If you are using a printed copy of this procedure, and not the on-screen version, then you MUST make sure the dates at the bottom of the printed copy and the on-screen version match.
The on-screen version of the Collider-Accelerator Department Procedure is the Official Version.
Hard copies of all signed, official, C-A Operating Procedures are available by contacting the ESSHQ Procedures Coordinator, Bldg. 911A

C-A OPERATIONS PROCEDURES MANUAL

9.1.15.a TANDEM Experiment Target Record

Hand Processed Changes

HPC No.	Date	Page Nos.	Initials
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Approved: ___________***Signature with Date on File***_______________
Collider-Accelerator Department Chairman Date

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Note2: Leave no blanks. Indicate 'Not Applicable (N/A)', where appropriate.

Title and Preparer

TANDEM 28 MeV Proton Experiment

N. Simos

Instructions

	a. Radioactivity of each nuclide at end of bombardment (EOB), at 8 hours and 24 hours post EOB.	
7.	**Expected Dose Rate (e.g., R/h at 1 m)** [provide expected dose rate using *Microshield or equivalent* calculations for the combined and separate target and can irradiated. Provide expected dose rate at EOB at Tandem and expected dose rate when delivered to TPL]	17
8.	**Additional Safety Requirements** [address hazardous issues related to volatiles and or corrosive materials used and any additional equipment required for this experiment; hazardous materials information must be submitted to the C-AD ESSHQ Division Head for concurrence]	18
9.	**Special Operating Instructions and List of References or Supporting Documents**	18
10.	**Appendix** [provide additional support information as required]	19-28

1. Overview

An irradiation experiment as a first step towards micro-structural evolution of novel materials of interest in particle accelerators as well as next generation reactors is proposed to be performed at the BNL Tandem facility using the **28 MeV, 1 μA proton beam** that it can deliver on target. Specifically, a multitude of different material specimens will comprise a special array in which interaction of the Tandem proton beam with some of the materials interested in the proton-matter interaction will intercept the 28 MeV protons while the surrounding array of specimens, mostly interested in the interaction with spallation neutrons that will be generated by the primary protons, will be passively irradiated by the spallation products. The ability of the Tandem facility to focus the 28 MeV primary proton beam down to few hundred micrometer beam spot is a great advantage in that proton irradiation of a small volume can be achieved enabling the accumulation of fluence that can trigger changes in the materials despite a limited irradiation time. In addition, by limiting the affected volume, the post-irradiation characterization through x-ray diffraction (EDXRD) at the BNL NSLS synchrotron will enable the focusing of the x-ray beam and the study of the effects over a volume that is compatible with such characterization while at the same time minimization and localization of the activity in the test sample can be achieved.

A series of such experiments is envisioned to be conducted at the Tandem facility utilizing both the 28 MeV protons and the array of ion beams that can be delivered on target. In this first phase of the overall experimental activity an array of specimens under study for the Large Hadron Collider (LHC) Luminosity upgrade phase, the Long Baseline Neutrino Experiment (LBNE) and next generation reactors are being considered to form the "target volume". Due to the small current and tight beam spot, a small volume of target material will intercept and arrest the 28 MeV protons while the surrounding array will be exposed with spallation productes (neutrons, gammas and electrons). The array includes (a) molybdenum-graphite and copper-diamond specimens that are primary proton beam interceptors and are of interest to the LHC, (b) graphite and carbon composite specimens that are of direct interest to the LBNE and finally alumina-titania and amorphous iron coated steel and Ti6Al4V samples which are placed in the periphery of the array to intercept fast neutrons that are generated by spallation.

In summary, the following material samples will be associated with **Tandem_Experiment_1**:

- Six (6) 2mm x 2mm x 42mm molybdenum-graphite (MoGR) composite material
- Six (6) 2mm x 2mm x 42mm copper-diamond alloy (CuCD) samples
- Three (3) 2mm x 2mm x 42mm alumina-coated Ti6Al4V samples
- Three (3) 2mm x 2mm x 42mm alumina-coated 4140 steel samples
- Two (2) 1mm x 6mm x 42mm Glidcop samples (dogbone type)
- Four (4) 1mm x 6mm x 42mm graphite samples (dogbone type)
- Four (4) 1mm x 6mm x 42mm amorphous iron on steel samples (dogbone type)

