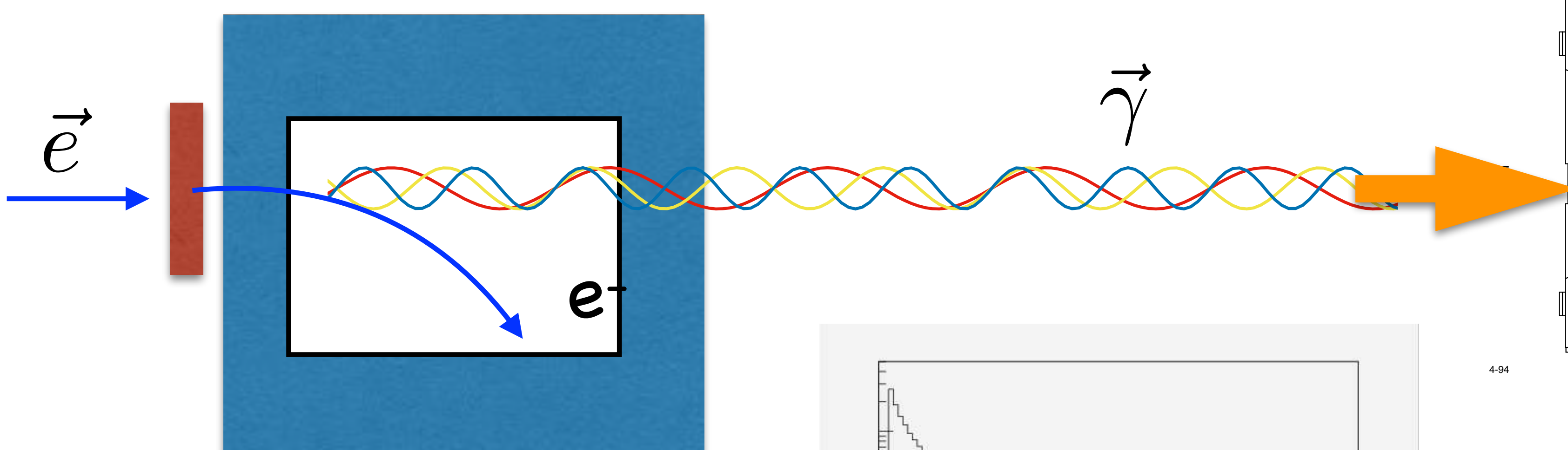
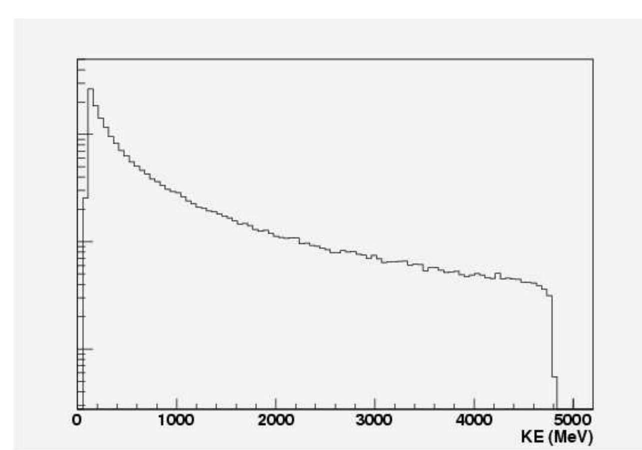
Compact Photon Source: Science Opportunities and Concept

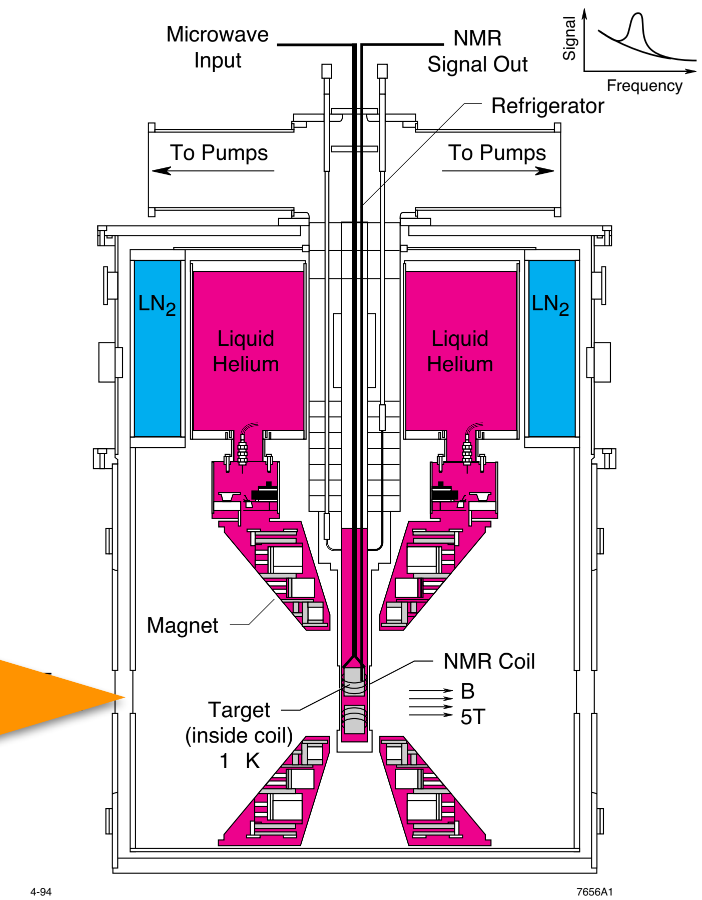
Donal Day

University of Virginia

for the many*







Jefferson Lab

Hall C Winter Meeting

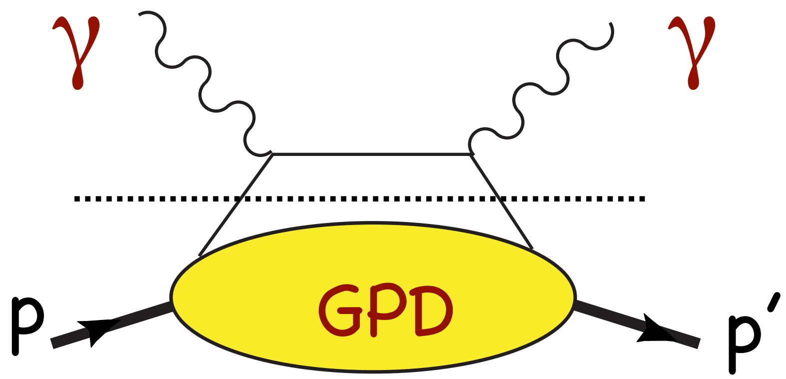
January 23, 2018

Pavel Degtiarenko
Rolf Ent
David Hamilton
Tanja Horn
Dustin Keller
Cynthia Keppel
Gabriel Niculescu
Igor Strakovsky
Bogdan Wojtsekhowski
Jixie Zhang

Outline

- Polarized WACS - the original motivation
- DNP Polarized targets have their limitations
    - Evolution of a pure photon source
- The CPS
    - Some detail, post-conceptual design and engineering
    - Radiation studies
- List of other potential experiments
- What's next? - Thia led discussion this evening.

Wide Angle Compton Scattering



- One of the most fundamental processes yet it is still not well understood at medium energy

Provided that s, t, u >> Λ^2 the handbag mechanism involves factorization of the amplitudes into:

- Hard photon-parton scattering
- Soft emission and re-absorption of parton by proton

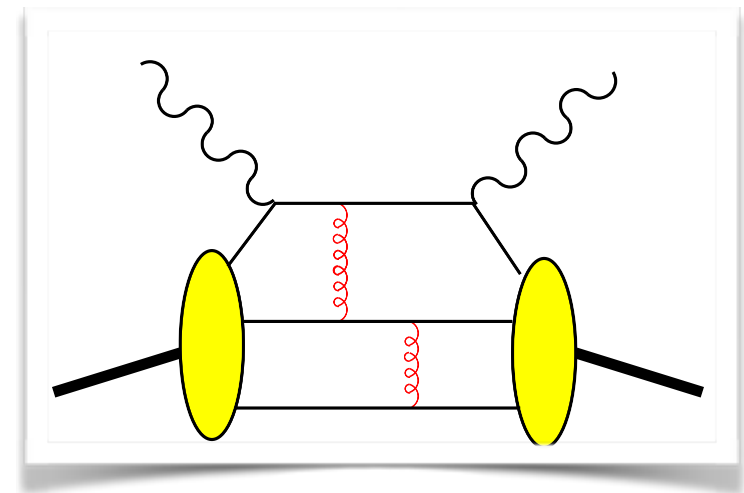
WACS provides complimentary information to elastic FF at high Q^2 and DVCS, TCS, DDVCS, DVMP

- Common thread: large energy scale leading to factorization of scattering amplitude into a hard perturbative kernel and a factor expressing soft non-perturbative WF

Polarized observables can provide access to information not otherwise available

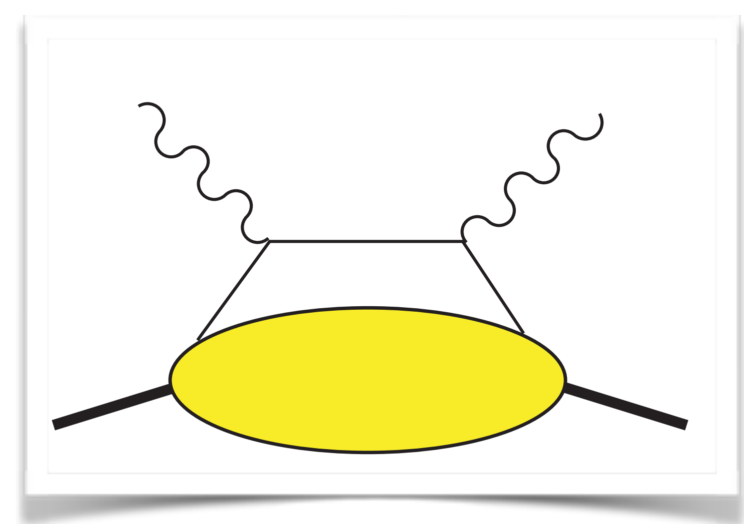
Wide Angle Compton Scattering

Multiple theoretical approaches have been proposed over the years:



- pQCD (two hard gluon exchange)
- Regge exchange and VMD models
- GPD-based soft overlap mechanism
- Soft collinear effective theory (SCET)
- Relativistic constituent quark model
- Dyson-Schwinger equations

- How does the reaction mechanism factorize?

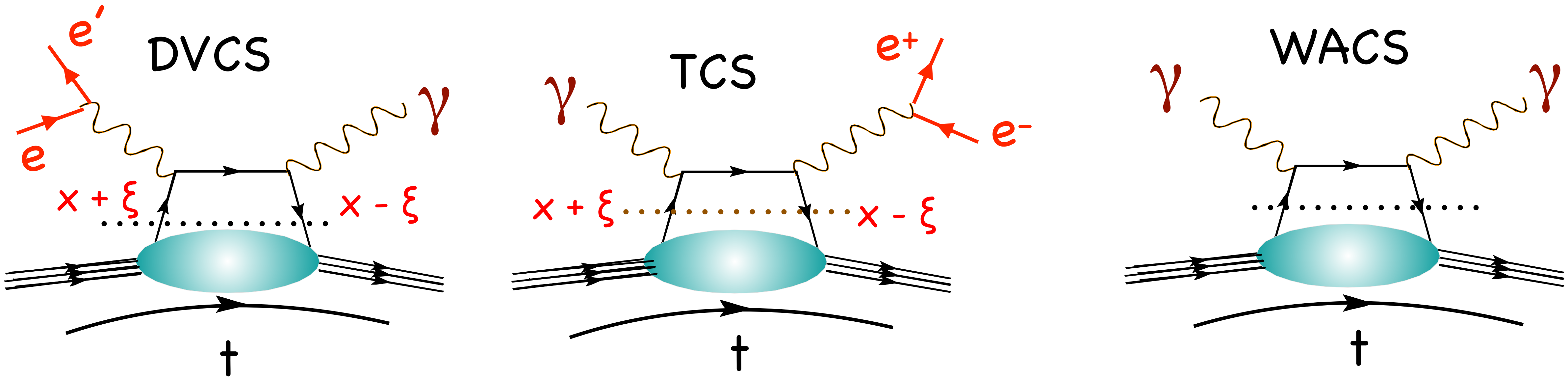


- What new insights on the non-perturbative structure of the proton are accessible?

$$A_{LL}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma(\downarrow\uparrow)}{dt}\right]$$

$$A_{LS}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{d\sigma(\uparrow\rightarrow)}{dt} - \frac{d\sigma(\downarrow\rightarrow)}{dt}\right]$$

Common Treads



small t and large Q^2 large t and large s

at large Q^2 : QCD factorization theorem ➡ hard exclusive processes can be described by 4 Generalized Parton Distributions:

Vector : $H(x, \xi, t)$ Axial-Vector : $\tilde{H}(x, \xi, t)$

Tensor : $E(x, \xi, t)$ Pseudoscalar : $\tilde{E}(x, \xi, t)$

The factorization[1] is applicable for $|t|/Q^2 \ll 1$ for DVCS and TCS but for WACS[2] when $-t$ (and $-u$) are large but the photon virtuality is small or even zero ($Q^2/t \ll 1$)

1: X. Ji, Phys. Rev. D 55 (1997) 7114-7125; A.V. Radyushkin,Phys. Rev. D 56 (1997) 5524-5557, J.C. Collins, L. Frankfurt, and M. Strikman, Phys. Rev. D56 (1997) 2982-3006.

2: A. V. Radyushkin, Phys. Rev. D 58, 114008 (1998) [hep-ph/9803316]; M.Diehl, T.Feldmann, R.Jakob and P.Kroll, Eur. Phys. J.C8,409(1999) [hep-ph/9811253].

Wigner distributions

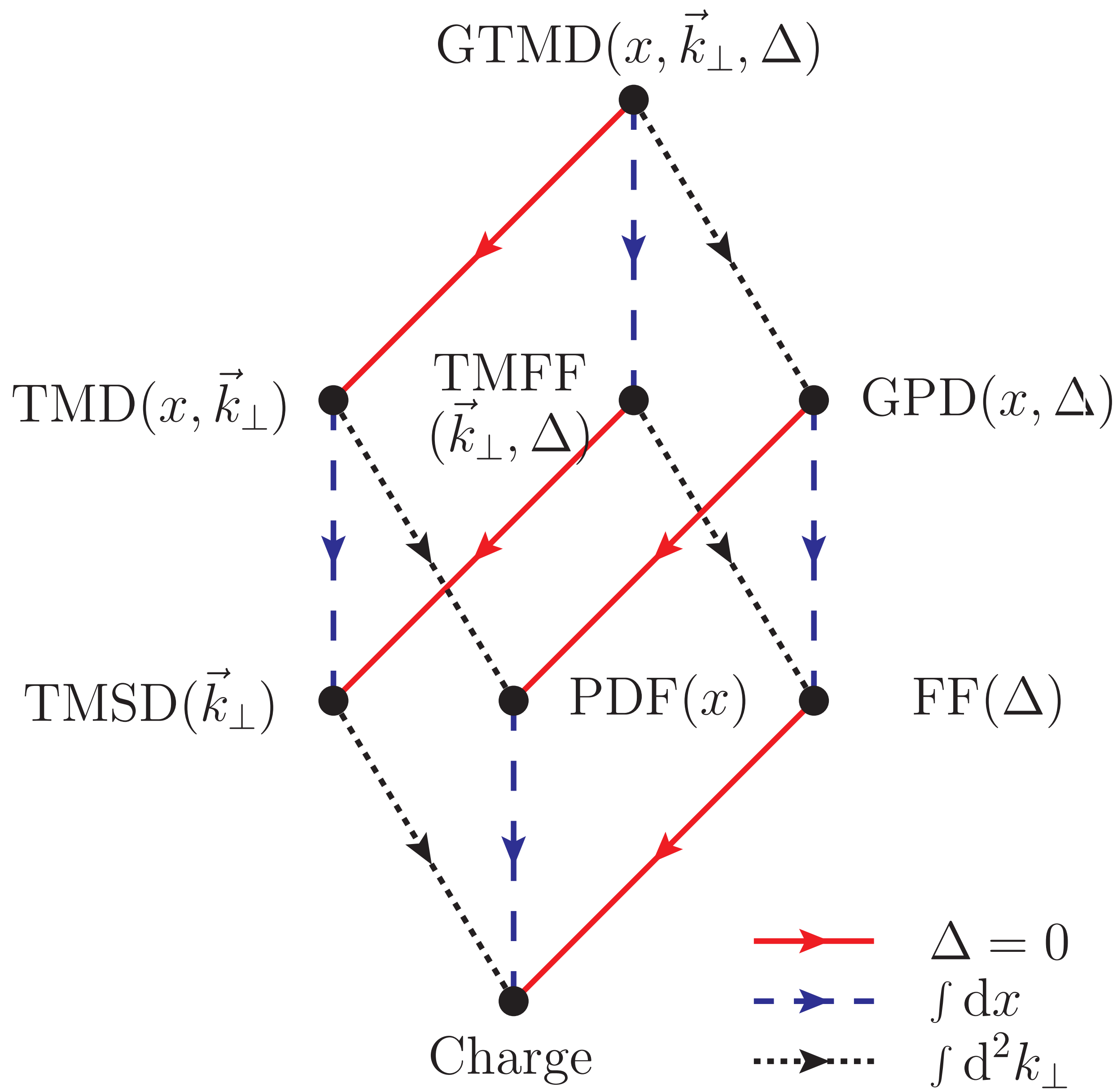


Fig. 1. Representation of the projections of the GTMDs into parton distributions and form factors.

Exclusive Reactions

DVCS

TCS

DDVCS

DVMP

WACS

WACS Polarization Observables

Status

- K_{LL} (θcm=120) – HB, CQM,SCET, Miller – YES, pQCD – NO
- K_{LL} (θcm=70) – CQM,SCET,HB,pQCD – NO
- Relation between K_{LL} and A_{LL}
  - pQCD: $K_{LL} = A_{LL}$ but < 0
  - HB: $K_{LL} = A_{LL}$
  - SCET: $K_{LL} = A_{LL}$
  - CQM: K_{LL} != A_{LL} at large angles
- K_{LS} small and > 0
  - HB: $K_{LS} = -A_{LS}$
  - pQCD: $K_{LS} = A_{LS} = 0$
  - CQM: $K_{LS} = A_{LS} = 0$
- HB, pQCD, SCET, CQM all have predictions for s-dependence and θ-dependence
- What if:
  - $K_{LL} = A_{LL}$; HB/SCET on track and we provide constraints on GPDs, and data need to refine theory
  - K_{LL} and A_{LL} about equal
    - Kroll: learn about helicity flip
    - Kiev (SCET): learn about power corrections
    - K_{LL} != A_{LL} SCET gets a reset, HB (Kroll) can be interpreted in terms of helicity flip

Non-Perturbative Proton Structure

$\gamma p \longrightarrow \gamma p$

$ep \longrightarrow ep$

Compton form factors

$$R_V(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x,0,t)$$

$$R_A(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} \ \mathrm{sign}(x)\, \hat{H}^a(x,0,t)$$

$$R_T(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} E^a(x,0,t)$$

Elastic form factors

$$F_1(t) = \sum_a e_a \int_{-1}^{1} dx\, H^a(x,0,t)$$

$$G_A(t) = \sum_a \int_{-1}^{1} dx\, \mathrm{sign}(x)\, \hat{H}^a(x,0,t)$$

$$F_2(t) = \sum_a e_a \int_{-1}^{1} dx\, E^a(x,0,t)$$

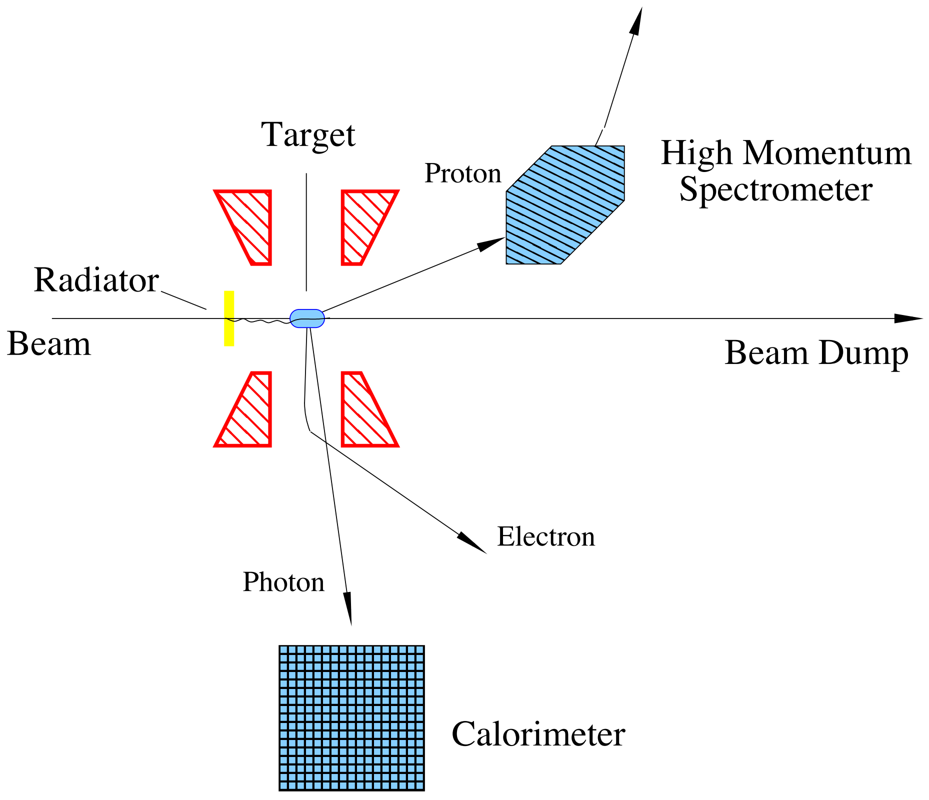
$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}_{KN} \left\{ \frac{1}{2} \left[R_V^2 + \frac{-t}{4m^2} R_T^2 + R_A^2 \right] - \frac{us}{s^2+u^2} \left[R_V^2 + \frac{-t}{4m^2} R_T^2 - R_A^2 \right] \right\}$$

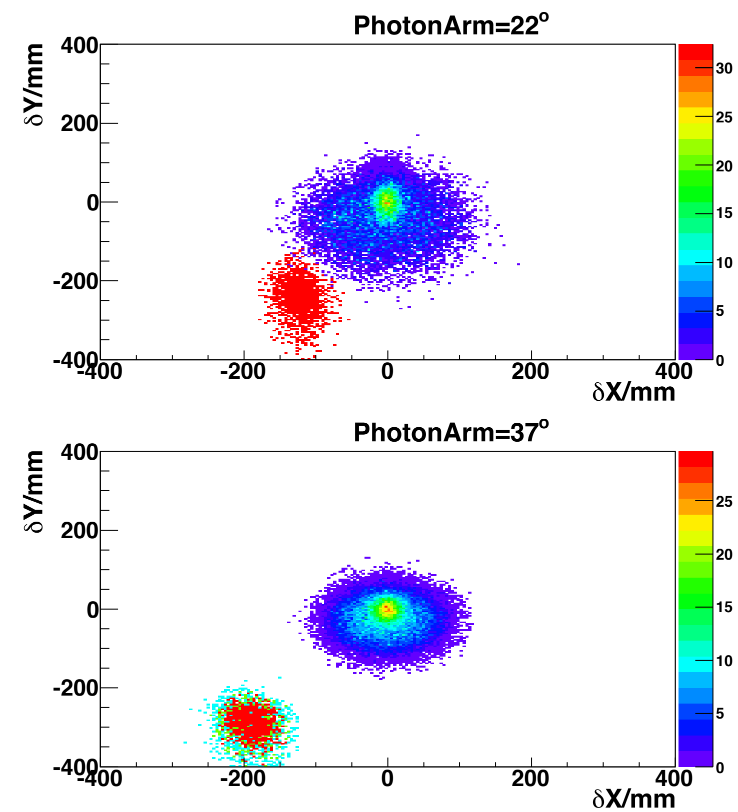
$$A_{LL} = K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{KN}$$

$$A_{LS} = -K_{LS} = A_{LL} \left[\frac{\sqrt{-t}}{2m} \frac{R_T(t)}{R_V(t)} - \beta \right]$$

Non-perturbative physics encoded in vector, axial-vector and tensor form factors which can be related to 1/x moments of high momentum transfer, zero skewedness GPDs H, H~ and E.

