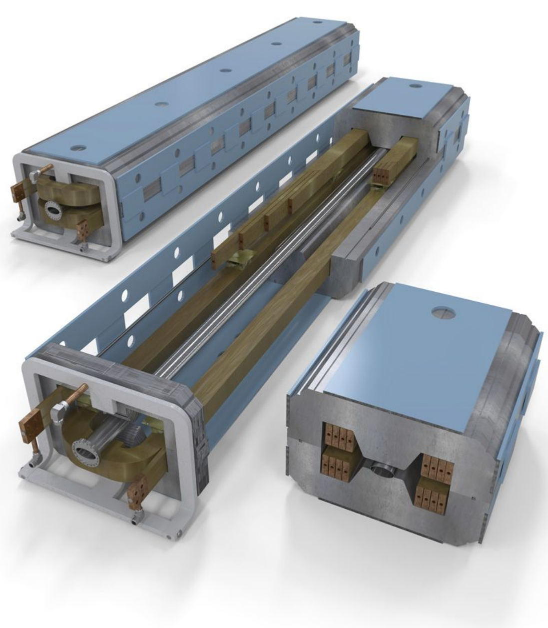
I

CPS at Hall-D.

Why we need 3 m long Dipole.



$p(\gamma, K_0)\Sigma^+$, $n(\gamma, K_0)\Lambda$, $n(\gamma, K_0)\Sigma_0$

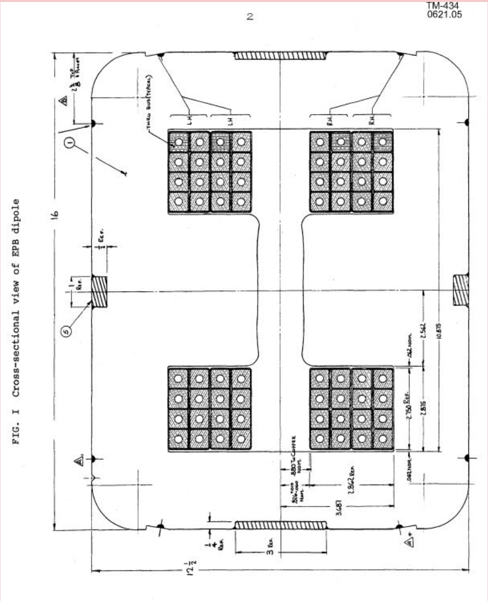

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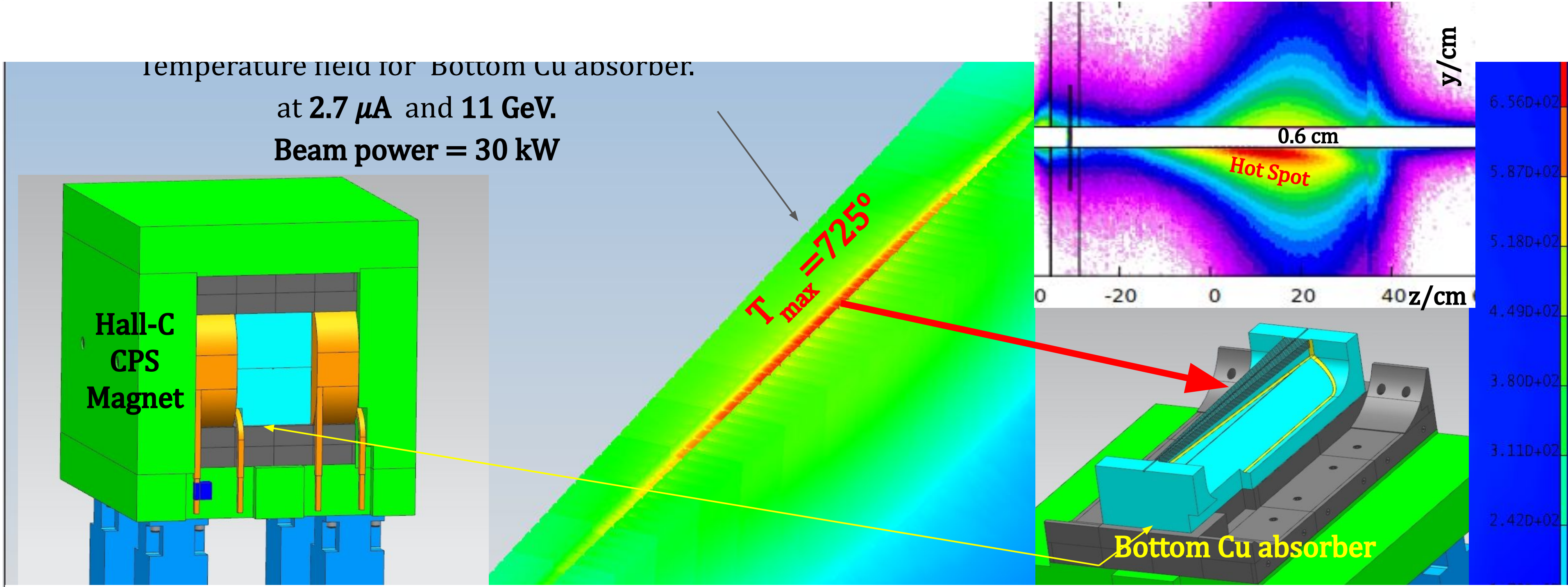
FIG. I Cross-sectional view of EPB dipole

Hot Spot Temperature for CPS design from HALL-C .



