

# Faraday cup on the FETS-FFA

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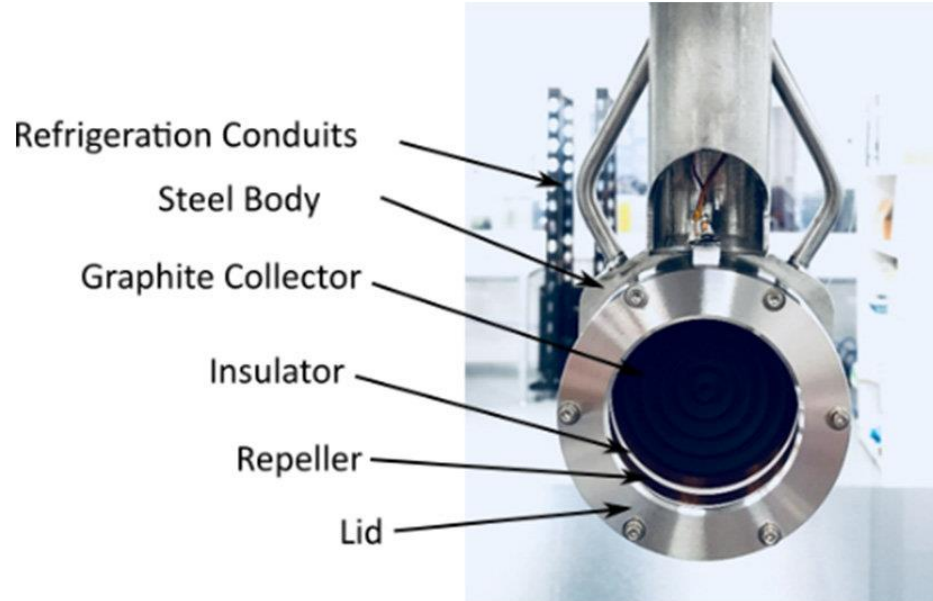


ISIS Neutron and  
Muon Source

# FETS-FFA Faraday Cup

Faraday cup is a shielded insulated cup thick enough to catch the charged beam and measure the resulting current from it.

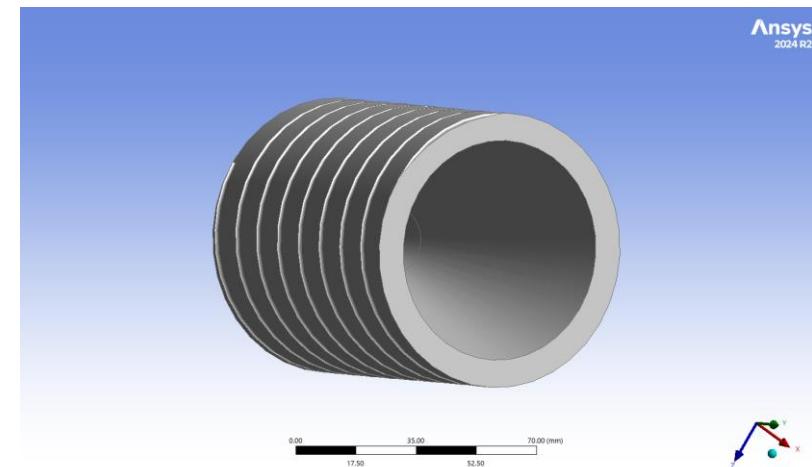
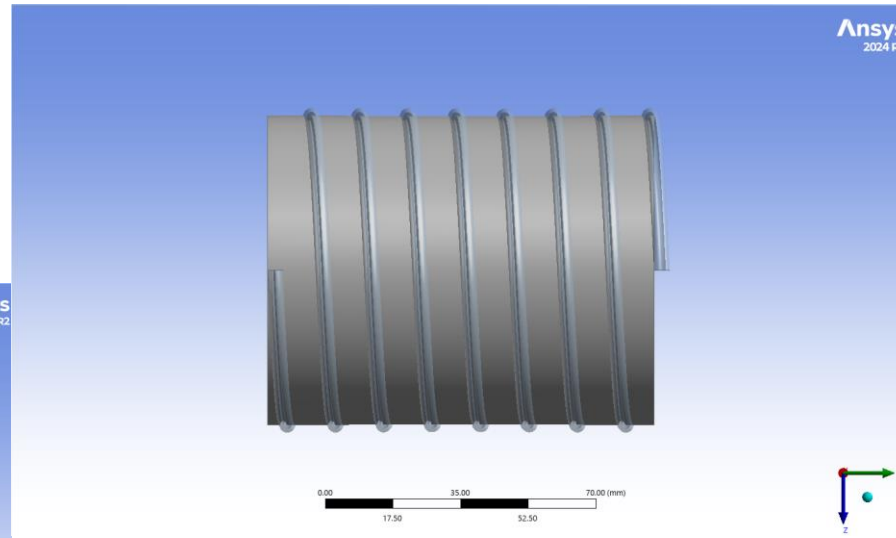
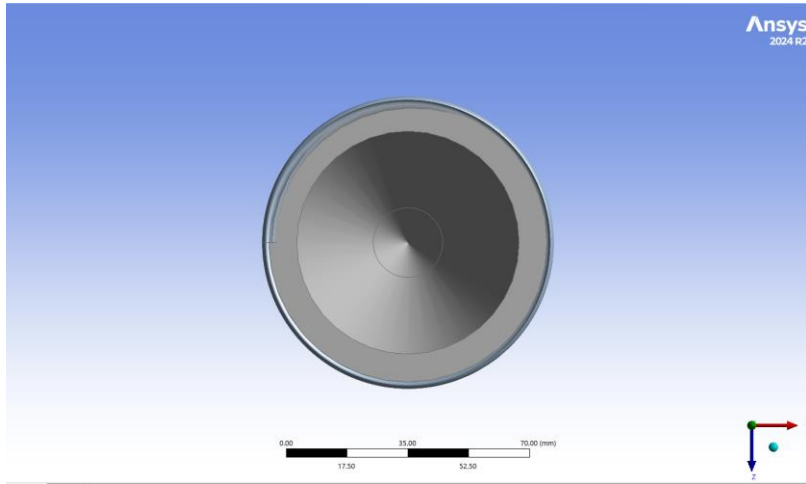
For FETS-FFA, it is to be installed on the FETS beam line to identify the injection profile of H- beam (max intensity of  $3E11$  ppp).



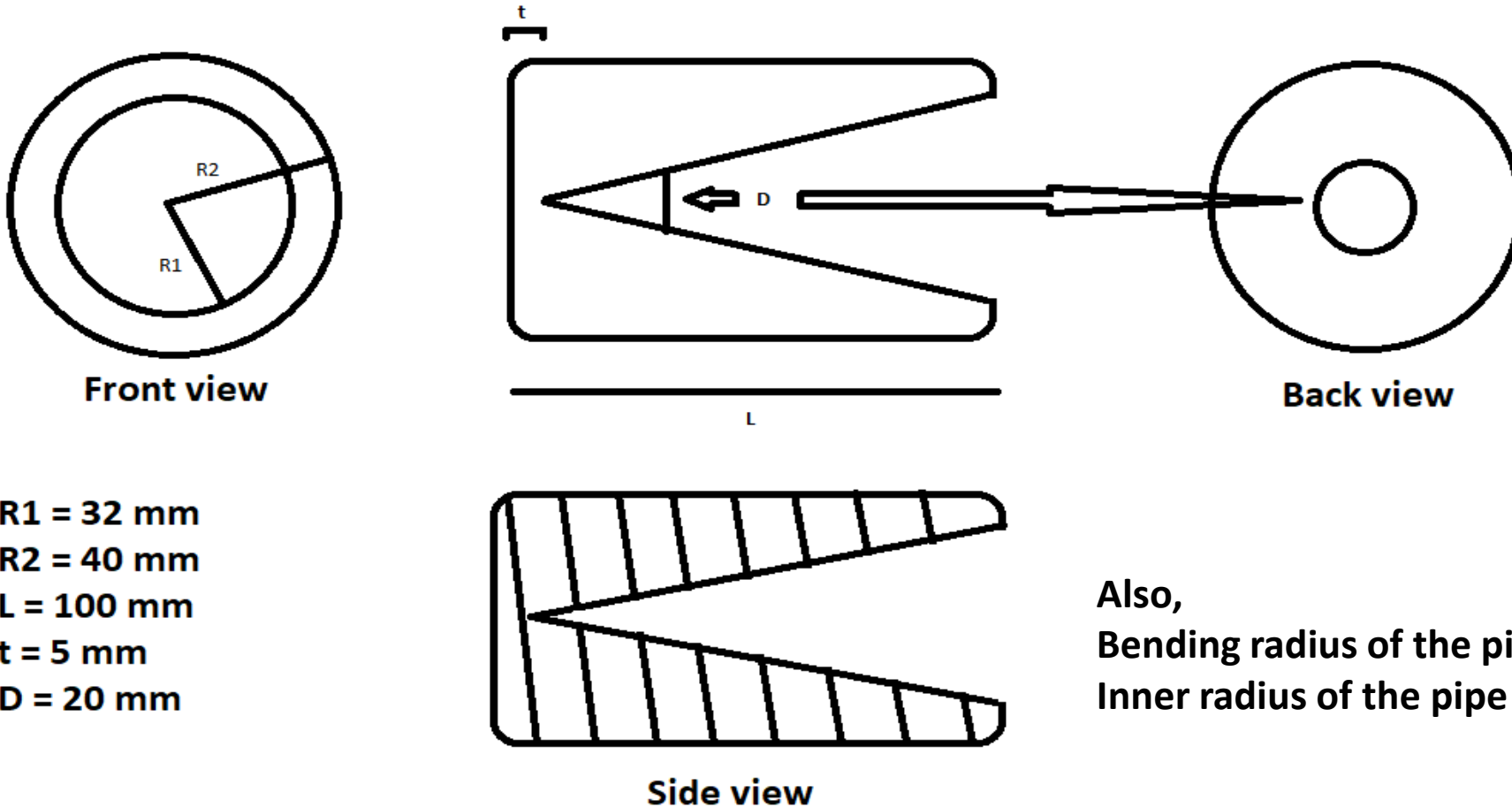
A. R. Páramo *et al*, [Design of the ESS MEBT Faraday Cup](#), IBIC 2019, Sweden, Sep 2019.



# Design of the Faraday cup



# Dimensions of the Faraday cup



**$R1 = 32$  mm**  
 **$R2 = 40$  mm**  
 **$L = 100$  mm**  
 **$t = 5$  mm**  
 **$D = 20$  mm**

**Also,**  
**Bending radius of the pipe = 40 mm**  
**Inner radius of the pipe = 2 mm**

# Thermal Calculation



# Instantaneous Temperature Calculation



# FETS approximate beam profile

FETS transverse beam profile: “Round beam and approximately gaussian with a rms radius of 1.5 mm”.

Round and uniform 2d gaussian function with A as Amplitude,  $\sigma$  being radial spread:

$$f(r, \phi) = A e^{\frac{-r^2}{2\sigma^2}} \quad (\text{No } \phi \text{ dependence})$$

Here, for a round beam,  $\sigma = 1.5\text{mm}$ . Using this and solving the equation:

$$N = \int_{-\infty}^{\infty} \int_0^{2\pi} f(r, \phi) r \, dr \, d\phi = \int_{-\infty}^{\infty} \int_0^{2\pi} A r e^{\frac{-r^2}{2\sigma^2}} \, dr \, d\phi$$

Give us:

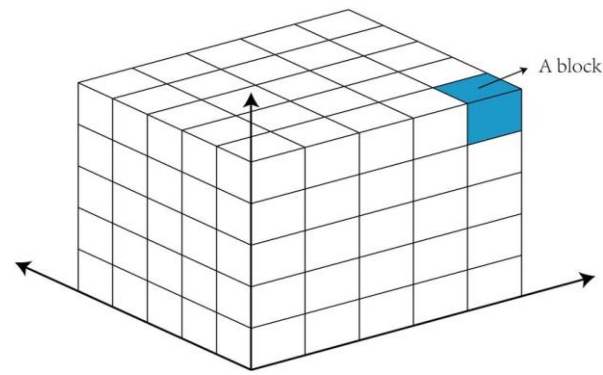
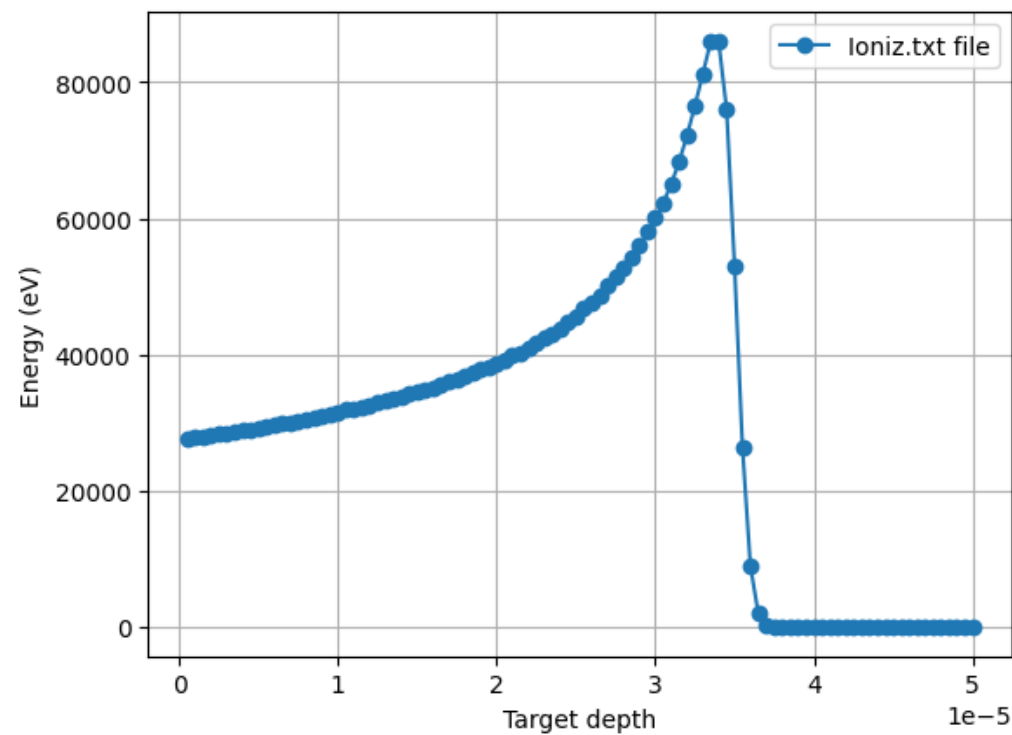
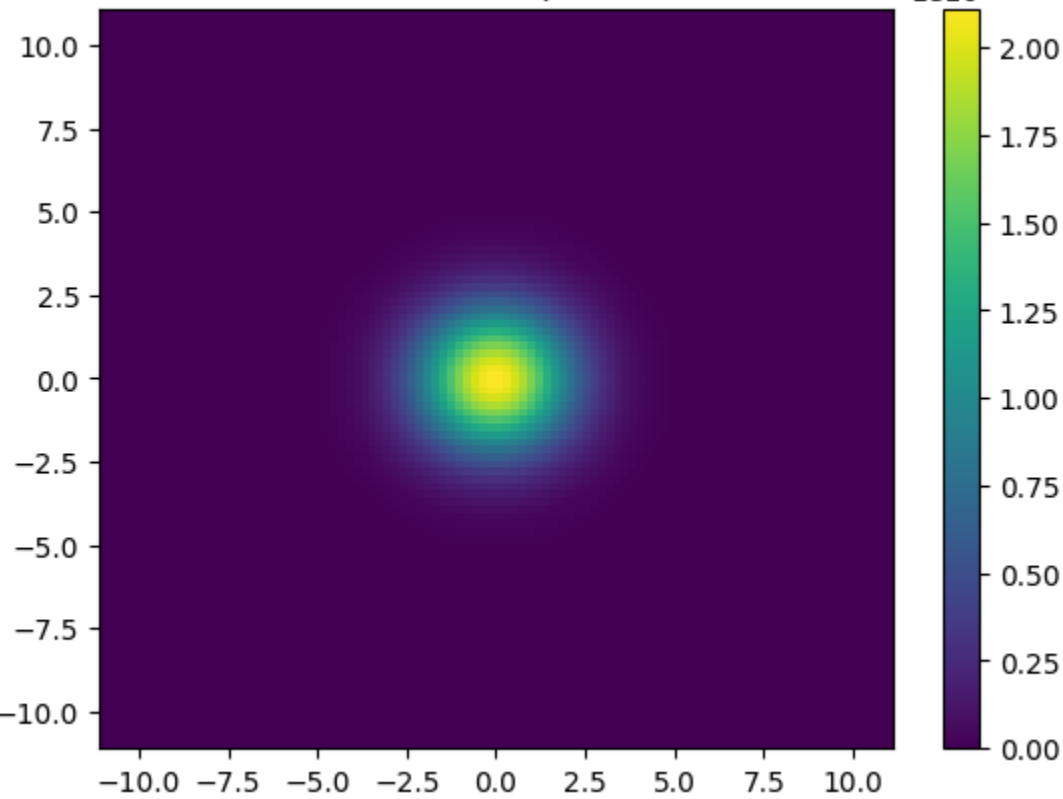
$$\text{Amplitude}(A) = \frac{N}{2\pi\sigma^2}$$

This calculation gave me the amplitude(A) of  $2.122\text{e}10$  particles /  $\text{mm}^2$  which is the maximum number of particles per area in the FETS beam profile.



# FETS max energy deposited calculation

FETS beam profile



# FETS Temperature rise calculation

For temperature rise calculation,

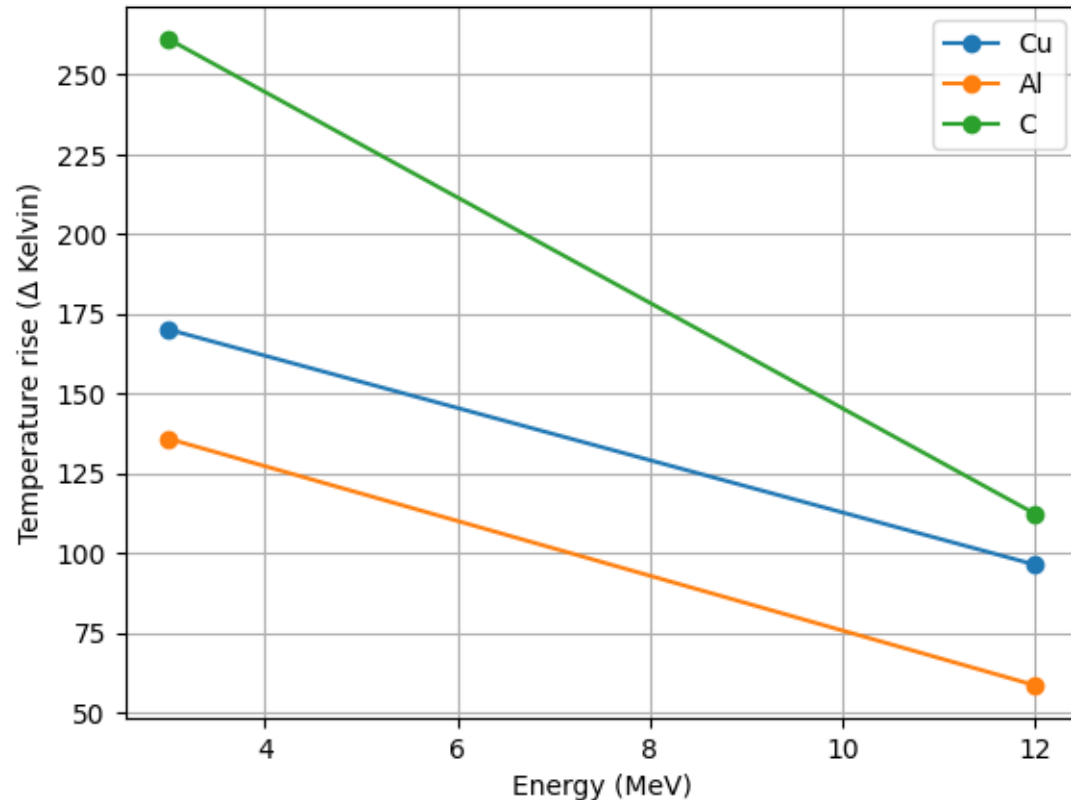
$$\Delta T = \frac{E_{max}}{d * s}$$

where  $\Delta T$  is temperature rise ( $\Delta K$ ),  $E_{max}$  is maximum energy deposited per mm cube ( $J / mm^3$ ),  $d$  is density ( $g / mm^3$ ) and  $s$  is specific heat of the material ( $J/g K$ ).

Materials	Melting point (K)
Copper	1357.77 K
Aluminium	933.473 K
Carbon	4098 K

(Royal Society of Chemistry)

Using Ionix.txt file



# Steady State Simulations:

The design is fixed as conical Faraday Cup (FC) with helical water-cooling wrapped around it. And material is fixed to be Copper (Cu).



# Heat Load Calculation:

Using the FETS transverse beam distribution with the longitudinal structure of FETS-FFA to create the worst possible thermal case.



# FETS beam profile

FETS transverse beam profile: “Round beam and approximately gaussian with a rms radius of 1.5 mm”.

Round and uniform 2d gaussian function with A as Amplitude,  $\sigma$  is gaussian sigma:

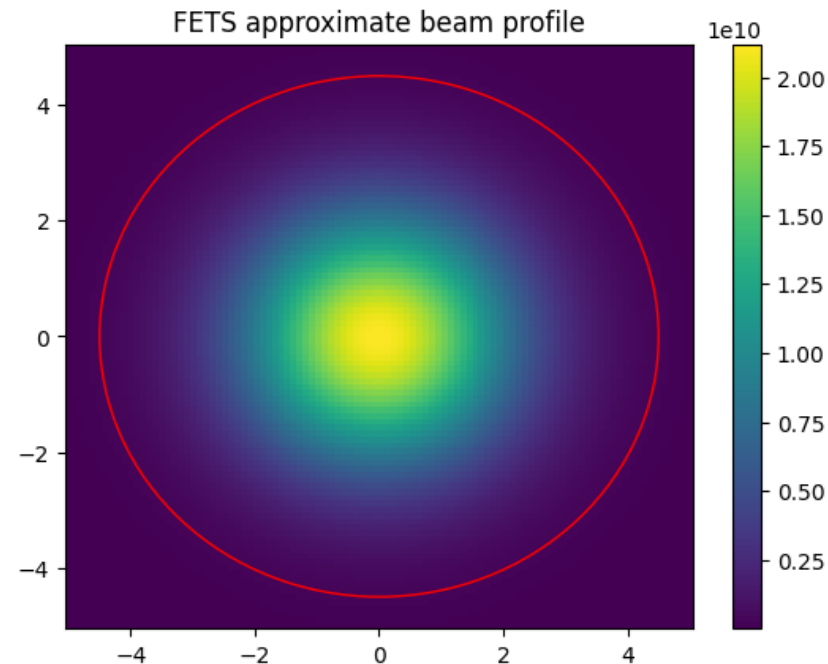
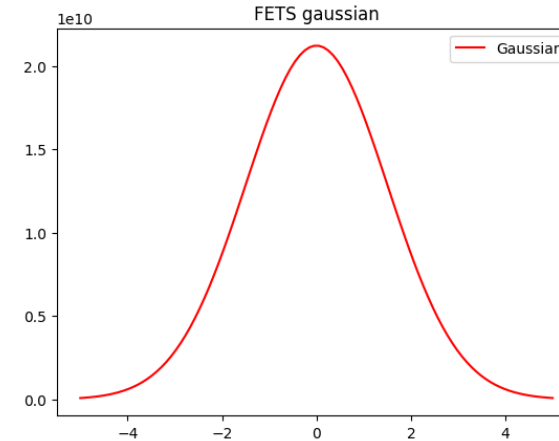
$$f(x, y) = \frac{N}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Here,  $\sigma = \sigma_x = \sigma_y = 1.5$  mm.

As we know,  $\pm 3\sigma$  of a gaussian distribution contains 99.73 percent of the total data.

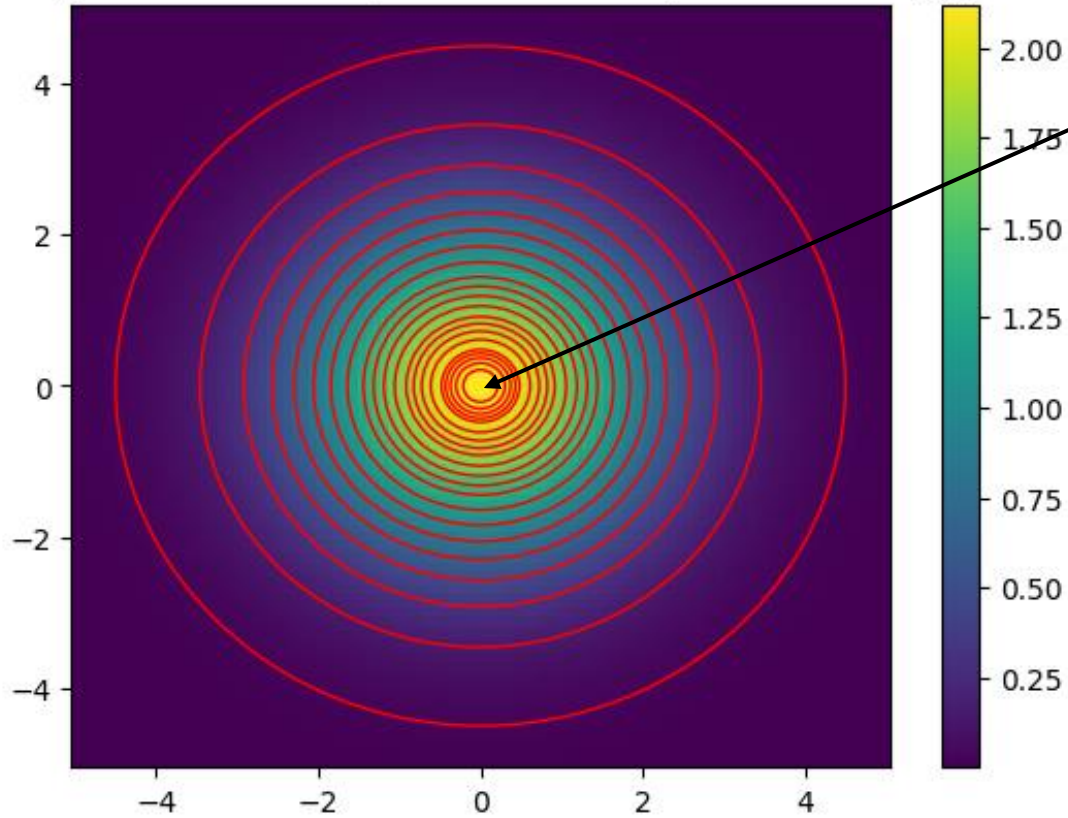
So,  $\pm 3\sigma = 3 \times 1.5$  mm =  $\pm 4.5$  mm

And it contains almost the entire FETS beam.



