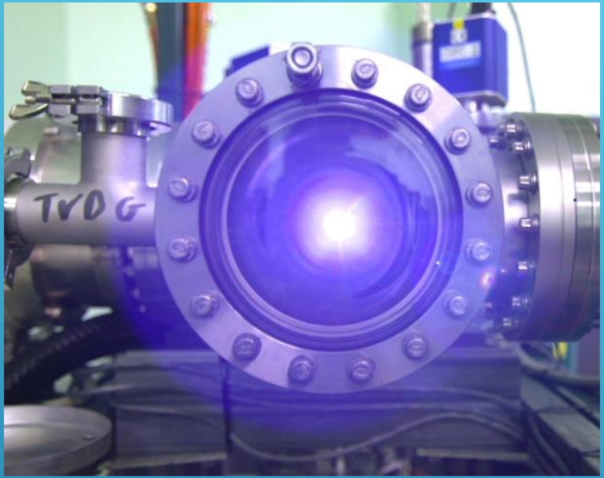
A Windowless Window to the Universe



Vacuum Separation by a Plasma Window for Nuclear Astrophysics Research
(and Various Applications)

Ophir Ruimi, Physics Ph.D. Student

HUJI Fundamental Interactions Group, Prof. Guy Ron

JGU Mainz & HIM, MAM Section, Prof. Dmitry Budker

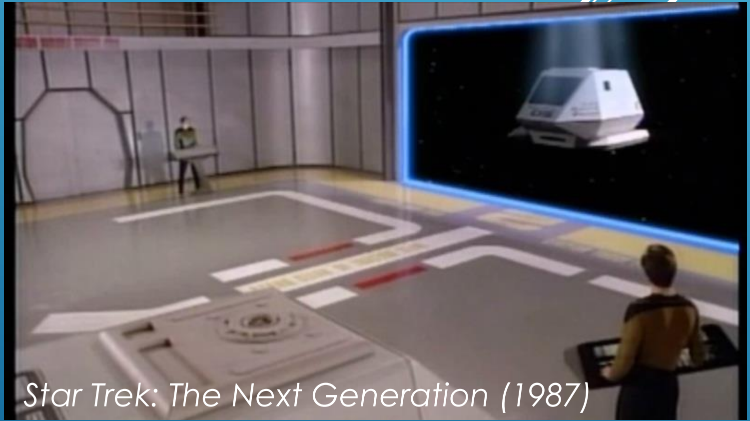
MPA Summer School – Fraueninsel, September 13th, 2023

What is a Plasma Window?

The **Plasma Window** is a novel apparatus that utilizes a stabilized plasma arc as an interface between vacuum and atmosphere or pressurized targets without solid material. It’s useful in non-vacuum electron-beam welding, as well as in some Physics experiments.

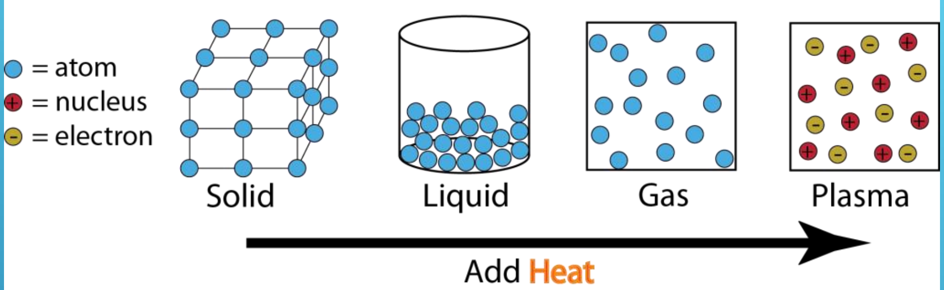
Talk Outline

- Why Plasma Windows
- Operation principles, applications, Sci-Fi
- Motivation: electron, ion and photon beam transmission from vacuum to atmosphere
- Example: Stellar nucleosynthesis
- Nuclear Astrophysics at SARAF: Liquid Lithium and enriched water targets
- Results, conclusions and future work
- Answer questions



Star Trek: The Next Generation (1987)

The states of matter and the idea behind a Plasma Window



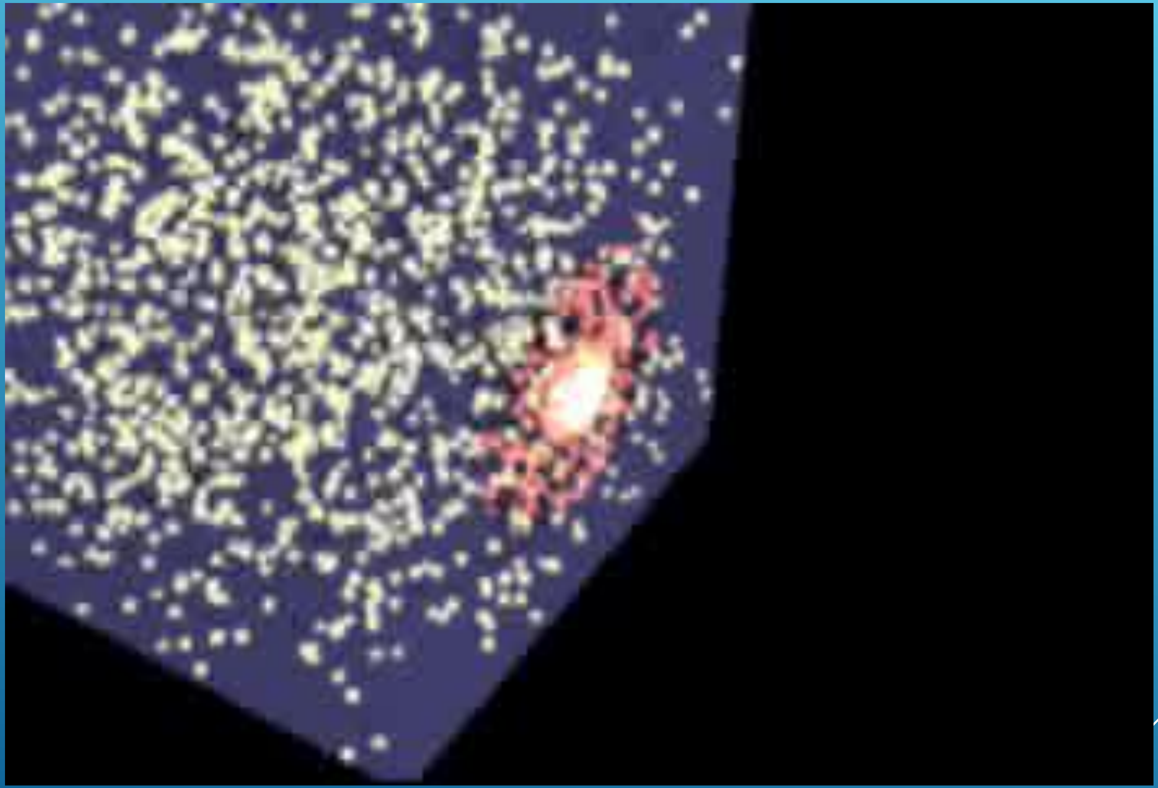
Plasma is ionized gas comprising of ions and electrons. Just like any other gas, plasma exerts pressure. Electric and magnetic fields exert forces on plasmas, which can confine plasmas in vacuum whose pressure can block, curb or confine other fluids. In a Plasma Window, electric and/or magnetic fields confine plasmas, whose pressure is large enough to balance atmospheric pressure (or even higher).

A plasma is **much less dense** than a gas when both are at the same pressure.

Plasmas have a **much larger resistance to flow (viscosity)** than gases.

A plasma "plug" or "window" can slow down the flow of gases with little effect of fast particles passing through it.

Simulation of a cube in empty space filled with air having a hole plugged by a Plasma Window; Courtesy of Jeffery Mitchell (BNL)



Operation Principles

Ideal Gas: ***p = nkT***

Where p is the partial pressure, n is the density and T is the temperature of the gas or the plasma, k is the Boltzmann constant.

Viscosity: $$\boldsymbol{Q = \frac{\pi d^4}{16\eta l} p_a (p_1 - p_2)}$$

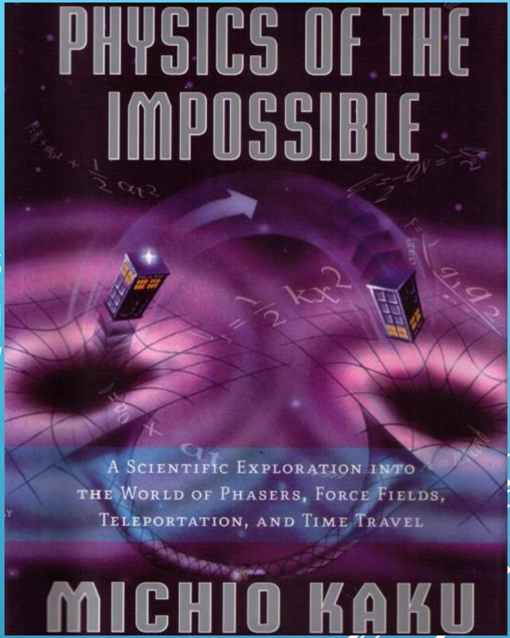
Poiseuille equation for the gas flow rate Q, where d and ℓ are the tube radius and length, η is the gas viscosity, and p_a is the arithmetic mean of p_1 and p_2.

