Power Deposition in Graphite Targets of Various Radii

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The Issue

"Thermal shock" by pulsed beams incident on solid targets will be greatest at the point of peak energy/power deposition (and greater for beams of lower duty cycle).

In large targets (beam dumps/hadron calorimeters), the longitudinal profile of energy deposition has a "shower maximum" ~ 1 pion interaction lengths into the target.

Where is the peak energy deposition in a "pencil" graphite target, of radius ~ 8 mm, as considered for a Muon Collider/Neutrino Factory?

Facts: graphite density ~ 1.8 g/cm^3,
dE/dx = 1.5 MeV/(g/cm^2),
pion interaction length ~ 72 cm,
radiation length ~ 24 cm.

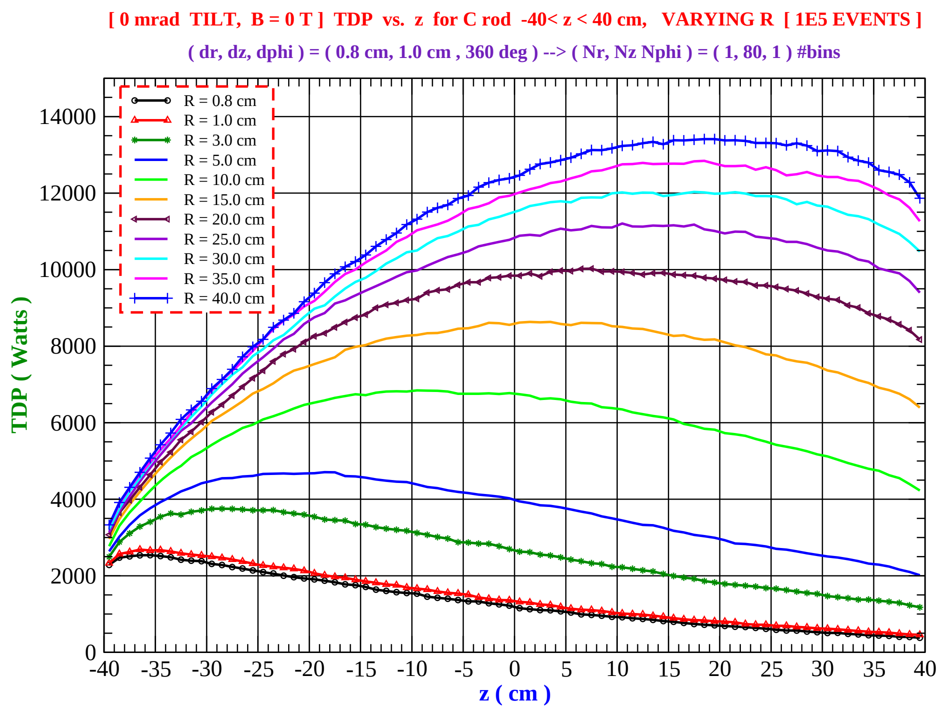
The studies were done for a 4-MW beam of 6.75-GeV-kinetic-energy protons.

The studies reported here were done with MARS15(2014), and FLUKA(2011).

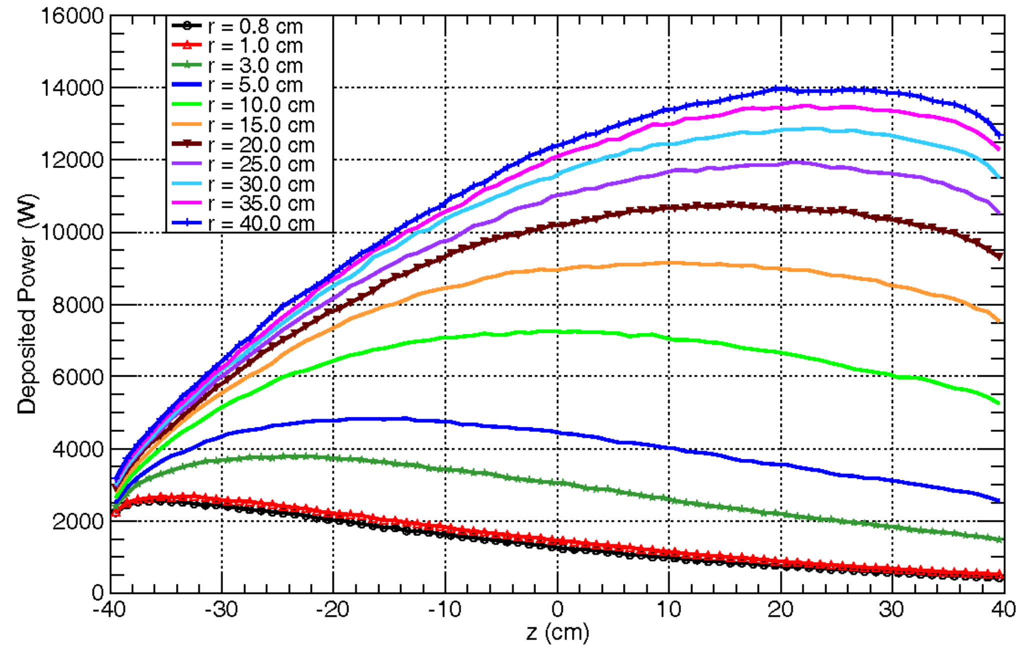
Target at 0°

For a first study, we consider graphite targets at 0 to the magnetic axis, in 0- and 20-T uniform magnetic fields.

