Conceptual Design of Compact Photon Source for KLF

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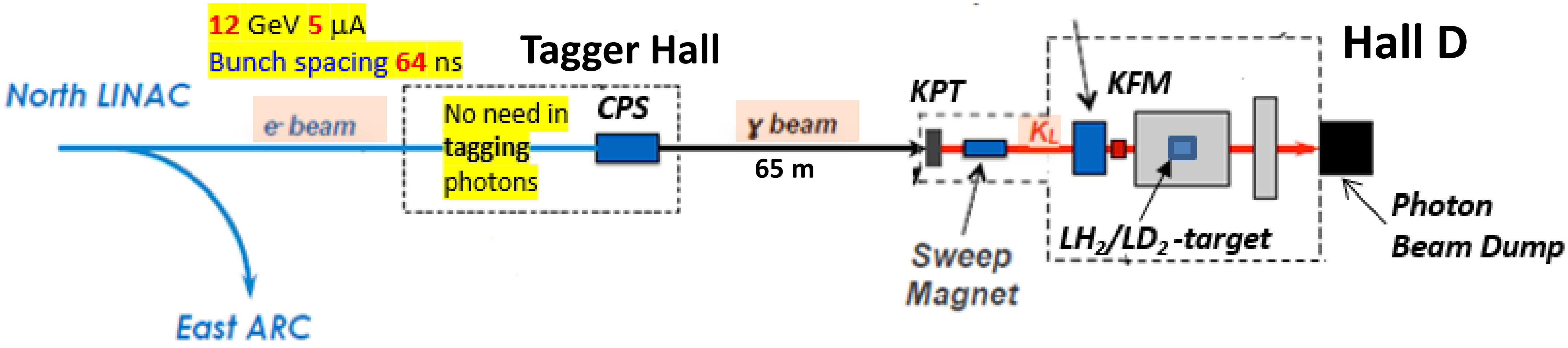
Overview

- Requirements for CPS
- Model Description
- Photon Beam from CPS
- Radiation Environment
- Temperature in CPS absorber
- Electron Beam Requirements for CPS
- Summary

Introduction

KLF Layout

- KLF experiment needs to produce high intensity photon beam upstream of KPT.
- CPS stands for Compact Photon Source; it has been proposed as the photon source.
- The only possible location for such a source is the Tagger Hall.
- CPS beamline will require major modifications to GlueX photon beamline.



Review Charge Items

- Is there any R&D needed to be done prior to start the construction of the Klong Facility? ✓
- What is the status of the Compact Photon Source (CPS)? Specifically:
  a) the conceptual design ✓
  b) the evaluation of the produced radiation. In particular, the following points should be discussed: ✓
    1. the approximations made in the Monte Carlo simulations and which code has been used; ✓
    2. the energy deposition and the absorber temperature; ✓
    3. the prompt dose and activation around the CPS and the Tagger Hall; ✓
    4. the magnet performance and its coils lifetime; ✓
    5. ~~the water-cooling system and possible contaminations.~~ (Tim's talk)
- Will civil constructions be needed to contain the radiation in the Tagger Hall? Not needed
- What will the photon beam quality be? ✓
- What are the requirements of the electron beam on the CPS? ✓
- What is the decommissioning plans for the K-Long Facility (CPS, KPT,….) and the activated components? A brief outline is sufficient. ✓

CPS Requirements

- Intense photon flux of $\Phi_\gamma > 10^{12}$ photons per second with $1.5\ \text{GeV} < E_\gamma < 12\ \text{GeV}$.
- Photon beam spot size at KPT with $2 \cdot \text{FWHM} < 6\text{cm}$ to make full use of KPT size.
- Radiation environment in the Tagger Hall similar or better than what GlueX would get with 5μA electron beam on nominal GlueX diamond radiator.
  - Prompt equivalent dose rate of ~20 rem/h.
  - Activation does rate <5 mrem/h after 10000 hours of operations and 1 hour of cool-down time.
  - RadCon limits <1 mrem/h for prompt equivalent dose rate outside of the Tagger Hall.
- Cooling system design that is sufficient to handle ~54 kW power delivered to CPS.
  - It will need to be closed-circuit system to avoid activation/contamination.
- GlueX beamline should be restored relatively quickly without disassembly of CPS.
  - GlueX photon beamline is wider than CPS beam channel and is under vacuum.
  - We decided to build a movable platform to move CPS beam-left.
  - There is sufficient space in the tagger hall for the current CPS design.

Used Software

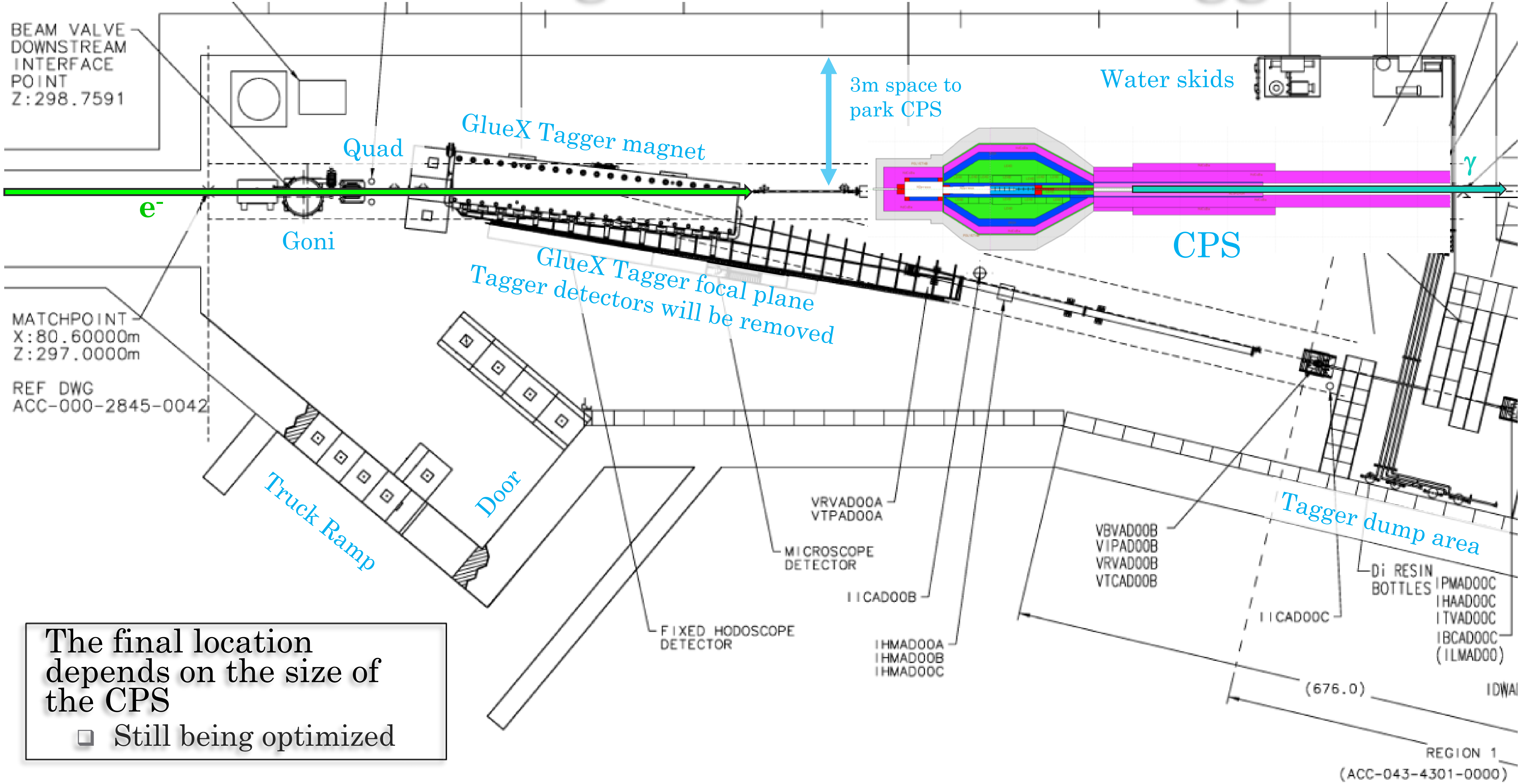
- FLUKA 2021.2.9
  - CPS design
  - Prompt radiation levels
  - Activation levels
  - Accumulated doses
  - Power deposition in the materials

- OPERA 18R2
  - Magnet prototyping
  - Magnetic field calculations

- ANSYS Workbench 2022 R2
  - Thermal analysis
  - Stress and deformation analysis

- Wolfram Mathematica 13.1.0
  - Thermal analysis

CPS Positioning in the Hall D Tagger



The final location depends on the size of the CPS

- Still being optimized

CPS Model

Development of the Design

- We started will Hall C version of the CPS.
  - Very compact design
    - Small footprint in the hall.
    - The radiator, magnet, and the absorber are in the same region.
    - High power deposition densities leading to high temperatures in the core.
    - Requires a magnet with high magnetic field B > 3 Tesla.
  - Hall C design costs $2M or more mainly due to the use of tungsten as shielding material.
- Considered two different models with lower magnet field during last year.
  - Vitaly Baturin developed a model in the summer of 2022.
  - Pavel Degtiarenko proposed another model in the fall of 2022.
  - After studying both models, we chose one for further optimization and engineering design.
- Currently we are in process of optimizing the conceptual design.
- People involved in CPS design work:
  - Physicists: V. Baturin, P. Degtiarenko, H. Egiyan
  - Engineers: T. Whitlatch
  - We may recruit a mechanical engineer to work of engineering design in the fall.