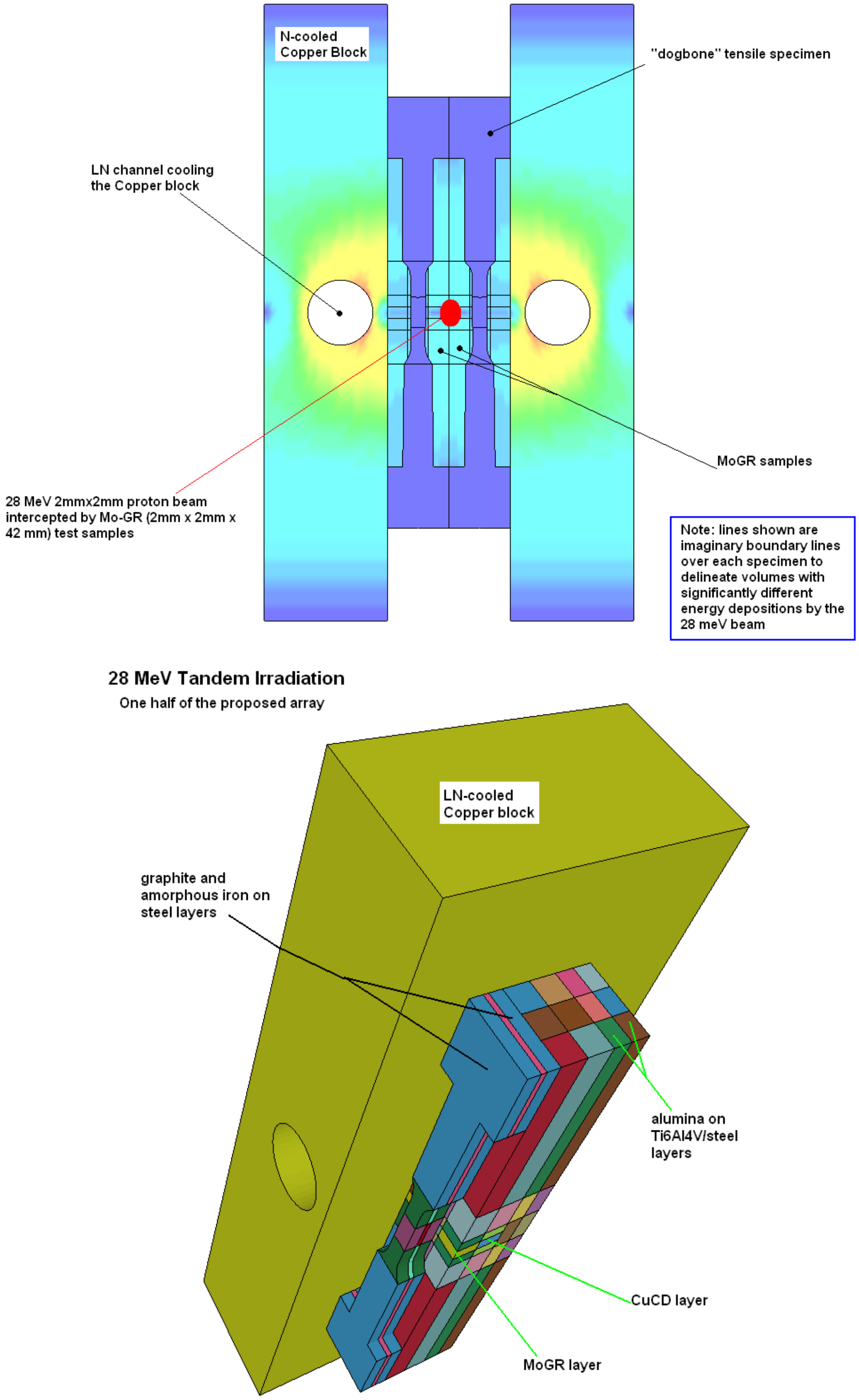

Figure 1: Layout of the Tandem target array

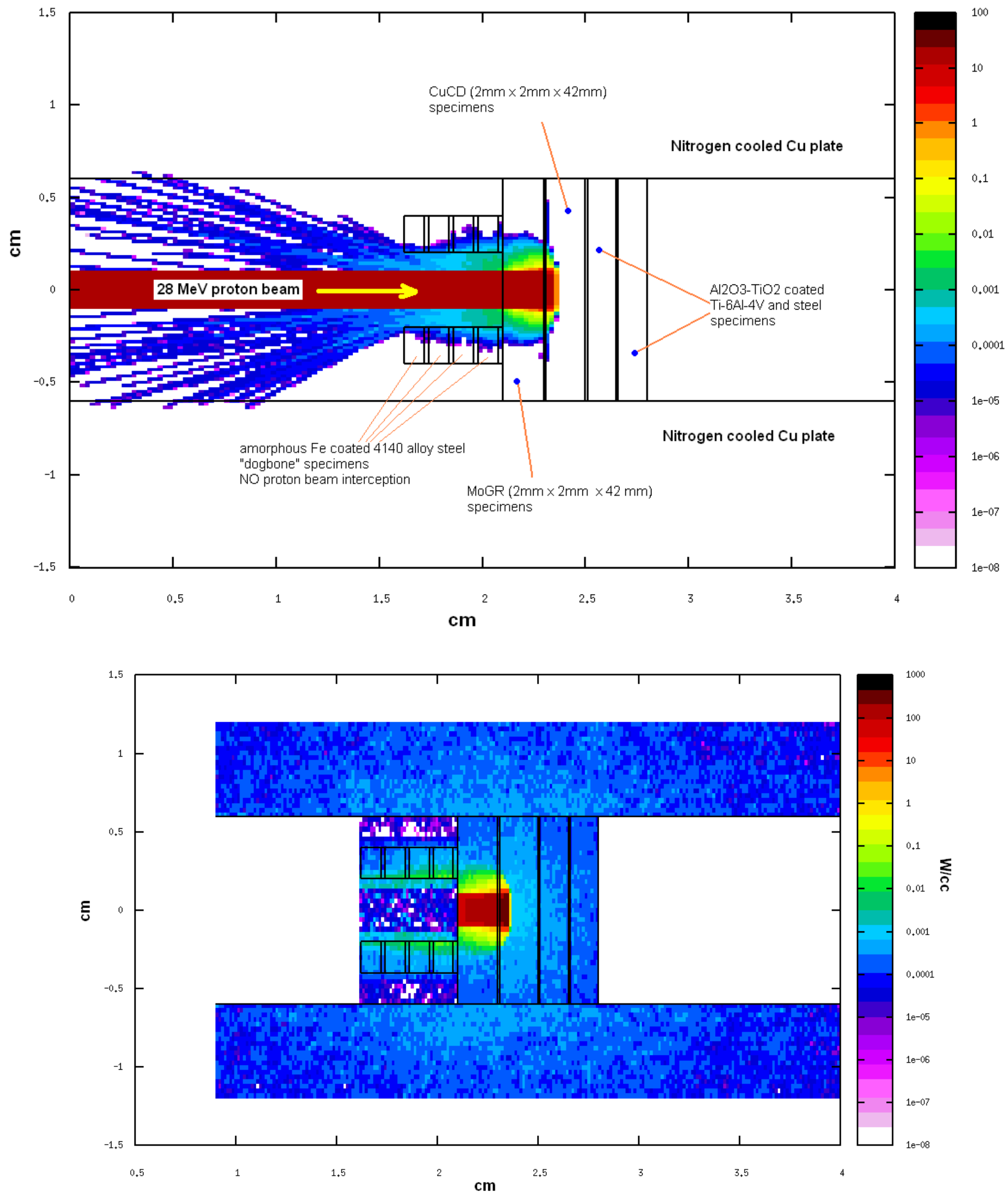

Figure 2: Predicted 28 MeV proton beam interaction with the proposed array and energy deposition profile through out the experimental array.

Following irradiation at Tandem and cooling time sufficient for transport to Building 801 Rm 66 Fume Hood, the target array will be transported to the TPL hot cells by standard procedures. At Rm 66 fume hood area, the samples will be encapsulated in a Kapton® polyimide film and silicone adhesive designed for high temperature applications and will be inserted into specially designed cassettes. The two cassettes will be transported to NSLS X17B1 endstation where they will be inserted into the hermetically sealed volume of the x-ray diffraction stage that has been designed and fabricated meeting high vacuum specifications. Upon completion of the EDXRD diffraction experiment that has been fully approved with full consideration of the dose and activity levels of the samples that will be irradiated at the Tandem and transported to NSLS (full coordination with NSLS-HP and submission of Safety Assessment Form has been completed and approved).

To address the different aspects of the irradiation experiment, the following codes/versions were utilized:

Transport codes for beam energy degradation/energy deposition/activation and dose:

SRIM - Version 2008.04

FLUKA-2012

Thermo-mechanical analysis and modelling/meshing

LS-DYNA - Version 9.71

TrueGrid Version 2.3.4 (meshing software)

2. Target Array Materials and Properties						
Target Material – 4140 Steel with amorphous Fe coating						
Purity or Grade	99.5%					
Chemical Formula	4140 Steel					
Physical Characteristics at 70 °F or 21 °C	**Grey to black metal, odourless, tasteless**					
Physical Form	**Foil**	**yes**	**Powder**	**no**		
	L-W-thick (mm)	**42mm x 6mm/1.2 mm**	**Pressed (Torr)**	**n/a**		
Elements (%)	4140 Composition (Element Weight %) C 0.38-0.43/Mn 0.75-1.00/P 0.035 (max)/S 0.04 (max)/Si 0.15-0.30/Cr 0.80-1.10/Mo 0.15-0.25 – Balance Fe					
Melting Point	**1416**	**°C**	**2580**	**°F**		
Boiling Point	**n/a**	**°C**	**n/a**	**°F**		
Thermal Conductivity	**42.7W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**			
Density	**8.0**	**g/cm^3**				
Specific Heat	**473**	**J/kg.K**				
Target Material Reactions / Properties						
Does the Target material react with any of the following?	Aluminium	no	Air	no	CO_2	no
	H_2O	insoluble	Lead	no	Zinc	no
	Inconel 600	no	S/Steel	no	Copper	no
Tandem Target Material – Glidcop (LHC)						
Purity or Grade	99.5%					
Chemical Formula	**Glidcop AL-15**					
Physical Characteristics at 70 °F or 21 °C	**Golden metal, odorless, tasteless, shiny**					
Physical Form	**Foil**	**yes**	**Powder**	**no**		
	L-W-thick (mm)	**42mm x 6mm/1mm**	**Pressed (Torr)**	**n/a**		
Elements (%)	Copper 99.813% , Al_2O_3 0.187%					
Melting Point	**1083**	**°C**	**1981**	**°F**		

Boiling Point	**4790**	**°C**	**8654**	**°F**	
Thermal Conductivity	**365 $W.m^{-1}.K^{-1}$**	**Temperature dependence**	***(if available)* n/a**		
Density	**8.93**		**g/cm^3**		
Specific Heat	**391**		**J/kg.K**		

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

Mo-Graphite (LHC)

Target Name:	*MoGr_LHC*		

Target Material - Molybdenum-Graphite				
Purity or Grade	99.5%			
Chemical Formula	Mo-GR			
Physical Characteristics at 70 °F or 21 °C	**Grey to black metal, odorless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	L-W-thick (mm)	**42mm x 2mm/2mm**	**Pressed (Torr)**	**n/a**
Elements (%)	**Mo 21.515%, 78.485% Graphite**			
Melting Point	**2505**	**°C**	**4541**	**°F**
Boiling Point	**n/a**	**°C**	**n/a**	**°F**
Thermal Conductivity	**320 $W.m^{-1}.K^{-1}$**	**Temperature dependence**	***(if available)* n/a**	
Density	**3.7**		**g/cm^3**	
Specific Heat	**574**		**J/kg.K**	

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

Copper Diamond (LHC)

Target Material Cu-CD				
Purity or Grade	99.5%			
Chemical Formula	Cu-CD			
Physical Characteristics at 70 °F or 21 °C	**Grey to black metal, odorless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	L-W-thick (mm)	**42mm x 2mm/2mm**	**Pressed (Torr)**	**n/a**
Elements (%)	**Copper (23.590%), Diamond (75.458%), Boron (0.932%)**			
Melting Point	**1083**	**°C**	**1981**	**°F**
Boiling Point	**n/a**	**°C**	**n/a**	**°F**
Thermal Conductivity	**490 W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**	
Density	**5.4**		**g/cm^3**	
Specific Heat	**420**		**J/kg.K**	

