Abstract

Neutral beam heating of LTX-β plasmas with flat temperature profiles have been observed. A challenging environment for efficient coupling of the 20 keV NBI, experimental confirmation of beam heating was achieved by optimizing plasma and beam parameters and increasing the beam tangency radius through an intentional misalignment of the ion source. The amount of observed heating remains below that predicted by NUBEAM modeling and is thought to be a result of a strong dependence on the variation in plasma and beam parameters during the discharge, along with the presence of tearing mode activity. Planned upgrades to re-aim the NBI from a tangency radius of 19 cm to 33 cm and extend the pulse length will enable more efficient beam coupling and stronger heating. The more robust coupling will relax the dependence on variations during a discharge and allow for experimental observation of heating at a wider range of plasma and beam parameters and up to the maximum beam energy of 20 keV. LTX-β is now in a vented maintenance phase during which a Neutral Particle Analyzer (NPA) and a 2D wire-calorimeter will be installed for diagnostic access to the coupled fast-ion population and beam profile for each discharge. The NPA (from UW-Madison) is being repaired and recalibrated, and the wire calorimeter is being designed and prototyped to be installed in the beam line between the beam source and vessel entry. These diagnostics and will give shot specific beam information which will further constrain beam deposition predictions. Modeling of each diagnostic and its repair/development status will be presented.

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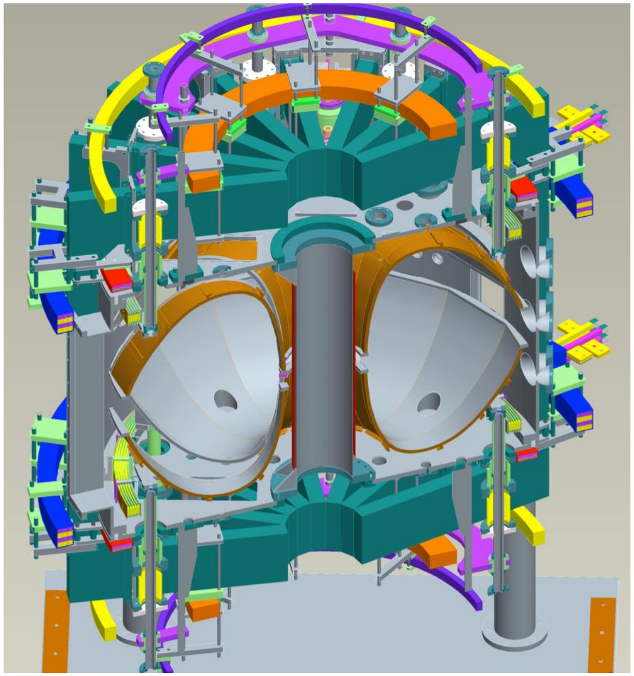
Motivation

Maximum Parameters		LTX	LTX-β
Major/Minor Radius	R/a	40/26 cm	
Toroidal Field	B_T	0.18 T	0.3 T
Plasma Current	I_p	85 kA	135 kA
Flattop Duration	t_{flat}	~15 ms	~35 ms
Electron Temperature	T_{e}	~250 eV	~400 eV
Ion Temperature	T_{i}	~100 eV	~200 eV
Energy Confinement	τ_{E}	~2 ms	~5 ms
Neutral Beam Current	I_{nbi}	-	~35 A
Neutral Beam Energy	E_{nbi}	-	13-20 keV
Neutral Beam Duration	t_{nbi}	-	5-10 ms



Neutral beam injection provides access to numerous investigations:

- LTX- β provides testbed for study of energetic particles (EPs) in low-recycling boundary plasmas
- Flat T_e profiles observed in LTX and LTX-β remove (or diminish) temp-gradient modes
- Fueling essential for plasma sustainment during low-recycling phase (no gas puffing)
- Auxiliary heating probes energy scaling in low-recycling plasmas

Beam coupling has been a challenge

- Since being installed in 2019 progress has been made to improve beam coupling
  - Initial experiments showed no evidence of heating
  - Modest heating was observed in higher current plasmas but NBI still operating in transition region and suffers from significant diminishing effects such as prompt loss, shinethrough, and possible mode interactions
- Recent experimental campaigns have:
  - Established estimates of global recycling and backed operation in “low-recycling” regime
  - Extended flat temperature regime to include liquid walls, increased duration, and sustained density
  - Made first measurements of beam heating in flat (peaked) temperature profile plasmas
- Planned upgrades to beam- increased tangency radius, longer pulse, will provide better coupled, larger fast ion population for heating & fast ion studies
- Installation of NBI and fast ion diagnostics during vent
  - Neutral Particle Analyzer will directly measure fast ion population energy distribution
  - 2D wire calorimeter will provide beam footprint information for each discharge

Summary and Status

- NBI re-orientation is underway which should significantly improve beam coupling, allowing for a larger range of plasma parameters over which heating is observed and energy scaling can be studied

$$r_{tan} = 19 \ \rightarrow 33\ \text{cm}$$

- The Neutral Particle Analyzer has been repaired, the power supply refurbished. Calibration and installation is planned within the next few months, data from plasmas expected during next year's operation

- 2D wire-calorimeter has been designed and is being built and tested at UW. Plan to install during vent. Data on beam footprint expected when operation resumes

THE UNIVERSITY of WISCONSIN MADISON

U.S. DEPARTMENT OF ENERGY | Office of Science

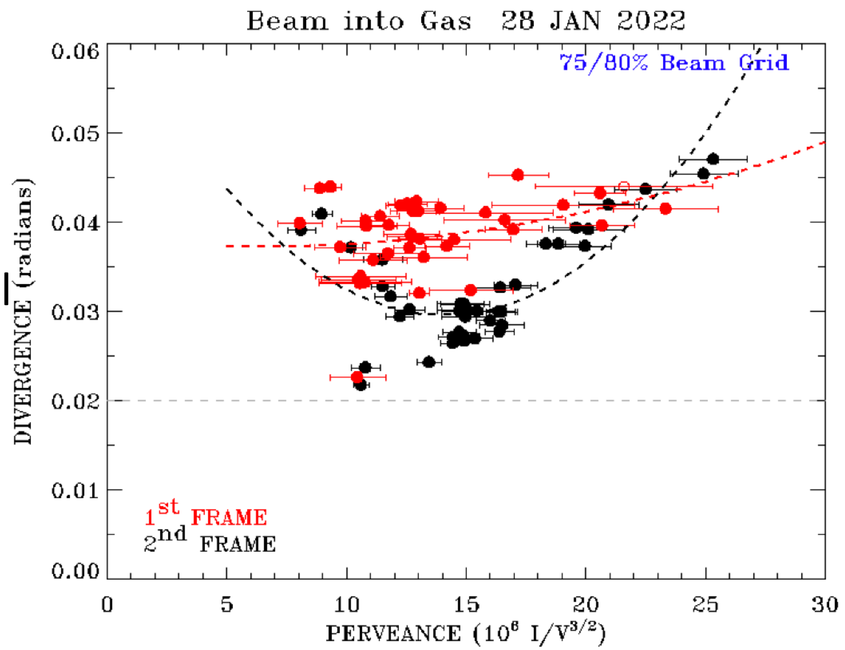
LTX-β

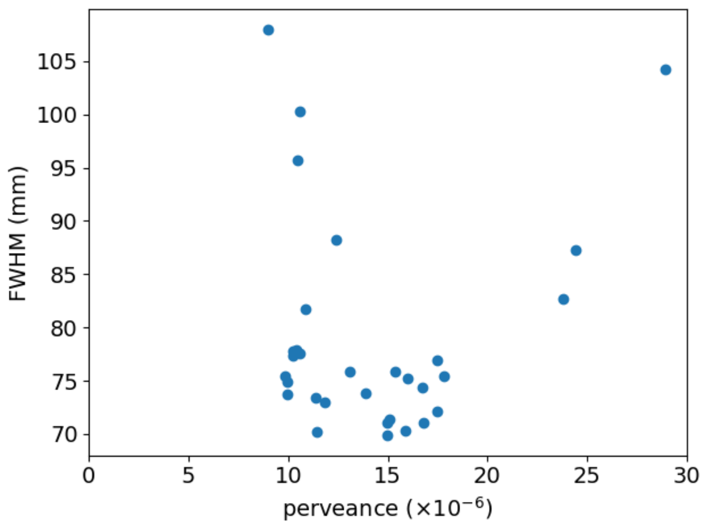
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Supported by US DOE award DE-SC0019006

Need for wire calorimeter

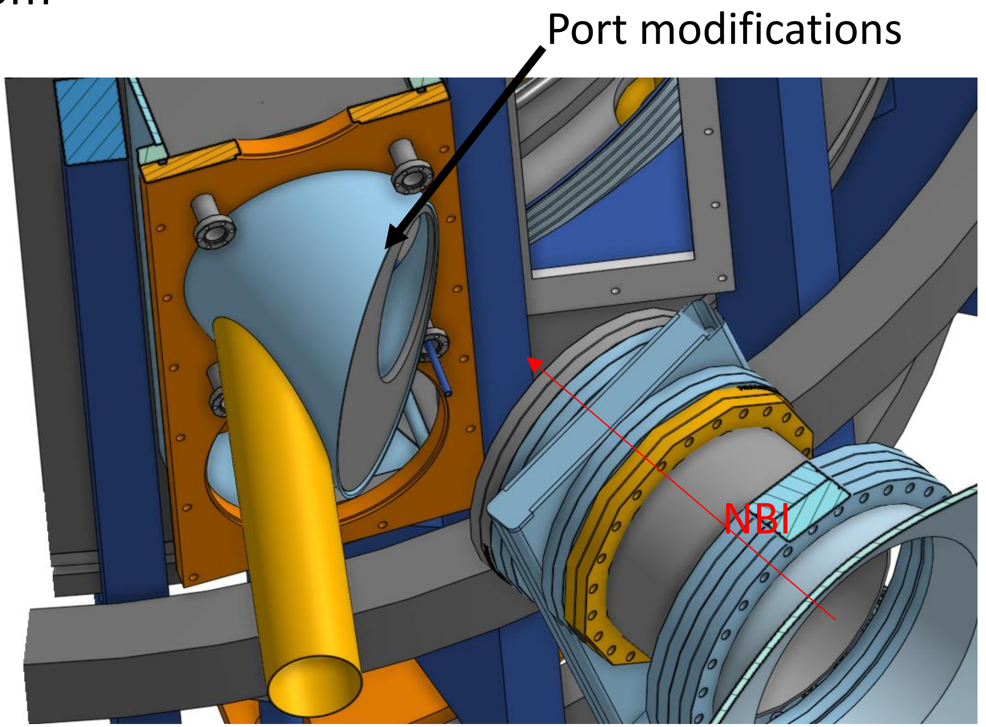
- Beam optimization in 2022
  - resulted in data consistent with CHERS
  - Energy to calorimeter consistent with original operation
- Some questions remain regarding beam geometry
  - CHERS peak fitting suggested < 0° beamlet divergence
  - Under filling of HV grid used to explain, but a direct measure of beam performance is desirable
- Wire calorimeter can give direct measure of beam footprint during discharge