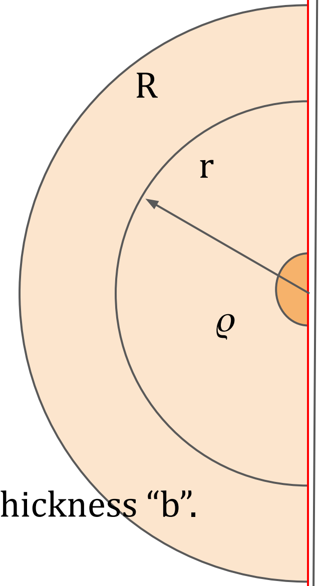
Temperature field for Bottom Cu absorber.
at **2.7 μA** and **11 GeV.**
Beam power = 30 kW

- In this design WCu alloy between coils is replaced with Cu.
- Do we expect **twice higher temperature** at   beam power **60 kW ?**
- How can we   **respond to**   **potential**   **challenge**?

II

Hot spot Temperature vs Energy Deposition in simple models of copper Disk and Bar.

Heating of ¼ Disk by e-beam $I=5\ \mu A$, 12 GeV, hot spot radius $\varrho = 0.25$ cm.



Outside T=100 C

- Energy deposition rate inside the ¼ -disk a**s in Reference design**: sector $\varphi = \frac{1}{4}\,2\pi$.

  $dE/dt = \mathbf{b}\ dE/dzdt$, where dE/dz is energy deposition of secondaries in Hot Spot.
- For energy balance in stationary case at heat conductivity $\varkappa$ we write :

  $$dE/dt = \mathbf{b}\ dE/dzdt = -\varphi r \mathbf{b} \varkappa\ dT/dr \quad \Rightarrow \quad dE/dzdt = -\varphi r \varkappa\ dT/dr \quad \Rightarrow$$

  $$dT/dr = -(\varphi\varkappa)^{-1}\ dE/dzdt\ \ r^{-1}$$; integrate over $r < R$,

  $$T(R)-T(r) = -\ (\varphi\varkappa)^{-1}\ dE/dzdt\ \ln(R/\varrho),$$

  $$\mathbf{T(\varrho)=T(R) + (\varphi\varkappa)^{-1} dE/dzdt\ \ ln(R/\varrho).}$$

- Assume realistic $\varrho=0.25$ cm and R=100 cm.
- **Copper** $\varkappa=3.98$ [W/cm•K] ; (Al = 2.4 , Brass =1.1 [W/cm•K]) <= Why using copper!
- For **reference design** dE/dV/e =**2.3 [GeV/cm³/e]**

E/dVdt=**2.3E+9 [eV/cm³/e]**0.6E+19 [e/As]1.6E-19 [J/ev]5.E-6 [A] =**11.E+3** [W/cm³].

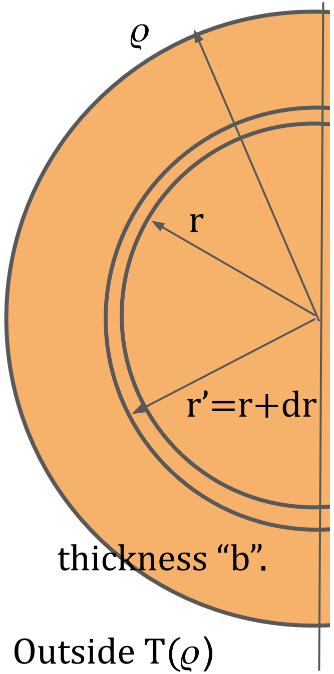
- Estimate **dE/dzdt** = $\pi\varrho^2$ dE/dVdt = 3.14 * 0.25² [cm²] * 11.E+3 [W/cm³] = **2.16 E+3** [W/cm].
- From direct FLUKA “measurements ” **dE/dzdt** = **2.54 E+3** [W/cm].

  ΔT=T(ϱ)-T(R)= **(3.98*½ *3.14)⁻¹** [cm*K/W]*2.54E+3 [W/cm]*ln(25/0.25)= 1871 K, **2440 K for ¼ coin.**
- For Long Magnet (3 m•0.1 T) and ½ (2π) **dE/dzdt is ~4 times lower => 240 K , for ½ coins**

  and 120 K for full “coin”.

- $T(\varrho)$ = 1815 C ; **reference magnet,** I= 5 μA ; T(R)=35 C is maintained at r > R cm. How?
- $T(\varrho)$ = 1045 C ; reference magnet, I=2.7 μA .

Simple model for heating INSIDE the HOT SPOT. I=5 μA of 12 GeV.



