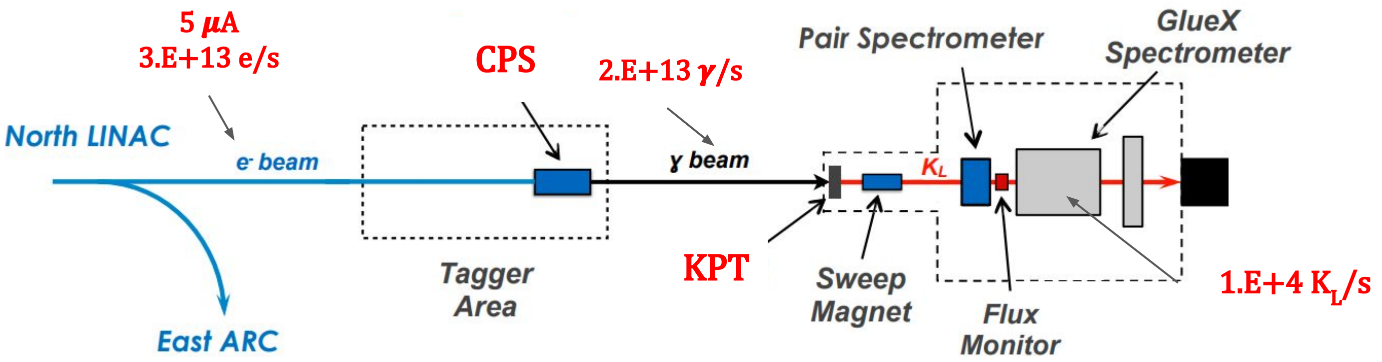
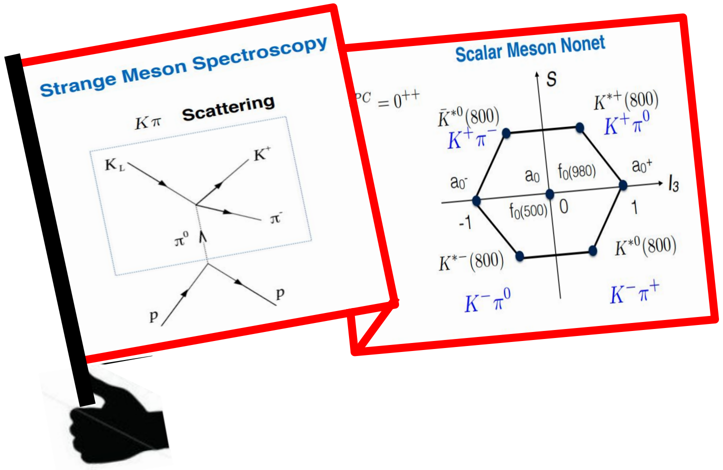
Compact Photon Source and K_L Beam for Hall D.





Strange Hadron Spectroscopy with Secondary KL beam in Hall D

Moskov Amaryan

Old Dominion University
Norfolk, VA, USA

KLF Collaboration Meeting, Feb. 12, 2020 at JLab

The FLUKA Simulations for K-long beamline in Hall D.

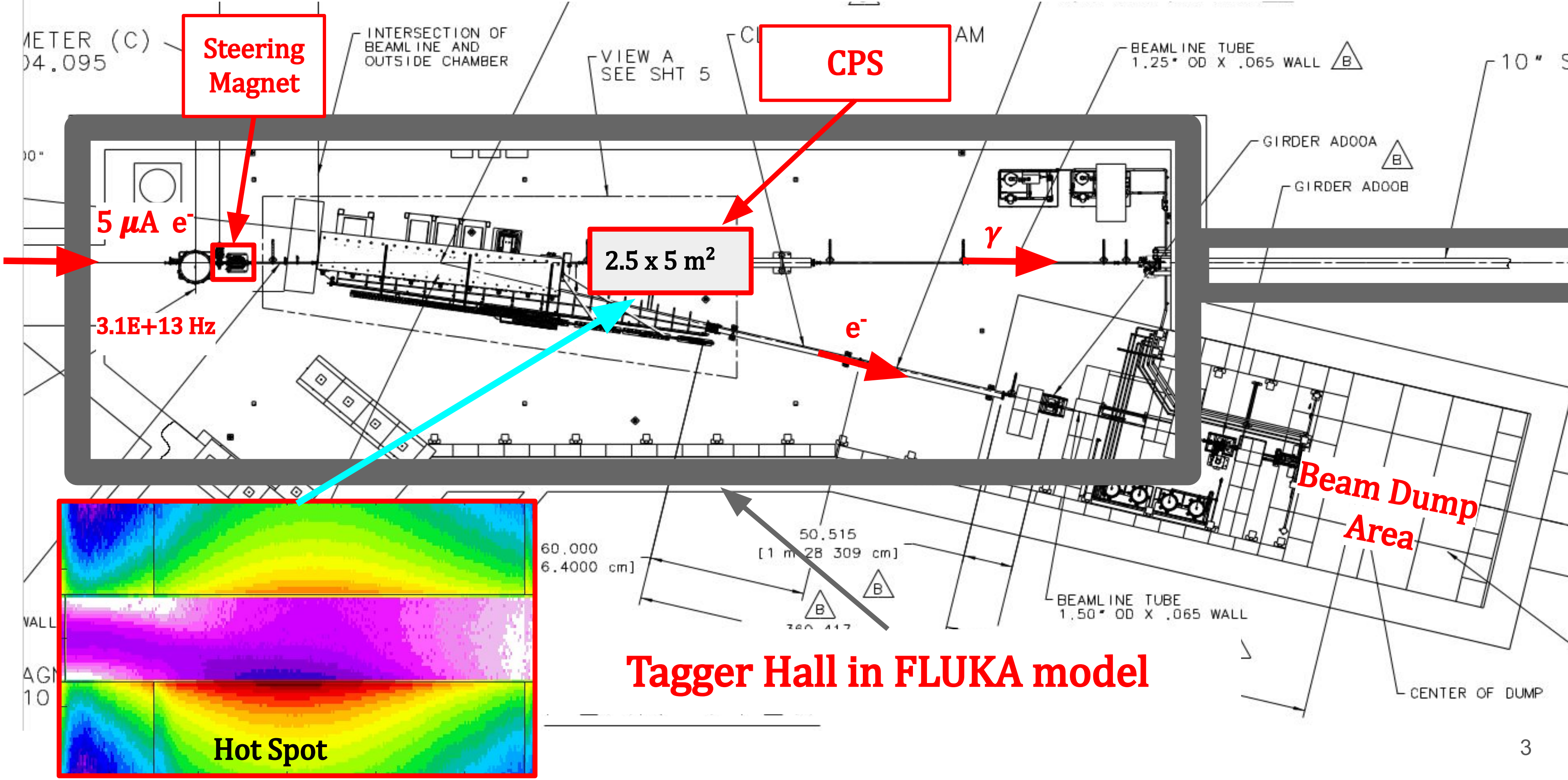
Electron beam 12 GeV , 5 μA ($3.1\times10^{+13}$ s^{-1}), FWHM=2.5 mm.

For KLF Collaboration
V. Baturin , Old Dominion University, Norfolk,VA
03/02/2023.

Outline

1. **CPS** and **KPT** in FLUKA model. Location, Design, Alignment .
2. **Radiation** and **Temperature** inside **CPS**.
3. Photon **Beam Quality**.
4. **Radiation** in CPS **Magnet** and its **Lifetime**.
5. Prompt **Dose and Activation** around CPS.
6. Tritium **Contamination** in Soil and Cooling Waters.
7. **Lifetime of** construction **materials**.
8. Conclusion and Outlook.

CPS location in Tagger Hall. Beam 5 μA , Gaussian, FWHM=2.5 mm.



Steering Magnet

CPS

5 μA e^-

3.1E+13 Hz

2.5 x 5 m^2

γ

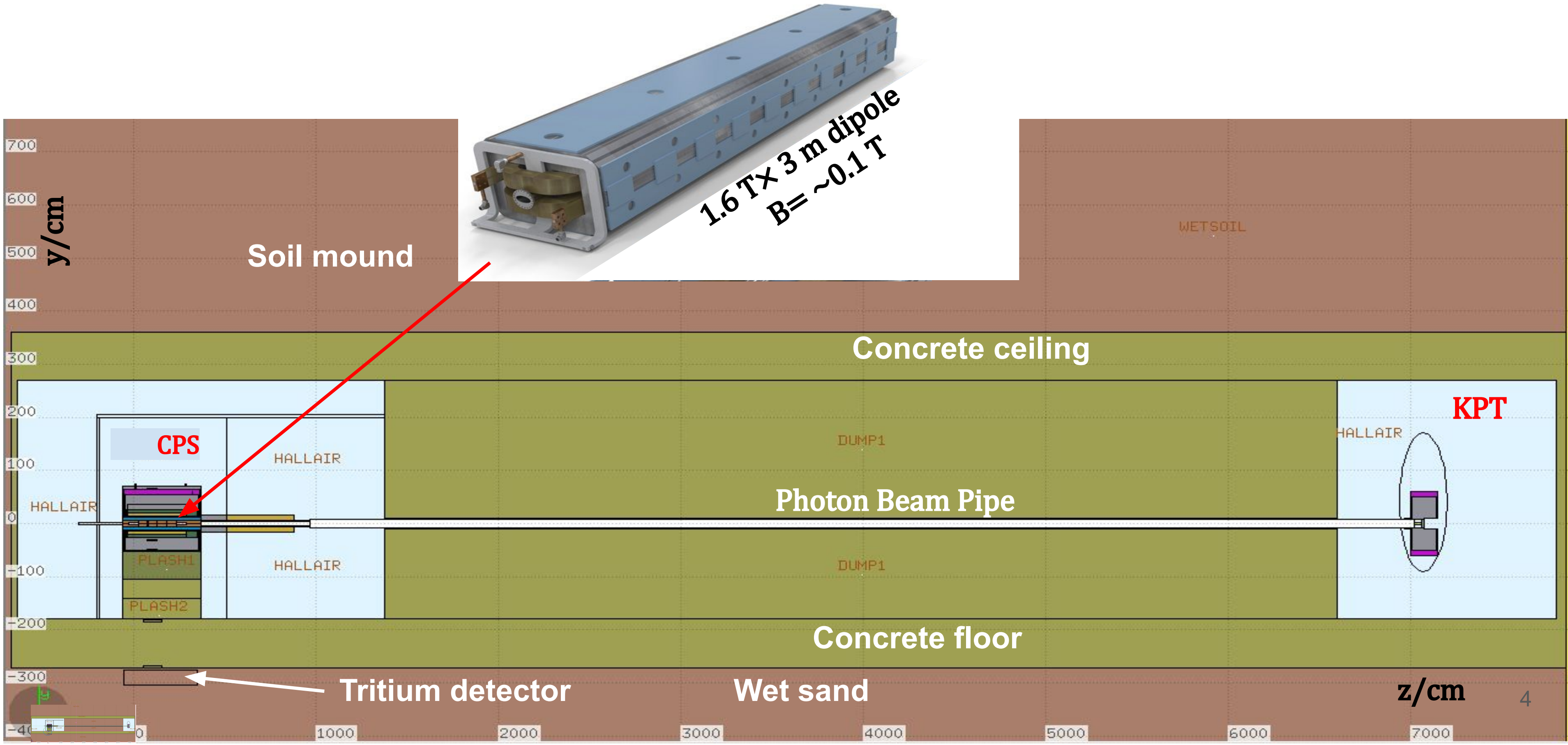
e^-

Beam Dump Area

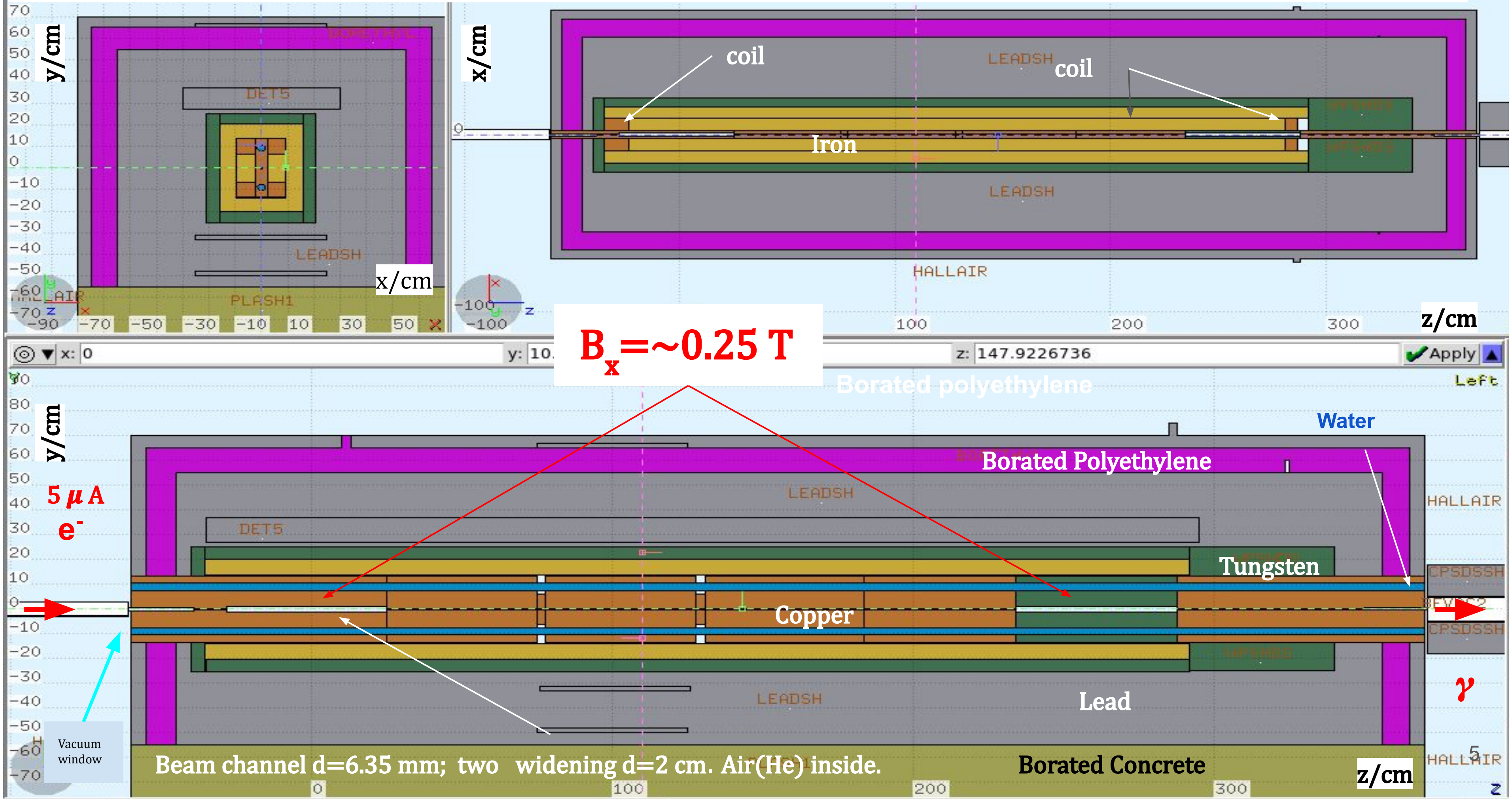
Hot Spot

Tagger Hall in FLUKA model

CPS, Tagger Hall, KPT and Magnet Prototype in FLUKA model.



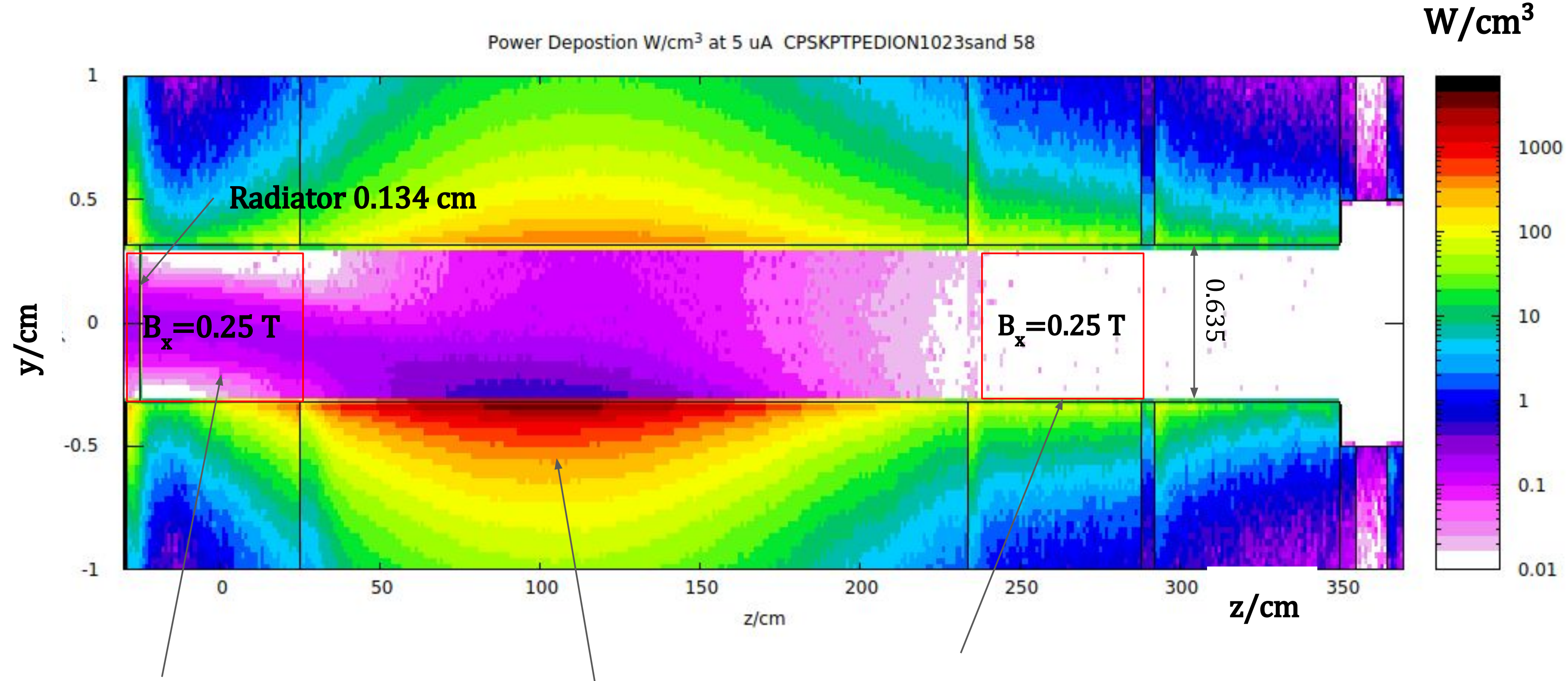
CPS in FLUKA: Magnet Yoke/platform, Two Coils, Cu Absorber, and 4 shield layers.



B_x=~0.25 T

Beam channel d=6.35 mm; two widening d=2 cm. Air(He) inside.