E05-101 & E12-14-006, Polarized WACS



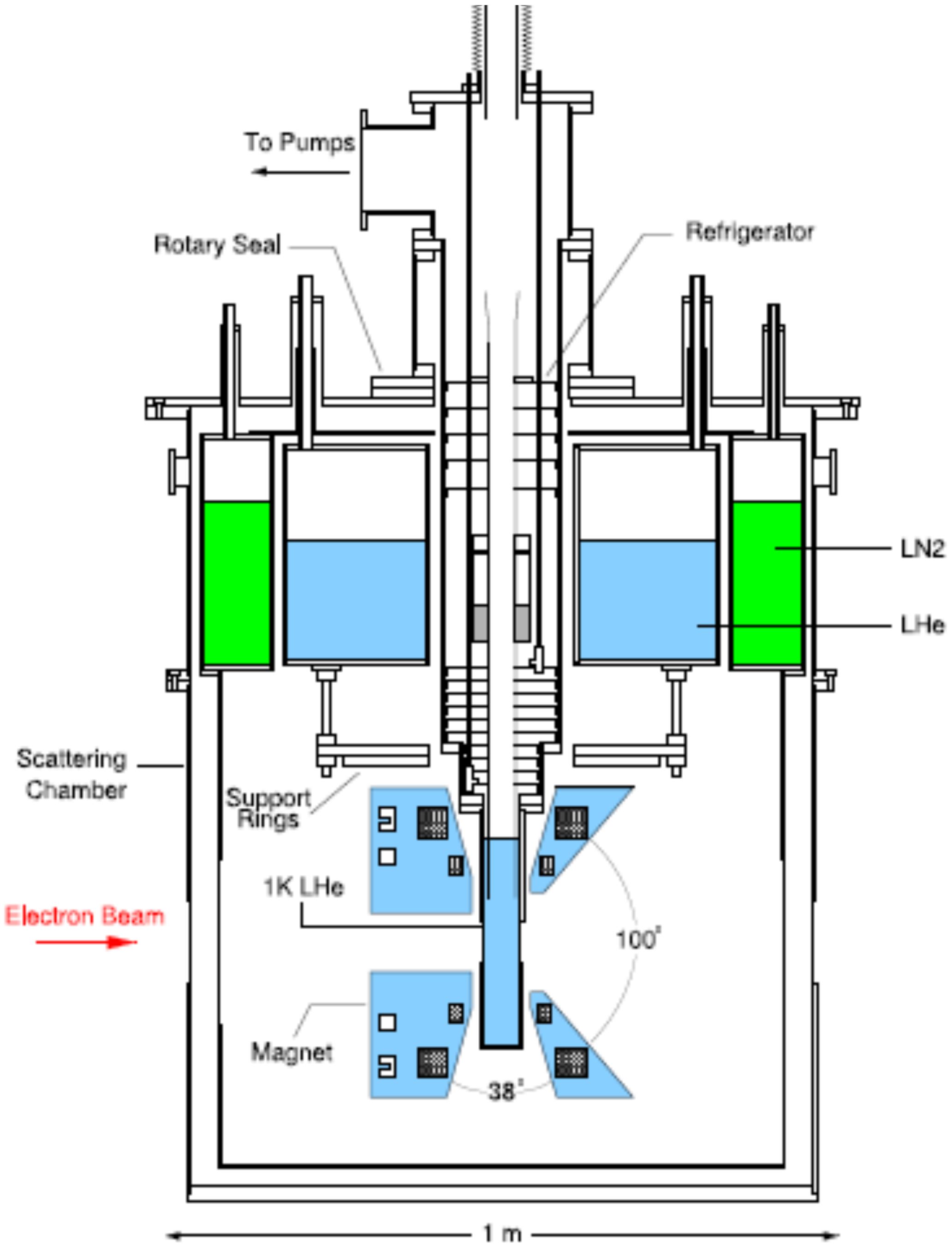


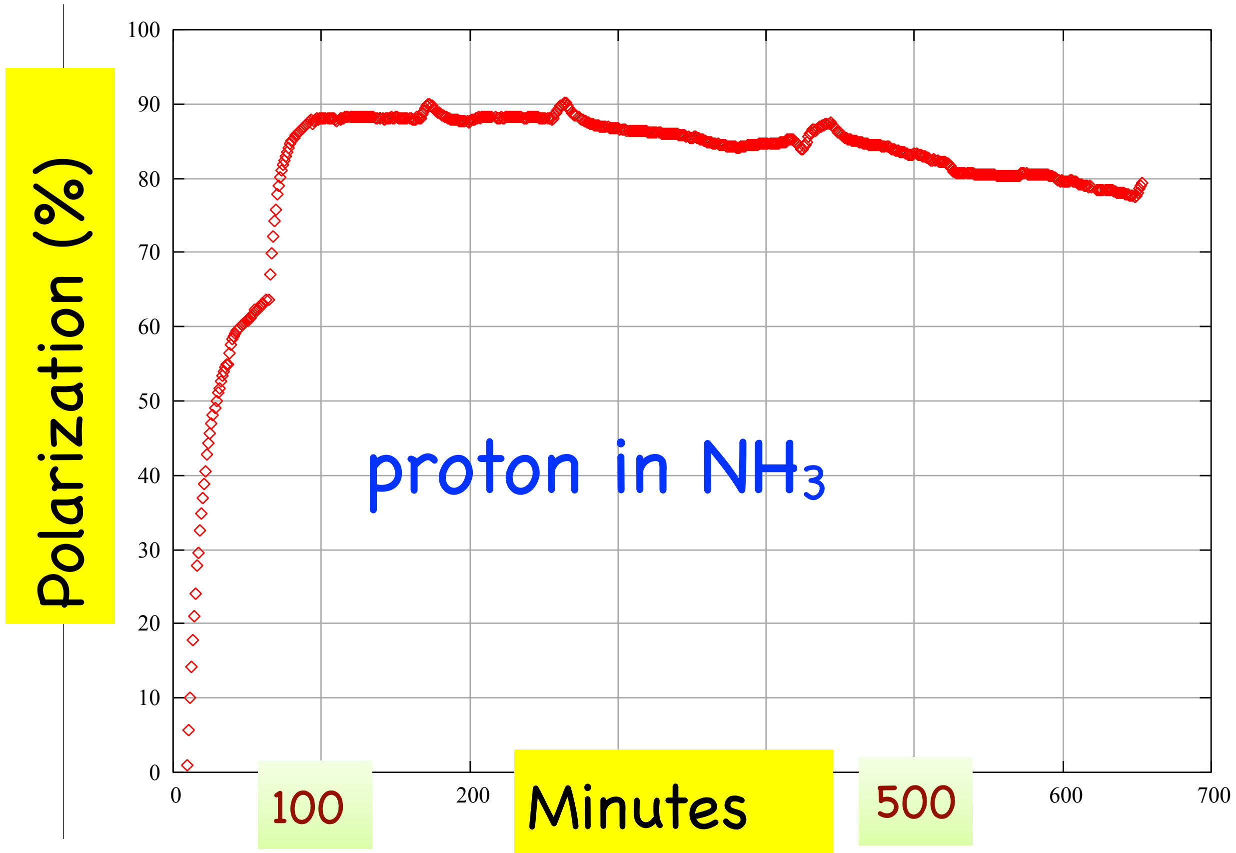
- 4.4 GeV
- E05-101/E12-14-006 approved to measure A_{LL} - 14 and 15 days respectively
- Target field displaces electrons in calorimeter
- s = 9 GeV, 2 < t < 6 GeV; marginally in region of Madelstam variables where factorization should be valid
- Mixed photon/electron beam , I = 90 na; photons: 3(10) γ/s

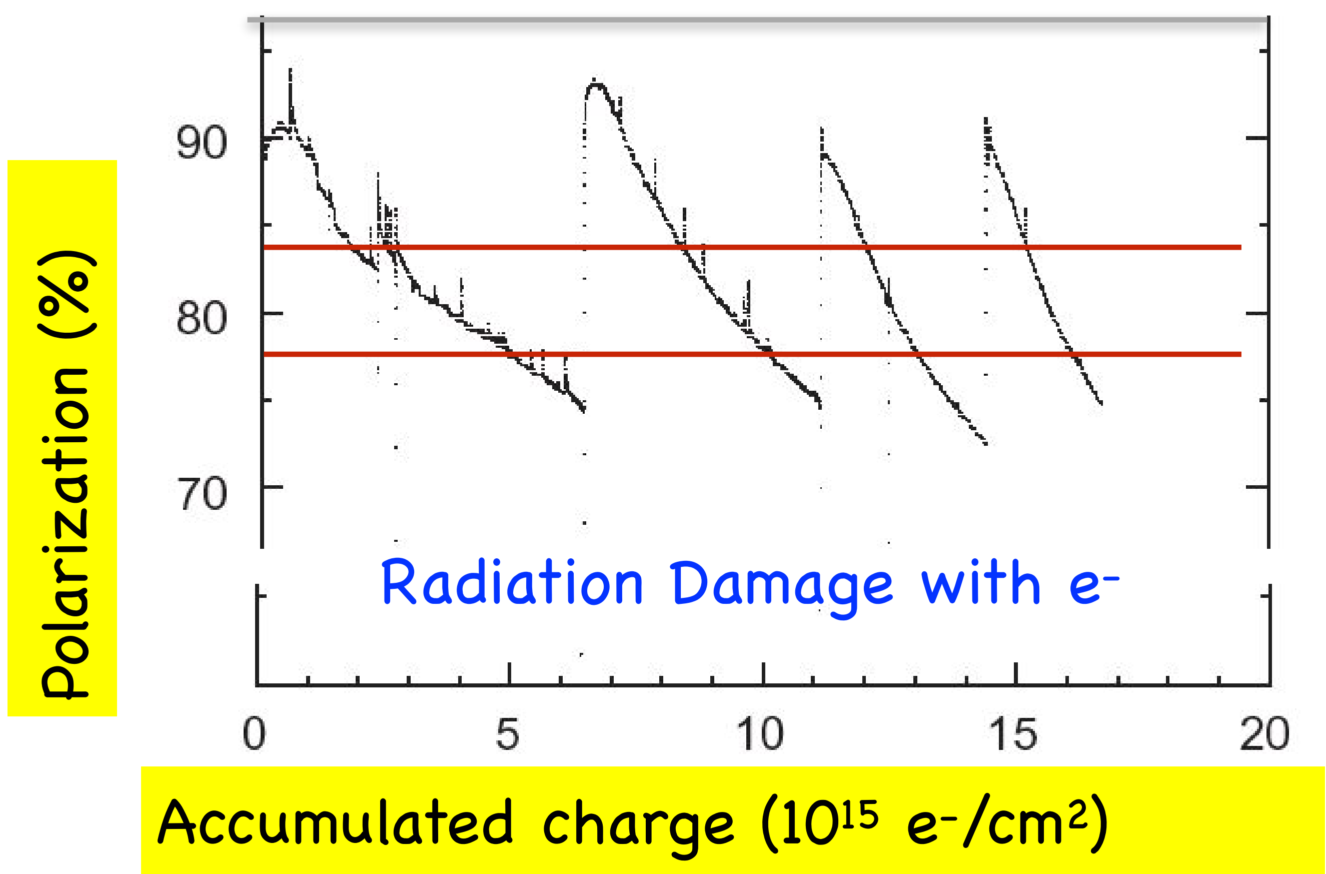
Solid Polarized Target

Solid polarized proton target, NH_3

- ^4He evaporation refrigerator, 1K
- 5 T polarizing field
- Dynamic Nuclear Polarization







DNP targets

- 5 Tesla SC magnet
- Target material cooled to 1K
- 140 GHz microwaves
- NMR system
  - TEs
- Radiation damage
  - Anneal 2/day
  - Swap material, 1/wk
- Max current = 90 - 100 nA e-

Annealing Procedure

```
ANNEALING TARGET
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Assumptions:
  Fridge running - all pumps on

Prepare NMR:
  Stop beam, if necessary
  Turn off Microwaves, if necessary
  Put NMR into Monitor Mode

Prepare Fridge:
  Stop Roots Blower 3 by pressing the RB3 Stop Button (in electronics room)
  Wait 2 minutes for pump to spin down
  Stop Roots Blower 2 by pressing the RB2 Stop Button (in electronics room)
  Wait 2 minutes for pump to spin down
  Stop Roots Blower 1 by pressing the RB1 Stop Button (in electronics room)
  Open Main Gate Valve, PV91141, if necessary (in electronics room)
  Close Bypass RB3 Valve, PV91142, if necessary (in electronics room)
  Close Roughing Valve, PV91143, if necessary (in electronics room)
  Place Run Valve, EV91120, into Manual Mode (cryo computer)
  Close Run Valve by entering a manual setpoint of zero
  Close Bypass Valve, EV91121, if necessary, by entering a position of zero
  Put the Separator Valve, EV91127, into Computer Control (not Manual Mode)
  Enter a value of 60 into the Set Val box of the EV91127 control

Empty the Tail of Helium:
  DO NOT move the target without first informing MCC - you'll trip all Halls
  Move the target to the Top position, write in logbook
  Load the Anneal program (icon on desktop)
  Run the Anneal program (click white arrow on left of toolbar)
  Type in a setpoint of 60 (K) and hit "Send to ITC", write in logbook
  Hit the "Goto Setpoint" button to turn on the heater
  Observe the liquid level in the tail drop (7% is about the minumum reading)
  Wait 5 minutes after the liquid is gone
  Open the Run Valve to 0.3, write in logbook
  Move the target to Empty position, write in logbook
  (If Run Plan needs to do Carbon runs, this position is also OK)
  Use Lower camera to see the He4 pressure (Rack B, Device 5), write in logbook

Begin the Anneal:
  Wait until all three sensors stabilize at 60K, write in logbook
  Type the desired Anneal temperature into the setpoint, Hit "Send to ITC"
  Note in the logbook the time when the anneal temperature is reached
  Log Top Platinum, Top T/C, Bottom T/C, and He4 Pressure every 5-10 minutes
  Leave the target at the Anneal temperature for the desired number of minutes
  To stop the anneal, hit the "Stop Anneal" button, write in logbook
  Let the anneal program continue to run, to document the cooldown process

Cool Down the Refrigerator:
  Change the setpoint of the Bypass Valve to 1.0
  Change the Manual setpoint of the Run Valve to 1.0
  Wait until the Nose Level, LL91112, reaches about 80%
  Change the setpoint of the Bypass Valve to 0.0
  Change the Run Valve back to computer control (not Manual Mode)
  Enter a value of 32 into the Set Val box of the EV91127 (Separator) control
  The the Stop button on the toolbar of the Anneal Program, and then close it
  Wait for the Nose Level to (mostly) stabilize
  Observe the He4 pressure
  If the pressure is not below 12 torr, temporarily close the Run Valve
  Once the pressure is below 12 torr, start RB1 (electronics room)
  Wait for the pressure to drop below 2.2 torr
  Start RB2
```

....2 hours later we start to polarize

1/week the material has to swapped out

The idea to dump electrons is not new

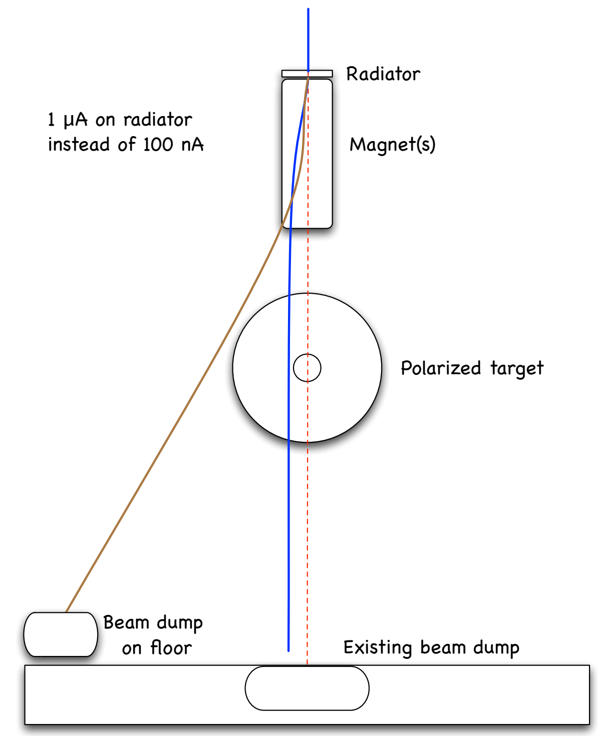
SLAC-PUB-605
July 1969
(EXPI)

