# High Heat Flux Testing of Castellated Graphite Plasma Facing Components

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APS-DPP
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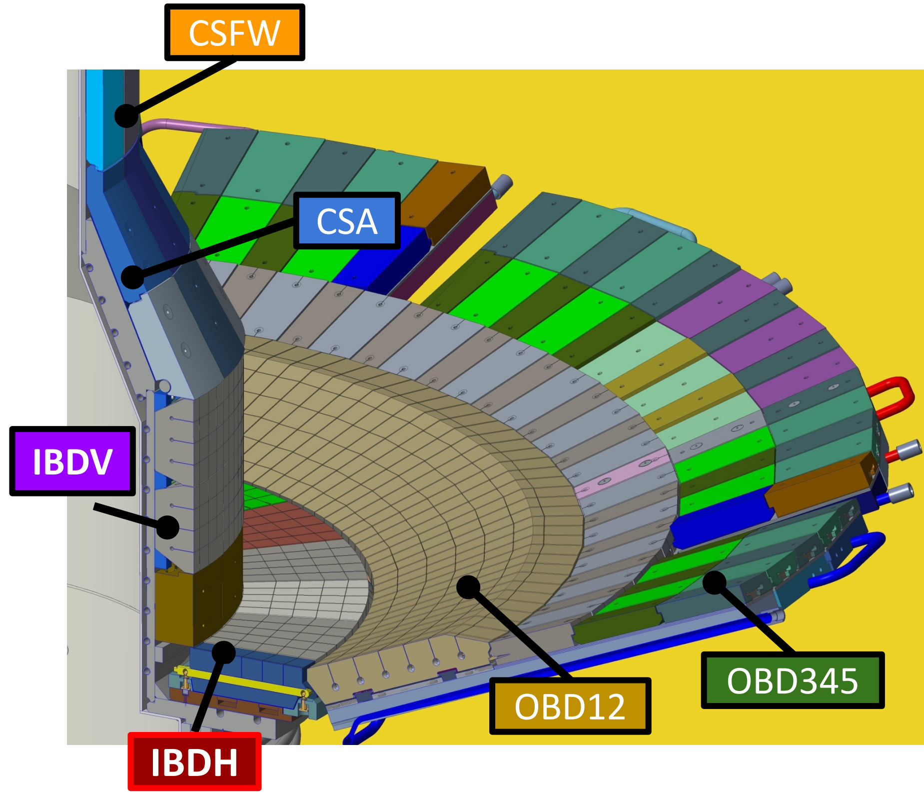
# NSTX-U PFC tiles were re-designed to accommodate increased thermal loads

- Upgrade results in increased heat flux as well as halo loads on PFCs
- Tiles are designed to be <u>temperature limited</u> rather than <u>stress limited</u>
  - Will use graphite PFCs to minimize risk to research program
- Resulted in a castellated PFC tile design
  - Relieves internal stress
  - Increases tolerable heat fluxes above older PFC designs





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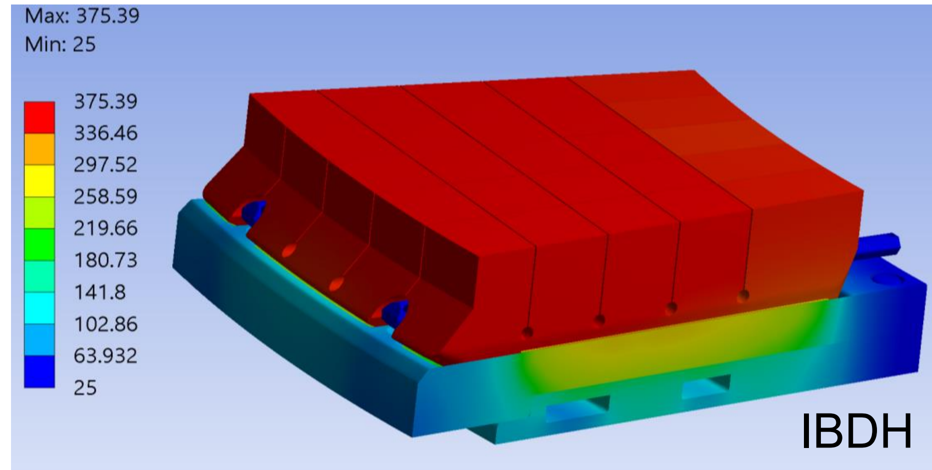
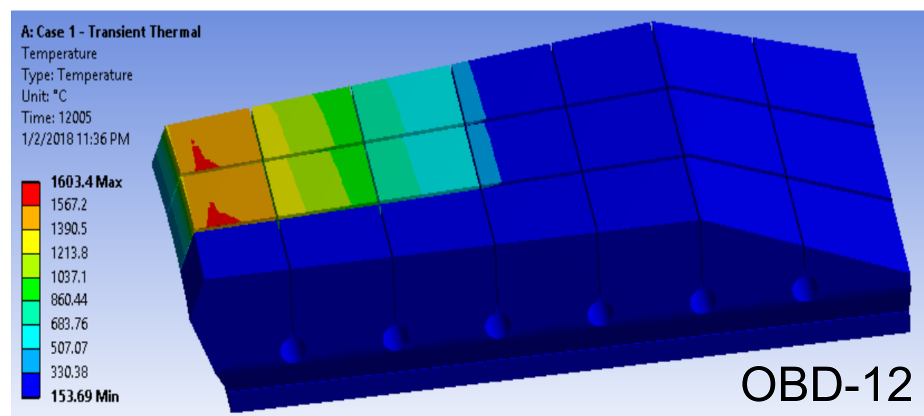
# Castellated PFC tile designs have been extensively analyzed using ANSYS

- Models were generated to evaluate new heat flux requirements
  - Iterative process with physics requirements/research program




- Original analysis assumed uniform heat flux on the surface

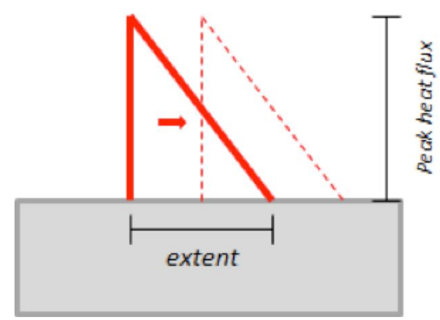
- Further refinement lead to the application of heat flux patterns indicative of a strike point