B = 0 T, MARS



B = 0 T, FLUKA



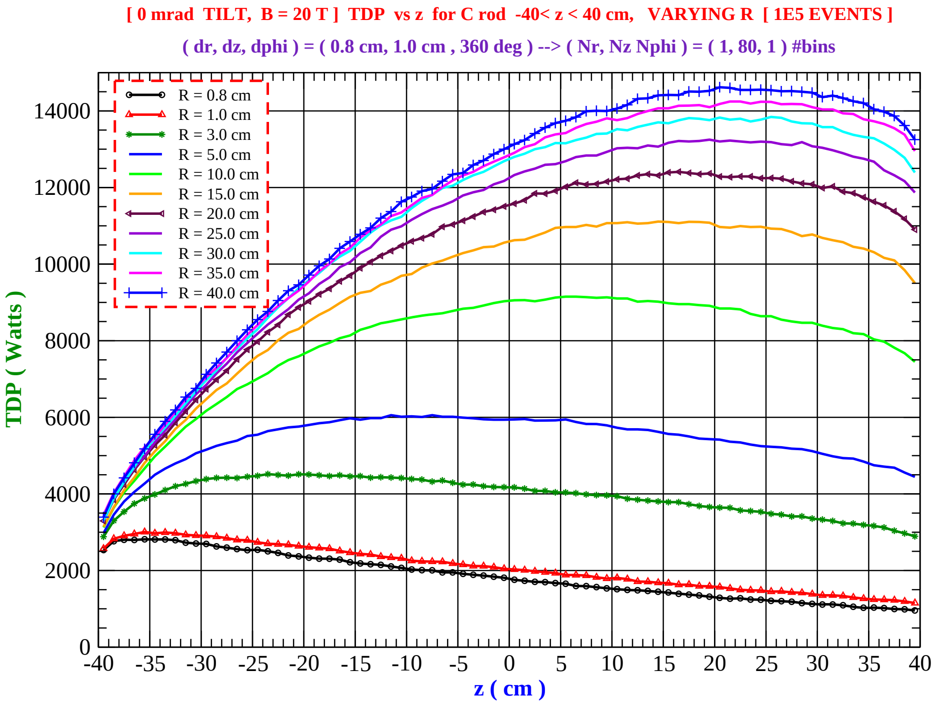
The plots show the total power deposited in 1-cm-thick disks, for target of various radii.

⇒ Largest power deposition only 4 cm into a "pencil" target, but at ~ 60 cm in targets with large radius.

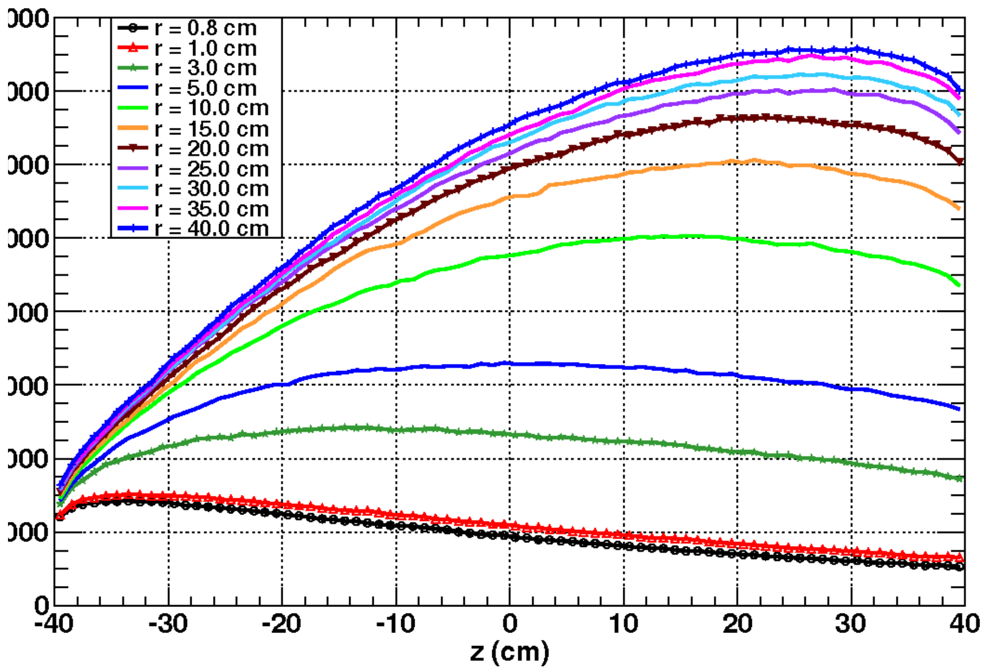
⇒ dE/dx only deposits about 1870 Watts in 1 cm of graphite, for a 4-MW beam.

