Compact Photon Source for Hall D.

Design and simulation using FLUKA at 5 μA e-beam, FWHM=2.5 mm.

For KLF Collaboration

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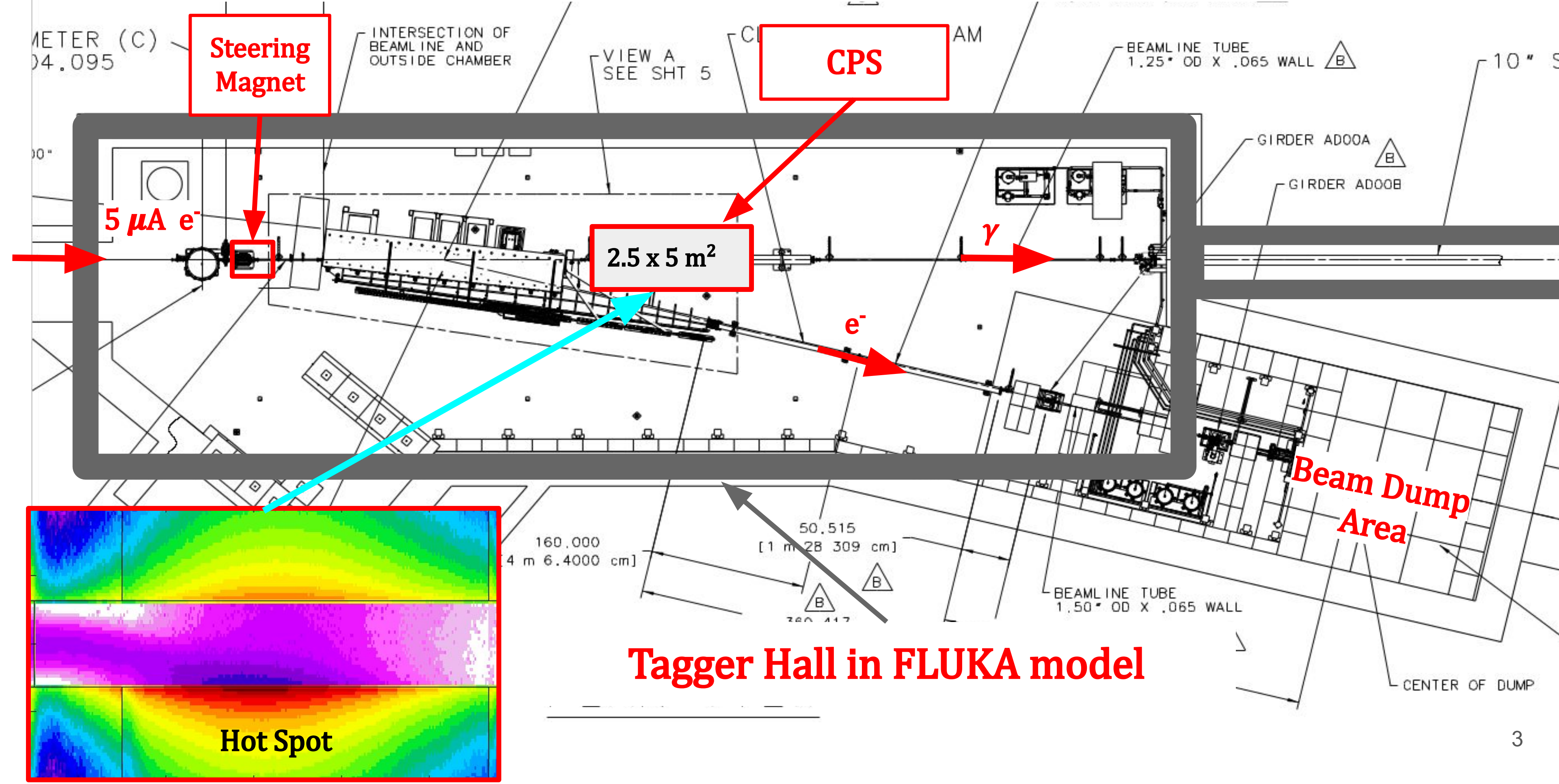
Last edit 01/18/2023.

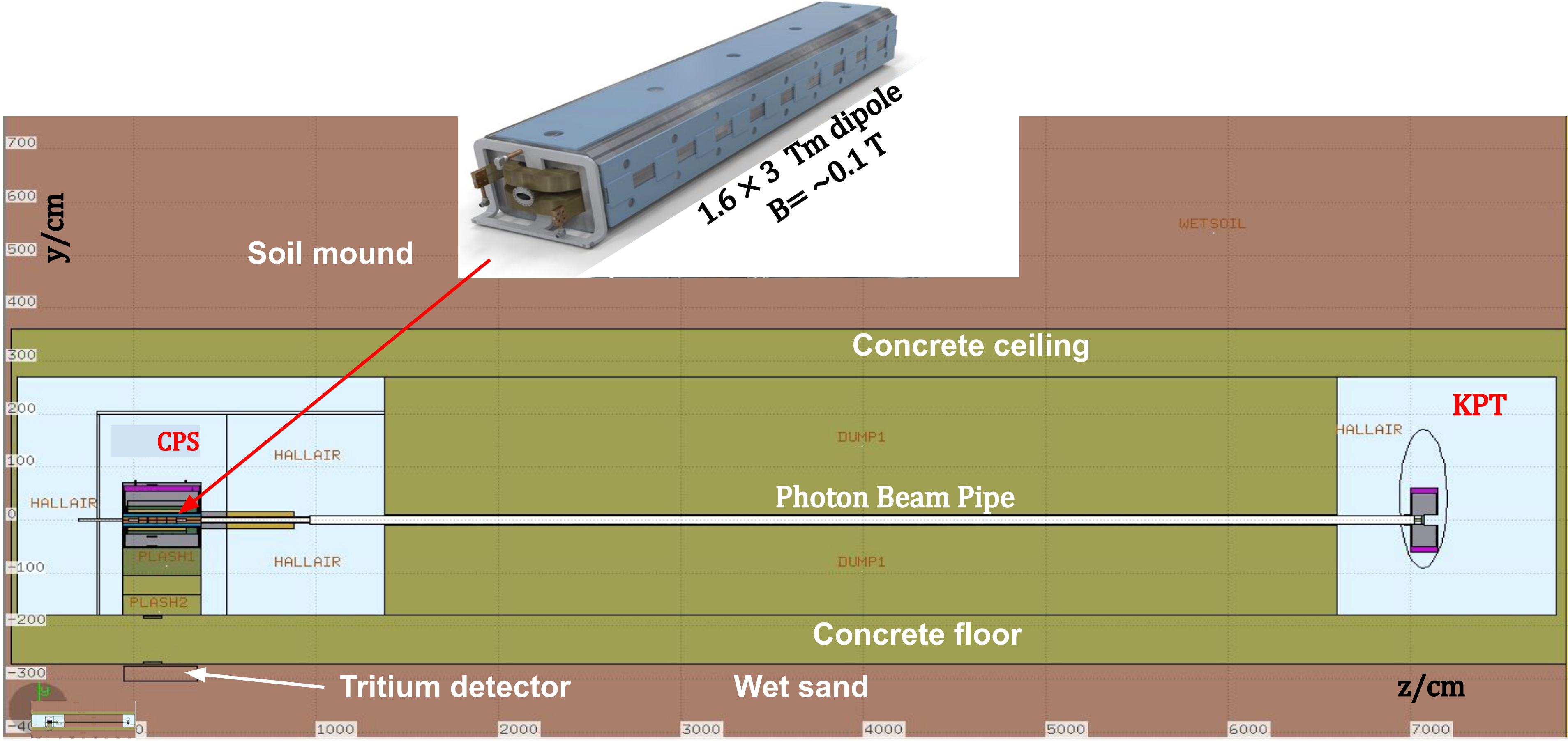
OUTLINE

1. CPS in FLUKA. Location, Design, Alignment.
2. Energy Deposition and Absorber Temperature.
3. Photon Beam Quality.
4. Radiation in Magnet and Insulation Lifetime.
5. Prompt Dose and Activation around CPS.
6. Tritium Contamination in Soil and Cooling Waters.
7. Lifetime of various materials.
8. Weight/Cost. 2023 Charge.
9. Conclusion and Outlook.

