

# ASTA Low Energy Absorber Thermal Analysis

Version 5, June 08 2012

C. Baffes and I. Rakhno

Beam Doc DB ID: Beams-doc-4063

Design review held on Jan 11 2012: Updates relative to that review are shown in green.

Re-analysis at 55MeV beam energy completed June 08 2012:  
Results documented in Appendix 2.

# Scope and Review Charge

---

- Review Charge: please review the configuration and thermal analysis of the low energy dumps and assess whether
  - Absorber configuration is appropriate
  - Analysis assumptions, method, and results are reasonable
  - System is ready to move on to detailed mechanical design
- Included in the scope of this review
  - Configuration of the ASTA Low Energy Dumps
  - Thermal analysis methodology and results
- Excluded from the scope of this review
  - Radiation analysis and shielding assessment

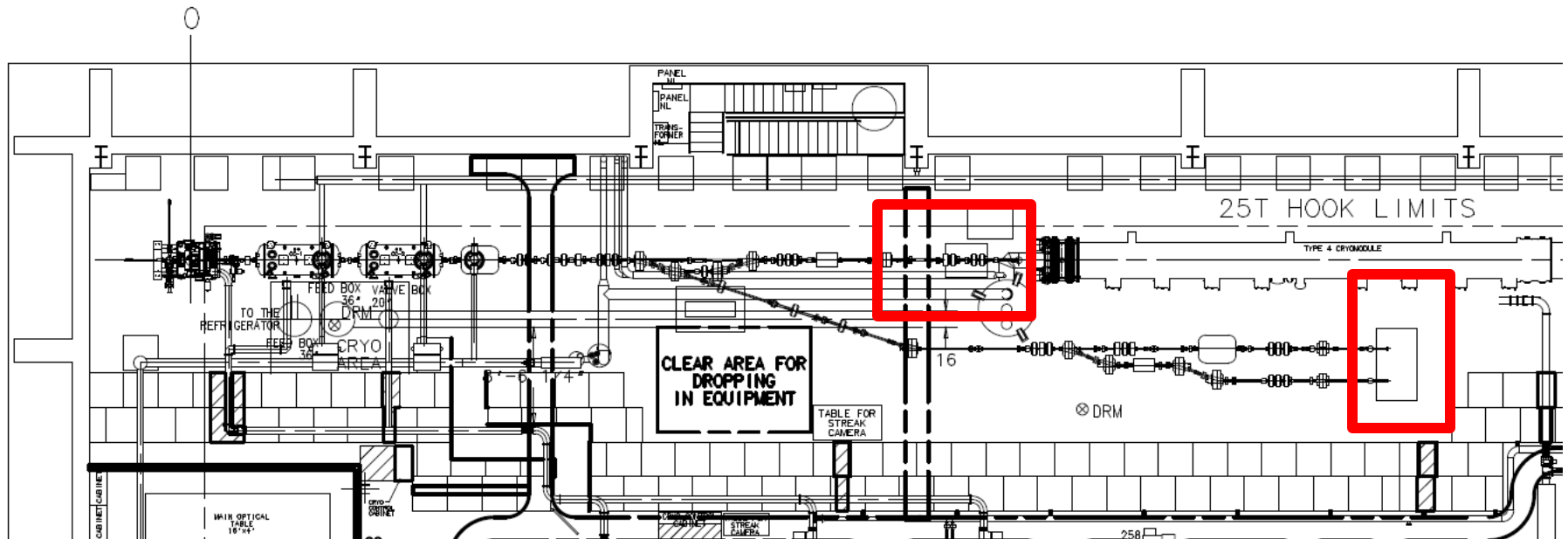
# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions
- Appendix 1 – Reduced Intensity Cases.
- Appendix 2 – 55MeV Analysis

# Absorber Locations

There will be up to three Low Energy Dumps (LEDs)



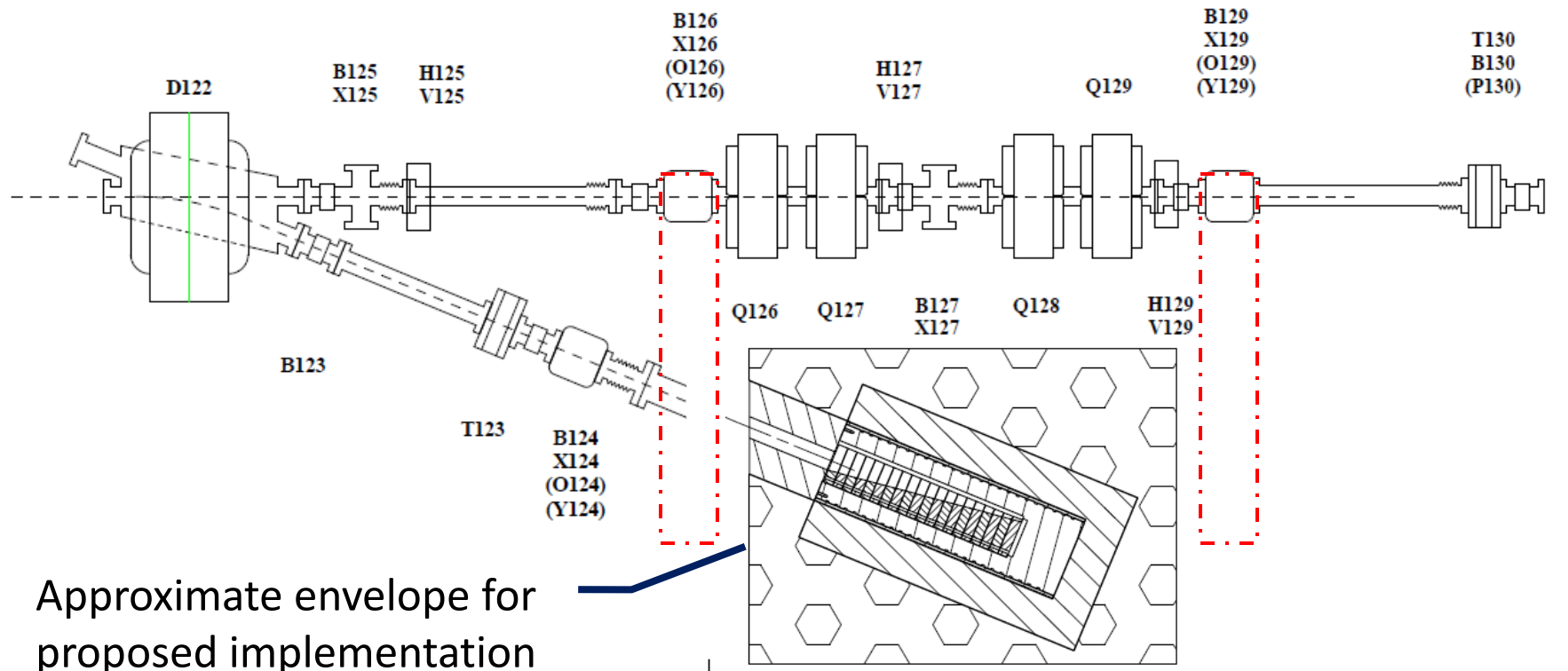
# Beam Parameters

---

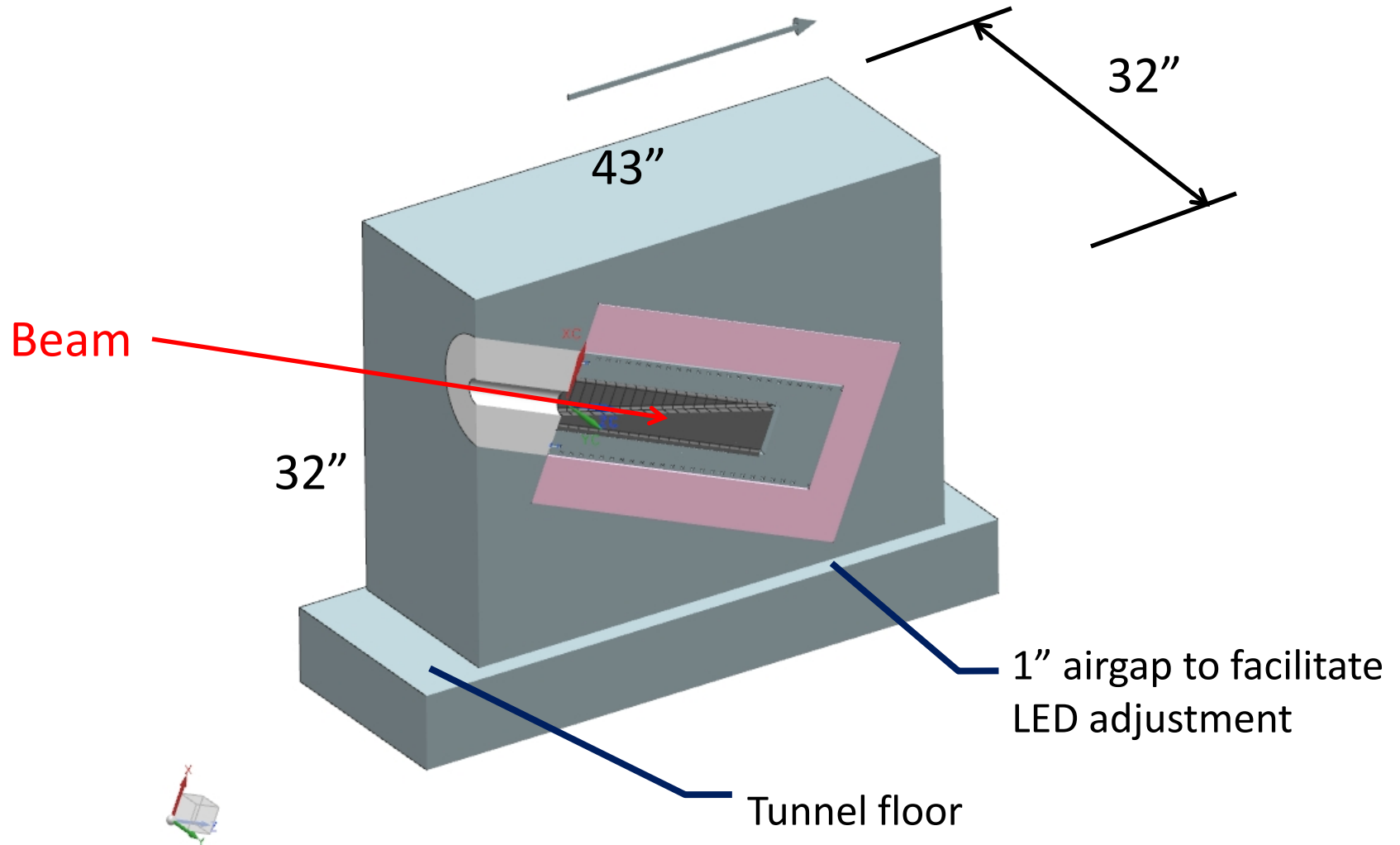
- Beam Parameters
  - electron beam at 50 MeV, 3.33 nC/bunch
  - $6.24 \times 10^{13}$  e-/pulse, 5 pulses/s,  $3.12 \times 10^{14}$  electrons/s
  - Pulse duration 1ms
  - 2.5kW average beam power
- Absorber shall be capable of accepting beam continuously (i.e. steady state operation)

# Packaging Constraints

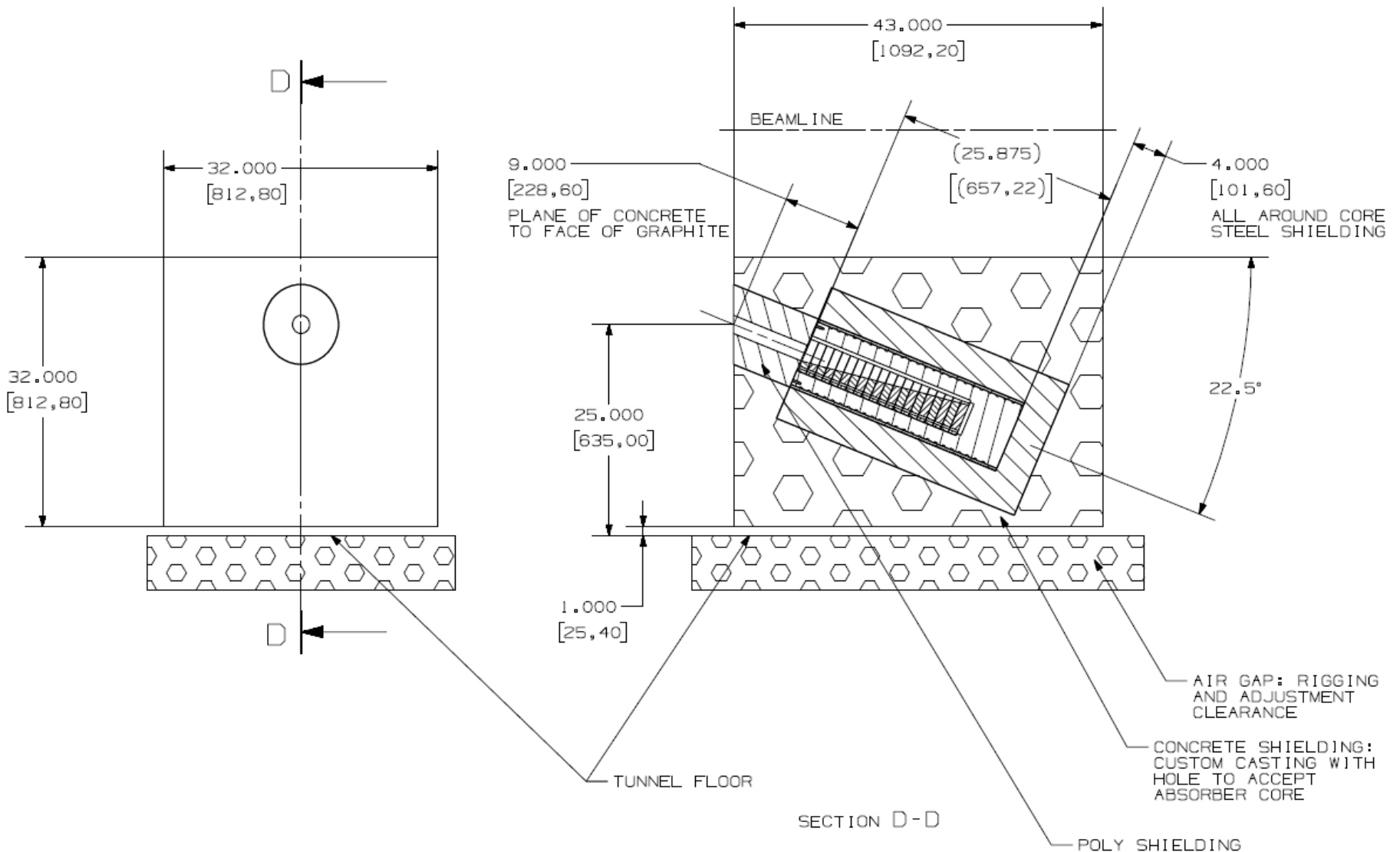
LED 1 must clear beamline components, particularly radia beam cross X126. Cross at X129 will likely be rotated away from the LED (about the beam pipe) and does not pose a hard constraint



# Absorber Configuration (Section View)

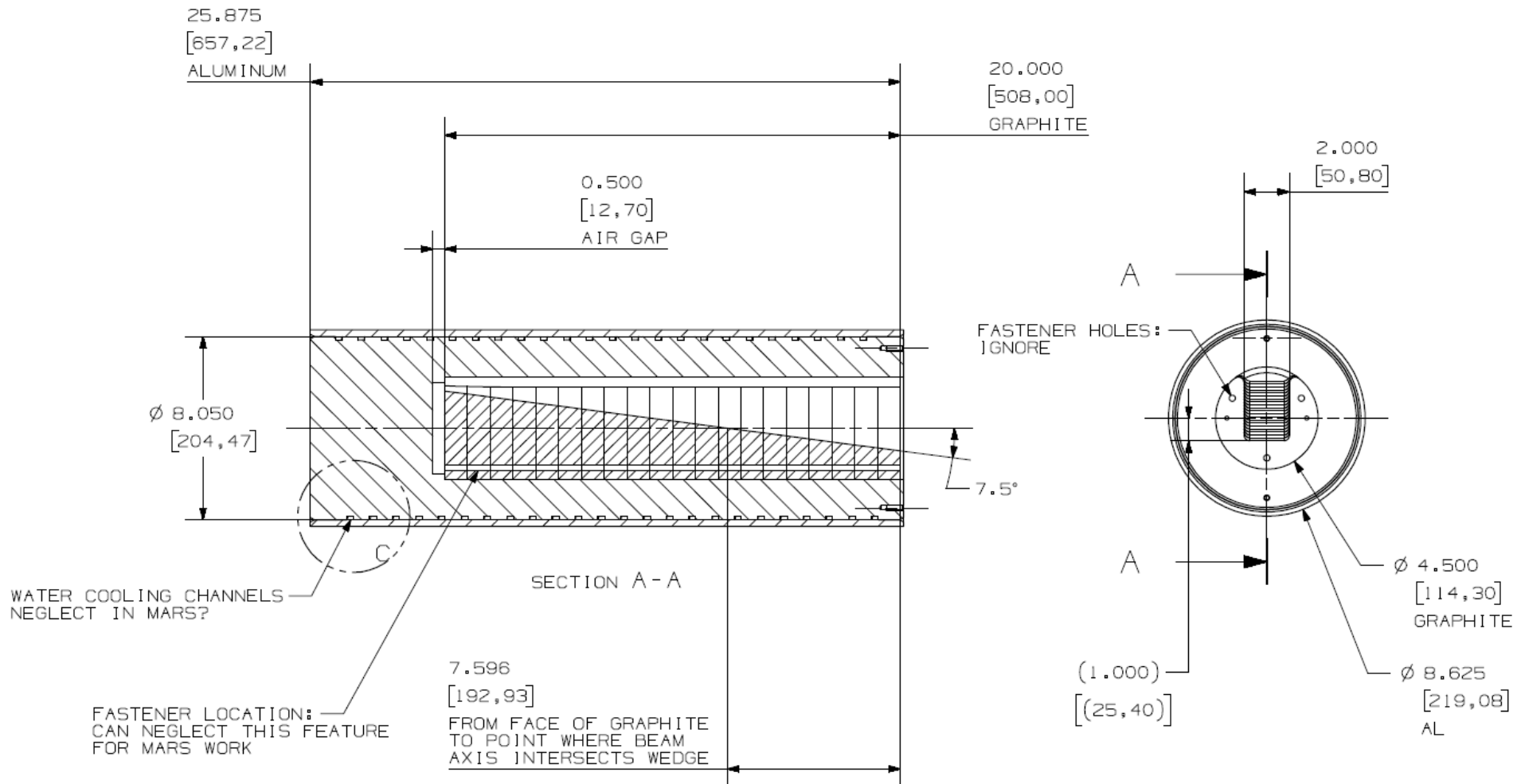


# Absorber Configuration

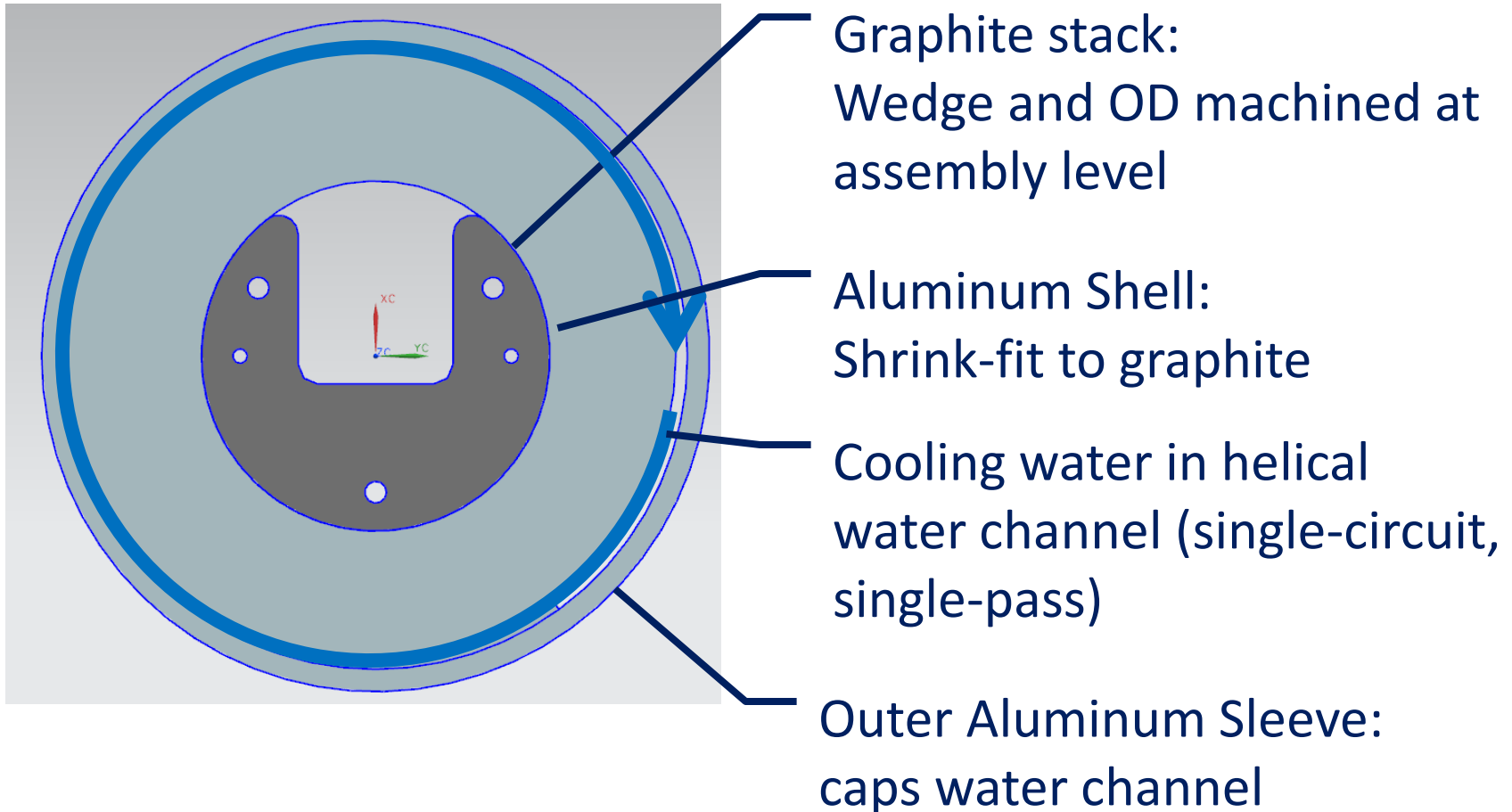




# Absorber Core



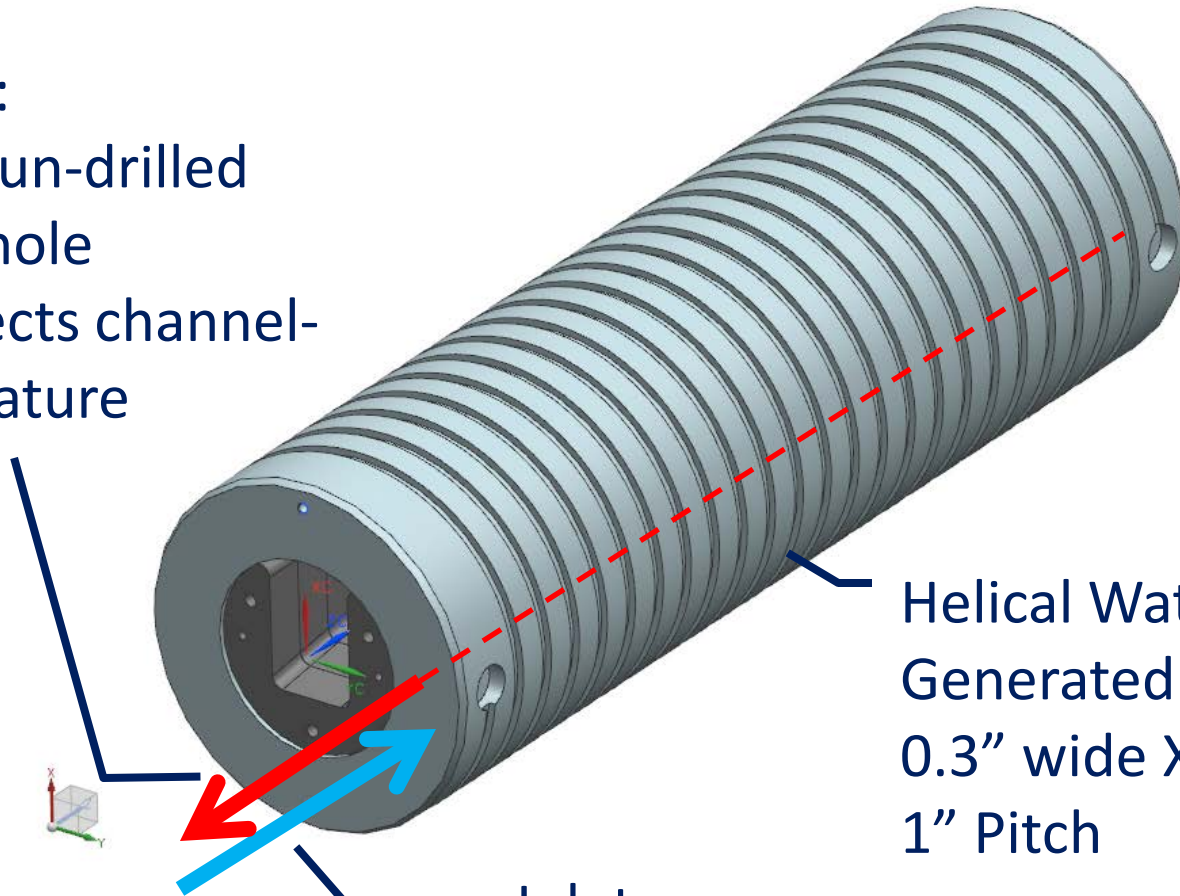
# Graphite/Aluminum Contact Architecture



# Helical Water Channel

Outlet:

Long gun-drilled  
cross-hole  
intersects channel-  
end feature



Helical Water Channel  
Generated on screw machine  
0.3" wide X 0.15" deep  
1" Pitch

Inlet:

Short cross-hole intersects  
channel-start feature

# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- **MARS Analysis Inputs**
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions

# Data Processing Approach

---

- Step 1: I. Rakhno produces MARS results
- Step 2: Process MARS results in Excel
  - Tabulate X, Y, Z and heat generation for each MARS element
- Step 3: Generate mechanical FEA models in NX/Ansys
  - Symmetric half-model used for all analyses
  - Tabulate FEA mesh nodal and element XYZ locations
- Step 4: Interpolate MARS results onto FEA mesh in Matlab
  - Use MARS radiation damage estimates to assign material properties
  - Map heat generation results from MARS mesh onto arbitrary FEA mesh
  - Calculate heat generation at each FEA element
  - Generate Ansys text input using BFE/HGEN
- Step 5: Run Ansys to recover temperatures