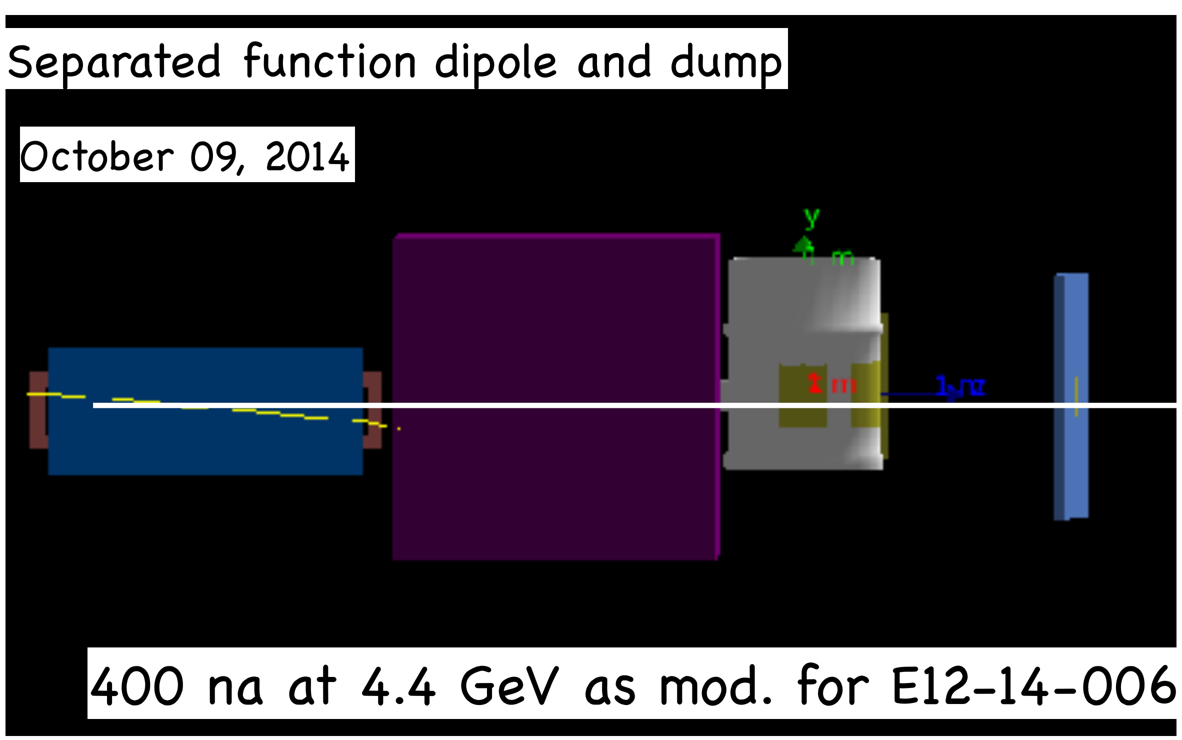
A BEAM MONITOR SYSTEM FOR HIGH-INTENSITY PHOTON BEAMS IN THE MULTI-BEV RANGE*

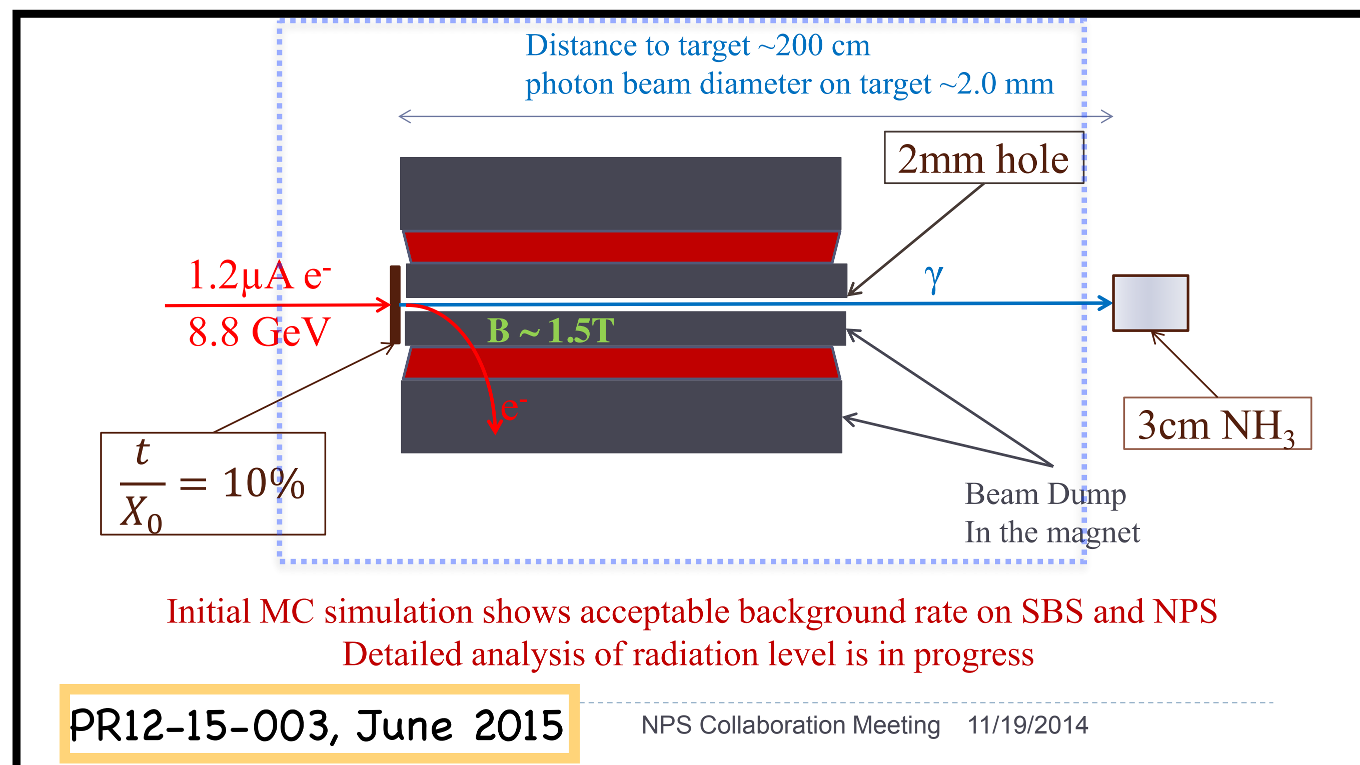
The bremsstrahlung photon beam at End Station A at SLAC (see Fig. 1) is produced by a high-power momentum-analyzed electron beam striking an aluminum radiator typically 0.03 radiation length thick. After passing through the radiator, the electron beam is bent downward into a water-cooled dump capable of absorbing up to 300 kilowatts of power. The bremsstrahlung beam is collimated to reduce

The rest of the text tells the reader that the dump was some 50 m from the target!

At Hall C Workshop January 7, 2006

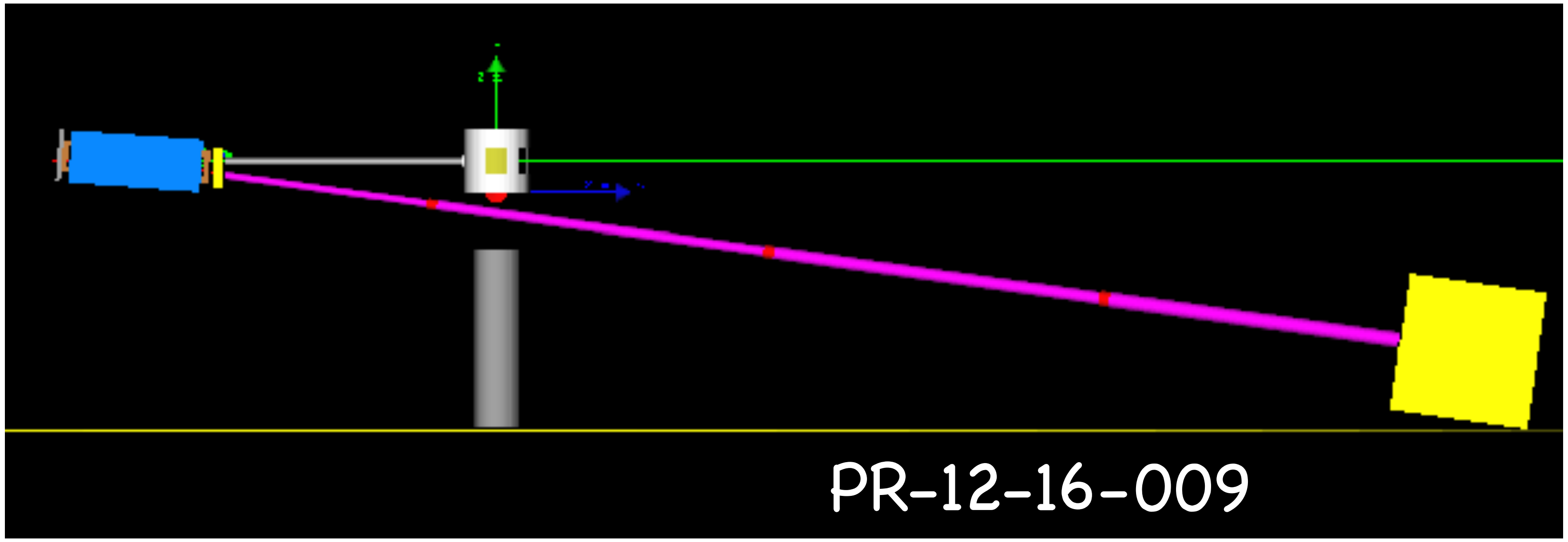


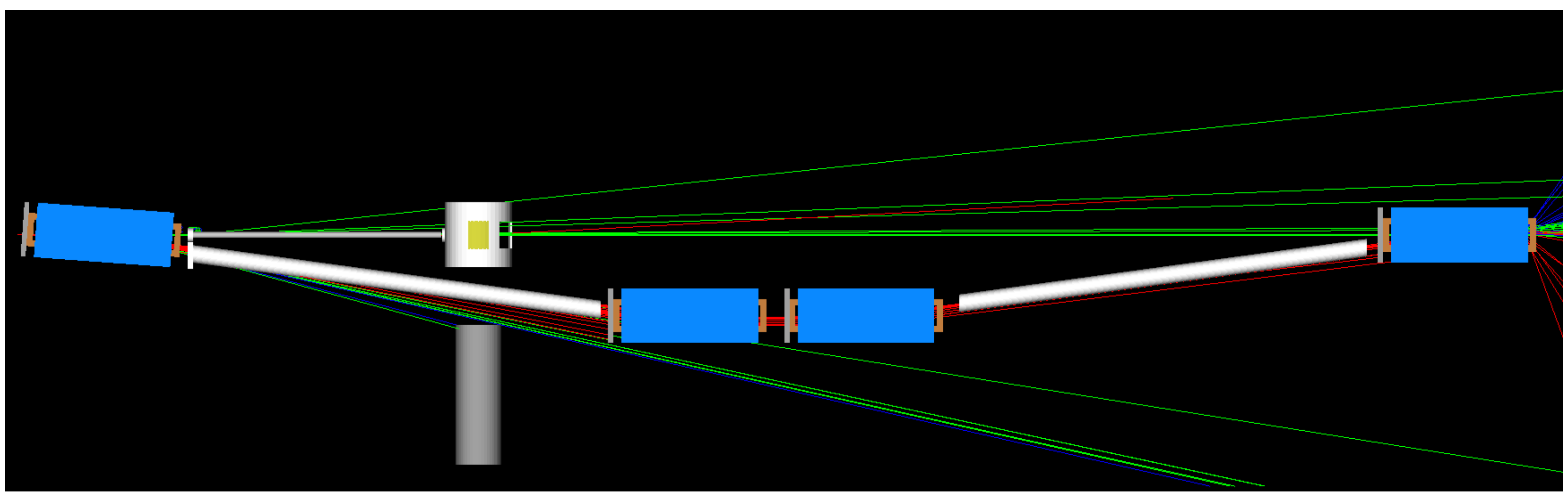




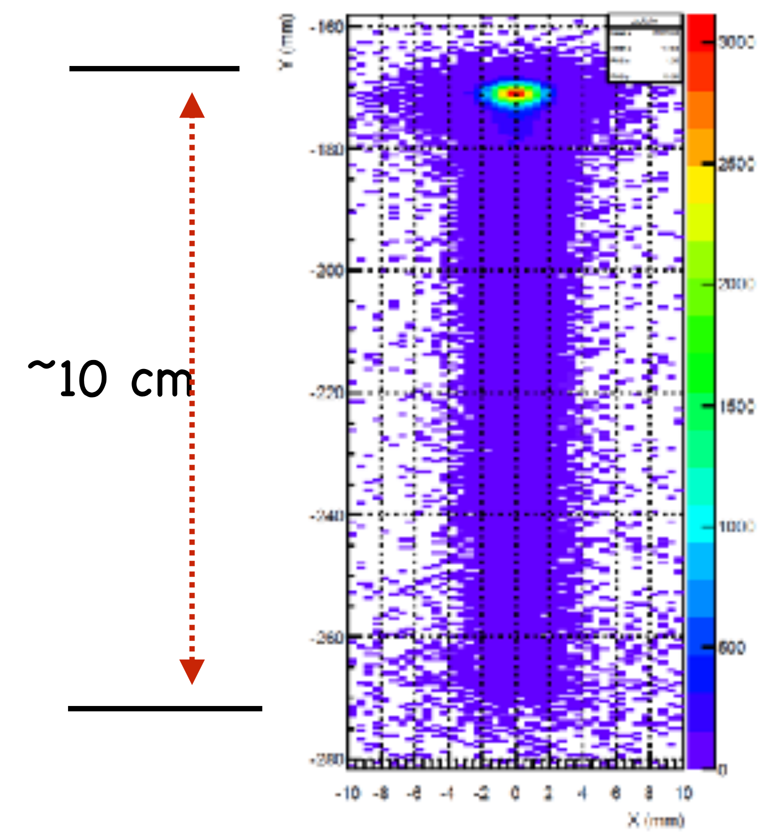
N.B. 4.4 GeV@400nA, then 8.8 GeV@1.2μA and, as you will see 11 GeV@2.6μA, a total of a factor 36!

Other options surfaced in PR12-16-009, a measurement of A_{LL} and A_{LS}





While these both moved the dump away from the pivot they suffered from the 'sheet of flame' - the dispersion of the beam after the dipole due to bremsstrahlung and multiple scattering in the radiator



This problem, with effort, could likely be solved, but study showed that, in fact the combined dipole/dump - the CPS idea can work: acceptable radiation at the pivot

Convergence

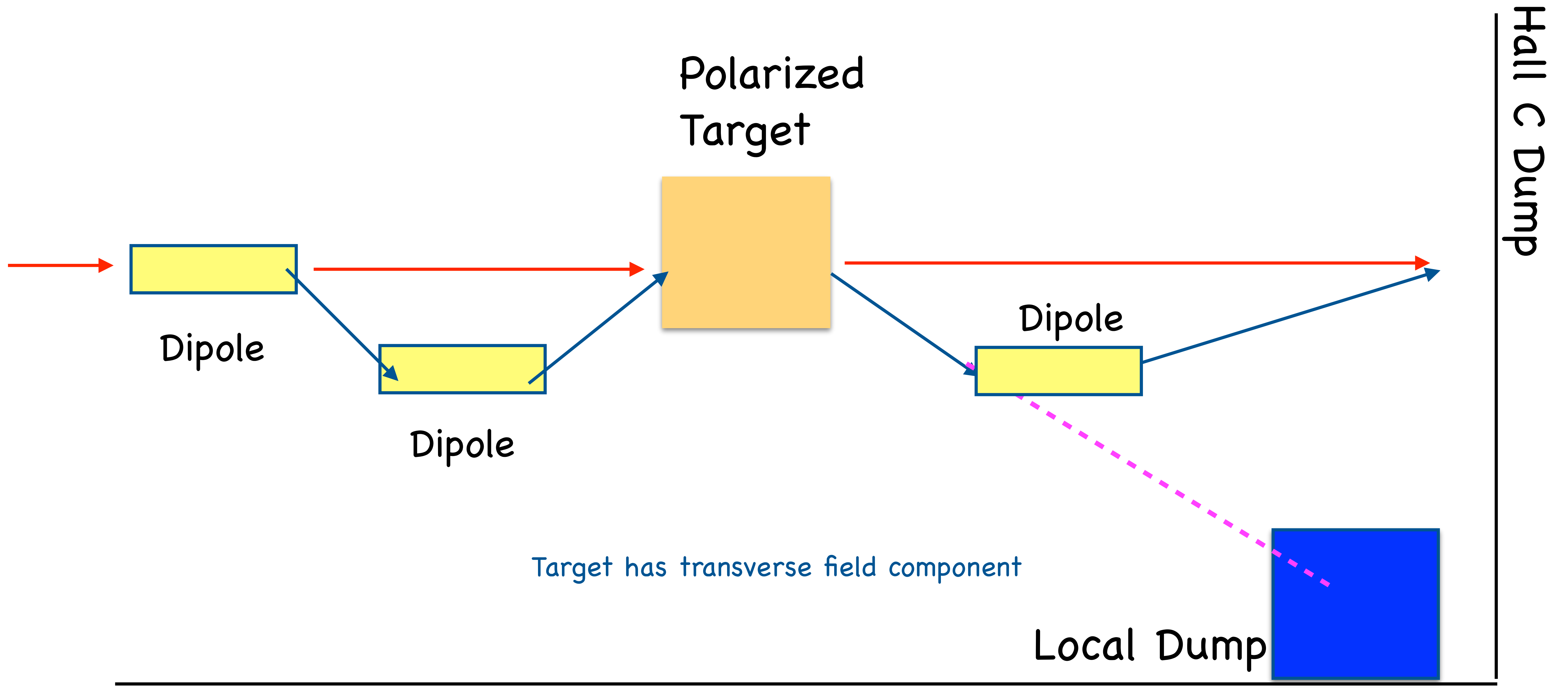
Leadership from PAC and laboratory lead those interested to work together. Study determined that a Compact Photon Source would likely work. The concept is based on the one revealed in PR12-15-003.

Collaboration submitted a new proposal to PAC45 and it was conditionally approved - C12-17-008 for its full request of 45 days

Many aspects of the CPS have been thoroughly investigated, optimized and technical issues resolved. Prompt and induced radiation responses have been studied extensively. Ready to move to the next stage.

Photon flux is about 30 time greater than with 100 na mixed photon electron beam and with ‘normal’ target overhead.

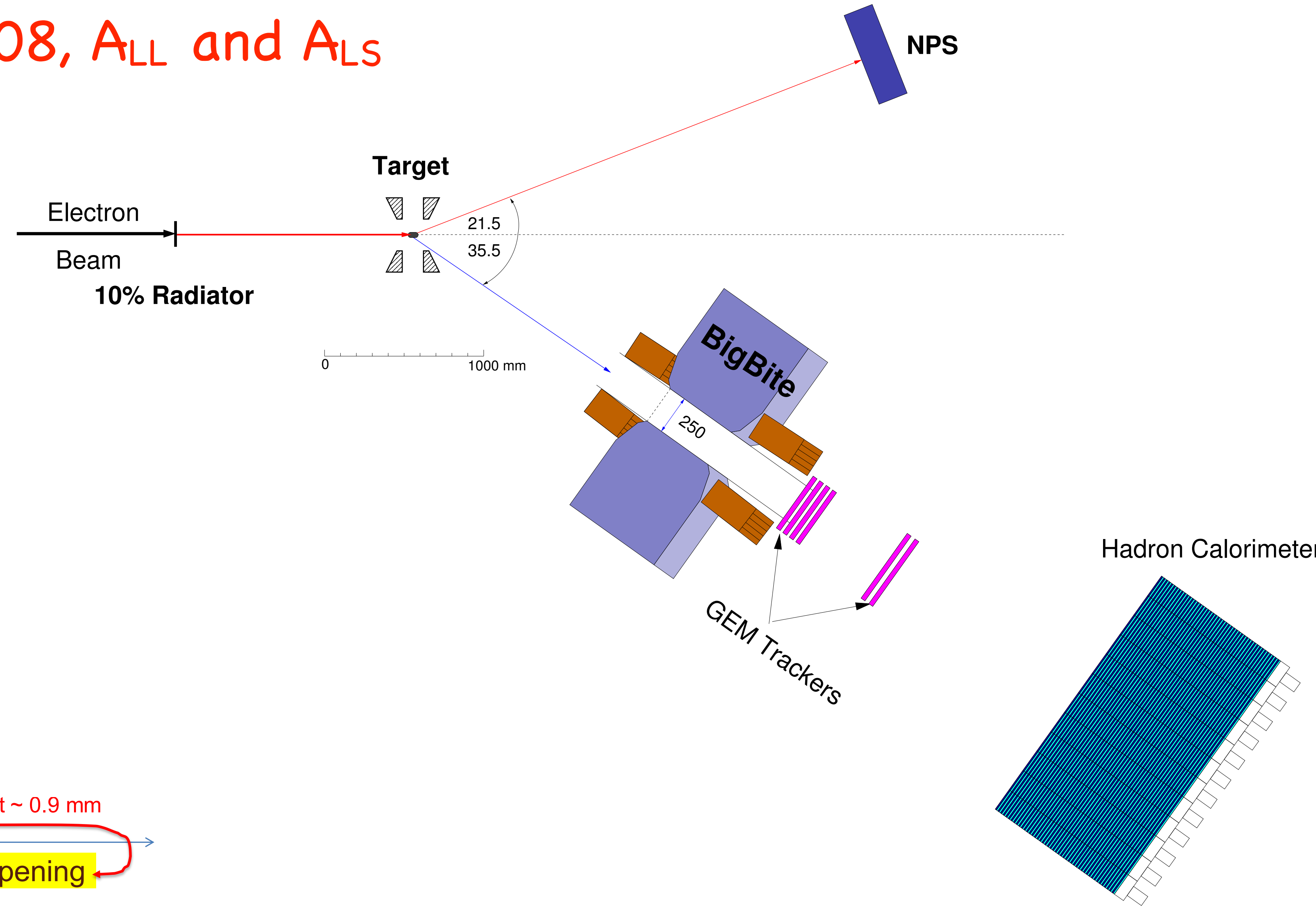
Transverse Running demands a Beam Line Chicane

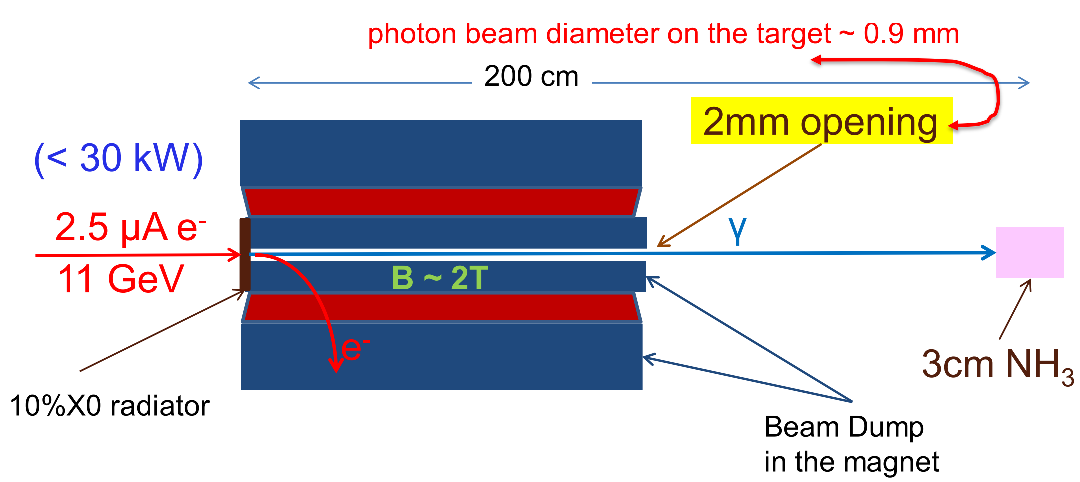


Pure photon beam does not!