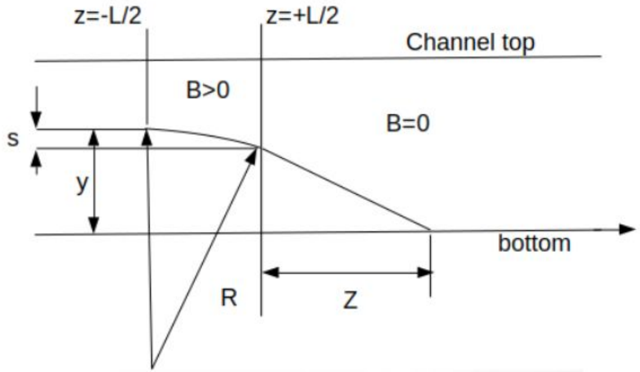
Source of radiation. Hot spot in the absorber. Power deposition



- Upstream magnet forms the Hot Spot; Downstream - cleans the photon beam.
- The **wider is** the Hot Spot - **the lower** is deposited power/temperature in the maximum.

Magnetic Field, Beam Channel, and Hot Spot Size.

Effect of vacuum pipe window and of air inside CPS beam channel



y-**electron** entry **coordinate**.
R-**trajectory** radius , R ∝ B^{-1}.
z -counts from **L/2** - **coil area** length, where B>0.
z'-counts from z=0.
L_M - length of **Beam Channel and Absorber**.
<z'>=$L_M/2$ is constrained to be in the middle of Channel.

From two triangles on this figure we find:

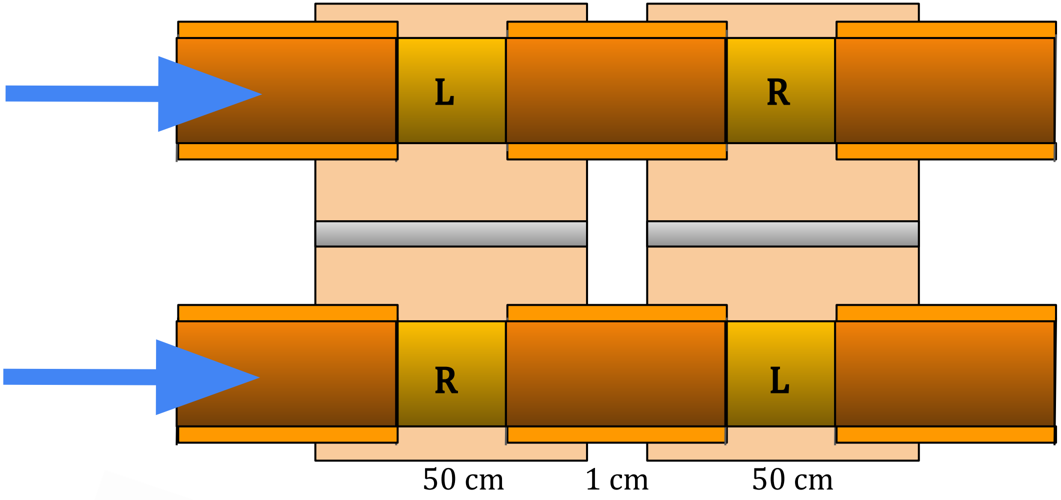
$$(R-s)^2+L^2=R^2, \quad => \quad s\approx\frac{L^2}{2R},$$
$$\frac{L}{R-y}=\frac{y-s}{z},$$
$$z\approx\frac{R}{L}(y-s)=\frac{R}{L}y-\frac{L}{2},$$
$$<z'>\approx<y>\frac{R}{L},$$
$$\mathrm{rms}(z')\approx\mathrm{rms}(y)\frac{R}{L}=<z'>\frac{\mathrm{rms}(y)}{<y>}.$$

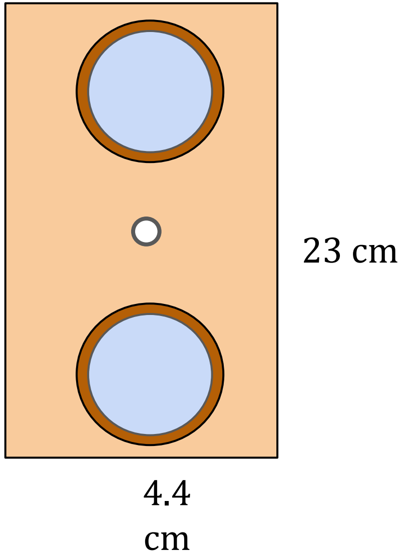
$$\mathrm{rms}(z')=2<z'>\frac{\mathrm{rms}(y)}{d}=\frac{L_M}{d}\mathrm{rms}(y)$$

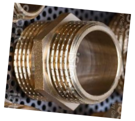
- At given **rms(y)** and **channel length L_M** for a **lower power** deposition and temperature **reduce** channel diameter.
- However, keep $d > d_{min}$ =~2 **rms(y),** otherwise beam tail hits the Channel.

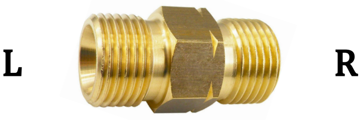
CPS Absorber
and
Alignment.

Segmented Copper Absorber - possible solution.



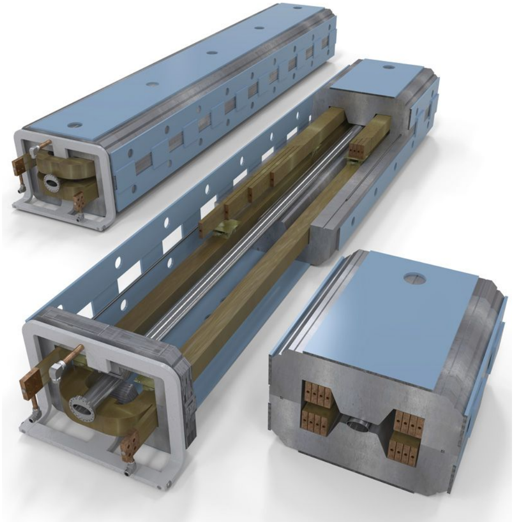




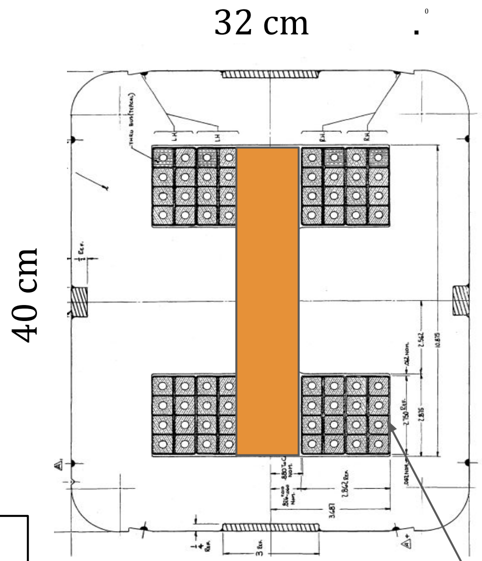


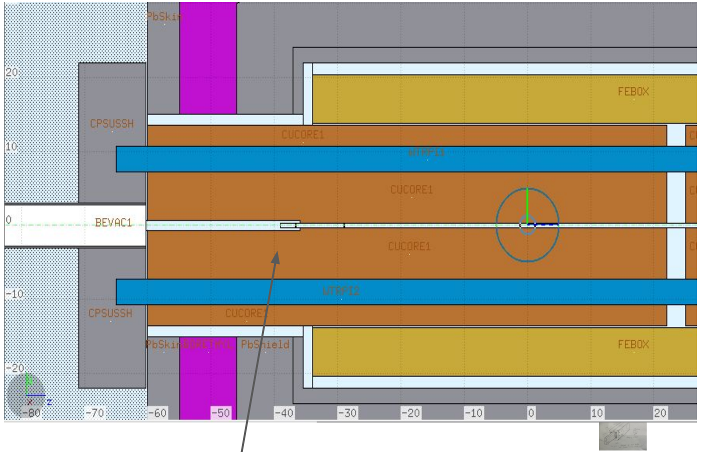
- Segments ~4.4×20×50 cm^3, **round** beam **hole.** => Edvantage compared square holes.
- (1) No problem of **thermal contact** between 2 parts (if squared hole) and (2) may be **vacuumized**.
- Segments are connected by fittings with **left/right-**hand threads; may be **brazed**.
- Provides direct **copper-water contact** inside segments: => no interface; **better cooling**.

Magnet Yoke as Precise Platform for Absorber



Fermilab Beamline Dipole 1.6×3 Tm,
I_{max} =1.8 kA, Cooling ~20 kW.

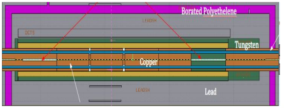




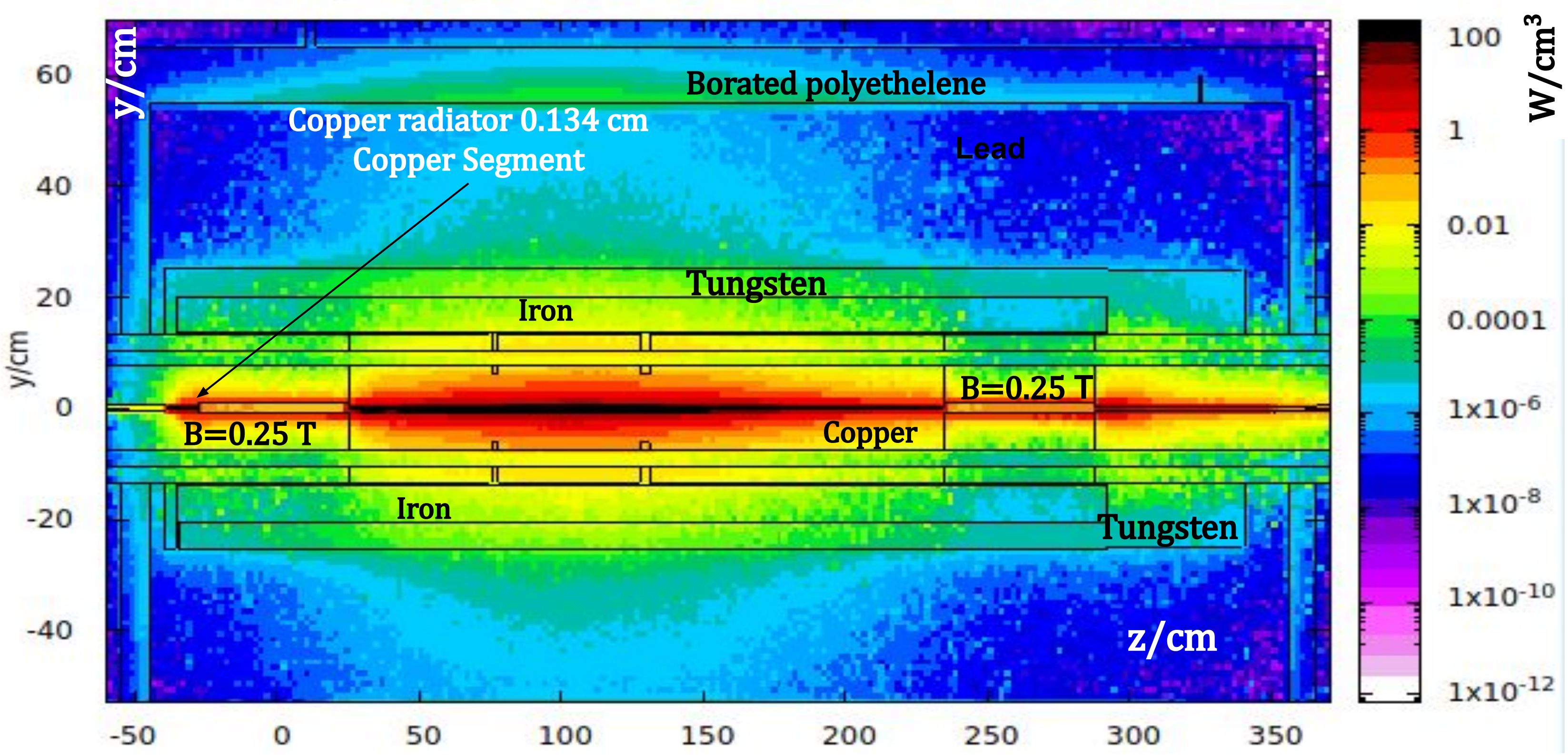
B=1.6 T - 16 wires 1.7×1.7 cm^2
B≤0.6 T - 6 wires.

1. **<u>Iron shield</u>** and **precision <u>platform</u>** for Absorber. Specified **flatness** within **500 μm.**
2. **<u>Housing</u> for all parts** with narrow beam channels, **including protruded segments.**
3. **<u>Precision Assembling</u>** at a bench and **in-hall <u>Alignment</u> with 5 DOF** only.

Energy deposition
and
Temperature of CPS components.



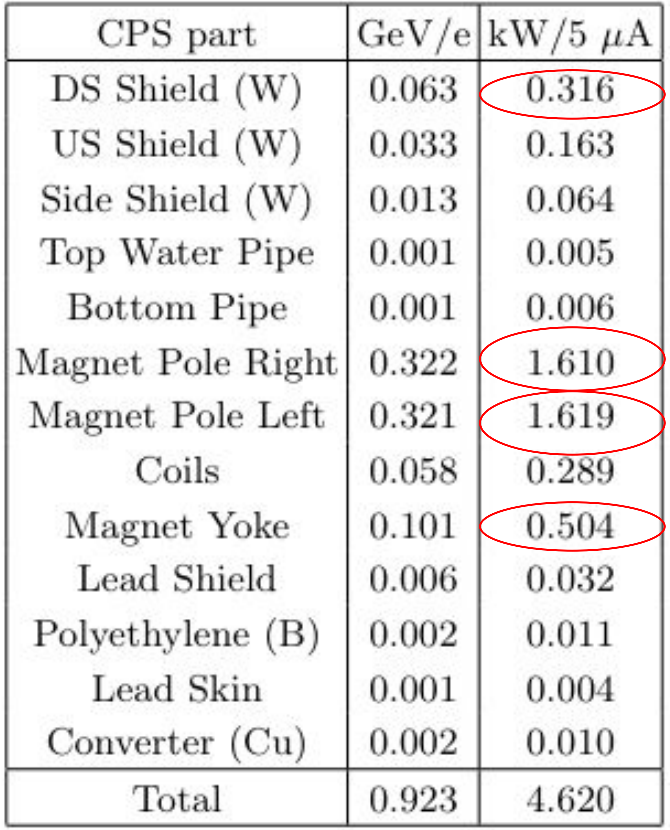
Power Deposition in -0.5<x/cm<0.5 layer. Coarse mesh 0.5 cm.



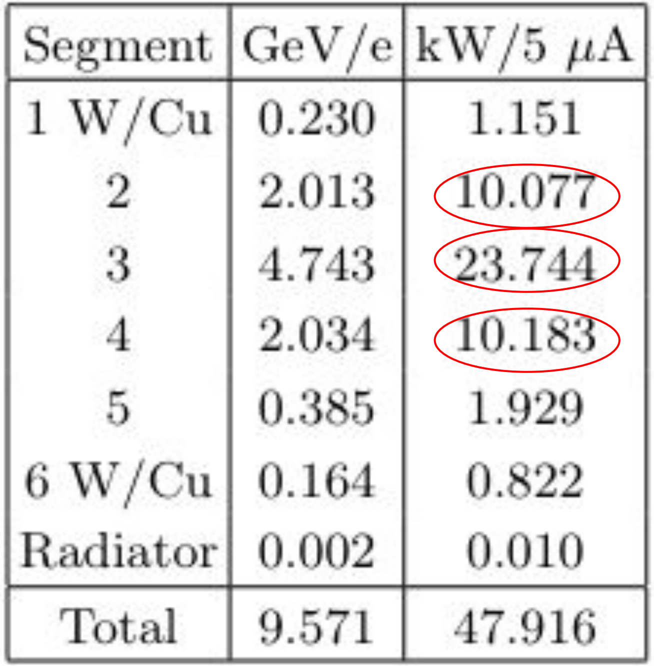
- Protruding **copper segment** around Radiator to mitigate lead overheating.
- T°-calculations **in progress**. Channel widening in coil area - to **reduce dose** rates.

```
[baturin@hallal1 PEDFASTGUN4]$ ls -lt *.inp | grep or
-rw-r--r-- 1 baturin clas 49936 Feb  9 11:07 CPSKPTLEAD1712narrGUNvacTRP_org.inp
```

Power breakdown between CPS components .



