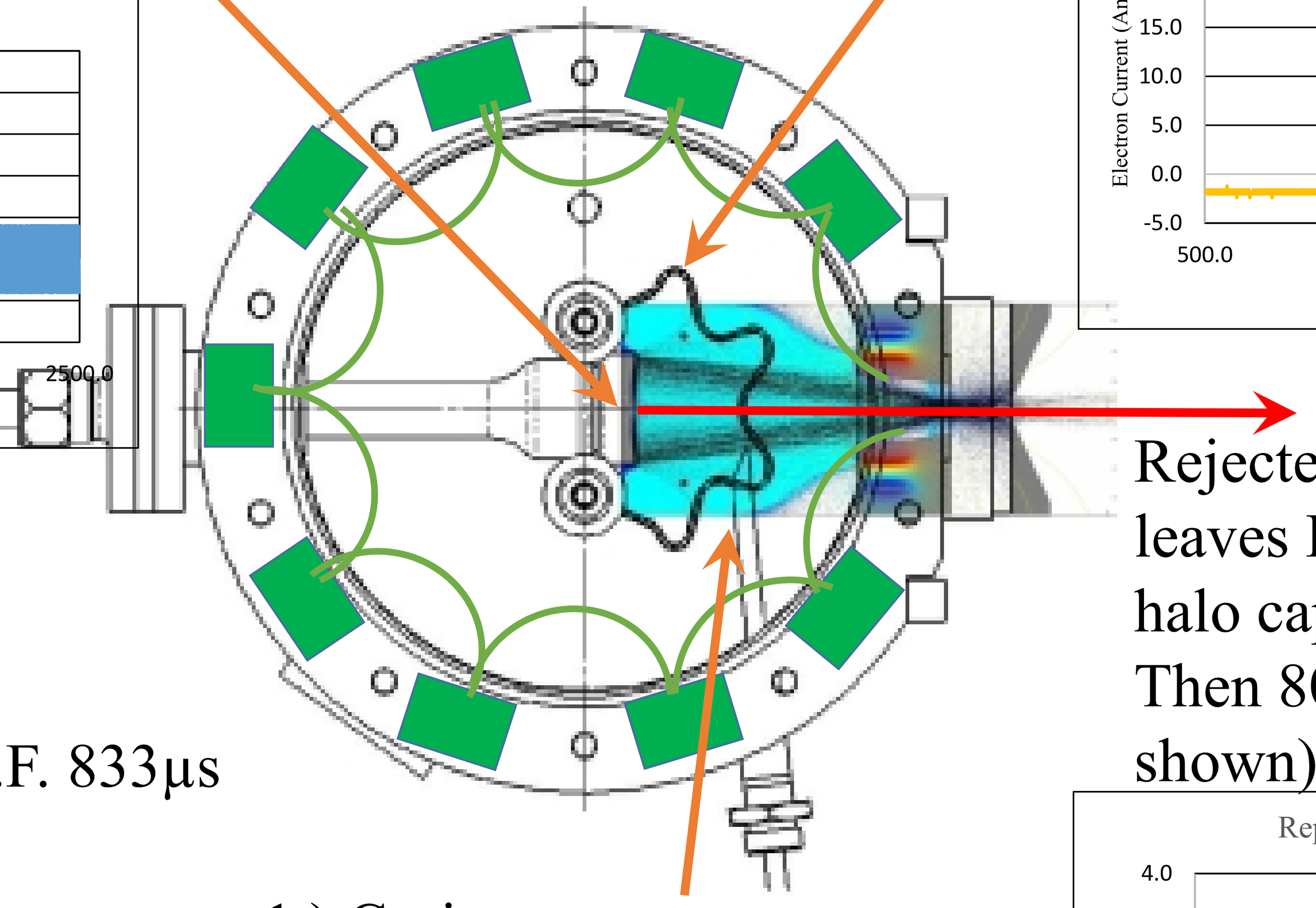
H- Ion source operation

3.) Convertor:
Negative potential bias attracts H+ ions low work function Cs gives up electrons to make H- ions.