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

Ti-6Al-4V coated with Al_2O_3				
Purity or Grade	99.5%			
Chemical Formula	Ti6Al4V-Al_2O_3			
Physical Characteristics at 70 °F or 21 °C	**Grey (Ti6Al4V)/black (Al_2O_3) metal, odorless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	L-W-thick (mm)	**42mm x 2mm/2mm**	**Pressed (Torr)**	**n/a**
Elements (%)	**Substrate - Al (5.5-6.7%); Vanadium (3.5-4.5%), C<0.08%, Fe <0.25%, O_2<0.2% - Titanium (90%)** **Coating – Al_2O_3**			
Melting Point	**Ti-6Al-4V** **Al2O3**	**1649 °C** **2072°C**	**3000 °F** **3762 °F**	
Boiling Point	**n/a**	**°C**	**n/a**	**°F**

Thermal Conductivity	**Ti-6Al-4V – 7.2 W.m^{-1}.K^{-1}** **Al2O3- 30W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**
Density	**Ti-6Al-4V – 4.42** **Al2O3 – 4.1**		**g/cm^3**
Specific Heat	**Ti-6Al-4V – 560** **Al2O3 – n/a**	**J/kg.K**	

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

Target Samples - Graphite & C/C

Purity or Grade	99.5%			
Chemical Formula	Carbon			
Physical Characteristics at 70 ^{o}F or 21 ^{o}C	**Grey to black, odourless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**2.375/60.325**	**Pressed (Torr)**	**n/a**
Elements (%)				
Melting Point	**C/C: 3500**	**^{o}C**	**6,332**	**^{o}F**
Boiling Point	**n/a**	**^{o}C**	**n/a**	**^{o}F**
Thermal Conductivity	**460 W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**	
Density	**1.7-2.1**		**g/cm^3**	
Specific Heat	**830**	**J/kg.K**		

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

3. Target Canning Process

N/A

The array of test samples which (a) intercepts the 28 MeV and (b) is showered by spallation products is not enclosed by any additional can. The ORTEC target chamber which operates under vacuum and is hermetically seals the target system from the outside is utilized as the enclosure envelope.

4. Beam Characteristics		
Maximum Instantaneous Current Desired	**n/a**	**mA**
Average Current Desired	**1**	**µA**
Total Integrated Current Desired	**12**	**µA - hrs**
Maximum Proton Energy on Target Material	**28**	**MeV**

Beam Conditions

A beam spot of 2mm x 2mm will be required for the proposed irradiation at the Tandem (a condition that is easily achievable) and with the maximum beam current that can be delivered which is ~1 µA. Estimates of energy deposition, dose and activation presented in later sections are based on the ability of the Tandem to deliver 1 µA of beam. As shown in Figure 2 the 28 MeV protons first interact with the MoGR layer and get fully arrested in the CuCD layer (upstream part). The proton-intercepting volume is limited, based on the 2mm x 2mm beam cross-section) and therefore most of the sample volume will be exposed to the secondary field (spallation products).

5. Experiment Description

5.a Procedure for irradiation of Tandem Target Array:

The Tandem experiment target array is shown in Figure 1. The rectangular part of the volume which consists of a packed 42mm/2mm/2mm rectangular specimens (total width of 12mm) is held tight by the two copper blocks on either side by a clamp. The copper blocks are made such that liquid nitrogen at 70K is flowing thru the channel cooling the target array. Based on FLUKA analysis (and as shown in Figure 2) only the first layer and partially the second layer of specimens will be intercepting and arresting the 28 MeV protons. In particular only four (4) 42mm x 2mm x 2mm specimens will be irradiated by protons over a volume of 2mm x 2mm (beam footprint). The rest of the array will be exposed to spallation products. Upstream of the proton intercepting first layer dog-bone type specimens of 4140 steel will be placed (two specimens per layer as shown with total width of 12mm). The shape of these specimens is such that the primary 28 MeV protons will completely bypass them and continue on to the first intercepting layer. These upstream specimens will be irradiated by the spallation products (shown in Figure 3 is the spallation neutron profile). Graphite dog-bone type specimens will be placed upstream of the 4140 steel specimens (which are coated with amorphous Fe) and downstream after the last rectangular specimen layer (consisting of Ti-6Al-4V 42mm x 2mm x 1 mm coated with Al_2O_3). The array held tightly together by the LN-cooled Cu blocks will be placed in the ORTEC target chamber (~36" diameter with 3"-thick stainless steel wall) which represents the target volume at the end of the beamline delivering the 28 MeV. The ORTEC chamber operates in vacuum and it is equipped to supply LN at 70K for cooling through special hoses thus removing the heat load induced by the 28 MeV, 1 µA current beam. Following extensive analyses of the prompt dose inside and outside the ORTEC target chamber, it has been decided that a 6"-thick layer of polyurethane that surrounds the entire chamber will be used as additional shield during the 12-hour (max) irradiation with protons thus minimizing the dose around the chamber. The Target room where irradiation will be taking place will be inaccessible during irradiation minimizing further dose concerns.

At the end of the 12-hour irradiation, the target array will cool-down for one week and at the end of this period will be transported to the HEPA-filtered hood area of Hot Cell Room 66 of Building 801 through coordination with the HP group at 801.

While at 801, and in preparation for the subsequent x-ray diffraction studies at NSLS, each individual sample will be encapsulated in Kapton film. The array of encapsulated specimens will be inserted into the specially designed cassettes and will be transported with the supervision of HP to NSLS X17B1 beamline enclosure where they will be inserted into the high vacuum stage designed specifically for the EDXRD studies.

5.b Target array: N/A

5.c Thermal analysis of target material and target can (attach analyses if any):

A detailed thermo-mechanical analysis of the Tandem target array was performed using energy depositions produced by FLUKA. A detailed finite element model using the capabilities of the LS-DYNA numerical code was performed based on most conservative scenarios.

Shown in Appendix 2 are excerpt results of the conducted analyses on the targets and the can.

5.d Transport of irradiated target to TPL, target opening and processing:

Following the 12-hour irradiation of the Tandem target array, the dose outside the chamber will be measured periodically to confirm the estimated by analysis levels. A special small transport pig used to transport low-dose samples from BLIP to 801 will be used to transport the array (total volume 42mm x 12mm x 16mm) to building 801 where the specimens will (a) measured for activity, (b) isotopic composition using the Ge detector in 801, (c) be encapsulated in Kapton and (d) inserted in the special cassettes for transport to NSLS X17B1 beamline. Upon completion of the approved experiment at NSLS the encapsulated specimens will be transported back to 801 for macroscopic analysis in the Rm. 66 hot cells.

5.e Disposal of waste:

Al target body will be disposed with other target bodies as solid non compactable waste as per CAD OPM 19.3.5.6 & 19.3.5.7.

6. Activation Analysis of Target Material and Can

To help create guidelines for radiation protection during and after the completion of the experiment a series of very detailed analyses of beam transport and interaction with the target array and the target envelope (consisting of the ORTEC chamber and outside shielding) were performed. The configuration, as close to the actual experimental one, was implemented into the FLUKA transport code and analyses of beam interaction, dose, activation, decay and isotope generation were performed. Special attention was given to the prompt dose that will be induced during the experiment around the target and in the target room. Several options of additional shielding were analysed. These included (a) the use of 6-inch thick polyurethane that encloses the ORTEC chamber (b) the use of 6” thick lead brick shielding and (c) a hybrid shield made of 3” polyurethane and 3” lead. The detailed FLUKA dose calculations revealed that the first option, i.e. 6” polyurethane, is the most effective one in keeping the dose outside the target chamber to a minimum.

