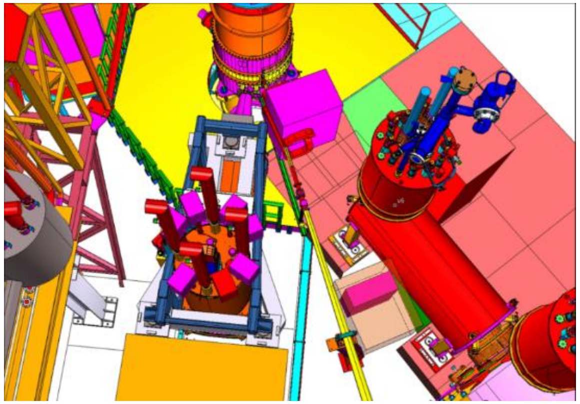
High intensity Compact Photon Source

… and the…

Neutral Particle Spectrometer



Tanja Horn

Spokesperson for the Neutral Particle Spectrometer (NPS) Collaboration

THE CATHOLIC UNIVERSITY of AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

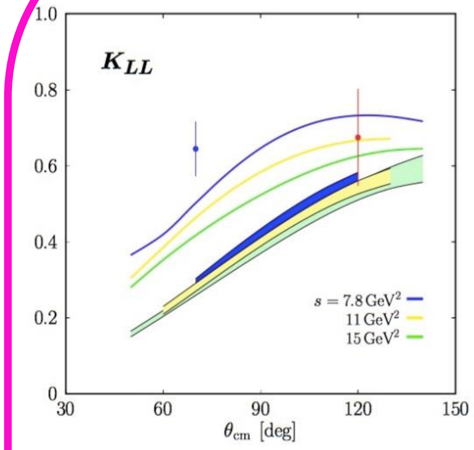
Program Advisory Committee Meeting (PAC45)

10-14 July 2017, Jefferson Lab

Outline

- ❑ Developments since PAC44
    - High-Intensity Photon Workshop
    - Working Group Activities
- ❑ Compact Photon Source (CPS) – General Concept and Implementations
    - Similarities for Halls A/C and K_L/Hall D implementations
- ❑ CPS Feasibility Studies
    - Radiation Calculation Benchmarking
    - Prompt Radiation and Dose Rate Calculations
    - Engineering Aspects
- ❑ Engineering Concepts
- ❑ Summary

Multiple Science Opportunities With Compact Photon Source (and NPS)

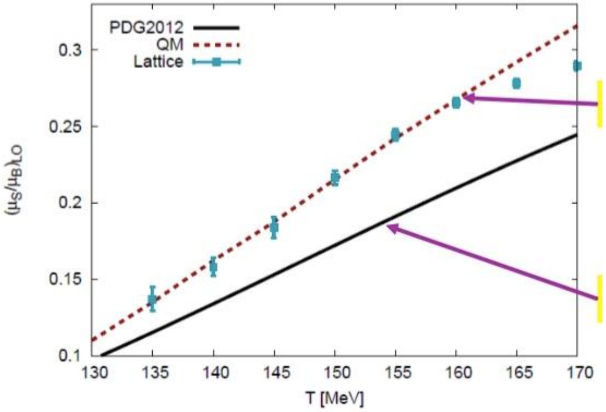


Polarization observables Wide Angle Compton Scattering (PAC45)

(K_{LL}, A_{LL}, K_{LS}, $A_{LS,..}$)

Hadron Spectroscopy with secondary K_L beam (PAC45)

Cross sections and polarization of Λ, Σ, Ξ, Ω hyperons



measured yields of different hadron species in heavy ion collisions

Additional Science Topics under study

- ☐ WACS exclusive photoproduction
- ☐ Timelike Compton Scattering
- ☐ Short Range Correlations
- ☐ Photoproduction of Few Body Systems
- ☐ *Also: Missing mesons, Phi production,…*

Science Gain with a Compact Photo Source

Impact of a high intensity photon source for hadron physics at JLab:

- WACS must reach several GeV^2 in s, t, and u, but since the WACS rates drop with ~1/s$^{7.5}$ this science needs a luminosity boost.
- The K$_L$ project is based on a 5 kW photon intensity (>100 times above the 15 W design level for the Hall D beam line) to do “prime physics with a secondary beam”.

Impact of the photon source for WACS:

- The heat/radiation load is a limiting factor for luminosity with the polarized target. The target can take 20 times more photons than electrons.
- **The experiment productivity is improved even more (30 times)** due to higher target polarization averaged over the experiment, and reduced overhead time for the target annealing procedure.

Impact of the photon source for the K$_L$ project:

- The hermetic CPS concept allows **2 decades increase** of the beam intensity in the existing photon Tagger Area without major rebuilding of the facility.

Timeline

- **PAC43 on PR12-15-003**

  “The PAC is impressed by the concept for a new photon source. It strongly encourages the proponents to work with the members of the previously approved E12-14-006 in order to see whether it could be possible be incorporated here.“

- **PAC 44 on PR12-16-009**

  “We recommend that the laboratory provide resources for a workshop focused on developing the physics case, as well as an optimized compact photon source and beam dump, organized jointly by the spokespersons of the PR12-16-009, PR12-15-003, and E12-14-006 proposals.“

- **New Opportunities with High-Intensity Photon Sources workshop**

  6-7 February 2017 @ Catholic University of America

  Organizers: T. Horn, C. Keppel, C. Munoz-Camacho and I. Strakovsky

  All spokespersons of E12-14-006, PR12-15-003 and PR12-16-009, and also the spokespersons of PR12-17-001 (Hall D K_L beam effort) actively involved.

  HIPS conclusion: Lab will set up a meeting with interested groups to fix goals and timeline to benchmark and finalize Compact Photon Source concept

  Detail and proceedings: https://www.jlab.org/conferences/HIPS2017/

HIPS 2017

New Opportunities with High-Intensity Photon Sources

This workshop aims at producing an optimized photon source concept with potential increase of scientific output at Jefferson Lab, and at refining the science for hadron physics experiments benefitting from such a high-intensity photon source. The workshop is dedicated to bringing together the communities directly using such sources for photo-production experiments, or for conversion into K_L beams. The combination of high precision calorimetry and high intensity photon sources can provide greatly enhanced scientific benefit to (deep) exclusive processes like wide-angle and time-like Compton scattering. Potential prospects of such a high-intensity source with modern polarized targets will also be discussed. The availability of K_L beams would open new avenues for hadron spectroscopy, for example for the investigations of "missing" hyperon resonances, with potential impact on QCD thermodynamics and on freeze-out both in heavy ion collisions and the early universe.

February 6-7, 2017
Catholic University of America
Washington, DC U.S.A.

