LBNF/DUNE Hybrid Targets

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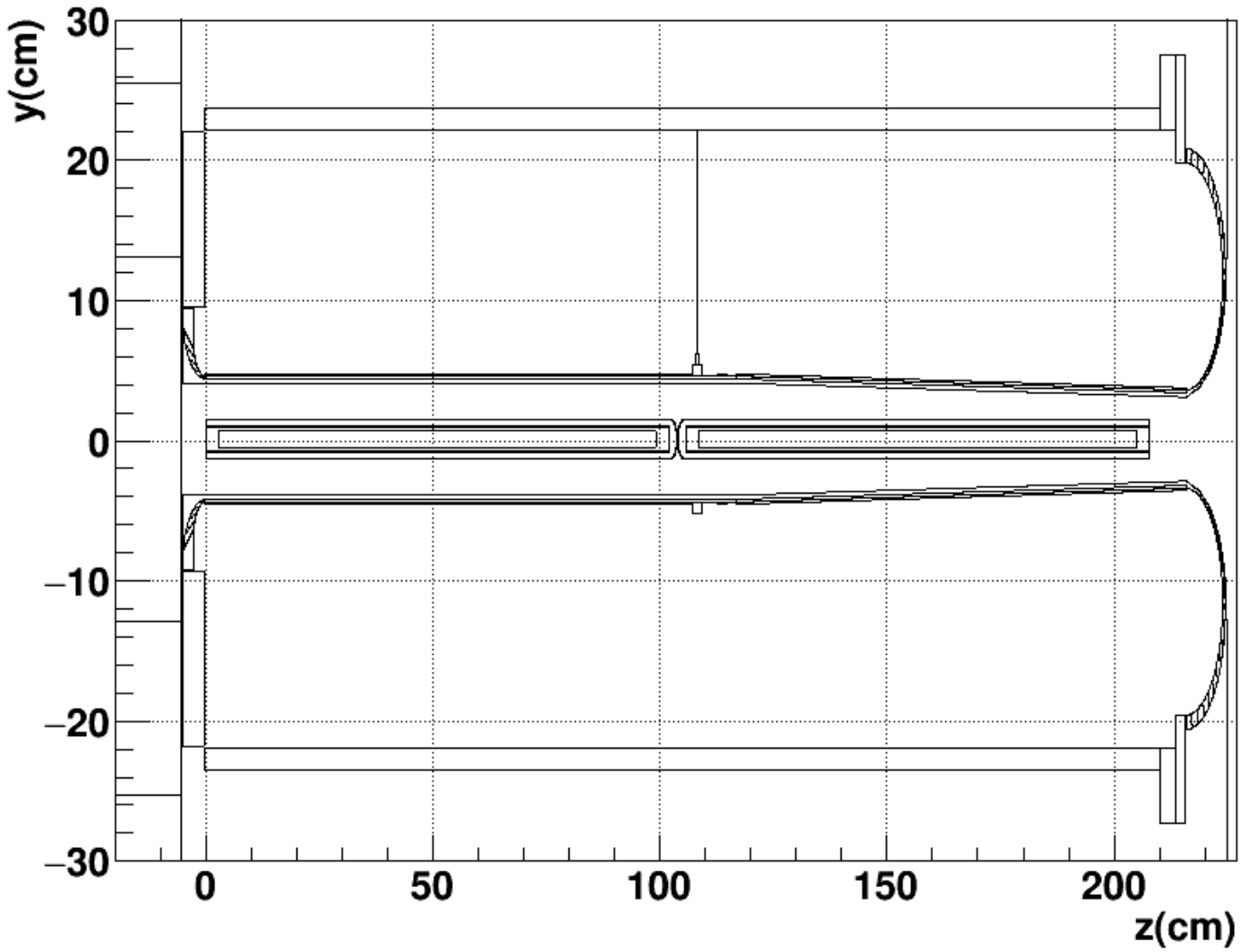
9th March 2017

DUNE DocDB 2437

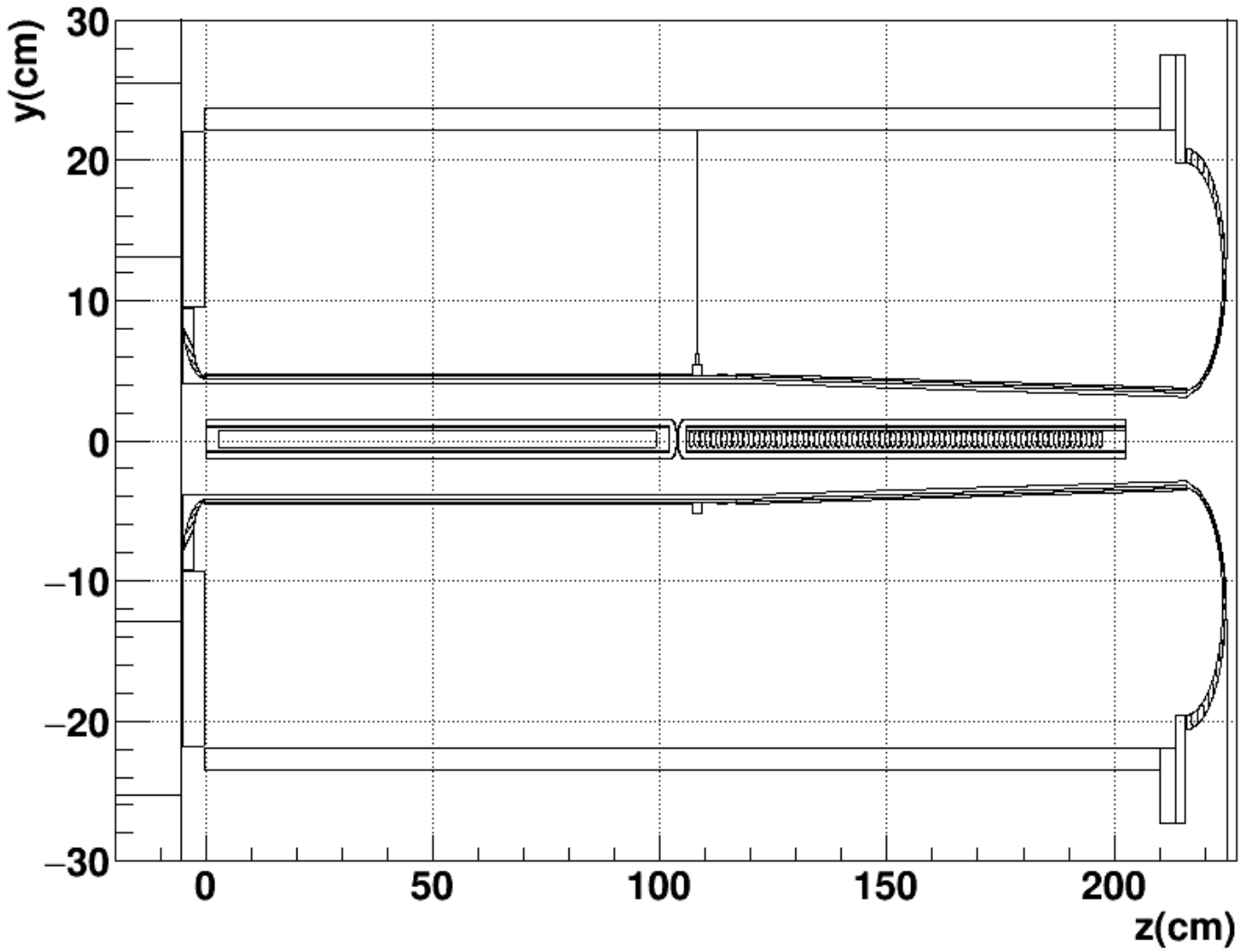
Introduction

- Investigation of physics performance of LBNF/DUNE hybrid targets
  - Splitting up cylindrical graphite target into two
  - Splitting up beryllium Spherical Array Target (SAT) into two
  - Low–Z (graphite cylinder/Be SAT) followed by high–Z SAT
  - Low–Z core & High–Z "jacket" cylindrical targets
- `G4LBNF` simulation with optimised 3 horn set–up (L. Fields)
  - `LBNFOptimConceptDesignHornX` macro options
  - He–cooled target modules with 1 mm thick titanium casings (RAL design)
  - ν flux CP sensitivity used to measure target performance (`GLoBES`)
- `FLUKA` (2011.2c.5) used for high–Z energy deposition estimates

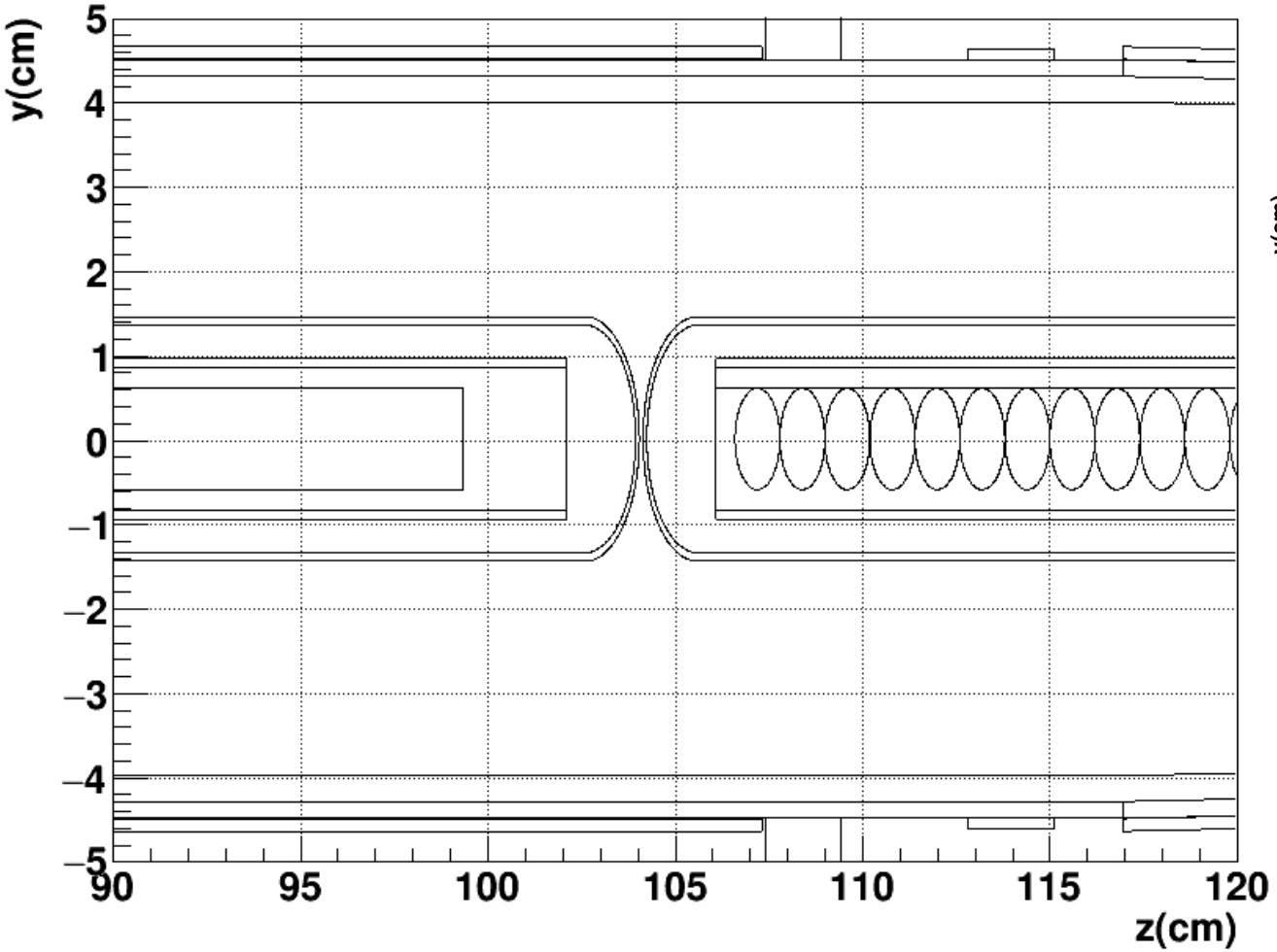
Geometry: two mirror image 2λ graphite cylinders

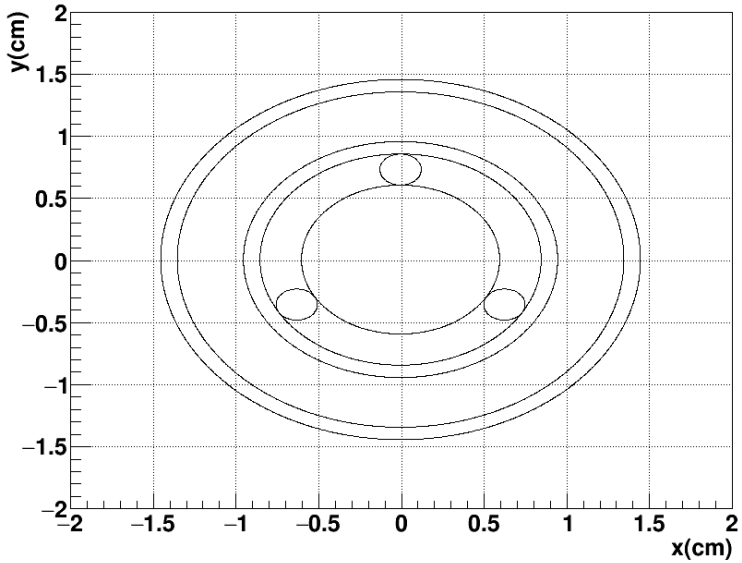


Geometry: 2$\boldsymbol{\lambda}$ graphite cylinder & 8$\boldsymbol{\lambda}$ tungsten SAT



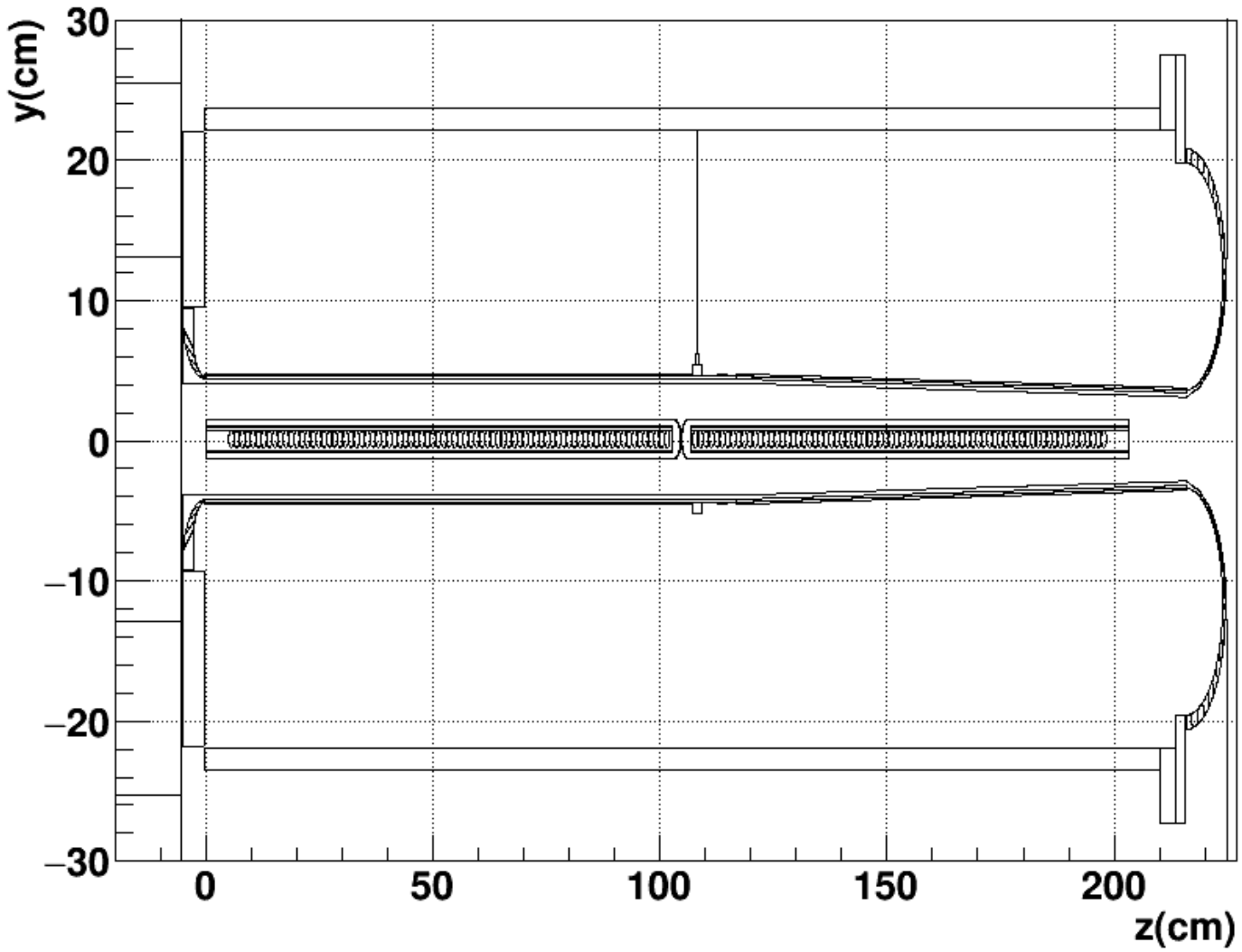
Geometry closeup: 2$\boldsymbol{\lambda}$ graphite cylinder & 8$\boldsymbol{\lambda}$ tungsten SAT





SAT cross-section

Geometry: 2$\boldsymbol{\lambda}$ beryllium & 8$\boldsymbol{\lambda}$ tungsten SAT



