ASTA Low Energy Absorber Thermal Analysis

Version 4, Feb 07 2012

C. Baffes

Beam Doc DB ID: Beams-doc-4063

Design review held on Jan 11 2012

Updates relative to that review are shown in green

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

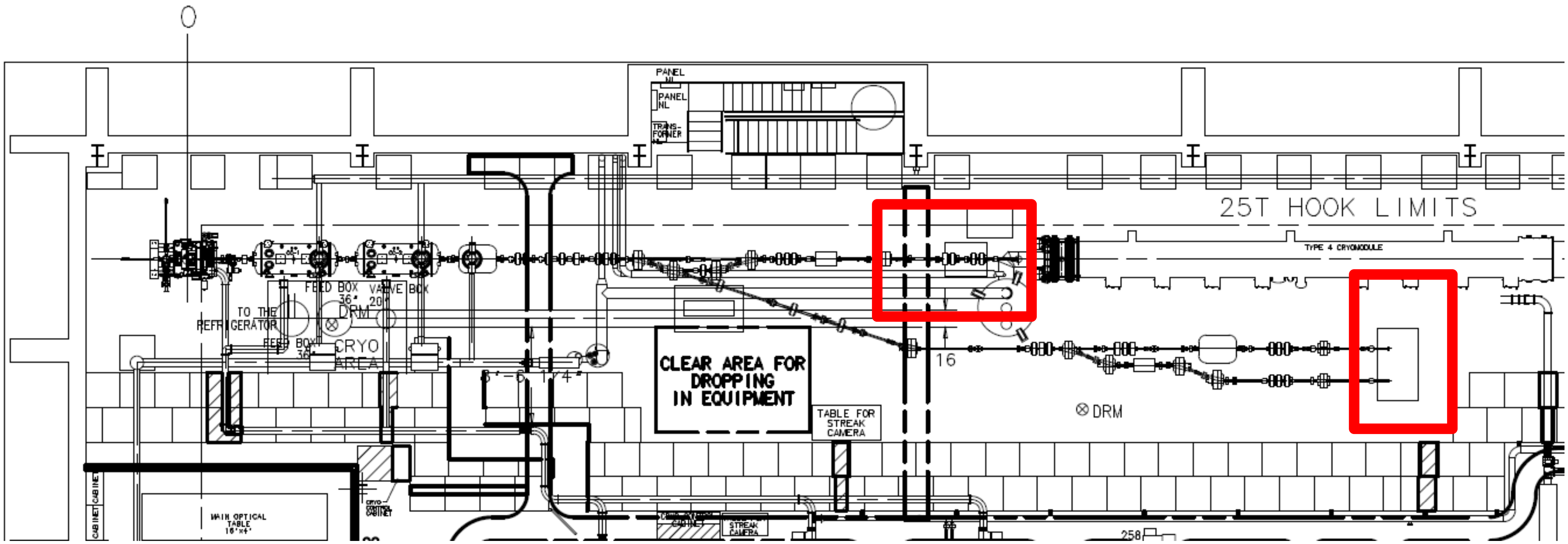
- Included in the scope of this review
  - Configuration of the ASTA Low Energy Dumps
  - Thermal analysis methodology and results
- Excluded from the scope of this review
  - Radiation analysis and shielding assessment

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 – Reduced Intensity Cases.

Absorber Locations

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



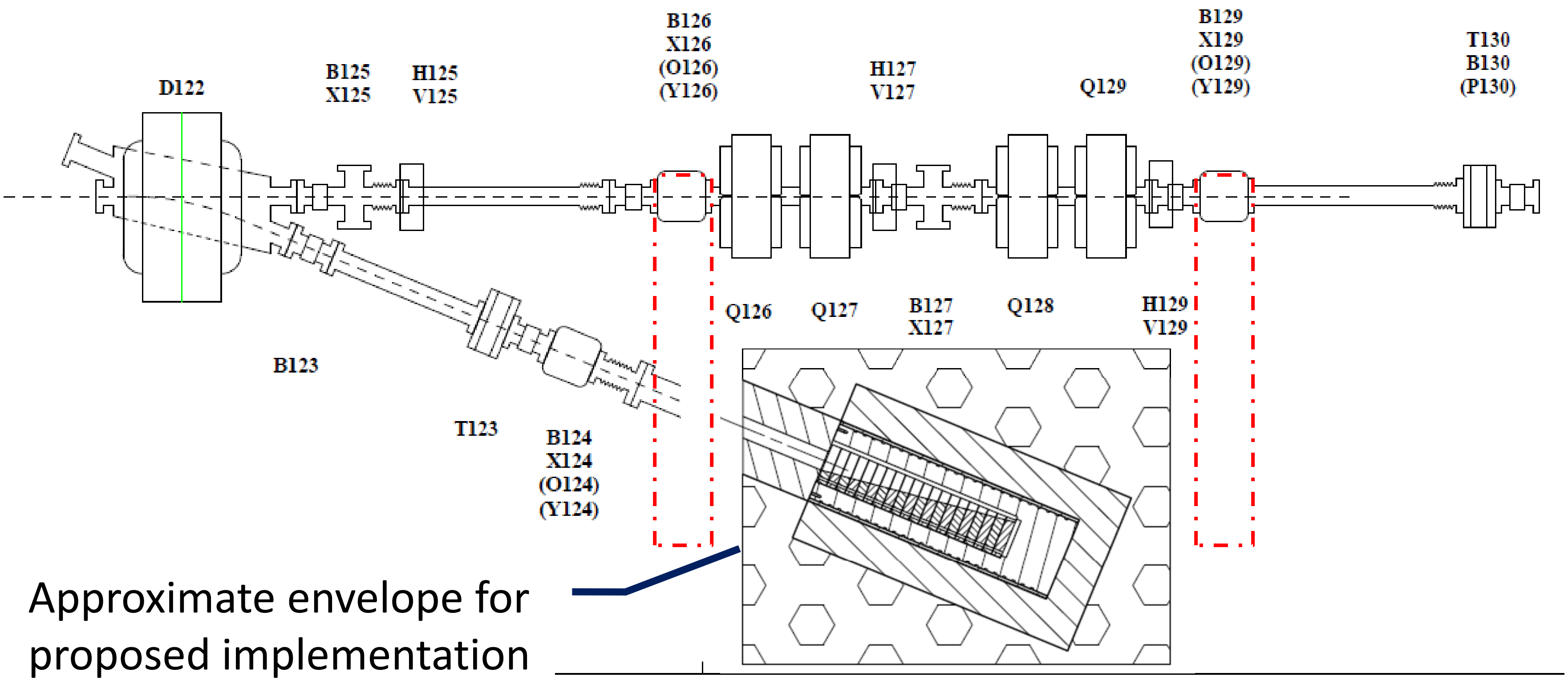
Beam Parameters

- Beam Parameters
  - o electron beam at 50 MeV, 3.33 nC/bunch
  - o 6.24E13 e-/pulse,   5 pulses/s,   3.12 E14 electrons/s
  - o Pulse duration 1ms
  - o 2.5kW average beam power

- Absorber shall be capable of accepting beam continuously (i.e. steady state operation)

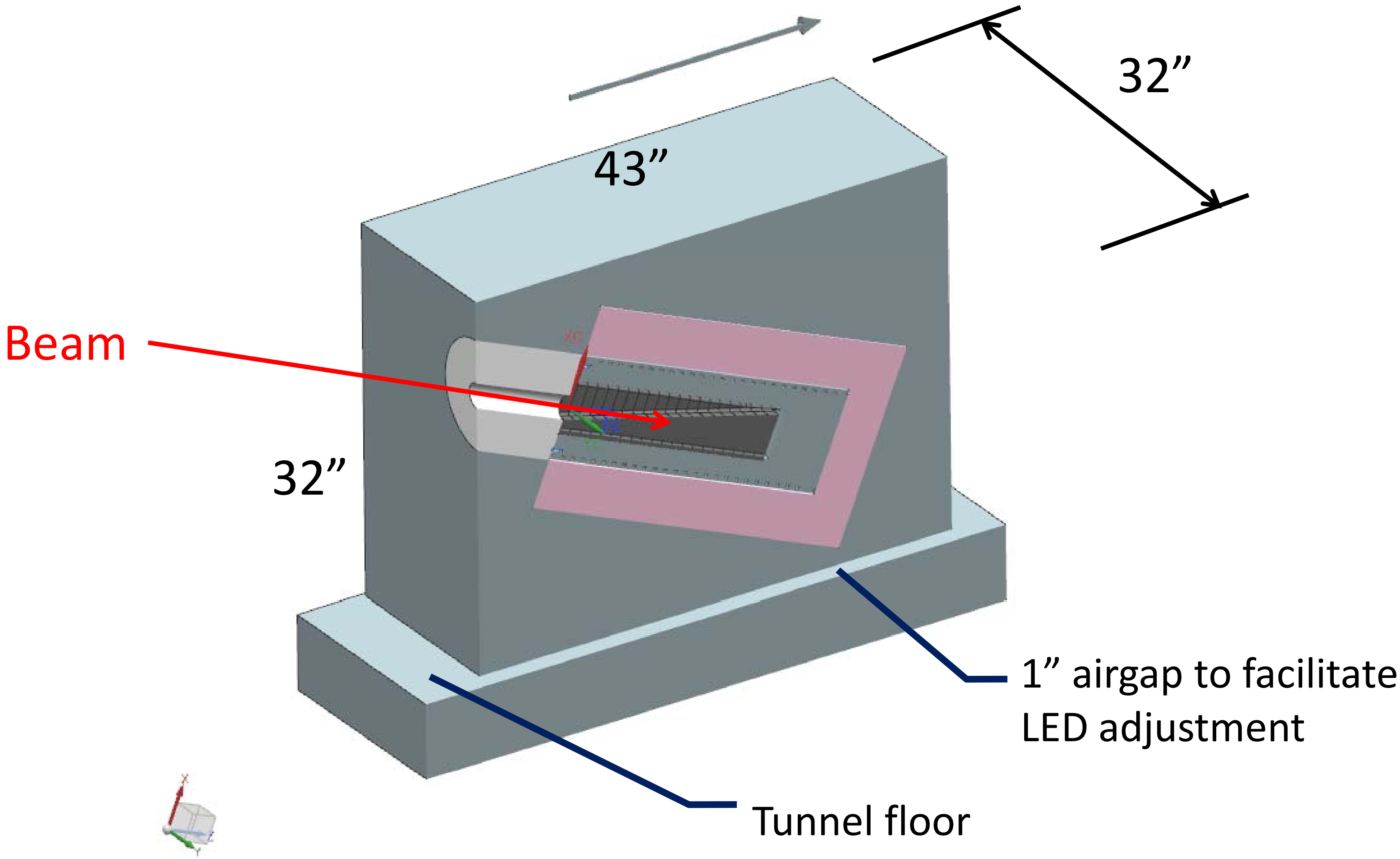
Packaging Constraints

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

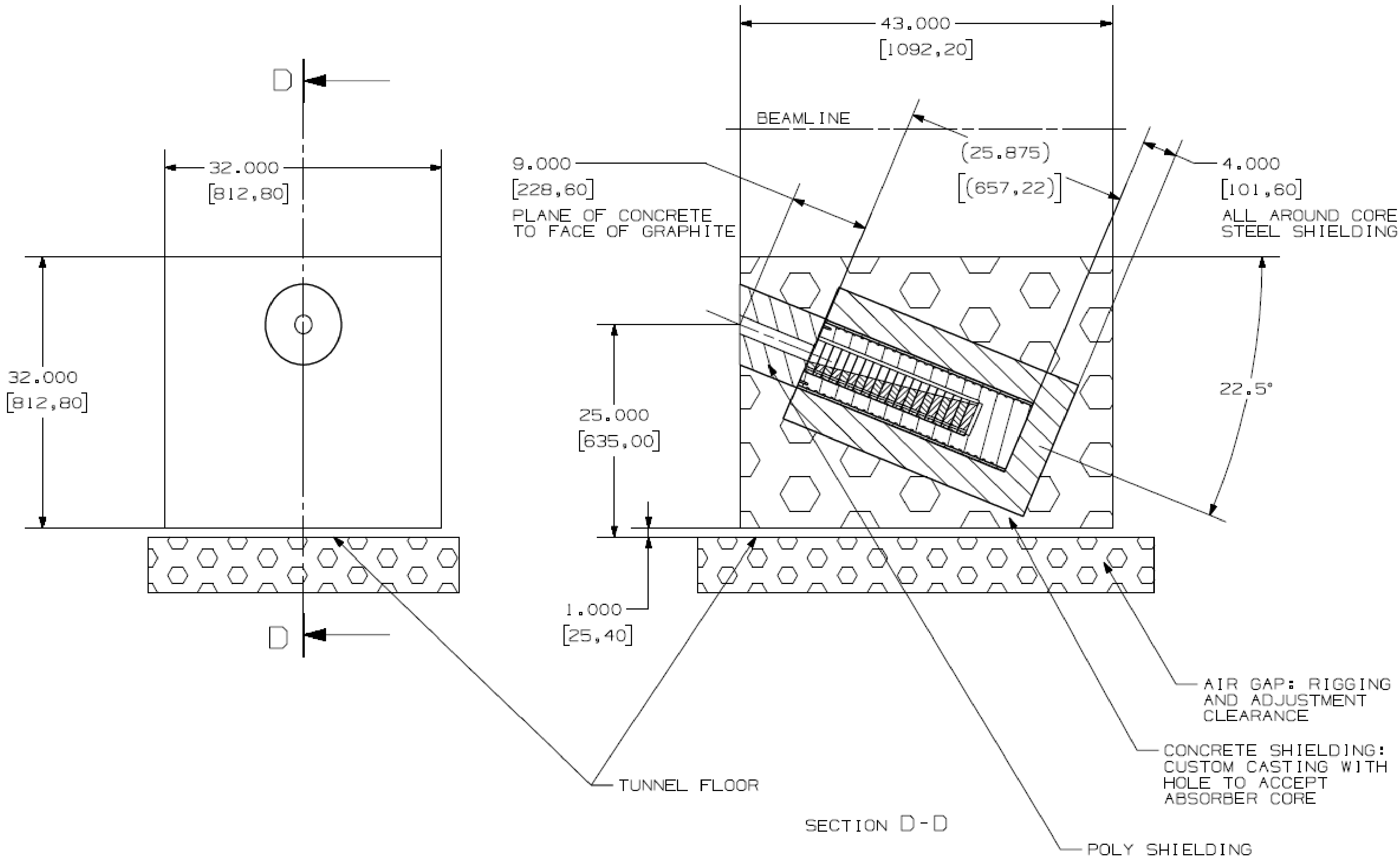


Approximate envelope for proposed implementation

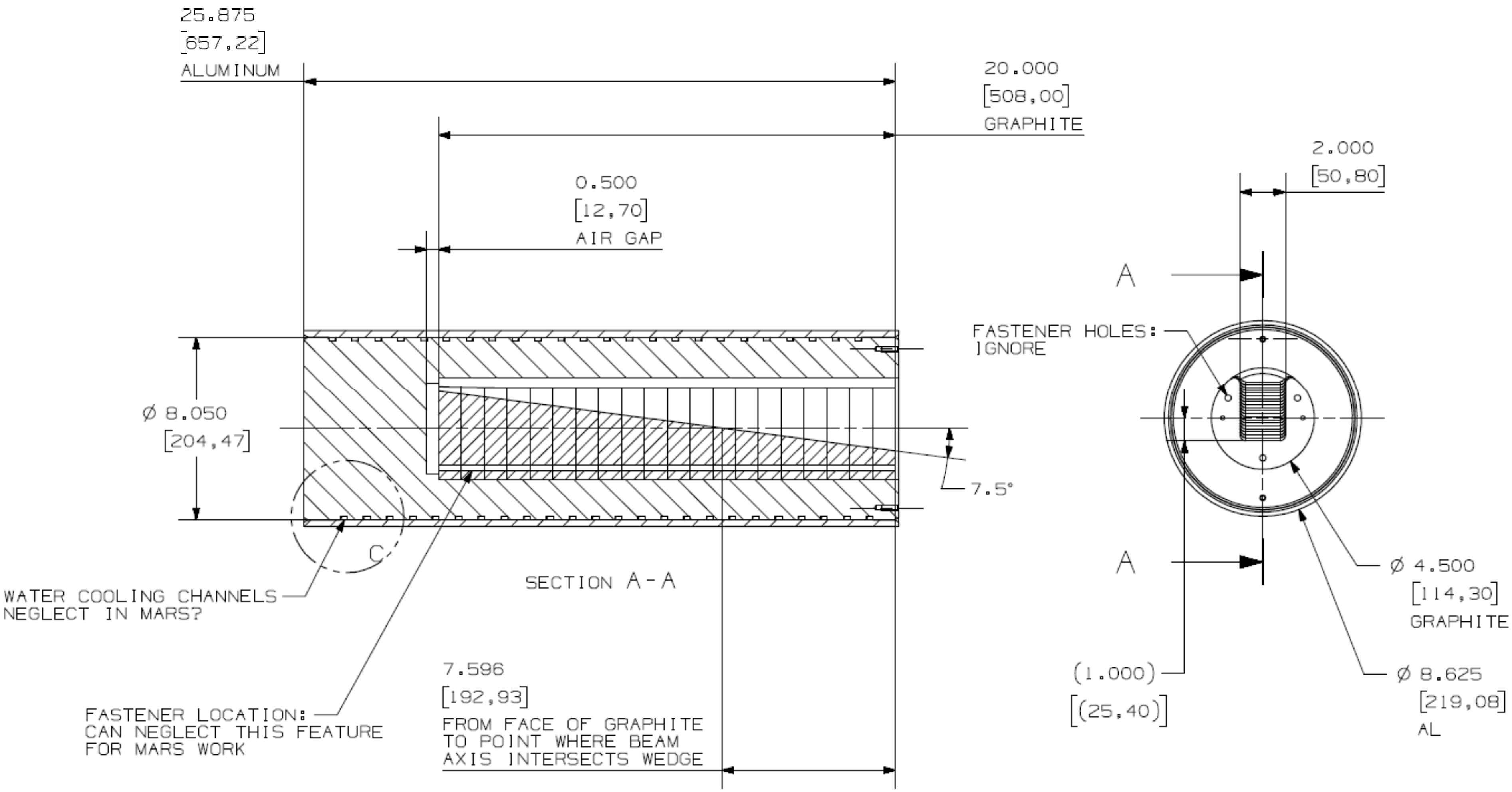
Absorber Configuration (Section View)



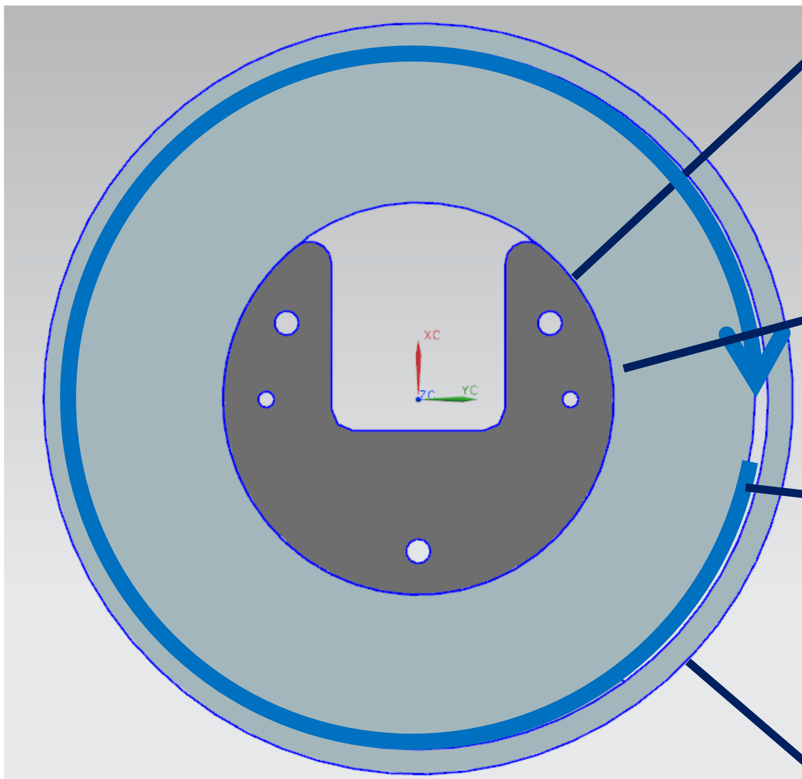
Absorber Configuration



Absorber Core



Graphite/Aluminum Contact Architecture



Graphite stack:
Wedge and OD machined at assembly level

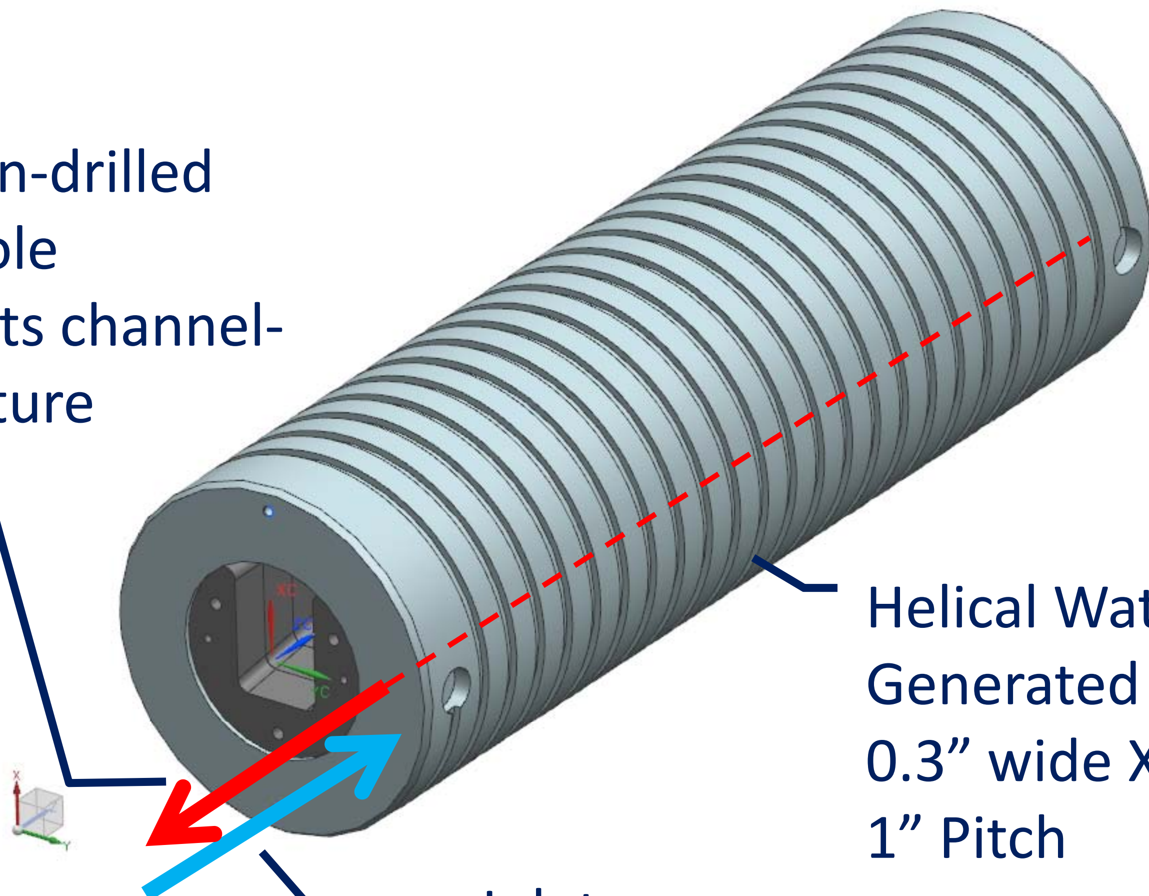
Aluminum Shell:
Shrink-fit to graphite

Cooling water in helical water channel (single-circuit, single-pass)