# Overview of PFC Heat Flux Requirements

- Complete listing of thermal requirements for all PFC regions is specified in NSTX-U Requirements document
- In general, PFC tiles will be limited to:
  - $T_{surf,\ peak}$ < 1600 °C at end of 5 sec pulse
  - No leading edges are allowed for forward helicity cases
    - Led to the addition of a 1° fish scale
  - For reverse helicity, tiles shall be designed so that local $T_{surf}$ < 2000 °C

| **IBDH** | **Case # ->** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|
| **Range of Application** | m | 0.47 < R < 0.6 | | R < 0.6 | R < 0.47 |
| **Extent** | cm | 15 | full | full | full |
| **Max Angle** | degrees | 1.0 | 5.0 | -1 | 4.0 |
| **Min Angle** | degrees | 1.0 | 5.0 | -5 | 1.0 |
| **Heat Flux** | $MW/m^2$ | 6.5 | 5.4 | 1 | 3.5 |
| **Duration** | sec | 1.5 | 5 | 1 | 5 |
| **Reference Scenario** | --- | Stationary High Ip/Bt w/ large poloidal flux expansion | High Ip/Bt Long Pulse Swept Case | Reversed Helicity Requirement | Spill Over From HHF Regions |



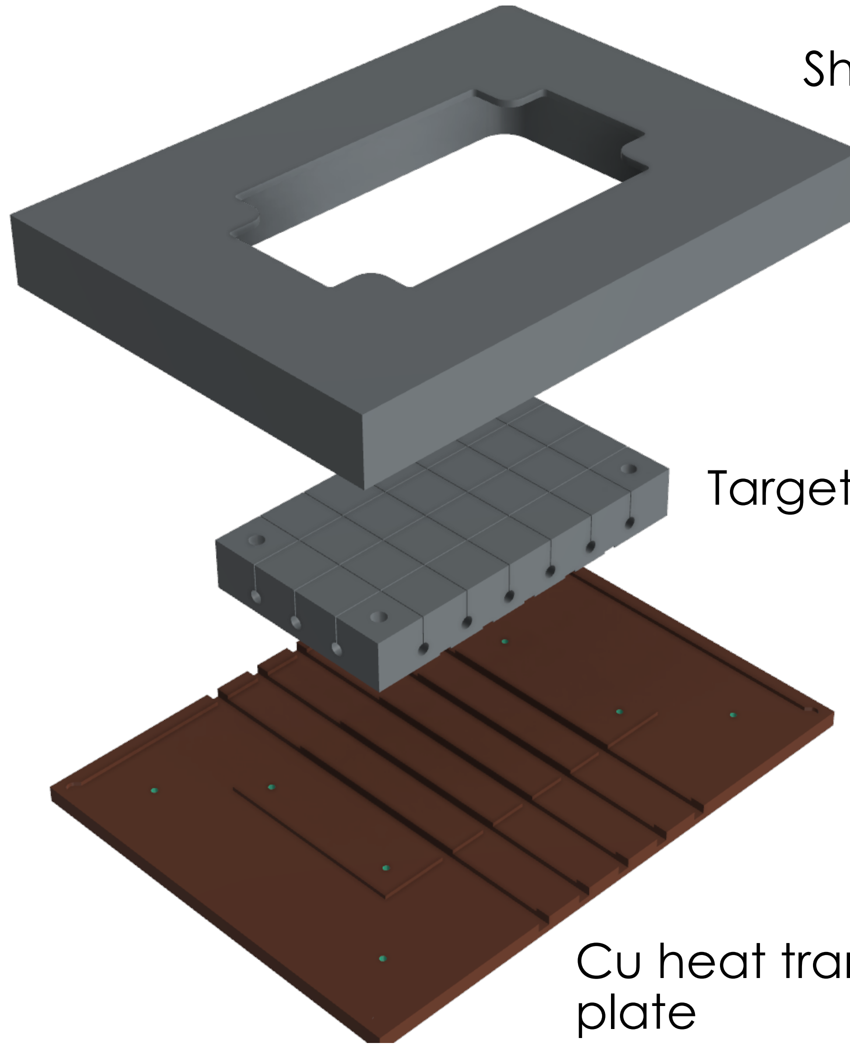
# Castellated Target Assembly was designed to evaluate high heat flux testing facility

- Designed to:
  - Mimic castellated geometry of NSTX-U Recovery PFC tiles
  - Machined out of POCO graphite

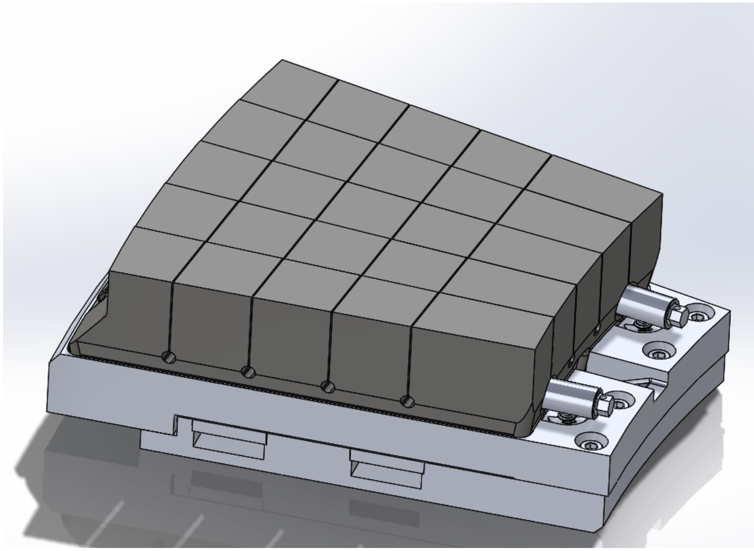
- However this castellation target was not designed to with stand high heat fluxes

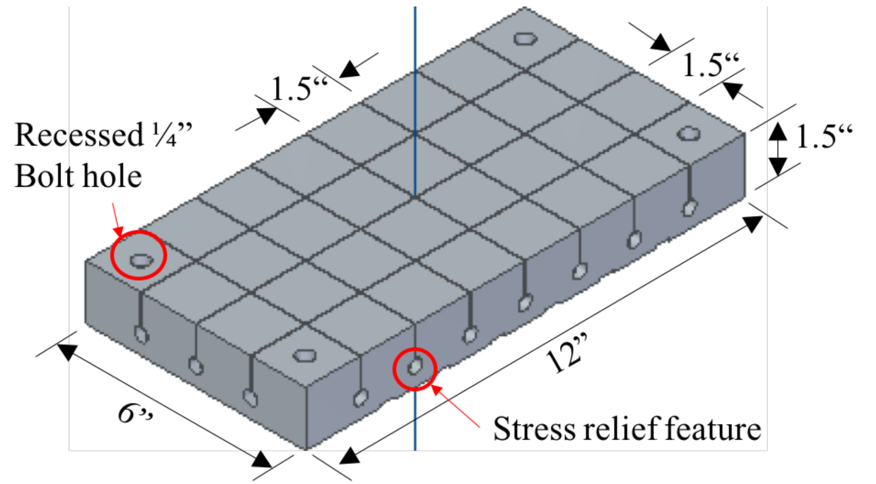
- Needed to evaluate whether heat flux could be quantified in the Electron Beam (EB) facility

