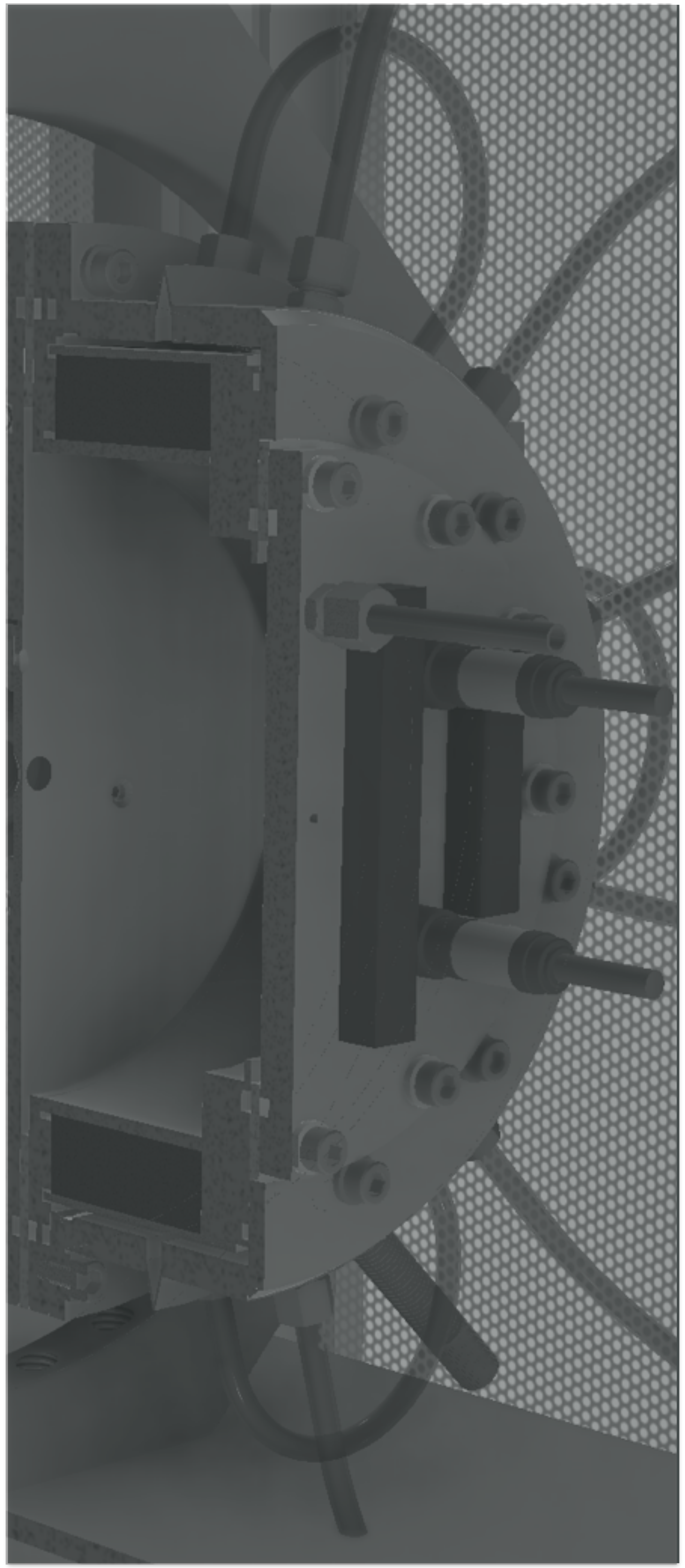

DAEδALUS
IsoDAR

# The front-end of IsoDAR

ICHEP 2016

4 Aug 2016, 18:40

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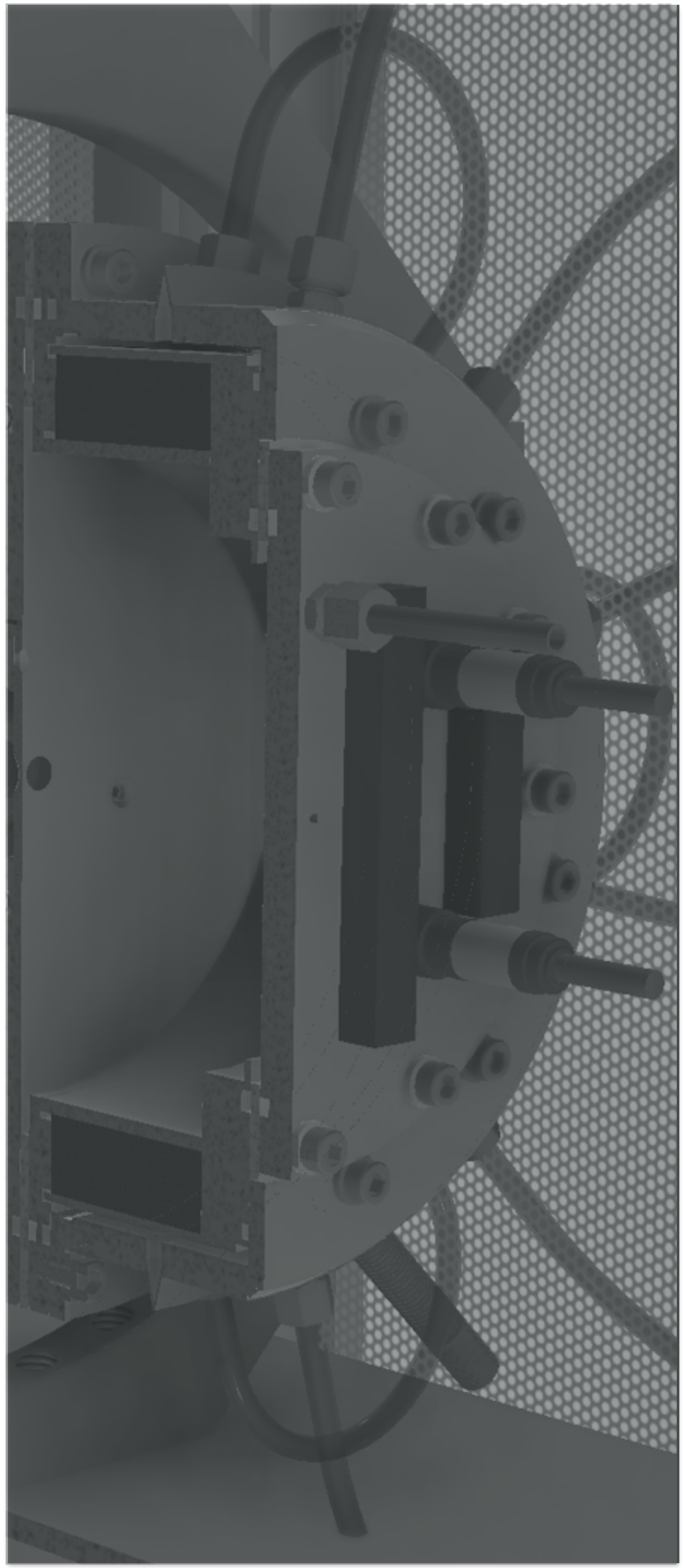
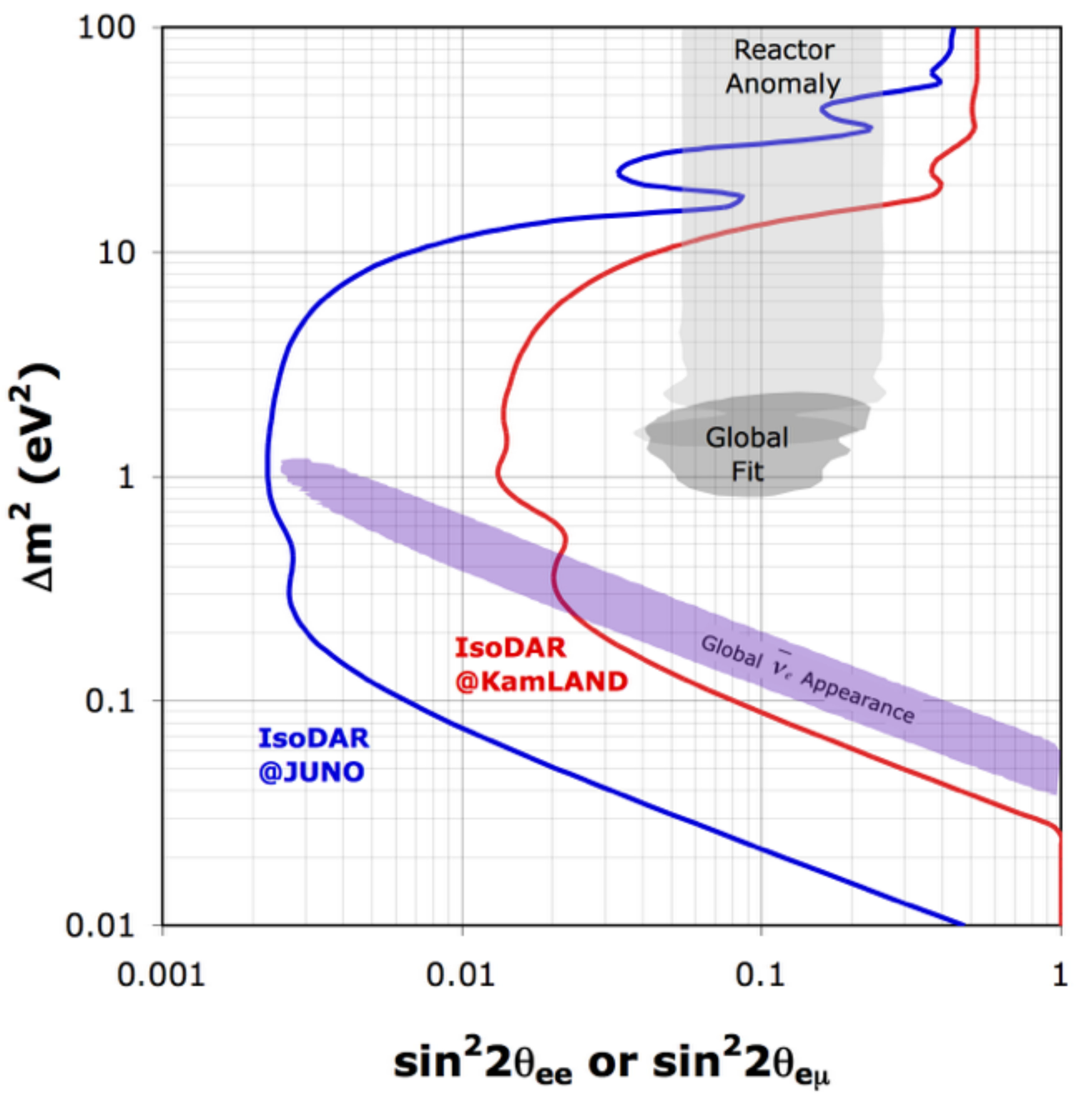


# OUTLINE

# IsoDAR: motivation and goals

IsoDAR is motivated by observed anomalies in neutrino oscillation experiments that point to the potential existence of sterile neutrinos — non-interacting partners of the Standard Model neutrinos.

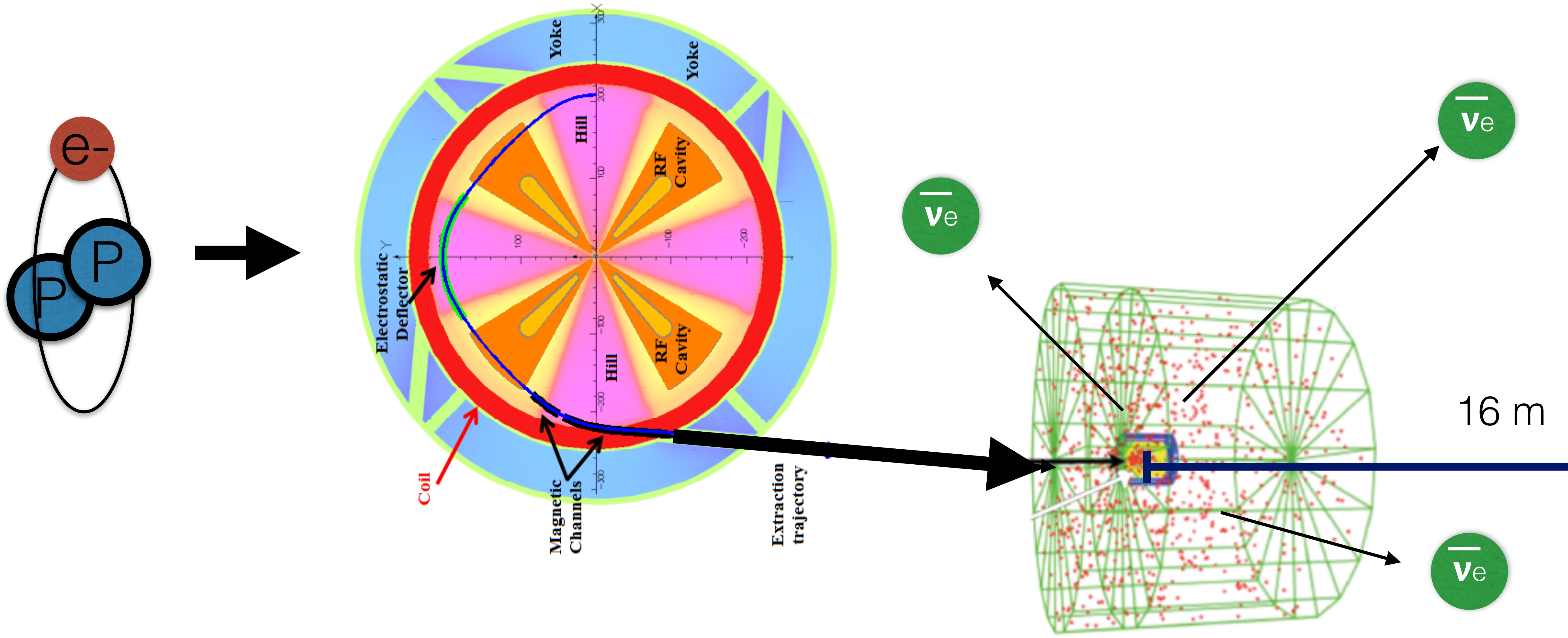
| LSND Anomaly | MiniBooNe Low Energy Excess | The Reactor Anomaly | Gallex/Sage Anomaly |
|---|---|---|---|

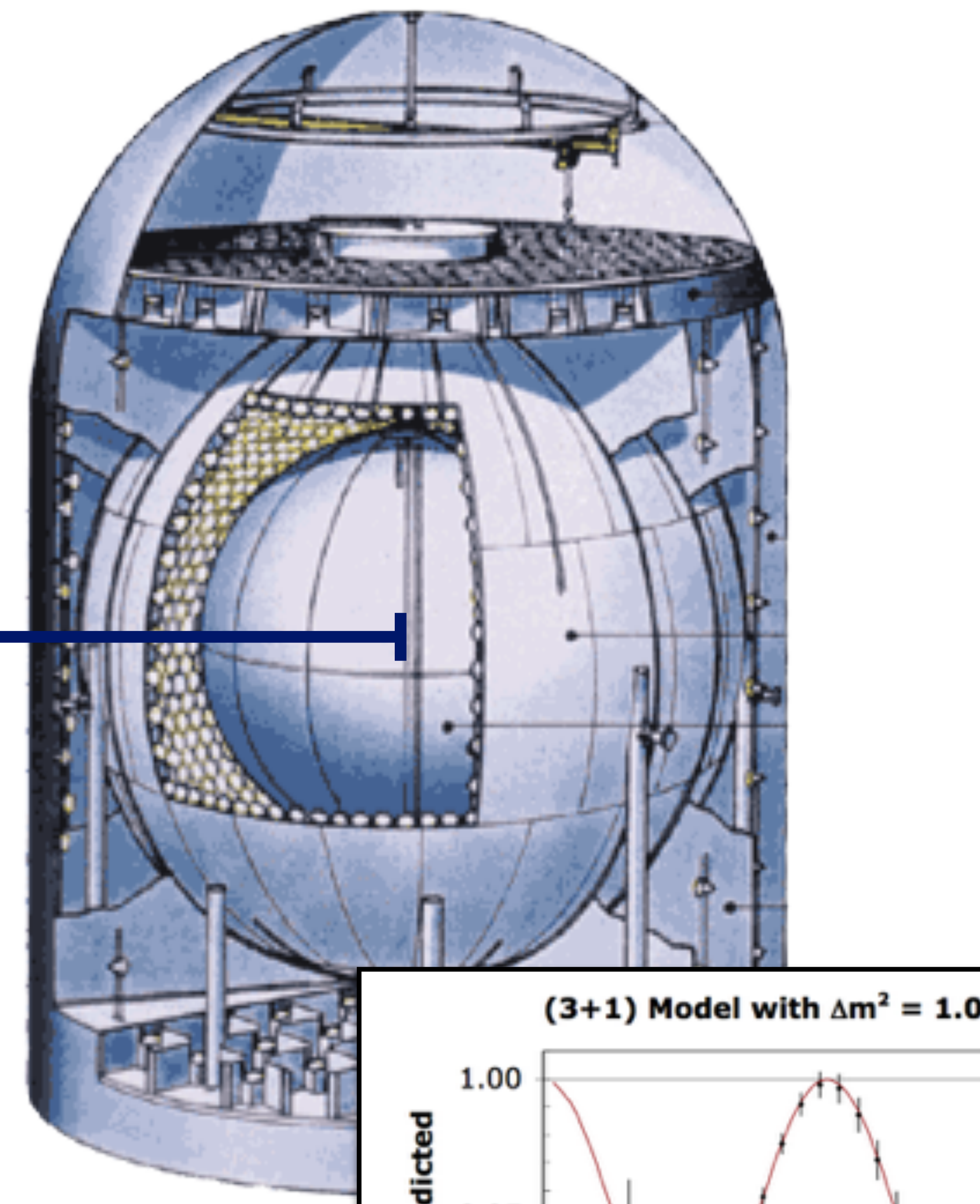


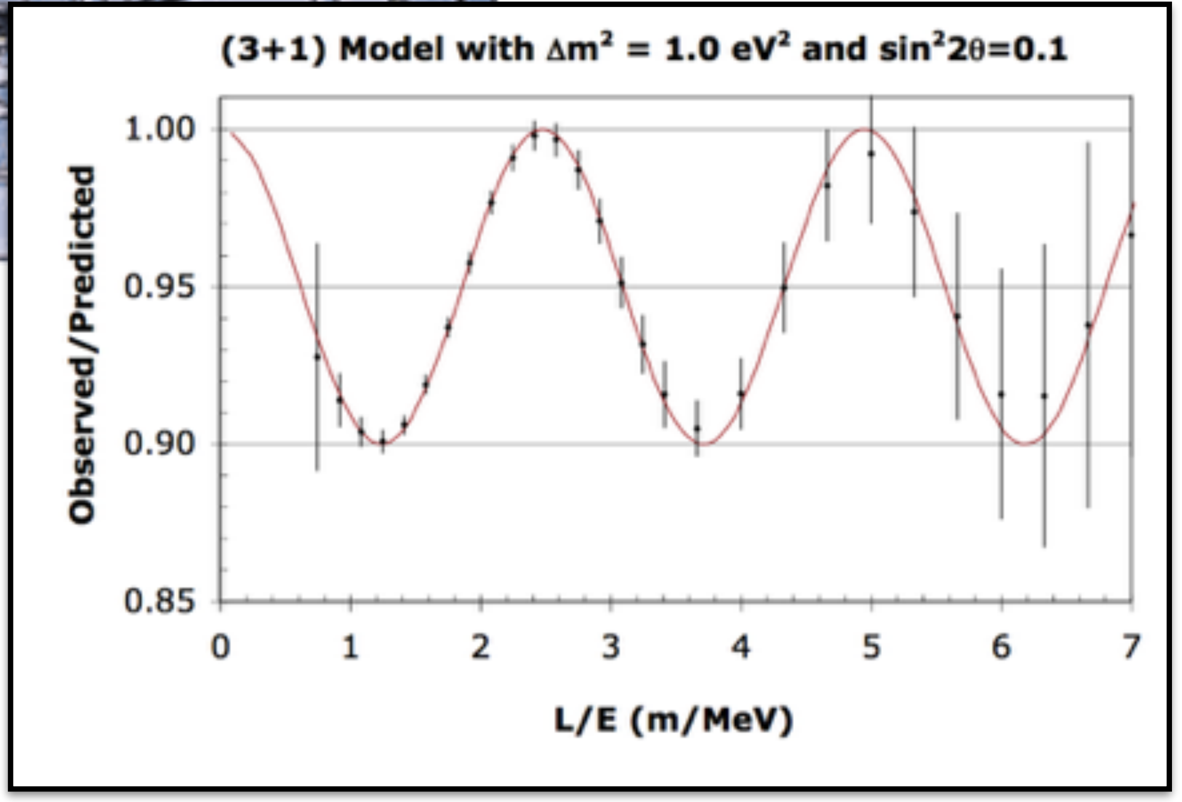

- A novel neutrino factory capable of producing $3 \times 10^{22}$ well understood $\bar{\nu}e$ per year.
- Paired with a kiloton scale detector, IsoDAR can decisively test the sterile neutrino hypotheses and accurately measure the oscillation parameters if a sterile neutrino exist.
- Distinguish between 3+1 versus 3+2 sterile neutrino model.
- Collect the largest sample of a $\bar{\nu}e$ elastic scattering events. (This could shed light into the NuTeV anomaly)