Organizing Committee:
Tanja Horn – CUA
Cynthia Keppel – JLab
Carlos Munoz-Camacho - IPNO
Igor Strakovsky – GWU

https://www.jlab.org/conferences/HIPS2017/

Compact Photon Source Working Group

- ☐ **Working group established composed of Hall A/C Leader, NPS spokesperson, Physics AD, RadCon, and 2-3 members each from Hall A and Hall C WACS efforts, and Hall D K_L effort.**

  T. Keppel, T. Horn, R. Ent, P. Degtiarenko, D. Day, D. Keller, J. Zhang, G. Niculescu, B. Wojtsekowski, I. Strakovsky (and D. Hamilton in last meetings)

- ☐ **Working Group Meetings on CPS**
  - **March 28:** **Organizational meeting, define benchmark simulation input**
  - **April 20:** **Benchmark radiation/activation results with toy CPS models**
  - **May 11:** **Followup radiation/activation simulations, power deposition estimates**
  - **May 18:** **Converged common CPS concept presented at NPS meeting, letter sent to Bob McKeown**

These meetings led to a common CPS concept, with many similarities be it in Halls A/C for WACS or in Hall D for the K_L beam

Compact Photon Source (CPS) – Concept

- ☐ Strong magnet after radiator deflects exiting electrons
- ☐ Long-bore collimator lets photon beam through
- ☐ No need in tagging photons, so the design could be compact, as opposed to a Tagger Magnet concept
- ☐ The magnet itself is the electron beam dump
- ☐ Water-cooled W-Cu core for better heat dissipation
- ☐ Hermetic shielding all around and close to the source to limit prompt radiation and activation
- ☐ High Z and high density material for bulk shielding
- ☐ Boron outer layer for slowing, thermalizing, and absorbing fast neutrons still exiting the bulk shielding

Example: CPS in Polarized WACS

- ❑ Beam intensity is the key at high *s* & *t*: need dN/dE_γ ~ few * 10^{12} equivalent quanta/s
- ❑ It is critically important to have

  a) a small beam spot at target (~1 mm, for background suppression)

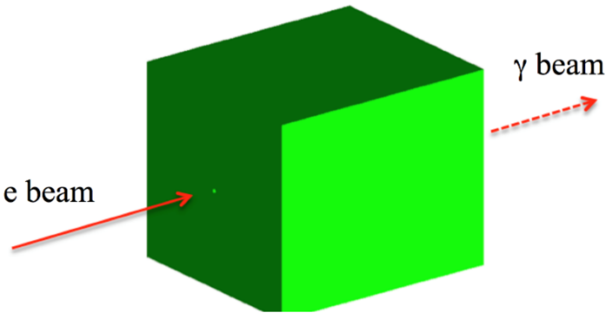
  b) low radiation at detectors (it sets a practical limit in many expts).

  Use of a collimator is not effective because of loss of beam intensity.

  A better solution is to ensure a short distance between the radiator and the target.

- ❑ The short-distance requirement for an 11 GeV beam energy is solved by means of use of a 2 Tesla, one meter long magnet – It tolerates a high radiation level.

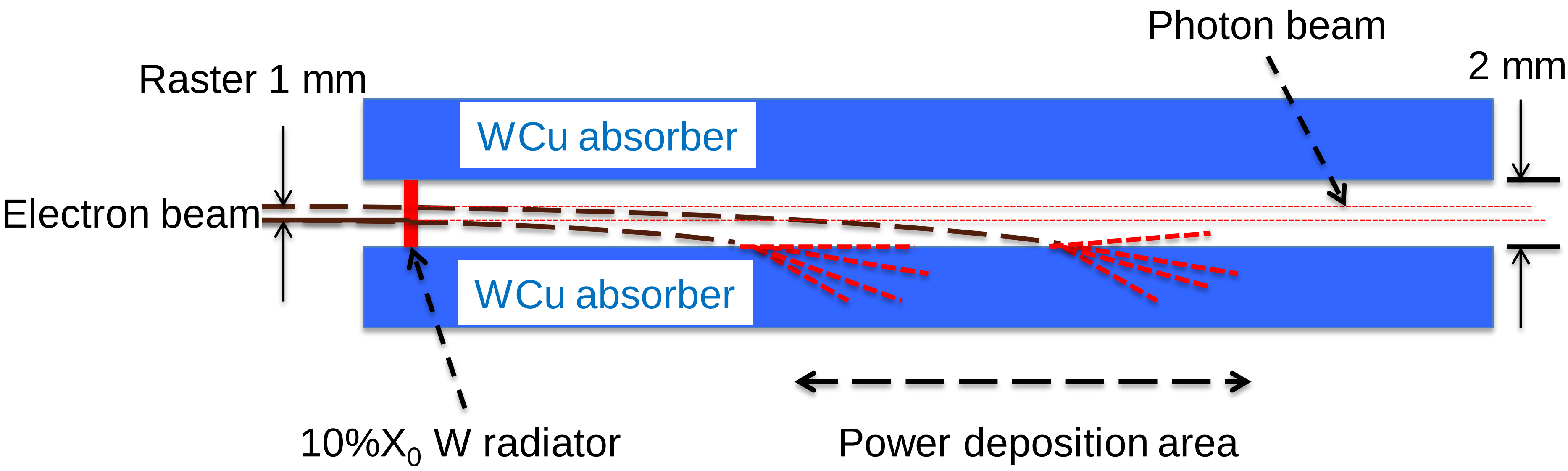
- ❑ Key item of a photon source is a beam dump. The solution is a hermetic box (CPS) which results in low radiation outside.



~ 2m x 2m x 2m structure

The openings for the incident electron beam and produced photon beam are very narrow compared with the box size.

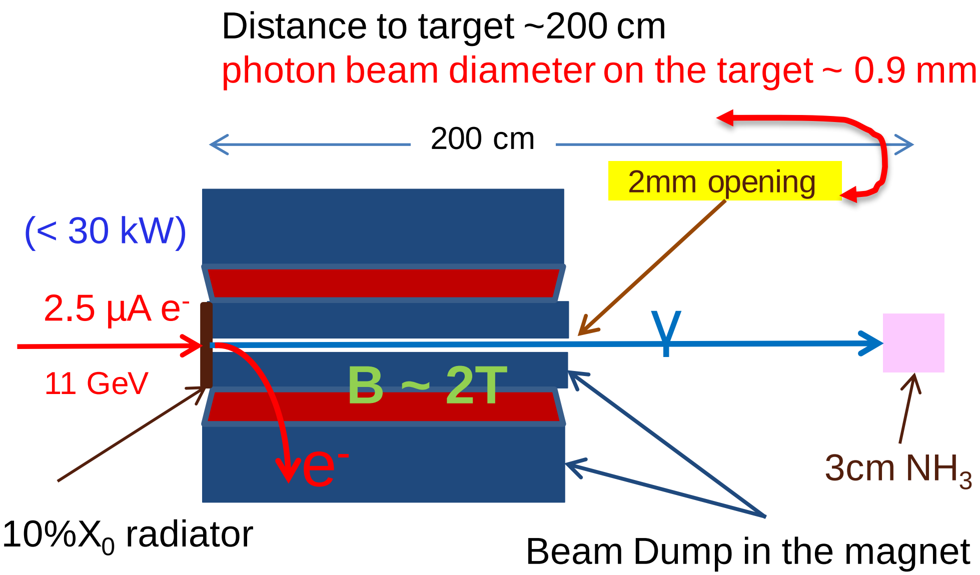
General design concept Hermetic CPS



- ❑ Key problem of a beam dump is high power density in an absorber. The solution is a small impact angle with a small (1 mm) raster in a narrow channel (2 mm).
- ❑ A 30 kW configuration was proven via G4 and heat dissipation calculations. Larger space available in the Hall D/K_L project application will allow twice higher beam power (60 kW).