Exploded CAD rendering of Castellated Target Assembly



# Comparison of IBDH prototype tile and castellated target tested






| IBDH Prototype Tile Design | |
|---|---|
| Castellation Area | 1" x 1" |
| Castellation Depth | 1.25" |
| Material | SGL R6510 |

- Rail and pin mounting scheme for each tile
- Grafoil used between tile and mounting plate

| Castellated Target | |
|---|---|
| Castellation Area | 1.5" x 1.5" |
| Castellation Depth | 0.875" |
| Material | POCO |

- Simple 4-corner bolt restraining target
- Grafoil used between tile and Cu mounting plate

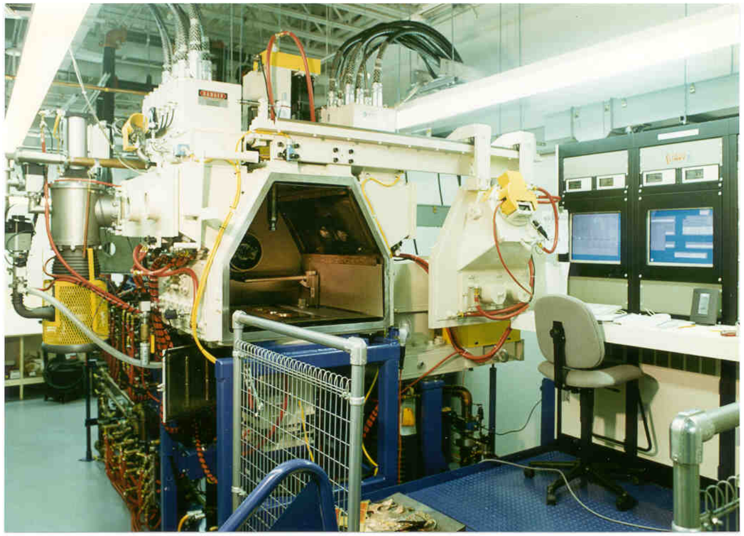
# Electron Beam (EB) Facility at ARL is primarily used for Physical Vapor Deposition (PVD) of thin-films

- Uses multiple electron beams to:
  - Vaporize materials
  - Maintain temperature of deposition substrate
  - 6 gun ports, 4 routinely used
  - Limited to 10 Hz raster rate

- For High Heat Flux (HHF) testing,
  - Used a single electron beam @ 17 kV
  - Impingement angle of 47° on target

- Addition of a "new" raster controller allowed deposition of strike-point-like heat flux deposition patterns
  - Using the raster controller from the EB60 system formerly at Sandia NL

EB  Facility @ ARL

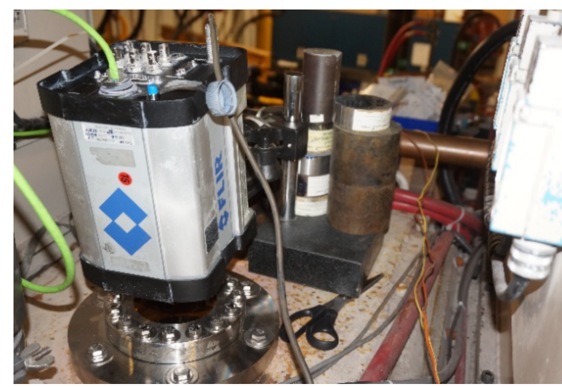


Castellated target installed in EB Facility

# Additional Instrumentation Installed on EB Facility

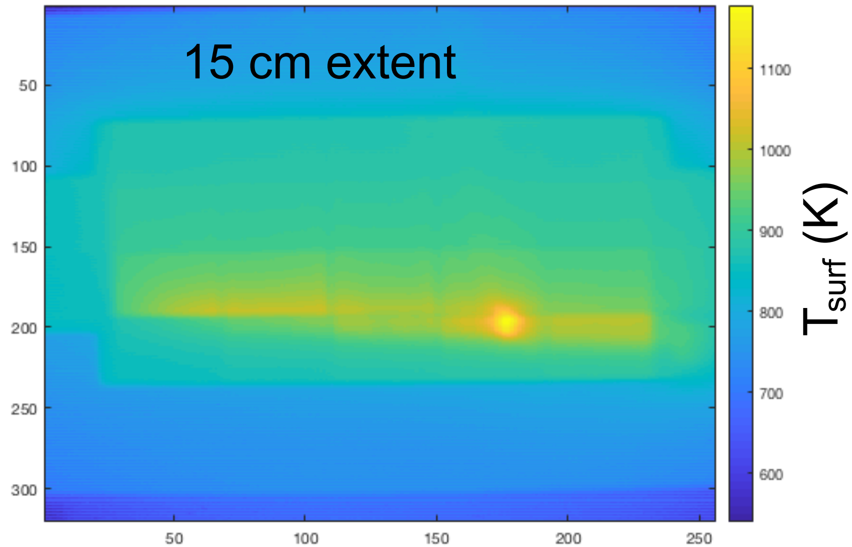
- Imaging:
  - MIRO camera for fast visible images
    - 100 Hz
  - FLIR SC4000 for IR measurements (30 Hz)
    - Calibrated on-the-bench @ ARL up to 1200 C
- Instrumented graphite tile
  - Embedded TC in each castellation
  - Calibrated TCs with Fluke 743B
    - 2 point cal. @ 100 and 1200 C
  - Digitized using off the shelf Instrunet DAQ
    - 10 Hz acquisition rate
- Beam and diagnostic timing was controlled manually

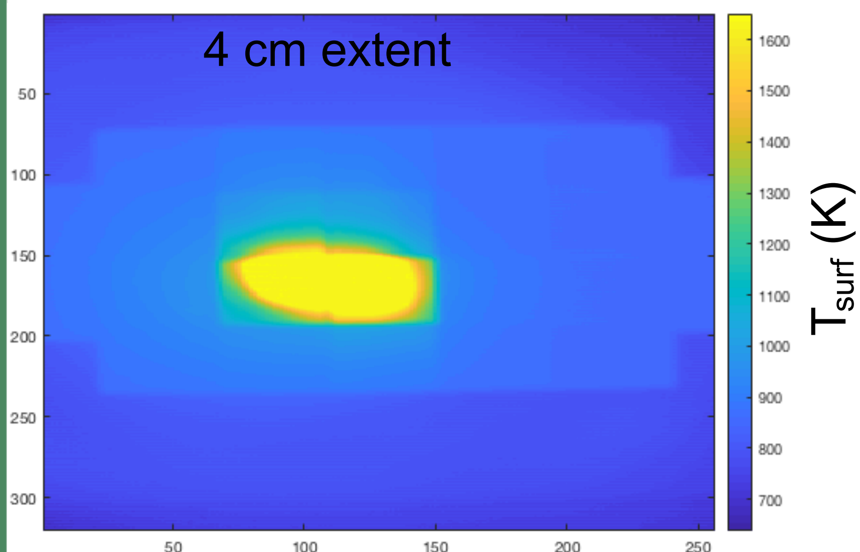
Chamber Set-up HHF, Sciaky 2-20-2018 (17)