CPS part	GeV/e	kW/5 μA
DS Shield (W)	0.063	0.316
US Shield (W)	0.033	0.163
Side Shield (W)	0.013	0.064
Top Water Pipe	0.001	0.005
Bottom Pipe	0.001	0.006
Magnet Pole Right	0.322	1.610
Magnet Pole Left	0.321	1.619
Coils	0.058	0.289
Magnet Yoke	0.101	0.504
Lead Shield	0.006	0.032
Polyethylene (B)	0.002	0.011
Lead Skin	0.001	0.004
Converter (Cu)	0.002	0.010
Total	0.923	4.620

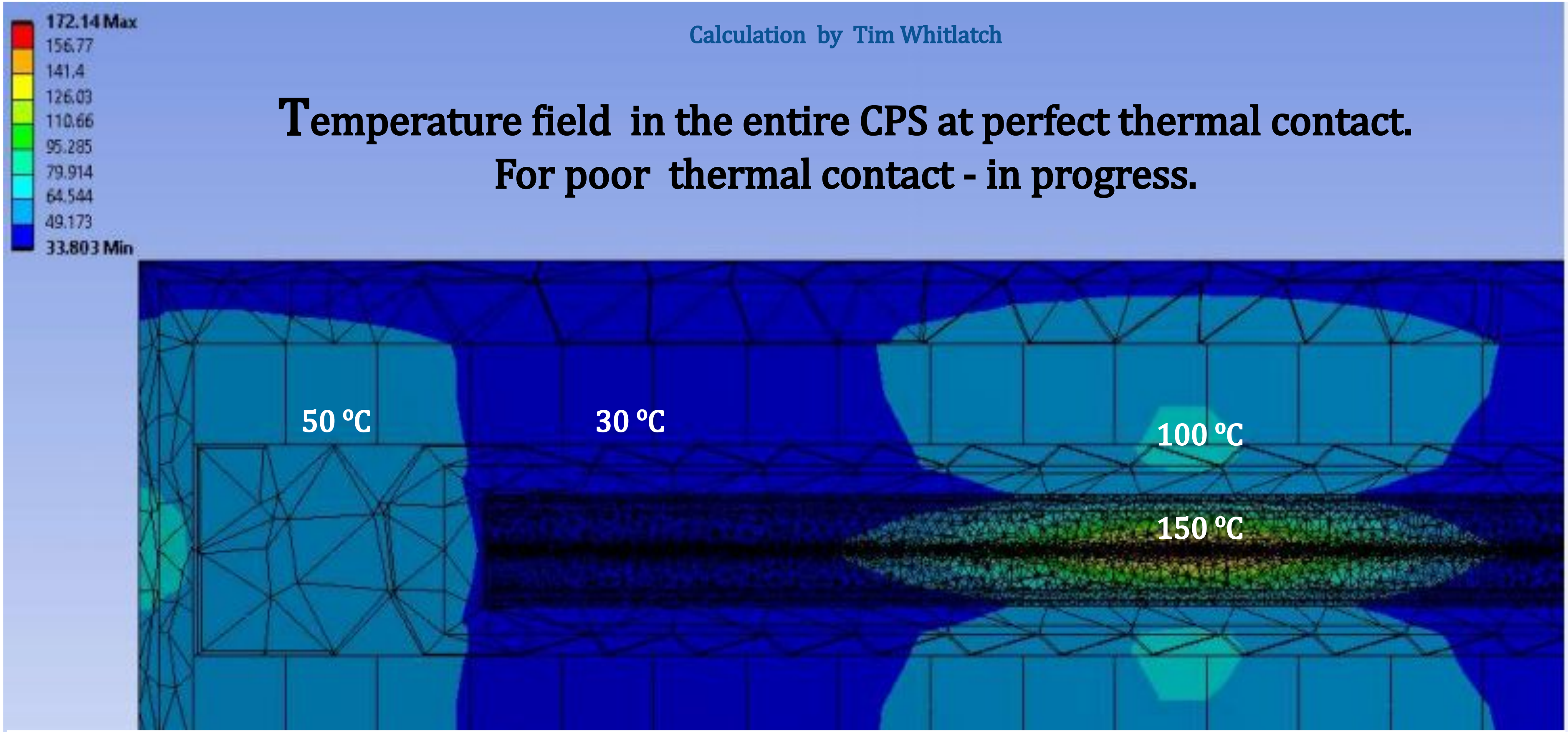


Segment	GeV/e	kW/5 μA
1 W/Cu	0.230	1.151
2	2.013	10.077
3	4.743	23.744
4	2.034	10.183
5	0.385	1.929
6 W/Cu	0.164	0.822
Radiator	0.002	0.010
Total	9.571	47.916

- **Total deposition 53 kW out of 60 kW of e-beam.**

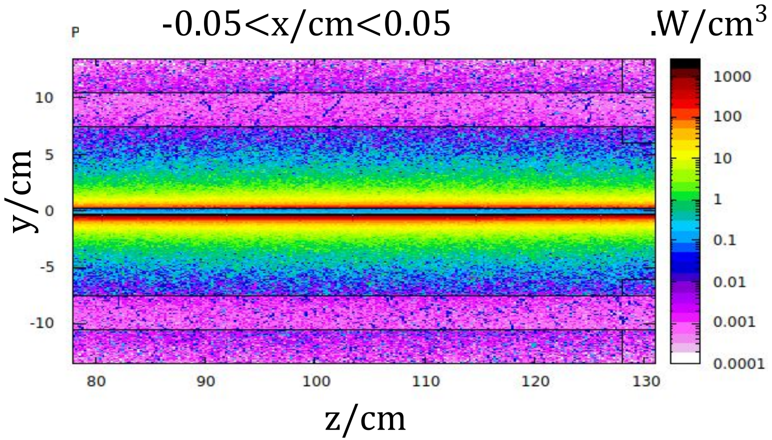
Calculation by Tim Whitlatch

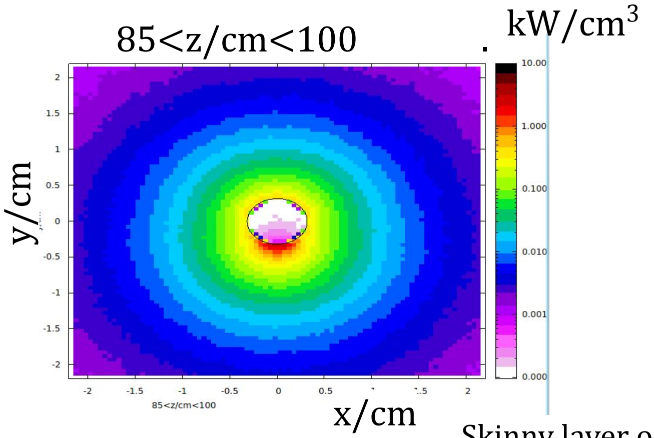
Temperature field in the entire CPS at perfect thermal contact. For poor thermal contact - in progress.

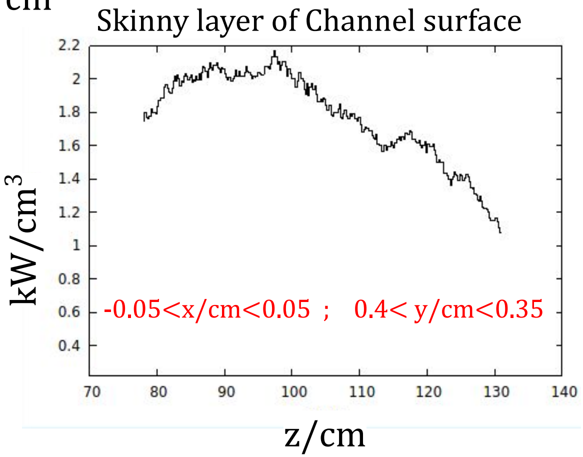


- **Copper (T_m=1084° C)** in Absorber Channel **does not melt**: **T< 250° C .**
- **Lead (T_m=327° C) and Iron (T_m=1538° C) temperatures - below melting points: T<100° C ? and 150° C.**

Power Deposition in Hot Segment . Fine mesh 0.05 cm



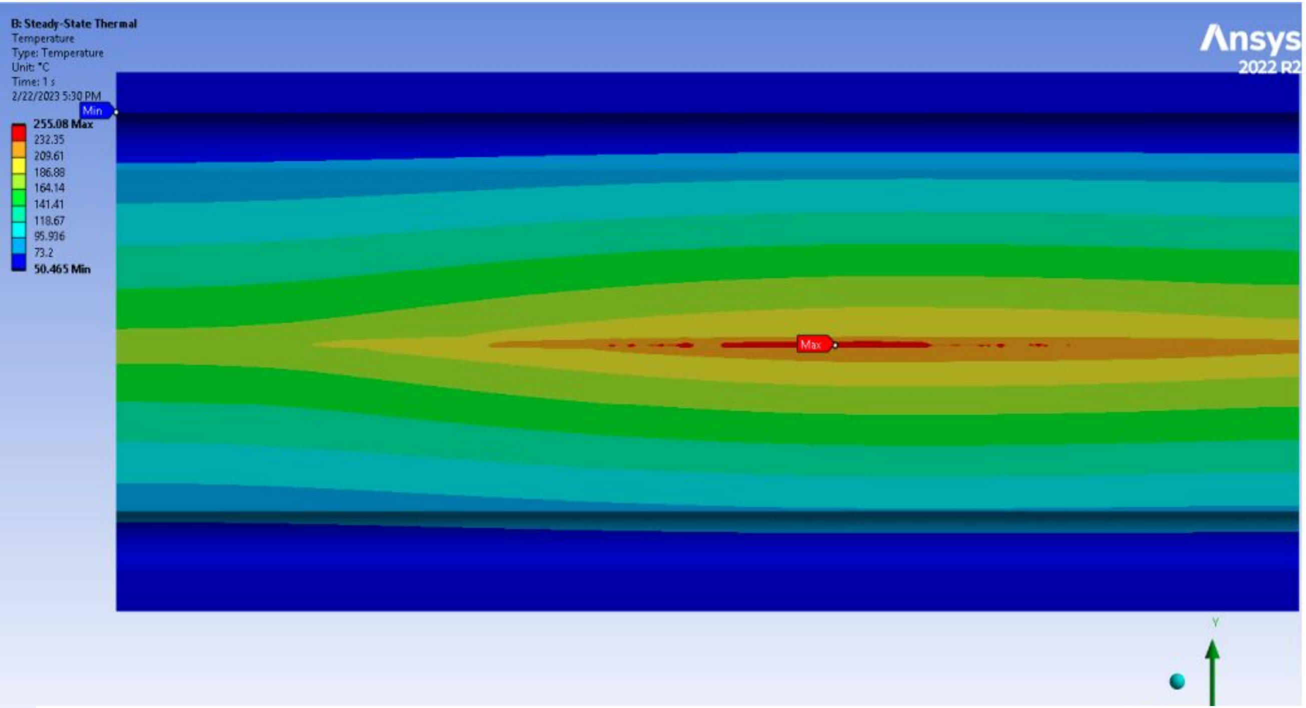


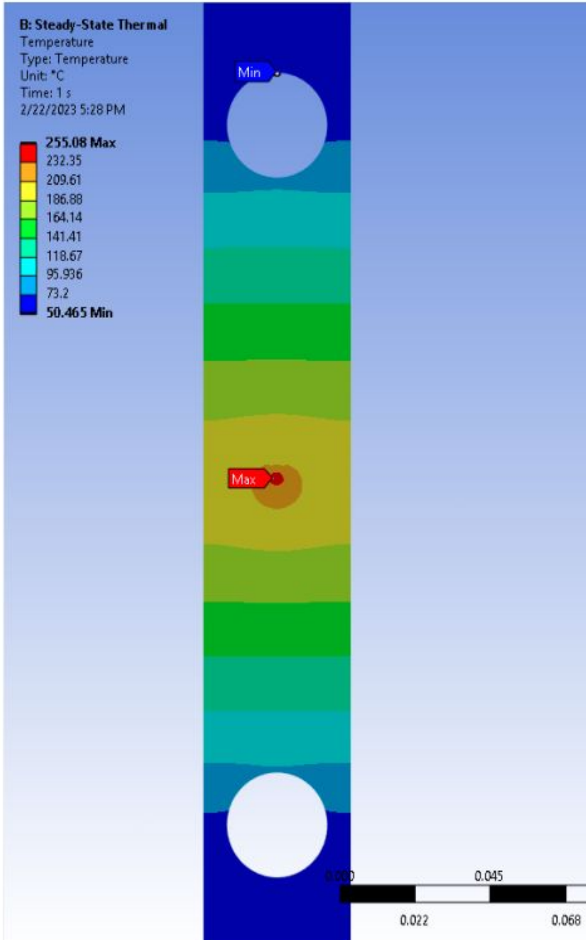


- Maximum **dP/dV = ~2 kW/cm^3**
- **Temperature calculations** are done by Tim Whitlatch (JLab) using ANSYS and this Power Deposition Map.

Calculation by Tim Whitlatch

Temperature field in the Hot Segment at Heat Transfer Coefficient 9 kW/m^{2}C.



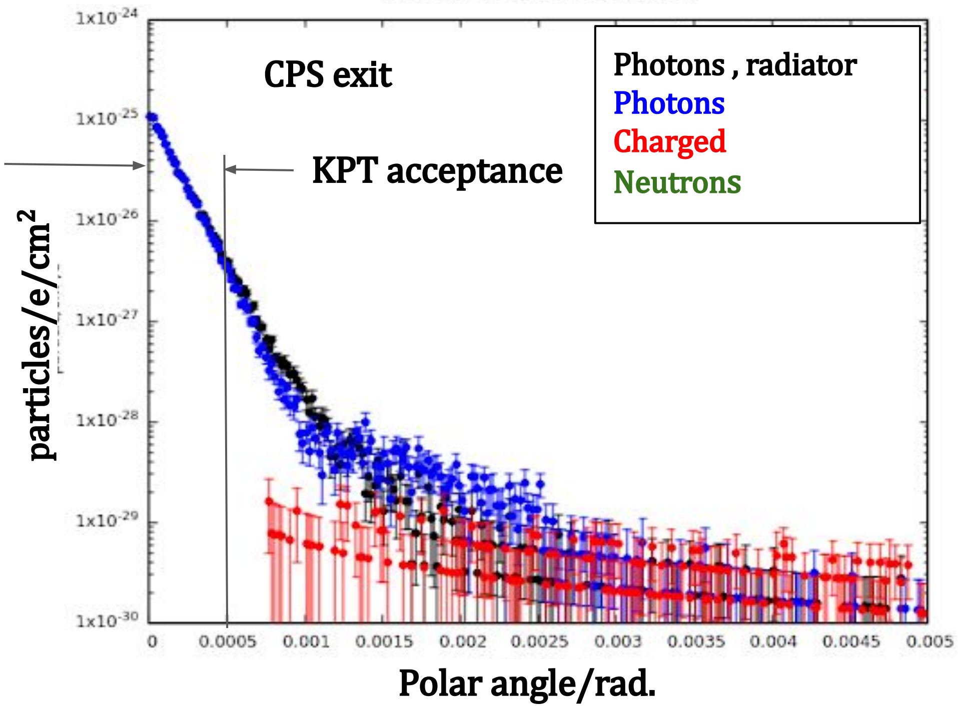


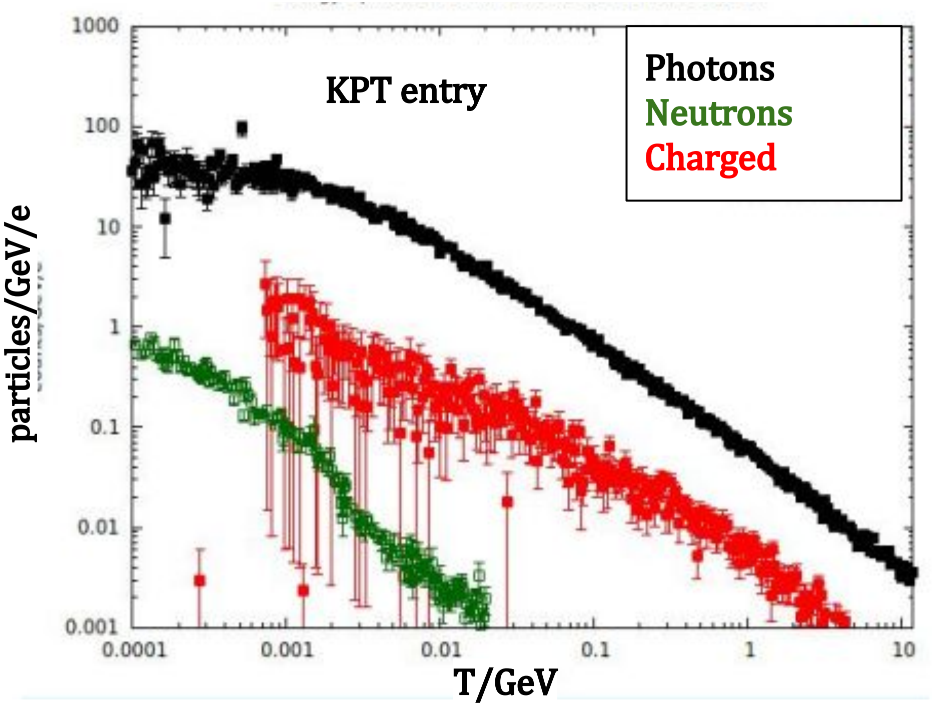
“Hot” Absorber (Cu), 53 cm long, 6.35mm Beam Hole with Air,
30 mm Water Channel (**9 kW/m^2 C**) evacuates 29 kW at **T_{water}~40 °C.**

- **Maximum Copper Temperature 255 °C (melts at 1,084 °C).**

Photon Beam Quality at KPT

Particles exiting from the CPS . Angular profile.

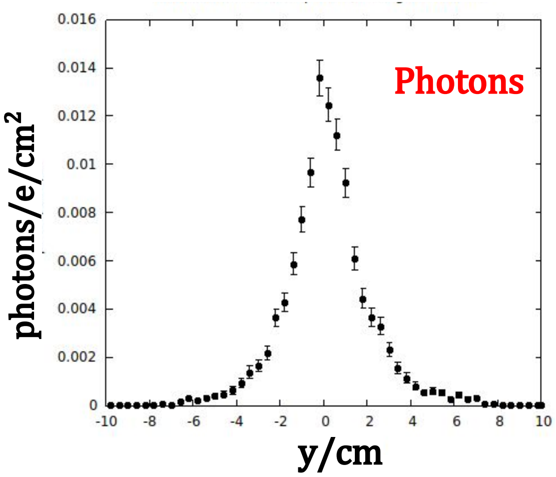




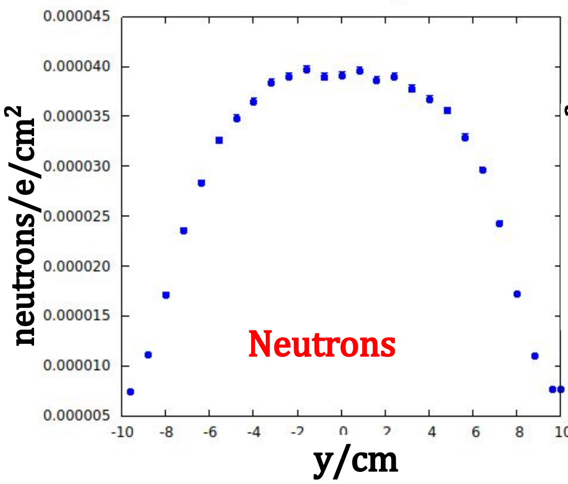
- Photon beam at the CPS exit **looks very clean** (< 1.E-3). Left plot.
- What happens to the beam **after 67 m of beam line?** - Right plot.

Beam quality at KPT.

