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Thermal Analysis of the LANSCE H+ RFQ Test Stand Faraday Cup*

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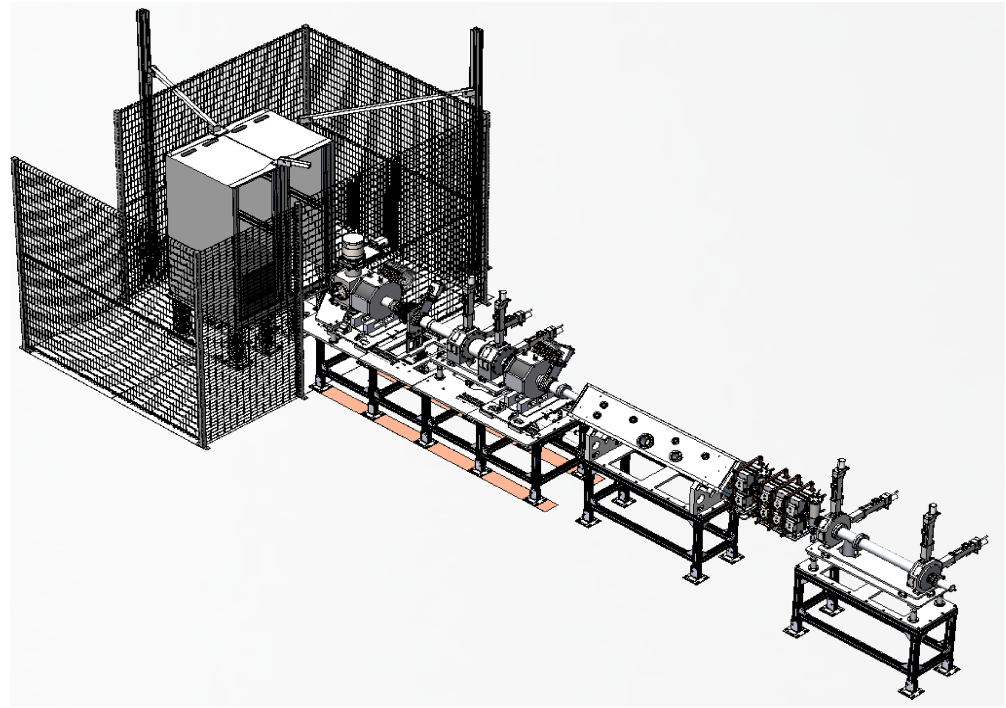
Background

The Los Alamos Neutron Science Center (LANSCE) operates one of the nation's most powerful linear accelerators, which supports fundamental science for a wide variety of projects including isotope production, materials research, proton radiography, and more. Currently the facility utilizes two 750 keV Cockcroft-Walton based injectors for transporting H^+ and H^- beams into the 800 MeV accelerator. A high current accelerating structure, a Radio Frequency Quadrupole (RFQ), is being assembled at the LANSCE H^+ RFQ Test Stand injector lab to evaluate the new system intended to replace the aging Cockcroft-Walton injectors.

LANSCE Cockcroft-Walton injectors



Rendering of the LANSCE H^+ RFQ Test Stand phases 1-3

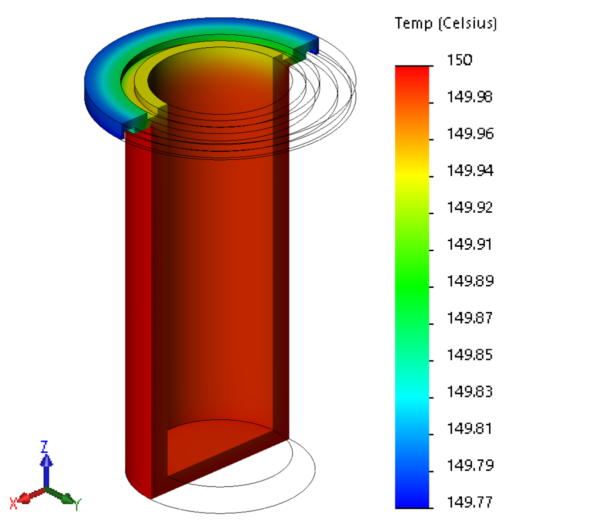
Faraday Cup Design

An important component of the RFQ Test Stand is the Faraday cup that is located at the end of the Low Energy Beam Transport (Phase 1 LEBT) and Medium Energy Beam Transport (Phase 3 MEBT). The Faraday cup functions simultaneously as a current monitor, beam stop, and water cooling jacket for each of the three project phases.