Chamber Set-up HHF, Sciaky 2-21-2018 (11)

# Tested strike-point-like heat flux deposition patterns on target

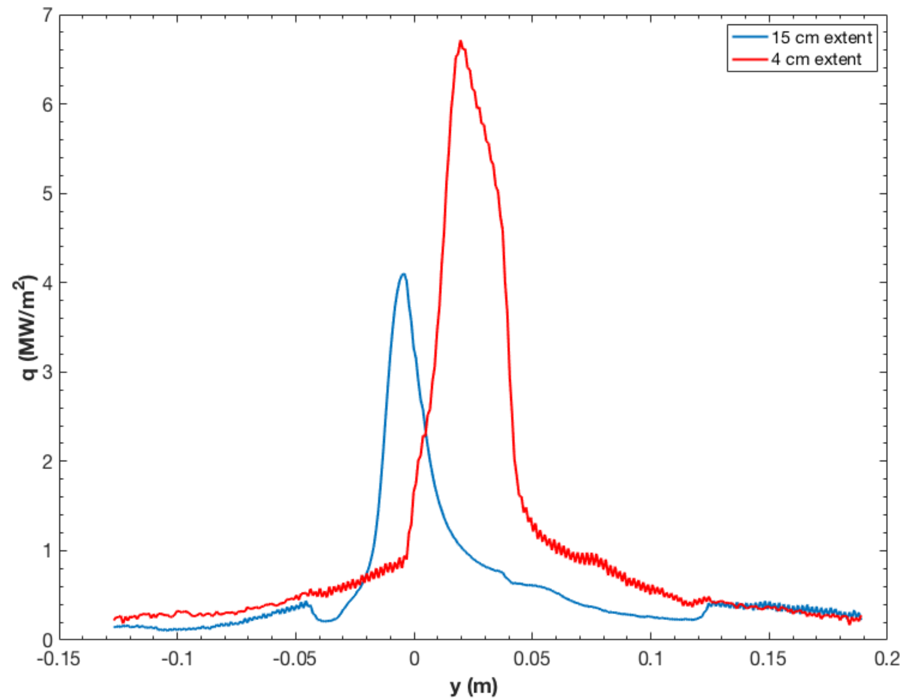


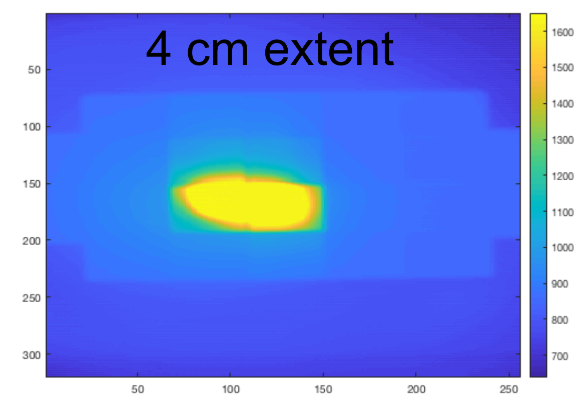




- Tested several heat flux extents
  - Large extent = 15 cm
  - Small extent = 4 cm
  - Failure Test (extent = 2 cm)
    - e-beam was focused onto a single castellation
- Scanned electron beam current for each pattern
  - 100 mA ≤ $I_{beam}$ ≤ 1500 mA
  - 10 sec long depositions

# Incident heat flux calculated from a semi-infinite heat conduction model

- Comparable 1000 mA shots with different extents
  - 10 sec durations
- 4cm extent shots placed most of the beam power onto ~2 castellations
  - Resulting in much higher $T_{surf}$ and heat fluxes
  - $T_{surf}$ > 1600 C by end of the shot
- Subsequent shots ($I_{beam} \geq 1000$ mA) showed "ablative behavior"

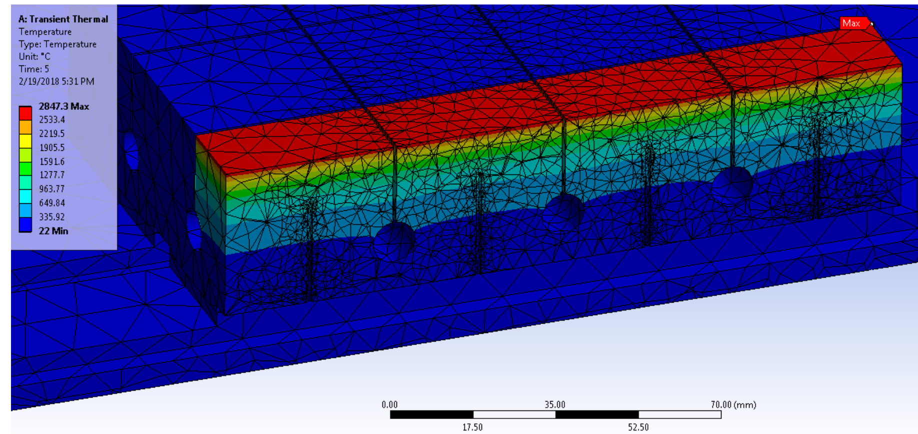


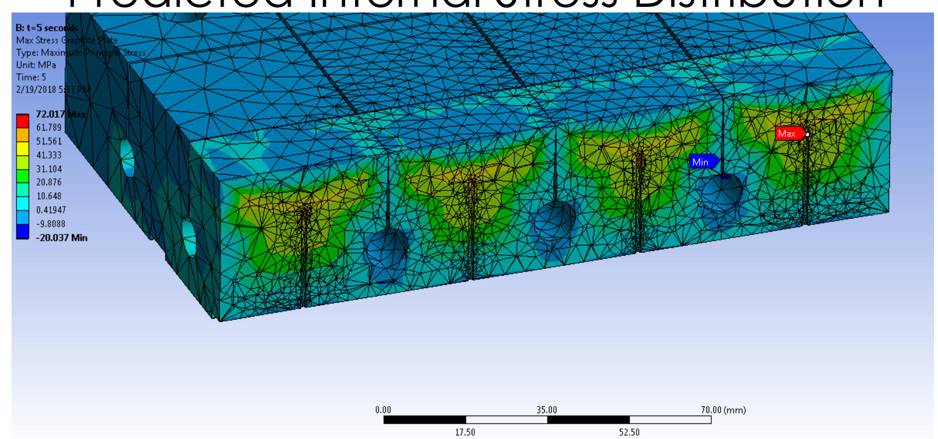
# Finite Element Analysis (FEA) predicts localized stress concentrations around thermocouple diagnostics