Outer Aluminum Sleeve:
caps water channel

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

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Data Processing Approach

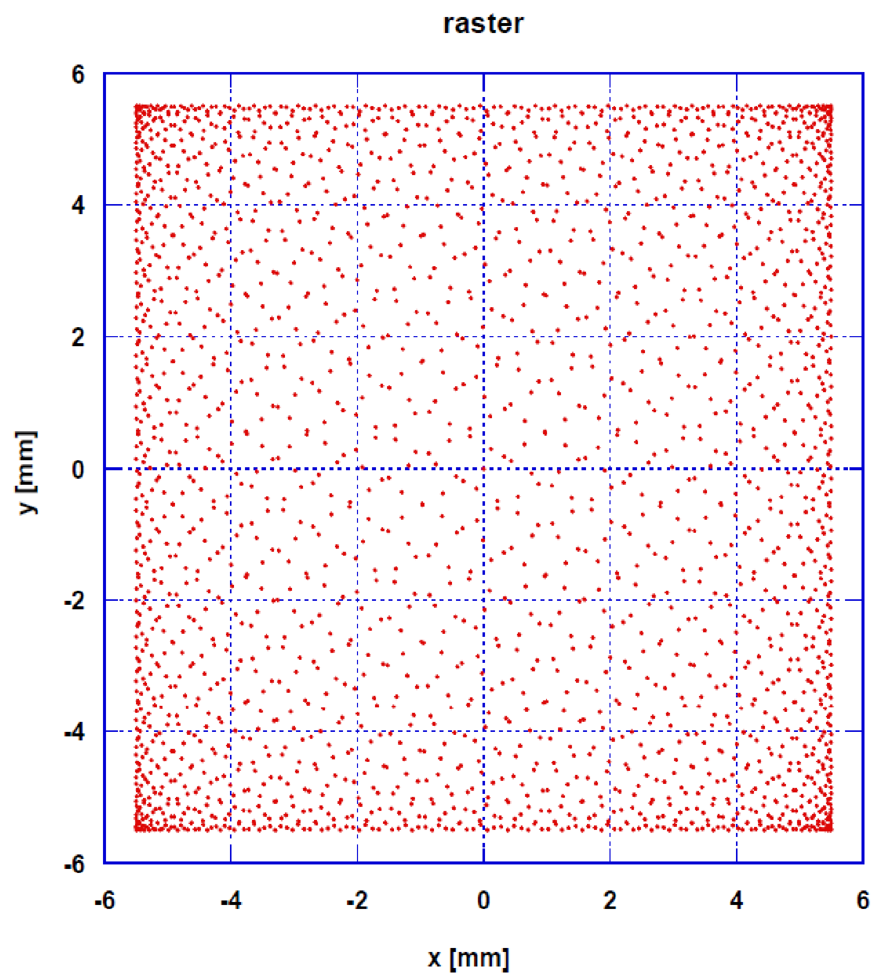
- Step 1: I. Rakhno produces MARS results
- Step 2: Process MARS results in Excel
  - Tabulate X, Y, Z and heat generation for each MARS element
- Step 3: Generate mechanical FEA models in NX/Ansys
  - Symmetric half-model used for all analyses
  - Tabulate FEA mesh nodal and element XYZ locations
- 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
  - o50 MeV, 3.33 nC/bunch, 3MHz, 1ms pulse @ 5Hz
  - o 3.12 E14 electrons/s
  - o 2.5kW beam
  - o Complex LED geometry faithfully modeled in MARS
- MARS energy deposition results are element-wise
  - o I.e. results are averages over the volume of each element
- Beam-sweeping implemented in MARS
  - o MARS energy deposition results represent temporal average
  - o Stand-alone model used to evaluate single-pulse effects

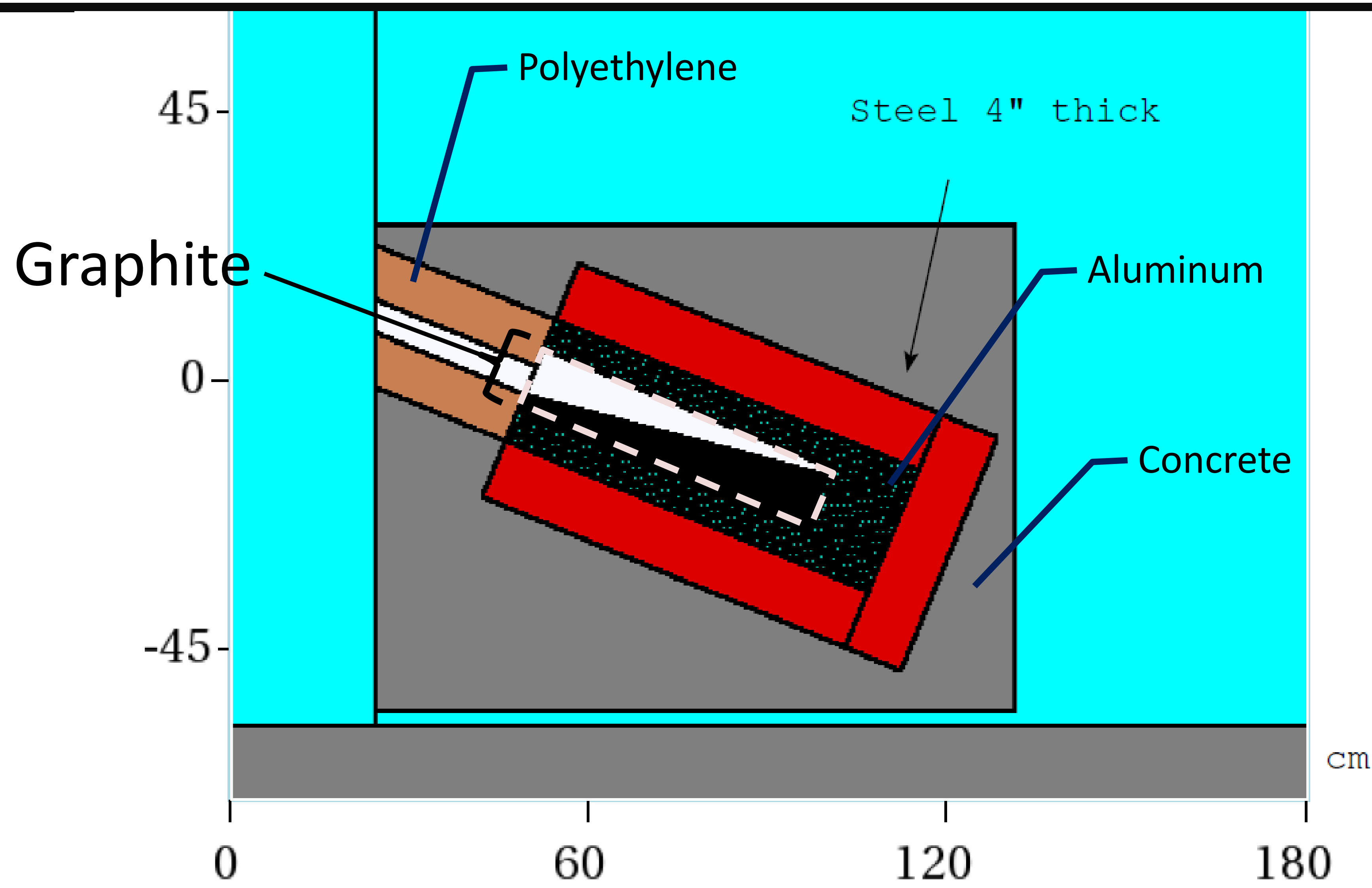
Beam Sweeping

- 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

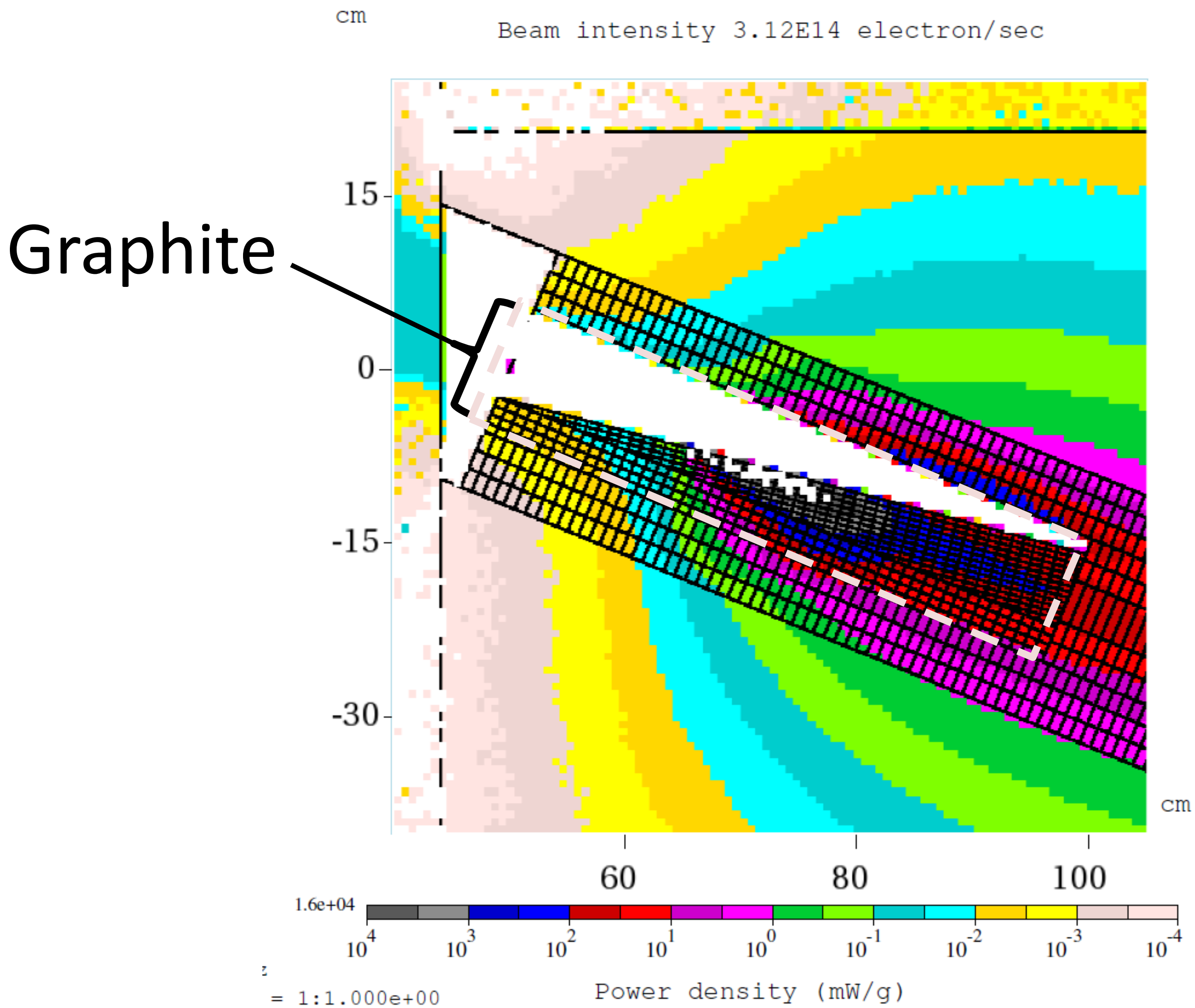


Cross section transverse to beam
Red spots are individual beam pulses

MARS Model: Geometry

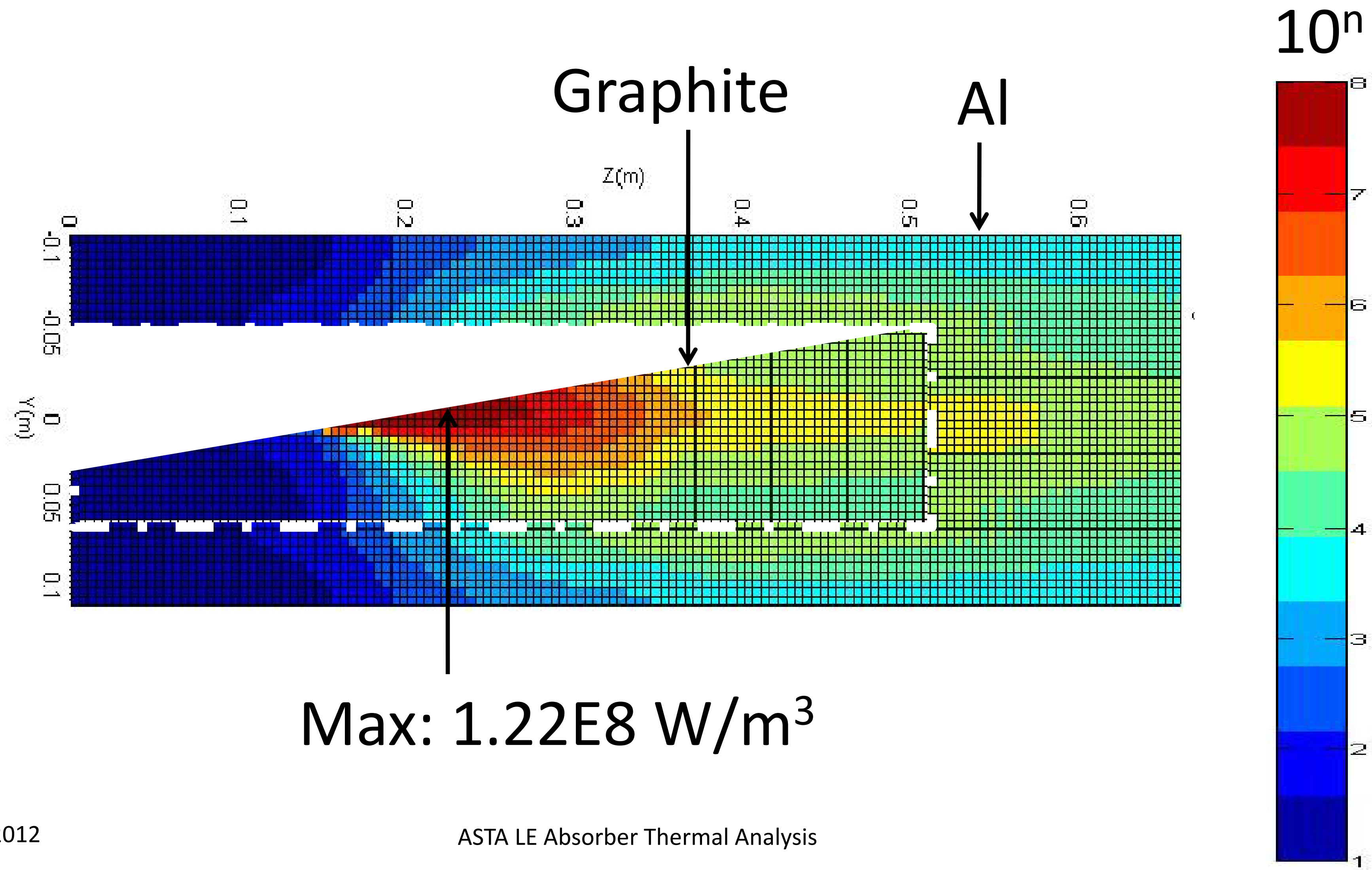


MARS Results:
Energy Deposition (mW/g)



MARS Results

Heat Generation (W/m^3): log color scale



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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^3)	E (GPa)	α (ppm/°K)	k (W/m^{2}°K)	c (J/kg°K)	Flexural Strength (MPa)	Comp. Strength (MPa)	Gruneisen parameter $\gamma=\alpha E/c\rho$	FOM_1 $=\{\alpha E/c\sigma_{min}\}$ normalized to min	FOM_2 $=\{FOM_1/k\}$ 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^2 °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^2 °K at a contact pressure of 35psi

Thermal Analysis Parameters

Cooling water convection coefficient:

$h = 12{,}100\ W/m^2\ °K$

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 $\Delta T = 10\ °K$
- 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

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FEA Model

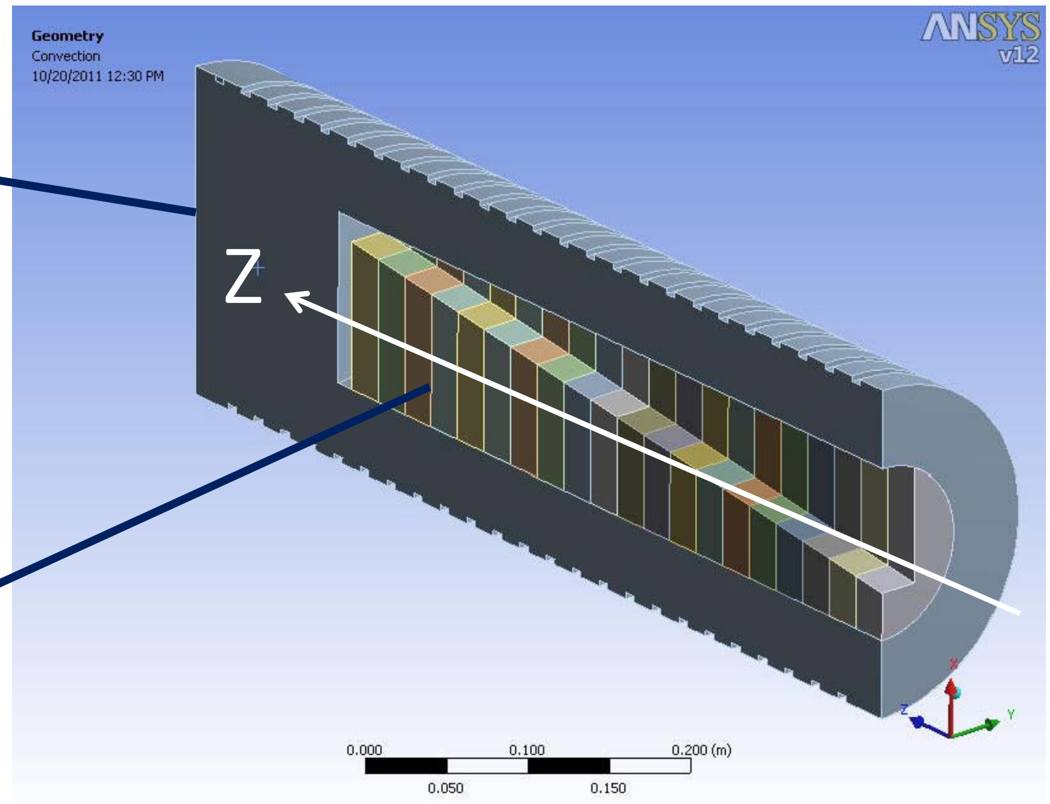
- A system model with “half” symmetry is used to assess steady-state temperatures

- 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
  - (2.5kW – 2.35kW) = 150W is neglected by the thermal model. This is acceptable