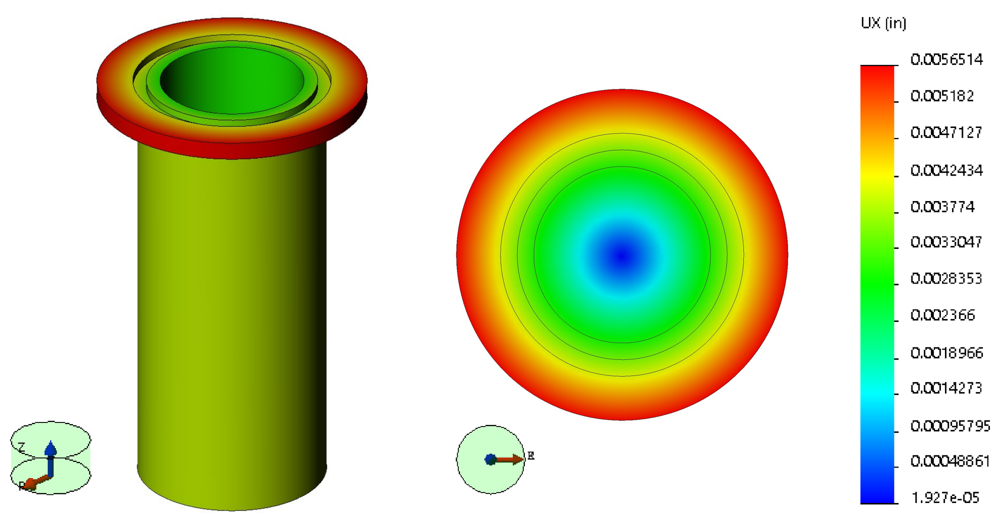
Individual components of the Faraday cup, assembly, and internal section view

Thermal Expansion Analysis

The graphite cone is captured inside the copper cup using a tight interference fit to improve heat transfer. A finite element analysis (FEA) of the copper thermal expansion evaluated the tolerance of the component interface. The analysis confirmed that the uniform heating at 150 °C with free air convection leads to sufficient expansion for the graphite to fit properly.