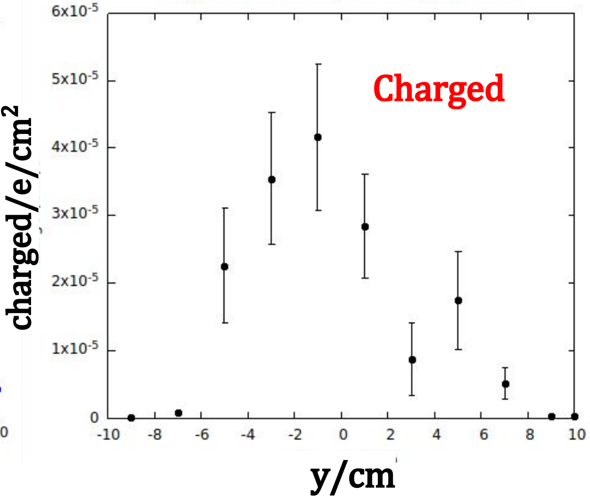
S=0.91 γ/e



S=1.2E-2 n/e

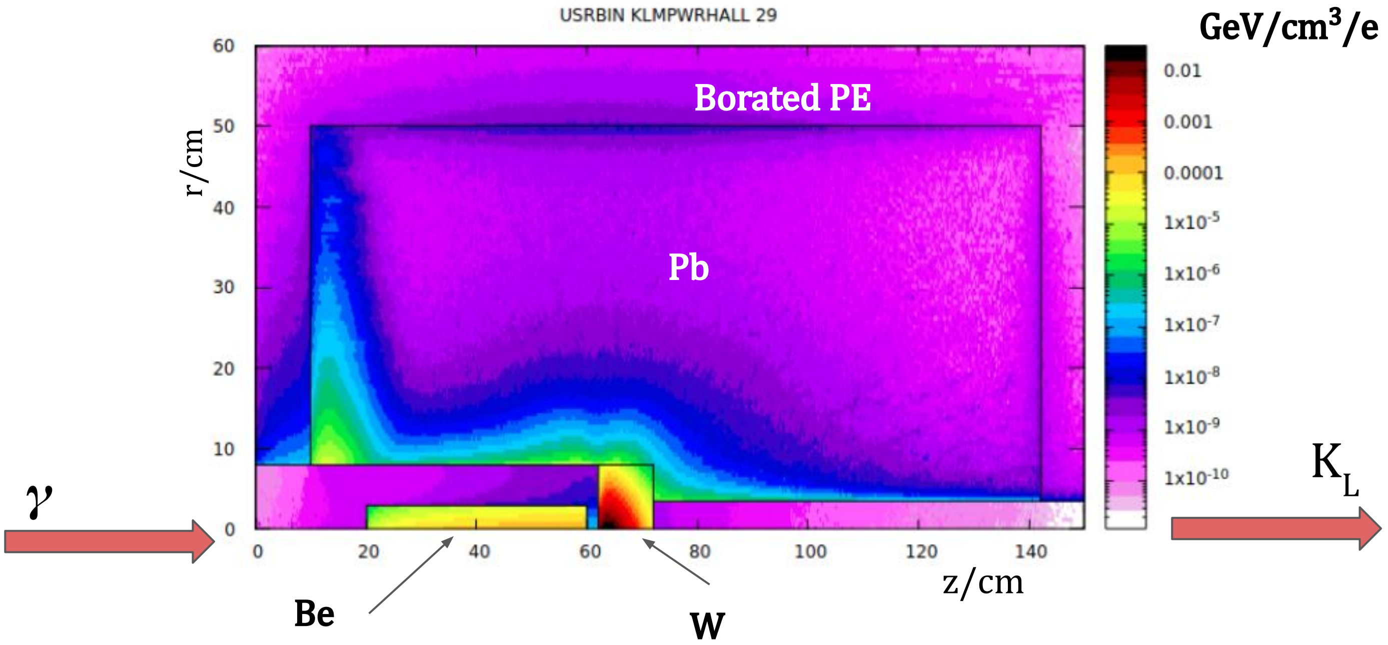


S=0.6E-2 e-1



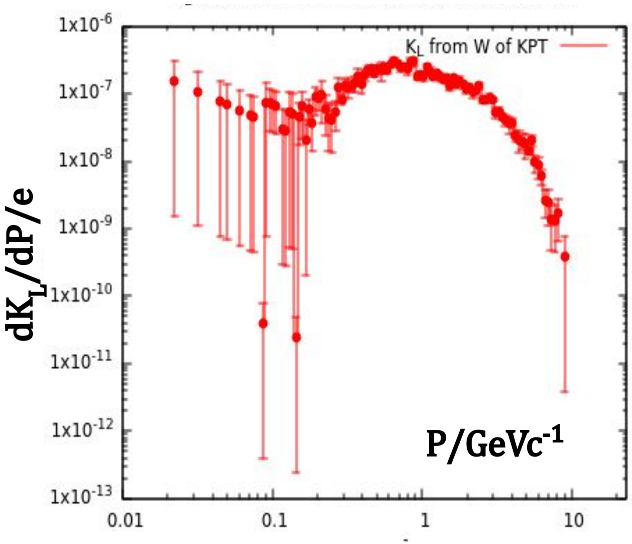
- **After 67 m of beam line** the total **background** of charged particles and neutrons is of **2. %.**
- Be target acceptance r=2.5 cm; => **80%** of photon beam hits the Be target of KPT.
- Photon beam **intensity at KPT entry ~ 2.8 E+13 photons/s.**

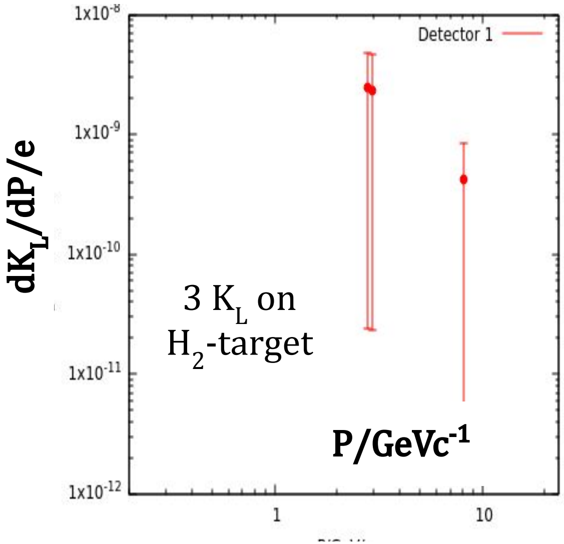
Energy deposition in KPT. Effect of photon beam.



- T^{o}-field is **calculated** using this map and **cooling** system **designed** by T. Whitlatch.

K_L from KPT and on H_2-target of GlueX detector.





- K_L beam **intensity** on H_2-target ($\Delta\Omega = 1.3$E-3 sr) is not a primary goal.
- From the right plot we may estimate it on H_2 target: **$dK_L/dt \sim 10^4$ Hz.**
- **Agrees** with the **KLF proposal**.

Radiation in CPS Magnet

and

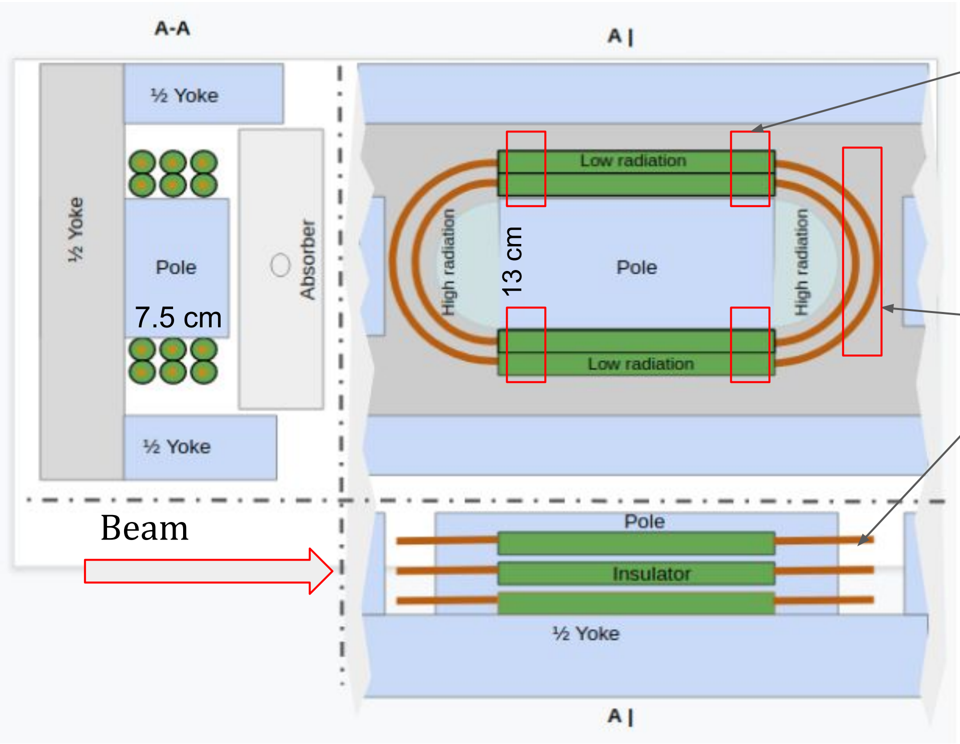
Coil insulation lifetime.

For a closed shielding can : $S = 4/3\ \mu\, t/D$ where μ - the permeability (relative) t : material thickness D : Shielding Diameter.

For a long hollow cylinder in a magnetic transverse field : $S = \mu\, t/D$.

For a cubic shielding box : $S = 4/5\ \mu\, t/a$; a - box side length.

Coil Design and Insulation Exposure to Radiation.



Hot area for insulation.

Very hot area,

Air insulation,

Gap between

wires

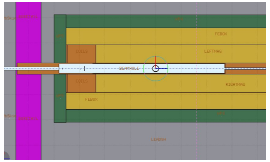
~8 mm.

Ampere's force law:

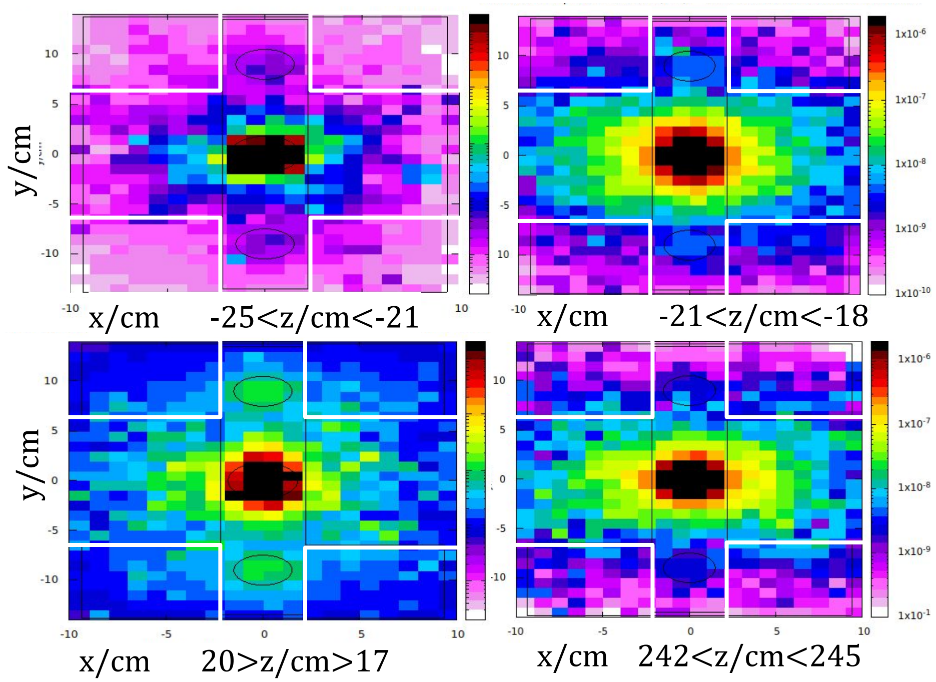
$dF/dl = (\mu_o / 2\pi)\ (I^2/d) = \sim 25\ N/m$

at $I = 1800\ A$; $d = 2.5\ cm$; $\mu_o = 4\pi E\text{-}7\ N/A^2$

- **Attractive force of bent parts F = 25 N/m* 0.3 m = 7.5 N.**
- **Copper 1.7 cm -wires (tubes) will not touch. Attractive deformation ~ 12 microns only!**

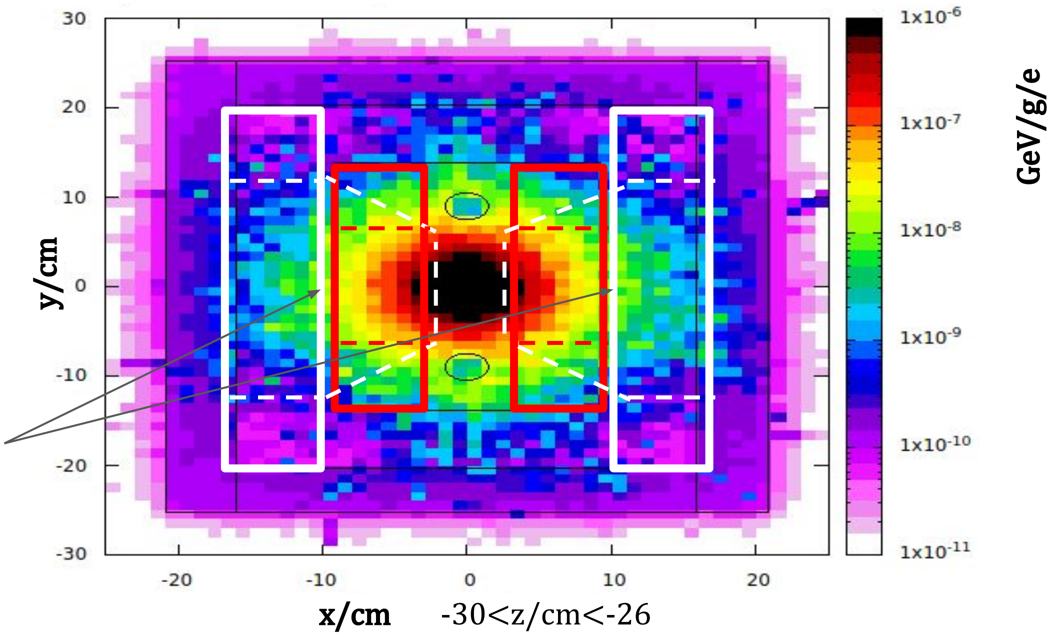


Prompt Dose in Coils and Insulation Lifetime (straight part).



- **Dose 2.E-8 GeV/g/e** ×1.6E-10 J/Gev=3.2E-18 Jg^{-1}e^{-1} =3.2E-15 Gy/e;
- **Translates** to 3.2E-15 [Gy/e]×3.E+13 [e/s] ≅ **0.1 [Gy/s]**.
- **Fiberglass** cloth withstands **50 MGy** => **Lifetime** =5.E+8 s **= 15 years.**
- Bent part dose rate is ~10 times higher.

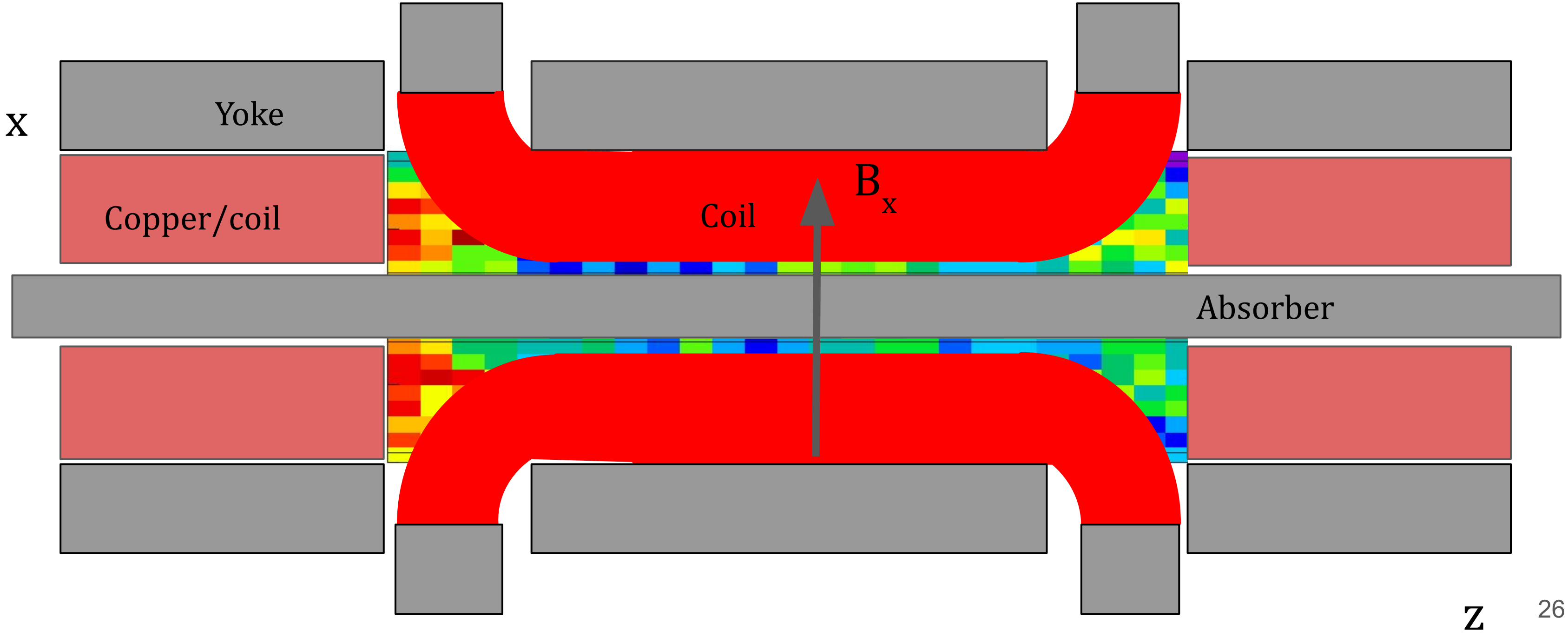
Benefit of wider magnet (+14 cm).



Critical points

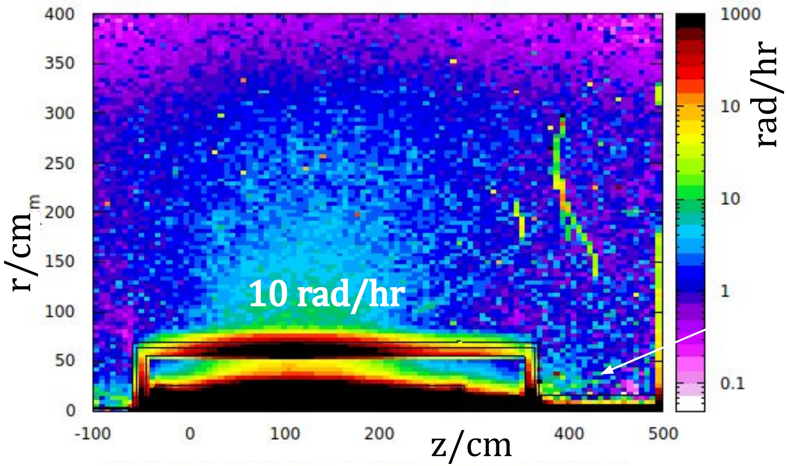
- Dose rate in critical points **0.1 Gy/s** (**2.E-8 GeV/g/e**).
- For 14 cm wider Magnet Insulation Lifetime in Coil return area is of **15 years.**

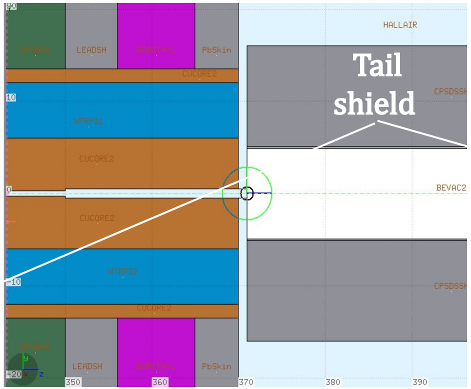
Tim Whitlatch's solution.

