I Executive Summary (Tanja)

This document describes the feasibility of a compact, high intensity photon source (CPS) with large gain in figure-of-merit to be used with dynamically polarized targets to measure processes such as Wide-Angle and Timelike Compton Scattering (WACS and TCS). The design is flexible allowing the CPS to be converted into a K_L beam for spectroscopy experiments. PAC43, PAC44 and PAC45 at Jefferson Lab have seen a few proposals and several LOIs related to these photoproduction topics. One of these is C12-17-008 (Polarization Observables in Wide-Angle Compton Scattering at large s, t, and u), which was conditionally approved w/ Technical Review. The issues stated in the PAC45 report to be addressed are:

- Finalize the design and price estimate for CPS
- Clearly establish the expected maximum photon intensity

This goal of this document is to address these PAC45 technical comments for full approval of C12-17-008.

II Motivation: Science Gain with CPS (David H., Donal, Dustin)

A Polarization Observables in Wide-Angle Compton Scattering (David H.)

The experimental challenges associated with double-polarization measurements of photon-induced reactions at high momentum transfer are formidable. Detector rate capabilities and radiation hardness are both severely tested in beam-recoil measurements as a result of a rapid decrease in recoil proton polarimeter analyzing power at high $-t$. Utilization of a mixed electron-photon bremsstrahlung beam, on the other hand, limits luminosity in beam-target measurements due to loss of target polarization, primarily as a result of electron-induced heat load. In preparation of a 12 GeV Jefferson Lab experimental proposal on polarized wide-angle Compton Scattering (WACS), a completely new experimental approach was developed, based on deploying a high-intensity compact photon beam source and a polarized target. This new technique opens up physics possibilities that have hitherto been inaccessible at tagged photon facilities and results in a significantly improved figure-of-merit (of a factor of $\sim$30) over all previous double-polarization measurements involving photon-induced reactions.

B Limitation of Polarized Targets (Donal, Dustin)

C Target Rotation (Donal, Dustin)

D A Pure Photon Source

III The Compact Photon Source (Bogdan)

A Conceptual Design

A traditional source of bremsstrahlung photons includes a radiator, a deflection magnet with large momentum acceptance and a beam dump for the used electrons. Such a configuration requires significant space along the beam direction and heavy shielding due to the large openings in the magnet and the beam dump and a many meter length of the system. In addition, it leads to a large size of the photon beam at the target due to divergence of the photon beam and a long path from the radiator to the target. The beam spot size contributes to the angular and momentum reconstruction accuracies of the reaction products which experimentalists want to study. A new solution for a photon source was proposed in the report at the NPS collaboration meeting in November 2014.

The concept of a new source takes advantage of the narrowness of the photon beam relative to the angular distribution of the secondary particles produced in the electron-nuclei shower. Without loss of photon intensity, a channel (a collimator for the secondary radiation but for not the photon beam) around the photon beam could be as narrow as the photon beam size with natural divergence plus the size of the beam raster. After passing through the radiator the electron beam should be removed from the photon line by means of a magnet. Another idea is to combine the magnet with the dump, allowing us to reduce dramatically the magnet aperture and length, as well as the weight of the radiation shield, due to the reduction of the radiation leak though the openings and the short length of the source.

The beam dump has two problems which need to be solved: the beam power absorption and radiation shielding. The small size of the opening/channel (3 mm by 3 mm) in combination with comparable raster size (2 mm by 2 mm) leads to a large longitudinal spread for the electron entering point (10-15 cm) where the electron trajectory enters the absorbing material and the shower starts. This consideration opens a practical way to combine the magnet and the dump because it naturally leads to a reduction of power deposition density in the copper absorber where the maximum temperature is below 400°C (the case of a 11 GeV 30 kW beam and a 10% X_0 radiator).