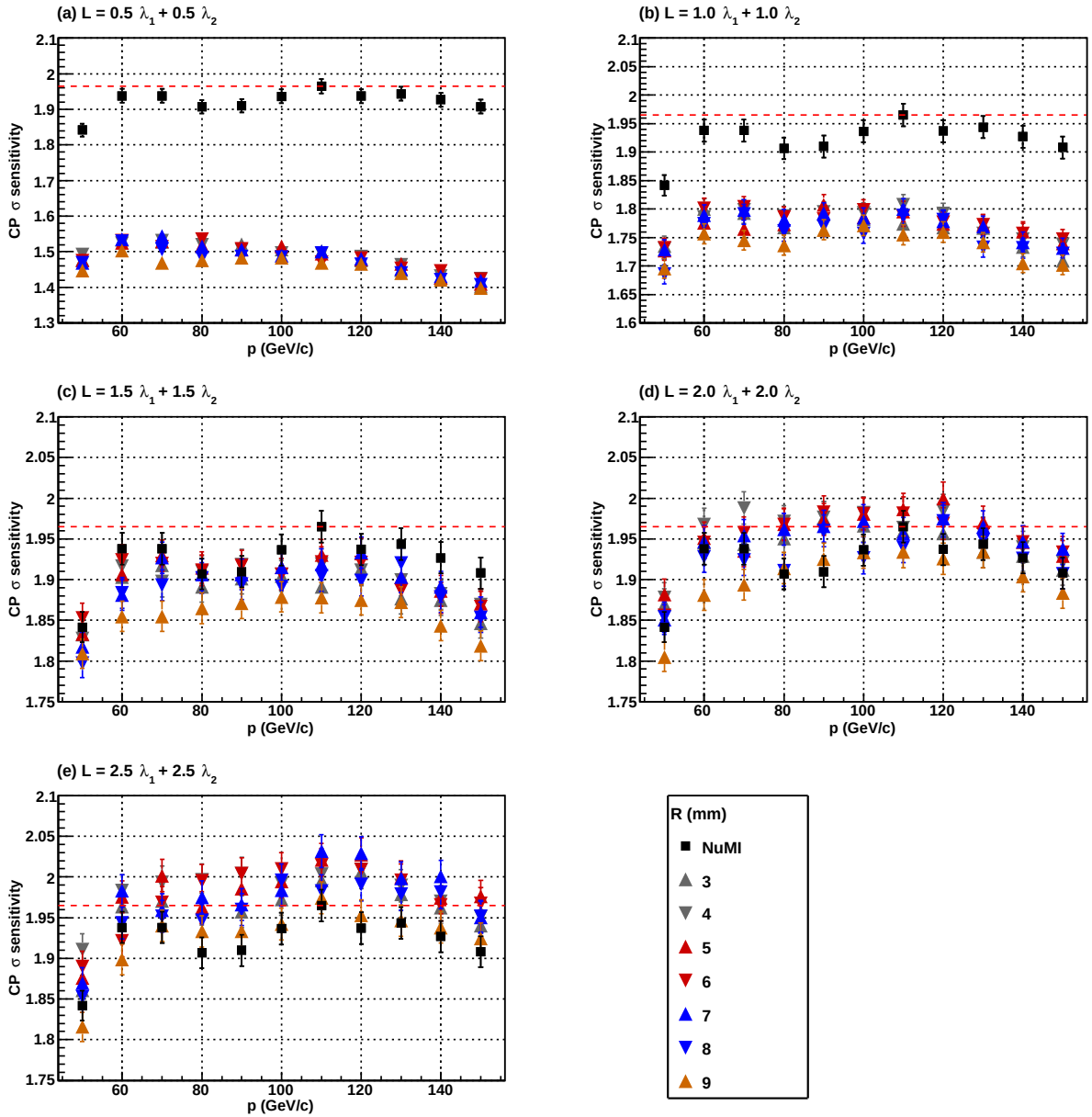
G4LBNF simulation parameters

- Proton beam: $p = 50$ to 150 GeV/c, Gauss $\sigma_b = 1$ to 3 mm, 1.2 MW power
- Target: two "mirror image" RAL design modules V_1 and V_2
  - radius $R_1 = R_2 = 3\sigma_b = 3$ to 9 mm

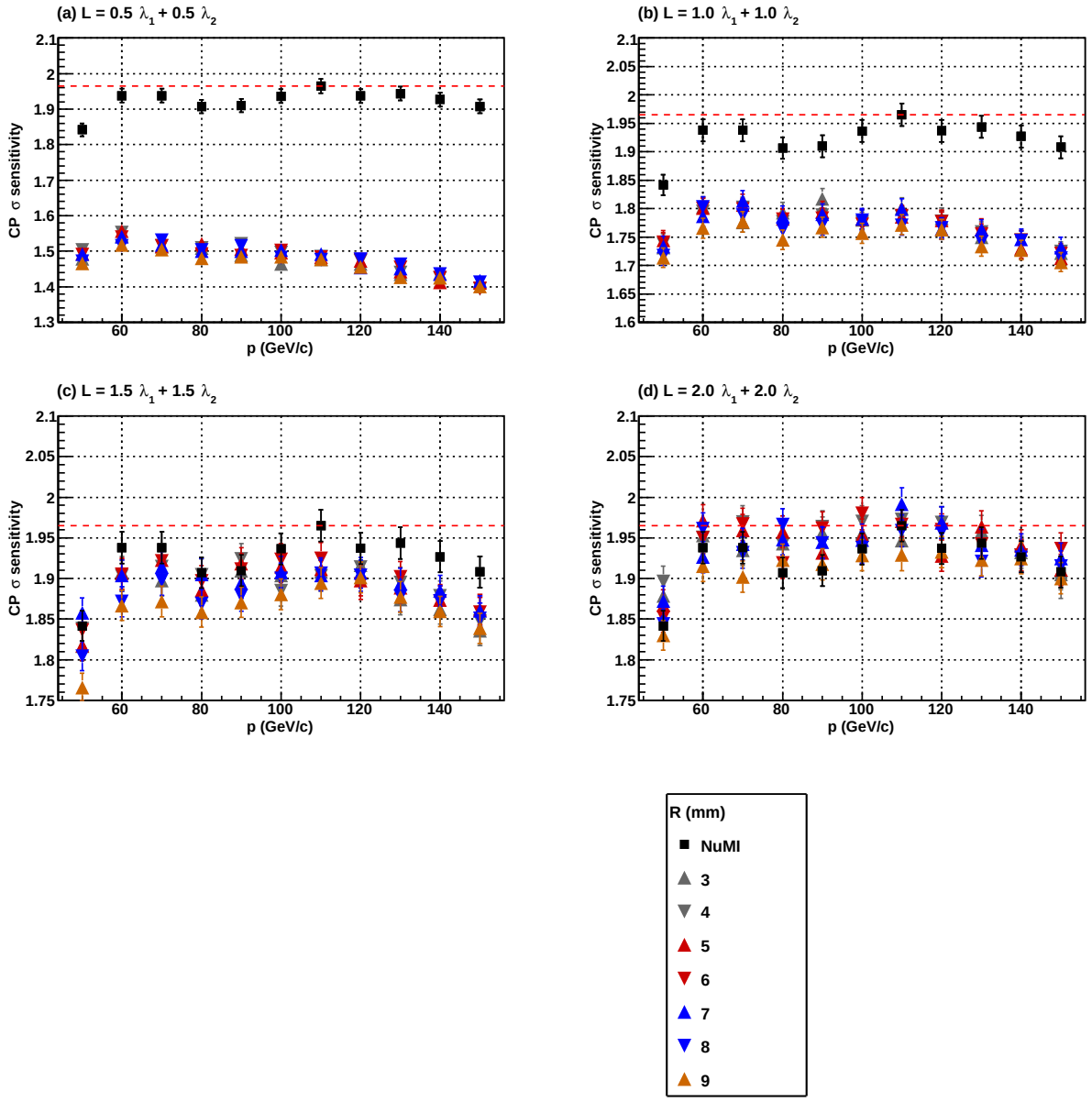
- Target length in multiples of interaction length λ (up to $L \approx 2$ m):
  - Two equal graphite cylinders each 0.5λ to $2.5\lambda \Rightarrow 1$ to 5λ total length
  - Two equal Be SATs each 0.5λ to $2\lambda \Rightarrow 1$ to 4λ total length
    Gaps between spheres means SAT needs to be $\sim 15\%$ longer for equivalent cylinder λ
  - 2λ or 3λ graphite cylinder with $n\lambda$ tungsten, Inconel-718 or titanium SAT

- Following plots: CP sensitivity $\sigma_{\rm CP}$ = significance for top 75% δ_{CP} values
- "Baseline" target = 2 m–long (4λ) NuMI–like segmented graphite target
- Each figure shows $\sigma_{\rm CP}$ vs p for given total target length
  - Coloured points for different target radii (NuMI baseline = black)
  - Red dotted line is maximum NuMI $\sigma_{\rm CP}$ value
  - Find target arrangements with $\sigma_{\rm CP}$ at/above this red line

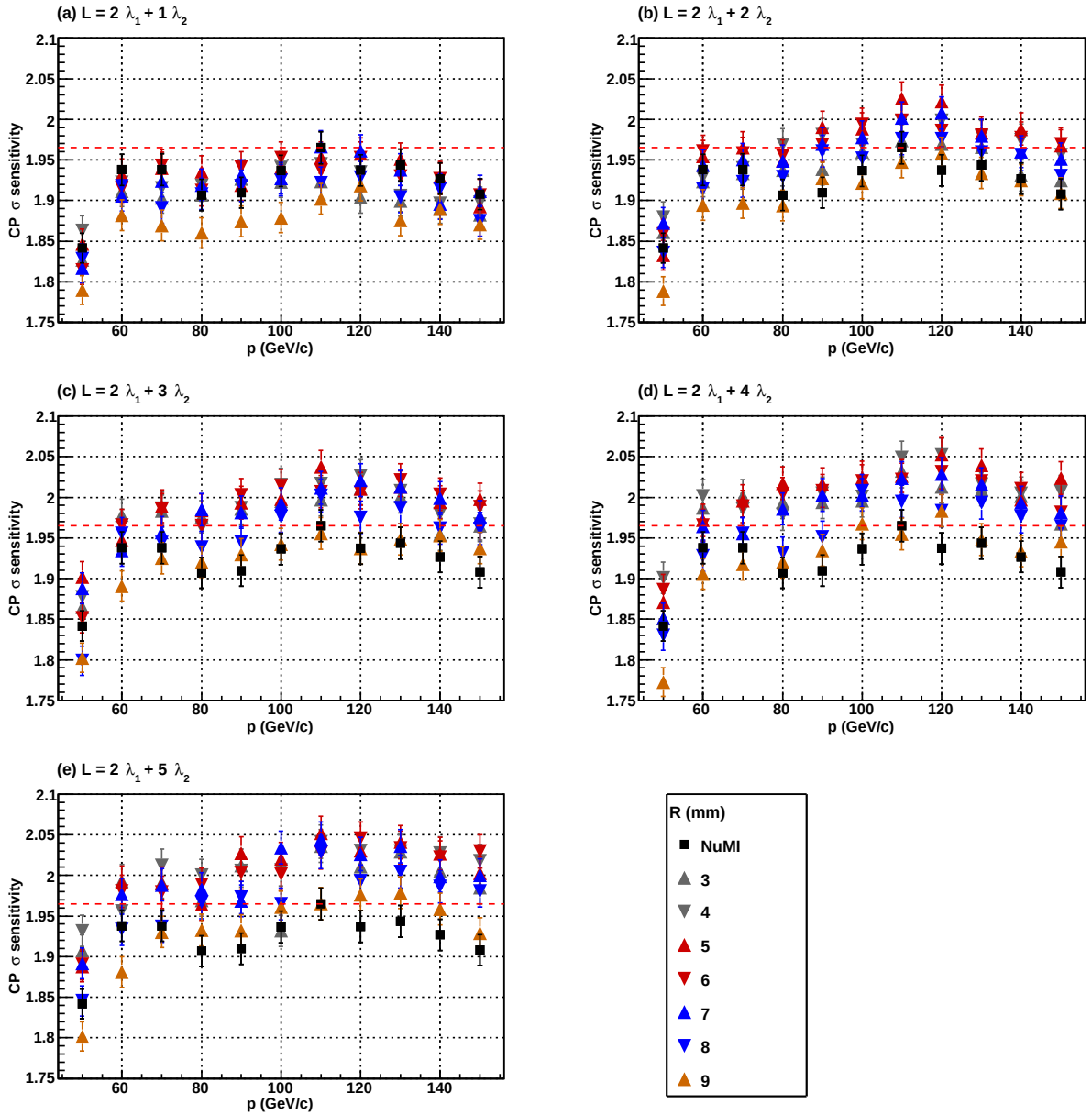
Two mirror image graphite cylinder modules: 1 to 5λ



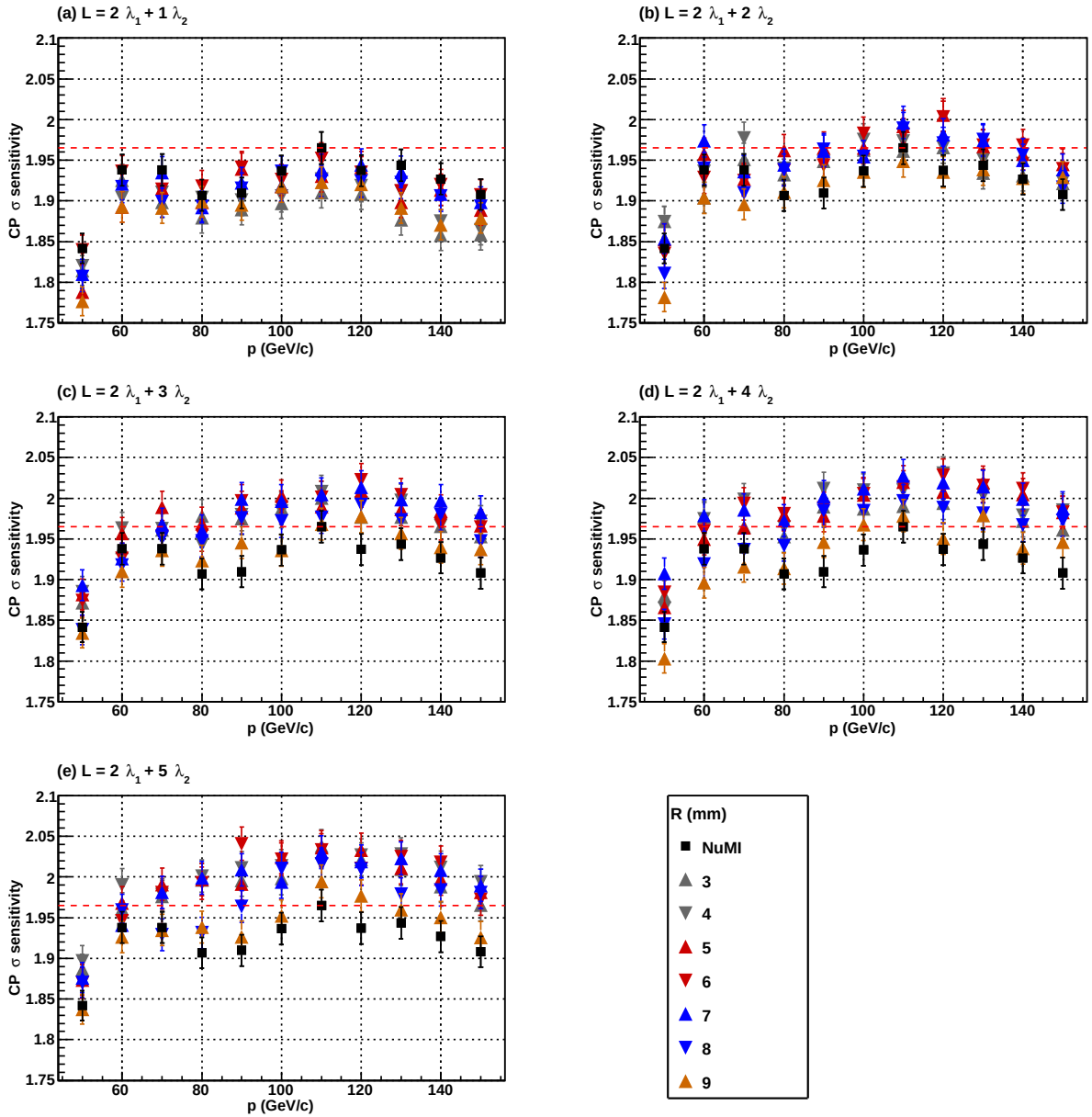
Two mirror image beryllium SAT modules: 1 to 4λ



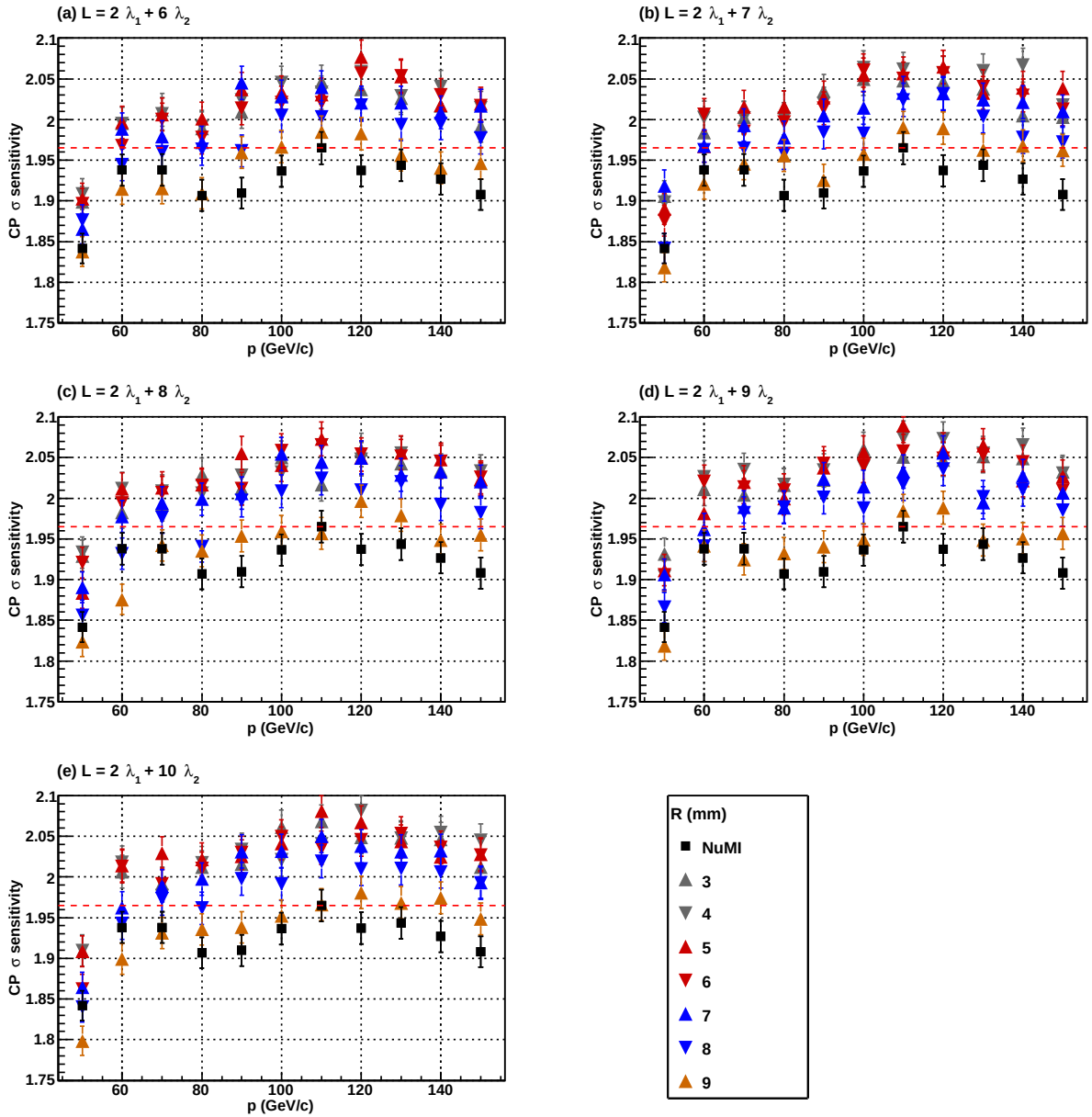
2λ graphite cylinder & 1 to 5λ tungsten SAT