# How does IsoDAR work?

$H_2^+$ production → Acceleration → $\overline{\nu}_e$ production → $\overline{\nu}_e$ detection via IBD

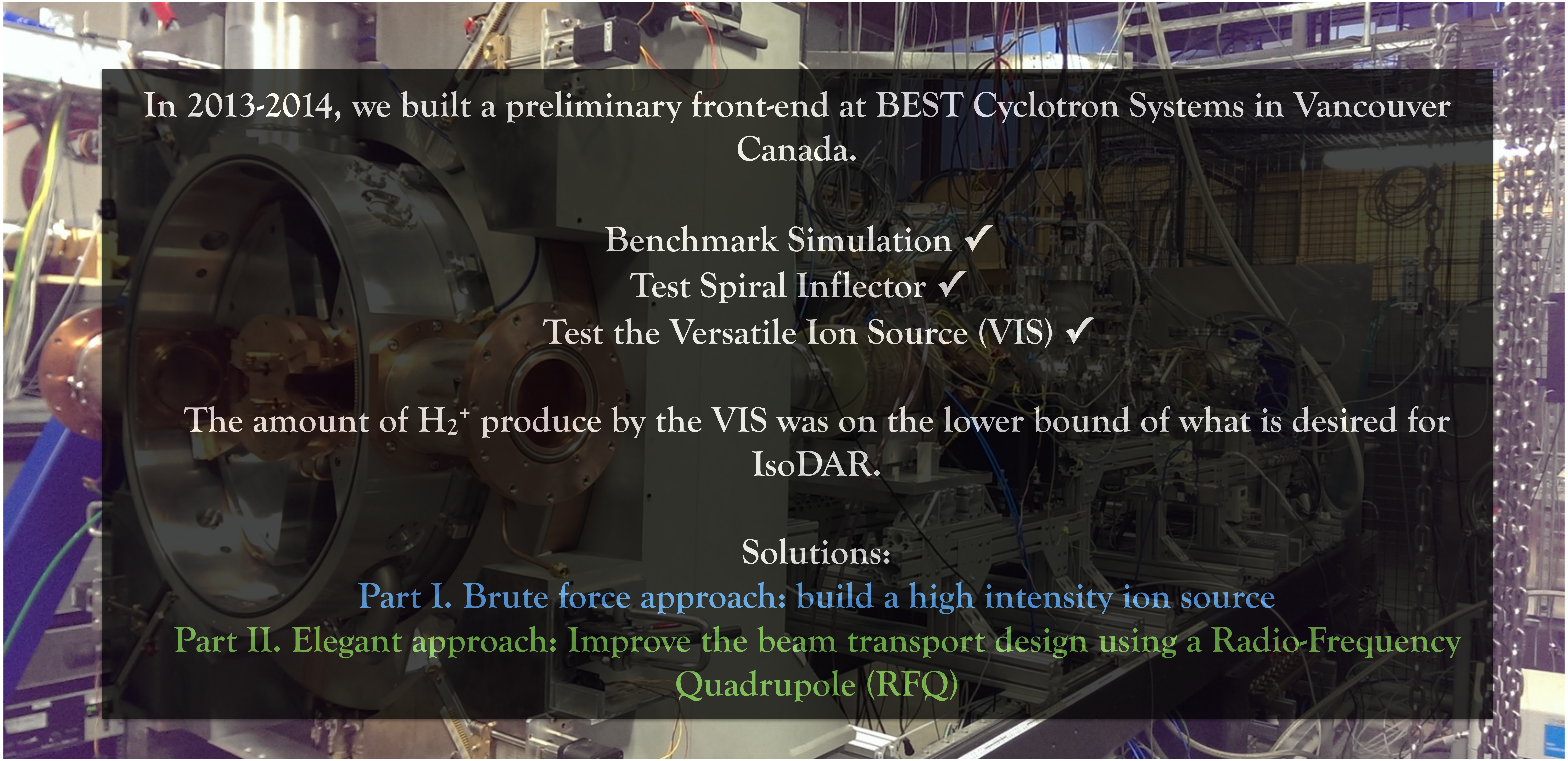





1. Produce and inject a high current $H_2^+$ beam into a cyclotron (front-end)
2. Accelerate 5 mA of $H_2^+$ to 60 MeV/amu
3. Impinge on a $^9$Be target. $^7$Li+n → $^8$Li → $^8$Be + $e^-$ + $\overline{\nu}_e$
4. Map out oscillation anti-electron neutrino disappearance within a kiloton scale detector

# Our front-end work



In 2013-2014, we built a preliminary front-end at BEST Cyclotron Systems in Vancouver Canada.

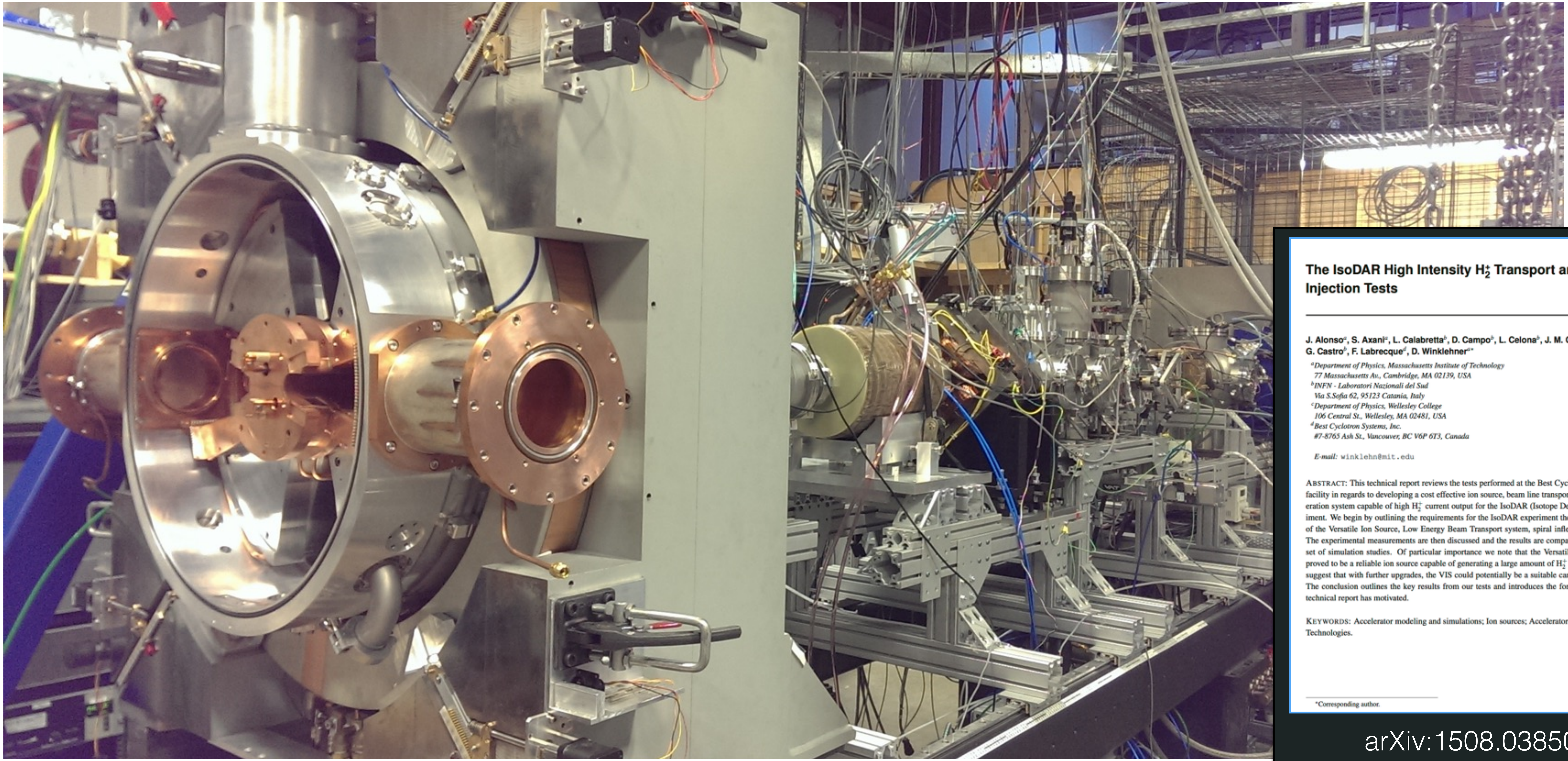
Benchmark Simulation ✓
Test Spiral Inflector ✓
Test the Versatile Ion Source (VIS) ✓

The amount of $H_2^+$ produce by the VIS was on the lower bound of what is desired for IsoDAR.

Solutions:
Part I. Brute force approach: build a high intensity ion source
Part II. Elegant approach: Improve the beam transport design using a Radio-Frequency Quadrupole (RFQ)

*The ion source was developed as a H+ source, not $H_2^+$, so this was expected.

# Our front-end work



### The IsoDAR High Intensity $H_2^+$ Transport and Injection Tests

J. Alonso[a], S. Axani[a], L. Calabretta[b], D. Campo[b], L. Celona[b], J. M. Conrad[a], A. Day[c], G. Castro[b], F. Labrecque[d], D. Winklehner[a*]

[a]*Department of Physics, Massachusetts Institute of Technology*
*77 Massachusetts Av., Cambridge, MA 02139, USA*
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*106 Central St., Wellesley, MA 02481, USA*
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*E-mail:* winklehn@mit.edu

ABSTRACT: This technical report reviews the tests performed at the Best Cyclotron Systems, Inc. facility in regards to developing a cost effective ion source, beam line transport system, and acceleration system capable of high $H_2^+$ current output for the IsoDAR (Isotope Decay At Rest) experiment. We begin by outlining the requirements for the IsoDAR experiment then provide overview of the Versatile Ion Source, Low Energy Beam Transport system, spiral inflector, and cyclotron. The experimental measurements are then discussed and the results are compared with a thorough set of simulation studies. Of particular importance we note that the Versatile Ion Source (VIS) proved to be a reliable ion source capable of generating a large amount of $H_2^+$ current. The results suggest that with further upgrades, the VIS could potentially be a suitable candidate for IsoDAR. The conclusion outlines the key results from our tests and introduces the forthcoming work this technical report has motivated.

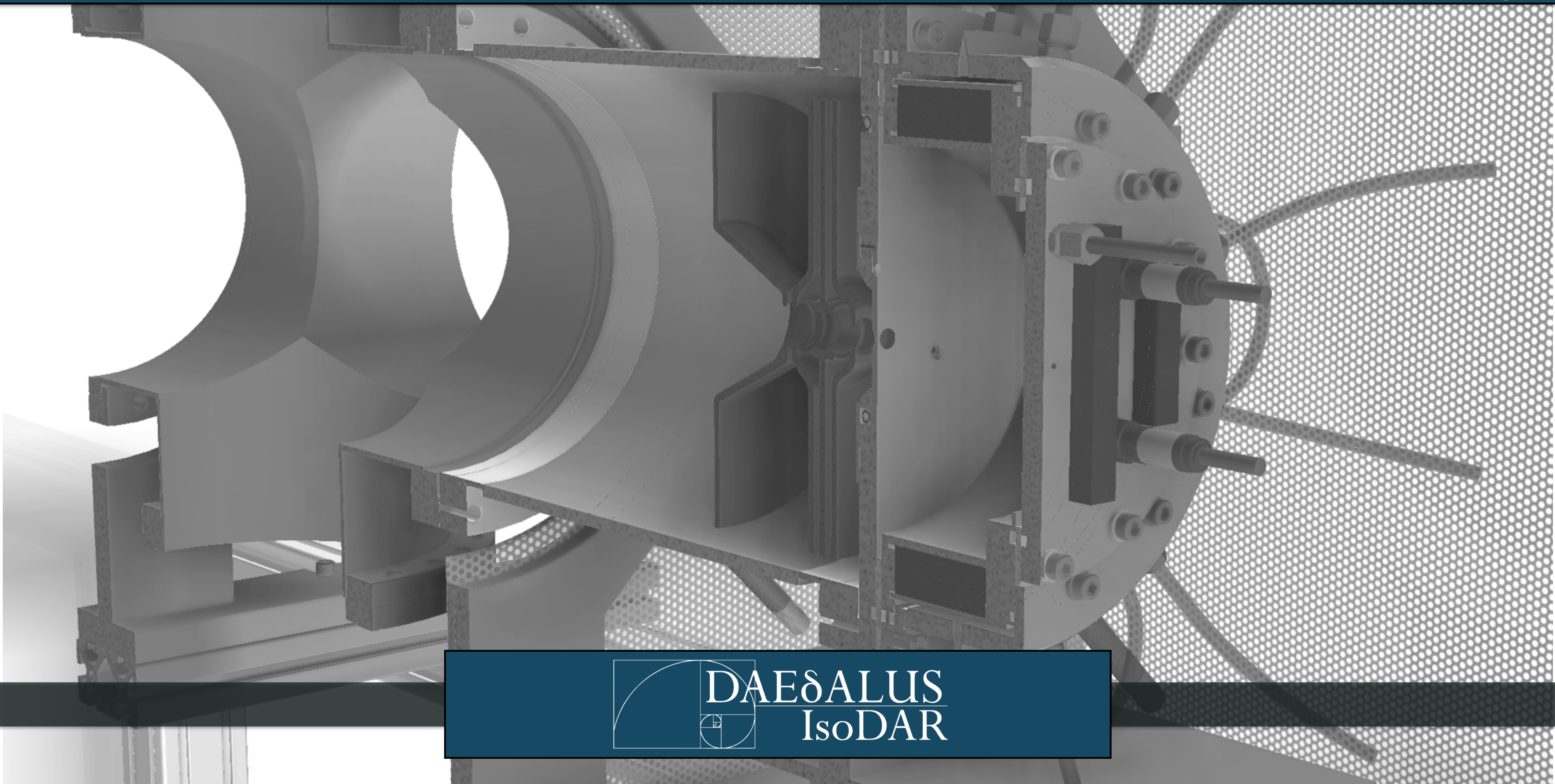
KEYWORDS: Accelerator modeling and simulations; Ion sources; Accelerator Subsystems and Technologies.

*Corresponding author.

arXiv:1508.03850

Multicusp Ion Source Technology at MIT

# PART I
# Our new ion source: MIST-v1



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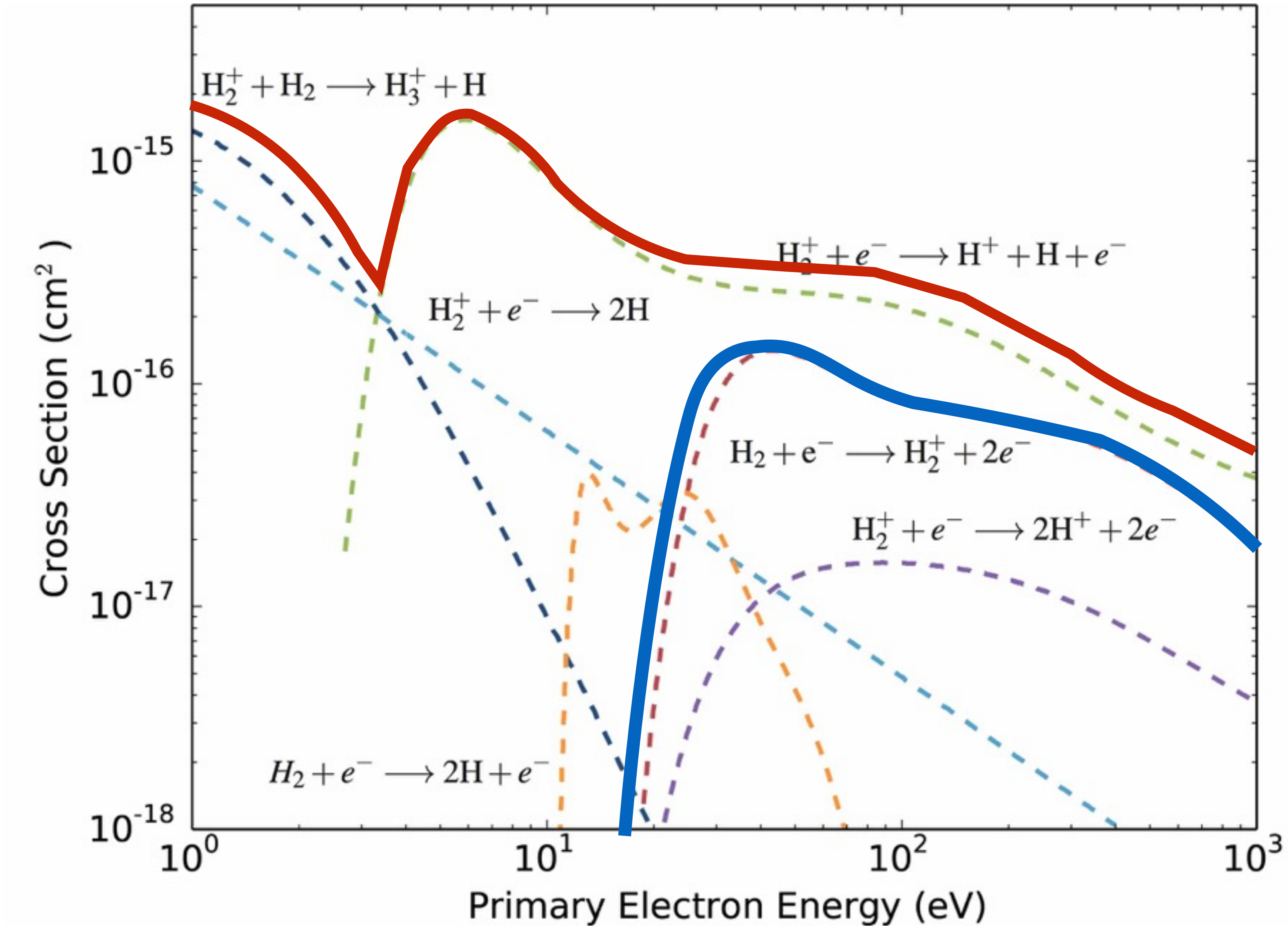
IsoDAR

# $H_2^+$ ion sources

IsoDAR's use of $H_2^+$:

1. reduces the space charge "perveance" by factor of 1.4
2. delivers two protons per ion on target