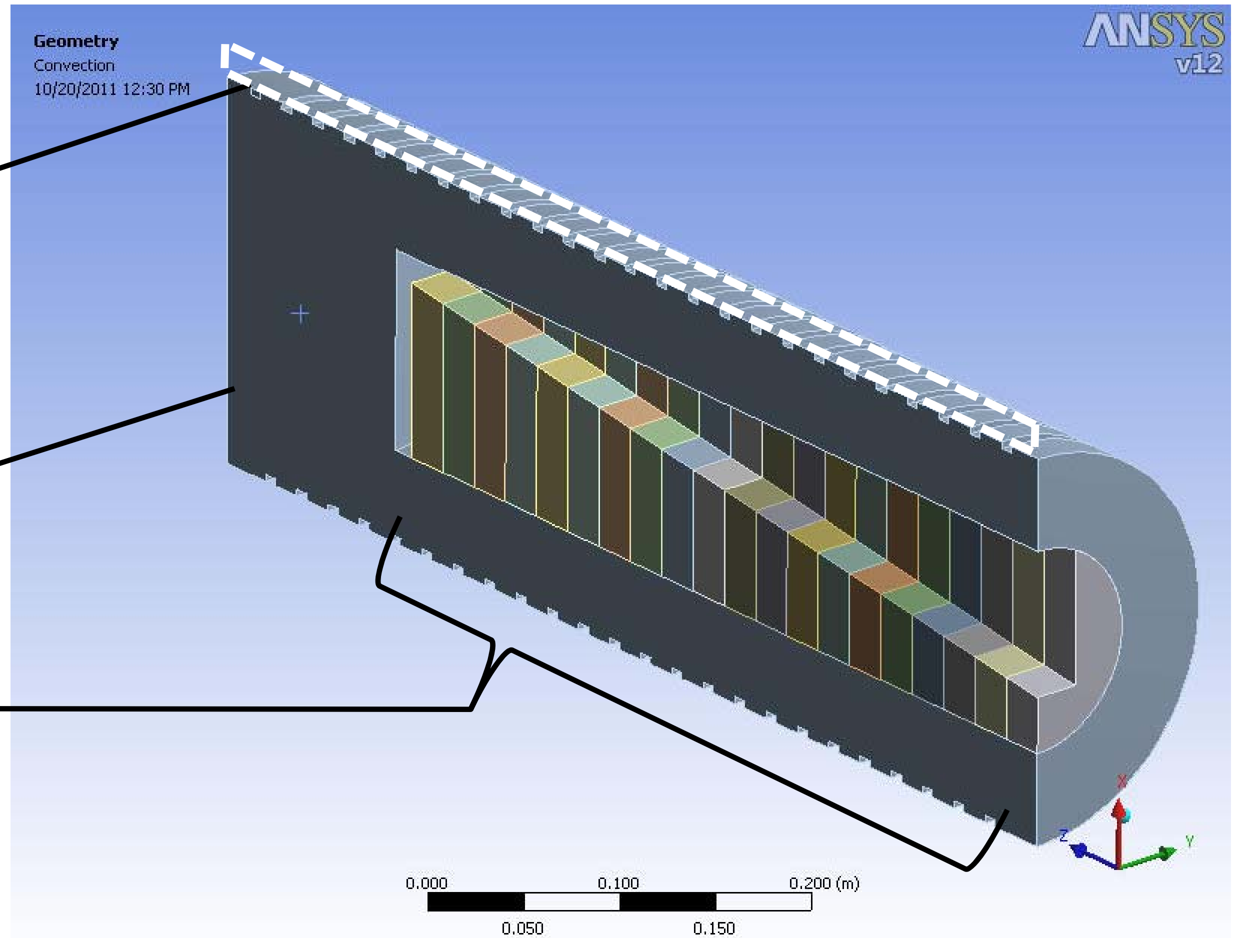
System Model
Underlying Solid Geometry

Bilateral symmetry about YZ plane

Lamina are modeled individually. Contact thermal resistances included



System Model
Materials

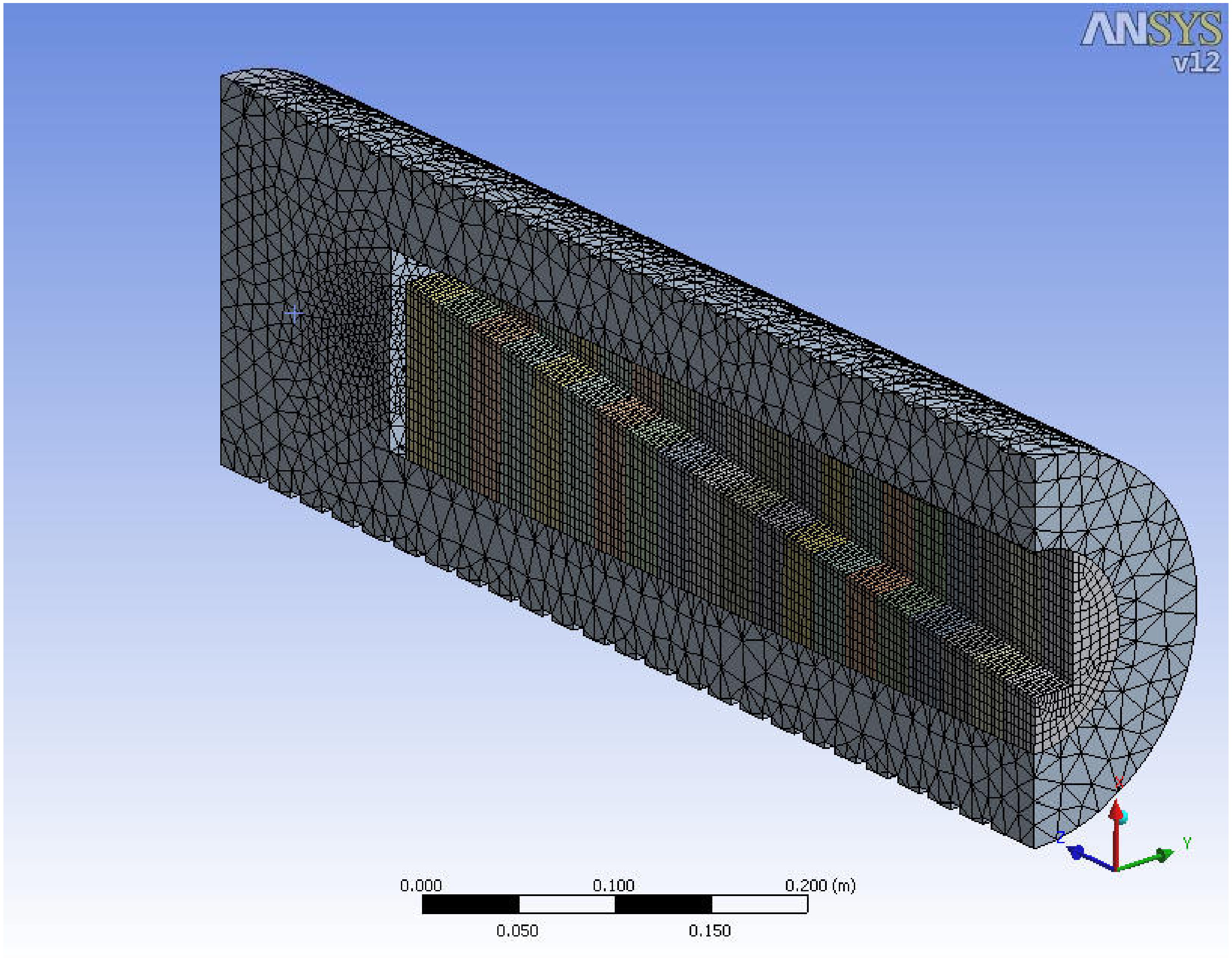


Al Shell (cover for water channels) not included in thermal model

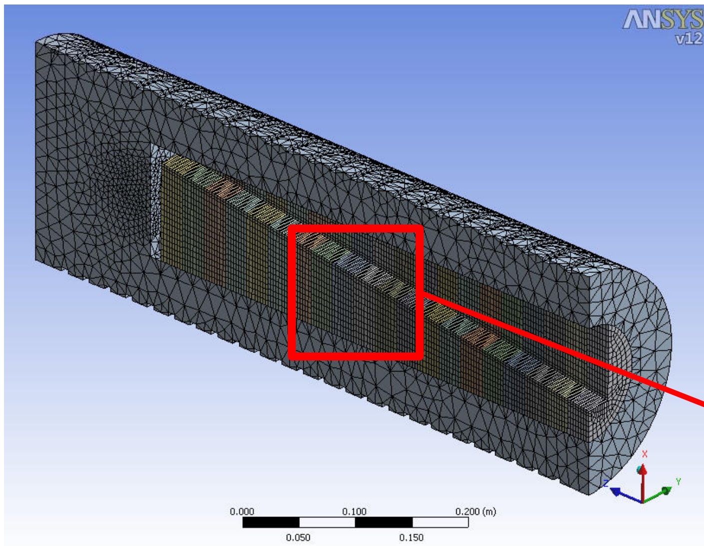
Monolithic Al Core
Al 6061 T6

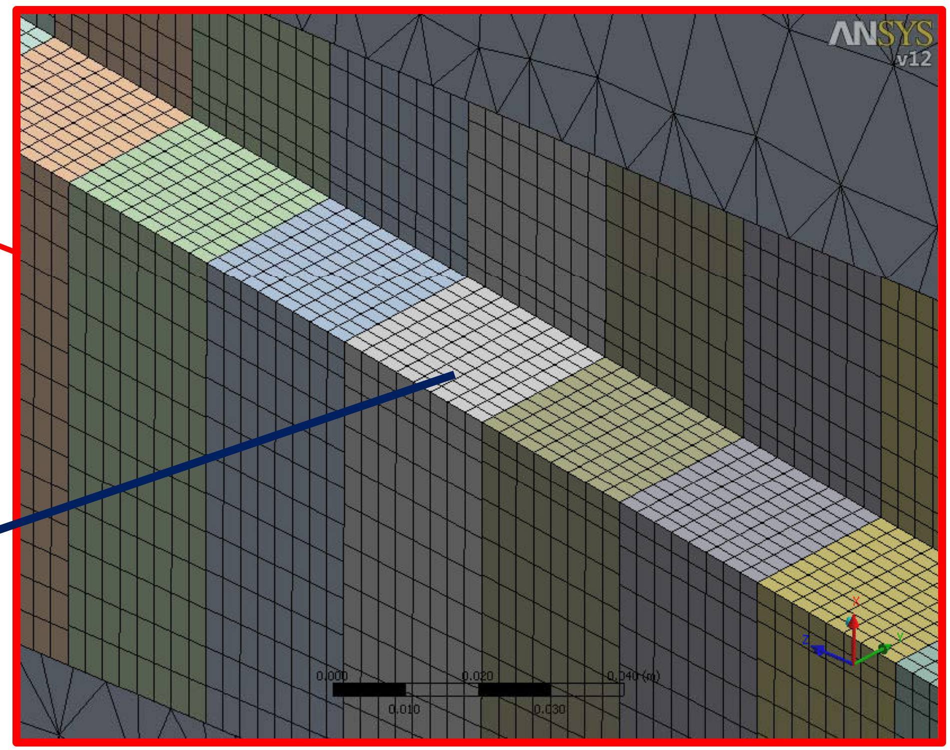
1" thick plates
20 layers
Graphite IG-110

System Model FEA mesh



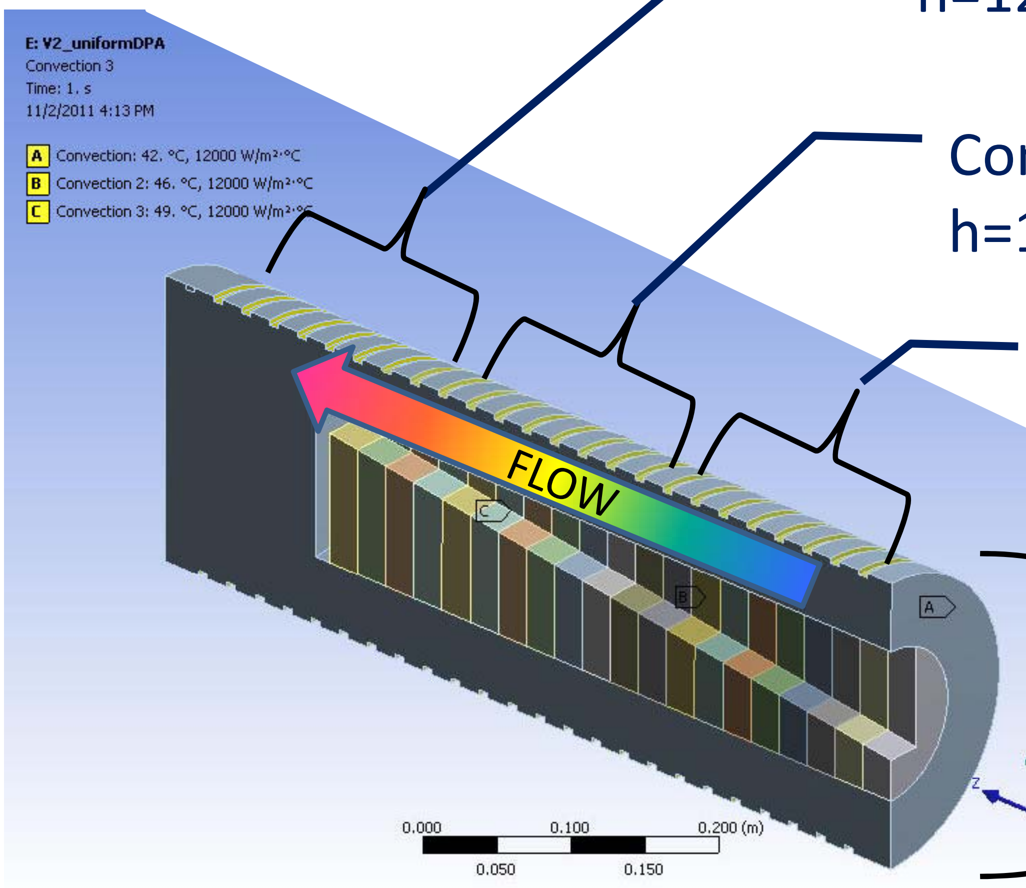
System Model FEA mesh





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

System Model Thermal Loads



Convection
h=12,100 W/m^{2}K, T_f=49°C

Convection
h=12,100 W/m^{2}K, T_f=46°C

Convection
h=12,100 W/m^{2}K, T_f=42°C

Element Body Force heat generation uniquely defined for each element

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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

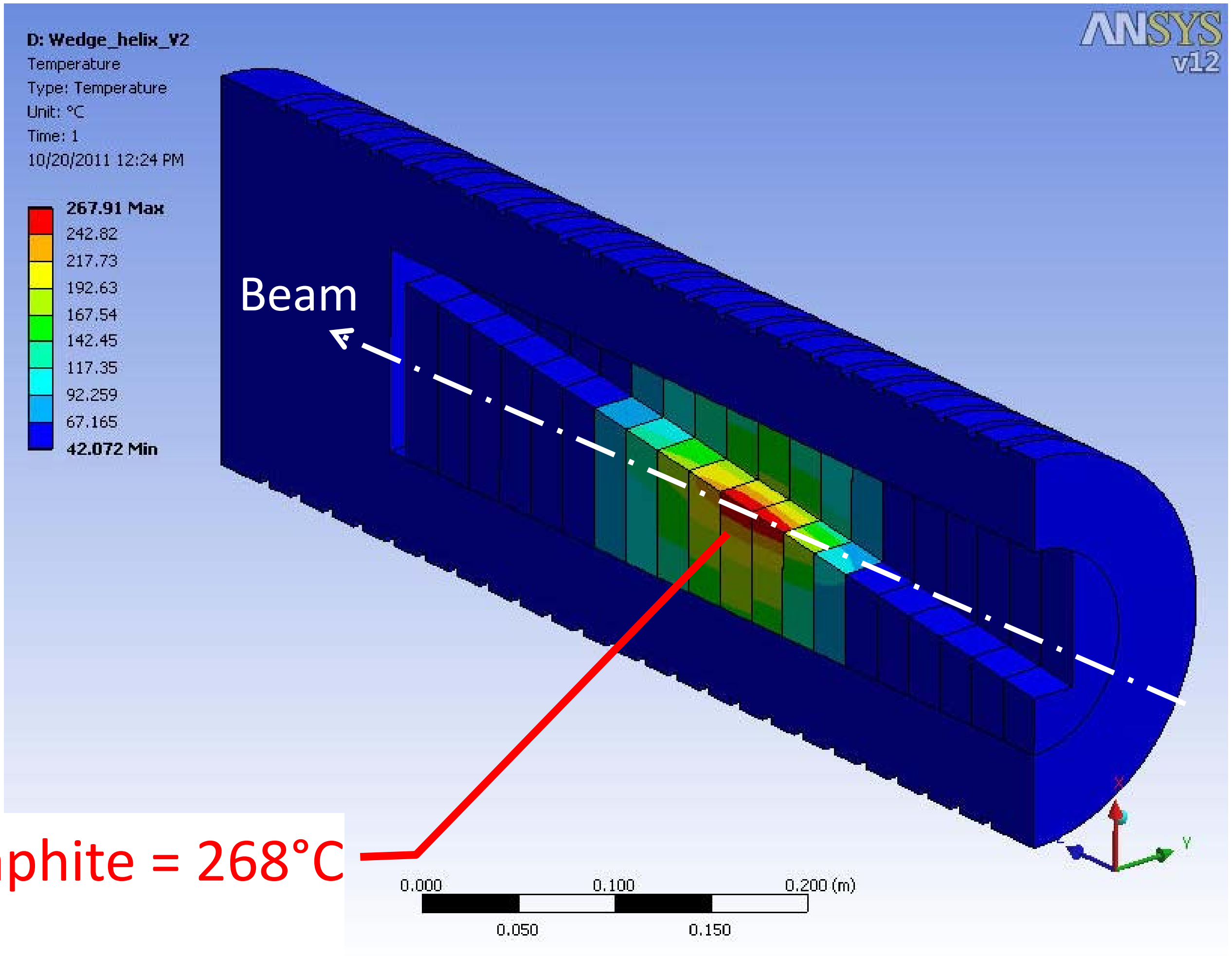
Maximum temperature in graphite and system

Key inputs:

-Graphite/Al thermal contact 500 W/m^{2}K

-Swept beam (i.e. temperatures represent temporal average)

-Graphite with undamaged BOL material properties



Max Temp. in Graphite = 268°C

System Model Steady State

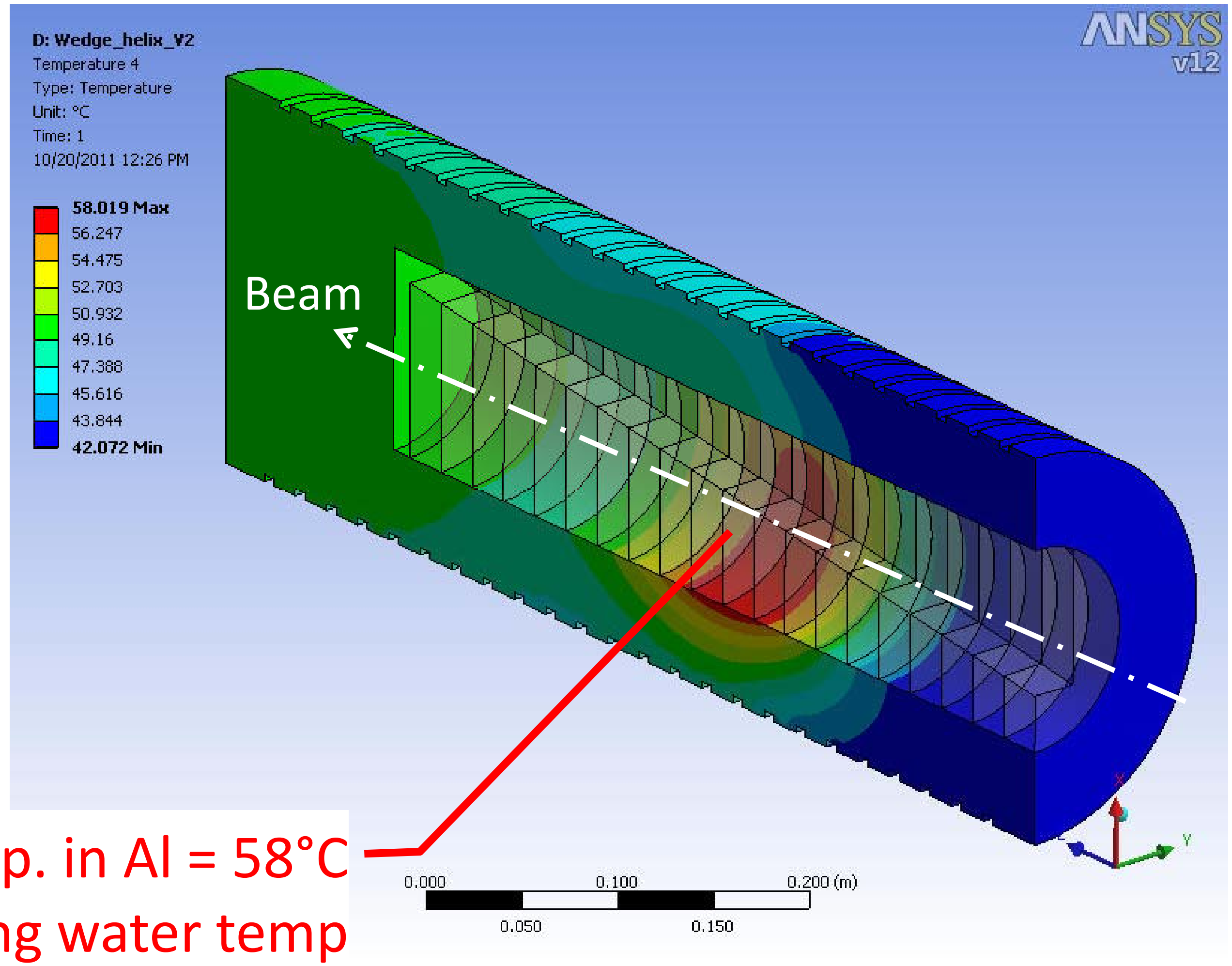
Maximum temperature in Aluminum

Key inputs:

-Graphite/Al thermal contact 500 W/m²K

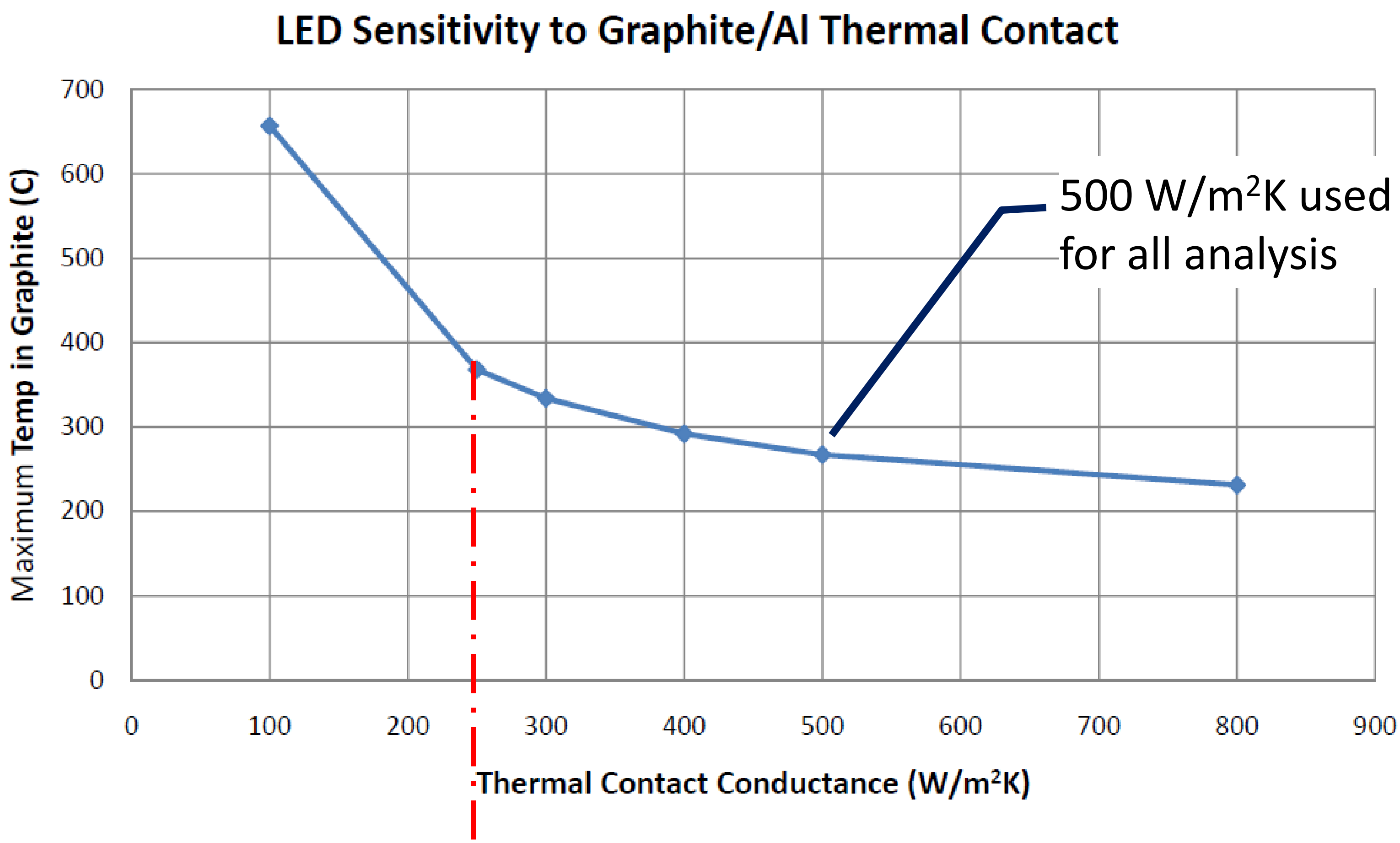
-Swept beam (i.e. temperatures represent temporal average)