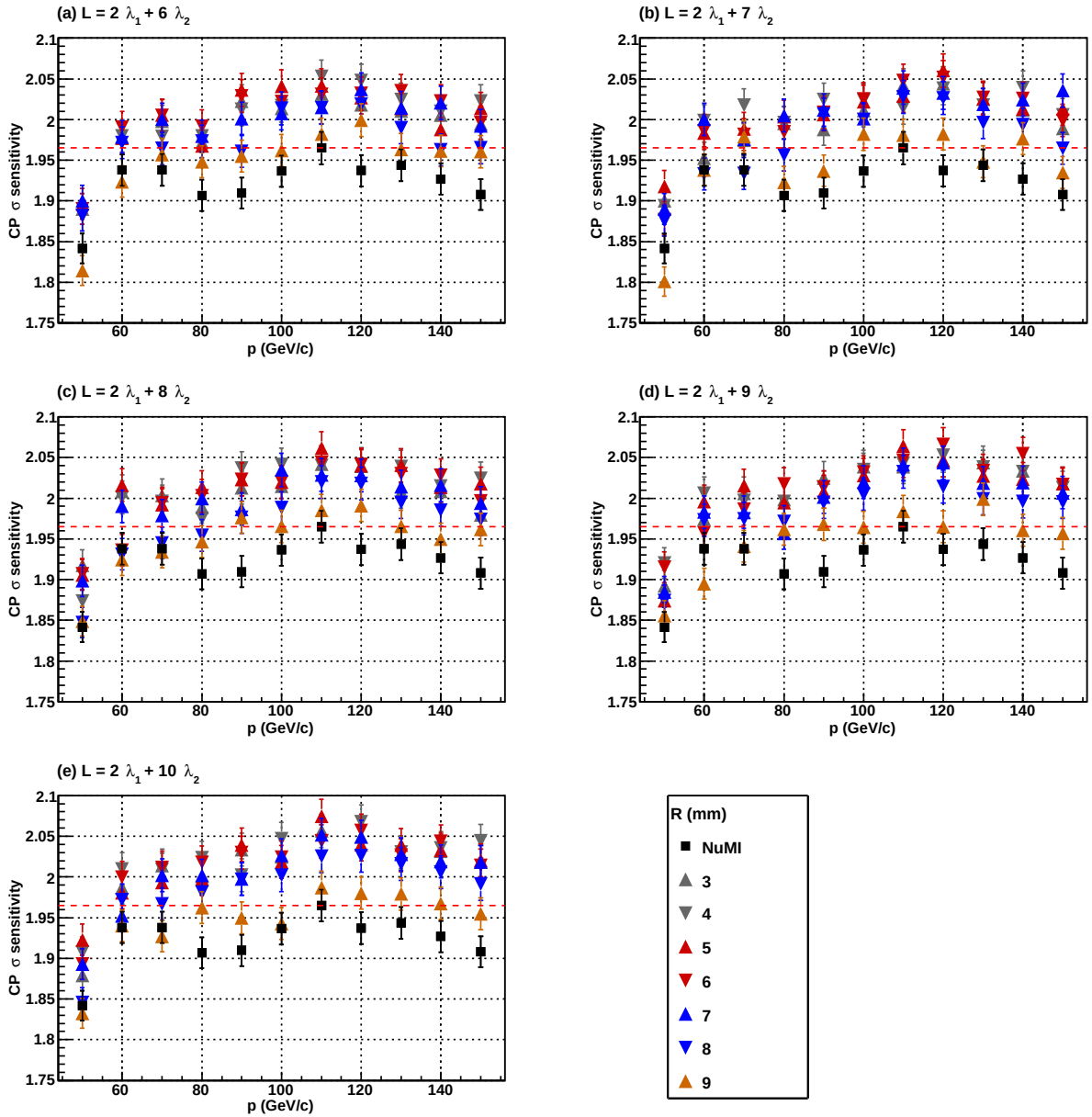
2λ beryllium SAT & 1 to 5λ tungsten SAT



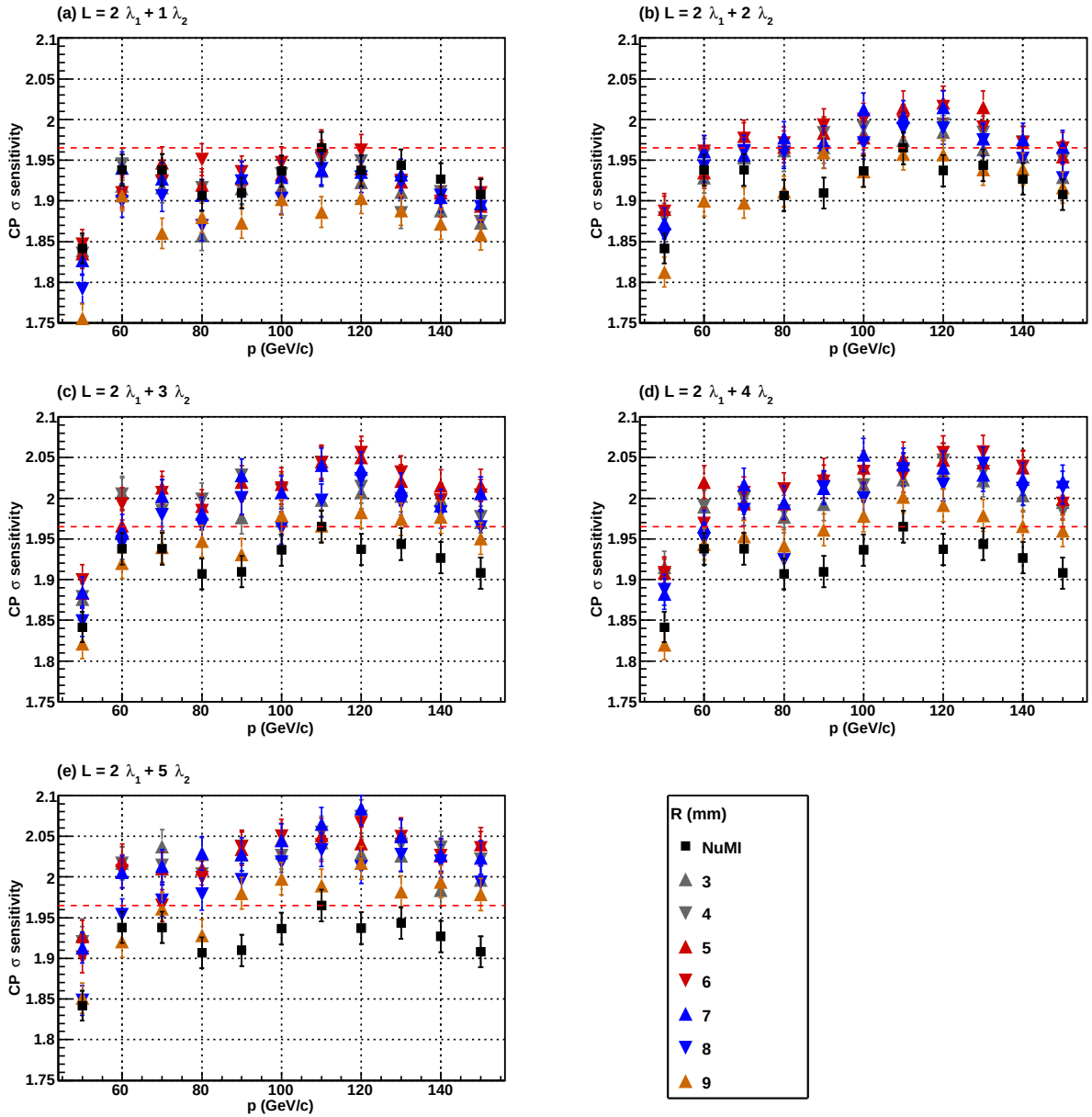
2λ graphite cylinder & 6 to 10λ tungsten SAT



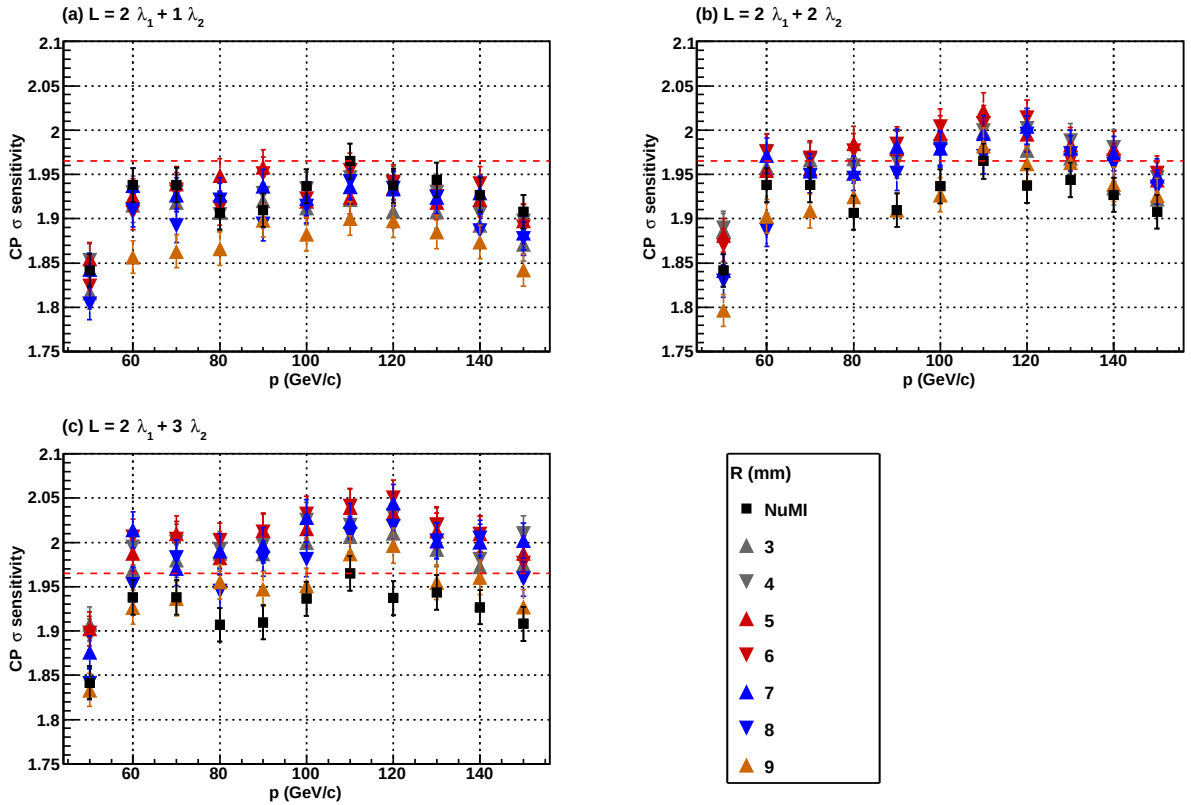
2λ beryllium SAT & 6 to 10λ tungsten SAT



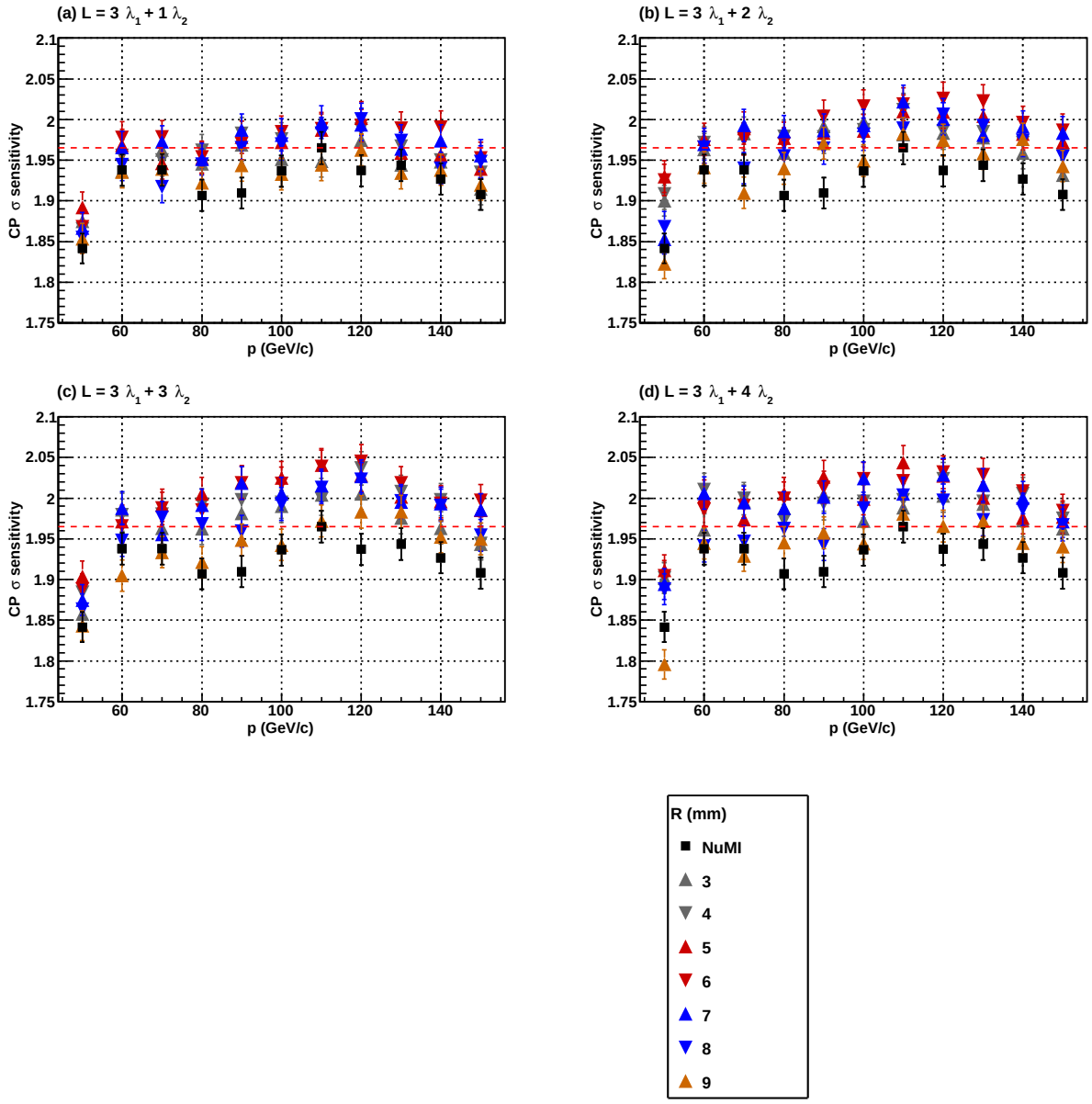
2λ graphite cylinder & 1 to 5λ Inconel-718 SAT



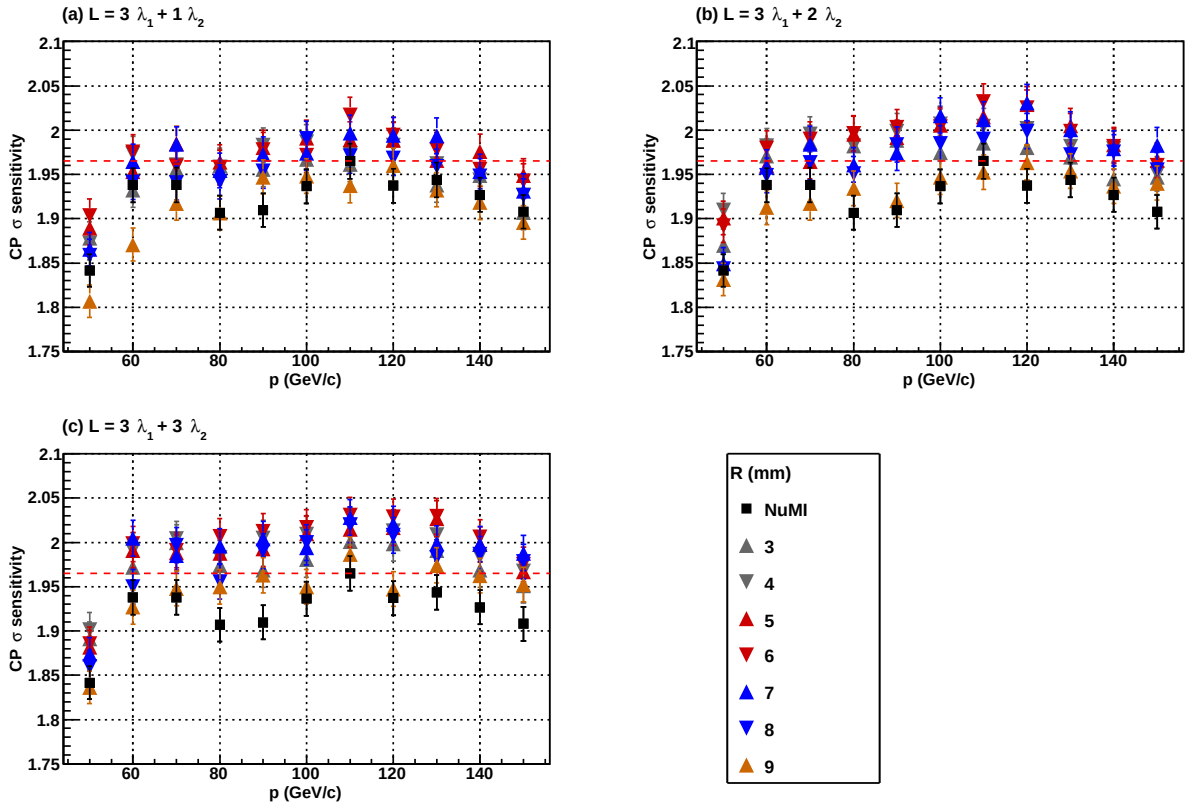
2λ graphite cylinder & 1 to 3λ titanium SAT