B Magnet

Normal conducting magnets for high levels of radiation have been constructed at several hadron facilities, e.g. the neutron spallation source at ORNL and the proton complex JPARC. In fact, the radiation level expected in the source allows modest cost kapton tape based insulation of the coils. We designed the magnet with permendur poles taped in two dimensions, which allows us to reach a strong magnetic field (3.2 Tesla) at the upstream end of the magnet, and moved the coils to 20+ cm from the source of radiation.

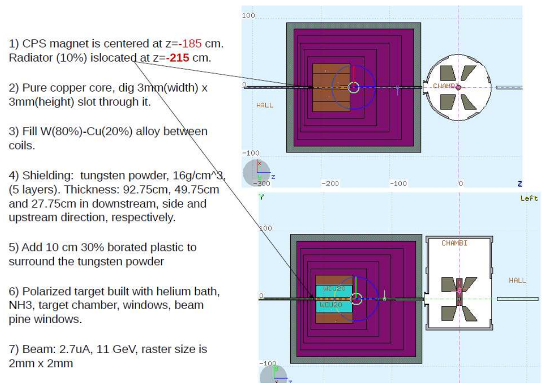

Figure 1: CPS components.

C Central absorber

The beam power absorber is made of copper, whose high heat conductivity helps to manage the power density. Water cooling tubes are located at 10-15 cm from the beam line where the temperature of the copper insert drops to a level below 100°C.

D W-powder shield

The amount of material needed for radiation shielding is defined by the neutron absorption length, which is 125 g/cm^2 (for high energy neutrons) and the required radiation reduction factor ($\sim$ 1000). This results in a total thickness of 850 g/cm^3. For the shield outside the magnet, the current design uses tungsten powder, whose high density (16.3 g/cm^3) helps to reduce the total weight of the device.

IV Hermetic Shielding - Radiation Calculations (Tanja, Thia, Rolf)

The goal of the Compact Photon Source is to convert beam energies of up to 12 GeV with currents of up to 5 μA into a high-intensity source of collimated photons. For the Hall-D adaptation, the 5 μA beam current is limited by the design of the Hall D Tagger Magnet alcove. This corresponds to a 60 kW power limit. For the Halls A/C adaptation, the beam energy is limited to 11 GeV. Many experiments will opt to use the traditional method for photon beam experiments, with the high-current electron beam striking a 10%

radiation length Cu radiator. The Compact Photon Sources gain in Halls A/C is foreseen for use with Dynamically Nuclear Polarized targets. Electron beam currents for use with such targets is typically limited to 100 nA or less, to reduce heat loading and radiation damage effects. The equivalent heat load for a pure photon beam impinging such targets corresponds to a photon flux originating from a 2.7 μA electron beam current striking a 10% Cu radiator. Hence, the Compact Photon Source design for Halls A/C should be able to absorb 30 kW in total (corresponding to 11 GeV beam energy and 2.7 μA beam current).

In addition, the typical beam time we assume for an approved experiment at Jefferson Lab is 1000 hours ($\approx$40 PAC days). For such a Compact Photon Source experiment, one needs to fulfill the following radiation requirements:

- Prompt dose rate in hall $\leq$ several rem/h at 30 feet from device.
- Prompt dose rate at the site boundary $\leq$ 1 μrem/r (2.4 μrem/h corresponds to a typical experiment at Jefferson Lab not requiring extra shielding).
- Activation dose outside the device envelope at one foot distance is $\leq$ several mrem/h after one hour following the end of a 1000 hour run.
- Activation dose at the pivot in the experimental target area, where operational maintenance tasks may be required, is dominated by the dose induced by a pure photon beam, and at one foot distance from the scattering chamber $\leq$ several mrem/h after one hour following the end of a 1000 hour run. *i.e.*, the additional dose induced by radiation of the main beam absorbed in the Compact Photon Source is negligible.