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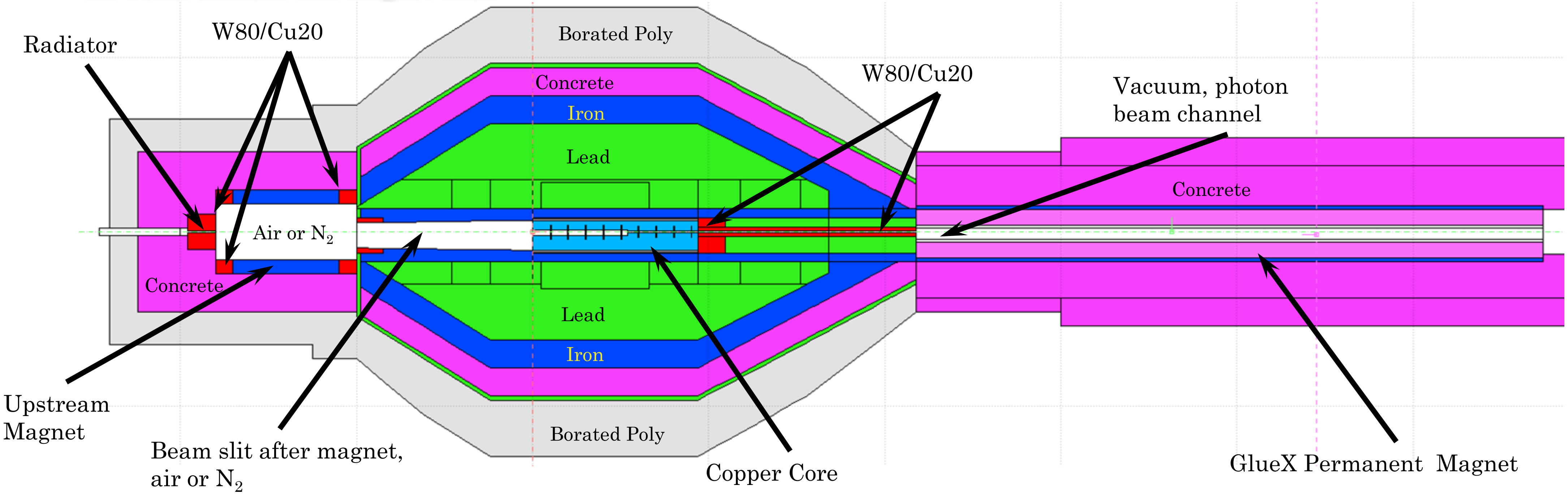
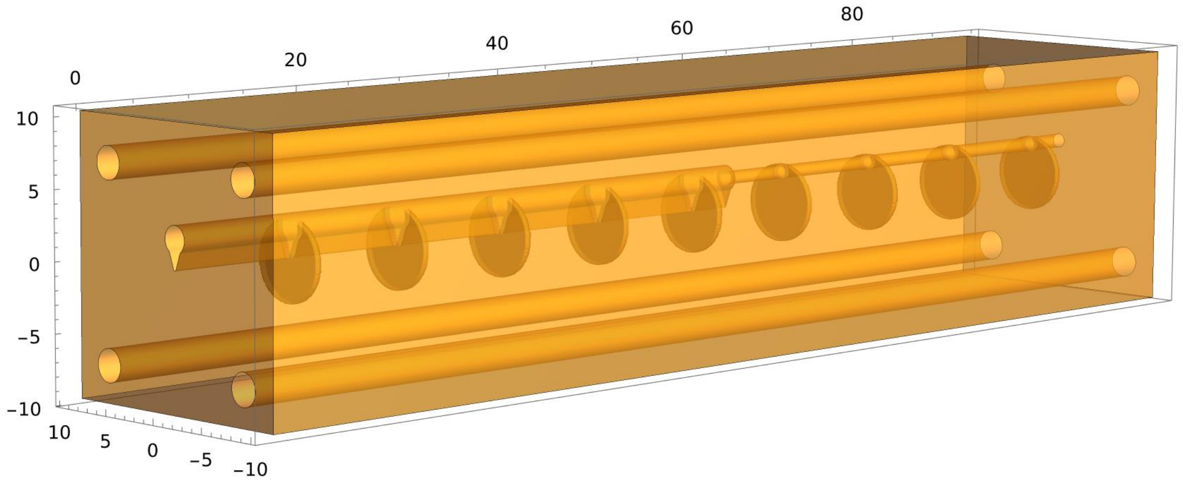
Hall D CPS Model

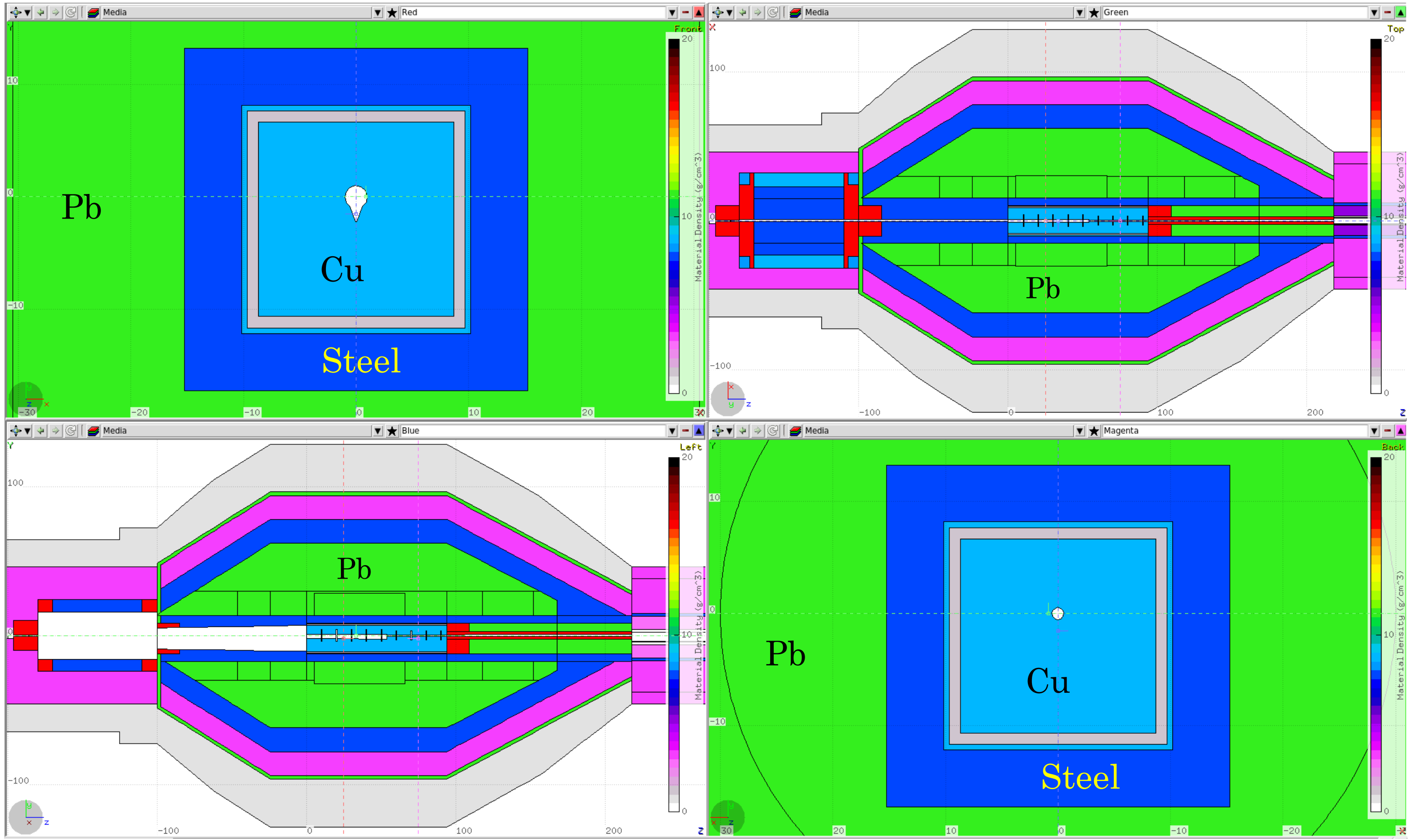
- Magnet and the absorber are separated by 1 meter .
  - No heat load on the magnet poles and coils from the core.
  - Low radiation exposure to the magnet.
- Clean-up magnet downstream for charged particles.
  - Utilize the existing permanent magnet used in GlueX beamline.
- No tungsten is used in the CPS shielding.
  - We save cost by using lead instead.
  - Small amount of a tungsten-copper mix is used for shielding the beam channel and magnet coils.
- Total estimated weight of CPS is approximately 76 metric tons.
  - Includes downstream beamline shielding.
  - Movable platform will add more weight.
  - Tagger Hall should easily handle CPS weighing 100 tons.
- Estimated cost of the current design is ~$1M for CPS
  - Upstream beamline instrumentation will be extra.
- Tim Whitlatch will discuss engineering and cost related aspects in detail.



CPS Absorber

- Copper core with dimensions of 20cm x 20cm x 94cm.
  - To absorb and dissipate the power.
  - Copper is not ferromagnetic and is a very good heat conductor.
- Varying size beam channel to trap the secondary particles from the electromagnetic shower.
  - Wider cavity upstream for trapping electrons and EM shower remnants.
  - Narrow conical channel with diameter ~1cm for outgoing photons.
- Cooling channels for water flow capable of evacuating ~54 kW power.
- Copper absorber is surrounded by air, steel, and W/Cu mix.
  - No contact with lead.