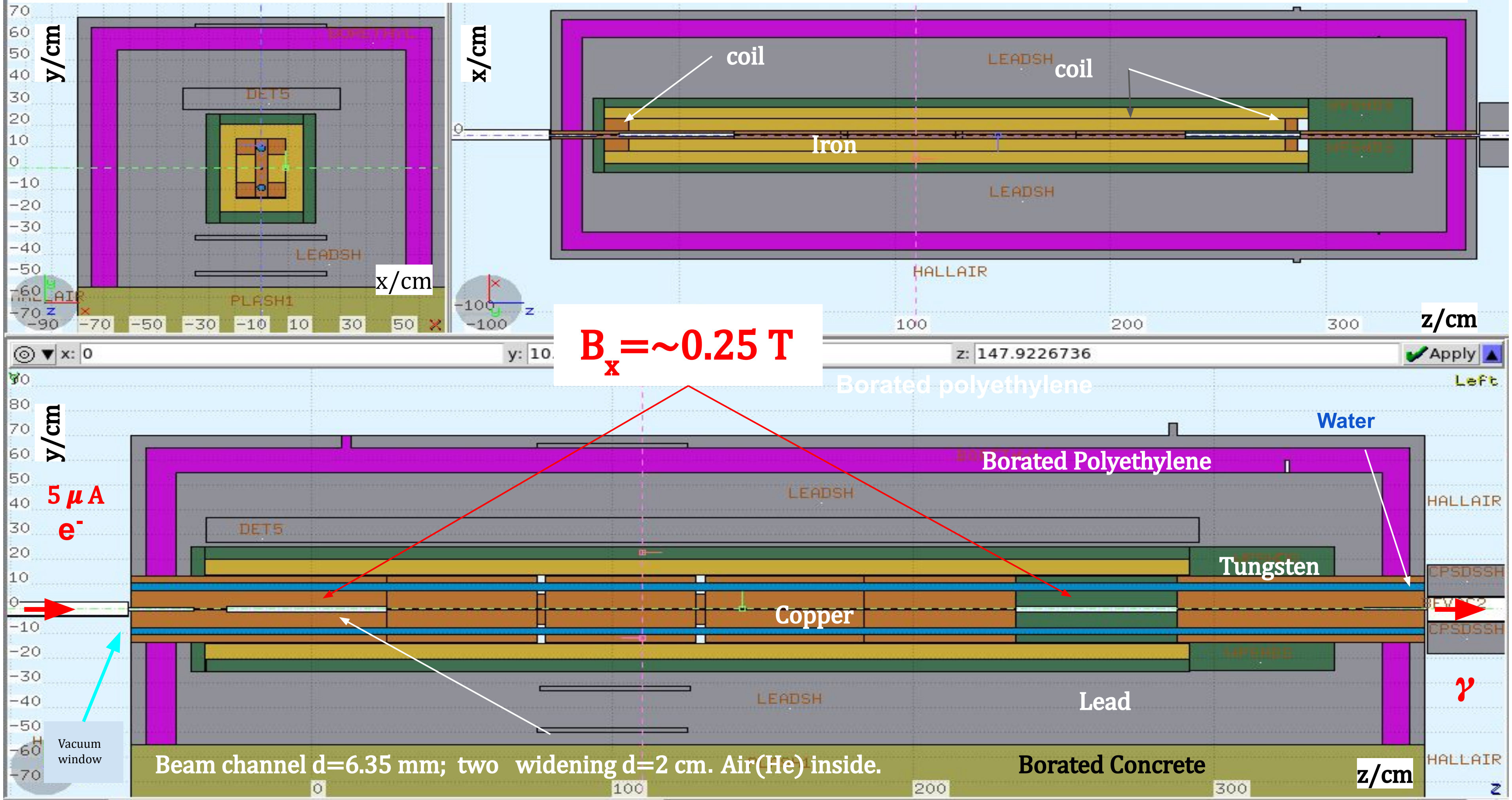
CPS location in Tagger Hall. Beam 5 μA , Gaussian, FWHM=2.5 mm.



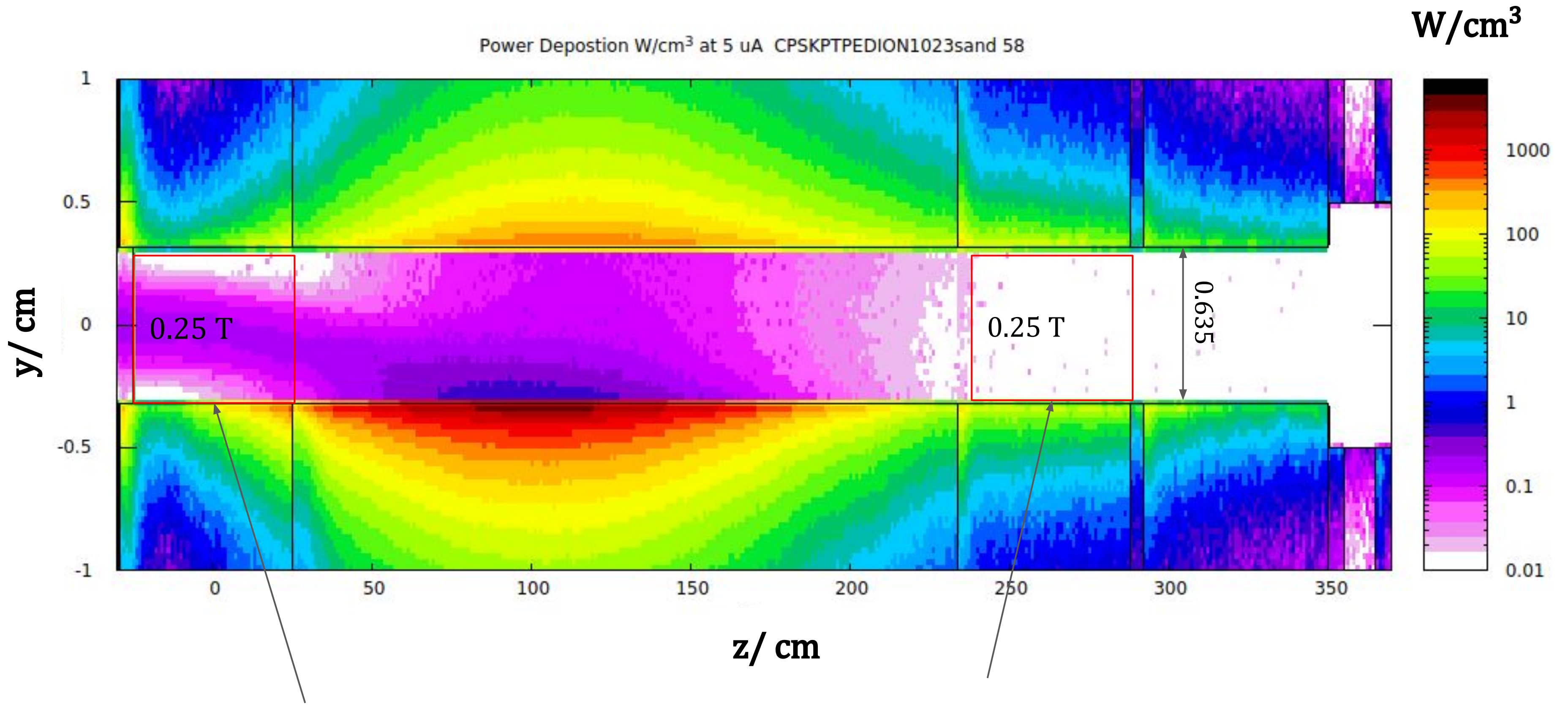
CPS, Tagger Hall, KPT and Magnet prototype in FLUKA model.



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



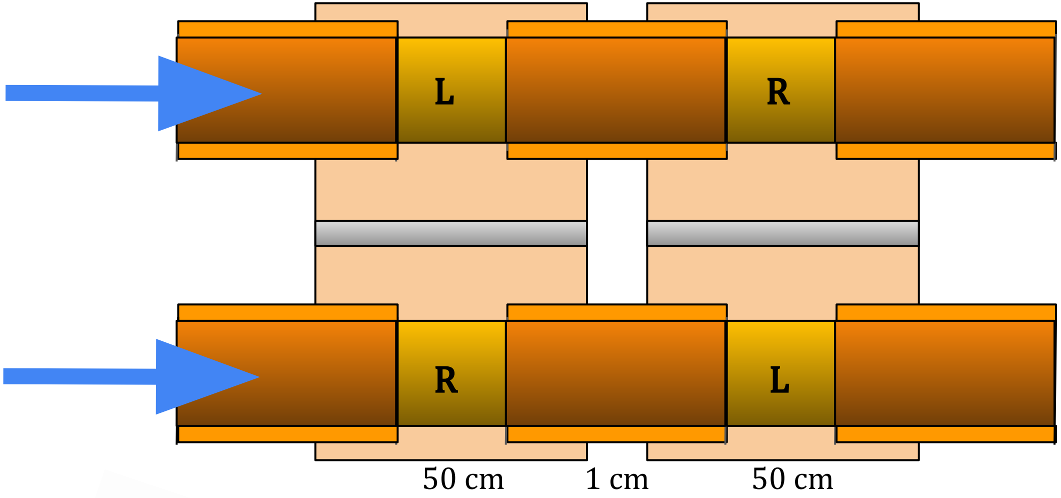
Source of radiation. Hot spot in the absorber. Power deposition

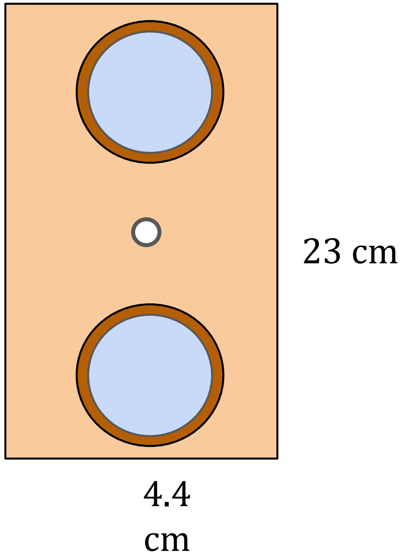


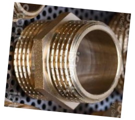
- Upstream magnet forms the Hot Spot; Downstream - cleans the photon beam.

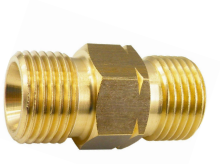
CPS Absorber
and
Alignment.

Segmented Copper Absorber - possible solution.



