Award # DE-SC0019651 Title: **Novel methods for *in situ* high-density surface cleaning (scrubbing) of ultrahigh vacuum long narrow tubes to reduce secondary electron yield and outgassing**

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About PVI:

- PVI is a system engineering and manufacturing company specializing in high vacuum and thermal process technologies.

- Current and previous products include tools used for thin film deposition, thermal diffusion systems, rotating grade titanium processing systems, and a variety of high temperature vacuum processing equipment.

Abstract

Electron clouds in existing accelerators limit machine performance through dynamical instabilities and associated vacuum pressure increases. Bare metal vacuum walls have shown to prevent electron cloud formation. Proper scrubbing of stainless steel, copper, or niobium vacuum walls can mitigate the problems of electron clouds and increase accelerator luminosity. Present scrubbing by ion beams and plasmas has resulted in unsatisfactory surface cleaning by not scrubbing all surfaces and poor debris pumping-out due to low-density plasma generation. Novel plasma discharge cleaning techniques and tools are being developed for *in-situ* scrubbing long, small diameter tubes by generating high-density plasmas to completely affect each exposed surface. One technique involves high plasma density magnetron mole, the other is based microwave plasma injection that generates high-density plasma. High-density plasma scrubbing in the viscous gas flow range can reach all surfaces and pump out all debris effectively.

- **Relevance:**
  - Scrubbing in e.g. RHIC, is performed with ion beams by filling the rings with 25 GeV proton beams. Short bunches fill RHIC with about $2.2\text{x}10^{13}$ protons resulting increase in pressure rise of up to 10^{-7} Torr. Problems: gas is in molecular flow range and plasma is confined by magnetic fields. Consequently, plasma does reach all vacuum surfaces with the limitation being poor pumping out of debris (affecting other accelerators e.g. LHC.
  - Project guiding principle is to ensure plasma cleaning of all exposed surfaces and pump-out of debris by generation of non-magnetized high density, relatively high-power plasmas, which in absence of magnetic fields and/or other plasma confinement mechanisms cannot sustain gradients, ensures complete coverage of all vacuum surfaces. The high-density results in viscous flow range of plasma/gas mixture that can be pumped-out effectively through 6.9 cm ID of the RHIC cold bore pipes.

Two Approaches to Intense Discharge Cleaning Plasma Generation:

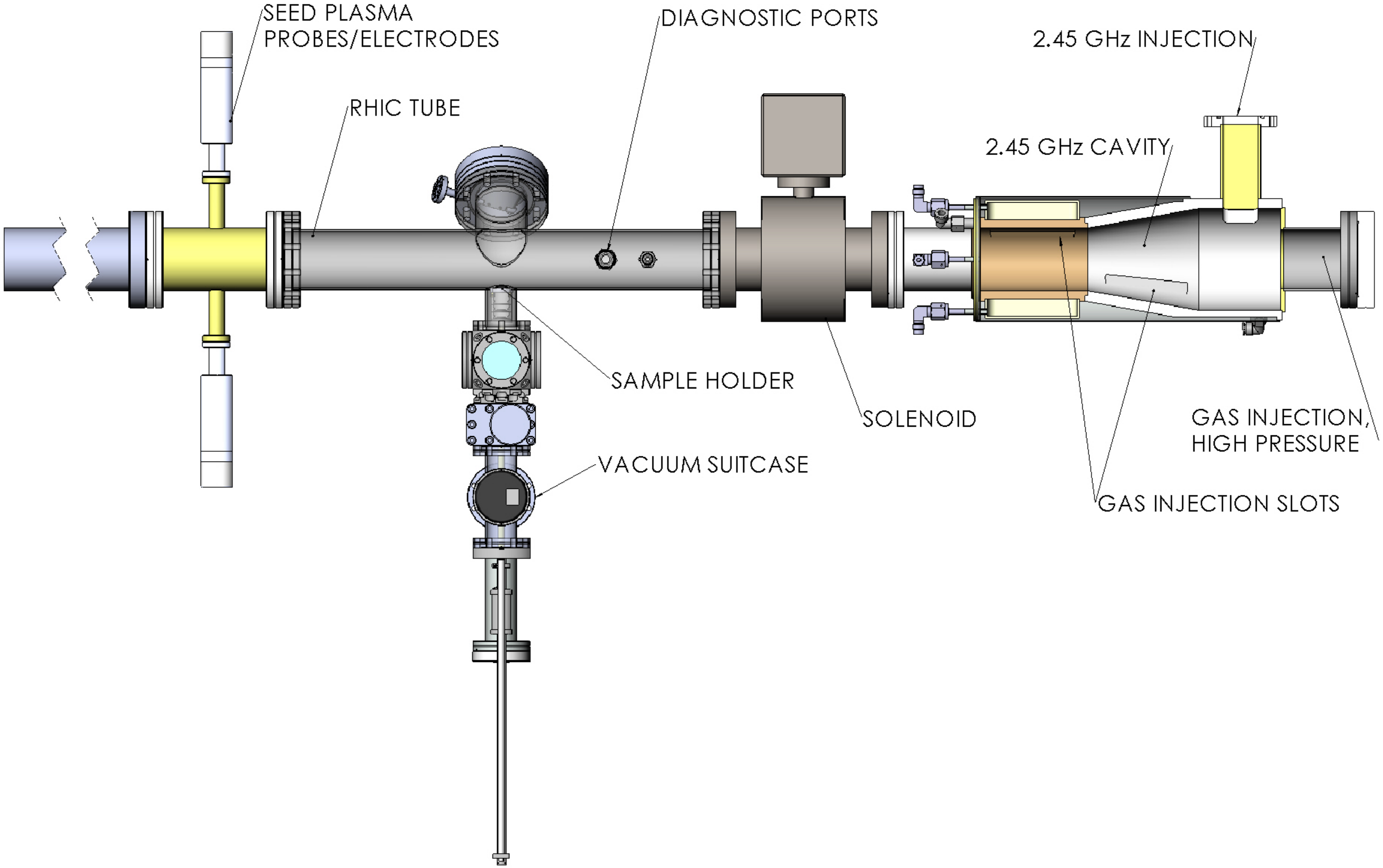
Launching Microwaves

Magnetron Mole

Microwave Plasma Generation Approach:

- Since RHIC cold bore is 6.9 cm explore 18 GHz 1.66 cm wavelength
- Cleaning 8 RHIC arcs require about ½ MW microwave power. High frequency microwave systems are cumbersome (use of gyrotrons) and very expensive about $170M not palatable for an end user. Additionally these systems may not fit in the RHIC tunnel.
- Similar power 2.45 GHz microwaves will cost about $1M.
- But, 2.45 GHz has a wavelength of 12.24 CM > 6.9 cm
- Nevertheless in collisional plasma 2.45 GHz has been absorbed in tubes of less than 4 cm (exceeding plasma frequency factor more than 20) and even factor of 103 [N. Chalyavi, P. Doidge, R. Morrison and G. Partridge, *J. Anal. At. Spectrom.*, 1988 **32**, (2017)]. Furthermore the 2.45 GHz microwaves generate these plasmas without seed plasmas; we plan to generate first generate seed plasma with electrodes (BPMs in RHIC) (successfully shown in phase I) before microwave injection.
- The collisional approach is being pursued.
- Backup revert to the original plan of using a grating system to convert 12.24 cm wavelength to shorter plasma waves, it simpler to launch the 2.45 GHz microwaves into a relatively dense seed plasma, since microwave absorption is likely to succeed due to plasma collisionality.

- Initial 2.45 GHz microwave injection setup



Simulations Plasma Propagation

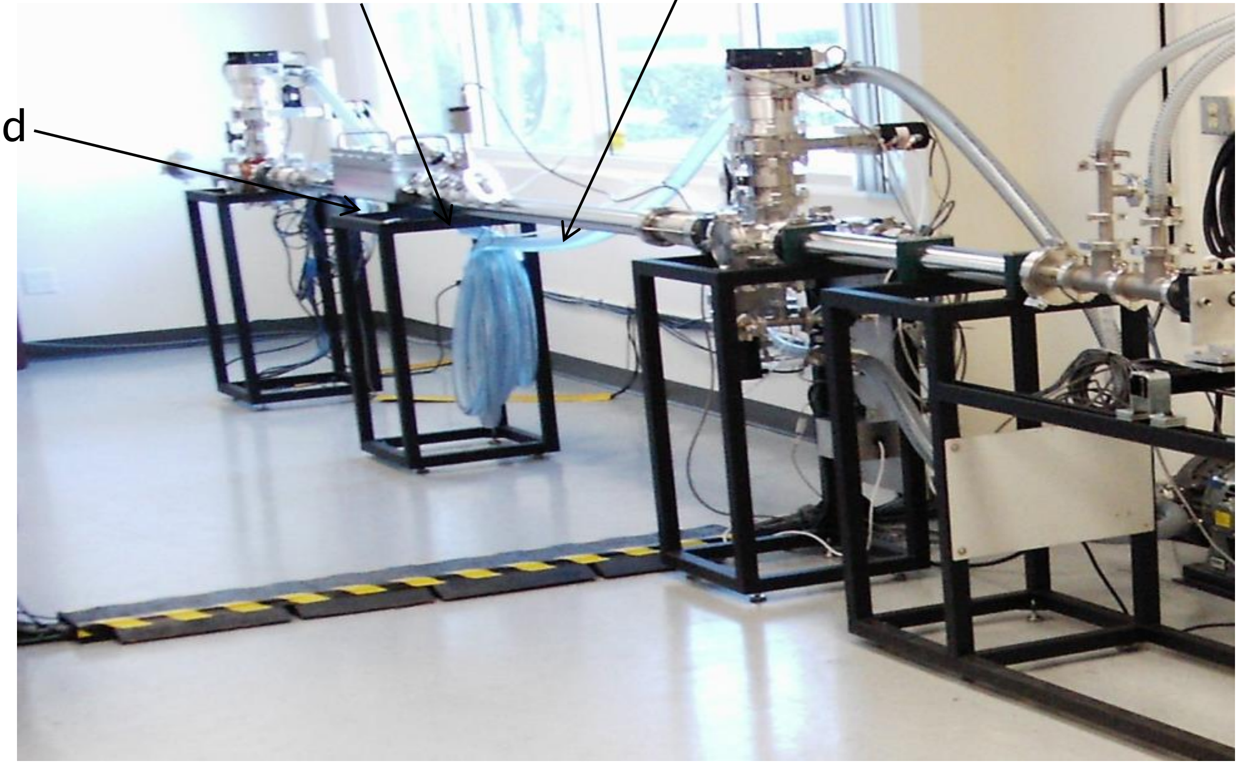
Computational fluid dynamics indicated that gas injection through nozzles in the cavity at 100 Pa and 1000 Pa indicate that at pressure of 7.5 Torr (or higher) vortex formation that propels the plasma into the RHIC Pipe.

Utilize **ExB** in the solenoid section for further propagation enhancement

Seed plasma generation was successfully demonstrated in phase I with RHIC CeC Beam Position Monitors. Here retractable probes utilized for seed plasma generation and possibly diagnostic (depending on plasma parameters)

Magnetron Mole

- PVI has had good experience with magnetron mole discharge cleaning!
- However, the system needs to be completely rebuilt for UHV operation. Old system is shown in photo