-Graphite with undamaged BOL material properties



Max Temp. in Al = 58°C
<16°C above cooling water temp

Thermal Contact Sensitivity



For good performance, need to achieve contact conductance > 250W/m^2K

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:

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

- So, the assumed contact thermal conductance of 500 W/m^2 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

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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

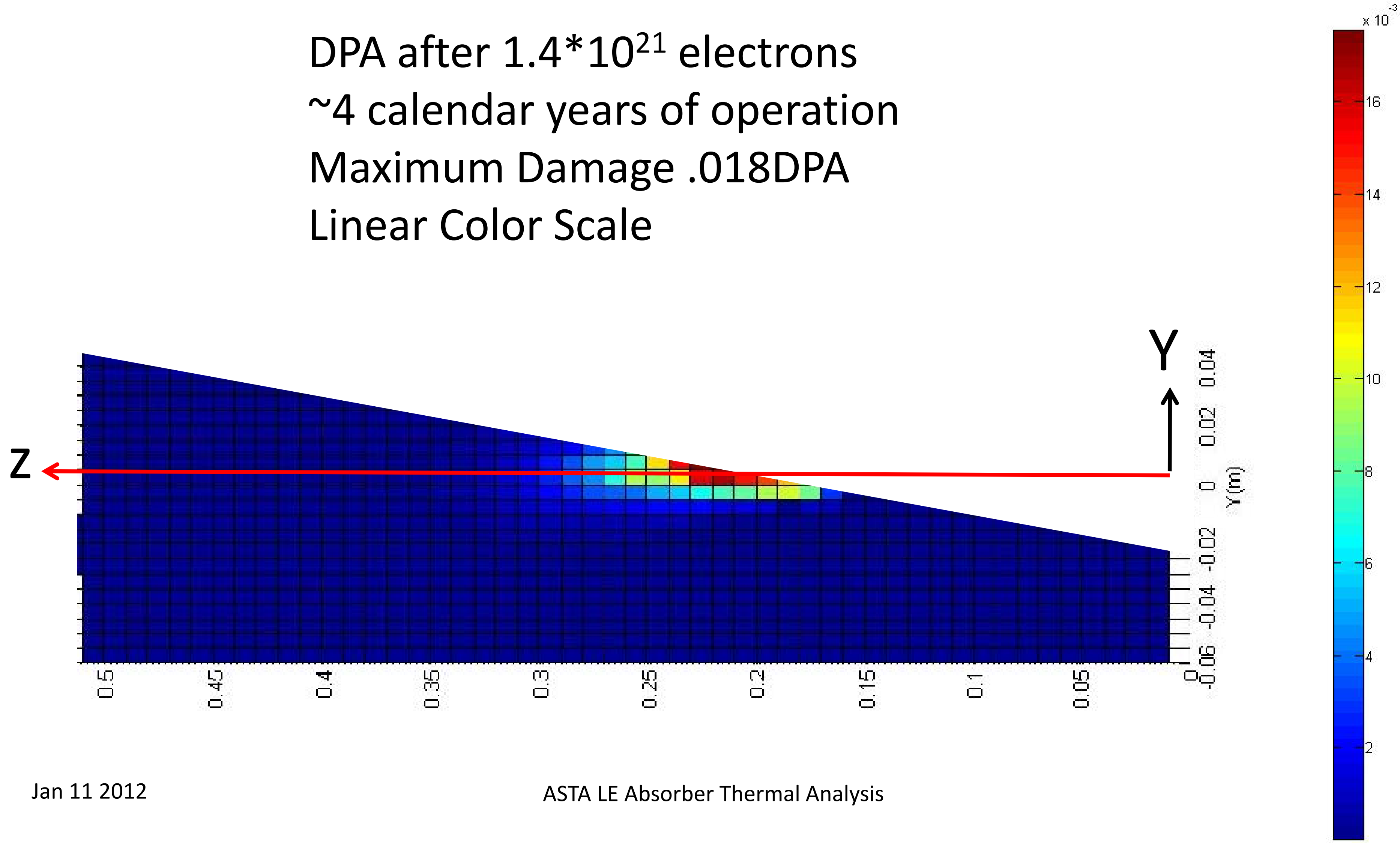
- Mike Church defined the following duty cycle:

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 < ~500°C
- Analysis of damaged LED was iterated until temperatures at End-of-Life approached 400°C (leaving some headroom for pulse effects). This occurred at 1.4E21 electrons, or about 4 calendar years of operation

MARS Results:
DPA during expected lifetime in graphite

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



MARS Results:

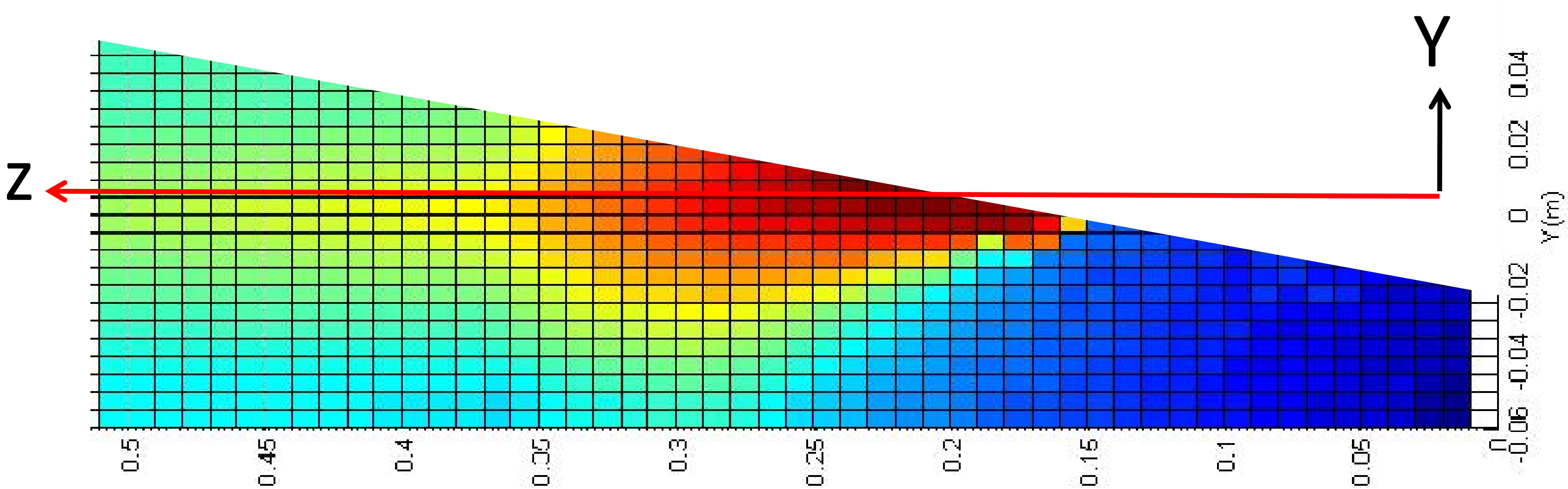
DPA during expected lifetime in graphite

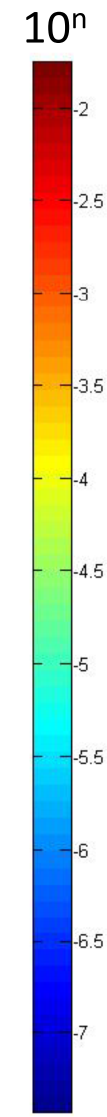
DPA after $1.4*10^{21}$ electrons

~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: ~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, α are also accounted for
  - In the FEA, assign each element to one of these damage bins

Radiation Effects: Example Data

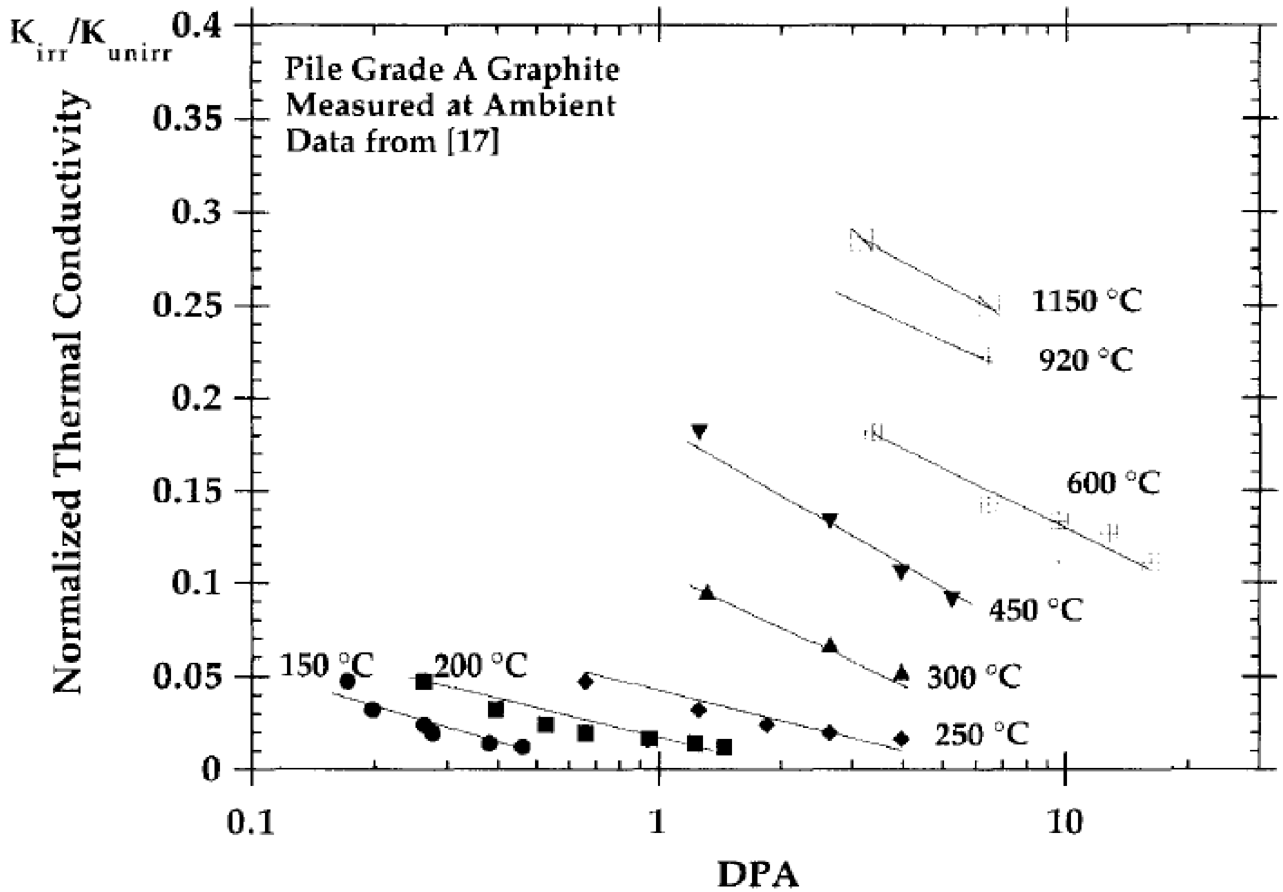
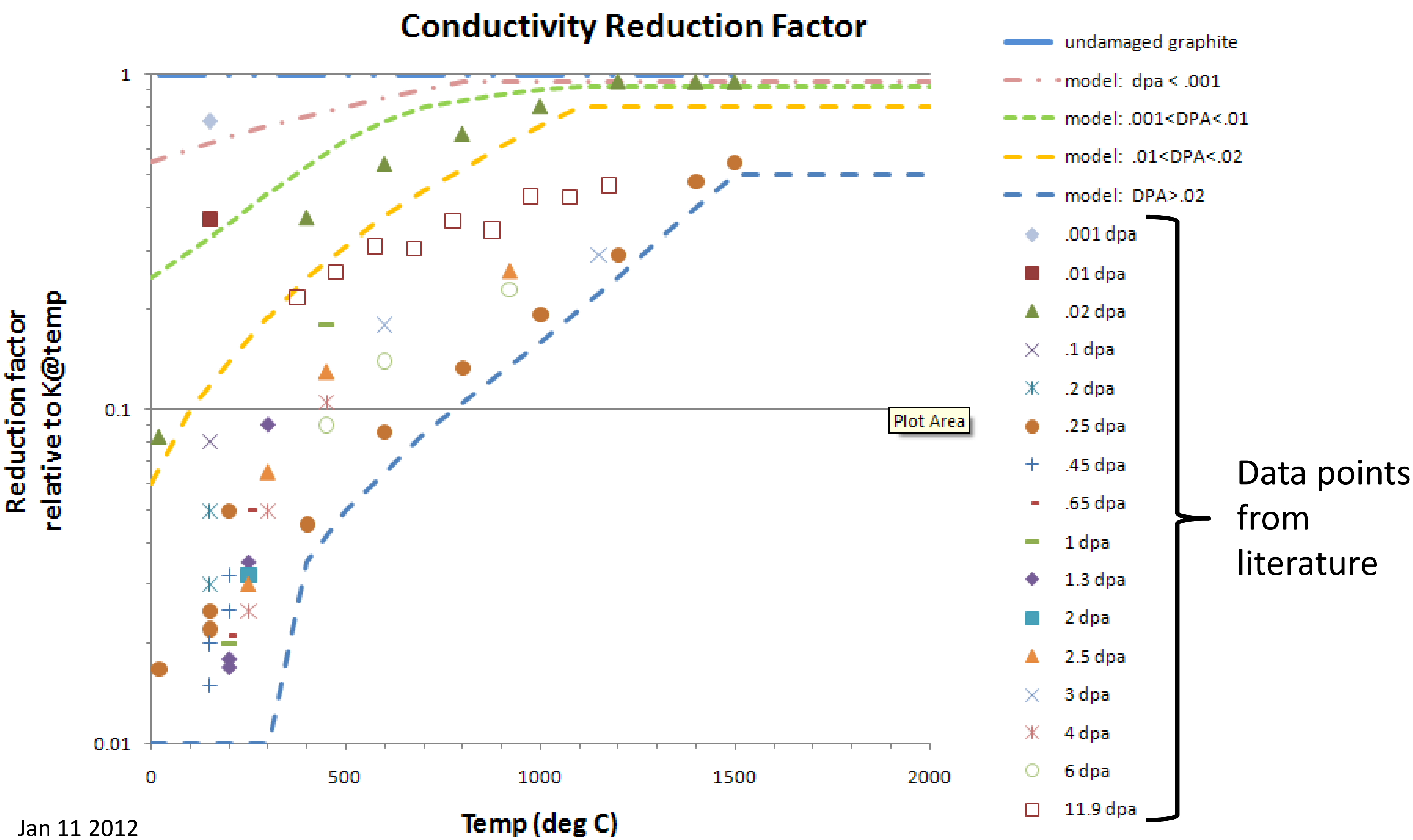


Fig. 5. Normalized thermal conductivity of pile Grade A graphite [17].

L. Snead, T. Burchell / Journal of Nuclear Materials 224 (1995) 222–229

Radiation Effects: Modeled k Reduction Factor



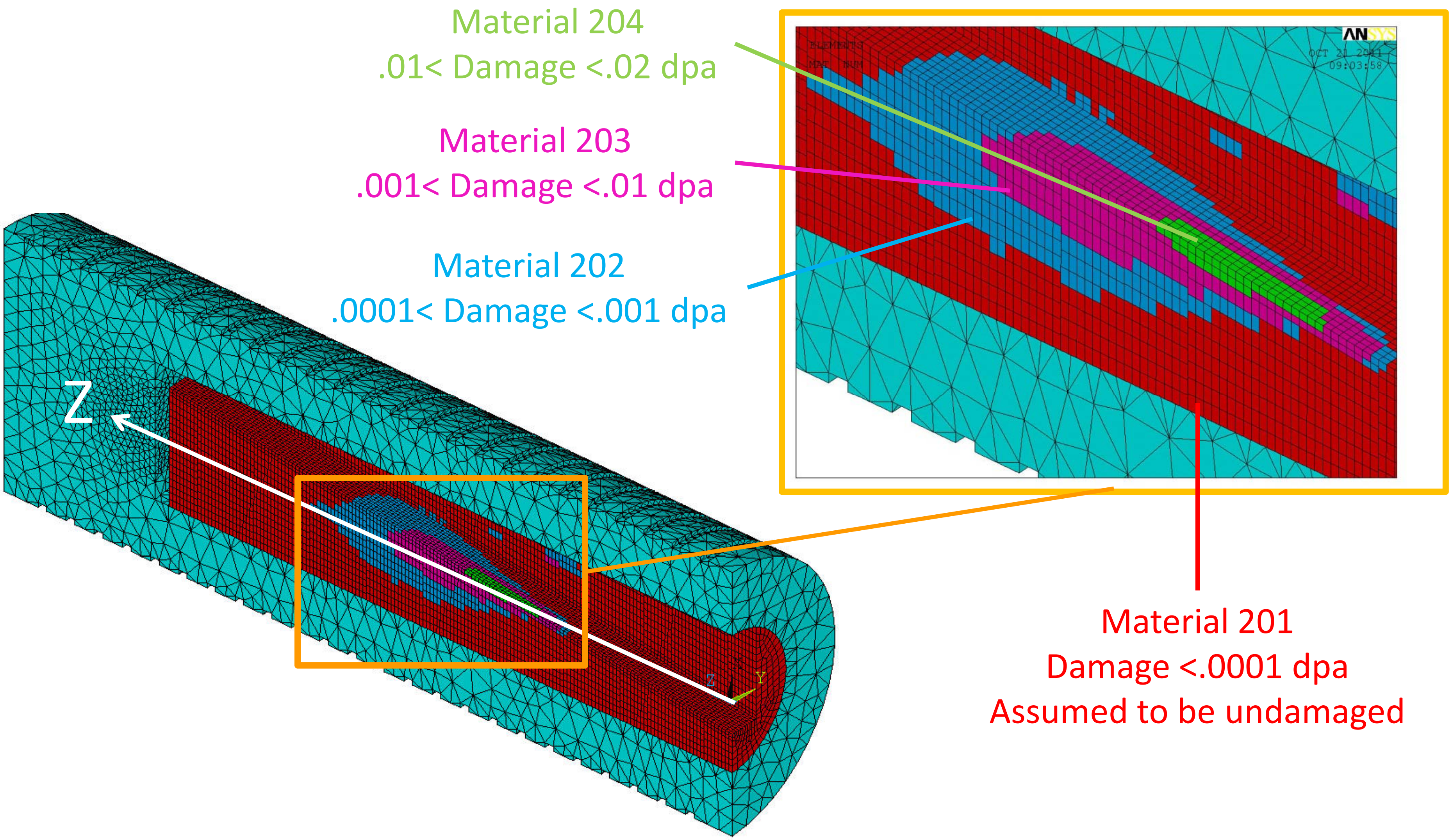
Damage Mapping on FEA model

- As shown on the previous slide, discrete materials were defined with thermal conductivity as a function of damage and temperature.

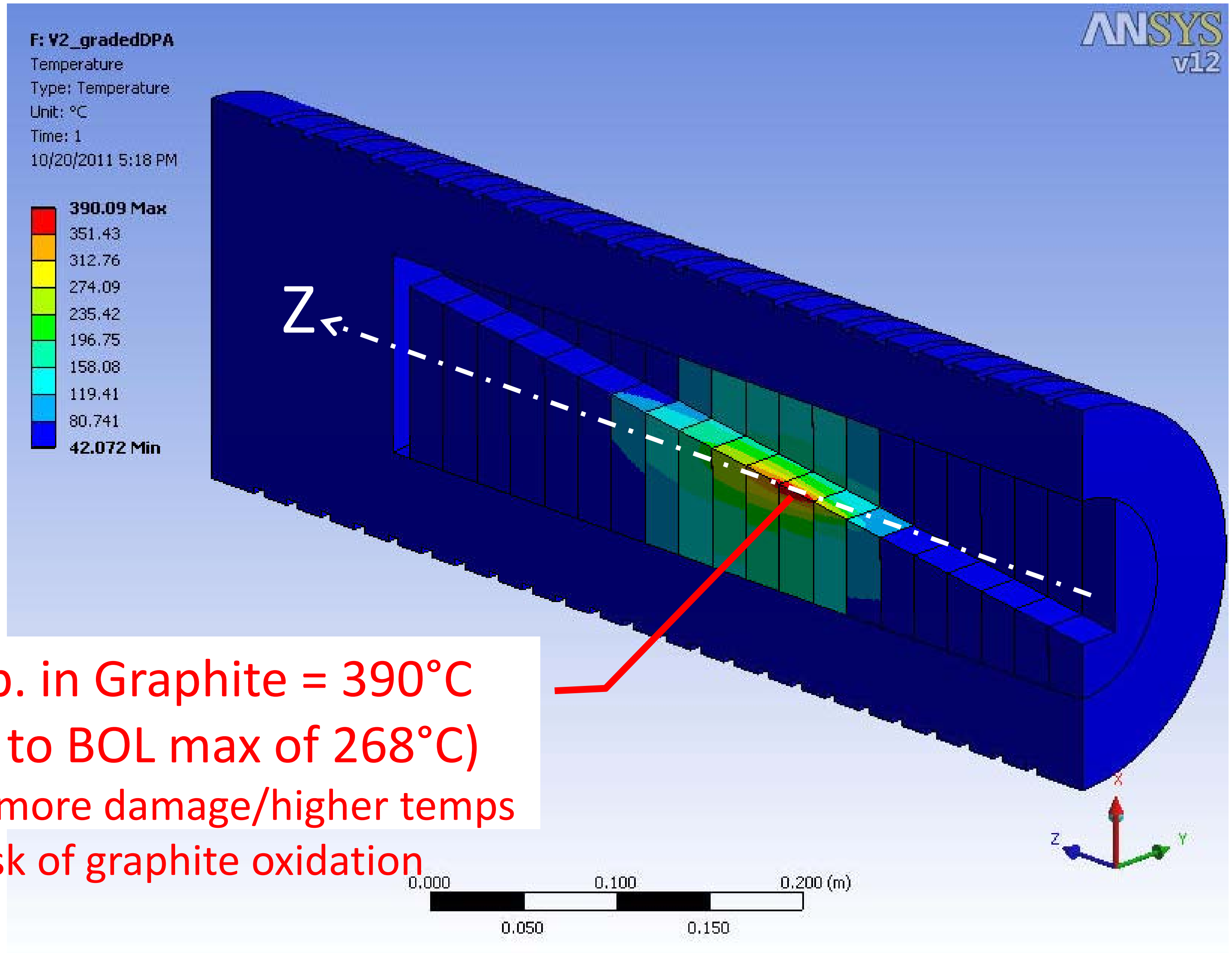
- MARS damage estimates were mapped onto the FEA mesh. Individual elements were "binned" by damage level.
  - Damage mapped from iteratively-determined end of life case, i.e. after fluence of 1.4E21 electrons