- Applied a 5 sec, uniform heat flux on target surface of 10 $MW/m^2$
- FEA also predicts internal stresses lead to target failure
  - Assumes a uniform heat flux
  - $T_{surf,\ fail}$ >> 2000 C
- However, the predicted $T_{surf}$ at failure is above the sublimation temperature of graphite

Predicted Temperature Distribution

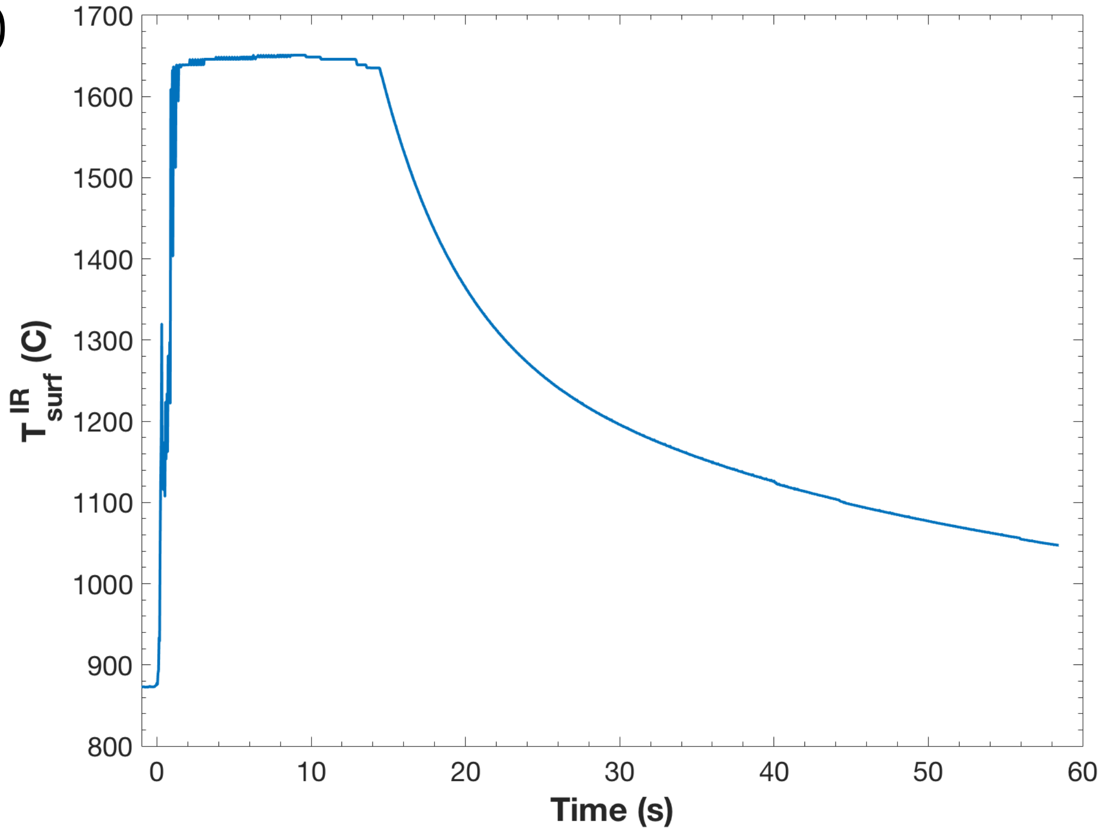



Predicted Internal Stress Distribution



# Target failure is prevented by ablation of graphite from the surface of the target

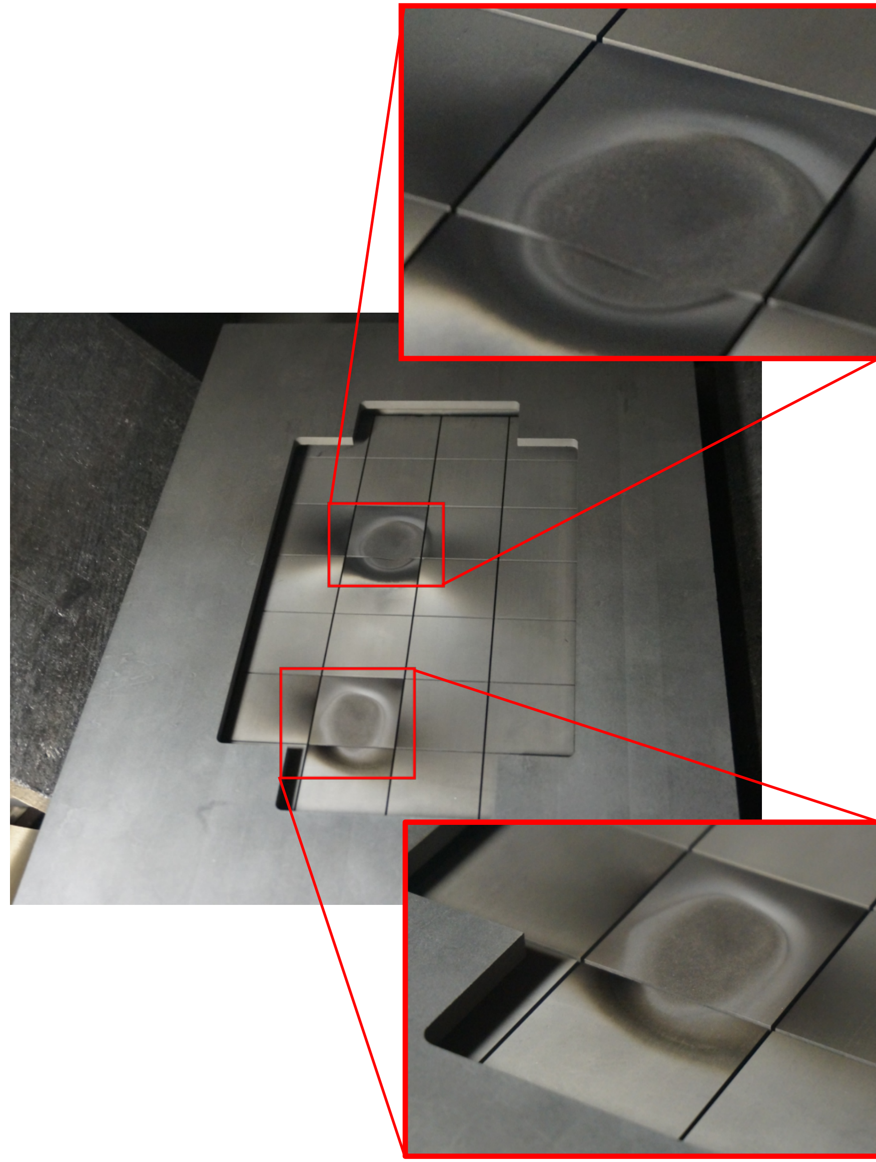
- IR measurements show clamping of $T_{surf}$ ~ 1650 C
  - Camera is close to saturation
  - Likely behaving non-linearly
- The quantitative measure of $T_{surf}$ is suspect
- Based on post-exposure inspection, showed evidence of ablation