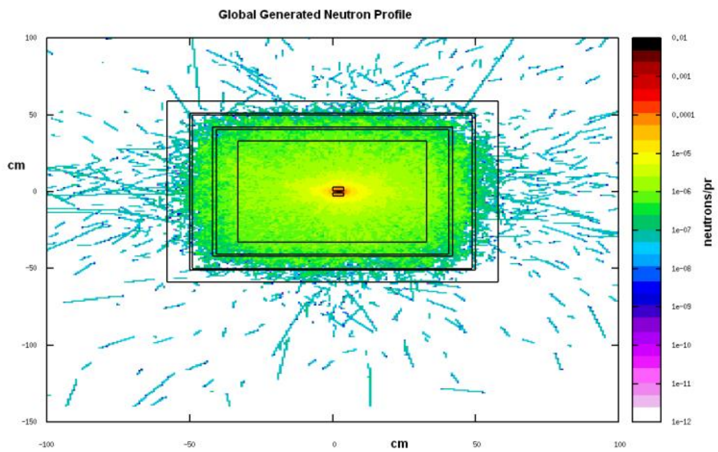

Figure 3: Global profile of spallation neutrons generated by the 28 MeV protons

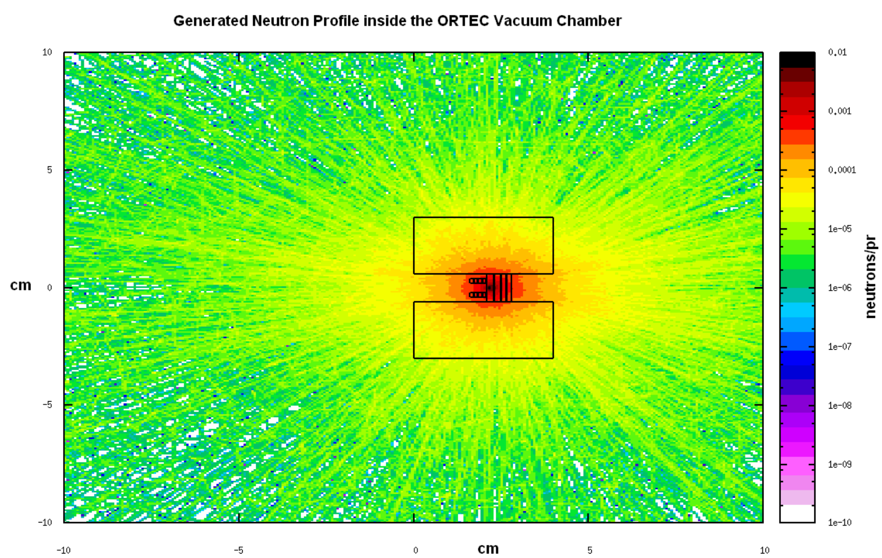

Figure 4: Spallation neutrons generated by the 28 MeV protons within the ORTEC chamber

Shown below are excerpt results of both the prompt dose and of the decay dose. The decay dose is calculated based on 12-hour irradiation at 28 MeV with 1 μA beam current. Only results for the optimal choice are shown (results of the other options are also available upon request).

To help create guidelines for radiation protection during and after the completion of the experiment a series of very detailed analyses of beam transport and interaction with the target array and the target envelope (consisting of the ORTEC chamber and outside shielding) were performed. The configuration, as close to the actual experimental one, was implemented into the FLUKA transport code and analyses of beam interaction, dose, activation, and decay and isotope generation were performed. Special attention was given to the prompt dose that will be induced during the experiment around the target and in the target room. Several options of additional shielding were analysed. These included (a) the use of 6-inch thick polyurethane that encloses the ORTEC chamber (b) the use of 6" thick lead brick shielding and (c) a hybrid shield made of 3" polyurethane and 3" lead. The detailed FLUKA dose calculations revealed that the first option, i.e. 6" polyurethane, is the most effective one in keeping the dose outside the target chamber to a minimum. Shown below are excerpt results of both the prompt dose and of the decay dose. The decay dose is calculated based on 12-hour irradiation at 28 MeV with 1 μA beam current. Only results for the optimal choice are shown (results of the other options are also available upon request).

Activation:

The activation analysis revealed that the samples directly intercepting the 28 MeV proton beam, with the exception of recordable activity in the amorphous iron on steel specimens, show recordable activation. Specifically, the two central MoGR specimens that intercept the beam show the most activity (48 mCi at EOB which decays to 1.46 mCi after one day and to 17.5 μCi after one week). The steel specimen with the amorphous iron coating shows activity of 11.2 mCi at EOB which reduces to 326 μCi after one week)

A detailed list of the activities associated with the LHC irradiated array at BLIP and the isotopes is included in **Appendix 3.** Specifically, activity results are listed for EOB, one (1) day of decay and 120 days of decay.

Similarly activation results using the FLUKA model and decay analysis were generated at EOB, 1 hour, 24 hours, 1 week, and 2 weeks after EOB. The FLUKA analyses were performed (N. Simos). Excerpt results are also shown **in Appendix 3**.

For a detailed description see Appendix 3

Decay Requirements

Decay analyses using the capabilities of the FLUKA code were performed following the exact irradiation and decay path of the experiment and taking into consideration the shielding specifics surrounding the ORTEC chamber at Target Room 1 of Tandem as well as the transport process in order to determine decay requirements prior to array transport from Tandem to Building 801 Rm 66 Fume Hood and eventually to the NSLS X17B1 beamline for x-ray diffraction.

7. Expected Dose Rate

Prompt Dose

Shown in Figure III.1 below is the effective dose (prompt) distribution inside and outside the target space.

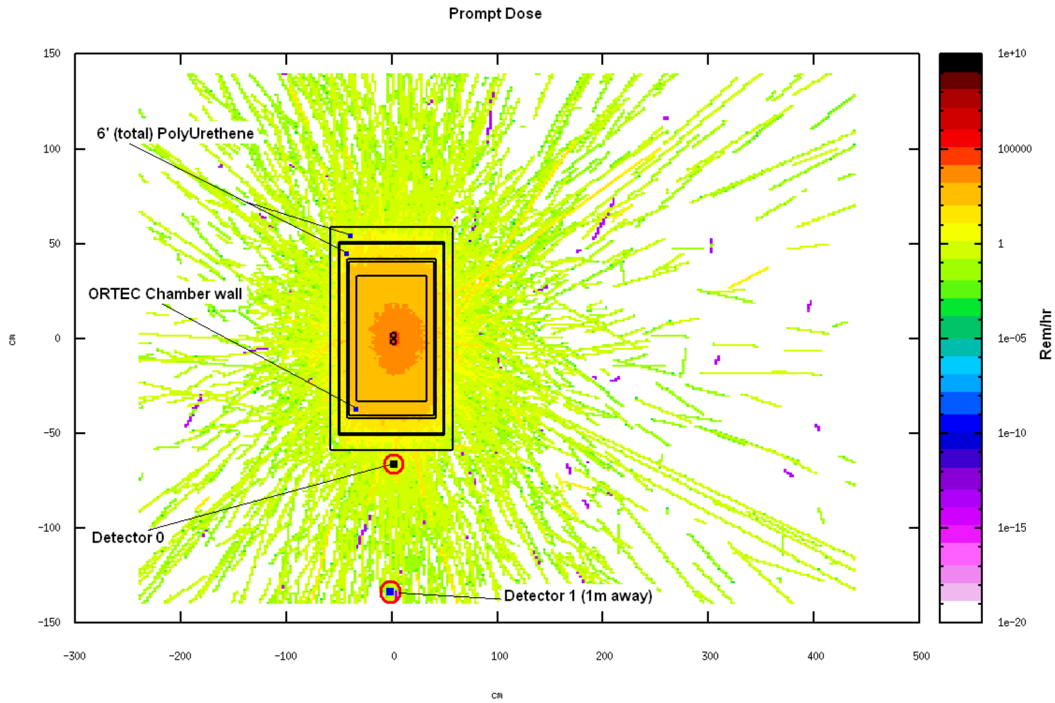

Figure 5: Effective dose profile during the 28 MeV Tandem experiment

Important to note are the following:

- The estimated dose at the outer surface of the ORTEC Chamber (outer surface of the polyurethane shield) is ~1.75 Rem/hr
- The prompt dose at about 30 cm away from the chamber is 0.3 Rem/hr (300 mRem/hr
- The prompt dose one (1) meter away from the chamber is 0.21 R/hr (210 mRem/hr)

DECAY Dose

The decay dose following completion of the irradiation phase of the experiment was estimated for different periods and different scenarios. Specifically, dose from decay of the target array and the entire surrounding envelope (ORTEC chamber wall and polyurethane shielding) was estimated for End of Bombardment (EOB), one hour, 24 hours, 1 week, and 2-week cool-down periods. Additional scenarios, but with the same cool-down periods were considered and include the case of the dose after the polyurethane is removed. To complete the process of identifying all the radiation-safety related elements, dose and activity calculations for the irradiated target array as a whole and as individual specimens were performed. Figure 2 depicts the decay dose profile for EOB and 24-hour cool-down period. Important to note that with the 6" polyurethane shield the contact dose on the outside surface of the polyurethane reduces dramatically and to levels of a few mRem/hr

1 hour – on contact with polyurethane = 6.54 mRem/hr

24 hour– on contact with polyurethane = 1.6 mRem/hr

Another dose/activation analysis estimated the doses that would exist if the polyurethane is removed (which will be the case when the target array is to be retrieved from the chamber and taken for post-irradiation analysis). Therefore, the decay process in this case eliminated the shielding properties of the 6" polyurethane and doses were estimated for 1 hr, 24-hour, 1one week and two week cool-down periods. In the process contact doses at the outside surface of the ORTEC chamber and contact doses inside the chamber (needed for the handling of the array together with the copper blocks were calculated). The estimates extracted from the detailed analysis are the following:

Following one hr of decay (upon completion of irradiation), the contact dose with the ORTEC chamber (polyurethane removed) is 6.7 mRem/hr.