# FETS Heat flow region

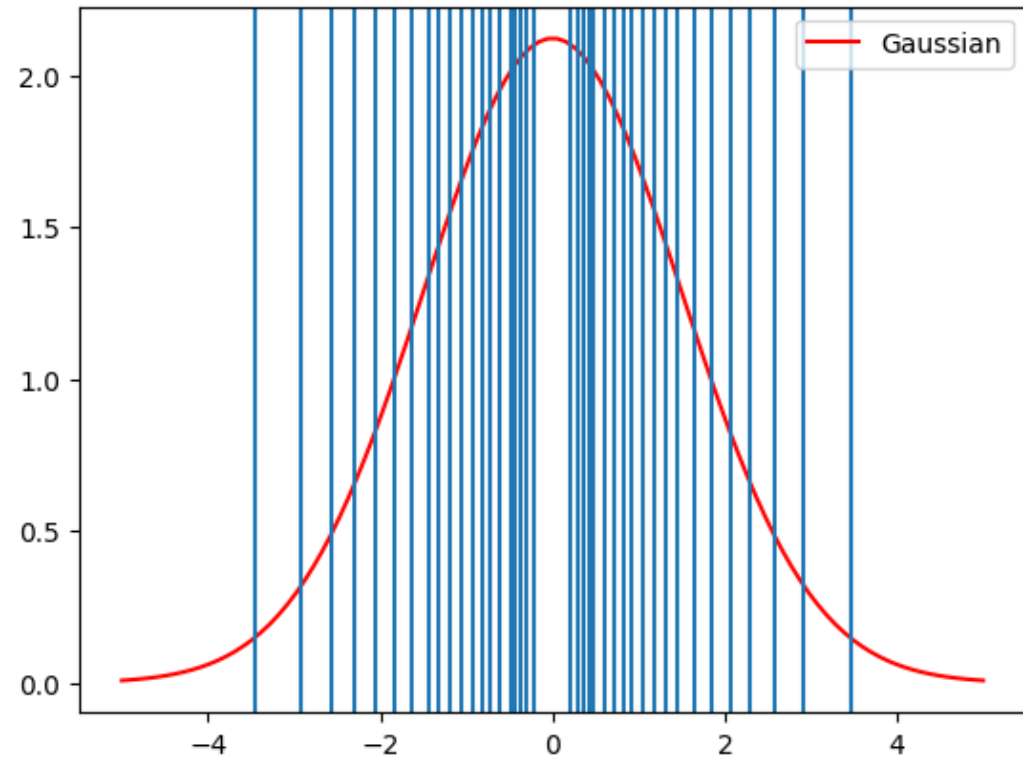
FETS approximate beam profile with multiple heat flow regions



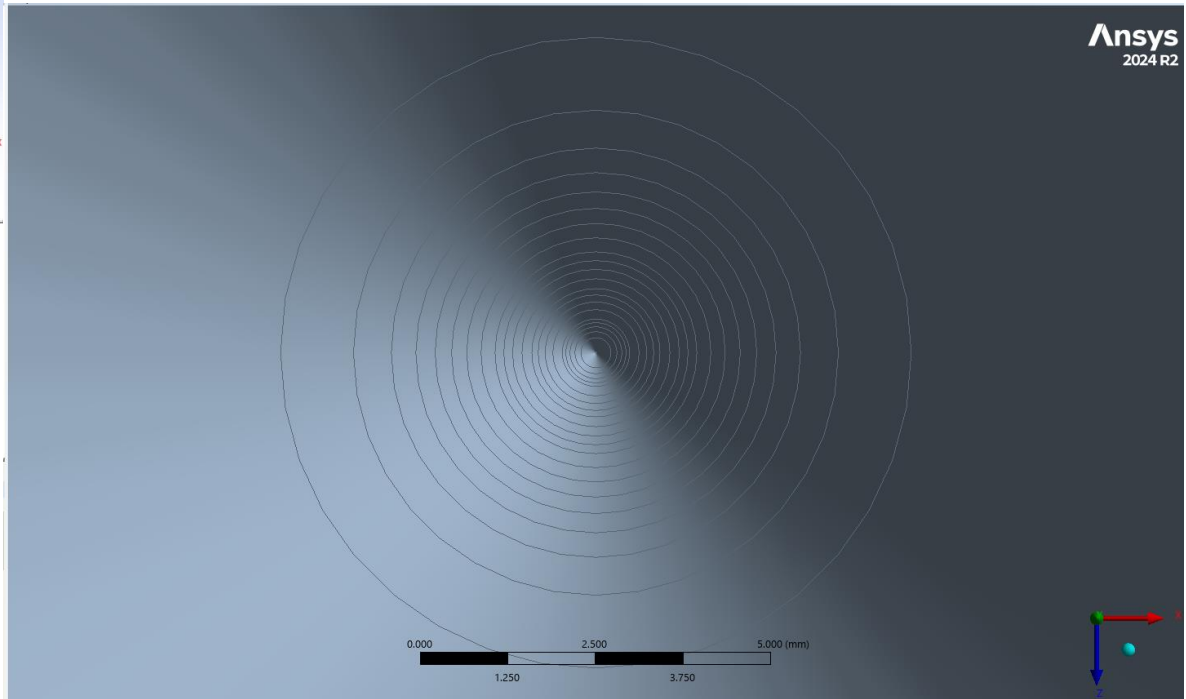
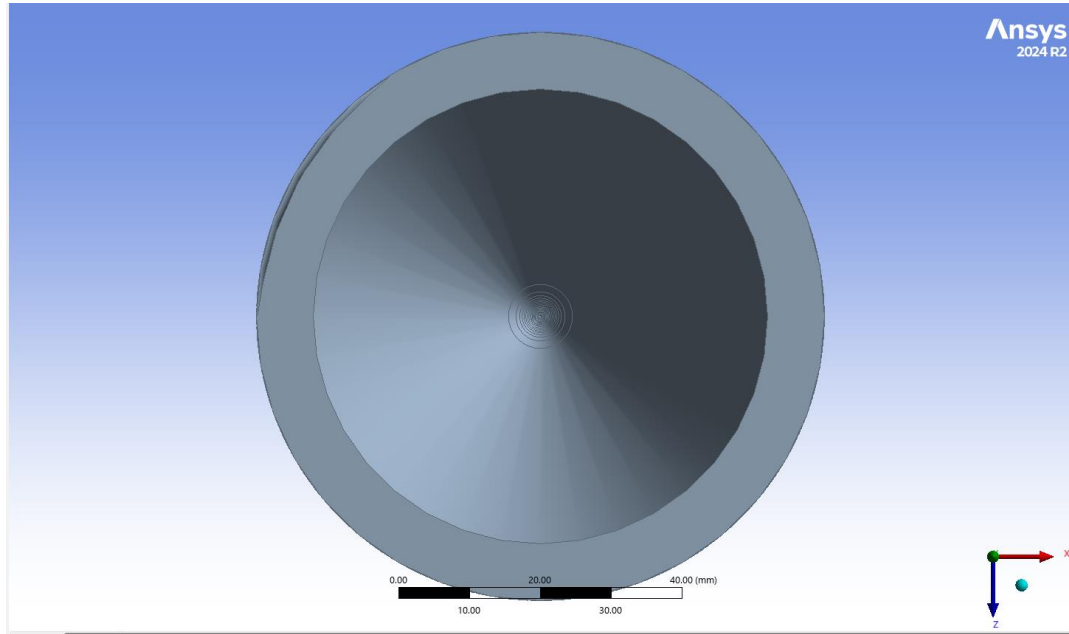
- Peak protons density of the 2D FETS gaussian is  $2.12 \times 10^{10}$  per  $mm^2$ .
- Protons density of the first circle is  $2.11 \times 10^{10}$  per  $mm^2$ .

Difference is ~0.50 percent.

1e10 FETS 2D gaussian into 1D with heat flow radiuses



# Transverse heat flow distribution



# Heat Sink Calculation



# Reynolds Number calculation

Different numbers are calculated to estimate the convection coefficient of water cooling, needed in the Ansys simulation:

1. Prandtl number (Pr.) at 22 °C = 6.62 dimensionless
2. Reynolds number:

$$Re_D \equiv \frac{\rho u_m D}{\mu} = \frac{u_m D}{\nu}$$

(“Fundamental of Heat and Mass Transfer” by Incropera et.al)

Here,

density of water at 22 °C ( $\rho$ ) = 998 kg / m<sup>3</sup>

mean velocity of water ( $u_m$ ) = 1 m / s

inner diameter of pipe (D) = 2 mm

dynamic viscosity of water at 22 °C ( $\mu$ ) = 959 × 10<sup>-6</sup> Pa · s

This gives us the value of Reynolds number is 2081 dimensionless.



# Convection Coefficient Calculation

To calculate the Convection Coefficient of water, the Nusselt number is also needed. In the book, the formula for the Nusselt number is given as:

$$Nu_D = \left[ \left( 3.66 + \frac{4.343}{a} \right)^3 + 1.158 \left( \frac{Re_D(D/C)^{1/2}}{b} \right)^{3/2} \right]^{1/3} \left( \frac{\mu}{\mu_s} \right)^{0.14}$$

$$Nu_D \equiv \frac{hD}{k}$$

where

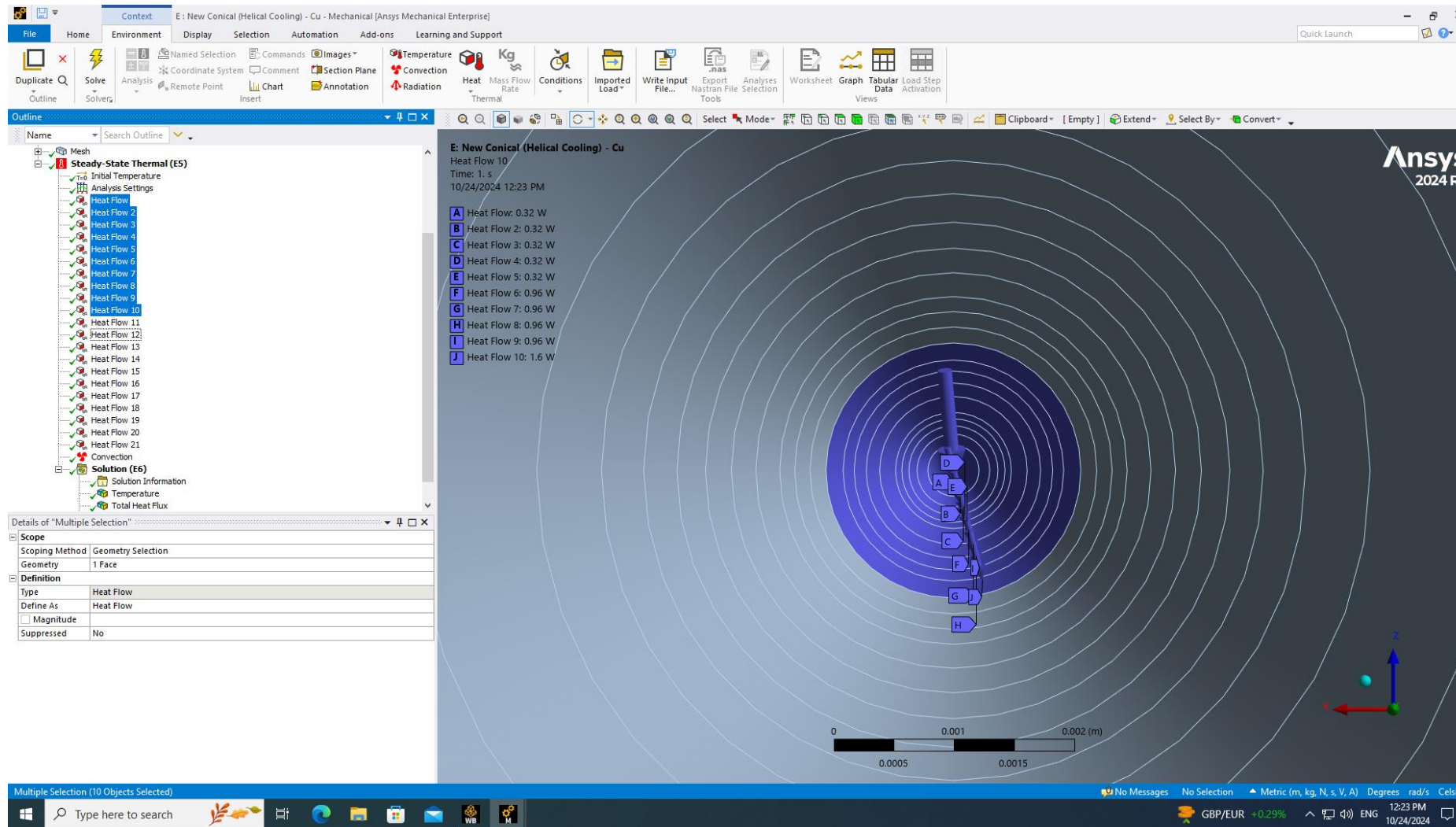
$$a = \left( 1 + \frac{927(C/D)}{Re_D^2 Pr} \right) \quad \text{and} \quad b = 1 + \frac{0.477}{Pr}$$
$$\left[ \begin{array}{l} 0.005 \lesssim Pr \lesssim 1600 \\ 1 \lesssim Re_D(D/C)^{1/2} \lesssim 1000 \end{array} \right]$$

Here,  $k$  is thermal conductivity of water  
At 22 °C, it is 0.6 W/m K.

Here, I have made one assumption that  $\mu \approx \mu_s$  (Viscosity of water in the middle is the same as at the surface of the pipe).