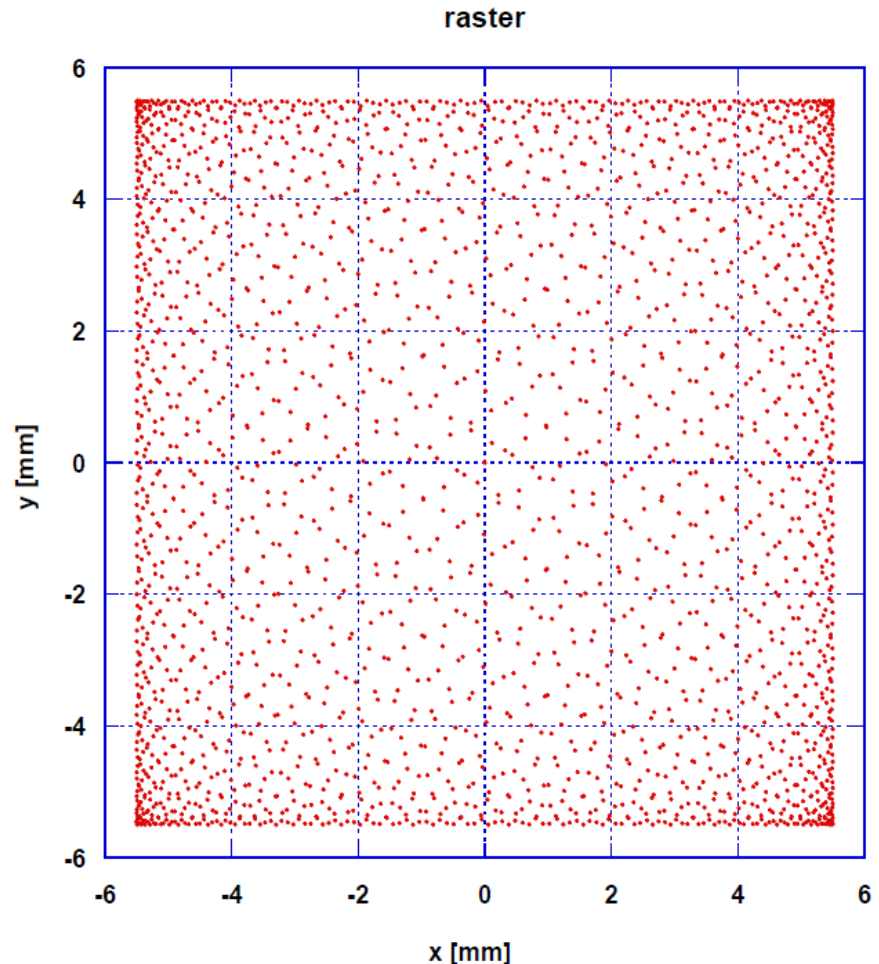
# MARS Input: Comments

---

- MARS analysis performed by Igor Rakhno
- Input Parameters
  - 50 MeV, 3.33 nC/bunch, 3MHz, 1ms pulse @ 5Hz
  - $3.12 \times 10^{14}$  electrons/s
  - 2.5kW beam
  - Complex LED geometry faithfully modeled in MARS
- MARS energy deposition results are element-wise
  - I.e. results are averages over the volume of each element
- Beam-sweeping implemented in MARS
  - MARS energy deposition results represent temporal average
  - Stand-alone model used to evaluate single-pulse effects

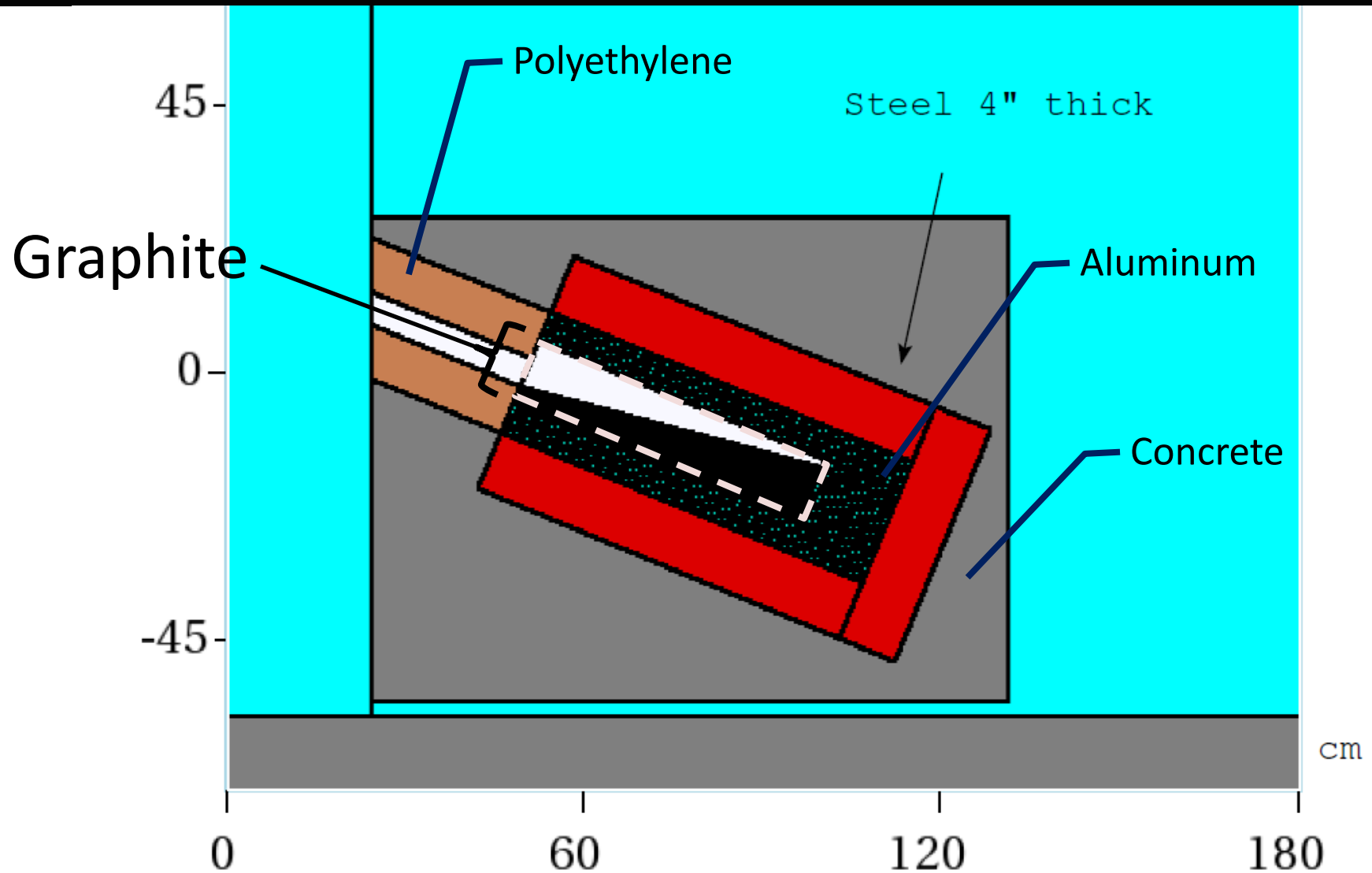
# Beam Sweeping

- Preliminary modeling showed high temps in the graphite
- In order to mitigate this, slow-beam sweeping was implemented
  - Beam sweeps sinusoidally in X and Y
  - 11mm \* 11mm area
  - 3.079 Hz in X
  - 2.939 Hz in Y
- This slow beam sweeping implemented in MARS, and therefore assumed in all steady-state analyses



Cross section transverse to beam  
Red spots are individual beam pulses

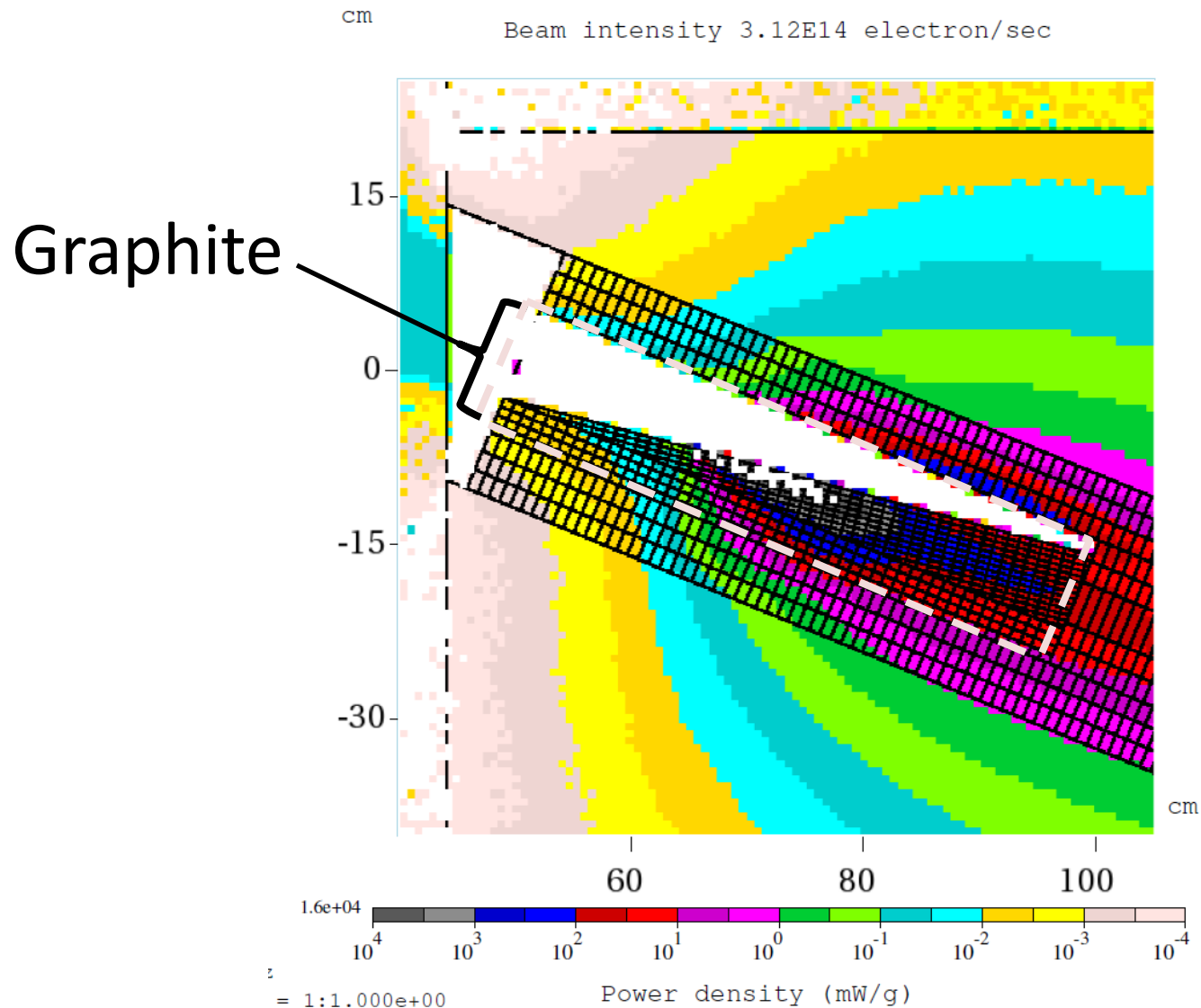
# MARS Model: Geometry





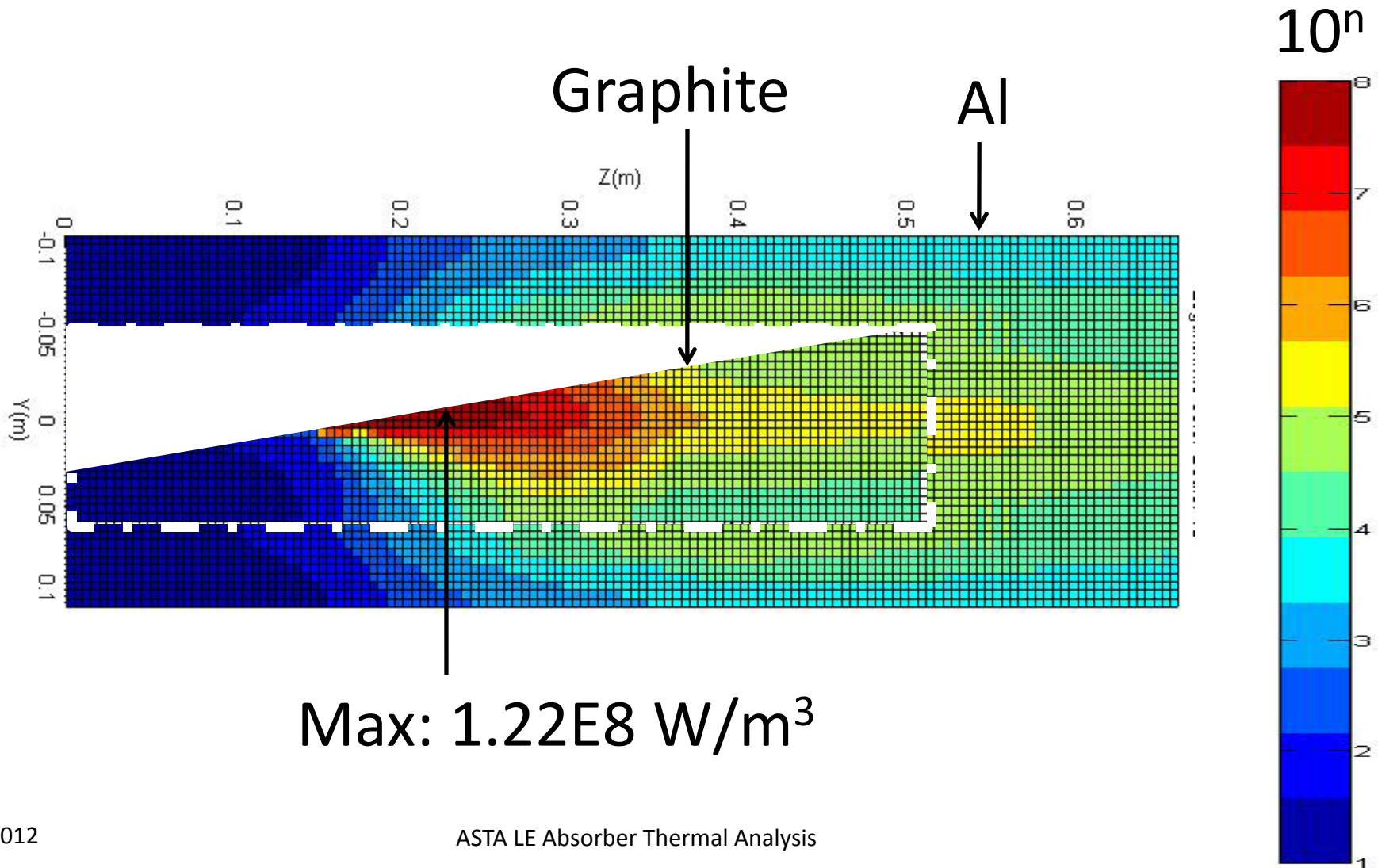
# MARS Results:

## Energy Deposition (mW/g)



# MARS Results

Heat Generation ( $\text{W}/\text{m}^3$ ): log color scale



# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- **Material and Fluid Analysis Inputs**
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions

# Material Selection

---

- For the absorber core, we will use Toyo Tanso IG-110
  - Quasi-isotropic Nuclear-grade graphite
  - Spare material on hand from high energy absorber build
  - Material properties modeled as a function of temperature and radiation-induced damage (see next slide)
- For the Aluminum Shell, we will use AL-6061 T6
  - Readily available in the required forms
  - Temperature dependant material properties per MIL-HDBK-5H

# Graphite Properties

1.000=Best

Material		Density (kg/m <sup>3</sup> )	E (GPa)	$\alpha$ (ppm/°K)	k (W/m <sup>2</sup> °K)	c (J/kg°K)	Flexural Strength (MPa)	Comp. Strength (MPa)	Gruneisen parameter $\gamma = \alpha E / c p$	FOM <sub>1</sub> = $\{\alpha E / c \sigma_{\min}\}$ normalized to min	FOM <sub>2</sub> = $\{\text{FOM}_1 / k\}$ normalized to min
Graphite	@ 20 C	1720	10.5	2.9	90	568	45	90	0.031	2.514	1.000
SGL R7340	@ 500 C			3.3	63	1750			0.012	1.000	1.000
Graphite	@ 20 C	1770	9.8	4.5	120	550	39	78	0.045	4.339	1.294
IG-110	@ 500 C			5	79.2	1500			0.018	1.904	1.514
Worst Case Direction		LOW	HIGH	HIGH	LOW	LOW	LOW	LOW			
Radiation Damage Sign		↑	↑	↓ or ↑	↓↓		↑	↑			
Damage scale factor		1	1.1	1.1	function	1	1	1			
Graphite model:	@ 20 C	1720	11.55	5.0	> 0.9	550	39	78	0.060	5.625	223.735
110 or 7340	@ 500 C			5.5	> 3.1	1500			0.025	2.468	50.155

- At the End of Life (EOL), the performance of the graphite will have degraded significantly due to radiation damage
- This will be covered in Radiation Damage section

# Thermal Analysis Parameters

## Thermal Contact Coefficients

Material Interface	Coefficient (W/m <sup>2</sup> °K)	Source
Al/Graphite (radial load path)	500 See note 1	Derating of existing test data See note 2
Graphite/Graphite (axial load path)	100	Conservative low value

[1] Sensitivity to this value was assessed see slide 34

[2] J. Kidd: “A high intensity beam dump for the Tevatron Beam Abort System”, 1981, reported a C/Al value of 1600 W/m<sup>2</sup> °K at a contact pressure of 35psi

# Thermal Analysis Parameters

---

Cooling water convection coefficient:

$$h=12,100 \text{ W/m}^2 \text{ }^\circ\text{K}$$

This is based on an empirical correlation calculation with the following key assumptions and parameters:

- Single channel/single pass system
- Full 2.5kW beam power is rejected through cooling water
- Design cooling water temperature rise  $\Delta T = 10 \text{ }^\circ\text{K}$
- Flow rate of 0.06 l/s (1 gallon/minute)
- Internal flow in rectangular 0.3"X 0.15" channels
- Fully developed turbulent flow:  $Re=17,400$
- Gnielinski-Petukhov empirical correlation

# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- **Thermal Model**
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions



# FEA Model

---

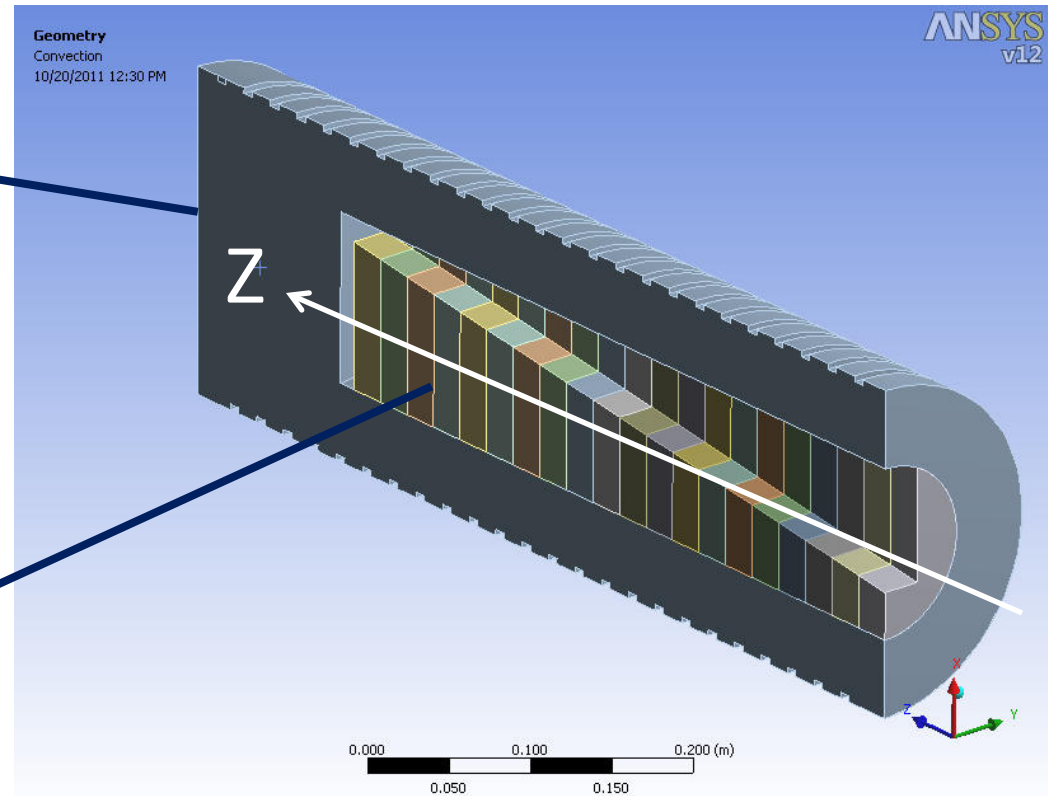
- A system model with “half” symmetry is used to assess steady-state temperatures
- Only the graphite/Al absorber core was modeled
  - 2.50 kW total beam power
  - 2.47 kW is dissipated in the volume of the MARS model
  - 2.35 kW is dissipated in the graphite/AL core
  - $(2.5\text{kW} - 2.35\text{kW}) = 150\text{W}$  is neglected by the thermal model. This is acceptable

# System Model

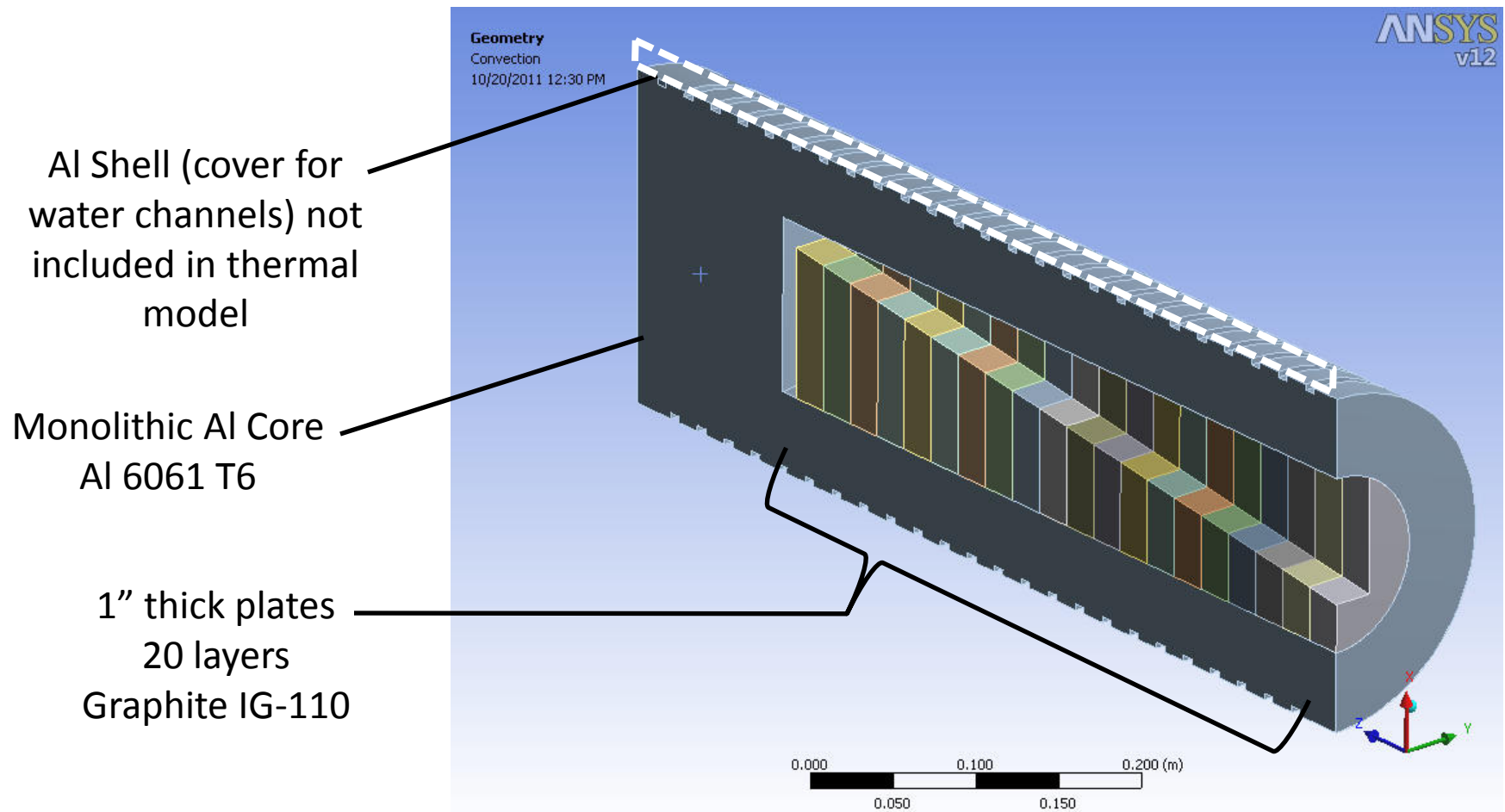
## Underlying Solid Geometry

Bilateral symmetry  
about YZ plane

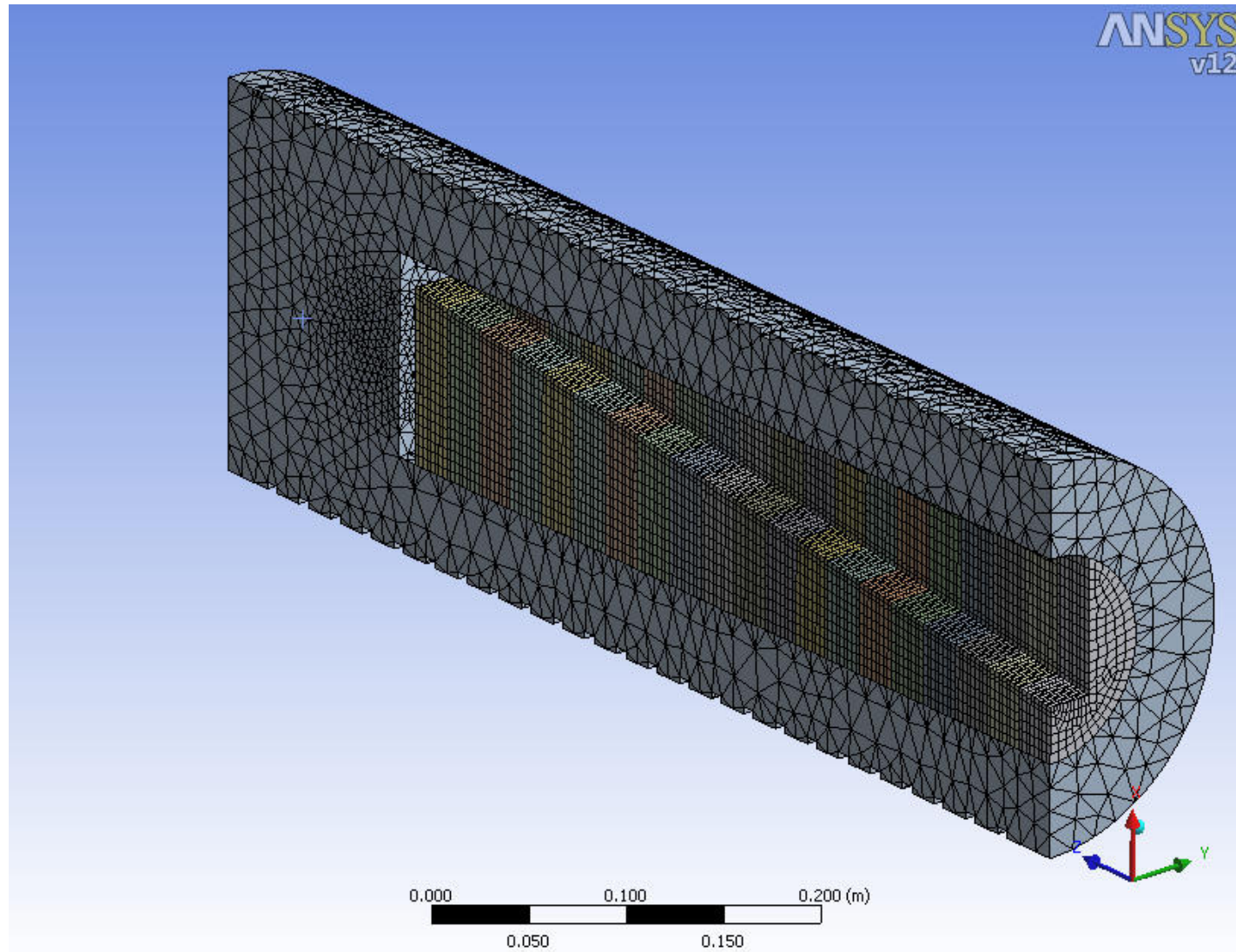
Lamina are modeled  
individually. Contact thermal  
resistances included