For the same cooldown period of one hour, the contact dose of the copper blocks holding the array inside the chamber is 12.4 Rem/hr.

- After 24 hours of cool-down, the contact dose on the outside wall of the ORTEC chamber has fallen to 690 µRem/hr and the contact dose of the copper blocks to 1.36 Rem/hr.
- After one (1) week of cooldown the contact dose on the outside of the ORTEC chamber is estimated to be 170 µRem/hr and the contact dose on the copper blocks is 310 mRem/hr.
- After two weeks of cooldown, the contact dose on the outer face of the ORTEC chamber is 46 µRem/hr and on contact with the copper block holding the target array 92 mRem/hr

8. Additional Safety Requirements

N/A

9. Special Operating Instructions

Use and supply monitoring of the LN cooling the Copper blocks.

A Carbon/Carbon Composite block will be used downstream of the entire array with the role of auxiliary beam stop instrumented by a thermocouple that will be monitored during the experiment. The block will have dimensions of 12mm width, 24 mm thickness and 40 mm height.

Supporting Documentation	
References	
OPMs	19.2.22, 19.3.5.6, 19.3.5.7, 19.4.5.2, 19.4.5.3.
Drawings	

Appendix 1 – Proton Energy Profile

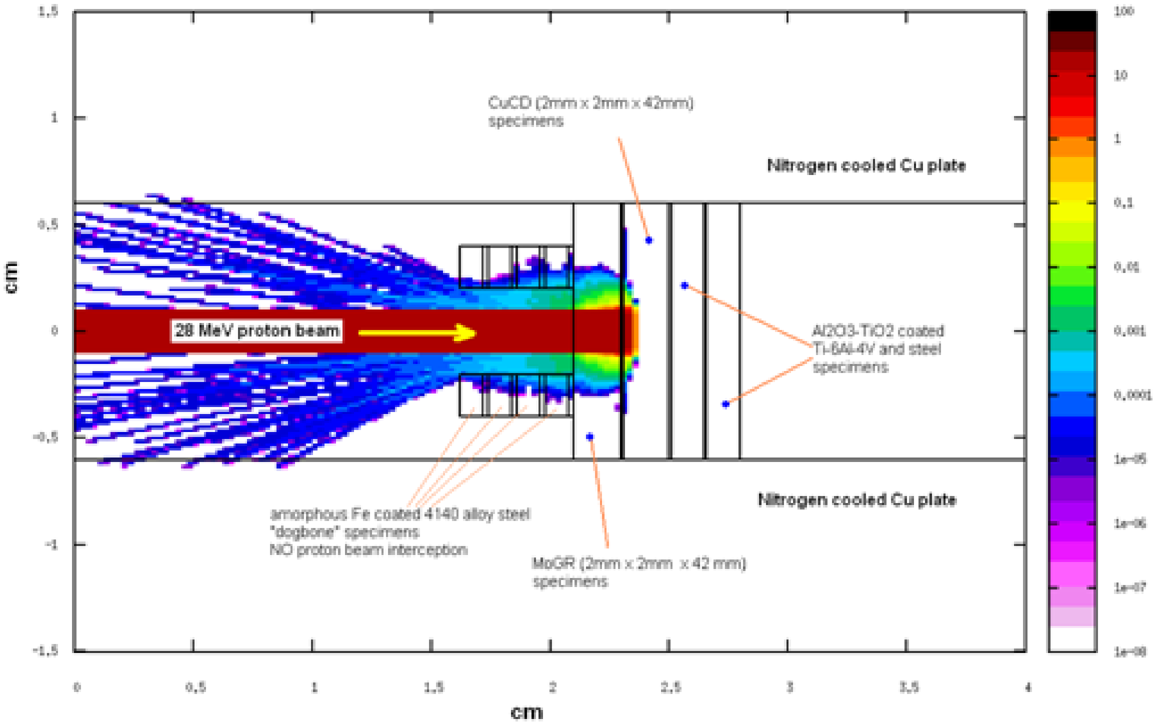

Figure A1.1: Proton energy profile as predicted by the FLUKA model. The analysis depicted in the figure shows that the 28 MeV protons will be fully arrested by the Cu-CD samples of layer 2 and in particular their upstream face

Appendix 2

Thermal analysis

Analysis Performed on Tandem Target Array based on estimated by FLUKA energy deposition estimates. The thermo-mechanical analysis was performed using the LS-DYNA Version 9.71 code along with the finite element meshing software TrueGrid Version 2.3.4. Analysis performed by N. Simos	Excerpt details of the comprehensive finite element analysis are attached in following pages.
Irradiation Experiment Conditions Tandem Beam Proton Energy: 28 MeV Linac Beam Current: 1 μA 100% beam on target array Thermal load removal from target array is provided by the Copper Holding blocks that keep the array together that are cooled by 70K L-Nitrogen supplied through a special channel through the block volume.	**Summary & Conclusions** The peak temperatures experienced by the 28 MeV intercepting target samples are ~ 506K under nominal conditions and ~800K for the most conservative scenario bothbsignificantly below the melting point of MoGrh and CuD which are the two material samples that will intercept and arrest the proton beam. The rest of the samples surrounding the proton-intercepting samples will experience very low energy depositions and the temperatures will remain low and in the 110K regime.

Thermo-Mechanical Analysis

This section contains excerpt results of a comprehensive finite element analysis. It depicts results for the vacuum degrader and for the Molybdenum target capsule which experiences the highest thermal loads. Analysis results of all target capsules are available and can be provided upon request.