# Steady state simulation



# Steady state simulations

So, steady state simulations were performed with these varying parameters (that cannot be fixed until the development of FC):

- Number of helical turns.
- Tube inner diameter (ID).
- Mean Velocity of water (m/s).
- Convection Coefficient ( $W/m^2K$ ).

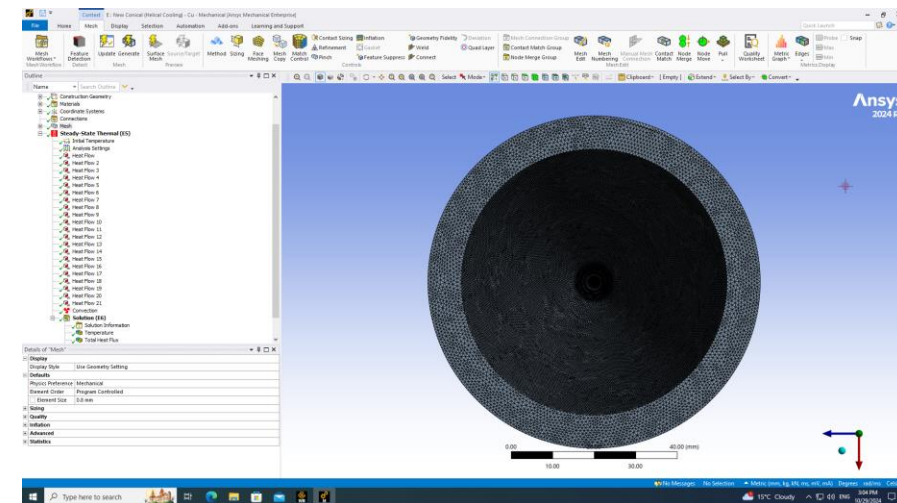
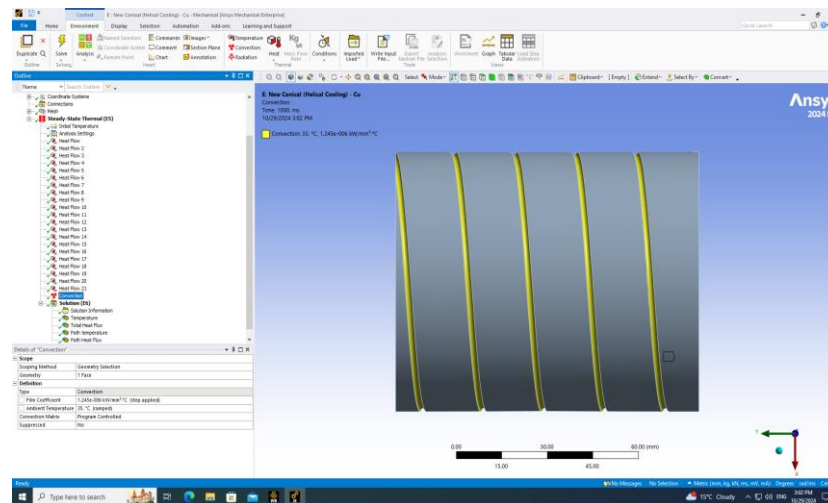
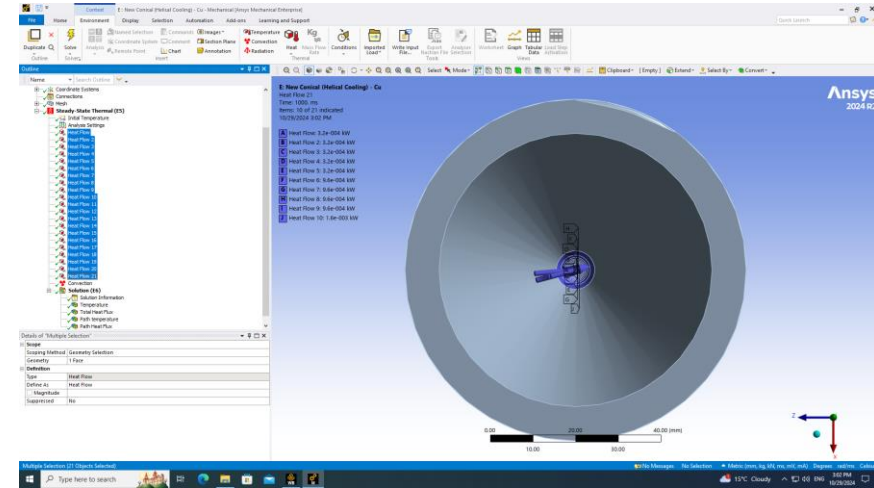


# Steady state simulations

While there are parameters varied over the simulation, there also are some of the things not changed in any of all the simulations performed.

They include:

- Design and geometry (Conical shape).
- Material (Copper).
- Convection region.
- Heat flow region.
- Mesh and element size (0.8 mm on average overall).
- Transverse heat flow distribution (Gaussian as estimated).



# Steady state simulations

So, results from steady state simulations:

Each tube is 50 percent immersed inside the FC.

Fixed tube Inner diameter (ID) at 2 mm:

Number of helical turns	Mean velocity of water (m/s)	Convection Coefficient ( $W/m^2K$ )	Highest Temperature ( $^{\circ}C$ )	Lowest Temperature ( $^{\circ}C$ )
3	0.01	1245	49.552	45.629
	0.1	2585	41.622	37.825
5	0.01	1245	45.089	41.265
	0.1	2585	41.622	37.825
	0.5	4225	39.343	35.693
	1	5725	39.073	35.693
10	0.01	1245	41.728	37.994
	0.1	2585	39.982	36.289
	0.5	4225	39.343	35.693
	1	5725	39.073	35.693



# Steady state simulations

## Fixed tube Inner diameter (ID) at 4 mm:

Number of helical turns	Mean velocity of water (m/s)	Convection Coefficient ( $W/m^2K$ )	Highest Temperature ( $^{\circ}C$ )	Lowest Temperature ( $^{\circ}C$ )
8	0.1	1710	39.943	36.215
8	0.5	3370	39.151	35.496
8	1	4715	38.909	35.301

## Fixed Inner diameter (ID) at 6 mm:

Number of helical turns	Mean velocity of water (m/s)	Convection Coefficient ( $W/m^2K$ )	Highest Temperature ( $^{\circ}C$ )	Lowest Temperature ( $^{\circ}C$ )
5	0.1	1430	40.45	36.635
5	0.5	3015	39.353	35.619
5	1	4245	39.058	35.374



# Conclusions:

- Water cooling is surely needed for the Faraday Cup (especially helical cooling for better contact and heat transfer).
- Tube inner diameter and mean velocity of water can be changed depending on availability, but the water mass flow rate should be kept constant as calculated, presumably ~10 g/s. However, if possible, maximising the water flow rate is only advantageous.
- Thermal contact between tube and FC cylinder should be maximised with the number of helical turns of the water-cooling tube.
- Even though the instantaneous temperature rise is seen to be very high, average temperature could be kept significantly down with the water cooling.
- Only temperature rise is taken into consideration excluding the thermal stress on the target material.



# Secondary Electrons Suppression



# Secondary Electrons (SEs)

$I_0$  = Incident electrons or ions.

Types of Secondary Electrons:

$I_b$  = Backscattered electrons (electron-induced only)

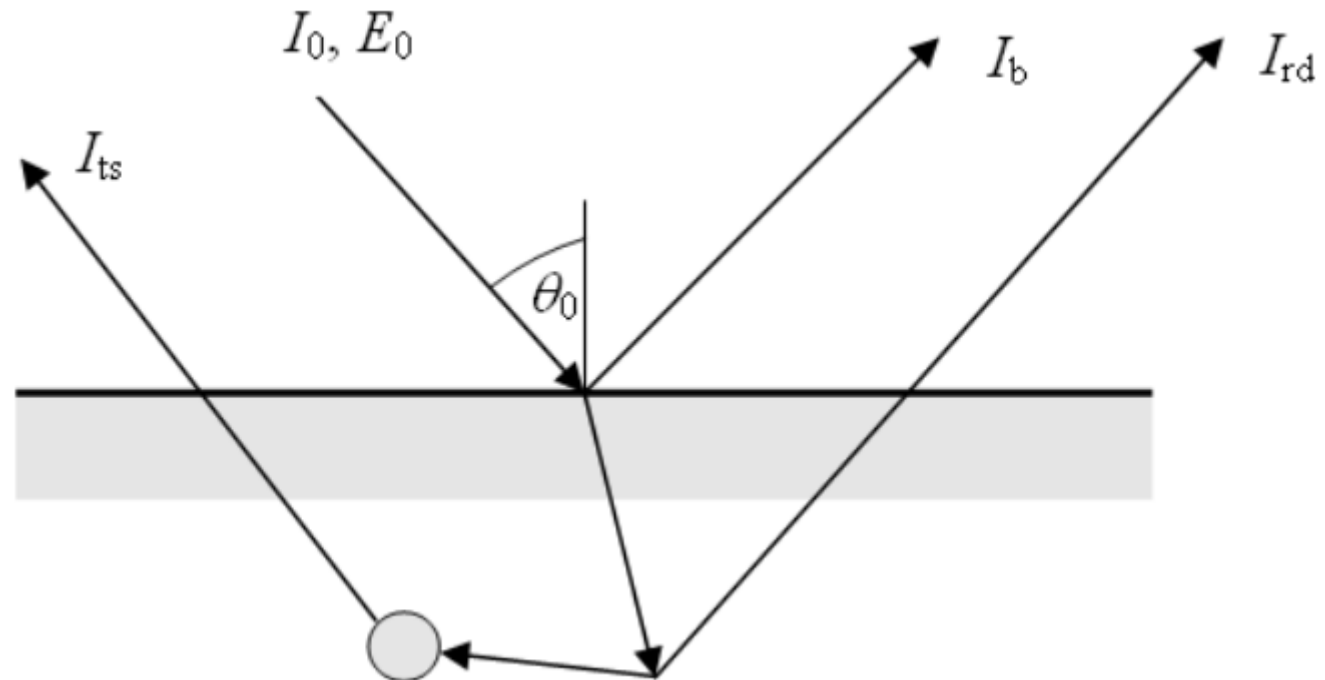
- An incident ion undergoes an elastic collision at the surface of a material, and it is reflected.

$I_{rd}$  = Rediffused Electrons (electron-induced only)

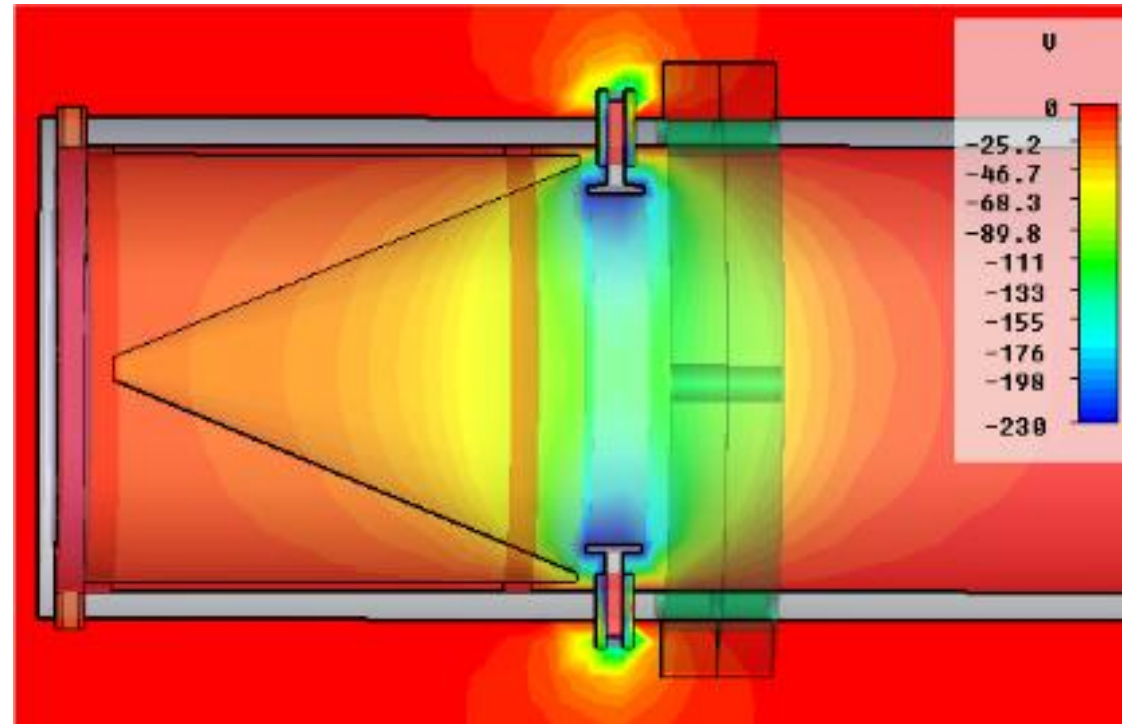
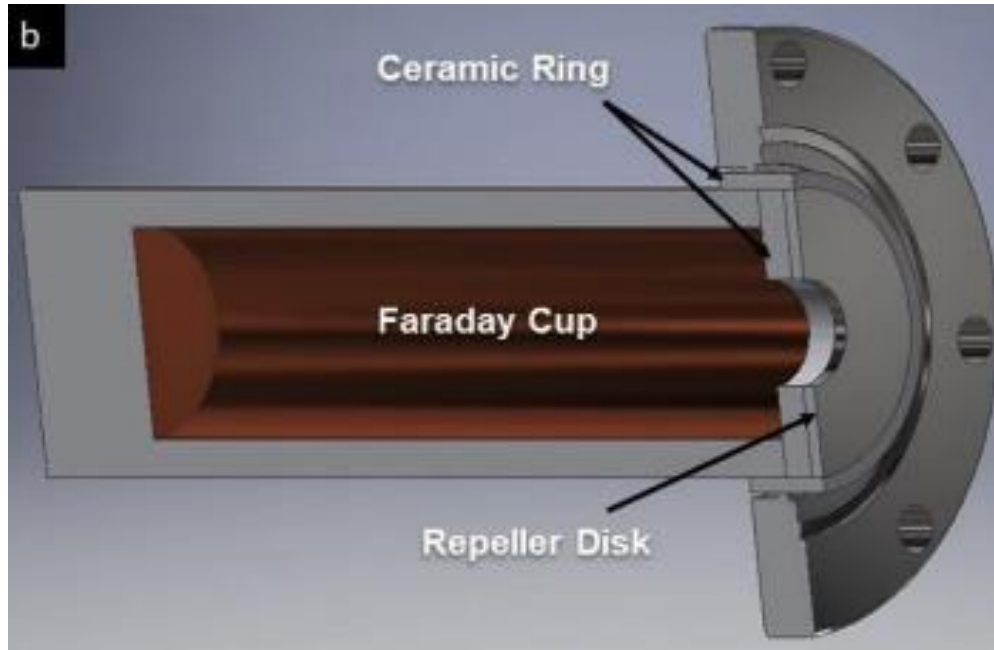
- An incident electron moves into a material, but it is scattered back out of the material.