Target at 0°, II

B = 20 T, MARS



B = 20 T, FLUKA



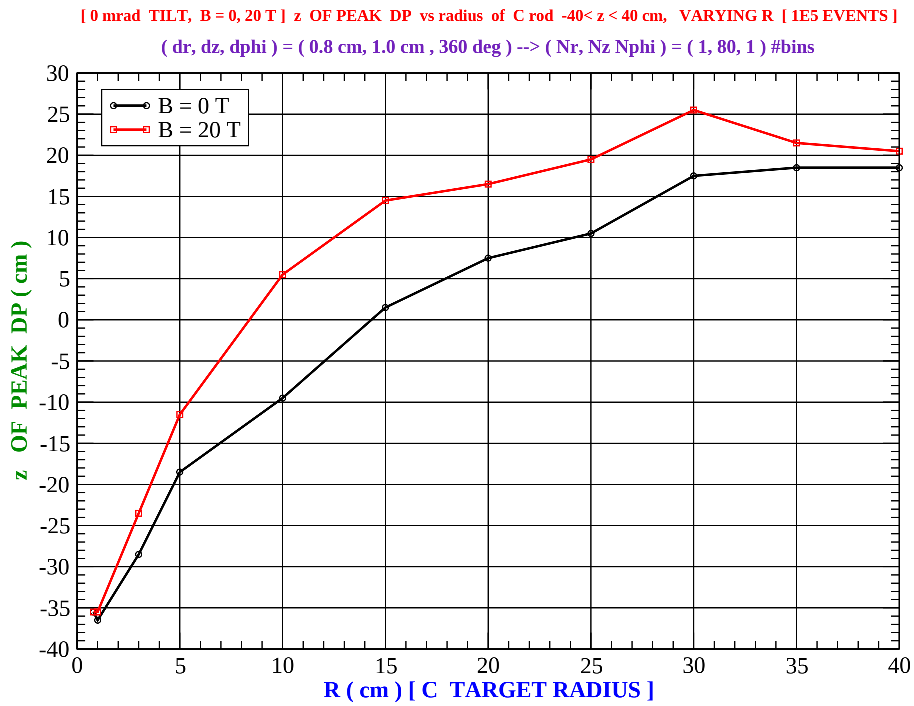
FLUKA indicates 5-10% more power deposition in this comparison.

The FLUKA beam is parallel, with rms radius = 2 mm, while the MARS beam is focused with spot rms radius of 2 mm and β^* = 80 cm.

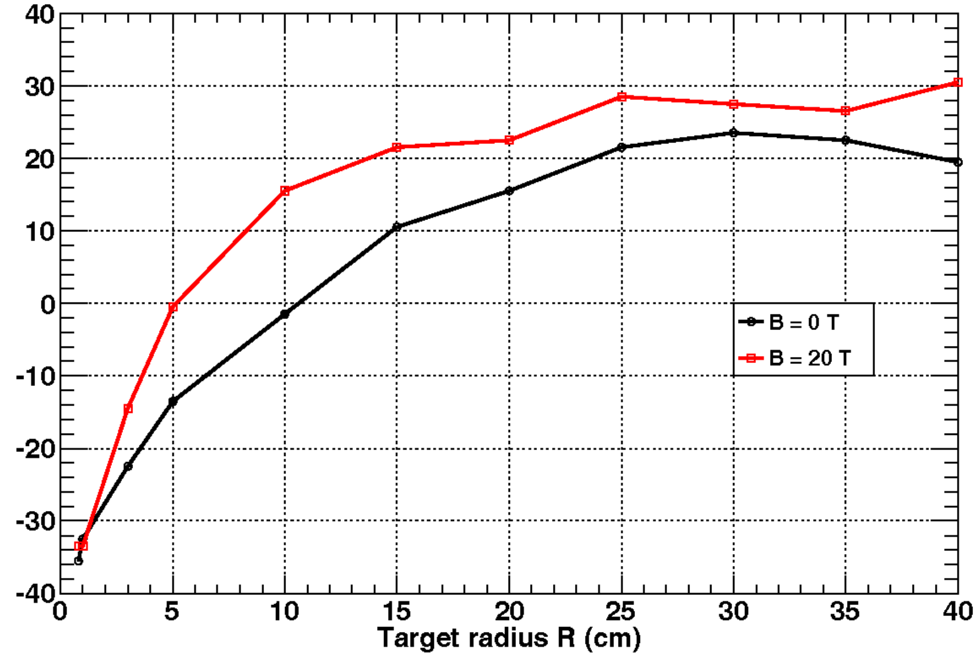
Target at 0°, III

The z-coord. of the target slice with peak power density is constant for radii > 30 cm.