- In and out power for the ¼ o-ring (r, r'=r+dr):

  $dE^{+}/dt = -\tfrac{1}{2}\,\pi r d\,\varkappa\ dT/dr$; $dE^{-}/dt = +\tfrac{1}{2}\,\pi r' d\,\varkappa\ dT/dr'$

- Energy balance for o-ring:

  $dE/dt = \mathbf{dE/dVdt\ \tfrac{1}{2}\ \pi b\ rdr} = dE^{+}/dt\,(r) + dE^{-}/dt(r') = \mathbf{-\tfrac{1}{2}\,\pi b\,\varkappa\ dr\ d(r\,dT/dr)/dr}$;

  $-dE/dVdt\ rdr = \varkappa\, d\,(r\,dT/dr)$; simplify and integrate r

  $-dE/dVdt\ \varkappa^{-1}\,\tfrac{1}{2}r^{2} + A = r\,(dT/dr)$; divide by r

  $dT/dr = Ar^{-1} - dE/(dVdt)\ \varkappa^{-1}\ \tfrac{1}{2}r$; what is A?

- From the previous slide $dT(\varrho)/dr = -\tfrac{1}{2}\,\varrho\,\varkappa^{-1} dE/dVdt$; must be same ; => A=0!

  $-dE/dVdt\ \varkappa^{-1}\tfrac{1}{2}r = dT/dr$; integrate

  $T(r) = B - dE/(dVdt)\ \varkappa^{-1}\ \tfrac{1}{4}(r^{2}-\varrho^{2})$; from the boundary condition $B=T(\varrho)$

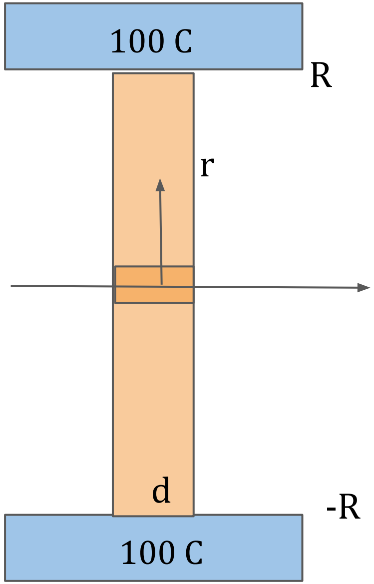
  $T(r) - T(\varrho) = dE/dVdt\ \varkappa^{-1}\,\tfrac{1}{4}(\varrho^{2} - r^{2})$; $T(r=0)$?

$T(0)-T(\varrho) = \mathbf{\tfrac{1}{4}}\ (\pi\varkappa)^{-1}\,\mathbf{\pi\varrho^{2}\ dE/dVdt} = (3.98\pi)^{-1}$ [cm*K/W] **2.54E+3** [W/cm] = 204 K ;

dE/dzdt= 2.54E+3 [W/cm] **T(0)=T(ϱ)+204 K.**

- **T(ϱ) = 1815 C** provided T(R)=35 C temperature is maintained at R=25 cm.
- **T(0) = 2020 C** in the center of HOT SPOT; **reference design** at **I = 5 μA .**
- **T(0) = 1250 C** in the center of HOT SPOT; **reference design** at **I = 2.7 μA . 1140 C** FEA, Hall-C.

Heating of Copper Bar by electron beam $I=5\,\mu A$, 12 GeV.



Bar $d \times a \times 2R$ cm^3

- Energy deposition rate = $d \times dE/dzdt$;
- Energy balance in stationary case : $d \times dE/dzdt = -\,2\,da\,\varkappa\,dT/dr$.

$$\Rightarrow \quad dE/dzdt = -\,2a\varkappa\,dT/dr\,.$$

$dT = -(2a\varkappa)^{-1}\,dE/dzdt\;dr$; integrate **$r < R$** ,

$$T(R)-T(r) = -\,(2a\varkappa)^{-1}\,dE/dzdt\;(R-r).$$

$$\mathbf{T(r)=T(R) + (\,2a\,\varkappa\,)^{-1}\,dE/dzdt\;(\,R-r\,)}$$

- **Assume realistic $R=8$ cm, $a=3.7$ cm**
- **Copper $\varkappa = 3.98$ W/cmK**
- **For reference design $dE/dV/e = 2.3$ [GeV/cm^3/e] ; $dE/dzdt = 2540$ [W/cm]**