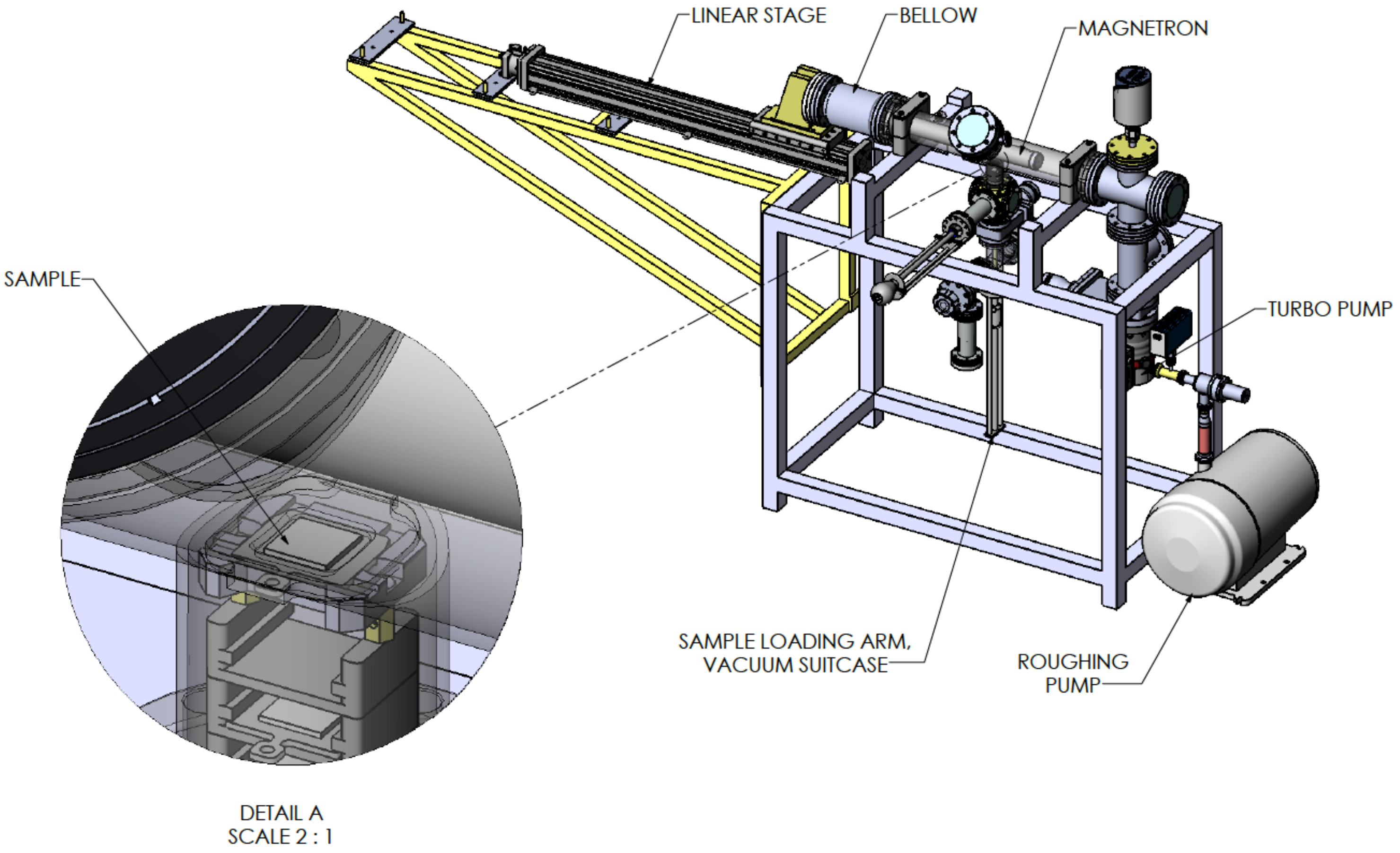


View Ports

Accelerator Tubing

Sample Load Chamber

Proof of Principle Magnetron Test



Cryogenic Temperature Copper Conductivity Reduction by Oxygen and Other Impurities

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Cryogenic Temperature Copper Conductivity Reduction by Oxygen and Other Impurities

Theoretically, copper resistivity to a good approximation may be viewed as the sum of a term due to phonon-electron scattering, and a constant term. The electron-phonon term follows the Bloch-Gruneisen formula and goes to zero as T^5 at low temperature (at high T, →T). The constant term corresponds to scattering off defects and magnetoresistance. To minimize resistivity, the constant term should be kept as small as possible. Coatings of 10 μm thick copper films were deposited on stainless steel RHIC pipes; their RF conductivity measured. One deposition had RRR of 1.2, while another deposition resulted in RRR of 2.3. Multiple measurements (FIB, EDS, SEM TEM etc.) reveal that in both depositions copper purity was about 93%, which is surprising given the higher RRR. Additionally, grain structure and lattice defects look identical as well. The only difference between these copper depositions was in the miniscule quantity of oxygen contamination 0.125% versus 0.03% respectively; qualitatively consistent with predictions. Measurements, are probably first “conclusive” results, showing the adverse effect of minute oxygen contamination on copper conductivity at cryogenic temperatures qualitatively. But, quantitively there are new unresolved questions

Focused Ion Beam Measurements

Impurity % ► RRR ▼	**X-section direction**	**Cu**	**Fe**	**Cr**	**Ni**	**C**	**O**
2.3	Along pipe axis	93.25	3.7	0.8	0.8	0.95	0.03
2.3	At 90º	92.1	3.6	0.8	0.7	0.9	0.03
1.2	Along pipe axis	92.35	3.7	0.75	0.7	0.8	0.12
1.2	At 90º	93.15	3.6	0.8	0.8	0.9	0.13

Literature

Landolt-Bornstein published "Physikalisch-chemische Tabellen," in which it's not clear what's experimental or theoretical data. It claims that O content must be >0.1% in order to avoid adverse affect on Cu conductivity at cryogenic temperatures; new edition no O.