- 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



Max Temp. in Graphite = 390°C
(Compare to BOL max of 268°C)
Cannot allow more damage/higher temps due to risk of graphite oxidation

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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 discreet pulses
  - 1ms pulse @5Hz, 6.24E13 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

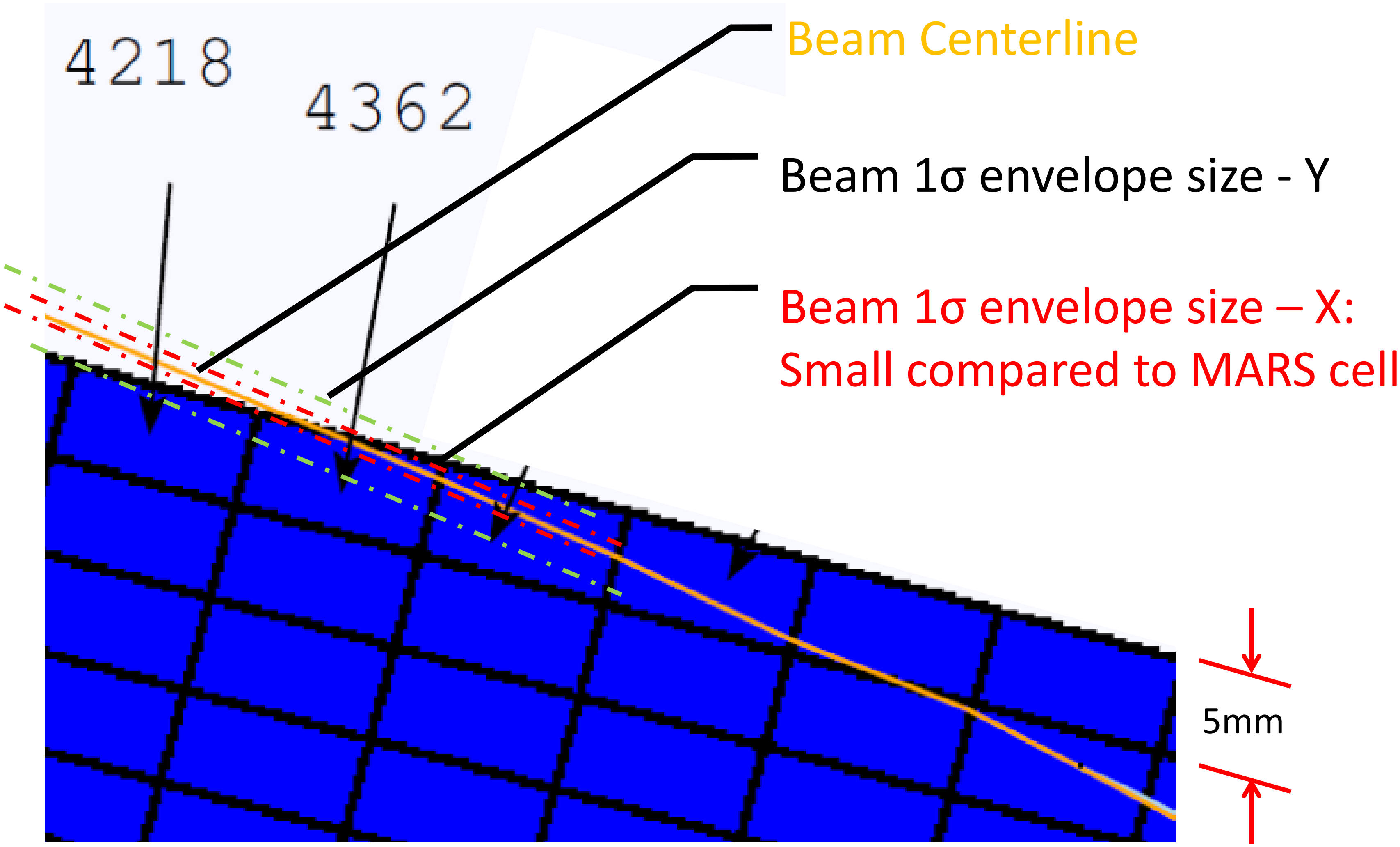
Beam Size vs. MARS Cell Size

- 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 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 (σx=0.3mm). 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 >> beam size

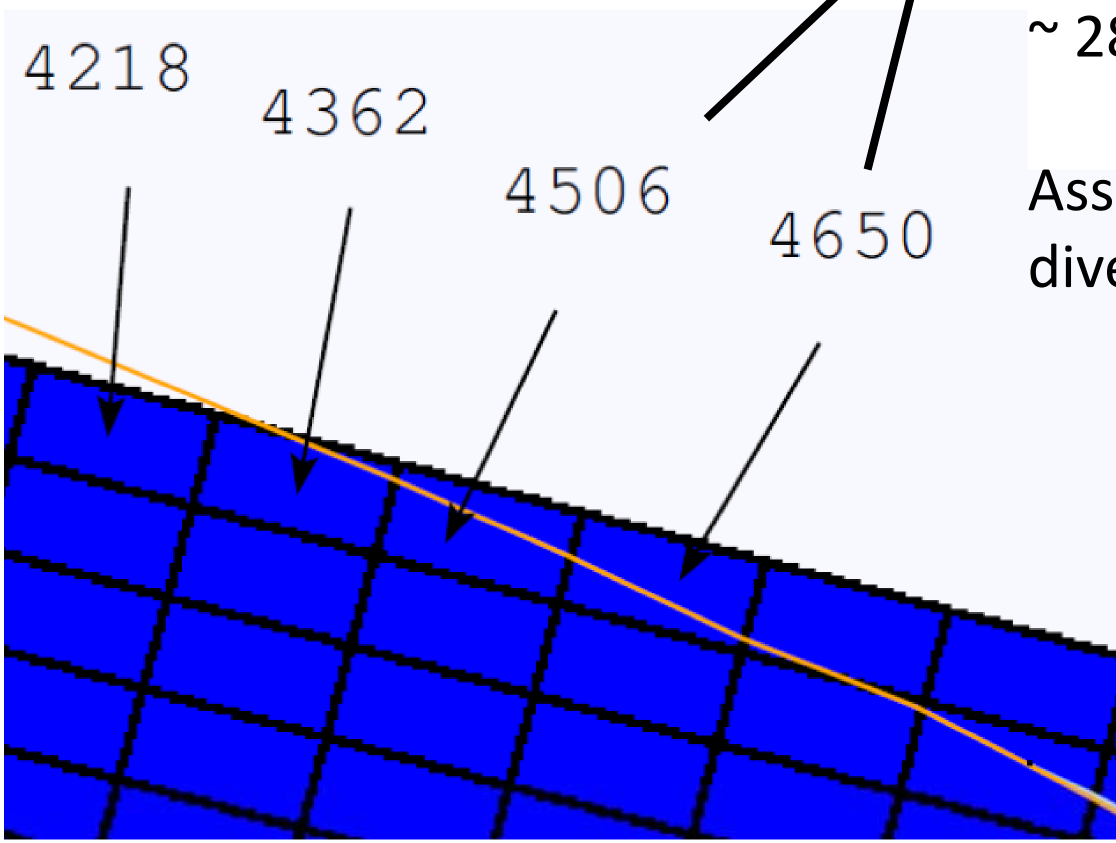
  [Volumetric-average Energy deposition reported for cell (W/m^3)]
  is proportional to [1/Cell Volume]

- 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

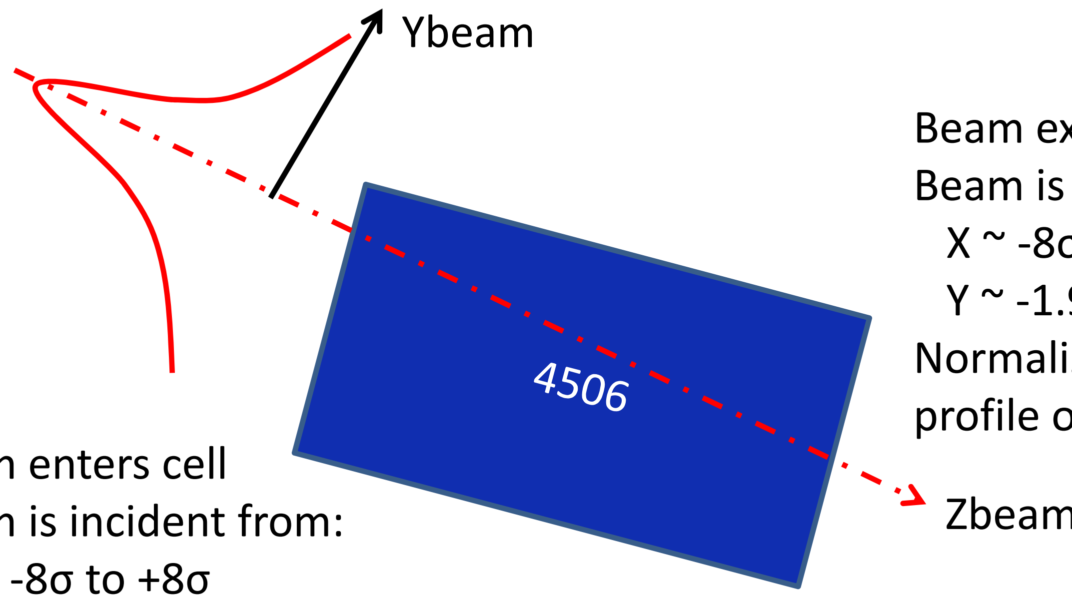
Beam Incidence



Max energy deposition occurs in these two cells ~ 28J/pulse

Assume beam is un-diverged in cell 4506

Beam Profile at Incidence

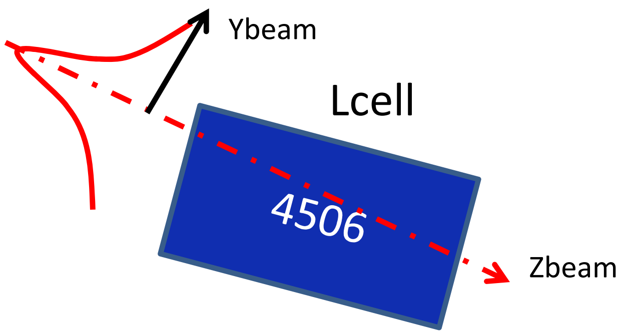


Beam enters cell
Beam is incident from:
  X ~ -8σ to +8σ
  Y ~ -2.8σ to +1σ
Normalized Integral of beam profile over this area =0.84

Beam exits cell
Beam is incident from:
  X ~ -8σ to +8σ
  Y ~ -1.9σ to +1.9σ
Normalized integral of beam profile over this area =0.94

Averaging these, we estimate that an area fraction Fa=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



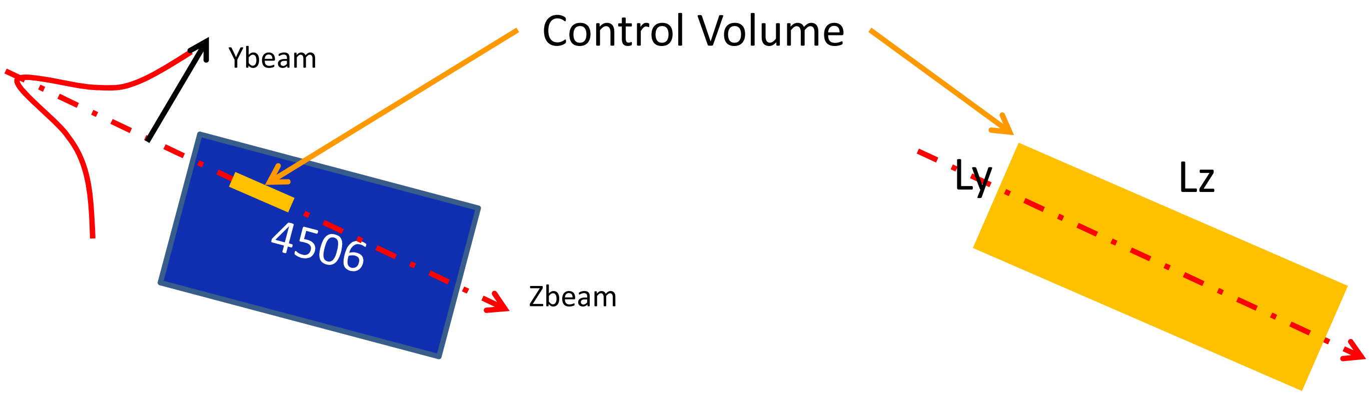
Now, we can estimate the linear energy deposition associated with the beam

EDpcell = 27.5 J/pulse	Energy deposition per pulse, direct MARS result
Fa = 0.89	Area fraction of beam profile passing through this cell
Lcell = 10mm	Length of cell along beamline, as modeled in MARS

EDp = EDpcell/(Fa * Lcell)

= 3.09 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

$Lx = 0.1\sigma x = 0.03mm$

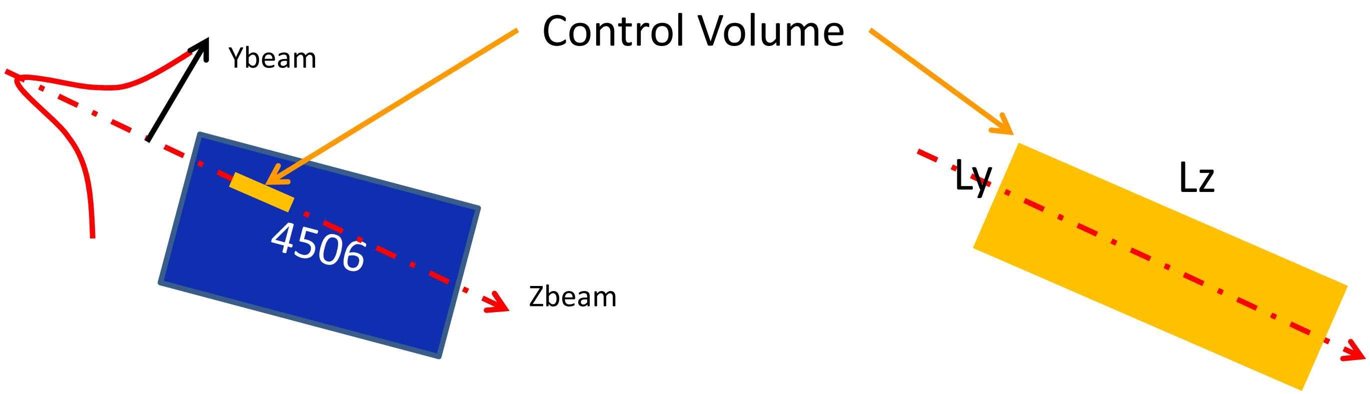
$Ly = 0.1\sigma y = 0.13mm$

$Lz = 1mm$

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

Integrating a Gaussian profile over the 0.1σx*0.1σy footprint of the control volume, we calculate that the control volume will receive a fraction of the beam profile equal to Fcv=0.00159. Note that if the size of σx or σy were to change, this result would be the same.

Energy Deposition at Beam Incidence



Now, we can calculate energy deposition within the control volume

EDcv = EDp * Fcv * Lz
= 3.09 J/mm/pulse * 0.00159 * 1mm
= 0.00491 J/pulse in the control volume

Now, given the density and specific heat of graphite, we can calculate ΔT
p = 1720 kg/m3
c = 550 J/kg*K

ΔT = EDcv / (Vcv * p * c)

Single-Pulse Temperature Rise

ΔT = EDcv / [Vcv * p * c]

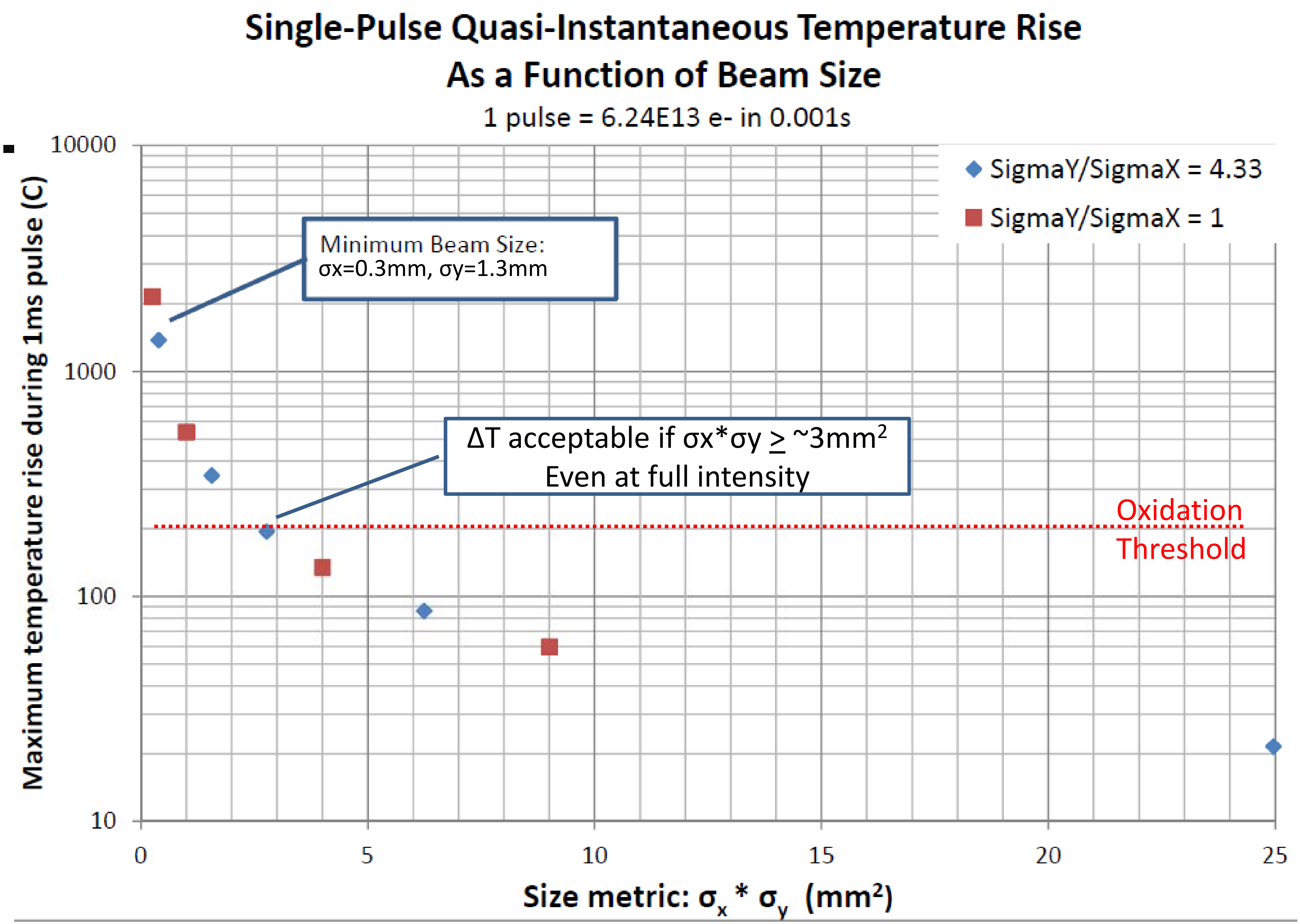
= [0.00491 J/pulse] / [3.9E-12 m^3 * 1720 kg/m3 * 550 J/kg*K]

= 1380°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 ΔT of 1460 °K

- Given stress an oxidation limits in the graphite, we can only handle an instantaneous temperature rise of ~200°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 1.25E13 e-/pulse



Single-Pulse Quasi-Instantaneous Temperature Rise
As a Function of Beam Size
1 pulse = 6.24E13 e- in 0.001s
Maximum temperature rise during 1ms pulse (C)
10000
1000
100
10
0
5
10
15
20
25
Size metric: σx * σy (mm²)
SigmaY/SigmaX = 4.33
SigmaY/SigmaX = 1
Minimum Beam Size:
σx=0.3mm, σy=1.3mm
ΔT acceptable if σx*σy ≥ ~3mm²
Even at full intensity
Oxidation
Threshold

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 $\sigma x * \sigma y \geq \sim 3mm^2$
  - Implement fast beam sweeping at $f \geq \sim 350Hz$
  - 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

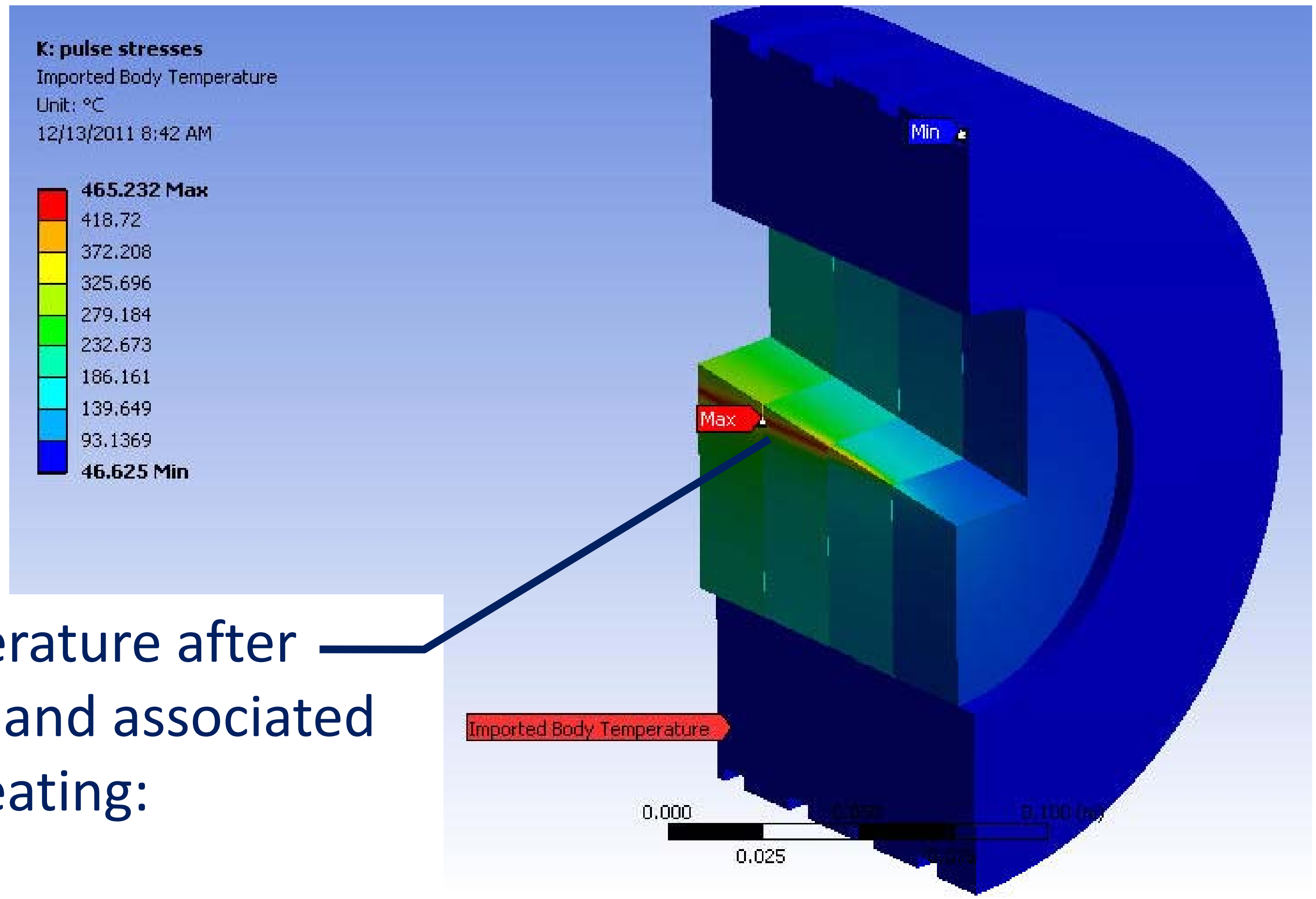
- Now, we assess the stress state in the graphite as a result of the pulse transient thermal condition
- Assume mitigation scenario where temperature/oxidation constraint limits maximum beam size to $\sigma x * \sigma y \geq$ ~3mm2
- To see whether stress constraints are more stringent than the oxidization constraint, we assess the stress condition under the following conditions
  - o Full intensity: 6.24E13 e-/per pulse
  - o $\sigma x * \sigma y = 3mm^2$, $\sigma x = \sigma y = 1.7mm$
  - o Single pulse instantaneous rise calculated near the beam incidence location, beam divergence assumed to be small
  - o 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)