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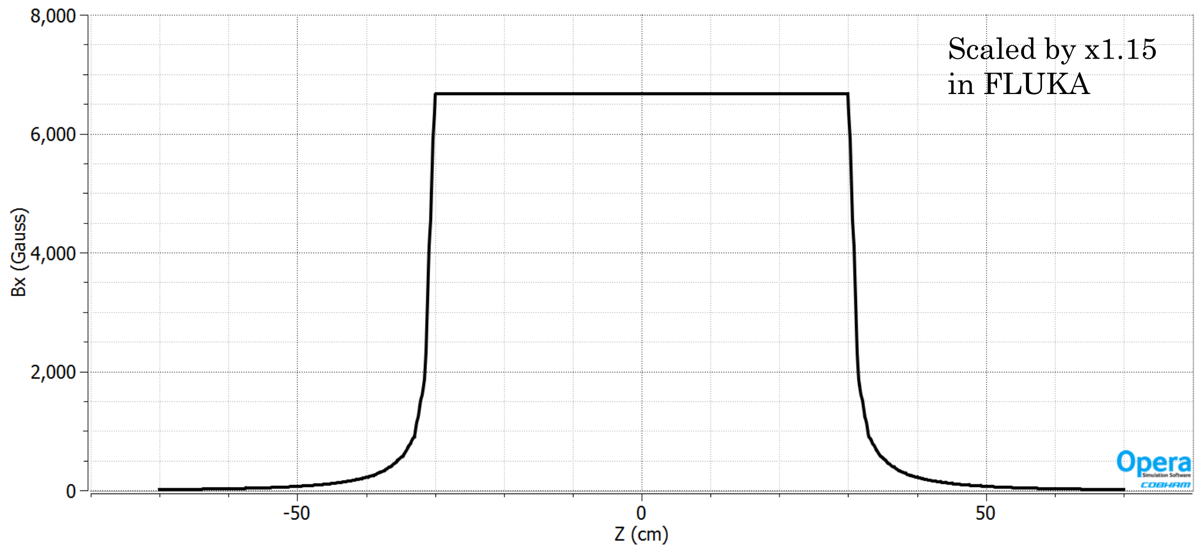
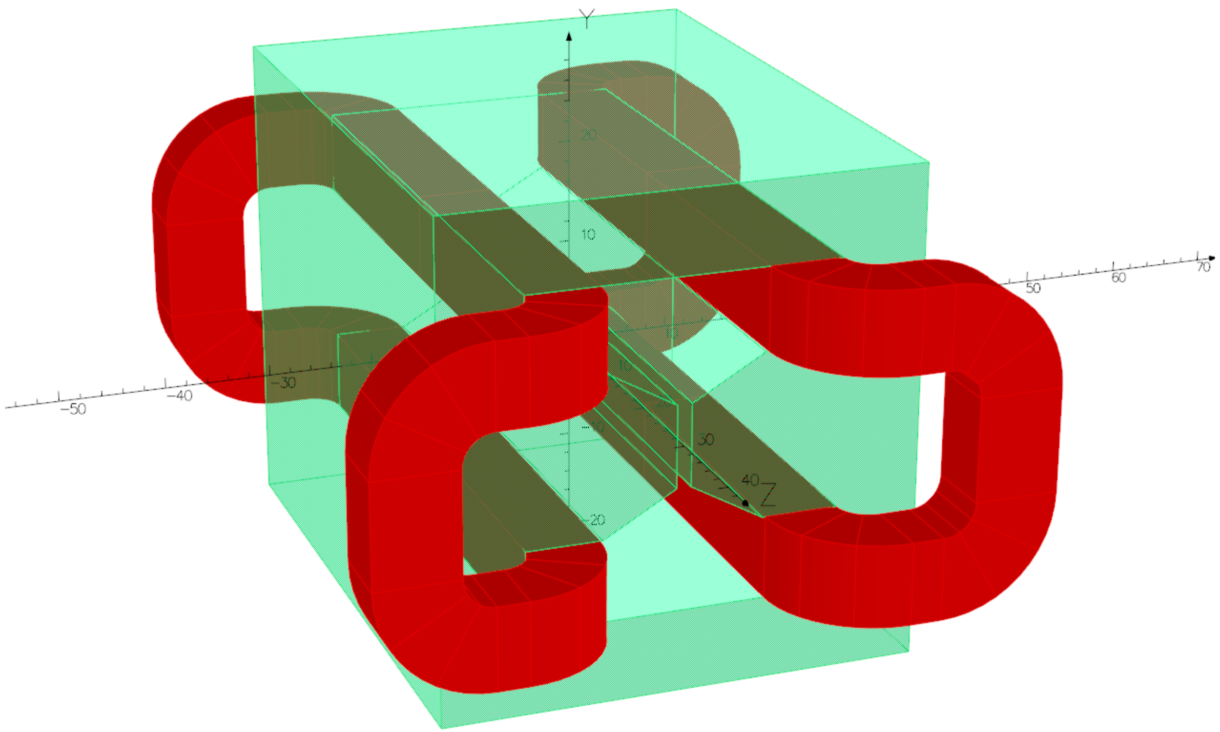
Upstream Magnet

- Current CPS design requires ~0.48 T·m magnetic field in the x-direction.
- We developed a draft model of the magnet.
  - Magnet has 60 cm long coils.
  - Bedstead shape of coils for less radiation exposure.
  - The closest distance from coils to the beam center is ~11cm.
- The gap should be on the order 1 cm or more to avoid interaction with beam tails and halo.
  - Current design assumes 1.4 cm gap.
- Iron yoke with 8 cm thickness.
  - Total length of the yoke is 60cm
  - The transverse size of the yoke is 46cm x 48 cm.
- Chamfered iron poles.
- We used OPERA to calculate the field in the model.
  - The model can provide a dipole field of 0.67 T at 67 A/cm² current density in the coils.
    - Should be able to use Tagger Magnet power supply.
  - The field in the yoke is far from saturation point.
  - Field map is used in FLUKA simulations, scaled by a factor x1.15 .

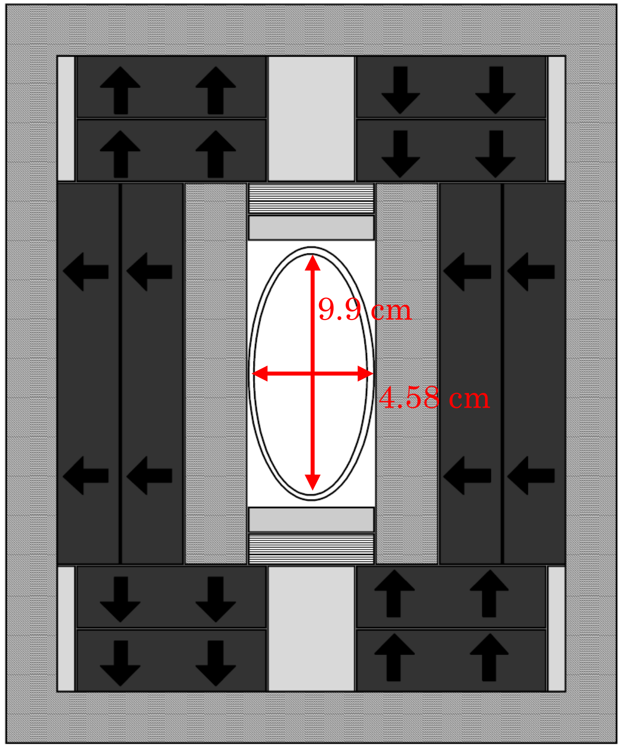


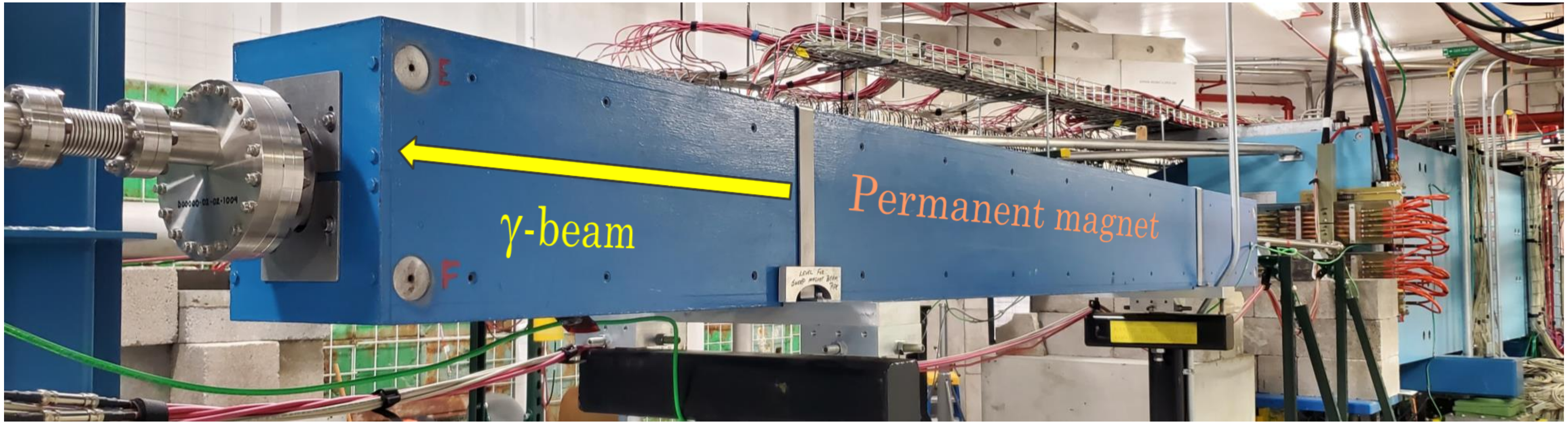


Downstream Magnet

- GlueX uses a 140” long permanent magnet from FNAL beamline to prevent electrons from leaking into the main hall.
  - Electron beam is interlocked to tagger magnet current at the power supply.
    - Leaks are only possible for short bursts when the tagger magnet trips.
  - KLF still needs it to prevent electron from accidentally penetrating to the hall.
- FNAL PDV magnet provides $\int B \cdot dL = 0.822$ T·m field integral.
  - The exact field of this magnet is not important for CPS itself.
- The magnetic material is made of strontium ferrite.
  - Can handle over 10^7 Gy radiation dose, according to the specs.

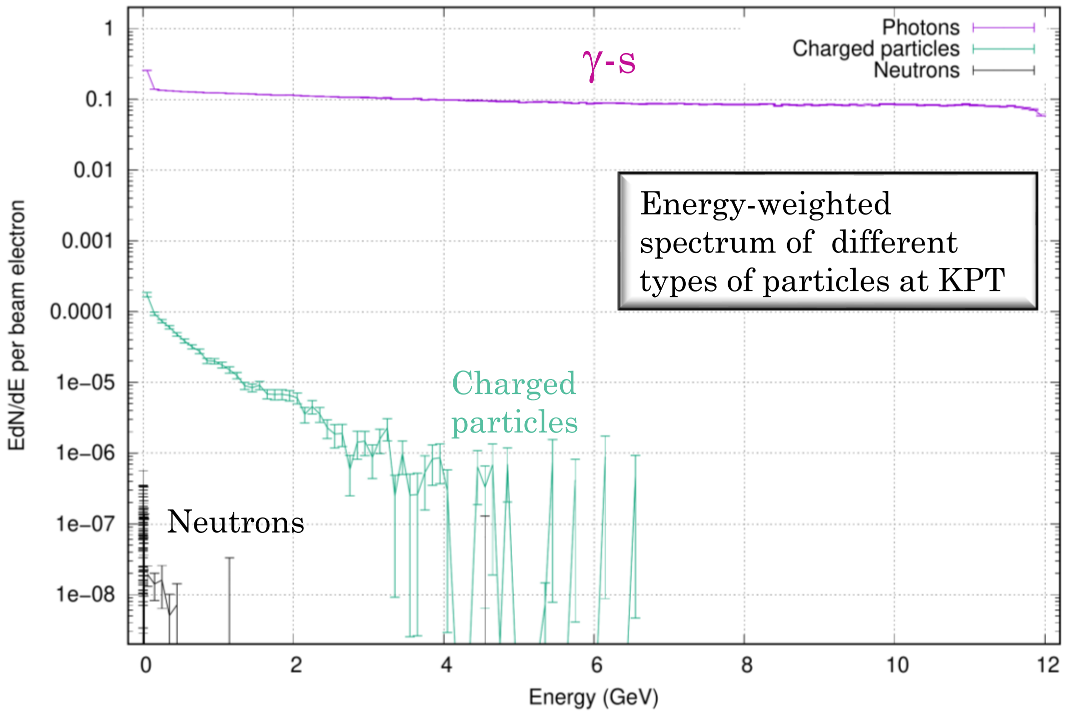
Cross section of the FNAL PDV magnet used by GlueX in the tagger hall.