# Clear evidence of graphite ablation from the target in post-exposure inspection

- Ablation craters generated during failure tests
  - E-beam was focused onto single castellations
- Ablation craters were ~ 1mm in depth
- No mechanical failure of target was found during inspection

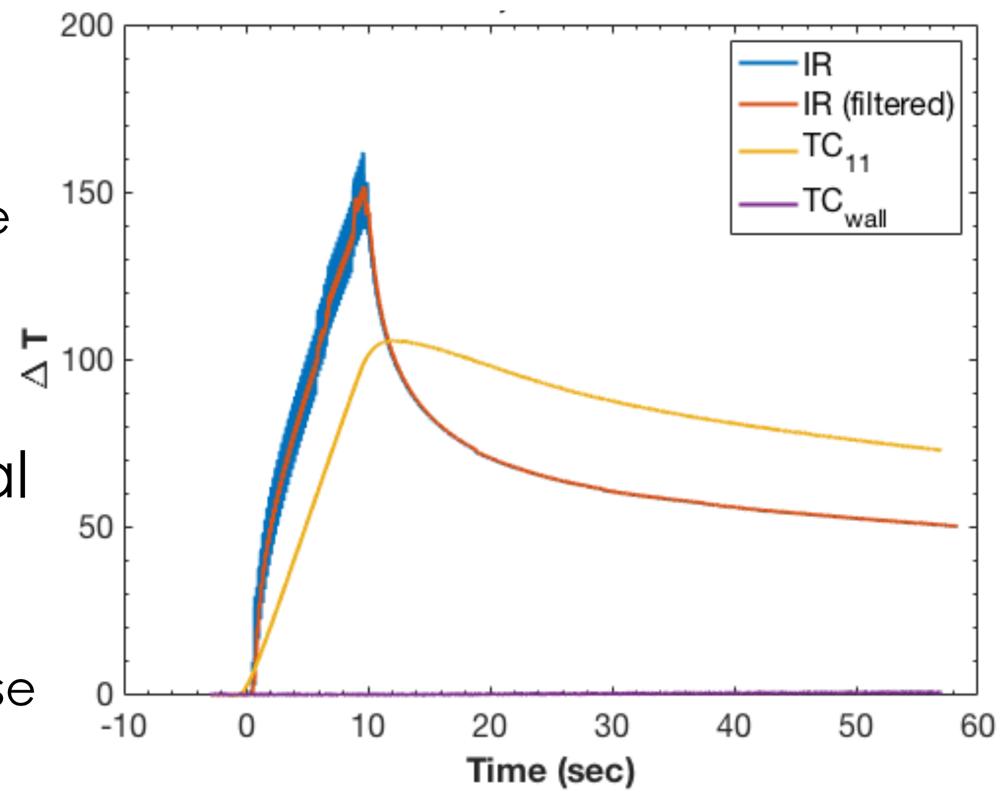
Visible image of castellation during cool-down



# Typical time trace of measured temperature rise during shot

- 6 Hz beat frequency observed on IR measurements
  - Filtered with a moving average

- TC on bottom of target assembly showed minimal increase over pulse + 50 sec cool down
  - Slowly ratcheted up over course of the day



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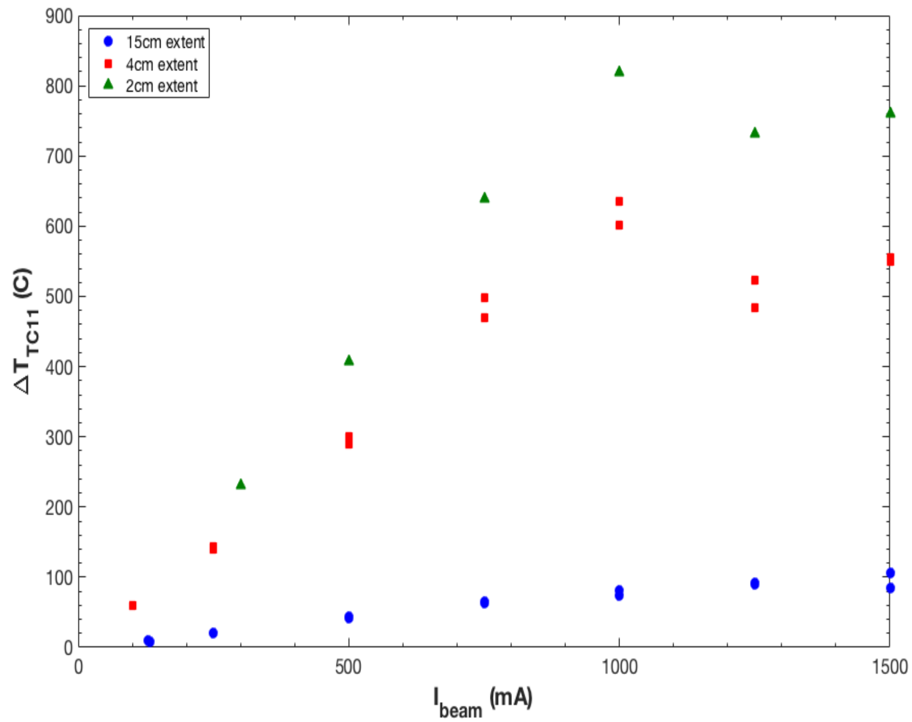
# Rise in Thermocouple Temperatures was linear until $I_{beam}$ = 1000 mA

- As the extent of beam narrowed, $\Delta T_{TC}$ increased for a given beam current