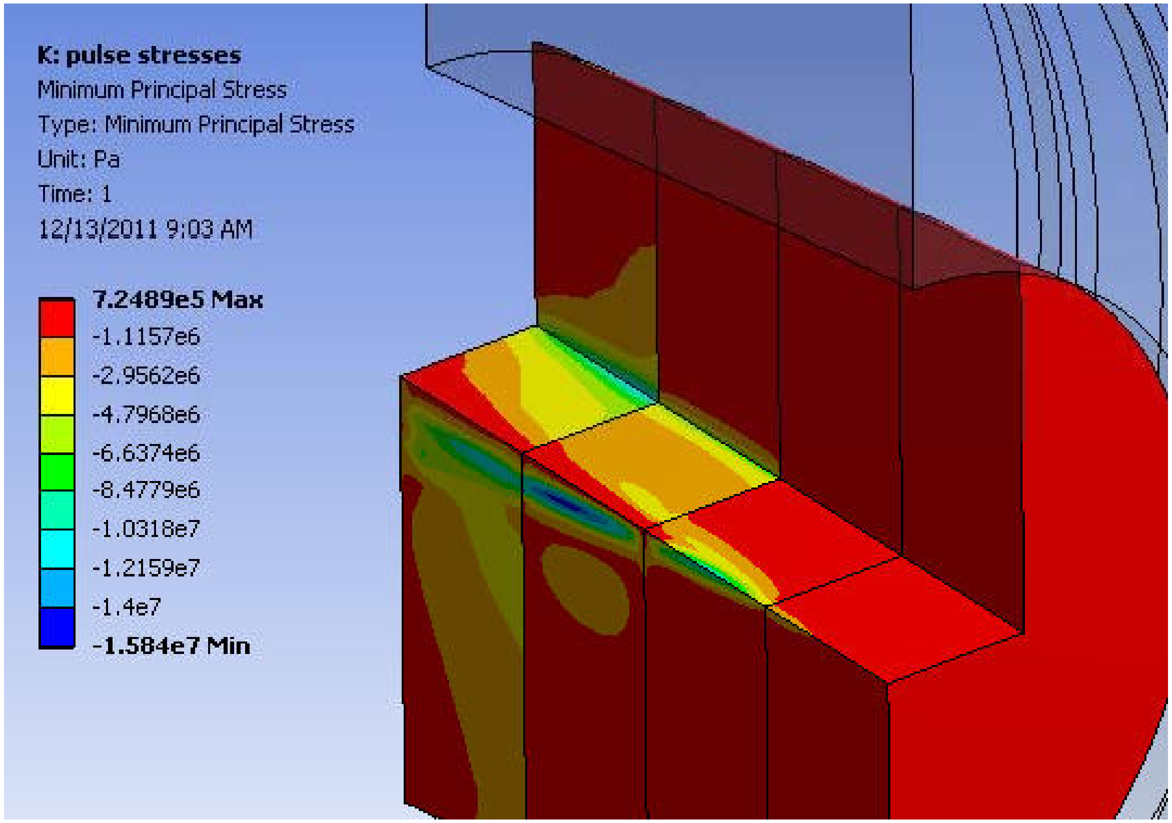
- Calculate graphite stresses as follows:
  - Compare maximum principal stress to flexural strength
  - Compare minimum principal stress to compressive strength

Pulse Transient: Temperature Field



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

Pulse Transient: Induced Stresses



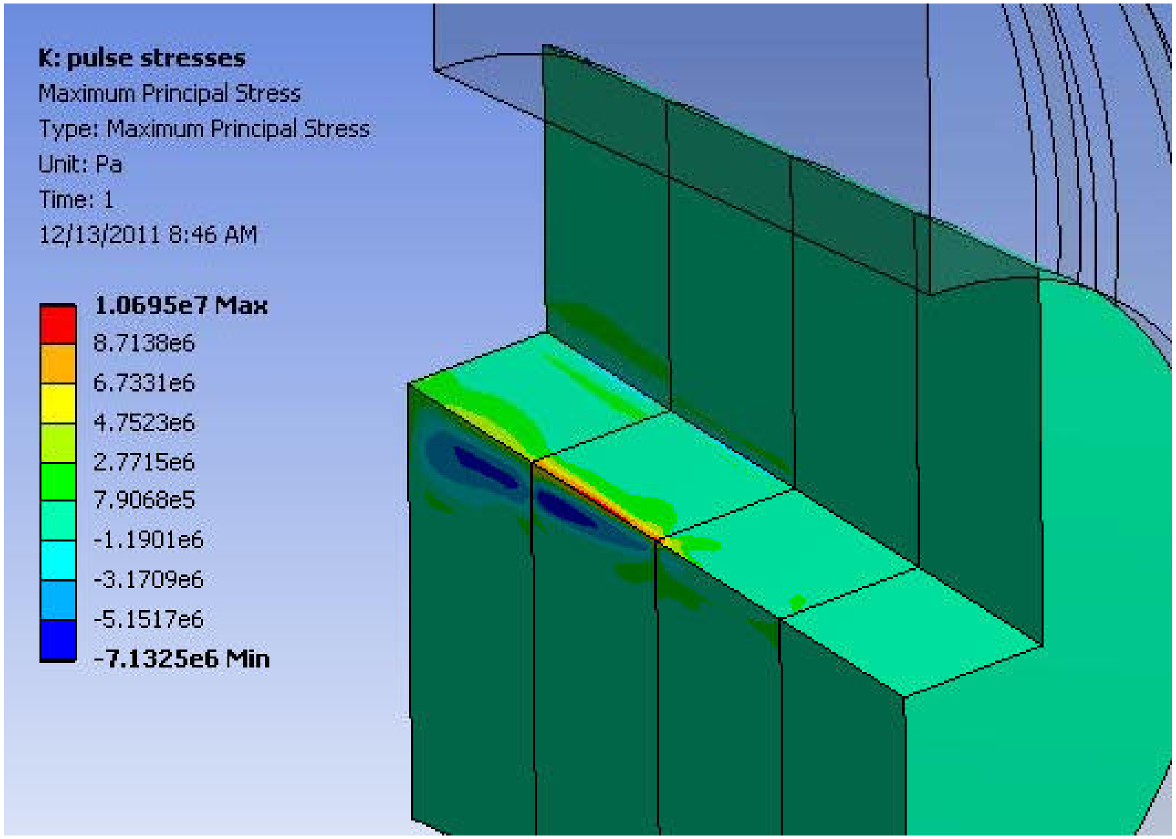
Minimum principal stress in graphite:

-15.8 MPa (-2.3 ksi)

Compare to strength of 78MPa

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

FOS = 39/10.6 = 3.7

Pulse Transient: Stress Conclusions

- Mechanical stresses are acceptable at beam size condition $\sigma x * \sigma y = 3mm^2$. 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 $\sigma x = 0.3mm / \sigma y = 1.3mm$ beam size at full intensity

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- Pulse Transient
- System Transient Analyses
- Conclusions

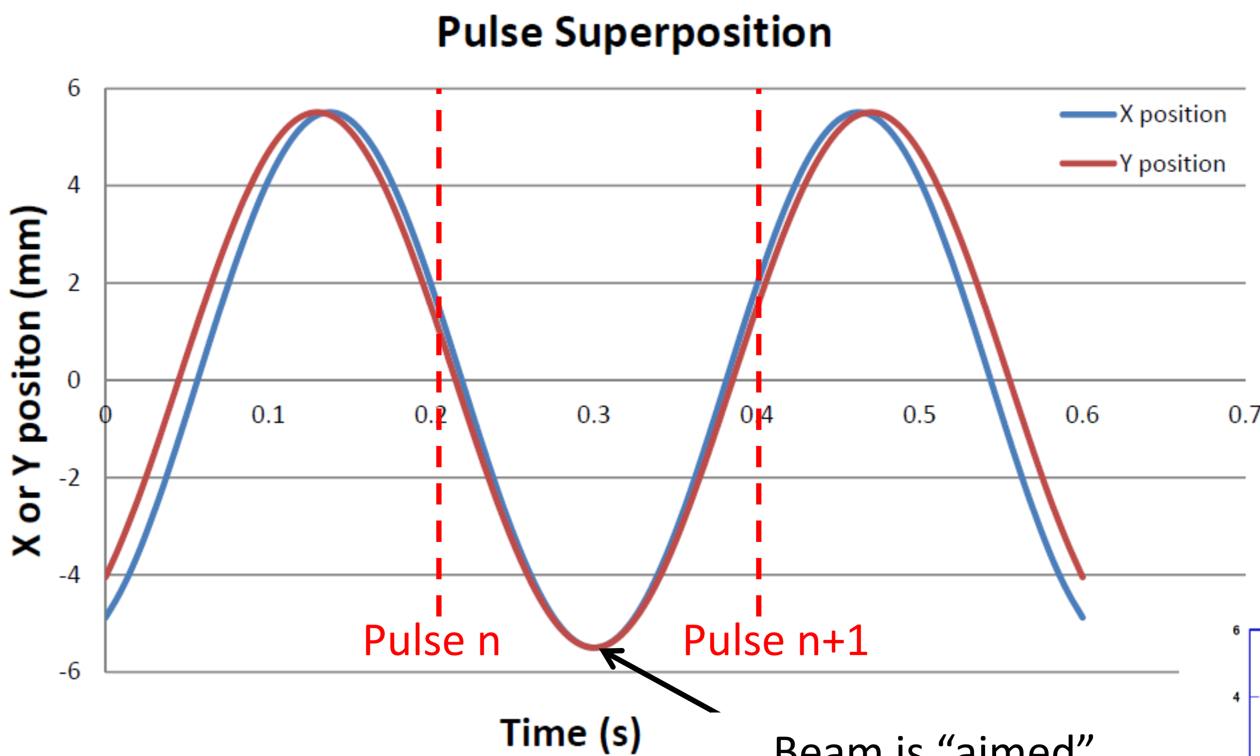
System Transient Analyses

- 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

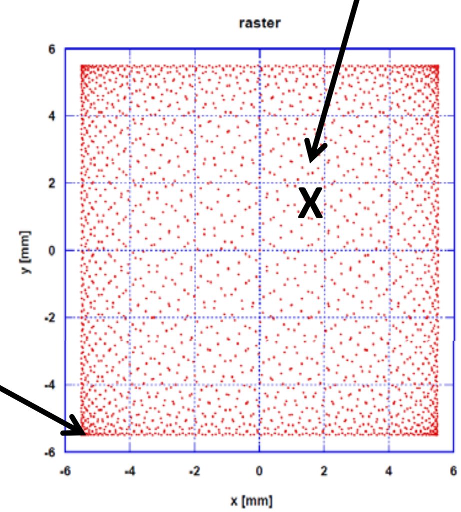
- Recall that beam sweeps sinusoidally in X and Y, at slightly different frequencies
- Assume that time-phasing between X and Y sweeping functions will be random
- A case exists where two subsequent pulses land in the same location of the absorber
  - This occurs when the both X and Y sweeping functions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

Pulse Superposition: Rare but possible condition



Pulse n+1 lands on top of pulse n here

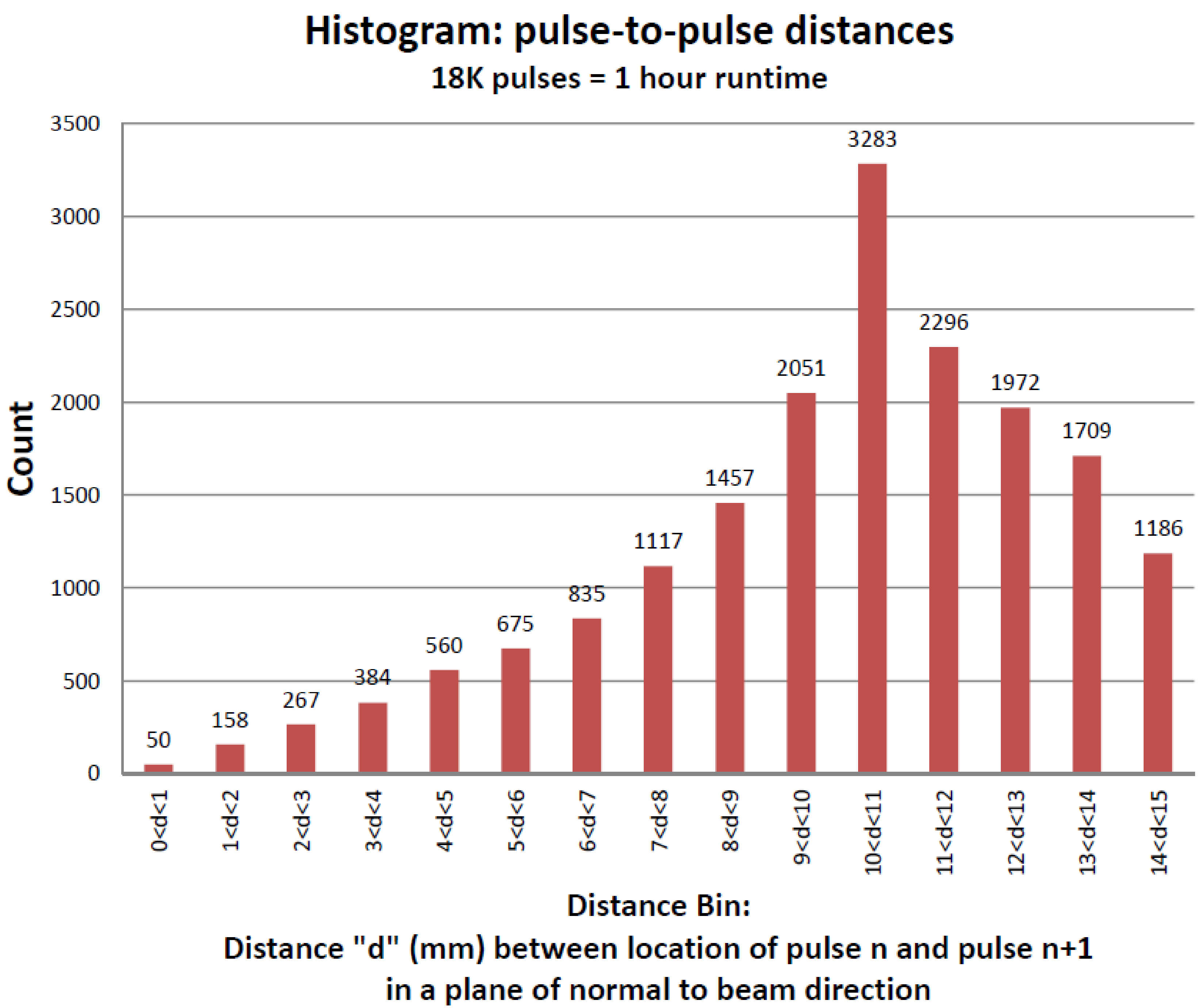
Beam is "aimed" towards this corner (but no pulse fires)



Pulse Superposition

- How often can this happen?

- Monte-Carlo analysis was run to assess this
  - Random seed parameter: time phasing between X and Y sweeping function at t=0 is random on interval 0:0.34s (i.e. one period of the Y function)
  - Pulse timing fixed at 0,0.2,0.4… s
  - Pulse-to-pulse distances calculated in a plane normal to beam direction for each pulse over a 1 hour / 18k pulse time period


Histogram: pulse-to-pulse distances
18K pulses = 1 hour runtime
Count
3500
3000
2500
2000
1500
1000
500
0
50
158
267
384
560
675
835
1117
1457
2051
3283
2296
1972
1709
1186
0<d<1
1<d<2
2<d<3
3<d<4
4<d<5
5<d<6
6<d<7
7<d<8
8<d<9
9<d<10
10<d<11
11<d<12
12<d<13
13<d<14
14<d<15
Distance Bin:
Distance "d" (mm) between location of pulse n and pulse n+1
in a plane of normal to beam direction

Pulse Superposition

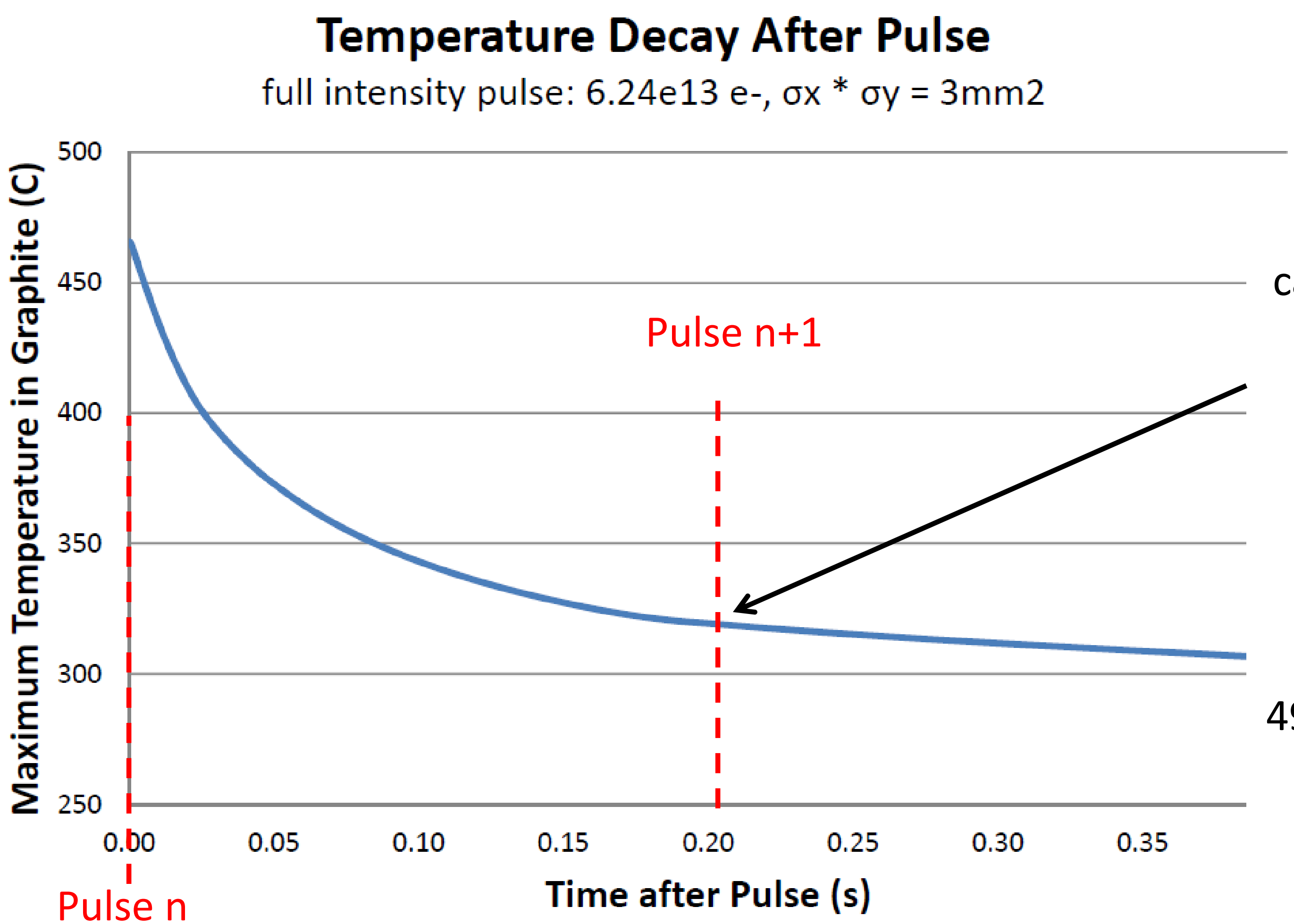
- Pulse superposition is only a concern when the overlap is < ~1σ
- Over a 1-hour period in which 18k pulses are fired, the average metrics (over many Monte-Carlo instances) are:
  - 211 cases where next-pulse-distance < 2mm (1.2%)
  - 151 cases where next-pulse-distance < 1.7mm (0.8%)
    {where 1.7mm corresponds to the lowest permissible beam σ}
  - 55 cases where next-pulse-distance < 1mm (0.3%)
- So this will happen!