$I_{ts}$  = True electrons

- An incident electron moves into a material and due to collisions, electrons other than the incident one are scattered out of the material.



# FC Electron Suppressor



# CST Particle Tracking Simulation



ISIS Neutron and Muon Source

 [www.isis.stfc.ac.uk](http://www.isis.stfc.ac.uk)

  [@isisneutronmuon](https://www.instagram.com/isisneutronmuon)

 [uk.linkedin.com/showcase/isis-neutron-and-muon-source](https://www.linkedin.com/showcase/isis-neutron-and-muon-source)



# SEE on CST:

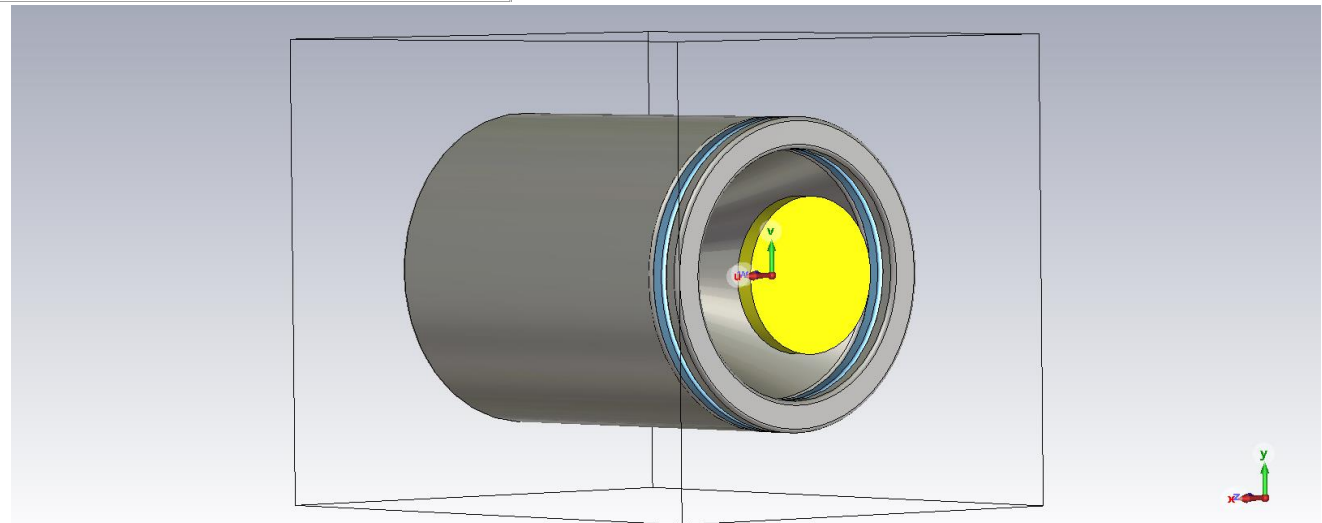
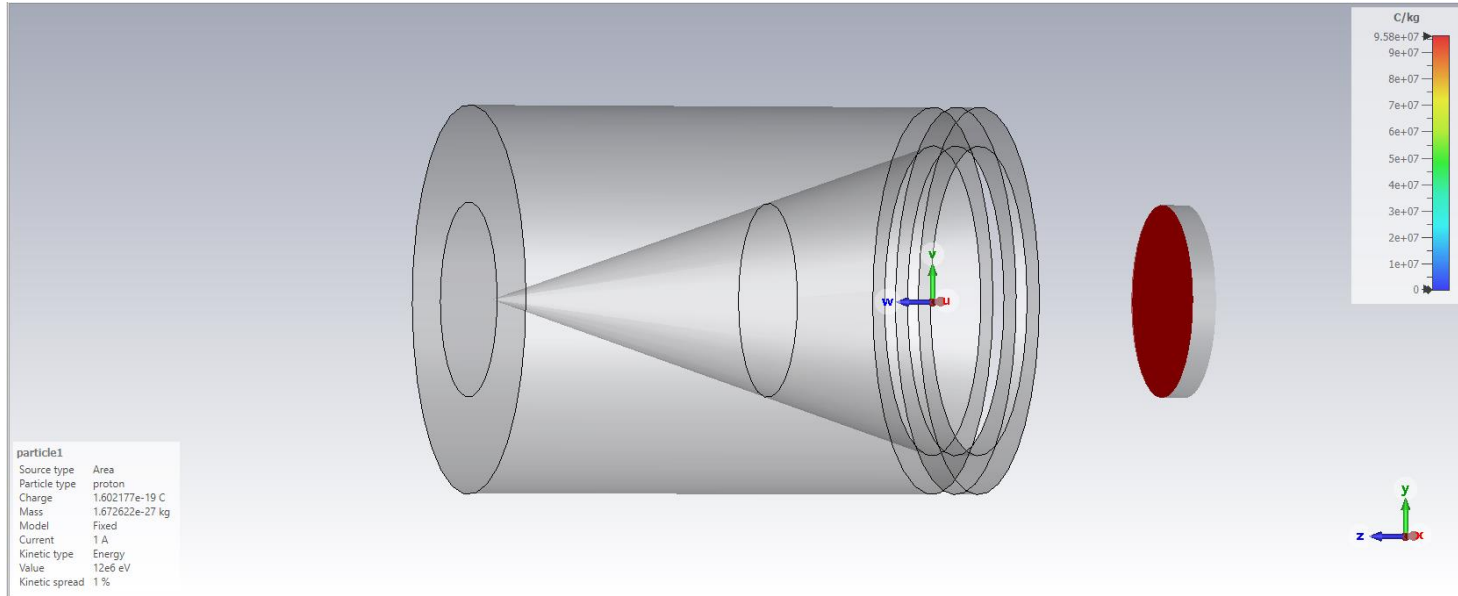
While SE source is used for SE suppression mostly, there is also another way of simulating SEs on CST studio suite: to induce the SEs from proton bombardment.

CST has in-built model for Secondary Electron Emission (SEE) covering both types of emission: Electron-induced SE and ion-induced SEs.

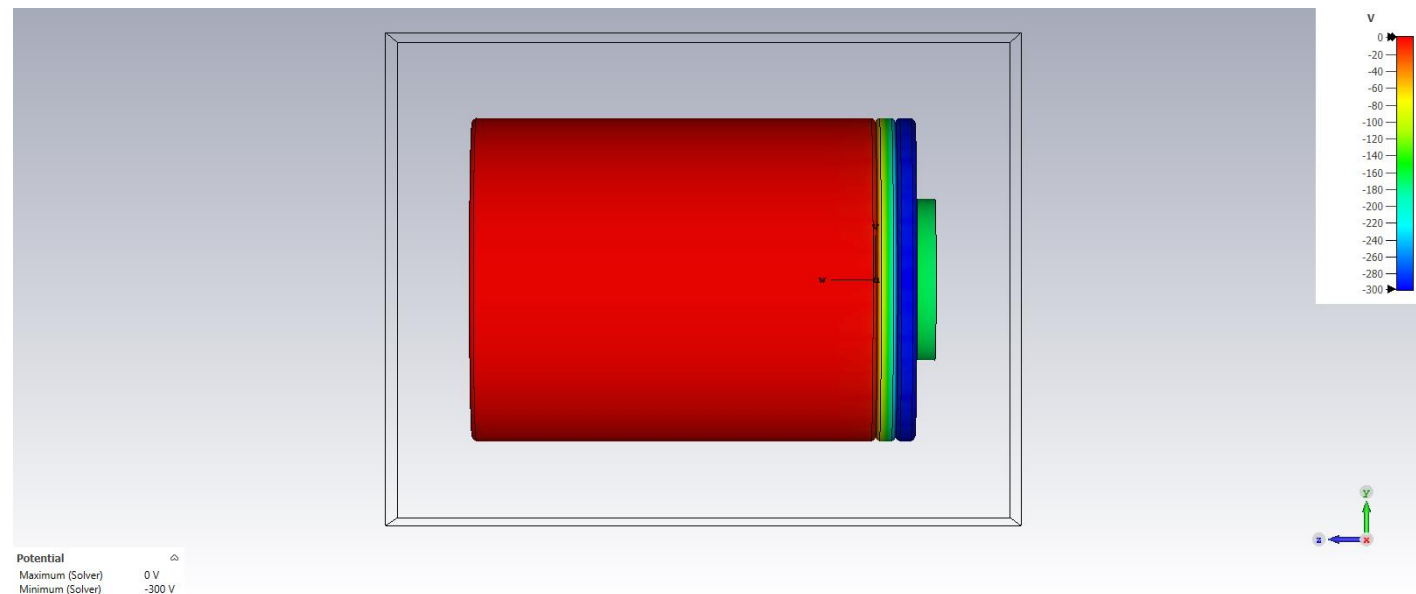
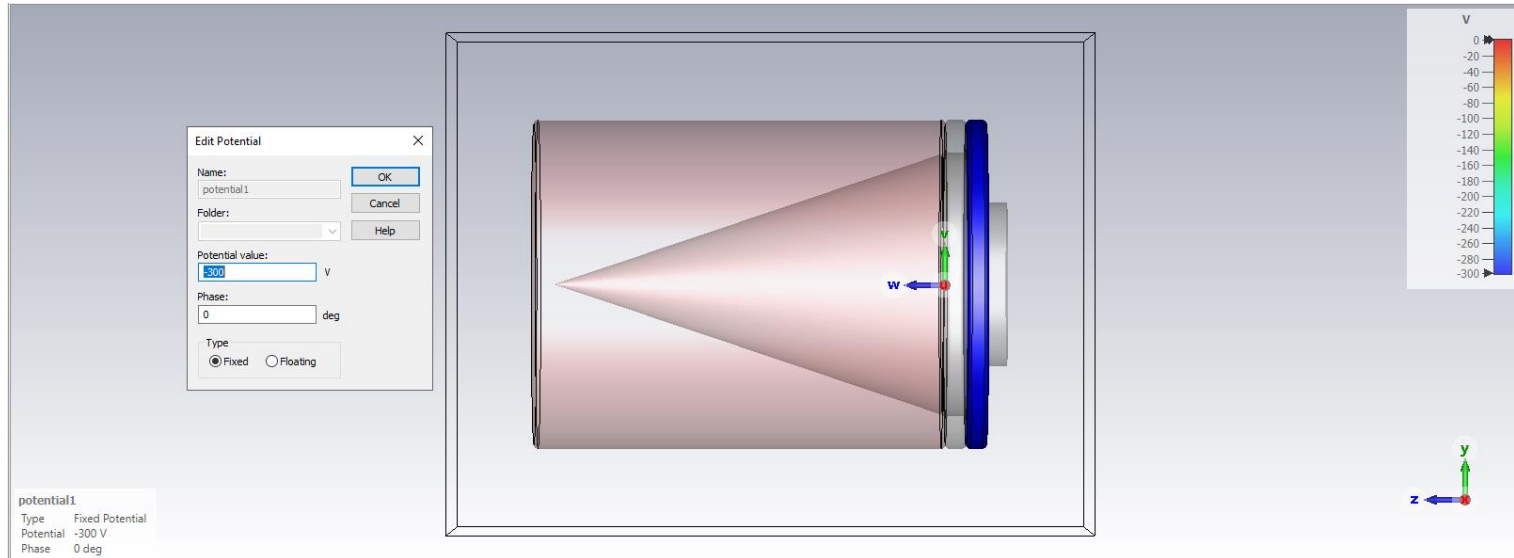
- For electron-induced SE: Either Furman or Vaughan model can be used, or one can also import the data themselves.
- For ion-induced SE: SE yield data is imported, and the most probable energy of SEs (temperature value) is also needed.