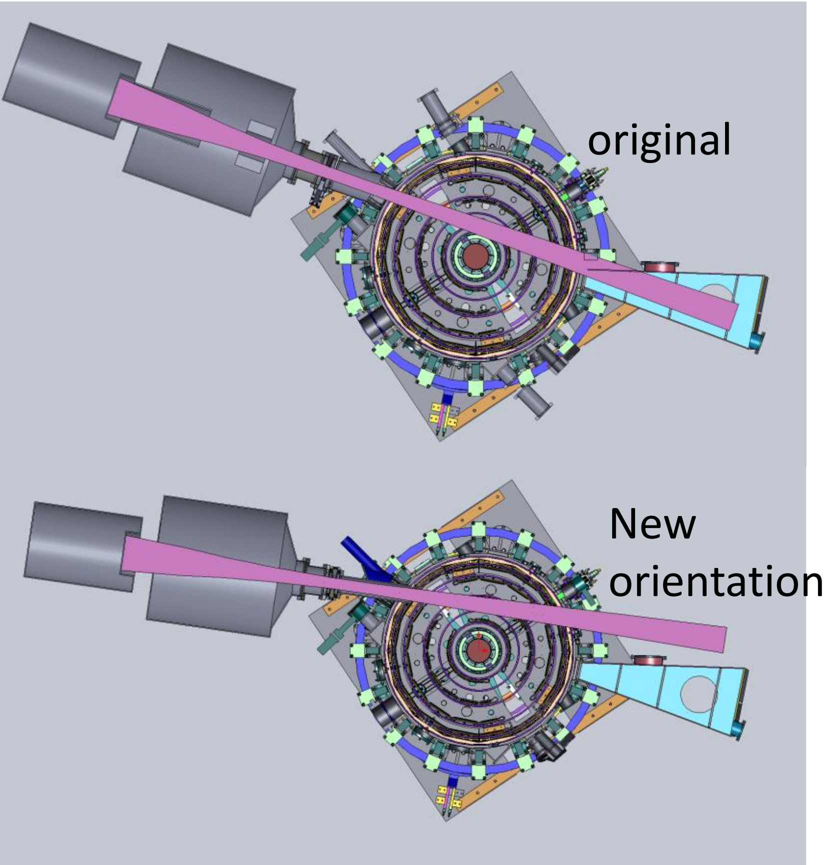


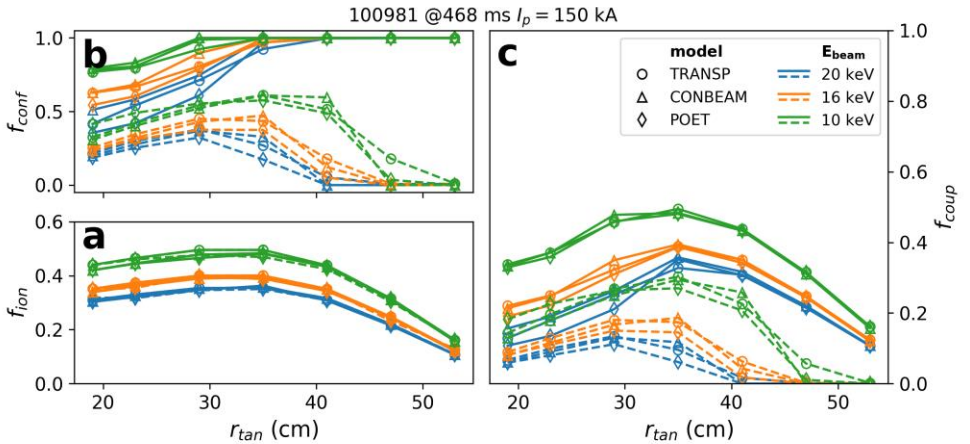


Larger tangency radius will increase coupling

- Beam is currently being re-aimed from tangency radius of 19 to 33 cm
- Port redesigned to accommodate larger beam angle
- $r_{\tan}$ near optimum predicted by models

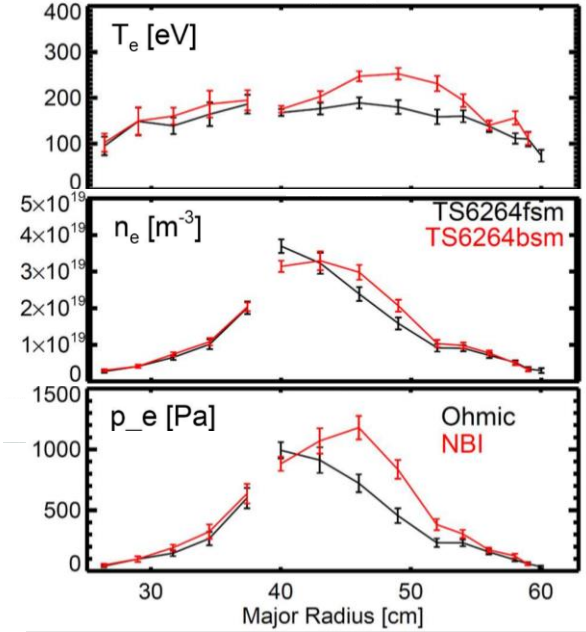


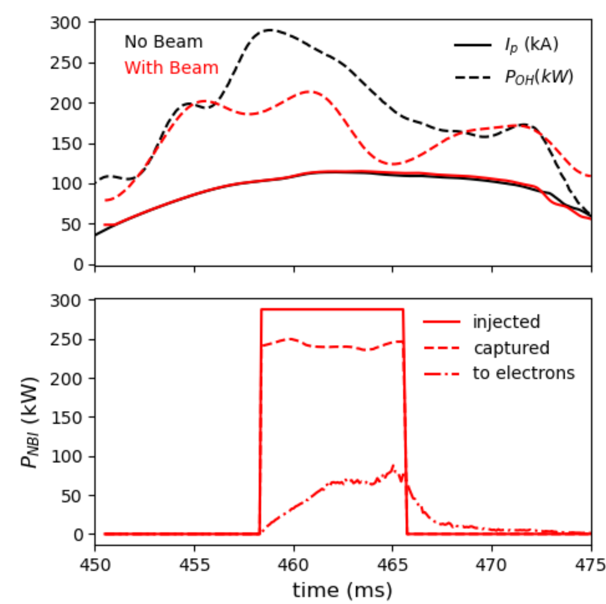


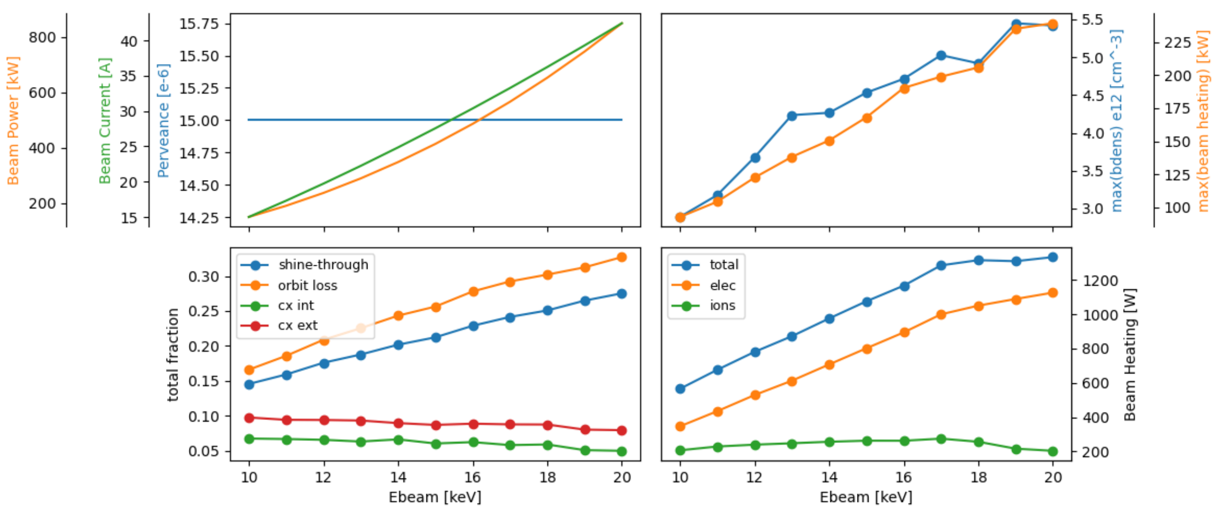


Need for neutral particle analyzer

- Experimentally good beam heating appears to be very sensitive to plasma and beam parameters
- TRANSP NUBEAM modeling predicts increasing heating over available energy range despite increasing first-orbit and shine-through losses
- NPA will provide first direct observation of fast ion population in LTX-β
    - Measurement of beam (and potentially bulk) ion energy distribution evolution
- Onsite at PPPL on loan from UW-Madison (prior install on MST)