After deferred proposals in 2015 and 2016 'Success' with C12-17-008, A_{LL} and A_{LS}

- A 3 μA polarized electron beam incident on a 10 % radiator inside a Compact Photon Source (CPS) produces a high-intensity untagged photon beam.
- The proton target is the UVA/ JLab solid polarized ammonia target.
- The recoil proton is detected with the BigBite spectrometer equipped with GEM trackers and trigger detectors.
- The highly-segmented PbWO4 NPS calorimeter is used to detect the scattered photon

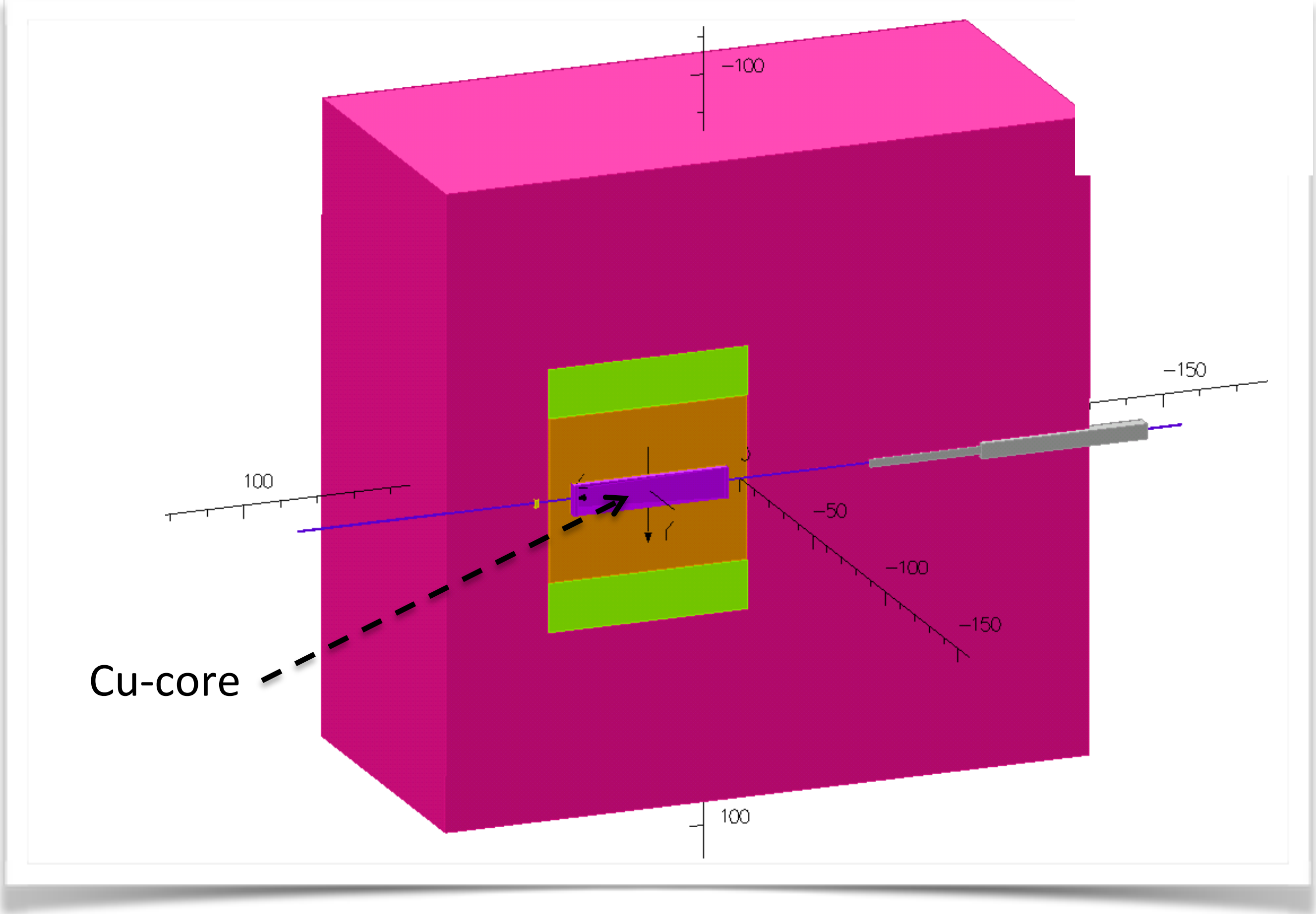




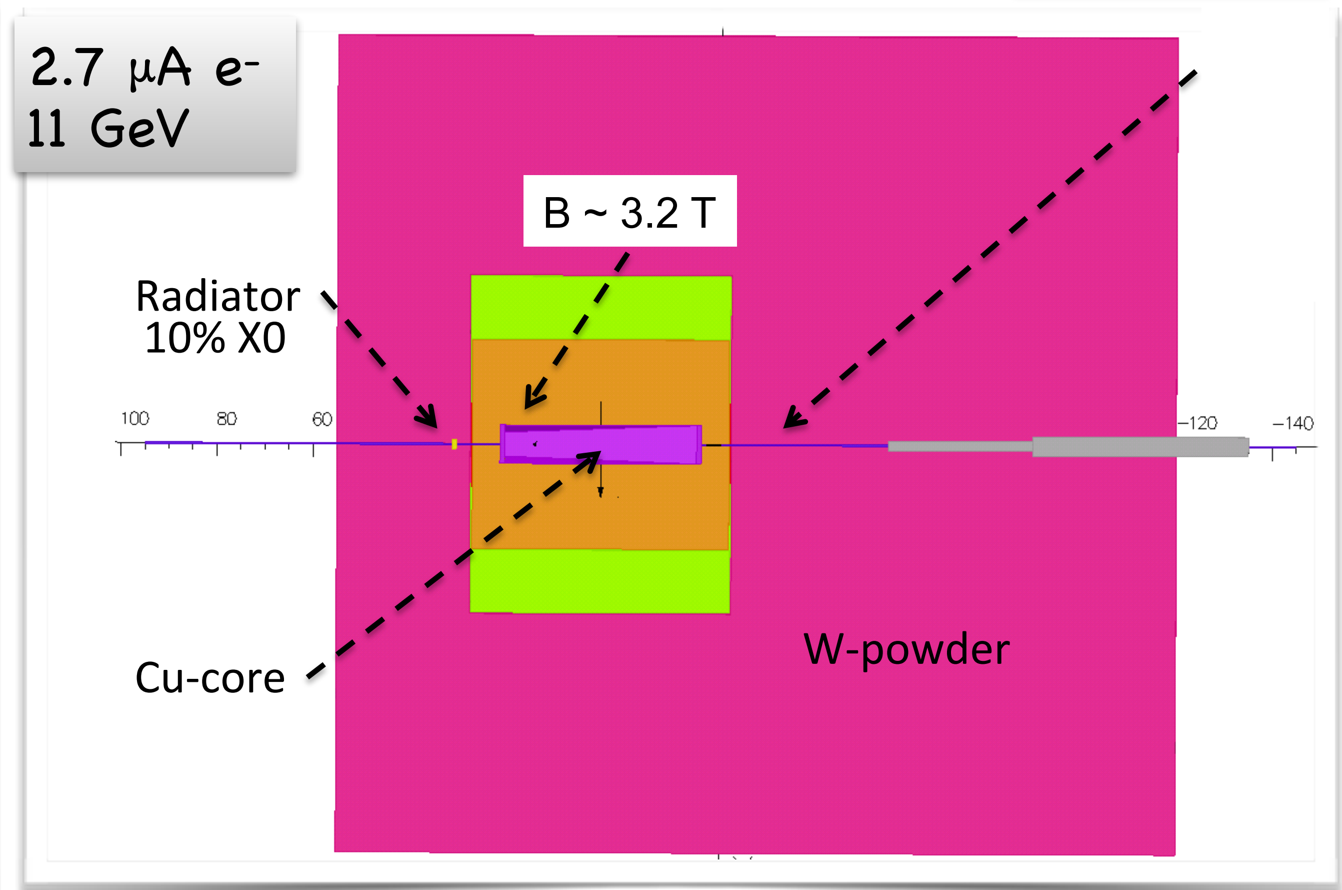
The use of the CPS and BigBite results in a significantly improved figure-of-merit over all previous experiments and opens up a new range of polarized physics opportunities at JLab.

A_{LL} and A_{LS} at invariant s in the range of 9 to 20 GeV^2 and scattering angles of θ_{cm} = 70°, 90° and 110° such that range in $-t$ is from 2.8 to 8.1 GeV^2

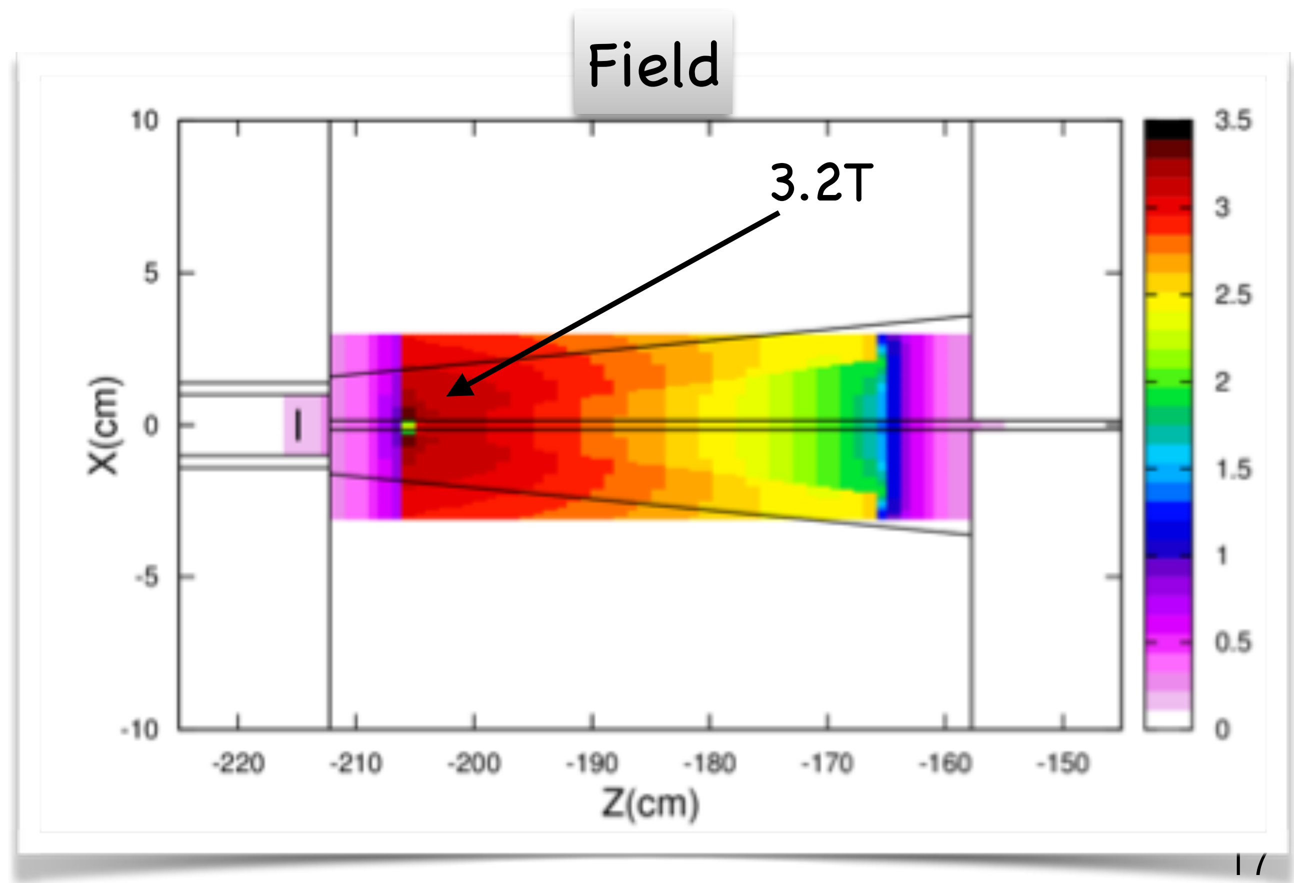
CPS: Some Details



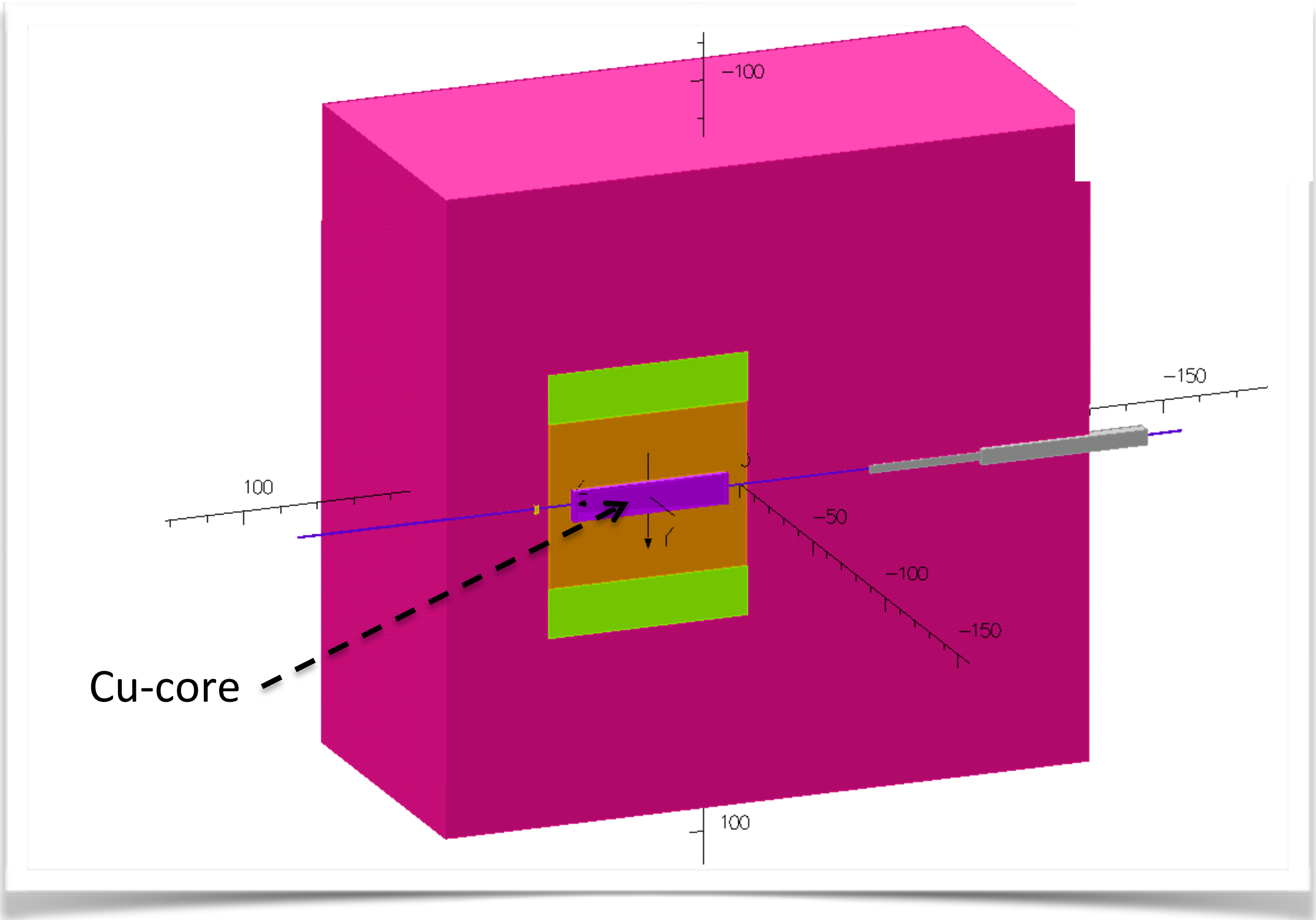
3 x 3 mm hole

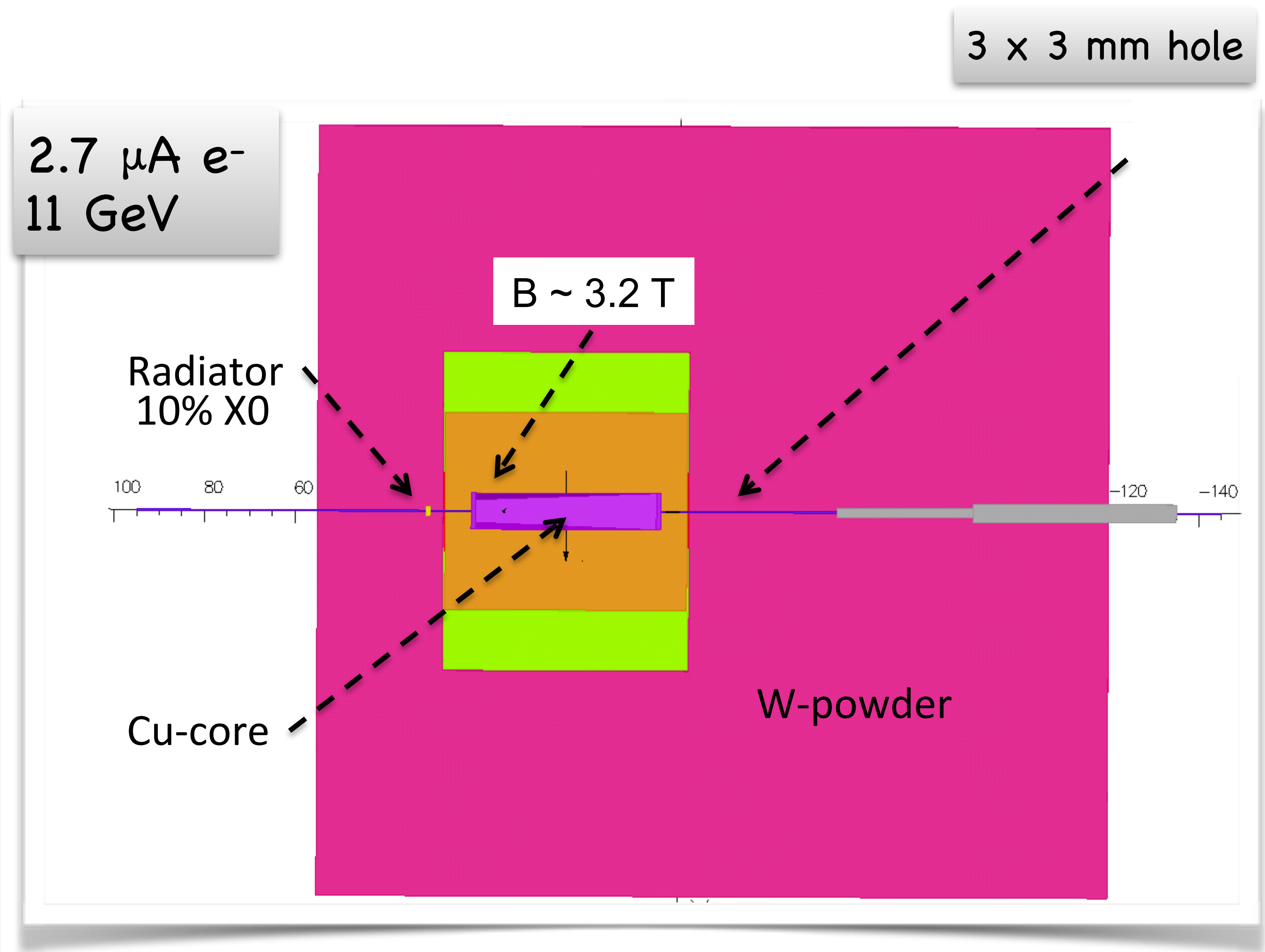


- The raster is 2 mm x 2 mm (requires pol. target rotation)
- Tapered magnet pole to boost the B field to 3.2 T and shorter magnet and more shielding downstream along with a wedged absorber.
- The central absorber is Cu which has 1.9 x better heat conductivity and 4.2 x longer radiation length than the alternative W-Cu (20%) alloy.
- W-powder external shield (16 g/cm3 density) for better shielding.
- Gradual "stepped" opening of the beam line for radiation leak reduction.
- Shielding requirement logic: The radiation from the source should be a few times than that from the photon beam interaction with the material of a polarized target.