MARS



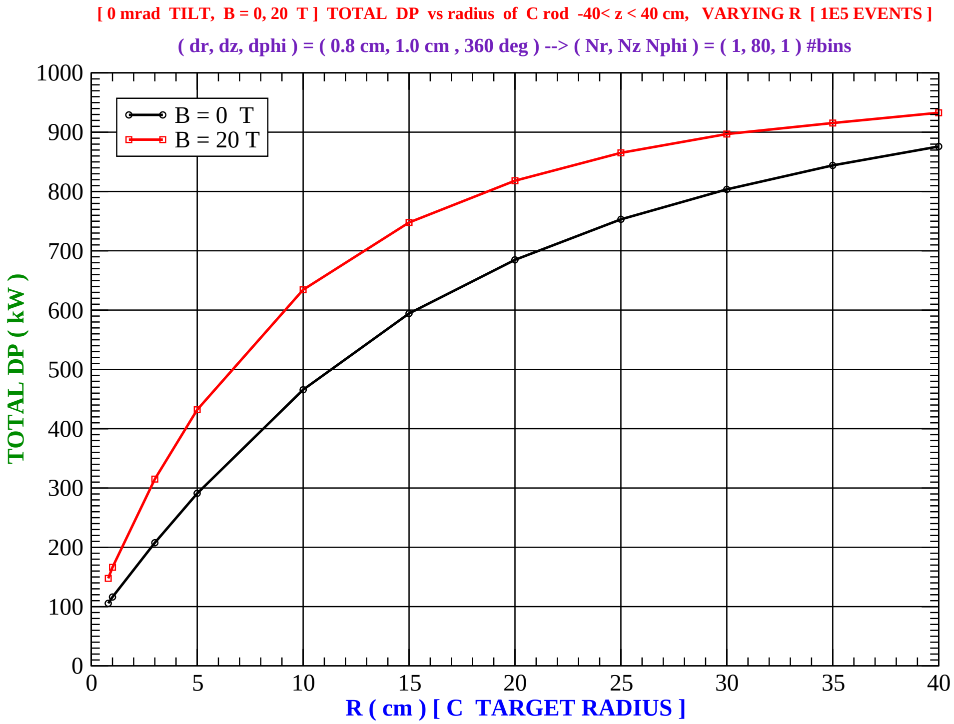
FLUKA



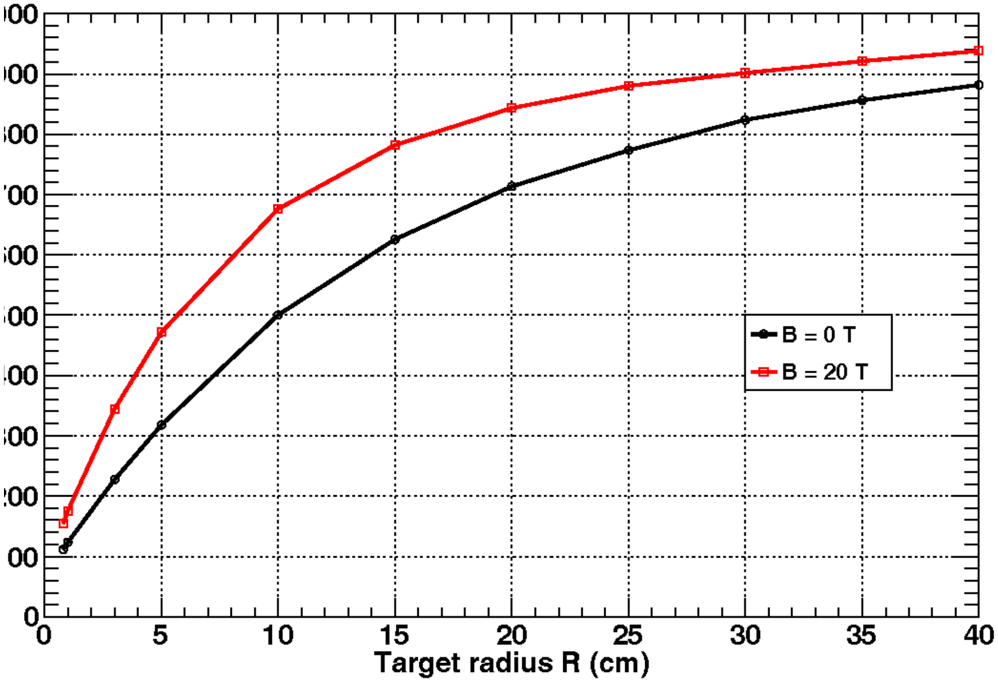
Target at 0°, IV

The total power absorbed in the target increases from ~ 150 kW in a "pencil" target (length = 80 cm, radius = 8 mm) to about 1 MW (out of 4 MW) in a target of 80 cm length and 40 cm radius.