From NIST

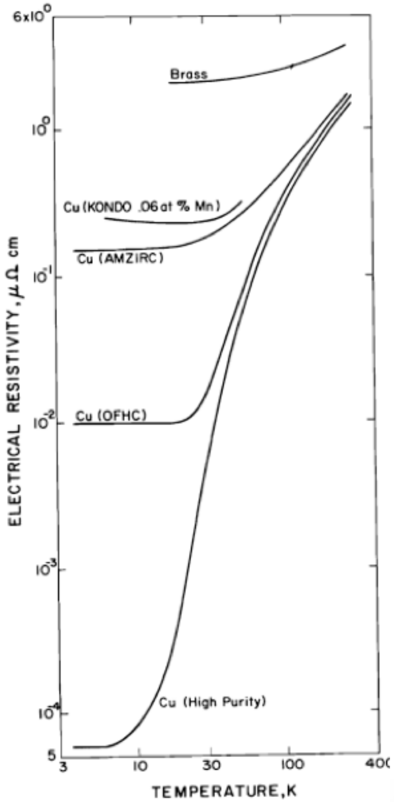
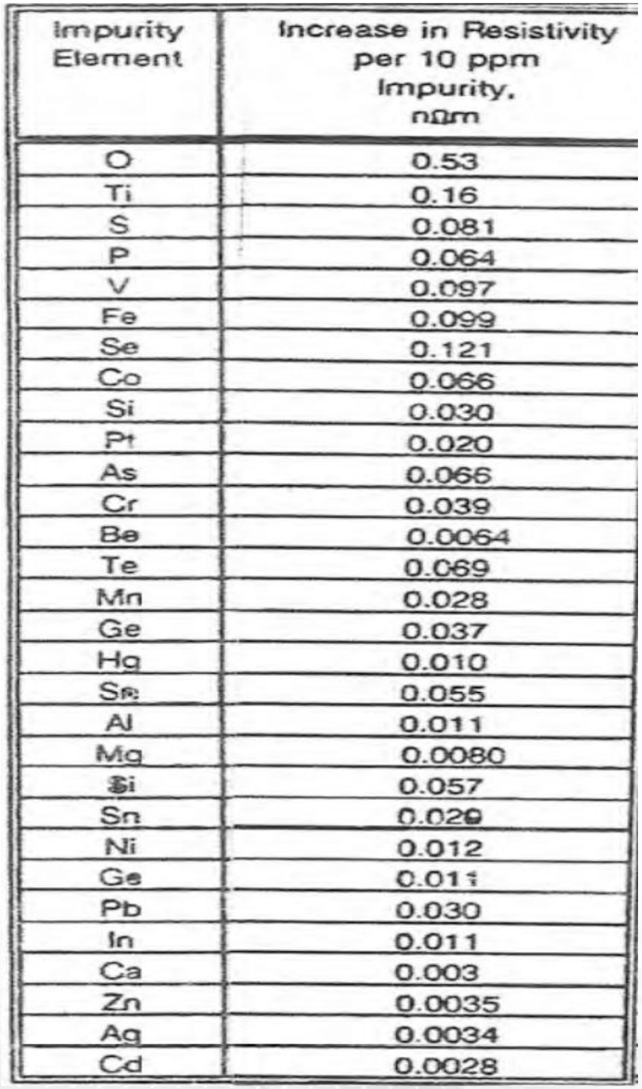


Fig. 7. Low temperature behavior of the electrical resistivity of a number of "pure" coppers and copper alloys.



Impurity Element	Increase in Resistivity per 10 ppm Impurity, nΩm
O	0.53
Ti	0.16
S	0.081
P	0.064
V	0.097
Fe	0.099
Se	0.121
Co	0.066
Si	0.030
Pt	0.020
As	0.066
Cr	0.039
Be	0.0064
Te	0.069
Mn	0.028
Ge	0.037
Hg	0.010
Se	0.055
Al	0.011
Mg	0.0080
Si	0.057
Sn	0.029
Ni	0.012
Ge	0.011
Pb	0.030
In	0.011
Ca	0.003
Zn	0.0035
Ag	0.0034
Cd	0.0028

Electrical resistivity increase with impurity elements present singly in a solid solution.

◀ Numbers have estimated uncertainty of 20% to 30%. It's for room temperature; RRR can be calculate from a complex equation within 15%.

Both table and graphs are from NIST monograph https://nvlpubs.nist.gov/nistpubs/Legacy/MONO/nistmonograph177.pdf

Some comments on literature

Although it’s not clear whether data in the Landolt-Bornstein tables experimental or theoretical, until very recently the indication that oxygen content must be less than 0.1% in order to avoid adverse affect on Cu was taken very serious (in the newest edition of those tables oxygen was taken out).

Resistivity based on Bloch-Gruneisen formula does go to zero as roughly T^5 at low temperature; but, at high temperature it’s proportional to T. In the NIST monograph, there is a complex formula, based partially on empirical data (containing 7 constants), which seems consistent with Bloch-Gruneisen, on which figure 7 in the previous slide based on.

Summary Conclusion Further Studies

1. **Why? Short answer might be: Oxygen level in RRR = 1.2 is 0.125% > 0.1% (gray not B/W). Some arcing reported during RRR = 1.2 deposition.**