2.) Filaments:
Arc pulse ionizes H_2, creates plasma confined by multi-cusp field

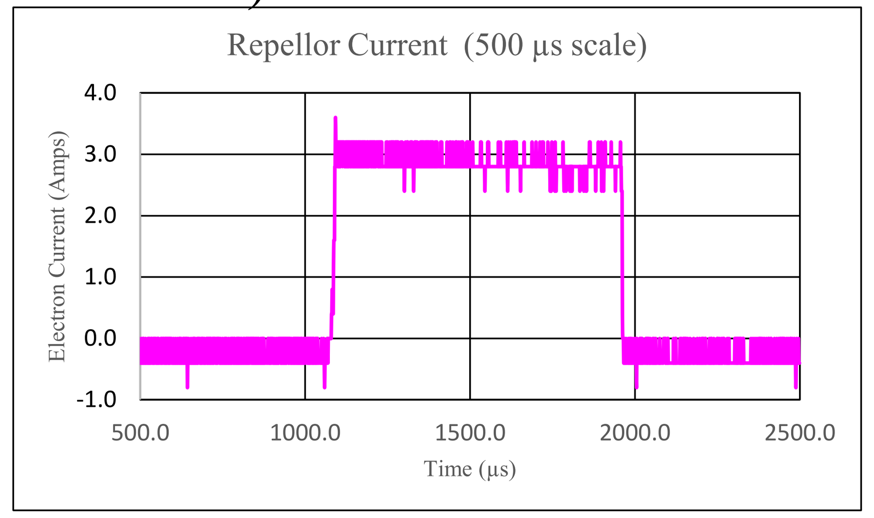




4.) H- beam
Rejected from Convertor leaves Ion source. Electron halo captured by Repeller. Then 80 kV Extraction (not shown)

Pulse information:
Timing: 120 Hz, 10% D.F. 833µs
Arc: 25-45 Amps
Convertor: 1-3 Amps
Repellor: 1-4 Amps
H- Beam: 14-16 mA

1.) Cesium:
Transfer tube deposits Cs continuously on convertor surface. Replaces Cs sputtered during beam pulse



ISIS Neutron Source

A H- ion source feeds a magnetic LEBT, RFQ, and DTL, for charge exchange injection into a rapid cycling synchrotron. Beam is accelerated to 800 MeV and directed onto tungsten and graphite targets to produce neutrons and muons for materials studies.

Science and Technology Facilities Council

Sources

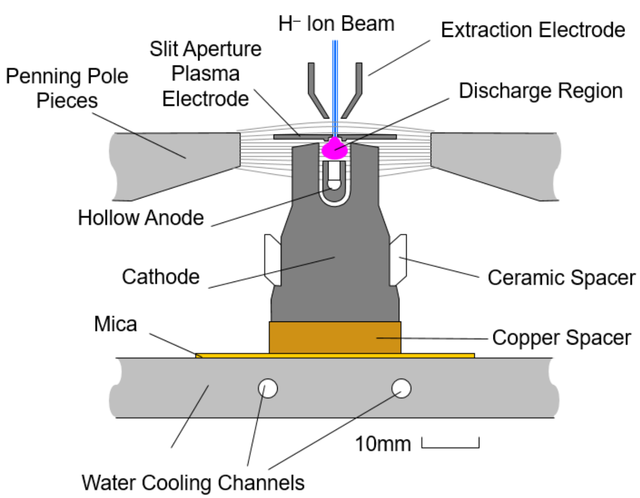
Operational Source – Caesiated Penning source, ions extracted into 90° dipole with cooling to trap Cs, pictured below.

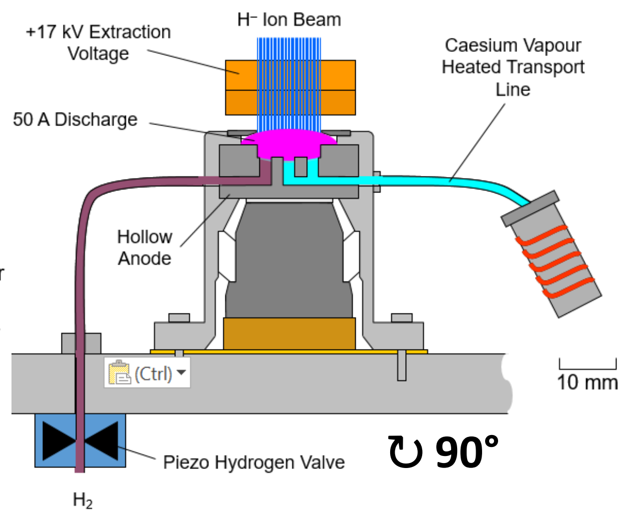
VESPA – operational source without dipole, developed to facilitate diagnoses, characterise the plasma, experiment with performance.