A critical assumption, gas is incompressible. Compressibility can be neglected if the Mack number M satisfies $0.5\,M^2 \ll 1$. Some of the assumptions are no longer valid once a discharge is initiated, since the flow becomes compressible and nonisothermal. Therefore, a thorough analysis of such a gas and plasma flow requires solution of Naviar-Stokes equation for the gas. For electrons and ions, the relevant transport equations are the continuity, momentum transfer and viscosity equations:

- $\frac{D}{Dt} n_{e,i} + n_{e,i} \nabla \cdot \underline{V}_{e,i} = 0$
- $m_{e,i} n_{e,i} \frac{D}{Dt} \underline{V}_{e,i} = -\nabla p_{e,i} - \nabla \cdot \underline{P}_{e,i} + q_{e,i} n_{e,i} \left[\underline{E} + \underline{V}_{e,i} \times \underline{B} \right] + \underline{R}_{e,i}$
- $\eta_i = 2 \times 10^5 \mu^{1/2} \frac{k}{\lambda_i} T_i^{5/2}$
- $\eta_e = 2.5 \times 10^7 \frac{k}{\lambda_e} T_e^{5/2}$
- $\eta_{gas} = a T^x$

Where m is the particle mass and q its charge. $\underline{R}$ is the species total momentum transfer, p its partial pressure and $\underline{P}$ is the stress tensor, $D/Dt = \partial_t + \nabla \cdot \underline{V}$; η is the viscosity, λ is the Coulomb logarithm. The Naviar-Stokes equation is basically the momentum equation without the electric and magnetic field terms. **Note viscosity dependence on temperature *x>1* for gases.**

The Sky is not the Limit – When Sci-Fi Meets Reality: Plasma Window Has Captured People's Imagination

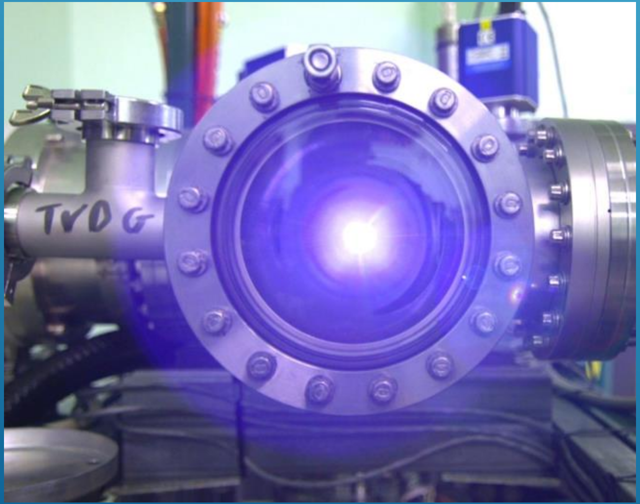


Featured in popular science magazines, newspapers, Michio Kaku's book **Physics of the Impossible** and in an accompanying syndicated article **10 Impossibilities Conquered by Science** @#8 **PW** is listed under **Creating force fields.**

Star Trek Shuttle's Bay Door

Star Trek: The Next Generation (1987)

A Plasma Window at BNL



Force fields

Star Wars: A New Hope (Episode IV), George Lucas 1977

The shield around the USS Enterprise

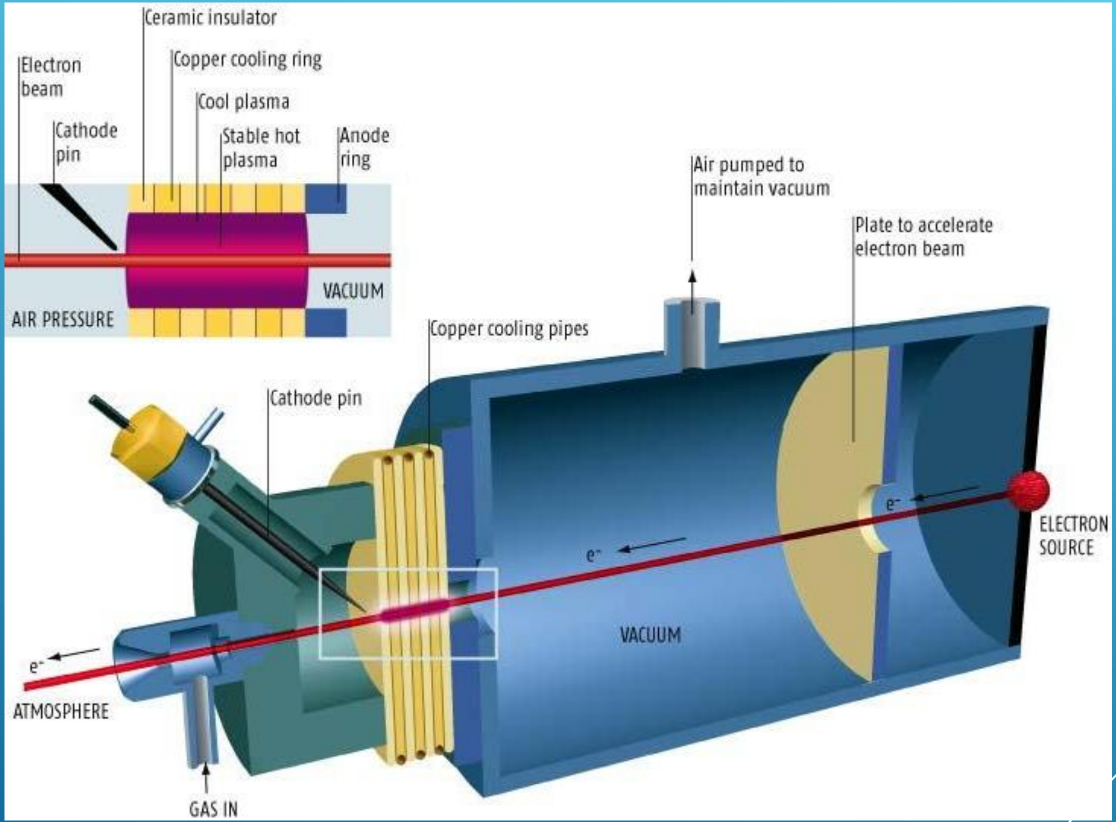
Dome in the battle of Wakanda

Avengers: Infinity wars (2018)