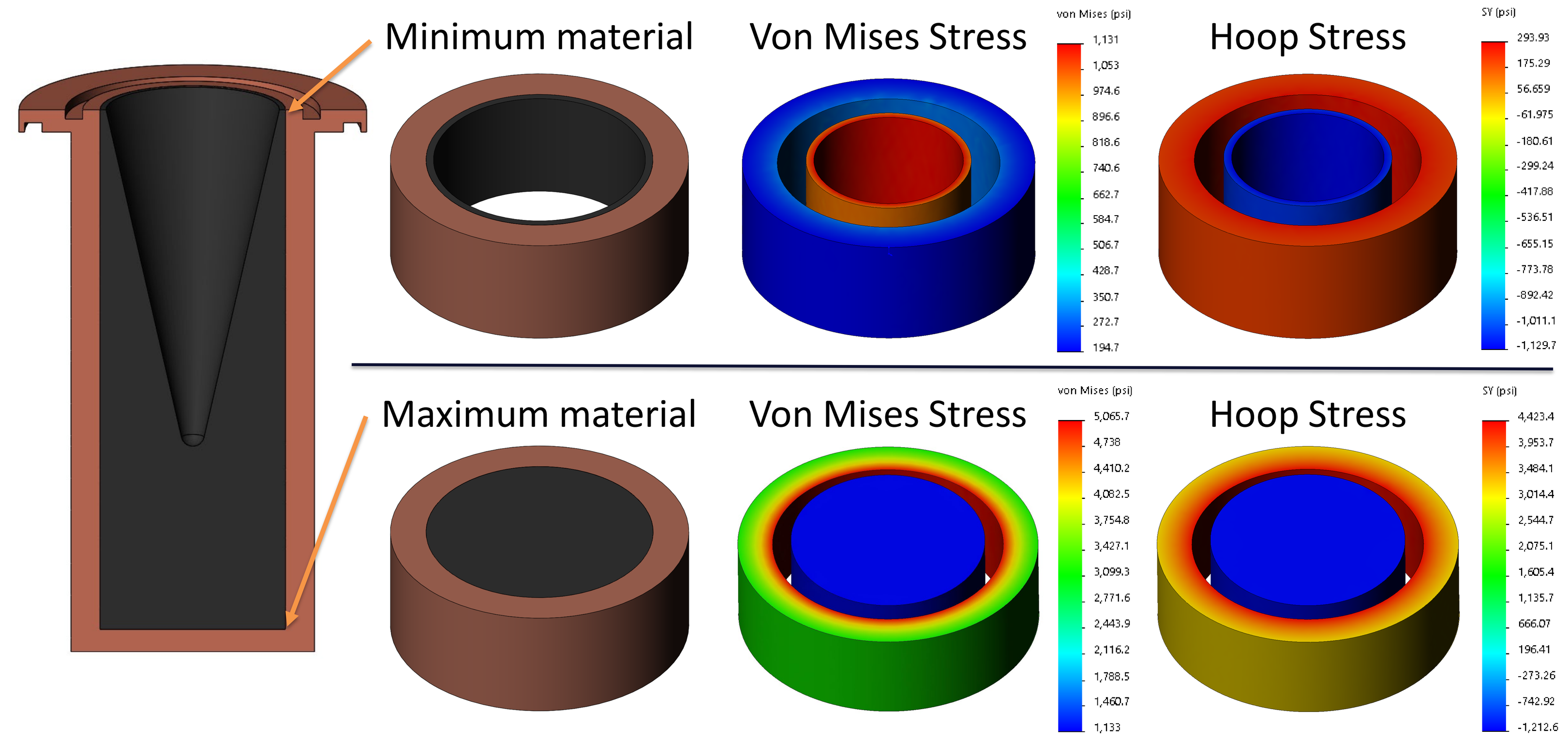
Thermal contour plot from heating



Radial displacement contour plots about center axis

Interference Fit Analysis

The stresses resulting from the press fit assembly of the graphite cone and copper cup were analyzed to ensure material yield limits were not exceeded. An FEA was done on the interference fit which had a 0.003 inch overlap. This analysis took two conditions into consideration: the thinnest graphite section at the top, and the solid graphite bottom.



Two conditions for interference fit

Deformed stress contour plots for each case

$$p = \frac{\delta}{\left[\frac{1}{E_0}\left(\frac{r_0^2+R^2}{r_0^2-R^2}+v_0\right)+\frac{1}{E_i}\left(\frac{R^2+r_i^2}{R^2-r_i^2}-v_i\right)\right]} \qquad \sigma_{t_i} = -p\left(\frac{R^2+r_i^2}{R^2-r_i^2}\right) \qquad \sigma_{t_o} = p\left(\frac{r_0^2+R^2}{r_0^2-R^2}\right)$$

Equations for calculating contact pressure and hoop stress to compare with analytical values

Beam Power Distribution

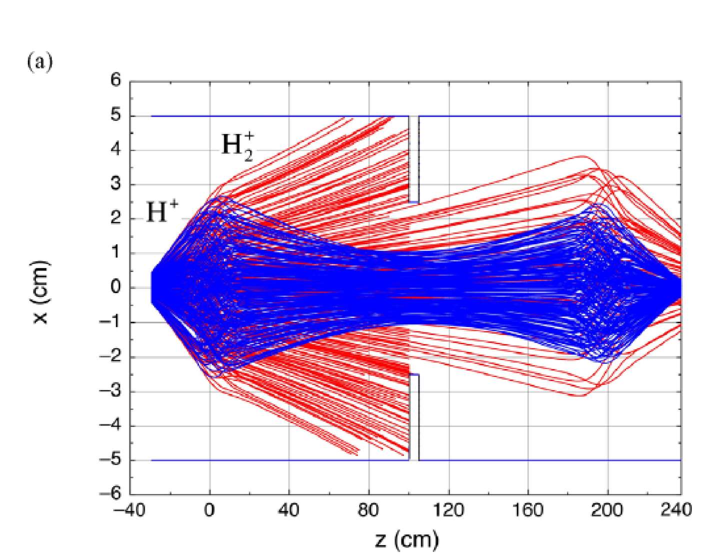
Beam power in phase 1 LEBT and phase 3 MEBT is modeled as a Gaussian distribution with the beam diameter as estimated in the figure below "Beam dynamics in LEBT with collimator" [1]. A center axial symmetric distribution was used to determine diameters of the split surface sections on the graphite cone and calculate heat flux on each surface. Total H^+ beam radius was estimated to be near 2.3 cm (0.9 in).