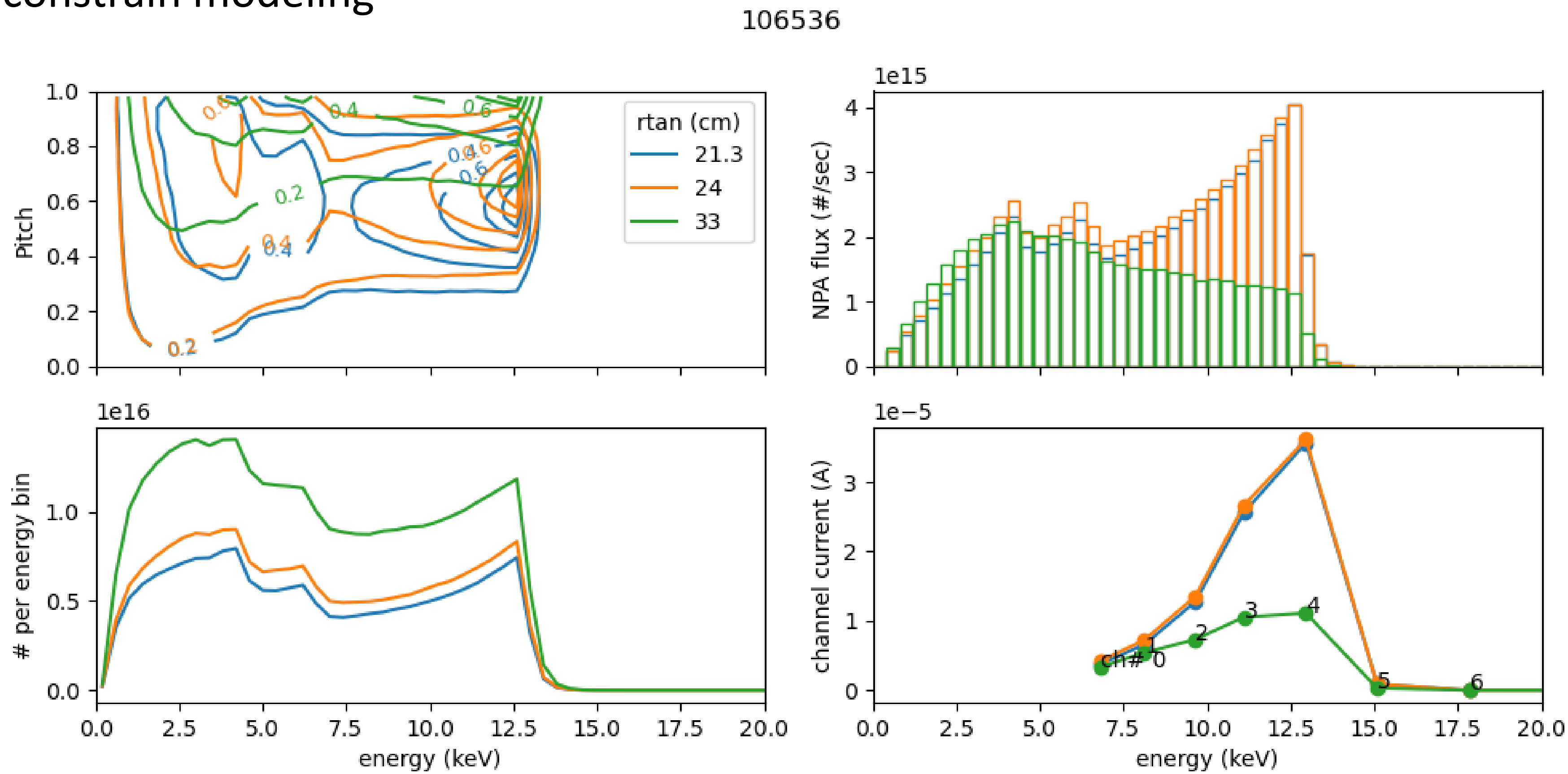






NPA signal improves at larger beam tangency

- Larger beam tangency produces higher pitch fast ion population and overall larger population due to better confinement and lower first orbit losses
- Although NPA also has viewing tangency of 33 cm in this case, predicted flux decreases due to tangency occurring outside beam neutral footprint
- Precise location, viewing geometry, and wiggle room for LTX ports will further constrain modeling

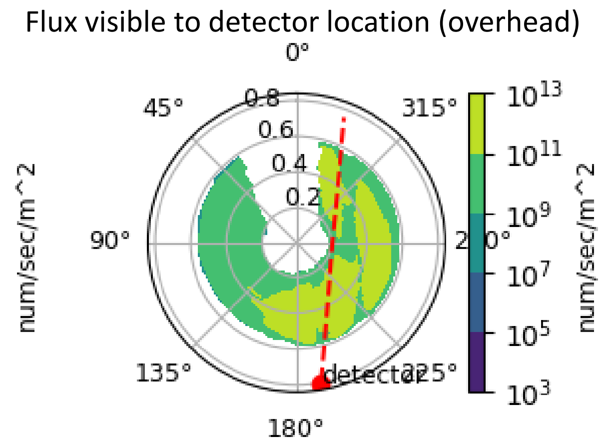


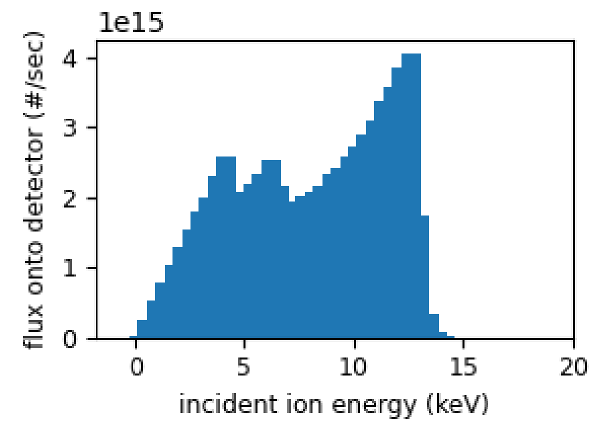
Beam neutral halo will improve NPA signal

- NPA signal relies on charge exchange with neutrals; Low neutral inventory of LTX-β plasmas (particularly in core) would lead to an edge-dominated and overall low signal levels on NPA

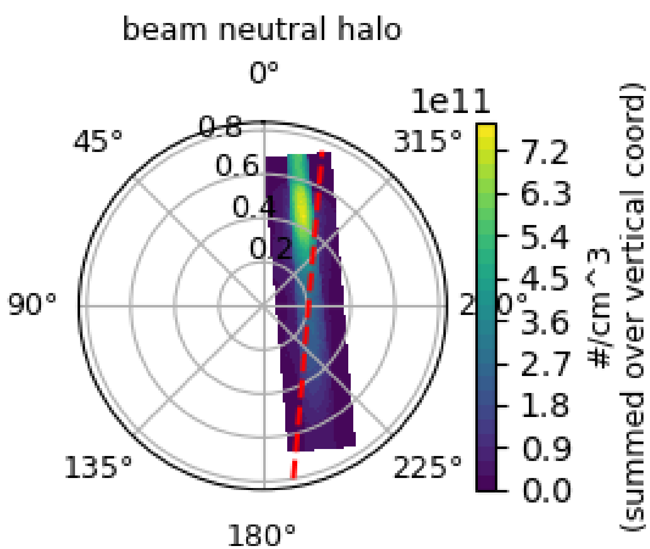
$$\Gamma_{NPA} = \int_L {\color{red} n_0} n_{fi} \langle \sigma v \rangle_{cx} \delta(\gamma - \gamma_c)(1 - f_r) dl$$

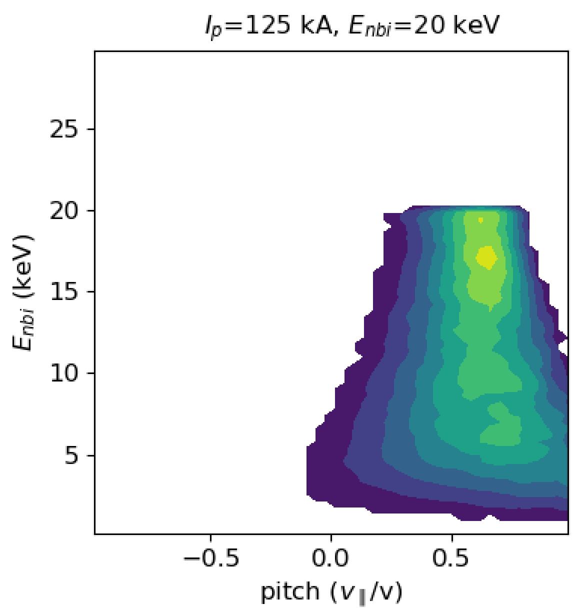
- By utilizing the neutral halo created by NBI, NPA signal increases and becomes more sensitive to fast ion population in the core





Modeling of predicted flux to NPA





TRANSP NUBEAM modeling of 3D neutral halo and fast ion distribution

NPA refurbishment

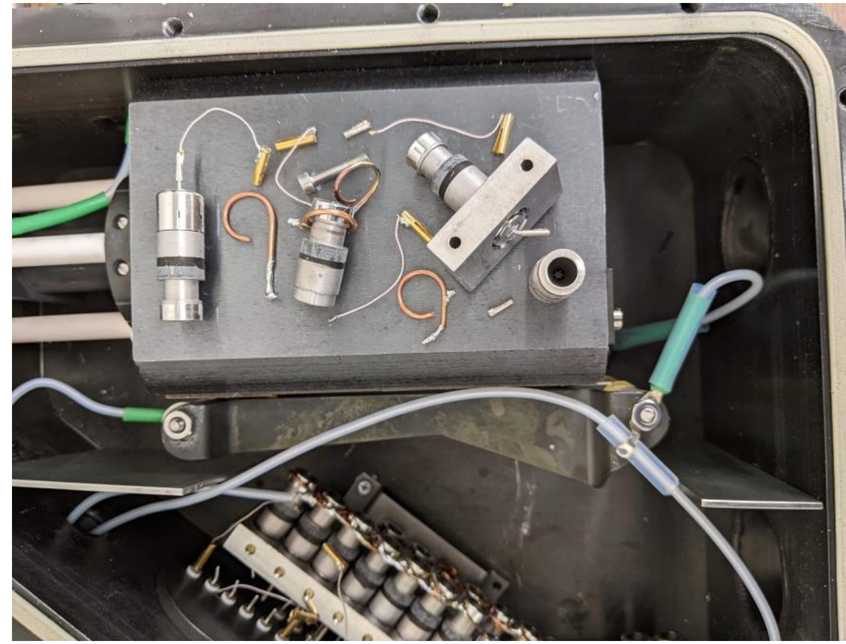
Much work needed in transition from use on MST to LTX-β