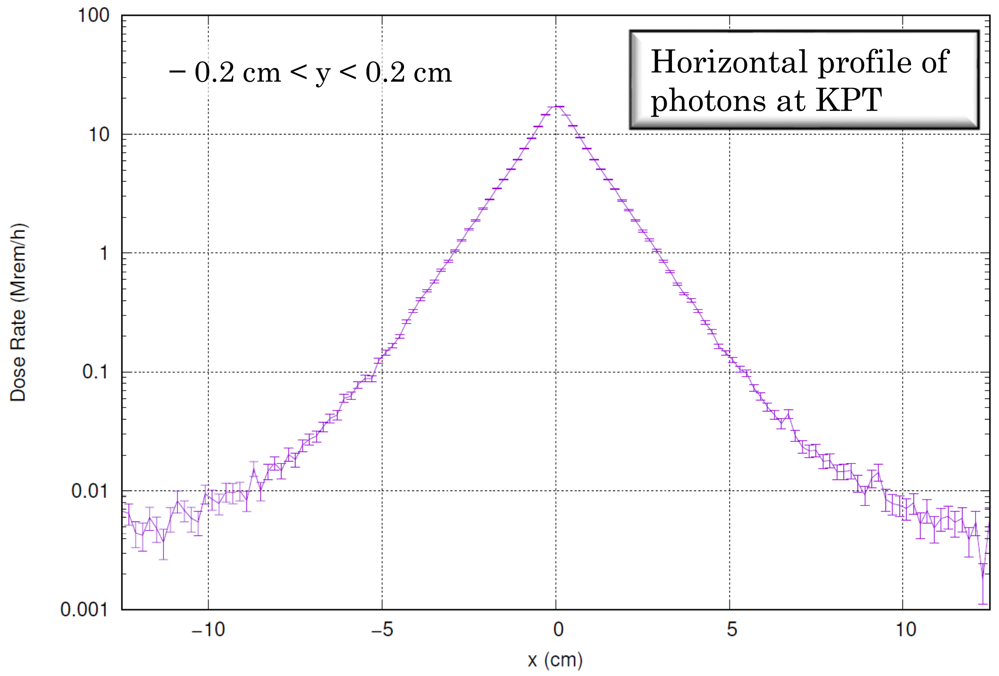


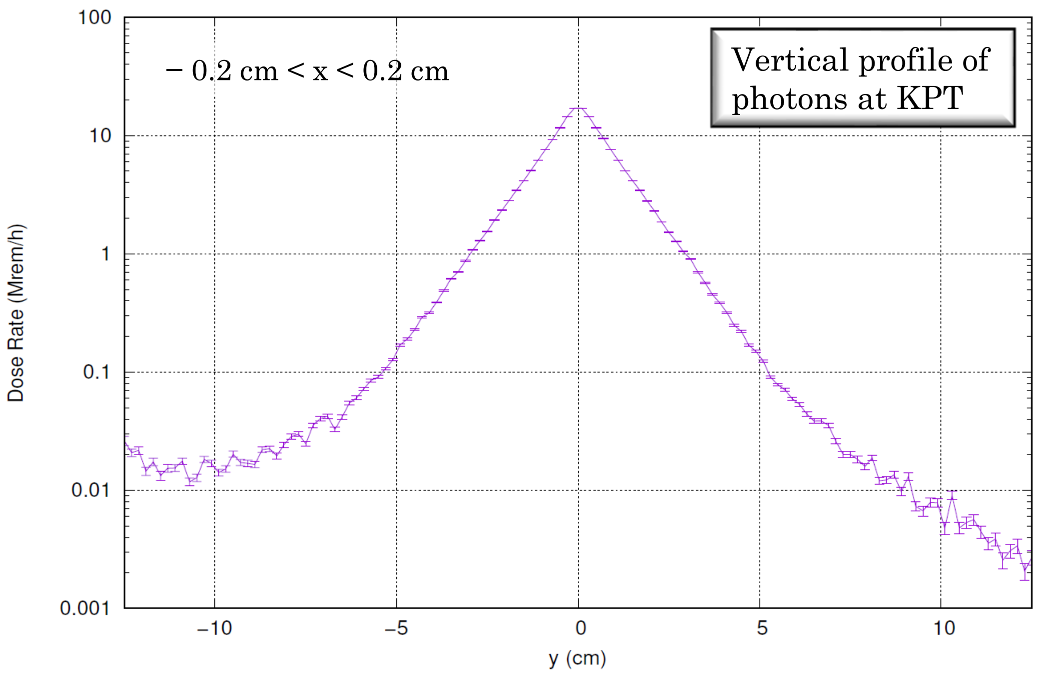


Photon Beam

- We used FLUKA to estimate the beam profile at KPT.
- Clean photon beam profile with $\sigma_\gamma \approx 1.5$ cm width.
  - The photon beam width at KPT is dominated by multiple scattering in the 10% radiator.
  - Vertical distribution has a slight asymmetry (on 0.1% level) favoring negative y-s.
- Charged particle and neutron rates from CPS measured at the KPT location is expected to be very small compared to the photon flux.







Radiation Environment

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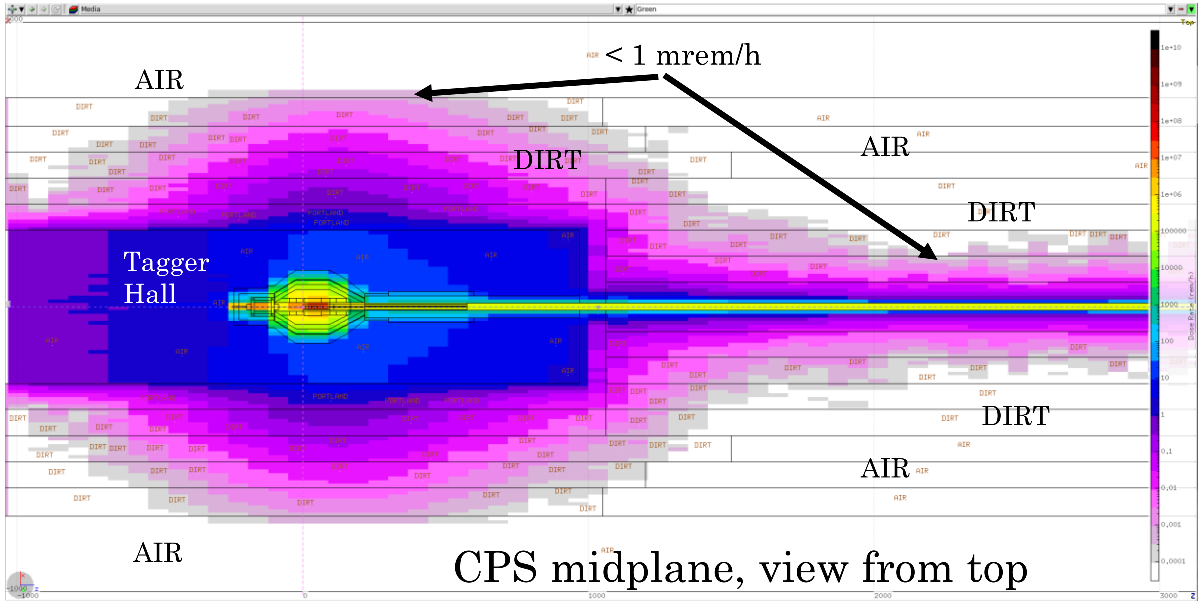
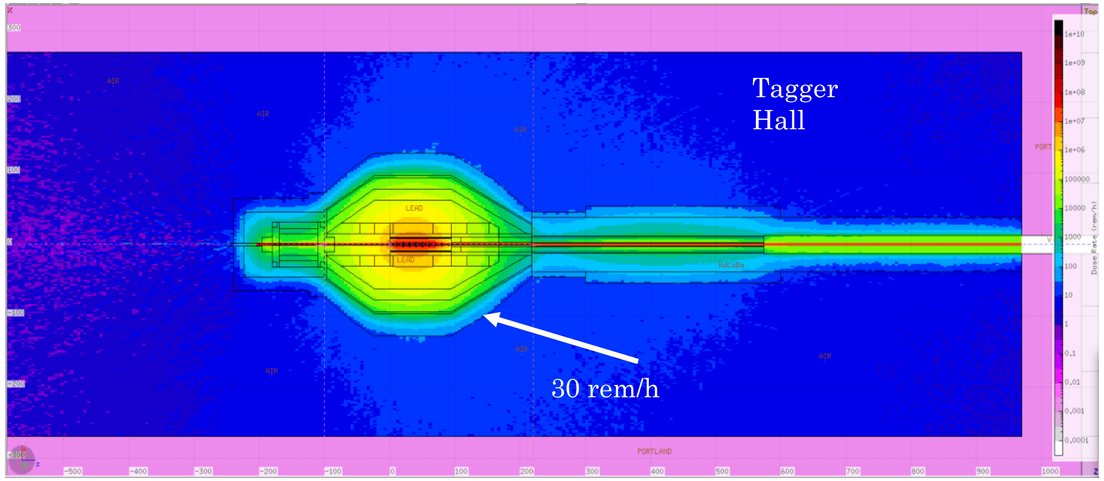
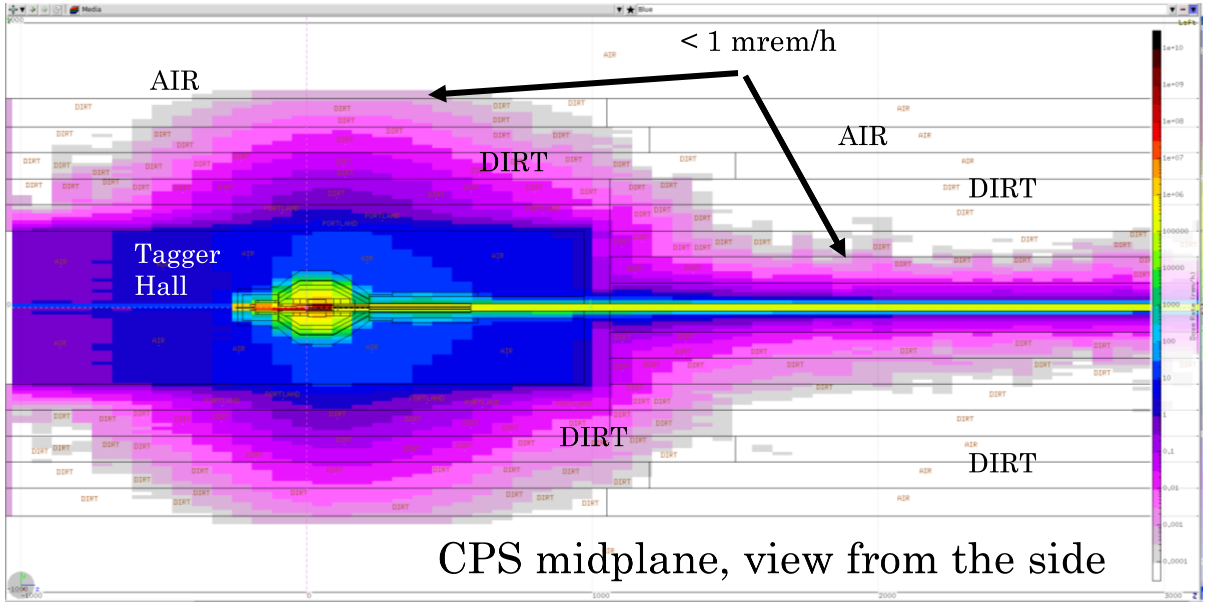
Prompt Dose Rates