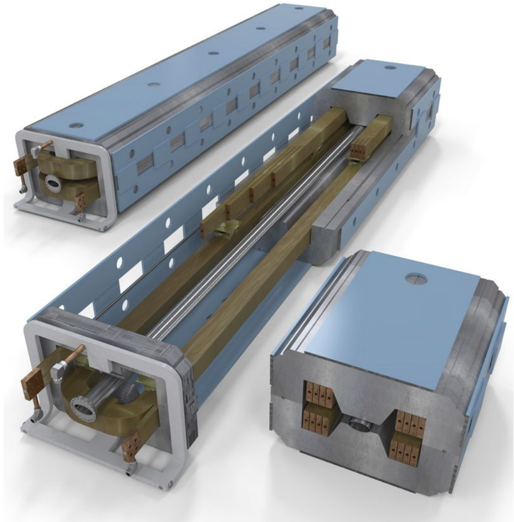




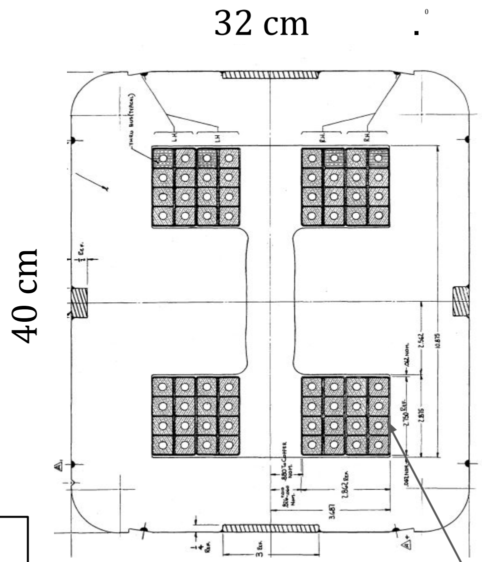
L  R

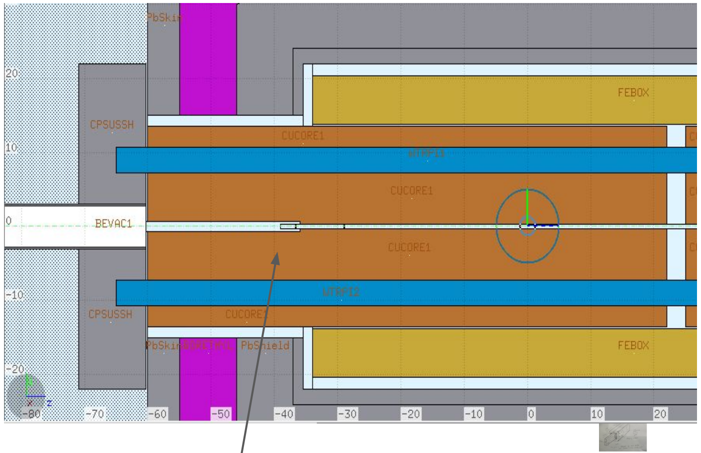
- Segments ~$4.4\times20\times50$ cm^3, **round** beam **hole:** => (1) no problem of thermal contact between 2 parts and (2) may be vacuumized.
- Segments are connected by fittings with **left/right-**hand threads; may be brazed.
- Provides direct **copper-water contact** inside segments: => no interface; better cooling.

Magnet as precise platform for Absorber



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

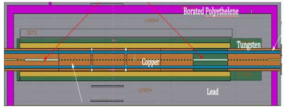




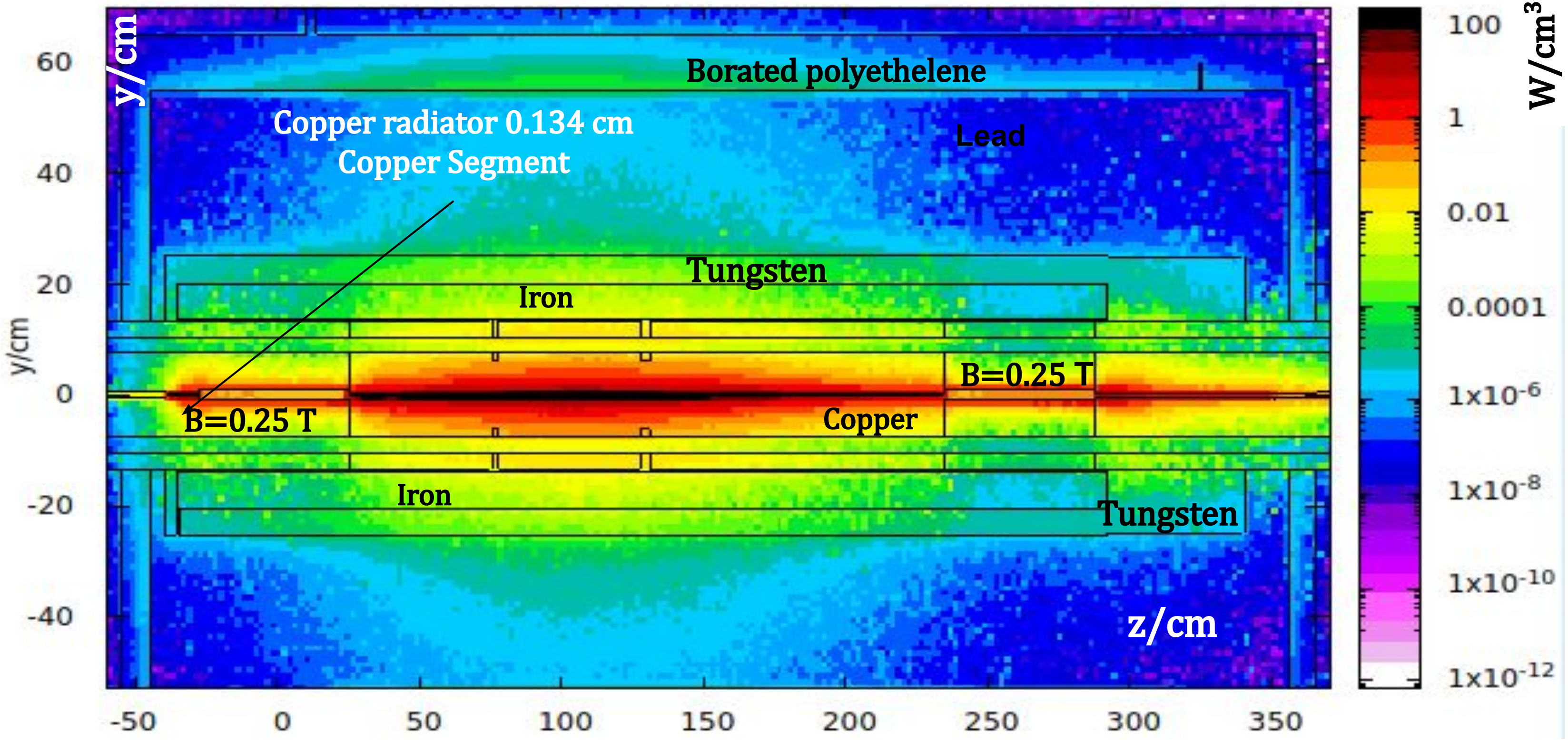
B=1.6 T - 16 wires 1.7×1.7 cm^2
B≤0.6 T - 6 wires.

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

Energy deposition
and
Temperature of CPS components.



Power Deposition in in -0.5<x/cm<0.5. Current model. Course map.



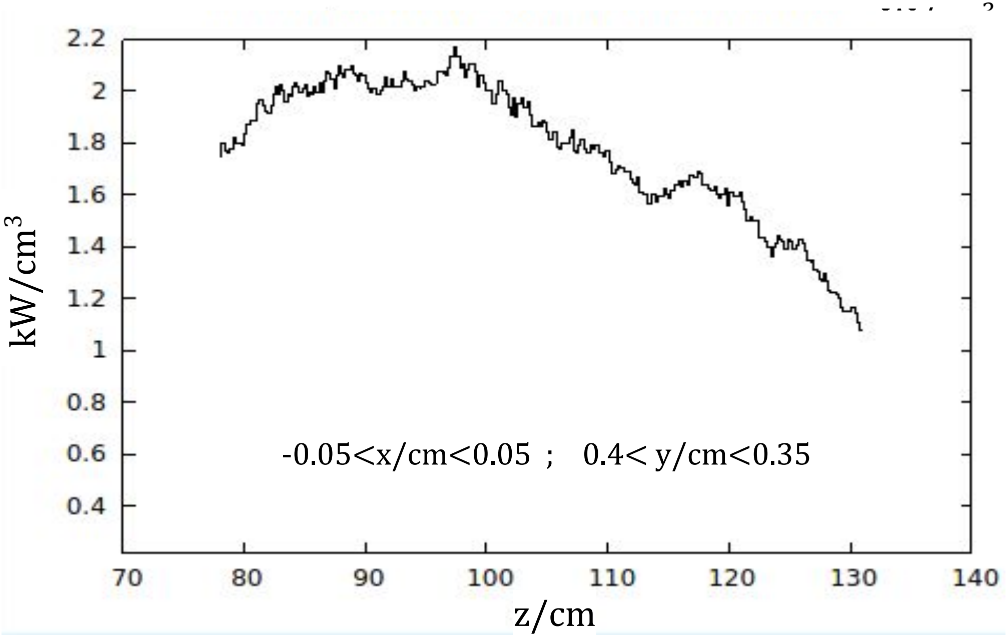
- Protruding **copper segment** around Radiator to mitigate lead overheating.
- T°-calculations **in progress**. Channel widening in coil area - to **reduce dose** rates.
- [baturin@hallal1 PEDFASTGUN4]$ ls -lt *.inp | grep or
- -rw-r--r-- 1 baturin clas 49936 Feb 9 11:07 CPSKPTLEAD1712narrGUNvacTRP_org.inp

Power breakdown between CPS components .

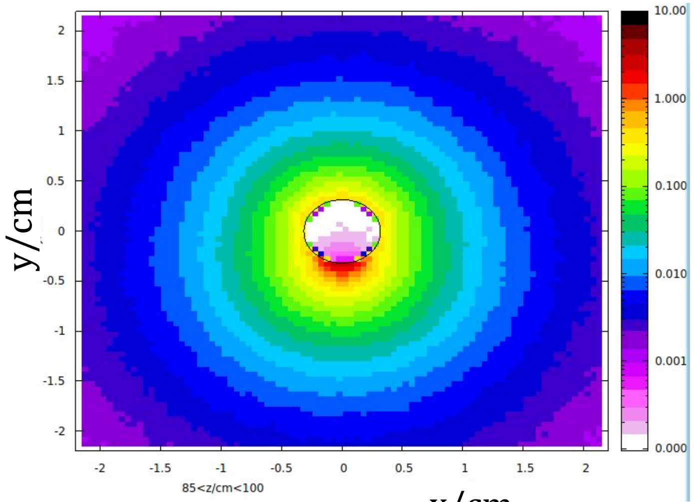
CPS part	GeV/e	kW/5 μA
DS Shield (W)	0.063	0.316
US Shield (W)	0.033	0.163
Side Shield (W)	0.013	0.064
Top Water Pipe	0.001	0.005
Bottom Pipe	0.001	0.006
Magnet Pole Right	0.322	1.610
Magnet Pole Left	0.321	1.619
Coils	0.058	0.289
Magnet Yoke	0.101	0.504
Lead Shield	0.006	0.032
Polyethylene (B)	0.002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

Power Deposition in skinny layer of Hot Segment . Fine map.