The Compact Photon Source design should combine in a single properly shielded assembly all elements necessary for the production of the intense photon beam, including that the operational radiation dose rates around it are acceptable as outlined in the requirements above. Much of this is achieved by keeping the overall dimensions of the setup limited, and by shielding induced radiation doses as close to the source as possible, and by careful choice of materials. Compared to the traditional bremsstrahlung photon source, the proposed solution will present several advantages, including much lower radiation levels, both prompt and post-operational due to the beam line elements radio-activation, as will be shown later.

The Compact Photon Source conceptual design has been established with extensive and realistic simulations. As validation of the simulation tools used, we have also performed a benchmark comparison using tools such as GEANT3, GEANT4, FLUKA and DINREG. The benchmark results are further described in Appendix B. After benchmark validation, we have performed an extensive series of radiation calculations to:

- Determine the size and layering of the shielding around the magnet, and the choice of materials (Cu, Cu-W alloy, concrete, borated plastic, etc.).
- Determine the magnet field requirements in terms of peak field, gap size, and field length.
- Determine the radiation level on the magnet coils and based on these results identify radiation hardened materials that might be used in building the coils.

- Determine the radiation level on the polarized target electronics.
- Determine the radiation level immediately next to the device as well as at the experimental hall boundary.

The logic behind the CPS hermetic shielding design is that radiation (γ, n) from the source should be a few times less than from a photon beam interaction with the material of a polarized target. The CPS is designed to meet the accpetable radiation level requirements specified in Appendix 2 for electron beam current of 2.7μA (30 kW), run time of 1000 hours, and the photon source as close to the target as possible. The shielding design consists of tungsten powder and 10cm of 30% borated plastic. The addition of the latter has considerable impact in reducing the neutron flux, illustrated in Figure 2.

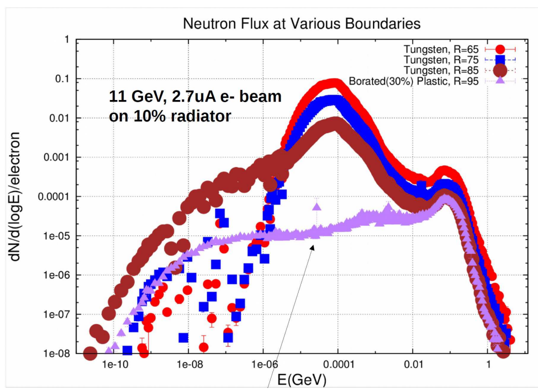

Figure 2: Impact of boron on shielding properties.

V Radiation Studies - realistic shielding concept and radiation resistant magnet (Jixie, Rolf)

- Dose rate estimates in μR/hr at the RBM-3 boundary condition for the benchmark calculations (3m iron vsl 1.5m W sphere) are: iron: 0.24 μR/hr total, W: 2.4 μR/hr total
- With proper material and ordering choice of iron and W, and a 10cm outer layer of borated polyethylene, the boundary dose can be tuned below the 2.4 μR/hr that corresponds to a typical run not requiring additional local shielding, per the radiation budget
- For HallD: the design is compatible with the site boundary as the conditions for regular taggger magnet running dumps 60 kW in a local beam dump and now 60 kW is dumped in the CPS itself. The Hall D tagger vault is designed for this, but additional local shielding may be required.

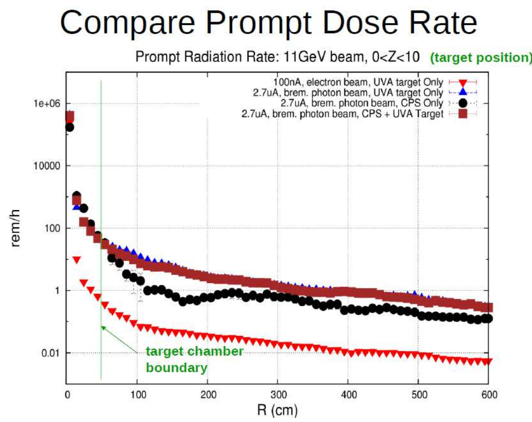

Figure 3: Comparison of prompt dose rates.