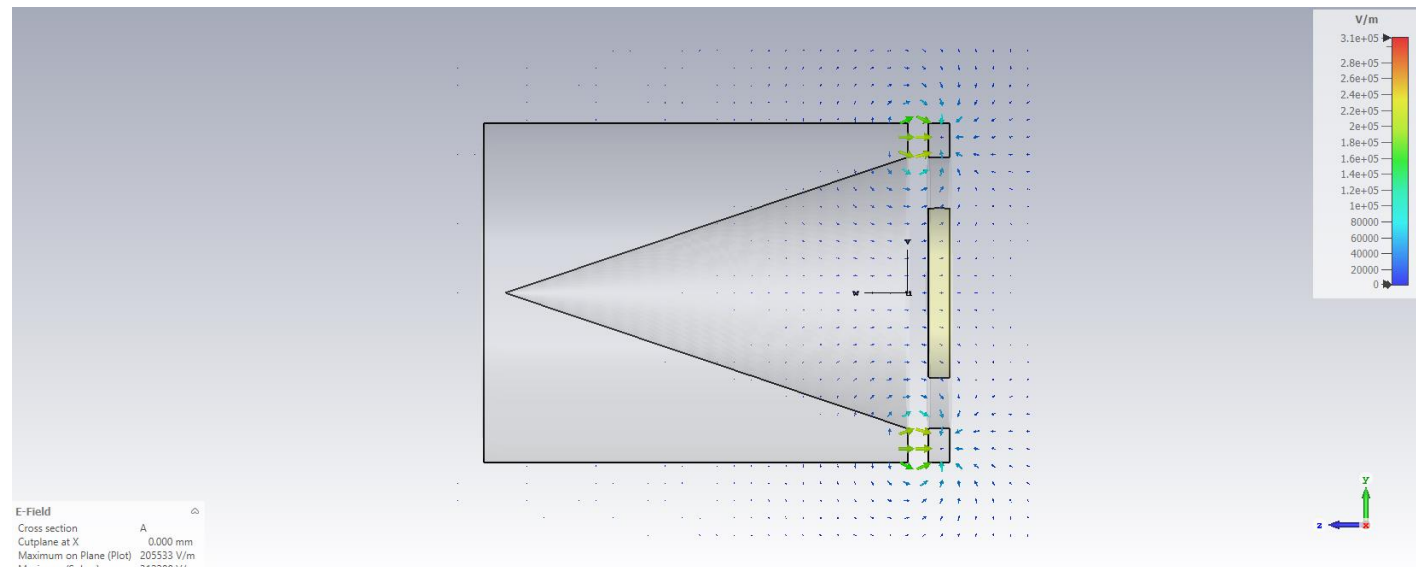
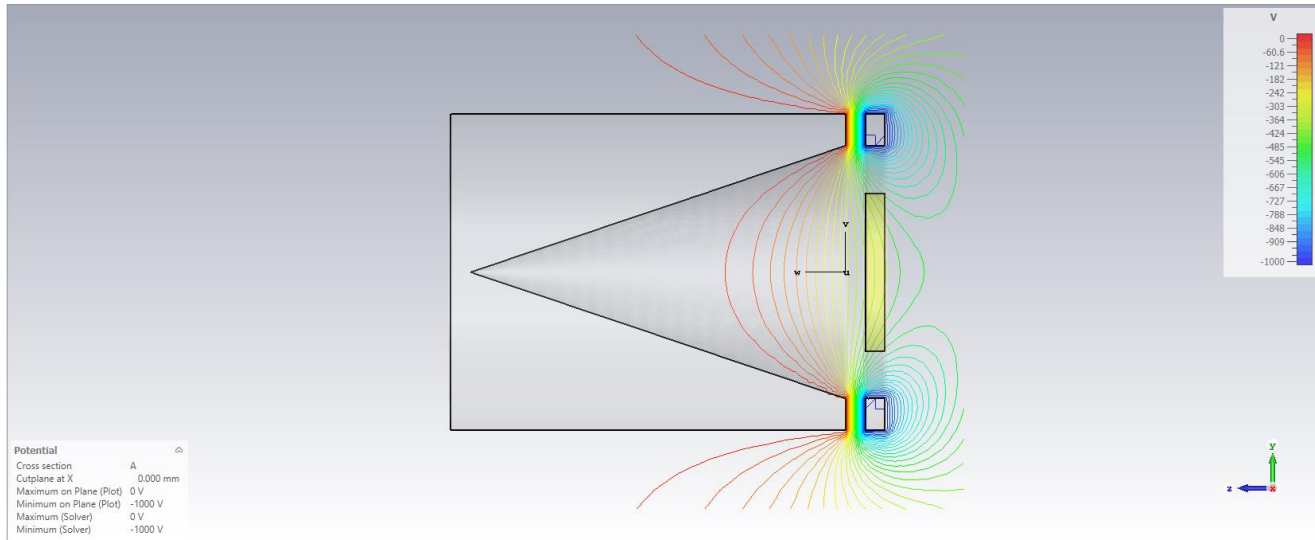
# Proton-induced SE emission:



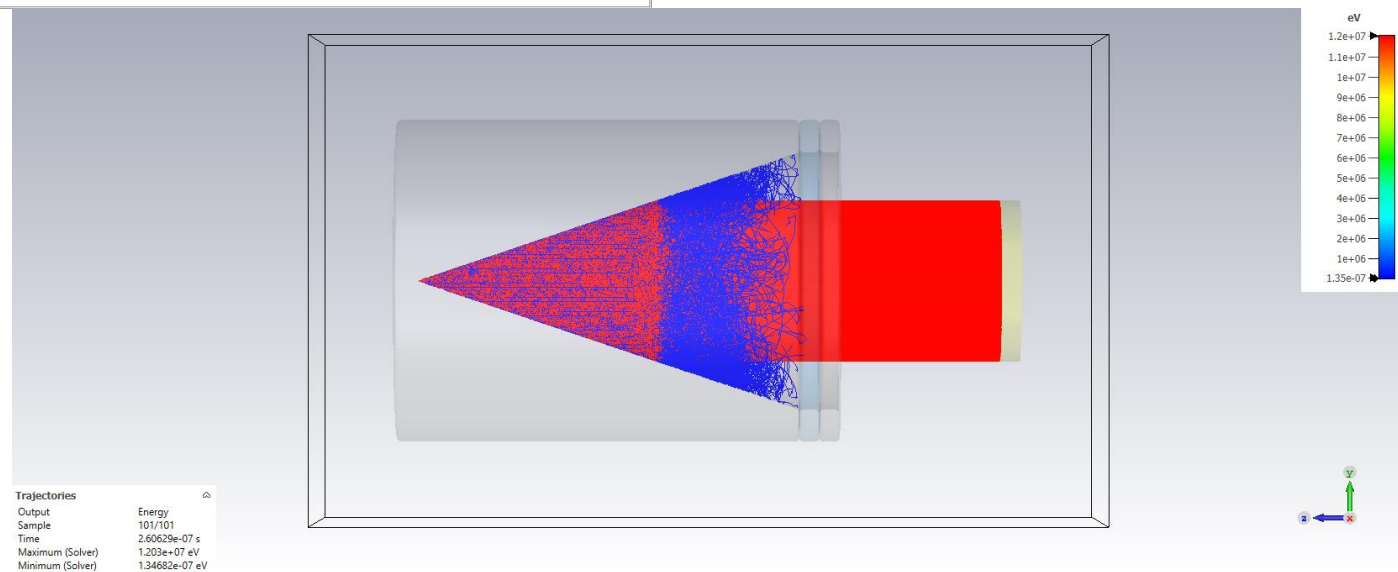
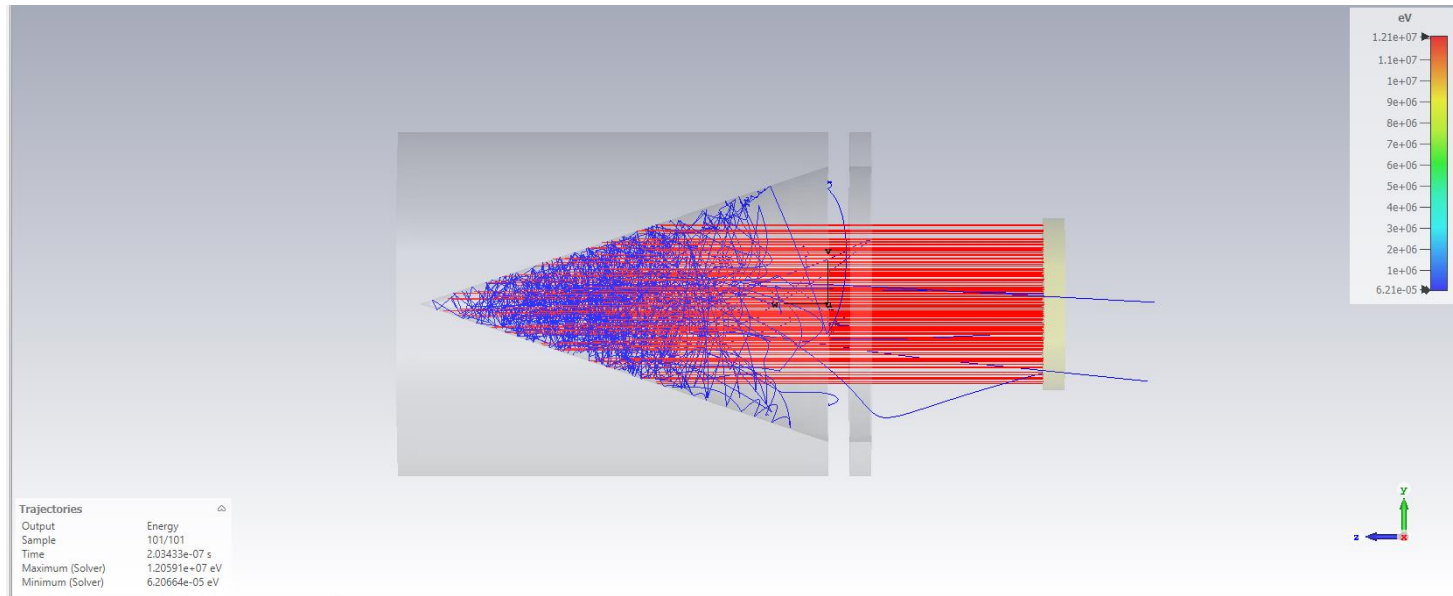
# Electric Potential:



# SE-Suppression Field



# Proton-induced SE emission:



# Running Simulation:

A Python code was developed, which determine the number of SEs leaving the FC using their last position from the trajectories file exported from the simulation. Energy of the SE was also calculated.

Particle tracking simulations were performed with changing parameters:

- Number of protons: ~10000 to ~100000.
- Absolute current: 1.6 mA or 80 mA.
- Voltage: 0 V to -1000 V.



The proton source 50 mm away from the front of the FC:

# Simulation Results

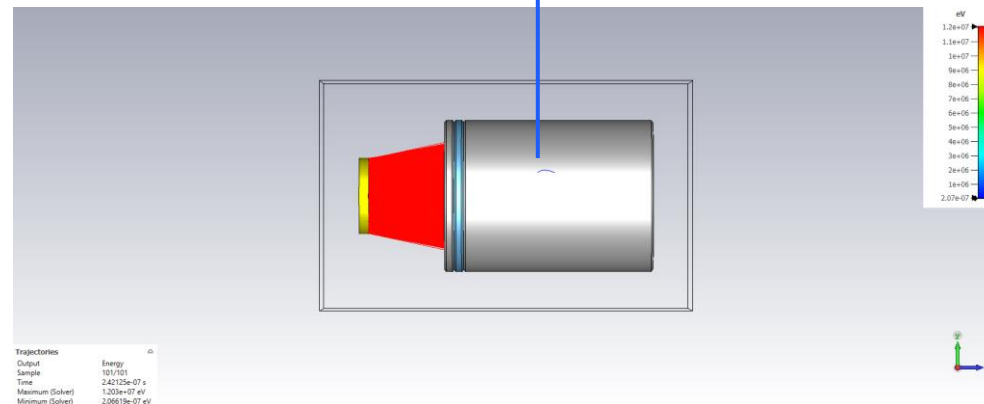
Number of protons	Voltage applied to the electron suppressor (V)	Absolute current from proton source (mA)	Protons incident angle from the source	SEs escaping the FC (%)
20248	0	1.6	0°	5.54 (1340 / 24177)
20248	-100	1.6	0°	0.0072 (2 / 27992)
20248	-200	1.6	0°	0 (0 / 277300)
45204	-200	1.6	0°	0 (0 / 62239)
88682	-200	1.6	0°	0 (0 / 119357)



The proton source 50 mm away from the front of the FC:

# Simulation Results

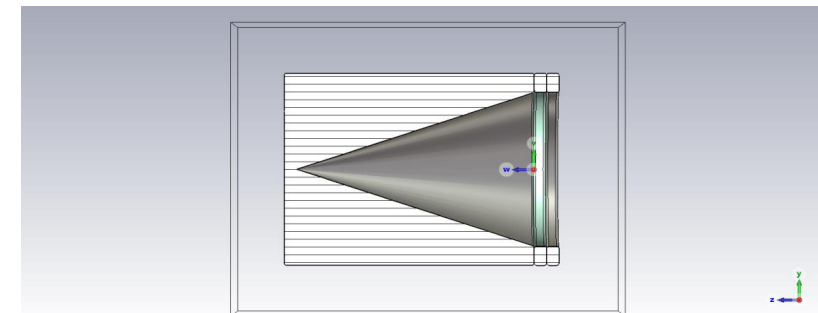
Number of protons	Voltage applied to the electron suppressor (V)	Absolute current from proton source (mA)	Protons incident angle from the source	SEs escaping the FC (%)
20248	-200	1.6	10°	0 (0 / 27093)
45204	-200	1.6	13°	3.34e-3 (2 / 27992)
45204	-200	80	13°	0 (0 / 56543)



Incident proton current  
Is 80 mA.