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:
    - o Full intensity: 6.24E13 e-/per pulse
    - o $\sigma x * \sigma y = 3mm^2$, $\sigma x = \sigma y = 1.7mm$
    - o Single pulse instantaneous rise calculated near the beam incidence location, beam divergence assumed to be small
    - o Incident beam centered on absorber. This is slightly conservative, because pulse superposition can only occur 2-3mm off-center

Pulse Decay



Temperature jump caused by pulse n+1 will occur here. Hand-calculated dT = 176° C (per method shown starting on slide 55)

Max temperature in graphite will jump to 494°C. Approaching, but below, self-imposed oxidization limit

Pulse Decay Case: Conclusions

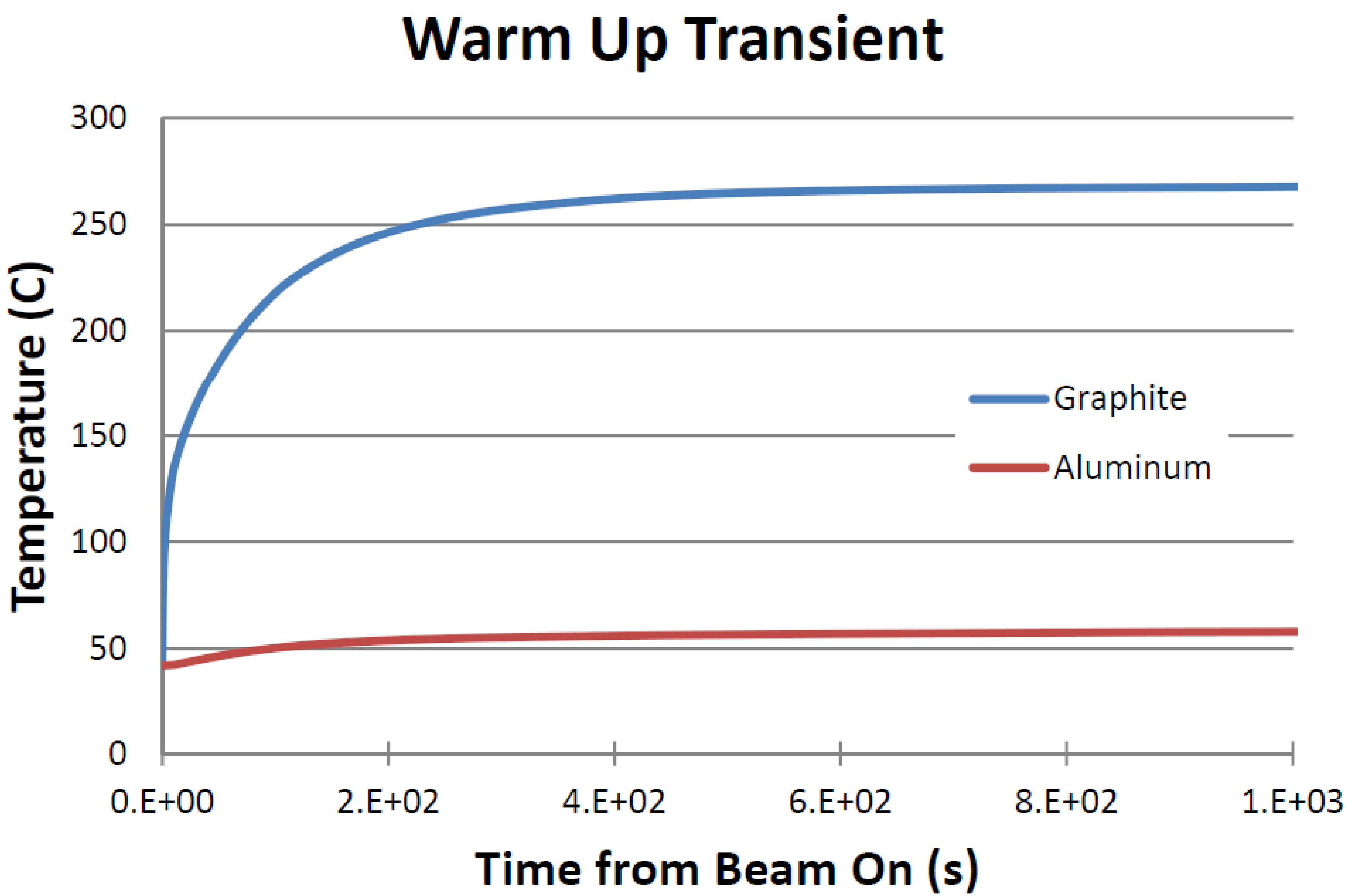
- After the 0.2s inter-pulse period temperatures have decayed >75% of the way back to their steady-state value
- In the case where subsequent pulses hit the same area, we will see temperatures approaching our limit of 500° C
  - This is for the derived-minimum-limit beam size ($\sigma x = \sigma y =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

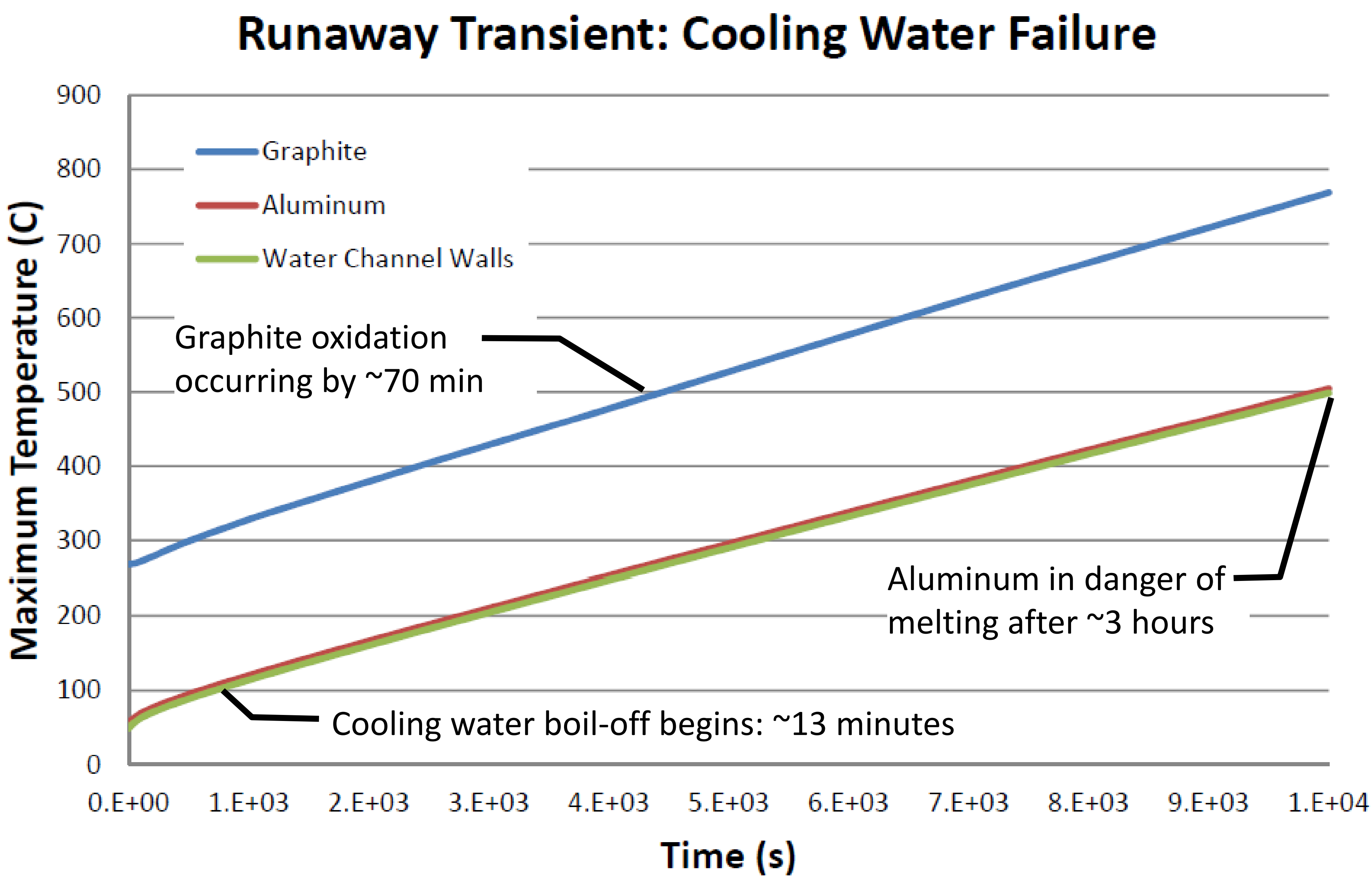
- Assumptions
  - 2.5kW temporally-averaged energy deposition
  - Same model and parameters as presented in steady-state analysis section
  - Absorber starts at assumed cooling water temperature of 40°C

- Conclusion: temperature profile is fully developed after ~10 minutes

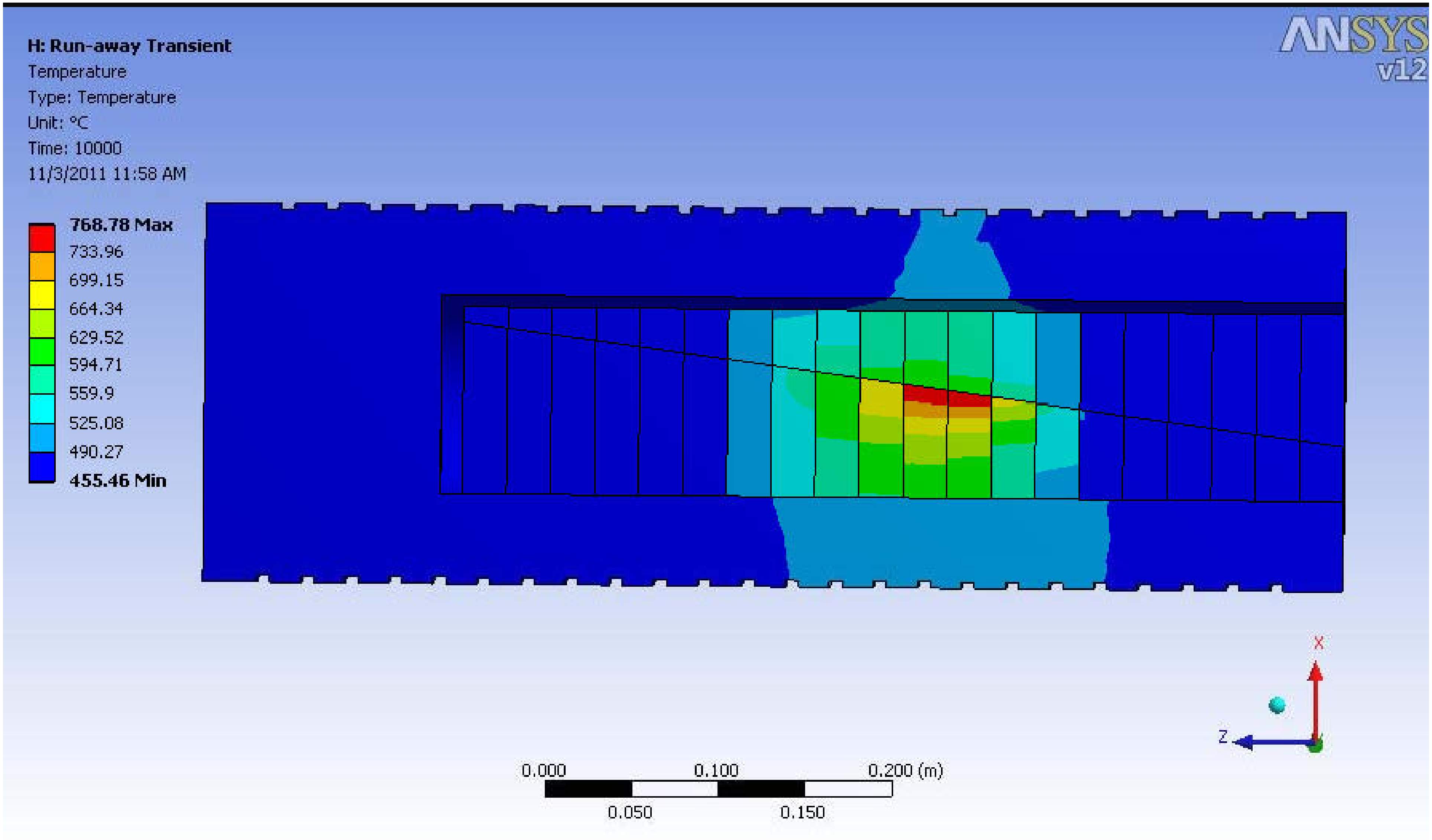

Warm Up Transient
Temperature (C)
300
250
200
150
100
50
0
0.E+00
2.E+02
4.E+02
6.E+02
8.E+02
1.E+03
Time from Beam On (s)
Graphite
Aluminum

Runaway Transient

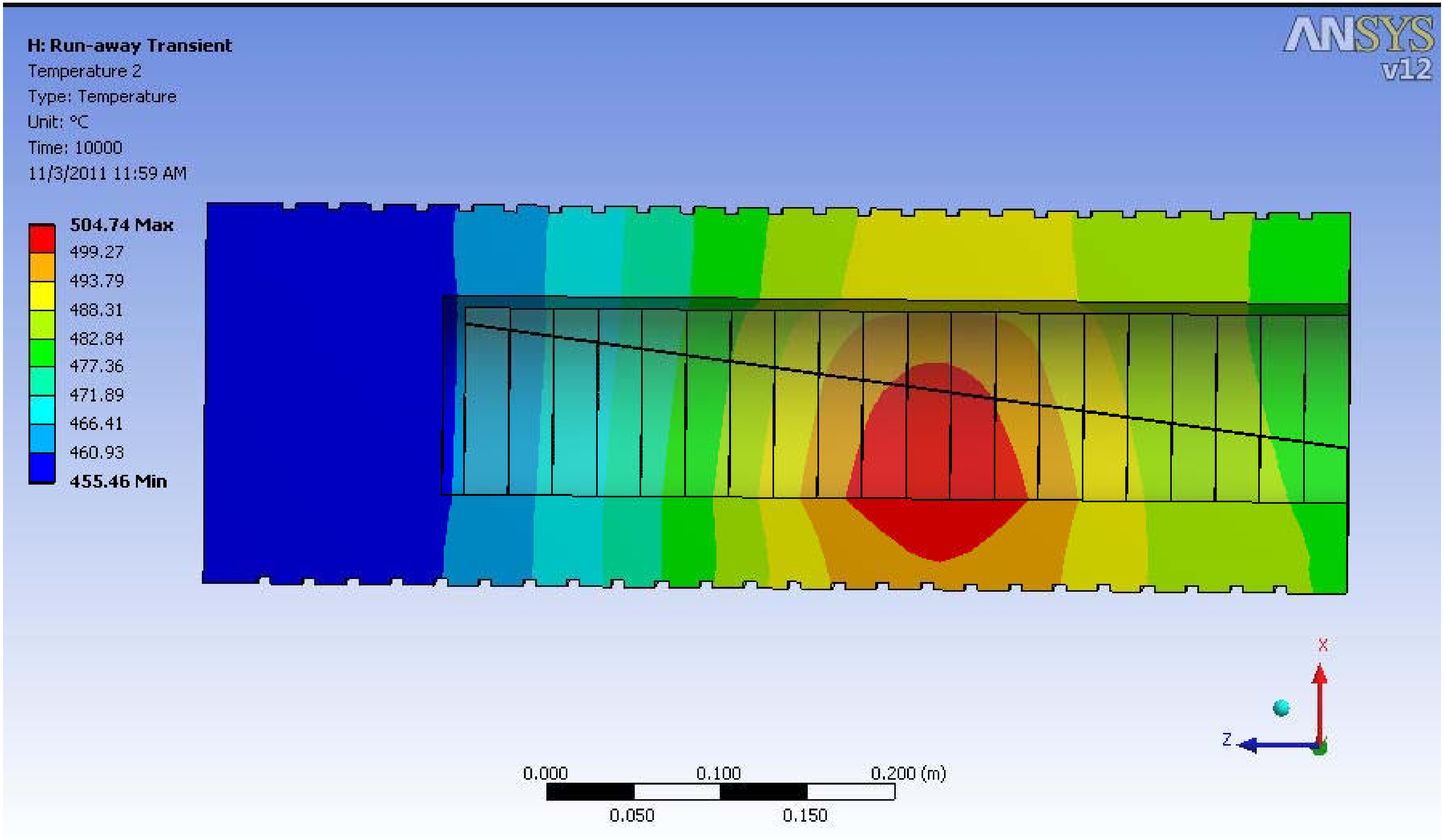
- As a possible accident scenario, case of cooling water failure was considered.
- How long do we have before something fails?
- Assumptions
  - Neglect natural convection and conduction to steel
  - Neglect phase change (boil-off) in cooling water
  - Assume continued application of 2.5kW beam power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


Runaway Transient: Cooling Water Failure
Maximum Temperature (C)
900
800
700
600
500
400
300
200
100
0
Graphite
Aluminum
Water Channel Walls
Graphite oxidation occurring by ~70 min
Aluminum in danger of melting after ~3 hours
Cooling water boil-off begins: ~13 minutes
0.E+00
1.E+03
2.E+03
3.E+03
4.E+03
5.E+03
6.E+03
7.E+03
8.E+03
9.E+03
1.E+04
Time (s)

Runaway Transient @BOL
System temperatures after 10,000s



Runaway Transient @BOL
Aluminum temperatures after 10,000s



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

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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 ~250 W/m^2K. 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 $\sigma x * \sigma y \geq$ ~$3mm^2$
  - Implement fast beam sweeping at f > ~350Hz
  - Limit intensity at the LED to 1.25E13 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

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- Appendix – Reduced Intensity Cases.

Appendix – Reduced Intensity Cases

- The analyses described above…
  - Identified a stress and temperature issue caused by individual beam pulses at the *maximum* possible intensity (6.24E13 e-/pulse) and the *minimum* possible beam size (σx= 0.3mm, σy=1.3mm)
  - Presented three possible mitigations:
    - At full intensity, ensure a large spot size such that $\sigma x * \sigma y$ > ~3mm2
    - Implement fast beam sweeping at f > ~350Hz
    - Limit intensity at the LED to 1.25E13 e-/pulse
  - Focused on the beam spot size mitigation option

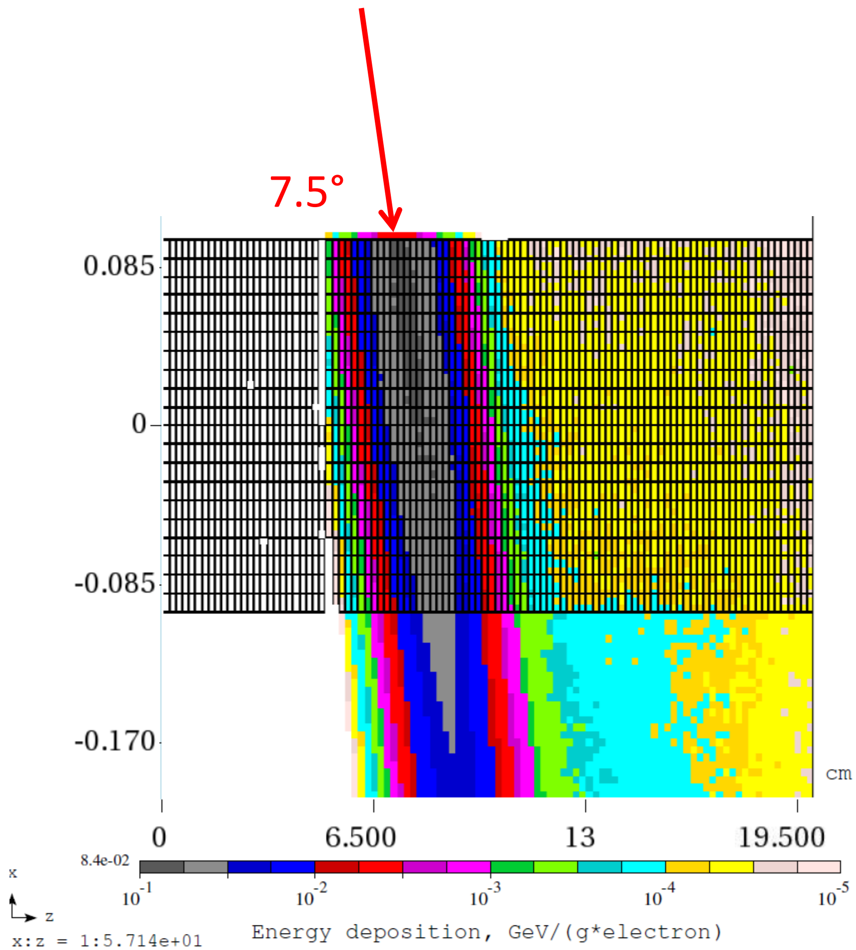
Appendix – Reduced Intensity Cases

- 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: $0.1\sigma x$ X $0.1\sigma x$ X 1mm
  - Peak energy deposition compares well (~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.