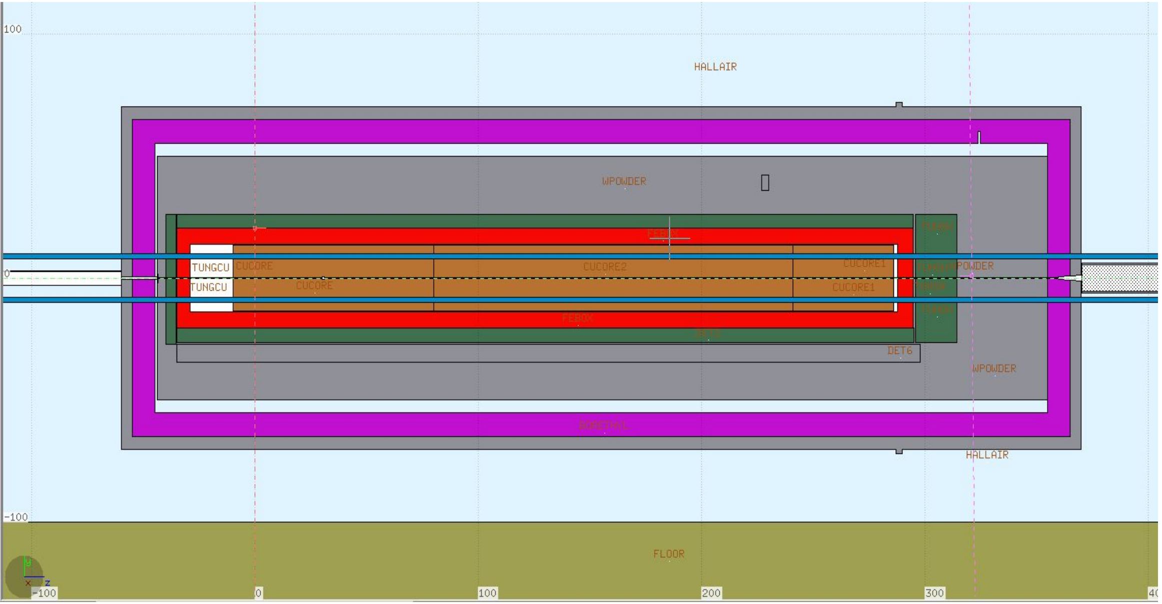
T(0)-T(R)= (**2***3.7*3.98)$^{-1}$ [K/W]*2.54E+3 [W/cm]* 8 [cm]= **690 K.**
If no top/bott heat contact = 1380 K
For 3m*0.1T magnet 4 times lower =170 K.
T(0)=T(R) +690 K =790 K

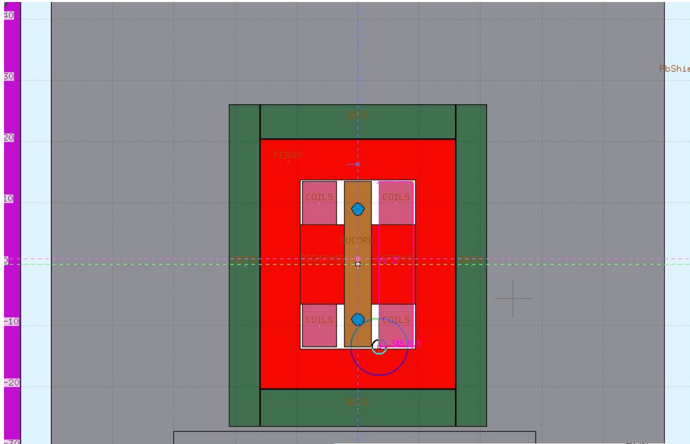
- **Ref. Magnet.** T(0) = 990 C provided T(R)=300 C **temperature is maintained at r > R cm via cooling** !
- Critical parameters for **reference design** are “a=a(z)” and “R=?”. What should be T(R) to evacuate 50 kW?

III

3 m Long Magnet Performance.

Magnet B=0.1 T × 3 m. Fermilab prototype 1.5 T × 3 m.
Beam FWHM = 0.25 cm, Hole = 0.6×0.6 cm^2, Cu Converter t = 0.134 cm.





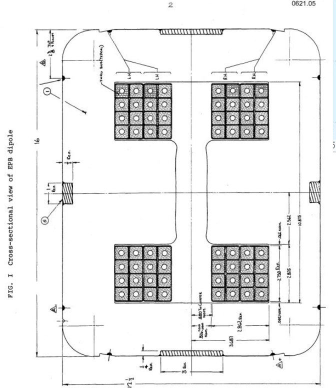

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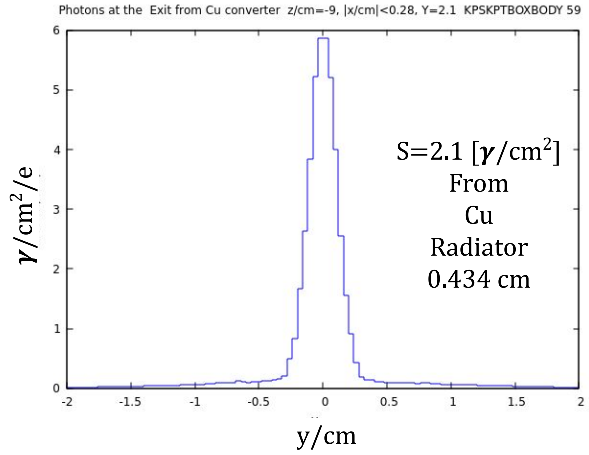
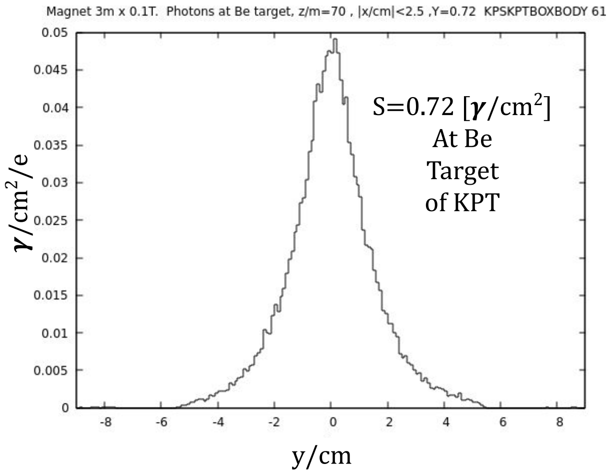
FIG. I Cross-sectional view of EPB dipole