- We estimated the prompt dose rates around the Tagger Hall.
  - More detailed simulation may need to be done.
- The results show that the rates on the surface of the berm will be below 1 mrem/hour.
  - No civil construction will be needed around Tagger Hall to contain radiation.
- The prompt dose rate around the 10" beam pipe between Tagger Hall and Collimator Cave above the dirt is negligible.
- Prompt dose rate inside Tagger Hall around CPS is ~20 rem/h.
  - ~30 rem/h right at the CPS surface.
  - <10 rem/h far away from CPS



CPS midplane, view from top





CPS midplane, view from the side

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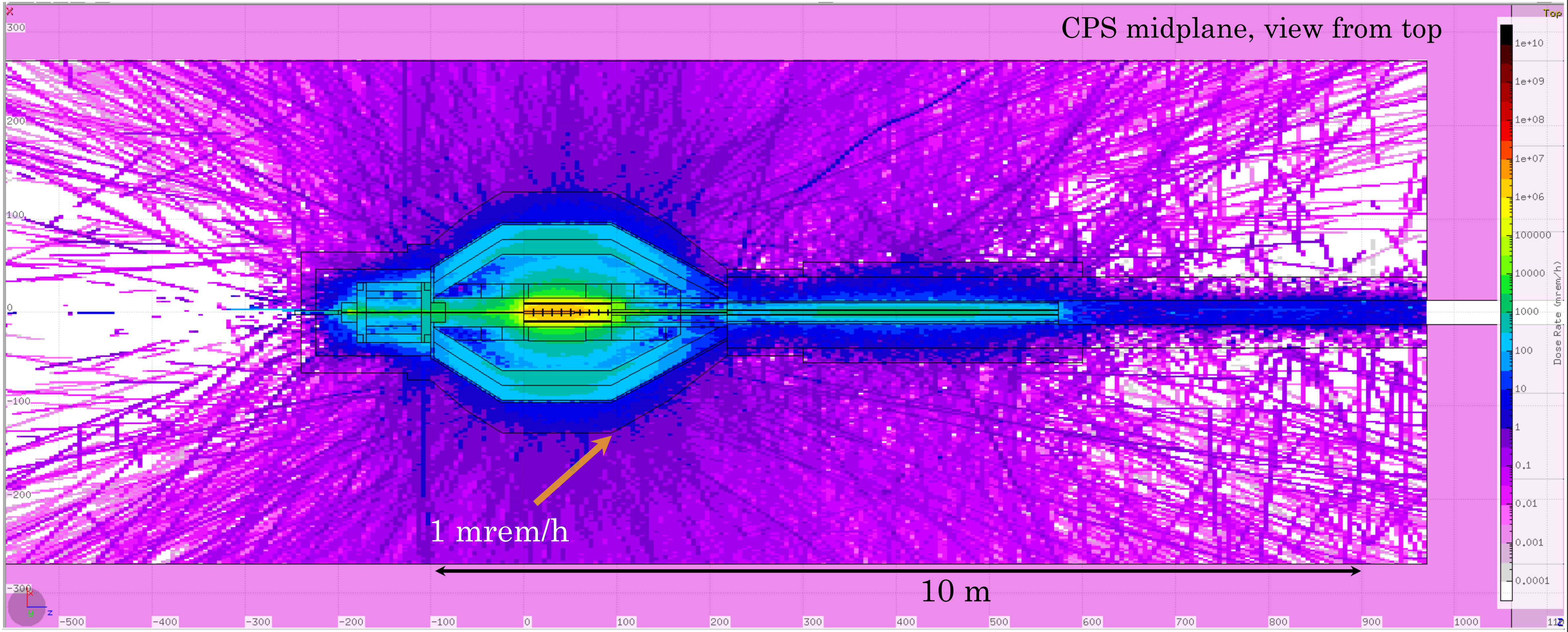
Activation Dose Rates

- We evaluated activation dose rate after 10000 hours of continuous operations and 1 hour cool-off time.
- The rates outside of CPS are expected to be <1 mrem/h, that is well within JLAB limits.



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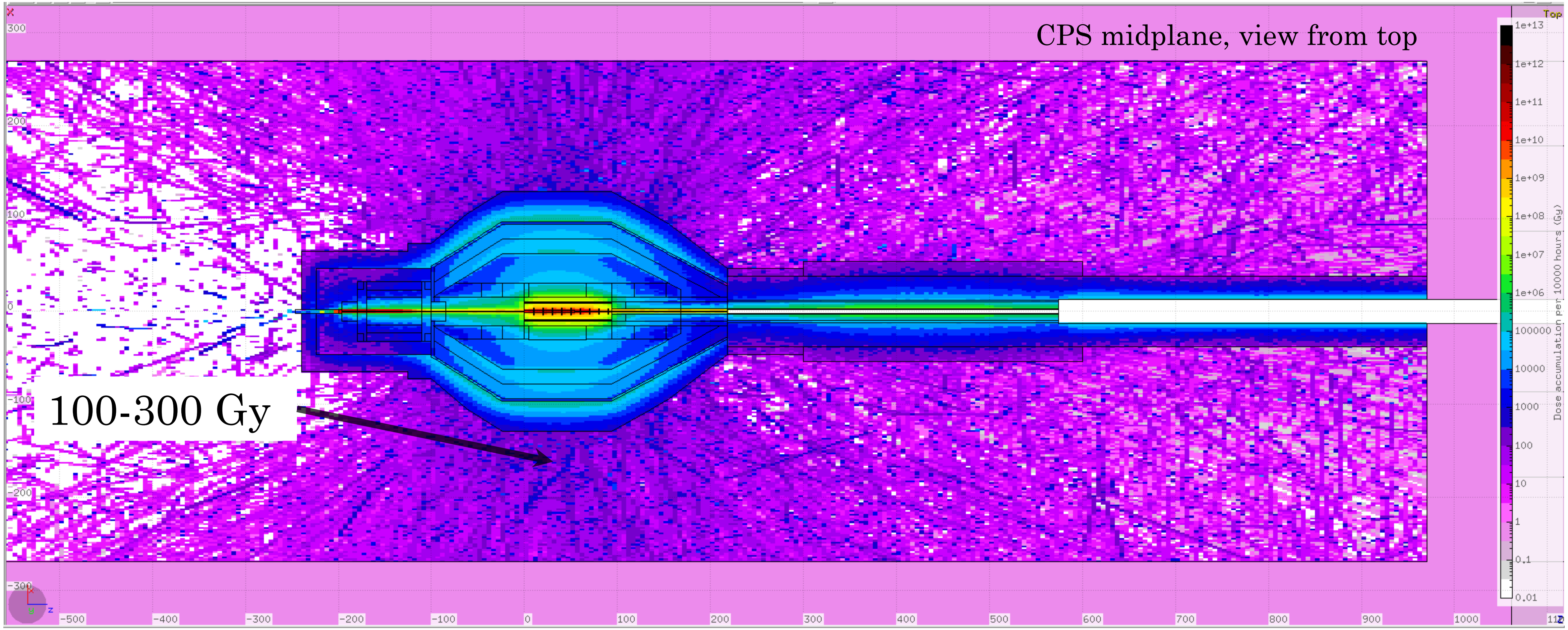
Accumulated Dose in 10000 hours

- Accumulated doses are evaluated outside of CPS.
  - We will use this map for equipment installations in the tagger hall.
- CPS is not expected to be disassembled for a very long time.
  - It can be moved aside to restore GlueX photon beamline.



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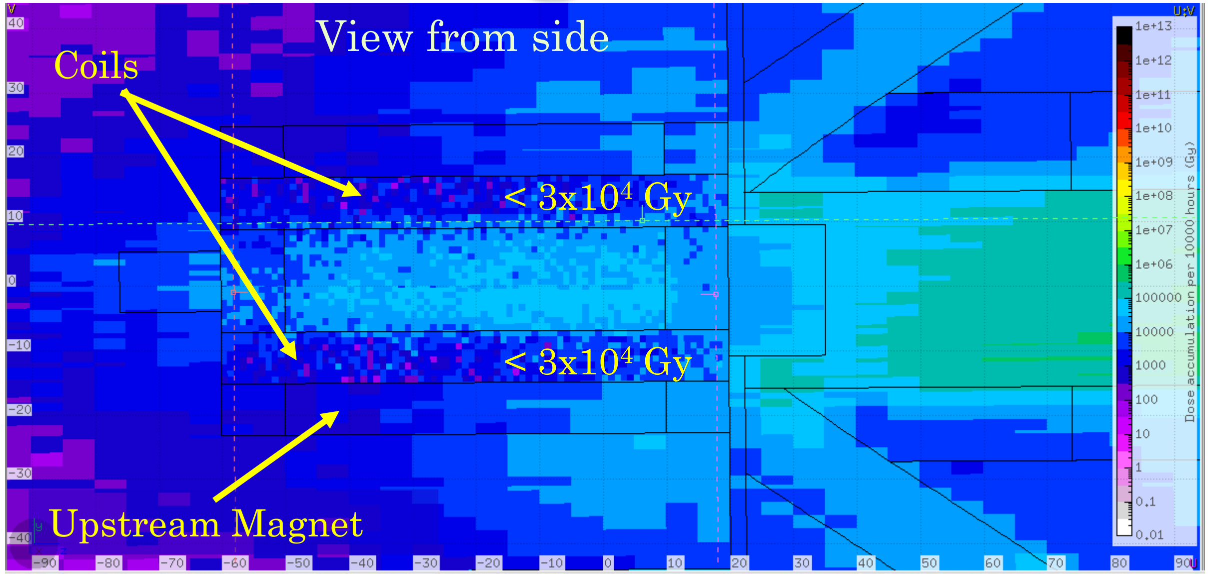
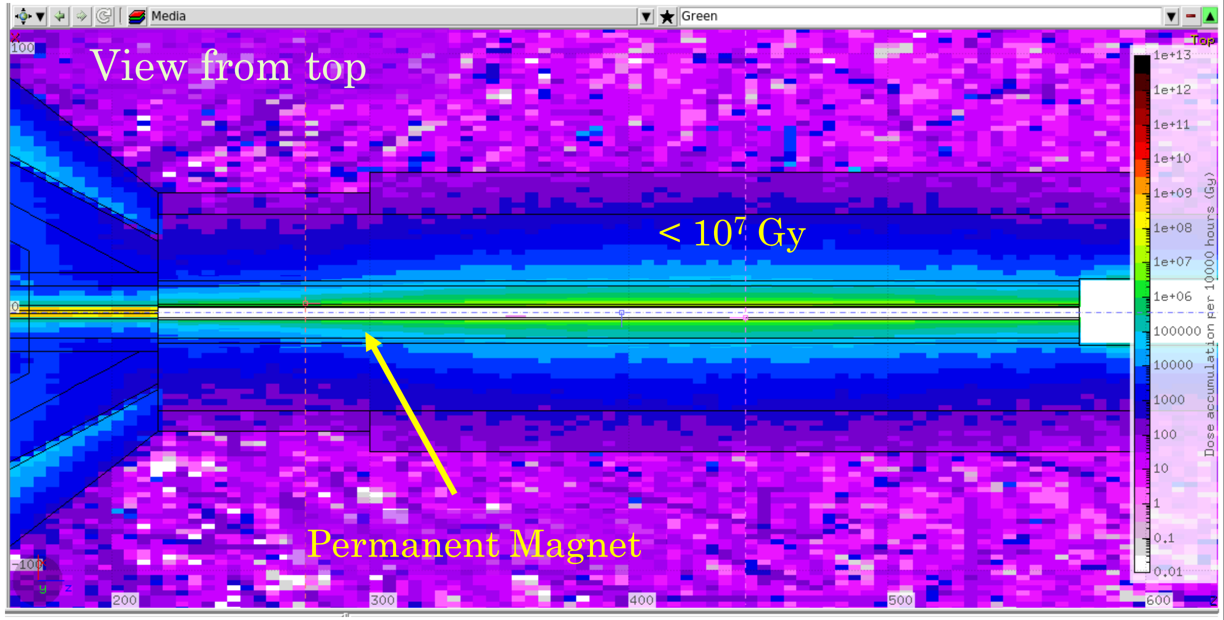
Accumulated Doses in the Magnets