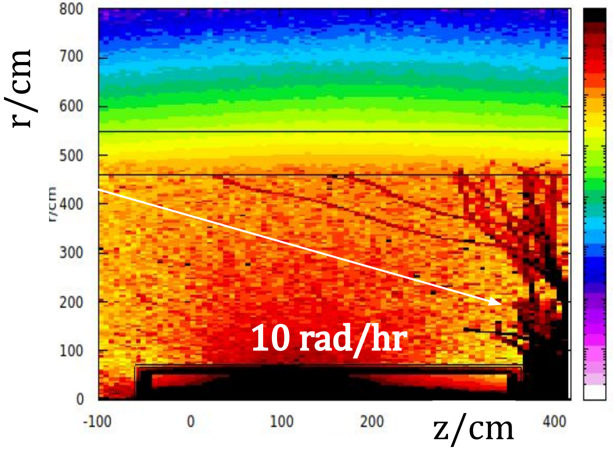


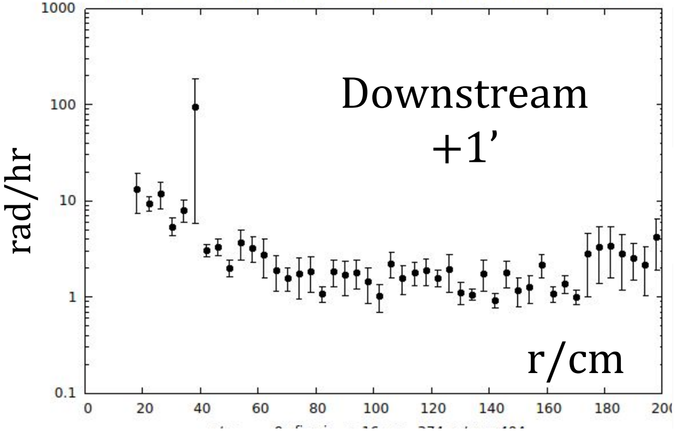
Prompt Dose (equipment)
and
Activation (human)
around CPS

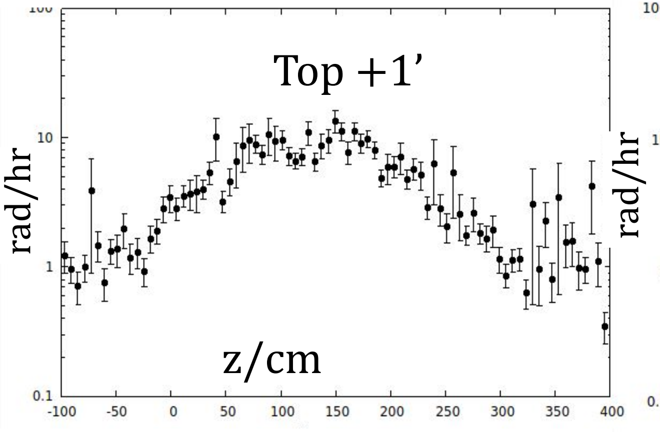
Prompt Dose Rate around CPS < 10 rad/hr . Effect of Tail shield .

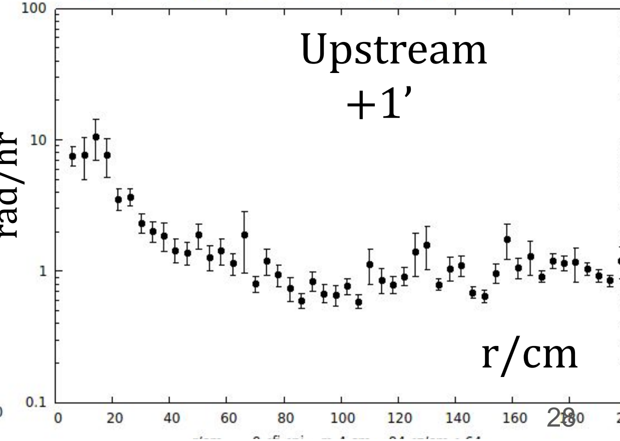


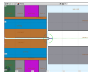




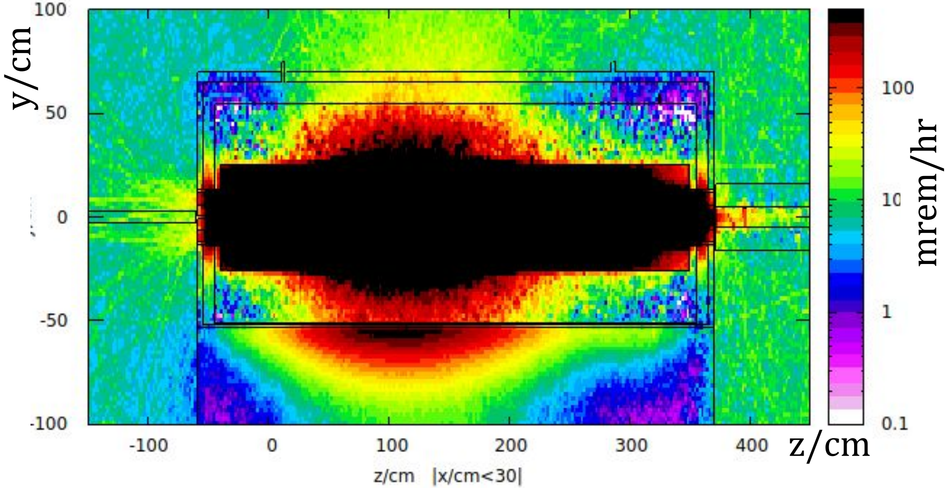


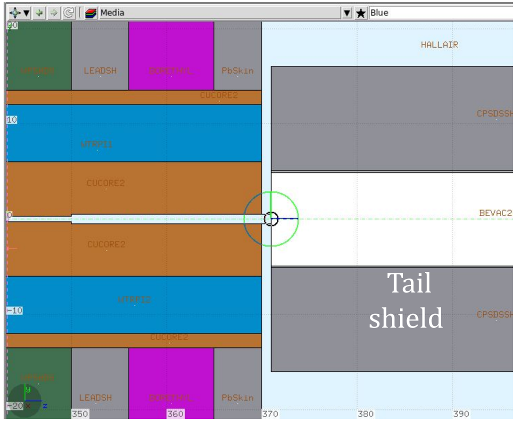




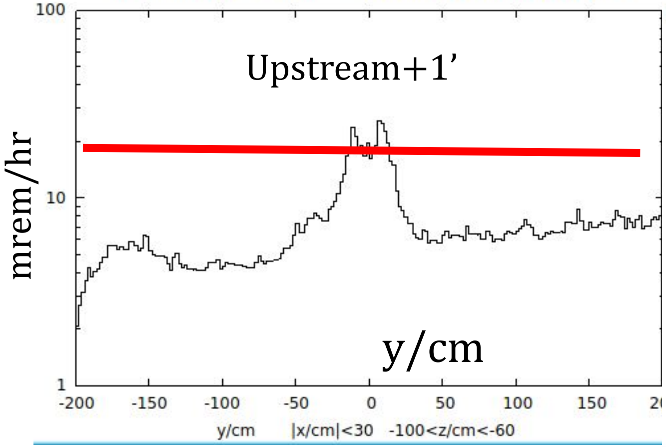


Activation After 1000+1 hr < 20 mrem/hr.

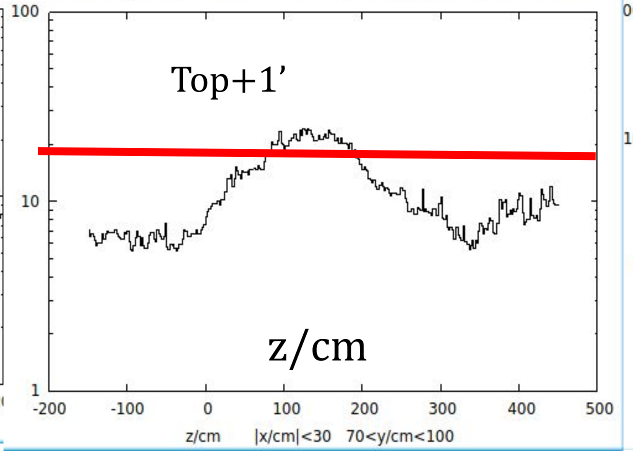




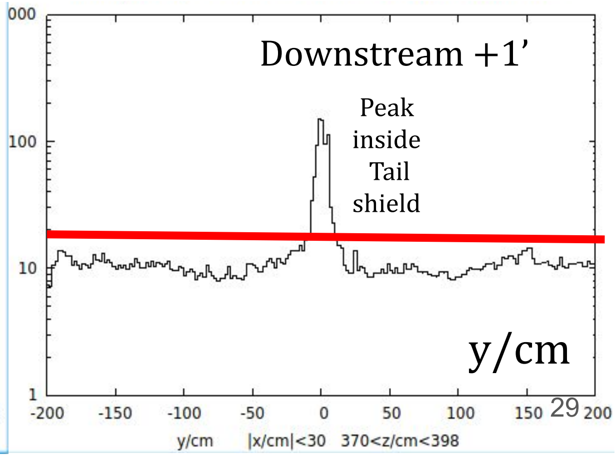
Tail shield



Upstream+1’



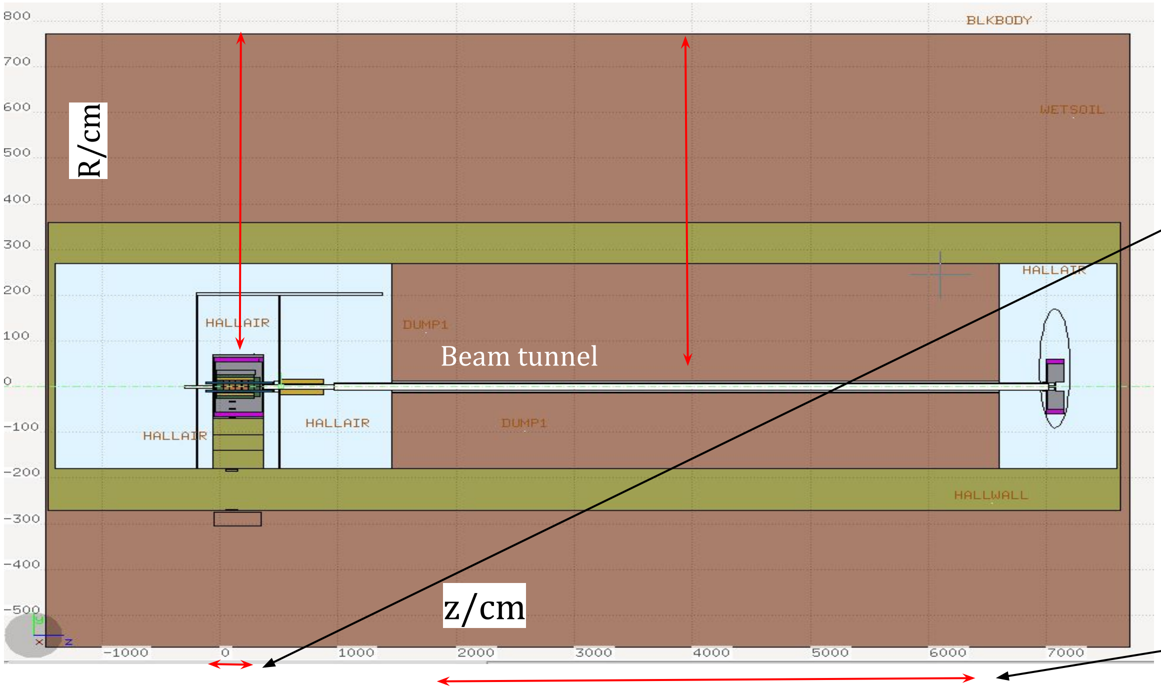
Top+1’

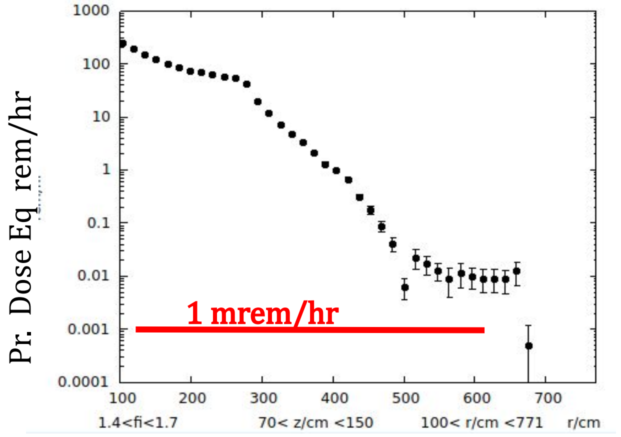


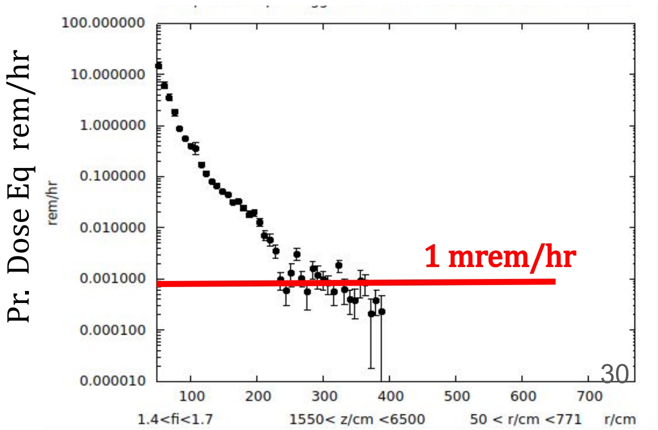
Downstream +1’

Peak inside Tail shield

Prompt Dose Equivalent on top of Tagger hall and Beam Channel.



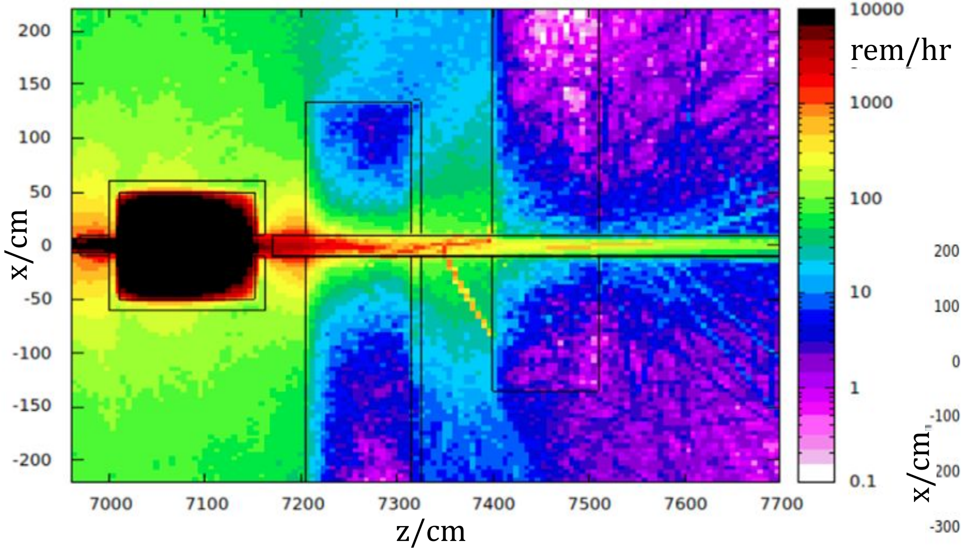




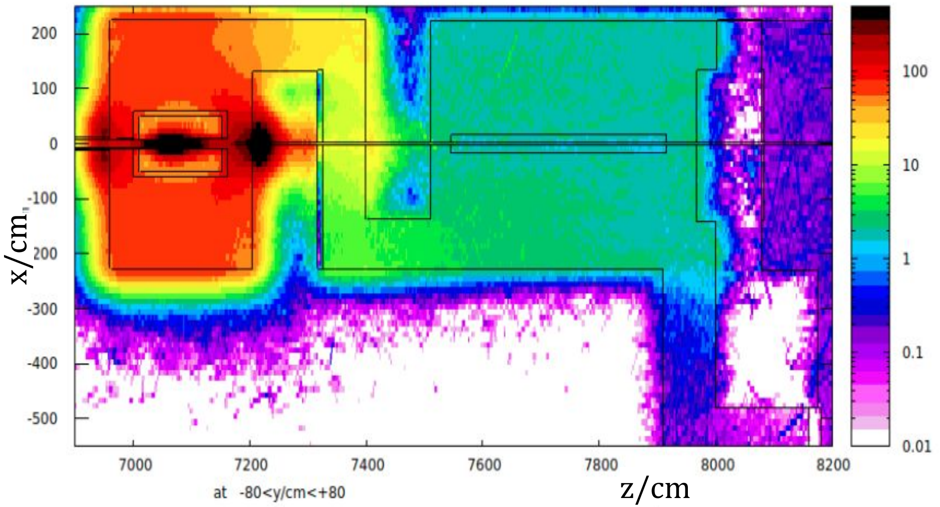
- Prompt DE is below **1 mrem/hr** at R = ~2.5 on top of Beam Tunnel.
- Prompt DE on top of hall mound R=7.7 m   below **1 mrem/hr.**

Prompt Dose Equivalent and Activation in KPT Alcove.

Prompt Dose Equivalent



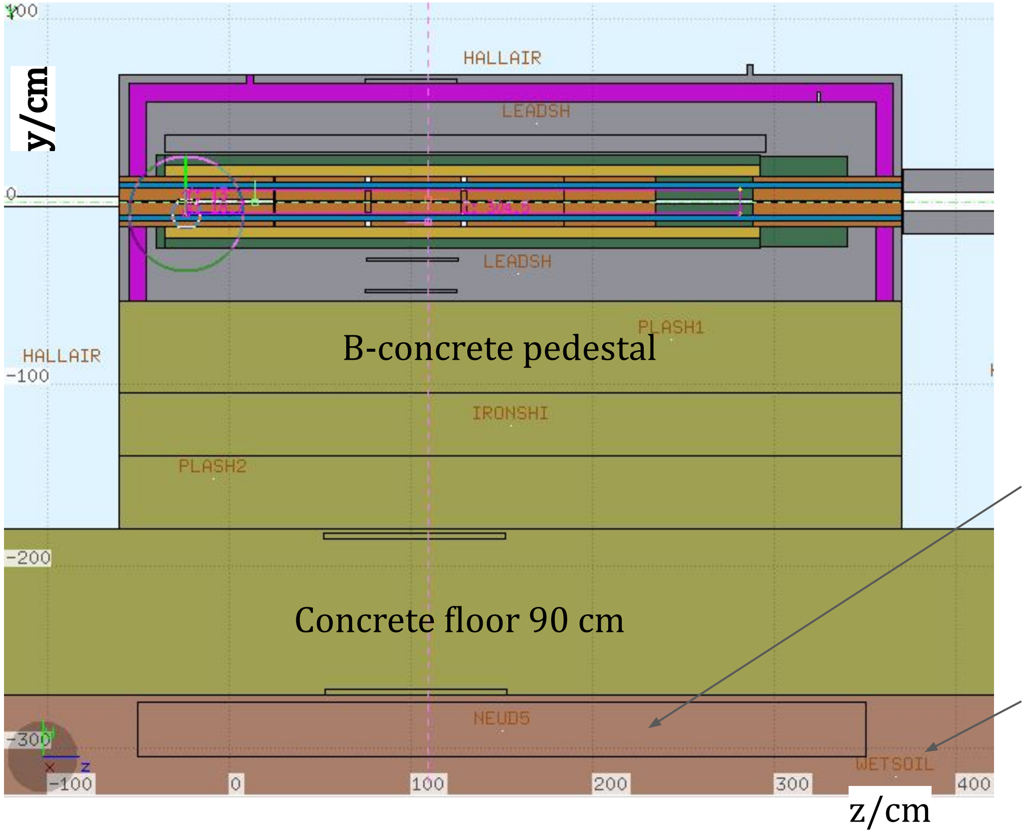
Activation: Dose Equivalent after 1000+1 hr



- Dose rates meet JLab radiation safety requirements.