- Fermilab Magnet cooling provides 20 kW heat sink at maximum current.
- May be used at 10% of maximum current. Wider gap between poles?
- More room for cooling pipes through the Cu absorber; close to the hot spot.
- Thermal Contact between Cu Absorber and magnet poles and yoke ?

Photon Beam quality and Hot Spot power in CPS with 3 m × 0.1 T Dipole.

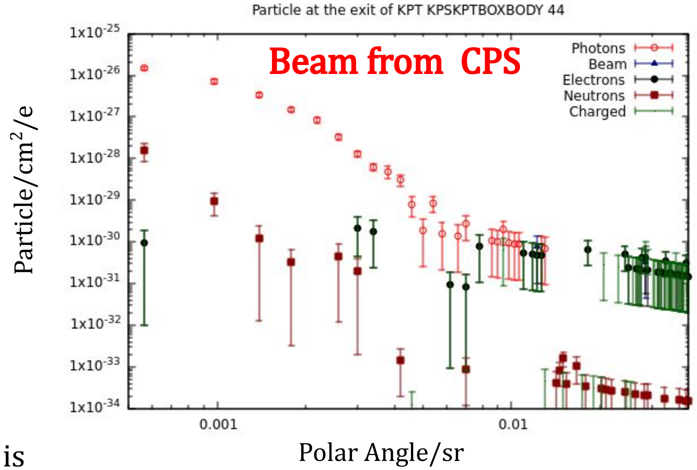

Photons at the Exit from Cu converter z/cm=-9, |x/cm|<0.28, Y=2.1 KPSKPTBOXBODY 59

S=2.1 [γ/cm^2]
From
Cu
Radiator
0.434 cm

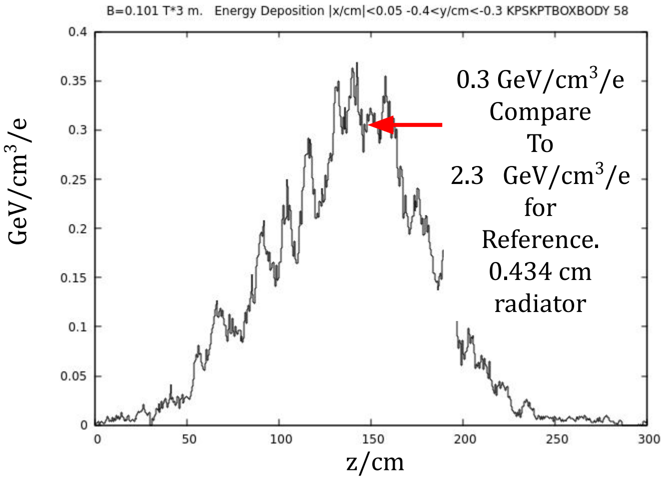

Magnet 3m x 0.1T. Photons at Be target, z/m=70 , |x/cm|<2.5 ,Y=0.72 KPSKPTBOXBODY 61

S=0.72 [γ/cm^2]
At Be
Target
of KPT

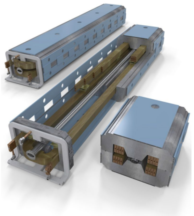
- Photon beam is OK.
- Maximum Energy deposition is 0.3 [GeV/cm^3/e] (factor 1/7) With 0.434 cm radiator .