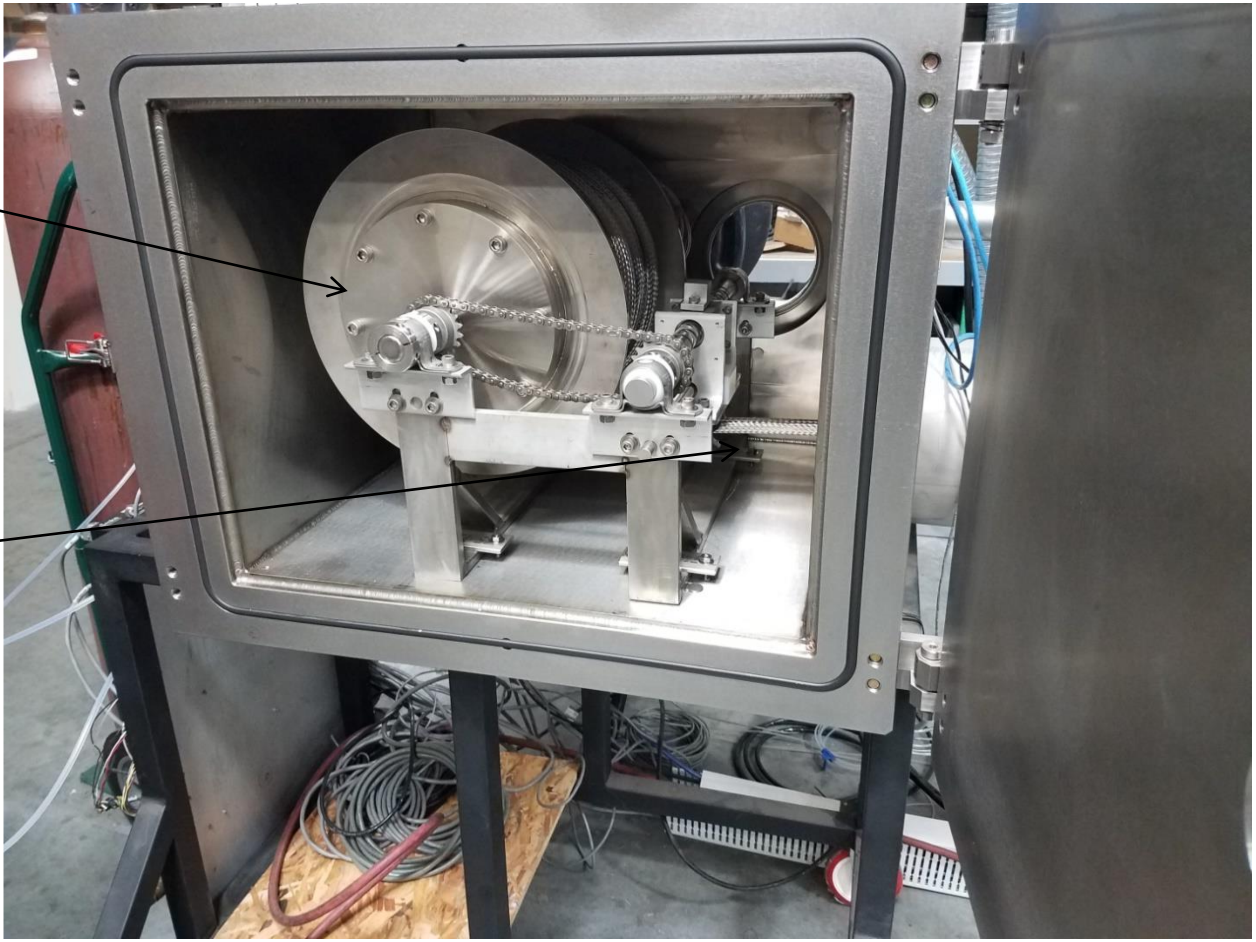
2. **Oxygen in copper increases electrical resistivity more than any other element especially at cryogenic temperature** (including NIST and Landolt-Bornstein tables). **But, examining the Fe/O ratio** (based on NIST table)**, iron contamination should have more of an effect. Landolt-Bornstein tables were adjusted after these results were revealed to my CERN colleagues!**

3. **Surprisingly RRR = 2.3 was achieved with copper content of only 93%. Quantitatively the ratio of oxygen contaminations does not explain the RRR differences.**

4. **Utilizing the same magnetron for both discharge cleaning & deposition was a mistake: contaminates deposited on cathode during discharge cleaning and mixed with copper during deposition.**

5. **Future copper coating should performed with two magnetrons: one for discharge cleaning the other for coating at an UHV base pressure. Further studies of the copper conductivity degradation by oxygen should be done with controlled oxygen leak during deposition generating many samples ($$$).**

Chamber for Umbilical and Electrical, Cooling and Gas Delivery



Feed Reel

Umbilical with process lines

Figure displays the discharge cleaning magnetron mole in discharge cleaning position (left) and out of the beam line (right).