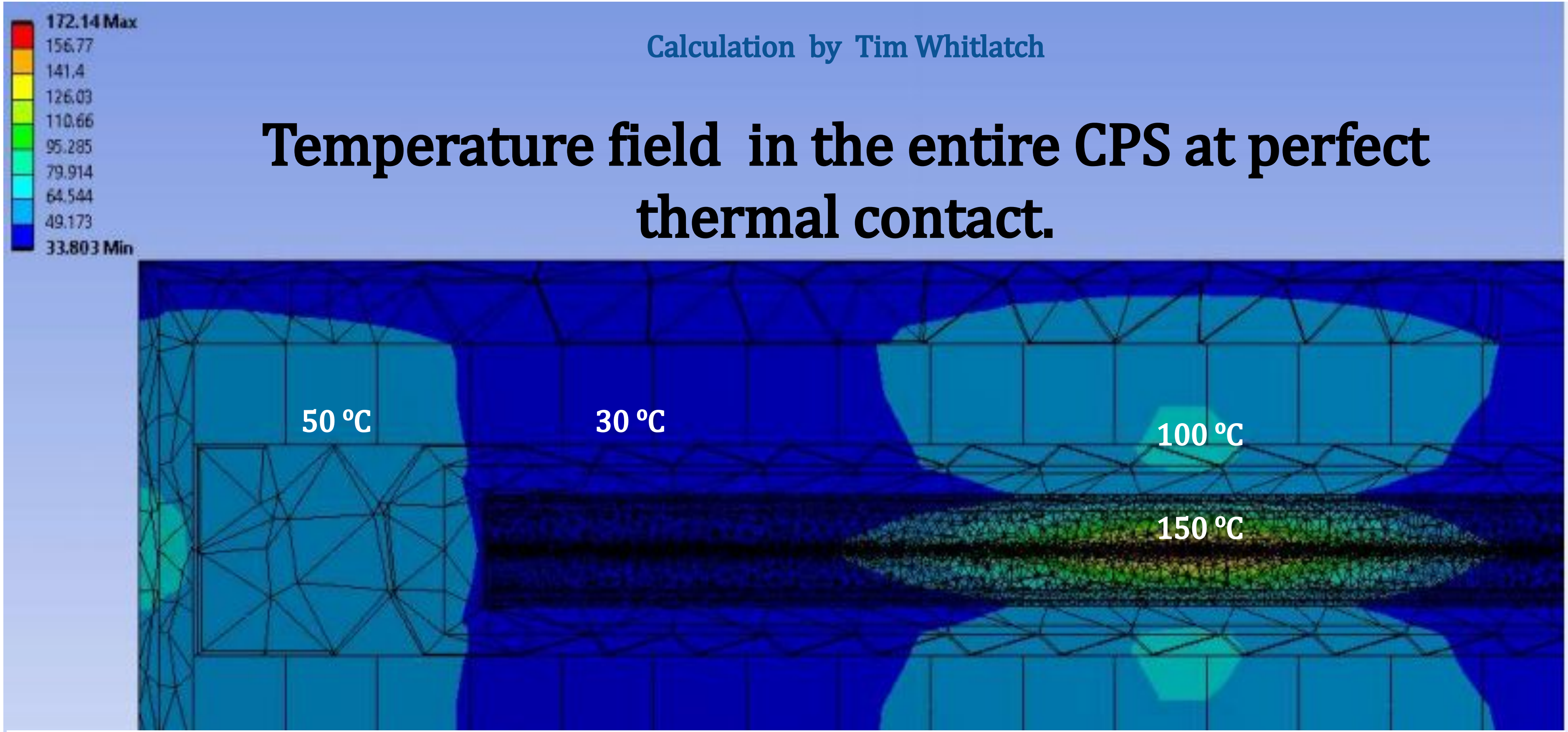
85<z/cm<100 kW/cm3



- Maximum **dP/dV = 2 kW/cm^3**
- **ANSYS calculations** to be done by Tim Whitlatch using this Map.
- Copper **does not melt**; expected channel surface temperature **T_{max}= ~230 C^o.**

Calculation by Tim Whitlatch

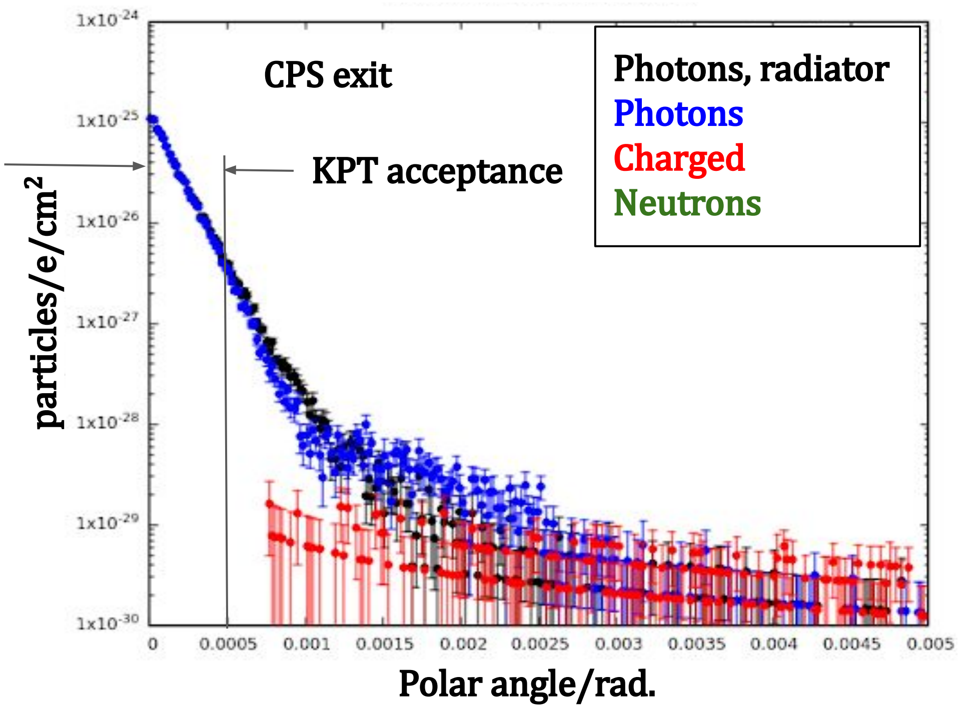
Temperature field in the entire CPS at perfect thermal contact.

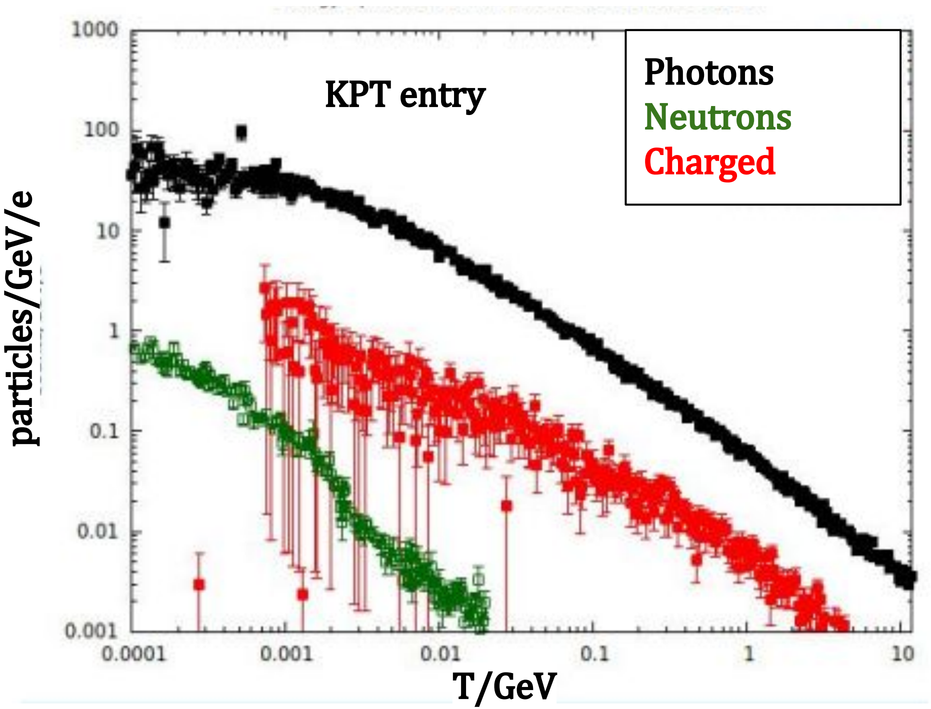


- **Copper (T_m=1085º C)** in Absorber Channel **does not melt**: **T< 200º C .**
- **Lead (T_m=327º C) and Iron (T_m=1538º C) temperatures - below melting points: T<100º C ? and 150º C.**

Photon Beam Quality

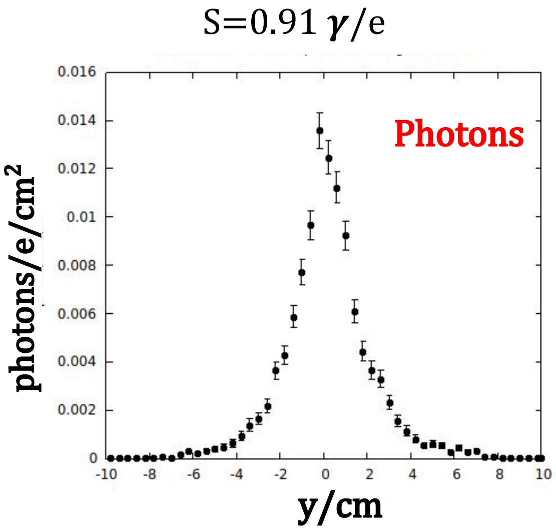
Particles exiting from the CPS . Angular profile.