Particle at the exit of KPT KPSKPTBOXBODY 44

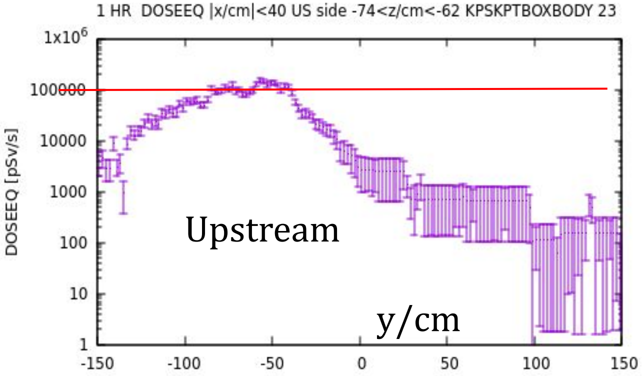
Beam from CPS

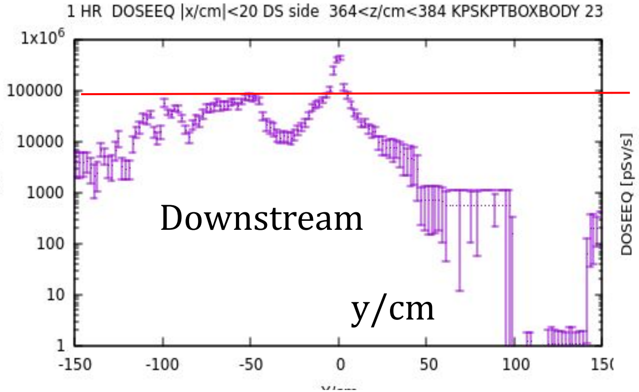

B=0.101 T*3 m. Energy Deposition |x/cm|<0.05 -0.4<y/cm<-0.3 KPSKPTBOXBODY 58

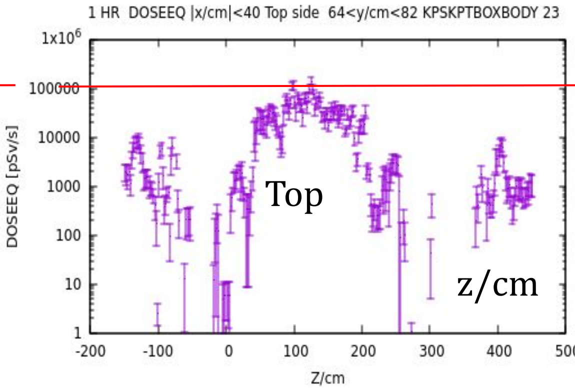
0.3 GeV/cm^3/e
Compare
To
2.3 GeV/cm^3/e
for
Reference.
0.434 cm
radiator

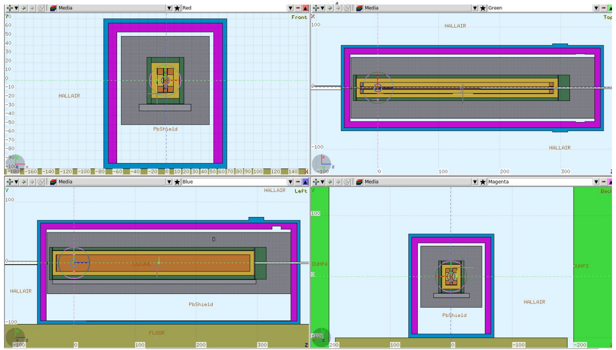


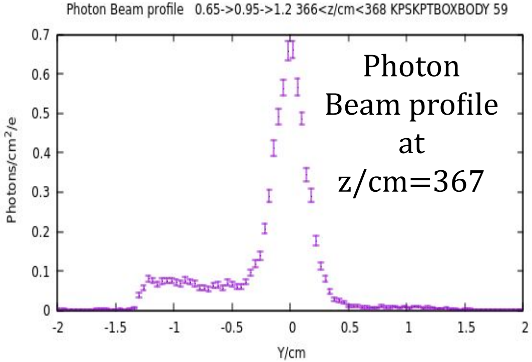
Safety with 3m Dipole B=0.35 T (Fermilab prototype).
Cu absorber. W shield. Concrete Floor.
B=0.1 T in progress.