- Accumulated dose to upstream CPS magnet coils in 10000 hours is expected to be 3×10^4 Gy.
  - Magnet coil insulation made of cyanate ester resins can handle over 10^6 Gy dose.
    - Reference: P.E. Fabian, et al "Novel Radiation-Resistant Insulation Systems for Fusion Magnets," Fusion Engineering and Design, Vol. 61-62, pp. 795-799, 2002



- Accumulated dose in the permanent magnet in 10000 hours is expected to be on the level ~10^7 Gy.
  - Hall D strontium ferrite permanent do not change at such a dose.
    - FNAL did not observe any change in B-field after a dose of10^7 Gy.
    - FNAL gave an upper limit of 1% change, as specified in the magnet specs.



Absorber Temperature

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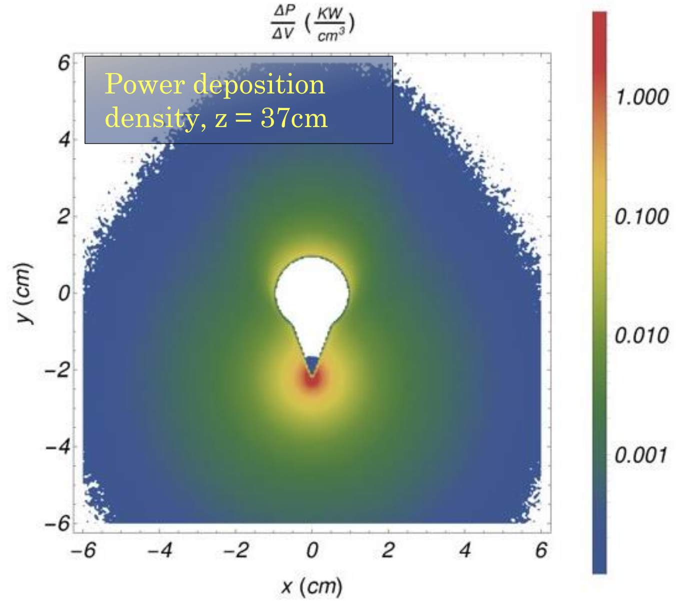
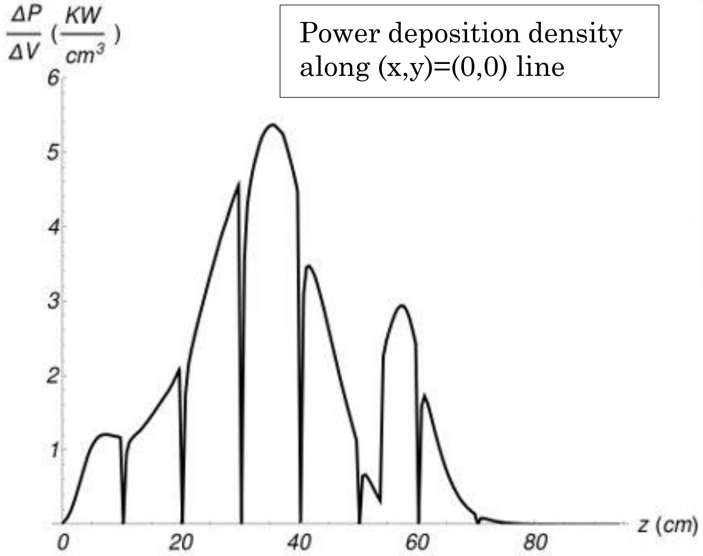
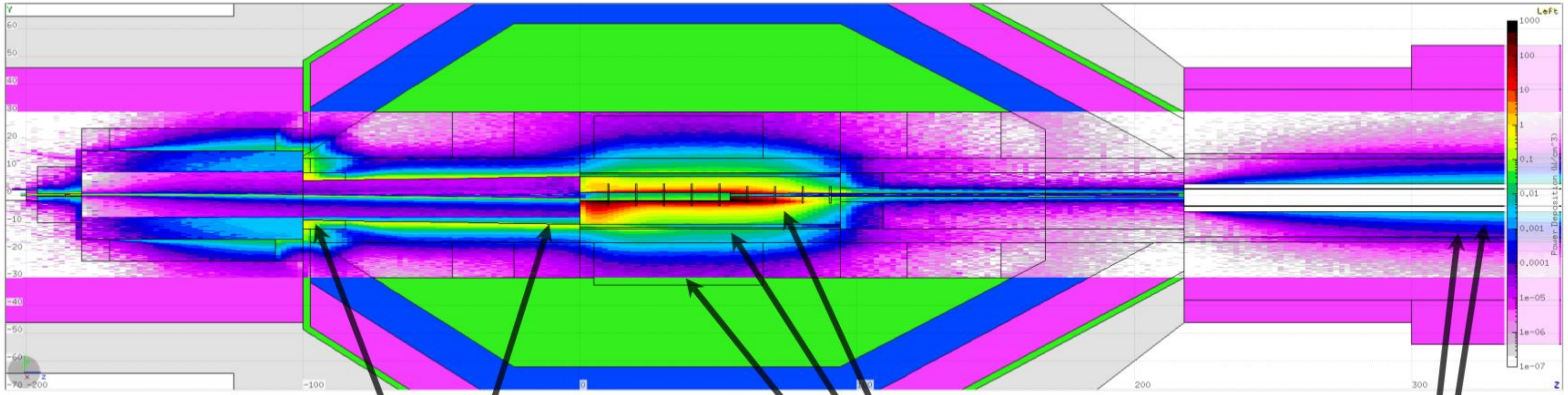
Power Deposition in the Absorber





- FLUKA provides an output file with power deposition densities in 3D.
  - 30M data points inside absorber
- Almost all of the remaining electron beam power (> 98%) is deposited into the copper absorber.
  - Most likely that only absorber needs cooling.
  - Must prevent heat transfer from absorber to surrounding volumes.

Color indicates power deposition density (kW/cm^3), x = 0 plane shown



CPS Entry Collar:	34 W
CPS Entry Iron:	156 W

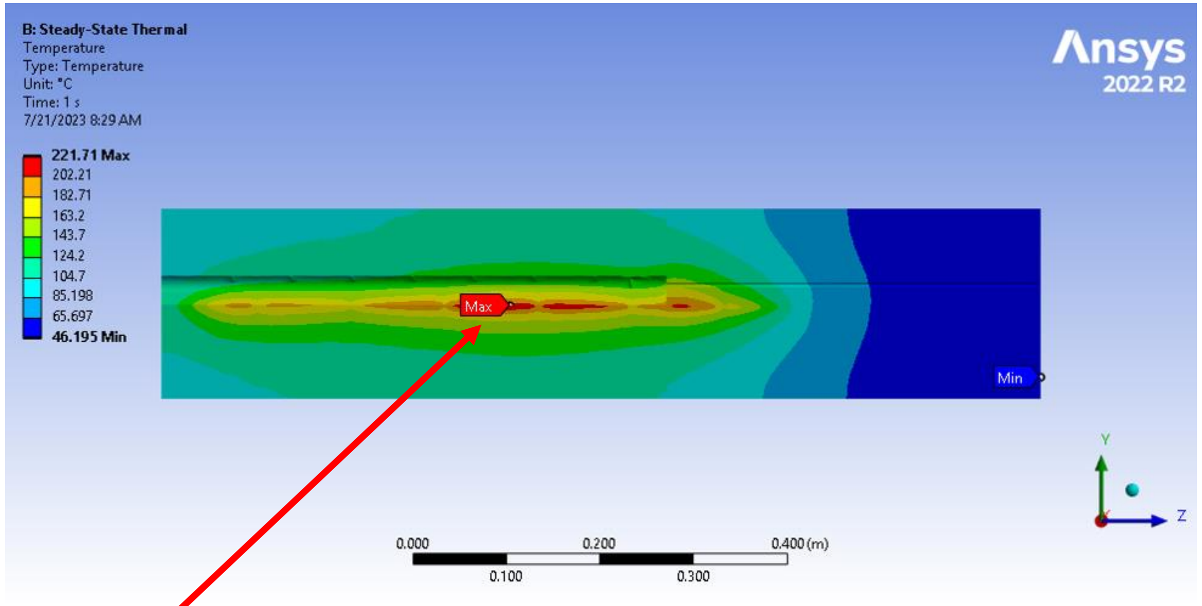
Absorber:	53.545 kW
Steel Base at Abs:	215 W
Lead around Abs:	156 W
Perm. Magnet Aluminum:	27 W
Perm. Magnet Body:	20 W