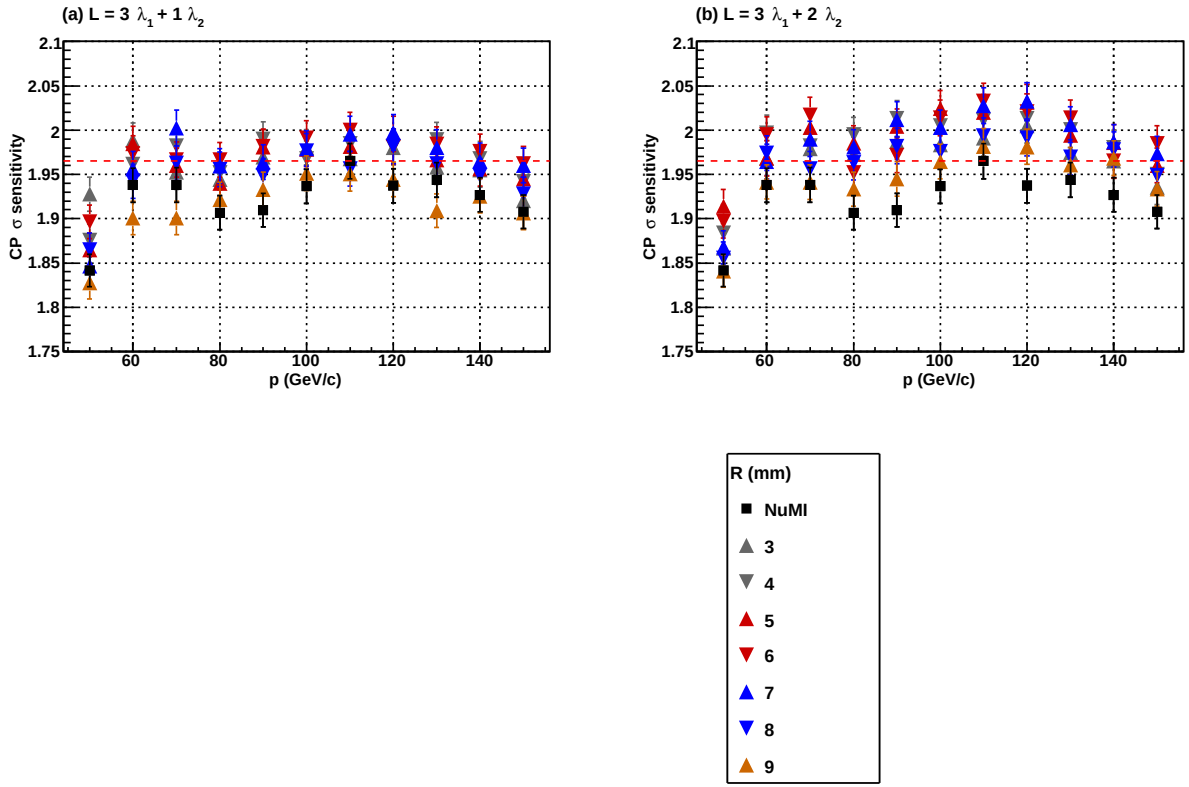
3λ graphite cylinder & 1 to 4λ tungsten SAT



3λ graphite cylinder & 1 to 3λ Inconel-718 SAT



3λ graphite cylinder & 1 to 2λ titanium SAT



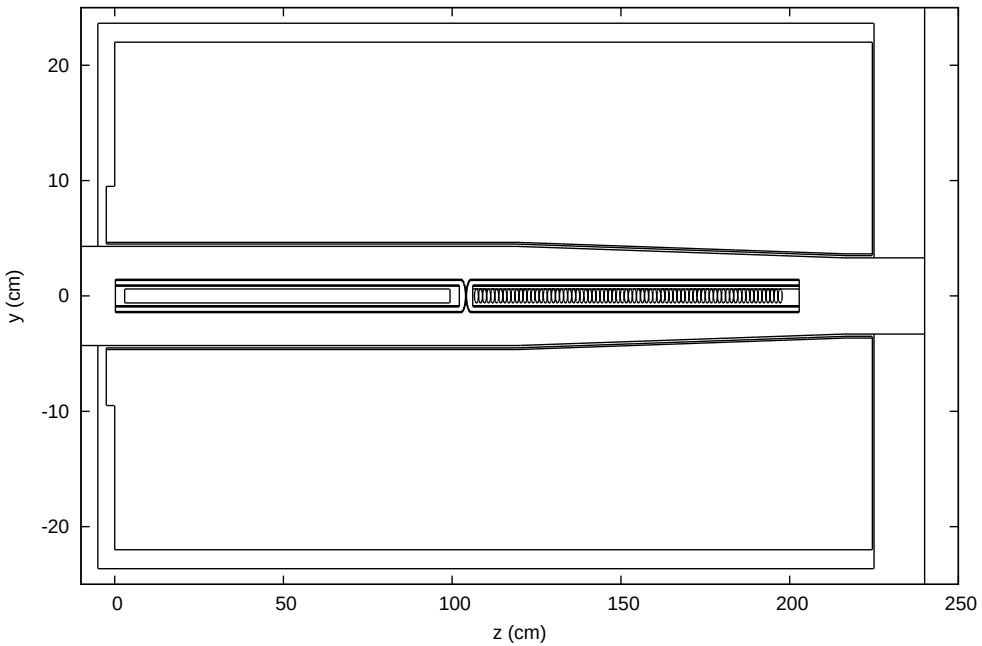
CP sensitivity findings

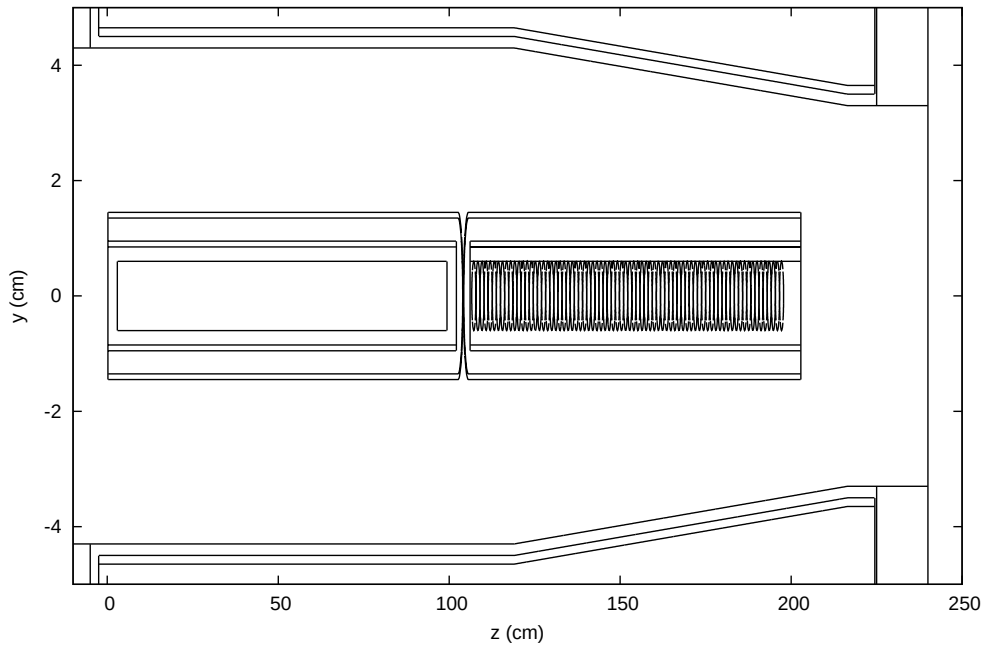
- $2 \times 2\lambda$ graphite cylinders or Be SATs $\approx$ performance of NuMI baseline
  $\Rightarrow$ splitting up the (low–Z) target into two equal sections does no harm

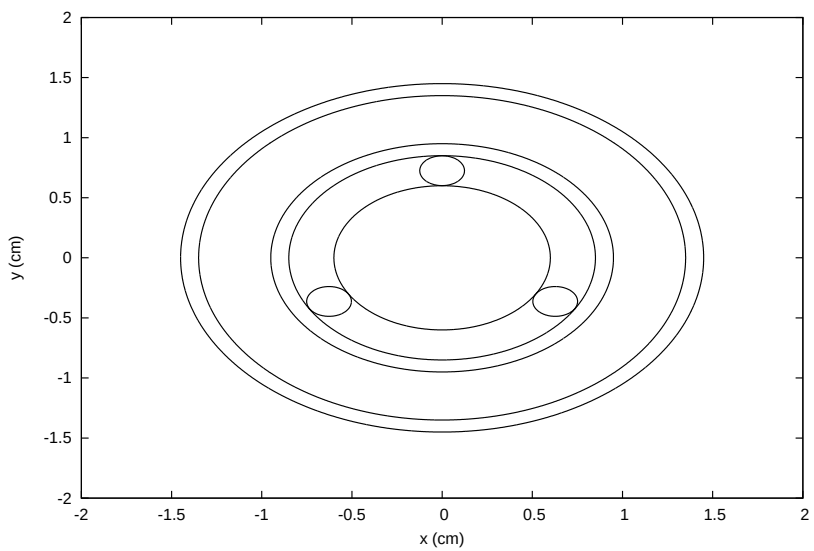
- Low–Z & high–Z hybrid targets can give slightly better performance:
  - e.g. fractional 6% $\sigma_{\rm CP}$ gain (or $\Delta\sigma_{\rm CP} = 0.11$) for 2λ graphite & 8λ W SAT $R_1 = R_2 = 6\,\mathrm{mm}$, $\sigma_b = 2\,\mathrm{mm}$, $p = 110\,\mathrm{GeV/c}$ compared to baseline max

- We now look at the hybrid energy depositions ($p = 110\,\mathrm{GeV/c}$, 1.2 MW):
  - `FLUKA` simulation, implementing 1$^{\rm st}$ horn & target modules geometry
  - Could realistically cool target if energy deposition rate $\lesssim 1\,\mathrm{kW/cc}$
  - Low–Z: 2λ (1 m) or 3λ (1.5 m) graphite cylinder with $R_1 = 6\,\mathrm{mm}$
  - High–Z: $n\lambda$ tungsten, Inconel-718 SAT or titanium (1m or 0.6m,R_2=6mm)
  - Compare Gaussian ($\sigma_b = 2\,\mathrm{mm}$) & annular ($r = 2$ to $4\,\mathrm{mm}$) beams

FLUKA geometry: $2\boldsymbol{\lambda}$ graphite cylinder & $8\boldsymbol{\lambda}$ tungsten SAT

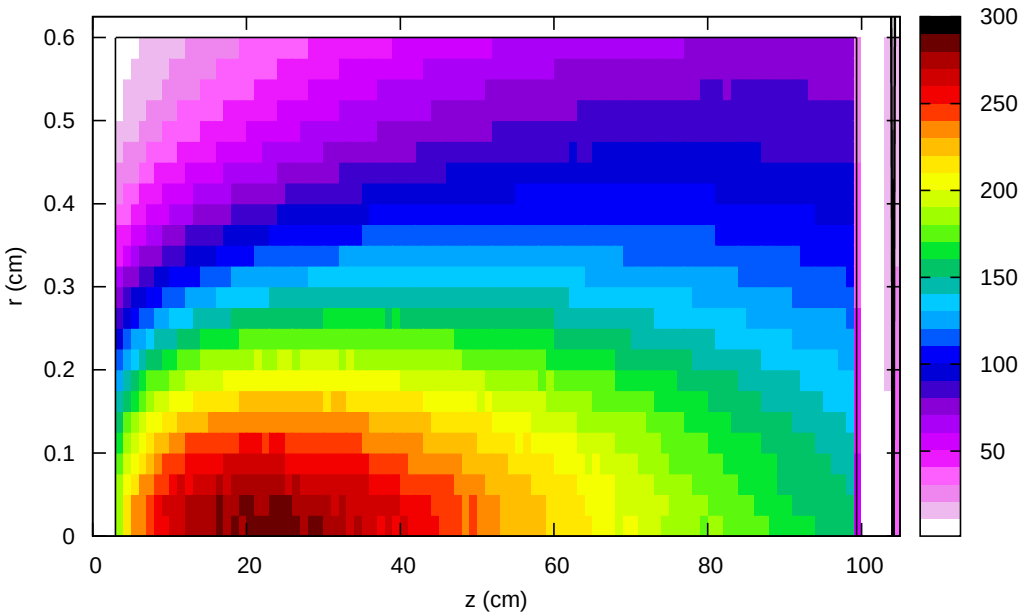


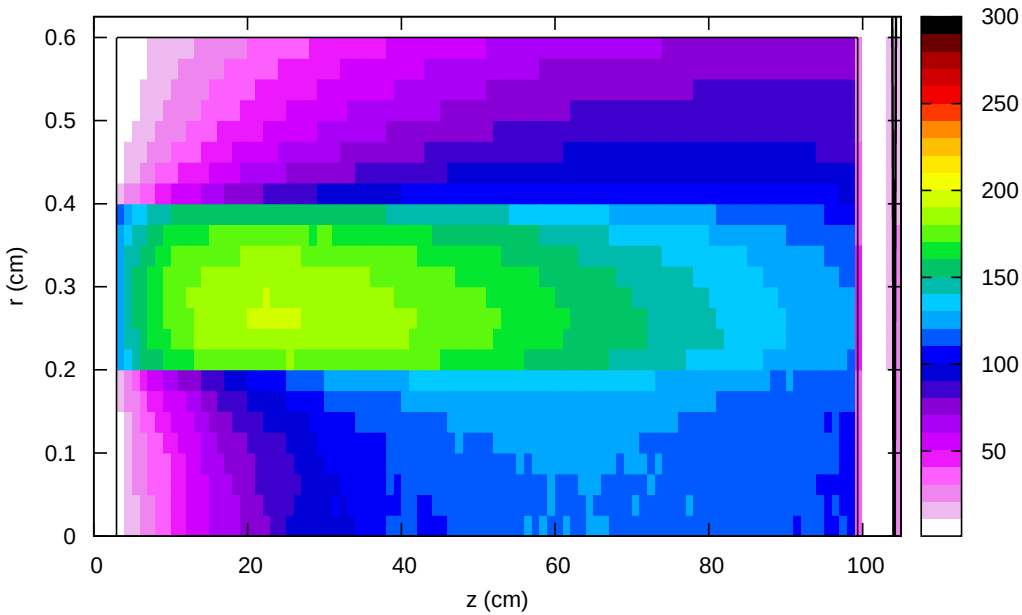




Top left: target and (simplified) horn
Top right: target modules close up
Bottom: example SAT cross-section
Target radius = 6 mm
Horn **B** field from G4LBNF sim
Proton beam:
$p = 110\,\mathrm{GeV/c}$
Total power = 1.2 MW
POT = 8.04×10^{13}/pulse (1.2 s)
Gauss $\sigma = 2$ mm or annular $r = 2-4$ mm

Graphite cylinder energy deposition (J/cc/pulse)