The Gungan handheld shields

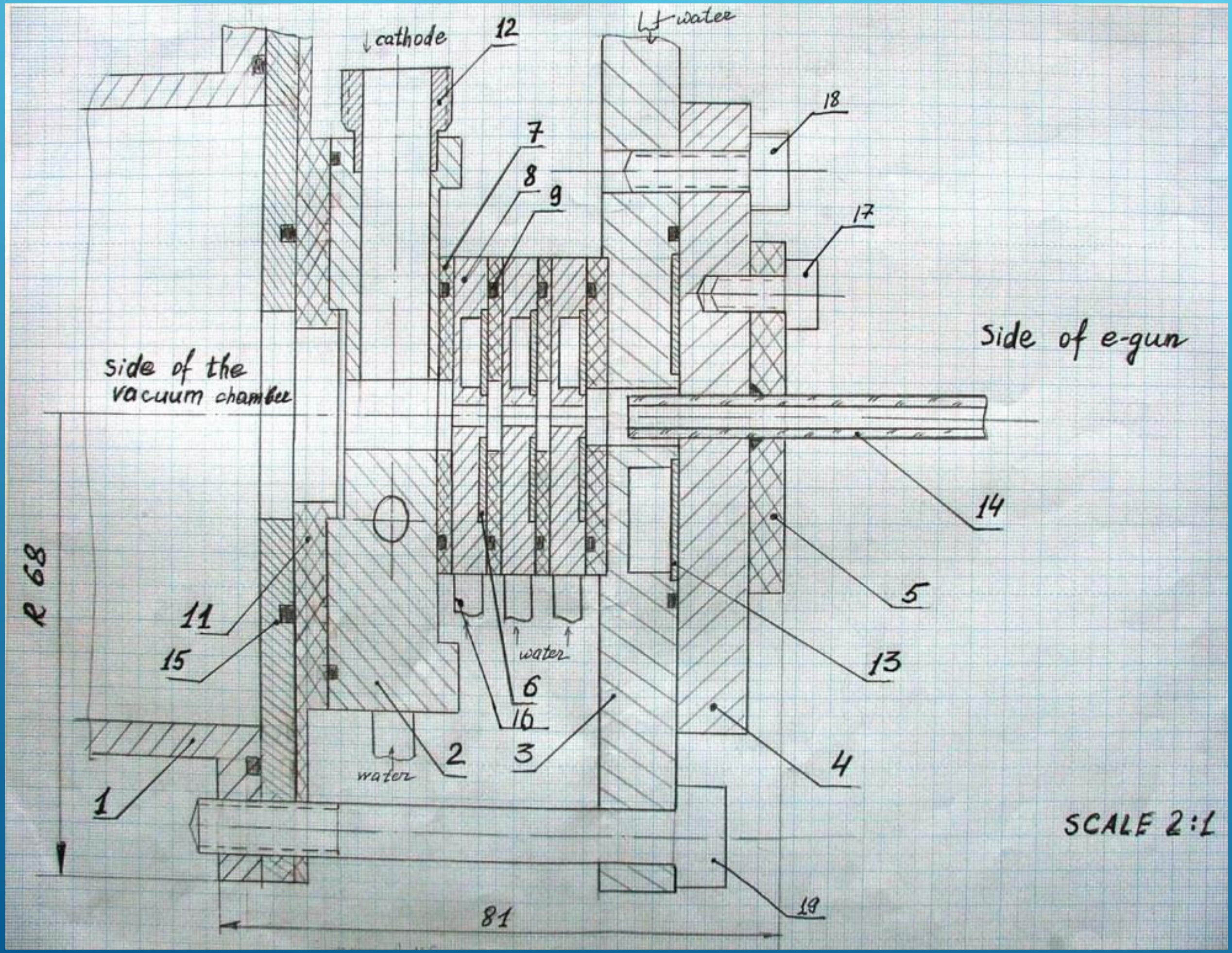
Down to Earth

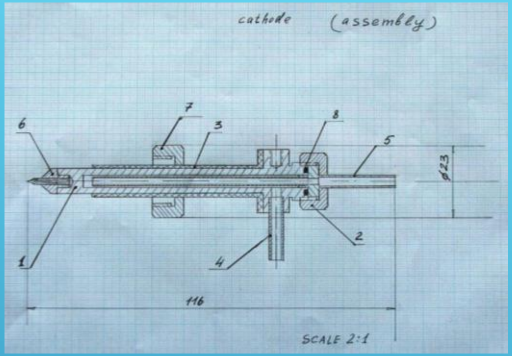
Schematic diagram of a Plasma Window

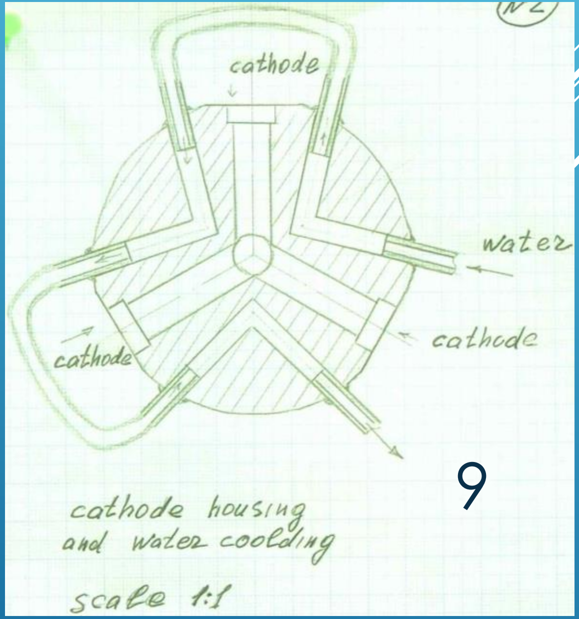


The stabilized plug of plasma seals the vacuum chamber to air but allows particle beams to pass through

Producing a 3D CAD model from hand-written drawings



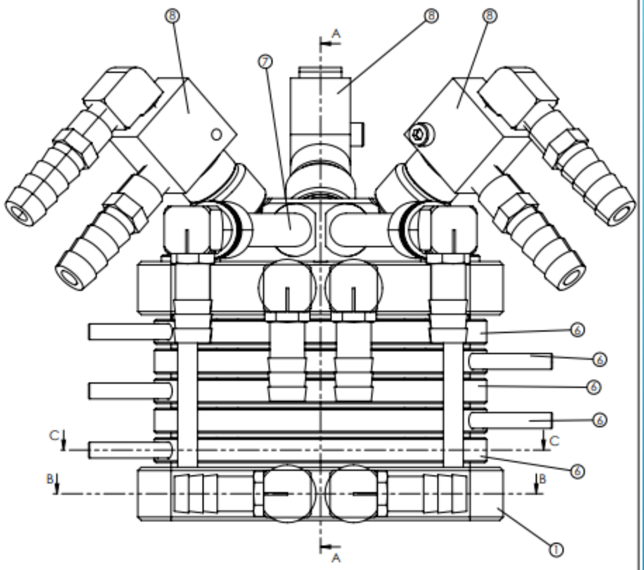




Producing a 3D CAD model from hand-written drawings

ITEM NO.	PART NUMBER	DESCRIPTION	Material	QTY.
1	Anode Assy		Material <not specified>	1
	Welded Anode Housing	Welded Anode Housing	See BOM	1
	Anode outer	Anode Outer	OFHCopper	1
	Anode inner	Anode Inner	OFHCopper	1
	N618A	N618A - CONN PLUG 1/8 BSP	Brass	2
2	Dowel ARC-RESISTANT FIBERGLASS ROD	0.25in Dowel ARC-RESISTANT ROD	FR-4	4
3	Oring 2-020	O-ring 2-020	FFKM VITON 70 shore-A	6
4	Outer Insulation Plate	Outer Insulation Plate	FR-4	6
5	Center Washer	Center Washer		6
6	Inner Cooling Stack Assy	Inner Cooling Stack Assy	See Bom	5
	Welded Inner Cooling Stack Assy	Welded Inner Cooling Stack Assy	See Bom	1
	Outer	Outer Cooling Plate	OFHCopper	1
	Inner	Inner Cooling Plate	OFHCopper	1
	Cooling Tube	Cooling Plates Inlets Tube	Brass	4
7	Cathode Housing Assembly	CATHODE HOUSING ASSEMBLY	See BOM	1
	Welded Cathode_Housing_Assembly	Welded Cathode_Housing_Assembly	See BOM	1
	Window cahtode housing	R67140_plasma window cahtode housing	OFHCopper	1
	Rear coolin channel cover	Rear Cooling Channel Cover	OFHCopper	1
	Cooling channel Front Cover	Cooling Channel Washer Cover	OFHCopper	1
	Cathode Inlet	CathodInletBushing	Brass	3
	BEP1810	R1/8" BSPT 100mm Brass extension DME	Brass	2
	N618A	N618A - CONN PLUG 1/8 BSP	Brass	2
	Insulation Buhsing	Insulation Buhsing	Peek	4
8	Cathode	CATHODE	See BOM	3
	CATHODE HOLDER	Cathod Holder	Brass	1
	Insulator TUBE	Cathod Holder Insulator Tube	Peek	1
	Cathode Tip Assy	Cathode Tip	See BOM	1
	Tungsten Holder	Tungsten Tip Holder	OFHCopper	1
	Tungsten_Rod	Tungsten Tip Rod	TUNGSTEN, 2% THORIUM, DIA .063 IN	1
	GW306K	GW306K/R1/8" Hose Nipple	Brass	1
	Cathode Needle Water Assenbly	CATHODE NEEDLE WATER TUBE	See BOM	1
	Welded Cathode Needle Water Tube	Welded Cathode Needle Water Tube	See Bom	1
	20090BSP Customized	20090BSP_Angle_Cutomized	Brass 200/300 90° BSP Elbows	1
	Cathode Needle Water Tube Holder	Cathode Needle Water Tube Holder	Brass	1
	Cathode NeedleWater Wube	CathodeNeedleWaterTube	Brass	1
	GW306K	GW306K/R1/8" Hose Nipple	Brass	1
	DIN 912 M4 x 6 --- 6C	M4 X 10 DIN 912	AISI 304	1
9	Cathode NUT	Cathode Nut	Brass	3
10	SVK209	SVK 90° Jiffy Matics	Brass	6
11	M6X85 DIN912 st.st	M6 x 85 DIN912	AISI 304	4
12	Washer ISO 7089 - 6	M6 Washer	AISI 304	4
13	ISO 7040-M6-C	M6 ISO 7040	1060 Alloy	4

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED



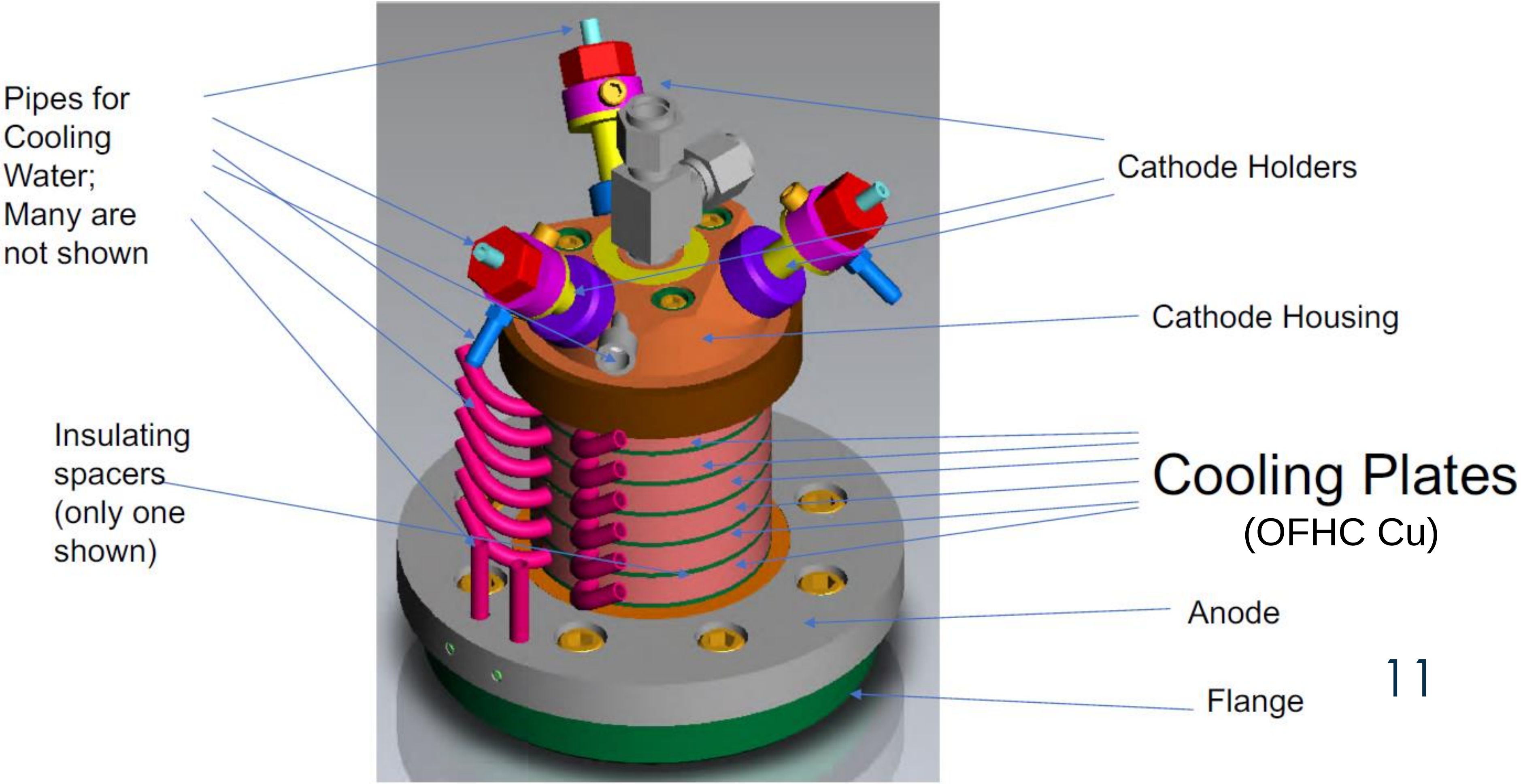
NOTES:

1. Break sharp edges.
2. All cutting edges must be deburred.

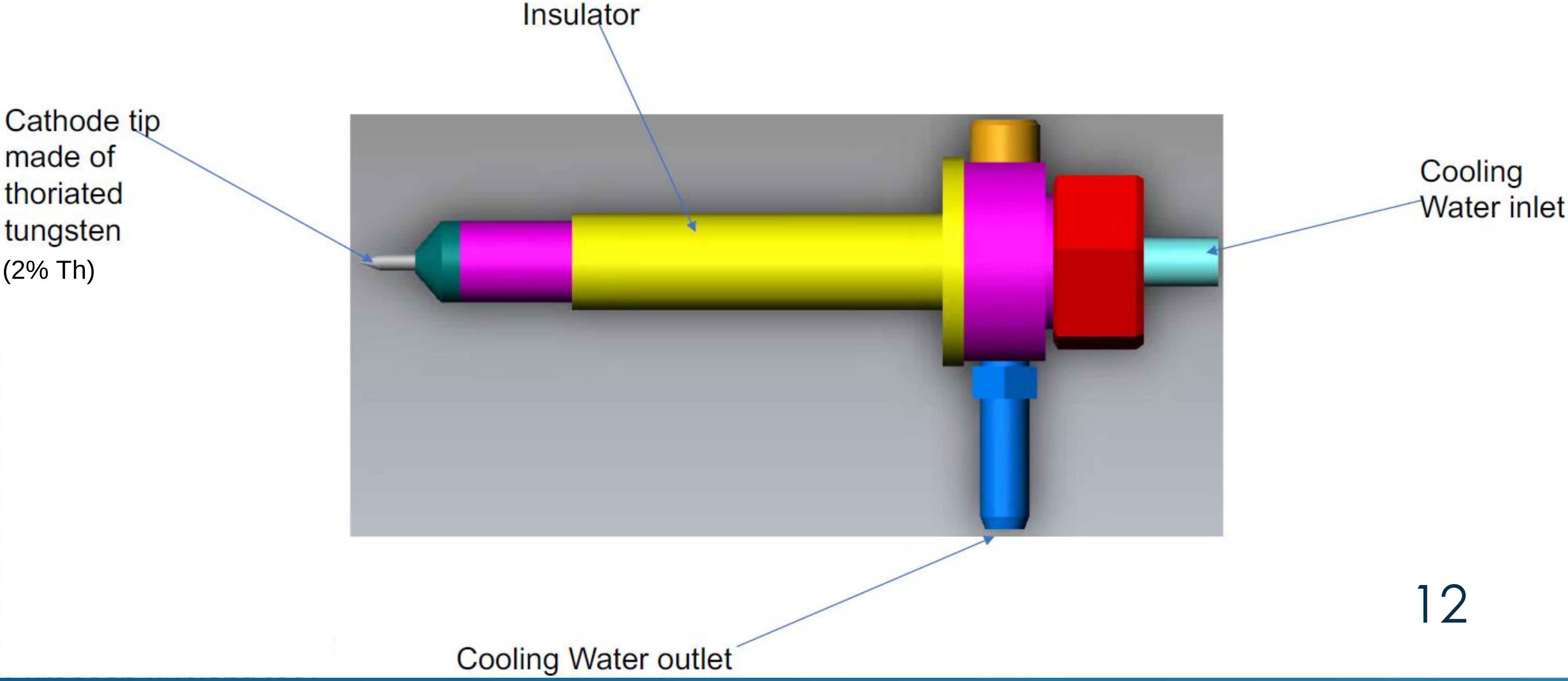
PART NAME
DRW NO (FILE NAME) PW ASSY
REV
THIS DESIGN IS PROPERTY OF SHTEKELMACHER Eng., CONFIDENTIAL INFORMATION
SHEET 1 OF 4
A3
MATERIAL:
FINISH:
MASS: gm
VOLUME: mm3
EXTERIOR FINISH:
COLOR:
TOOL NUMBER:
DATE NAME
DRAWN 01/01/1001
APPROVED
NOTES:
-TIP denotes true intersection point.
-TH denotes through hole.
-DFT denotes draft angle.
-(dim) denotes dimension to be optimized after molding
-℄ denotes center line of a symmetrical view.
-This drawing is for general information.
Use 3D file for full part definition.
-Break sharp edges.
-All cutting edges must be deburred.
-This product must comply with ROHS standard.
TOLERANCE
DIM. +/-
DEG. 30'
SCALE 1:1
VIEW METHOD

LAST SAVED: Sunday, May 16, 2021 11:41:55 AM

Plasma Window components' terminology



Cathode

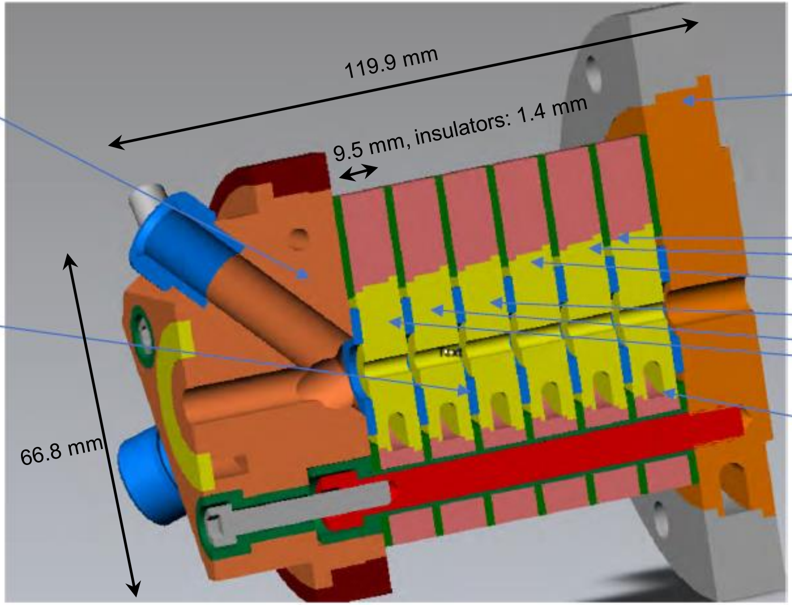


Insulator
Cathode tip made of thoriated tungsten (2% Th)
Cooling Water inlet
Cooling Water outlet

Plasma Window Terminology (cross section)

Cathode Housing

Anode



Insulating spacer: e.g. boron nitride (blue); FR4 [fire retardant form of G-10 (green); between them Viton O-ring)]

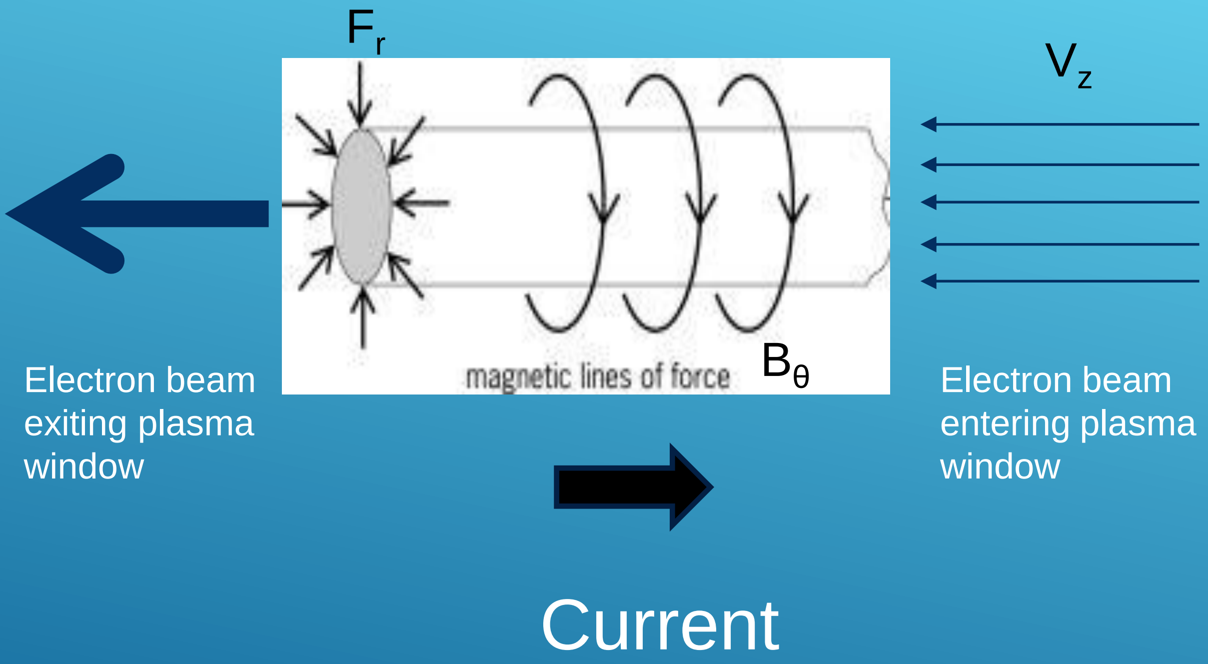
Cooling Plates
(OFHC Cu)