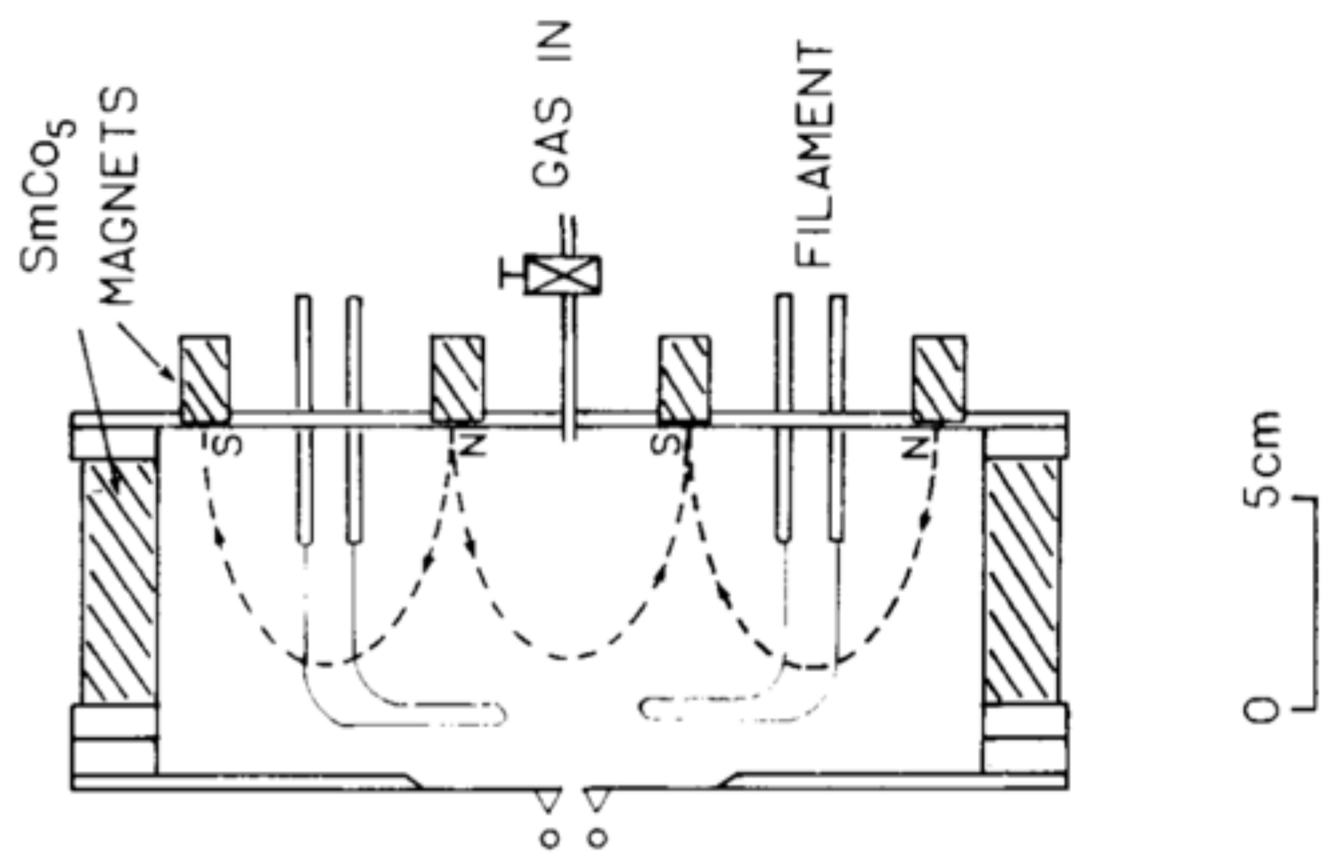


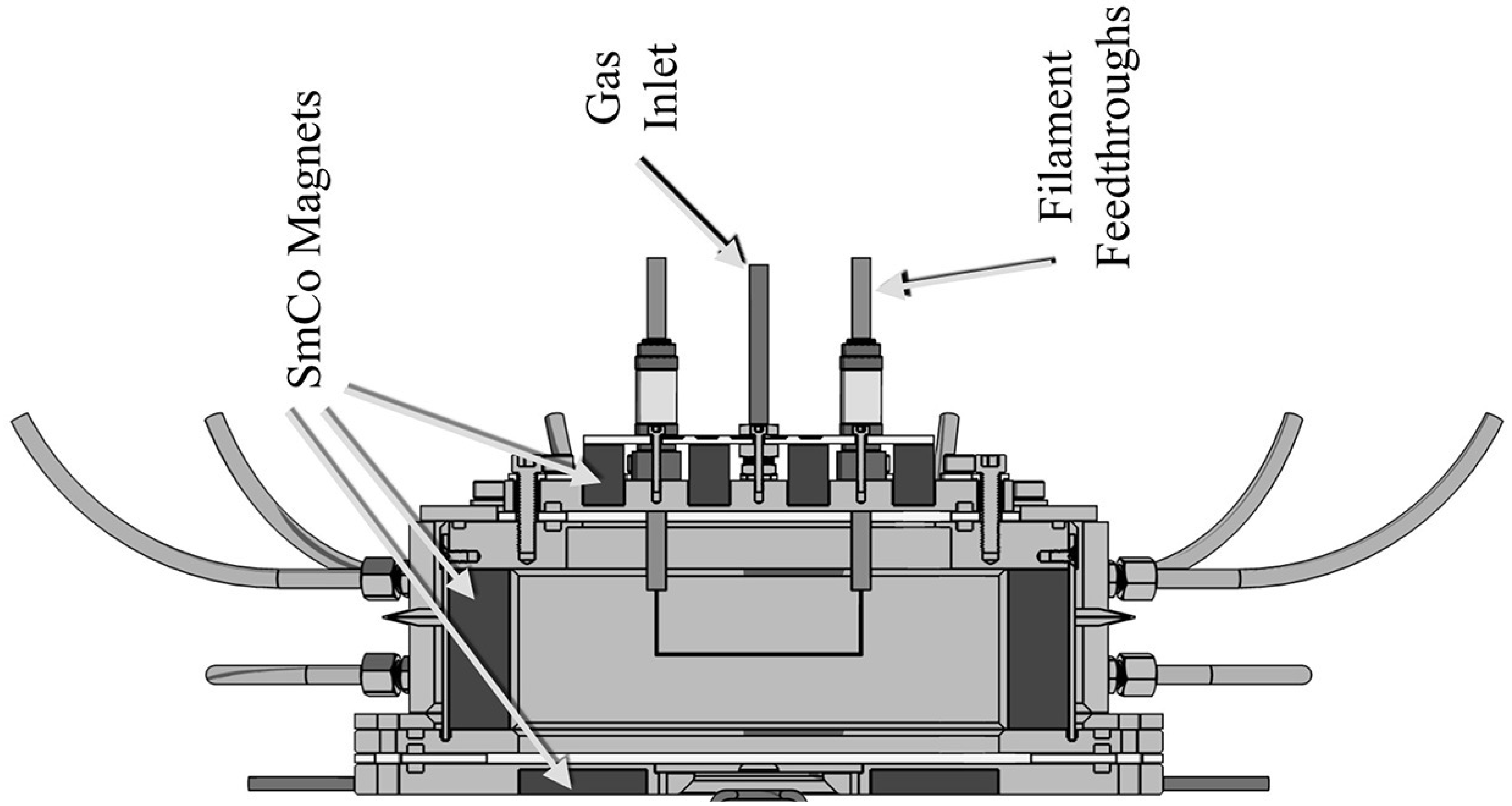

- Little work has been done since the 80s to develop $H_2^+$ ion source.
- Lawrence Berkeley Laboratory developed a high current source in 1983*:
  - $H_2^+$ fraction >70% ✓
  - Current density 110 mA/cm$^2$ ✓
- Key innovation: the plasma volume must remain small.
- $H_2^+$ will have a mean free path in the ion source of ~5 cm.

*Ehlers, K. W., and K. N. Leung. "High-concentration H2+ or D2+ ion source." Review of Scientific Instruments 54.6 (1983): 677-680.

# Innovations: MIST-v1

| Ehlers and Leung's LBL Source | MIST-v1 |
|---|---|
| 10 column of SmCo magnets | 12 columns of SmCo magnets |
| 10 cm radius by 9 cm length | 7.5 cm radius by 7 cm length |
| Axial plasma volume length: 2.0, 4.5 cm | Axial plasma volume length: 1.5 - 5.0 cm |
| Not water cooled. | Front plate and plasma chamber is water cooled |
| Back plate biasing (observed a 30% increase in extracted current) | Back plate biasing and plasma chamber biasing |
| Magnetic configuration: plasma chamber/back plate | Magnetic configuration: plasma chamber/back plate/front plate |

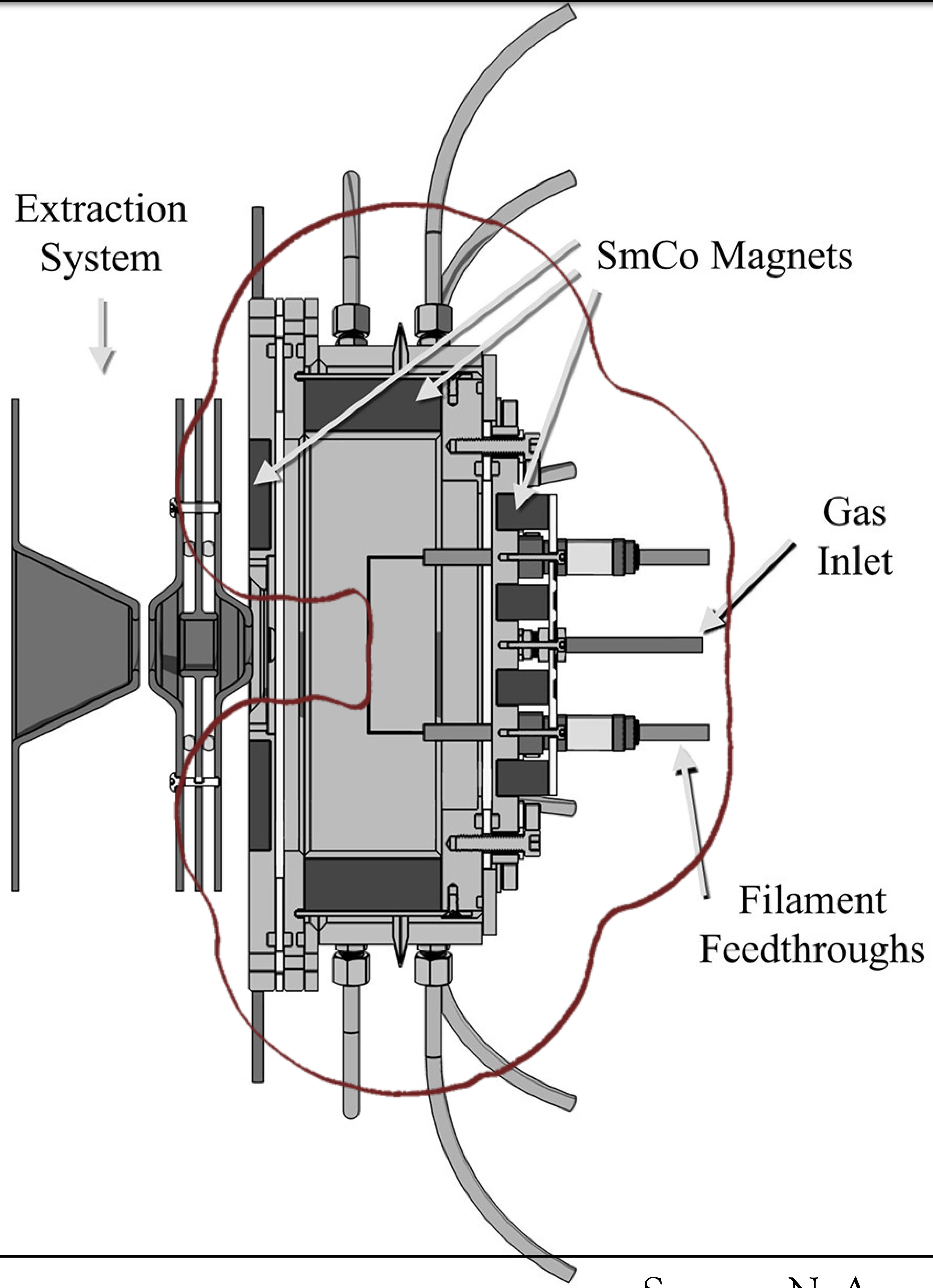



*Images show the relative size between ion sources

# MIST-v1 concept

- A multi-cusp magnetic field is generated around the ion source.
- The plasma chamber is filled with $H_2$ gas.
- Longitudinal electric field produced by individually biasing components.
- Pass a high-current through a tungsten filament.
- Electrons are ejected from the hot filament.
- They accelerate in the electric field, and gain sufficient energy to ionize the $H_2$ gas.
- $H_2^+$ diffuses out and extracted using high-voltage electrodes.



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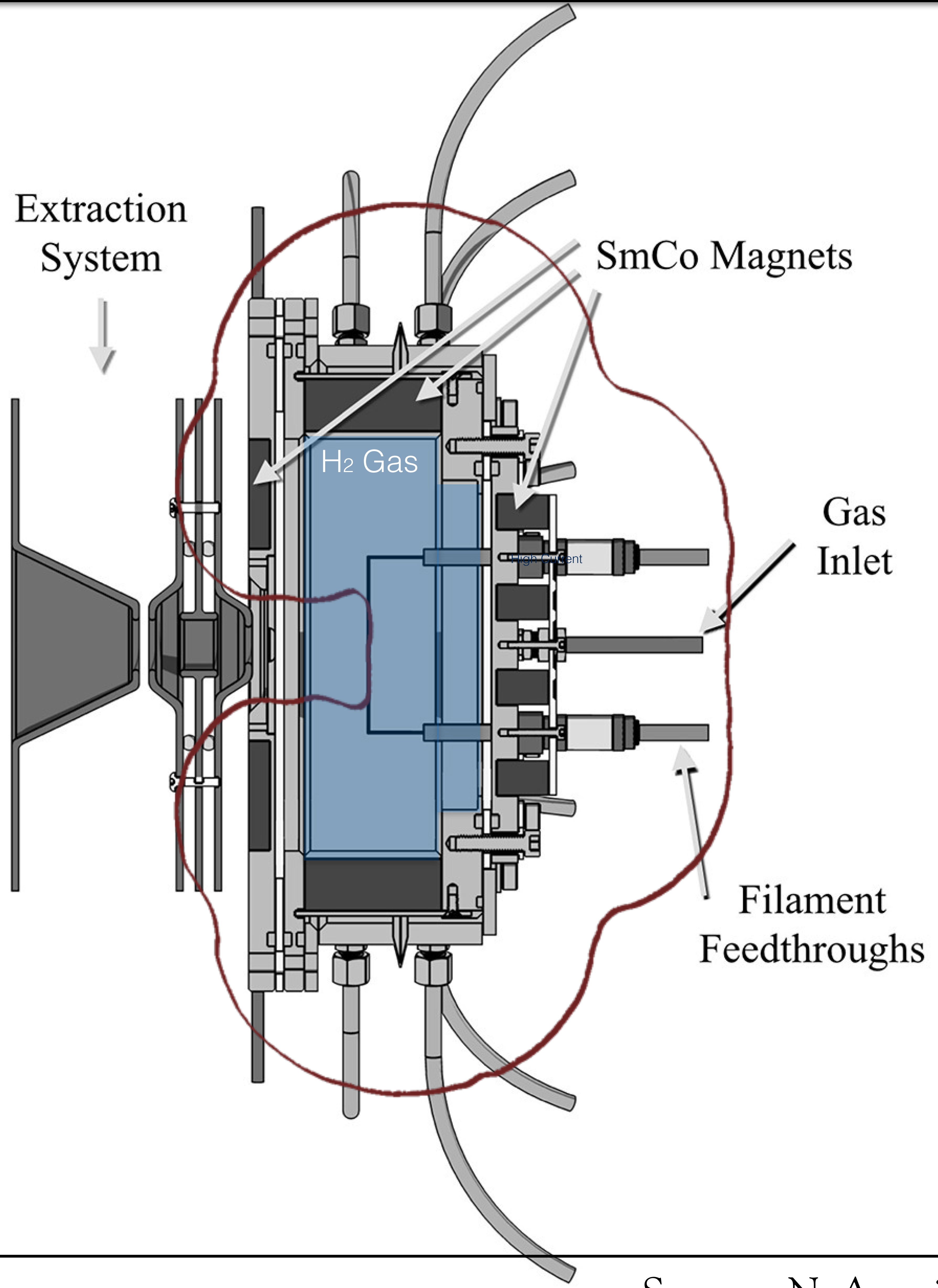

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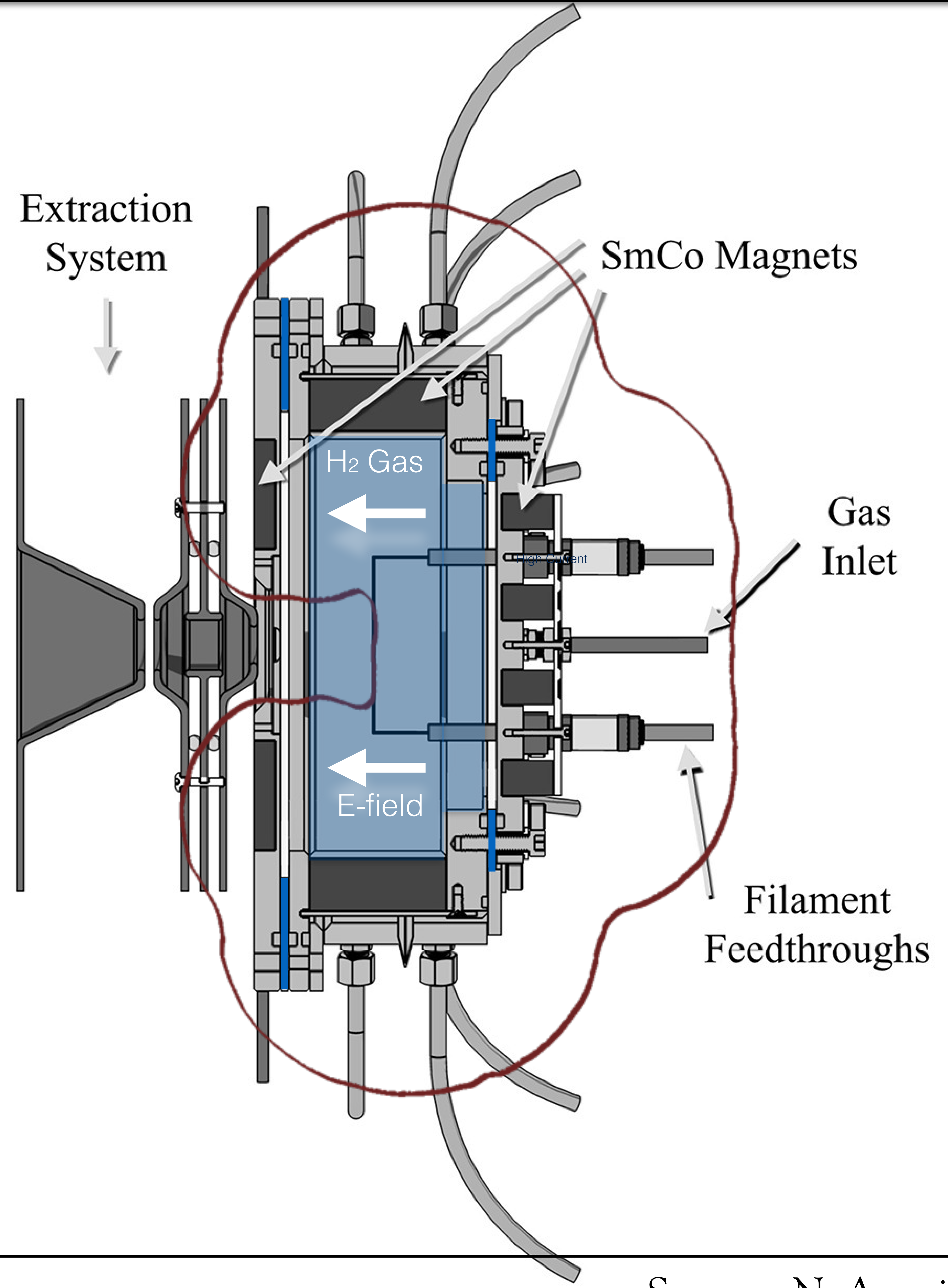