Gaussian beam $\sigma_b = 2\,\mathrm{mm}$

Max E density $= 288\,\mathrm{J/cc/pulse}$

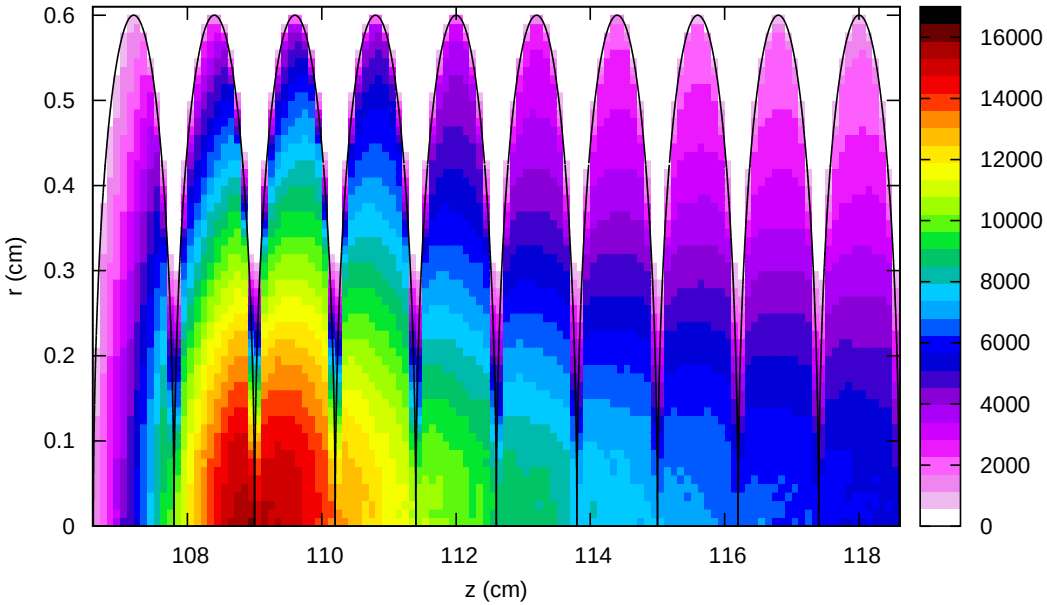
Average deposited power $= 9.2$ kW

Annular beam $r_b = 2$ to $4\,\mathrm{mm}$

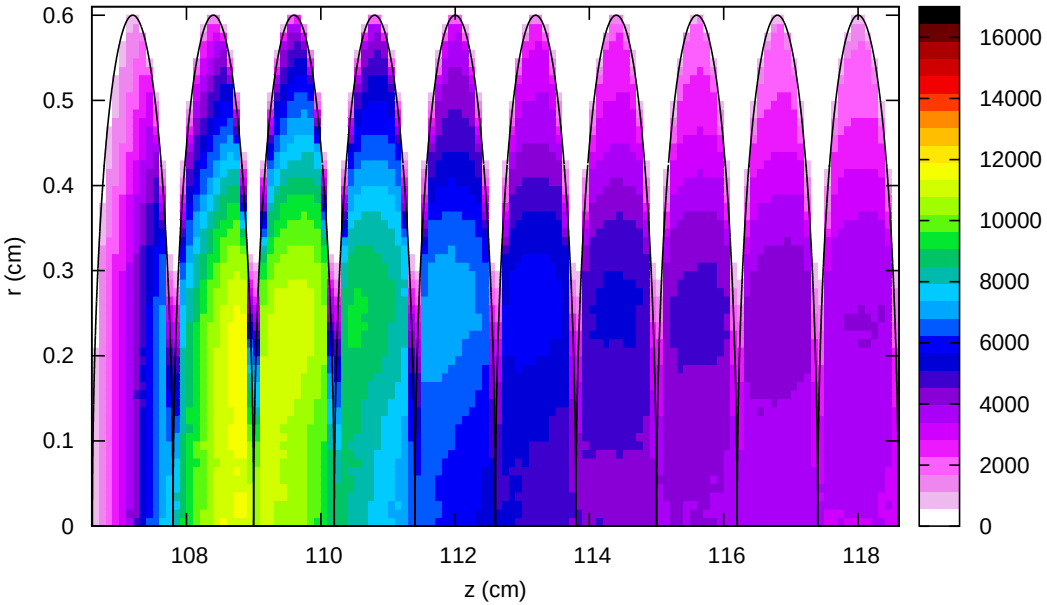
Max E density $= 192\,\mathrm{J/cc/pulse}$