RFQ Test Stand Section	Beam Energy (keV)	Duty Factor (%)	Peak Current (mA)	Average Current (mA)	Average Beam Power (W)	Beam Power Used For Analysis (W)
LEBT	35	15	50	7.5	263	300
MEBT	750	7.5	21	1.58	1180	1180

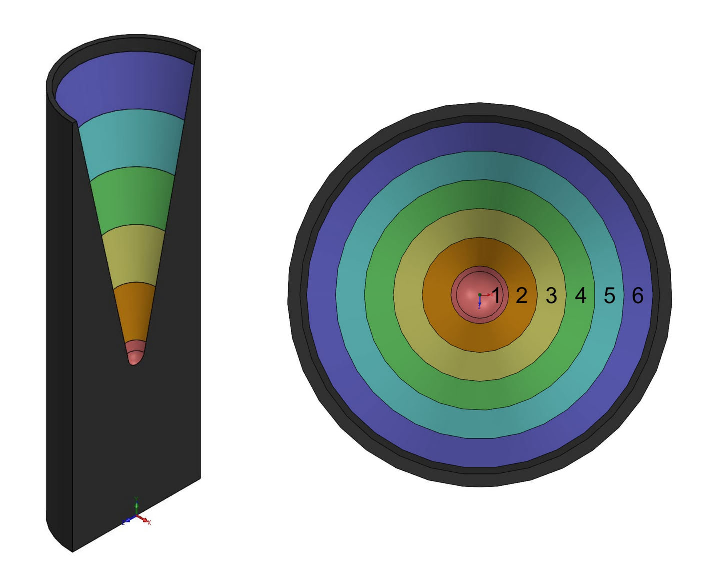
Beam characteristics for Phase 1 LEBT and Phase 3 MEBT

Faraday Cup Section	Gaussian Distribution (%)	Total Power Percentage (W)	Split Line Diameter (in)	Surface Area (mm²)	Heat Flux (kW/m²)
1	38.2	114.6	0.3	122.6	935.0
2	30.0	90	0.6	632.3	142.5
3	18.4	55.2	0.9	1051.6	52.5
4	8.8	26.4	1.2	1477.4	18.0
5	3.4	10.2	1.5	1896.8	5.4
6	1.2	3.6	1.8	2316.1	1.6

Calculated values for the split line diameters and heat flux in graphite cone for the 300 W LEBT. Heat flux was also calculated for MEBT with 1180 W total beam power



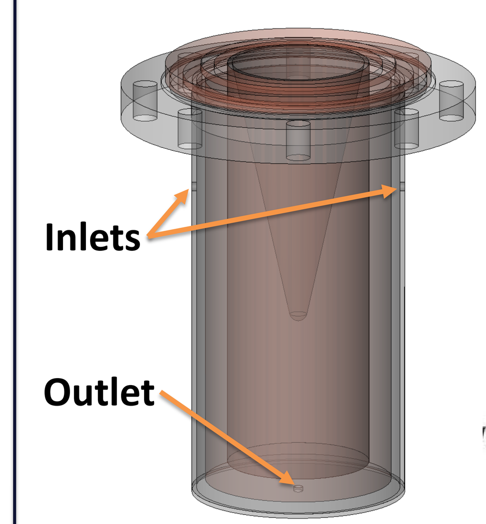
Beam dynamics in LEBT with collimator [1]



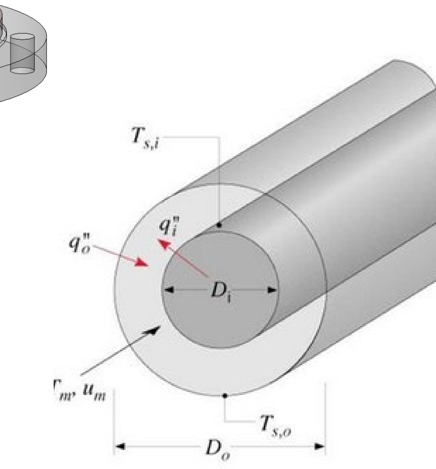
Split surface sections on graphite cone

Heat Transfer Coefficient

The steel water jacket was best represented as a concentric tube annulus for calculating the proper heat transfer coefficient. The cooling liquid is near room temperature water flowing at 1 gpm to induce an adequate temperature drop. The calculations below show the details of how the heat transfer coefficient was determined for the subsequent FEA below.