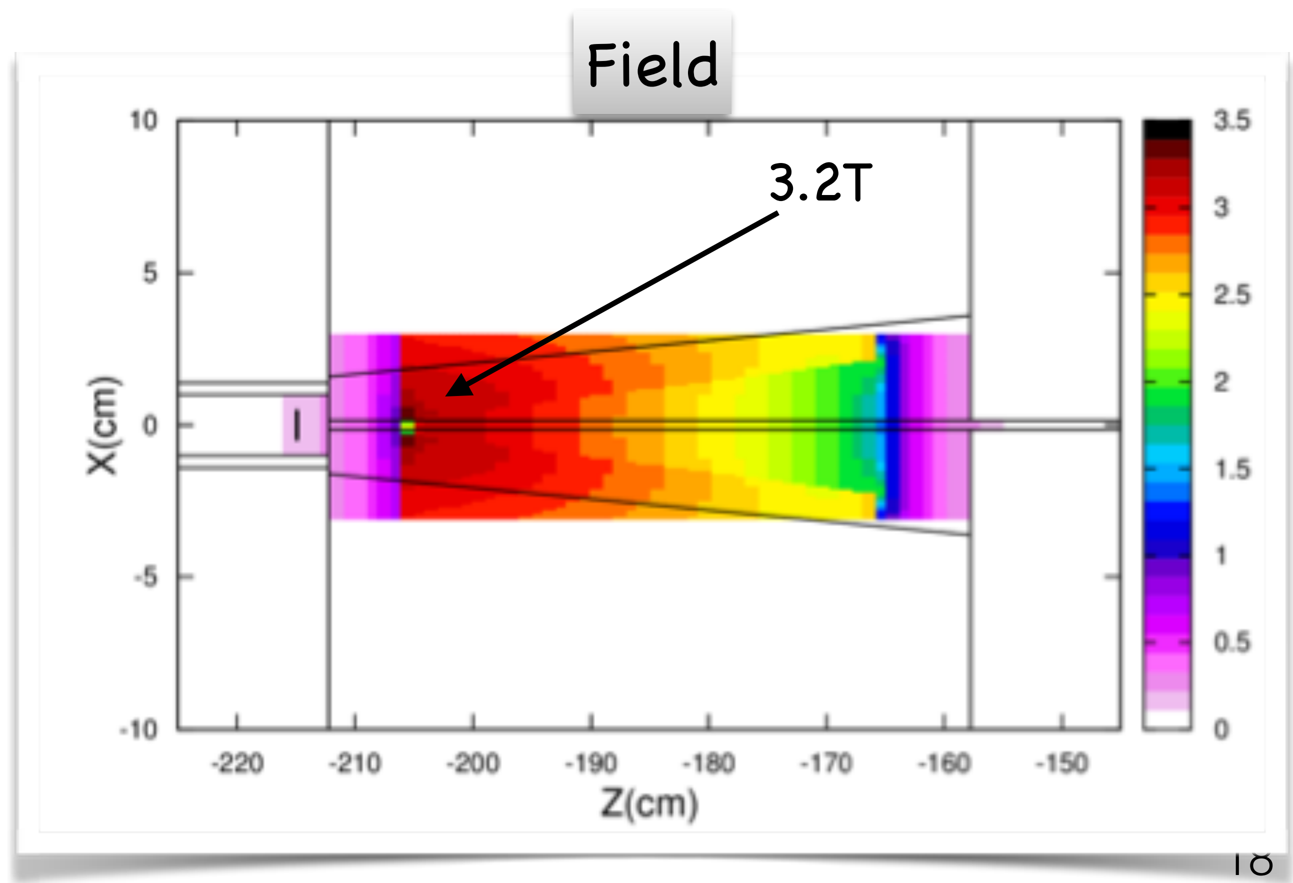


CPS: Some Details





1 x 10^{12} γ/s – more that 30 times that of 100 na mixed electron photon beam



Fluka Studies*

1. Radiation simulation with UVa target alone – comparing 100 na electron beam and (CPS-like but not CPS hardware) photon beams

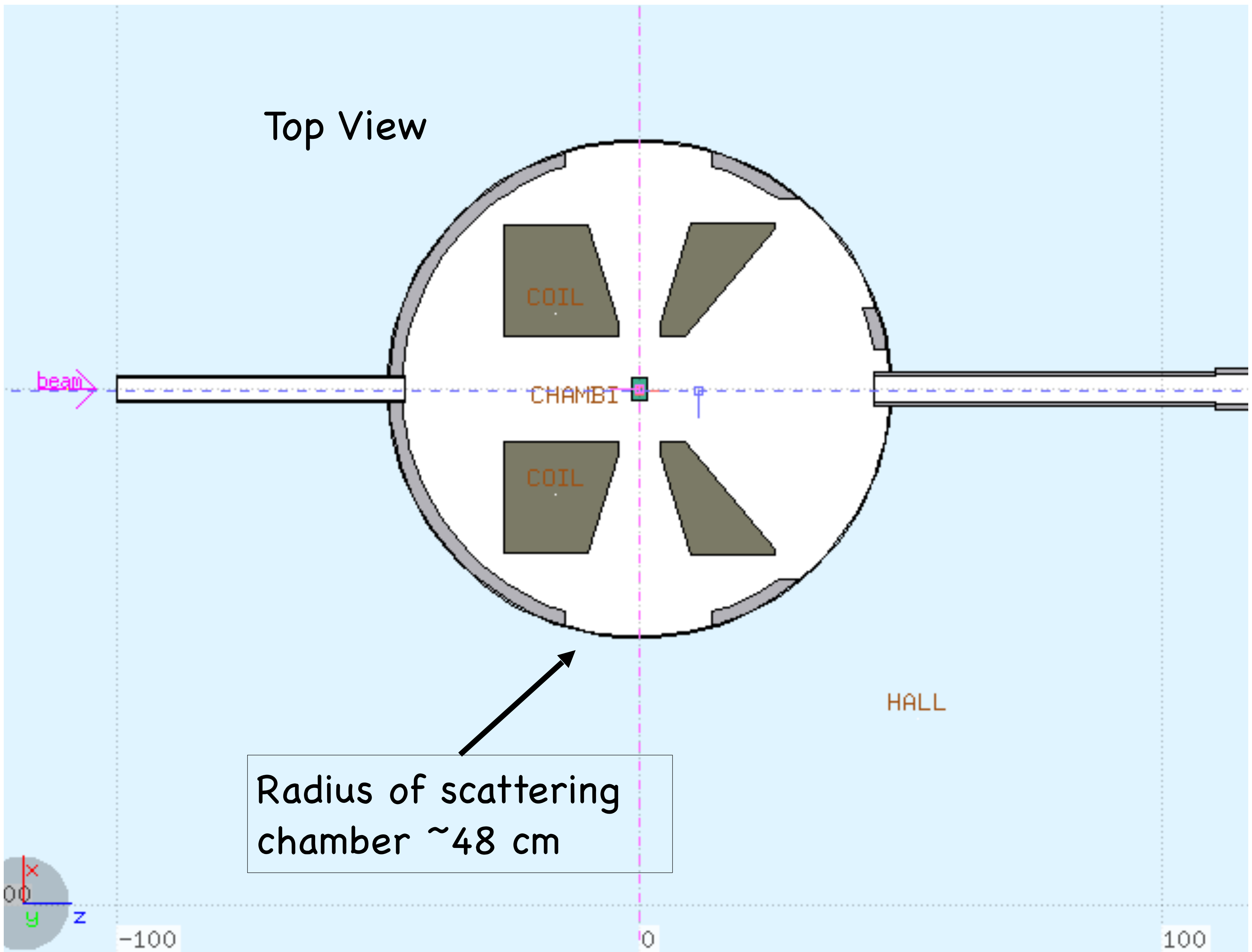
2. Radiation simulation of CPS upstream of an empty target chamber.

4. Summary

More details and plots, see the separate files:
https://userweb.jlab.org/~jixie/WACS/Jixie_CPS_12152017_summary.pdf
https://userweb.jlab.org/~jixie/WACS/Jixie_UVAPolTarget_11302017.pdf
https://userweb.jlab.org/~jixie/WACS/Jixie_CPS_11302017.pdf

*Work by Jixie Zhang with Donal Day, Rolf Ent and others as Devil's Advocates

UVA|Jlab Polarized Target



Known target geometry included:

1) target chamber window
2) coils
3) Target a mixture of solid NH_3 and liquid ^4He, 60% packing fraction
4) beam pipe with window (8-10 mil)

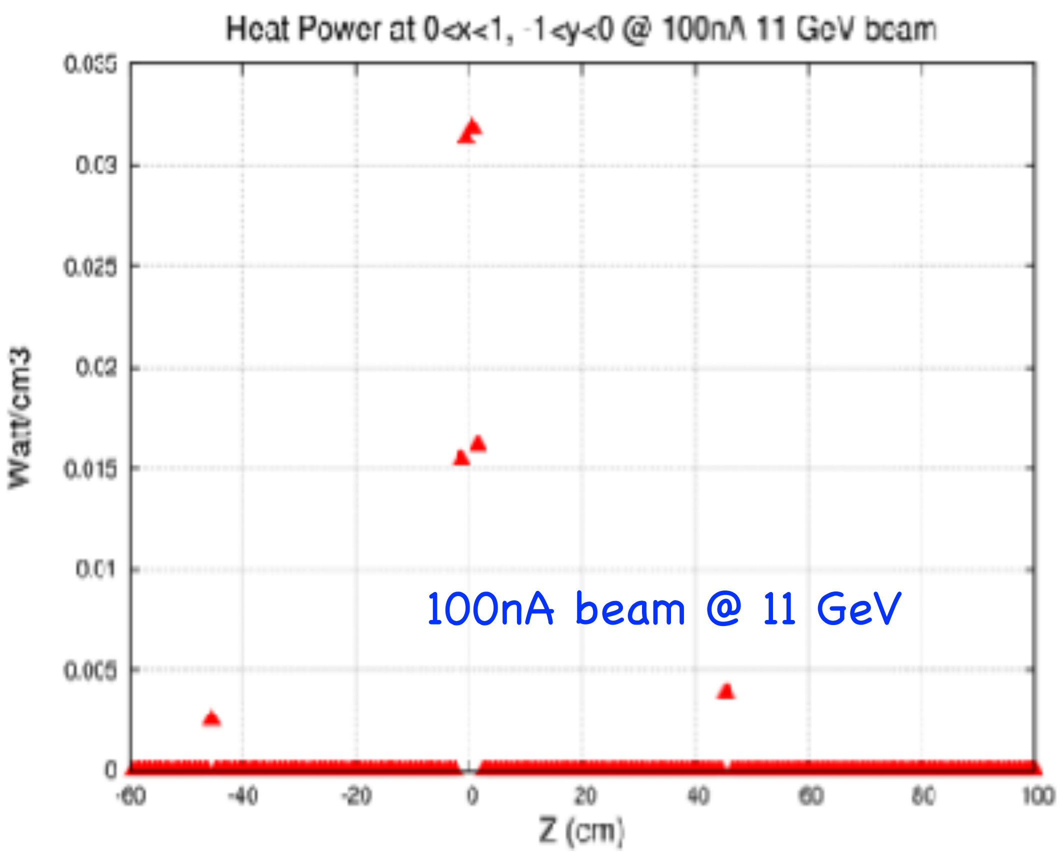
Two simulations have been run:

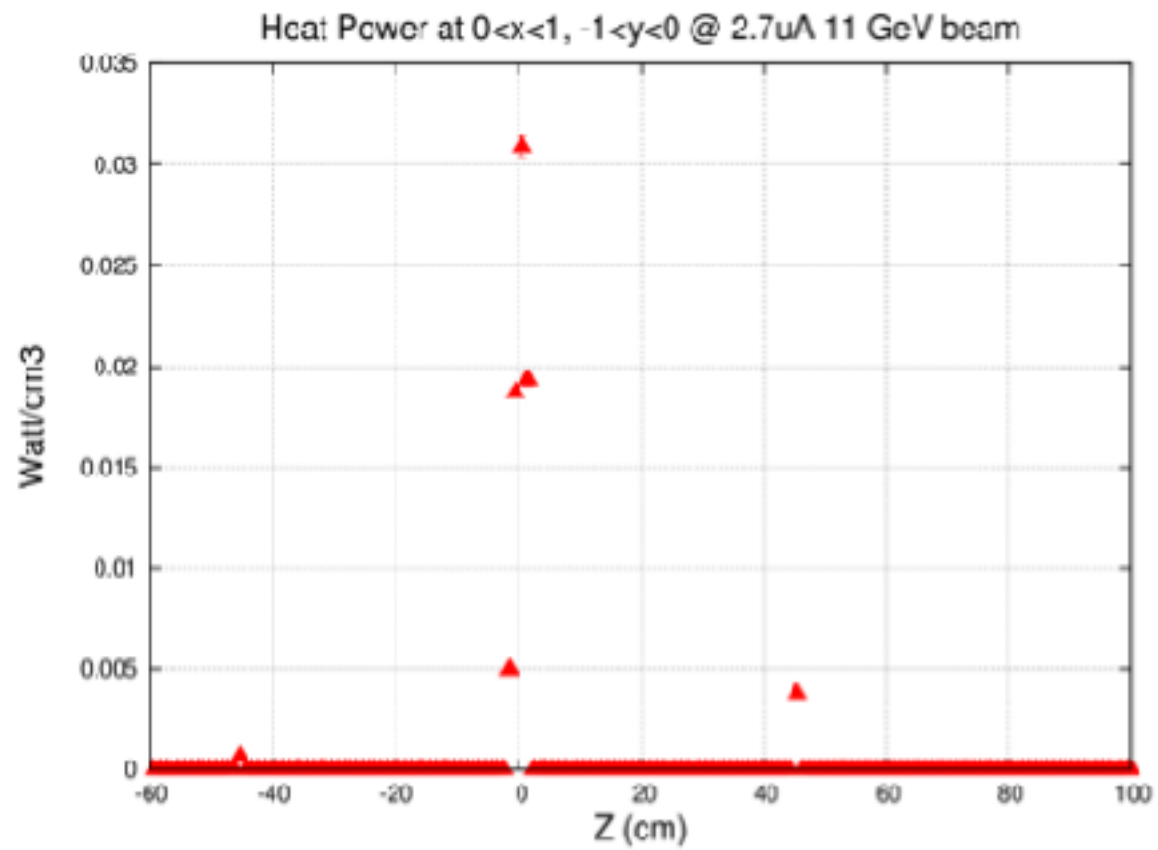
1) 100 nA e- beam

2) Pure photon beam equivalent in flux to a 2.7uA e- beam on a 10% radiator (CPS conditions). The pure photon beam is "made" using a fictitious strong magnet field and a black-hole to absorb any charged particles coming from the radiator

Heat Load in Target

Pure photon beam resulting from 2.7uA beam @ 11GeV on a 10% radiator



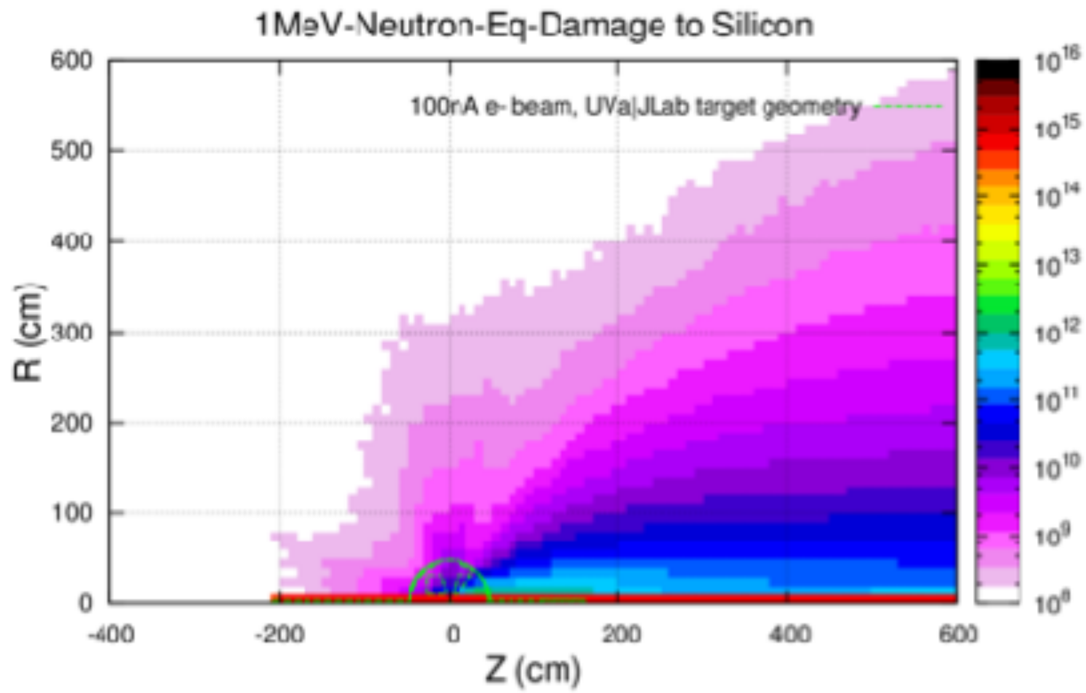


Only with UVA|JLab polarized target

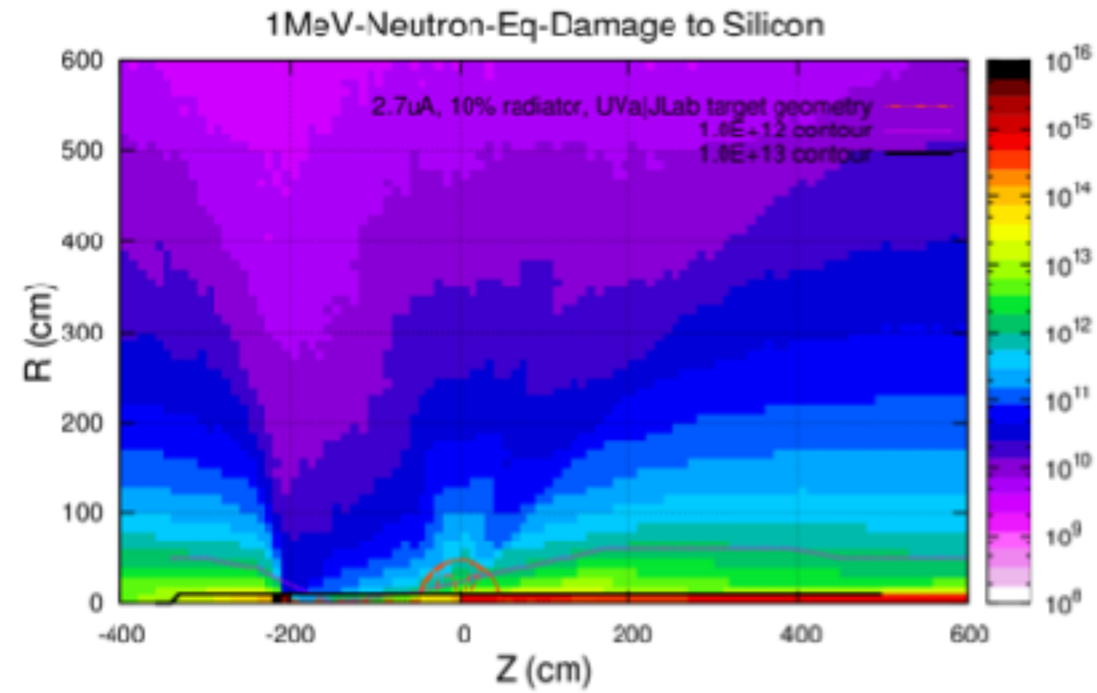
A fictional photon source was created (sweeping away all charged particles) to illuminated the target cell.

- The linear heat density in target is ~0.033 W/cm^2/bin, total heat power is ~0.3W.
- A Bremsstrahlung photon beam created from 2.7uA 11GeV electron beam on 10% radiator will have equivalent deposited heat power in target.
- This was per design: the heat load for the 100 nA electron beam and the photon beam as envisioned with a CPS was to be equal - this will allow 'normal' target operation.

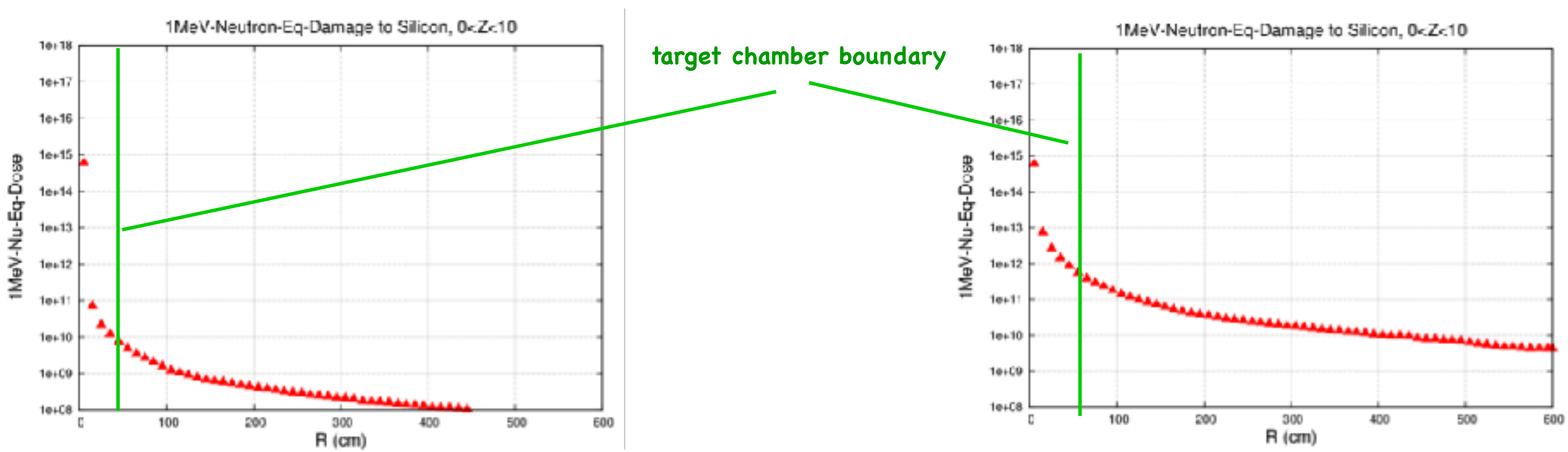
Accumulated Damage: e and γ



40 days, 100nA, 11 GeV beam

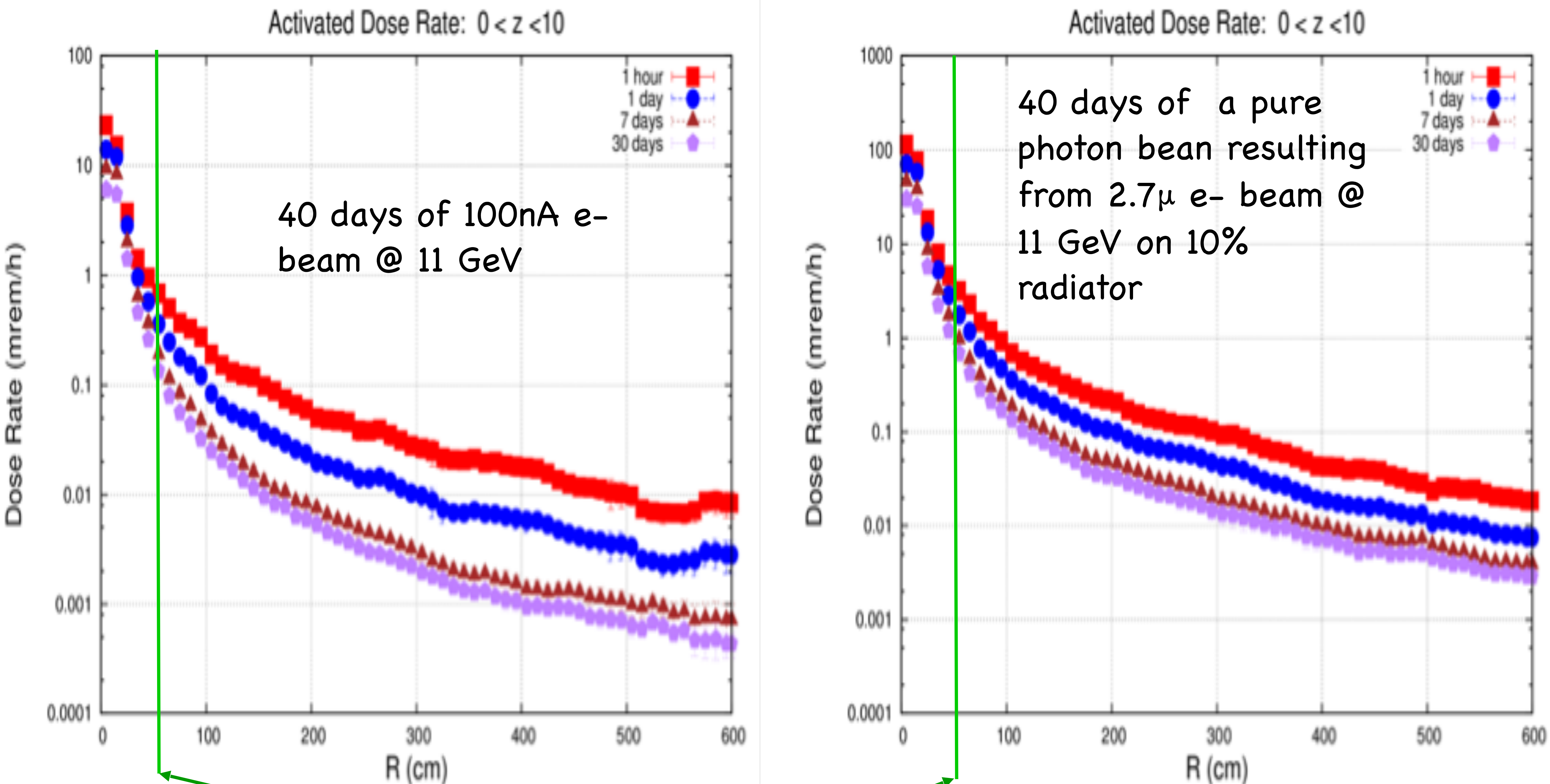


40 days, 2.7uA, 11 GeV beam on radiator



Conclusion: It is safe to place electronics at any location with R>10 (R > 20) cm.