Average deposited power $= 9.2$ kW

Tungsten SAT energy deposition (J/cc/pulse): spheres 1 to 10

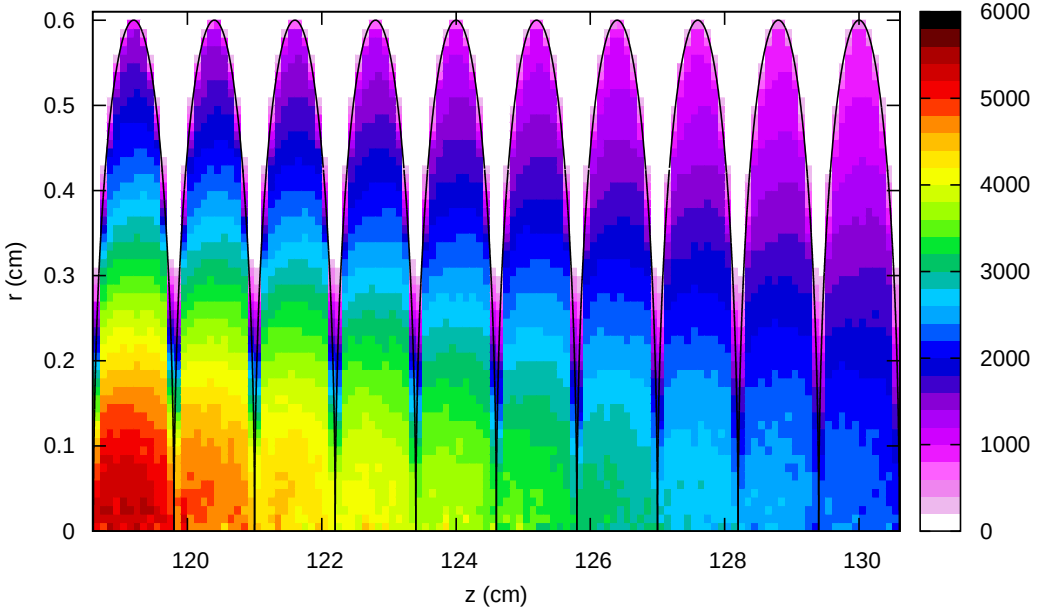


Gaussian beam

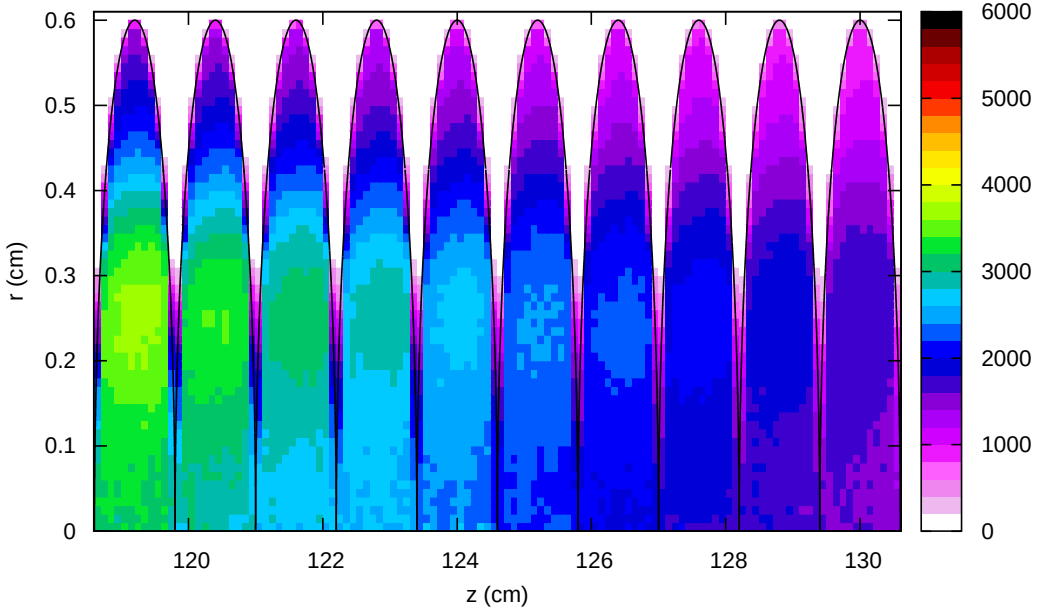


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 11 to 20

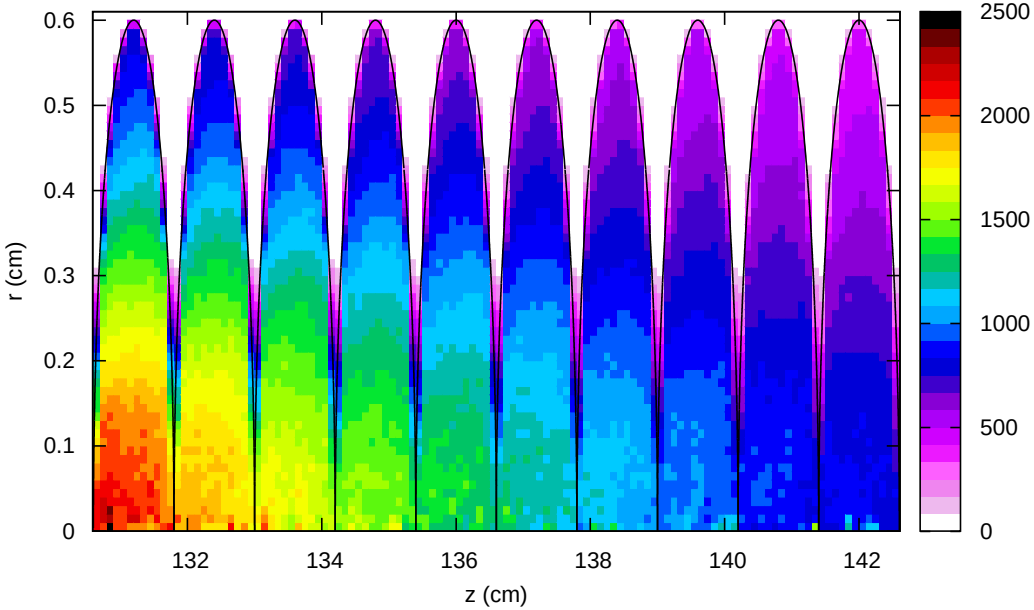


Gaussian beam

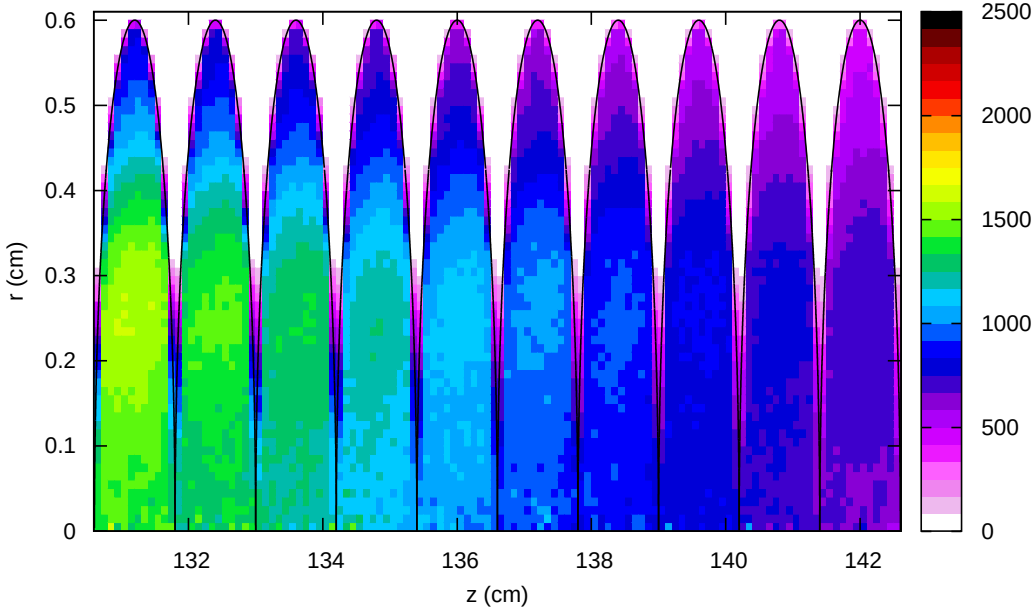


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 21 to 30

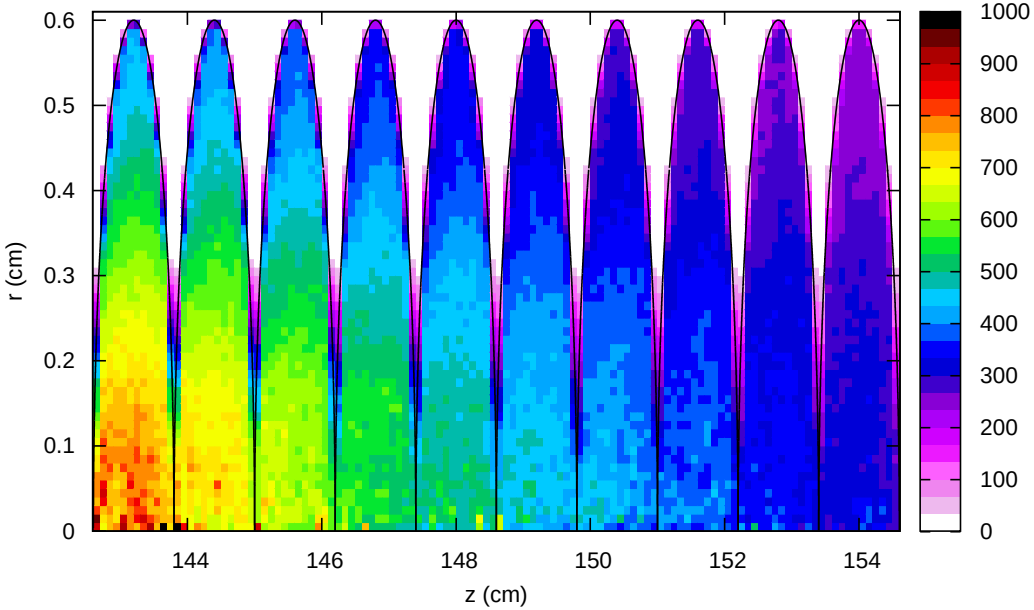


Gaussian beam

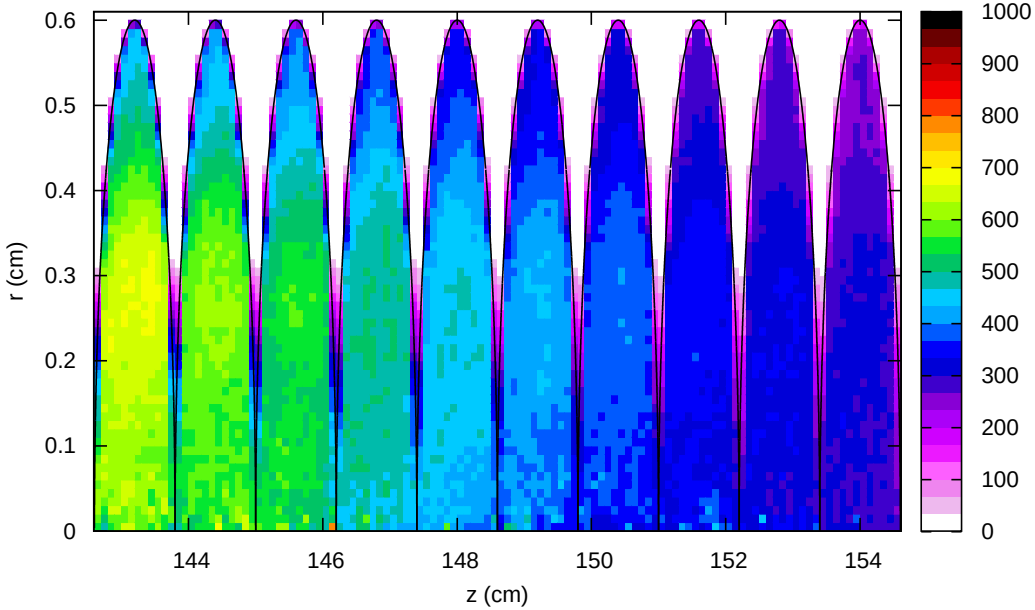


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 31 to 40

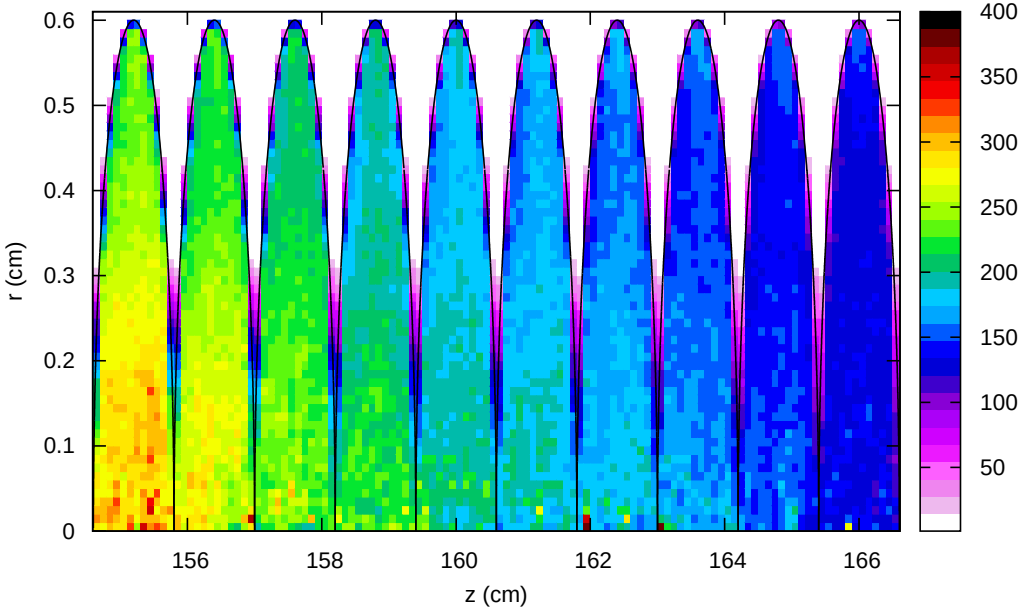


Gaussian beam

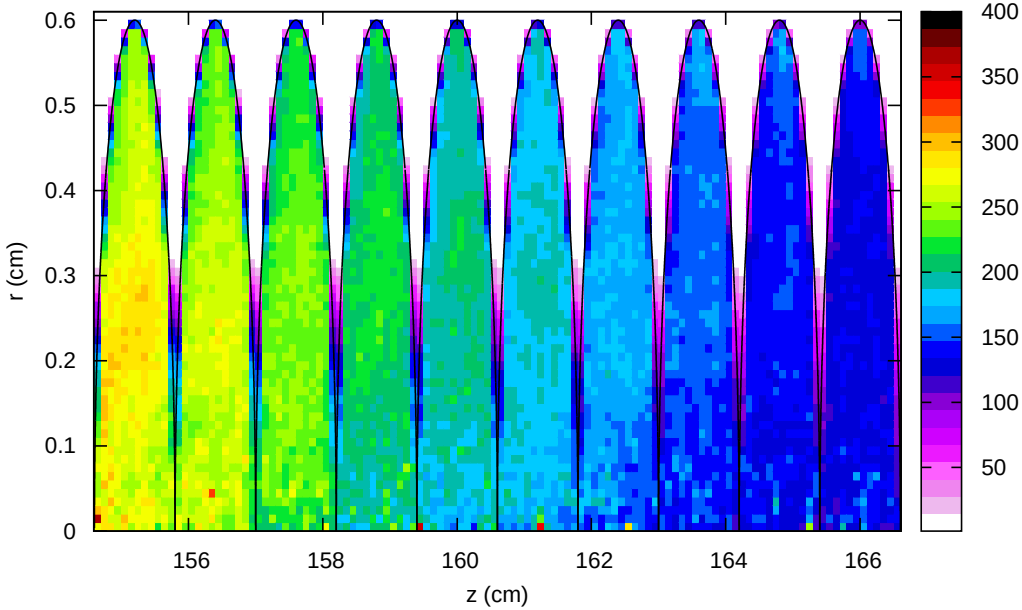


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 41 to 50

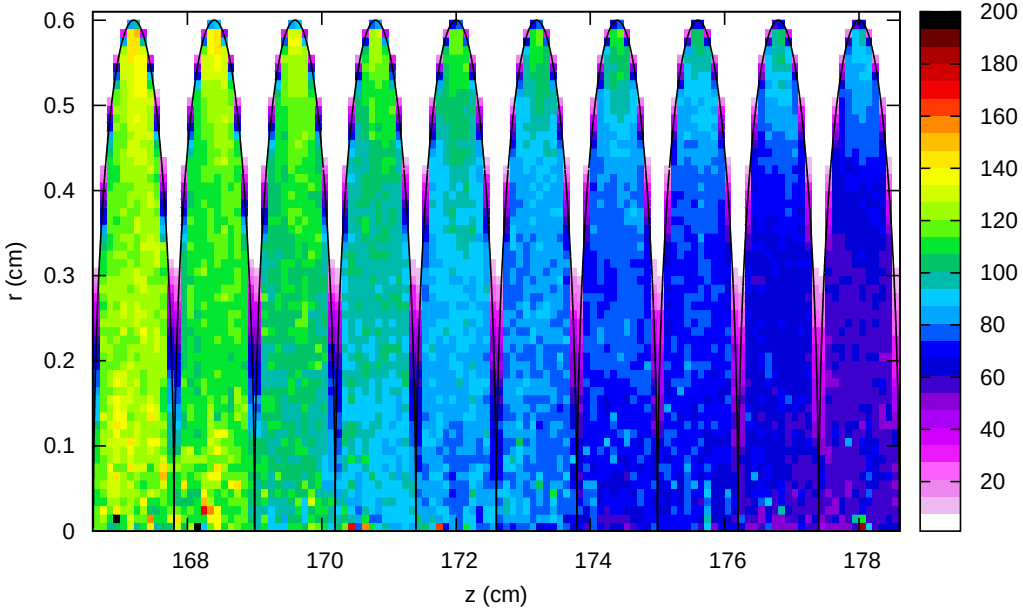


Gaussian beam

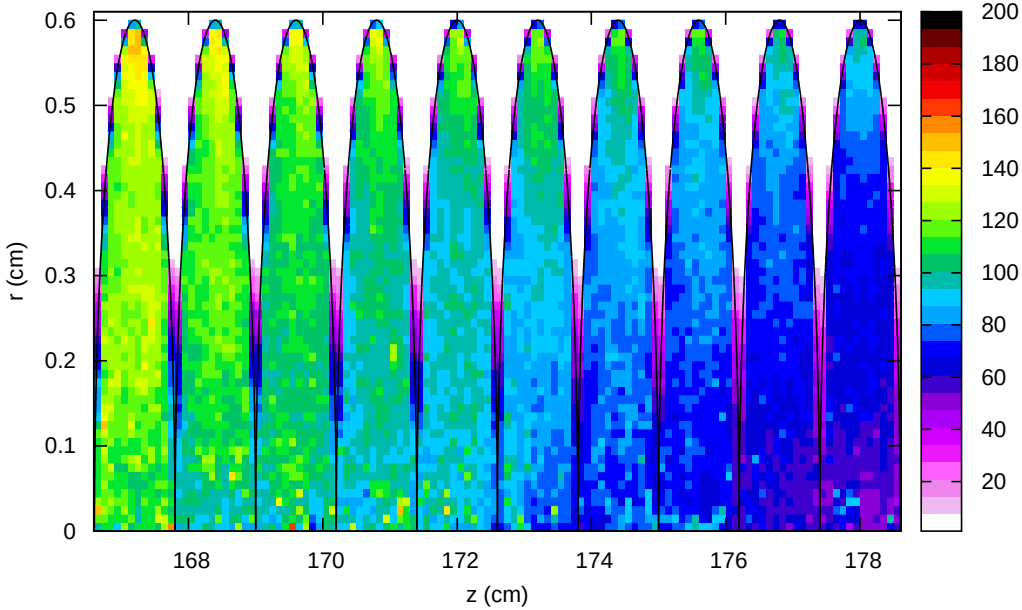


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 51 to 60

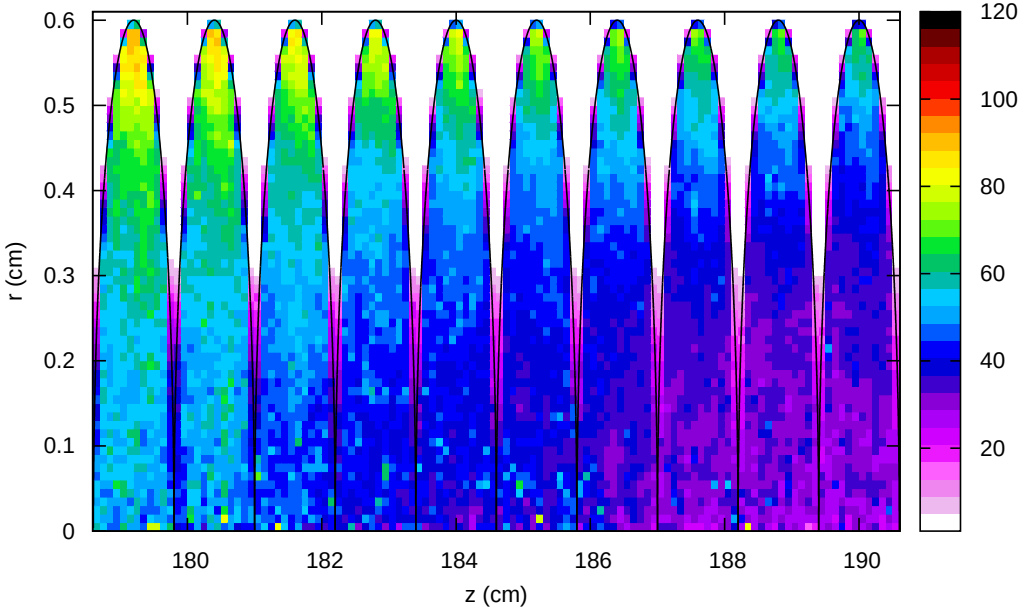


Gaussian beam

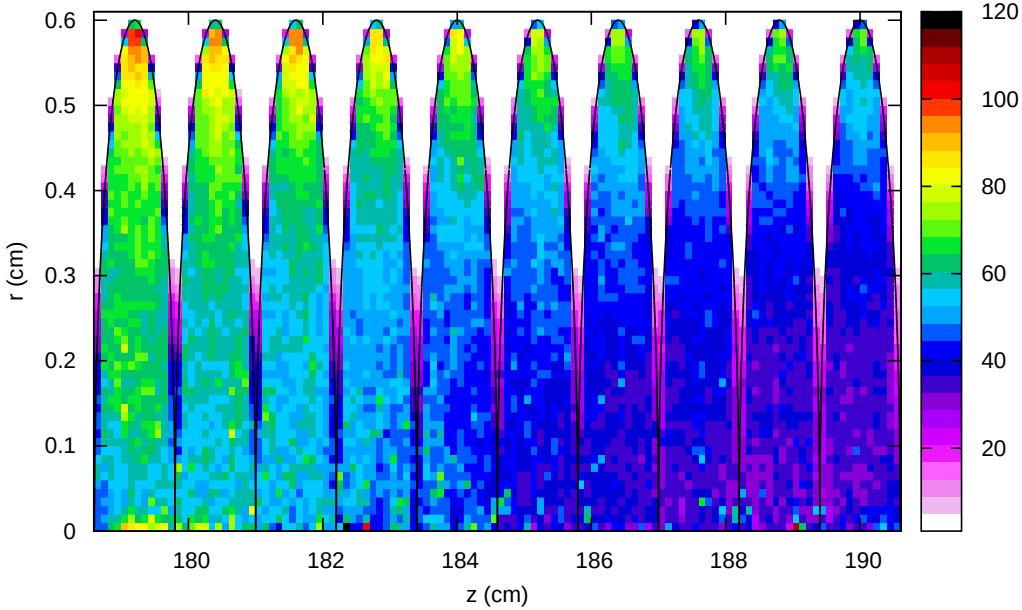


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 61 to 70

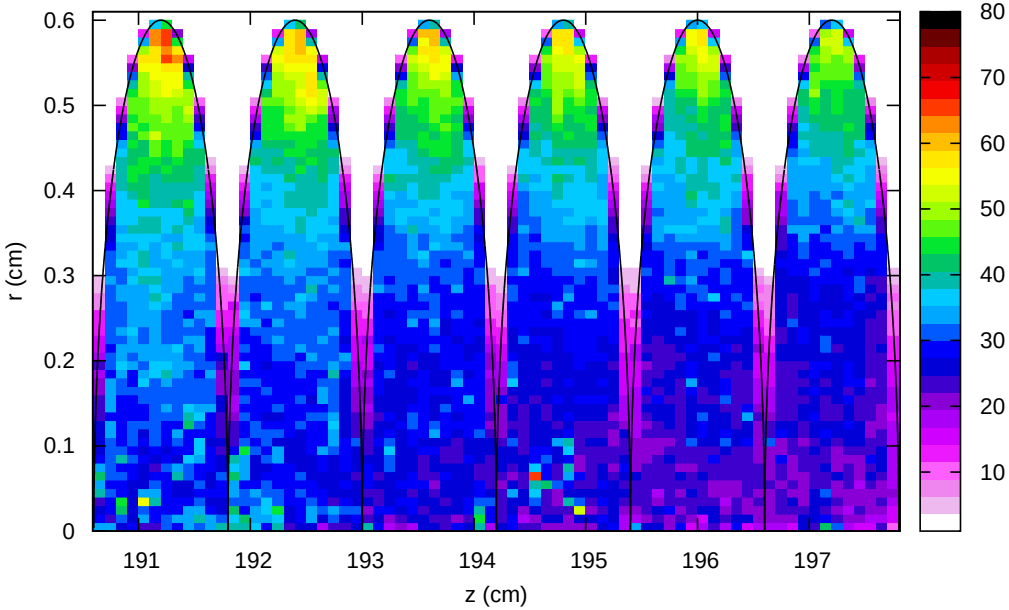


Gaussian beam