Water jacket flow channel



Concentric tube annulus model

Hydraulic diameter (D_h):

$$D_h = \frac{4(\frac{\pi}{4})(D_o^2 - D_i^2)}{\pi D_o + \pi D_i} = 0.245 \text{ in} = 6.2 \text{ mm}$$

Volumetric flow rate (Q):

1 gpm at 20 °C is 6.31×10^{-5} m³/s

Kinematic viscosity (ν):

$\nu = 1.052 \times 10^{-5}$ ft²/s $= 1.004 \times 10^{-6}$ m²/s

Cross sectional area (A):

$A = 1.057$ in² $= 6.8 \times 10^{-4}$ m²

Reynolds number (Re):

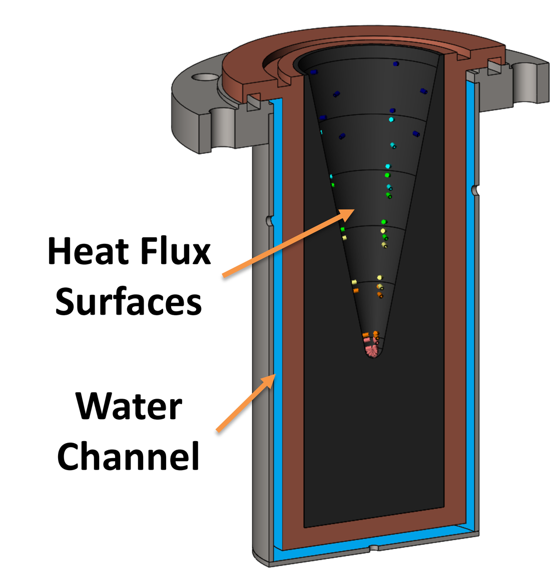
$$R_e = \frac{QD_h}{\nu A} = \frac{(63100\frac{mm^3}{s})(6.223\ m)}{\left(1.004\frac{mm^2}{s}\right)(682\ mm^2)} = 571.35$$

Water thermal conductivity (k): $0.606\ \frac{W}{mK}$

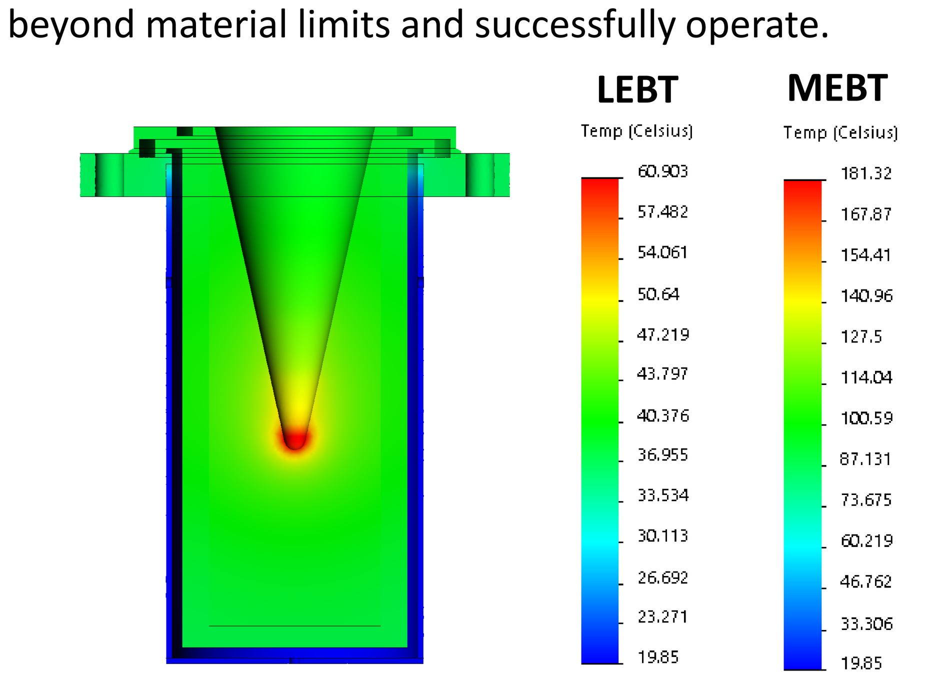
Heat transfer convection coefficient (h): $= (\frac{48}{11})(\frac{k}{D_h}) = (\frac{48}{11})(\frac{0.606\frac{W}{mK}}{0.006223\ m}) = 426.5\ \frac{W}{m^2K}$