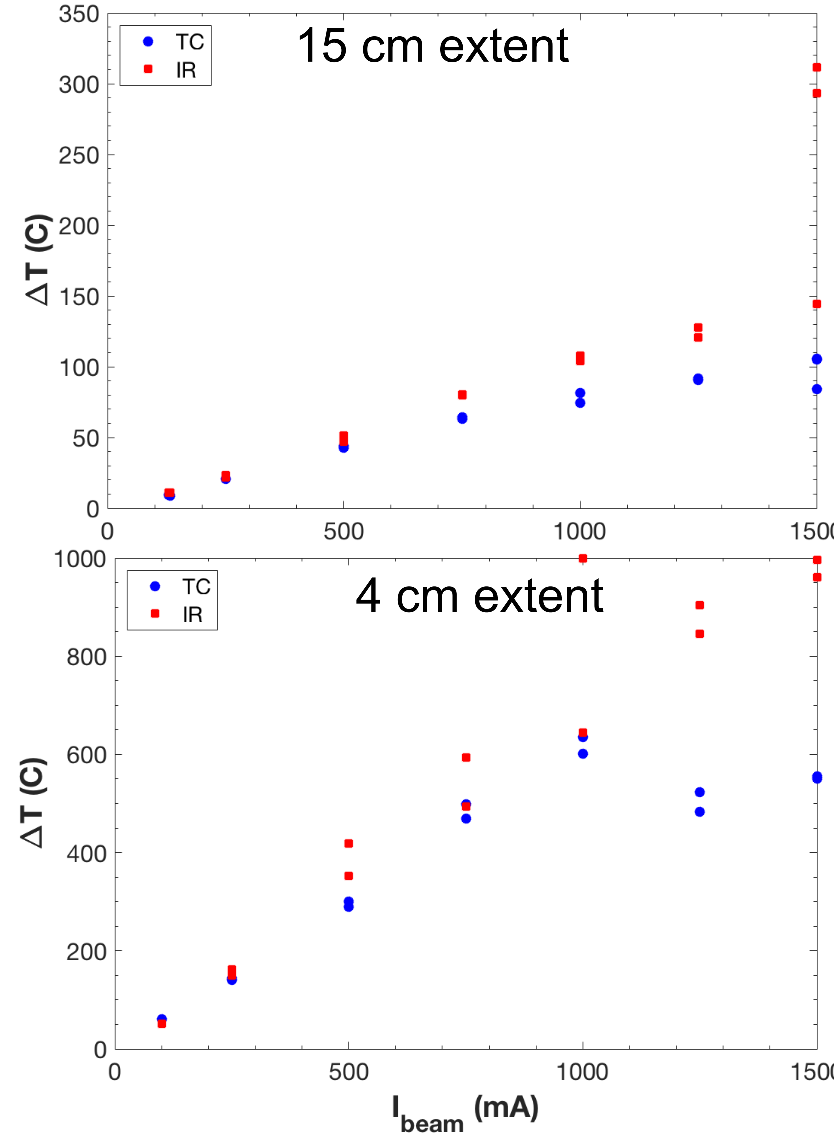
- Clamping of TC temperature was observed for $I_{beam}$ > 1A
  - Measurements past limits of IR calibration
  - Near upper temperature limit of type K TCs




Castellation #11 received the most energy

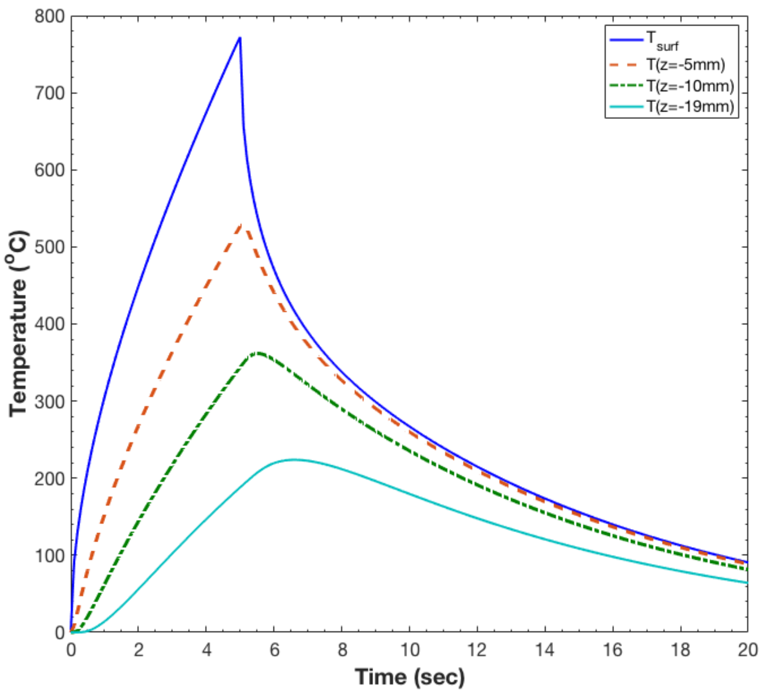
# Measurements of $T_{surf}$ show increase for shots where ablation occurred

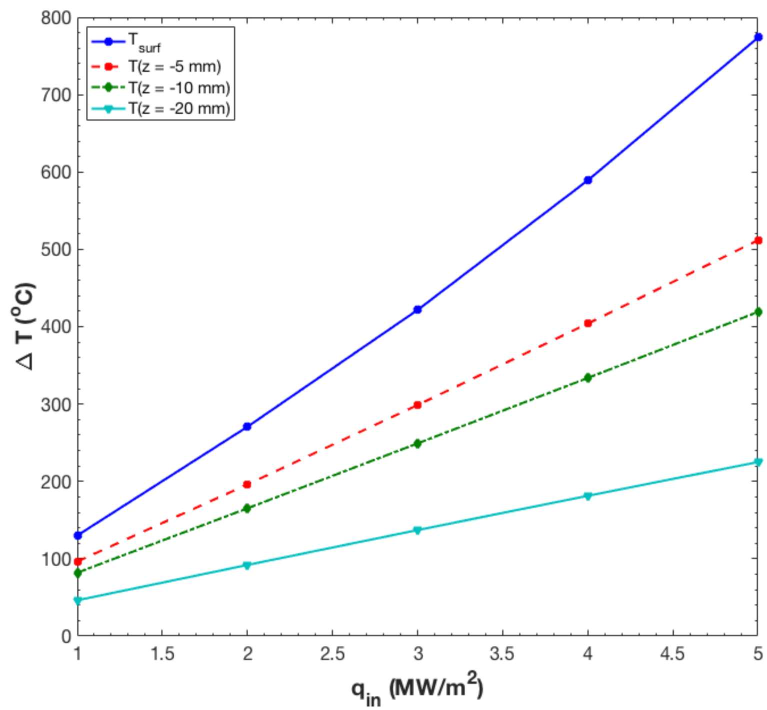
- As $I_{beam}$ is increased, $\Delta T_{surf}^{IR}$ increases while $\Delta T_{TC}$ decreases
- At $I_{beam}$ > 1000 mA, TC measurements are inconsistent with IR
- Indicative of graphite dust and particles in IR field of view
  - No longer thermally connected to target
  - Dust/particles radiate due to incident e-beam