Tritium activity in Soil
and
Cooling Water

Tritium detector in FLUKA model



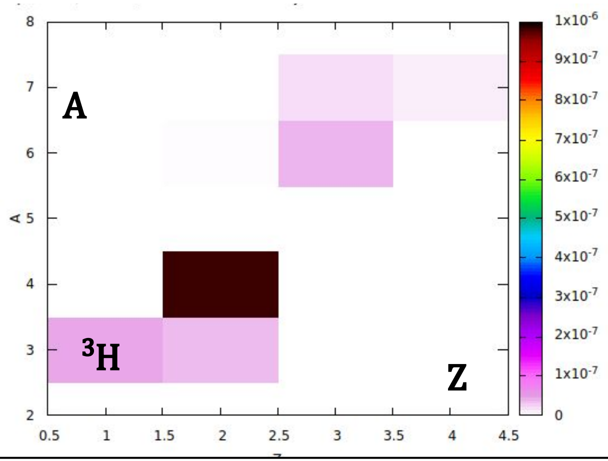
B-concrete pedestal

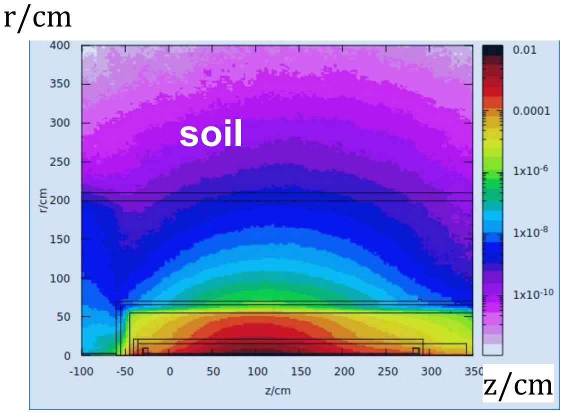
Concrete floor 90 cm

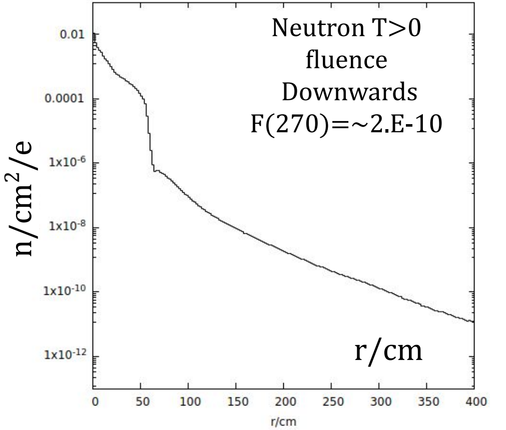
Tritium detector
$V=2*0.3*4\ m^3=$
$2.4\ m^3$

Soil.
Wet sand with 20% of water

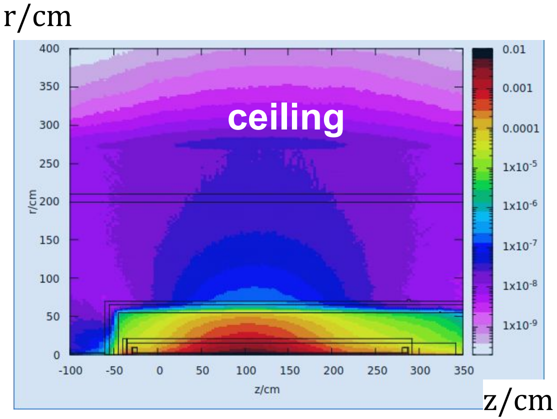
Neutron fluence and Tritium in ground waters (V=2.4 m^3).

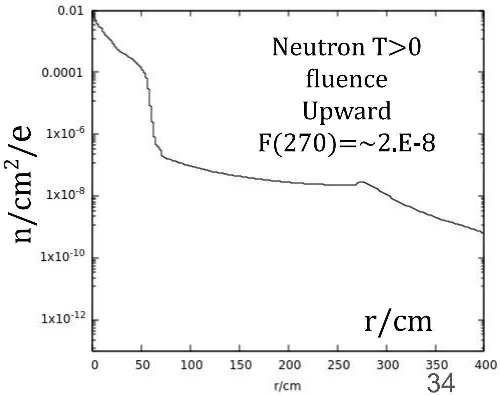






Neutron T>0
fluence
Downwards
F(270)=~2.E-10





Neutron T>0
fluence
Upward
F(270)=~2.E-8

^{3}H yield in V=2.4E+6 cm^3 **= 1.E-7 [T/e].**

^{3}H yield per year **N=**1.E-7 [T/e] 3.E+13 [e/s]3.14E+7[s] =**1.E+14.**

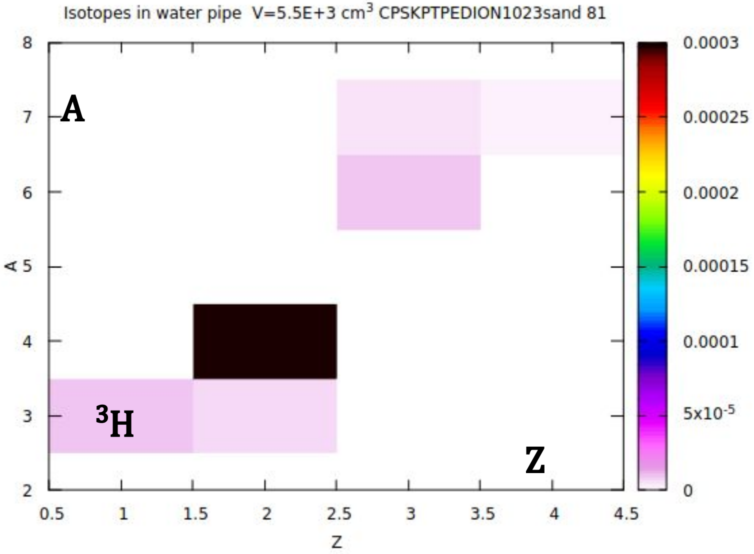
Activity of soil volume after one year:=

- dN/dt=1.E+14 / (12*3.14E+7 s) = **2.6E+4 Bq**

Or ~200 Bq/L in water (~20% by volume in soil).

- **Tritium activity in ground water is 3% of VA drink water limit 7000 Bq/L .**

Tritium in water of cooling pipes.



We read the yield of ^{3}H in the cooling water: **1.E-5 [T/e]**

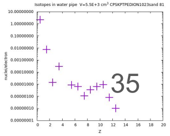
Number of T nuclei produced in one year: =

N_T=1.E-5 [T/e] 3.E+13 [e/s] 3.14E+7[s] =1.E+16 [T]

Actility:

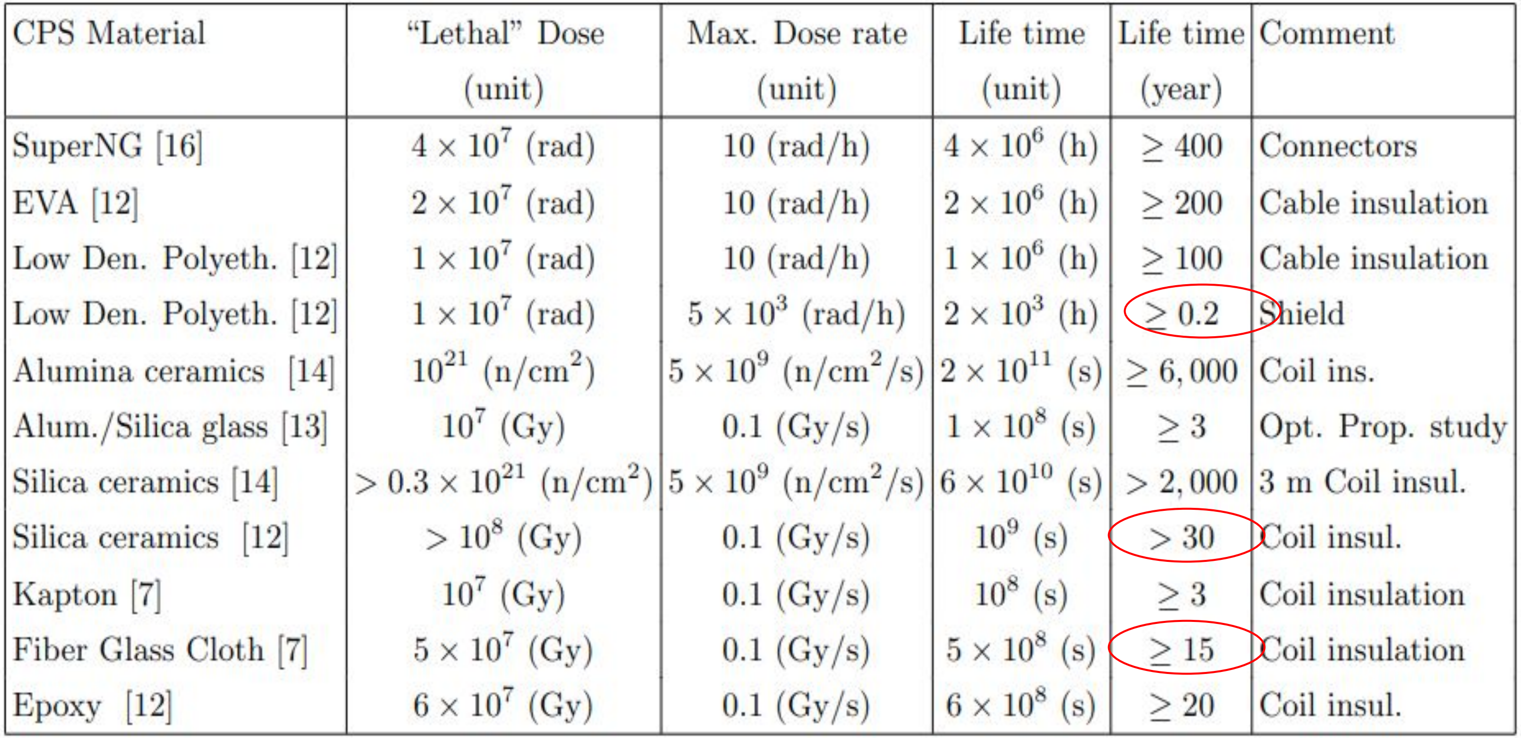
$-dN_T/dt$=1.E+16 / (12*3.14E+7 s) = **2.6 E+7 Bq**

- This amount of Tritium may be accumulated by tritium absorbers.



Lifetime of various materials from FLUKA simulations.

Material lifetime from FLUKA simulations



CPS Material	"Lethal" Dose (unit)	Max. Dose rate (unit)	Life time (unit)	Life time (year)	Comment
SuperNG [16]	4×10^7 (rad)	10 (rad/h)	4×10^6 (h)	≥ 400	Connectors
EVA [12]	2×10^7 (rad)	10 (rad/h)	2×10^6 (h)	≥ 200	Cable insulation
Low Den. Polyeth. [12]	1×10^7 (rad)	10 (rad/h)	1×10^6 (h)	≥ 100	Cable insulation
Low Den. Polyeth. [12]	1×10^7 (rad)	5×10^3 (rad/h)	2×10^3 (h)	≥ 0.2	Shield
Alumina ceramics [14]	10^{21} (n/cm^2)	5×10^9 (n/cm^2/s)	2×10^{11} (s)	$\geq 6,000$	Coil ins.
Alum./Silica glass [13]	10^7 (Gy)	0.1 (Gy/s)	1×10^8 (s)	≥ 3	Opt. Prop. study
Silica ceramics [14]	$> 0.3 \times 10^{21}$ (n/cm^2)	5×10^9 (n/cm^2/s)	6×10^{10} (s)	$> 2,000$	3 m Coil insul.
Silica ceramics [12]	$> 10^8$ (Gy)	0.1 (Gy/s)	10^9 (s)	> 30	Coil insul.
Kapton [7]	10^7 (Gy)	0.1 (Gy/s)	10^8 (s)	≥ 3	Coil insulation
Fiber Glass Cloth [7]	5×10^7 (Gy)	0.1 (Gy/s)	5×10^8 (s)	≥ 15	Coil insulation
Epoxy [12]	6×10^7 (Gy)	0.1 (Gy/s)	6×10^8 (s)	≥ 20	Coil insul.

- Blowing He through CPS may prevent oxidation and improve lifetime of some materials.

Conclusion

In our concept, the **CPS is** an **Orientable Unit** containing the **entire Beam Channel**.

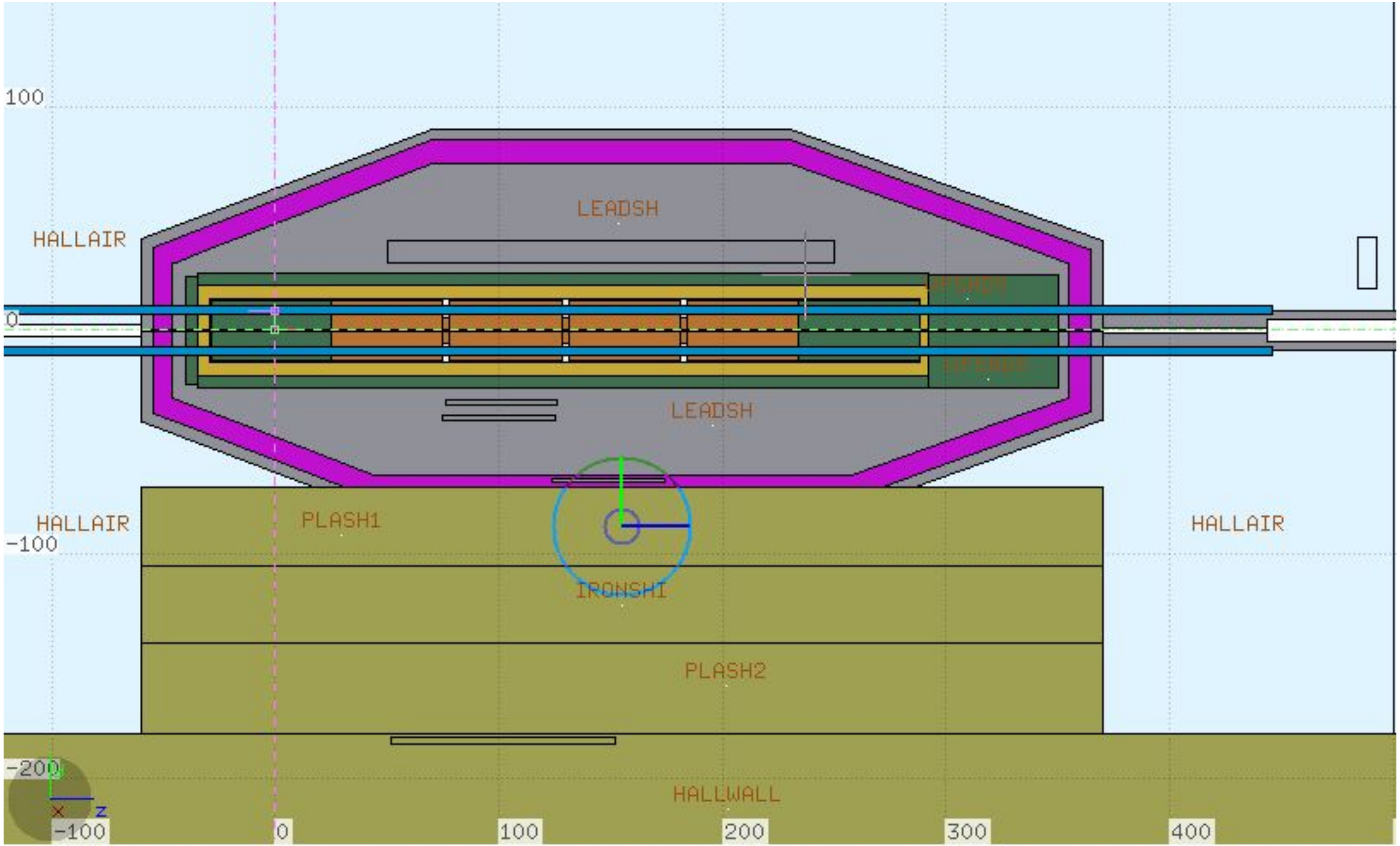
CPS is **surrounded** with several **layers of shielding** materials.

CPS provides a 98% **clear beam** of **2.E+13 photons/s** on KPT.

This concept allows **to avoid risks** and provide:

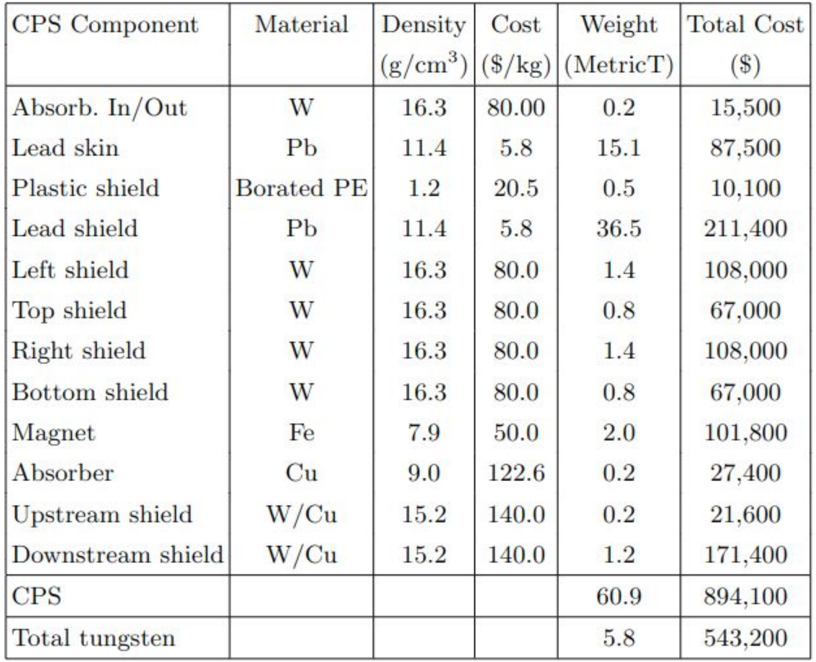
1. **No Overheating** of Copper Absorber ($T_{max} = 200^{o}$ C).
2. **No Short Circuit** in Magnet Coil for up to **15 years** with fiberglass based insulation.
3. **No Prompt Radiation** a > **10 rad/hr around CPS** and > **0.1 mrem/hr** on top of Tagger Hall.
4. **No Activation > 20 mrem/hr around** CPS after 1000+1 hrs of continuous operation .
5. **No Tritium Activity > 200 Bq/L** in ground and cooling waters. (~3% of VA limit).

Optimized CPS with external layers of “elliptical” shape.



Thank you for your attention.