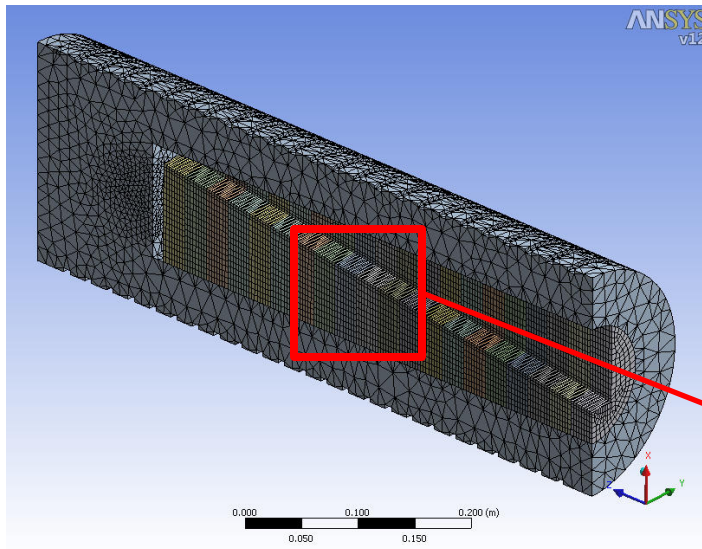
# System Model Materials



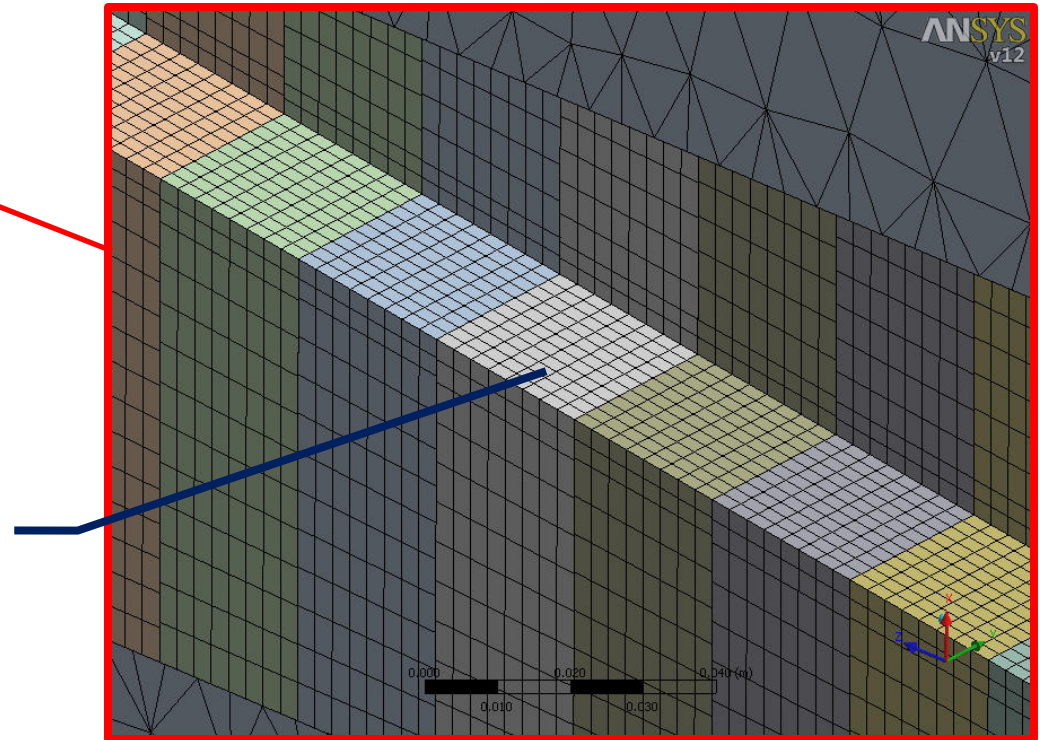
# System Model FEA mesh



# System Model FEA mesh

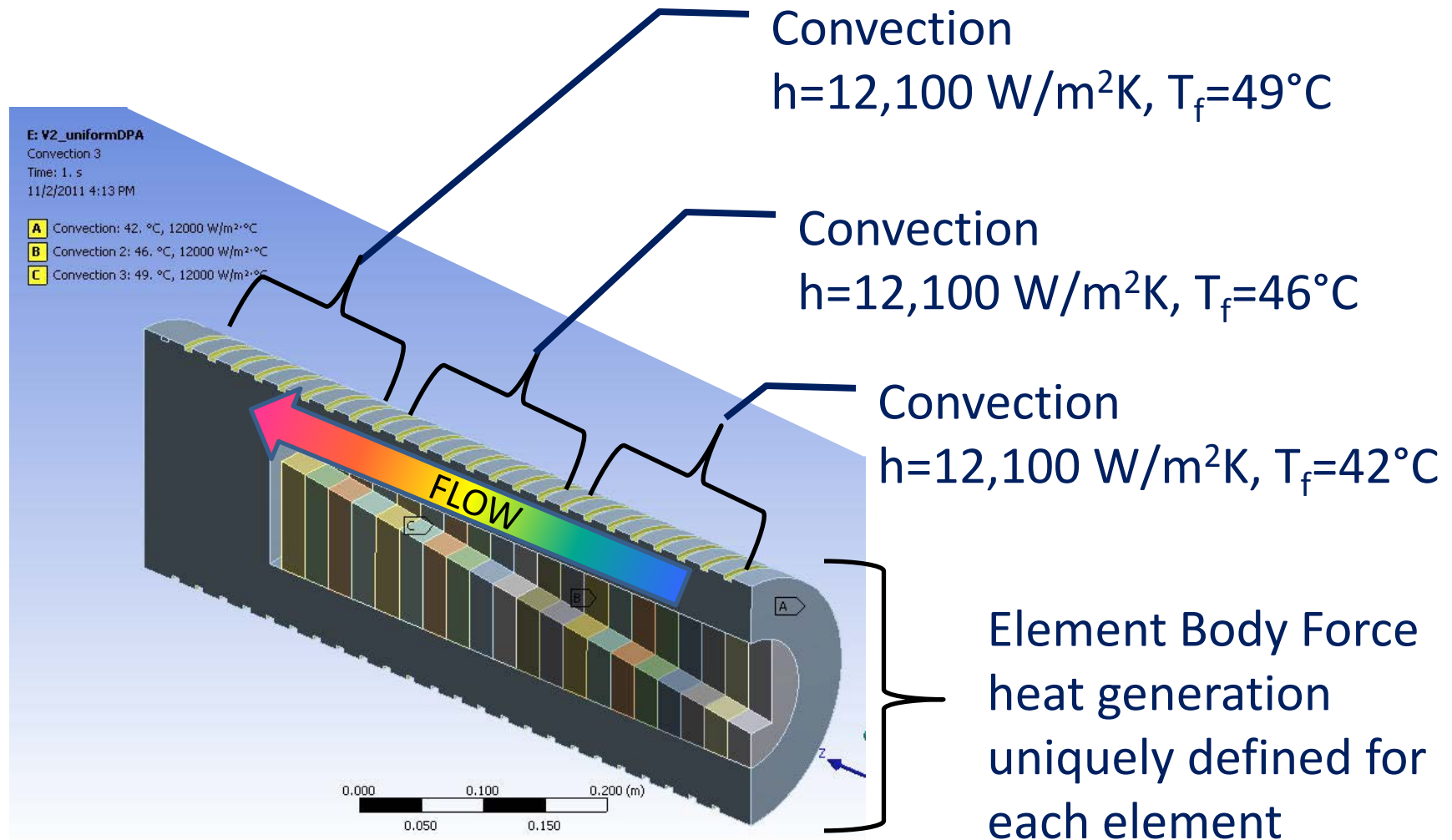


Element size refinement on  
face of wedge and in down-  
stream aluminum





# System Model Thermal Loads



# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- **Steady State Analysis and Beginning of Life Performance**
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions

# Steady State Analyses

---

- The steady state thermal analyses neglect the pulsed nature of the energy deposition, and assume constant and continuous beam power
- We use two sets of graphite properties:
  - Beginning of Life (BOL) – graphite properties not degraded by radiation damage (but still fully temperature dependant)
  - End of Life (EOL) – graphite damage categorized in bins, corresponding degraded material properties mapped onto the FEA mesh
  - EOL analyses are presented in the next section

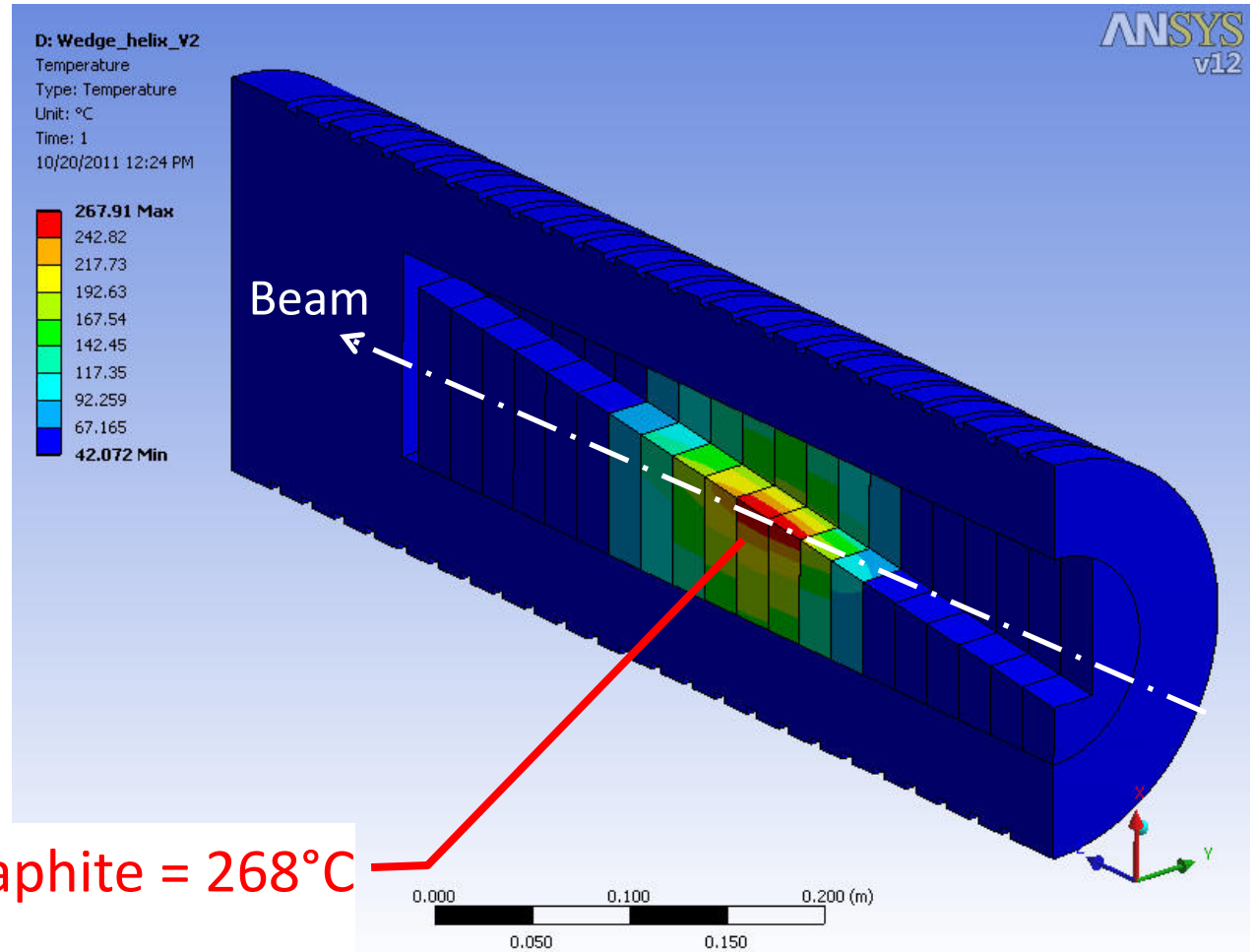


# System Model Steady State

Maximum temperature in graphite and system

## Key inputs:

- Graphite/Al thermal contact  $500 \text{ W/m}^2\text{K}$
- Swept beam (i.e. temperatures represent temporal average)
- Graphite with undamaged BOL material properties

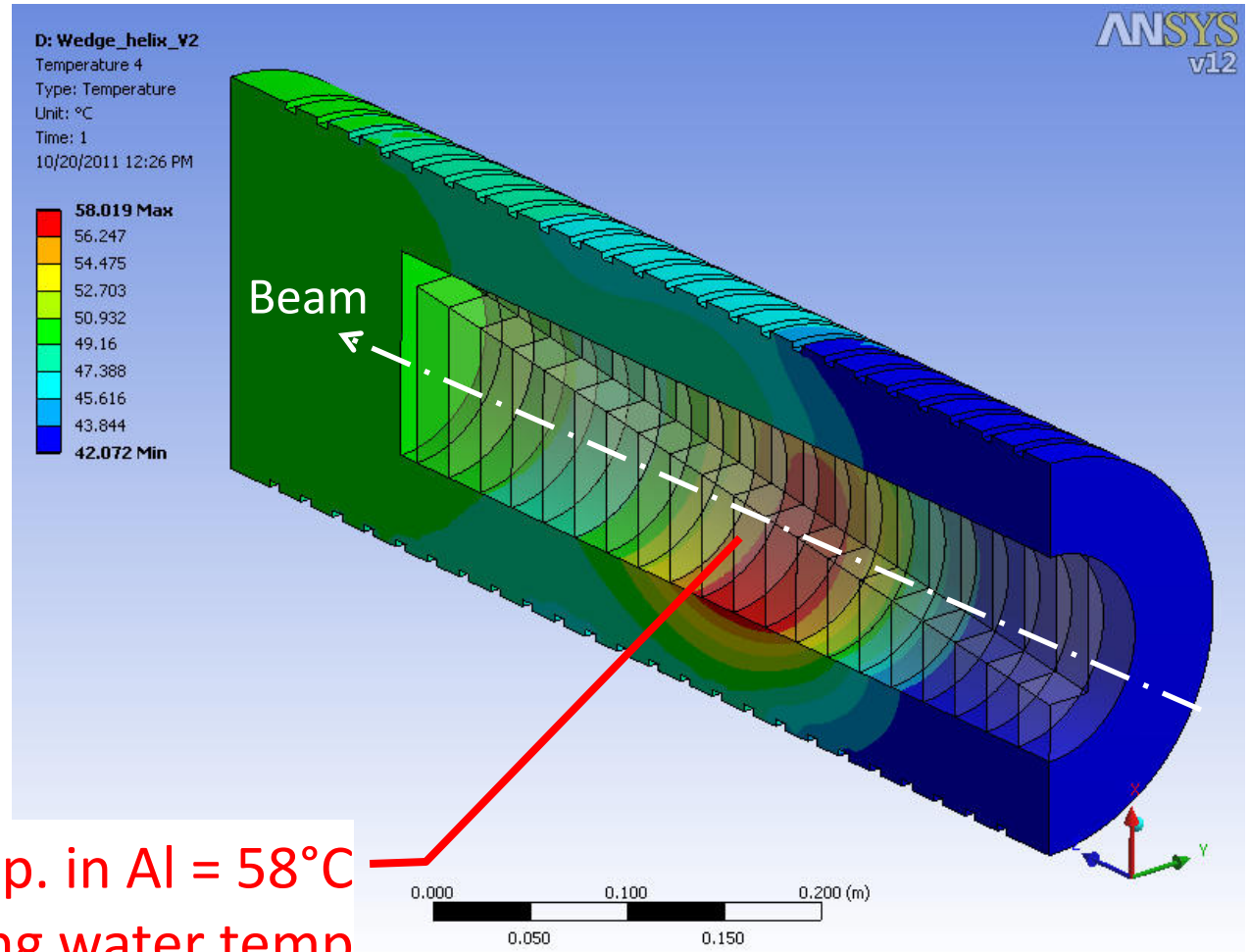


# System Model Steady State

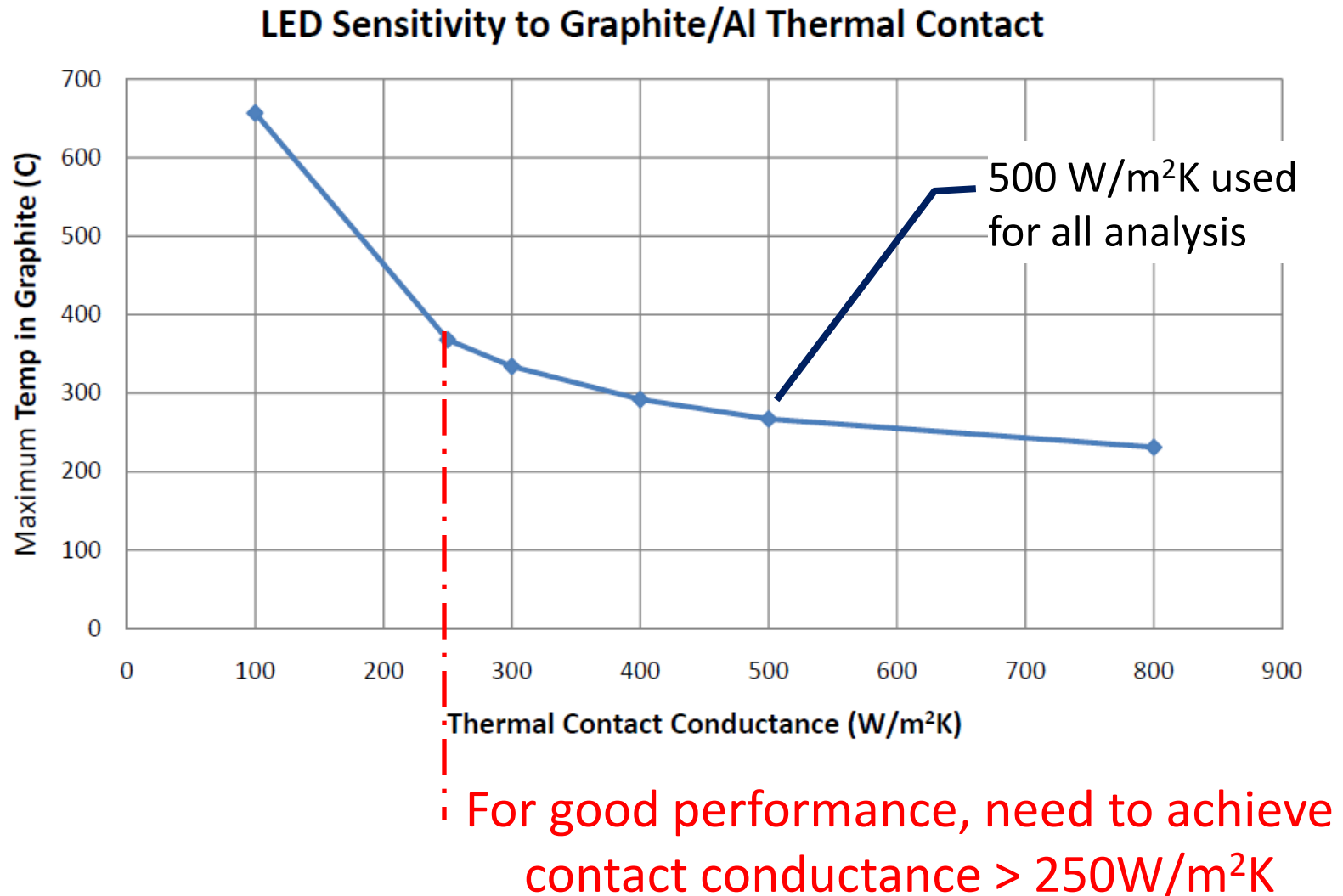
## Maximum temperature in Aluminum

### Key inputs:

- Graphite/Al thermal contact  $500 \text{ W/m}^2\text{K}$
- Swept beam (i.e. temperatures represent temporal average)
- Graphite with undamaged BOL material properties



# Thermal Contact Sensitivity



# Thermal Contact Sensitivity

(updated 7-Feb-2012)

- Given the acknowledged sensitivity to C/Al thermal contact, the reviewers recommended calculating a worst-case thermal contact by looking at conduction across a small (unintentional) air gap.
- The contact thermal conductance for a 30um air gap is given as:

$$C = k_{\text{air}}/t_{\text{gap}} = (.0263 \text{ W/m K}) / (0.00003\text{m}) = 876 \text{ W/m}^2 \text{ K}$$

- So, the assumed contact thermal conductance of 500 W/m<sup>2</sup> K is quite conservative. We can expect to be on the “flat” part of the curve shown on the previous slide

# Steady-State Thermal Analysis

## Conclusions

---

- Thermal design appears to be acceptable at BOL steady state
- System is sensitive to graphite/aluminum contact thermal conductance
  - Even if we have a small air gap, we should achieve acceptable contact
  - Testing planned in support of beam exit window design should help us to build confidence in the modeled values

# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- **Radiation Damage and End of Life Performance**
- Pulse Transient
- System Transient Analyses
- Conclusions

# Radiation Damage

---

- After exposure to radiation, the graphite core may undergo variation in mechanical properties and loss of material
- Changes in mechanical properties have been investigated in the analysis, and can be accommodated by the current design
  - Will limit lifetime of absorbers to  $1.4E21$  electrons (~4 calendar years **at full intensity**). More on this later
  - Low energy absorbers can be replaced, so this is acceptable
- Damage limit benchmarks:
  - 0.68 DPA – ~10% material loss seen in NuMI graphite
  - 0.25 DPA – limit established for ASTA high energy absorbers
  - 0.018 DPA – Predicted LED damage after  $1.4E21$  e-
  - 0.01 DPA – significant loss of thermal conductivity

# Duty Cycle

- Mike Church defined the following duty cycle:

Parameter	Value	Comments
Nominal Intensity	3.12E14 electrons/s	Design particle flux
Operation Fraction (up time)	0.7	10 months/year 6 days/week
Dump Fraction	0.1	Fraction of beam to any one LED
Intensity Fraction	0.5	(Average intensity) / (design intensity)
Yearly fluence, per LED	3.44E20 electrons/year	Design value for LED

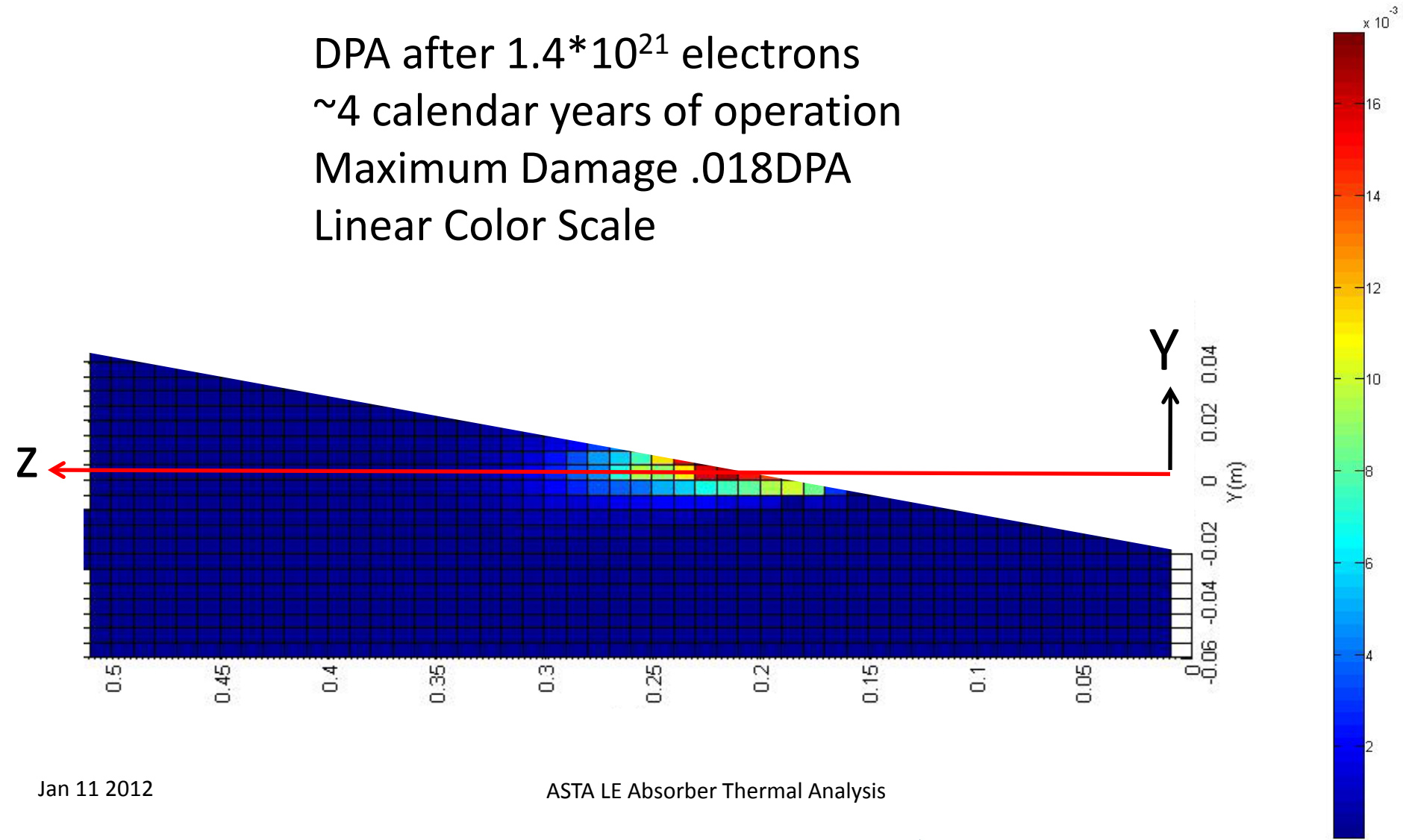
- Given that LED will operate in air, surface temperatures in graphite must be limited  $< \sim 500^{\circ}\text{C}$
- Analysis of damaged LED was iterated until temperatures at End-of-Life approached  $400^{\circ}\text{C}$  (leaving some headroom for pulse effects). This occurred at  $1.4\text{E}21$  electrons, or about 4 calendar years of operation