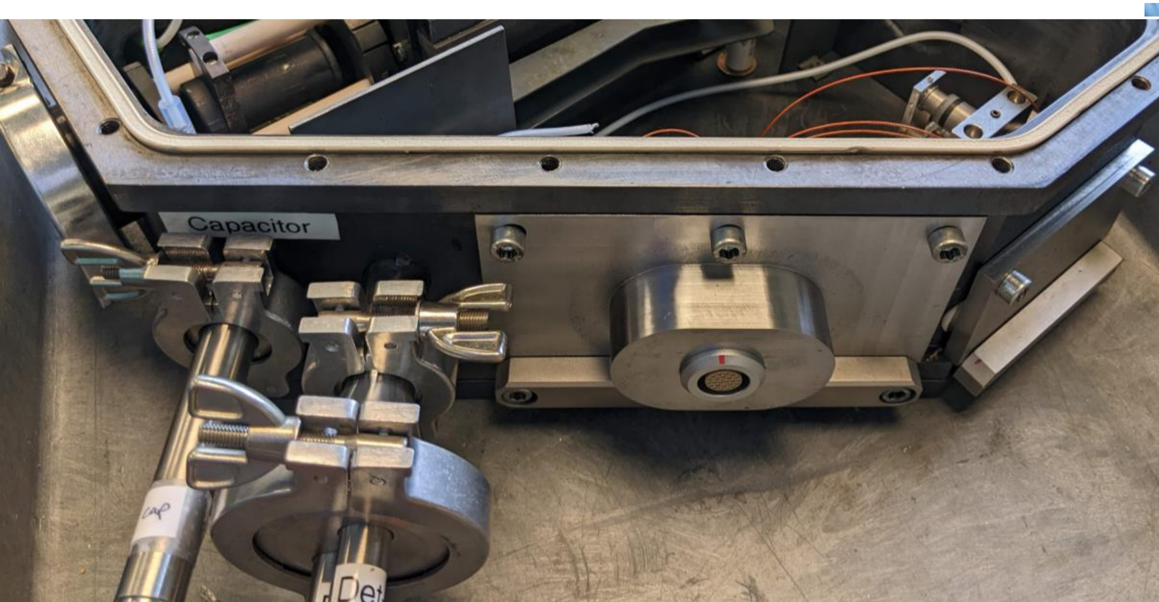
- NPA Repairs:
  - NPA damaged by years of wear and tear on MST
  - Significant damage in transit- broken/loose connections
- Power Supply:
  - Many disconnected wires and messy wiring due to iterations of improvements or alterations
  - Needs significant cleanup to be cleared for operation on LTX-β

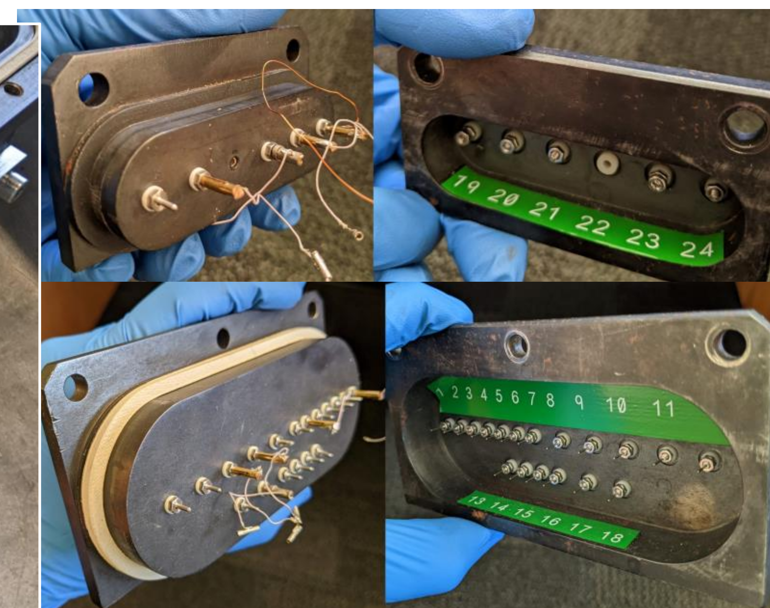
- Status:
  - Repairs have been completed, NPA is being vacuum prepped and will be calibrated soon before being installed on LTX-β
  - Power supply reconfiguration is nearly complete. Pending approval by electrical safety, ready to install alongside NPA

NPA Repairs

- Broken feedthrough pins: Redesigned 6-pin and 18-pin panels for single 24-pin LEMO connector
- Replaced internal wiring due to damage in transit



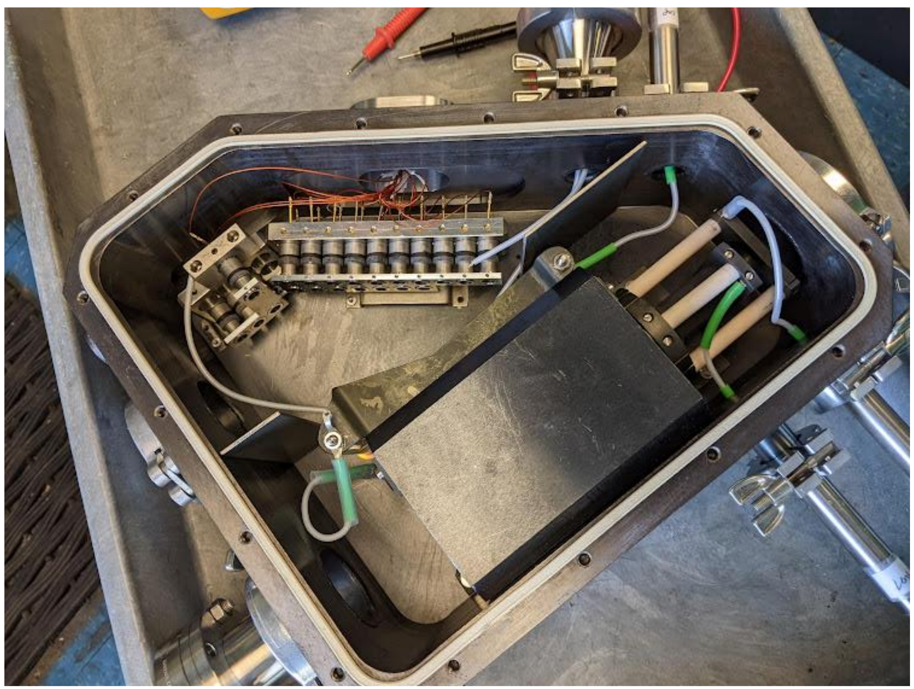


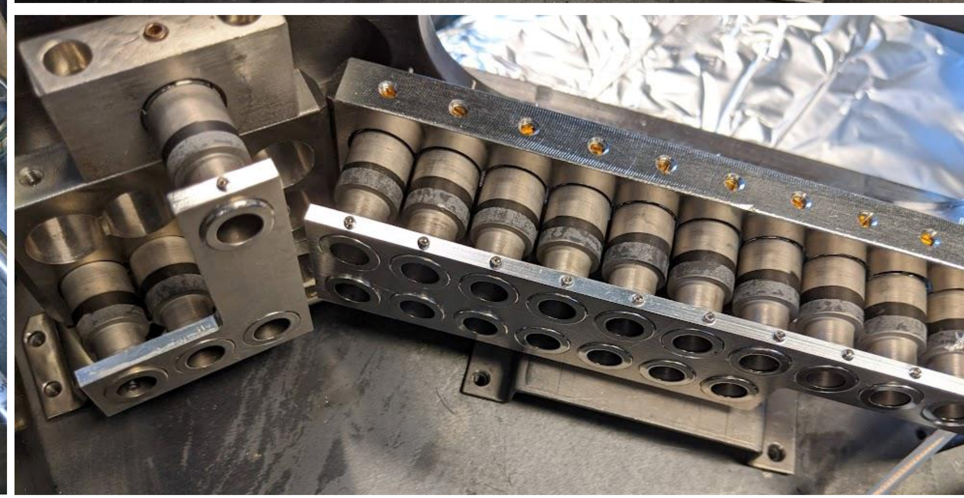


NPA Repairs cont.