CPS implementations in Halls A/C & K_L/Hall D

Basic CPS design concept for Halls A/C



Distance to target ~200 cm

photon beam diameter on the target ~ 0.9 mm

200 cm

2mm opening

(< 30 kW)

2.5 µA e^-

11 GeV

γ

B ~ 2T

e^-

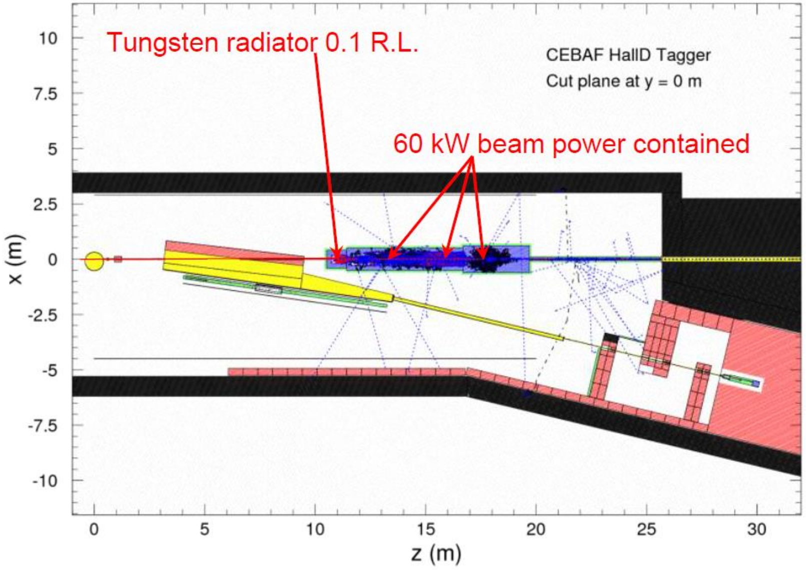
3cm NH_3

10%X_0 radiator

Beam Dump in the magnet

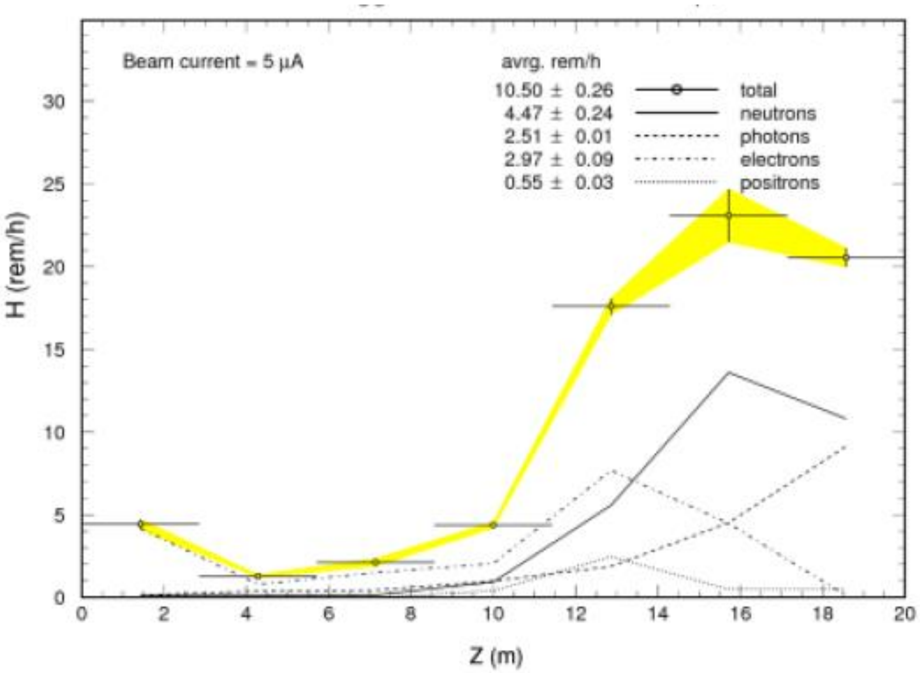
CPS in Hall D Tagger Vault

Concept similar, but need more space to achieve 60 kW beam power

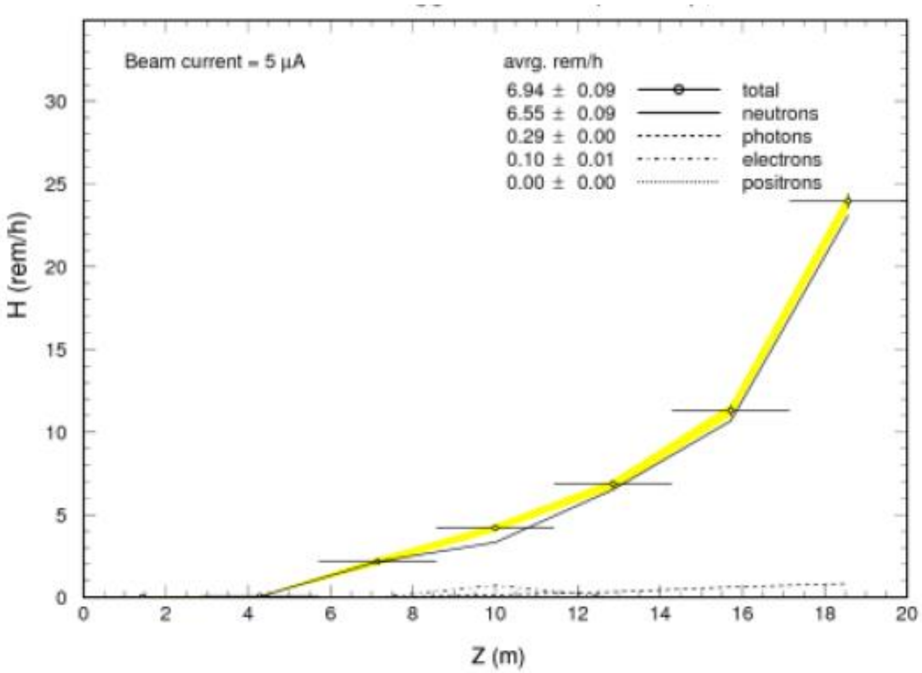


- ☐ If one uses a 2nd raster system for Hall D to compensate for the initial 1 mm raster, this can be an equivalent essential design
- ☐ Some differences…
  - ➢ Hall D alcove has more space, so simpler positioning and shielding placement
  - ➢ Hall D up to 60 kW (<5 µA @12 GeV), Halls A/C up to 30 kW (2.6 µA @ 11 GeV)
  - ➢ Different length/field magnet for Hall D
  - ➢ Shielding may differ

Hall D case: Dose Rate Evaluation an Comparison



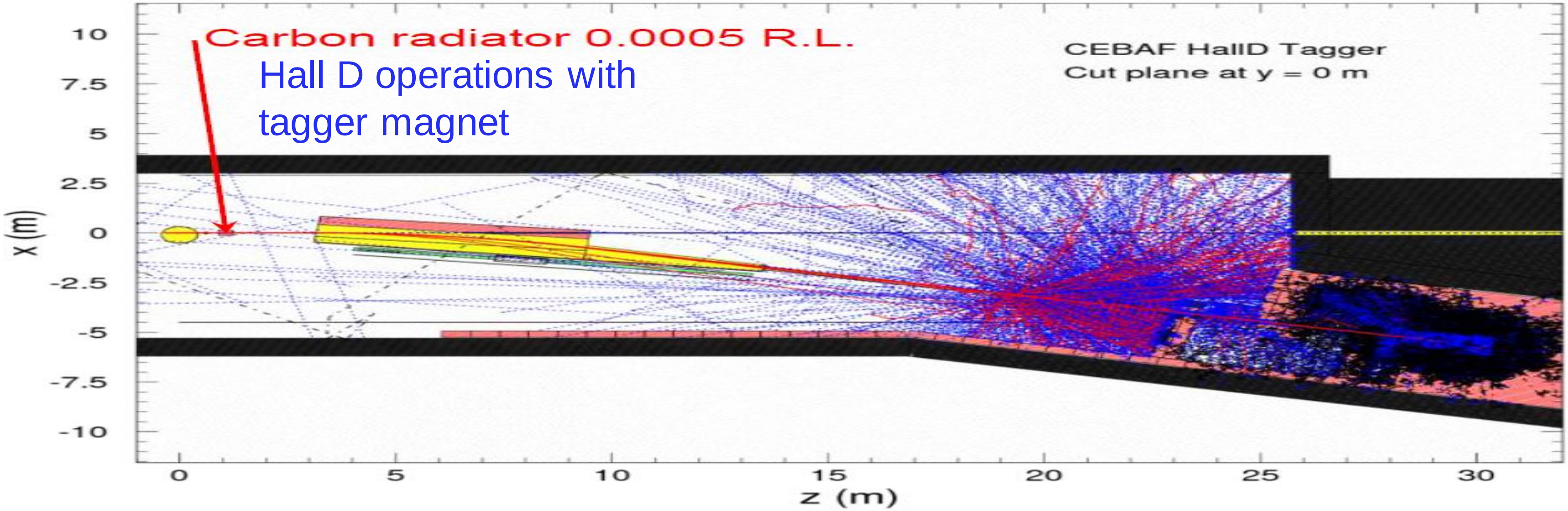
Hall D with Tagger Magnet, <5 μA and 0.0005X_0