# MARS Results:

## DPA during expected lifetime in graphite

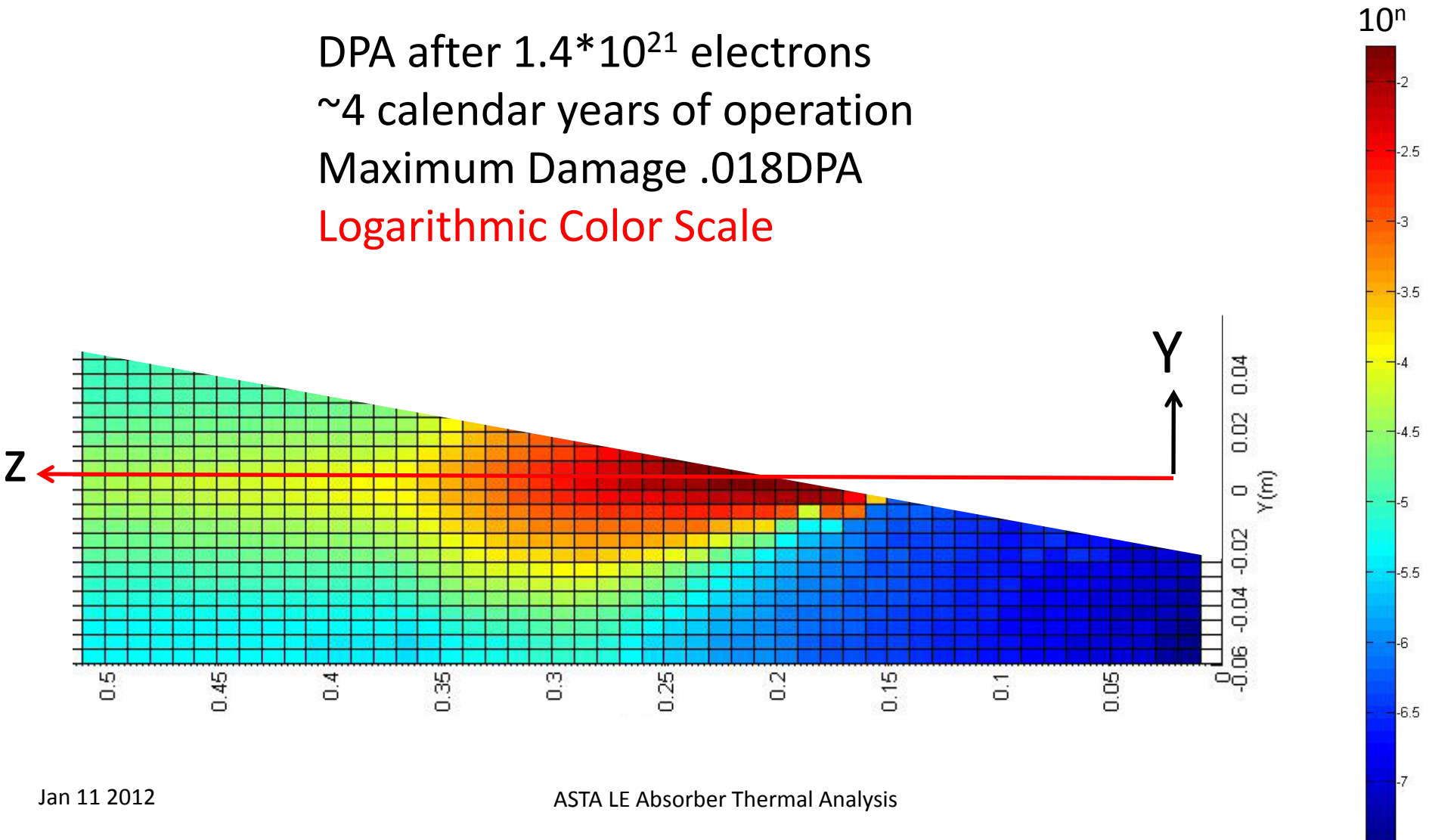
DPA after  $1.4 \times 10^{21}$  electrons  
~4 calendar years of operation  
Maximum Damage .018DPA  
Linear Color Scale



# MARS Results:

## DPA during expected lifetime in graphite

DPA after  $1.4 \times 10^{21}$  electrons  
~4 calendar years of operation  
Maximum Damage .018DPA  
Logarithmic Color Scale



# Radiation Effects:

## Thermal Conductivity Reduction

---

- Irradiation-induced defects collect at the crystal boundaries, and interrupt conduction between crystals.
- This causes the thermal conductivity to assume a complex radiation and temperature dependency.
- Data exist in the literature, but are not entirely consistent
  - Effect begins at low damage levels:  $\sim 0.001$  dpa
  - Effect is less pronounced at high temperatures (material is able to self-anneal to some extent)
- As such, we'll use an envelope approach to conservatively bound the conductivity at all temperatures and all radiation levels.
  - Define four damage levels enveloping the data
  - Define  $k(T)$  for each damage level
  - Comparatively minor variations in  $E$ ,  $\alpha$  are also accounted for
  - In the FEA, assign each element to one of these damage bins

# Radiation Effects: Example Data

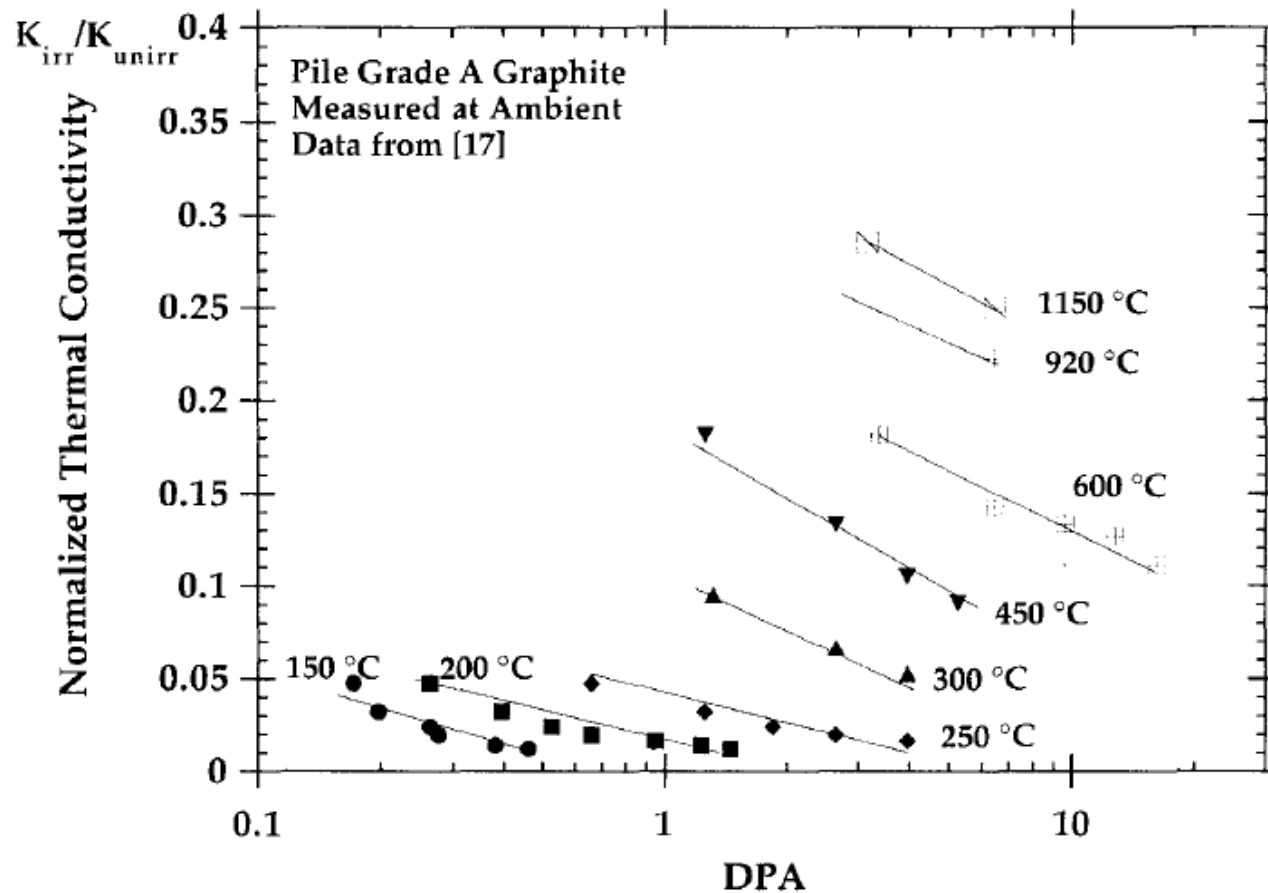
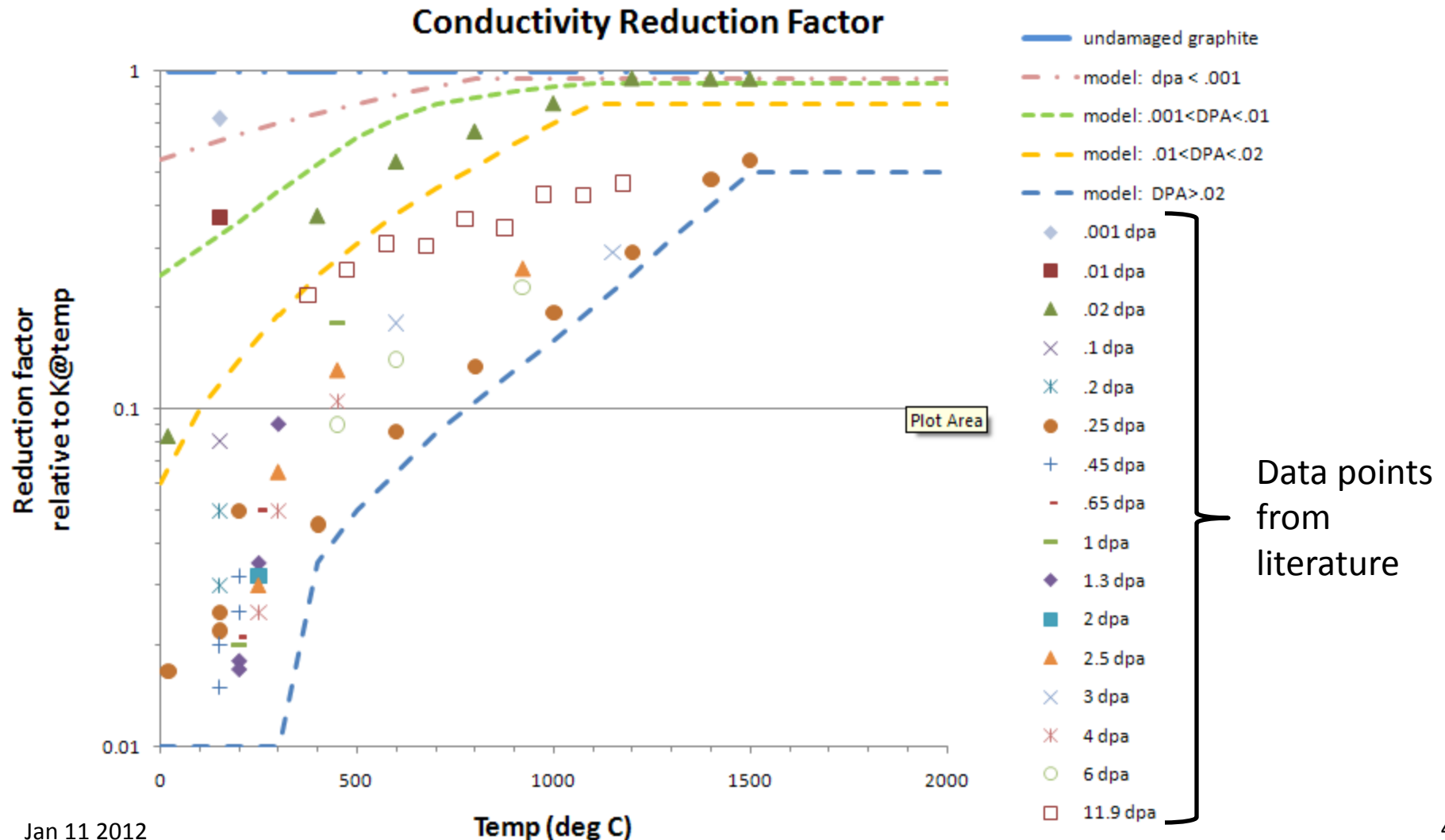


Fig. 5. Normalized thermal conductivity of pile Grade A graphite [17].

# Radiation Effects: Modeled k Reduction Factor

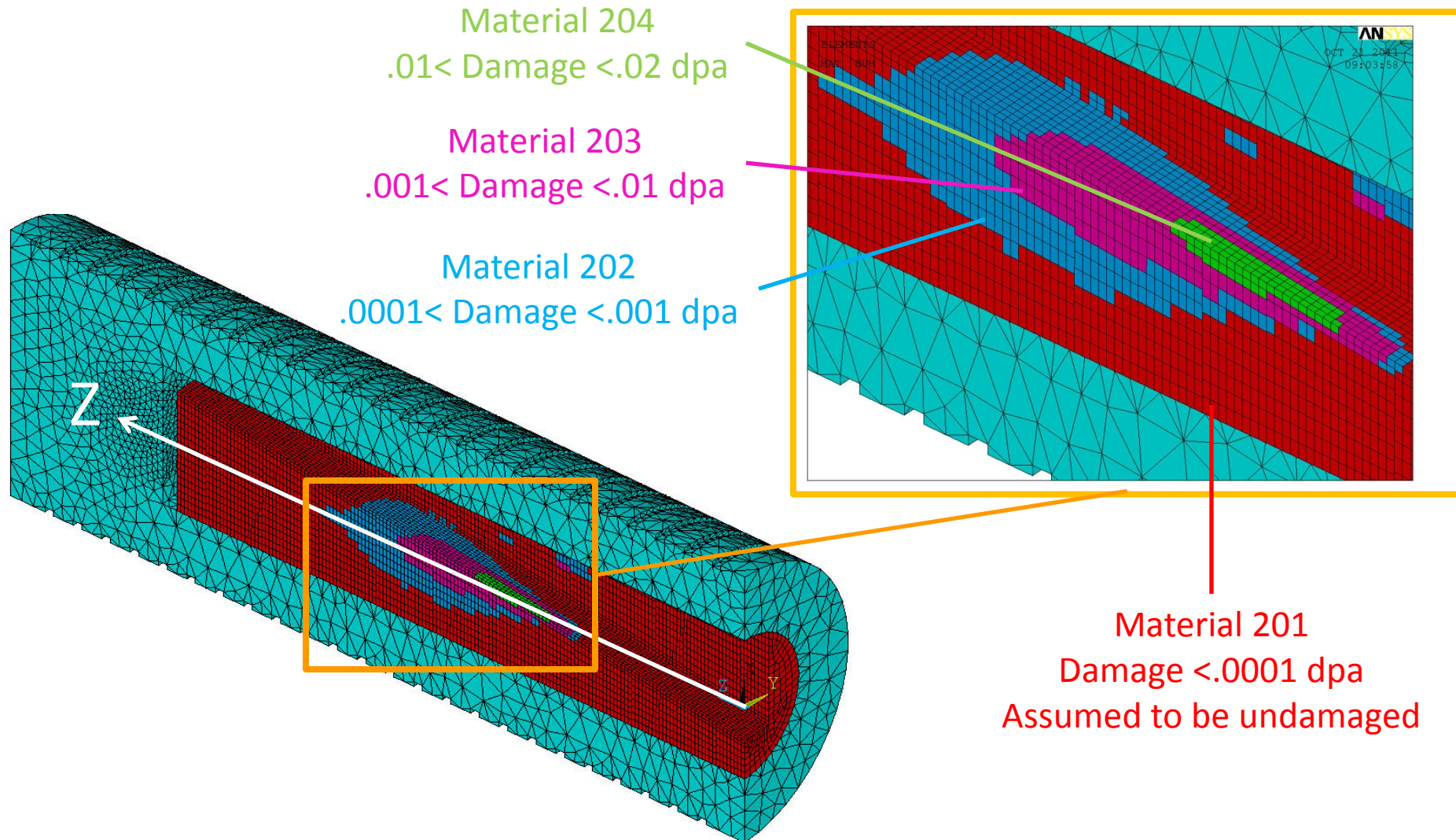


# Damage Mapping on FEA model

---

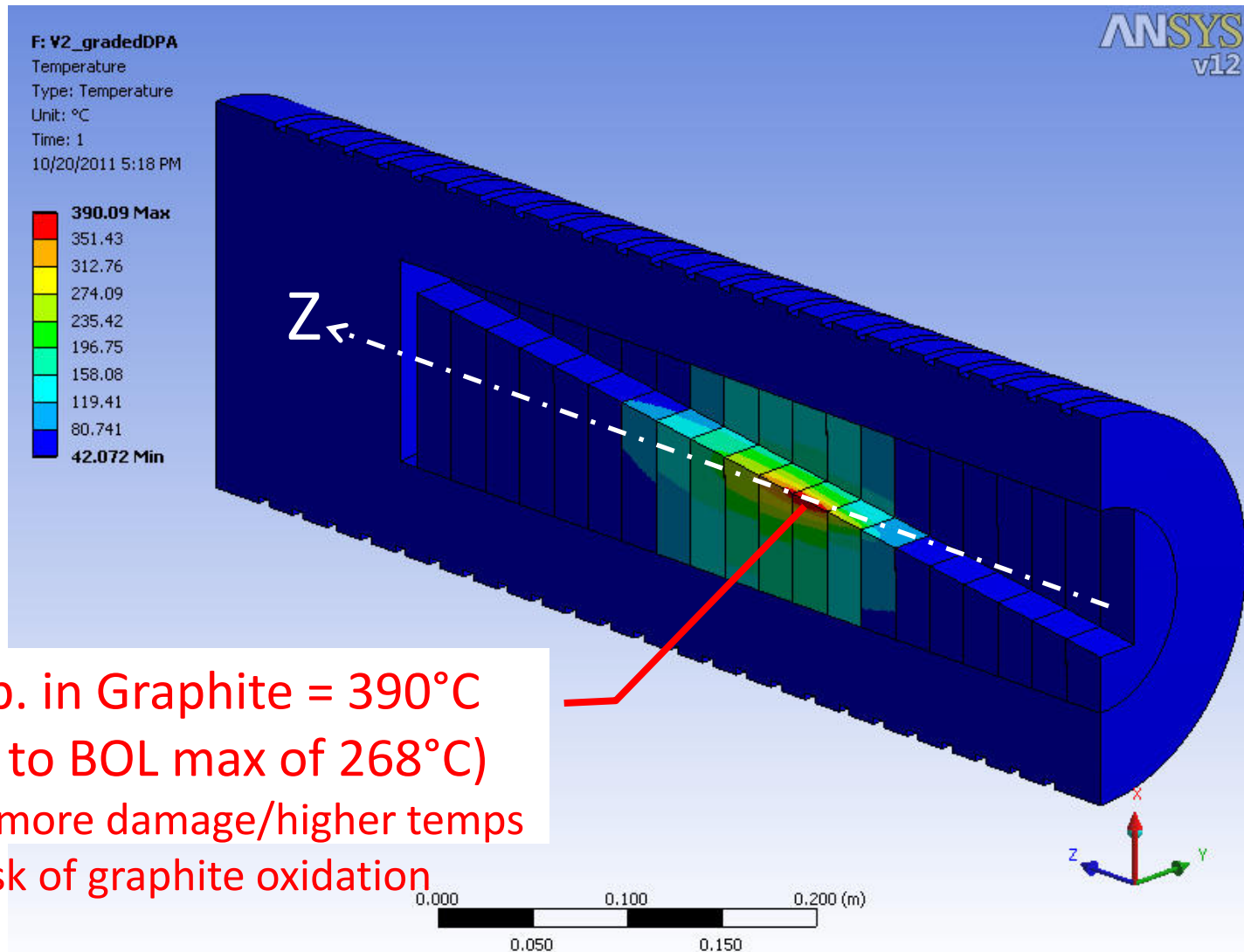
- As shown on the previous slide, discrete materials were defined with thermal conductivity as a function of damage and temperature.
- MARS damage estimates were mapped onto the FEA mesh. Individual elements were “binned” by damage level.
  - Damage mapped from iteratively-determined end of life case, i.e. after fluence of  $1.4E21$  electrons
- Materials were assigned to FEA elements on an element-by-element basis, based upon the MARS damage estimate

# Mapping of k Reduction at EOL on Graphite Core





# System Model Steady State At End-of-Life





# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- **Pulse Transient**
- System Transient Analyses
- Conclusions

# Pulse Transient

---

- Steady-state thermal results are a temporal *and* spatial average
  - Temporal average because we normalize per-electron results to e-/s particle rate
  - Spatial average because beam rastering is implemented in MARS before thermal analysis
- In reality, energy deposition occurs in discrete pulses
  - 1ms pulse @5Hz,  $6.24 \times 10^{13}$  e-/pulse
- Beam is essentially stationary during a pulse: sweeping at 3Hz results in negligible beam motion on the 1ms time scale

# Pulse Transient

---

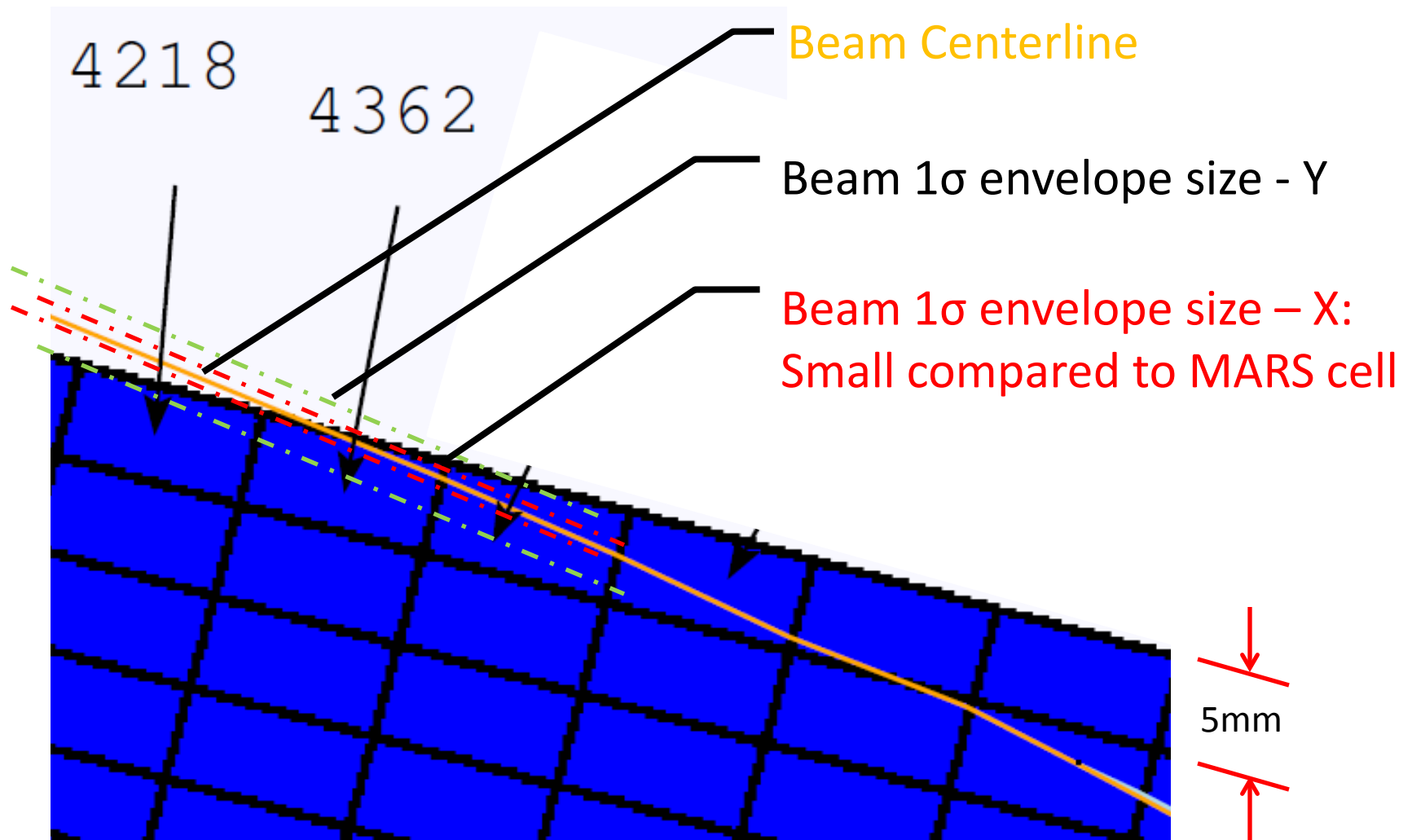
- Each pulse will then create a quasi-instantaneous temperature rise where it strikes the absorber
- The next pulse will affect a different area, due to the beam sweeping
- Neglecting conduction during the pulse, we can estimate the magnitude of the temperature rise
- This temperature rise will add linearly to steady-state temperatures we have calculated

# Beam Size vs. MARS Cell Size

---

- The MARS model was re-run with a non-swept beam to capture single pulse effects (This calculation was re-visited after the review, and expanded to various reduced intensity scenarios. See appendix 1 for this information)
- MARS cell cross section (in a plane whose normal is ~parallel to beam direction) is 5mm X 5mm
  - This is small compared to the swept beam area of 11mm X 11mm
  - This is large compared to the minimum beam size, particularly in the x direction ( $\sigma_x=0.3\text{mm}$ ). So near incidence, before the beam has fanned out, energy deposition will occur over a volume smaller than a MARS cell
- MARS results average energy deposition over the full volume of each element, “smearing” these local effects