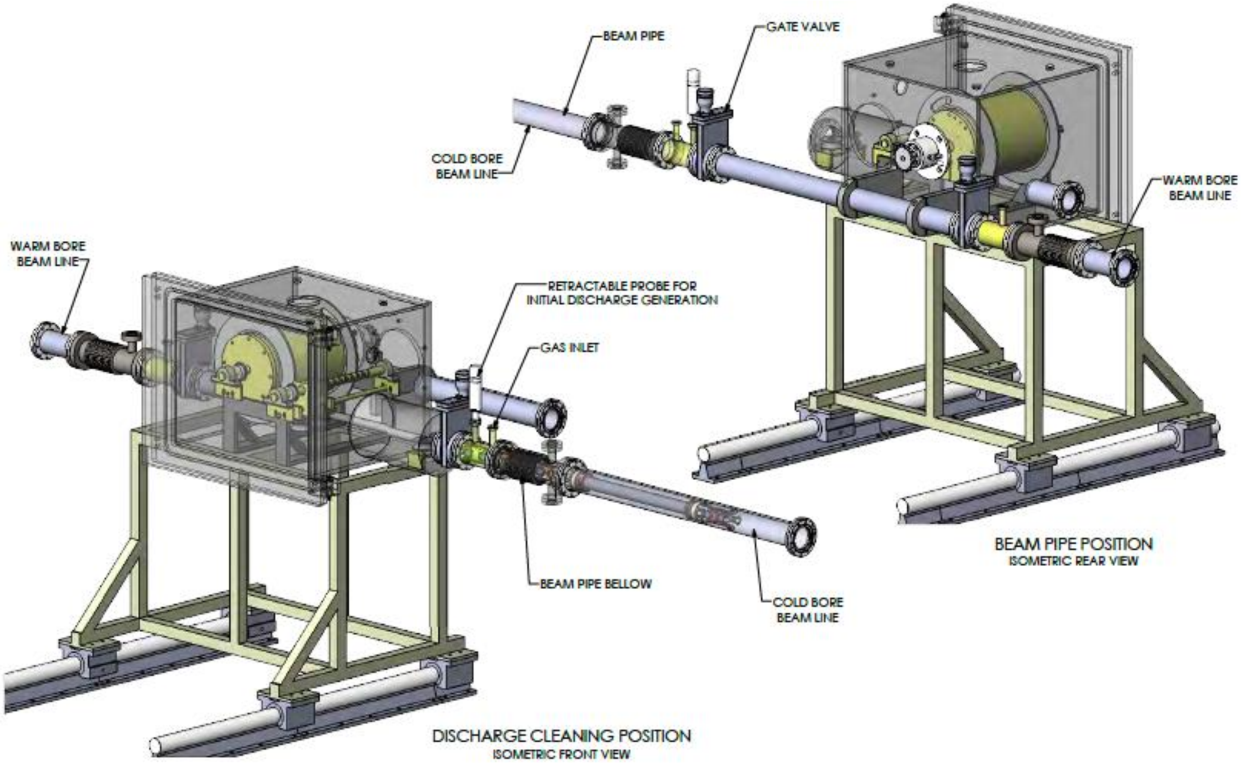


Figure displays the discharge cleaning magnetron mole side and top views

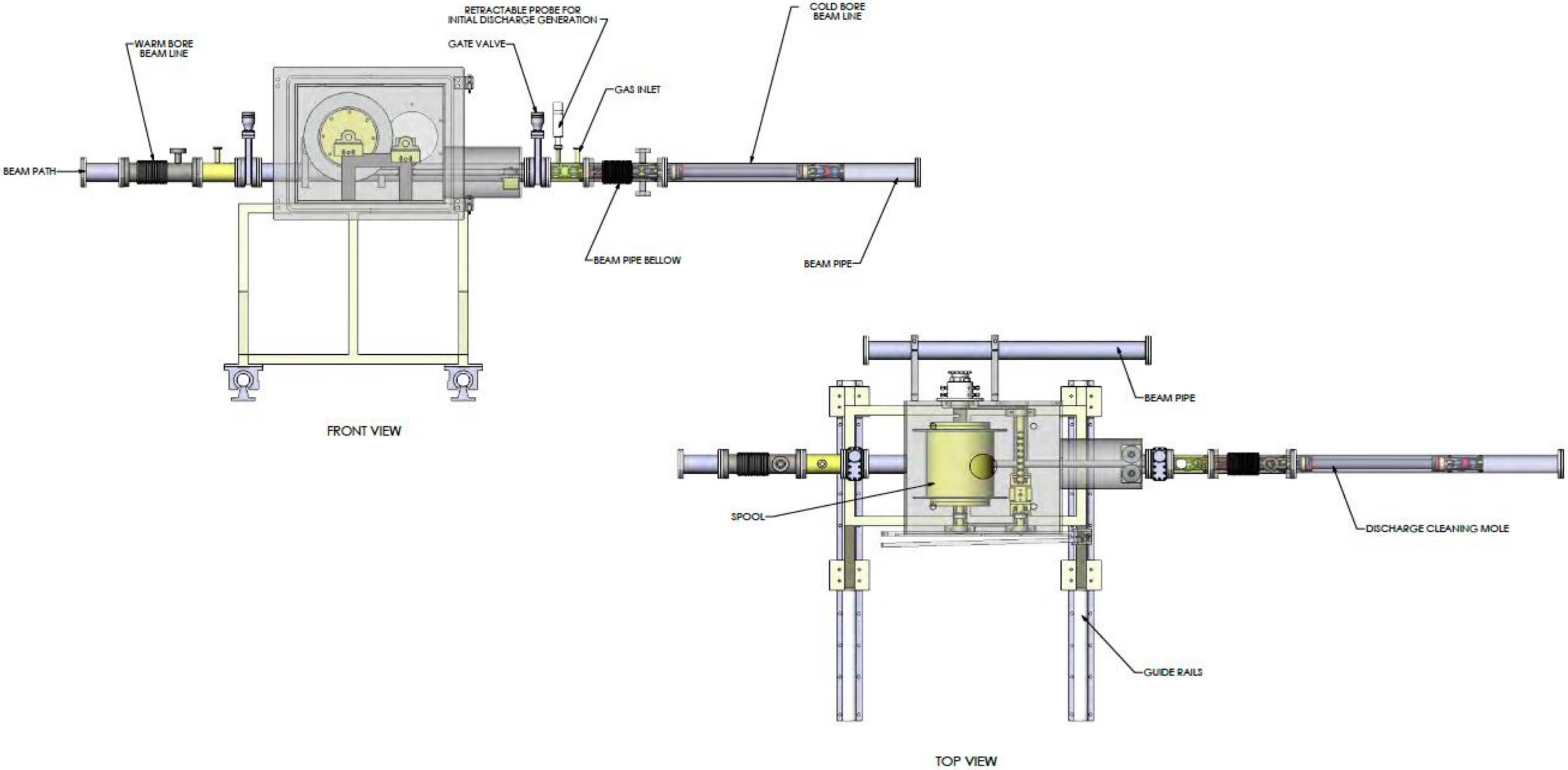


Figure displays the design of the UHV plasma testing system and details of the magnetron mole discharge assembly. The magnetron mole can be driven by a spool/umbilical system, in which cathode cooling with non-hydrogen containing cooling fluid is fed through flexible metal tubing and power feed is done by cable, isolated with ceramic beads If using a flexible umbilical becomes a schedule problem, an alternative method of using a linear drive assembly to facilitate the mole, (which was utilized earlier in the project) will be implemented. The main purpose is to prove plasma discharge cleaning feasibility.