- Channeltron arrays given new high voltage panels, removing the majority of in-vacuum soldering and points of failure
- NPA disassembled, cleaned, reassembled
  - Leak check and calibration underway
  - Install during vent

Old connections damaged in transit

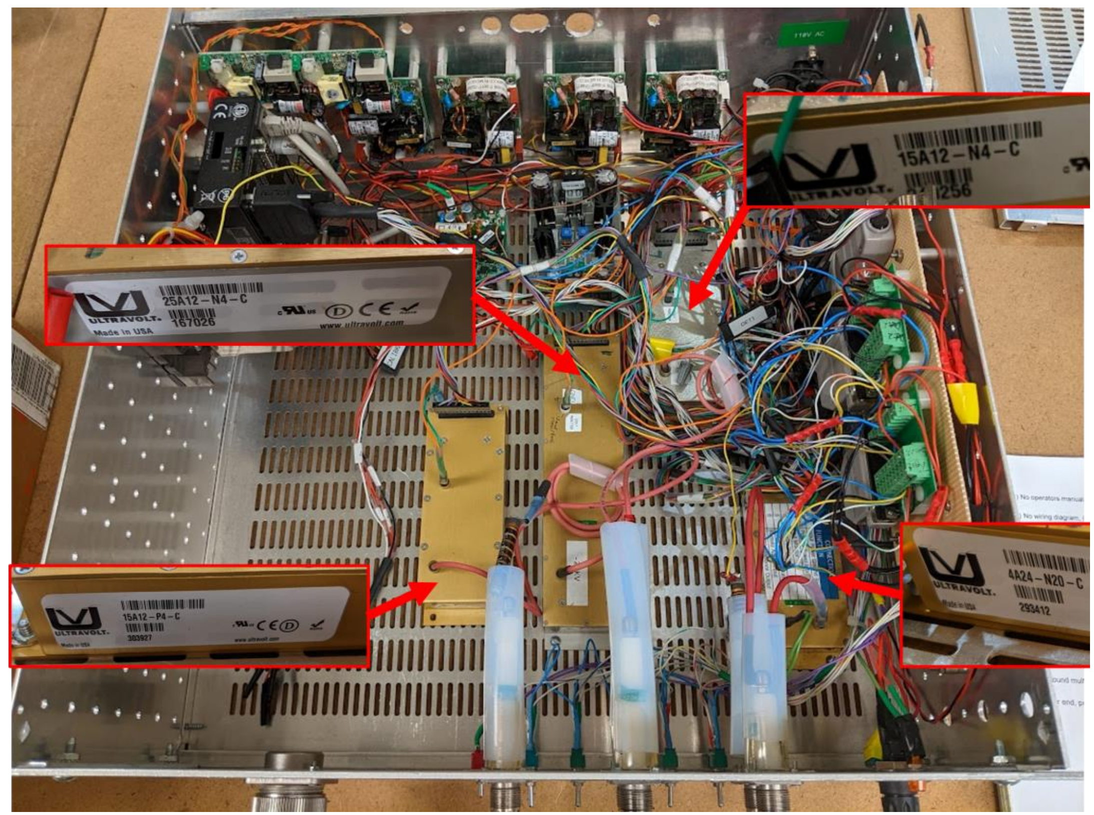




NPA Power Supply

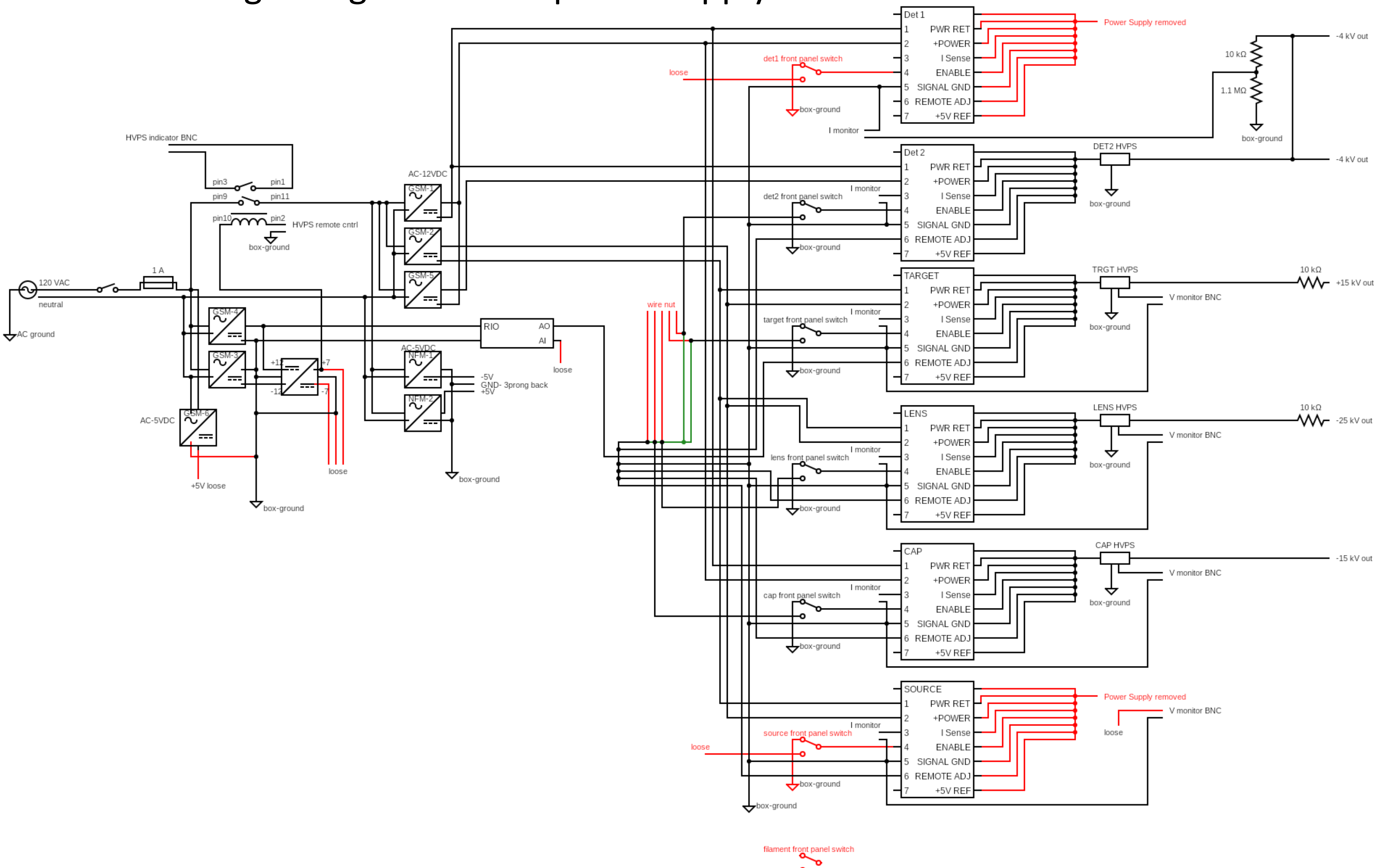
- Major repairs and modifications have been necessary for electrical safety operation of high voltage power supply, to include:
  - Removal of unused power supplies and connecting wiring
  - Clean up and organization of wiring
  - Removal of unused switches
  - Re-cabling of RIO output
  - Covering holes in supply box