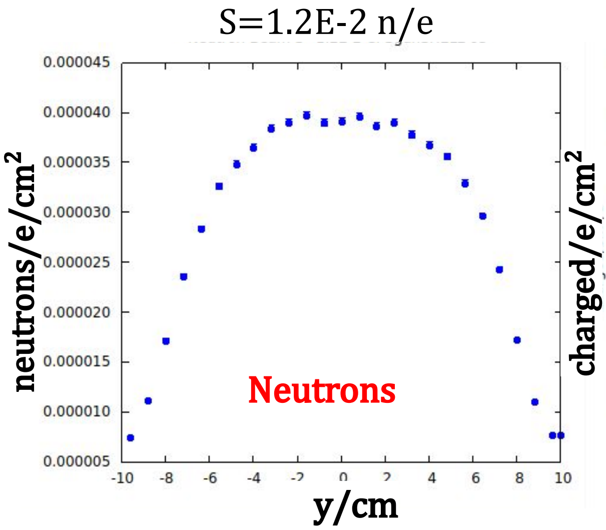


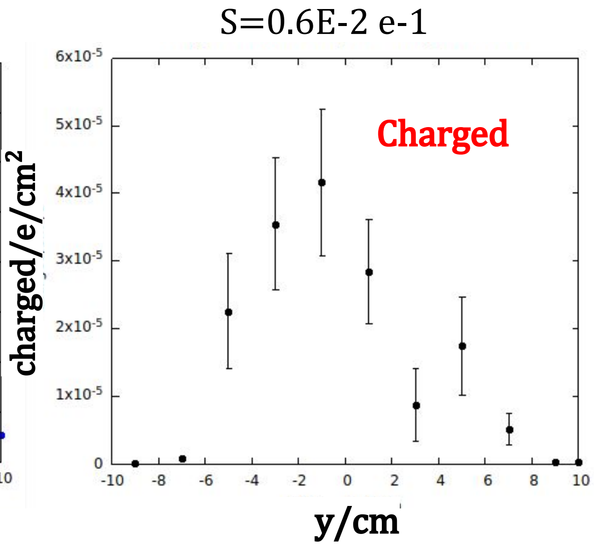


- Photon beam at the CPS exit looks very clean (< 1.E-3). Left plot.
- What happens to the beam after 67 m of beam line? - Right plot.

Beam quality at KPT.







- After 67 m of beam line the total **background** of charged particles and neutrons is <**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.**

Magnet performance.

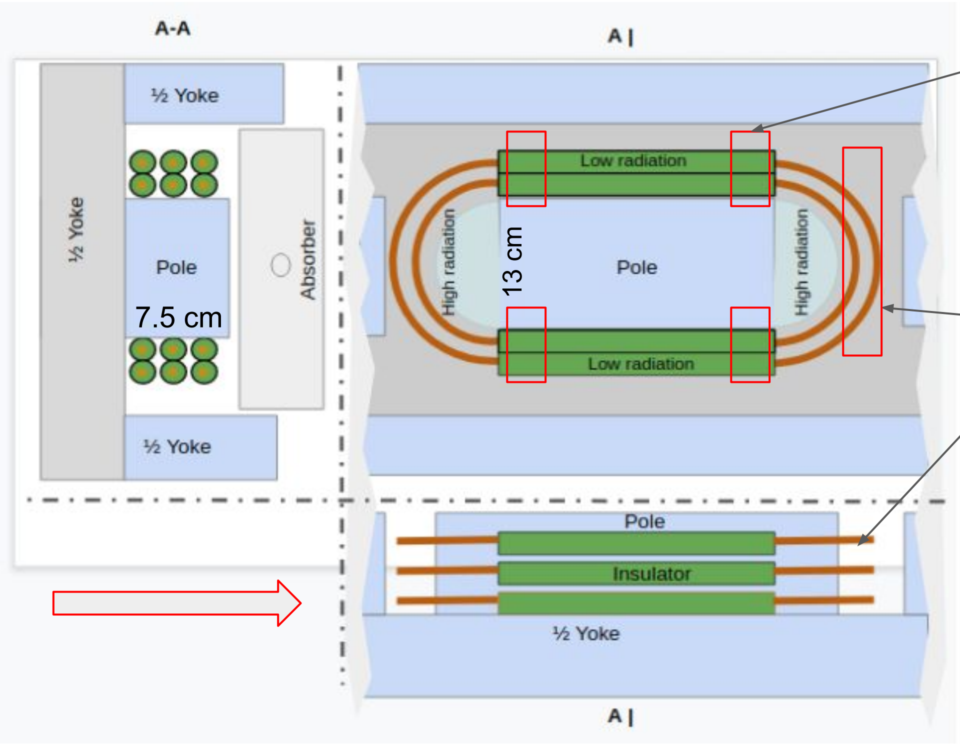
Coil insulation lifetime.

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.

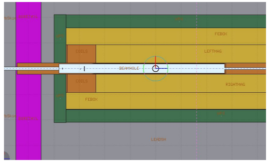
Ampere's force law:

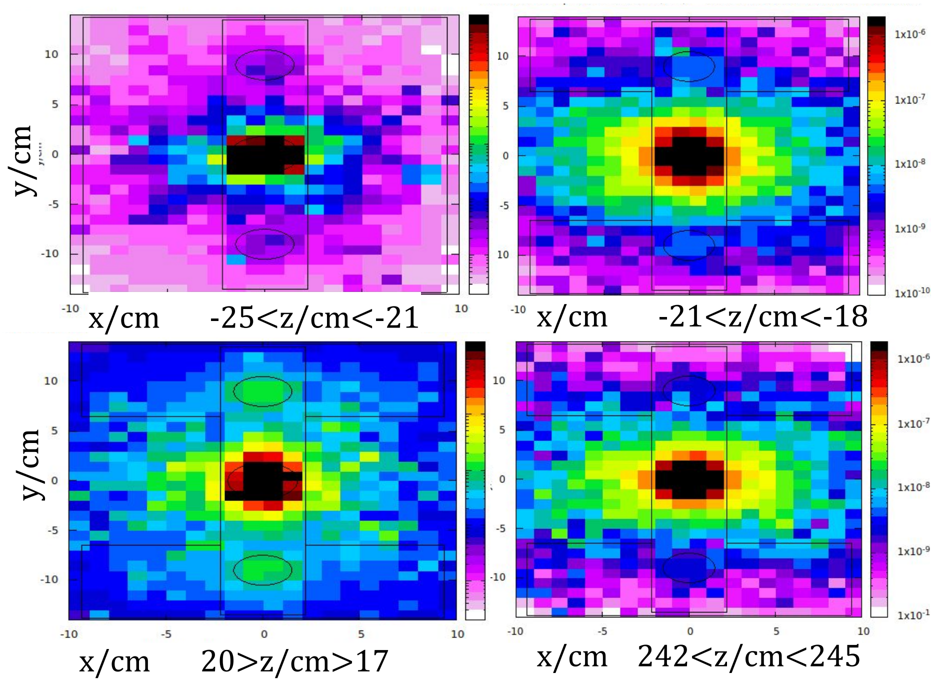
$dF/dl = (\mu_o / 2\pi)(I^2/d) = \sim 25$ N/m

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 .

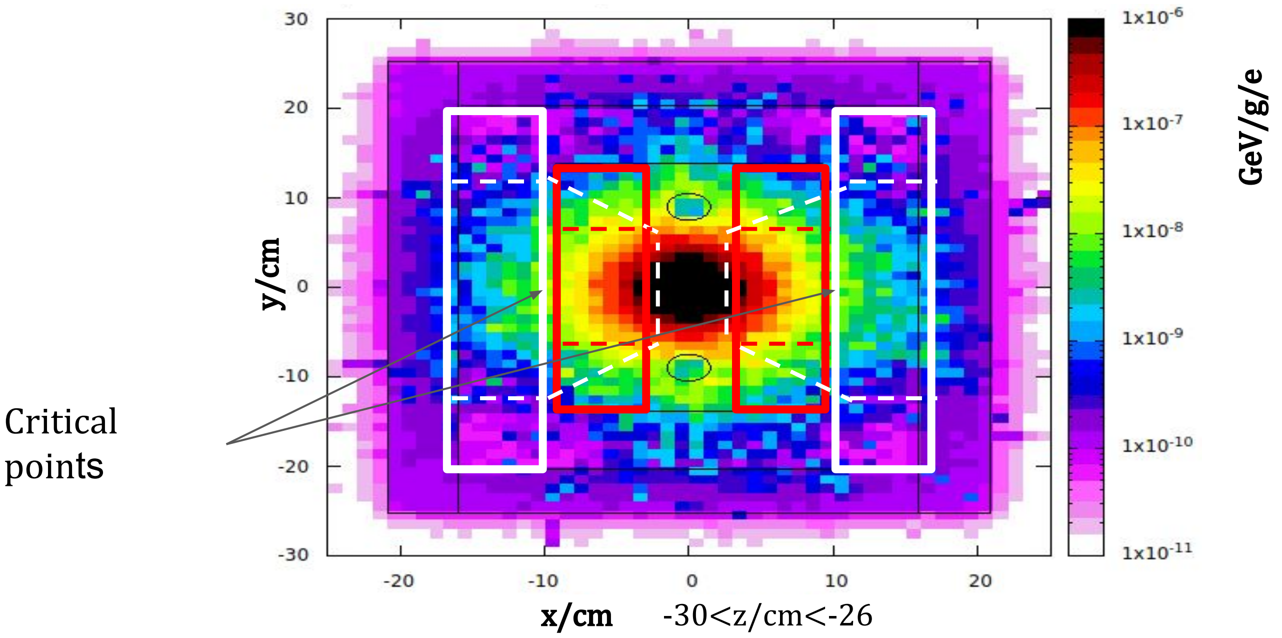
Prompt Dose in Coils and Insulation Lifetime (straight part).