Hall D with CPS, <5 μA and 0.10X_0

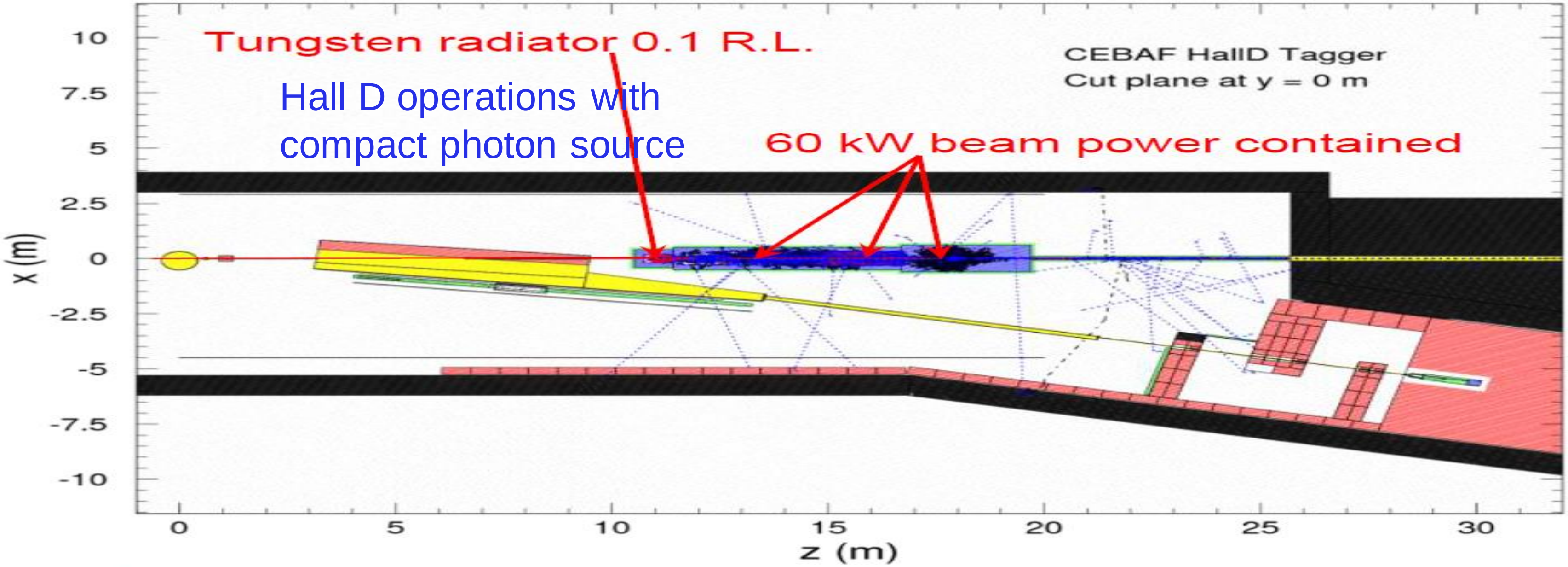
- ☐ Even though for the K_L beam/CPS setup a 10% r.l. radiator is used, compared to 0.05% r.l. for default Hall D operations, the **generated dose rates are similar**.
- ☐ The reason is the difference in radiation spectral composition. The hermetic and high-*Z* shielding close to the source of radiation removes photons, electrons and positrons, and leaves mostly high-energy neutrons. Thus, the activation levels will be similarly less.

Illustration Hall D – GEANT3 with 2000 Electrons



Carbon radiator 0.0005 R.L.

Hall D operations with tagger magnet



Tungsten radiator 0.1 R.L.

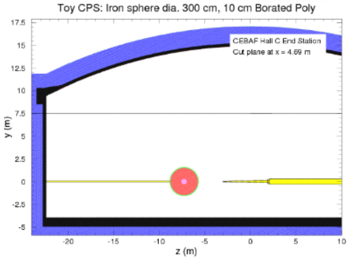
Hall D operations with compact photon source

60 kW beam power contained

Hermetic CPS – Radiation Calculations

❑ Goal of the Compact Photon Source (CPS): high energy photon beams

- Beam energies up to 12 GeV
    - Up to 60 kW beams in Hall D (current 5 μA)
    - Up to 30 kW electron beams in Hall A/C (current 2.6 μA)
- Runtime: 1000 hours
- Photon source as close to target as possible



Model of tungsten or iron sphere

❑ Parameters for feasibility studies and minimal set of requirements

- Prompt dose rates in the hall: < several rem/h at 10m from the device
- Activation dose rates outside the device envelope at 1 ft distance: < several mrem/h after one hour following the end of a 1000 hour run
- Prompt dose rates at the CEBAF site boundary <1μrem/h (2.4μrem/hr corresponds to a typical experiment not requiring extra shielding) during run

❑ Benchmarking of simulation models

- GEANT3/DINREG – prompt dose rates, site boundary (official)
- FLUKA – prompt dose rates and activation
- MCNP – prompt dose rates
- GEANT4 – prompt dose rates

CPS: Prompt Radiation Doses

Integrated prompt dose rates (rem/h) measured at points 90 degrees around spheres and at 3 m radial distance from the beam line

Material	**Source**	**No boron**	**No boron**	**No boron**	**No boron**	**No boron**	**With 10cm Boron**	**With 10cm Boron**	**With 10cm Boron**
Model		**DINREG GEANT3**	**FLUKA (5MeV E_γ cut)**	**MCNP6**	**FLUKA (7MeV E_γ cut)**	**GEANT4**	**DINREG GEANT3**	**FLUKA (5 MeV E_γ cut)**	**GEANT4**
Iron	neutron	146	10.0 +- 0.1%	11.5+-6%	9.5+- 0.39%	123.2	0.8	0.11+- 3.4%	0.28
Iron	γ	0.44	0.039 +- 0.6%	0.16+- 29%	0.025+- 0.9%	0.56	2.8	0.063+- 0.7%	0.56
Tungsten Powder	neutron	13.0	9.37+-0.9%	4.4+-11%	N/A	6.34	2.7	0.52+- 15.3%	1.76
Tungsten Powder	γ	0.06	0.001+- 10.3%	0.0002	N/A	0.33	0.003	0.0052+- 8.3%	1.28

- ☐ Must have an outer shielding layer of (10 cm) boron
- ☐ Prompt radiation doses in the Hall become 0(rem/hr), for run conditions in Hall C (or A).
- ☐ **In a more realistic configuration with 30 cm tungsten powder and 10 cm B the prompt dose (G4) is 5.6 rem/hr**
  - ➢ Well below the typical dose in the Hall D tagger vault (~25 rem/hr for 5 μA beam current)