Cooling channel (only one shown)

Central aperture: 5 mm

Plasma Lens

(Focuses charged particles similar to light focusing by an optical lens)

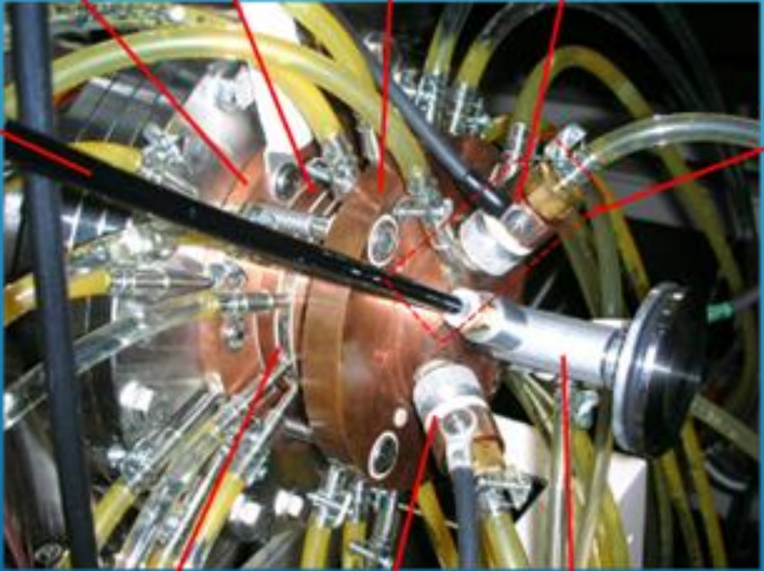


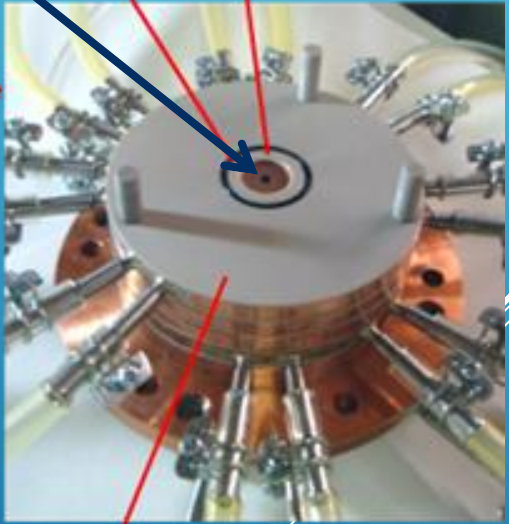
$$\underline{F_r} = q\underline{V_z} \times \underline{B_\theta}$$

RIKEN (RIBF) Plasma Window

(Wako Center)

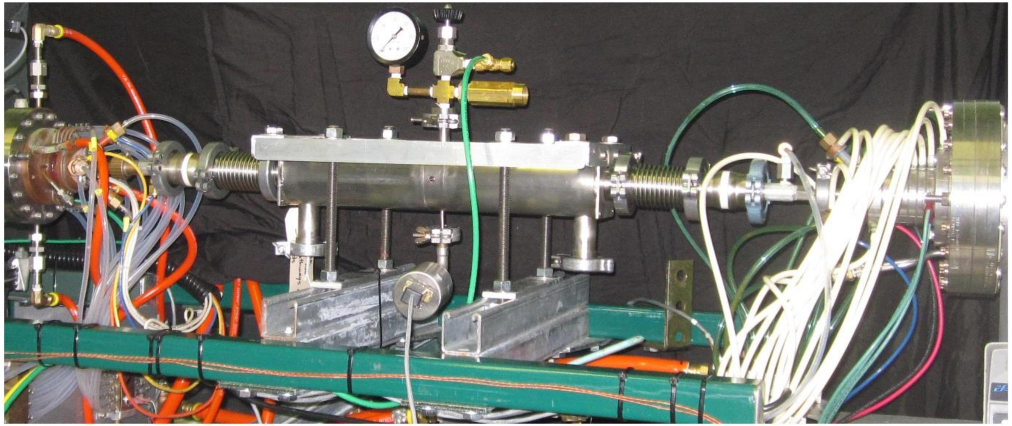
empty hole becomes window when filled with plasma

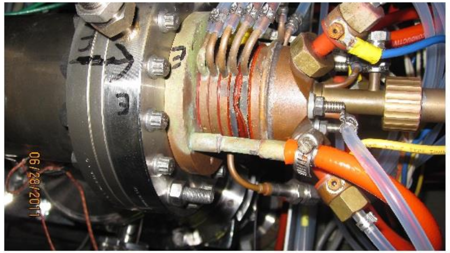


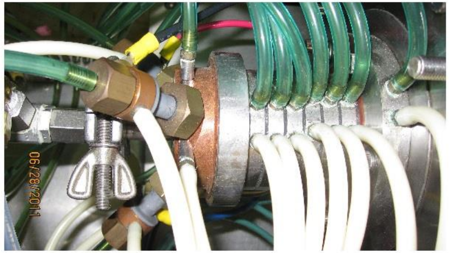


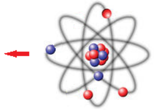
BNL Gas Stripper R&D for FRIB (MSU)

$$^{238}U^{34+} \rightarrow {}^{238}U^{71+}$$

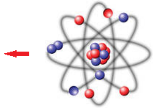


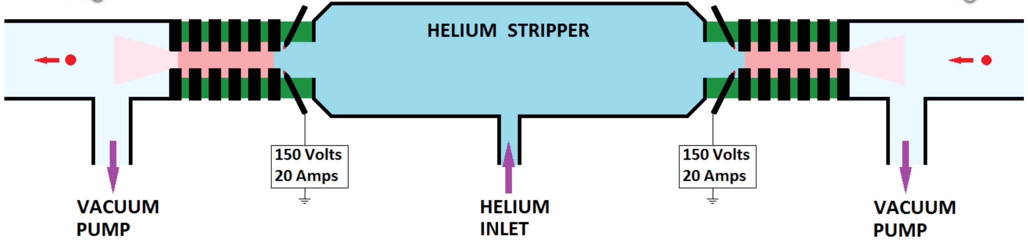


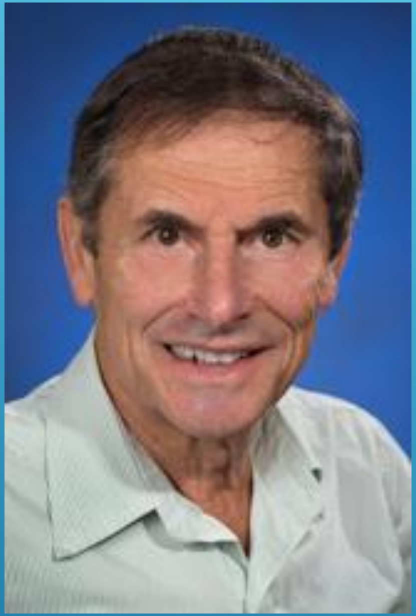




High velocity lead ions loose electrons but little energy by colliding with helium atoms. The higher electric charge facilitates further acceleration. The two plasma windows replace solid membranes that would melt.





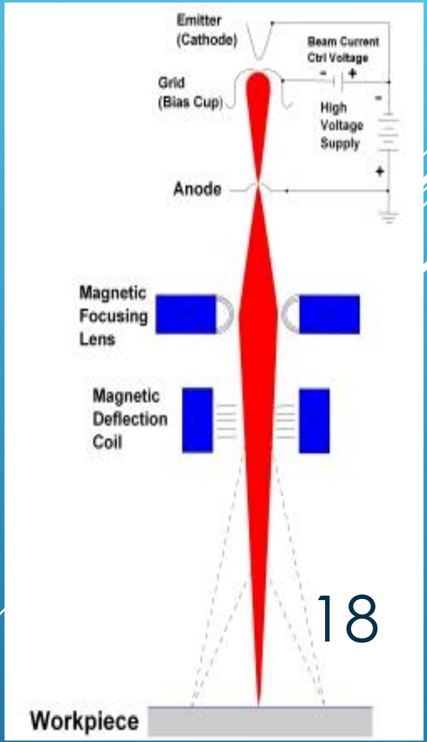


Ady Hershcovitch
(BNL, SUNY)