- Reference 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.

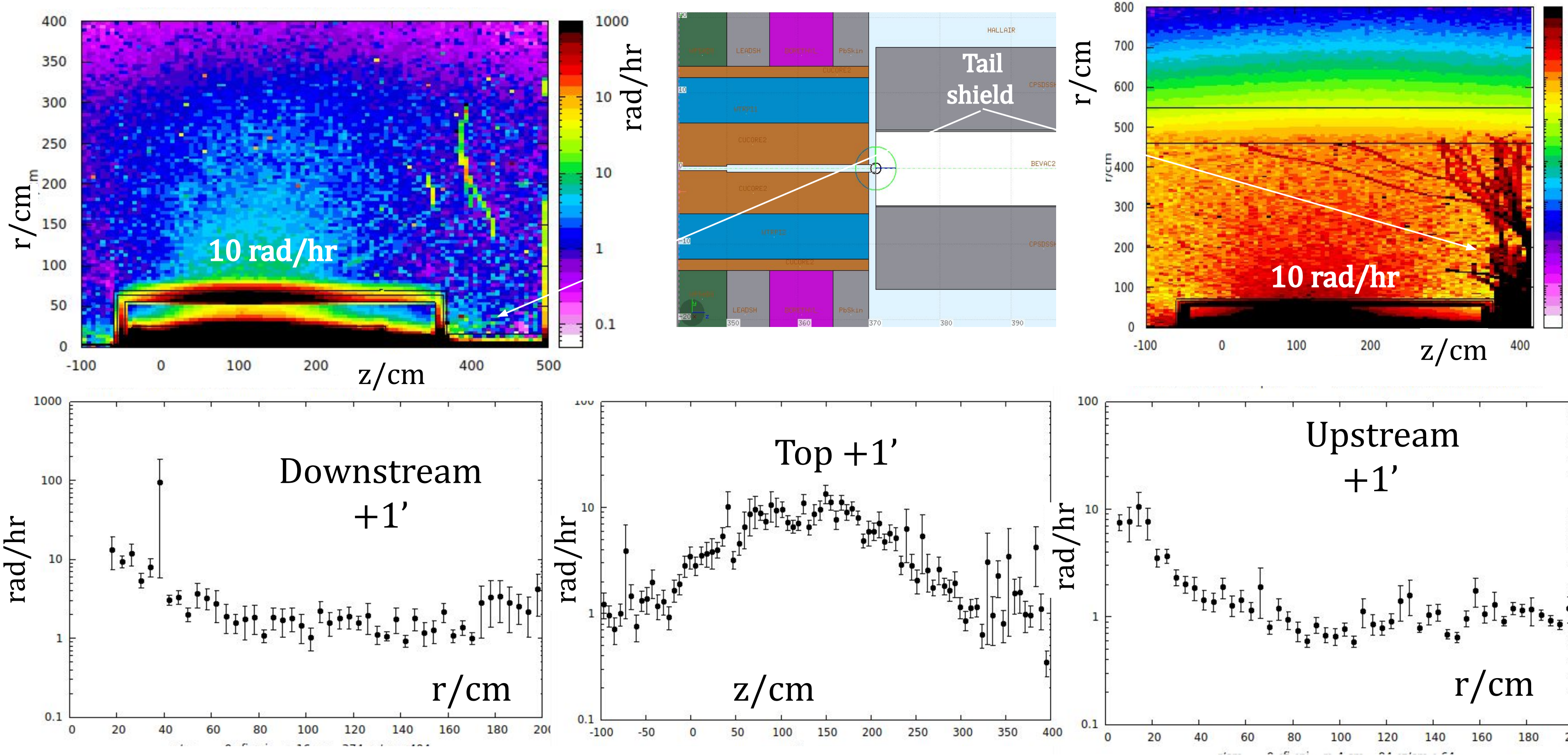
Benefit of wider magnet (+14 cm).



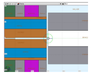
- Dose rate in critical points **0.1 Gy/s** (**2.E-8 GeV/g/e**)
- For 14 cm wider Magnet Insulation Lifetime in Coil return area is of **15 years.**

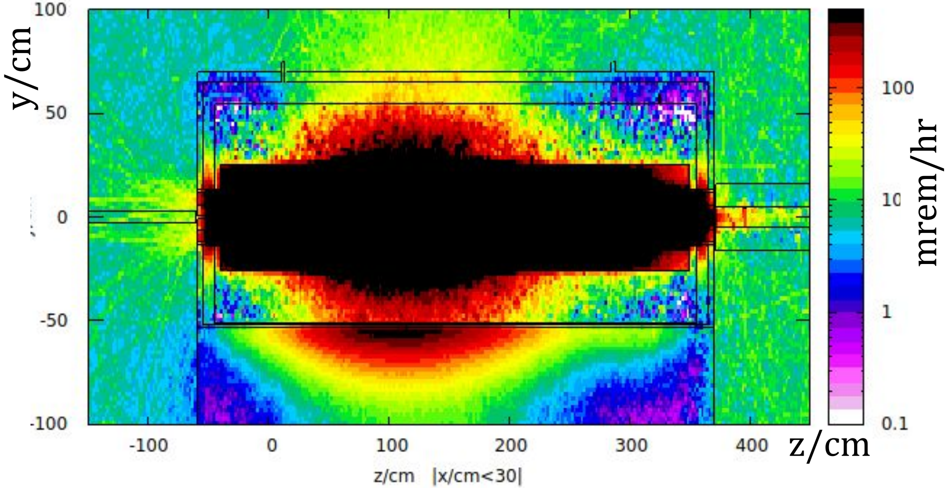
Prompt Dose and Activation around CPS

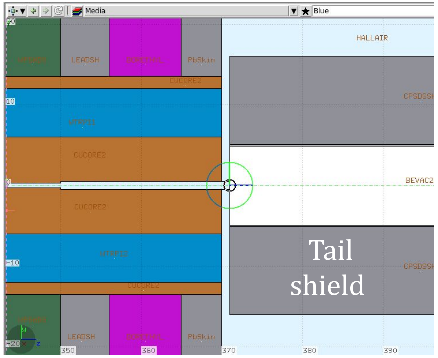
Prompt Dose Rate around CPS < 10 rad/hr . Effect of Tail shield .

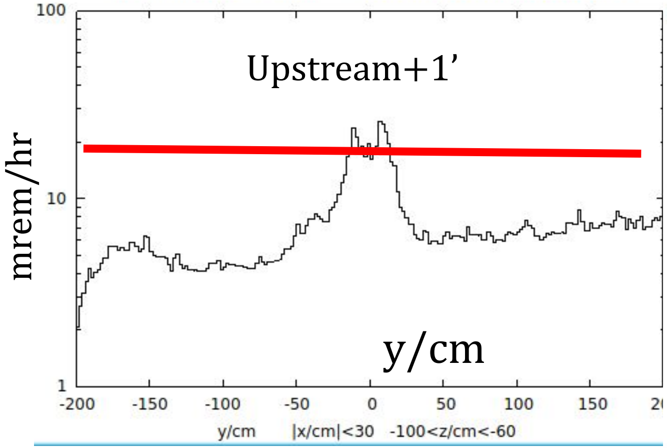


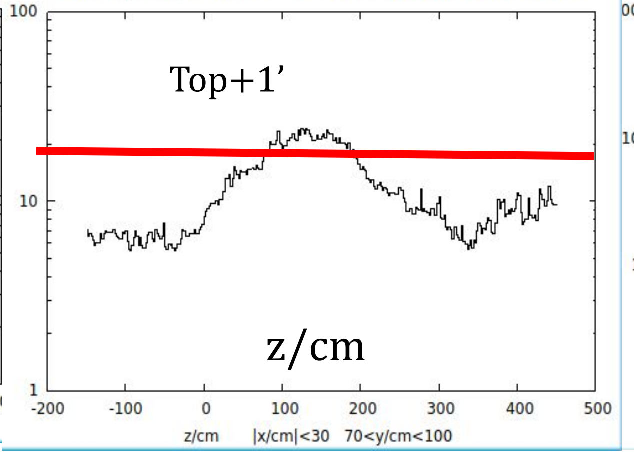
Activation After 1000+1 hr < 20 mrem/hr.