CPS – Dose Rates at the Boundary

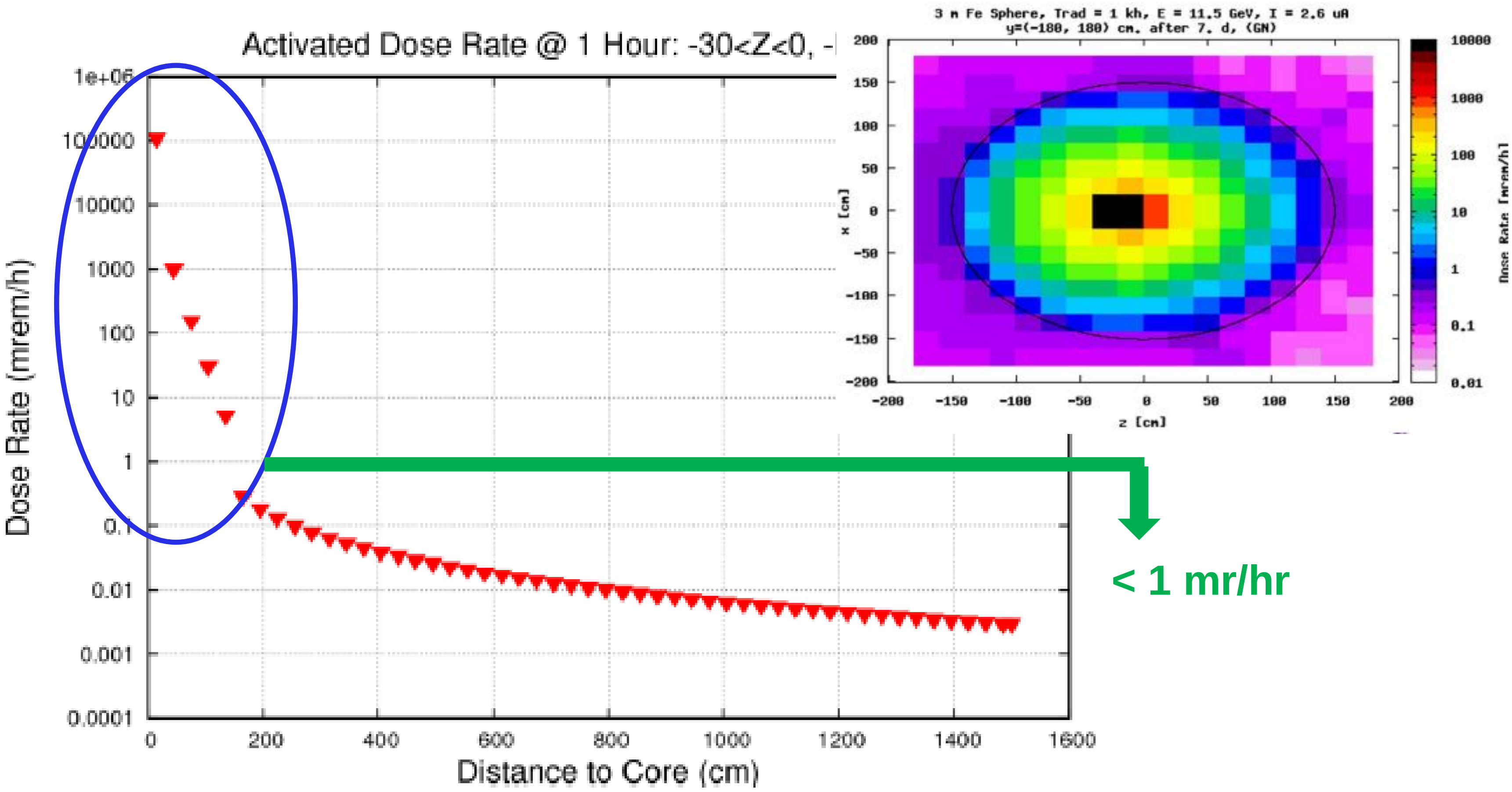
- ☐ Hall D/CPS for K_L beam:
  - ➢ Design compatible with the site boundary as the conditions for regular tagger magnet running dumps 60 kW in a local beam dump, and now the 60 kW is dumped in the CPS itself. **The Hall D tagger vault is designed for this (but additional local shielding may be required).**

- ☐ CPS in Hall C (or A) operation:
  - ➢ Dose rate estimates in μR/hr at the RBM-3 boundary condition for the benchmark calculations (3 m iron sphere vs 1.5 m tungsten sphere)
    - ○ iron: 0.24 μR/hr total (0.19 due to n, 0.05 due to γ)
    - ○ W: 2.4 μR/hr total (1.9 due to n, 0.5 due to γ)
  - ➢ With proper material and ordering choice of iron and W, and a (10 cm) outer layer of borated poly, **the boundary dose can likely be tuned below the 2.4 μR/hr that corresponds to a typical run not requiring additional local shielding, per the radiation budget.**

Note: a 1000 hour experiment would give 2.4 mr, and the total annual boundary dose is typically capped at 10 mr.

CPS – Activation Doses 1 Hour after 1000 Hour run

Worst-case calculation, activation dose 1 hour after 1000 hours at 11.5 GeV & 2.6 μA

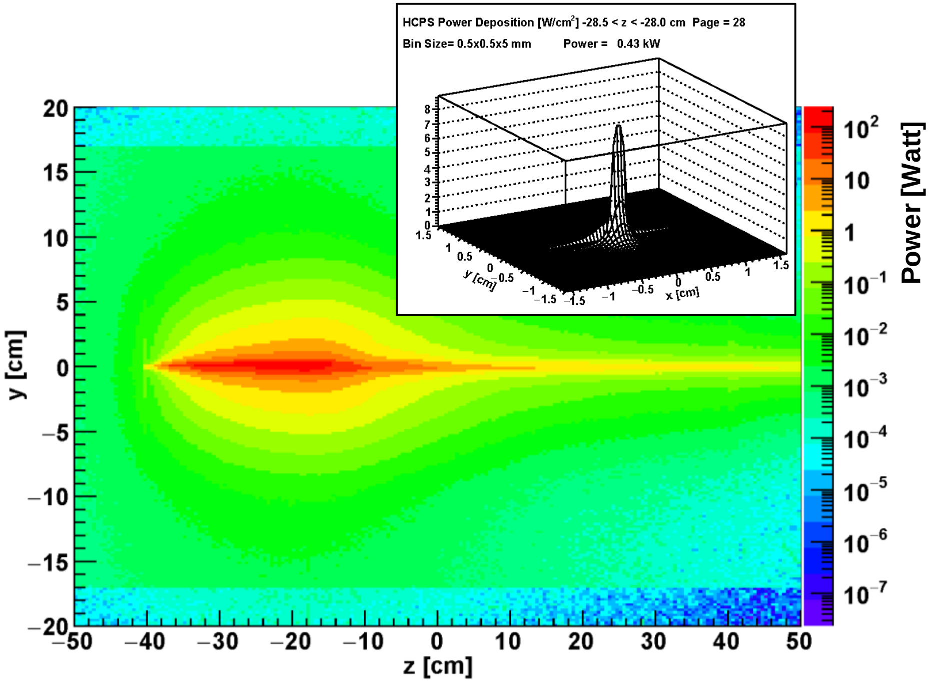


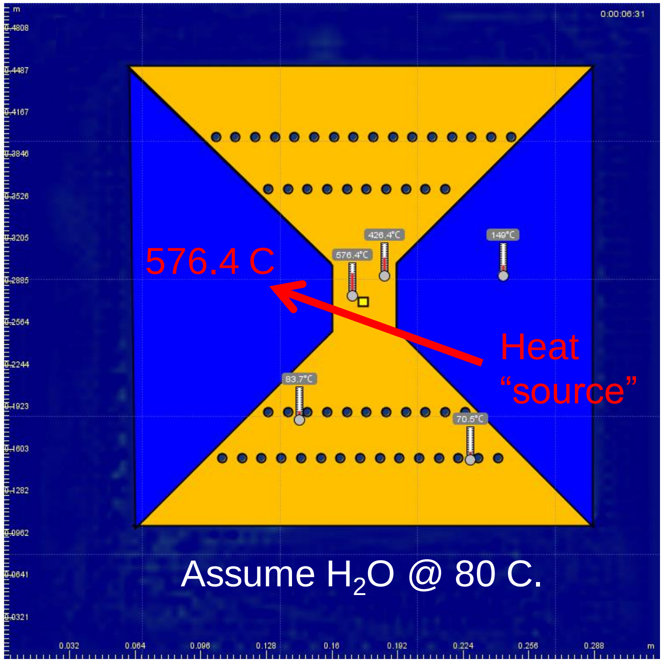
< 1 mr/hr

Activation doses inside the CPS remain large, but not outside the CPS

- ➢ Impact for considerations for de-assembly of CPS, not for general Hall maintenance or work/repairs

Engineering Aspects – Power Deposition





576.4 C

Heat “source”

Assume H_2O @ 80 C.