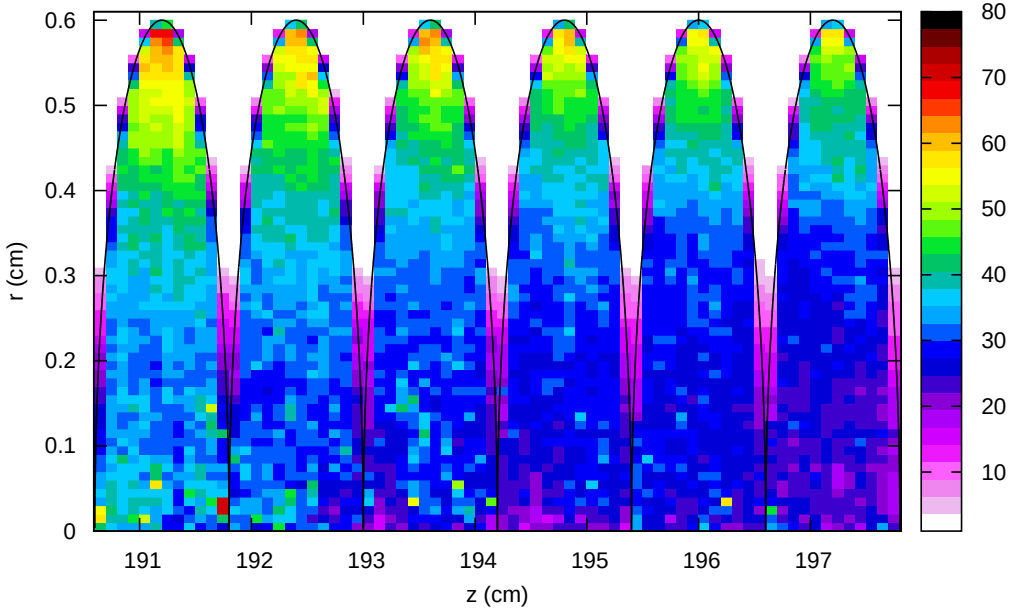


Annular beam

Tungsten SAT energy deposition (J/cc/pulse): spheres 71 to 76

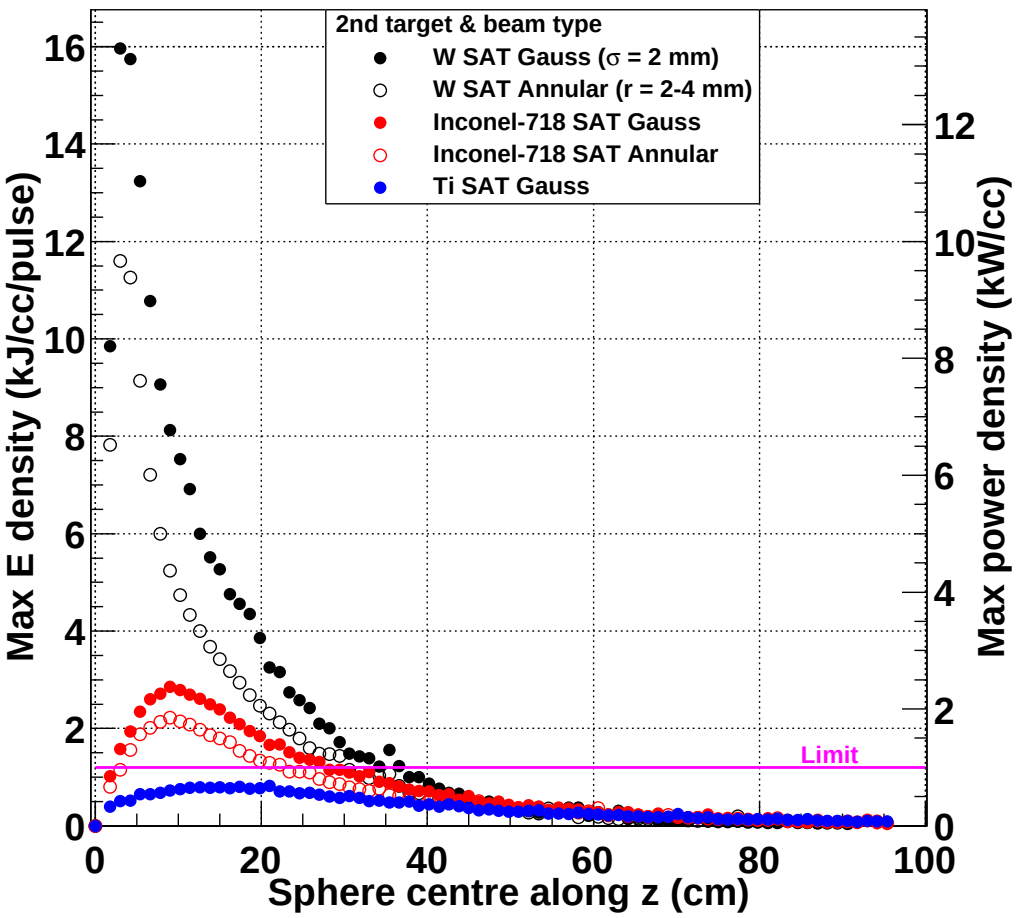


Gaussian beam

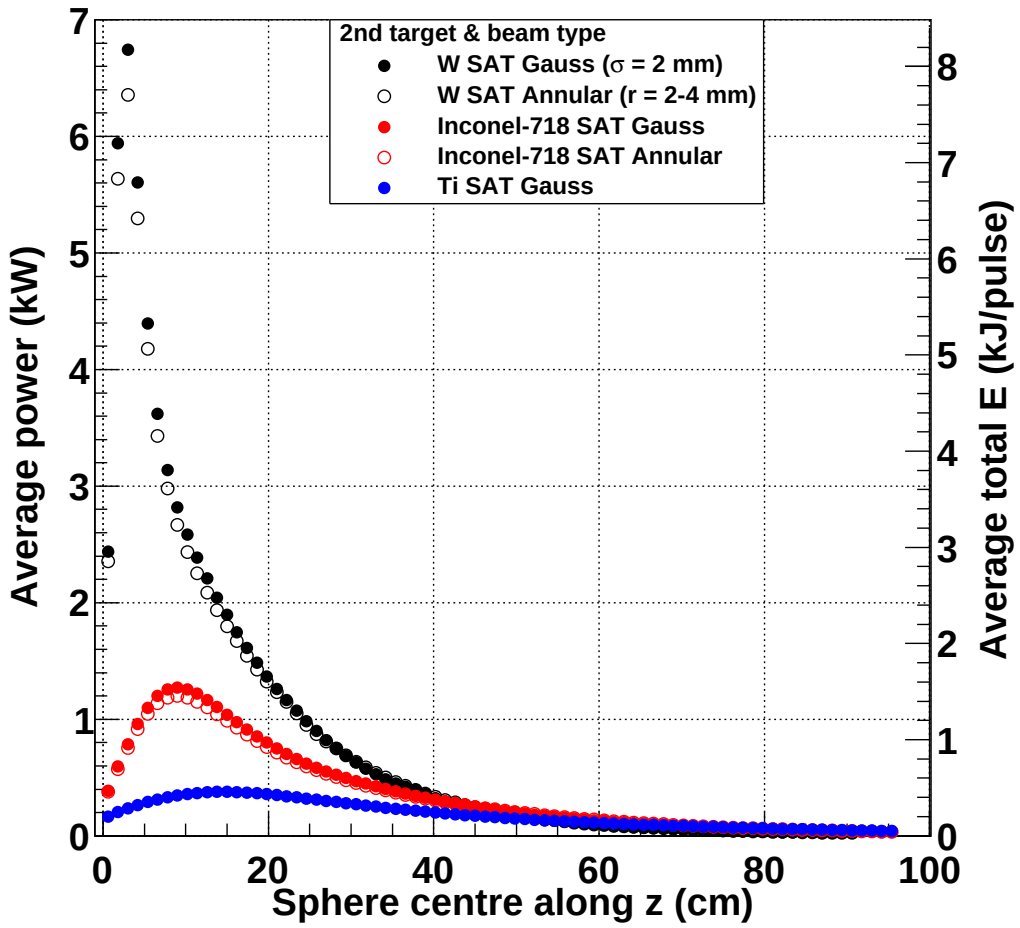


Annular beam

High–Z SAT energy deposition profiles with 1 m (2λ) graphite

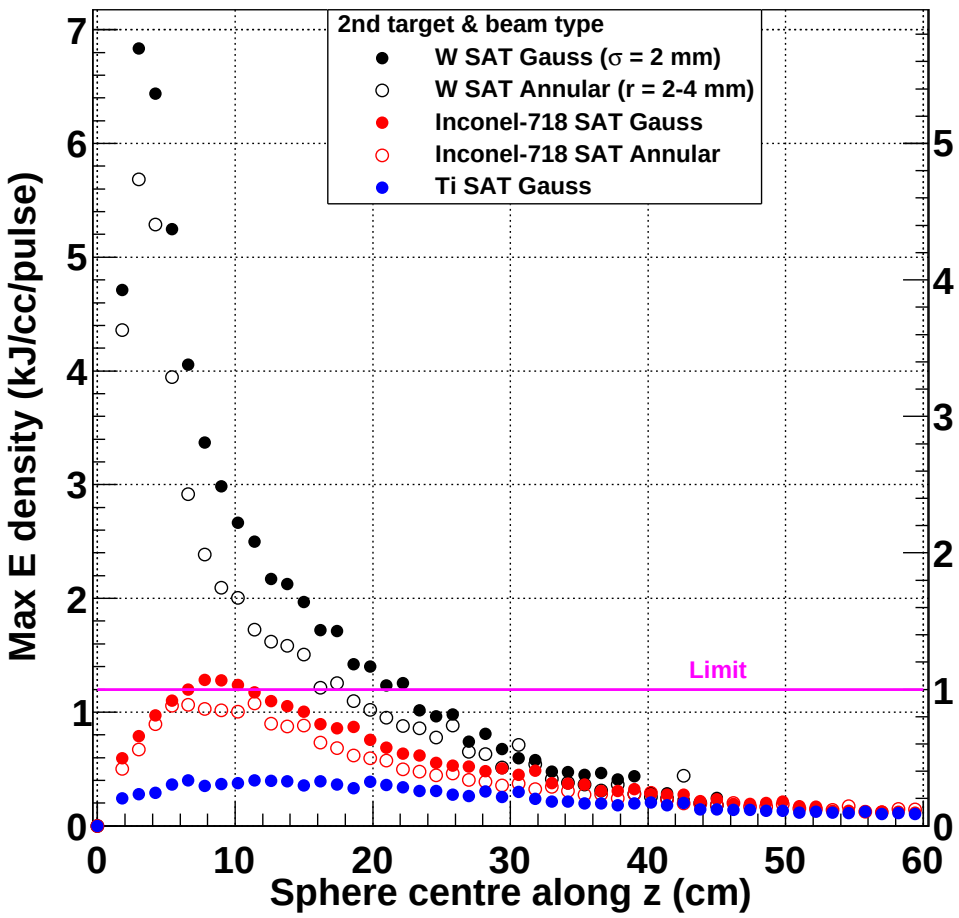


Peak energy density

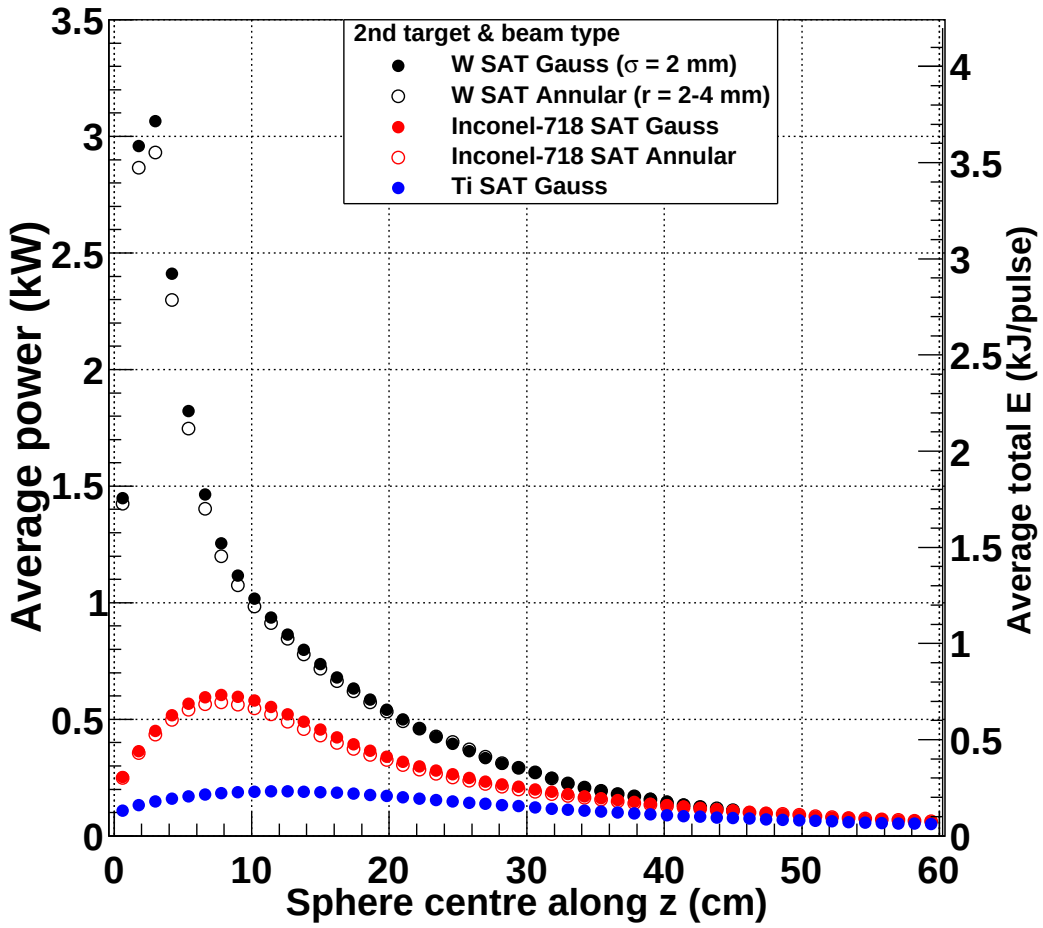


Average power

High–Z SAT energy deposition profiles with 1.5 m (**3λ**) graphite



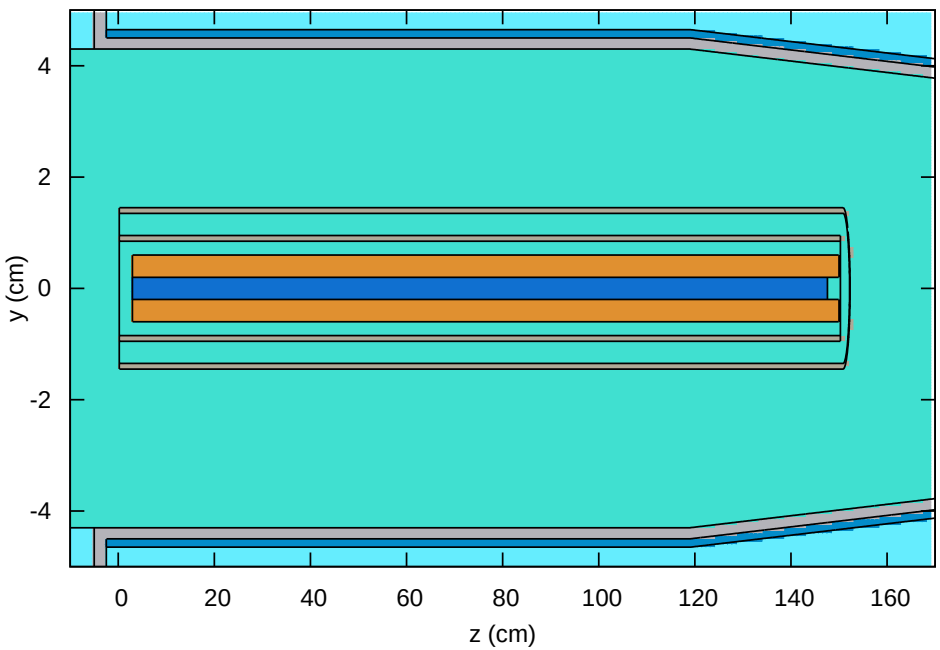
Peak energy density

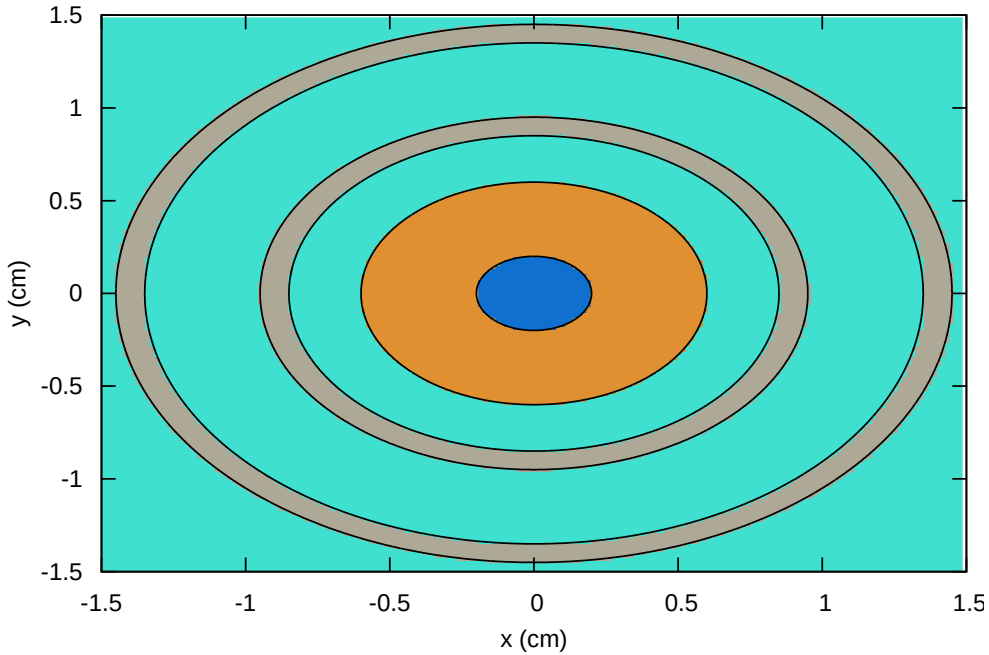


Average power

$2\lambda \rightarrow 3\lambda$ graphite $\Rightarrow$ roughly $\times 2$ reduction for high–Z max E density

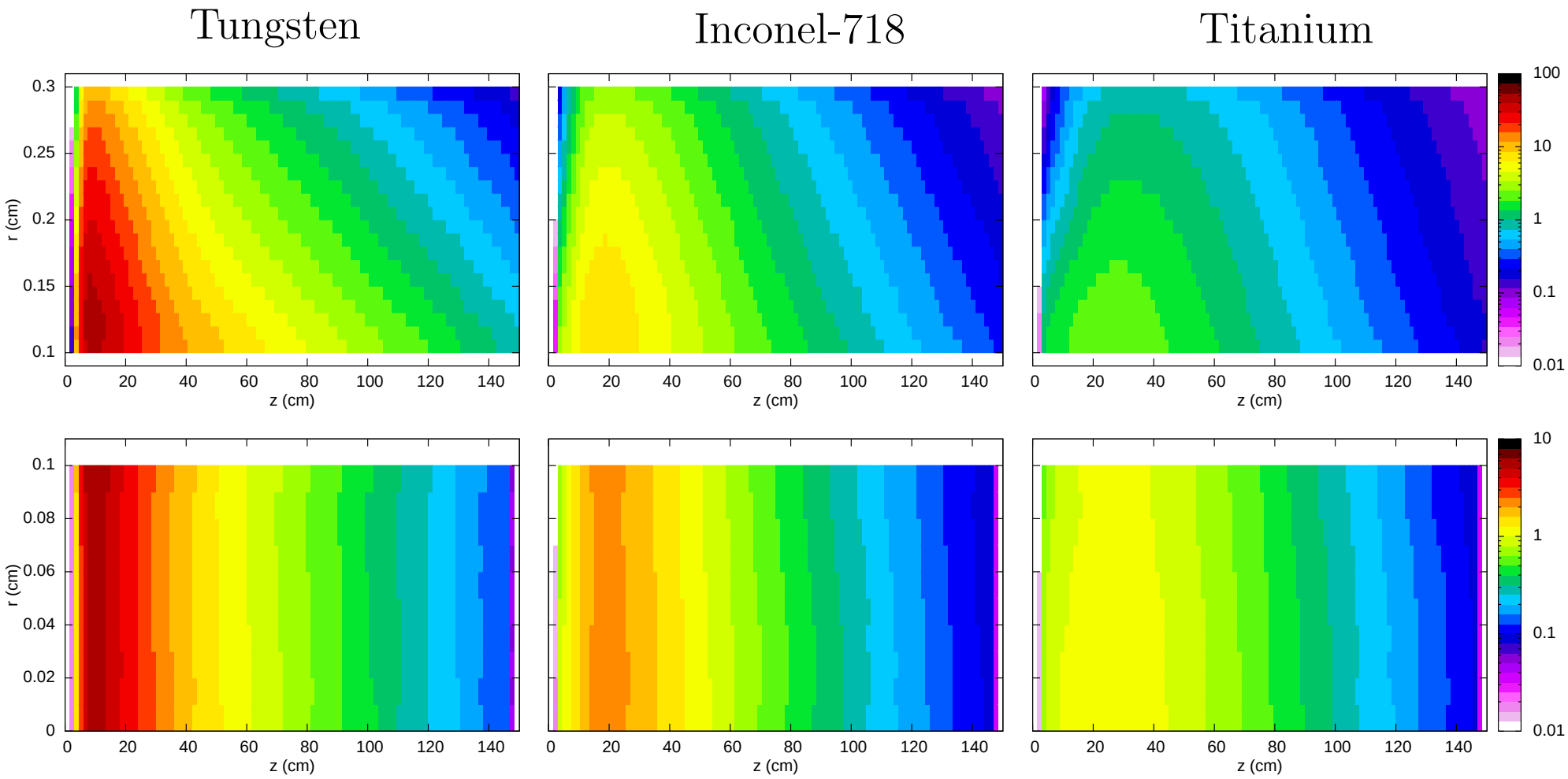
FLUKA geometry: **3λ** graphite cylinder & tungsten "jacket"





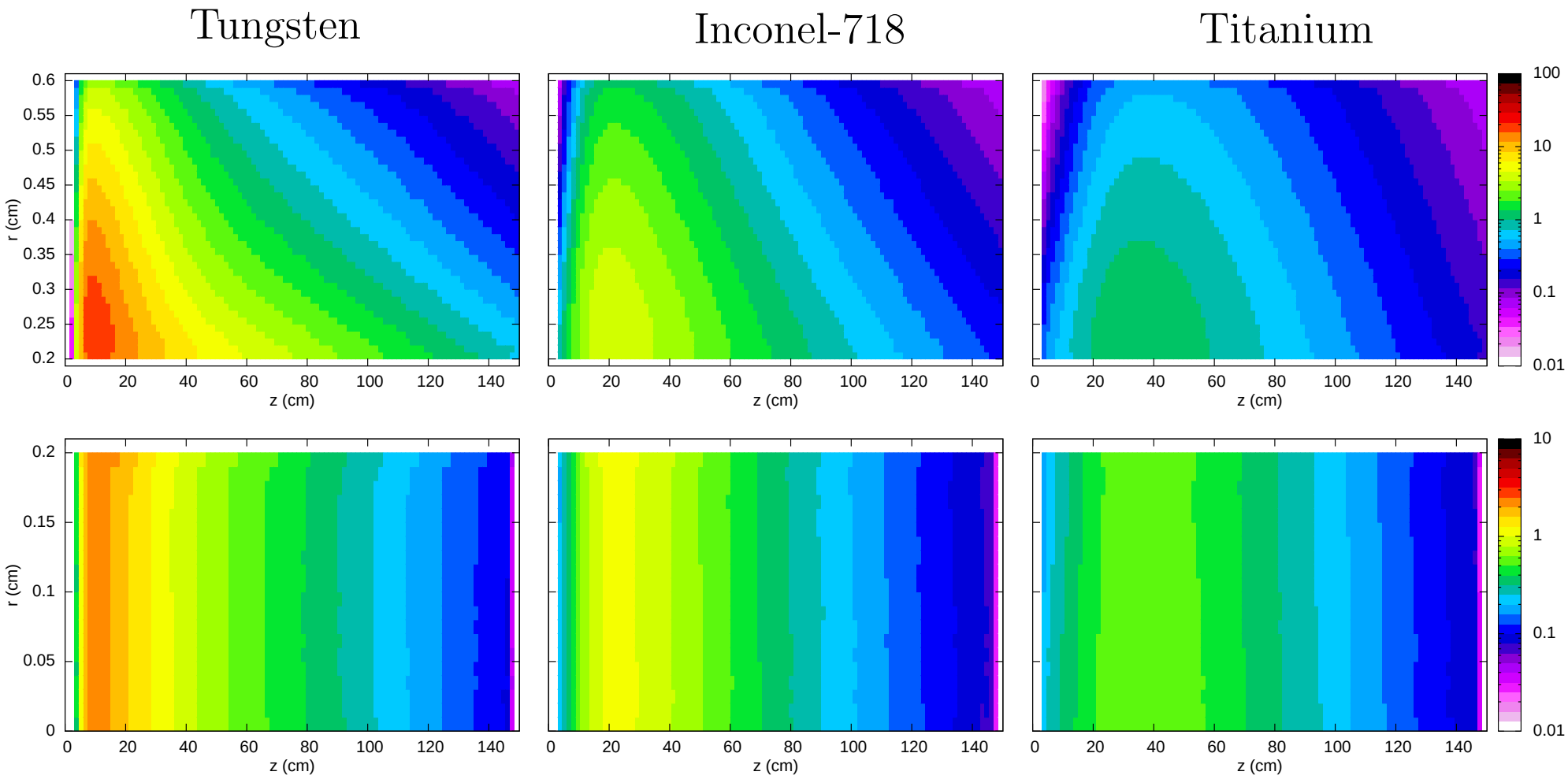
1.45 m graphite cylinder core, $R_1 = 1$, 2 or 3 mm
1.47 m tungsten cylinder jacket, $R_{2\mathrm{min}} = R_1$, $R_{2\mathrm{max}} = 3R_1 = 3$, 6 or 9 mm
Encased in titanium container filled with He cooling gas
Proton beam p = 110 GeV/c, 1.2 MW, Gaussian $\sigma_b = R_1$ (graphite core radius)