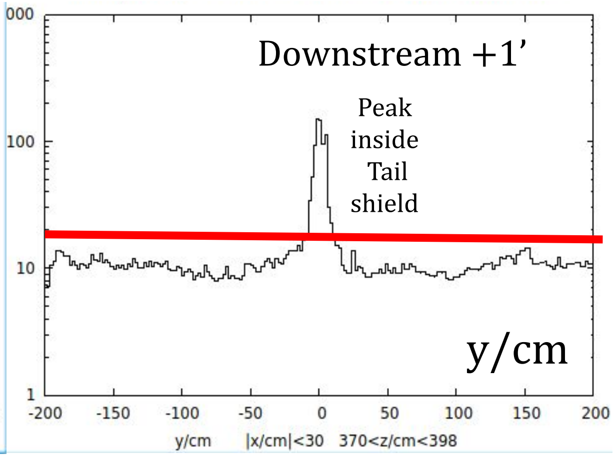




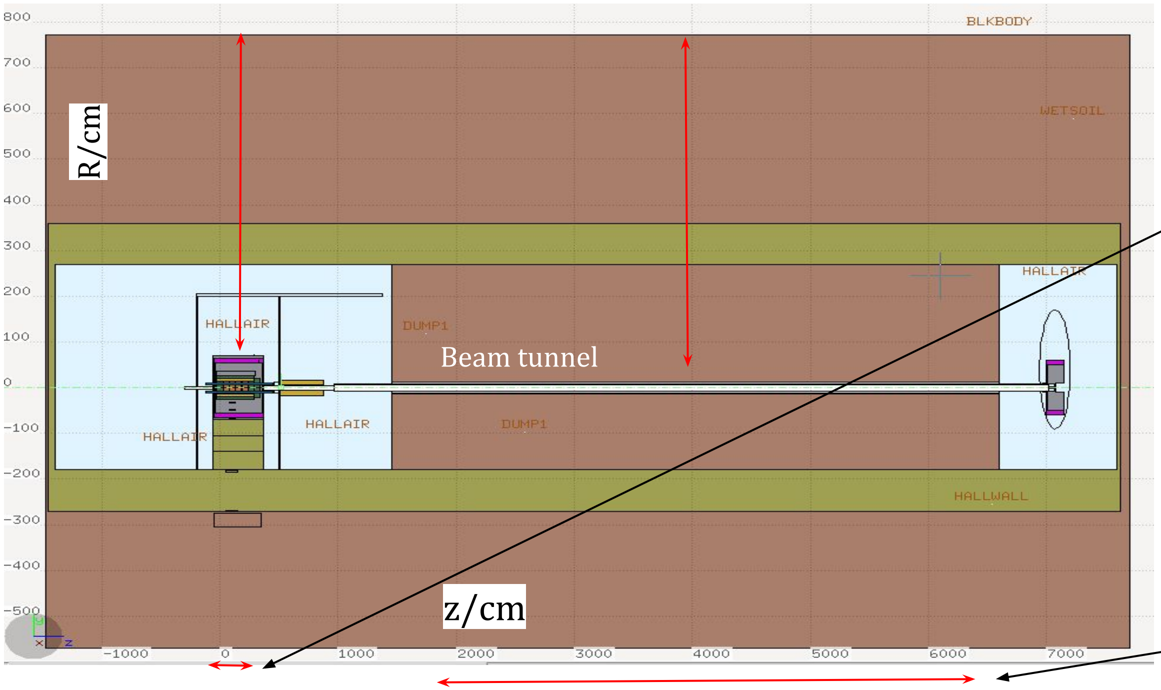


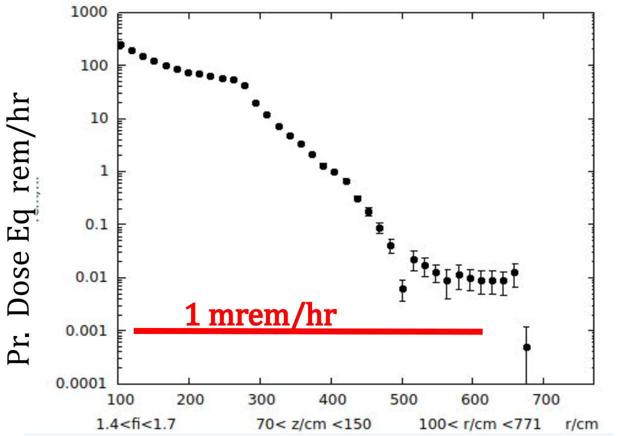


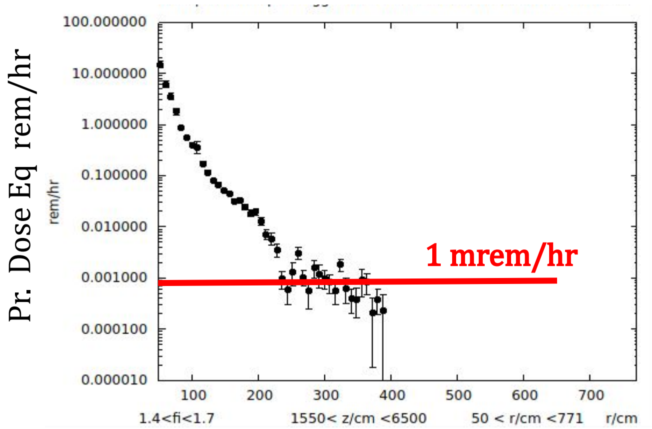




Prompt Dose Equivalent in Tagger hall and Beam Channel.



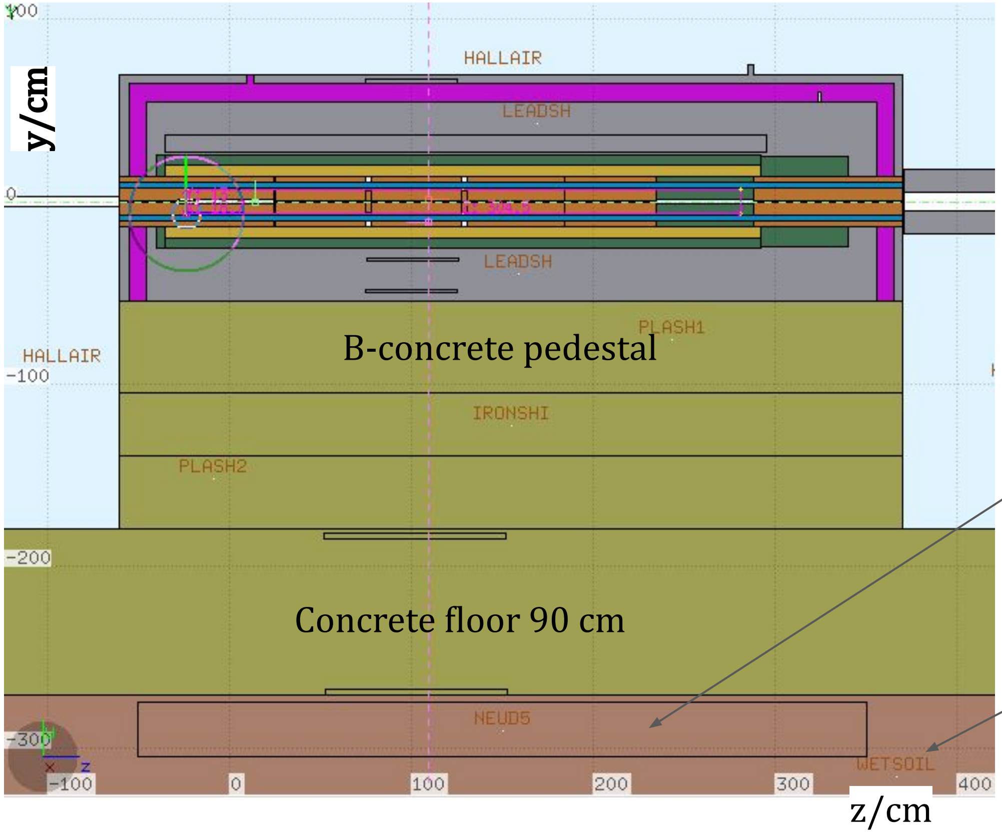




- Prompt DE is below **1 mrem/hr** at R = ~2.5 on top of Beam Tunnel.
- Prompt DE on top of hall mound R=7.7 m below **1 mrem/hr.**

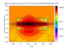
Tritium activity in Soil
and
Cooling Water

Tritium detector in FLUKA model

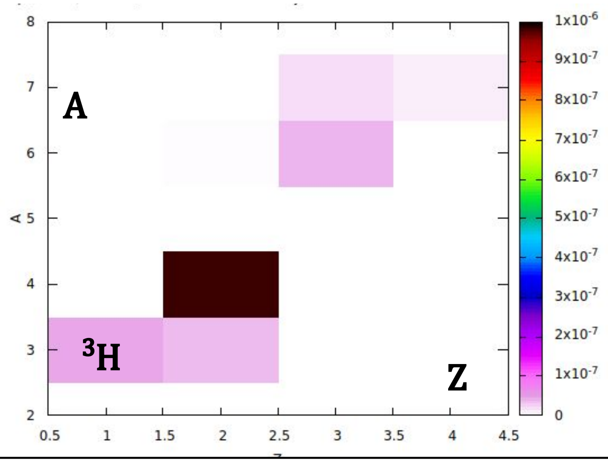


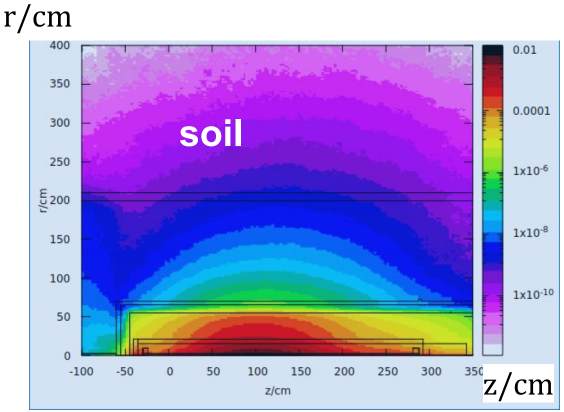
Tritium detector
$V=2*0.3*4\ m^3=$
$2.4\ m^3$

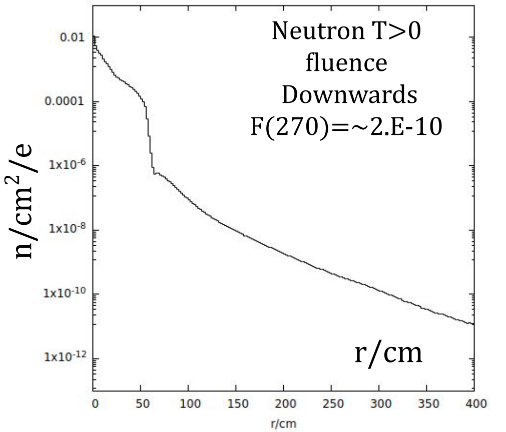
Soil.
Wet sand with 20% of water



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







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

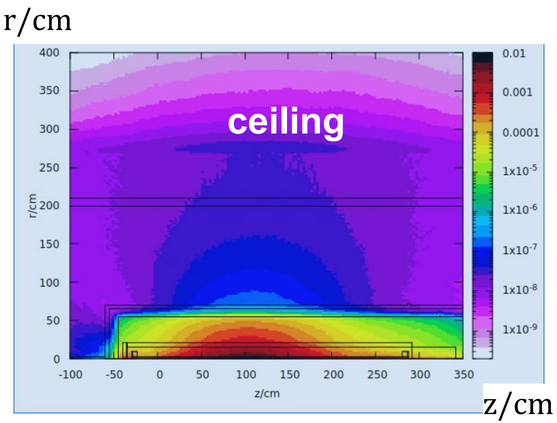
^{3}H yield per year **N=**1.E-7 [T/e] 3.E+13 [e/s]3.14E+7[s] =**1.E+14.**