- ❑ Power deposition in the central region of the CPS integrates to 27.001 kW ✓
- ❑ XY Power Deposition for a 5 mm z slice (0.5 x 0.5 mm^2 in x-y)
- ❑ Peak: ~0.7kW @ z=-18 cm
- ❑ Power deposition verified by FLUKA

- ❑ Input the power deposition data into a heat-flow simulator assuming various pipe configurations
- ❑ Log equilibrium temperature

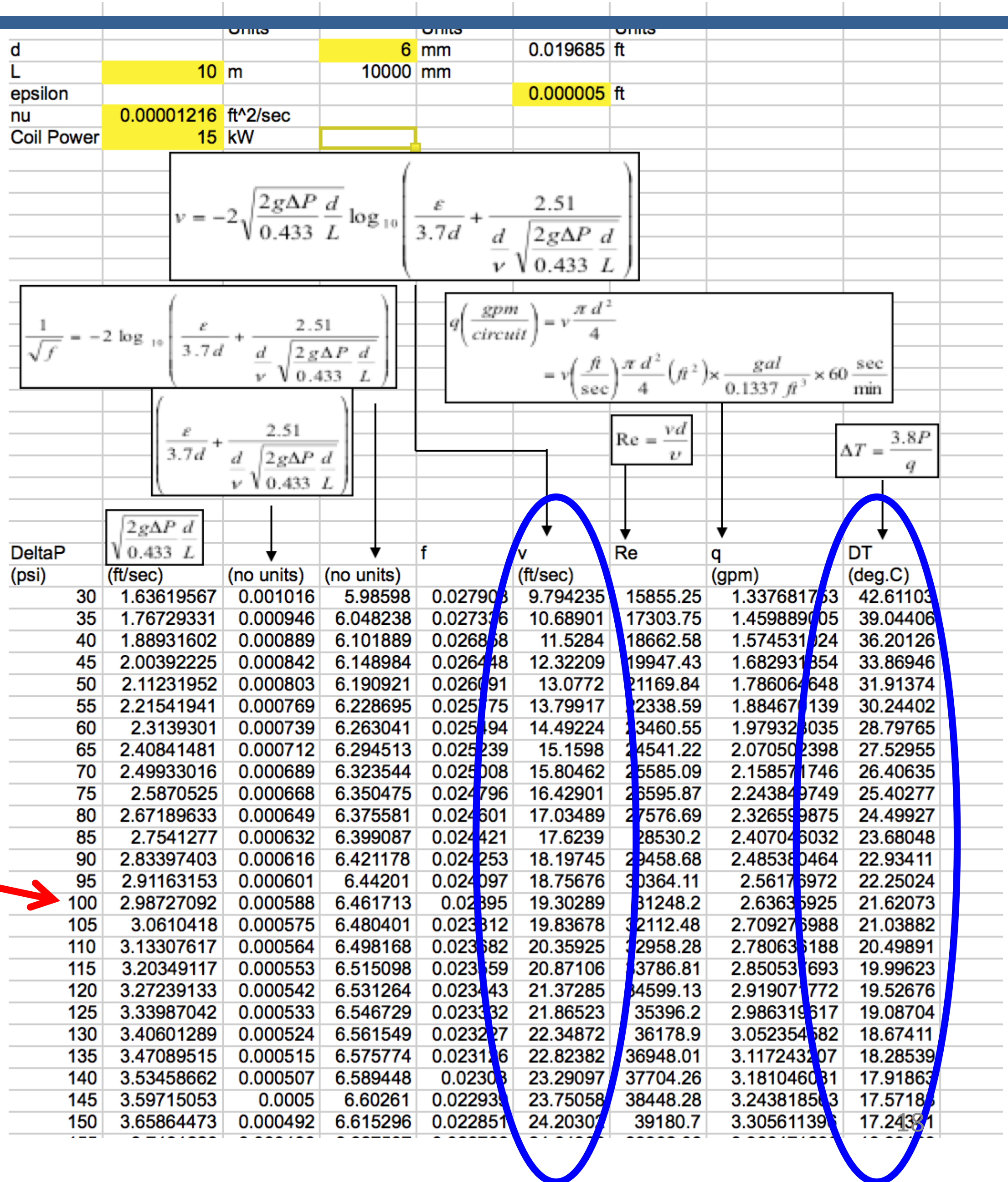
- ❑ *Temperature stabilizes at an acceptable value*

Engineering Aspects – Water Flow and ΔT

- ☐ Use the power deposition data to do heat-flow/cooling calculations
- ☐ Calculation of coolant flow
- ☐ 2D heat transport for z-slices of the central region

typical pressure

Manageable H_20 flow and ΔT.



		Units		Units		Units
d			6	mm	0.019685	ft
L	10	m	10000	mm		
epsilon					0.000005	ft
nu	0.00001216	ft^2/sec				
Coil Power	15	kW				

$$v = -2\sqrt{\frac{2g\Delta P}{0.433}\frac{d}{L}}\log_{10}\left(\frac{\varepsilon}{3.7d} + \frac{2.51}{\frac{d}{\nu}\sqrt{\frac{2g\Delta P}{0.433}\frac{d}{L}}}\right)$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7d} + \frac{2.51}{\frac{d}{\nu}\sqrt{\frac{2g\Delta P}{0.433}\frac{d}{L}}}\right)$$

$$q\left(\frac{gpm}{circuit}\right) = v\frac{\pi d^2}{4} = v\left(\frac{ft}{sec}\right)\frac{\pi d^2}{4}\left(ft^2\right)\times\frac{gal}{0.1337\ ft^3}\times 60\ \frac{sec}{min}$$

$$\left(\frac{\varepsilon}{3.7d} + \frac{2.51}{\frac{d}{\nu}\sqrt{\frac{2g\Delta P}{0.433}\frac{d}{L}}}\right)$$