# Beam Size vs. MARS Cell Size



# Beam Size vs. MARS Cell Size

---

- A simplified MARS study was done to determine how to scale maximum energy deposition results. The following relationship was confirmed

For cells near beam incidence whose size is  $\gg$  beam size

[Volumetric-average Energy deposition reported for cell ( $\text{W}/\text{m}^3$ )]  
is proportional to  $[1/\text{Cell Volume}]$

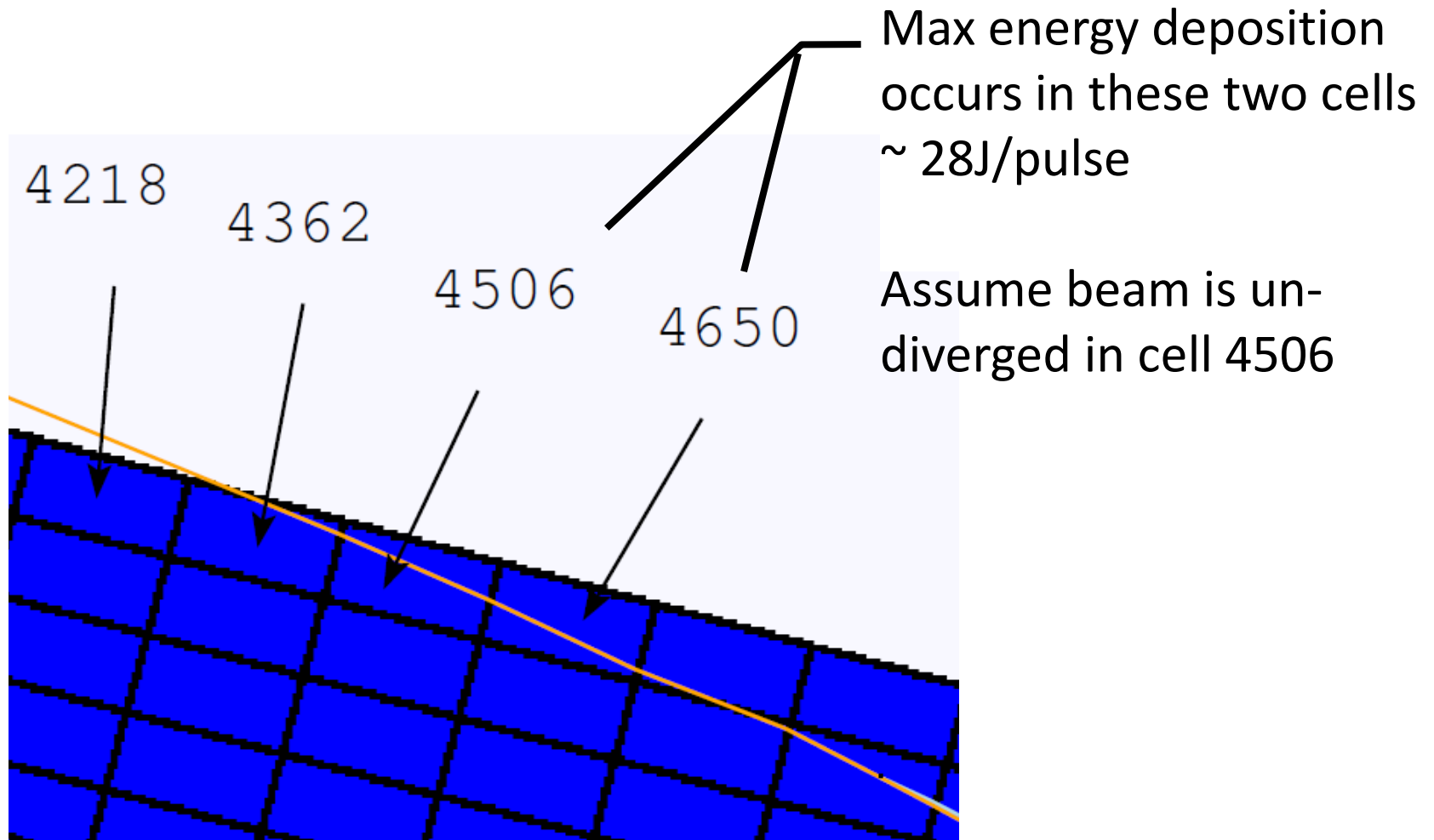
- In cases where the beam size is comparable to the cell size, it is necessary to calculate how much of the beam is hitting a given cell and apply compensation appropriately.

# Beam Size vs. MARS Cell Size

---

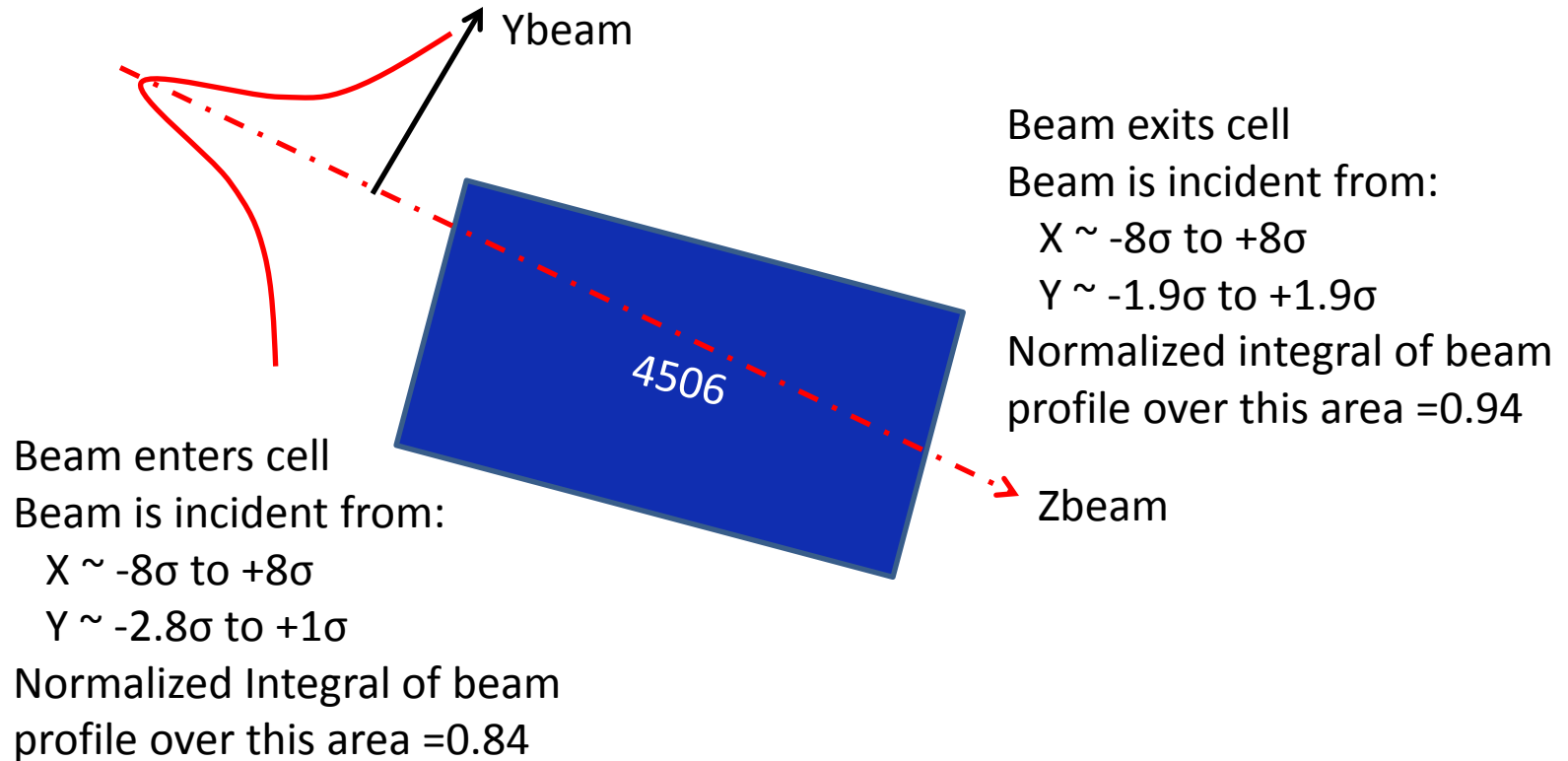
- So, we can use the following method to reconstruct the true peak value of the energy deposition
  - Find MARS cells near beam incidence, before beam has fanned out
  - Assume (conservatively) that beam size is unaffected as it travels through these first few cells
  - Determine area-fraction of the beam that passes through the given cells
  - Calculate the total energy deposited by the full Gaussian beam near incidence
  - Calculate the peak energy deposition of the Gaussian distribution
  - Calculate instantaneous temperature rise

# Beam Incidence



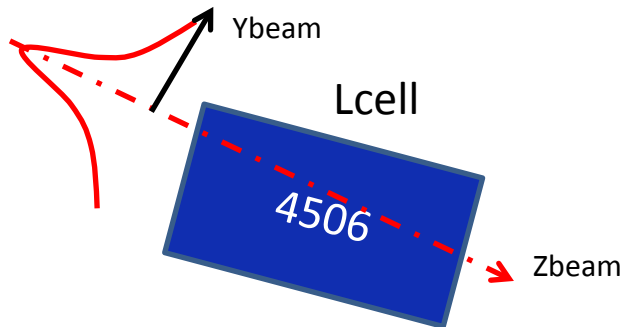


# Beam Profile at Incidence



Averaging these, we estimate that an area fraction  $F_a=0.89$  of the full beam profile is incident on this cell. I.e., if the cell were big enough to capture the full beam profile in Y as well as X, energy deposition reported for the cell would be larger by a factor of  $(1/0.89)$

# Energy Deposition at Beam Incidence



Now, we can estimate the linear energy deposition associated with the beam

$$ED_{pcell} = 27.5 \text{ J/pulse}$$

$$Fa = 0.89$$

$$L_{cell} = 10\text{mm}$$

Energy deposition per pulse, direct MARS result

Area fraction of beam profile passing through this cell

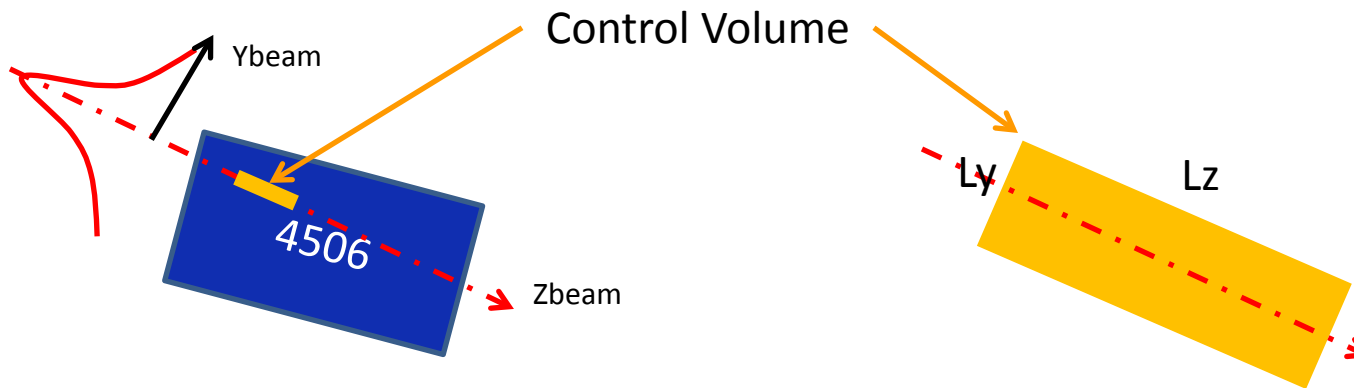
Length of cell along beamline, as modeled in MARS

$$ED_p = ED_{pcell} / (Fa * L_{cell})$$

$$= 3.09 \text{ J/mm/pulse}$$

Linear energy deposition of the full beam per pulse

# Energy Deposition at Beam Incidence



Now, we consider a control volume at the peak of the beam distribution

$$L_x = 0.1\sigma_x = 0.03\text{mm}$$

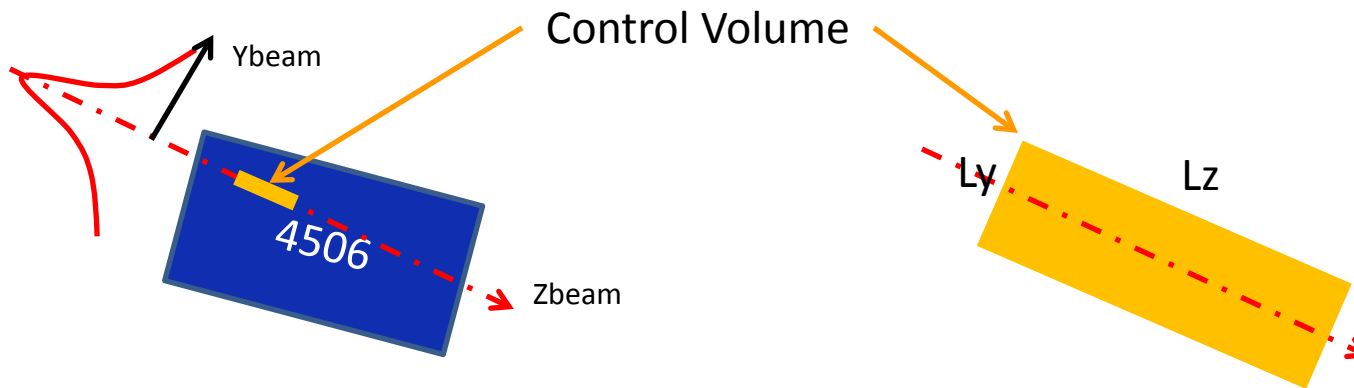
$$L_y = 0.1\sigma_y = 0.13\text{mm}$$

$$L_z = 1\text{mm}$$

$$V_{cv} = .0039\text{mm}^3 = 3.9\text{E-}12 \text{ m}^3$$

Integrating a Gaussian profile over the  $0.1\sigma_x \times 0.1\sigma_y$  footprint of the control volume, we calculate that the control volume will receive a fraction of the beam profile equal to  $F_{cv}=0.00159$ . Note that if the size of  $\sigma_x$  or  $\sigma_y$  were to change, this result would be the same.

# Energy Deposition at Beam Incidence



Now, we can calculate energy deposition within the control volume

$$\begin{aligned} ED_{cv} &= ED_p * F_{cv} * L_z \\ &= 3.09 \text{ J/mm/pulse} * 0.00159 * 1\text{mm} \\ &= 0.00491 \text{ J/pulse in the control volume} \end{aligned}$$

Now, given the density and specific heat of graphite, we can calculate  $\Delta T$

$$\rho = 1720 \text{ kg/m}^3$$

$$c = 550 \text{ J/kg} \cdot \text{K}$$

$$\Delta T = ED_{cv} / (V_{cv} * \rho * c)$$

# Single-Pulse Temperature Rise

$$\Delta T = ED_{cv} / [V_{cv} * \rho * c]$$

$$= [0.00491 \text{ J/pulse}] / [3.9\text{E-}12 \text{ m}^3 * 1720 \text{ kg/m}^3 * 550 \text{ J/kg}^{\circ}\text{K}]$$

$$= 1380^{\circ}\text{K instantaneous temperature jump per pulse!}$$

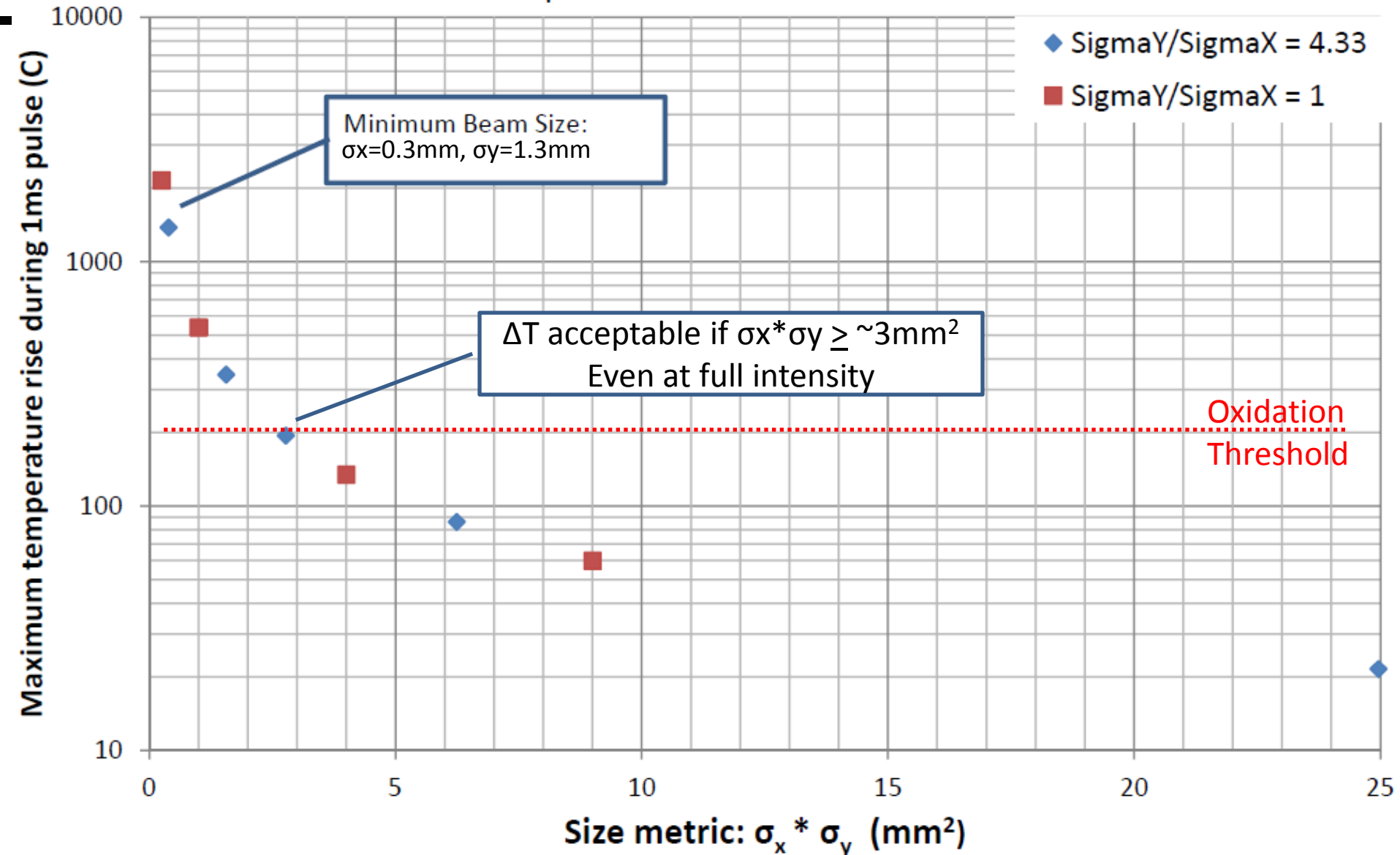
this is for the smallest possible beam at the highest possible intensity

This result was revisited using an explicit MARS model after the review. See appendix for results, predicting slightly higher  $\Delta T$  of 1460 °K

- Given stress and oxidation limits in the graphite, we can only handle an instantaneous temperature rise of  $\sim 200^{\circ}\text{K}$  or less
- Mitigation options include:
  - Increasing minimum beam spot size
  - Increasing effective spot size via fast beam sweeping
  - Decrease beam intensity
    - Temperature jump proportional to particles/pulse
    - Acceptable temperatures if we limited absorbers to  $1.25\text{E}13$  e-/pulse

# Single-Pulse Quasi-Instantaneous Temperature Rise As a Function of Beam Size

1 pulse =  $6.24 \times 10^{13}$  e- in 0.001s



# Pulse Transient: Temperature Conclusions

---

- At the minimum possible spot size and maximum possible intensity, the graphite would be subject to unacceptable damage during individual beam pulses
- Any one of the following measures would protect the graphite
  - At full intensity, ensure a large beam spot size such that  $\sigma_x \cdot \sigma_y \geq \sim 3\text{mm}^2$
  - Implement fast beam sweeping at  $f \geq \sim 350\text{Hz}$
  - Limit intensity at the LED to **1.25E13** e-/pulse (Mike C.'s preference)
  - Combined measures could be considered
- Performing a similar calculation for the Aluminum downstream of the graphite, temperature rise is negligible. The Aluminum portions of the absorber do not impose any constraints.

# Pulse Transient: Induced Stresses

---

- Now, we assess the stress state in the graphite as a result of the pulse transient thermal condition
- Assume mitigation scenario where temperature/oxidation constraint limits maximum beam size to  $\sigma_x \cdot \sigma_y \geq \sim 3\text{mm}^2$
- To see whether stress constraints are more stringent than the oxidization constraint, we assess the stress condition under the following conditions
  - Full intensity:  $6.24\text{E}13$  e-/per pulse
  - $\sigma_x \cdot \sigma_y = 3\text{mm}^2$ ,  $\sigma_x = \sigma_y = 1.7\text{mm}$
  - Single pulse instantaneous rise calculated near the beam incidence location, beam divergence assumed to be small
  - Temperature field in graphite imported for structural analysis

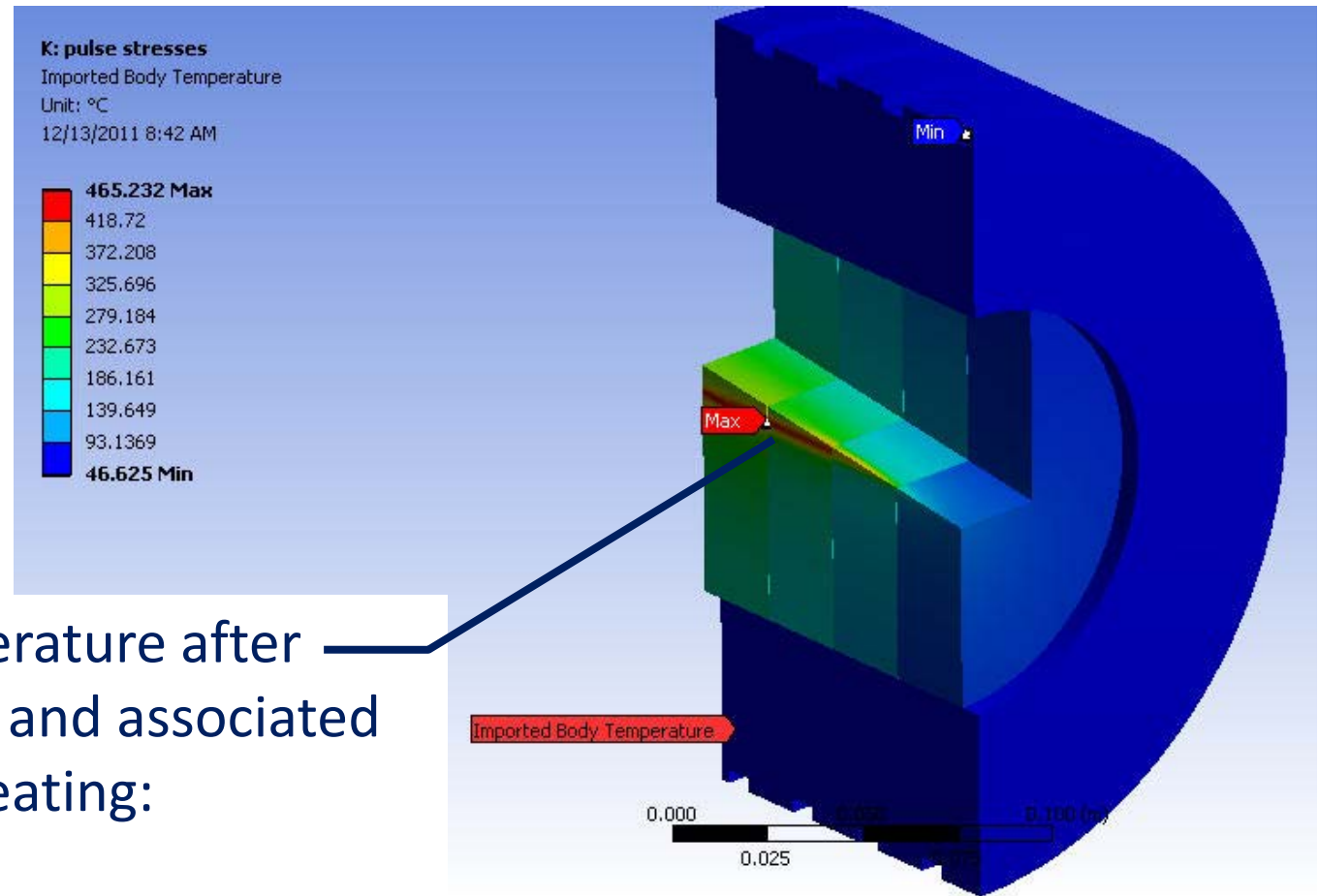


# Pulse Transient: Induced Stresses

---

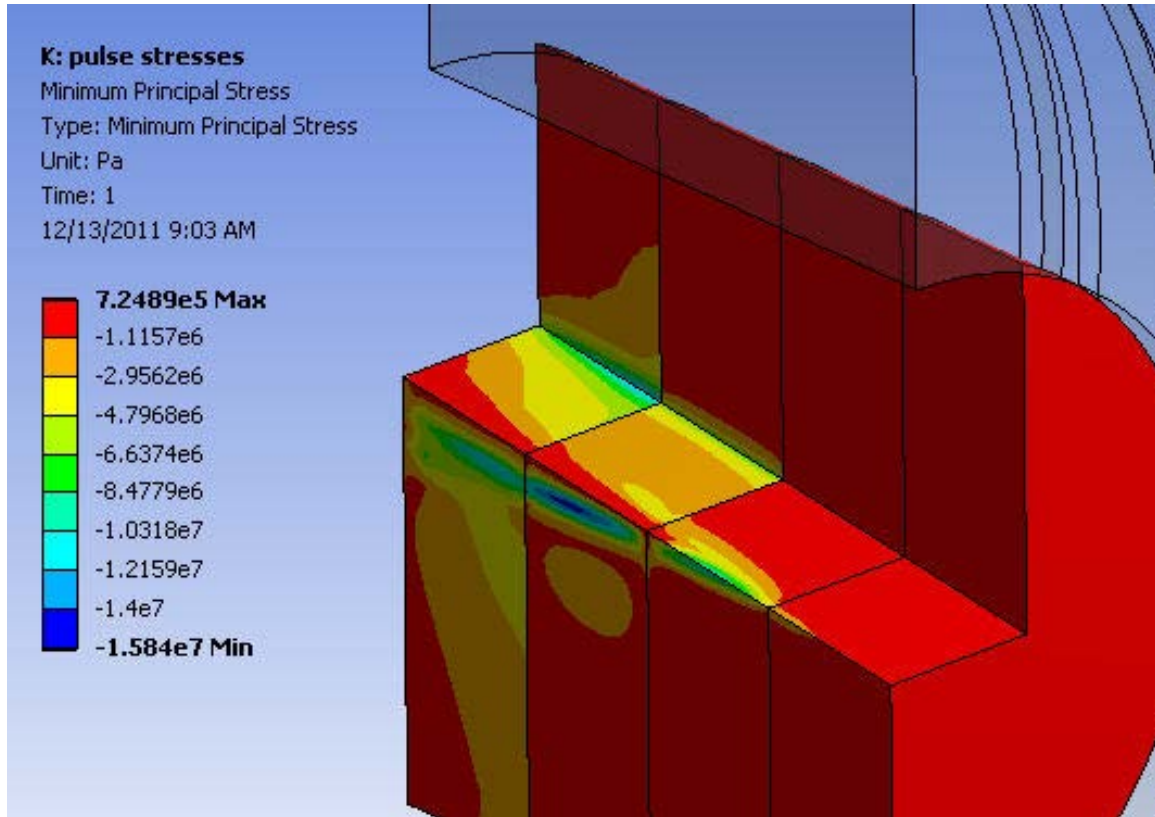
- Graphite IG-110 mechanical strength (per vendor datasheets)
  - Max flexural strength: 39MPa (5.5 ksi)
  - Max compressive strength: 78MPa (11 ksi)
- Calculate graphite stresses as follows:
  - Compare maximum principal stress to flexural strength
  - Compare minimum principal stress to compressive strength