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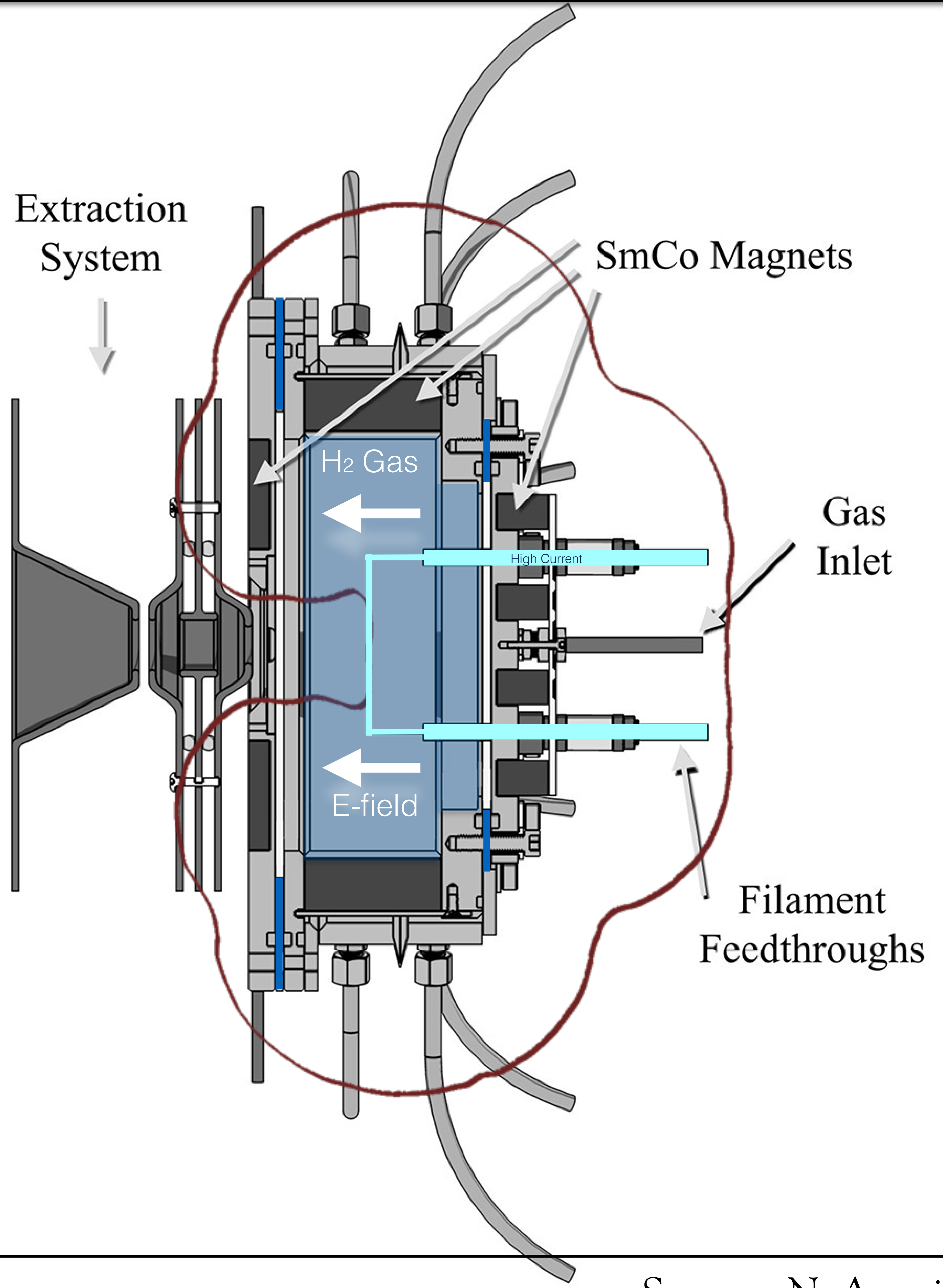

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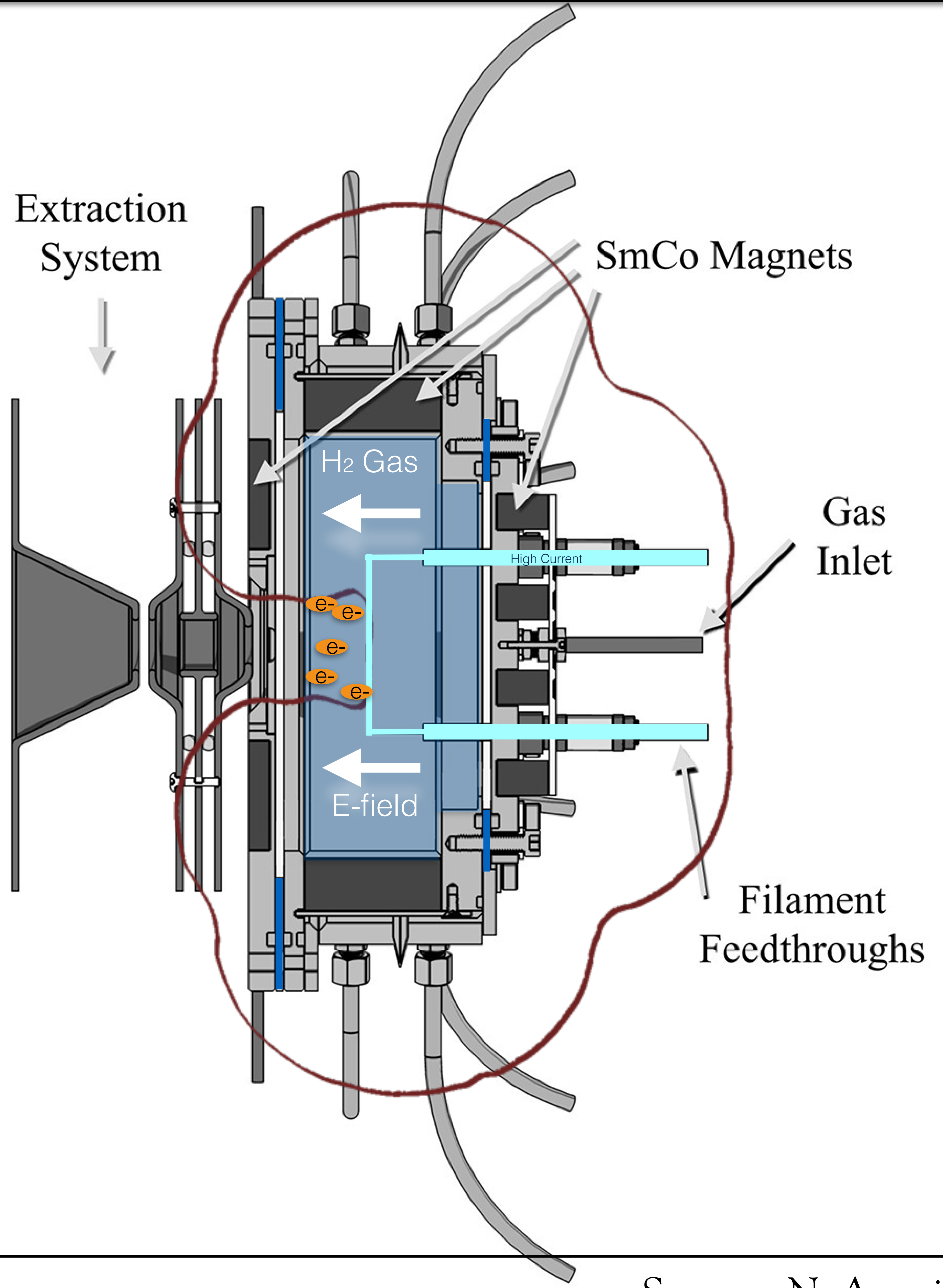

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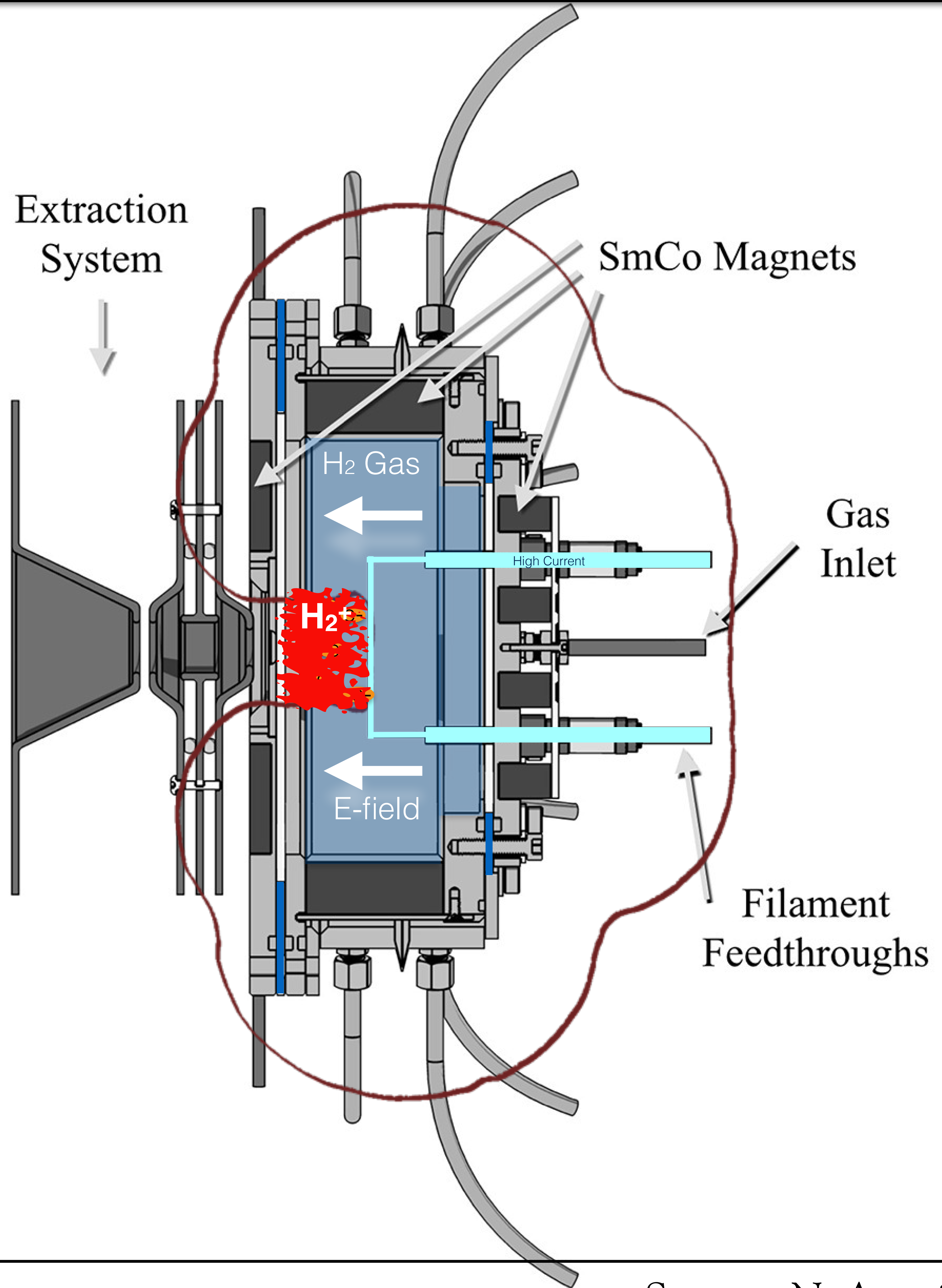

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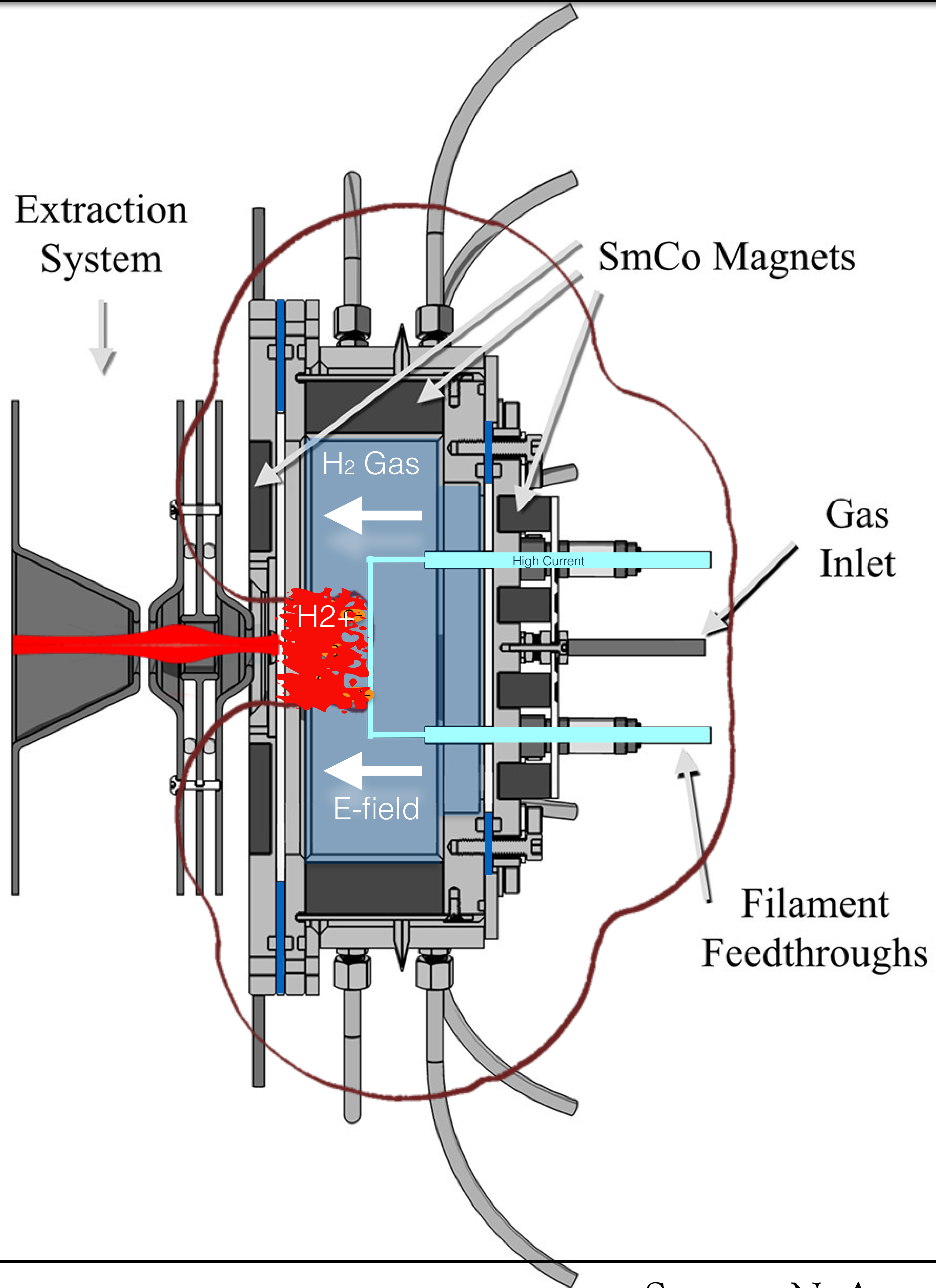
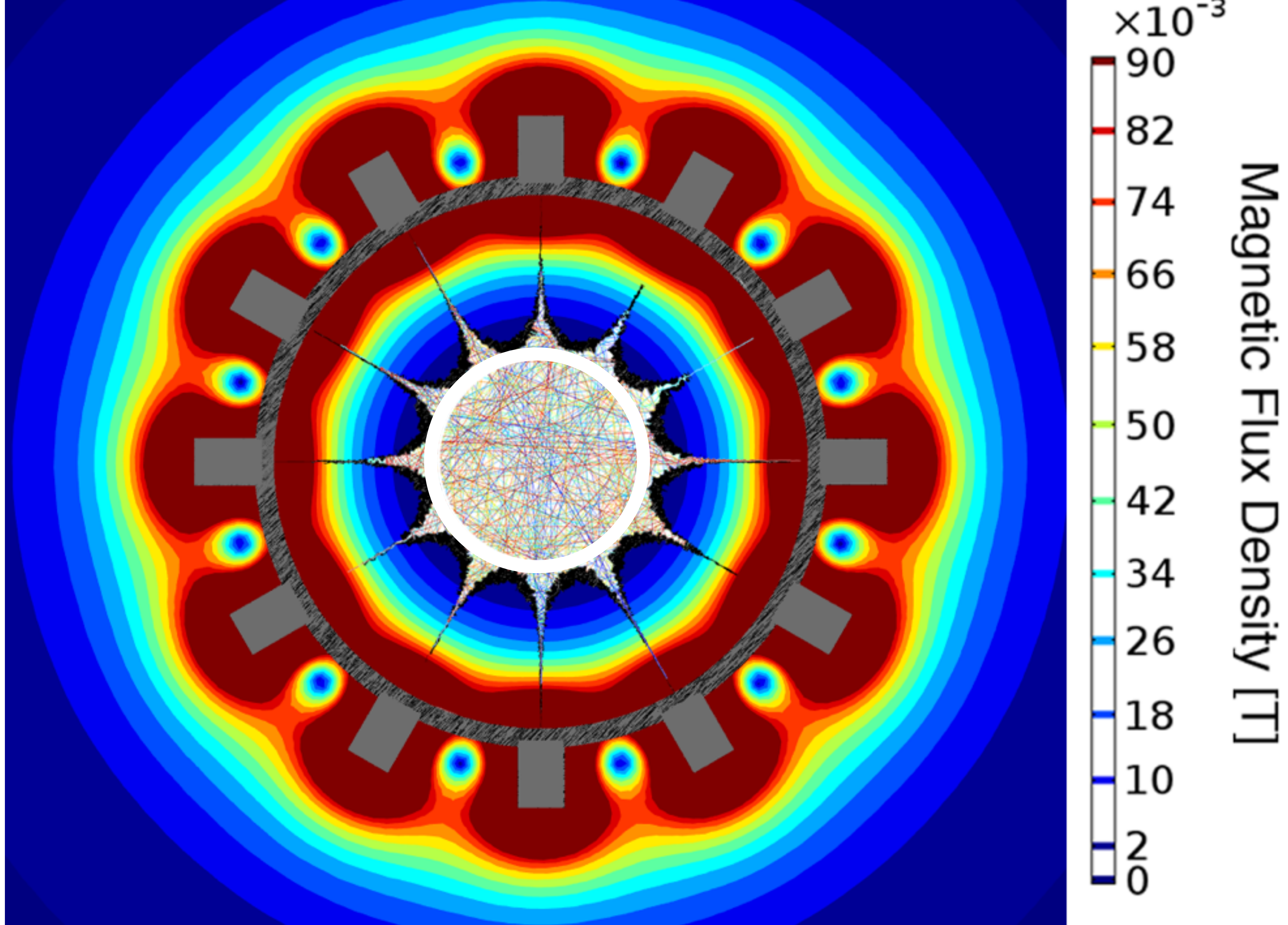