$$\mathrm{Re} = \frac{vd}{\upsilon}$$

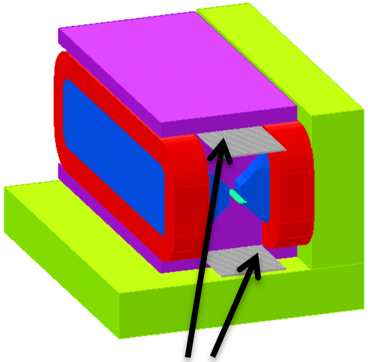
$$\Delta T = \frac{3.8P}{q}$$

DeltaP (psi)	$\sqrt{\frac{2g\Delta P}{0.433}\frac{d}{L}}$ (ft/sec)	(no units)	(no units)	f	v (ft/sec)	Re	q (gpm)	DT (deg.C)
30	1.63619567	0.001016	5.98598	0.027903	9.794235	15855.25	1.337681753	42.61103
35	1.76729331	0.000946	6.048238	0.027336	10.68901	17303.75	1.459889005	39.04406
40	1.88931602	0.000889	6.101889	0.026858	11.5284	18662.58	1.574531024	36.20126
45	2.00392225	0.000842	6.148984	0.026448	12.32209	19947.43	1.682931854	33.86946
50	2.11231952	0.000803	6.190921	0.026091	13.0772	21169.84	1.786064648	31.91374
55	2.21541941	0.000769	6.228695	0.025775	13.79917	22338.59	1.884670139	30.24402
60	2.3139301	0.000739	6.263041	0.025494	14.49224	23460.55	1.979328035	28.79765
65	2.40841481	0.000712	6.294513	0.025239	15.1598	24541.22	2.070502398	27.52955
70	2.49933016	0.000689	6.323544	0.025008	15.80462	25585.09	2.158571746	26.40635
75	2.5870525	0.000668	6.350475	0.024796	16.42901	26595.87	2.243849749	25.40277
80	2.67189633	0.000649	6.375581	0.024601	17.03489	27576.69	2.326599875	24.49927
85	2.7541277	0.000632	6.399087	0.024421	17.6239	28530.2	2.407046032	23.68048
90	2.83397403	0.000616	6.421178	0.024253	18.19745	29458.68	2.485380464	22.93411
95	2.91163153	0.000601	6.44201	0.024097	18.75676	30364.11	2.56176972	22.25024
100	2.98727092	0.000588	6.461713	0.02395	19.30289	31248.2	2.63635925	21.62073
105	3.0610418	0.000575	6.480401	0.023812	19.83678	32112.48	2.709276988	21.03882
110	3.13307617	0.000564	6.498168	0.023682	20.35925	32958.28	2.780636188	20.49891
115	3.20349117	0.000553	6.515098	0.023559	20.87106	33786.81	2.850537693	19.99623
120	3.27239133	0.000542	6.531264	0.023443	21.37285	34599.13	2.919071772	19.52676
125	3.33987042	0.000533	6.546729	0.023332	21.86523	35396.2	2.986319617	19.08704
130	3.40601289	0.000524	6.561549	0.023227	22.34872	36178.9	3.052354582	18.67411
135	3.47089515	0.000515	6.575774	0.023126	22.82382	36948.01	3.117243207	18.28539
140	3.53458662	0.000507	6.589448	0.02303	23.29097	37704.26	3.181046031	17.91863
145	3.59715053	0.0005	6.60261	0.022939	23.75058	38448.28	3.243818563	17.57186
150	3.65864473	0.000492	6.615296	0.022851	24.20302	39180.7	3.305611396	17.24381

Engineering Concepts - General

- ☐ Magnet with 32 mm gap and 2 Tesla field, with water cooled coils at large distance from the radiation source. Total electrical power 30 kW – 0.75 kA x 40 V
  - ➢ Example of radiation-hard magnet: JPARC

- ☐ Tungsten-Cu alloy insert with a narrow open channel for the beams and water cooling tubes at ~ 20 cm distance from the power deposition.

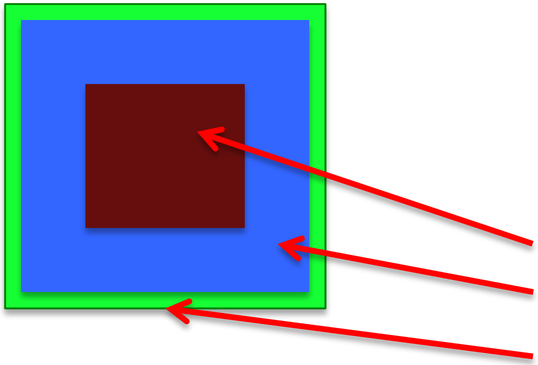


- ☐ Shielding requires ~ 1 kg/cm^2 of material. Minimum weight will be with Tungsten. The plan is to use W powder (16 g/cm^3) with a 10 cm layer of boron outside.

- ☐ The plan of development:
  - ➢ stage #1 engineering (minimize disassembling),
  - ➢ develop a concept of a 100% reliability raster with a power source,
  - ➢ develop a concept of focused raster scheme for the K_L case,
  - ➢ procure ~ 2 tons W powder for bench test of Monte Carlo.
  - ➢ study Hall integration

Shielding Concept – Material Choice and Weight

1 Leaks through the penetrations are tiny
2 Photons/electrons are stopped by $30X_0$ e.g. 10 cm W
3 Fast neutrons are slowed down by the mass of material
4 Slow neutrons are stopped in boron layer
5 Several-MeV photons from activated inner part are very well shielded by 1 kg of material



The Hermetic CPS weight totals ~ 50 tons:

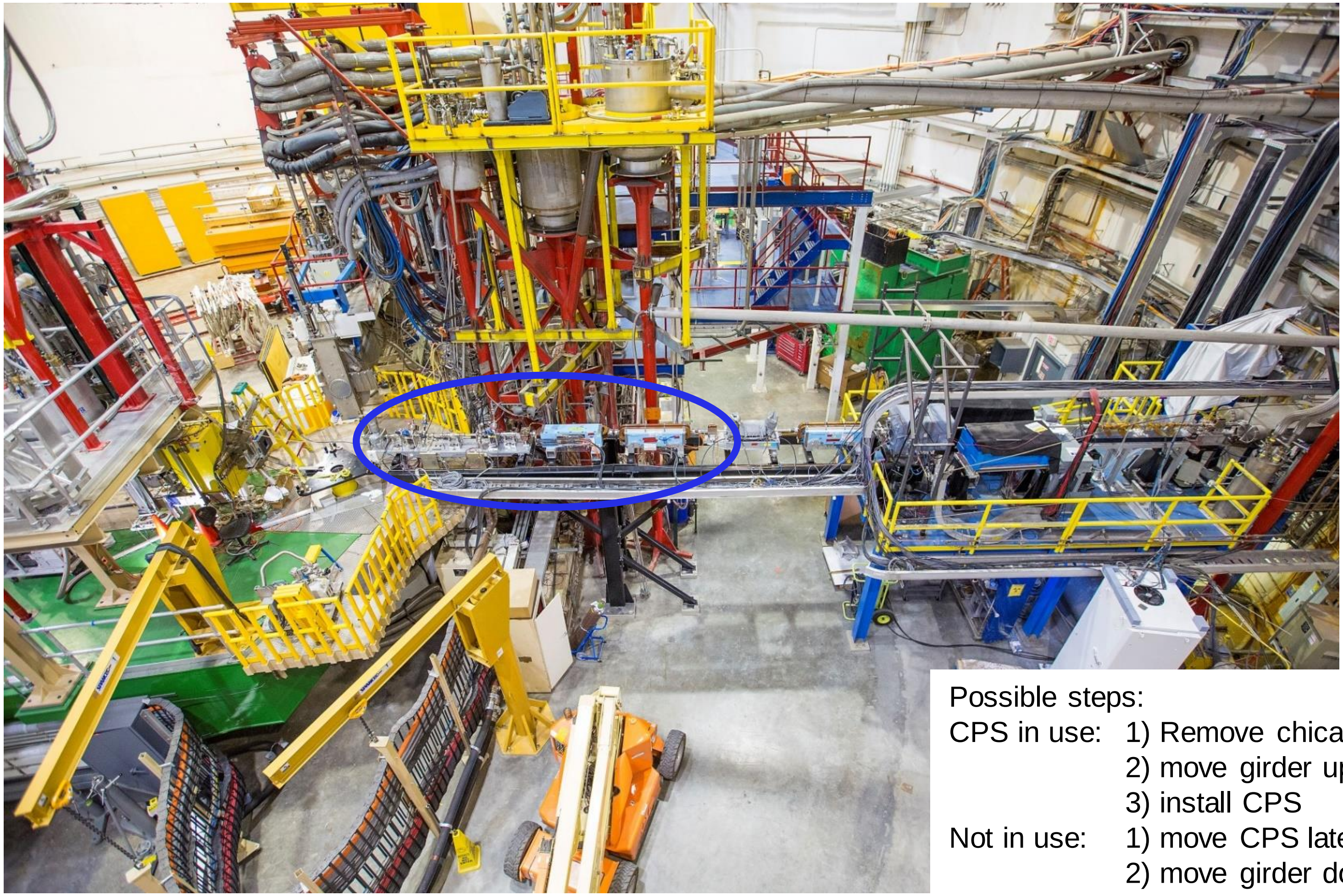
1 Magnet yoke+coils+WCu insert – 5 tons
2 Tungsten powder 30 cm – 40 tons
3 Outer layer boron 10 cm – 0.7 ton
4 Holding frame – 5 tons