# Pulse Transient: Temperature Field



Maximum temperature after  
passage of pulse and associated  
instantaneous heating:  
465° C

# Pulse Transient: Induced Stresses



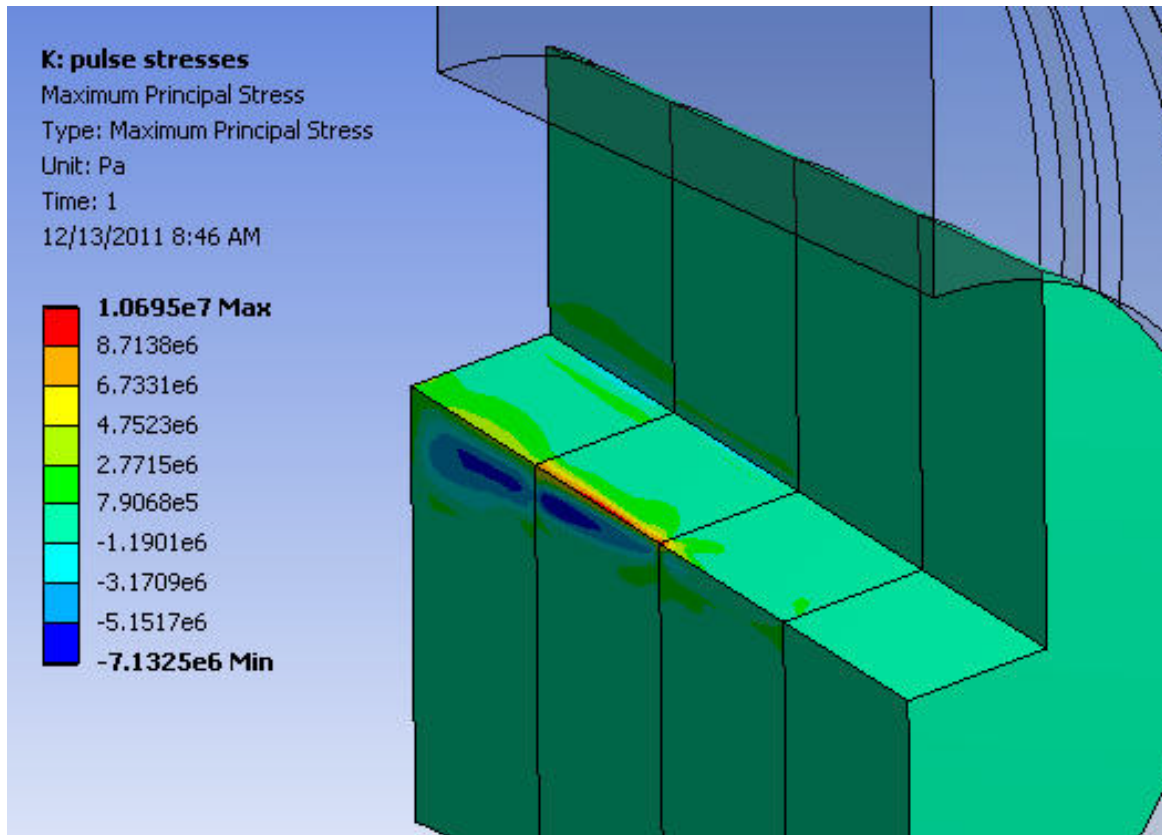
Minimum principal stress  
in graphite:

-15.8 MPa (-2.3 ksi)

Compare to strength of  
78MPa

$$\text{FOS} = 78/15.8 = 4.9$$

# Pulse Transient: Induced Stresses



Maximum principal stress  
in graphite just after  
passage of pulse:

10.6 MPa (1.5ksi)

Compare to strength of  
39MPa

$$\text{FOS} = 39/10.6 = 3.7$$

# Pulse Transient: Stress Conclusions

---

- Mechanical stresses are acceptable at beam size condition  $\sigma_x \cdot \sigma_y = 3\text{mm}^2$ . However, there is a preference for the intensity-reduction mitigation approach. See appendix for details.
- Maximum Principal Stress factor of safety of 3.7 is comfortable for a brittle material
  - If we defeated the oxidization constraint (for example by providing inert atmosphere) we could accept a slightly smaller factor of safety and go to a slightly smaller beam size
  - This would only be a marginal improvement – stress constraints would not permit the  $\sigma_x = 0.3\text{mm}/\sigma_y = 1.3\text{mm}$  beam size at full intensity

# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- **System Transient Analyses**
- Conclusions

# System Transient Analyses

---

- Three system transient analyses were run
  - Pulse decay case was run to characterize how long single-pulse temperature jumps persist and to look at pulse-superposition effects
  - The cold start beam-on transient case was run to characterize the warm-up time of the system
  - As a possible accident scenario, case of cooling water failure was considered.

# Pulse Decay Case

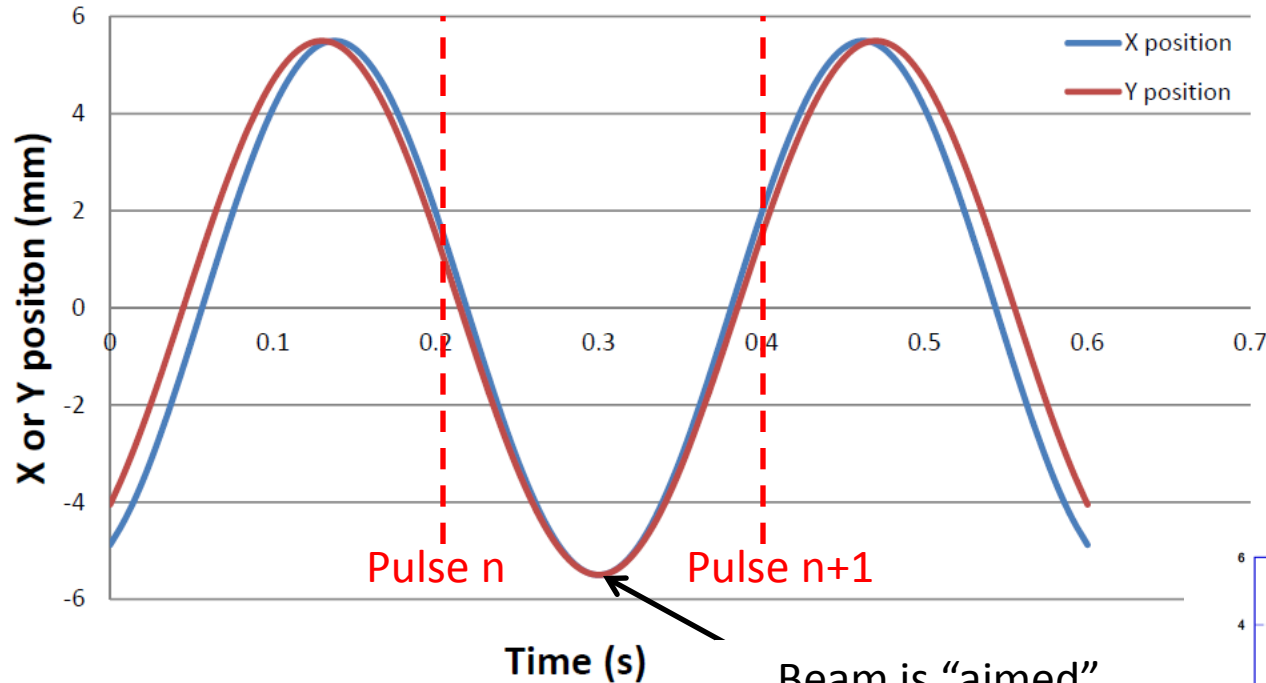
---

- Recall that beam sweeps sinusoidally in X and Y, at slightly different frequencies
- Assume that time-phasing between X and Y sweeping functions will be random
- A case exists where two subsequent pulses land in the same location of the absorber
  - This occurs when the both X and Y sweeping functions “aim” the beam at a corner of the sweeping pattern midway between two pulses

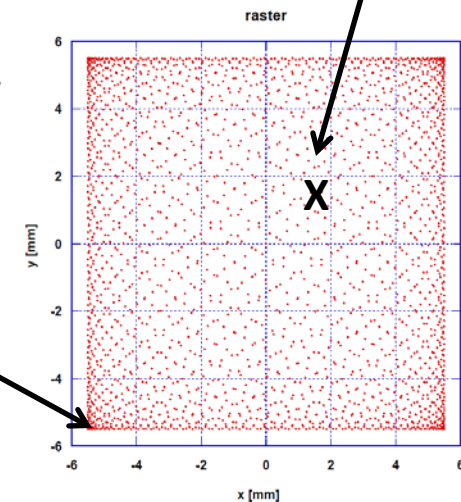


# Pulse Superposition: Rare but possible condition

Pulse Superposition

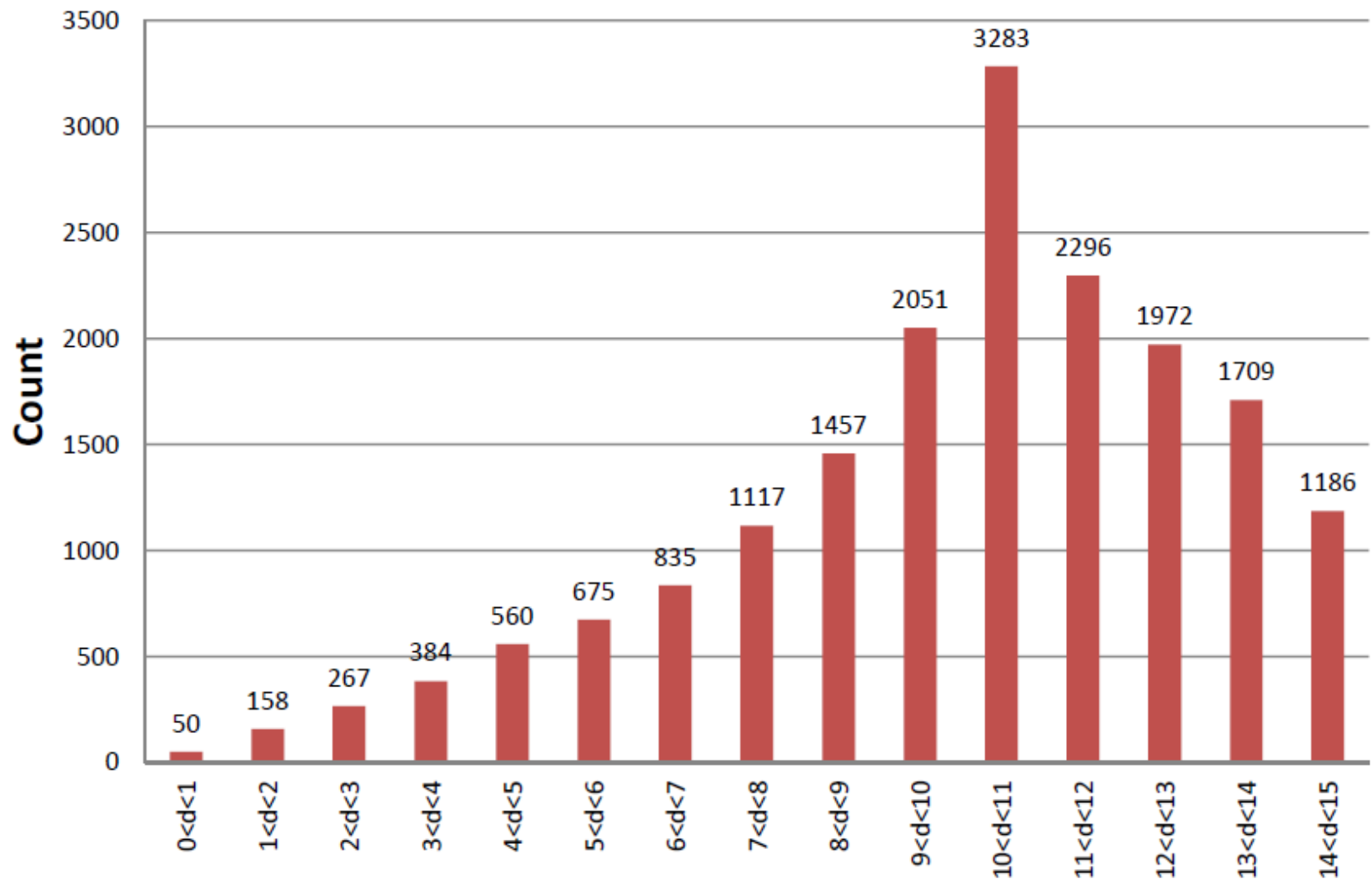


Pulse n+1 lands on  
top of pulse n here



# Histogram: pulse-to-pulse distances

18K pulses = 1 hour runtime



Distance Bin:

Distance "d" (mm) between location of pulse n and pulse n+1  
in a plane of normal to beam direction

# Pulse Decay Case

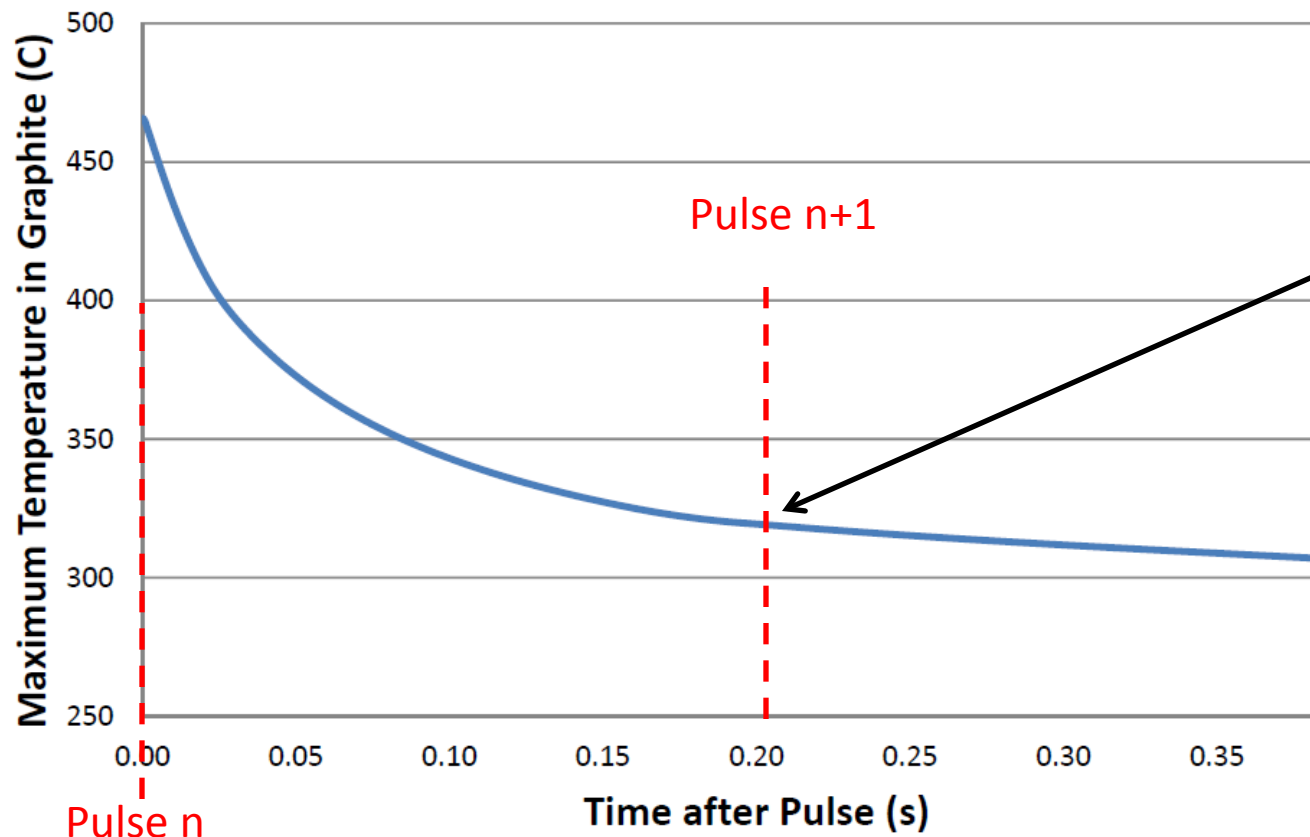
---

- Given that superposition will occur, how far have pulse-induced temperatures decayed after the 0.2s inter-pulse period?
- Assumptions
  - Same input pulse as stress analysis:
    - Full intensity:  $6.24 \times 10^{13}$  e-/per pulse
    - $\sigma_x * \sigma_y = 3 \text{ mm}^2$ ,  $\sigma_x = \sigma_y = 1.7 \text{ mm}$
    - Single pulse instantaneous rise calculated near the beam incidence location, beam divergence assumed to be small
    - Incident beam centered on absorber. This is slightly conservative, because pulse superposition can only occur 2-3mm off-center

# Pulse Decay

## Temperature Decay After Pulse

full intensity pulse:  $6.24 \times 10^{13} \text{ e-}$ ,  $\sigma_x * \sigma_y = 3 \text{ mm}^2$



Temperature jump caused by pulse n+1 will occur here. Hand-calculated  $dT = 176^\circ \text{C}$  (per method shown starting on slide 55)

Max temperature in graphite will jump to  $494^\circ \text{C}$ . Approaching, but below, self-imposed oxidization limit

# Pulse Decay Case: Conclusions

---

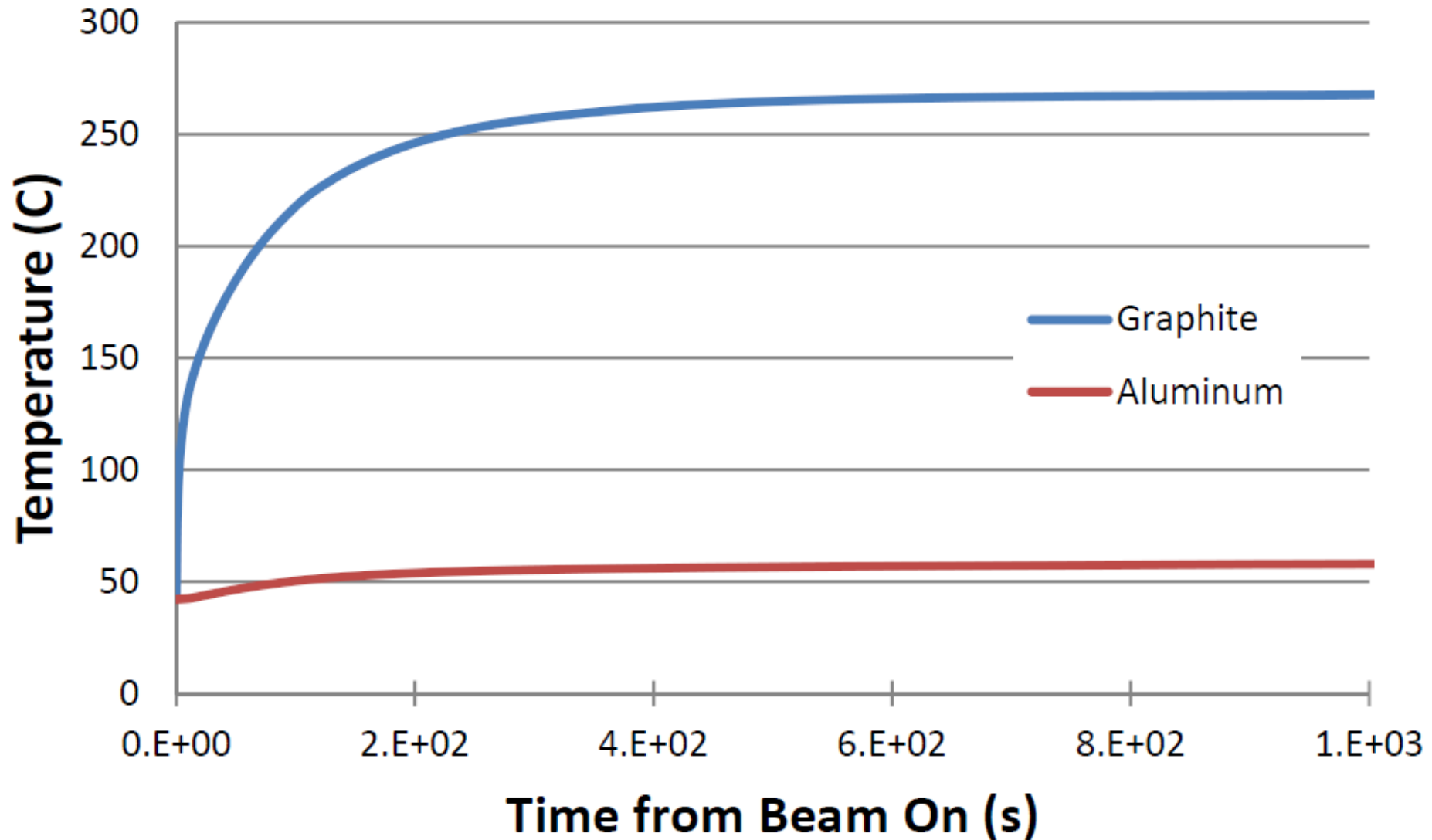
- After the 0.2s inter-pulse period temperatures have decayed >75% of the way back to their steady-state value
- In the case where subsequent pulses hit the same area, we will see temperatures approaching our limit of 500° C
  - This is for the derived-minimum-limit beam size ( $\sigma_x = \sigma_y = 1.7\text{mm}$ ), at maximum intensity
- In the more usual case where pulses hitting a given area are separated by  $\geq 0.4\text{s}$ , we will see very little effect from previous pulses

# Warm Up Transient

---

- When we introduce beam to a cold absorber, how long will it take for mature temperature profiles to develop?
- Assumptions
  - 2.5kW temporally-averaged energy deposition
  - Same model and parameters as presented in steady-state analysis section
  - Absorber starts at assumed cooling water temperature of 40°C
- Conclusion: temperature profile is fully developed after ~10 minutes

# Warm Up Transient



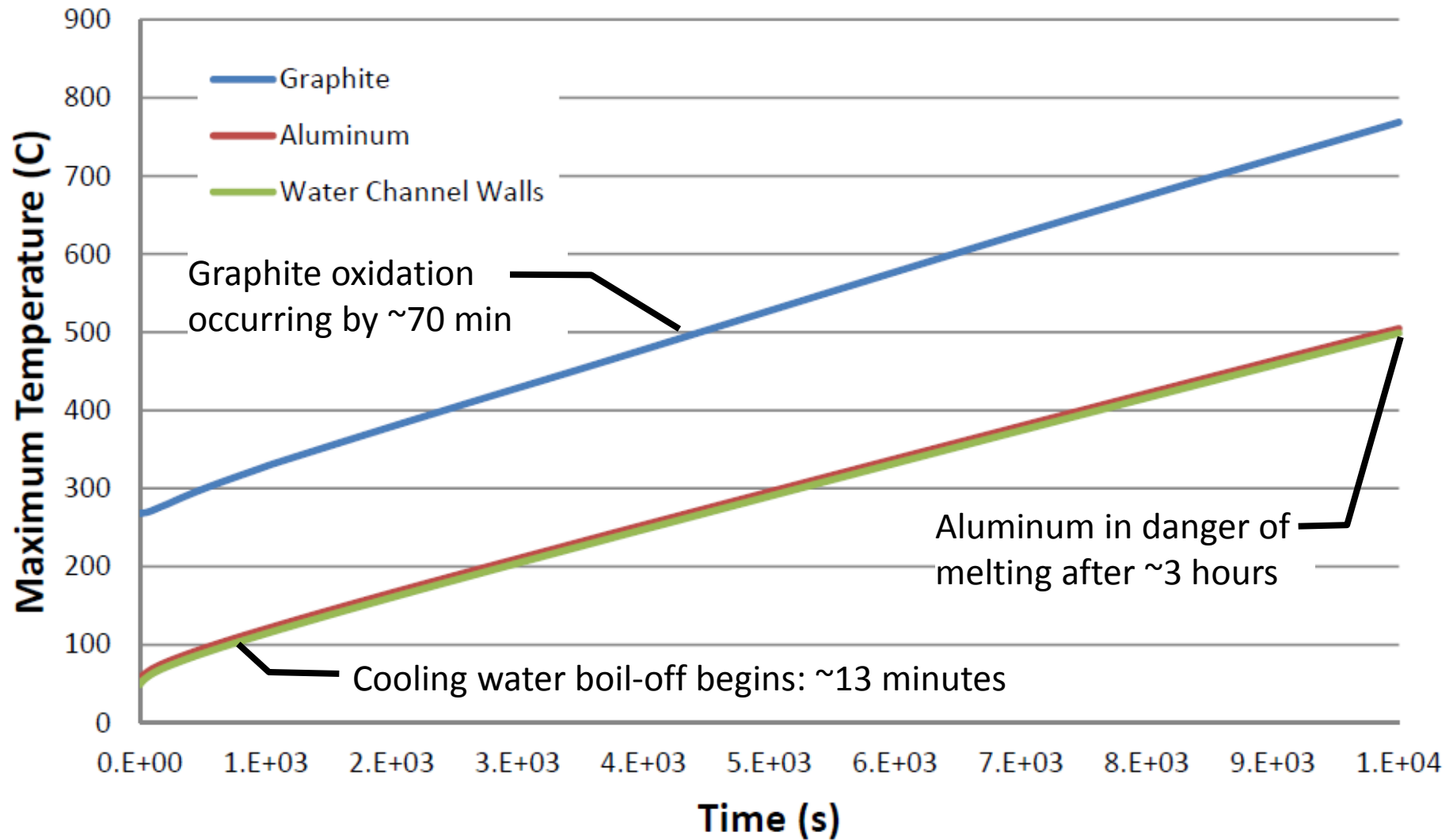
# Runaway Transient

---

- As a possible accident scenario, case of cooling water failure was considered.
- How long do we have before something fails?
- Assumptions
  - Neglect natural convection and conduction to steel
  - Neglect phase change (boil-off) in cooling water
  - Assume continued application of 2.5kW beam power
  - Beginning-of-life graphite material properties