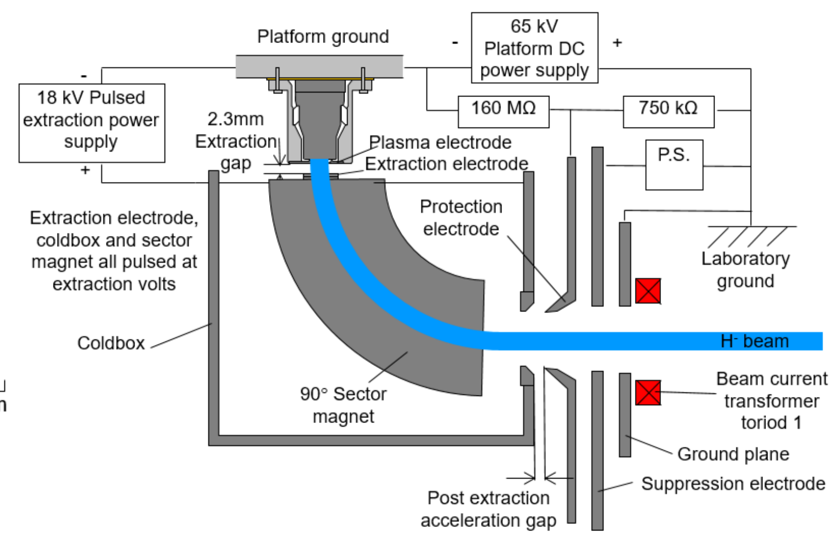
2X Scaled Source – operational source without dipole, plasma chamber and aperture dimensions each doubled to ease thermal load on electrodes. Used for long pulse experiments with potential for use on FETS.

RF Source (in development) – External antenna, 2MHz, uncaesiated source being designed and built to replace operational source, offering lifetime and reliability improvement. Design largely based on CERN Linac4 and SNS.

Operational	VESPA	2X Scaled	RF Source
Penning	Penning	Penning	Ext. Ant. RF
Op.	Exp.	Exp.	Devel.
55 mA	Up to 100 mA	75/150 mA	30mA
250 µs	Up to 1.2 ms	800/2000 µs	250 µs
Caesiated	Caesiated	Caesiated	Uncaesiated
All produce H-, repetition rate 50 Hz			







Glossary

Arc pulse – the arc discharge formed between the anode and cathode, from which ions are extracted
Arc oscillations – at the beginning of the arc pulse, interactions between power supply and plasma cause oscillations in arc current.
Aperture plate – a molybdenum plate with a slit, the geometry of which heavily influences beam emittance
Cold box – used to capture caesium leaking from the operational source, it contains the 90° dipole magnet
Discharge pulse – same as arc pulse
Droop – refers to the decrease in current observed towards the end of long beam pulses
FETS – Front End Test Stand, a linear accelerator in development at ISIS to test novel accelerator technologies. Requires long pulses >1 ms
MEBT Project – parallel to the development of the RF source is a new Medium Energy Beam Transport, which will reduce current losses between LEBT and RFQ
PyQT – a Python package based on a C++ library called QT. Used to make GUIs
PyVISA – a Python package designed to handle serial communications using VISA protocols. Very easy to work with.
Ramping – increasing or decreasing the arc discharge during beam extraction so that the resulting beam is not square

People attending NIBS 2020

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Further reading

https://www.isis.stfc.ac.uk/Pages/home.aspx

S. Lawrie's thesis:
Lawrie, S. R. Understanding the Plasma and Improving Extraction of the ISIS Penning H– Ion Source

Introductory texts:
Faircloth, D. & Lawrie, S. An overview of negative hydrogen ion sources for accelerators. *New J. Phys.* **20**, 025007 (2018).
Faircloth, D. Ion Sources for High-Power Hadron Accelerators. 39.

2X Source:
Faircloth, D. C. *et al.* 2X scaled Penning source developments. in 050028 (2018).
Faircloth, D. C. *et al.* High current results from the 2X scaled Penning source (2018).

RF Source:
Tarvainen, O. *et al.* The RF H– ion source project at RAL. in 050005 (2018).