# Particle trajectory and magnetic field simulation

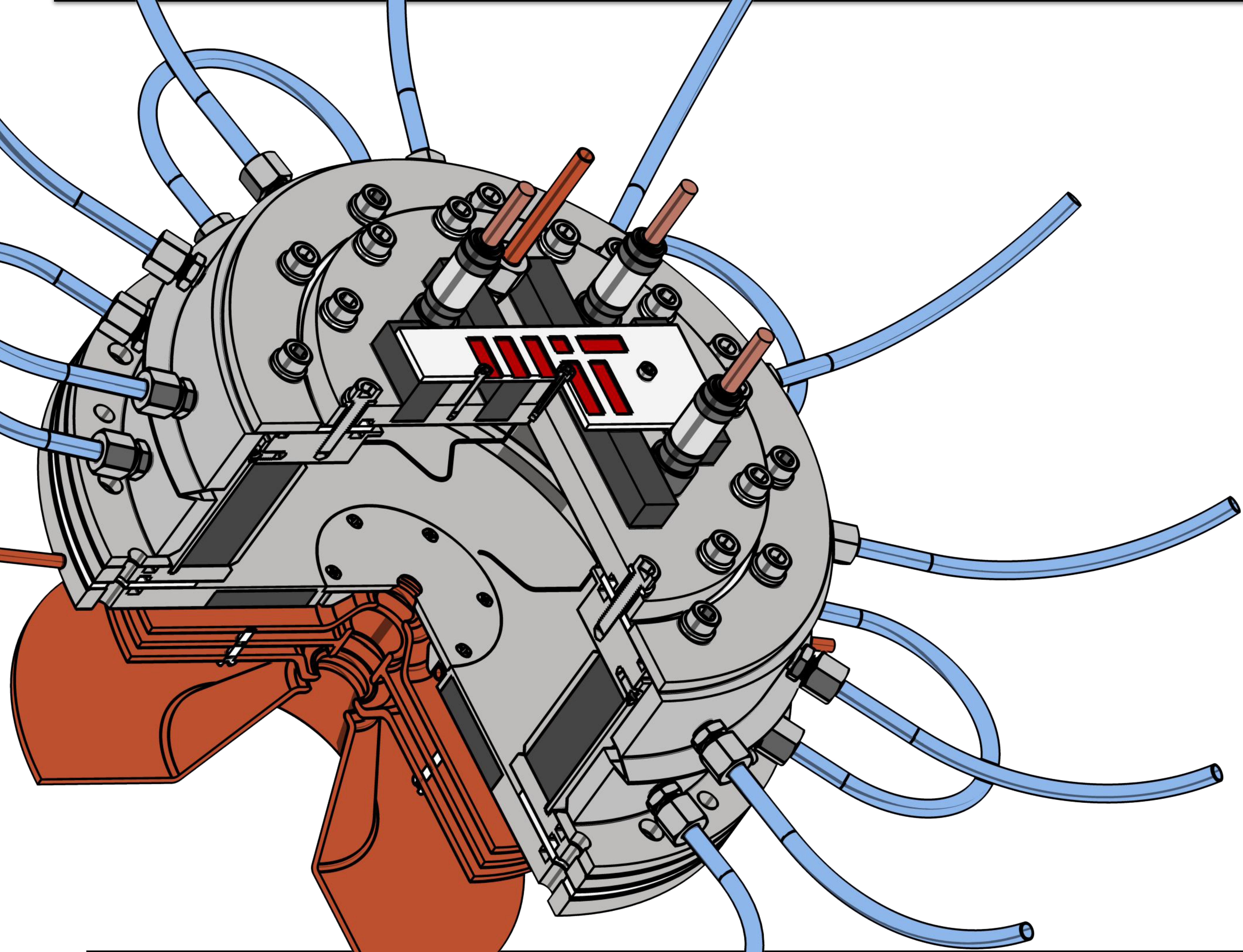
COMSOL Simulation

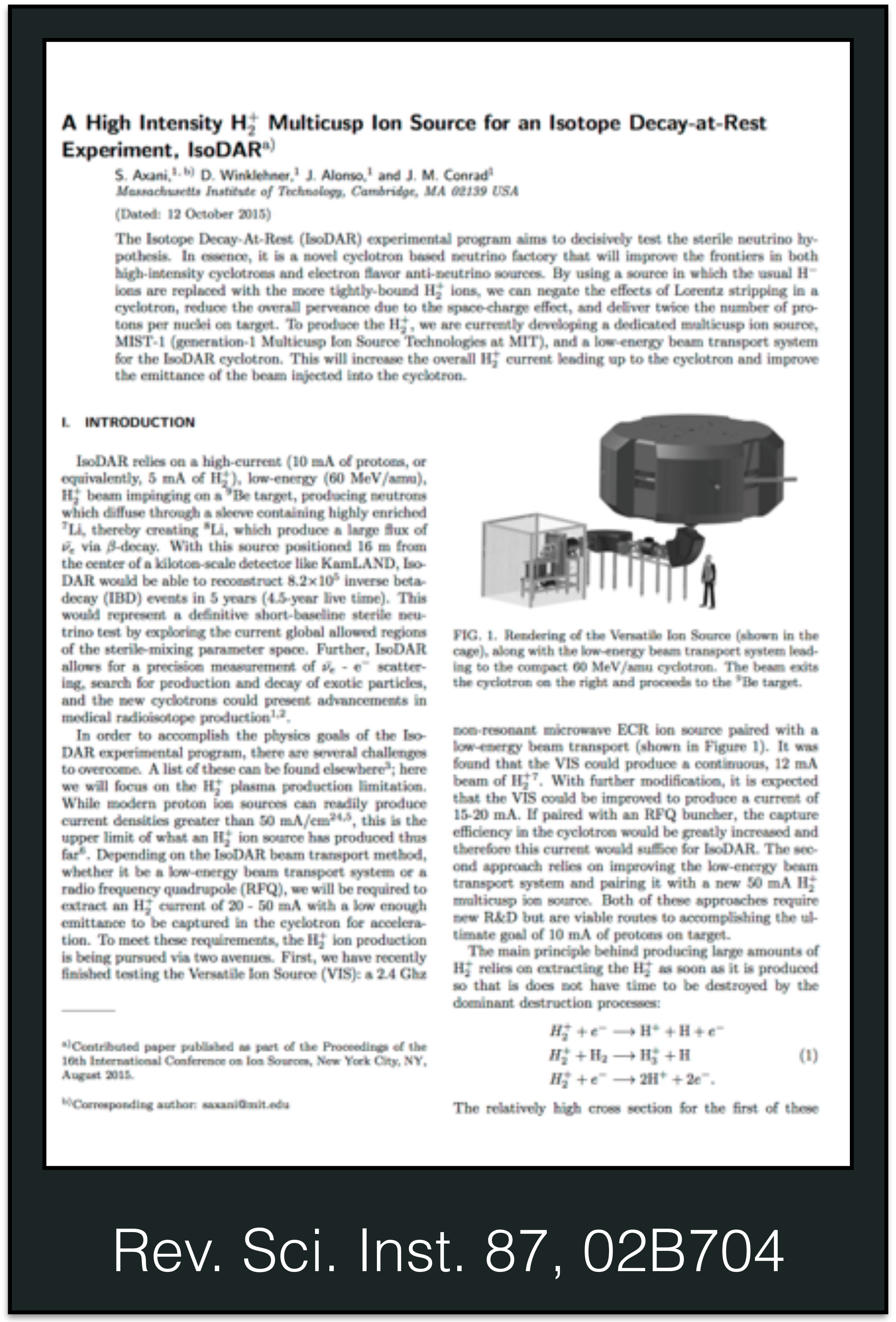



Magnetic flux density for a cross section of the ion source.

- 40-80 eV electrons were injected into the multi-cusp field.
- Electrons were found to be contained primarily in the sub-20 Gauss region (white circle).
- The multi-cusp field "reflects" the mobile charged particles back into the center of the ion source.

# MIST-v1 final design





## A High Intensity $H_2^+$ Multicusp Ion Source for an Isotope Decay-at-Rest Experiment, IsoDAR[a)]


S. Axani,[1, b)] D. Winklehner,[1] J. Alonso,[1] and J. M. Conrad[1]
*Massachusetts Institute of Technology, Cambridge, MA 02139 USA*



(Dated: 12 October 2015)



The Isotope Decay-At-Rest (IsoDAR) experimental program aims to decisively test the sterile neutrino hypothesis. In essence, it is a novel cyclotron based neutrino factory that will improve the frontiers in both high-intensity cyclotrons and electron flavor anti-neutrino sources. By using a source in which the usual $H^-$ ions are replaced with the more tightly-bound $H_2^+$ ions, we can negate the effects of Lorentz stripping in a cyclotron, reduce the overall perveance due to the space-charge effect, and deliver twice the number of protons per nuclei on target. To produce the $H_2^+$, we are currently developing a dedicated multicusp ion source, MIST-1 (generation-1 Multicusp Ion Source Technologies at MIT), and a low-energy beam transport system for the IsoDAR cyclotron. This will increase the overall $H_2^+$ current leading up to the cyclotron and improve the emittance of the beam injected into the cyclotron.


### I. INTRODUCTION

IsoDAR relies on a high-current (10 mA of protons, or equivalently, 5 mA of $H_2^+$), low-energy (60 MeV/amu), $H_2^+$ beam impinging on a $^9$Be target, producing neutrons which diffuse through a sleeve containing highly enriched $^7$Li, thereby creating $^8$Li, which produce a large flux of $\bar{\nu}_e$ via $\beta$-decay. With this source positioned 16 m from the center of a kiloton-scale detector like KamLAND, IsoDAR would be able to reconstruct $8.2\times10^5$ inverse beta-decay (IBD) events in 5 years (4.5-year live time). This would represent a definitive short-baseline sterile neutrino test by exploring the current global allowed regions of the sterile-mixing parameter space. Further, IsoDAR allows for a precision measurement of $\bar{\nu}_e$ - $e^-$ scattering, search for production and decay of exotic particles, and the new cyclotrons could present advancements in medical radioisotope production[1,2].

In order to accomplish the physics goals of the IsoDAR experimental program, there are several challenges to overcome. A list of these can be found elsewhere[3]; here we will focus on the $H_2^+$ plasma production limitation. While modern proton ion sources can readily produce current densities greater than 50 mA/cm$^2$[4,5], this is the upper limit of what an $H_2^+$ ion source has produced thus far[6]. Depending on the IsoDAR beam transport method, whether it be a low-energy beam transport system or a radio frequency quadrupole (RFQ), we will be required to extract an $H_2^+$ current of 20 - 50 mA with a low enough emittance to be captured in the cyclotron for acceleration. To meet these requirements, the $H_2^+$ ion production is being pursued via two avenues. First, we have recently finished testing the Versatile Ion Source (VIS): a 2.4 Ghz non-resonant microwave ECR ion source paired with a low-energy beam transport (shown in Figure 1). It was found that the VIS could produce a continuous, 12 mA beam of $H_2^+$[7]. With further modification, it is expected that the VIS could be improved to produce a current of 15-20 mA. If paired with an RFQ buncher, the capture efficiency in the cyclotron would be greatly increased and therefore this current would suffice for IsoDAR. The second approach relies on improving the low-energy beam transport system and pairing it with a new 50 mA $H_2^+$ multicusp ion source. Both of these approaches require new R&D but are viable routes to accomplishing the ultimate goal of 10 mA of protons on target.

FIG. 1. Rendering of the Versatile Ion Source (shown in the cage), along with the low-energy beam transport system leading to the compact 60 MeV/amu cyclotron. The beam exits the cyclotron on the right and proceeds to the $^9$Be target.

The main principle behind producing large amounts of $H_2^+$ relies on extracting the $H_2^+$ as soon as it is produced so that is does not have time to be destroyed by the dominant destruction processes:

$$
\begin{aligned}
H_2^+ + e^- &\longrightarrow \mathrm{H}^+ + \mathrm{H} + e^- \\
H_2^+ + \mathrm{H}_2 &\longrightarrow \mathrm{H}_3^+ + \mathrm{H} \qquad (1)\\
H_2^+ + e^- &\longrightarrow 2\mathrm{H}^+ + 2e^-.
\end{aligned}
$$

The relatively high cross section for the first of these

[a)] Contributed paper published as part of the Proceedings of the 16th International Conference on Ion Sources, New York City, NY, August 2015.

[b)] Corresponding author: saxani@mit.edu

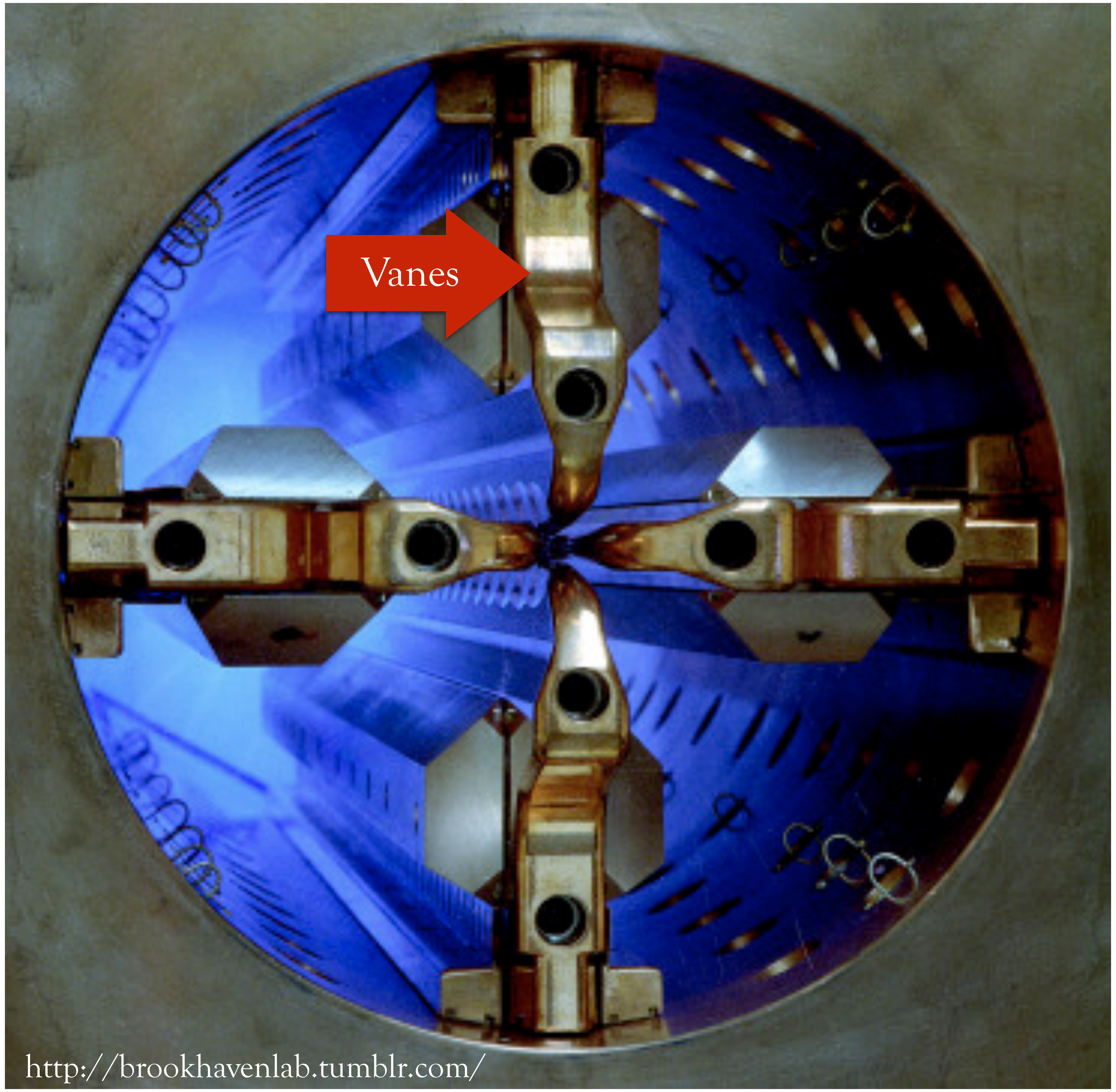
Rev. Sci. Inst. 87, 02B704

We should be able to test the ion source within the next few weeks.

# PART II
# Radio Frequency Quadrupole (RFQ) Injection Strategy

DAEδALUS IsoDAR

# What is an Radio Frequency Quadrupole (RFQ)



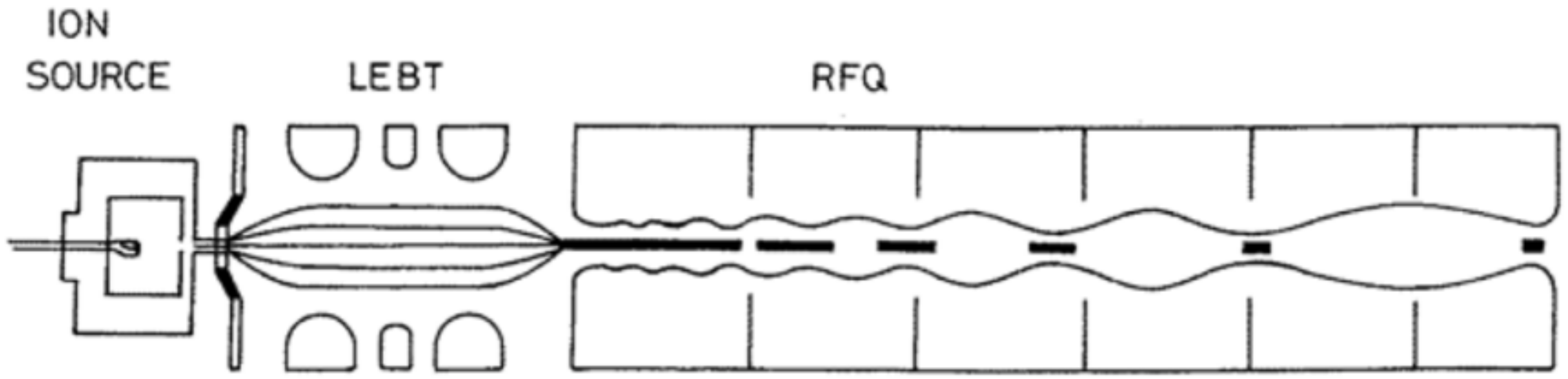
http://brookhavenlab.tumblr.com/

A single device that is able to both efficiently accelerate and bunch a high-current beam.

- great for accelerating low-energy ions
- very small emittance growth
- accelerates and focuses with a single field

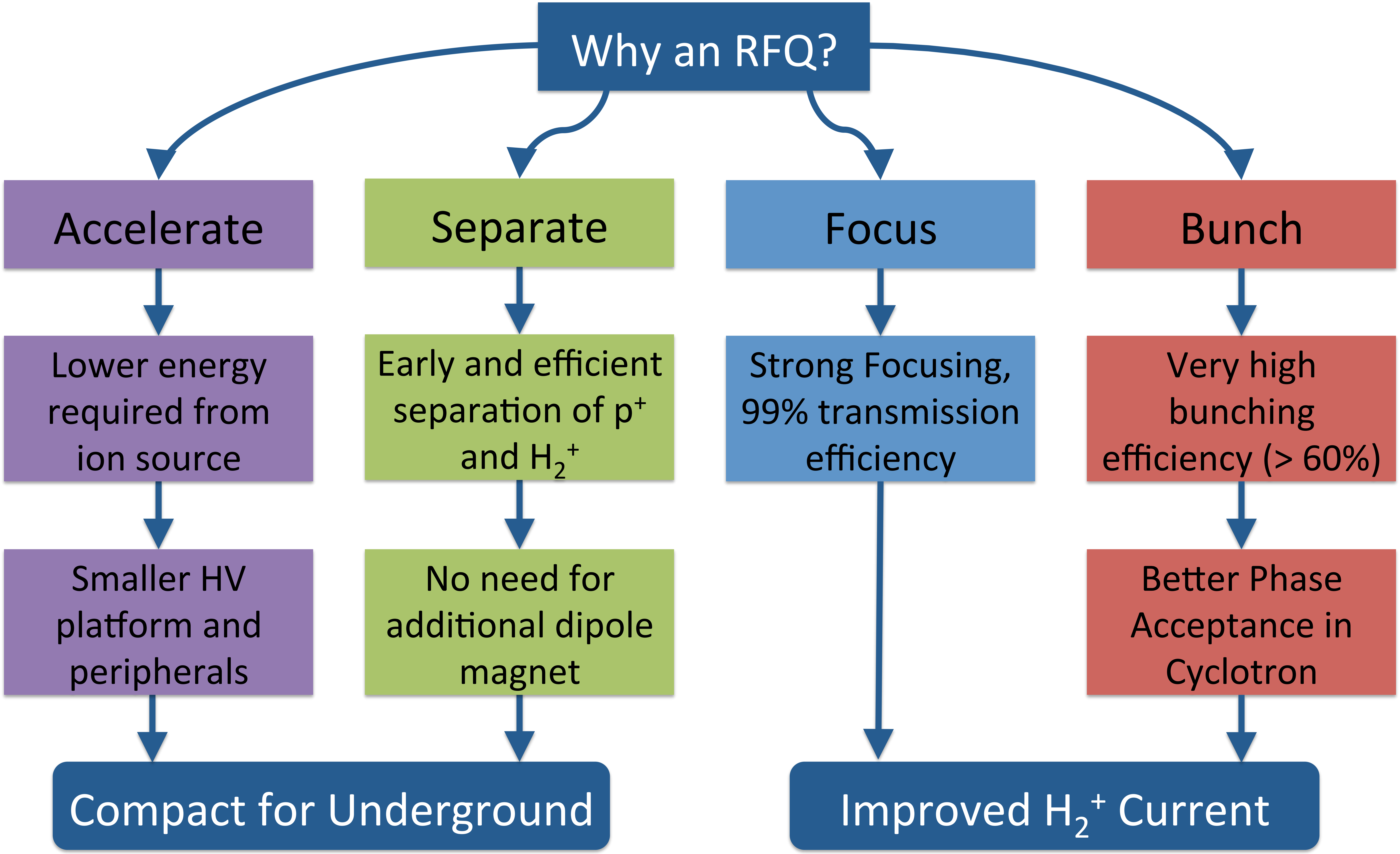
Modern technology. Becoming pervasive in intensity frontier complexes like Fermilab.

As of yet, using an RFQ as a buncher for axial injection into cyclotron has yet to be realized.