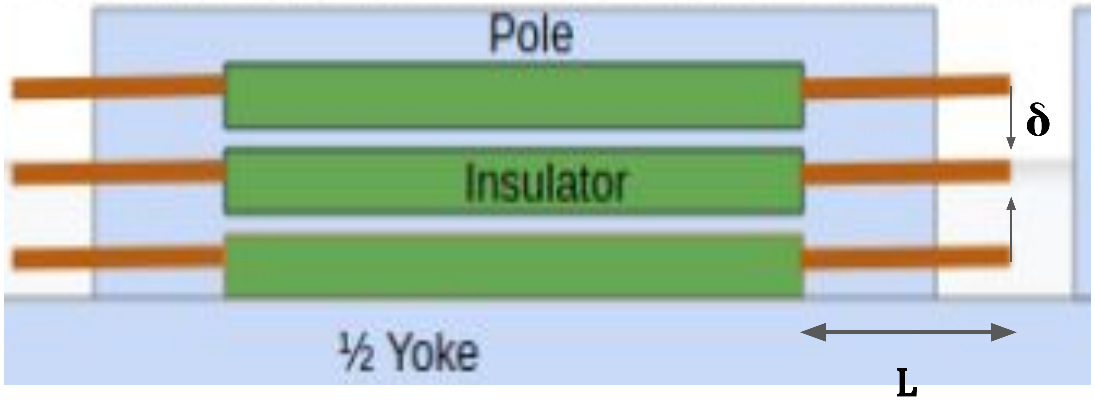
CPS Components. Weight and Cost.



CPS Component	Material	Density (g/cm^3)	Cost (\$/kg)	Weight (MetricT)	Total Cost (\$)
Absorb. In/Out	W	16.3	80.00	0.2	15,500
Lead skin	Pb	11.4	5.8	15.1	87,500
Plastic shield	Borated PE	1.2	20.5	0.5	10,100
Lead shield	Pb	11.4	5.8	36.5	211,400
Left shield	W	16.3	80.0	1.4	108,000
Top shield	W	16.3	80.0	0.8	67,000
Right shield	W	16.3	80.0	1.4	108,000
Bottom shield	W	16.3	80.0	0.8	67,000
Magnet	Fe	7.9	50.0	2.0	101,800
Absorber	Cu	9.0	122.6	0.2	27,400
Upstream shield	W/Cu	15.2	140.0	0.2	21,600
Downstream shield	W/Cu	15.2	140.0	1.2	171,400
CPS				60.9	894,100
Total tungsten				5.8	543,200

- CPS weight - 61,000 kg.
- CPS cost without magnet - \$793,000.
- Including Tungsten cost - \$543,000.

Coil Deformation due to Ampere's force.



Ampere's force law:

$f' = dF/dl = (\mu_o / 2\pi)(I^2/d)$

$= \mathbf{25\ N/m}$

at

$I = 1800$ A -current through wire

$d = 2.5$ cm -distance between wires

$\mu_o = 4\pi E\text{-}7\ N/A^2$

Consider a squared **Cu wire $S=(1.7\ cm)^2$**, **$L=20$ cm** as a rod with fixed end under load including gravitation **+25.5 N/m**, total **$f = f' + 25.5 = 50.5$ N/m.**

From **tabulated formula** the maximum sag at the end of the rod:

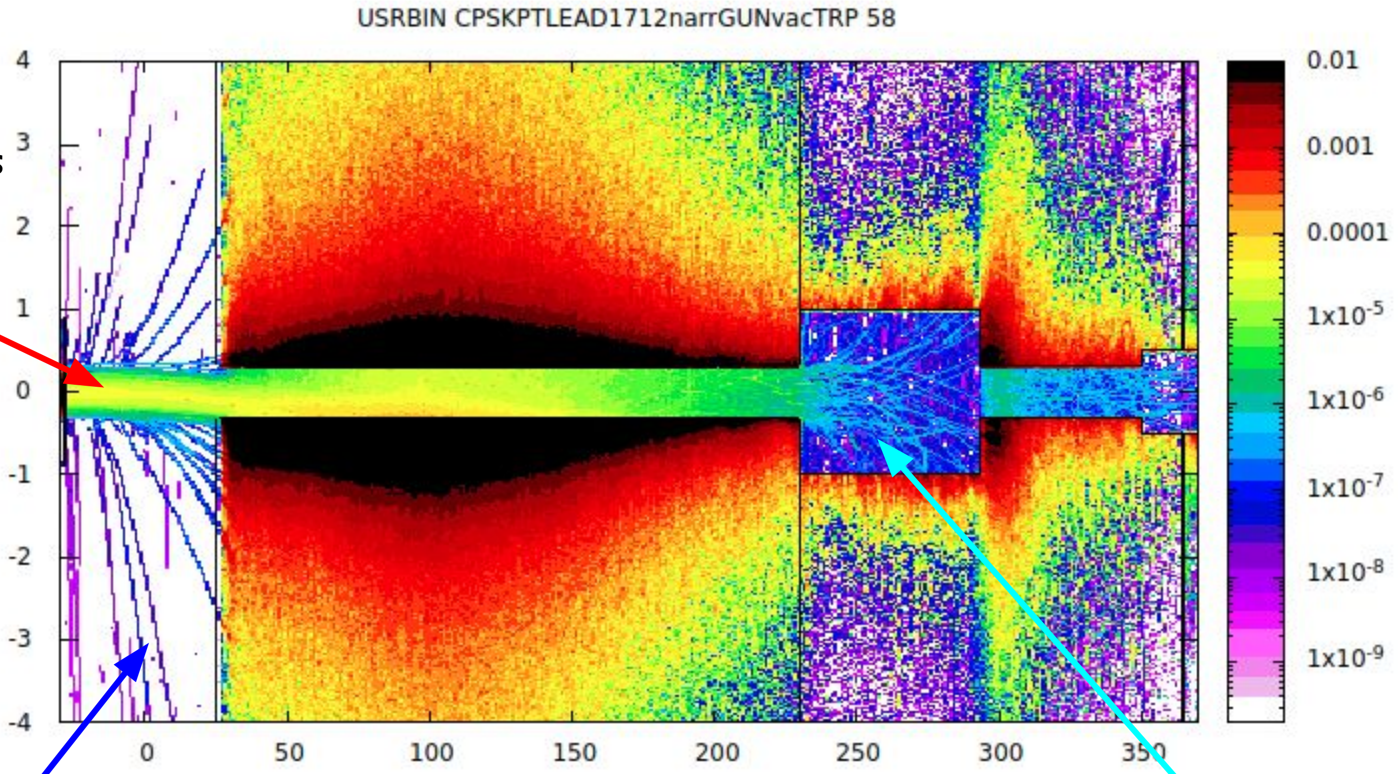
$$\delta = 3/2\ f\ (L/W)^4 E^{-1}$$

$$= 1.5*(50/1.2)*(20/1.7)^4*10^{-11}$$ = **12 microns** (compare with 8 mm gap)

where **$E=1.2E+11\ N/m^2$** - Young's module **tabulated for copper**.

- **Insulation is not required for Coil return in high radiation area.**

Magnet at CPS exit cleans photon beam.

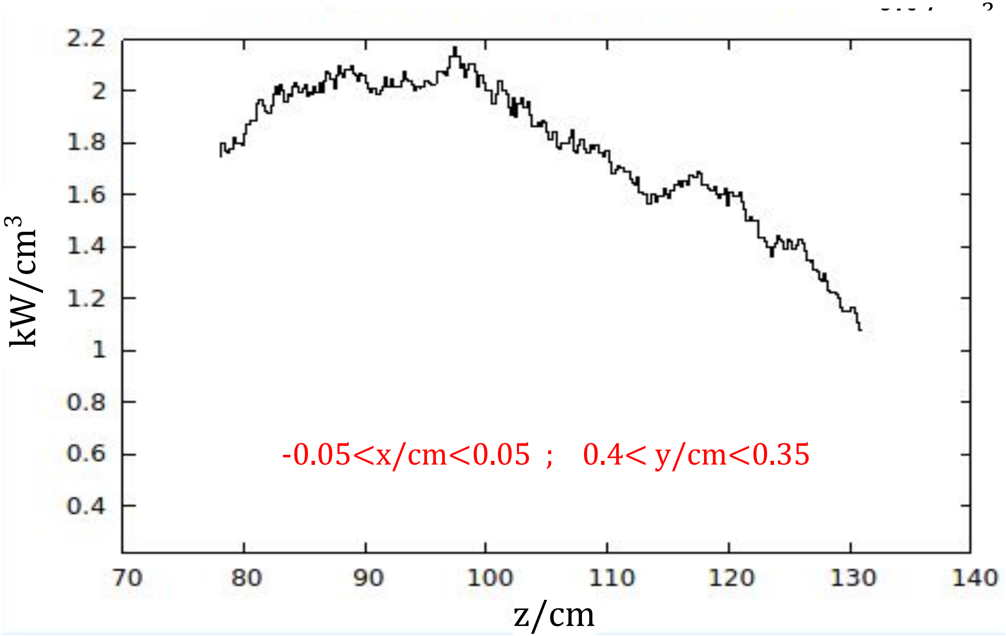


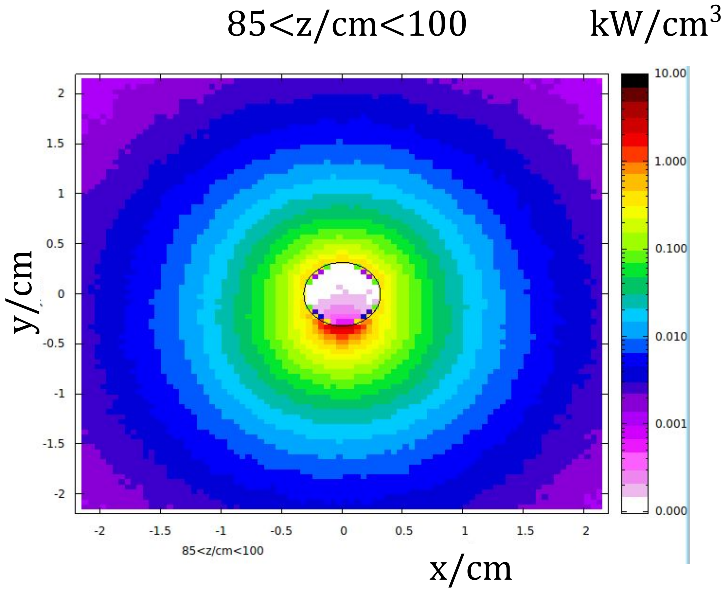
Electrons
from
radiator

Charged tracks from radiator.

Charged tracks from beam channel.

Power Deposition in Skinny Layer of Hot Segment . Fine map 0.05 cm.



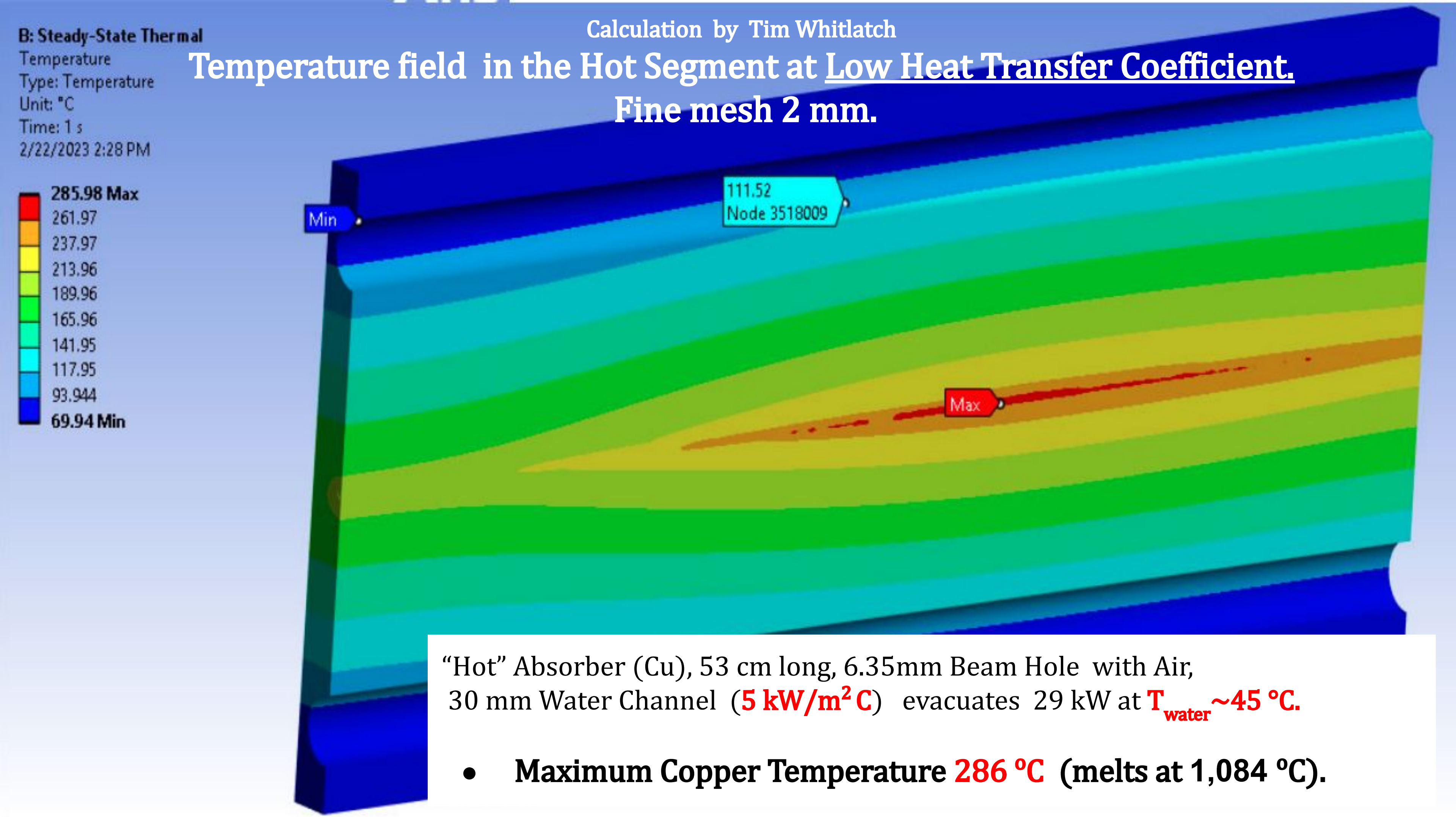


- Maximum **dP/dV = ~2 kW/cm^3**
- **ANSYS calculations** are done by Tim Whitlatch (JLab) using this Map.

Calculation by Tim Whitlatch

Temperature field in the Hot Segment at <u>Low Heat Transfer Coefficient.</u>

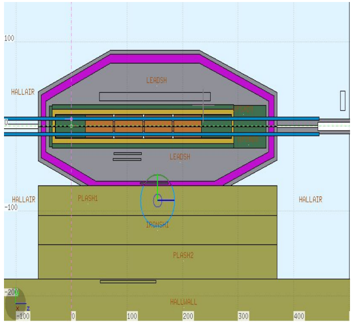
Fine mesh 2 mm.

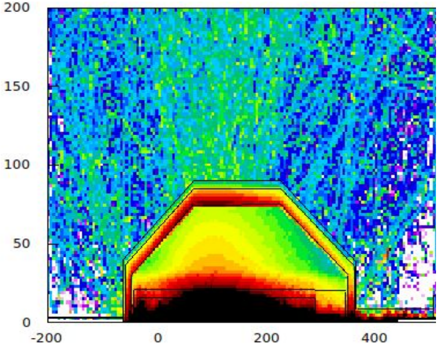


“Hot” Absorber (Cu), 53 cm long, 6.35mm Beam Hole with Air, 30 mm Water Channel (**5 kW/m^2 C**) evacuates 29 kW at **T$_{water}$~45 °C.**

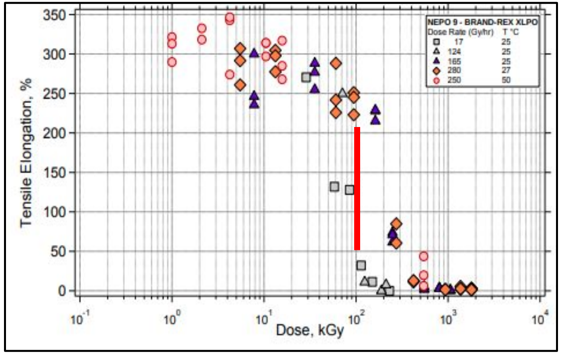
- **Maximum Copper Temperature 286 °C (melts at 1,084 °C).**

Prompt dose and Polyethylene lifetime.

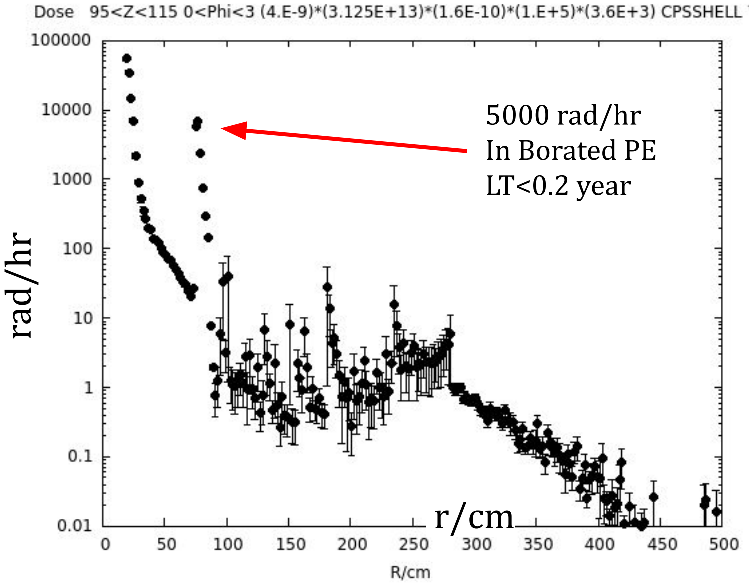




PE Tensile Strength vs Dose/kGy
1Gy=100 rd



S.A. Waters, G.V. Wite , R. Tandon, L. Serna, M.Celina, R.Bernstine, "An Overview of Basic Radiation Effects on Polymers ", Sandia National Laboratories, U.S. DOE, SAND2013-8003P, 2013.

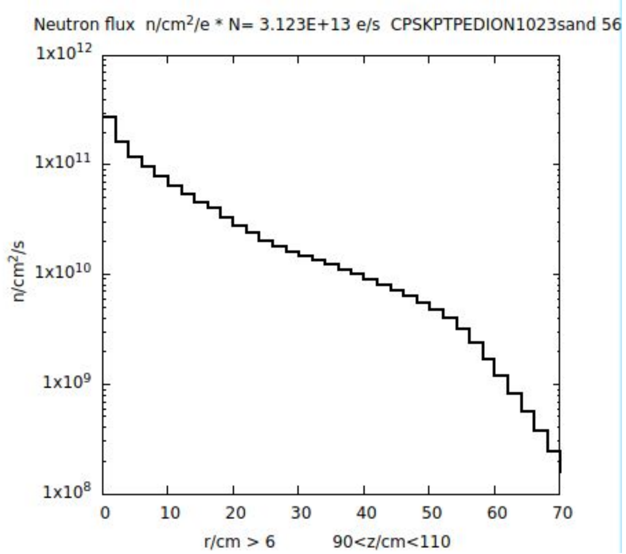


5000 rad/hr
In Borated PE
LT<0.2 year

- BPE elastic properties degrade significantly after **1.E+7 rad** / 5000 rad/hr = **~0.2 year**.
- Borated polyethylene can **not** be used as **construction material**.
- Possible **solution**:- BPE granules in **metal tanks** or containers.

https://www.osti.gov/biblio/4640611

Neutron Flux r-profile in Hot Spot. Steel is OK up to 10^{22} n/cm^2



https://www.osti.gov/biblio/4640611

Life Time $=10^{11}$ s $=3200$ years. Steel is OK up to 10^{22} n/cm^2.