MARS



FLUKA

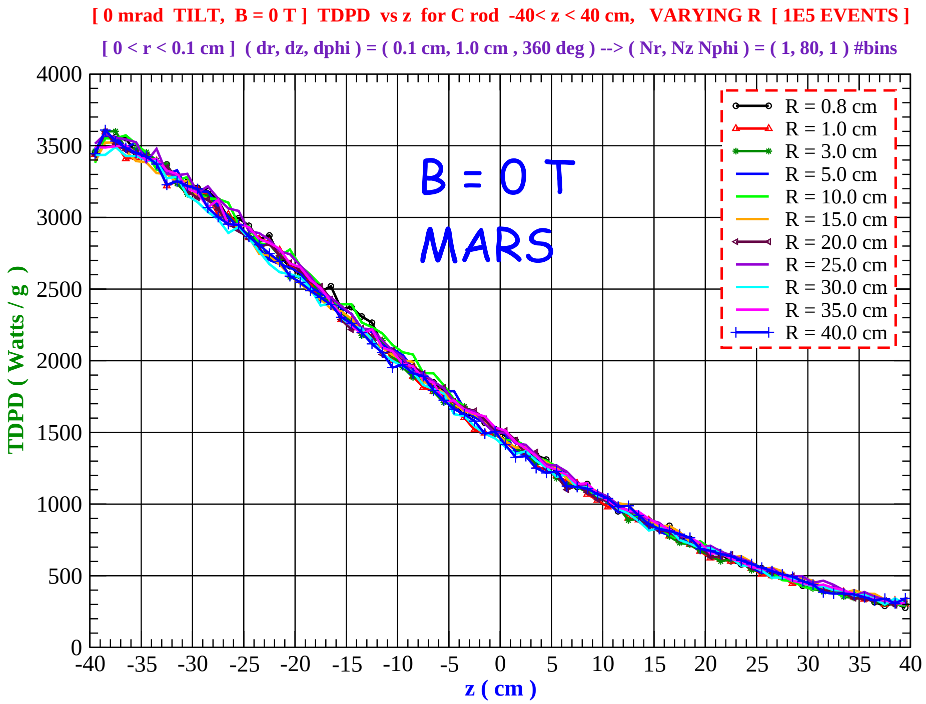


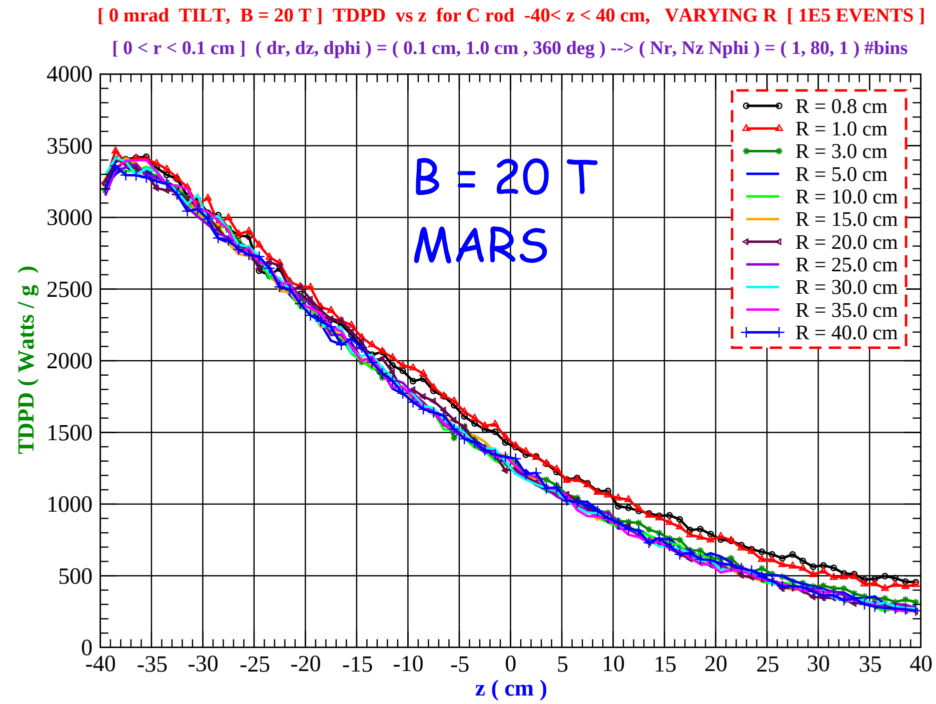
Target at 0°, V

We now want to locate the coordinates of the point with peak local power deposition.

A study not shown confirmed that this point has coord. $r = 0$.

To find the z coord., we plot the power deposition *vs.* z in a cylinder with $r = 1$ mm.