A comparison of the radiation simulation with polarized target and a 100nA pure electron beam and a pure photon beam (resulting from a 2.7μA electron beam interacting with a 10% radiator) is shown in Figure 4

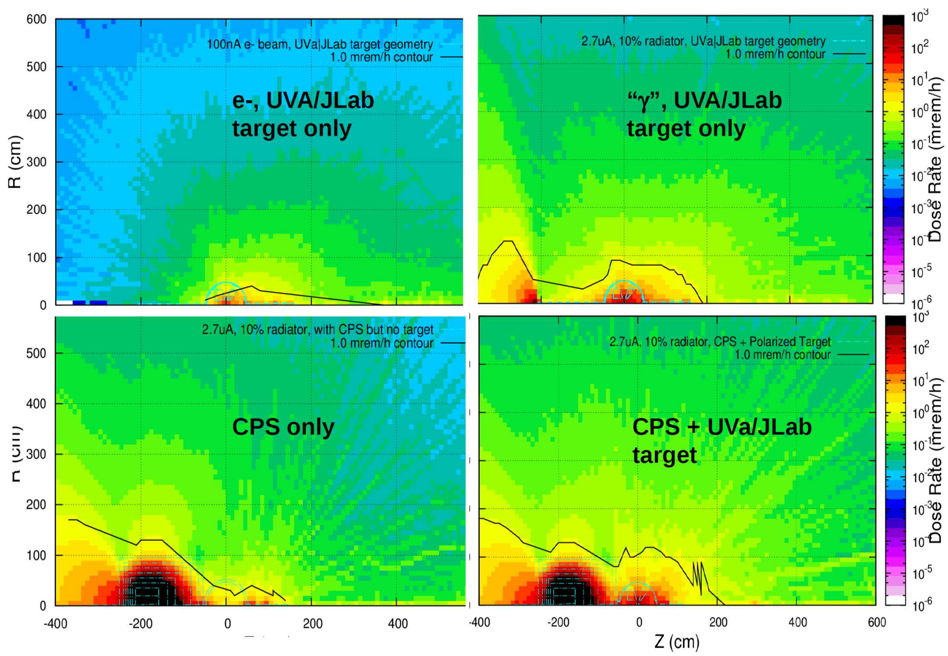

Figure 4: Comparison of activation doses for pure electron and pure photon beam. A bremsstrahlung photon beam created from a 2.7μA 11 GeV electron beam on a 10% radiator will create more activation dose in the target than a 100nA electron beam as more photons are available to activate.

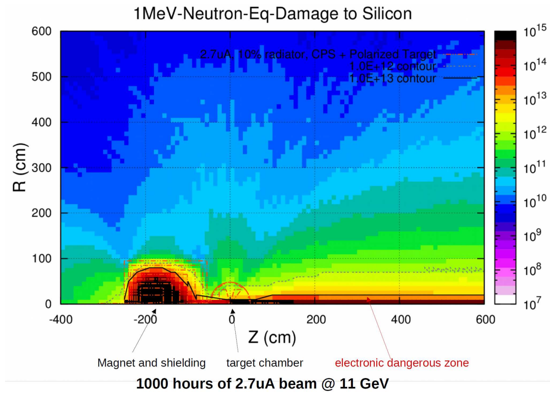

Figure 5: 1 MeV Neutron Equivalent Damage.

VI Safety and Engineering Aspects (Bogdan, Gabriel, Thia)

A Safety

From safety point of view the CPS device is a modest power (30 kW) beam dump installed in a middle of the hall. There are several safety aspects in this project. Here we show a list for the full scope including items which will be considered in future.