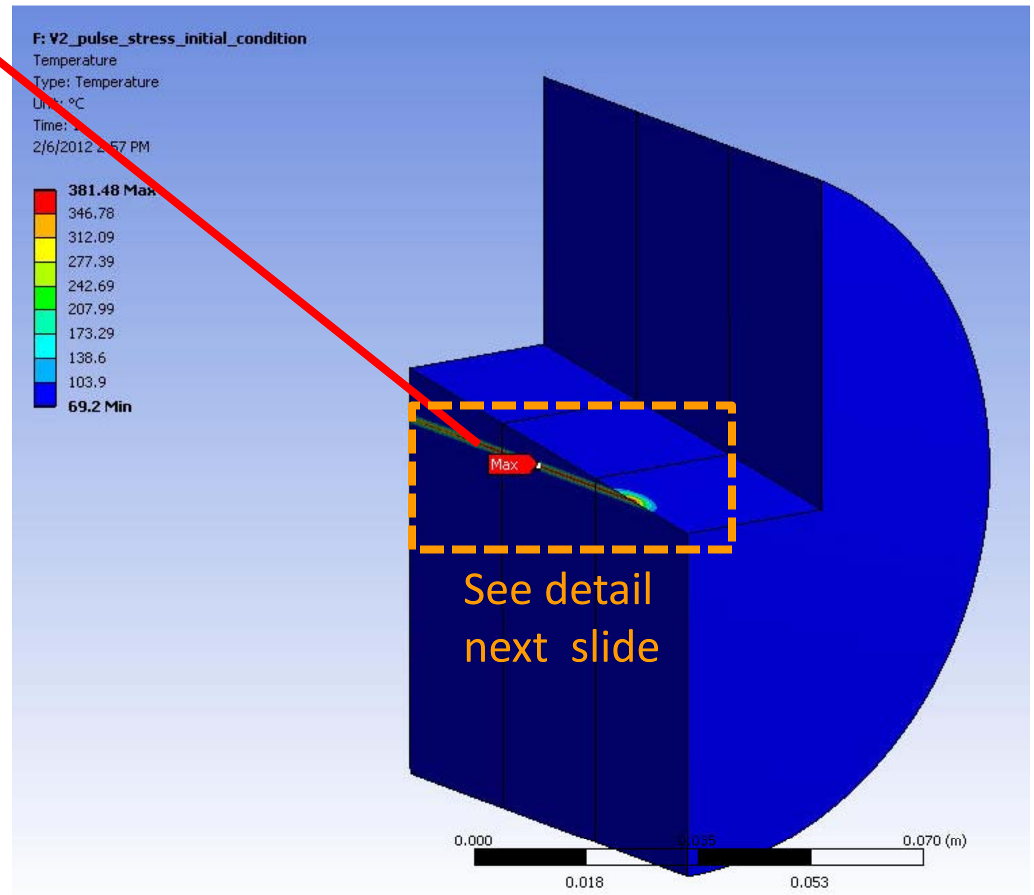
Analysis Approach for Reduced Intensity Cases

- 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

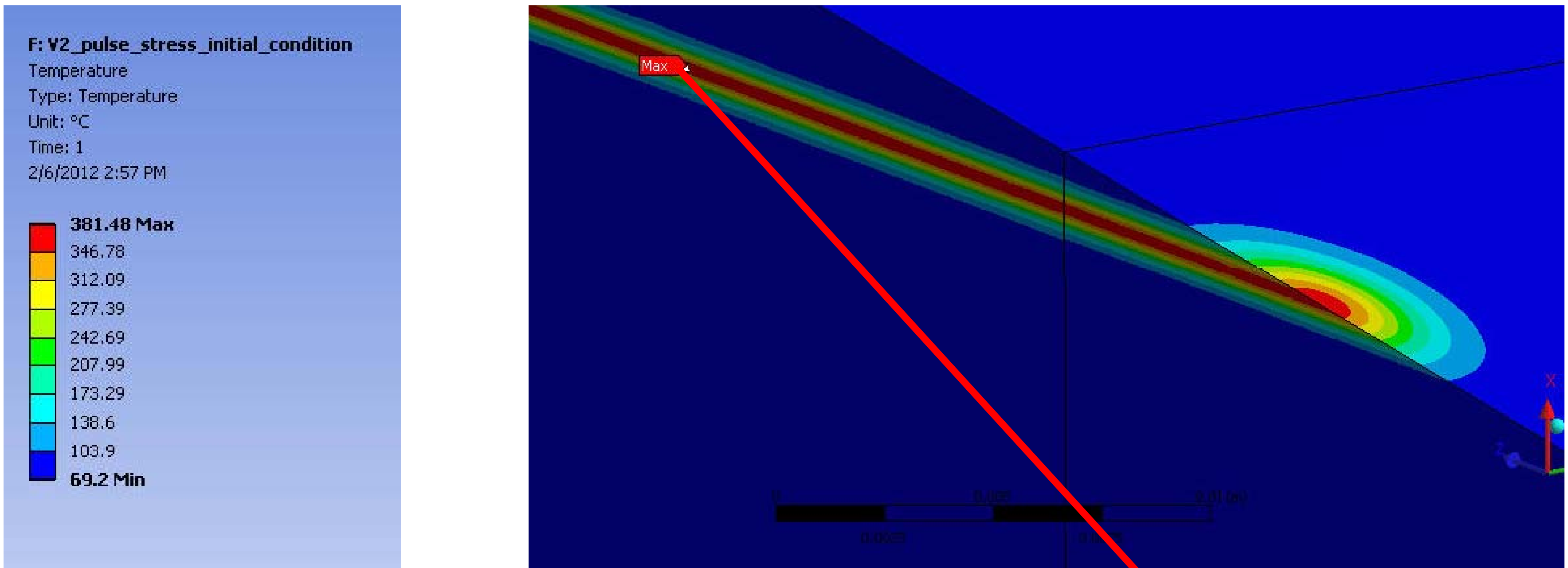
Example Result: Pulse Transient Temperature Field at 0.20X intensity

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



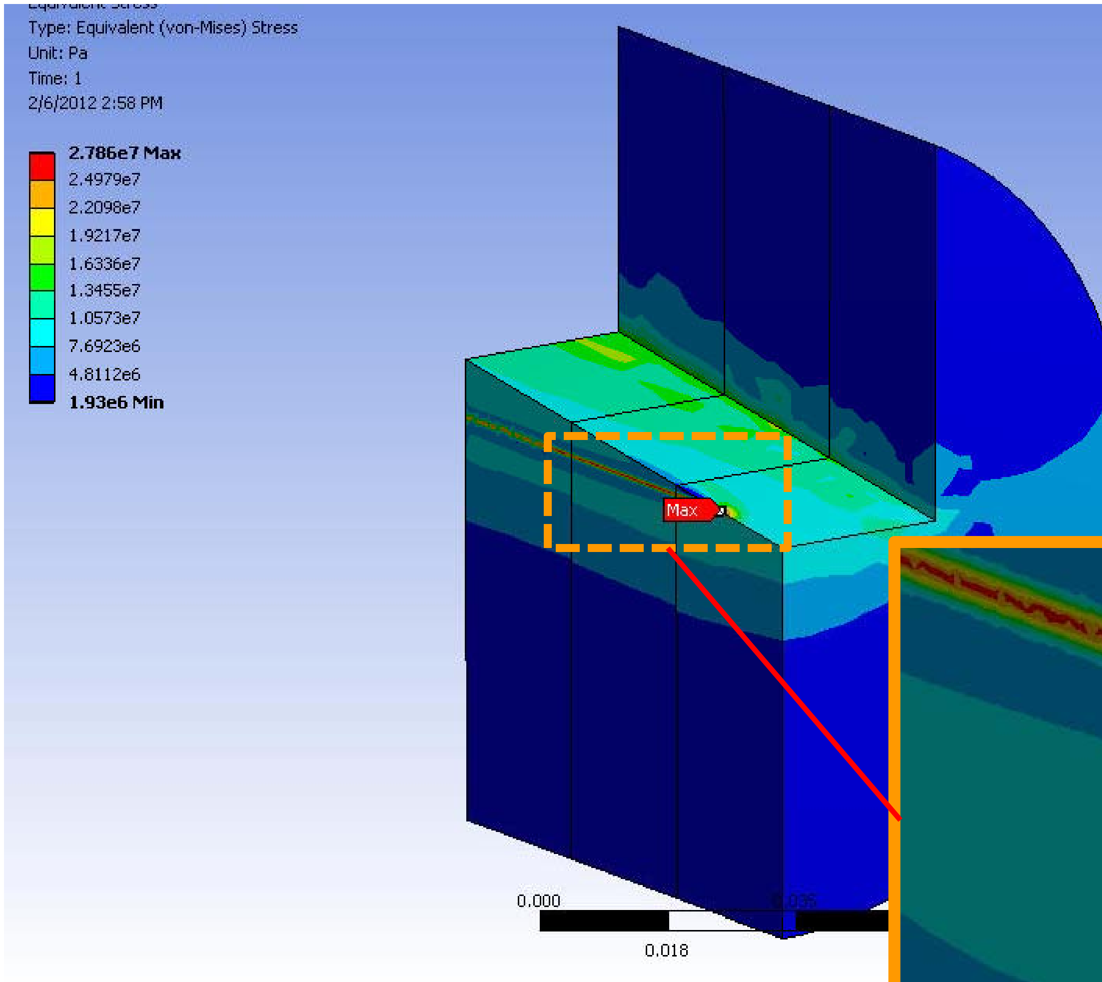
Maximum temperature after passage of pulse and associated instantaneous heating:
381° C (0.20X intensity)

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)

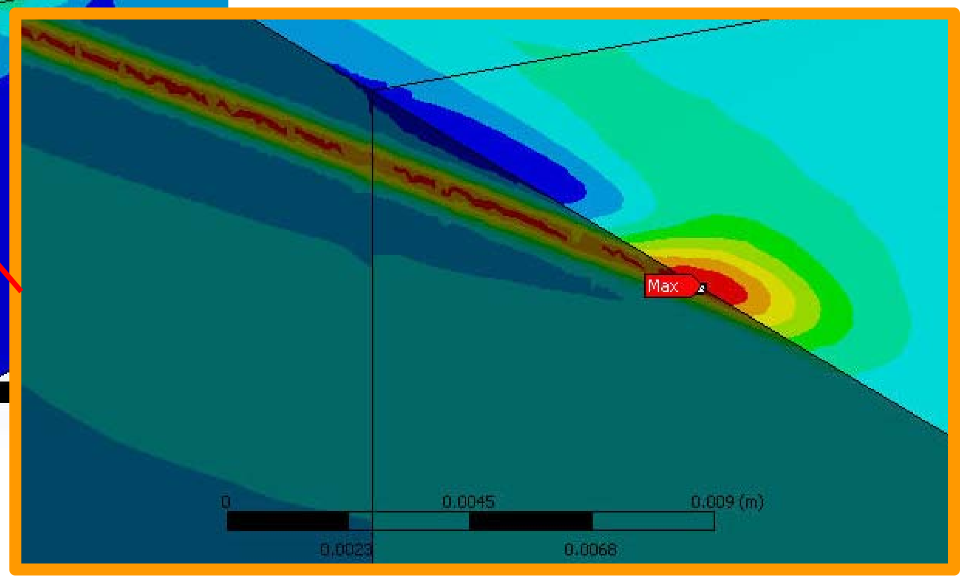
- Calculate graphite stresses as follows:
  - Compare maximum principal stress to flexural strength
  - Compare minimum principal stress to compressive strength

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



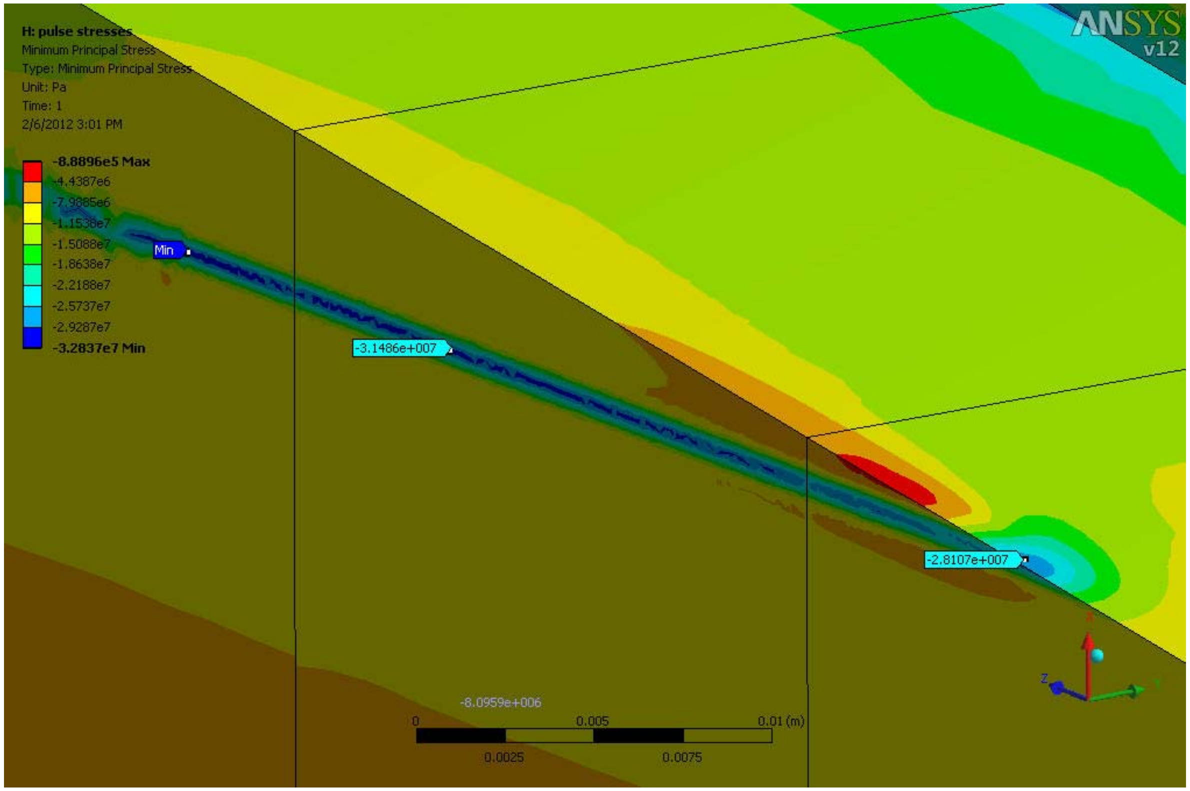
Von Mises Stress field just after passage of pulse:

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



Updated: Feb 07 2012

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



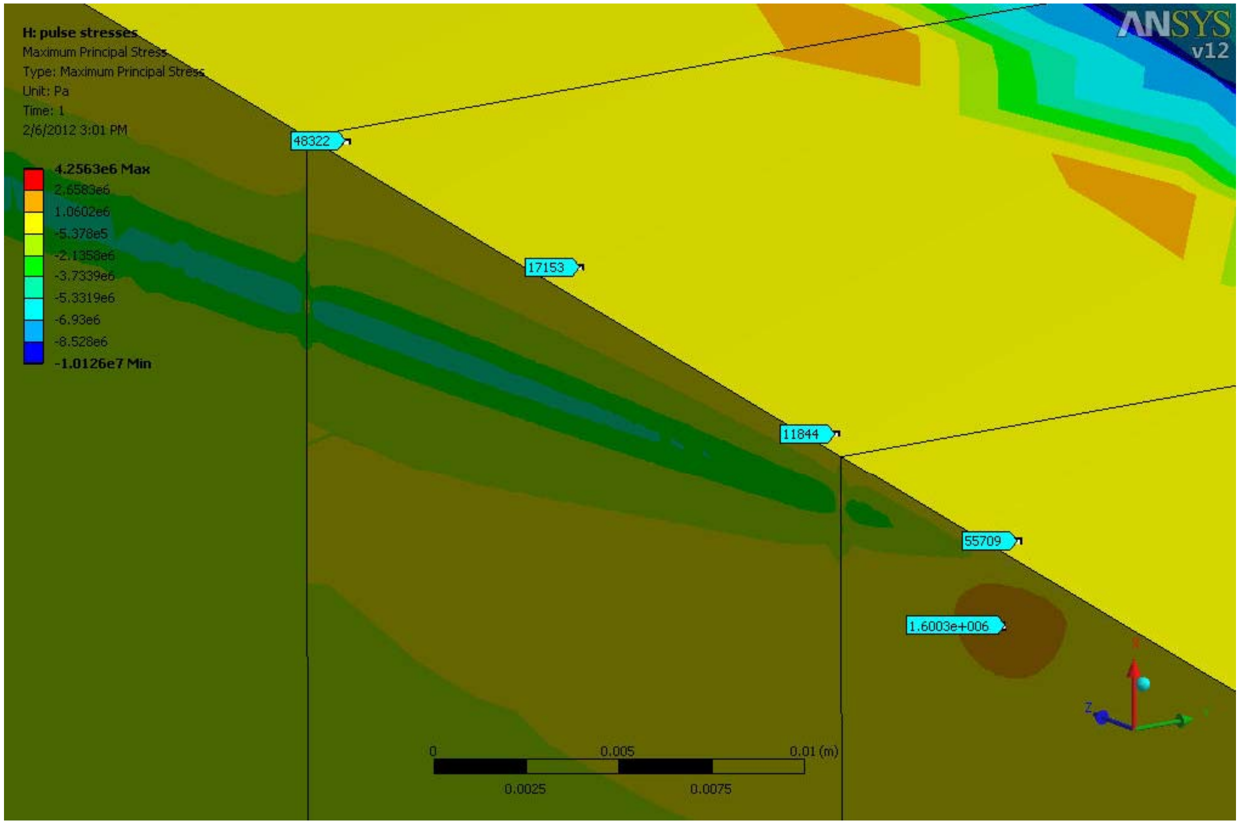
Min principal stress in graphite just after passage of pulse:

32.9 MPa (4.8ksi)

Compare to flexural strength of 78MPa

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:

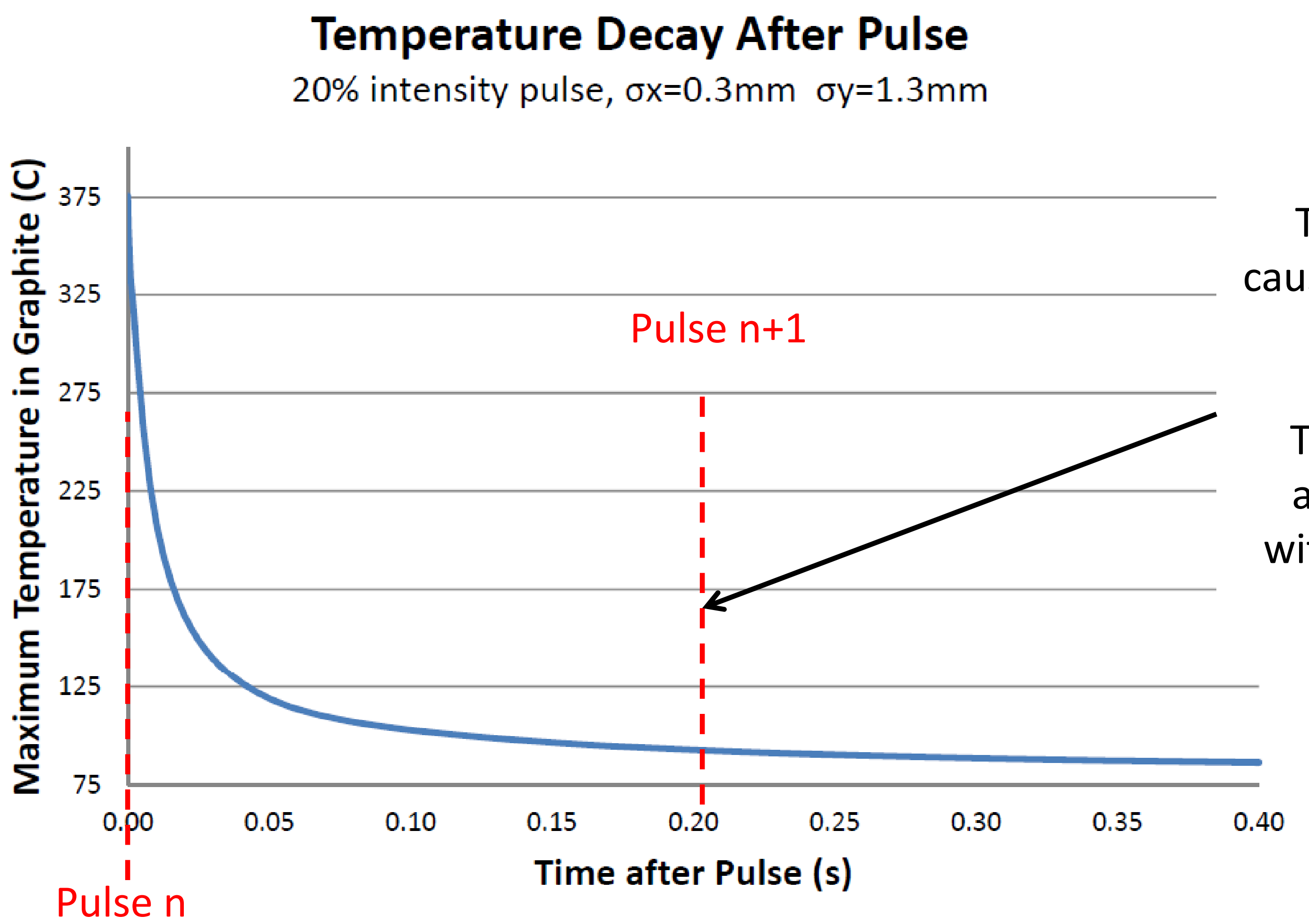
1.6 MPa (0.2ksi)

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 jump caused by pulse n+1 will occur here.

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

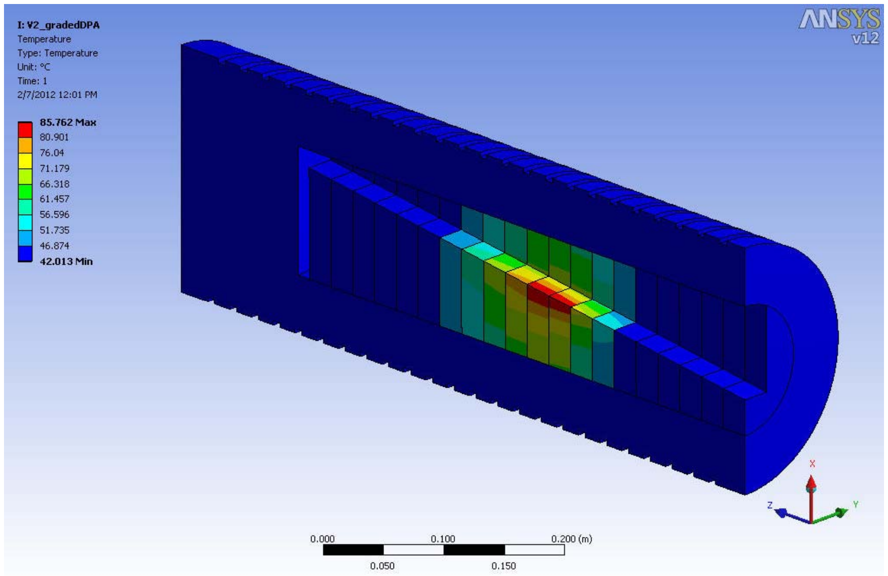
Reduced Intensity Pulse Decay Cases: Conclusions

- After the 0.2s inter-pulse period temperatures have decayed nearly all the way back to their steady-state value

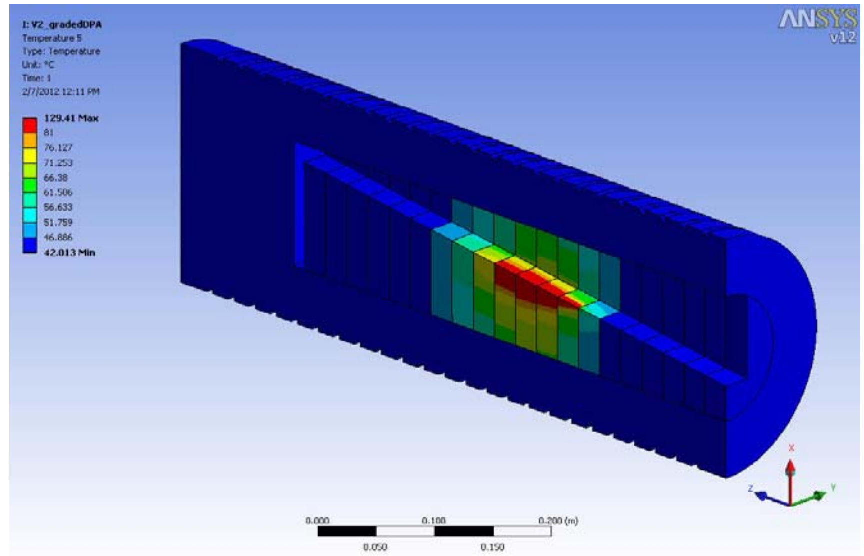
- Due to the smaller size of the affected volume and the lower energy deposited, the decay is much quicker in the reduced intensity cases.

- 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 1.4E21 electrons
  - This corresponded to ~4 calendar years at full intensity
  - More like ~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 that 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: σx=0.3mm σy=1.3mm

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≤1

Reduced Intensity: Observations

- For the smallest expected beam size, we can operate reasonably at 20% intensity, 1.25E13 e-/pulse
  - This limit is higher than the previously estimate of 9E12 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