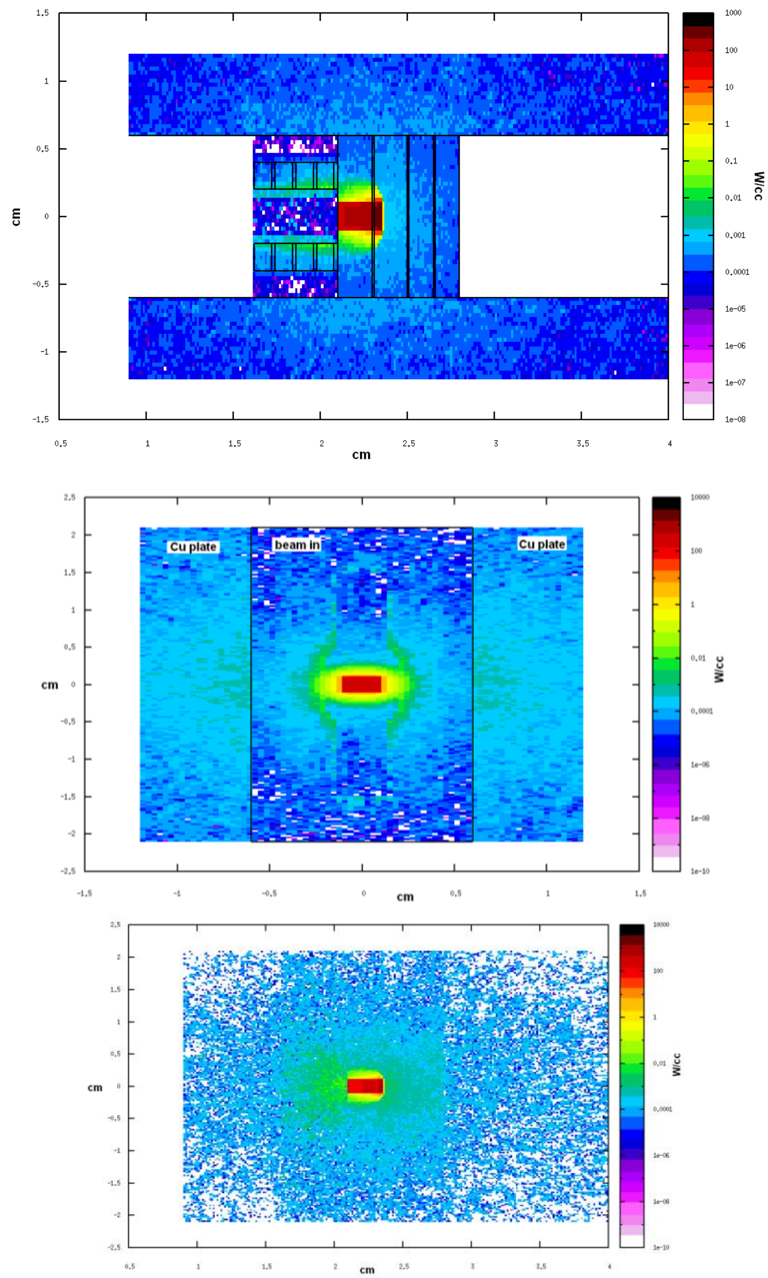

Figure A2.1: Energy deposited by the 28 MeV Tandem proton beam on the proposed array

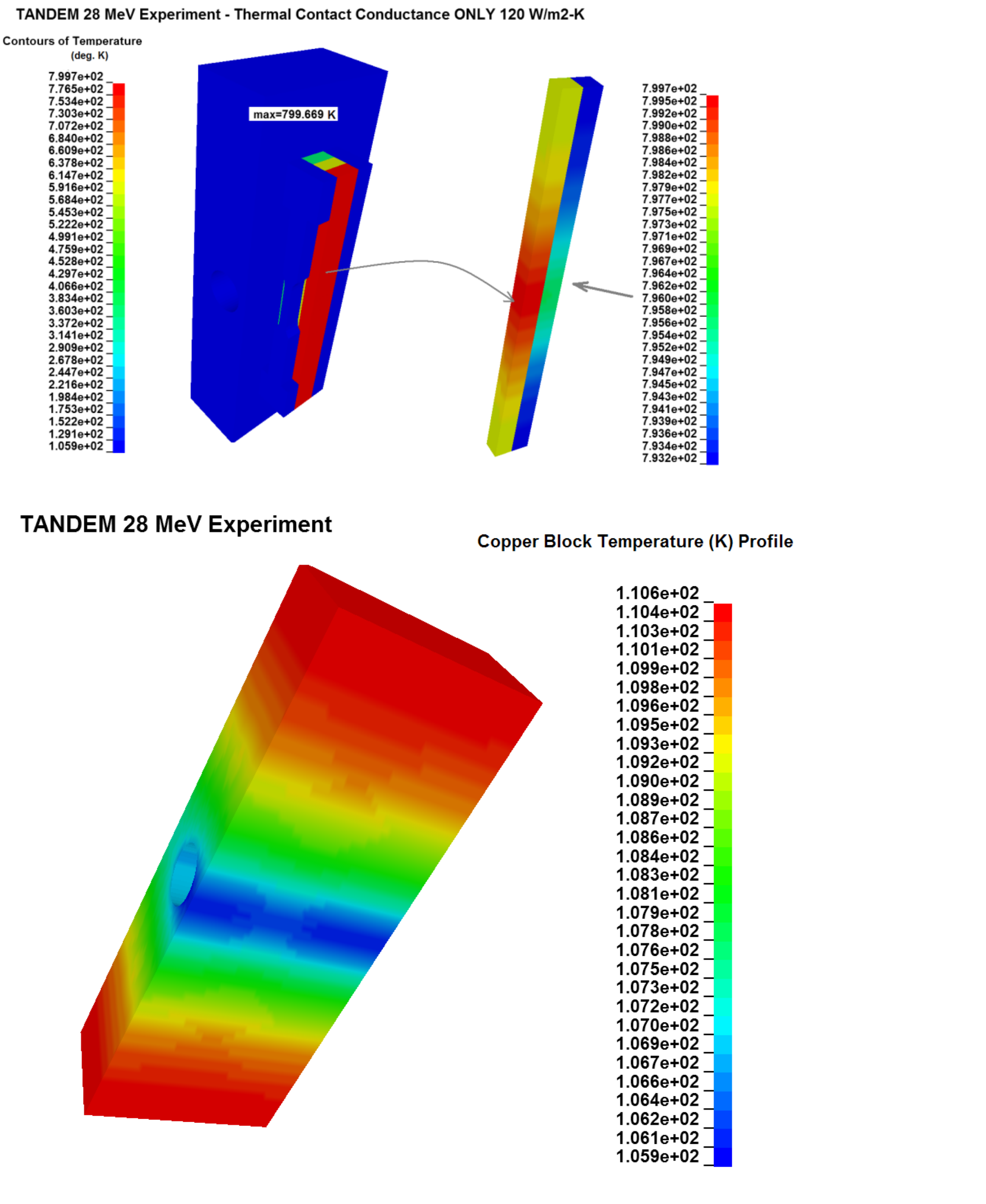

Figure A2.2: Thermal analysis results (temperature distribution) in the array and the copper blocks under the most pessimistic scenario of heat transfer across the contacting surfaces between the array samples and the copper block (120 W/cm^2-K of contact thermal conductance)

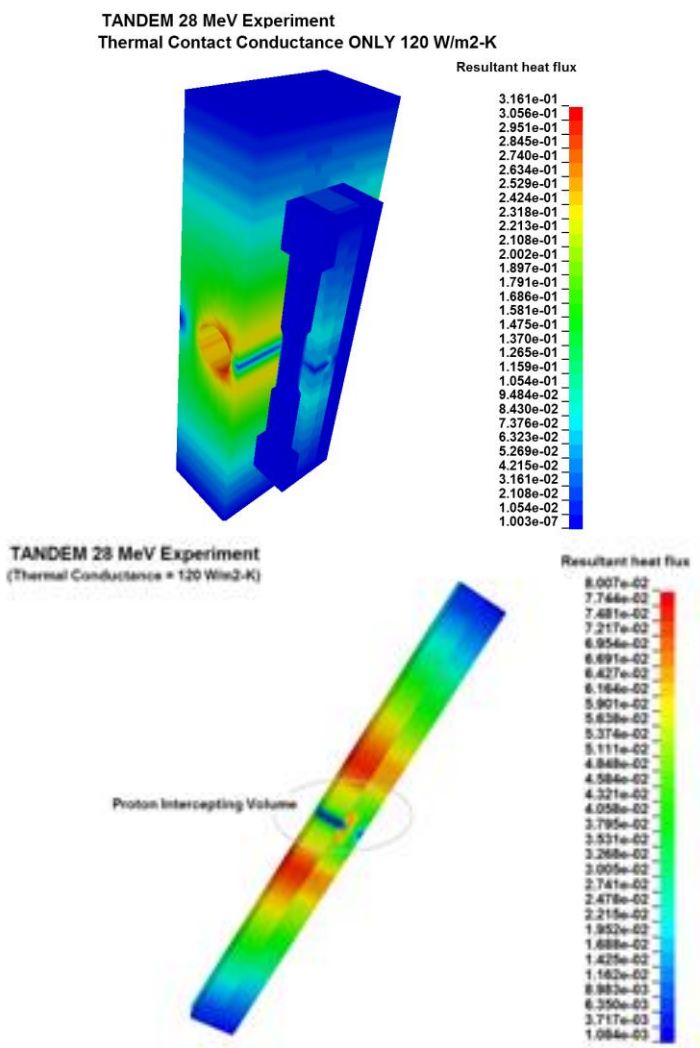

Figure A2.3: Thermal analysis results (heat flux) in the sample array and copper blocks