Hall D K-Long Facility E12-19-001. Experiment Readiness Review Phase I. Jefferson Lab , 2023 Charge.

- Is there any R&D needed to be done prior to start the construction of the KLong Facility? **No**

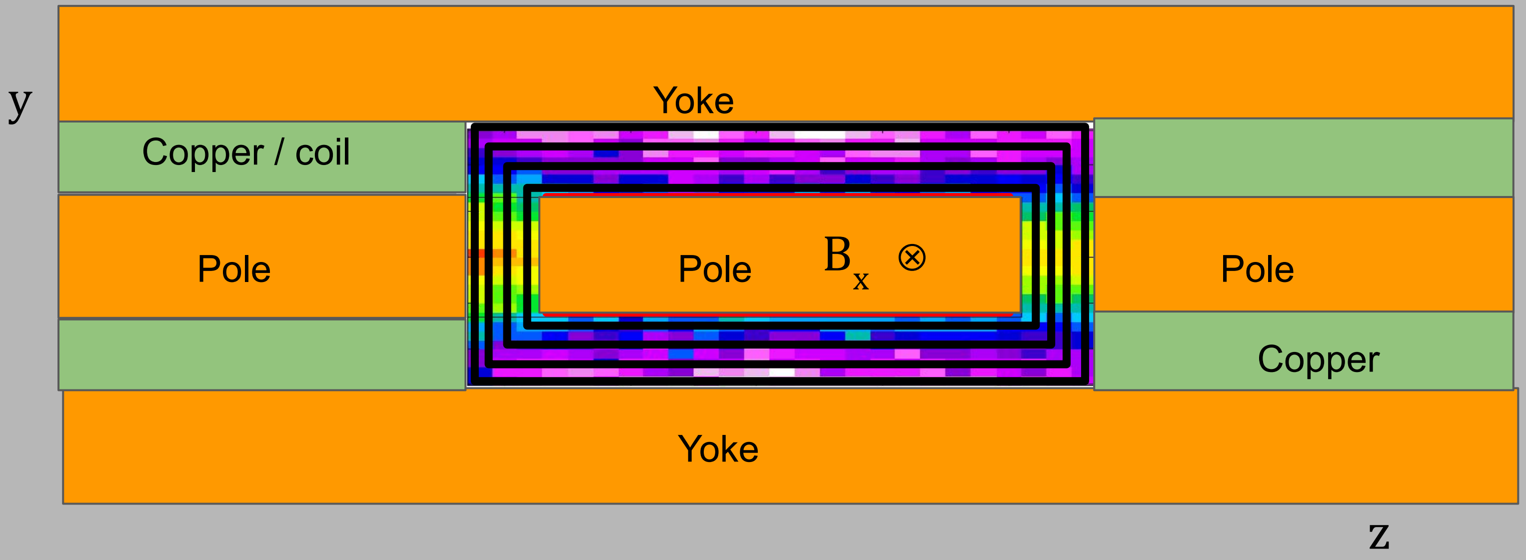
  5μA electron beam on the CPS FWHM=**2.5 mm**, **3.1E+13 e/s**, steering magnet.

- What is the status of the Compact Photon Source (CPS)? Specifically the :

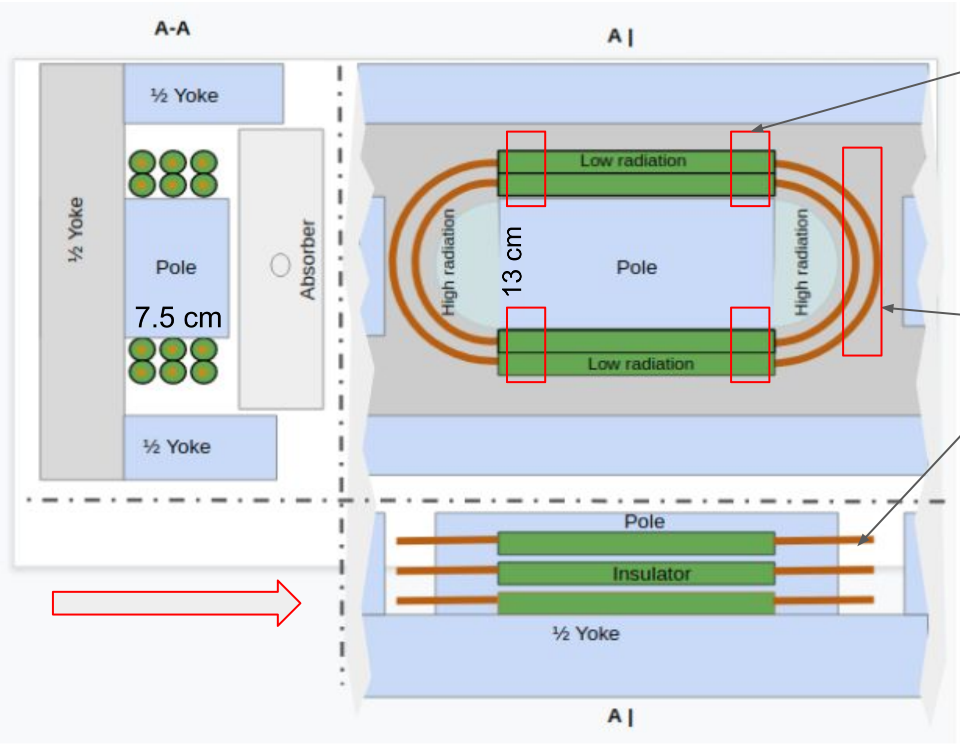
1. Conceptual design: Presented.
2. Evaluation of the **produced radiation**: < **1 mrem/hr** on top of Tagger Hall and Tunnel Mounds.
3. **Approximations** in the MC simulations and Code used: Simplified Tagger & KPT Halls. FLUKA2021.2.9.
4. Energy deposition , **Absorber** and Lead **temperature**: **2 kW/cm^3** , Cu Absorber < **200° C ,** **Pb** shield < **100° C.**
5. Prompt **dose** and **activation** around the CPS (Tagger Hall): Dose < **10** rad/hr , <**20** mrem/hr. Maps available.
6. **Magnet** and **insulation lifetime**: 0.25×0.5 Tm, I≤1.8 kA, 4-6 turns, wire 2×2 cm^2, T<**150ºC**, LT=**15** years.
7. **Cooling system** and **ground water contaminations**: Tritium Activity **2.6*10^7 Bq** and **200 Bq/L** after 1 year.

- What will the photon **beam quality** be: **1%** of neutrons and ± part . FWHM=4 cm, **3E+13** s^{-1}
- What are the **cost and schedule estimates** for the construction of the CPS: **800 k$** (no magnet).
- Will **civil constructions** be needed to contain the radiation in the Tagger Hall: **No**
- What is **Decommissioning Plan** for CPS and Activated Components: mounted on a platform, **move aside**.

Problem of High radiation in return part of Coils.



Coil Design and Insulation Exposure to Radiation.



Hot area for insulation.

Very hot area,

Air insulation,

Gap between

wires

~8 mm.

Ampere's force law:

$dF/dl = (\mu_o / 2\pi)\,(I^2/d) = \sim 25$ N/m

at I=1800 A ; d=2.5 cm; $\mu_o = 4\pi$E-7 N/A^2

- Attractive force of bent parts F = 25 N/m* 0.3 m = 7.5 N.
- Copper 1.7 cm -wires (tubes) will not touch .

Leakage Current between wires.

Current through gas :

$$dI/ds\ [A/cm^2] = n\ [e/cm^3] \times v\ [cm/s] \times e\ [C]$$

1. What is concentration of electrons n?
2. What is the drift velocity of electrons v?

Drift velocity of electrons and ions in dry and humid air and in water vapour H. RYZKO Institutet for Hogspbningsforskg vid Uppsala Universitet, Uppsala, Sweden MS. received 7th Septembw 1964
https://journals.aps.org/pr/abstract/10.1103/PhysRev.32.624#:~:text=From%20the%20measured%20rate%20of,because%20of%20several%20unavoidable%20errors.

1. What is n and Ionisation in Magnet Coil.

$$\mathbf{dI/ds\ [A/cm^2] = n\ [e/cm^3] \times \boldsymbol{v}\ [cm/s] \times e}$$

Assume **maximum dose D in space between coil winding**s is D= **1.E-5 [GeV/g/e]** (~10 × of **FLUKA** estimate).

Assume **10 eV** is required to produce one electron -ion pair .

Dose D translate to ion **pair production ~1.E+3[pair/g/e]** = 1.E-5 [GeV/g/e] / 1.E-8 [GeV]).

Ion pair production rate **per unit of mass** is at beam intensity 3.E+13 [e/s] :

dN/dt = **3.E+16 [pair/g/s]** = 1.E+3 [pairs/g/e] × 3.E+13 [e/s].

Assume we have **1 cm of argon** between windings (**ϱ_A=1.7E-3 [g cm^{-3}] = ~2.E-3**). Air – 1.3E-3 ; He – 0.17E-3

So we find the ion **production rate between coil wires** :

dn_p /dt= (dN/dt) ϱ_A = 3.E+16 [pairs g^{-1} s^{-1}] × 2.E-3 [g cm^{-3}] =**6.E+13 [pair cm^{-3} s^{-1}]**

This rate is **balanced by recombination** of argon ions and electrons.

Drift velocity of electrons and ions in dry and humid air and in water vapour H. RYZKO Institutet for Hogspbningsforskg vid Uppsala Universitet, Uppsala, Sweden MS. received 7th Septembw 1964
https://journals.aps.org/pr/abstract/10.1103/PhysRev.32.624#:~:text=From%20the%20measured%20rate%20of,because%20of%20several%20unavoidable%20errors.

1. What is n. Ionisation in Magnet Coil and Leakage Current.

$$dI/ds\ [A/cm^2] = n\ [e/cm^3] \times v\ [cm/s] \times e$$

$dn_p/dt = 6.E{+}13\ [\text{pairs cm}^{-3}\ s^{-1}]$ is balanced **by recombination** of argon ions and electrons defined as:

$dn_r/dt = \alpha\, n_+ n_-$, where $\alpha = 2.E{-}10\ [cm^3\ i^{-1}\ s^{-1}]$ recombination coeff. for Argon.

($\alpha = \sim 1.E{-}8\ [cm^3\ i^{-1}\ s^{-1}]$ for He, and $\alpha = 1.E{-}6$ — $1.e{-}7$ for Air.)

Assuming equal densities $n_+ = n_- = n$ for the equilibrium density of electrons **n** we write:

$\alpha\, n^2 = dn_p/dt = 6.E{+}13\ [\text{pairs cm}^{-3}\ s^{-1}]$ from the previous slide and

$n^2 = \alpha^{-1} dn_i/dt = 0.5E{+}10\ [\text{pairs s cm}^{-3}] \times 6.E{+}13\ [\text{pairs cm}^{-3}\ s^{-1}] = 3.E{+}23\ (\text{pairs/cm}^3)^2$.

- The equilibrium **density of electrons** yields $n = 6.E{+}11\ (\text{pairs/cm}^3)$.
- **Density of electrons** is **proportional** to the gas specific factor $(\alpha^{-1}\varrho_A)^{½}$.

Drift velocity of electrons and ions in dry and humid air and in water vapour H. RYZKO Institutet for Hogspbningsforskg vid Uppsala Universitet, Uppsala, Sweden MS. received 7th Septembw 1964
https://journals.aps.org/pr/abstract/10.1103/PhysRev.32.624#:~:text=From%20the%20measured%20rate%20of,because%20of%20several%20unavoidable%20errors.

2. What is v and Electric Field between Wires at 2 kA current.

What is Voltage between windings?

Copper resistivity $\varkappa$=**1.7E-6** [Ohm·cm]; L_w/S_w= 100 cm/3 cm^2 =25 cm^{-1}

=> Voltage between windings ($V= I \times R_w$ where $R_w=\varkappa \times L_w/S_w$)

V = 2000 [A]× 1.7E-6 [Ohm·cm] ×25 [cm^{-1}] = 2.E-6 ×5.E+4 [Ohm·A]

V = 0.1 V.

From **Top Plot** (1) we see **drift velocity as** $v=v(E/P)$ where

E -electric field, P=gas pressure.

In our case **E=0.1 [V cm^{-1}]** ; **P=~1000 [mmHg]** =>

E/P=1.E-4 [V cm^{-1}/mmHg]

From Top Plot we read **v(0.1)=2.E+6 [cm/s]** and linear interpolation yields:

v(1.E-4)=2.E+3 [cm/s].

From Bottom Plot for air we find v(1.E-4)=5.E+1 cm/s.

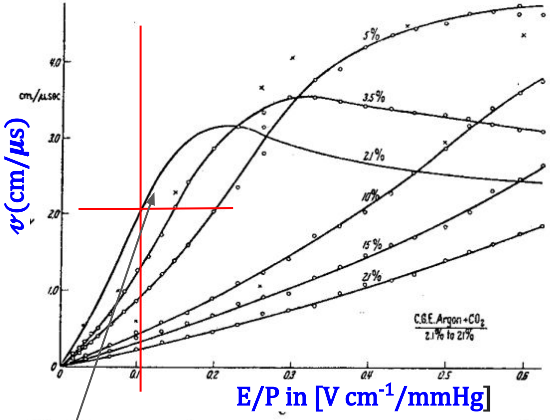


Fig. 29 Drift velocity of electrons in several argon-carbon dioxide mixtures12)

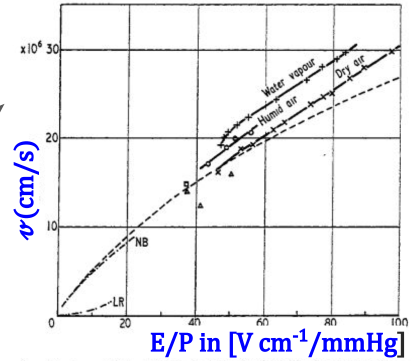


Figure 5. Electron drift velocity in dry air, humid air and water vapour as a function of reduced electrical field. Pressure readings reduced to temperature of 20 °c; humid air, p_w/p = 16%. Broken line, Townsend and Tizard 1913; △, Raether; □, Rieman 1944; NB, Nielson and Bradbury 1937; LR, Lowke and Rees 1963.

- (1) F. Sauli, "PRINCIPLES OF OPERATION OF MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS",

https://journals.aps.org/pr/abstract/10.1103/PhysRev.32.624#:~:text=From%20the%20measured%20rate%20of,because%20of%20several%20unavoidable%20errors.

2. What is leakage current between wires .

Current density between windings:

$$dI/ds\ [A/cm^2] = n\ [e/cm^3] \times v\ [cm/s] \times 1.6E\text{-}19\ [C/e] \qquad \propto \quad v\ (\alpha^{-1}\varrho_A)^{1/2}$$

Where $n=6.E+11\ [e/cm^3]$.

$v=2.E+3\ [cm/s]$.

For the current density we find **:**

$$\mathbf{dI/ds\ [A/cm^2]} = \mathbf{6.E+11[e/cm^3]} \times \mathbf{2.E+3\ [cm/s]} \times \mathbf{1.6E\text{-}19\ [C/e]} = 12 \times 1.6\ E(+11+3-19) =$$

$$= \mathbf{20.E\text{-}5\ [A/cm^2]}.$$

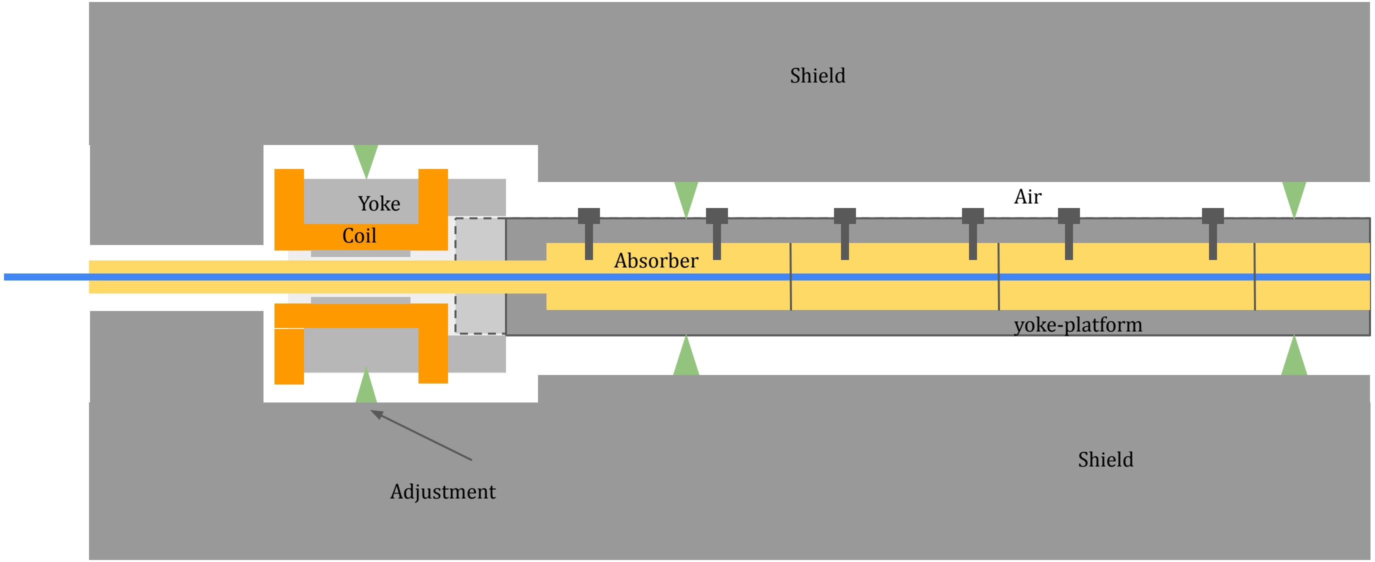
Wire area $S=2\ cm \times 100\ cm = \mathbf{2.E+2\ cm^2}$, and the maximum possible current yields:

$$\mathbf{I\ [A]} = 20.E\text{-}5\ [A/cm^2] \times 2.E+2\ [cm^2] = 40.E\text{-}3\ [A] = \mathbf{40\ [mA]}.$$ Compare to 2 kA !

- **Leakage is of 2.E-5 of the wire current. It does not affects the coil performance.**
- **For Helium the leakage is ~10 times lower - due to the gas specific factor $v\ (\alpha^{-1}\varrho_{He})^{1/2}$.**

(1)

https://journals.aps.org/pr/abstract/10.1103/PhysRev.32.624#:~:text=From%20the%20measured%20rate%20of,because%20of%20several%20unavoidable%20errors.


Shield
Yoke
Air
Coil
Absorber
yoke-platform
Shield
Adjustment