# FEA of single, 2D castellation predicted variation in TC response based on depth below surface

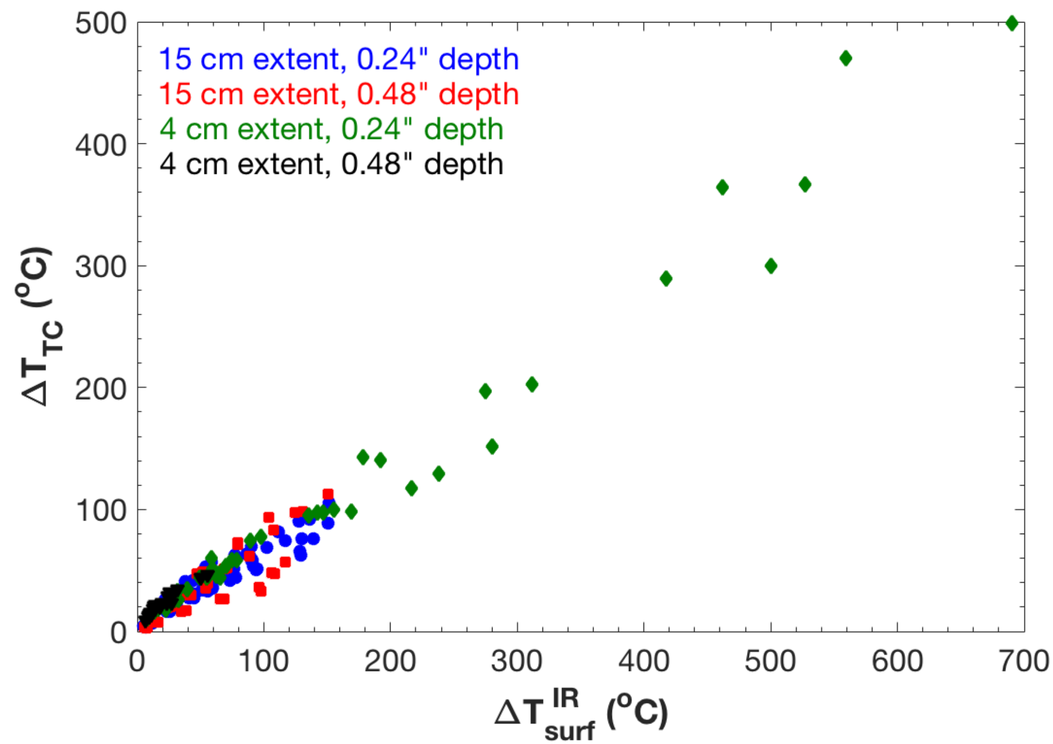
- Assuming 5 sec, uniform heat flux deposition
  - Castellation base held at constant T
  - Sides of castellation were allowed to radiate to environment
- TC depth was varied for a 1, 2, 3, 4 and 5 $MW/m^2$ of incident heat flux
- Predicted TC response was not found in experiments



# Experiments showed thermocouple response could be modelled as a semi-infinite solid

- Limited to shots without ablation
- Lower depth reduces stress concentrations in the castellation
- Data for $200 \leq \Delta T_{surf} \leq 700$ C was acquired with a single castellation/thermocouple
- Embedded TCs were found to have a sensitivity of 14 C per Joule of deposited energy into the castellation





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# Conclusions

- Target was transiently tested to greater heat fluxes than those required for NSTX-U
- Castellated graphite target design appears temperature limited rather than stress limited
  - Results in ablation of graphite from surface
  - $T_{surf}$ ~ 1650 C, but measurement is limited by ex-situ calibration and extrapolation to these surface temperatures
  - No testing of the prototype PFC tiles + mounting assembly has been performed
- Can treat individual castellations as semi-infinite solids on short time scales (< 10 sec)
  - Further, 3D FEA modelling is needed to fully understand this behavior
- Embedded TCs installed in castellations can be used as calorimeters to measure shot-integrated deposited energy
  - Sensitivity of 70 J/$^\circ$C was found

# Re-prints

# Future Work

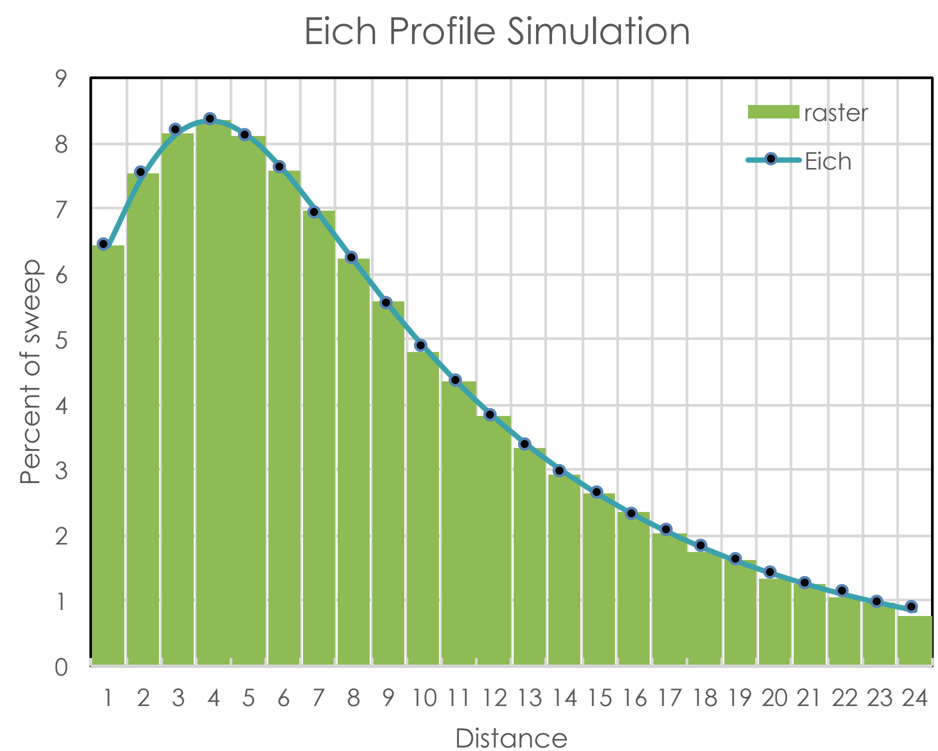
- Prototype PFC testing
  - Experimental planning is underway
  - Continued analysis to determine if desired peak heat fluxes can be achieved with a single e-beam
  - Higher temperature IR calibration
  - Review visible imaging for evidence of ablation

- Continued heat transfer analysis
  - Finite Element Analysis of target

- Continued investigation of use of integrated PFC calorimeters for use in real-time protection system

# Adapted the controller and software from EB60 system to be able to produce desired profiles

- EB60 system was originally at Sandia NL
- Installation of the controller and software @ ARL was successful
  - Modified in a few days
  - Allowed quick changes in beam positioning, raster pattern
- Allows programming of Diffusive-Gaussian (“Eich”) heat flux profiles




Example of pre-programmed Diffusive-Gaussian raster pattern

# Using Revised NSTX-U Heat Flux Requirements to Determine Testing Needs

- Heat flux requirements were revised for nearly all PFC surfaces
- Defined in terms of peak heat flux, duration and "extent"
  - Done to simplify specifications for modelling
- The most challenging of the requirements will be tested
  - Multitude of use cases are listed in the revised requirements

| Tile Design | Heat Flux ($MW/m^2$) | Extent (cm) | Duration (sec) |
|---|---|---|---|
| IBDH | 7.0 | 15 | 5 |
| OBD1-2 | 6.0 | 13 | 5 |