A. Schempp

# IsoDAR's interest in RFQs



# RFQ interfacing with the IsoDAR cyclotron

**Preliminary Design of an RFQ Direct Injection Scheme for the IsoDAR High Intensity $H_2^+$ Cyclotron**[a)]

D. Winklehner,[1, b)] R. Hamm,[2] J. Alonso,[3] J. M. Conrad,[1] and S. Axani[1]
[1)] *Massachusetts Institute of Technology, Cambridge, MA, USA*
[2)] *R&M Technical Enterprises, Pleasanton, CA, USA*
[3)] *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

(Dated: 21 September 2015)

IsoDAR is a novel experiment designed to measure neutrino oscillations through $\bar{\nu}_e$ disappearance, thus providing a definitive search for sterile neutrinos. In order to generate the necessary anti-neutrino flux, a high intensity primary proton beam is needed. In IsoDAR, $H_2^+$ is accelerated and is stripped into protons just before the target, to overcome space charge issues at injection. As part of the design, we have refined an old proposal to use an RFQ to axially inject bunched $H_2^+$ ions into the driver cyclotron. This method has several advantages over a classical low energy beam transport (LEBT) design: (1) The bunching efficiency is higher than for the previously considered two-gap buncher and thus the overall injection efficiency is higher. This relaxes the constraints on the $H_2^+$ current required from the ion source. (2) The overall length of the LEBT can be reduced. (3) The RFQ can also accelerate the ions. This enables the ion source platform high voltage to be reduced from 70 kV to 15 kV, making underground installation easier. We are presenting the preliminary RFQ design parameters and first beam dynamics simulations from the ion source to the spiral inflector entrance.

FIG. 1. Cartoon of the IsoDAR experiment. Detector image courtesy of the KamLAND collaboration. (Color online.)

I. INTRODUCTION

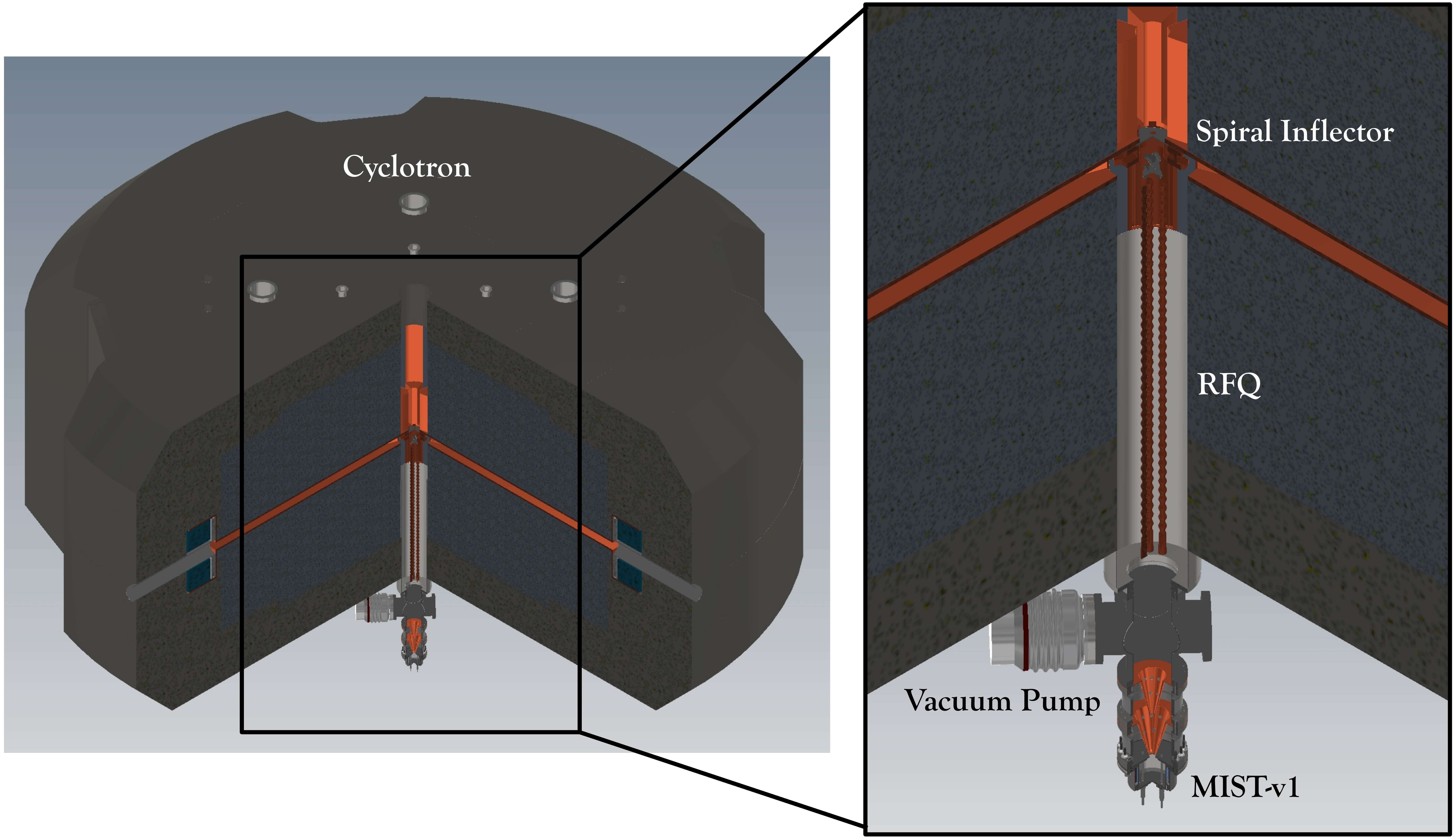
In the IsoDAR (Isotope Decay-At-Rest) experiment[1], $H_2^+$ ions will be delivered by a high performance ion source, accelerated to 60 MeV/amu in a compact cyclotron, and then stripped to protons and dumped on a beryllium target surrounded by a lithium sleeve. Neutrons generated by the protons hitting $^9$Be will be captured on $^7$Li, and the resulting $^8$Li will then beta decay-at-rest, producing a very pure $\bar{\nu}_e$ beam. This accelerator and target system will be placed close (16 m from the center) to an existing neutrino detector (e.g. KamLAND) to measure $\bar{\nu}_e$ disappearance from neutrino oscillations via inverse beta decay. This process is depicted in Figure 1. The short baseline will allow tracing out more than a full period of the oscillation wave inside the detector, thus presenting a definitive search for proposed sterile neutrinos that may participate in the oscillations but not in the weak interaction. In order to get definitive results over the course of a few years, a high neutrino flux and hence a very high primary proton beam intensity, are necessary.

In the summer months of 2013 and 2014, tests of high intensity $H_2^+$ production, transport, and injection into a cyclotron were conducted at Best Cyclotron Systems, Inc. (BCS) in Vancouver, Canada. The results are reported in Ref.[2]; in short: It was possible to extract ~ 12 mA of $H_2^+$ from the "versatile ion source" (VIS), an off-resonance 2.45 GHz ECR ion source. The transmission through a spiral inflector at beam currents on the order of 10 mA was ≈ 95%. The typical acceptance of an unbunched beam into the cyclotron RF bucket is on the order of 5% and with a 2-gap multiharmonic buncher, this acceptance can be increased to 10-20%. Based on the beam tests at BCS, we concluded that the nominal 5 mA of $H_2^+$ extracted from the cyclotron is achievable, but pushing the limits. We are exploring two avenues to improve the situation: (1) We are constructing a new ion source (multicusp) dedicated to the production of $H_2^+$[3], and (2) we are investigating the use of a Radio Frequency Quadrupole (RFQ) to replace the LEBT. The RFQ is a linear accelerator that can focus, bunch, and accelerate a continuous beam of charged particles at low energies with high bunching and transmission efficiencies. Because the basic RFQ concept can be implemented over a wide range of frequencies, voltages, and physical dimensions, it is an ideal structure to use for bunching an intense ion beam for injection into a cyclotron and has already been used in several cyclotron systems for radial injection of input beams[4]. It can also be used for axial injection at much lower energies as first proposed in 1981[5]. However, to date, direct axial injection into a compact cyclotron using an RFQ has not been realized.

[a)]Contributed paper published as part of the Proceedings of the 16th International Conference on Ion Sources, New York City, NY, August 2015.

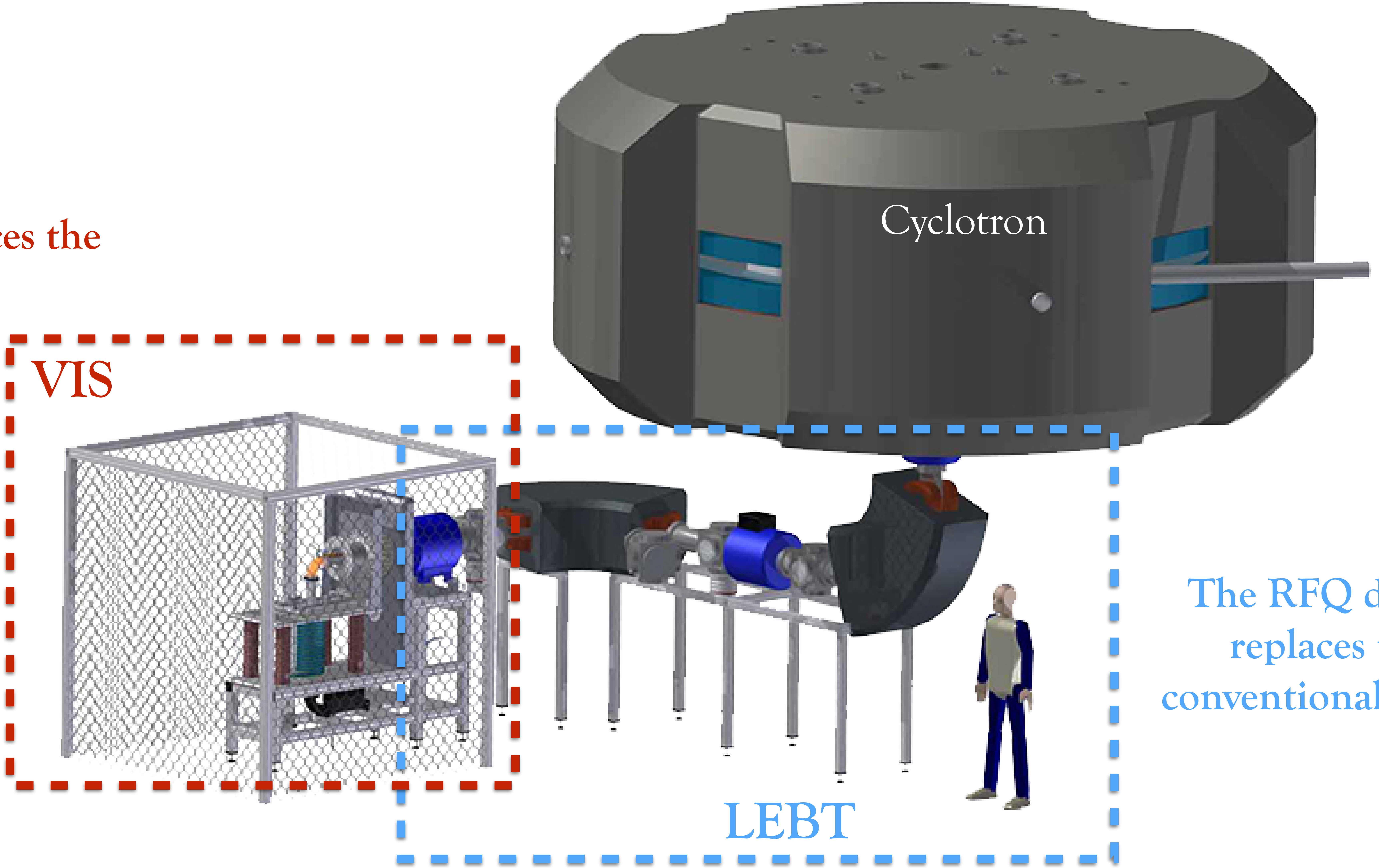
[b)]Corresponding author: winklehn@mit.edu

Rev. Sci. Inst. 87, 02B929



# Conventional low-energy beam transport (LEBT)

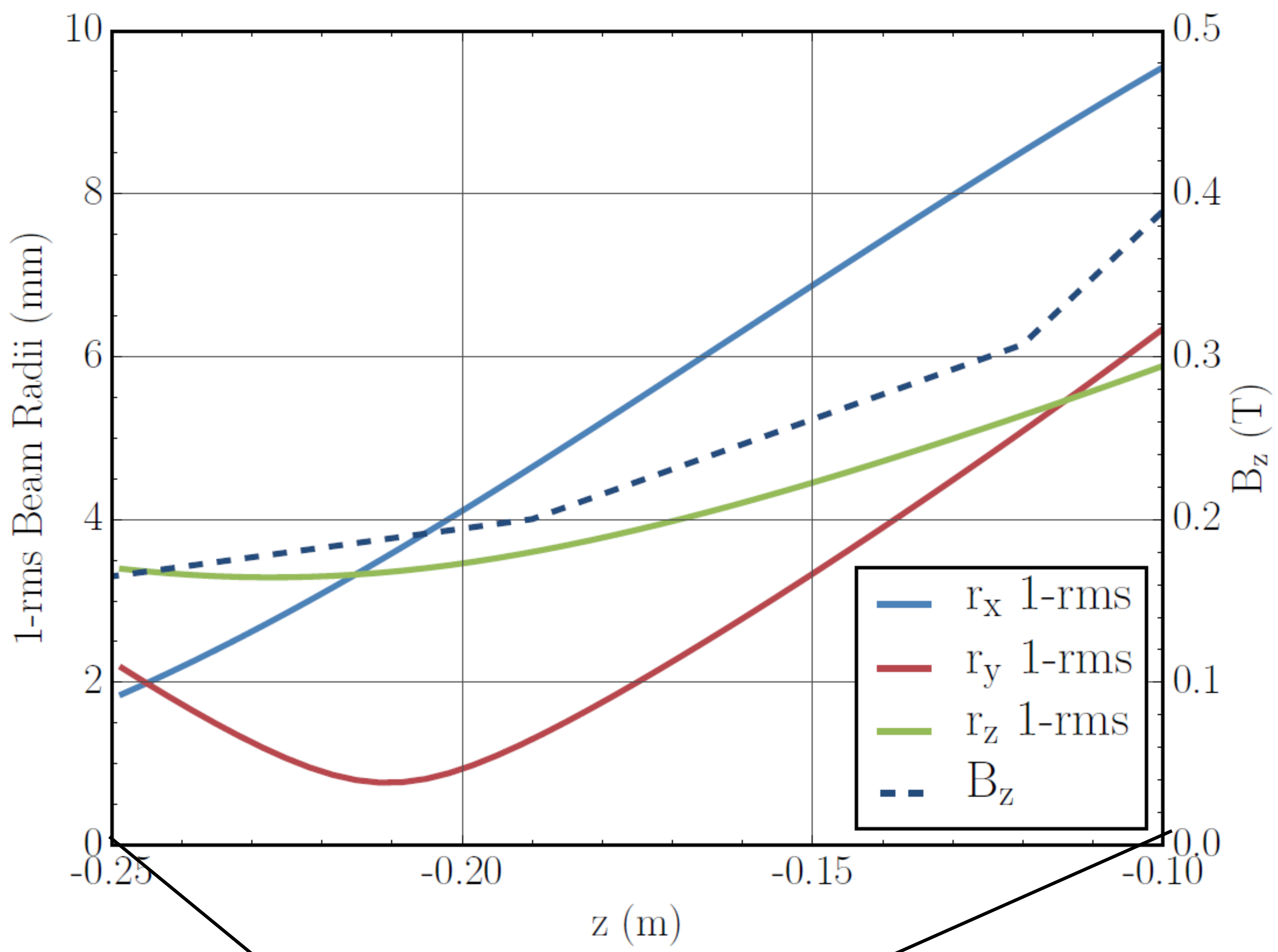
MIST-v1 replaces the VIS

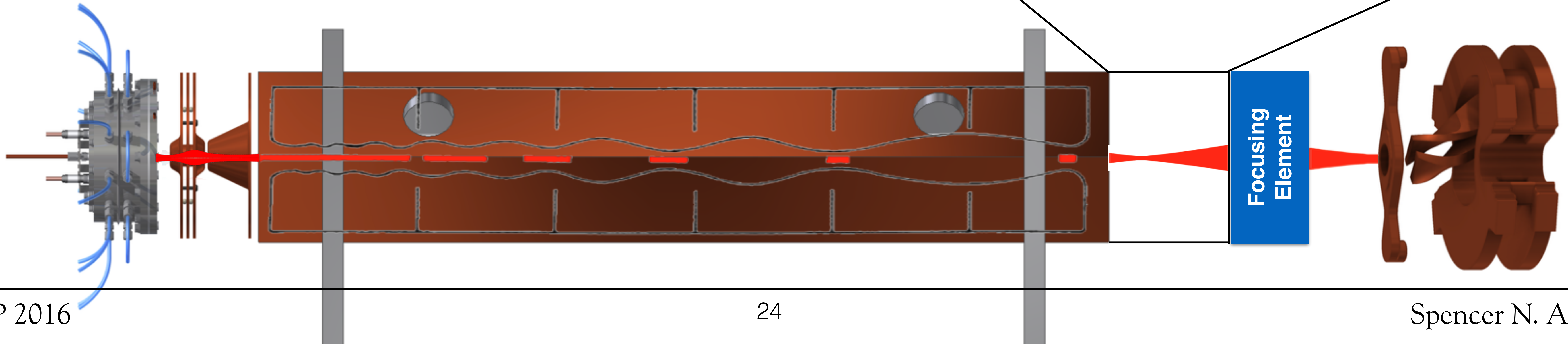



The RFQ design replaces the conventional LEBT

# Entering the cyclotron

- The design now needs to be optimized.
- We can see that at the exit of the RFQ, the beam is highly divergent.
- 15 cm from the exit, the 10 mA beam has increased from 3mm to 8 mm, nearing the limitations of our spiral inflector entrance aperture.



# Outlook

- Test stand for MIST-v1 is ready for initial beam characterization.
- We will hopefully be able to contribute to the high-intensity ion source community.
- Following the tests of MIST-v1, we will beginning investigating plasma heating via RF or ECR/Microwave.

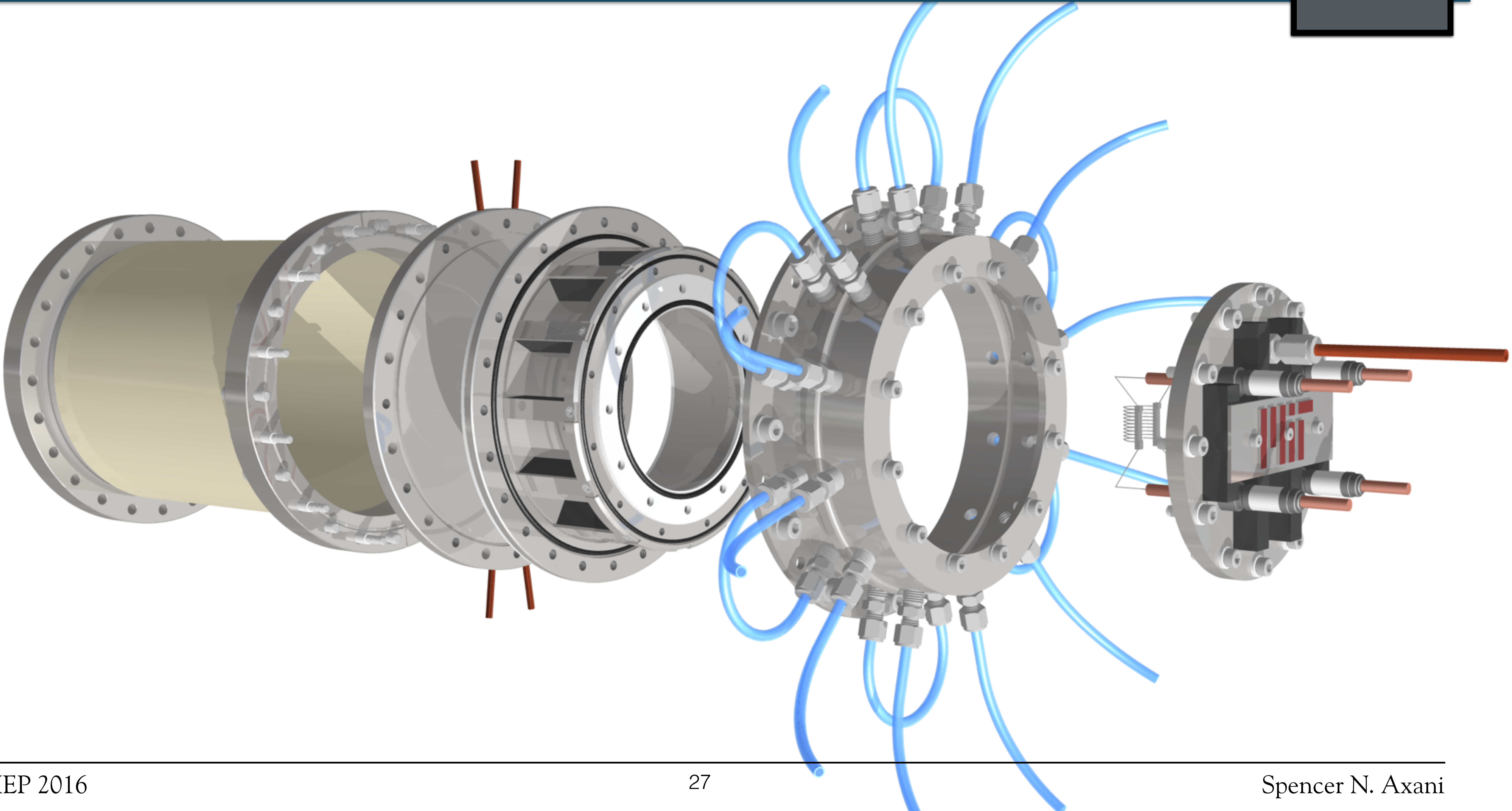
- We received funding through NSF for the RFQ injection scheme.
- Simulations and design are being refined.
- RFQ injection into a cyclotron could hold much scientific merit in the intensity frontier
- The preliminary design is promising but further in the design and mating to the cyclotron are still being investigated.