Power inside CPS for 5 µA, 12 GeV beam

All other parts get less than 20 W each

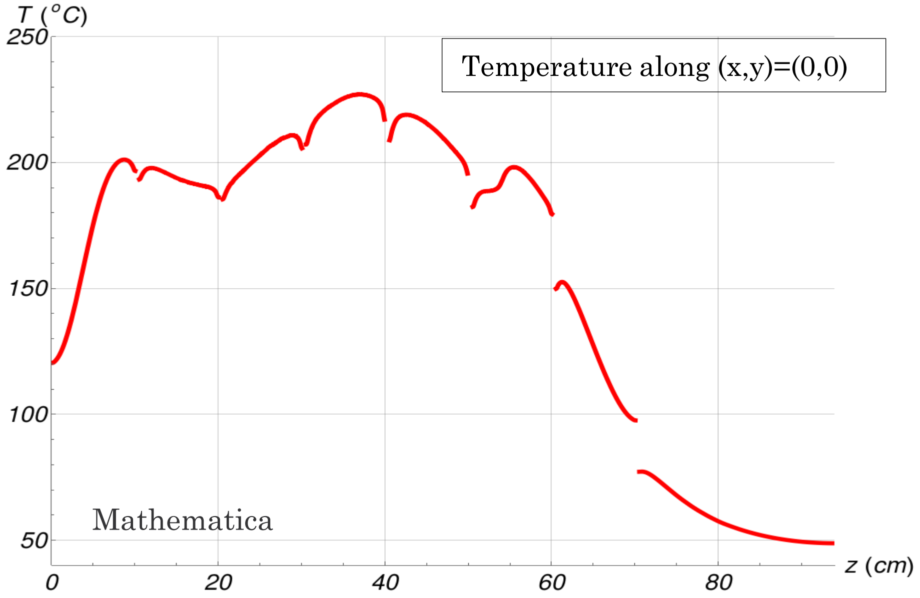
Temperature

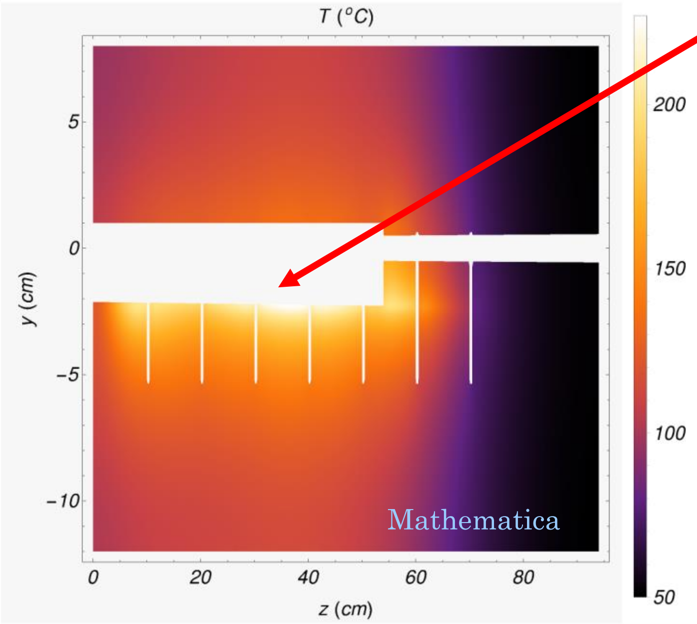
- Temperature calculations in the "isolated" absorber is done using power deposition maps obtained using FLUKA.
- Two independent calculations are done by two people using two different software packages:
  - ANSYS software, popular among engineers
  - Wolfram Mathematica software, popular among scientists
  - The results are in a good agreement.
- The temperature at the hotspot is expected to be ~230 ^{O}C at nominal beam parameters.
- There is no possibility for high temperatures at the outer boundaries of the absorber, except the front side.
  - Still need to perform ANSYS evaluation for the whole CPS.

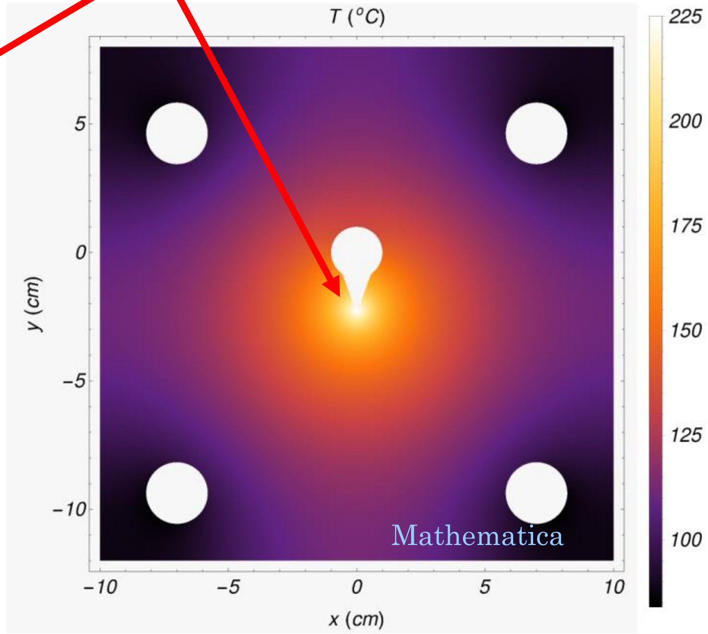


$T_{max} \approx 222\ ^{O}C$

$T_{max} \approx 230\ ^{O}C$

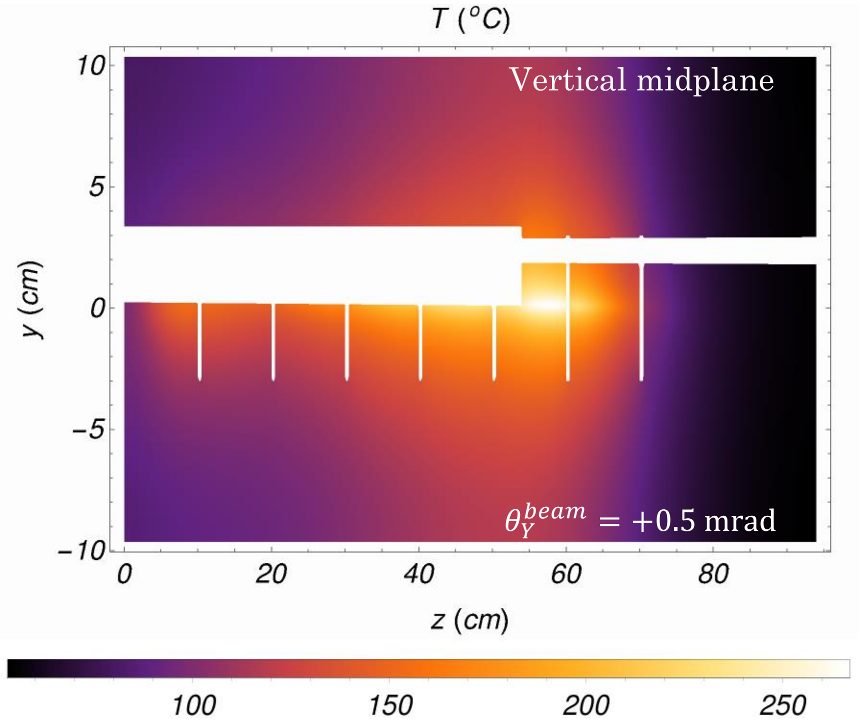






Temperature vs Beam Conditions

- Temperature in the copper core depends on the beam conditions.
- Expected temperature range is 200 ^{O}C < T_{max} < 300 ^{O}C.
- Deformations and stresses are being studied in ANSYS. See talk by Tim Whitlatch.

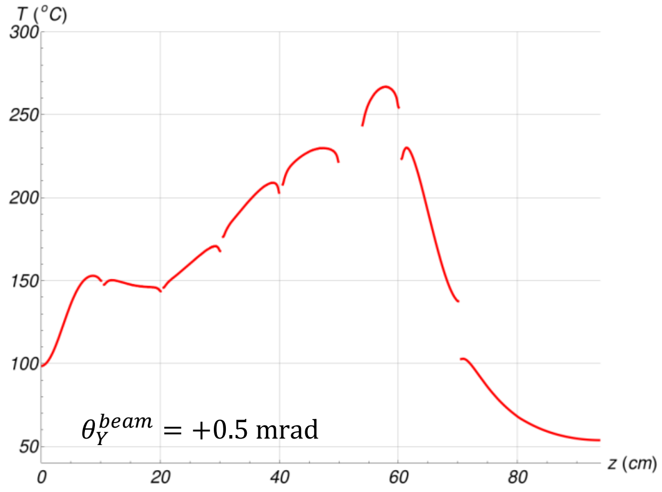


- Multiple beam conditions has been simulated with FLUKA and the resulting temperature distributions evaluated.
- Temperatures in all studied conditions appear to be manageable.
  - We will impose restrictions on the beam conditions.

Test Configuration Name	Z_{max} (cm)	T_{max} (°C)	T_{cold} (°C)
All Nominal	37	230	100
$\sigma^{(x,y)}_{beam}$ = 0.33 mm	43	290	105
$\sigma^{(x,y)}_{beam}$ = 1.5 mm	8.5	245	100
97% B-field	56.5	245	100
103% B-field	33	240	100
-1mm shift in Y	8	265	110
+1mm shift in Y	57	265	105
-0.5mrad angle in Y	8.5	265	110
+0.5mrad angle in Y	58	275	105
+1mm shift in X	8.2	260	100
+0.5mrad angle in X	8	260	100

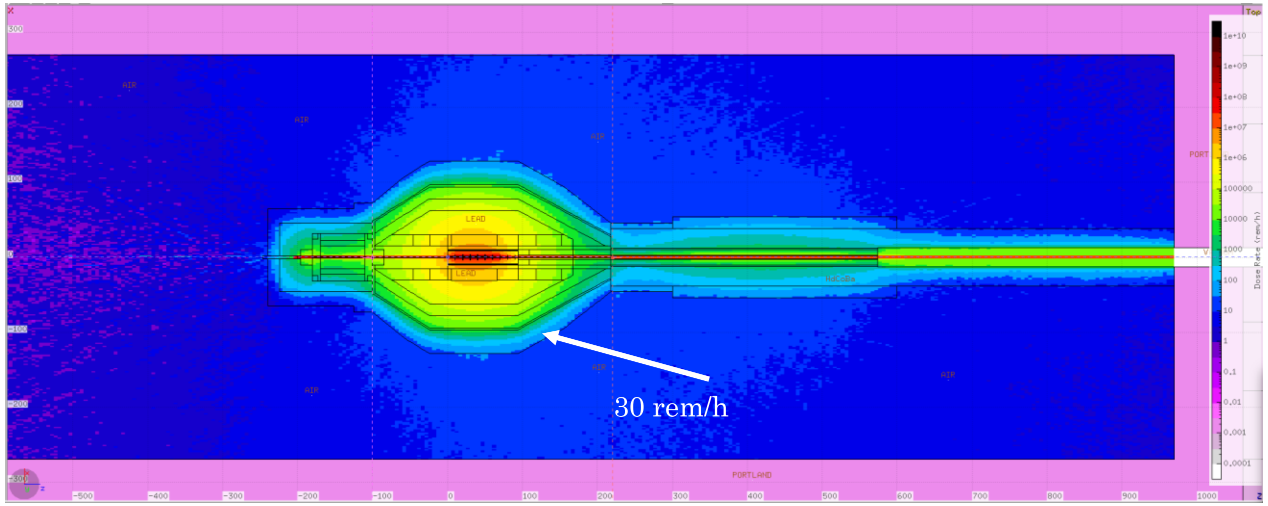
Conclusions

Electron Beam Requirements



- It is important to have a good beam tune on the radiator.
  - Excessive radiation in Tagger Hall.
  - Higher temperatures in the CPS absorber.
- We found that beam rastering will not be necessary.
  - We will need to make sure that beam profile is wide using wire scans at CPS.
- Install a girder just upstream of CPS with:
  - BCM to measure the beam current,
  - BPM to measure beam positions,
  - Wire scanner for beam widths.
- FSD trips on
  - Large electron beam positions excursions,
    - Use a collar and ion chambers.
  - Electron beam angle excursion,
    - Measure photon beam position at KPT.
  - Magnet current deviations.
    - Use power supply ADCs.
    - Field sensors or pickup coils inside the magnet
- Keep Hall D radiator scanner with ~10^4 dynamic range for the halo measurement.