Testing and install is expected within next two months

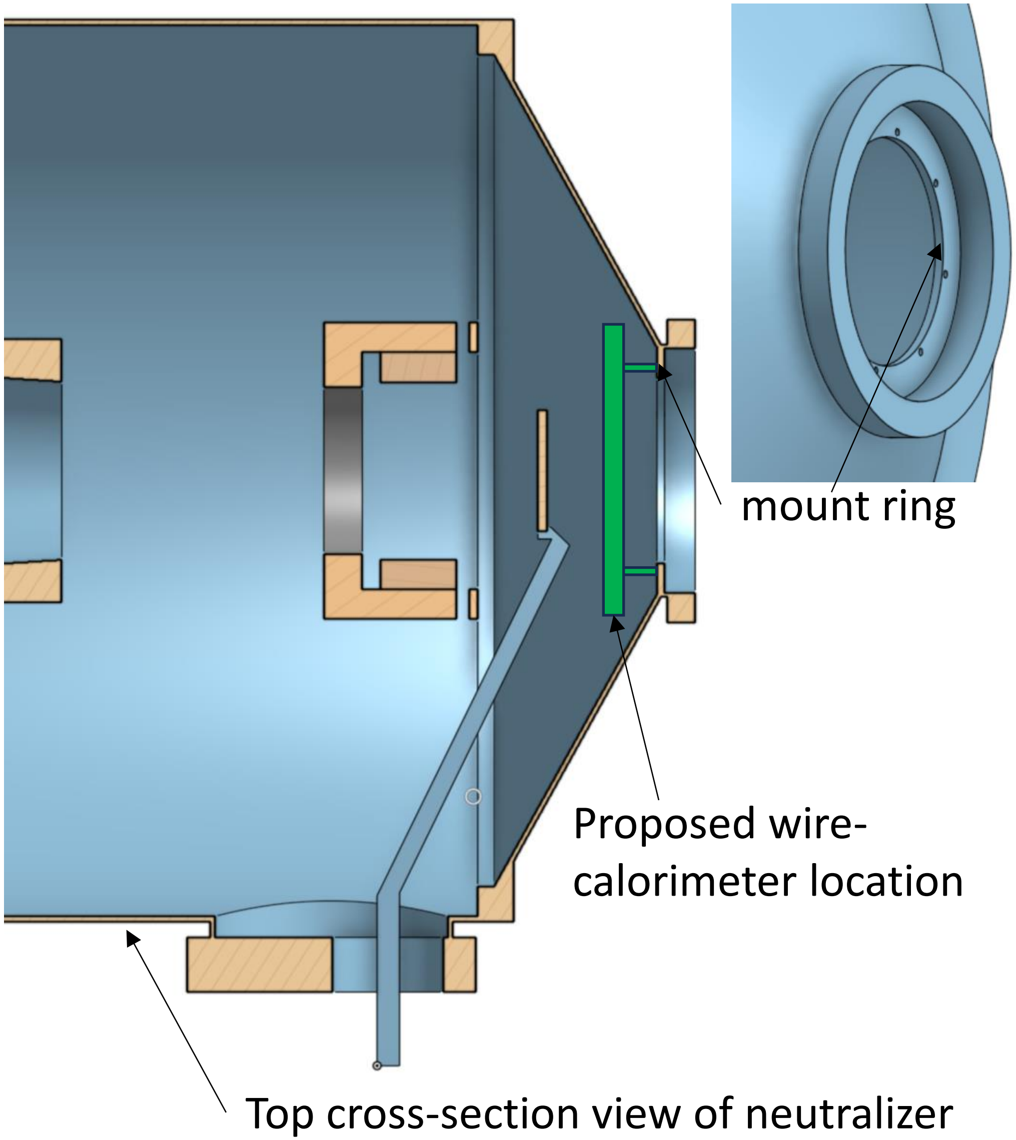


NPA Power Supply

- CWD tracking changes made to power supply



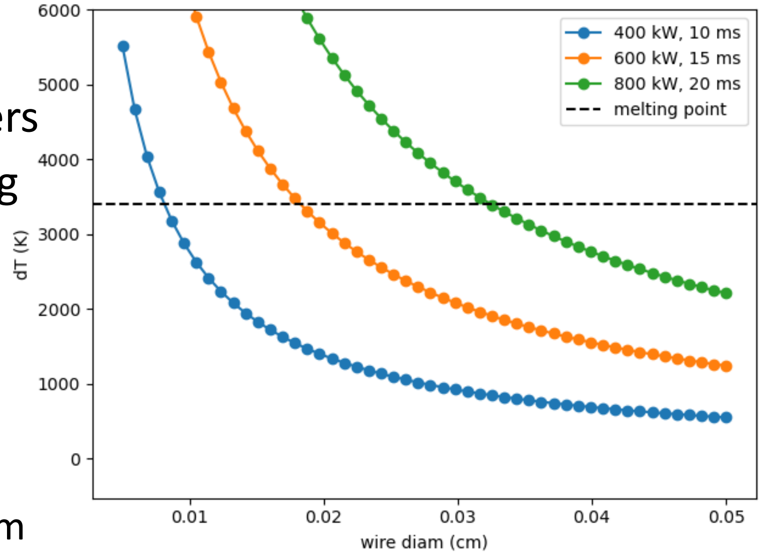
2D wire-calorimeter



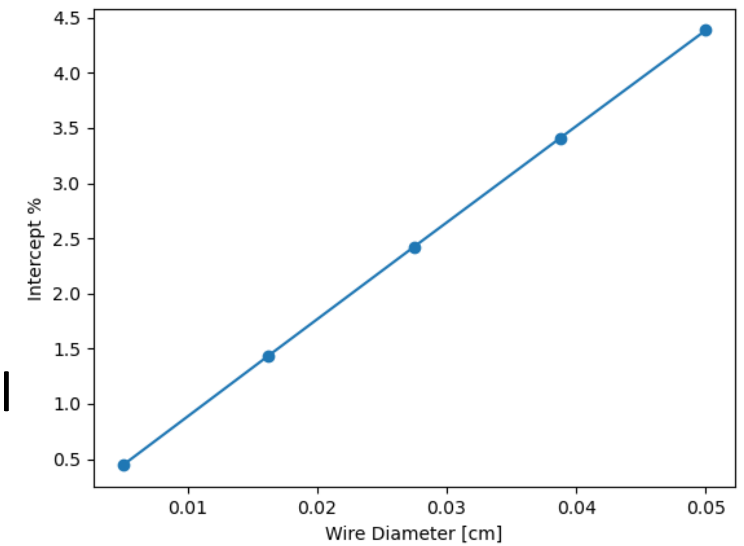
- Space along beamline into vessel extremely limited, plan to mount just inside neutralizer
- Conveniently unused mount ring, no modifications to tank are necessary
- Wiring through 4” port at tank bottom (not shown)
- Many positives:
  - Naturally beam-normal
  - Doesn’t require machine vent to access
- Potential drawbacks
  - Residual ion fraction could cause vertical asymmetry (but easy to determine and account for)

Wire diameter, spacing, number

- Wire diameter
  - Temperature rise depends on beam parameters
  - Plot peak temp rise vs wire diameter assuming no thermal transmission
  - Suggest 0.025cm diameter wire
    - Away from sharp rise in dT at small diameter
    - Not unnecessarily large (minimize beam blockage)
    - Larger wire diameter may be necessary if beam power/pulse length increase sufficiently



- Spacing and number
  - Plots show 0.75” spacing of 8x8 wire grid and assumes 8 cm FWHM beam profile
  - This reaches out to ~15% peak beam power contour
  - Intercepts ~2.5% of beam
- COMSOL modeling shows various thermal timescales

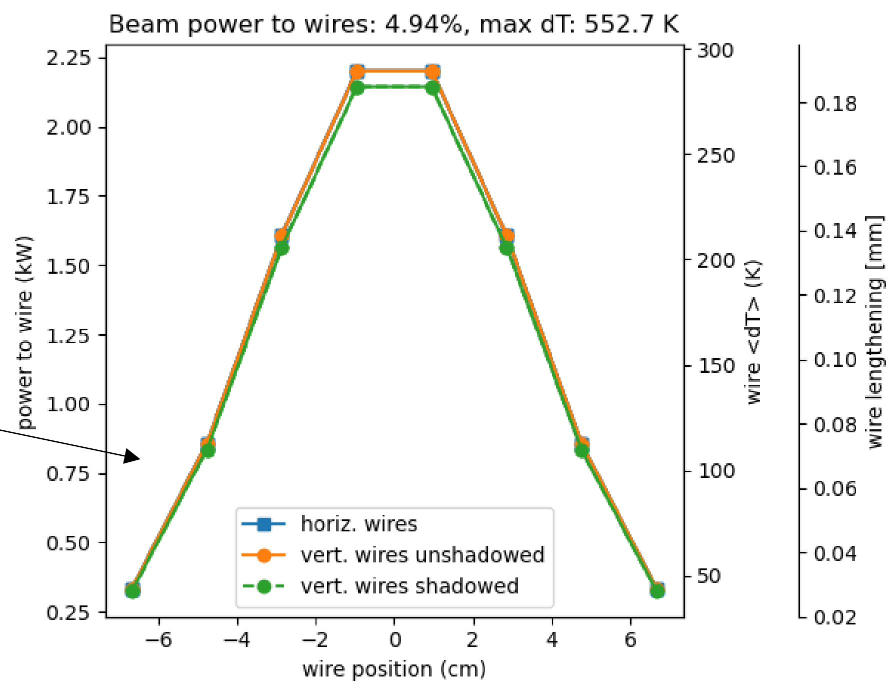


.75” wire spacing, 8x8 wire grid

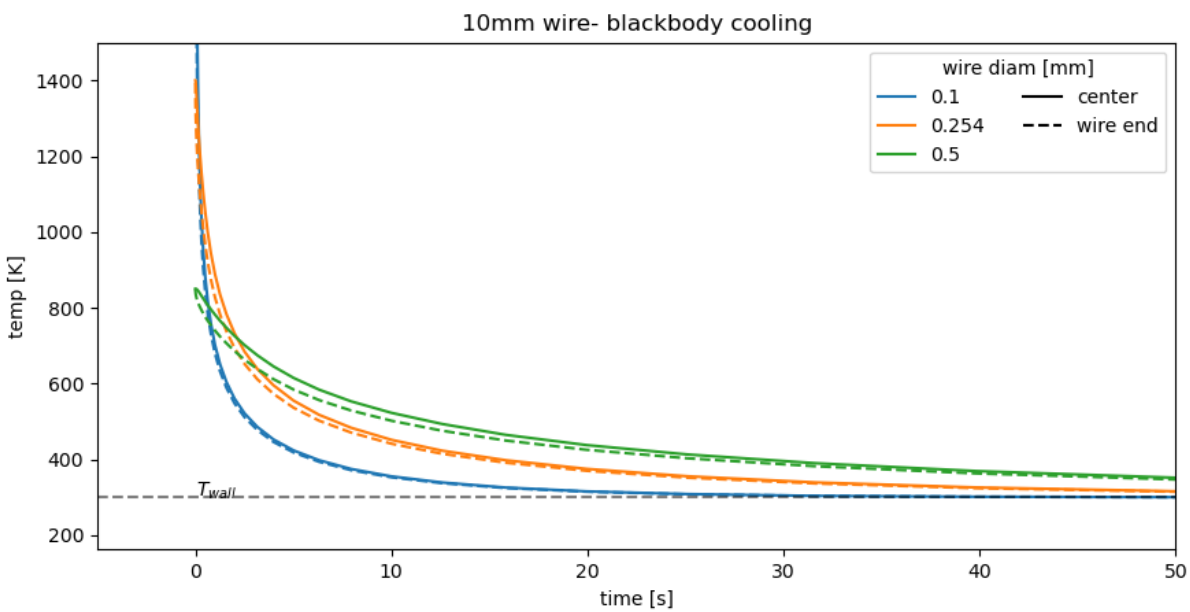
Cooling via blackbody

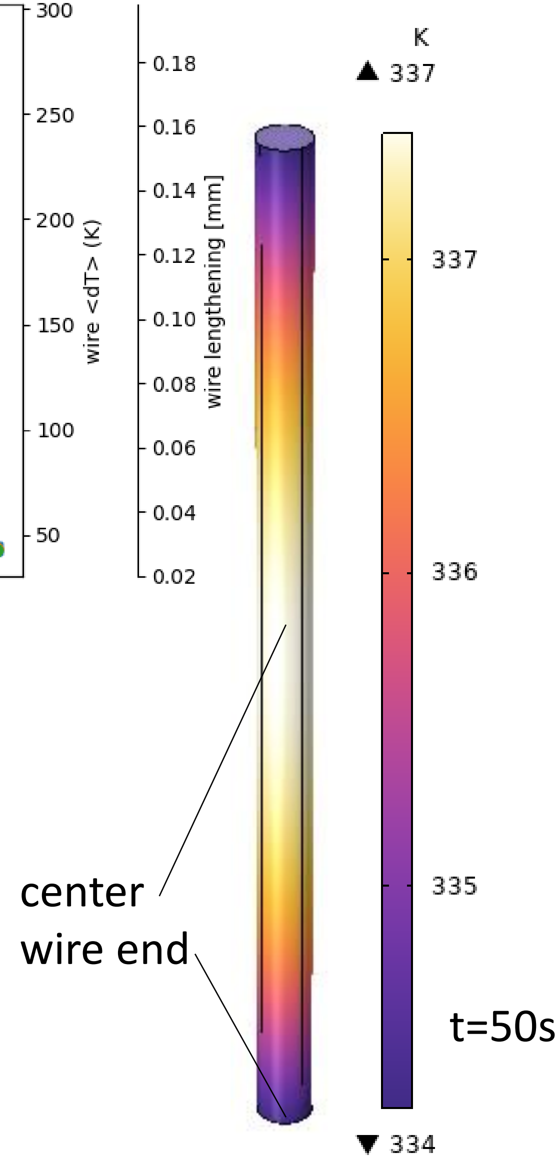
- Initial temperature using present beam parameters vs wire diameter:

Wire diam [mm]	Max dT [K]
.1	2750
.254	1100
.5	550



- Wires cool to wall temp on timescale of ~1 minute (won't limit shot cycle)





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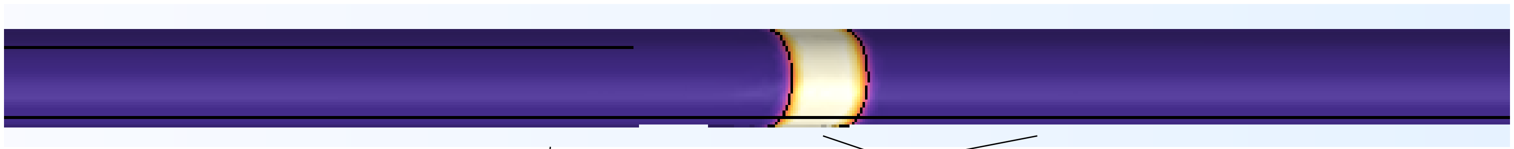
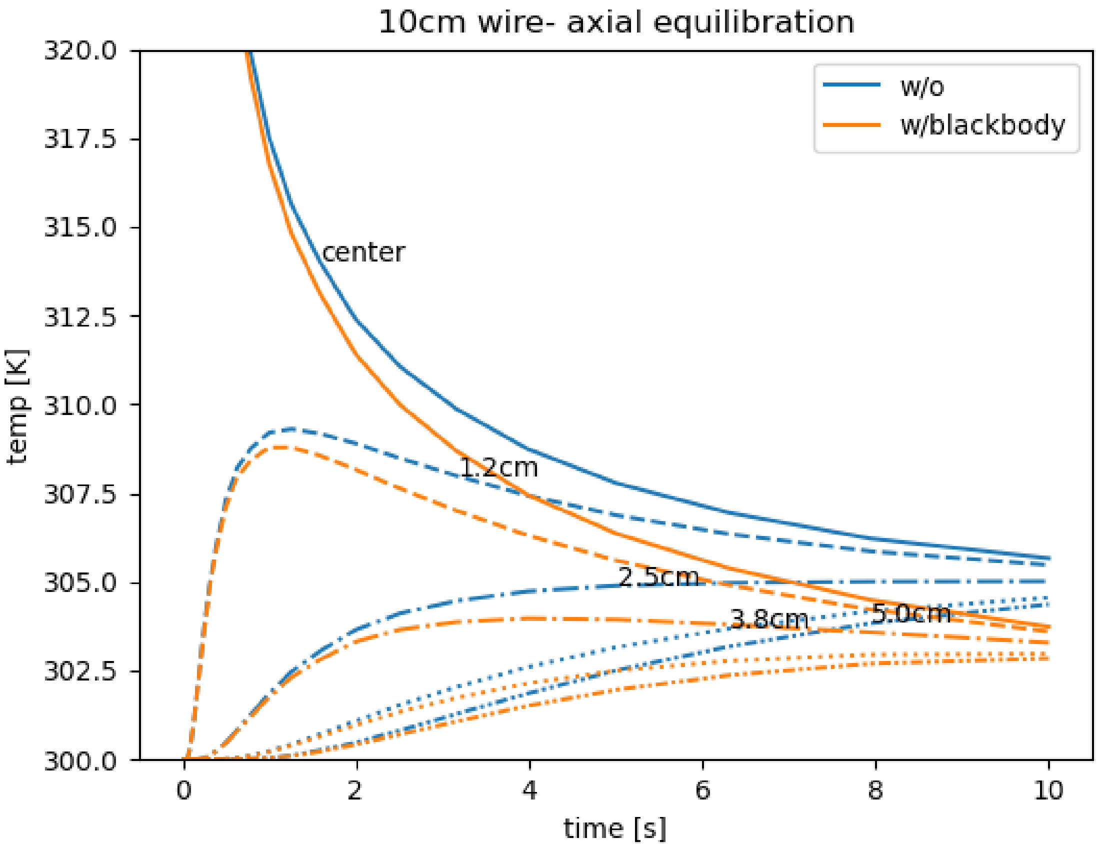
Axial equilibration

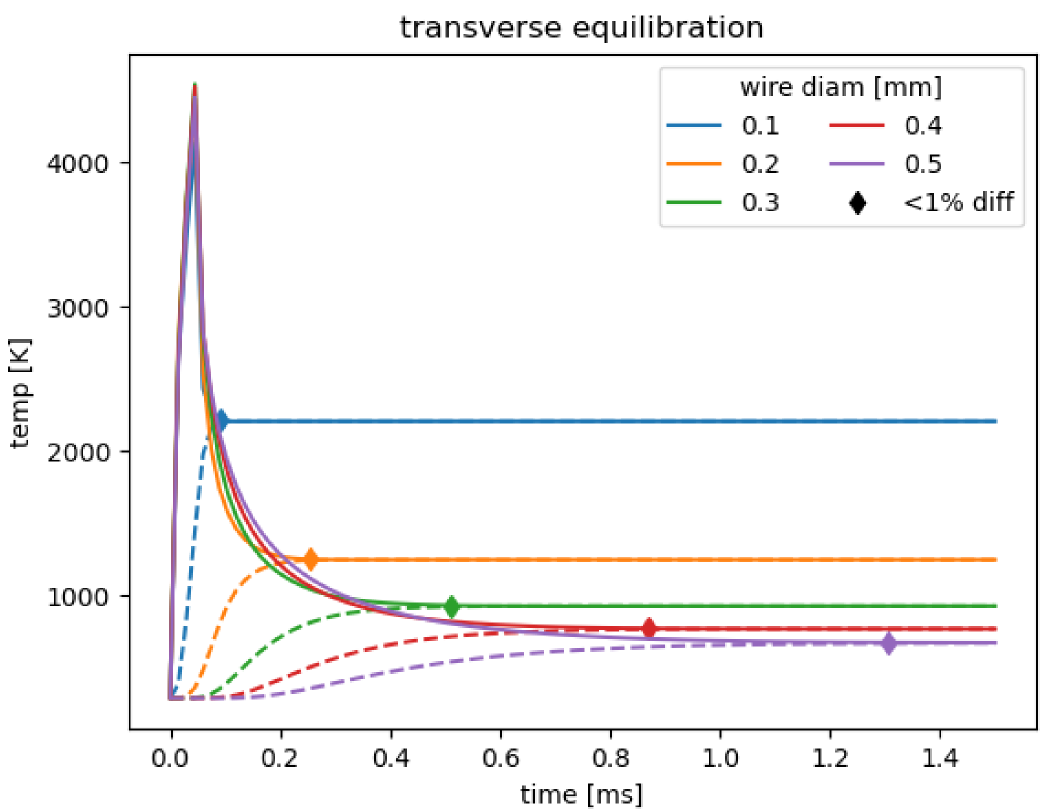


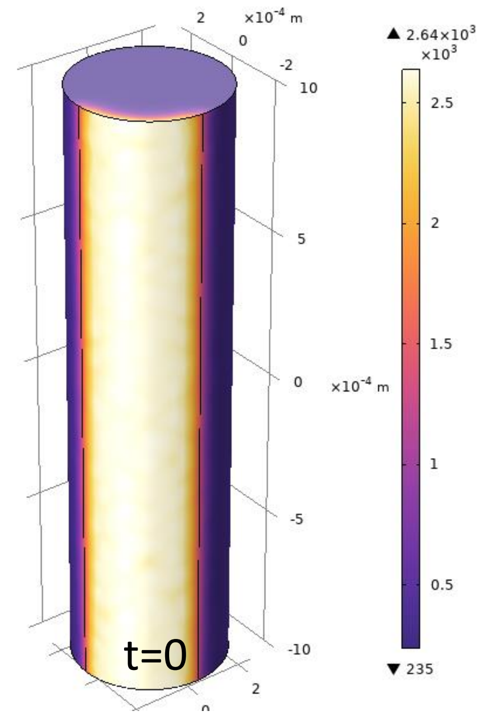


- Very hot central "wafer" started with Twall + 1000 deg allowed to equilibrate into 10 cm wire
- Including blackbody lowers wire temp, but only a few degrees after 10s
- Equilibrating back to Twall (=300deg here) instead of equal temperature along wire
- Equilibrates on timescale of seconds

Transverse equilibration

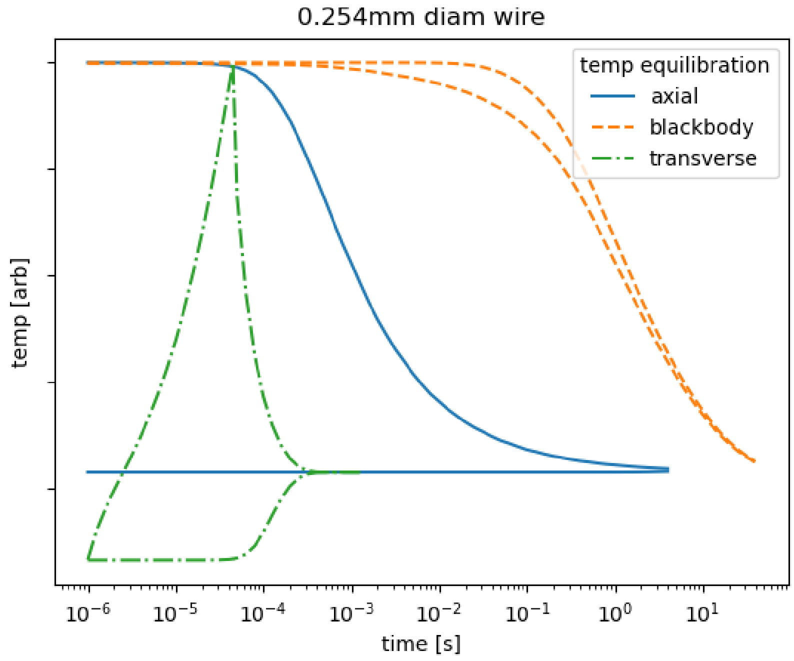
- Surface heating applied to one quadrant of wire for first few frames of simulation
- After heating turns off wire allowed to equilibrate, temp measured on front/back surface
- Equilibrates on timescale of milliseconds