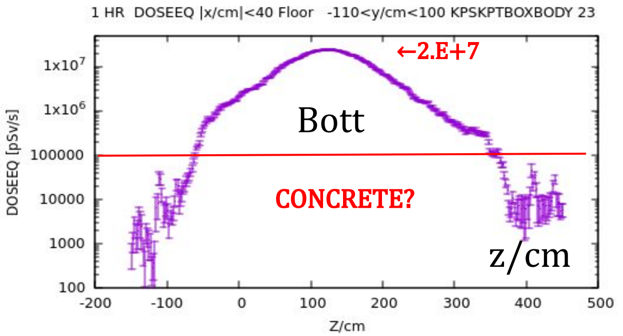

1 HR DOSEEQ |x/cm|<40 US side -74<z/cm<-62 KPSKPTBOXBODY 23


1 HR DOSEEQ |x/cm|<20 DS side 364<z/cm<384 KPSKPTBOXBODY 23


1 HR DOSEEQ |x/cm|<40 Top side 64<y/cm<82 KPSKPTBOXBODY 23




Photon Beam profile 0.65->0.95->1.2 366<z/cm<368 KPSKPTBOXBODY 59

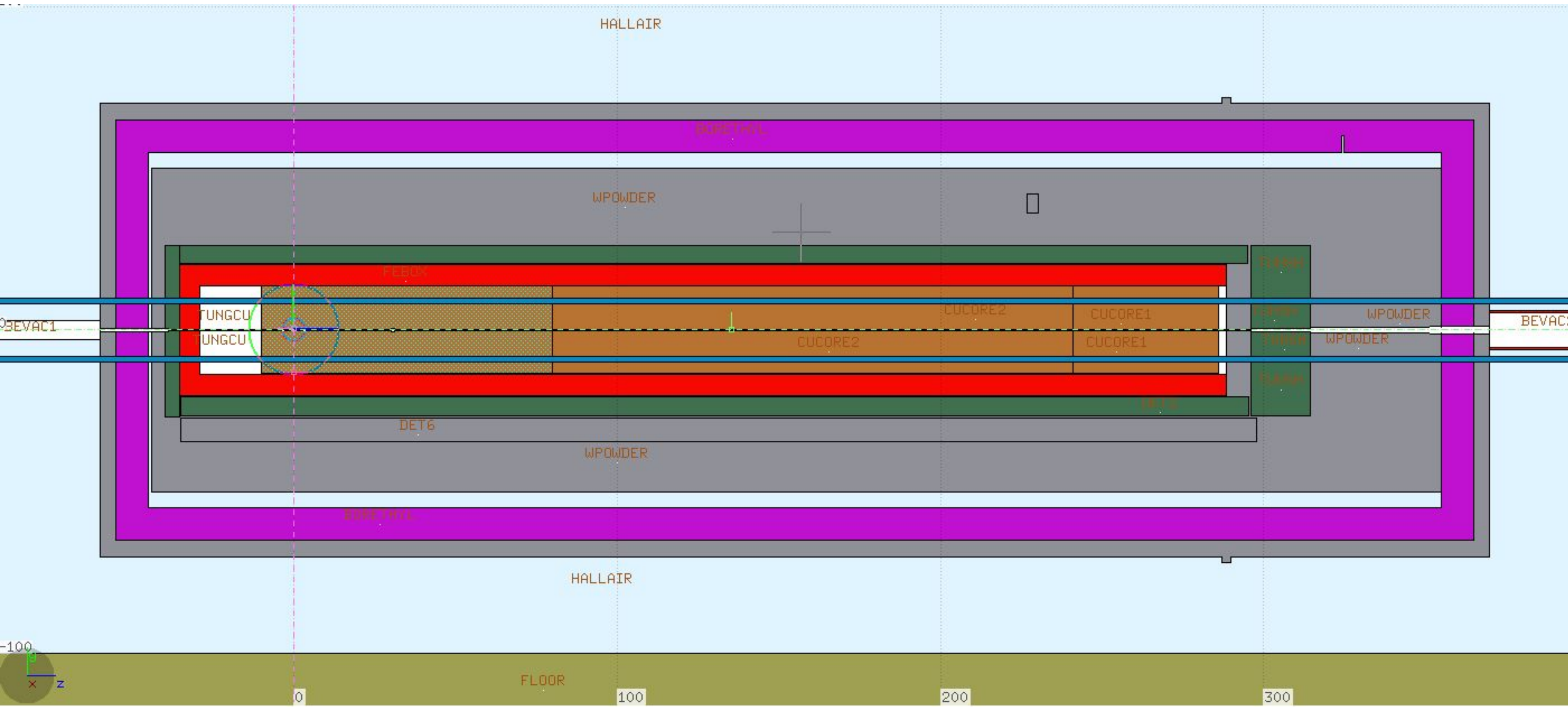

1 HR DOSEEQ |x/cm|<40 Floor -110<y/cm<100 KPSKPTBOXBODY 23

IV

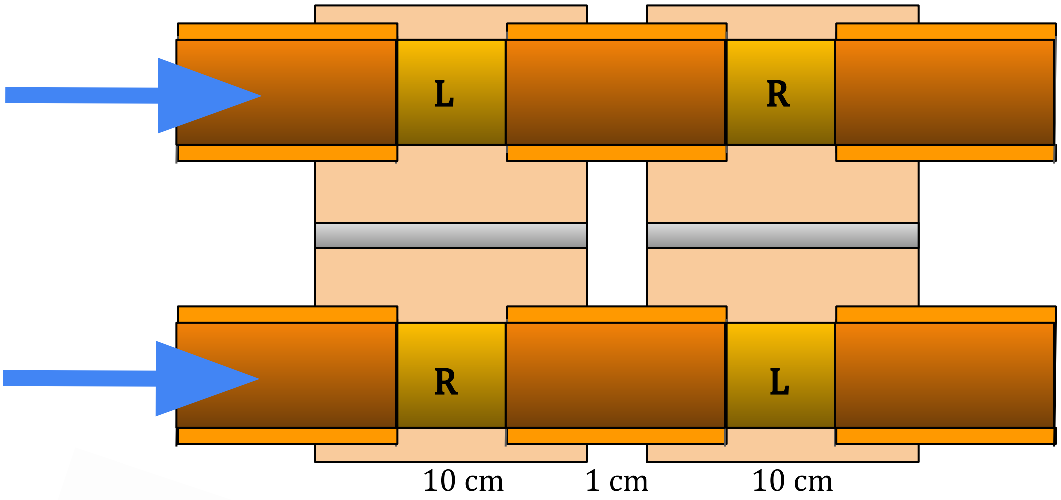
3 m Long Magnet Cooling.