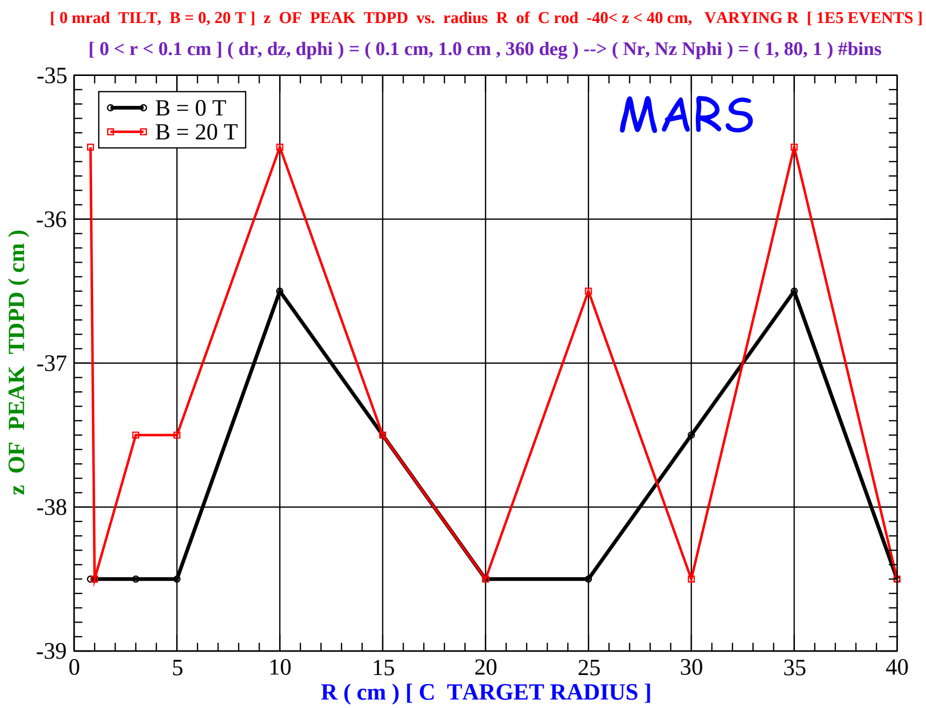


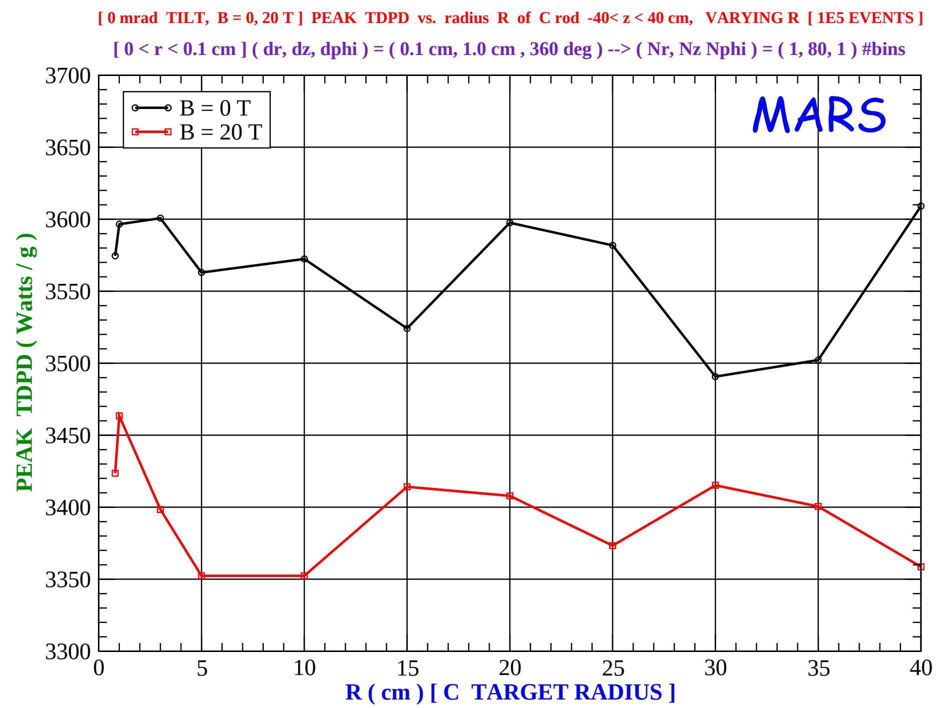
The curves are essentially independent of the target radius (for r_{target} > 8 mm).

Target at 0°, VI

The z-coord. of the point with peak local power deposition is 2-3 cm into the target, independent of the target radius, as shown in the left figure below.

The peak local power deposition is about 3600 W/g for 0 magnetic field and 4-MW beam power, and about 3400 W/g for 20 T field, as shown in the right figure below.