Activated Dose Rates around Target



target chamber boundary

Only with UVA|JLab target

A bremsstrahlung photon beam created from 2.7uA 11GeV electron beam on 10% radiator will create more activation dose in the target than a 100 nA electron beam - more photons available to activate.

Summary of electron vs photon beam, only with UVA/JLab Target (no CPS)

1. Two FLUKA simulations has been performed for UVA|JLab polarized target
   A. 100nA electron beam @ 11 GeV for 40 days directly on the target cell and
   B. a pure photon beam resulting from a (fictional) source from 2.7μA @ 11 GeV on a 10% radiator for 40 days directly on the target cell

2) The accumulated 1 MeV neutron equivalent damage to silicon for an area 20cm away from beam pipe is below 10^11 for the 100nA electron beam case, and below 10^13 for brem. photon beam.

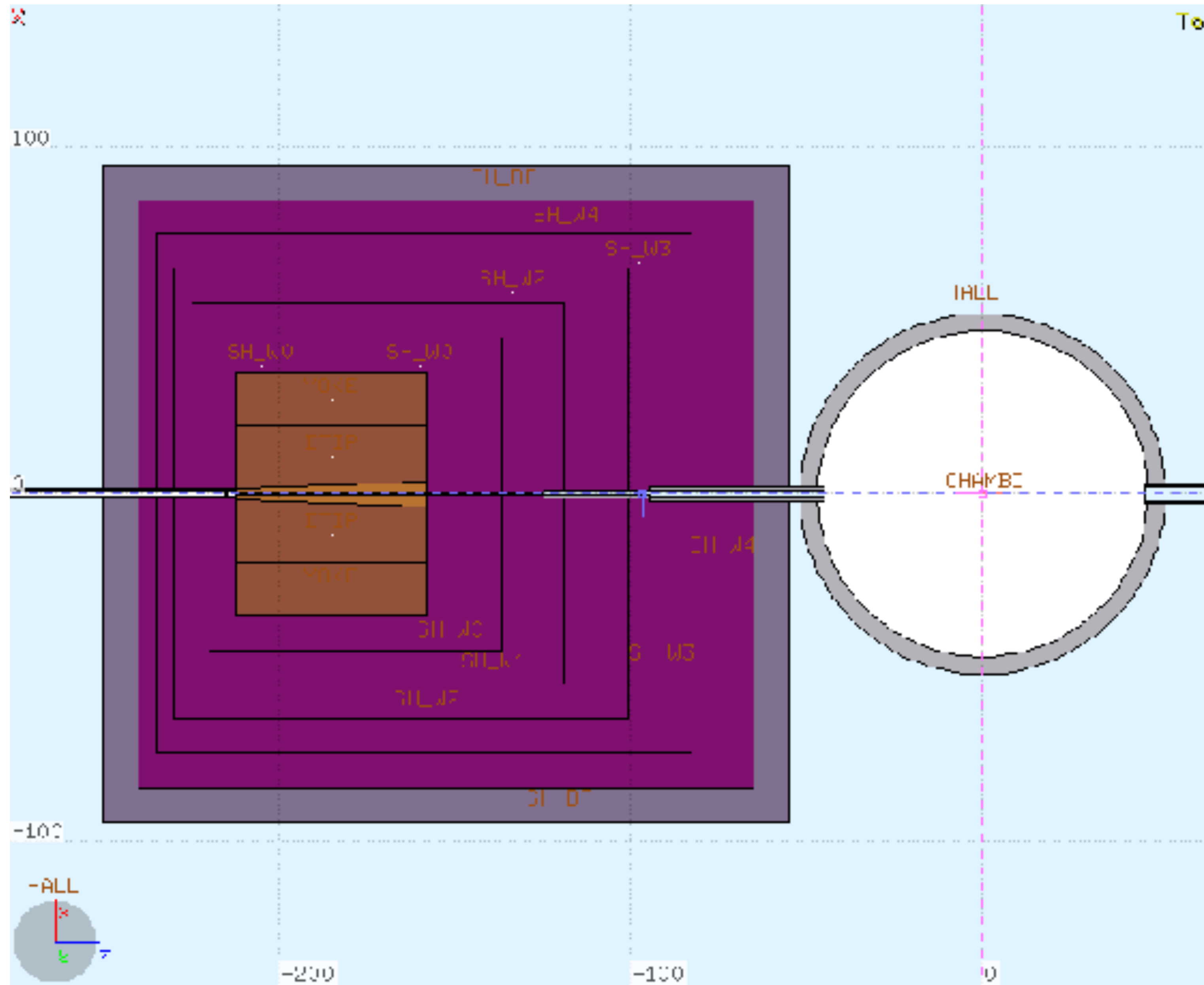
3) Heat load in target is about 0.033 watt per cm^2 and total heat power is about 0.3 watt, for both cases.

4) Dose rate from activation at target chamber boundary: below 1 mrem/h for 100nA electron beam, and ~4 mrem/h for brem. photon beam.

CPS + UVA/JLab Target Geometry: Top View

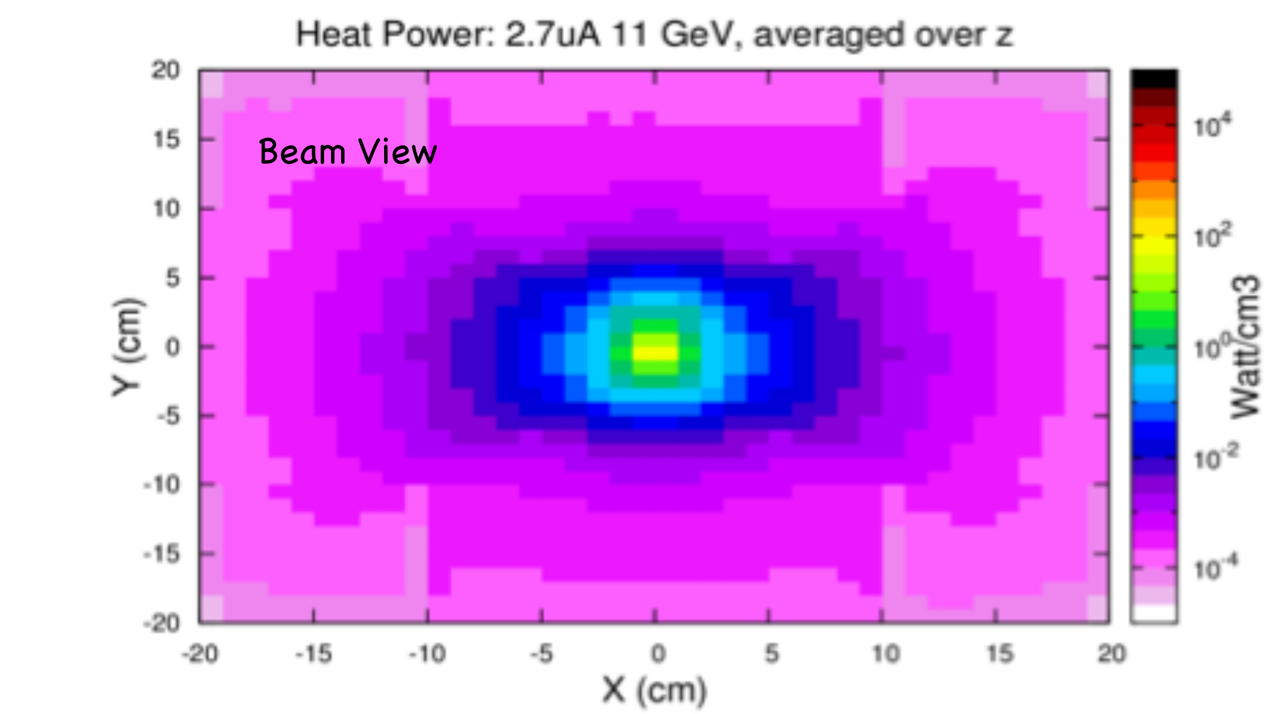
Design assumptions:

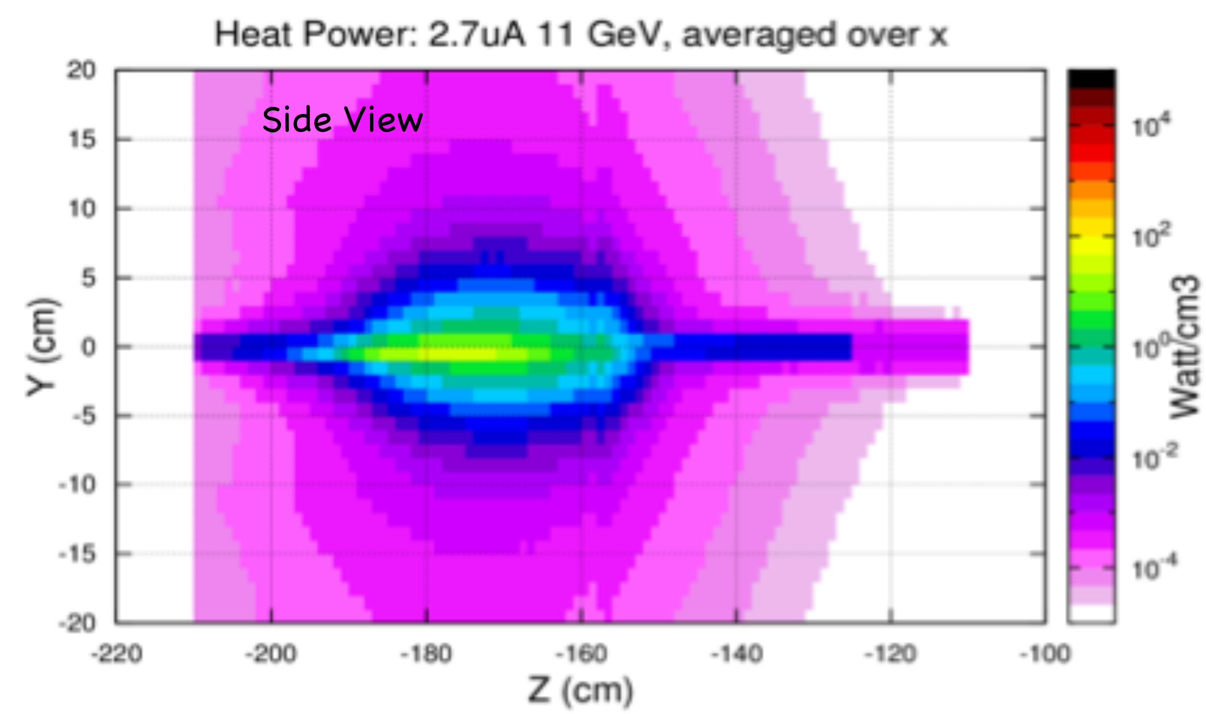
- Dipole Yoke: (70.5cm x 70.5cm x 54.5cm)
- Core: pure copper
- Slot: 3mm(width) x 3mm(height)
- Shielding: tungsten powder, 16g/cm^3, (5 layers)+ 10cm
- 30% borated plastic (1 layer).
- Shielding thickness is 92.75cm, 49.75 cm and 27.75 cm in downstream, side and upstream direction.
- Radiator: 10%, copper, located at z=-215cm
- Beam raster: 2mm x 2mm

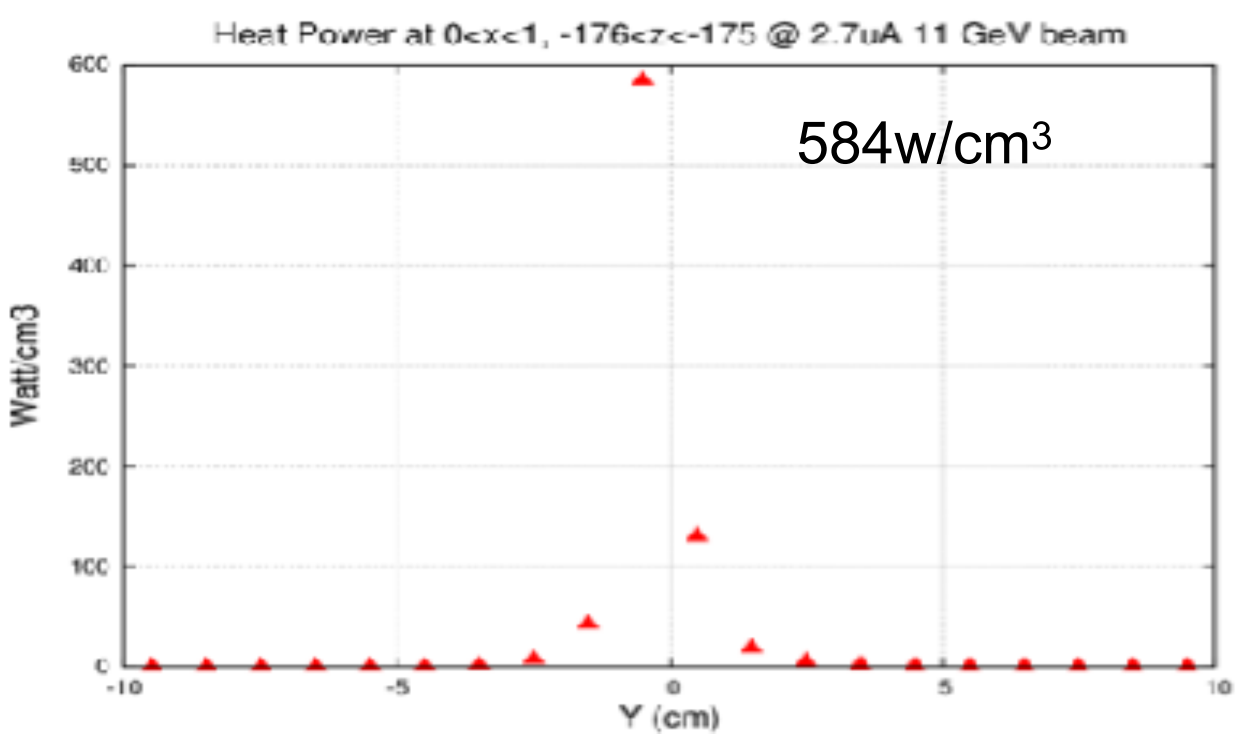


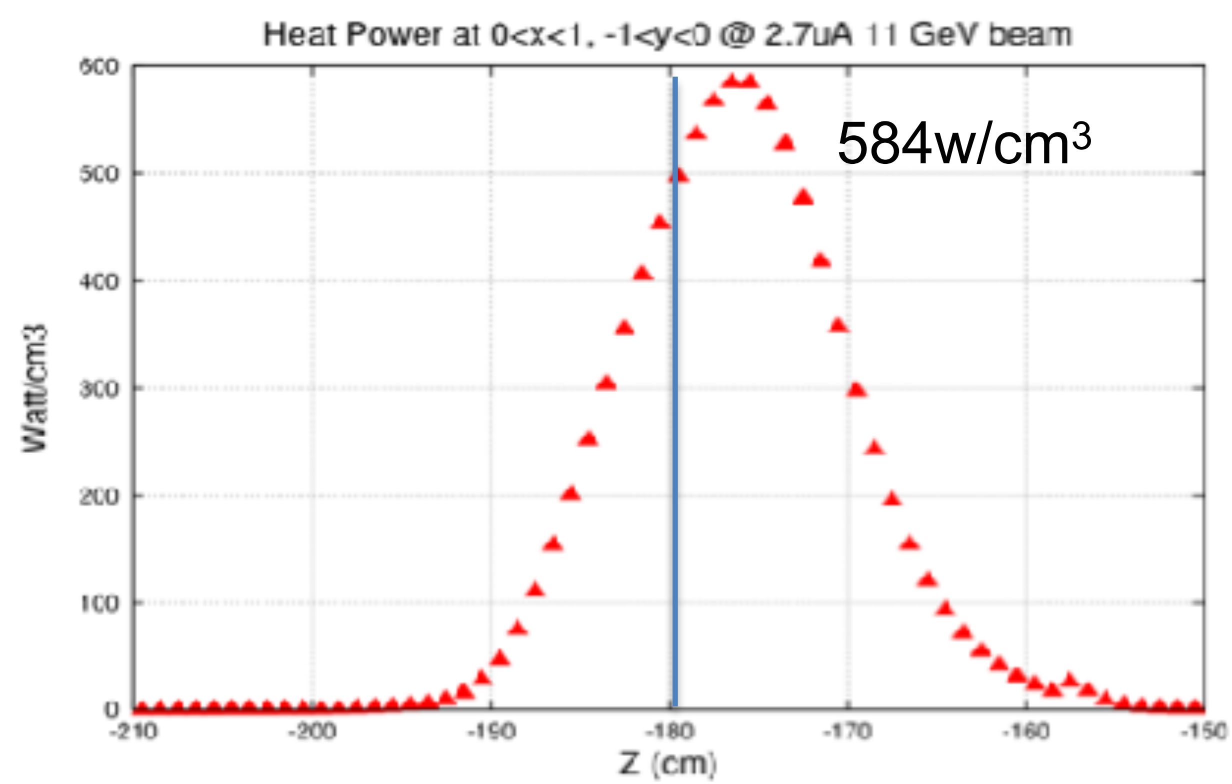
Layers indicated allow particle yields to be studied and “biasing”