Heat Transfer Analysis

The FEA used beam power levels for the LEBT and MEBT test phases as the heat load, and the calculated convection coefficient to represent cooling. Results found that the Faraday cup would not exceed temperatures beyond material limits and successfully operate.



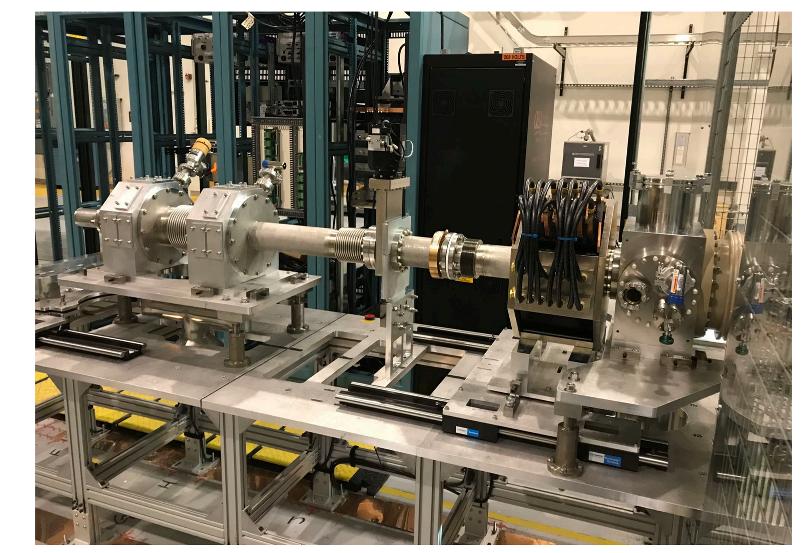
Convection and heat flux surfaces used for analysis



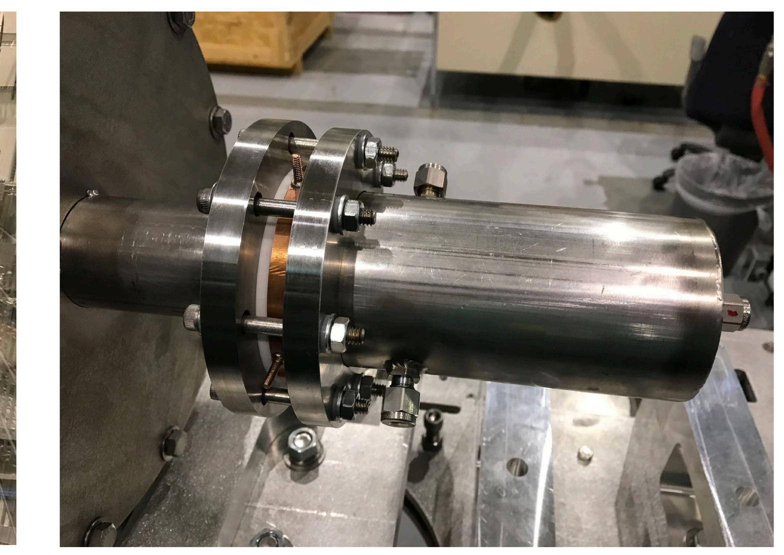
Thermal contour plot with values for LEBT and MEBT load case respectively

Conclusion

The analysis of the Faraday cup determined that the component would operate acceptably for each phase of the RFQ testing, and will be integrated into the production assembly in the future. This unique accelerator component design highlights the multifunctional potential of the Faraday cup and the critical analysis steps needed to ensure its proper operation prior to installation.



H^+ RFQ Test Stand LEBT assembly



Faraday cup located at the beamline end

REFERENCES

[1] Y. K. Batygin, et al., "Design of a Low Energy Beam Transport for the New LANSCE H+ Injector," NIMA 753 (2014), 1-8.

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