Energy deposition (kJ/cc/pulse) for core–jacket hybrid $\boldsymbol{R_1}$=1 mm



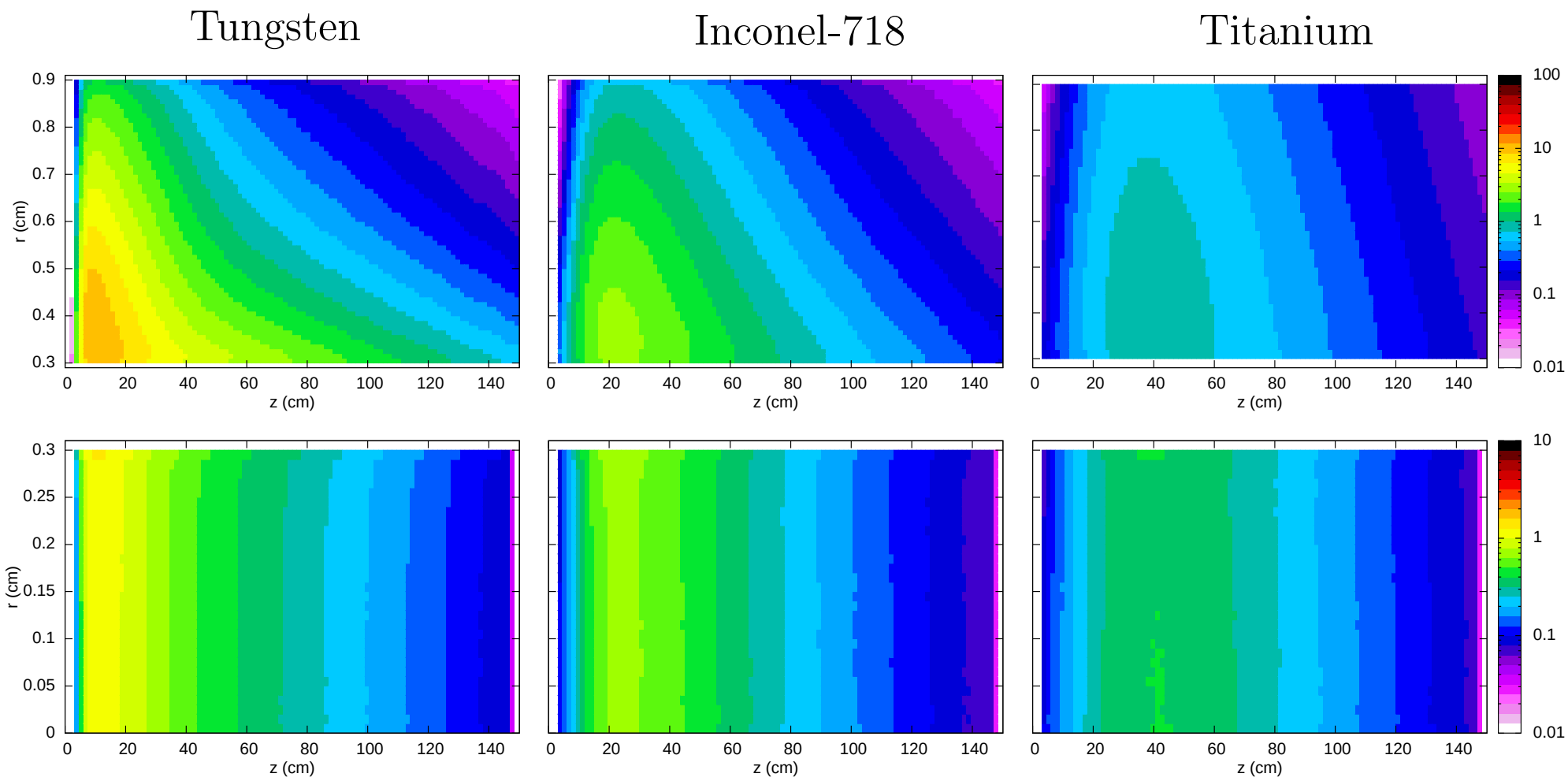
Top: High–Z outer jacket, Bottom: Graphite core

Energy deposition (kJ/cc/pulse) for core–jacket hybrid $\boldsymbol{R_1}$=2 mm



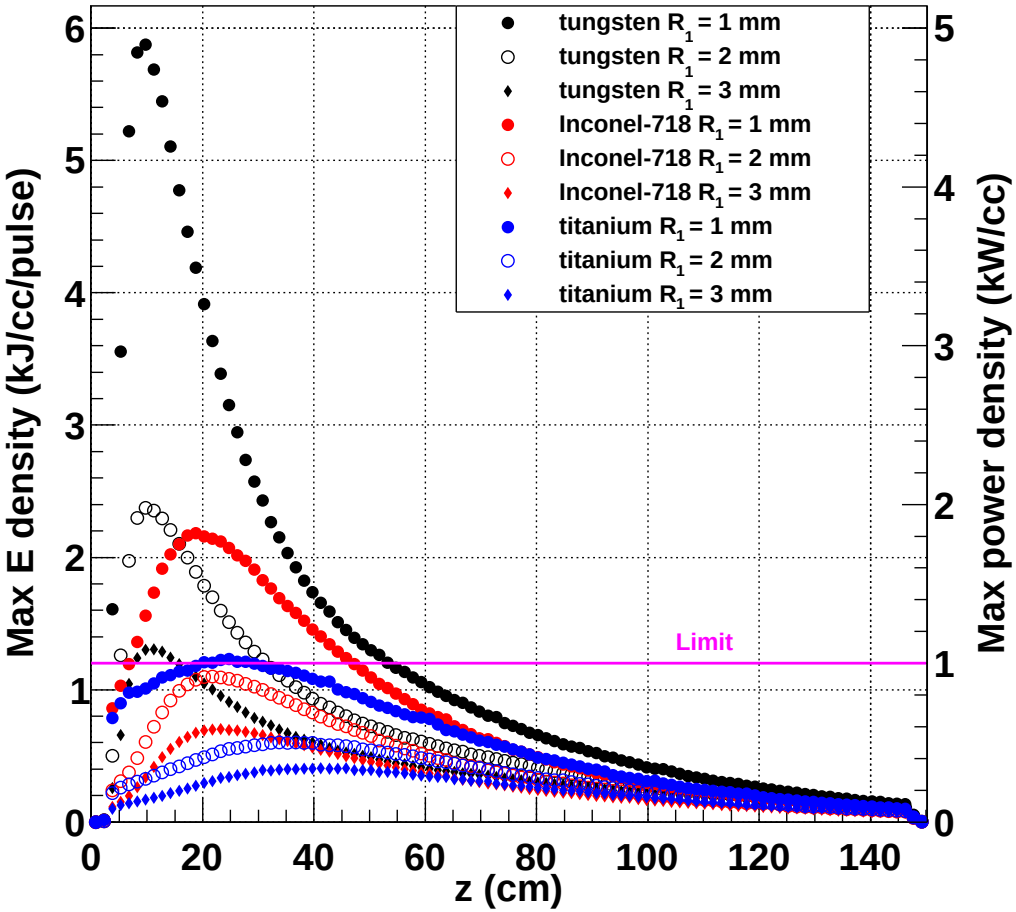
Top: High–Z outer jacket, Bottom: Graphite core

Energy deposition (kJ/cc/pulse) for core–jacket hybrid $\boldsymbol{R_1}$=3 mm

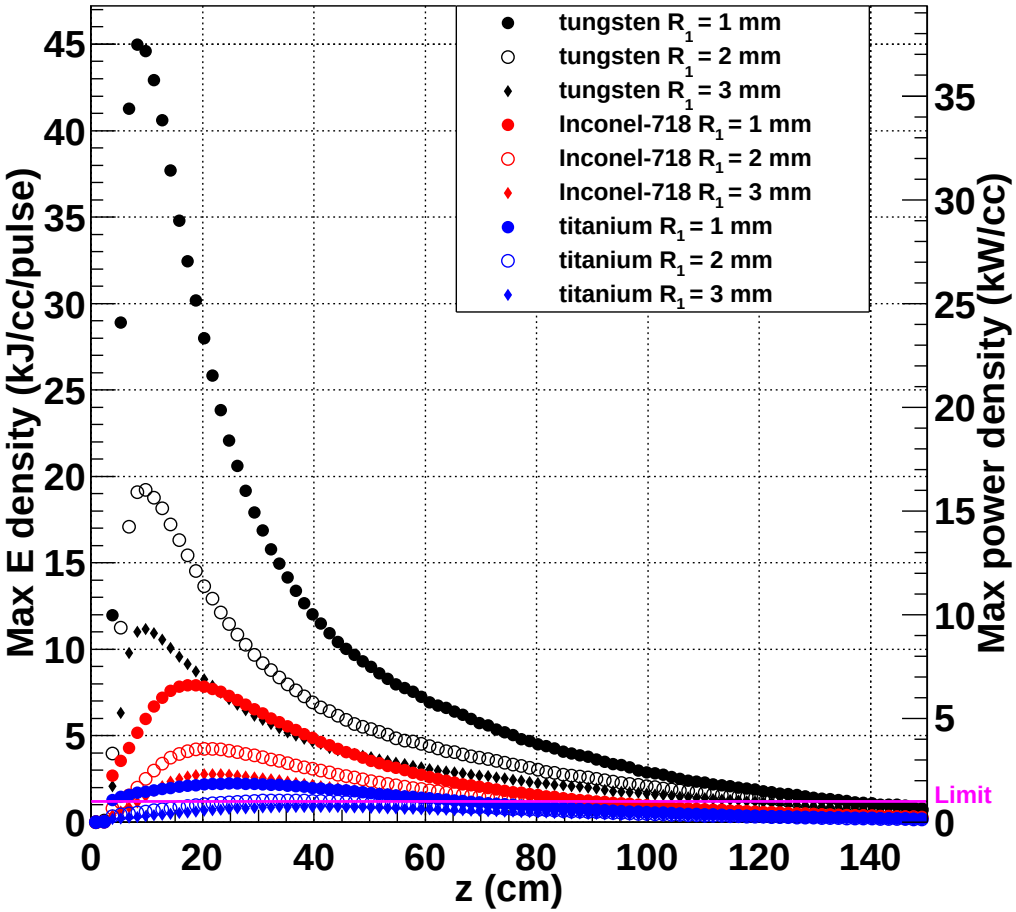


Top: High–Z outer jacket, Bottom: Graphite core

Peak energy density for core–jacket hybrid

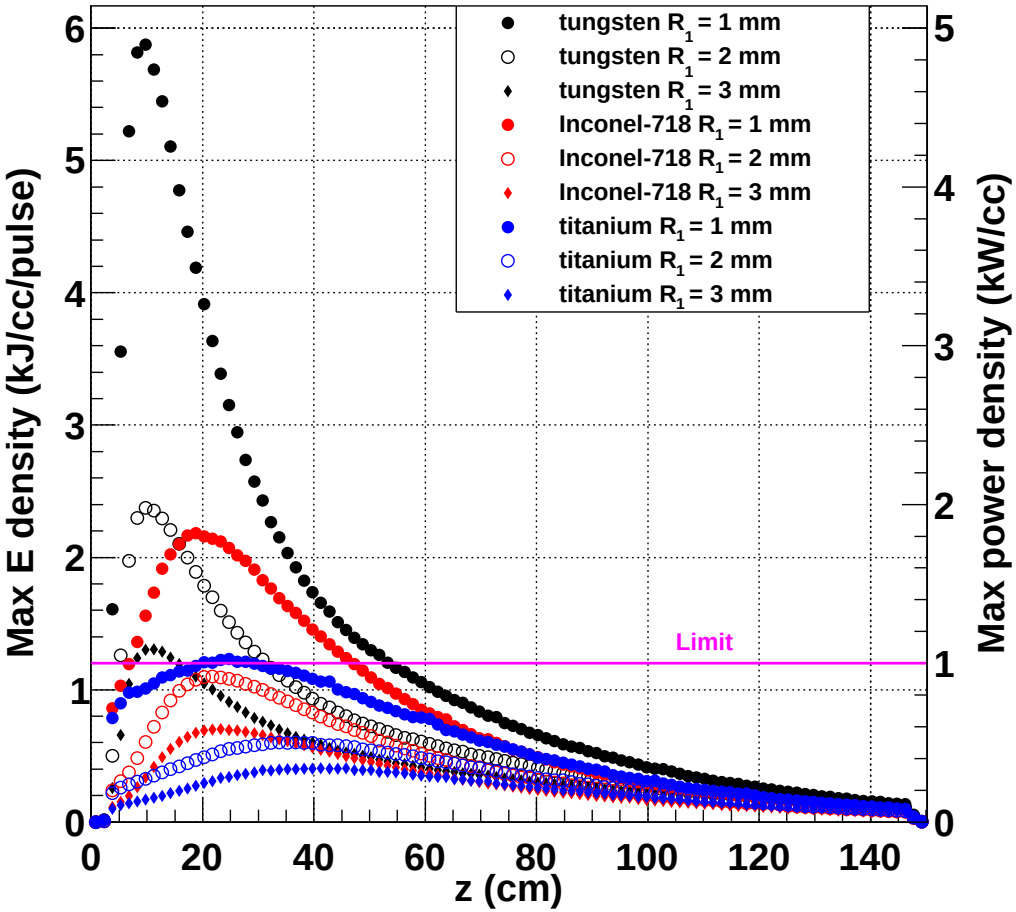


Graphite core

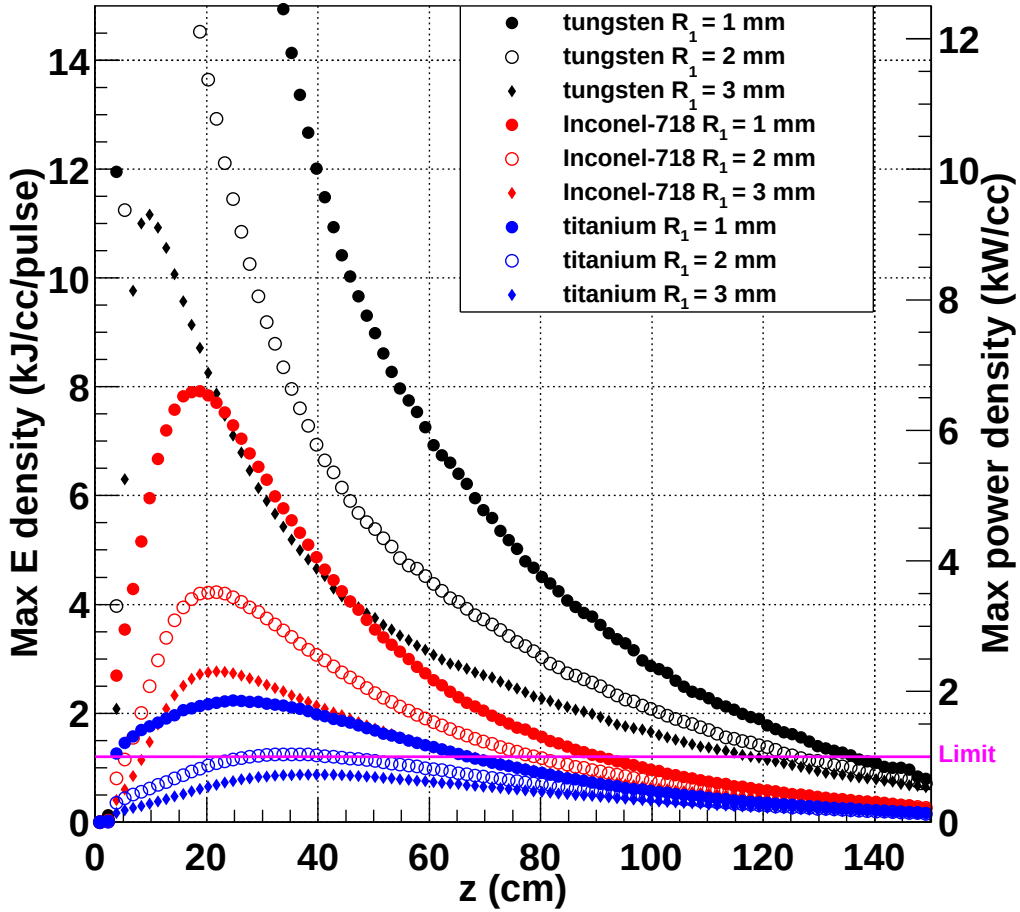


High–Z jacket

Peak energy density for core–jacket hybrid: zoom



Graphite core



High–Z jacket

Summary

- $2 \times 2\lambda$ graphite cylinders or Be SAT $\approx$ performance of NuMI baseline (4λ)
  $\Rightarrow$ OK splitting up the (low–Z) target into two equal sections ($R \lesssim 8\,\mathrm{mm}$)
  Would need to check effect of extra 2nd target support(s) not currently simulated

- Low– & High–Z hybrids can give slightly higher CP sensitivities, but in general they suffer from too high energy deposition
  - 2λ graphite: tungsten & Inconel-718 first $\sim 30\,\mathrm{cm}$ has $\mathrm{E_{dep}} > 1\,\mathrm{kW/cc}$
  - 3λ graphite: tungsten still too high, Inconel-718 at $1\,\mathrm{kW/cc}$ limit
  - Hybrid with downstream titanium SAT appears feasible: $\mathrm{E_{dep}} < 1\,\mathrm{kW/cc}$
  - Core–jacket concept unfeasible with tungsten & Inconel-718
    $\mathrm{E_{dep}}$ in graphite much higher owing to showering particles in high–Z
    $R_2 =$ 2-6 (3-9) mm titanium jacket is at (slightly below) limit

- Probably better to just use one or two (identical) low–Z targets ($L \sim 4\lambda$) for both engineering and physics performance i.e. target feasibility & reliability