Heat Power, CPS Setup





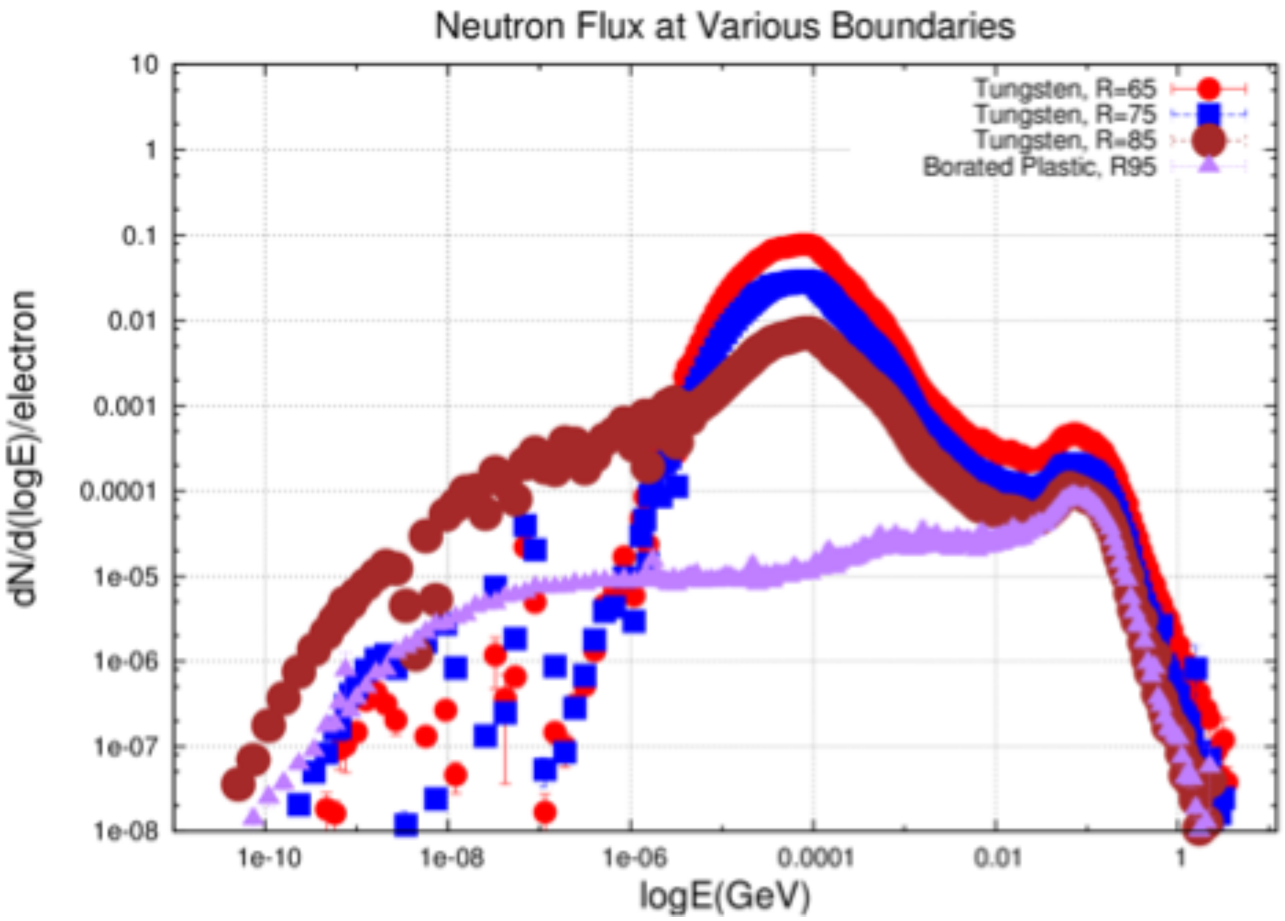




2.7uA beam @ 11 GeV

Neutron Fluence and Damage

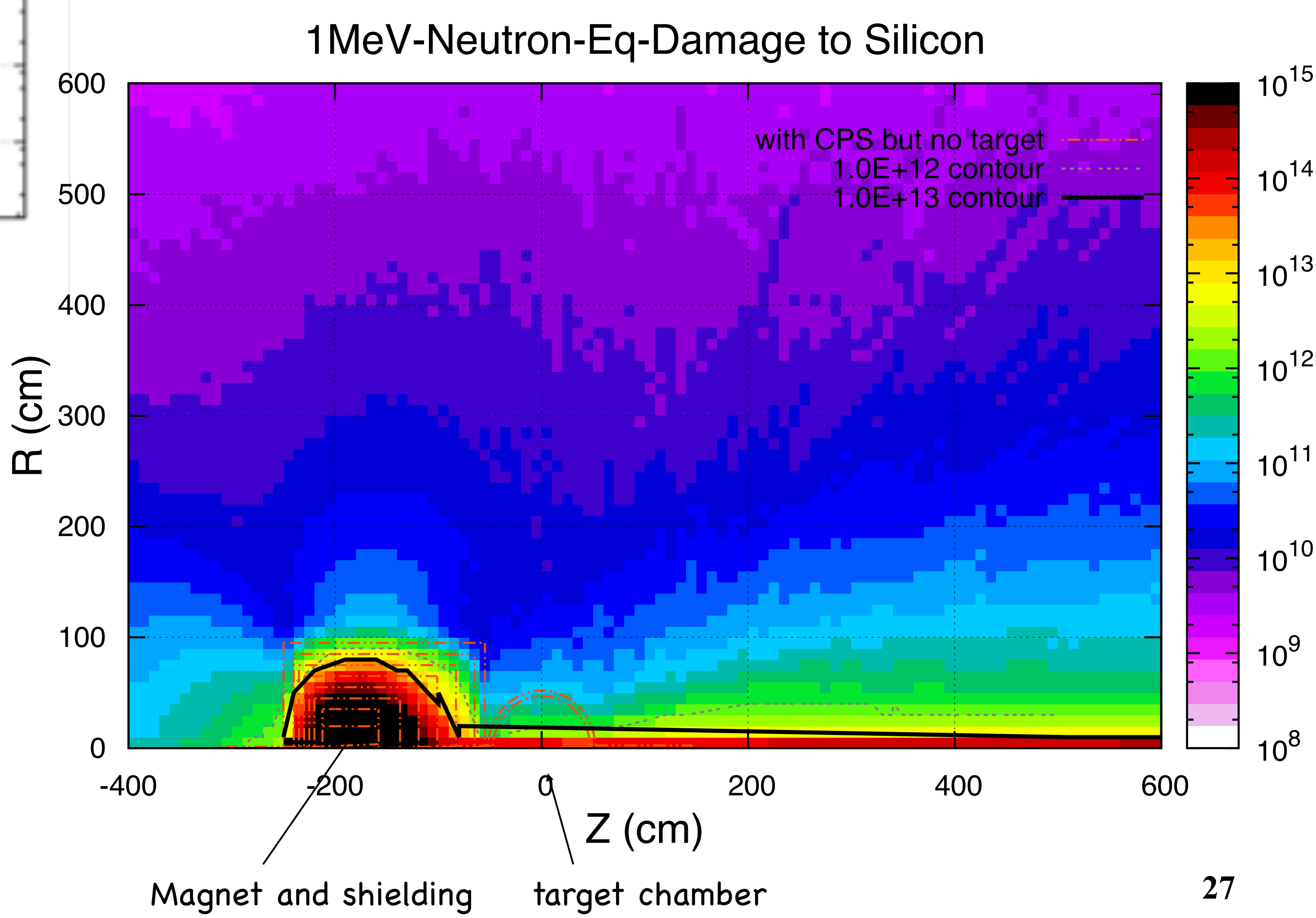
11 GeV, 2.7μA e- beam on 10% radiator



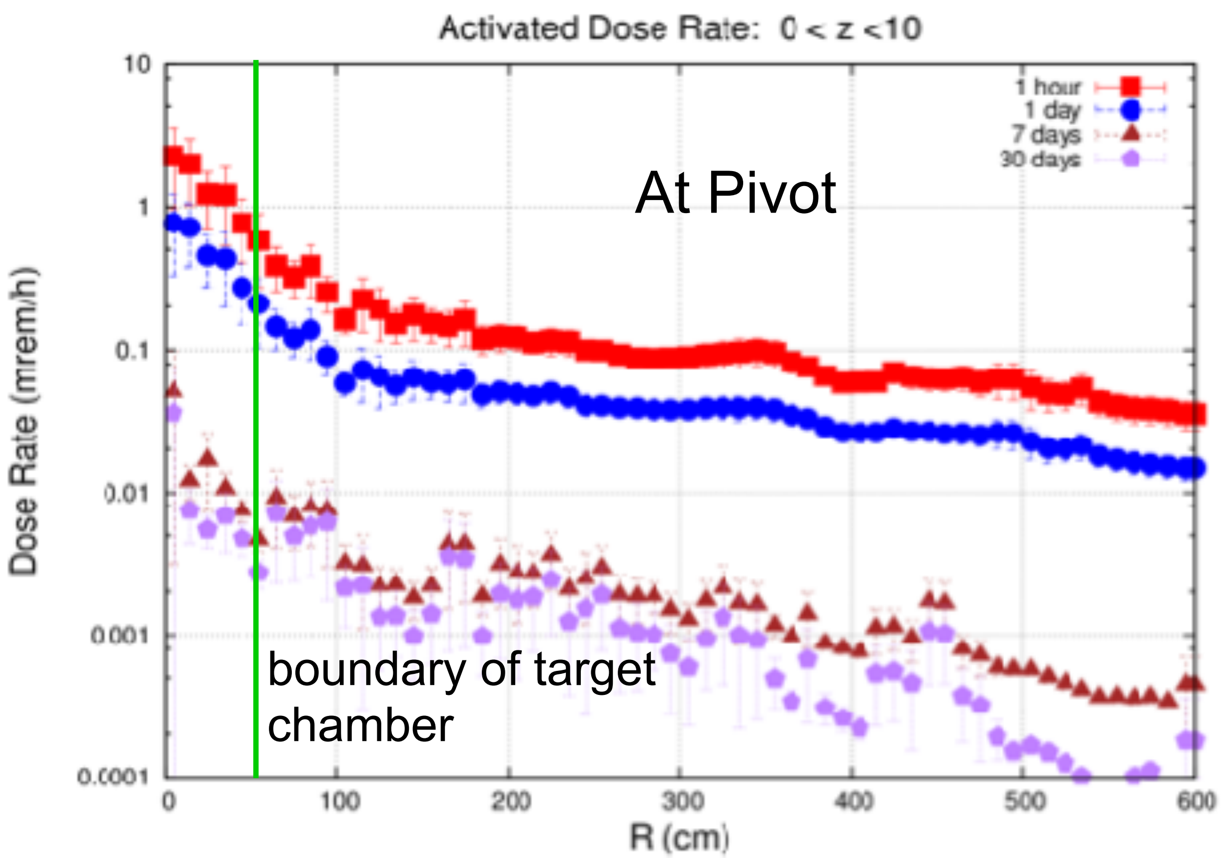
10cm thick 30% borated plastic layer very effective.