# Simulation Results

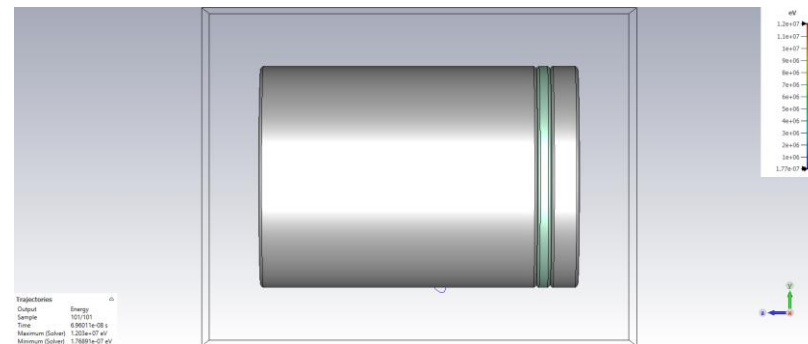
Number of protons	Temperature values (eV)	Voltage applied to the electron suppressor (V)	Incident protons angle from the source	SEs escaping the FC (%)
45204	7.5	-200	13°	0 (0 / 56543)
105898	7.5	-200	0°	7.2e-4 (1/139484)
105898	10	-200	0°	1.31e-3 (2 / 152956)
105898	20	-200	0°	0.0340 (68 / 199786)



Incident proton current  
Is 80 mA.

# Simulation Results

Number of protons	Temperature values (eV)	Voltage applied to the electron suppressor (V)	Incident protons angle from the source	SEs escaping the FC (%)
105075	20	-400	0°	0 (0 / 197811)
105075	50	-500	0°	9.72e-3 (29 / 298372)
105075	50	-700	0°	3.4e-4 (1 / 295050)
105075	50	-1000	0°	0 (0 / 292402)



# Alternative method



# CST SE energy spectrum function

Ion-induced SE energy spectrum is generated on CST using this function:

$$f(E) = \delta(E_0, \theta_0) \frac{E}{T^2} \exp\left(-\frac{E}{T}\right) P^{-1}\left(2, \frac{E_0}{T}\right)$$

$E$  : Energy

$T$  : Temperature in eV

$E_0$  : Incident energy

$\theta_0$  : Incident angle

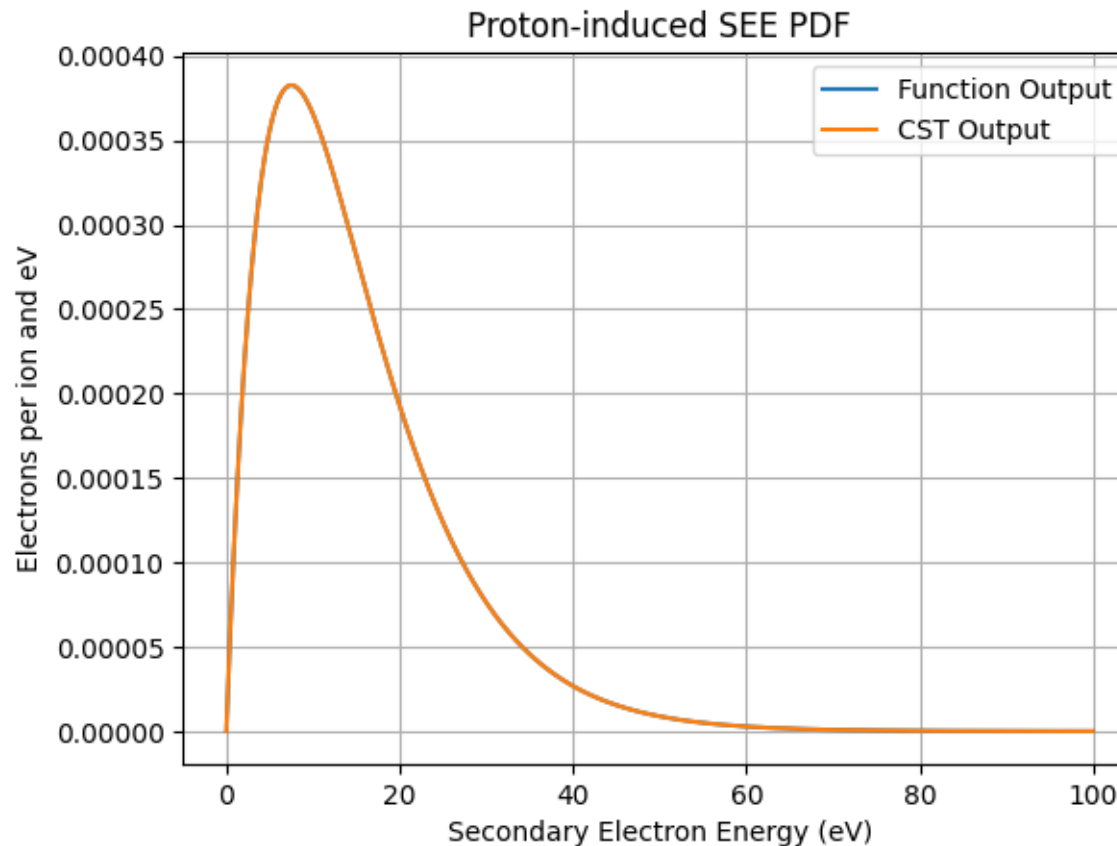
$\delta$  : Secondary electron yield

$P$  : Incomplete gamma function

Incident energy = 100 eV

Temperature = 7.5 eV

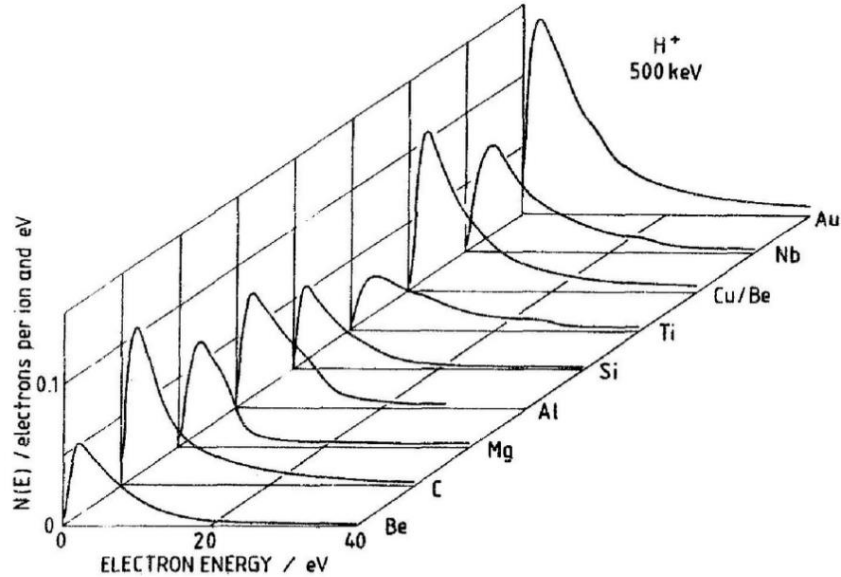
SEY = 0.0078



# SE energy spectrum comparison

The spectra given below is taken from “Ion-induced Secondary Electrons Spectra from Clean metals surfaces” by D. Hasselkamp et al. (1987).

**Important note: For light ion impact, the shape of the low-energy spectrum does not depend on the impact energy.** (From a book called “Particle induced electron emission II”)



**Fig. 5.11.** Low-energy spectra  $N(E) = d\gamma/dE$  induced by protons at 500 keV from different clean metals (from Hasselkamp et al. 1987a)

**Table 1**

Position of maximum  $E_{max}$  and half-width of the low-energy peak  $\Delta_{1/2}$  of nine metal targets for proton bombardment at 500 keV (see fig. 4). The estimated errors are  $\pm 0.2$  eV and  $\pm 0.4$  eV for  $E_{max}$  and  $\Delta_{1/2}$ , respectively.

	$E_{max}$ [eV]	$\Delta_{1/2}$ [eV]
Be	2.0	6.8
C	2.0	5.4
Mg	3.0	6.0
Al	2.0	8.2
Si	1.8	6.2
Ti	3.4	11.8
Cu/Be	2.4	6.8
Nb	3.6	9.0
Au	2.2	8.4



# SE energy spectrum comparison: Copper

Tried to replicate the SE energy spectra from the paper with given parameters:

Incident energy = 500 KeV

Temperature =  $2.4 \pm 0.2$  eV

SEY = 1.24 (for 500 KeV protons on Cu)

“Proton-induced secondary electron emission from elemental solids over the energy domain 1 keV–1000 MeV”.

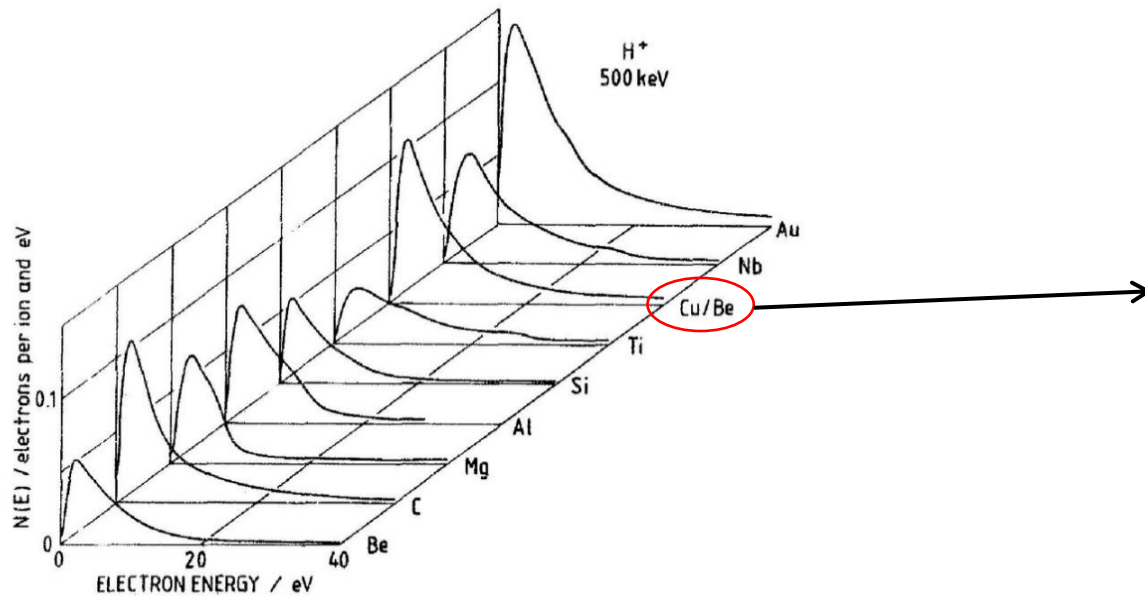
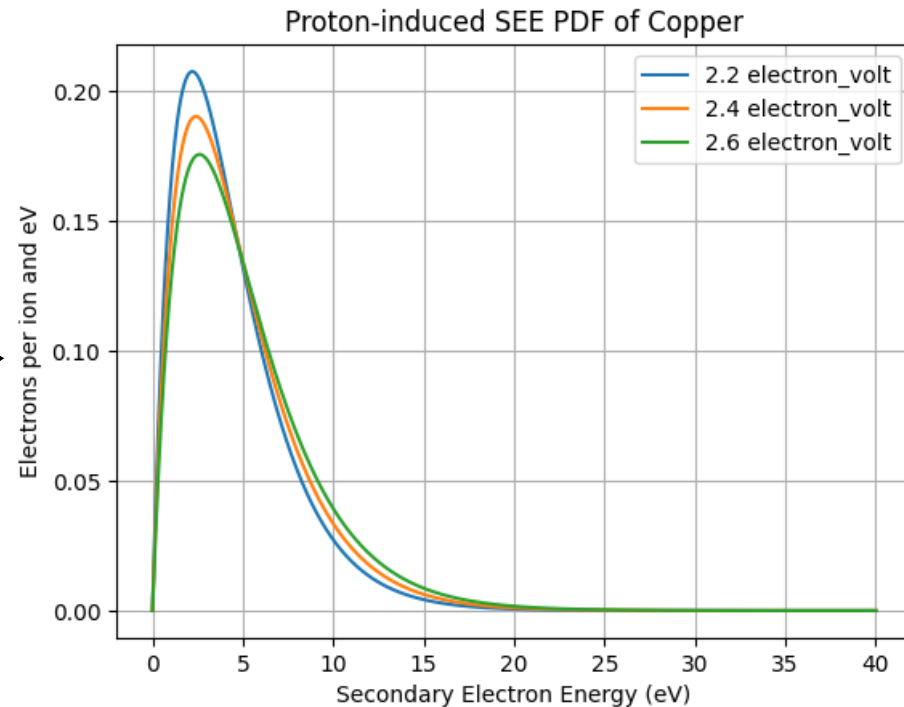


Fig. 5.11. Low-energy spectra  $N(E) = d\gamma/dE$  induced by protons at 500 keV from different clean metals (from Hasselkamp et al. 1987a)



Energy at peak of the spectrum (eV)	Width at half maximum (eV)
2.2	5.38
2.4	5.87
2.6	6.36



# SE energy spectrum comparison: Aluminium

Tried to replicate the SE energy spectra from the paper with given parameters:

Incident energy = 500 KeV

Temperature =  $2.0 \pm 0.2$  eV

SEY = 0.7 (for 500 KeV protons on Al)

“Proton-induced secondary electron emission from elemental solids over the energy domain 1 keV–1000 MeV”.