- Both studies are progressing rapidity and we hope to have measurements fairly soon.

Thank you for your attention!

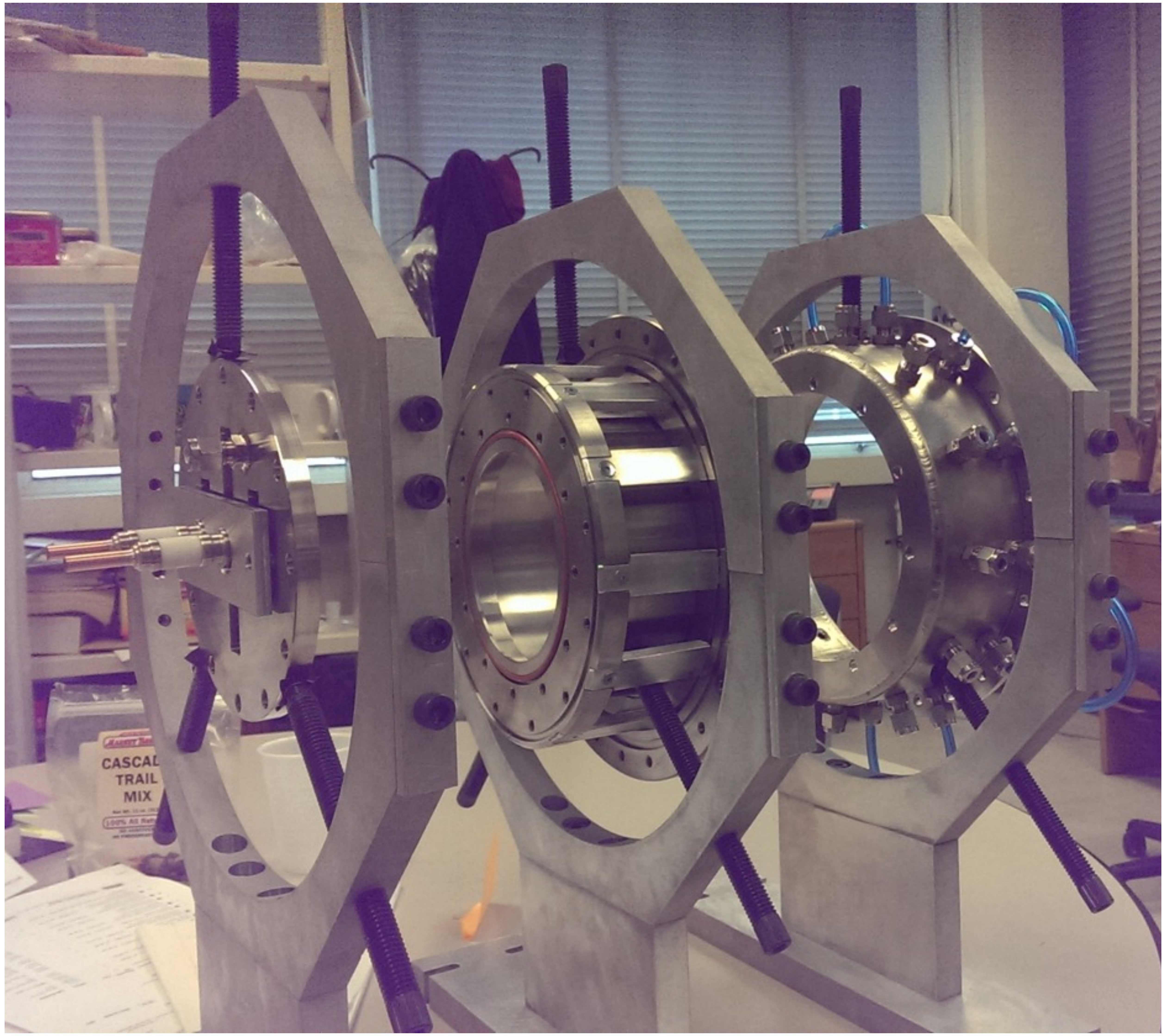
# Pictures...

Backup



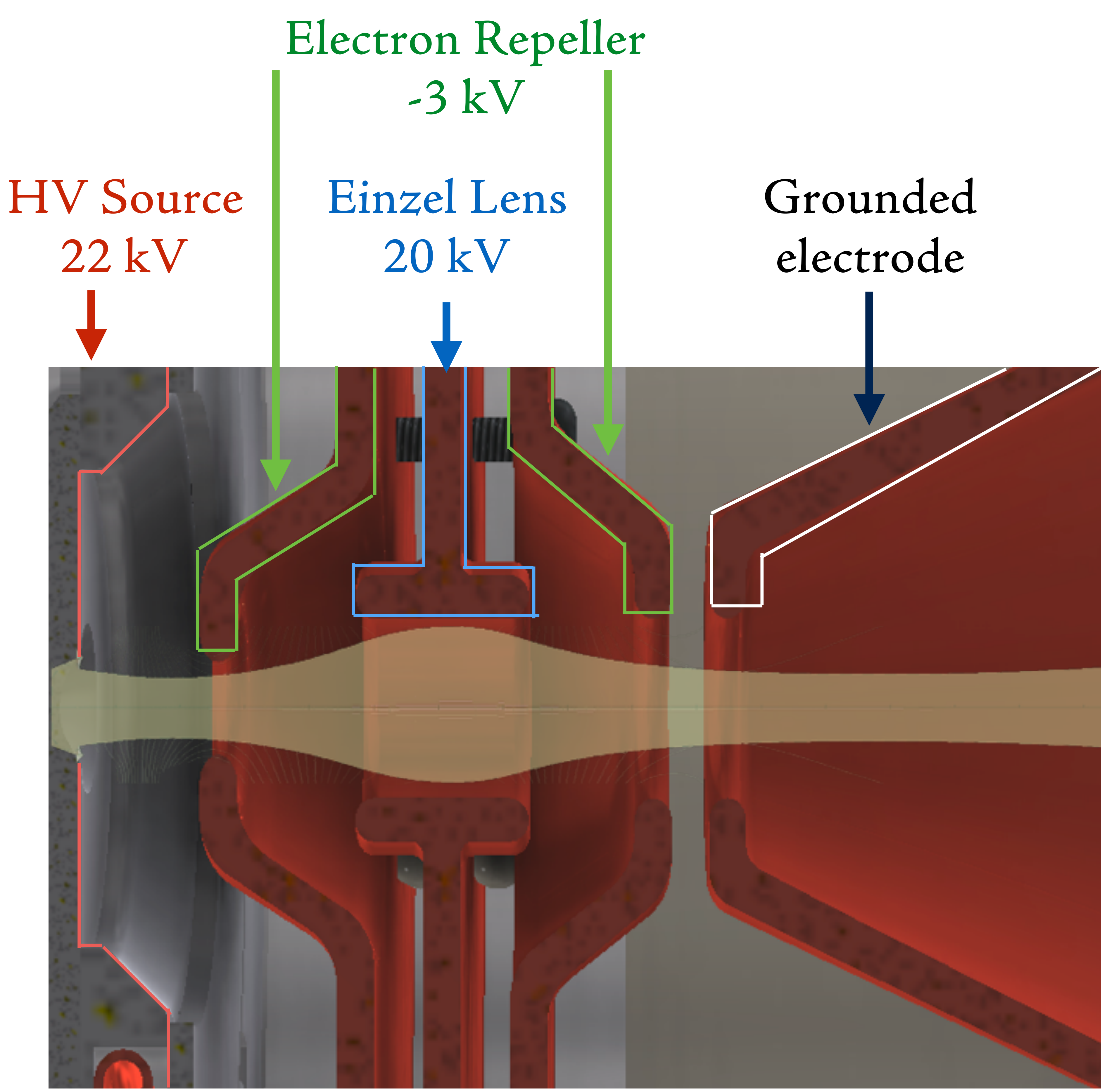
# Pictures…






# Pentode Extraction System

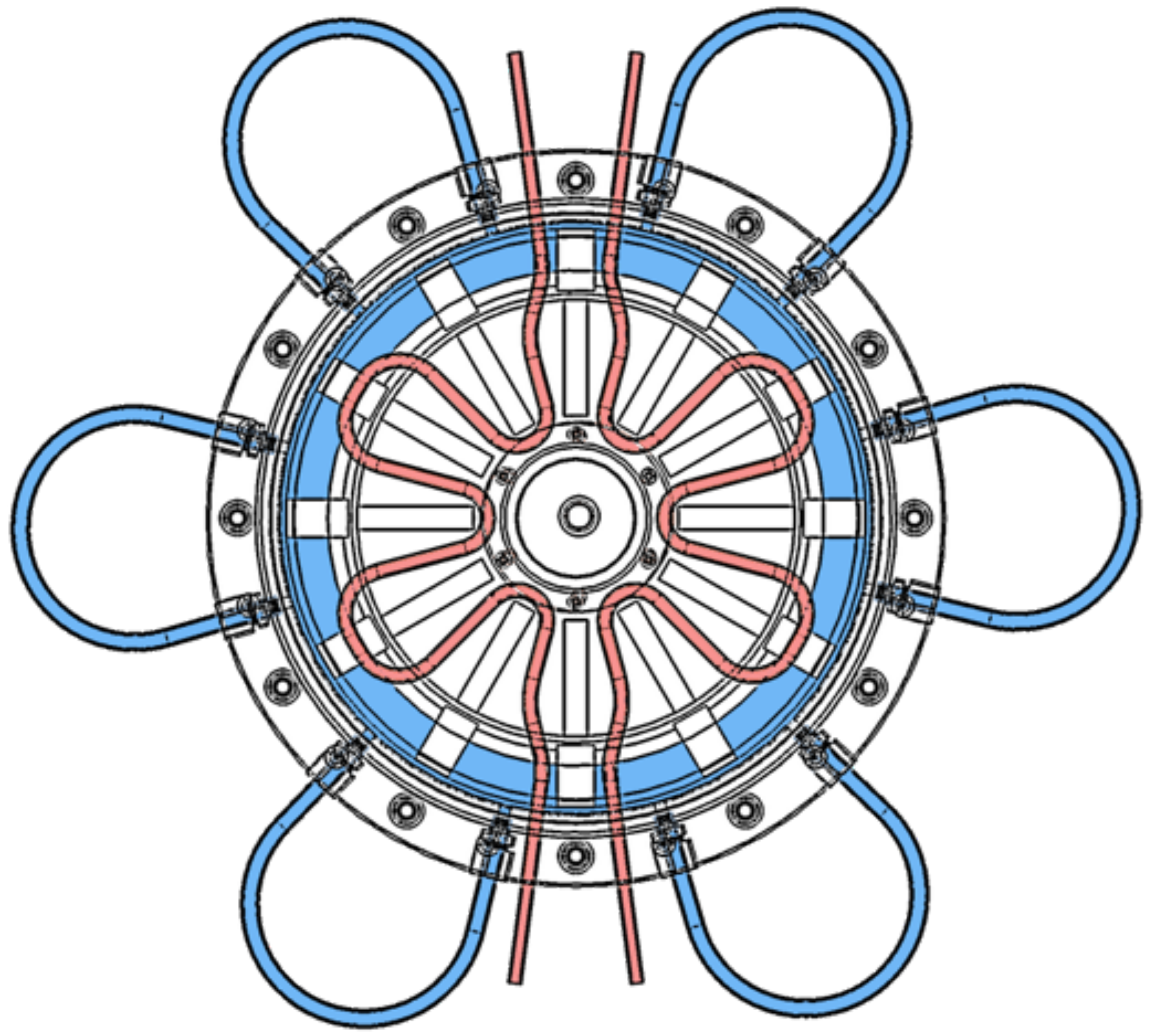
Backup



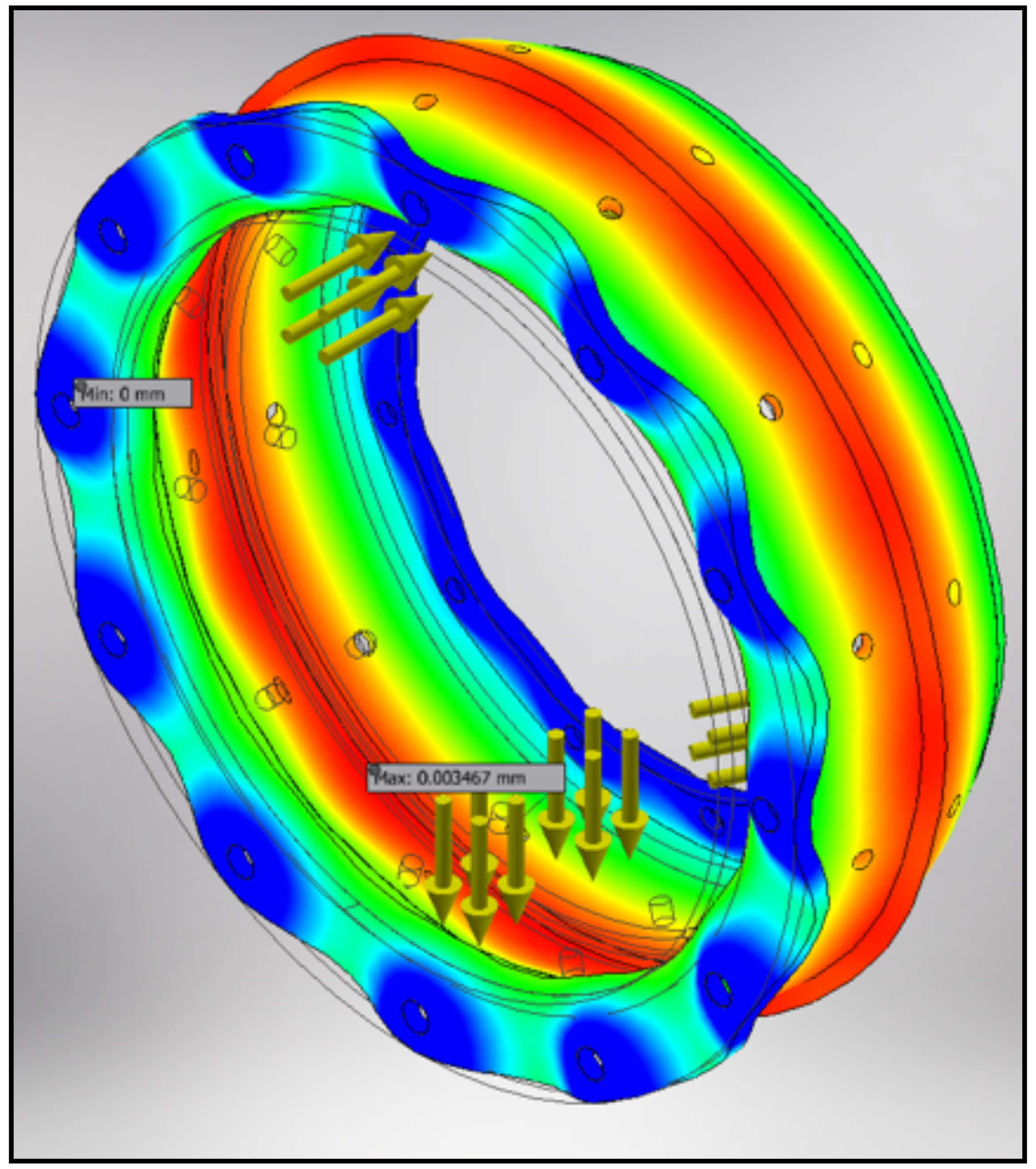

- The simulation was performed with the well-established 2D ion source simulation software IGUN.
- The electrode system is a pentode system with the plasma electrode at 15 – 22 kV, a puller at negative 1–5 kV, an Einzel lens at 13–20 kV, an electron repeller at negative 1 – 5 kV, and a grounded electrode.
- The simulation yields a 50 mA $H_2^+$ ion beam with a 2-rms diameter of 8 mm and a normalized 4-rms emittance of 0.6 π-mm-mrad at the end of the simulation.

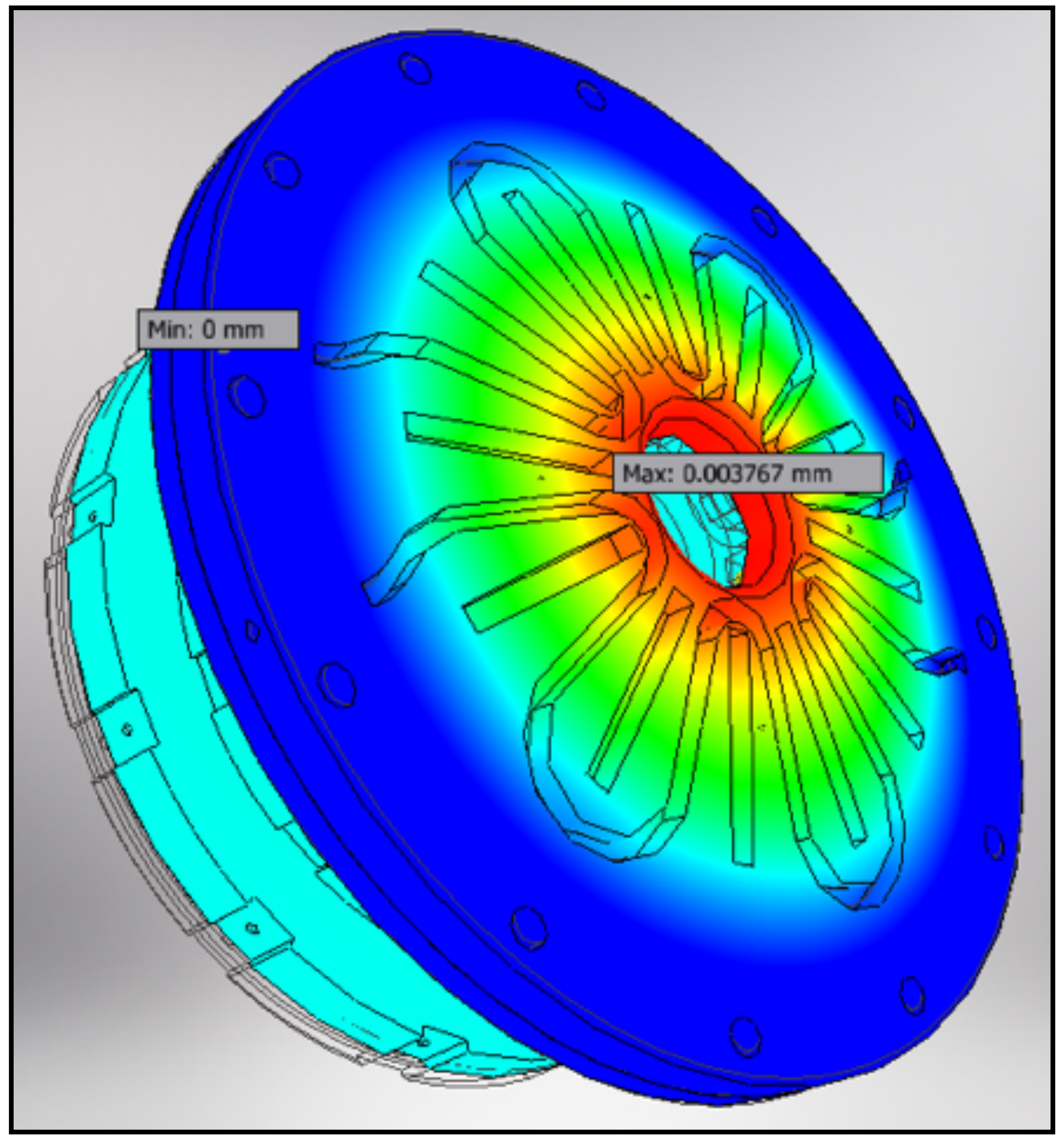
# Cooling system

Backup



- The front plate has embedded 3/16” copper cooling lines.
- The exterior of the plasma chamber is flooded by cooling water.