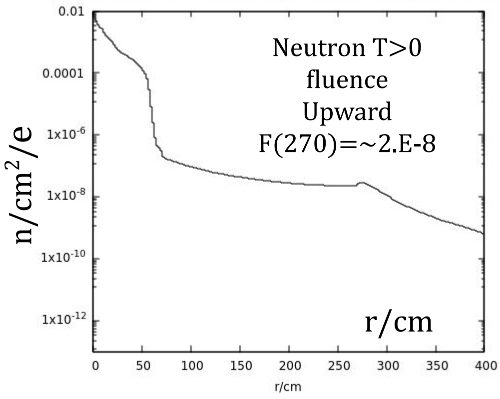
Activity of soil volume after one year:=

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

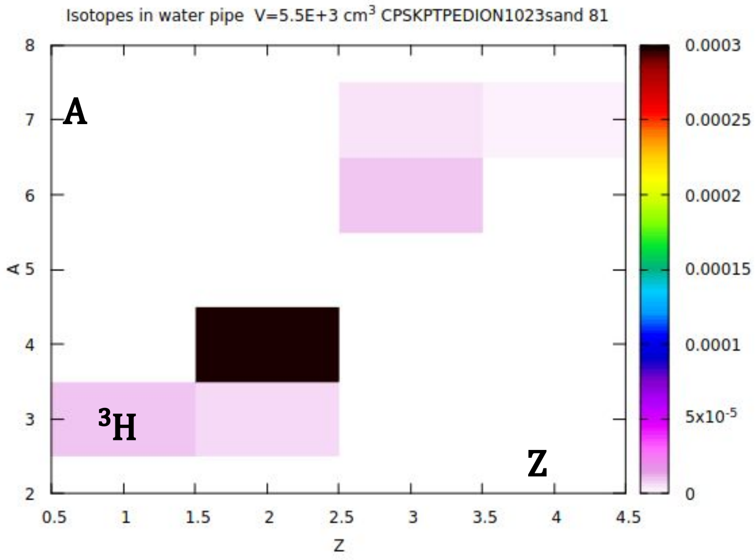
Or ~200 Bq/L in water (~20% by volume in soil).

- **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]**

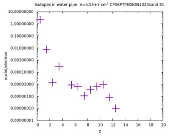
Number of T nuclei produced in one year: =

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.



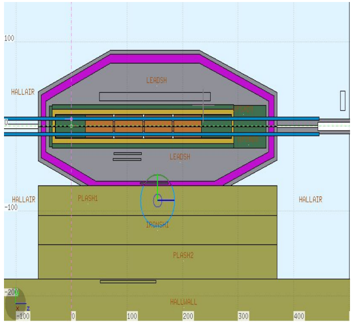
Lifetime of various materials from FLUKA simulations.

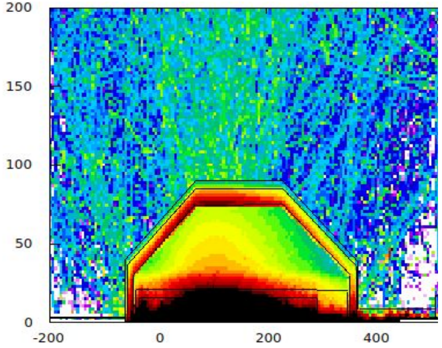
Material lifetime from FLUKA simulations

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.

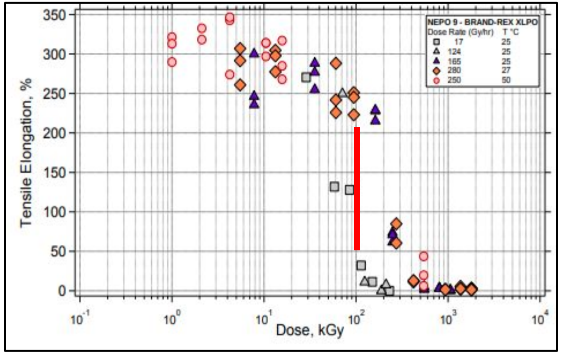
- Blowing He through CPS may prevent oxidation and improve lifetime of some materials.

Prompt dose and Polyethylene lifetime.

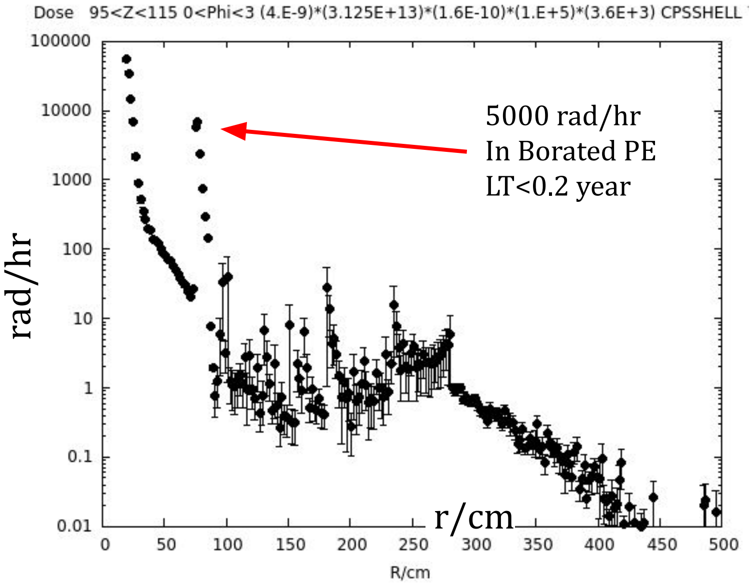




PE Tensile Strength vs Dose/kGy
1Gy=100 rd



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.



- 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.

CPS 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

- Cost without magnet - $793,000.
- Cost of Tungsten - $543,000.

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^o C** , **Pb** shield < **100^o 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<**150^{o}C**, 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**.

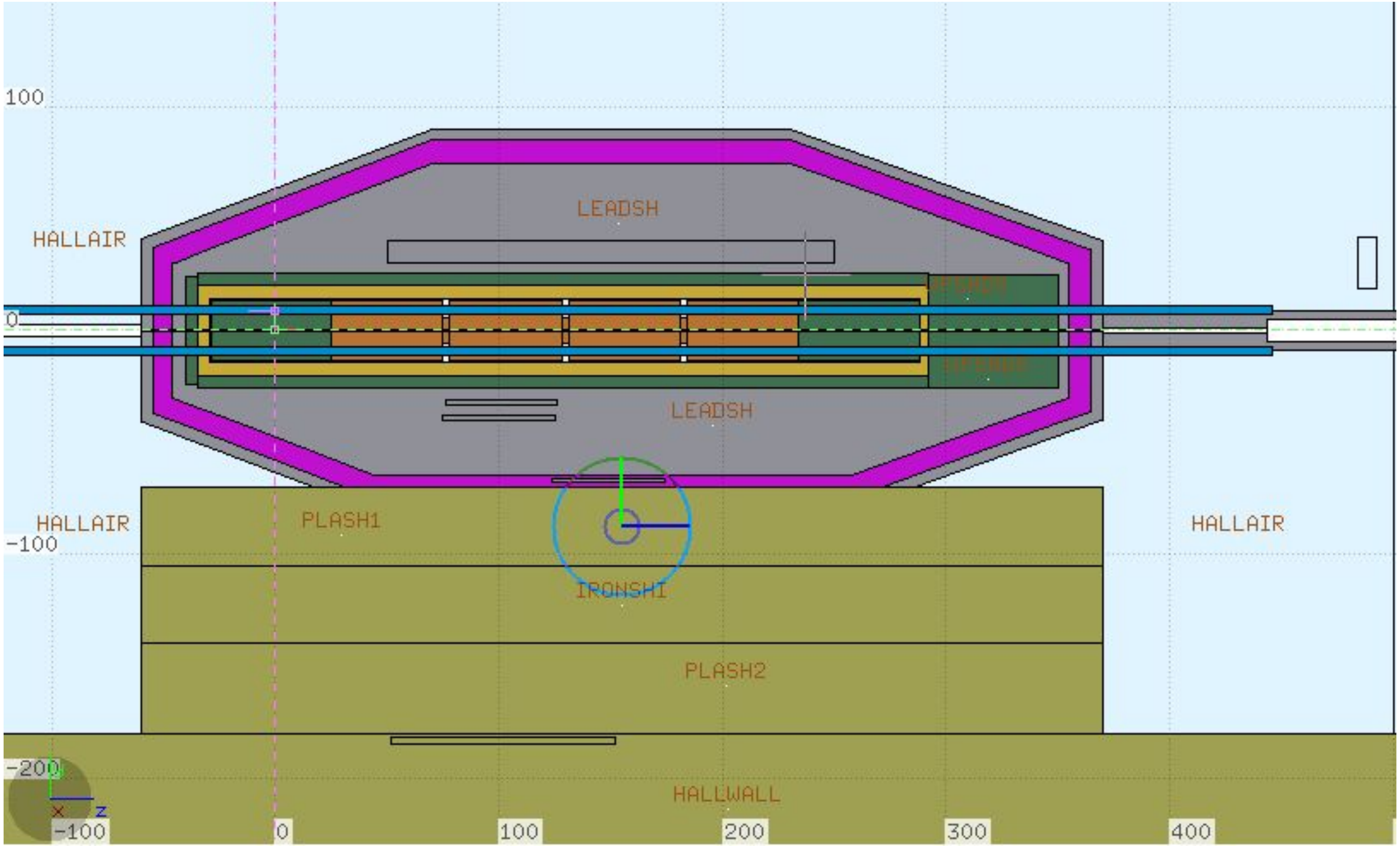
Conclusion

In our concept the **CPS is** an **Adjustable Unit** housing the entire Beam Channel. It is surrounded with several layers of shielding materials. CPS provides a 99% clear beam of 3.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.



The End