- Prompt radiation level in the hall
- Radiation level at the JLab boundary
- Residual radiation in the hall
- Radiation level at the polarized target coils (both prompt and residual)
- Radiation level at the detector electronics
- Radiation level at the magnet coils and absorber cooling water
- Removal of the CPS from the beam line after the experiment
- Fast raster trip detection and raster interlock
- Interlock system: temperatures, radiation, water flow
- Commissioning plan including engineering tests.
- Safety documentation, review, and approvals

Some of these items (radiation analysis) are already addressed in this document. Our approach to the radiation analysis includes both: studies of the radiation levels using FLUKA (also comparison with GEANT4) and comparison with data from typical experiments already performed at JLab.

B Engineering

The CPS is a relatively heavy device (∼50 tons). Its installation and removal from the beam line requires a new solution due to limited crane access near the hall center.

The CPS magnet will be located relatively close to the 5 Tesla solenoid of the polarized target whose mutual forces need to be taken into account in design of the support structure and may be require compensation.

Preliminary cost analysis was made by using vendor quotations for W-powder and actual cost for the similar size normal conducting magnets.

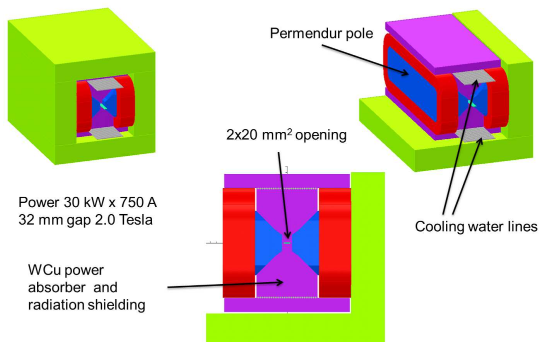

Figure 6: The magnet.

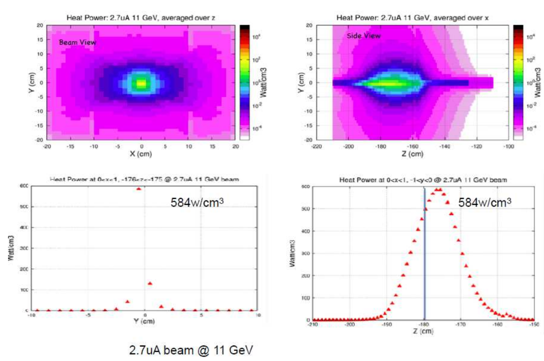

Figure 7: Heat power.

Appendix 1: Concept Transfer to Hall D (Igor)

The intense photon source is one component of the K_L beam. The experimental method can be summarized as follows: electrons hit a copper radiator, the resulting photons hit a Be target, and a beam to K_L is produced. The search for missing hyperons is a strong motivation for this setup.

- The CPS will be located downstream of the tagger magnet. The tagger alcove has more space than that available in Hall A/C, so positioning and shielding placement are simpler.
- Can go up to 60 kW (less than 5 uA at 12 GeV). The ceiling shielding of the Tagger hall above the CPS position is the same as it is above the existing 60 kW dump. No radiation increase at the site boundary is expected with respect to 60 kW operations using the existing dump.
- The floor in the area can hold a 100t CPS.
- A 30 kW CPS has been designed by an ENP working group for Halls C/A. The group intends to provide the design for a 60 kW device for Hall D. The latter device has to be somewhat larger, but the Tagger hall provides more available space than the Hall C location.
- Different length/field magnet. Shielding may differ
- If one uses a 2nd raster system for Hall D to compensate for the initial 1mm rater, this can be an equivalent essential design

Appendix 2: Benchmark comparison

contributors: P. Degtiarenko, J. Zhang, G. Niculescu

From the engineering standpoint, two of the most important aspects in the design and subsequent building of a Compact Photon Source are the ability to properly shield the radiation produced inside the source and to dissipate the resulting heat in a safe manner. While the latter point was addressed earlier in this document, in this Appendix we focus on the former issue, specifically detailing the steps taken to benchmark the simulations used in assessing the prompt, as well as the residual (activation) radiation level around the CPS and in the experimental Hall. Even though they have been mentioned before, it is worth reiterating the basic radiation level constraints associated with experiments at JLab:

From the radiological protection point of view the following set of limitations should be satisfied, conservatively assuming typical expected experimental run conditions:

- Beam energy: 11.5 GeV Beam electron beam
- Current: 2.6 μA
- Beam Power (based on the above) = 30 kW
- Run time: $\sim$ 1000 hours

For the typical, high current JLab experiment the radiation dose rate parameters must stay within the following limits:

- Dose rates in the Hall should be under several rem/h at 10 m from the device
- Dose rates at the boundary should be under 1 $\mu rem/h$ during the run
- Dose rates outside the device envelope at a foot distance from the device should be under several $mrem/h$ after one hour following the end of the 1000 hour run

In order to gain an understanding of the radiation levels likely to be produced by the CPS and to ultimately design the optimal shielding for it, one relies on Monte Carlo simulations and over the years the nuclear and particle physics community[1] has developed a series of very sophisticated simulation programs. In time these programs became more complex, with several physical processes that can be turned on and off, various thresholds and cutoffs that might greatly influence the result yet they are buried deep inside the code. Therefore, one has to be careful in using and interpreting the results of such simulations because, as suggested above, the same simulation can give vastly (i.e. orders of magnitude differences) different results with only (seemingly) minor changes in the input parameters.

Ideally one would want to **ground–truth** the simulation by **experimentally measuring** a small but relevant setup and verify that the simulation results agree with the measured radiation levels of that setup. For the current study this step was not done explicitly, though one can argue that one of the simulation programs used (Geant3) was extensively **ground–thruth–ed** as the JLab RadCon group compares the radiation levels measured at boundary of the experimental Halls with the Geant3 predictions.

To benchmark the simulations used in the CPS design a couple of relatively simple radiation scenarios were independently simulated using three different simulation programs (Geant3[2], Fluka[3], and Geant4[4]) by the three groups involved in this process, as follows:

- JLab group (led by P.D.): used Geant3
- UVa group (led by J.Z.): used Fluka
- JMU group (led by G.N.): used both Geant4 and Fluka

The geometry that was simulated was a simple sphere with a small cylindrical hole bored in it such that the 30 kW, 11.5 GeV beam interacts inside the sphere (at $z = 30$ cm for the Fe sphere and at $z = -15$ cm for the W sphere).

[1] As well as related areas such as nuclear medicine, astronomy, defense, etc.
[2] The only code currently setup for calculating the radiation at the JLab boundary is Geant3.
[3] Fluka is the only choice for activation calculations.
[4] The development of the Fortran–based Geant3 code has ceased long time ago and the community has/is migrating toward the C++ based Geant4.

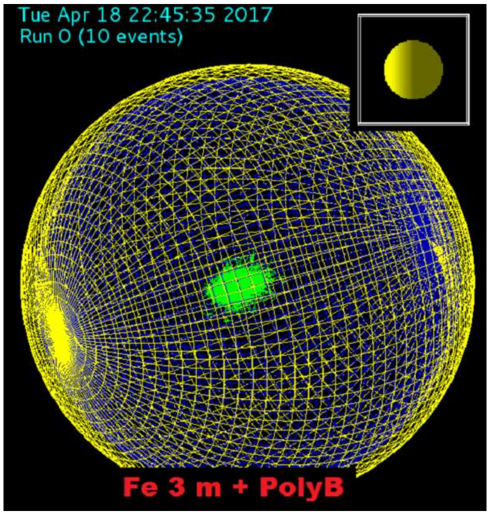

Figure 8: Fe sphere with the Borated Poly layer, as simulated in Geant 4.