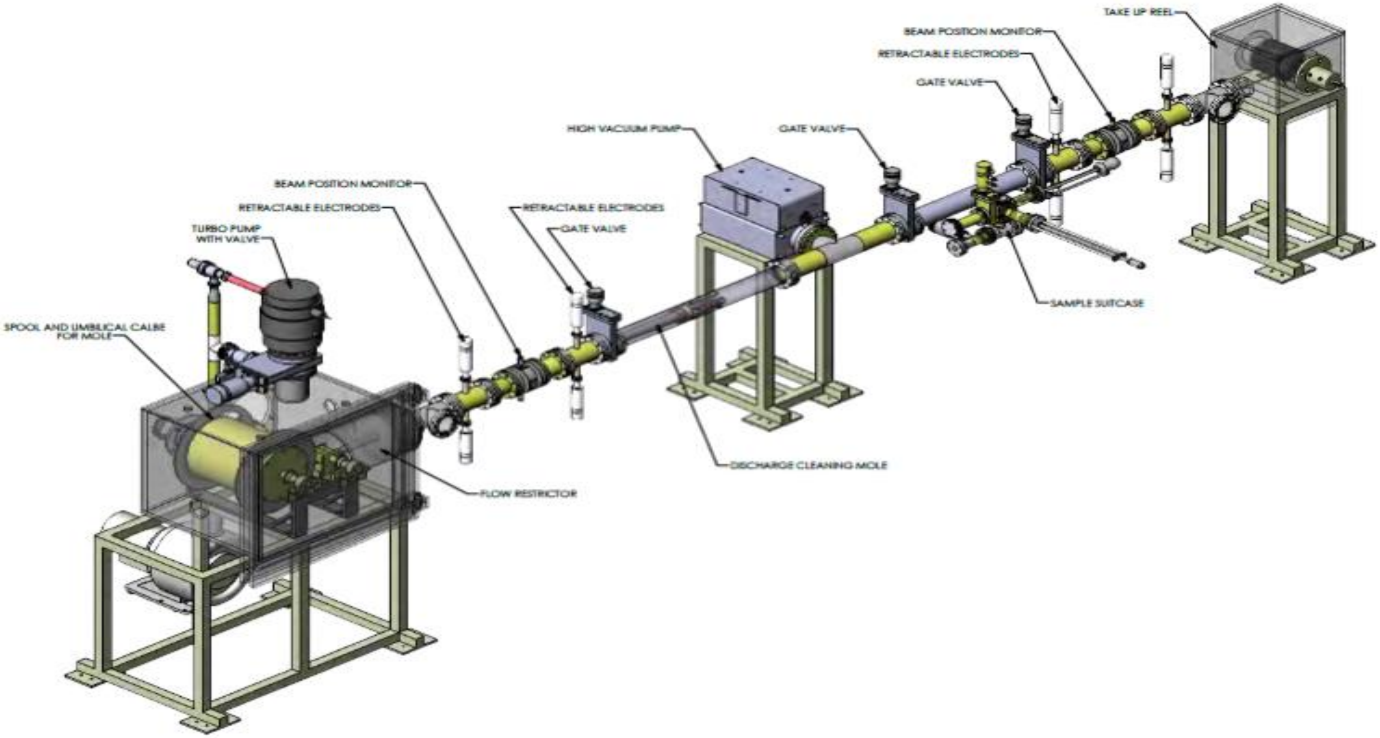
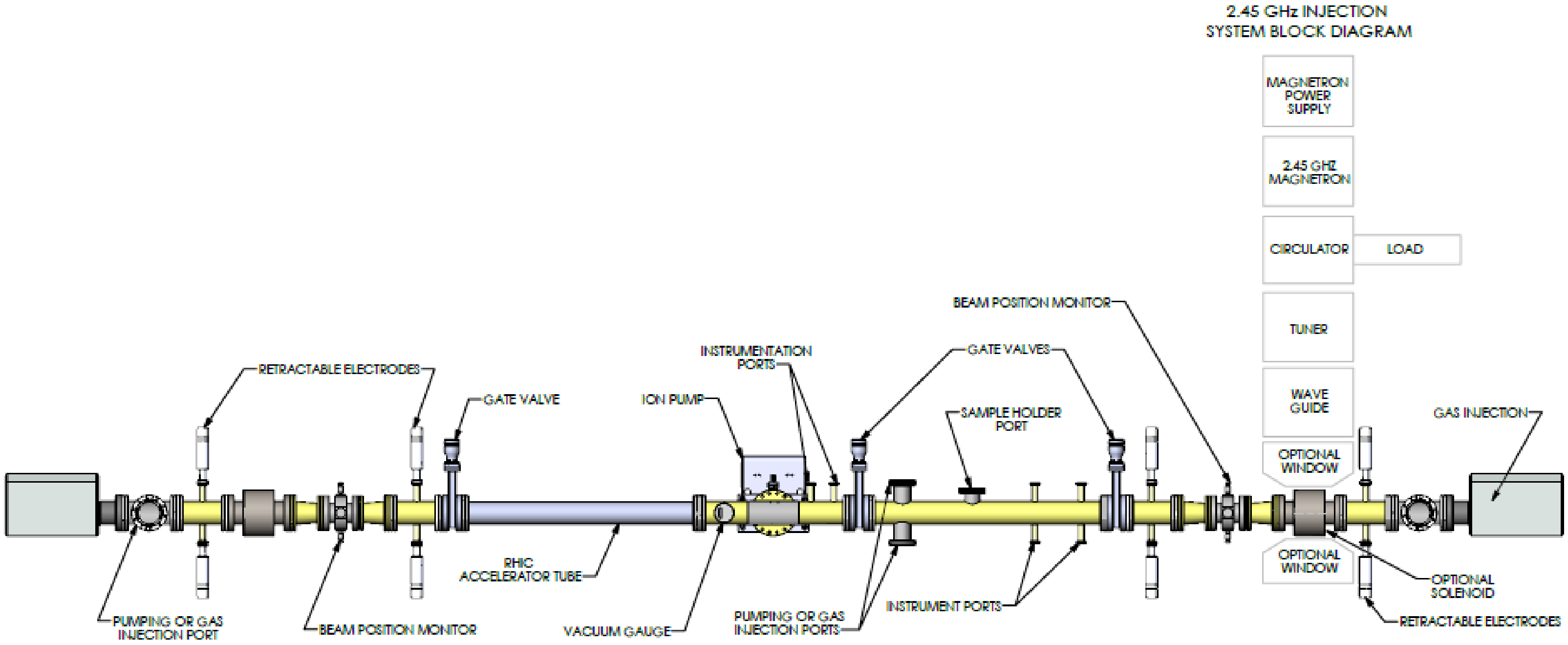
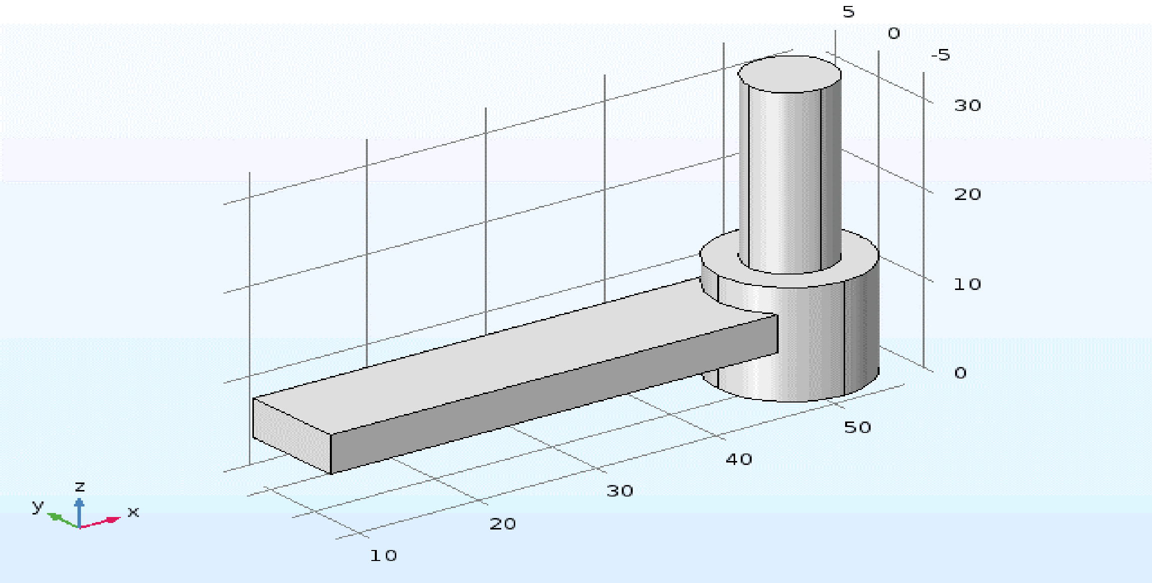
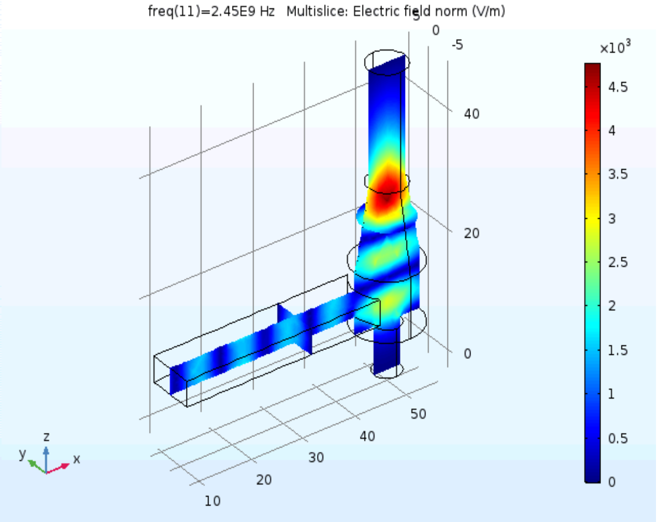