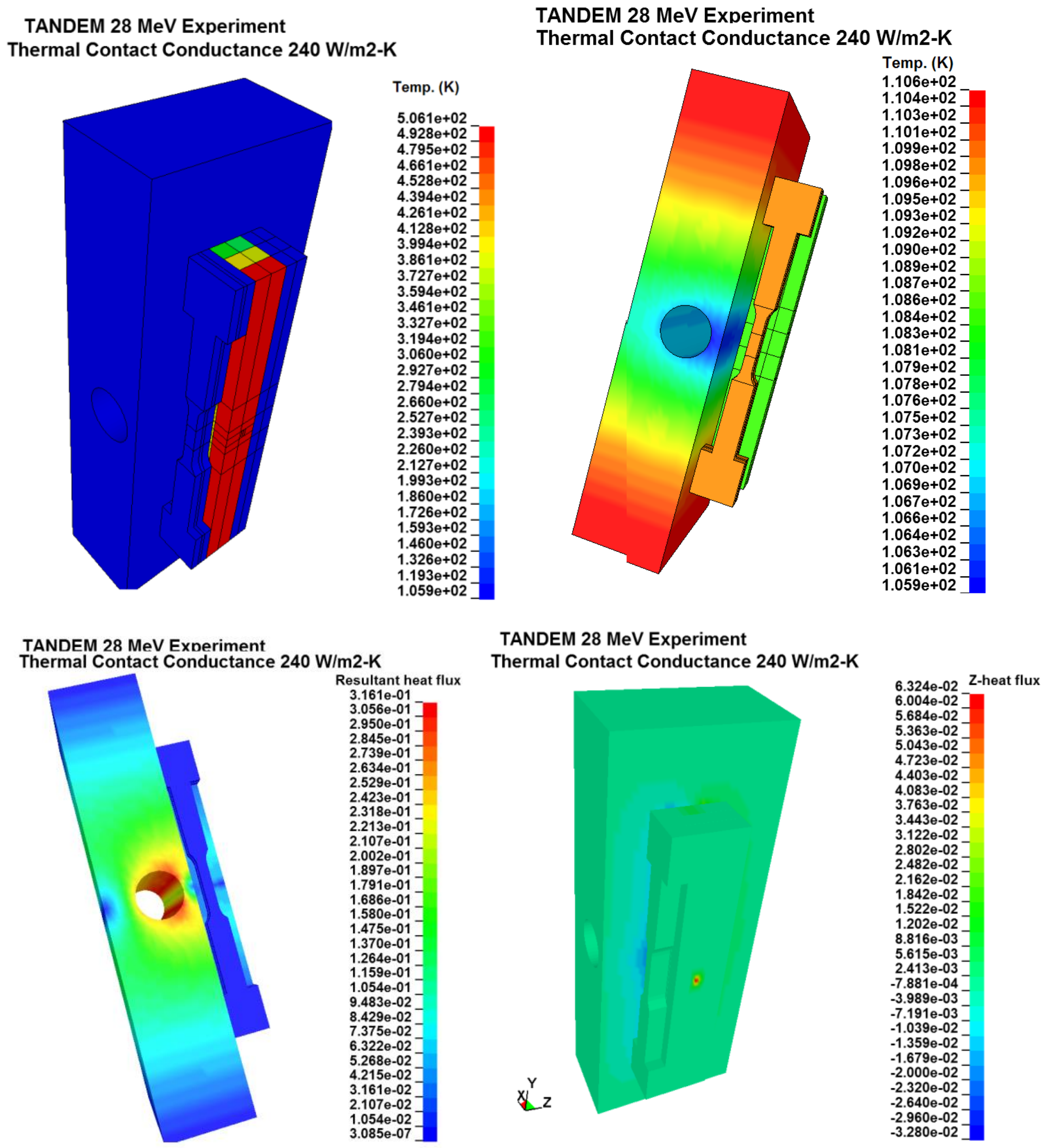

Figure A2.4: Thermal analysis results in the array and the copper blocks under a nominal scenario of heat transfer across the contacting surfaces between the array samples and the copper block (240 W/cm2-K of contact thermal conductance)

Appendix 3 - Dose and Activation analysis of Tandem Target Array using FLUKA code

Radionuclides and corresponding activities (and decay) were calculated using the FLUKA code through a detailed model that allowed the monitoring of activation per sample in the proposed array including the subsequent decay.

From the analysis the following has been deduced:

Only some of the samples in the array will show detectable activity. Because of the low proton energy and the concentration of the beam (2mm x 2mm) two specimens of the 1st layer (MoGR) and two specimens of the second layer (CuCD) will experience activation primarily from the protons. From the rest of the array, only the upstream dog-bone type specimens of 4140 steel with amorphous Fe coating show recordable activity that results from spallation products:

Specifically at **EOB** the following activity has been estimated (shown in parenthesis are contributing isotopes):

Mo-GR samples (proton intercepting): **48.3 mCi** (Be-7 3.3 μCi; B 11 16 mCi; Mo 91 4 mCi; Tc 93 3.8 mCi; Tc 94 3.721 mCi; Tc 95 2.18 mCi; Tc 96 0.753 mCi; Mo 99 0.16 mCi)

Cu-CD samples (proton intercepting): 4.3 mCi (Zn 65 7.2; Zn 63 3.98 mCi; Be-7 8 .0 μCi)

4140 Steel with amorphous Fe coating: 8.5 mCi (Co 55 0.9 mCi; Ni 57 0.316 mCi; Co 60 0.164 mCi; Mn 53 0.145 mCi)

Activity ONE WEEK following EOB:

Mo-GR samples: 0.405 mCi (Tc 96 0.256 mCi)

Cu-CD samples: 8 .0 μCi (mostly Be 7)

4140 Steel sample with amorphous Fe coating: 330 μCi

Appendix 4

Target Array Specimen Design & Post-Tandem Experiment Analysis

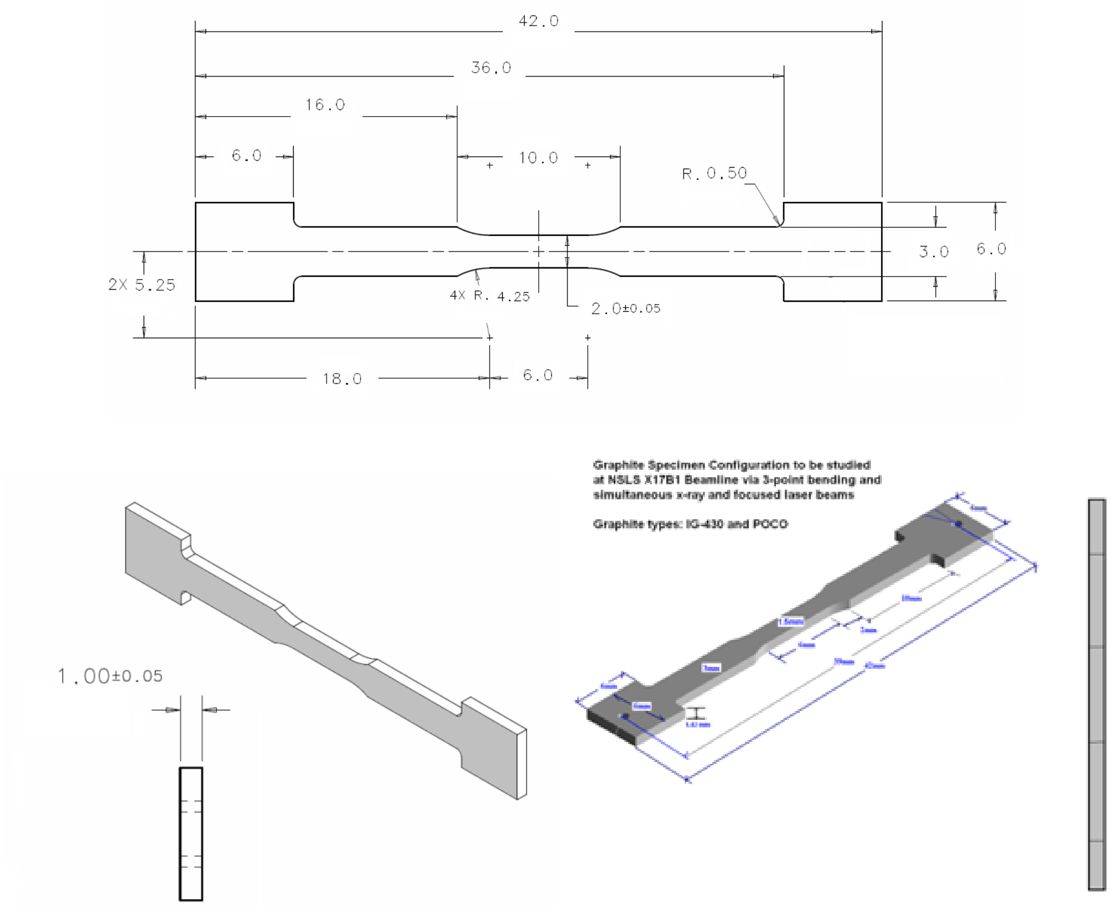

Figure A4.1: Design of dog-bone type of specimen used in the Tandem experiment array