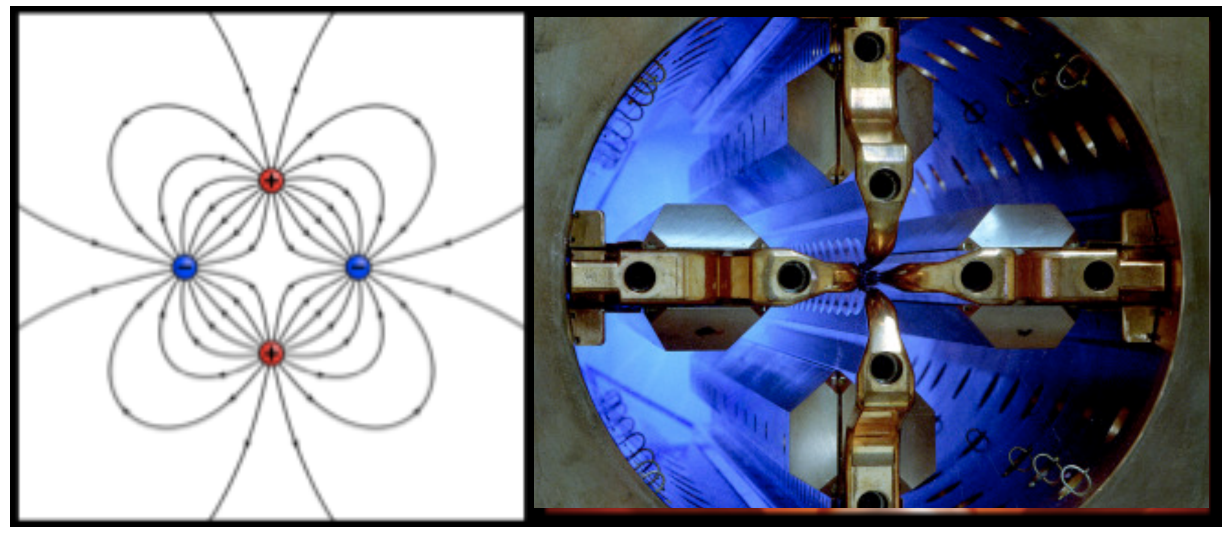




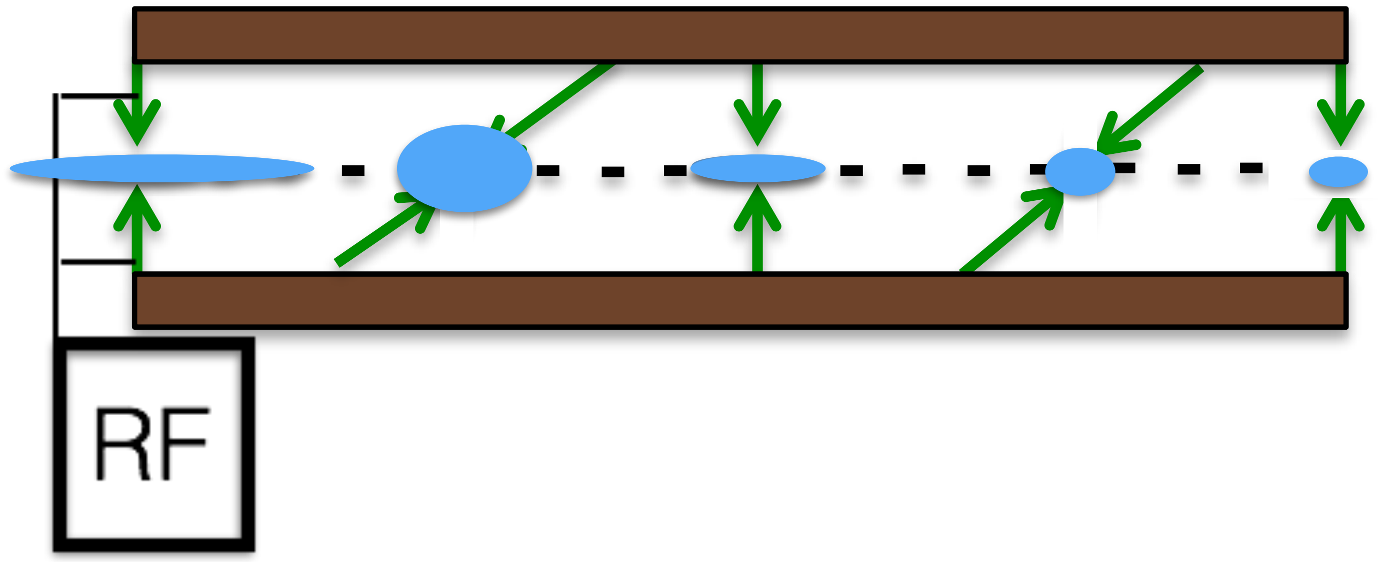

- 40 psi pressure simulations indicate a maximum deflection of 3.5 micro meters on the water jacket and 3.8 um on the front plate.
- O-ring surfaces have sub-um deflections

# How do RFQs work?

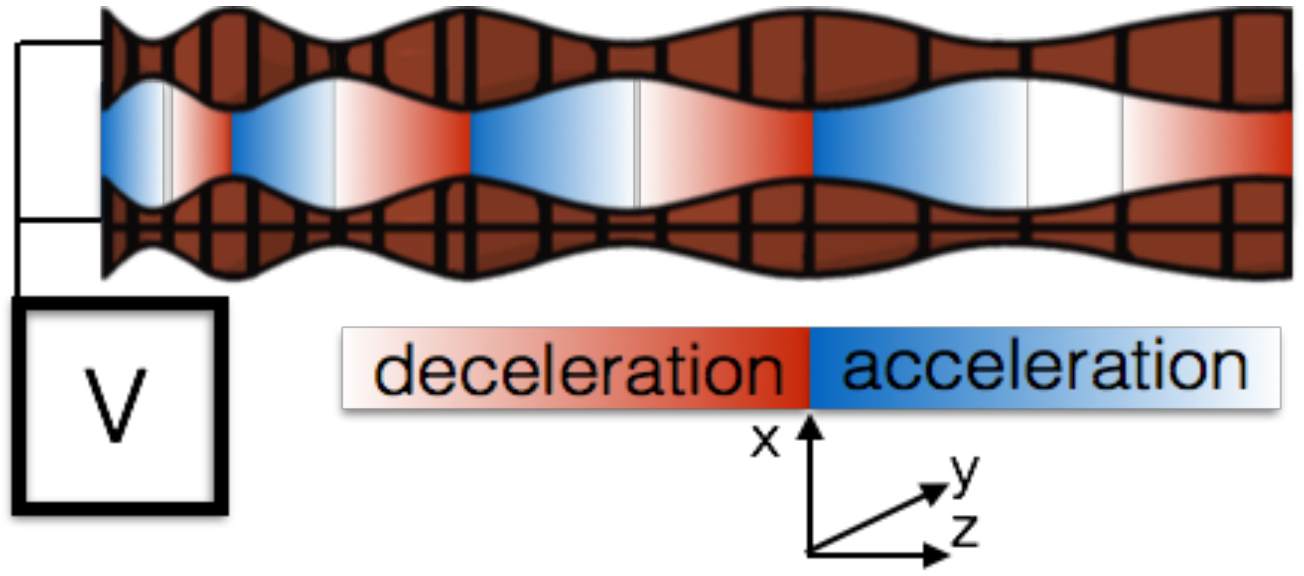
Backup



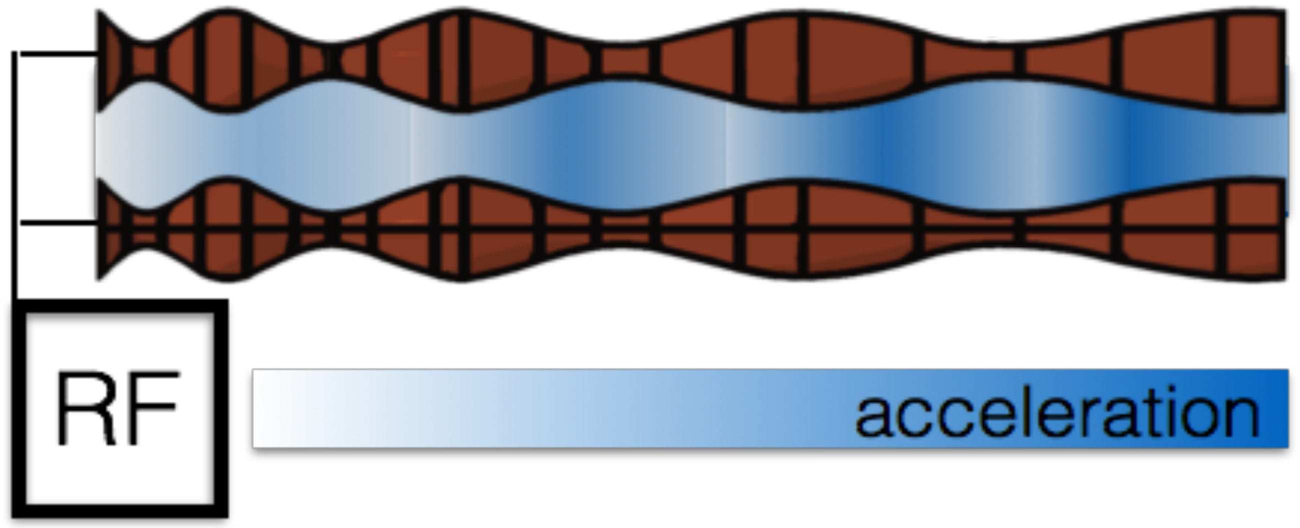
- Quadrupole transverse electric field produced by the 4-rod/vane design allows for focusing.




- Can continuously focus the beam when driven by RF.




- Modulations in the RFQ design make cause a longitudinal field (accel/decel cells).
- RF field adiabatically bunches
- Bunching from gradually changing synchronous phase



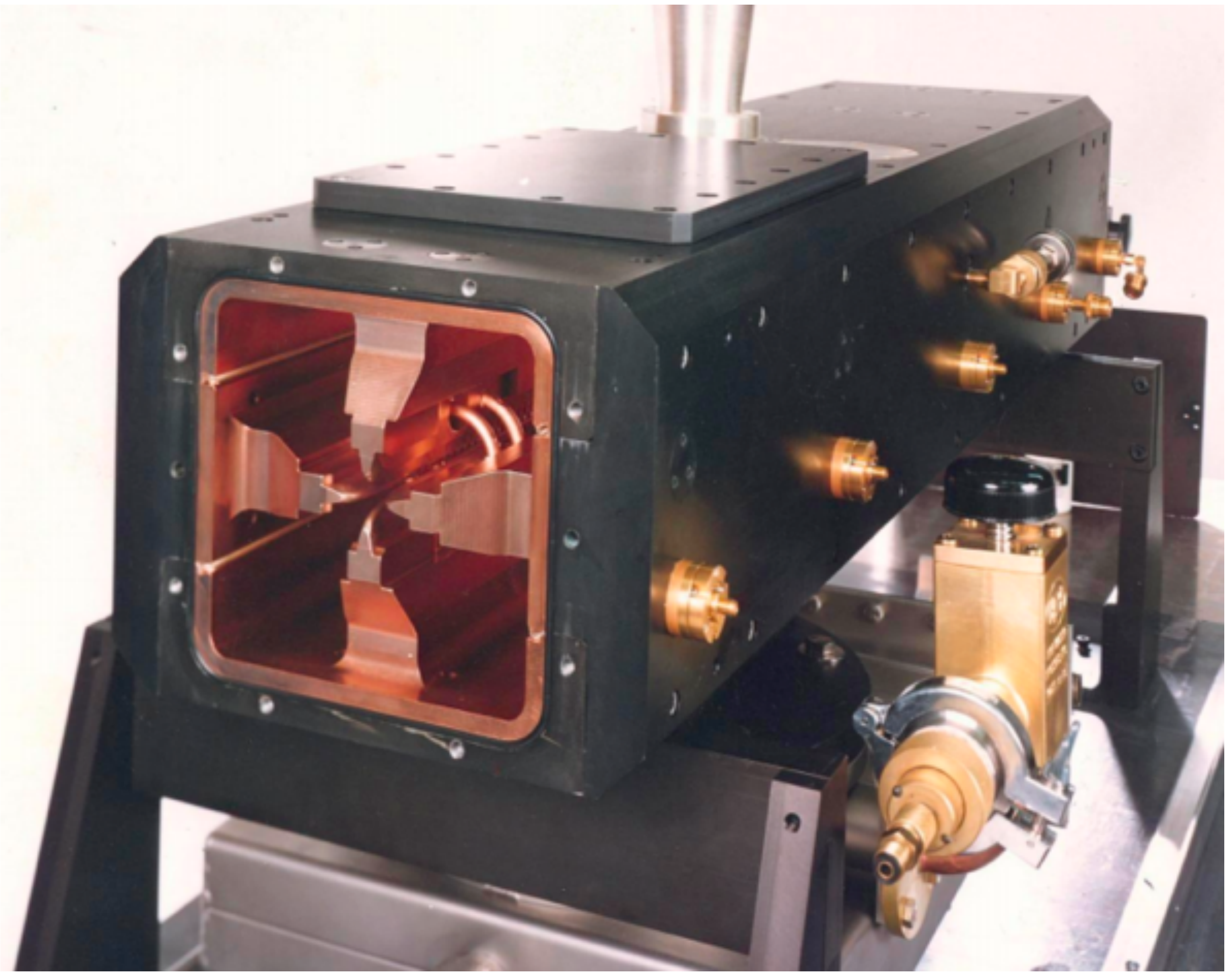

- Drive with properly tuned RF
  - Adiabatic bunching
  - and the particles with q/m see continuous acceleration

# Parmteq simulation parameters

Backup

Table 2: IsoDAR RFQ-Linac Injector Parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Operating frequency | 33.2 MHz | Bore radius | 1.27 cm |
| Injection energy | 15 keV | Maximum vane modulation | 1.94 |
| Final beam energy | 80 keV | Structure length | 1.09 m |
| Design input current | 10 mA | Peak RF field surface gradient | 4.66 MV/m |
| Current limit | 22 mA | Structure RF power | $<$ 9.5 kW |
| Transmission at 10 mA | 99% | Beam power | 0.64 kW |
| Inp. trans. emittance (6-rms, norm.) | 0.5 $\pi$-mm-mrad | Total input RF power | $<$ 10.14 kW |
| Nominal vane voltage | 43 kV | | |



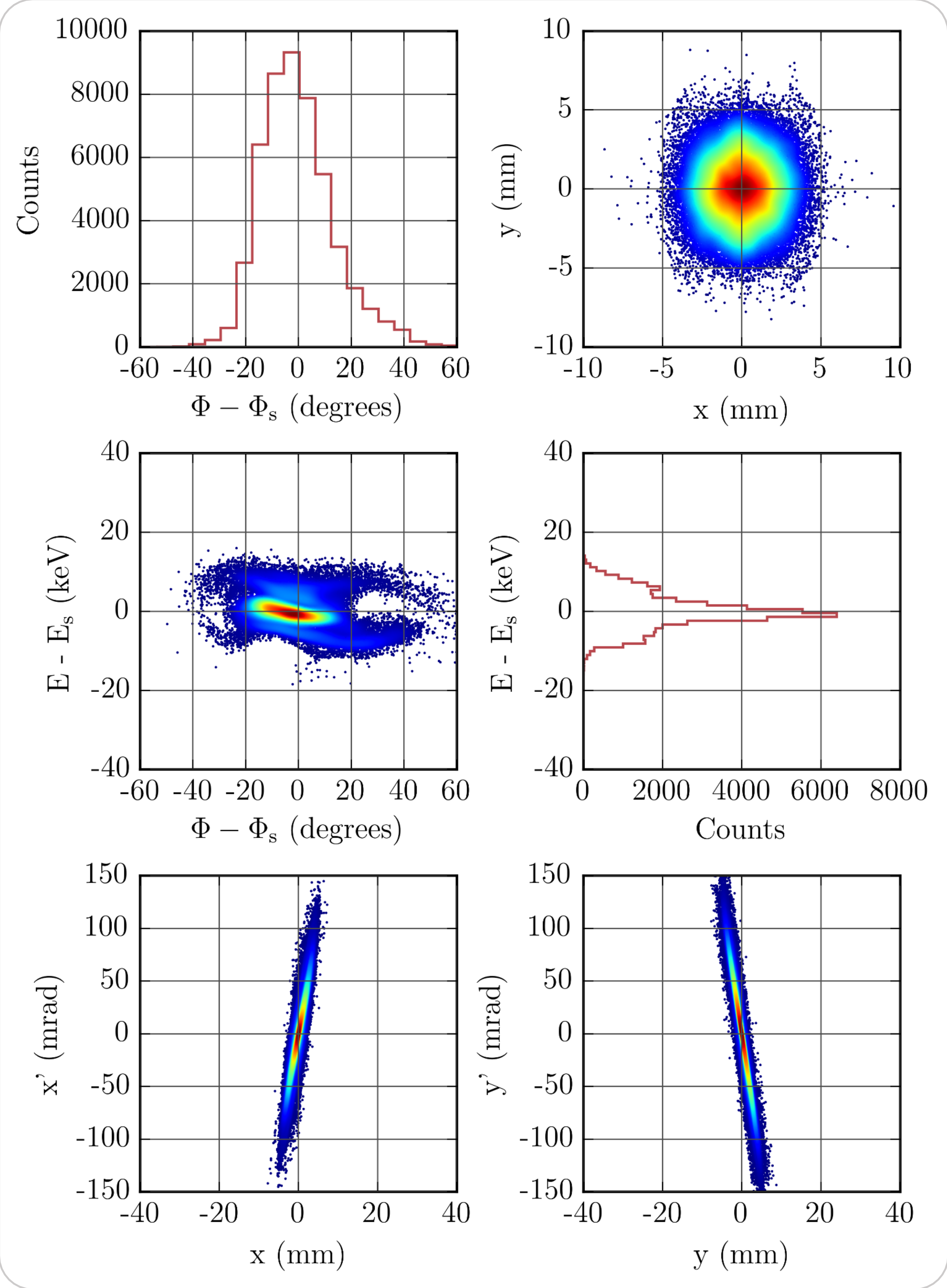
# Simulation results

Backup

The phase spread of each particle. 60% of the particles are contained within +/- 10 degrees of the synchronous phase

Energy versus particle phase

Horizontal phase space. We see it is diverging.




The beam at the exit of the RFQ is fairly round.
Roughly 3 mm in radius.

Energy distribution centered around the design energy (80 keV). 60% contained within +/- 2 keV

Vertical phase space. We see it is converging.

# Uncertainties and backgrounds

Backup

- KamLAND was designed to efficiently detect IBD. A standard analysis has a 92% efficiency for identifying IBD events.
- Vertex reconstruction resolution of 12 cm/E(MeV) and an energy resolution of 6.4%/E(MeV)
- IBD interaction has a well known cross section with an uncertainty of 0.2%
- The largest background comes from the 100 reactor antineutrino IBD events detected by KamLAND per year. The reactor antineutrino rate is dependent on the operation of the nuclear reactors in Japan which has been significantly lower in 2012 and 2013