# Runaway Transient: Cooling Water Failure



# Runaway Transient @BOL

## System temperatures after 10,000s

H: Run-away Transient

Temperature

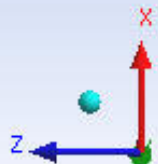
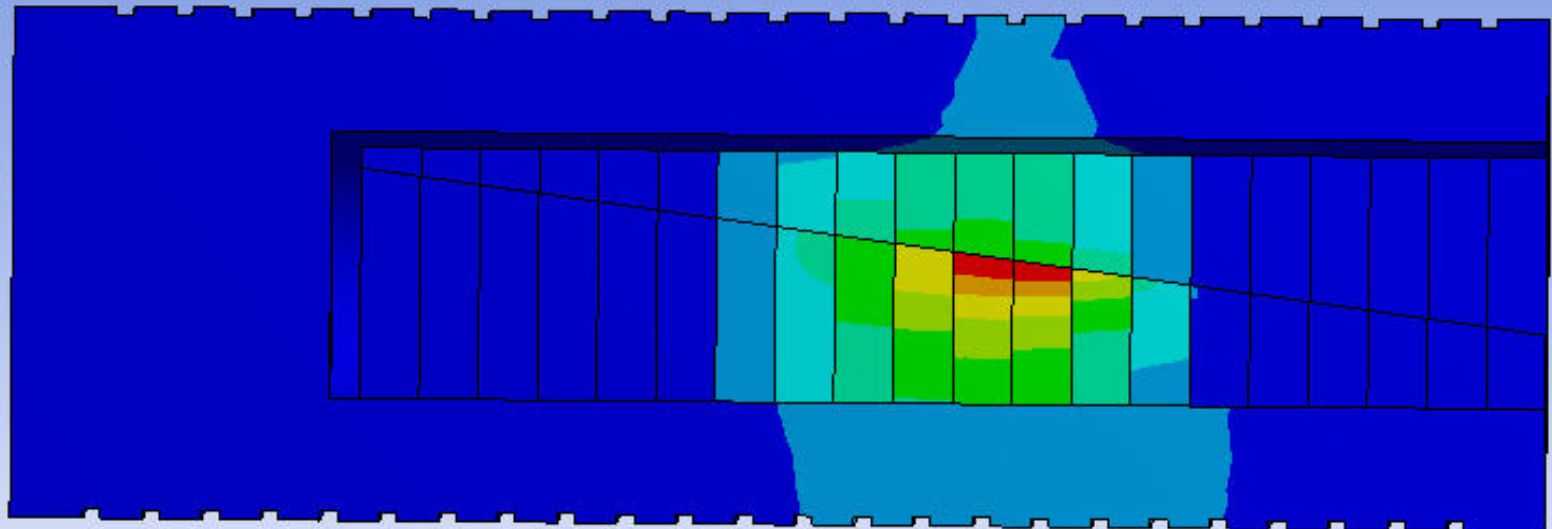
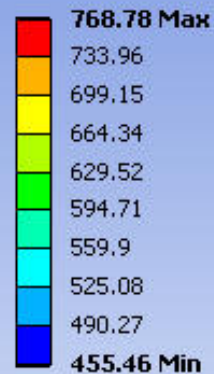
Type: Temperature

Unit: °C

Time: 10000

11/3/2011 11:58 AM

ANSYS  
v12



# Runaway Transient @BOL

## Aluminum temperatures after 10,000s

H: Run-away Transient

Temperature 2

Type: Temperature

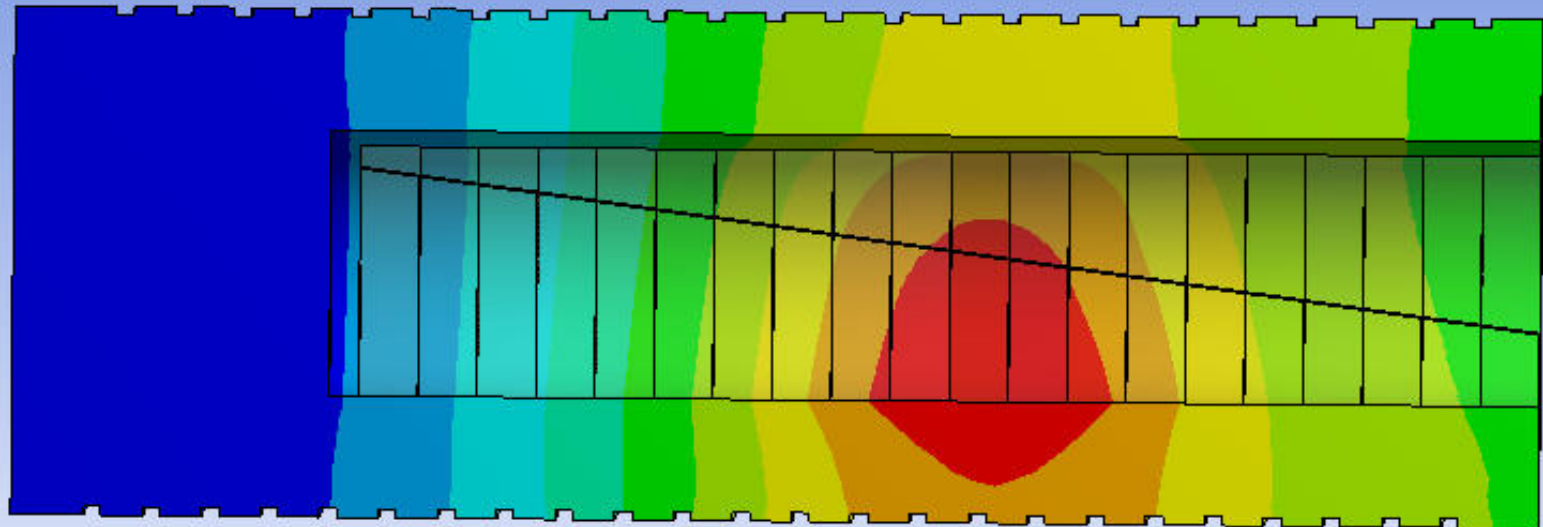
Unit: °C

Time: 10000

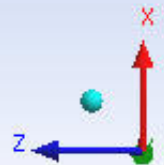
11/3/2011 11:59 AM

ANSYS  
v12

504.74 Max  
499.27  
493.79  
488.31  
482.84  
477.36  
471.89  
466.41  
460.93  
455.46 Min



0.000 0.100 0.200 (m)  
0.050 0.150



# Runaway Transient: Conclusions

---

- For the runaway transient, the considerable thermal capacitance of Aluminum shell allows us to survive an accident for a reasonable period of time
  - Permanent damage to LED would occur after ~1 hour
  - Catastrophic failure would occur after ~3 hours
- This should be plenty of time to detect the fault and turn the system off

# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions

# ASTA Low Energy Beam Absorber Thermal Analysis: Conclusions

---

- There are a few open issues that will need to be resolved by further testing and/or system wide decisions:
- Graphite/Aluminum thermal contact must achieve minimum value of  $\sim 250 \text{ W/m}^2\text{K}$ . Existing data and worst-case calculations indicate that this should not be a problem. However, we should get confirmation from planned window testing.

# ASTA Low Energy Beam Absorber Thermal Analysis: Conclusions

---

- In order to prevent graphite damage due to individual pulses, we must either:
  - At full intensity, ensure a large beam spot size such that  $\sigma_x * \sigma_y \geq \sim 3\text{mm}^2$
  - Implement fast beam sweeping at  $f > \sim 350\text{Hz}$
  - Limit intensity at the LED to  $1.25\text{E}13$  e-/pulse. (Preferred approach, see appendix for additional analysis)
  - Consider some combined measure
- Given that these open issues are tractable, the thermal design of the LED is acceptable

# Questions and Discussion

---

- Included in the scope of this review
  - Configuration of the ASTA Low Energy Dumps
  - Thermal analysis methodology and results
- Excluded from the scope of this review
  - Radiation analysis and shielding assessment
- Review Charge: please review the configuration and thermal analysis of the low energy dumps and assess whether
  - Absorber configuration is appropriate
  - Analysis assumptions, method, and results are reasonable
  - System is ready to move on to detailed mechanical design



# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions
- Appendix 1 – Reduced Intensity Cases.
- Appendix 2 – 55MeV Analysis

# Appendix 1 – Reduced Intensity Cases

---

- The analyses described above...
  - Identified a stress and temperature issue caused by individual beam pulses at the *maximum* possible intensity ( $6.24\text{E}13$  e-/pulse) and the *minimum* possible beam size ( $\sigma_x = 0.3\text{mm}$ ,  $\sigma_y = 1.3\text{mm}$ )
  - Presented three possible mitigations:
    - At full intensity, ensure a large spot size such that  $\sigma_x * \sigma_y > \sim 3\text{mm}^2$
    - Implement fast beam sweeping at  $f > \sim 350\text{Hz}$
    - Limit intensity at the LED to  $1.25\text{E}13$  e-/pulse
  - Focused on the beam spot size mitigation option

# Appendix – Reduced Intensity Cases

---

- In reviewing this analysis package, Mike C. determined that the intensity limitation mitigation would be the most practical to implement
- In a design review held on 11-Jan-2012, the review panel requested explicit analysis associated with the reduced intensity cases
- Specific review recommendations w.r.t. beam intensity
  - Rather than using a scaling approach, build an explicit MARS model to quantify peak single-pulse heating effects
  - Revisit stress and temperature analyses for low-intensity scenarios

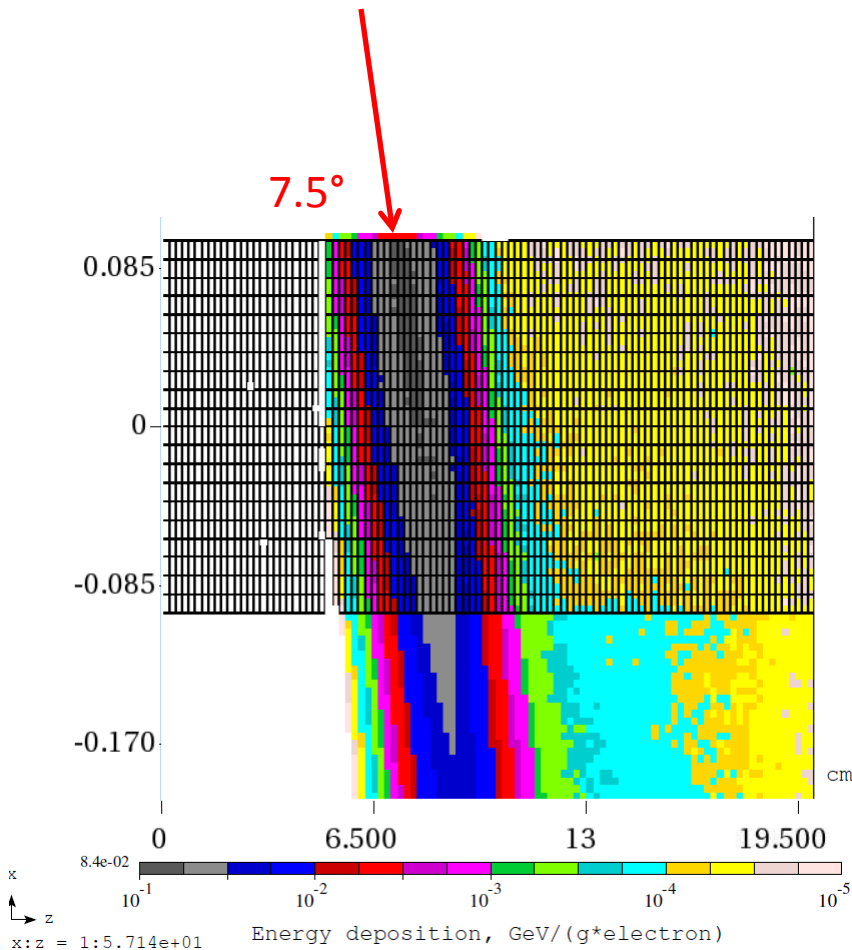
# Review Recommendations: MARS model for single-pulse effects

---

- In the presented analysis, a scaling approach was used to calculate the Gaussian peak of the local, instantaneous energy deposition associated with single pulses. (See slides 50-61)
- The review panel recommended building an explicit, fine MARS model to better capture beam incidence effects and confirm the scaling approach
- Igor Rakhno built such a model
  - MARS element sizes are very fine as compared to beam size:  
 $0.1\sigma_x \times 0.1\sigma_x \times 1\text{mm}$
  - Peak energy deposition compares well ( $\sim 10\%$ ) with that obtained by scaling approach
  - This explicitly modeled value is considered to be more accurate, and is used for subsequent single-pulse calculations in this appendix.

# Review Recommendations:

## MARS model for single-pulse effects



- Localized High-resolution MARS model built for beam incidence area
- Maximum energy deposition (very near beam incidence) = .0802 GeV/(g\*e-)
- This compares well with calculation done by large-cell scaling. This estimate is ~9% higher.

# Analysis Approach for Reduced Intensity Cases

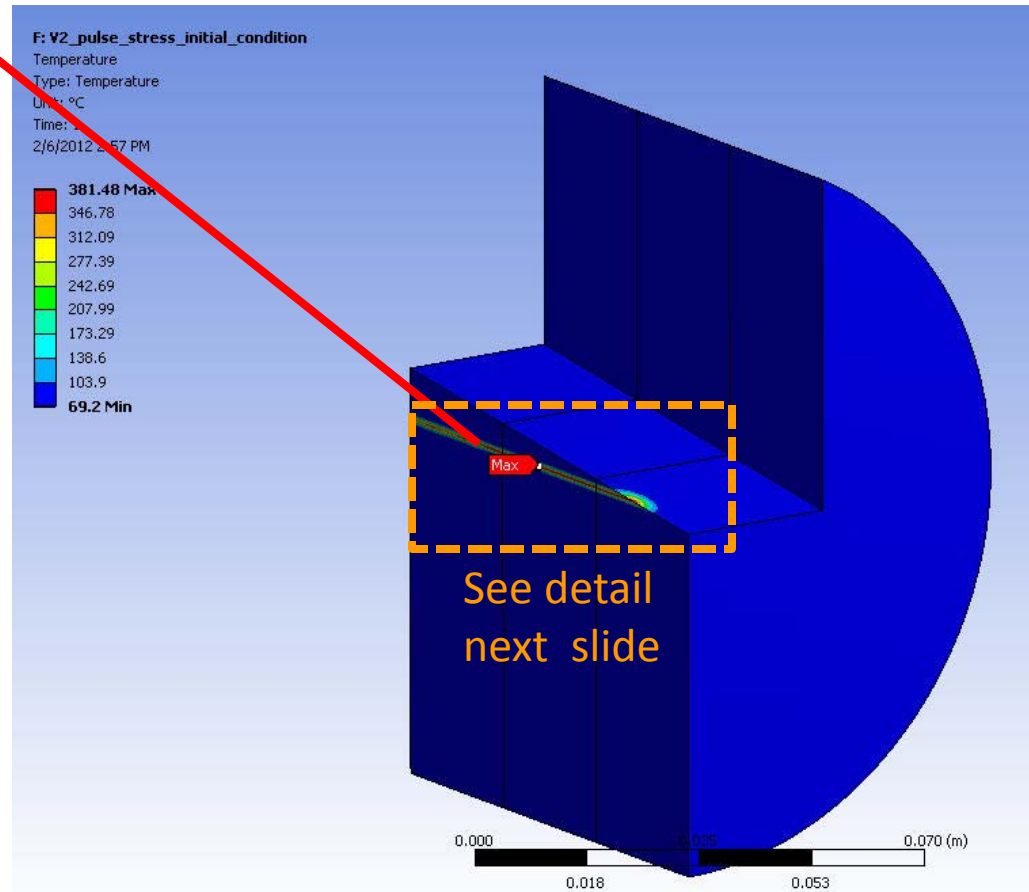
---

- Define intensity reduction factor
- Calculate “steady state” (temporal average) temperatures using BOL graphite properties
- Calculate single-pulse temperature rise, add to steady state temperatures
- Assess temperature and stress condition just after passage of pulse
- Assess pulse decay transient and EOL cases
- Determine intensity limits

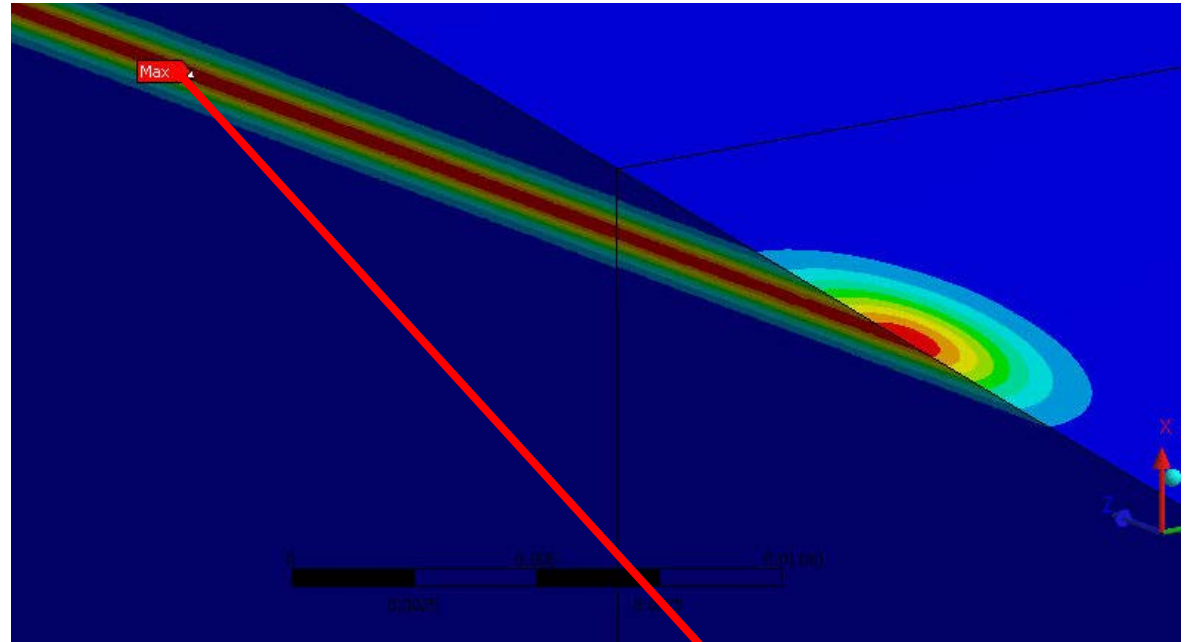
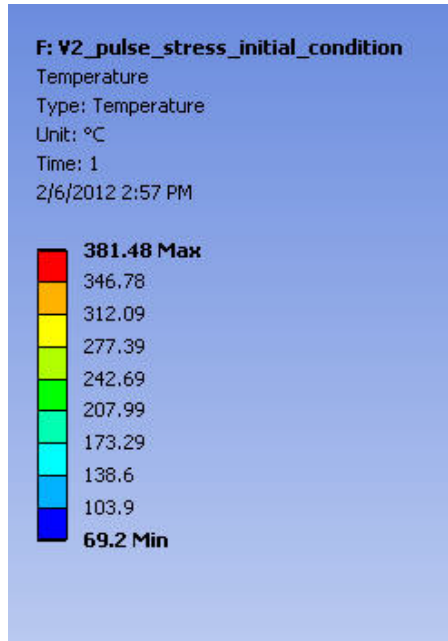
# Example Result: Pulse Transient Temperature Field at 0.20X intensity

Maximum temperature after passage of pulse and associated instantaneous heating:  
381° C (0.20X intensity)

This represents the temp. field of a single pulse added to a steady-state temp. profile. (Structure of steady state profile is not visible due to color map scaling)



# Example Result: Pulse Transient Temperature Field at 0.20X intensity



Maximum temperature after passage of pulse and associated instantaneous heating:  
381° C (0.20X intensity)

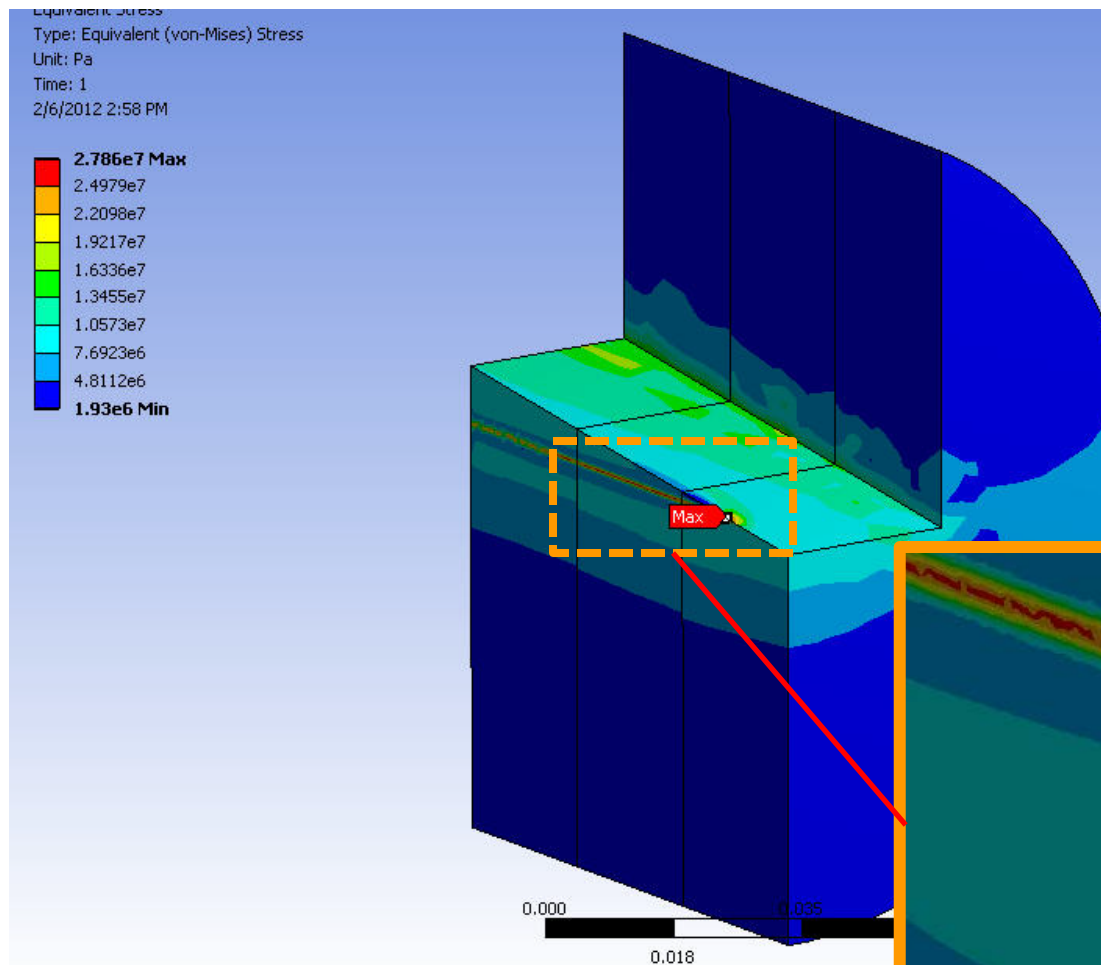


# Example Result: Pulse Transient Induced Stresses at 0.20X intensity

---

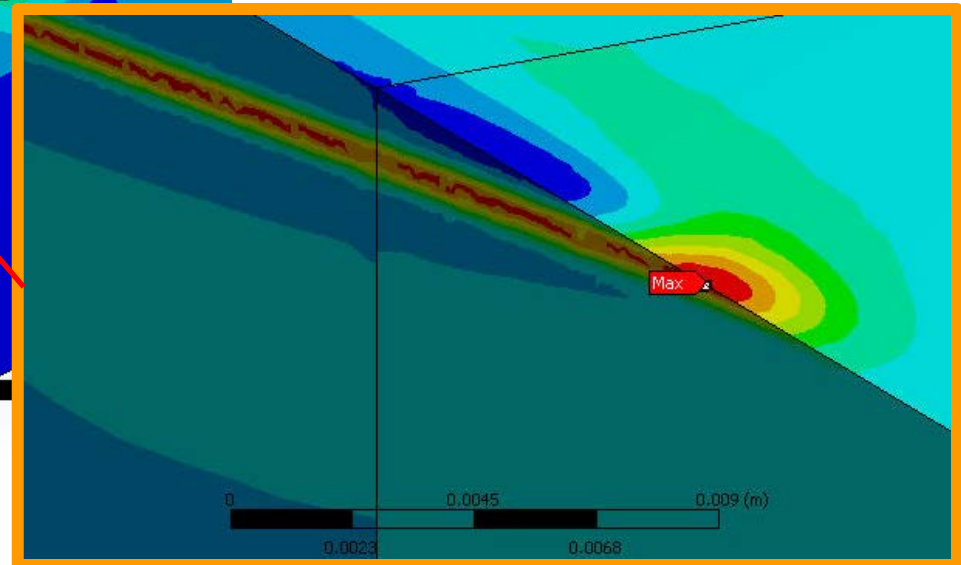
- Graphite IG-110 mechanical strength (per vendor datasheets)
  - Max flexural strength: 39MPa (5.5 ksi)
  - Max compressive strength: 78MPa (11 ksi)
- Calculate graphite stresses as follows:
  - Compare maximum principal stress to flexural strength
  - Compare minimum principal stress to compressive strength