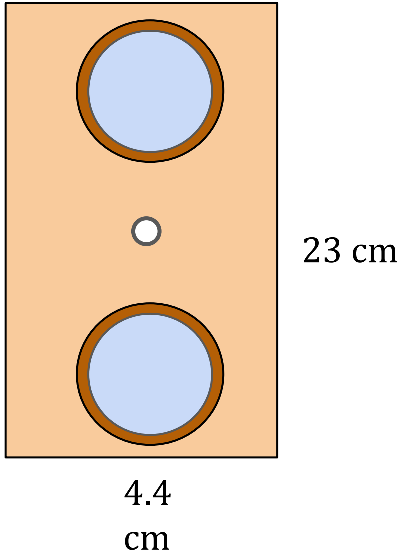
Copper absorber Cooling and Thermal Contact.

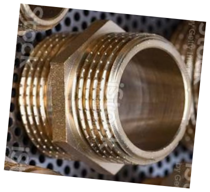
How to make it good with cooling liquid.

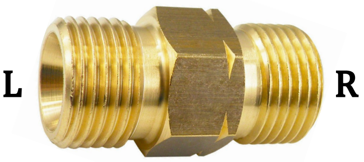


Magnet B=0.1 T × 3 m. Possible solution with Segmented Copper Absorber.









- 3m Mag provides 4-7 times lower power in hot spot. **Factor 0.25 in ΔT.**
- Absorber of **uniform** × **section** 4 ×20 cm^2 with **round** beam **hole**; no problem of thermal contact between “top” and“bottom” parts. **Factor 0.5 in ΔT.**
- **Direct contact to Cooling liquid** in each segment. Segments are connected by fittings with **left/right-**hand threads.
- Cooling water at v= 50 [cm/s] through the pipe S =5 [cm^2] evacuates 50 kW; 6 sec heating, C_v =4184 J·kg^{-1}·K^{-1} .

Can we run our long CPS Absorber without cooling?

Consider Cu absorber, bar sized for $20 \times 5 \times 300$ cm^3

Assume that Irradiation is the only way to evacuate the power P=50 kW.

$$P = \epsilon \sigma S T^4$$

Where

ϵ = 1 ; Emissivity; tabulated values for polished Cu: ϵ= 0.04 ; oxidized: ϵ=0.87.

S = 1.5 [m^2] ; bar area.

σ = 5.7 E-8 [W/m^2/K^4] ; Stefan–Boltzmann constant.

$T=(50\ [kW] / (5.7 \times 10^{-8}\ [W/m^2/K^4] \times 0.5\ [m] \times 3\ [m]))^{1/4}$ = **874 K** = 600 C ; this surface T is required to irradiate 50 KW !

Surface temperature plus “T-gradient” in order to get T of the hot spot:

T= 874 K at L=300 cm; In the hot spot T= 600 C + 340 C (gradient) =~940 C ; ½ coin. **cooling required** !

=~770 C ; slightly better for a full “coin”.

T=1260 K at L= 70 cm T= ~1900 C **; for reference design**

Irradiation between two bodies:

$P_{12}=\sigma S(T_1^4 - T_2^4)$=50 kW => $T_2^4+P_{12}/\epsilon_1 \sigma S = T_1^4$

$T_2^4+874^4 = T_1^4$

T_1 = 877 K ! Has Almost NO effect!

Can we cool down the Absorber? Risk estimate.

- Water speed required to evacuate 50 kW through a pipe d=3 cm, L=3 m, $S=7\ \mathrm{cm}^2$

  $dE/dt=C_v(T_{out}-T_{in})\ v\ S$; $5.E+4W = 4.2\ [JK^{-1}cm^{-3}]\ 70\ [K]\ 7\ [cm^2]\ v\ [cm/s]$; we find:

  v = 25 [cm/s].

- Heat transfer rate from absorber at T_a to liquid at $T_m = ½\ (T_{out}-T_{in})$ via area $A=2\ \pi d\ L= 6.\ E+3\ cm^2$

  $dQ/dt=k\ (T_a - T_m)\ A$; must be 50 kW,

- Where **k**=4.E-2 $[W\ cm^{-2}\ K^{-1}]$ is “heat transfer coefficient”; empirical, tabulated value:

  $dQ/dt=k\ (T_a - T_m)\ A = 4.\ E-2\ [Wcm^{-2}\ K^{-1}]\ 6.\ E+3\ [cm^2]\ 250\ [K]=50\ kW.$

- That corresponds to absorber surface **$T_a = 250\ C + 50\ C = 300\ C$** .
- We replace T(R) with T_a =300 C to get the Hot Spot temperature (see slide 6, bar model):

  $T(0) = T_a +170\ K = 470\ C$, if segments are a one piece doo.

- Water flow speed and heat flow looks consistent with our goal. No risk of melting.
- Model of absorber for FEA calculations is simple and should include irradiation (?)

Conclusive remarks

- There is a **high risk of overheating** for the reference design at 5 μA.
- 3m magnet provides 4 times lower energy deposition on the hot spot **.** (Beam channel size?)
- This allows to keep the **hot spot temperature**:

  ~ **470 C** with Active **Cooling System** (Irradiation is not accounted yet).

  ~ 770 C with **irradiation** only.
- Unfortunately **active cooling** requires **~300 C temperature drop** between absorber and cooling liquid.
- **To be safe**: **-** focus on **FEA analysis** of **3m Absorber** with Active Cooling System and Irradiation.