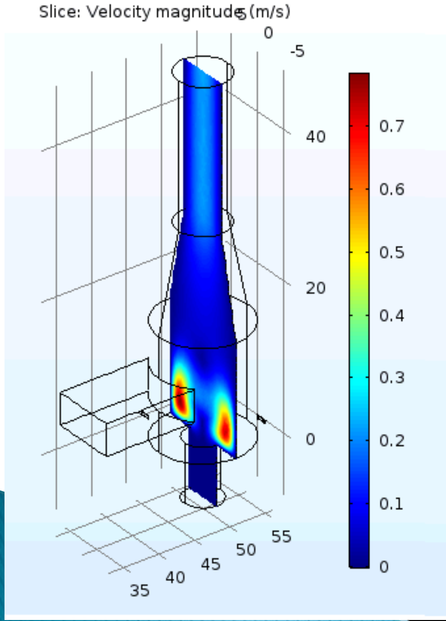
Figure displays a diagram of the 2.45 GHz discharge cleaning setup based on plasma collisionality coupling to a seed plasma. Back-up is to add a plan of using a grating system to convert 12.24 cm wavelength to shorter plasma waves

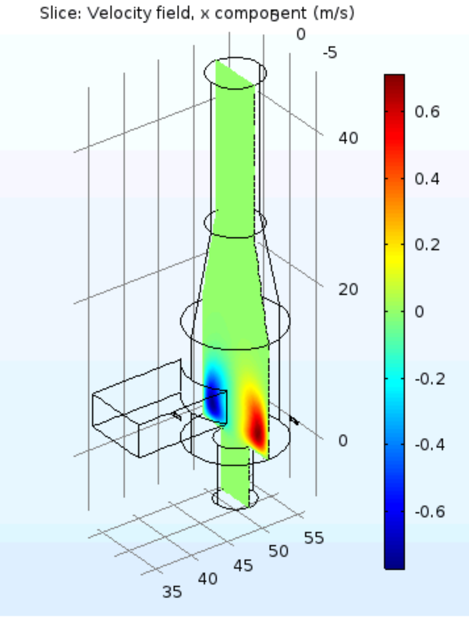


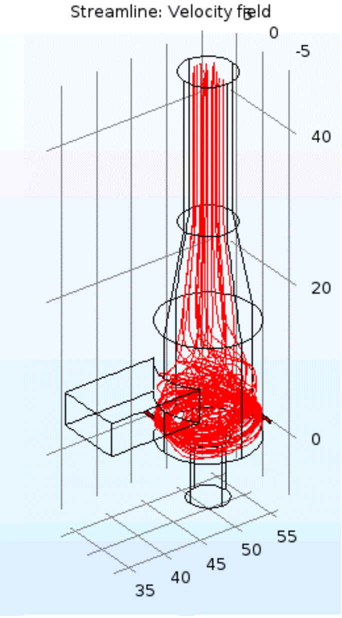
Simulations Electric Field & CFD at 1000 Pa




freq(11)=2.45E9 Hz Multislice: Electric field norm (V/m)


Slice: Velocity magnitude (m/s)


Slice: Velocity field, x component (m/s)


Streamline: Velocity field