# Example Result: Pulse Transient Von Mises Stresses at 0.20X intensity

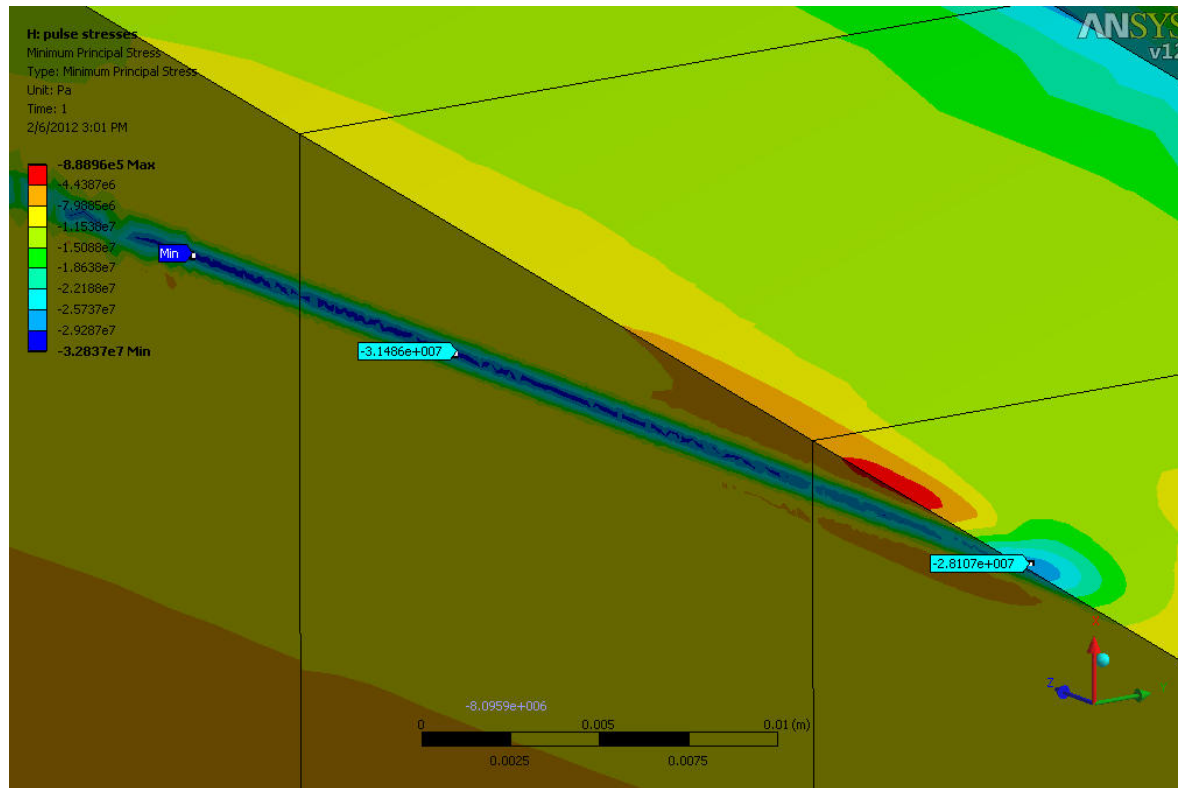


Von Mises Stress field just after passage of pulse:

Not a valid failure criterion for a brittle material, but informative about the interplay/imbalance between stress components



# Example Result: Pulse Transient Min. Principal Stress at 0.20X intensity



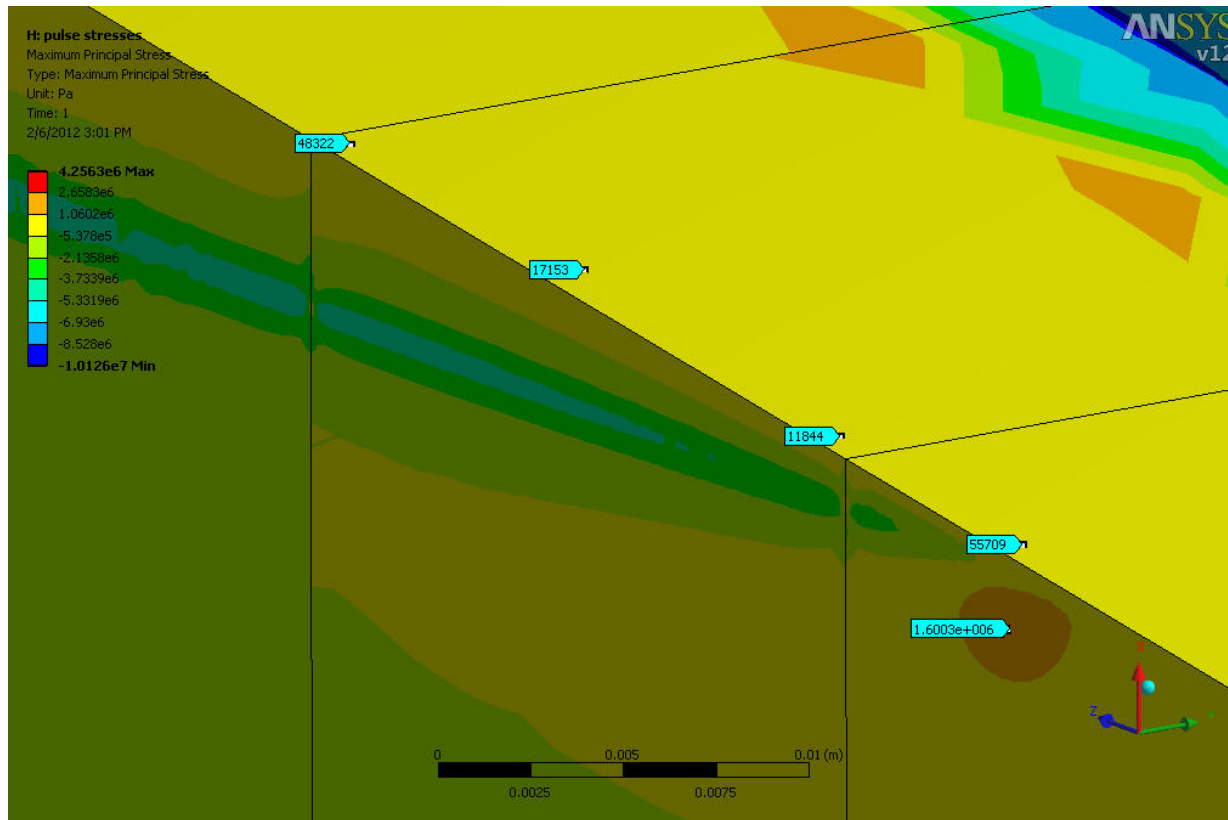
Min principal stress in  
graphite just after passage  
of pulse:

32.9 MPa (4.8ksi)

Compare to flexural  
strength of 78MPa

$$\text{FOS} = 78/32.9 = 2.3$$

# Example Result: Pulse Transient Max. Principal Stress at 0.20X intensity



Maximum principal stress in graphite just after passage of pulse:

1.6 MPa (0.2ksi)

Compare to flexural strength of 39MPa

$$FOS = 39/1.6 = 24$$

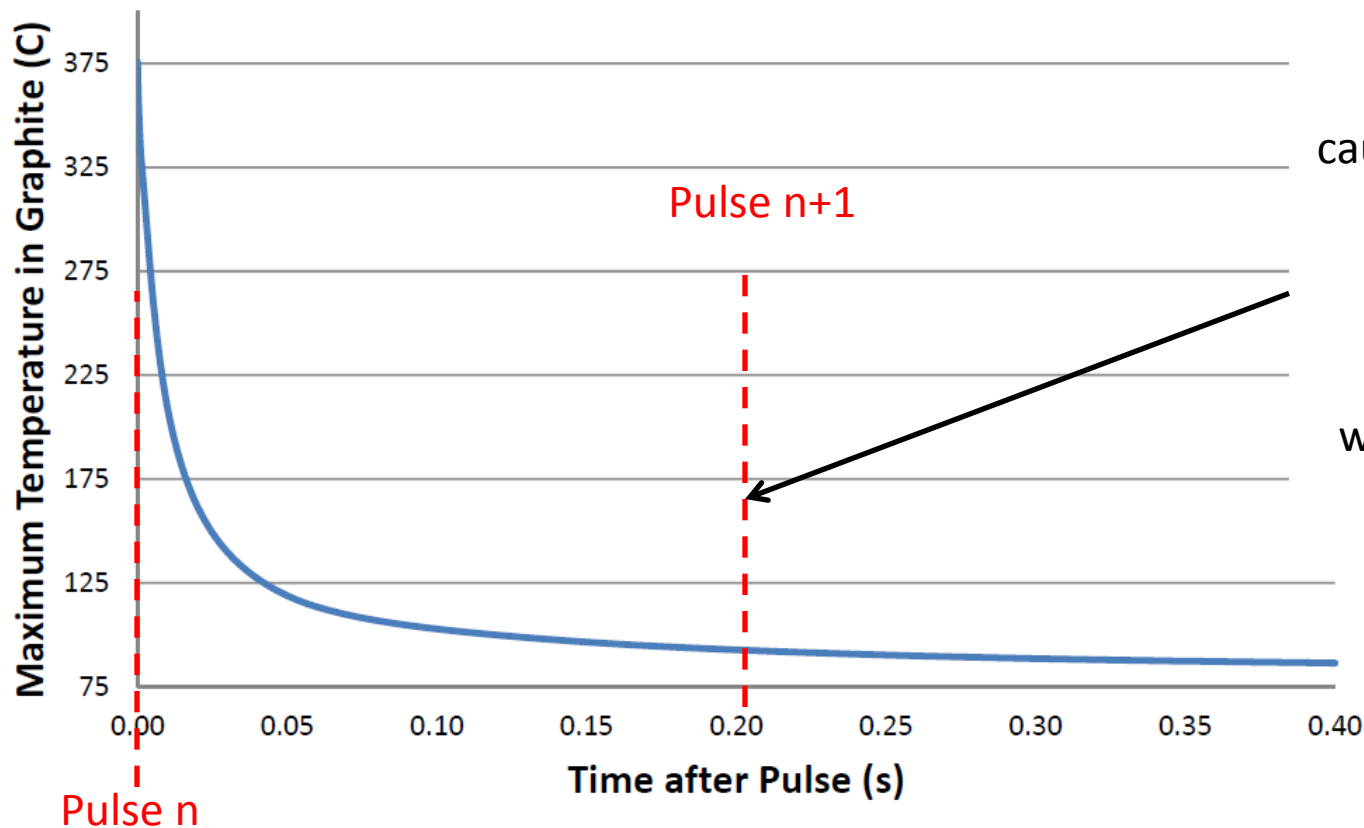
FOS on this tensile-type stress is high, in part because part is biased in compression by shrink fit

# Example Result: Pulse Transient

## Temperature decay at 0.20X intensity

### Temperature Decay After Pulse

20% intensity pulse,  $\sigma_x=0.3\text{mm}$   $\sigma_y=1.3\text{mm}$



Temperature jump caused by pulse n+1 will occur here.

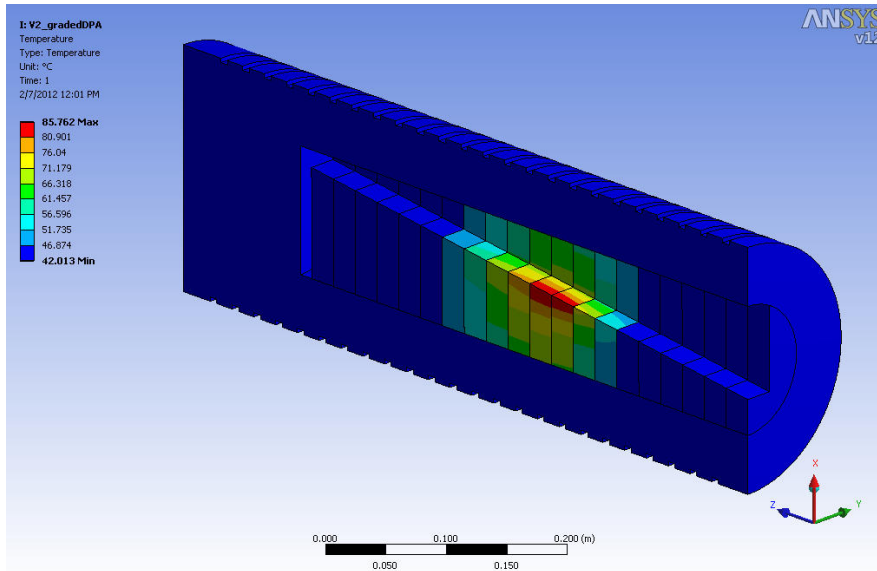
Temperatures have already decayed to within ~7°C of steady-state value

# Reduced Intensity Pulse Decay Cases: Conclusions

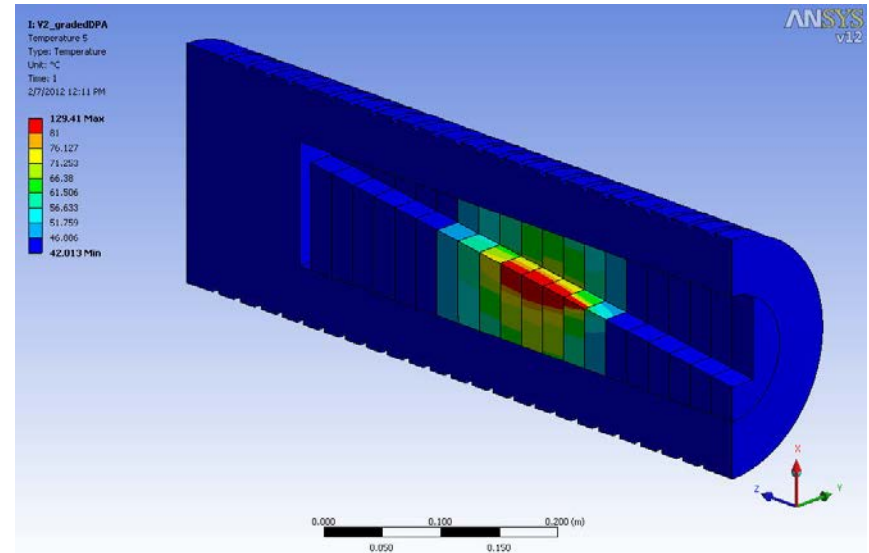
---

- After the 0.2s inter-pulse period temperatures have decayed nearly all the way back to their steady-state value
- Due to the smaller size of the affected volume and the lower energy deposited, the decay is much quicker in the reduced intensity cases.
- Occasional pulse superposition is not a concern at reduced intensity

# Example Result: BOL vs EOL Steady State Temps at 0.20X intensity



Beginning of Life (BOL)  
Max. Temperature = 86°C\*



End of Life (EOL)  
Shown on same color scale  
After 1.4E21 electrons total  
~ 20 calendar years  
See slide 47 for damage map  
Max. Temperature = 129°C\*

\* These are temporal-average temperatures; instantaneous single pulse effects add linearly to these

# BOL vs EOL Analyses at Reduced Intensity

- For all analyses, assumed damage caused by  $1.4\text{E}21$  electrons
  - This corresponded to  $\sim 4$  calendar years at full intensity
  - More like  $\sim 20$  calendar years at 20% intensity
  - On decade-ish timescales, absorber lifetime is more likely to be limited by other factors
- As damage accumulates...
  - Thermal conductivity is reduced, increasing temporal-average steady state temperatures modestly
  - Heat capacity and density are unchanged (to first order), **so magnitude of per-pulse temperature jumps is not affected (see slides 60-61 for relevant equation)**



# BOL vs EOL Analyses at Reduced Intensity

---

- In contrast to the full intensity/large spot size cases, in reduced intensity/small spot size cases, temperatures are driven much more by pulse effects than steady state temperatures
- For reduced intensity cases, though steady state temperatures increase modestly at EOL, this is a small contributor to overall stress and temperature limits
- Additionally, it would take much longer to achieve the assumed EOL damage condition at reduced intensity, making other failure modes more likely
- Graphite damage and EOL performance is much less of a driver at reduced intensity

# Reduced Intensity Results

---

- Preceding slides described the analysis method at one intensity condition (20% intensity)
- Similar analyses were performed at a few intensity conditions to establish an intensity limitation for this design
- Results tabulated on next slide

# Absorber Performance vs. Intensity Reduction

for smallest expected beam size:  $\sigma_x=0.3\text{mm}$   $\sigma_y=1.3\text{mm}$

Intensity Factor	e- per pulse	Max. Temp (C) [1]	Min. Factor of Safety [3]	Comments
1.00	6.24E13	1745°C	Not evaluated	By inspection, stresses unacceptable
0.50	3.12E13	890°C	0.9 [4]	Stresses unacceptable, even if temperature constraints were defeated by inert atmosphere
0.25	1.56E13	466°C [2]	1.9	Stresses and temperatures simultaneously becoming marginal
0.20	1.25E13	381°C [2]	2.3	Stresses and temperatures are reasonable

[1] Maximum instantaneous temperature at BOL just after pulse passage. In the absence of inert atmosphere, compare to material oxidation threshold of 500 °C

[2] Add ~45C at EOL

[3] Driving case was min. principal (compressive) stresses just after passage of a pulse, in all cases

[4] Material failure expected for  $FOS \leq 1$

# Reduced Intensity: Observations

- For the smallest expected beam size, we can operate reasonably at 20% intensity,  $1.25 \times 10^{13}$  e-/pulse
  - This limit is higher than the previously estimate of  $9 \times 10^{12}$  e- per pulse, which was based on a less rigorous calculation
- Absorber will be approaching oxidation and stress limits at 25% intensity. We could consider operating here, but there would be some risk to the absorber. The absorber is replaceable, so that risk might be acceptable.
- Stress limits are encountered at approximately the same intensity condition as oxidization limits. If we were to remove the oxidization concern by adding inert atmosphere, it wouldn't buy us very much.

# Reduced Intensity: Conclusions

---

- Recommend implementing an intensity limit of 20%,  
1.25E13 e-/pulse

# ASTA Low Energy Beam Absorber Analysis Outline

---

- System Overview and Configuration
- MARS Analysis Inputs
- Material and Fluid Analysis Inputs
- Thermal Model
- Steady State Analysis and Beginning of Life Performance
- Radiation Damage and End of Life Performance
- Pulse Transient
- System Transient Analyses
- Conclusions
- Appendix 1 – Reduced Intensity Cases.
- **Appendix 2 – 55MeV Analysis**

# Appendix 2 – 55MeV Analysis

---

- Component measurements suggest that we may be able to achieve higher-than-expected beam energy out of the injector
- Mike Church requested re-analysis at a beam energy of 55MeV
- Assumed “20% Intensity” Scenario for all re-analysis (1.25E13 e-/pulse, 10μA average beam current)
- Analyses performed
  - Single-pulse energy deposition
  - Steady state thermal condition at Beginning of Life
- Conclusion: Increase to 55MeV beam energy has very little thermal effect on the system

# Single-Pulse energy deposition @55MeV

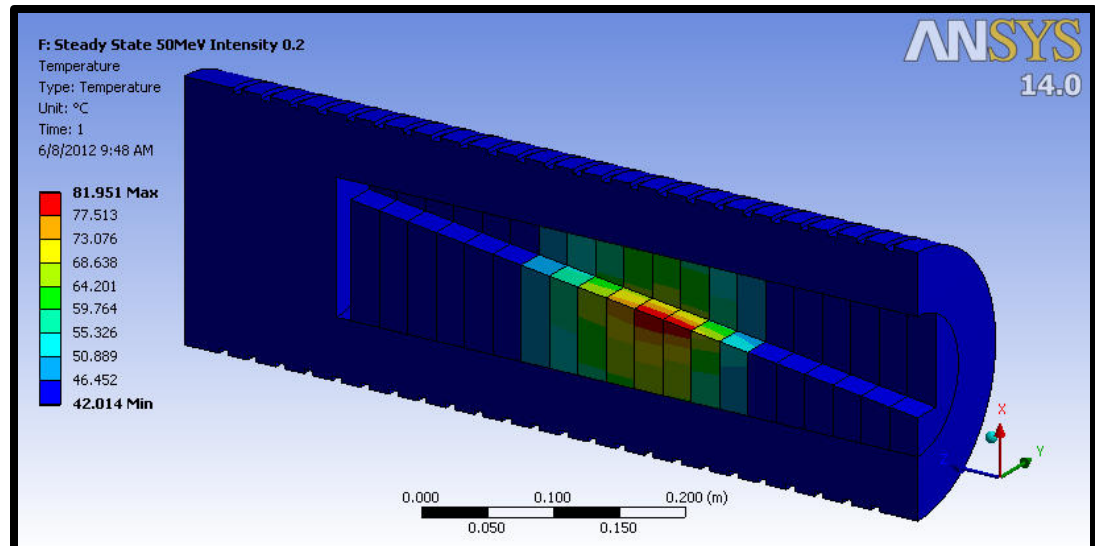
- A fine-meshed MARS model is used to assess peak values of energy deposition near the surface
- Analysis method is described starting on p.94 of this package
- Results at 55MeV are identical to results at 50MeV to within the precision of the calculation

Metric	Result @50MeV	Result @55MeV
Peak Energy Deposition (at surface)	.0802 GeV/(g*e-)	.0800 GeV/(g*e-)
Maximum pulse-induced instantaneous temperature rise, for 20% intensity scenario	$\Delta T = 300^{\circ}\text{C}$	$\Delta T = 299^{\circ}\text{C}$

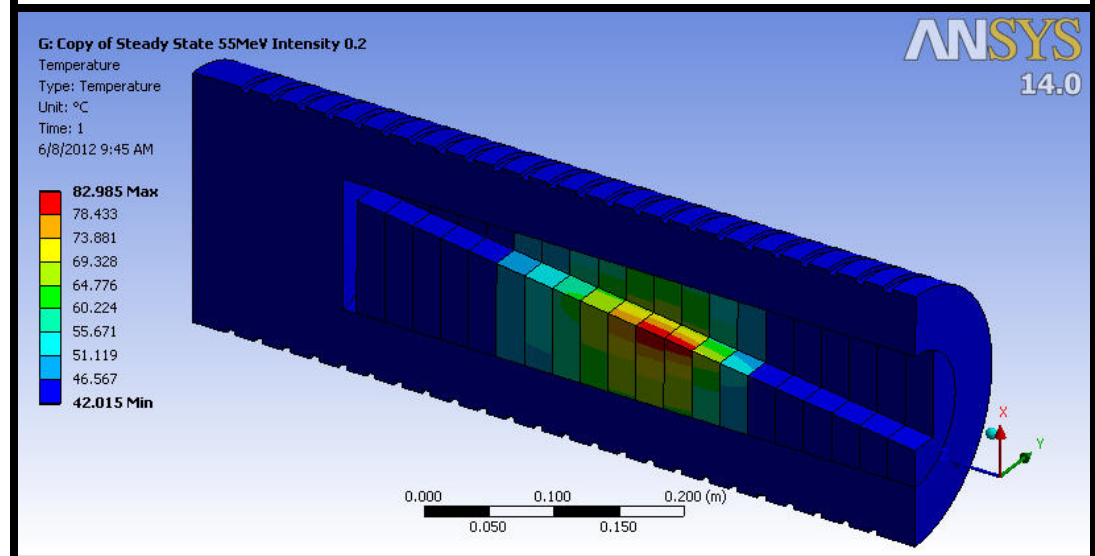


# Steady-State Thermal Condition @55MeV: Assembly Temperatures at Beginning of Life

50MeV Beam Energy  
20% Intensity  
82°C MAX\*



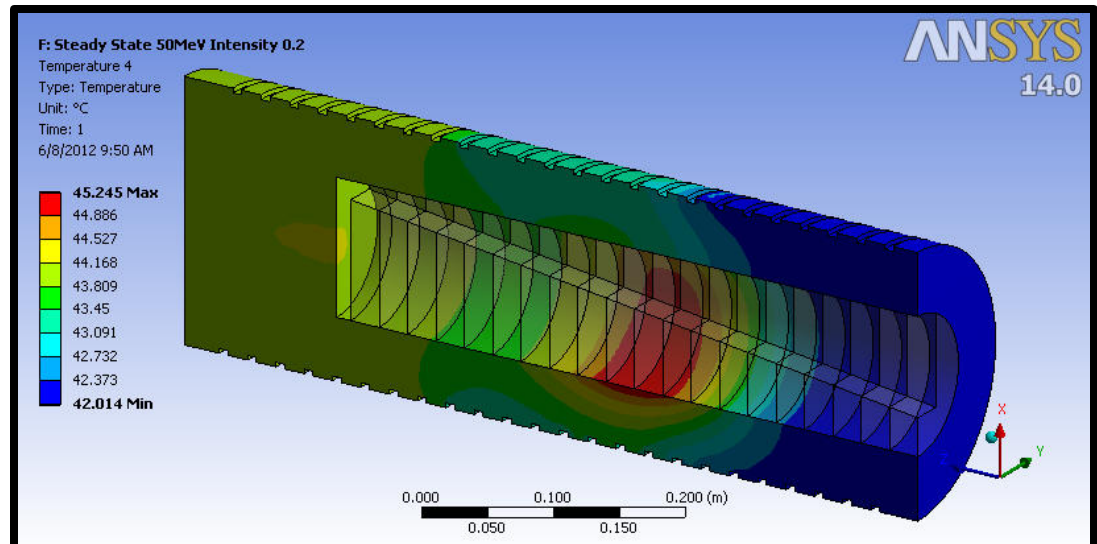
55MeV Beam Energy  
20% Intensity  
83°C MAX\*



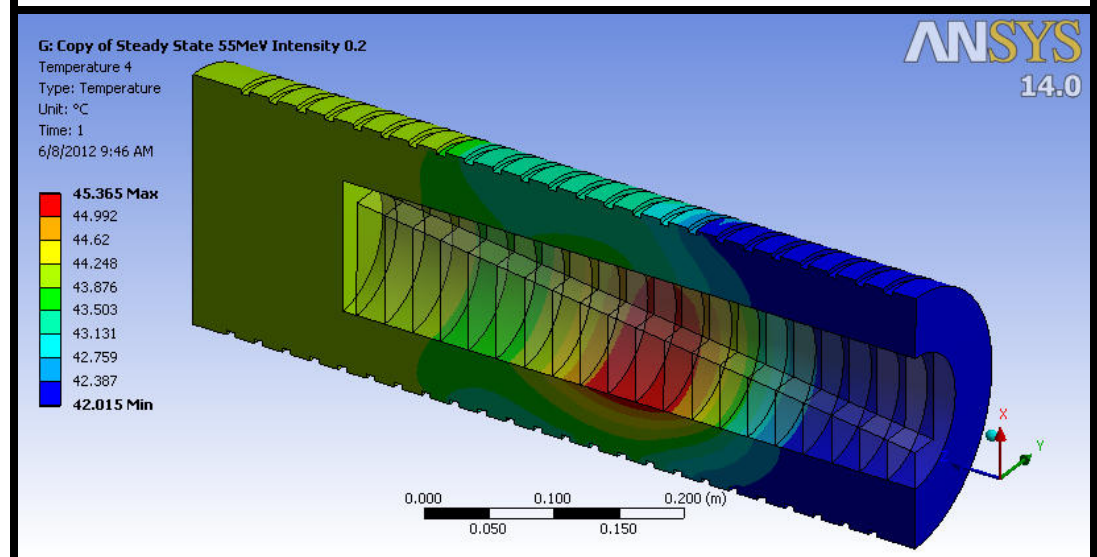
\* Instantaneous pulse  
effects add linearly to  
these temperatures

# Steady-State Thermal Condition @55MeV: Aluminum Temperatures

50MeV Beam Energy  
20% Intensity  
45°C MAX



55MeV Beam Energy  
20% Intensity  
45°C MAX



# Steady-State Thermal Condition @55MeV

Metric	Result @50MeV	Result @55MeV
Total Average Beam Power (20% intensity, 10μa beam current)	500W	550W
Beam power dissipated in graphite/aluminum absorber core and rejected to cooling water	449W	490W
Maximum “steady state” graphite temperature	82°C	83°C
Peak graphite temperature just after passage of a beam pulse	382°C	382°C
Maximum “steady state” aluminum temperature	45°C	45°C

# Conclusions – 55MeV Analysis

---

- Thermal performance of the absorber is nearly identical at 50MeV and 55MeV
- Based on the similarity of temperature conditions, stress analysis was not repeated for 55MeV cases
- From a thermal perspective, there is no issue running at 55MeV and 20% intensity