View along the beam

- ~50 tons weight should not be an issue for floor loading or the Hall C beam line posts (with a steel plate to spread the load) – for Hall C this is not much different than the very large shielded bunkers and magnets used before.
- For Hall D, the total estimated weight is anticipated to be at most ~100 tons

Engineering Concepts – Minimize Disassembly

- ❑ In Hall D Tagging Facility Alcove it is conceivable to leave the CPS in place as passive element when running tagged photon beam
- ❑ In Hall C a scheme of moving the CPS laterally when not in use looks promising



Possible steps:

CPS in use: 1) Remove chicane magnets
2) move girder upstream
3) install CPS

Not in use: 1) move CPS laterally
2) move girder downstream
3) re-install chicane magnets

Summary

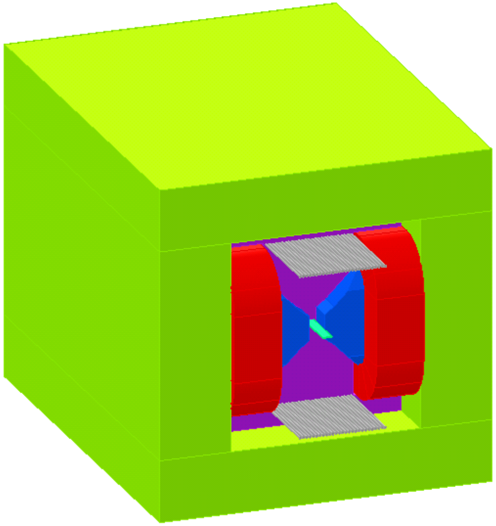
- ❑ Science at Jefferson Lab benefits from an optimized high intensity photon source

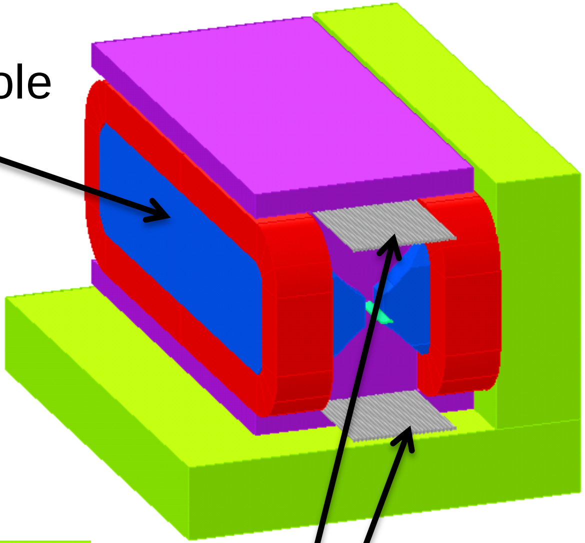
- ❑ CPS is a novel concept allowing for ***high photon intensity*** (equivalent photon flux: ~10^{12} photons/s) and ***low radiation*** (low activation: <1mrem/h after one hour) in the hall

- ❑ CPS implementations in Hall A/C and Hall D/K_L can be equivalent essential design (i.e., similar materials and shielding strategy), with some differences due to the locations (like more space in Hall D, perhaps longer magnet, ..)

- ❑ Strong interest by Hall A/C and Hall D/K_L to jointly further develop an as common as possible CPS design and seek funding for CPS

Magnet and Collimator Concept



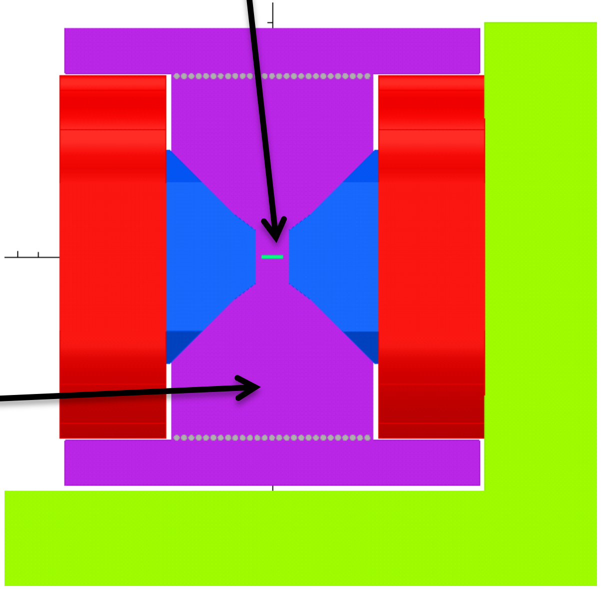


Permendur pole

Cooling water lines

2x20 mm^2 opening

Power 30 kW x 750 A
32 mm gap 2.0 Tesla



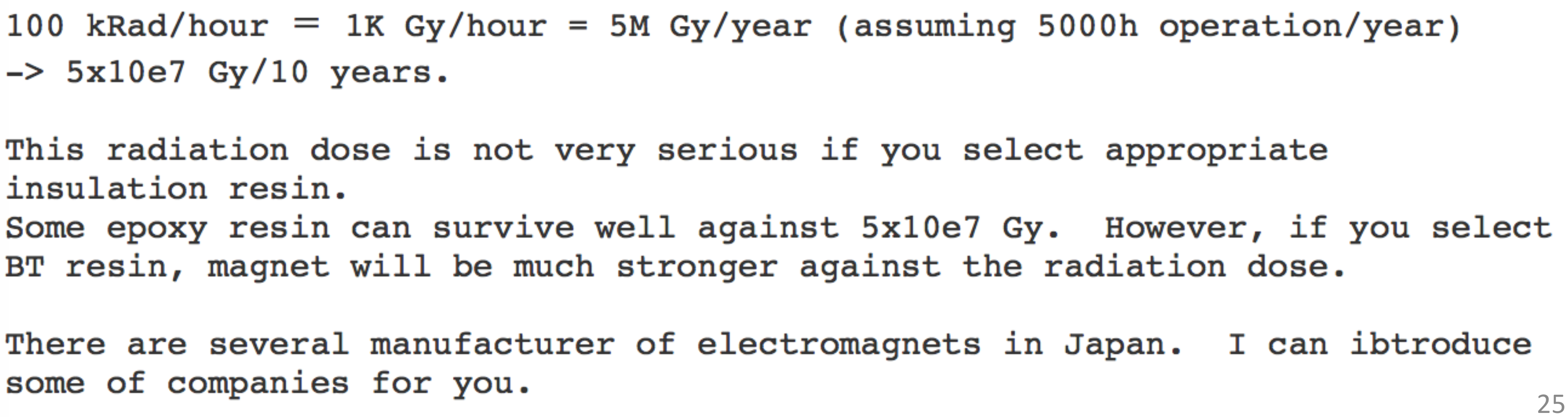
WCu power
absorber and
radiation shielding

Radiation Hard Magnet Example


fully inorganic magnet

J-PARC – warm magnet

e-mail from Dr. K. Tanaka:


100 kRad/hour = 1K Gy/hour = 5M Gy/year (assuming 5000h operation/year)
-> 5x10e7 Gy/10 years.

This radiation dose is not very serious if you select appropriate insulation resin.
Some epoxy resin can survive well against 5x10e7 Gy. However, if you select BT resin, magnet will be much stronger against the radiation dose.

There are several manufacturer of electromagnets in Japan. I can ibtroduce some of companies for you.