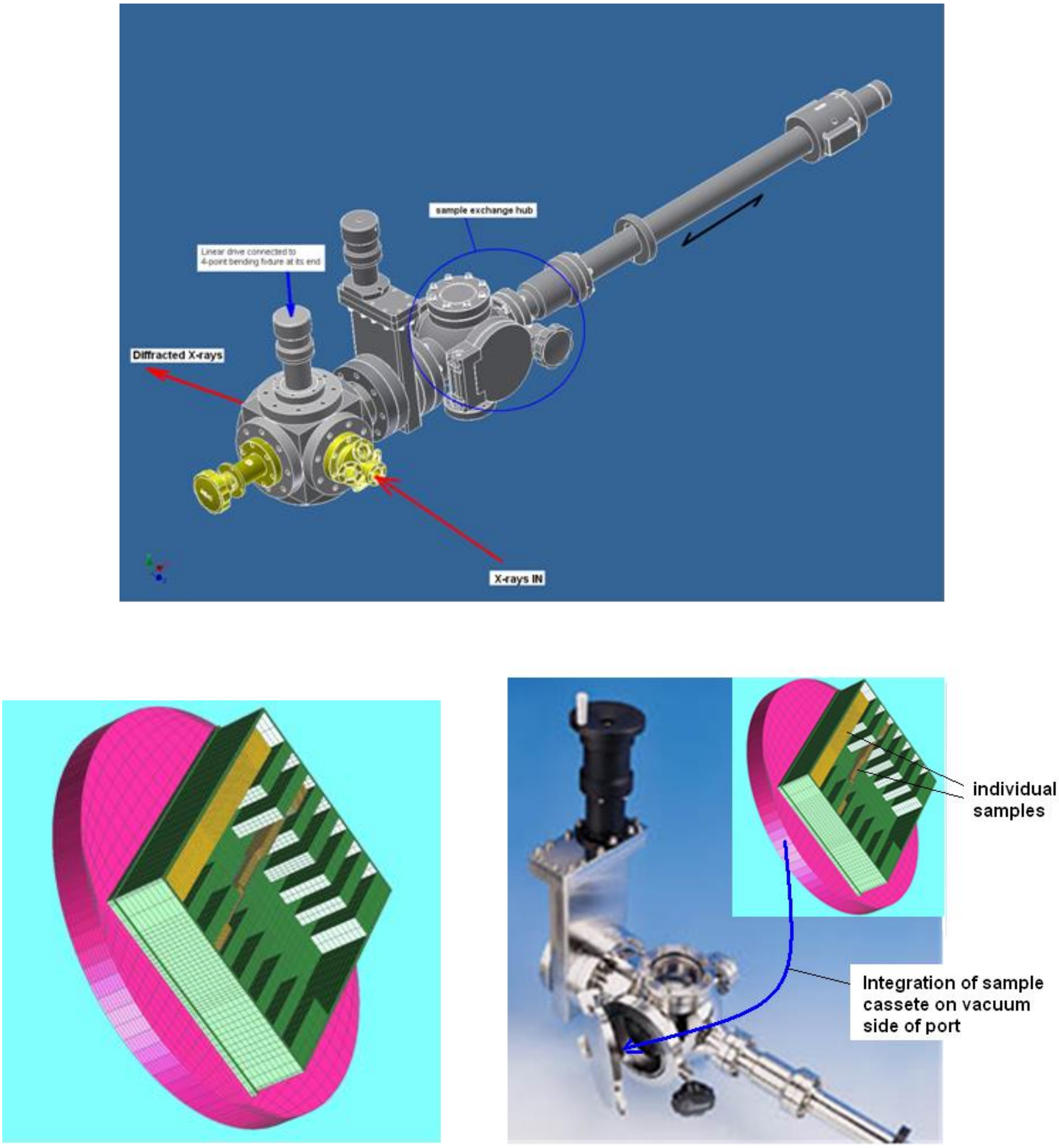

Figure A4.2: Post-Tandem experiment sample utilization for x-ray diffraction studies at NSLS via the integration with the special experiment stage (top) and with the use of the special sample cassette (bottom left) positioned within the vacuum volume of the stage (mounted on inner face of special port (bottom right)

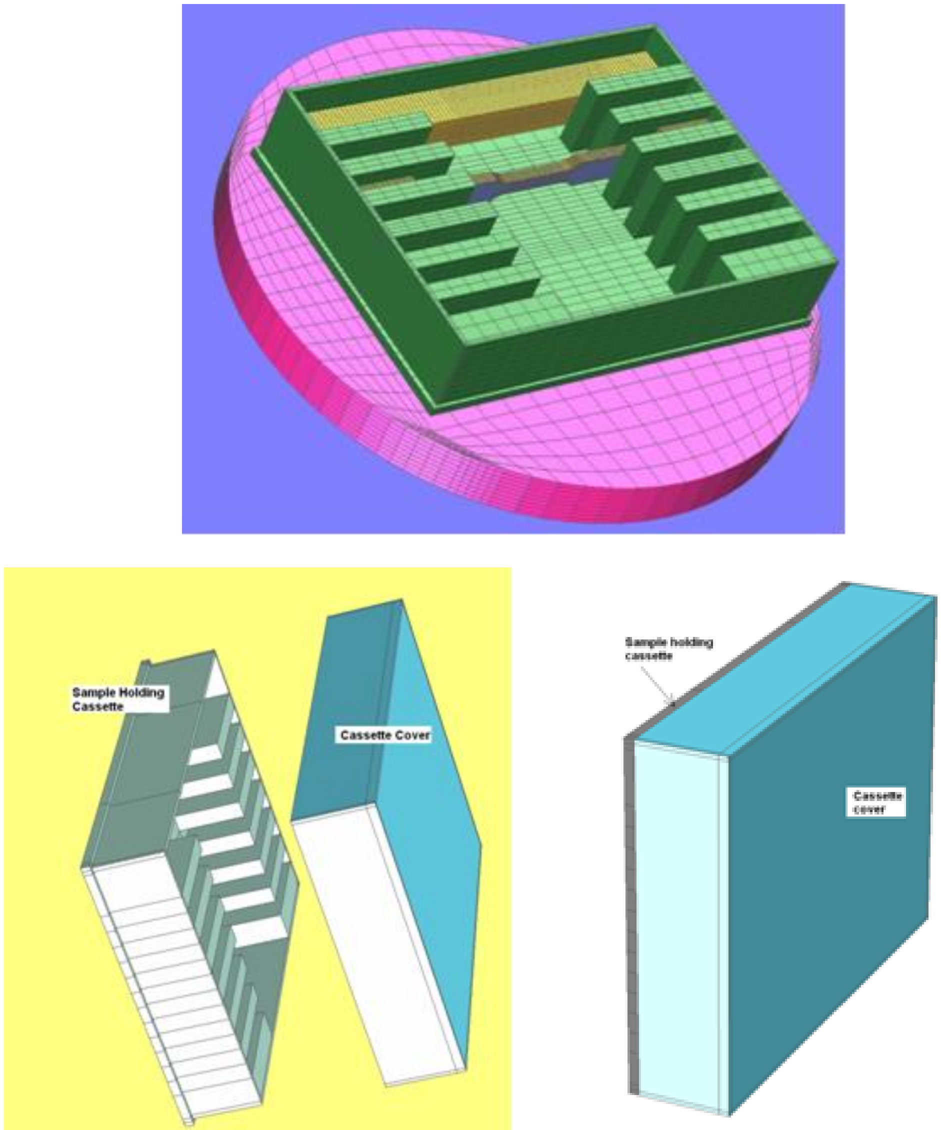

Figure A4.3: Multi-sample holding cassette and special cover providing additional safety envelope during transportation from Bldg 801 fume hood area to NSLS floor (X17B1 beamline hutch) and back upon completion of the diffraction experiment. Samples inserted in the appropriate positions in the cassette are encapsulated in Kapton tape, a process to be completed in Bldg 801 hot cell fume hood (Rm 66).