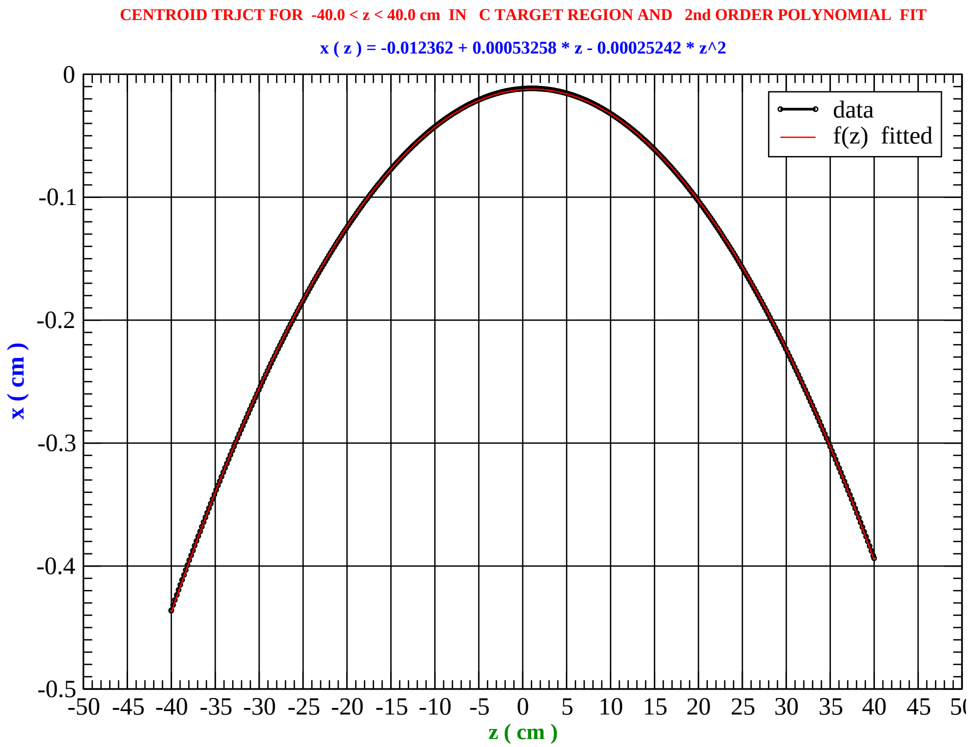


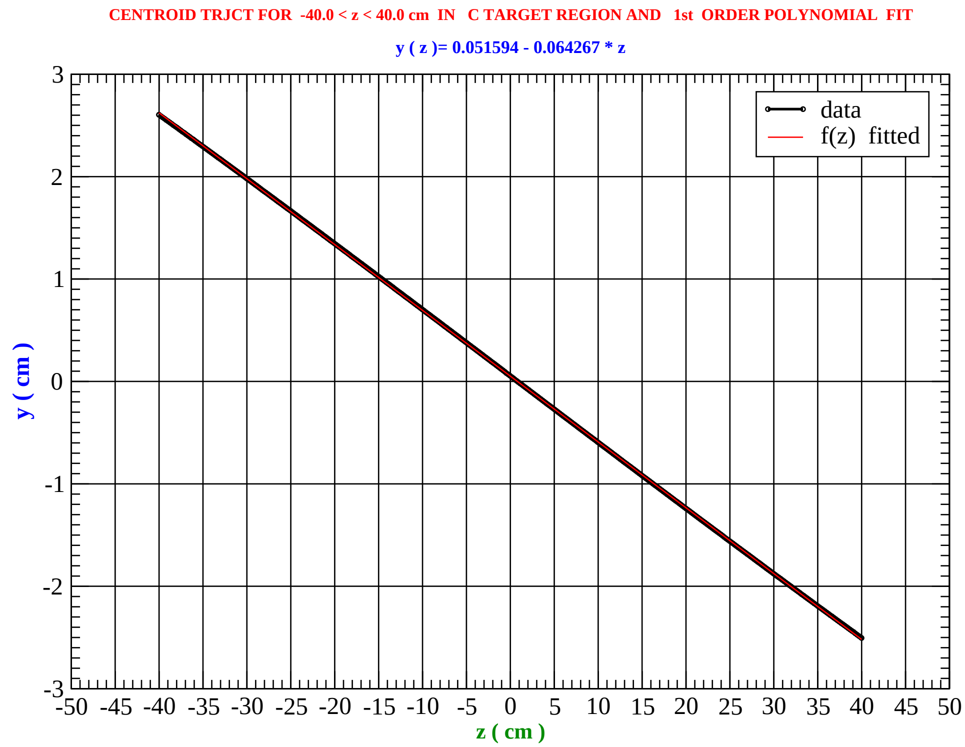


For 60-Hz beam structure, the peak energy deposition is only about 60 J/g (and 240 J/g for 15-Hz beam structure), for 4-MW beam power.

Target at 65 mrad

Trajectory of the central proton ray for 65-mrad tilt and 20-T field.





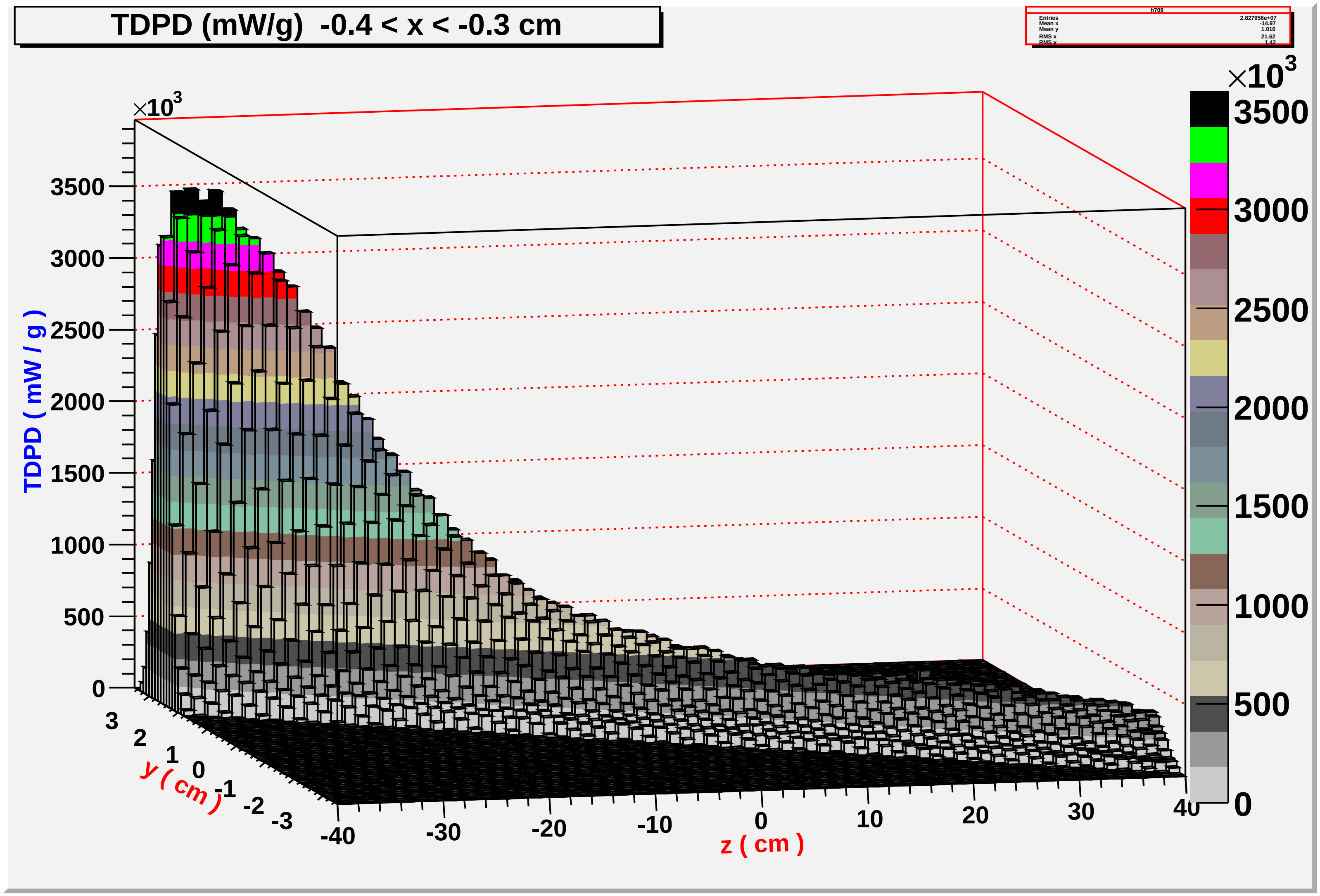
The *y*-coord. of the beam at any *z* inside the target is essentially the same as the *y*-coord. of the center of the target.

But, the beam enters the target offset in *x* by ~ 4.3 mm from the target center.

⇒ Peak energy deposition likely offset from the target center.

Target at 65 mrad, II

The peak energy deposition is 3598 J/g (~ same as for the 0° case), and occurs for (x,y,z) = (-0.35, 2.85, -37.5) cm (2.5 cm into the target).