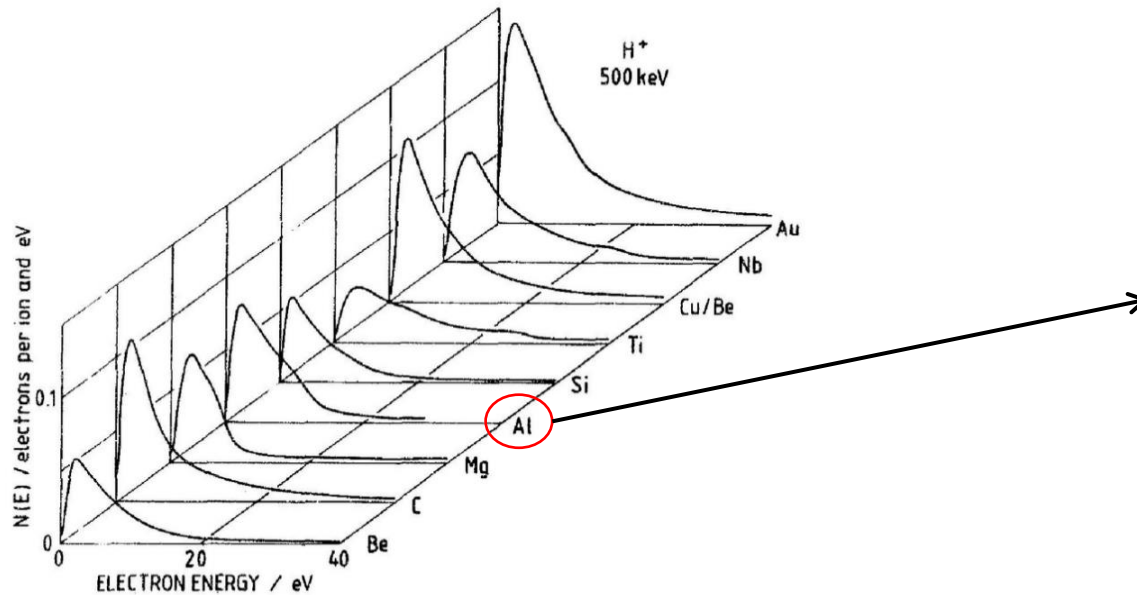
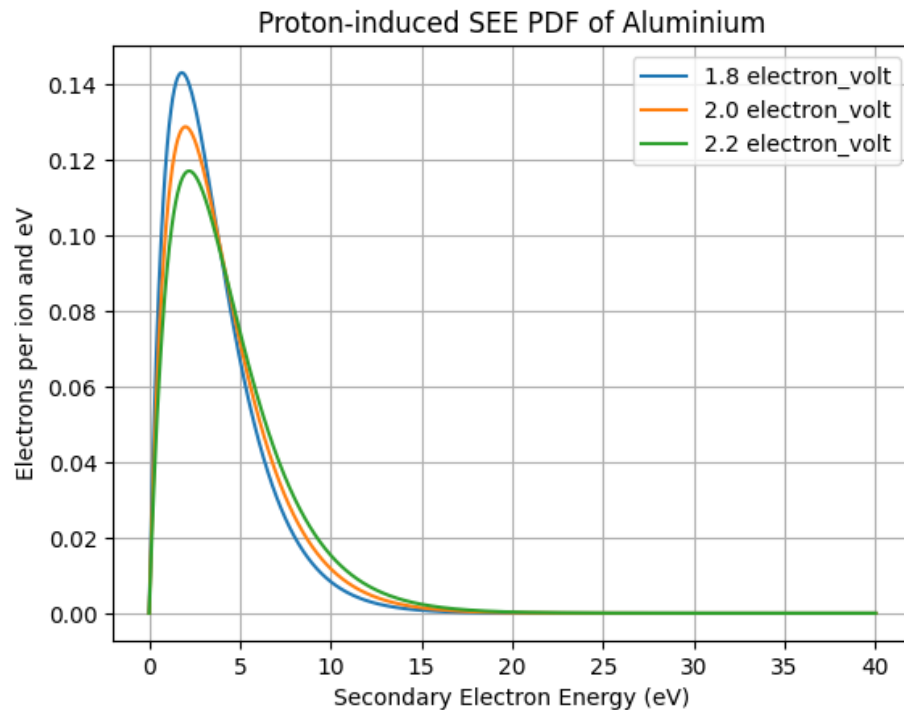


Fig. 5.11. Low-energy spectra  $N(E) = d\gamma/dE$  induced by protons at 500 keV from different clean metals (from Hasselkamp et al. 1987a)

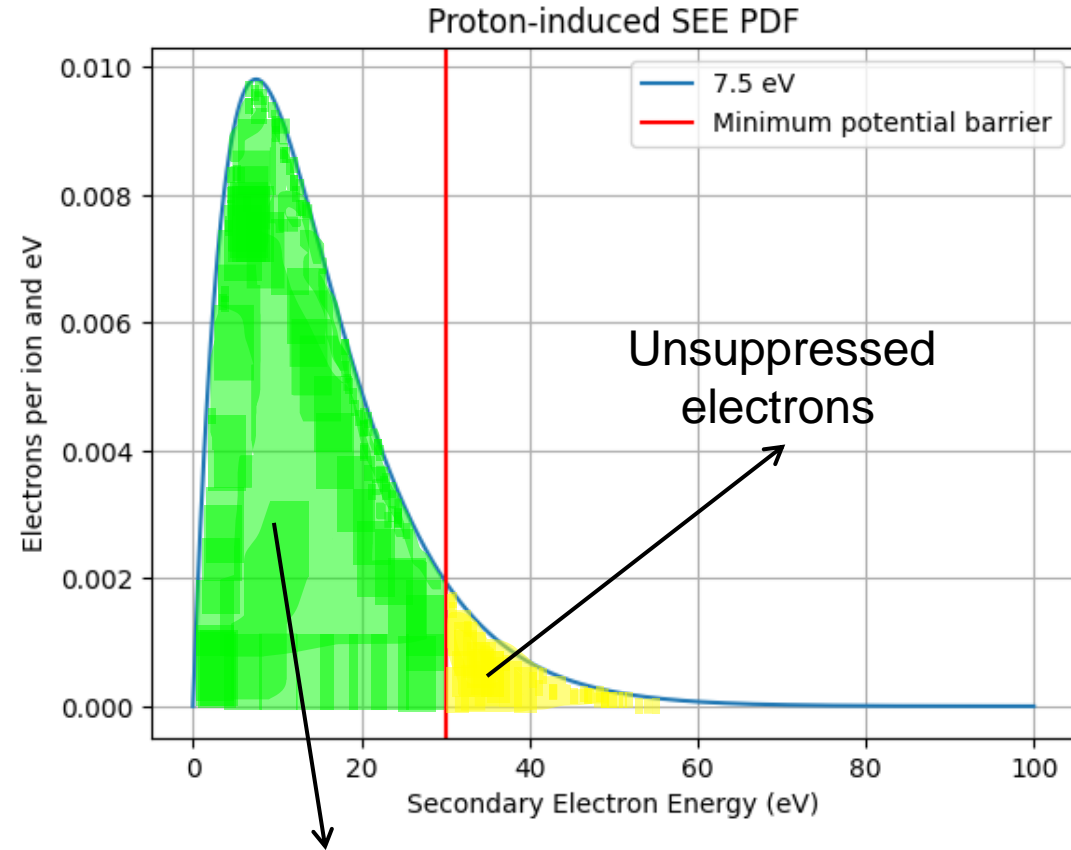
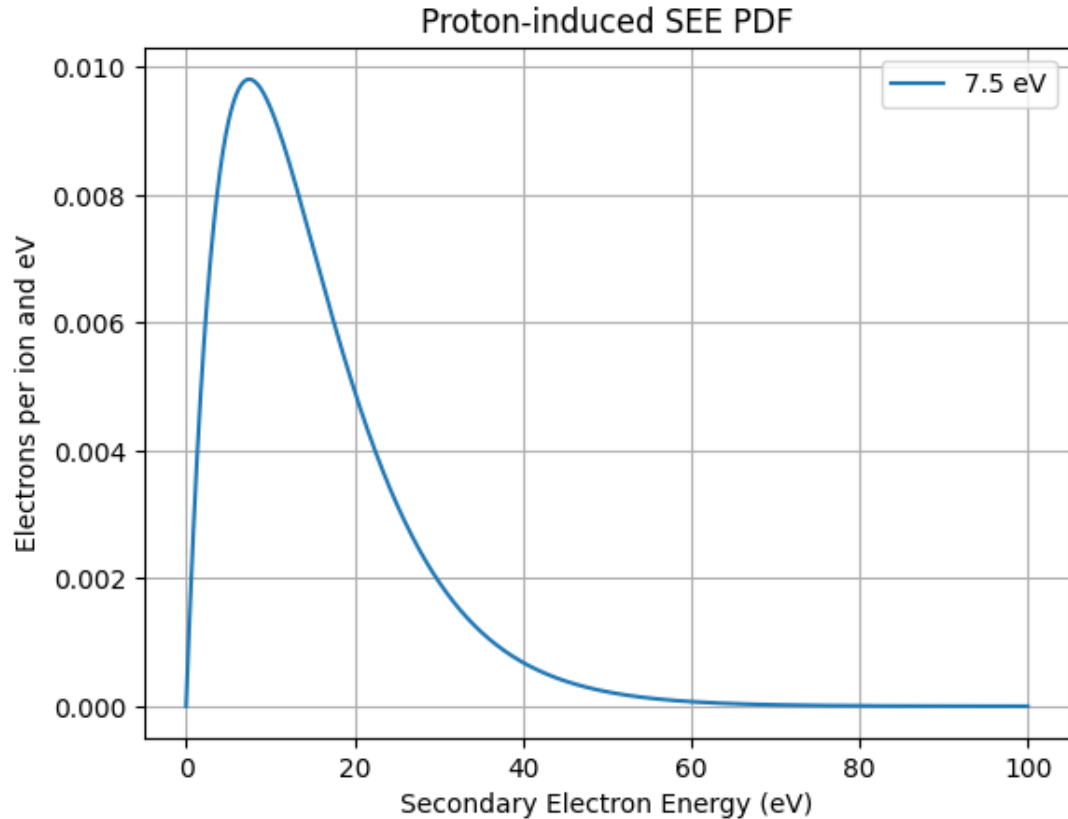


Energy at peak of the spectrum (eV)	Width at half maximum (eV)
1.8	4.40
2.0	4.9
2.2	5.38



# Unsuppressed Secondary Electrons

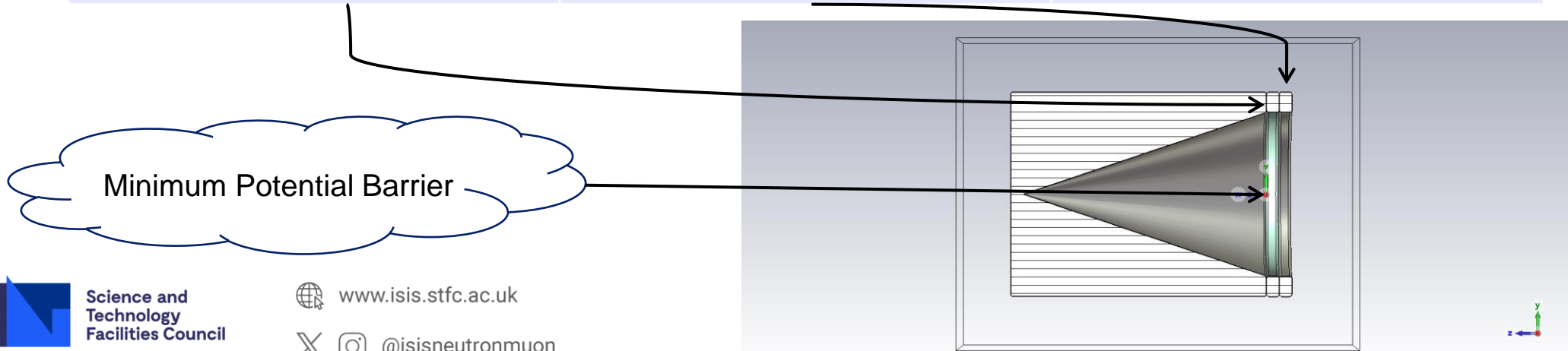
Idea was to calculate the ratio of unsuppressed electrons by integrating the SE energy spectrum.



# Potential barrier on FC

When 1KV voltage is applied to the secondary electron suppressor in the shape of a ring, the potential barrier is minimum at the centre of the FC entrance. Minimum potential barrier changes with the distance of the suppressor.

Distance from FC (mm)	Thickness of FC (mm)	Minimum potential barrier at 1KV voltage (V)
3	5	-335.47751
5	5	-340.69275
3	10	-390.37244
5	10	-386.51352



# Ratio of unsuppressed electrons

Assuming electrons more than 300 eV could not be suppressed, ratio of unsuppressed electrons was calculated at different temperature values.

**Potential barrier = -300 V: (Incident energy = 12 MeV)**

Temperature (eV)	Integrated total electrons (= SEY)	Ratio of unsuppressed electrons
2.4	0.2	6.52e-53
7.5	0.2	1.74e-16
10	0.2	2.90e-12
20	0.2	4.9e-6
50	0.2	0.0174
100	0.2	0.1991

Ratio is same even when the incident energy is 3 MeV



# Conclusions

- Only the use of the electric field was studied, excluding the possibility of using the magnetic field.
- 1 KV voltage should be enough to suppress the maximum number of secondary electrons (SEs).
- Ion-induced SEs were only taken into consideration for the analytical study of electron suppression.
- Even though it could not be explicitly concluded from the CST simulations, it has been found from the literature that having an electron suppressor ring, with 5 mm thickness, at a 3 mm distance (isolated with an insulator) could be best.
- And the bias ring could be made of Stainless Steel or Copper, isolated by the insulator made of Alumina ceramics.



# Thank you!



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