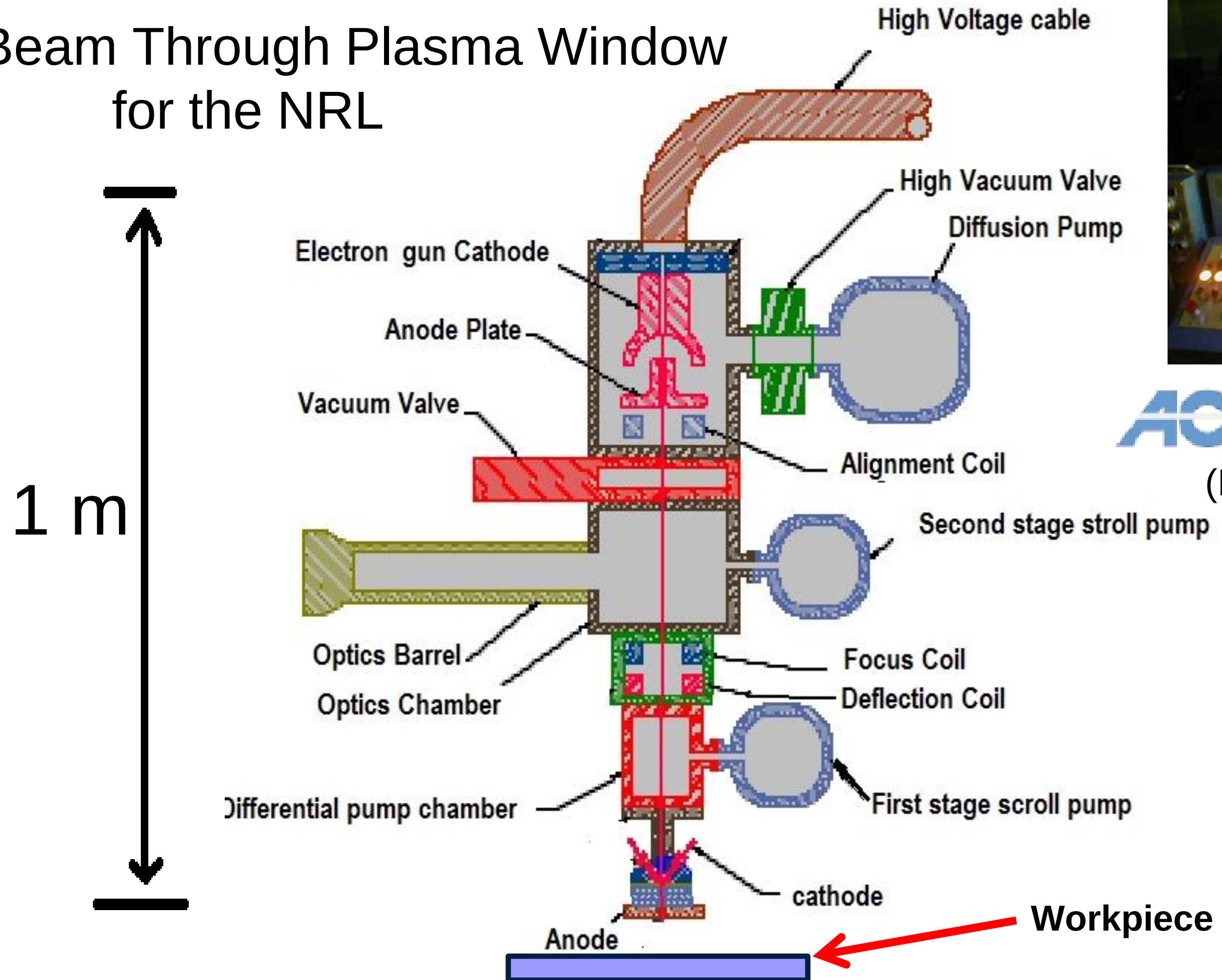
Motivation

The challenge: Particle beams and electromagnetic radiation are usually generated in vacuum. For some applications it is desirable to bring beams in air or pass the beams through internal gas targets. Such applications include Nuclear Physics experiment, as well as electron beams for welding, X-ray, VUV, EUV for use in microscopy, lithography, etc.

Electron-beam welding is the highest quality welding that can be performed. But, it's done in vacuum, resulting in low production rates and limits on object size. Double hull ship can't fit in a vacuum system.
Past in-air EBW: lower quality.



Electron Beam Through Plasma Window for the NRL



ACCELERON INC.
(East Granby, CT, USA)

Photons transmission via a Plasma Window

Thin solid windows are used for a whole spectra of high energy gammas; But, in some of these cases, these solid foils limit gamma outputs; i.e., machines are capable of generating higher intensities, the beam degrades, and the foil is damaged (two-fold problem).

Plasmas, including those in a PW, have a dual personality: electromagnetic radiation of frequency below the plasma frequency is severely attenuated, while the PW is **completely transparent** for electromagnetic radiation with frequency above the plasma frequency (unless there is a gas/plasma resonance).

The plasma frequency is the frequency at which electrons in a plasma oscillate: $\omega_p^{cgs} = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$

A PW opened to atmosphere has a plasma density of about 1.5x10^{17} cm^{-3}, for which the plasma frequency is ω_p = 3.5x10^{12} Hz; i.e., electromagnetic radiation with wavelength above 86000 nm are attenuated, while the PW is **completely transparent** for shorter wavelengths. There is no limit on radiation power that can pass through a PW. Furthermore, the bigger the radiation flux, the better the PW works (creating more ionization).

Experimental data, e.g.: Light from a HeNe 632.8 nm laser and UV radiation from NSLS (BNL), as well as X- and gamma-rays were passed through a PW open to atmosphere without any attenuation.

Cross sections for interaction of radiation from ultraviolet out into the hard x-ray regime, with individual particles is usually minuscule, e.g., for Thompson scattering σ = 2/3 b (1 b = 10^{-24} cm^2), i.e. mfp l ~ 10^7 cm.
At resonance, however, some photo-absorption and -ionization cross sections can reach the 10^{-19}–10^{-18} cm^2 level.
The typical target thickness of a PW nl ~ 1.5x10^{17} cm^{-2} is about four orders of magnitude lower than that of a conventional 250 µm beryllium window with nl ~ 2.5x10^{21} cm^{-2}. Electromagnetic radiation of an energy far from the absorption resonances of the working gas should have negligible interaction with a PW due to small target thickness coupled with low interaction cross sections.

Further applications: Commercial & Scientific

Several different types of accelerator systems can benefit from the utilization of the PW system.

Commercial Applications:

- Non-vacuum electron beam welding: With PWs, higher production rates, no limit on the size of target objects, and high quality electron beams in atmosphere.
- Non-vacuum material modifications by ion implantation, and dry etching, or micro-fabrication: Presently performed only in vacuum, since ion beams at energies used in these applications are completely attenuated by foils and by long differentially pumped sections.
- Electron beam melting: for manufacturing alloys is performed at a pressure of about 10^{-2} Torr. A major drawback of operating at this pressure range is the loss of elements with low vapor pressure. Consequently, it is desirable to raise the operating pressure to a higher level.
- Electron beam generation of photo-neutrons for the production of medical isotopes (e.g., Tc-99): A 40 MeV electron beam strikes a W target. Resultant radiation can dislodge a neutron (via a giant resonance) to create a new element. With a plasma window, the target can be in the air, sufficiently cooled to absorb an intense electron beam to generate photo-neutrons.
- Windowless gas targets for fast neutron radiography to detect nitrogen (weapons) and carbon (diamonds), as well as for other forms of neutron tomography and therapy (BNCT).
- Windows for high power lasers (especially high-pressure gas lasers) and LBW.

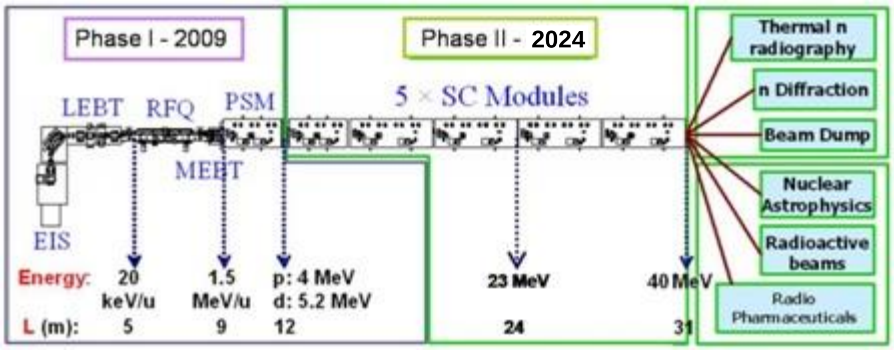
Scientific Applications:

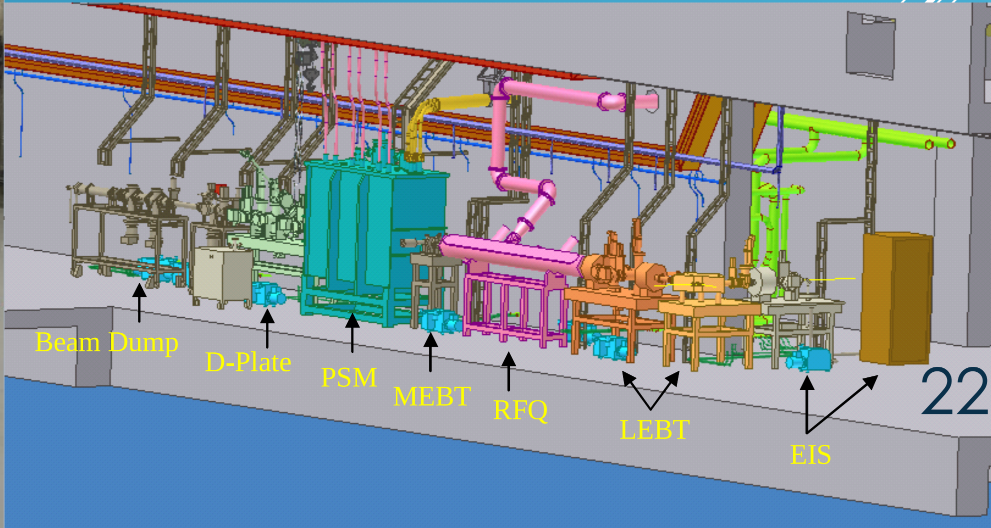
- Windowless beamlines for transmission of synchrotron radiation: Plasma windows offer many advantages over presently used beryllium windows: radiation passes through the window unaffected. A plasma window cannot be damaged by radiation. UV filter for rejection of ‘high-order’ light is of significant benefit to experiments like threshold photoionization spectroscopy, where contamination even at the 10^{-4} harmonic content can obscure the features of the spectrum of interest. X-ray microscopies, since it is free from the attenuation and spatial structure that attend the use of conventional window materials (e.g. beryllium or SiN), i.e., no scratches.
- Windowless gas targets for fast (fusion) neutron generation (neutron sources).
- Radioactive waste transmutation (ATW): protons are accelerated to 2 GeV unto a heavy metal target in air. Resultant spallation neutrons reduce radioactive waste. Presently, windows limit proton output.
- APT – tritium production by accelerator: Solid windows limit beam and tritium output.
- Spallation Neutron Source (SNS): To replace various solid windows with cooling problem.
- Windows for high power x-ray source (DARHT).
- Internal (gas or plasma) targets, strippers, lenses in storage rings: A plasma stripper/lens or an internal gas target "sandwiched" between two PWs. Examples: BNCT based on recirculating proton beams and various internal targets (including spin-polarized).
- Fast acting valves in UHV beamlines. In case of vacuum breach, plasmas can be ignited faster than mechanical valves without damage to beamline (unlike, presently used, msec spring loaded shutters).