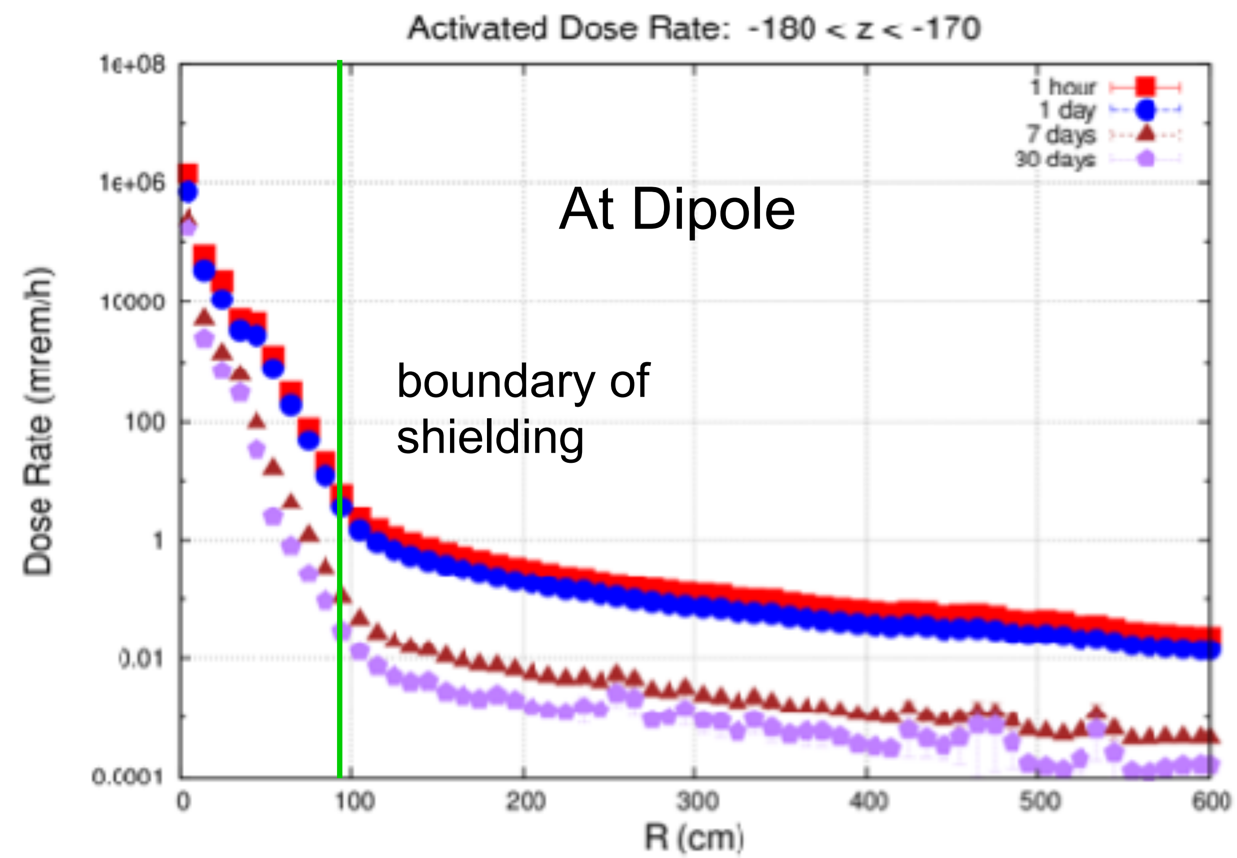
R is distance to beam line

1000 hours of 2.7uA beam @ 11 GeV

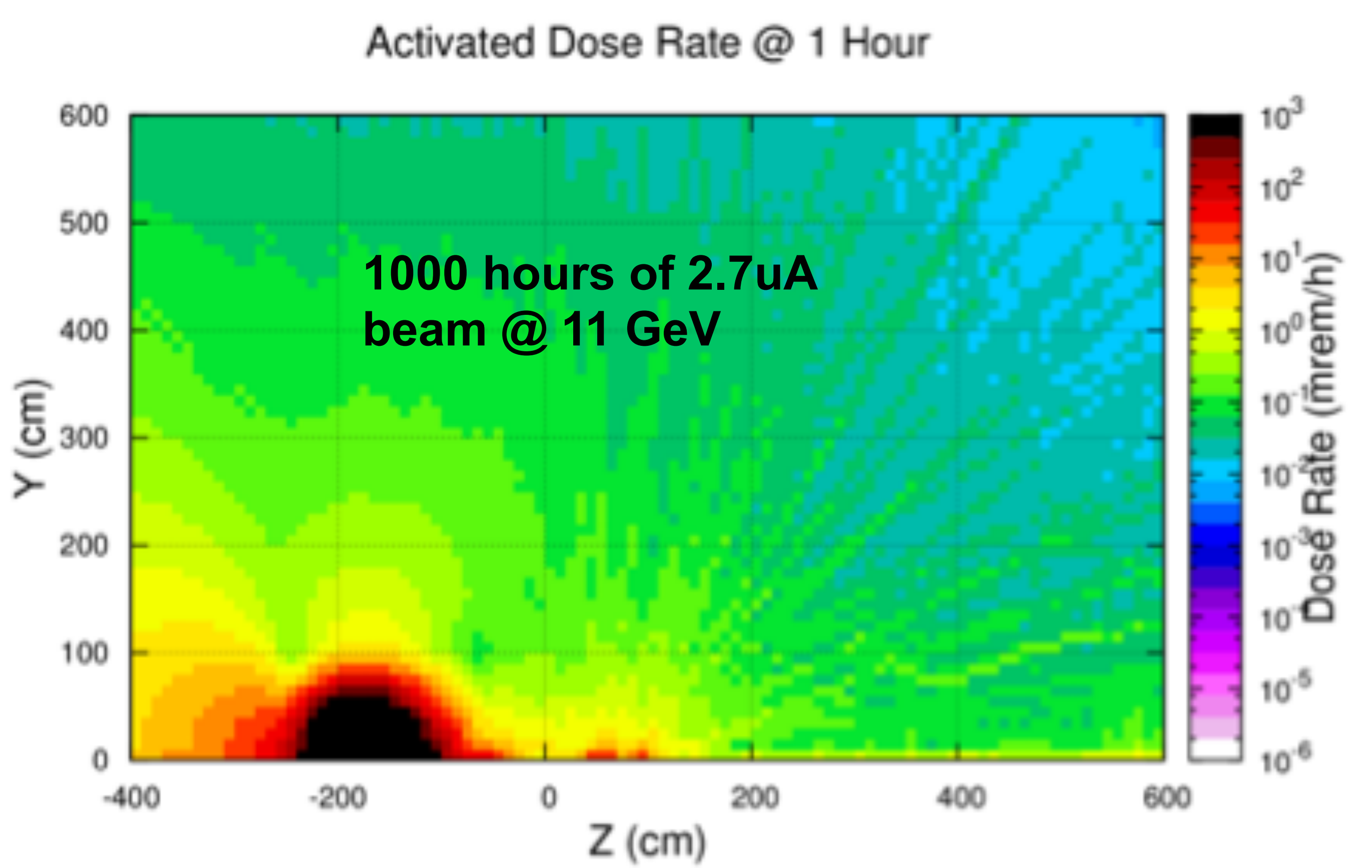


Dose Rate from Activation

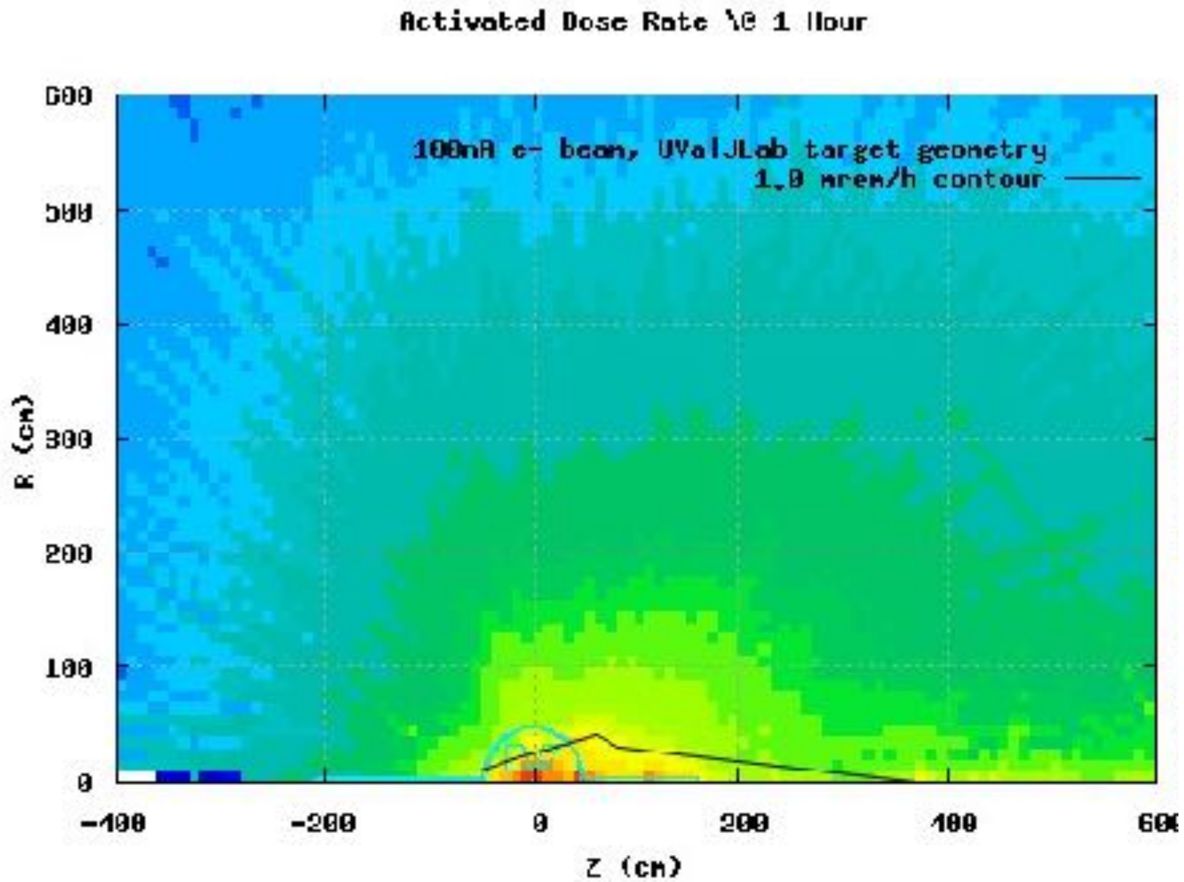


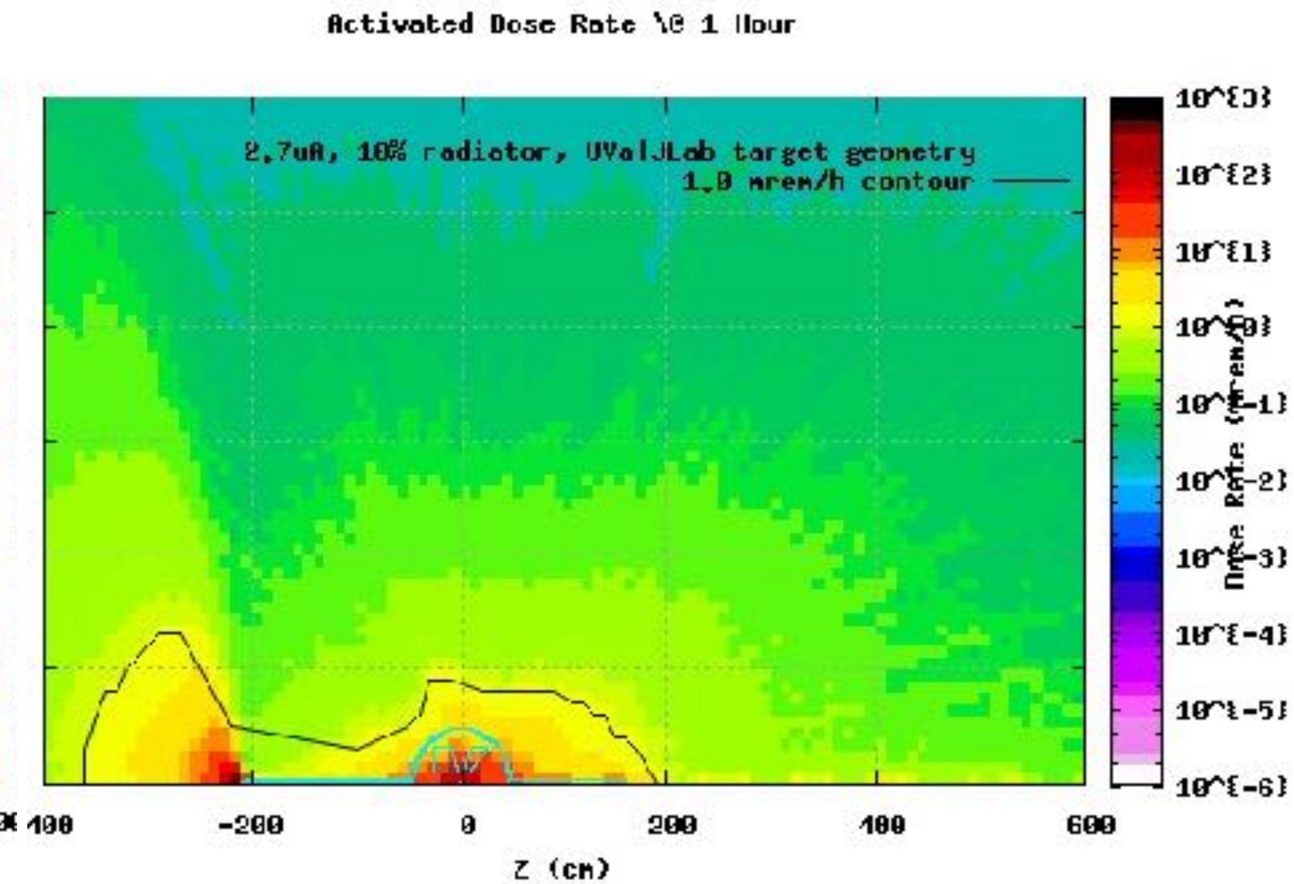


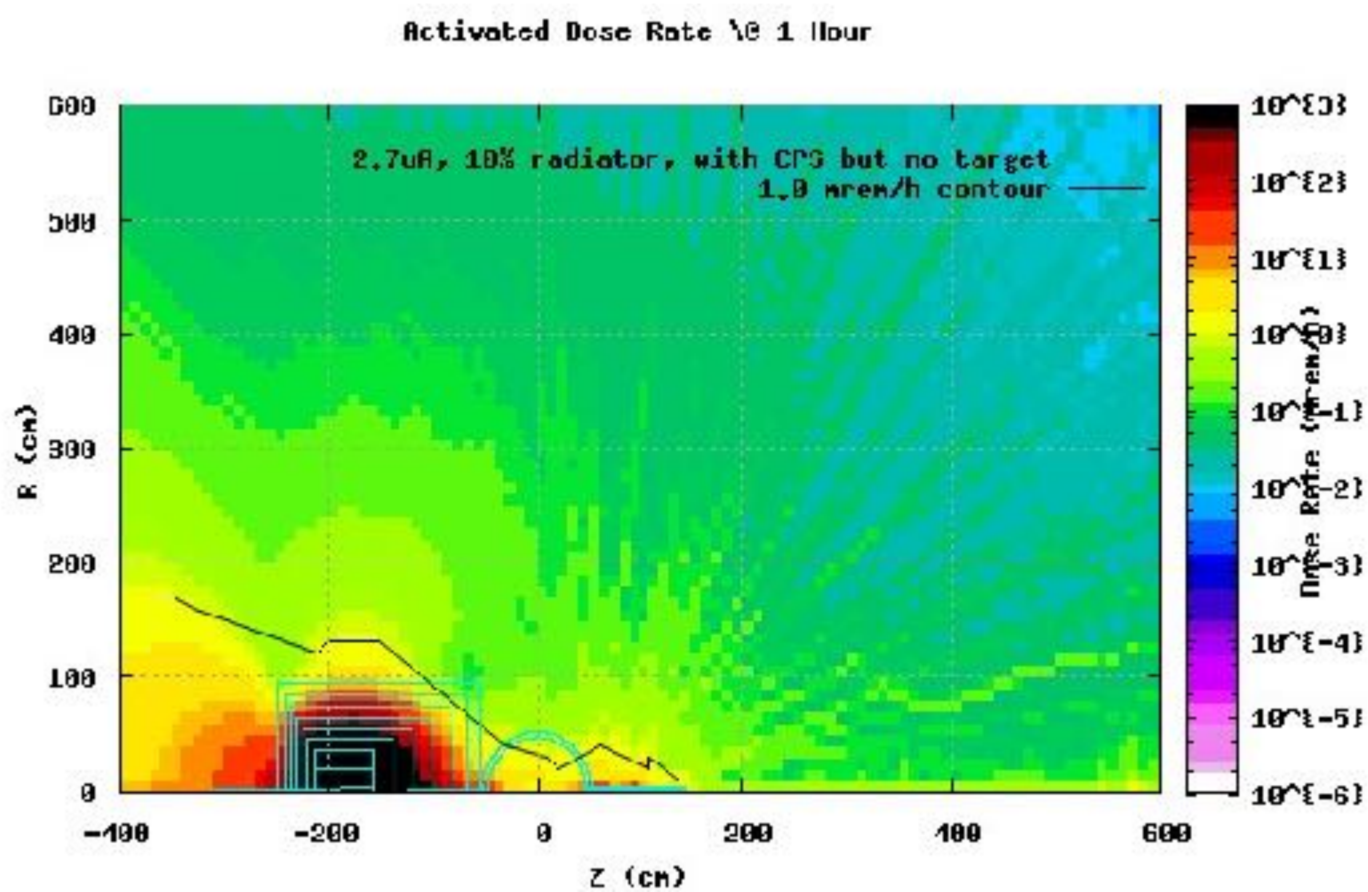
High radiation!!! Need more shielding in upstream of CPS



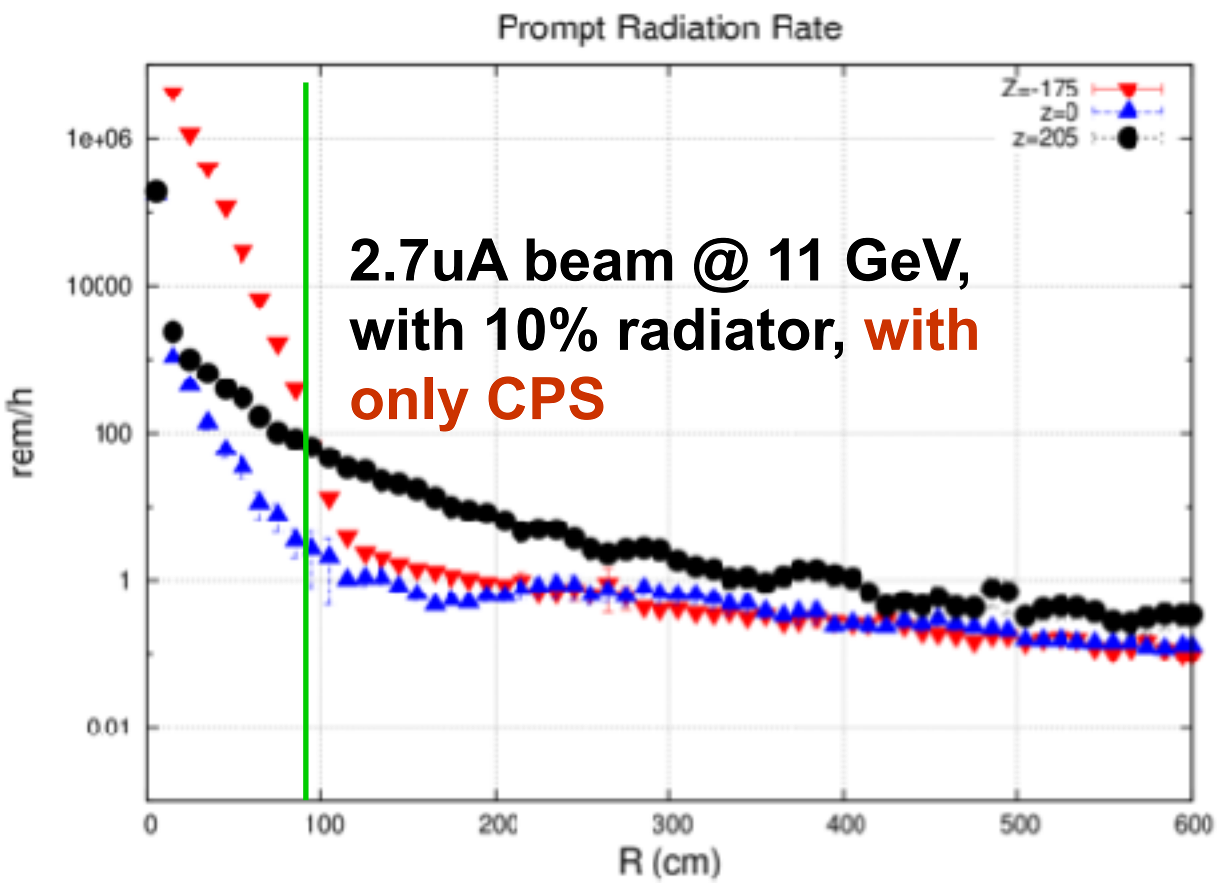
Compare Activated Dose Rate

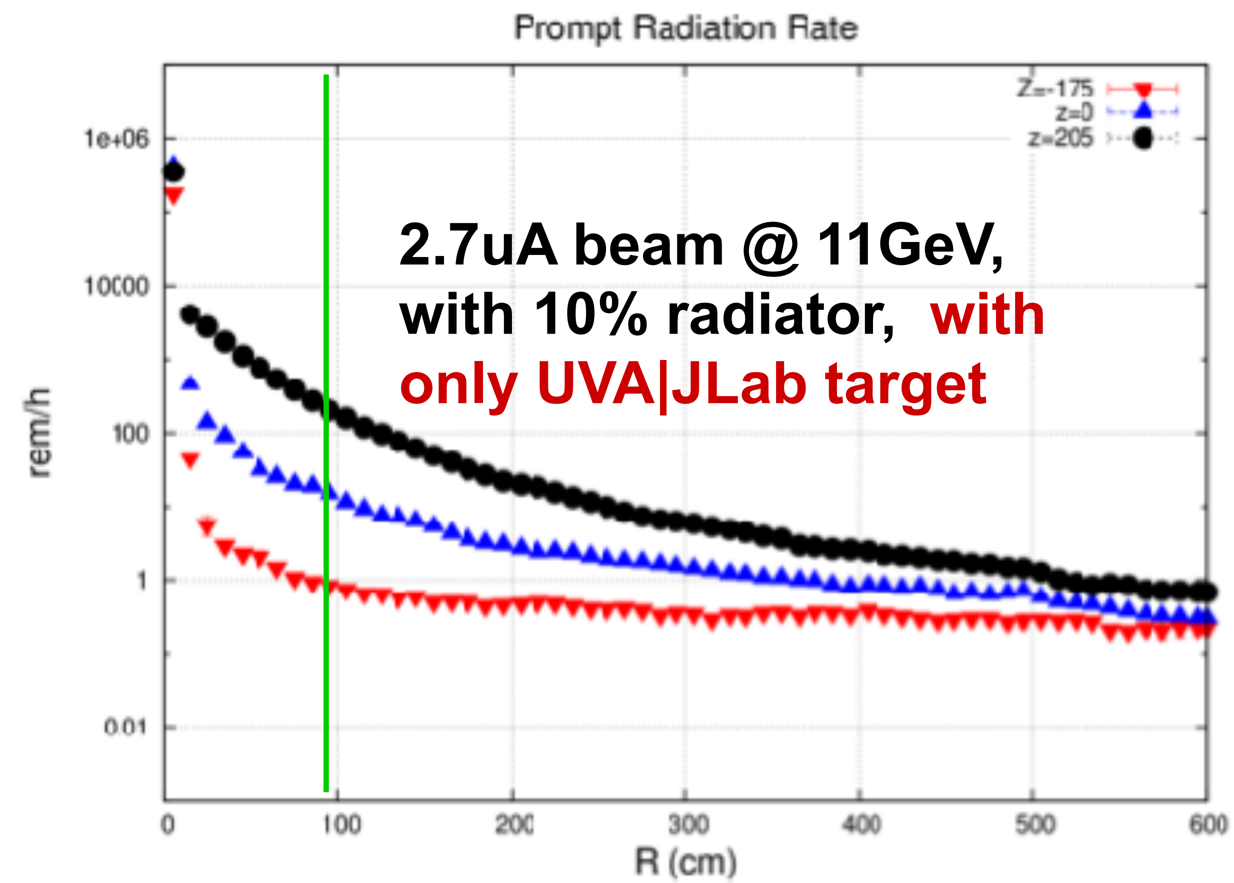


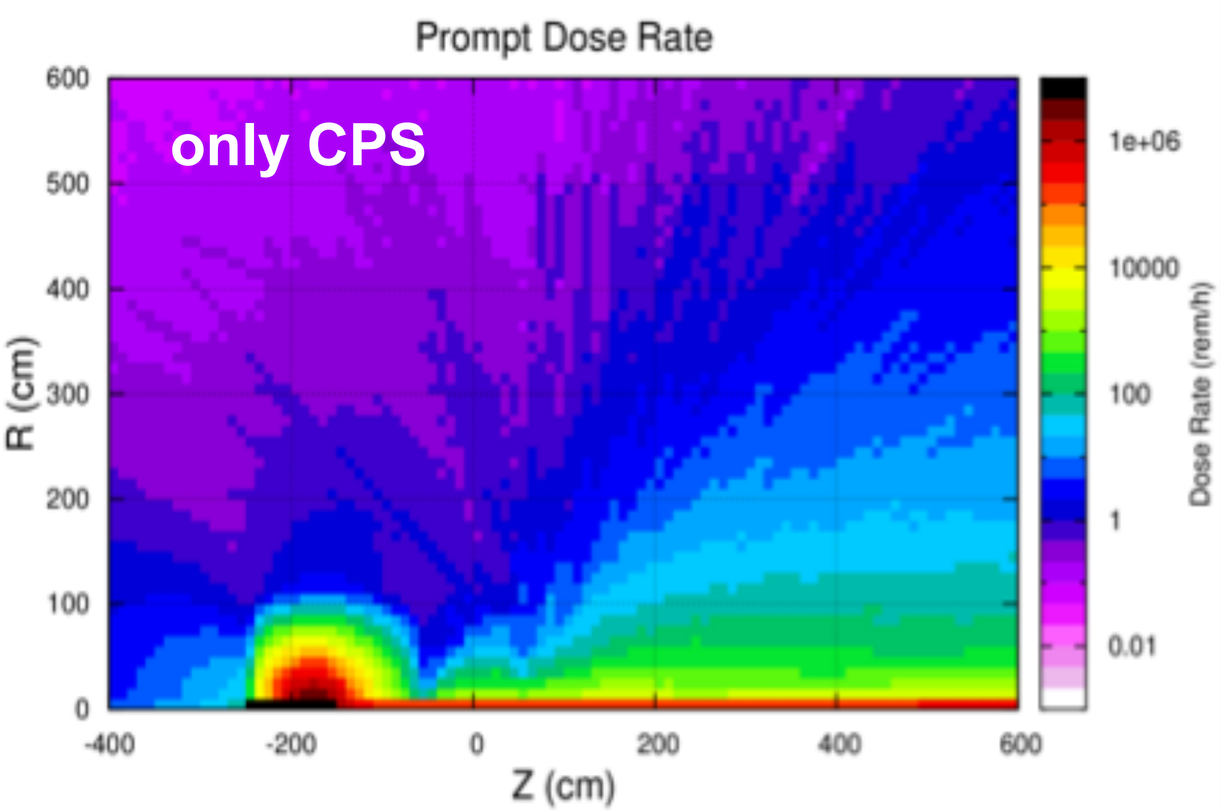


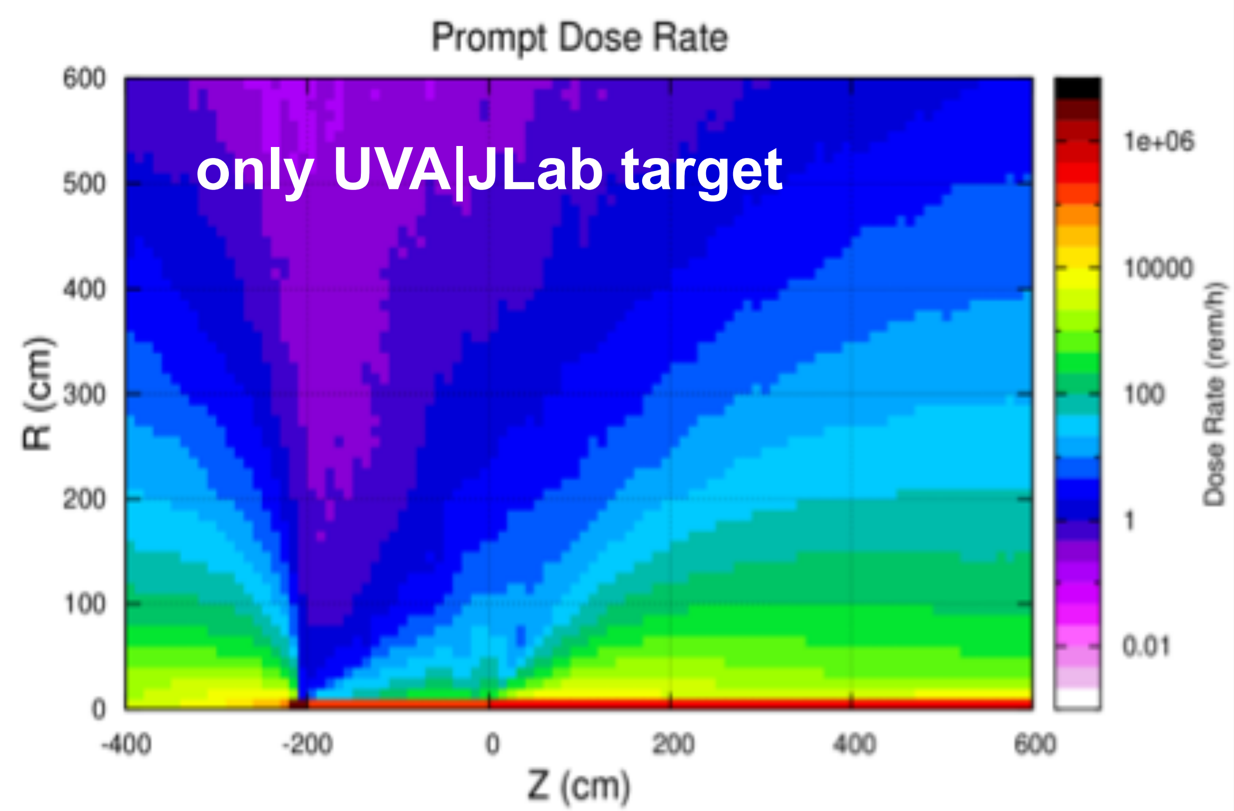


Compare Prompt Dose Rate









Summary

1) FLUKA simulation has been performed
   A. 100 na electron beam on NH_3 target
   B. Pure photon equivalent to 2.7 uA electron beam at 11.0 GeV on 10% radiator on NH_3 target.
   C. CPS adjacent to empty target chamber

2) For CPS setup, the maximum heat density in the core is ~584 watt/cm^3

3) 10 cm borated plastic shielding is very helpful to reduce neutron flux.

4) After 1000 hours, the accumulated 1-MeV-Nu damage to silicon at pivot (z=0) is less than 10^12 at 20cm away from beam line. Outside the borated plastic layer is several 10^11.

5) Dose rate from activation after 1 hour the beam is turned off: at the target chamber boundary is ~1 mrem/h, at 1.0m away from the dipole is ~6 mrem/h.
Need more shielding in upstream of the radiator!

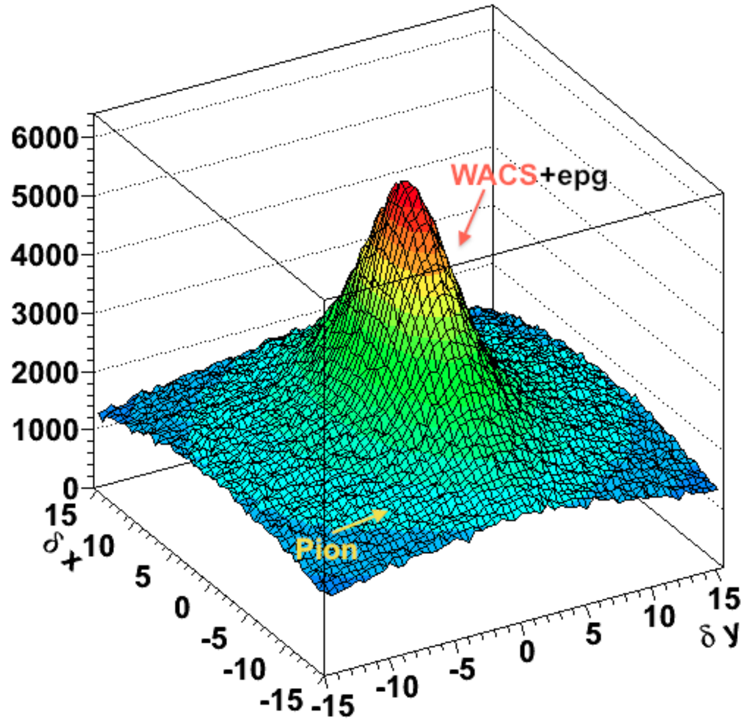
6) The indirect effect of the CPS on the pivot area is small as compared to the direct activation associated with a pure photon beam – the CPS design concept is maturing!

What physics can we do with a polarized target and our photon source?

Recall that the energy of the photon is not known. We have to determine it from the final states. Some experiments will be best served with large solid angle detectors.

- Polarized NH_3 target – TCS: $NH_3(\gamma, e^+e^- p)$
  - Listen to talks right after the upcoming break
- Polarized NH_3 target – exclusive pion: $H(\gamma, \pi^0 p)$ $H(\gamma, \pi^+ n)$
- Pion photo-production mechanism in GeV energy range
- Polarized NH_3 target – φ-proton spin-spin: $H(\gamma, K^+K^- p)$
- K_L secondary beam for use in Hall D experiments
  - Talk by Igor Strakovsky @7:40
- Polarized ND_3 target – $D(\gamma, p\ \pi^0)n$ in high energy regime - access to SRC (Frankfurt and Strikman)
- Mirror nuclei T/^{3}He: Test difference of (γ, pn) yields
- SRC in photo-induced disintegration: pn, pd, nd, … final states
- DK

Physics in the background



RCS peak sits on top of a huge π^o background

(Fanelli thesis, HallC recoil polarization expt.)

A new suggestion: a test of $A_{LL} = K_{LL}$ prediction in the π^o photo production

Recent comment from Peter Kroll via B. Wojtsekhowski :
Twist-3 would be important for A_{LL} in pion photo-production process

The WACS relations $A_{LL} = K_{LL}$ and $A_{LS} = K_{LS}$ also hold for pion photo production at the twist-2 level.

Twist-3 contributions will change these relations. Thus, for instance, from and experimentally observed difference between A_{LL} and K_{LL} in pion photo production one learns about the size of twist-3 contributions