Power deposition in the target slice -4 mm < x < 3 mm.

Power Deposition Due to dE/dx

The peak power deposition of 3600 W/g occurs about 37 cm from the center of the target.

The rms radius there is $\sigma_r = 0.2\ [1 + (37/80)^2]^{1/2} \sim 0.22$ cm, for $\beta^* = 80$ cm,
$\Rightarrow$ Effective area of a Gaussian beam = $2\pi\ \sigma_r^2 \sim 0.30\ \text{cm}^2$.

A 4-MW beam of 6.75-GeV protons has
$N = 4 \cdot 10^6\ \text{J/s} / (6.75 \cdot 10^9\ \text{eV} \cdot 1.6 \cdot 10^{-19}\ \text{J/eV}) \sim 3.7 \cdot 10^{15}\ p/\text{s}$.

dE/dx in graphite is 1.5 MeV/(g/cm^2).

The power deposition due to dE/dx at 3 cm into the target is
$N \cdot dE/dx\ /\ \text{Area} = 3.7 \cdot 10^{15}\ /\text{s} \cdot 1.5 \cdot 10^6\ \text{eV/(g/cm}^2) \cdot 1.6 \cdot 10^{-19}\ \text{J/eV}\ /\ 0.30\ \text{cm}^2$
~ 2950 W/g.

This suggests that the peak power deposition (in our "pencil" target) is only about 1.2 times that due to dE/dx.

Thermal Issues for Solid Targets

When beam pulse length t is less than target radius r divided by speed of sound v_{sound}, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if U = beam energy deposition in, say, Joules/g, then the instantaneous temperature rise ΔT is given by $\Delta T = U / C$, where C = heat\ capacity in Joules/g/K.

The temperature rise leads to a strain $\Delta r/r$ given by $\Delta r/\mathrm{r} = \alpha\, \Delta T = \alpha\, U/C$, where α = thermal expansion coefficient.

The strain leads to a stress P (= force/area) given by $P = E\, \Delta \mathrm{r}/\mathrm{r} = E \alpha\, U/C$, where E = modulus of elasticity.

In many metals, the tensile strength obeys $P \approx 0.002\, E$, $\alpha \approx 10^{-5}$, and $C \approx 0.3$ J/g/K, in which case $U_{max} \approx P\, C / \,E \alpha \approx 0.002 \cdot 0.3 / 10^{-5} \approx 60$ J/g.

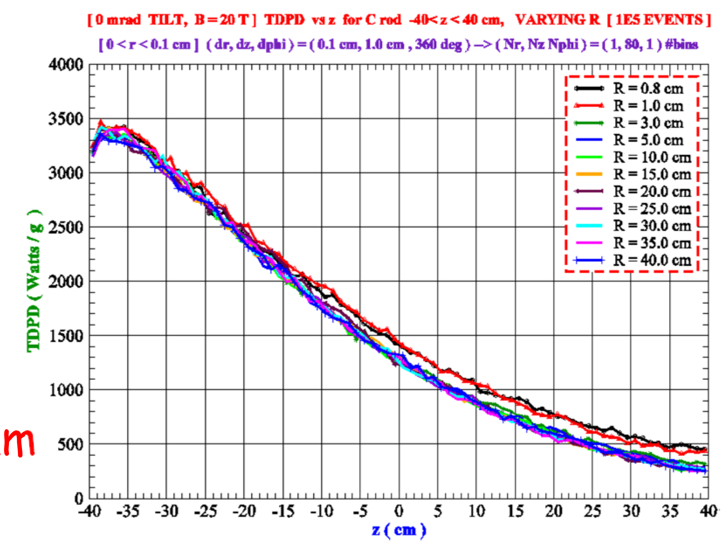
Graphite @ 1400° C: P = 42.4 Mpa, E = 7.2 Gpa, $\alpha = 4.8 \times 10^{-5}$, C = 1.4 J/g, $U_{max} \approx 1700$ J/g.
($\alpha \approx 1 \times 10^{-5}$ for carbon-carbon composite)

[A nickel target at FNAL has operated with $U_{max} \approx 1500$ J/g.]

These arguments are from *A Short Course on Targetry*, KTM, NuFact03 Summer Institute

How Much Beam Power Can a Solid Target Stand?

What is the maximum beam power this material can withstand without cracking, for a 6.75-GeV beam at 15 Hz with area 0.3 cm^2?



Ans: MARS15 indicates that the peak energy deposition in a "pencil" target is about 1.2 times that of dE/dx,
$\Rightarrow$ 1.8 MeV/(g/cm^2) for graphite.

Now, 1.5 MeV = $2.9 \cdot 10^{-13}$ J, so 1500 J/g requires a proton beam intensity of (1500 J/g)/($2.9 \cdot 10^{-13}$ J$\cdot$cm^2/g) $\approx 5 \cdot 10^{15}$/cm^2.

$\Rightarrow P_{max} \approx 15\ \text{Hz} \cdot (6.75 \cdot 10^9\ \text{eV}) \cdot (1.6 \cdot 10^{-19}\ \text{J/eV}) \cdot (5. \cdot 10^{15}\ /\text{cm}^2) \cdot 0.3\ \text{cm}^2 \approx 2.5 \cdot 10^7\ \text{J/s}$
= 25 MW.

If graphite cracks under singles pulses of > 1500 J/g, then "safe" up to 25-MW beam power @ 15 Hz and 6.75 GeV kinetic energy. (And would be "safe" up to 125 MW-beam power with a carbon-carbon target.)