Parameter	@ CPS Radiator	@ KPT
Beam Current	50 nA ≤ I_B ≤ 5 μA	N/A
Beam Size	0.5 mm ≤ σ ≤ 1.5 mm	σ ≤ 1 cm
Beam stability (@ 1 Hz)	σ ≤ 0.2 mm	σ ≤ 2 mm
FSD is tripped at	|Δx| > 1 mm or |Δy| > 1 mm	|Δx| > 1 cm or |Δy| > 1 cm
Beam halo (halo-to-peak)	< 10^{-4} at r > 5σ	N/A



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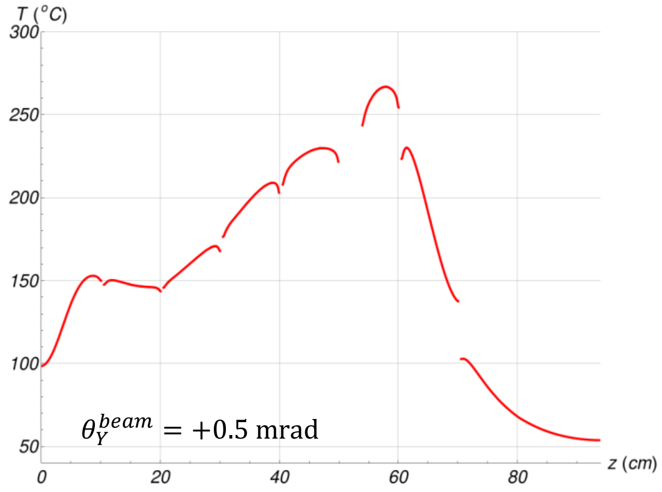

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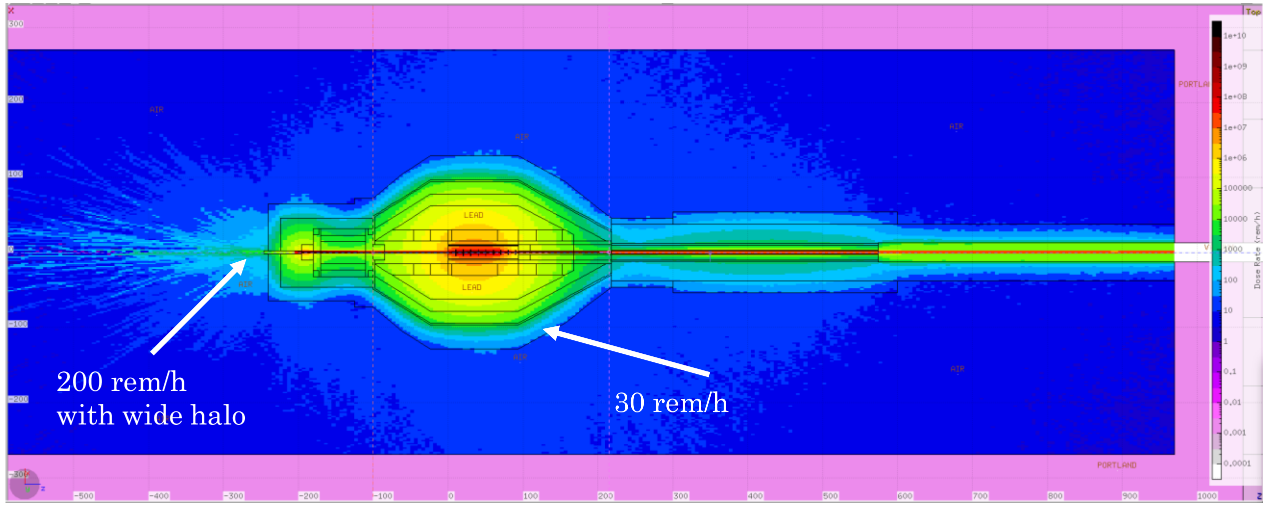


Summary

- We developed a conceptual design of CPS for Hall D.
  - It will provide photon beam at KPT that would meet KLF requirements.
  - We will use a movable platform to be able to restore GlueX beamline.

- No major R&D is anticipated for the design and construction of CPS.
  - Need to optimize CPS and develop engineering design.

- We performed FLUKA simulations to estimate the radiation levels around CPS.
  - Radiation environment should be similar to what GlueX would have at 5μA.
  - No civil construction is needed in tagger hall.

- We are in contact with Accelerator Division regarding beam requirements for CPS.
  - No show-stoppers are identified.

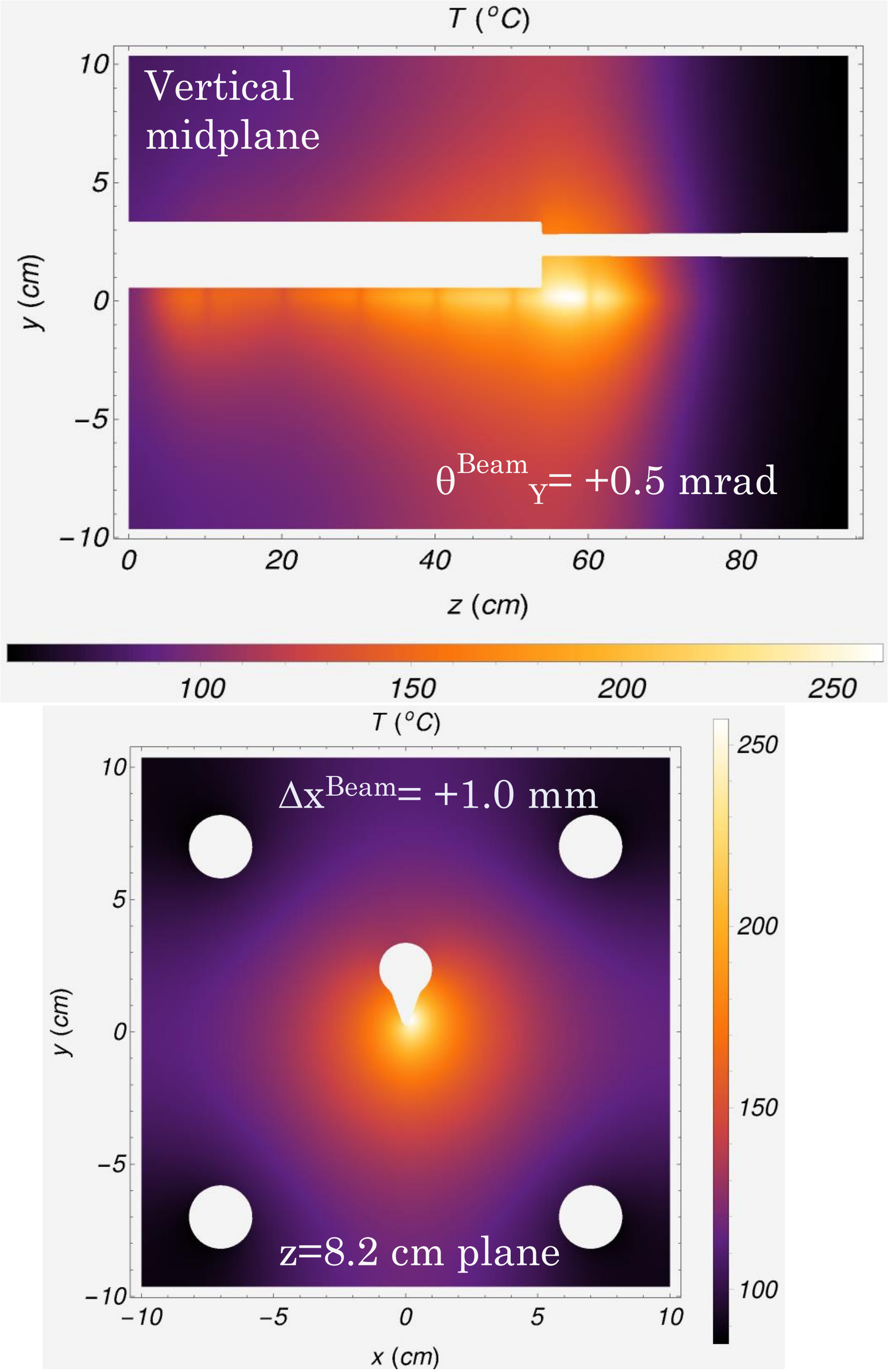
- Working on optimization of the basic design.
  - Check and optimize radiation environment with newer versions of FLUKA.
  - Optimize the absorber and magnetic field to further lower the temperature.

- Engineering design is the next step.

Potential Problems and Mitigations

- At very large vertical angles (500 μrad), the beam can penetrate deep into CPS and cause somewhat elevated temperatures (275 ^{O}C).
  - The radiation environment is probably not going to be affected much.
  - The photon beam position needs to be monitored and used in the beam interlock.

- At large horizontal shifts (~1 mm), the beam can impact the upstream wall of the absorber missing the keyhole and thus cause high temperatures (300 ^{O}C).
  - The radiation environment is probably not going to be affected much.
  - Beam position need to be monitored and beam needs to be shut off at large excursions.



Potential Optimizations

- Beam optimizations
  - Try slightly wider electron beam σ~1.2 mm.
- Absorber optimizations
  - Reduce the magnetic field of CPS.
  - Reduce the height of the beam entry cavity in the absorber.
  - Make beam entrance cavity in the absorber ~10cm longer in the downstream area.
  - Make smoother transition into the beam entrance cavity at the front of the absorber.
  - Add more vertical slits.
- Shielding optimizations
  - Simulate radiation background with new FLUKA.