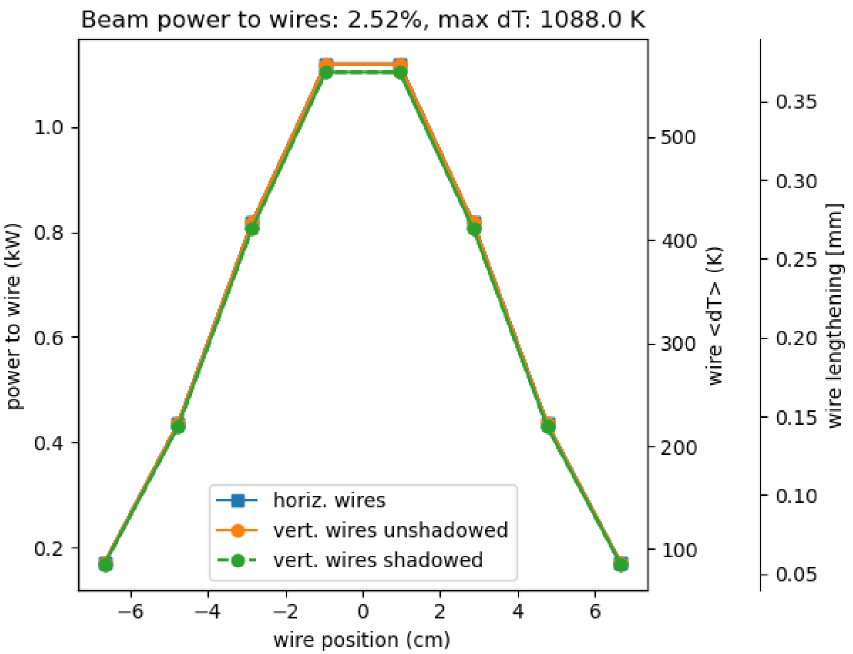




.254 mm wire analysis

- Max dT to wire center ~1000 deg
- Transverse heating timescale negligible (< 1ms including heating phase)
- Axial (10 cm wire here) nearly accomplished after 0.1 s before blackbody does much of anything
- Takeaway: timescales very separable





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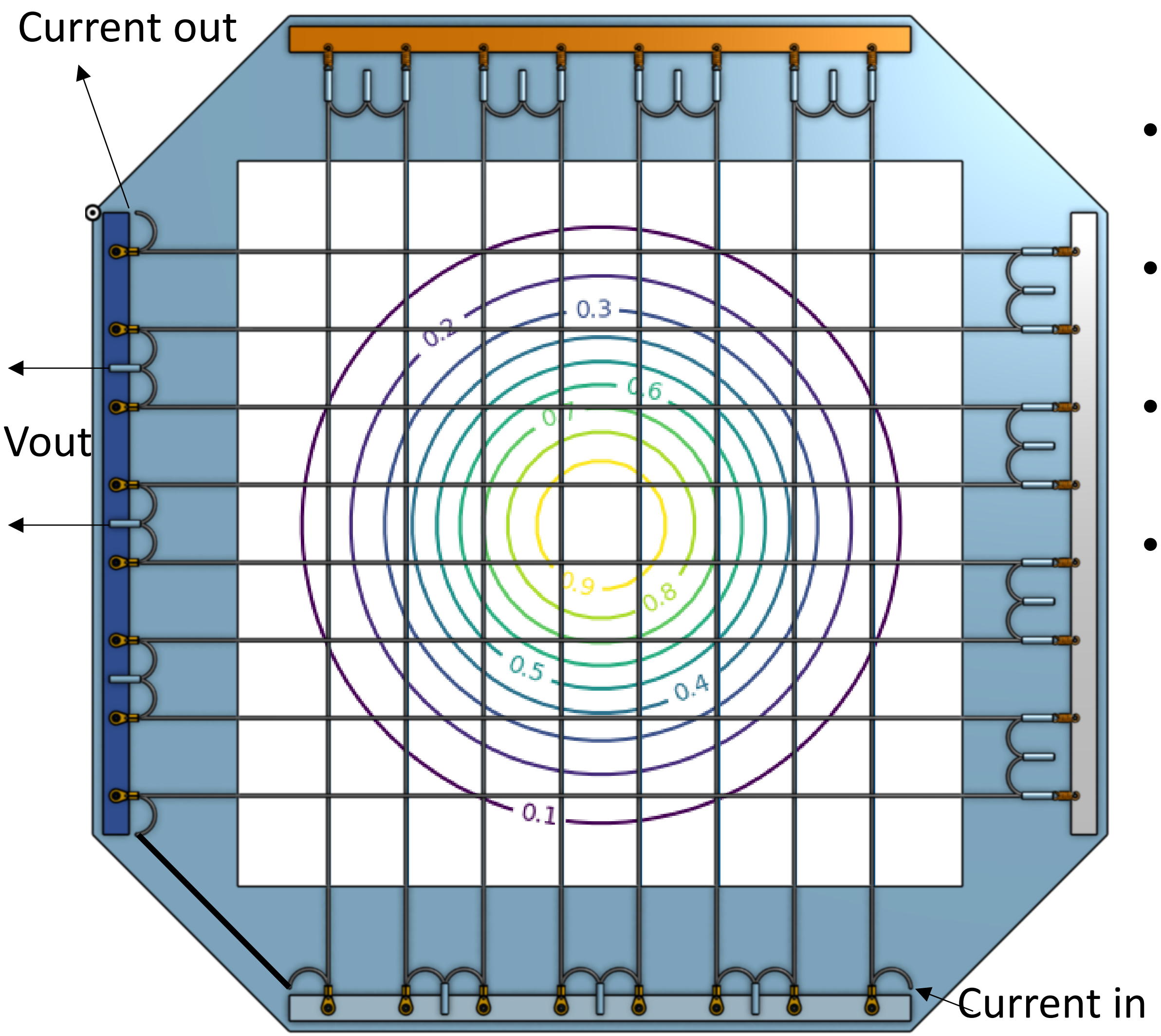
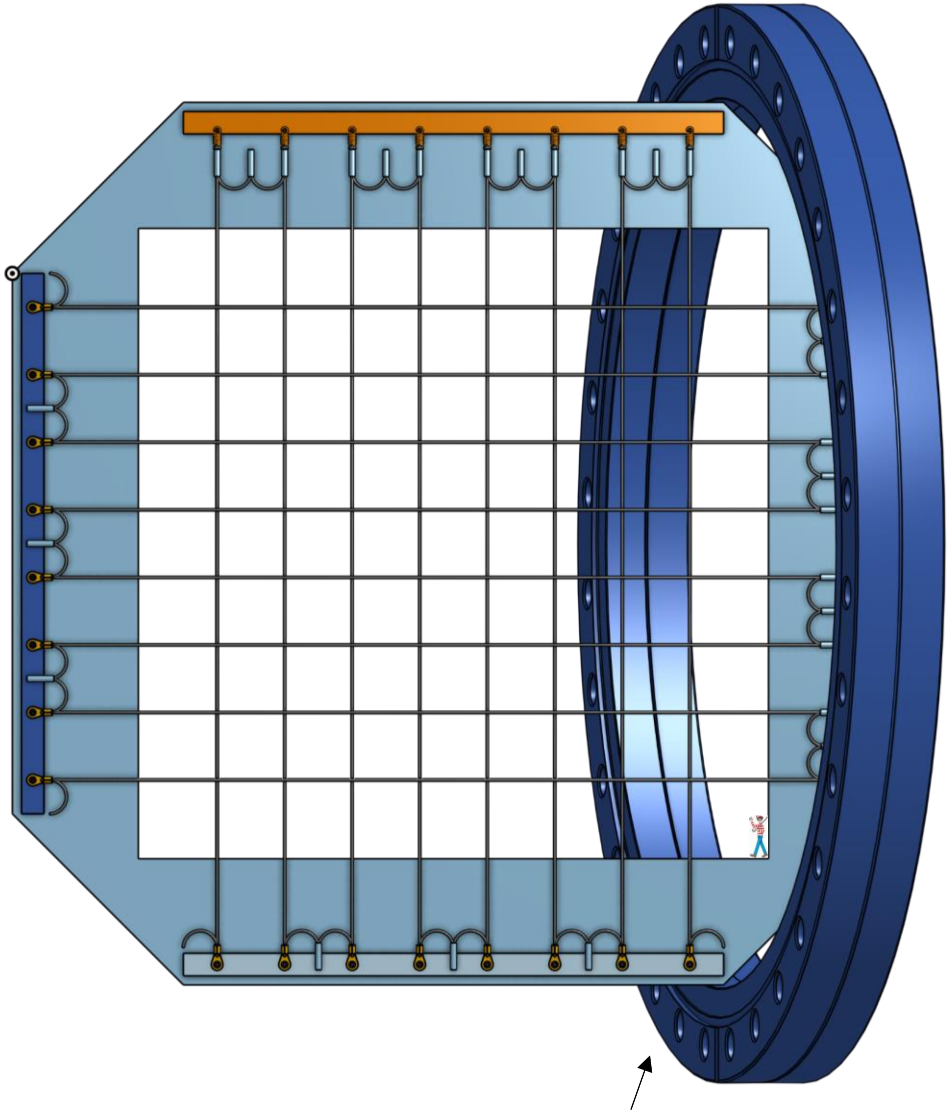
Wire-calorimeter design



- Spring tensioned on top and right
- Crimp connections for springs, ring terminals, Vout
- Small enough to fit through 12” conflat bore
- Modular build using individual wire segments crimped together
  - Easier repair
  - A relaxed connection between adjacent wires puts spring tension in alignment with wire

Wire-calorimeter status

- Next Steps:
  - Verify spring choice provides sufficient tension
  - Test build prototype
  - Power supply and digitization test on MST (dummy triggers)
  - Disassemble, transport to PPPL
- Install planned for January '24



12" conflat