Motivation

The **S**oreq **A**pplied **R**esearch **A**ccelerator **F**acility - **SARAF**

A multi-user and versatile particle accelerator. It is based on a proton/deuteron RF superconducting linear accelerator, with variable energy (up to 40 MeV) and a continuous wave (CW) high ion current (0.04-5 mA), located at the Soreq Nuclear Research Center.

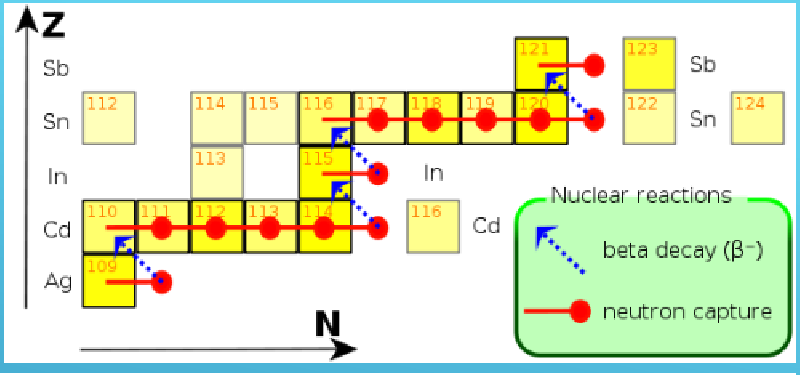




Motivation

Characterization of neutron-induced reaction rates on unstable isotopes is essential for understanding the nucleosynthesis occurring in astrophysical events involving massive stars (s-processes - e.g., the s-process acting in the range from Ag to Sb):

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



An enriched water ($H_2{}^{18}O$) target is under consideration at SARAF, for using the (p,n) reaction at an accelerated proton energy of 2.6 MeV in order to produce a 5 keV Quasi-Maxwellian neutron spectrum. So far, this reaction has been operated on solid targets, with corresponding low proton current and neutron flux. We aim to make use of the very high current available at SARAF-II to produce orders of magnitude more neutrons, and thus require a high-density target that is able to withstand high currents, which leads us to select a liquid based target. The only relevant liquid is $H_2{}^{18}O$.

$$MACS = \langle\sigma\rangle = \frac{\langle\sigma v\rangle}{v_{\mathrm{T}}} = \frac{2}{\sqrt{\pi}} \frac{\int_0^\infty e^{-E/kT}\sigma(E)EdE}{\int_0^\infty e^{-E/kT}EdE}$$

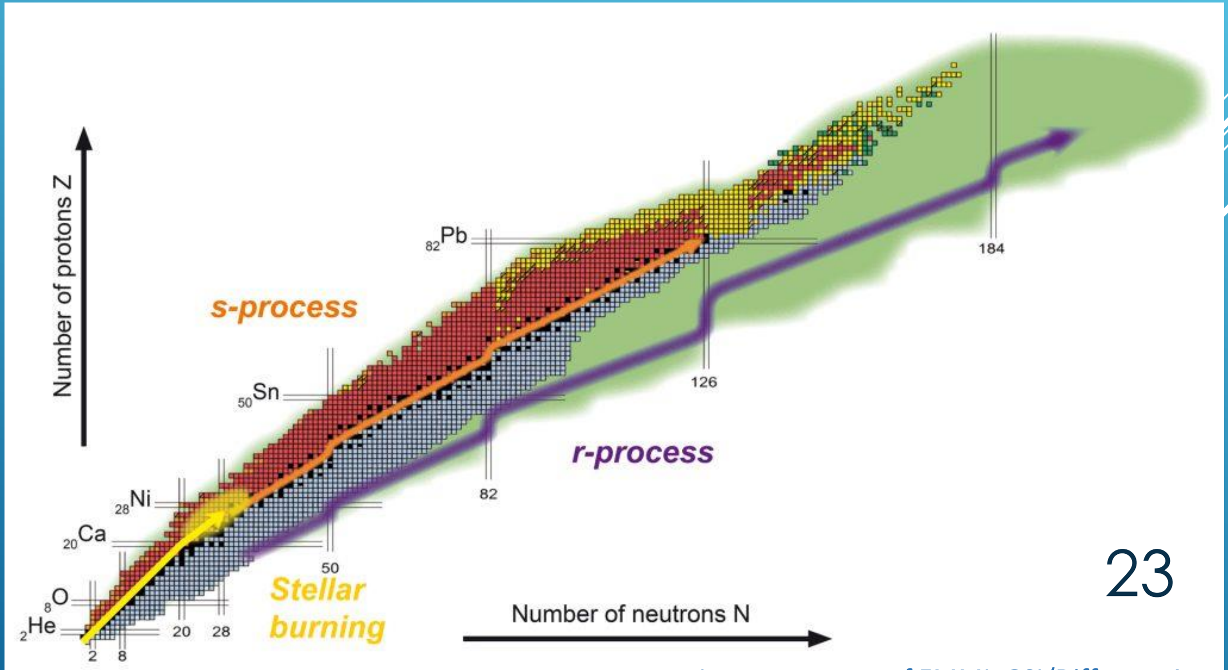
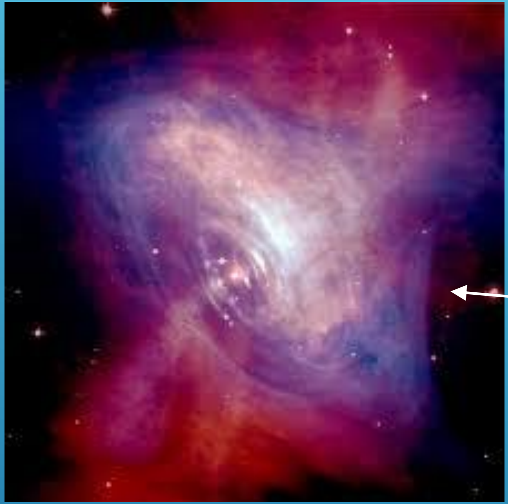
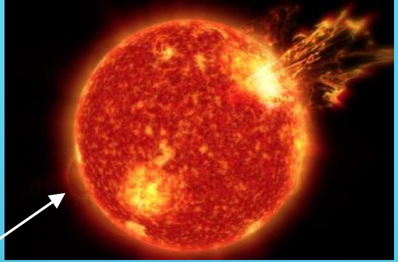


Image courtesy of EMMI, GSI/Different Arts.

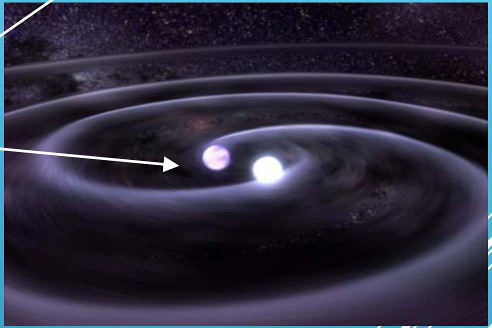
Motivation

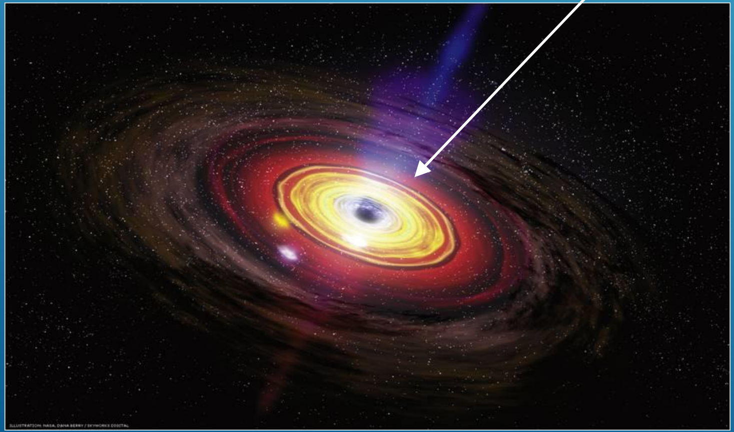


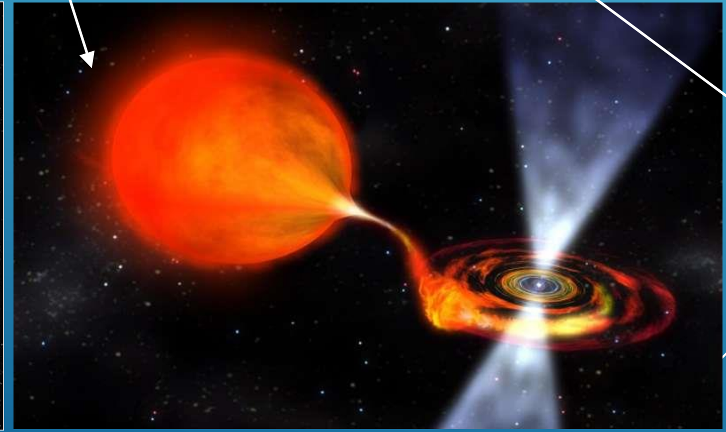


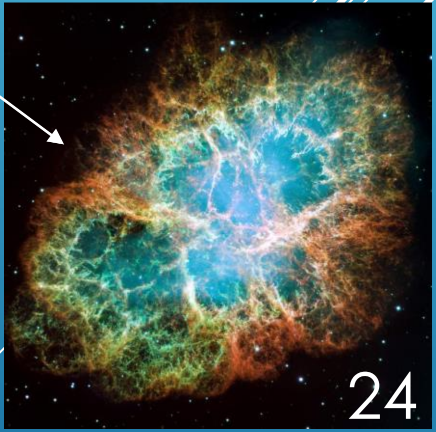
Endgoal – The better understanding of processes occuring in:

- Asymptotic giant branch stars
- Pulsars, binary mergers
- Active galactic nuclei
- Supernova explosions







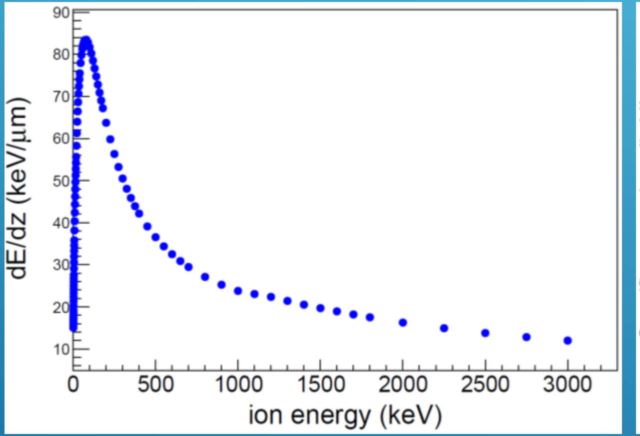


Data will be used in state-of-the-art nucleosynthesis codes simulating the interior of stars during different burning stages, in collaboration w/ Rene Reifarth’s gp. @GUF

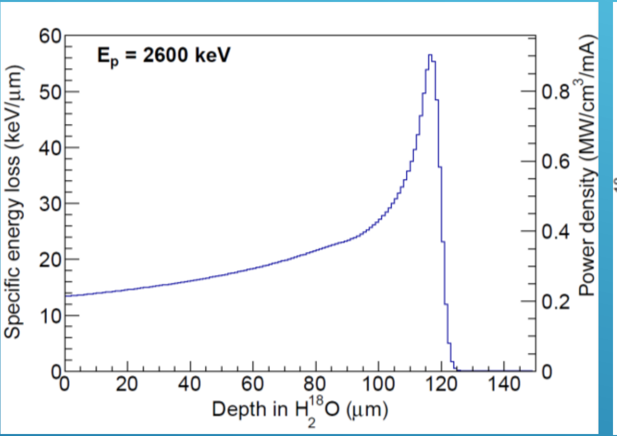
Simulation of H energy and heat deposition in $H_2{}^{18}O$ target – preliminary results

Energy loss and heat deposition probe of 2600-keV proton beam in $H_2{}^{18}O$. The volume power density plotted is the power deposited within one radial standard deviation.

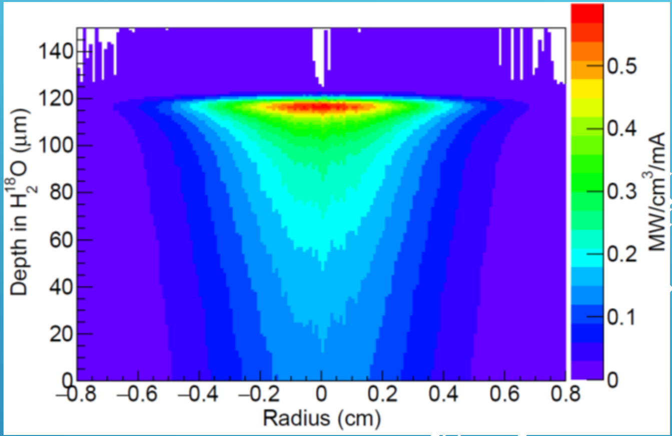
Energy loss rate vs. initial beam energy



Energy loss vs. depth in the target



Heat deposition



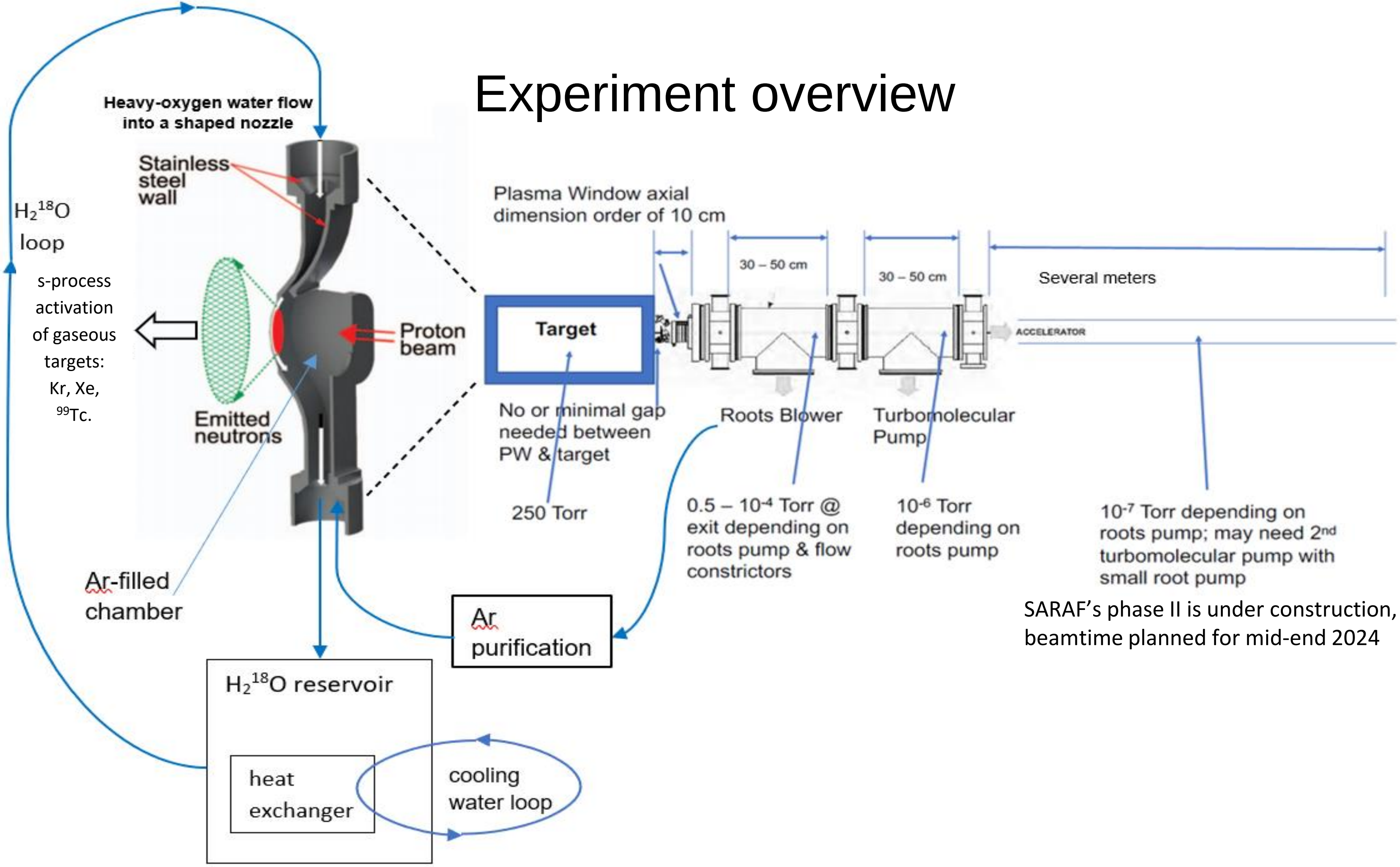
Conservation of the expensive $H_2{}^{18}O$ entails the use of a circulating target, containing a reservoir, a heat exchanger and a cooling loop, which controls the liquid's temperature and flow rate.

The high vapor pressure of $H_2{}^{18}O$ is incompatible with accelerator vacuum.
We opt to solve this by using a **Plasma Window.**

Required stream velocity on impact:

$$\frac{v}{i} \approx 38\ \frac{\mathrm{m}}{\mathrm{s \cdot mA}}$$

Experiment overview



SARAF's phase II is under construction, beamtime planned for mid-end 2024

Summary

- Plasma is the fourth fundamental state of matter. It contains a significant portion of charged particles – ions and electrons. The presence of these charged particles is what primarily sets plasma apart from the other fundamental states of matter. It is the most abundant form of ordinary matter in the universe, being mostly associated with stars. Plasma can be artificially generated by heating a neutral gas or subjecting it to a strong electromagnetic field.
- Plasma is much less dense and much more viscous than a gas when both are at the same pressure.
- A Plasma Window (PW) is an apparatus that separates between vacuum and atmosphere without any solid walls, and can hinder the flow of gases with little effect of fast particles passing through it.
- PWs have many applications in medicine (e.g. BNCT), industry (e.g. EBW, LBW) & science (e.g. in particle accelerators).
- PWs are used for scientific research in the fields of experimental particle physics, nuclear astrophysics, plasma chemistry, high-energy physics, accelerator physics and more.
- PWs have been used for the transmission of electrons, protons, photons and heavy ions at various energies.
- A particle beam passing via a PW can improve both the beam's and the PW's characteristics.
- Photon transmission through a PW is possible above the plasma frequency, typically ~10 THz (or at a wavelength below ~100 μm).
- What seemed to be science fiction ("force fields") 40 years ago is today's reality.
- PWs actively contribute to the noble cause of our better understanding of the universe we live in.

Thank You for your attention

Questions?