Four of these setups were simulated:

- A 300 cm diameter **Fe** sphere
- A 150 cm diameter **W** sphere
- A 300 cm diameter **Fe** sphere with an outer 10 cm Borated Polyethylene layer (5 % Boron by weight
- A 150 cm diameter **W** sphere with an outer 10 cm Borated Poly layer

The results of these parallel simulations are summarized in the Table below.

	Dose Rates [mrem/h]								
	JLab DINREG/Geant3			JMU Geant4			UVa Fluka		
	n	γ	total	n	γ	total	n	γ	total
3 m Fe	146	0.44	146.44	123.2	0.56	123.76	10	0.039	10.039
3 m Fe + Poly- B	0.8	2.8	3.6	0.284	0.56	0.844	0.11	0.063	0.173
1.5 m W	13	0.06	13.1	6.34	0.33	6.67	1.7	0.0002	1.7002
1.5 m W+Poly-B	2.7	0.003	2.7	1.76	1.28	3.04	0.15	0.0007	0.1507

Table I: Geant3, Fluka, and Geant4 prompt radiation comparison for Fe and W spheres.

Examining these results one notes the reasonable agreement between the Geant3 and Geant4 simulation, though factors of 1–2 could not be ruled out in the differences (and are to be expected in these types of estimations). The radiation levels predicted for these spheres leads one to conclude that the optimization of the CPS shielding satisfying the safety requirements in the Halls and outside ought to be possible. The addition of a borated polyethylene layer seems to be absolutely critical in moderating and absorbing low energy neutrons. This becomes very important if one choses[5] Fe as (part of) the shielding material.

One notes that a dose rate of $\sim$2.4 $\mu rem/h$ at the boundary correspond to a "regular" normal experiment, not requiring extra shielding measures, corresponding to about the "200% of allowable design boundary dose rate" (that is, the dose rate at which the dose accumulation would be 10 mrem if such conditions are run for a half of the calendar year continuously).

The Fluka simulation (carried out in parallel at UVa and at JMU) was able to provide residual radiation (due to activation) at various time intervals: 1 hour, 24 hours,

[5] For example for cost containment.

7 days, 30 days. Sample results for the 3 m Fe sphere, one hour after the end of the irradiation cycle (assumed to be 1000 hours of 11.5 GeV, 2.6 μA beam) are shown in the Figures below.

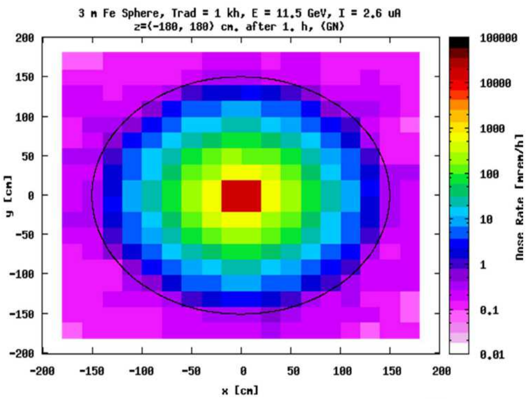

Figure 9: Radiation level one hour after the end of the irradiation period. Closeup view of the JMU Fluka result.

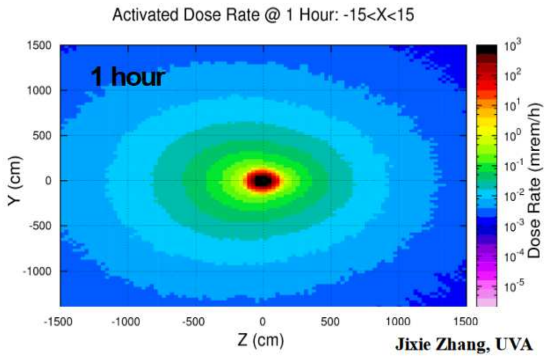

Figure 10: Expanded view of the radiation level one hour after the end of the irradiation period (UVa Fluka result). Both plots correspond to the 3 m Fe sphere.