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

9.1.15.a BLIP Target and Canning Record

Hand Processed Changes

HPC No.	Date	Page Nos.	Initials

Approved: _____***Signature with Date on File***_____
Collider-Accelerator Department Chairman Date

D. Beavis, C. Cutler

Note 1: Uncontrolled copy printed from electronic master that is valid at time of printing. Always check that you have the latest revision of this document before use.

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

Title and Preparer
LHC Collimator Material Irradiation at 200 MeV and 160 MeV Linac Beam Energies N. Simos

Instructions

Description	Page No.
1. Overview [short summary of purpose of experiment; name of principle investigator and researcher involved]	4
2. Target Material and Properties – [Provide physical properties of each component/material to be irradiated]	5-9
3. Target Canning Process – [provide images or drawings and reference the OPM procedures for closing and opening of target can]	10
4. Beam Characteristics [define required beam on target and total current required]	11
5. Proposed Experiment [Provide general description of a) how target will be supplied BLIP, b) target array in box 1 and box 2; c) thermal analysis of target material and target can d) transport of irradiated target to TPL; target opening and processing at TPL and e) disposal of waste. List persons responsible for conducting each task. If others are required to assist in the research irradiation, define level of skill of staff and contact time.]	12
a. Procedure for Irradiation of Target Material BLIP [Summarize steps for experiment including specialist and contact hours required for task]	12
b. Target Array [Define proposed target array for box 1 and box 2 including SRIM calculated entry and exit energy for each layer. Provide physical dimension of degraders, target can, materials and water gaps]	12
c. Thermal Analysis of Target Materials and Target Can [Provide full description of data provide to specialist for calculations and any	12

	assumption made on material for calculations]	
	d. Transport and Processing at TPL [Provide full description of task involved and responsible persons and contact hours required]	12
	e. Disposal of waste. [describe waste to be generated and how it will be disposed of]	12
6.	**Activation Analysis of Target Material and Can** [Provide full list of radionuclide produced and quantities, references used for calculations, as well as decay profiles if the dose rates exceed limit for removal from BLIP hot-cell. Ensure Health Physics has reviewed data and confirms decay requirement if they are dose related. Attach analyses if any.]	13
	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 BLIP and expected dose rate when delivered to TPL]	
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]	n/a
9.	**Special Operating Instructions and List of References or Supporting Documents**	n/a
10.	**Appendix** [provide additional support information as required]	26-58

1. Overview

This experiment is a follow-up irradiation damage study of materials considered for the collimation of the High Luminosity Upgrade of the LHC.

Newly developed grades of the compound Mo-Graphite (MoGR) will be irradiated and analysed in post-irradiation analysis to assess their vulnerability to proton beams and their resilience to damage. MoGR compound exhibits excellent beam impedance properties.

During the recent 200 MeV irradiation at BLIP (2013 and 2014 RUNS) a different grade of MoGR along with other novel materials (Copper-Diamond, Glidcop and Molybdenum) was irradiated to high fluence (>5 10^{20} protons/cm2). Because of the poor performance of the particular grade of MoGR under very high fluence, the two newly developed grades with lesser Molybdenum content are to be irradiated at lower fluences given that these materials are not expected to experience this level of fluence during LHC operation. Along with the MoGR a special graphite grade AC140K which was tested at BLIP back in 2006 also to high fluence will be irradiated with the MoGR compound.

The irradiation will take place in two (2) phases, one at 200 MeV and the second at 160 MeV. The two irradiation phases may take place with either order depending on beam and schedule availability. The irradiation at 200 MeV proton beam at 150 uA will occur simultaneously with the Thorium irradiation that is planned to occur in two 6-day intervals. During the 200-MeV irradiation Thorium foil will occupy the first position in Box 1 and the LHC array will occupy position 2 through 7. Six MoGR target capsules and one CFC graphite capsule will line up behind the Thorium foil target.

After completion of the 200 MeV irradiation which is expected to take place in two 6-day long intervals the second phase (Phase II) of the irradiation will commence. This irradiation phase will utilize 160 MeV protons from the Linac, and will only involve four (4) MoGR capsules and a new degrader appropriate for the array configuration. Specifically, four MoGR target capsules will be followed by a vacuum degrader that ensure both beam energy degradation and water column in the beam path (total water channel width), This irradiation is expected to last three weeks with beam current at 150 uA.

For both irradiation phases there will be no effect on the isotope production downstream.

Following irradiation at BLIP and cooling time sufficient for transport to Building 801 hot cells, the target array will be transported to the TPL hot cells by standard procedures. In the hot cell the target capsules will be opened, the enclosed specimens will be removed.

Of primary interest for the 200-MeV proton irradiation and for fluences reaching 1.0 10^{20} p/cm^2 will be the changes induced on key physio-mechanical properties that include (a) resistivity, (b) thermal conductivity, (c) dimensional changes and thermal expansion, (d) stress-strain behaviour and ductility loss and (e) thermal annealing characteristics, all crucial parameters for the LHC collimation operation. The comprehensive post-irradiation analyses will be conducted at the BNL Hot Material Test Facility that is equipped with the appropriate instrumentation and facilities to extract radiation damage information from the proposed material array.

Target Capsules #1 – #6 Molybdenum-Graphite			
Target Name:	*MoGr_LHC*	**Target & Canning No.** *Assign unique no*. (2016-001)	

Target Material Properties (Molybdenum-Graphite)				
Purity or Grade	99.5%			
Chemical Formula	Mo-GR			
Physical Characteristics at 70 ^{o}F or 21 ^{o}C	**Grey to black metal, odorless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**2.375/60.325**	**Pressed (Torr)**	**n/a**
Elements (%)	**Mo 13.215%, 86.785% Carbon**			
Melting Point	**2505**	**^{o}C**		**^{o}F**
Boiling Point		**^{o}C**		**^{o}F**
Thermal Conductivity	**320 W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**	
Density	**2.5187 g/cm3**		**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**

Canning Material Properties				
Chemical Formula	**304 Stainless Steel**			
Can Wall Thickness (inches/mm)	**0.012/0.3048**			
Can Dimensions (inches/mm)	**Can Diameter 2.75/69.9 Can Width 0.1815/4.6096**			
Melting Point	**1424**	**^{o}C**	**2600**	**^{o}F**
Thermal Conductivity	**16.2 W.m^{-1}.K^{-1}**	**Temperature dependence**	*(if available)* **16.2@100^{0}C, 21.4@500^{0}C**	
Density	**8**	**g/cm^{3}**		
Specific Heat	**500**		**J/kg.K**	

Target Capsule #7: CFC Graphite			
Target Name:	*CFC Graphite*	**Target & Canning No.** *Assign unique no*. (2016-002)	

Target Material Properties (CFC)				
Purity or Grade	99.5%			
Chemical Formula	Carbon-Fiber-Composite (graphite) plus 440 stainless steel layer			
Physical Characteristics at 70 ^{o}F or 21 ^{o}C	**Grey to black metal, odorless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**2.375/60.325**	**Pressed (Torr)**	**n/a**
Elements (%)	**Graphite (99.458%), Boron (0.0932%)**			
Melting Point	**1083**	**^{o}C**		**^{o}F**
Boiling Point		**^{o}C**		**^{o}F**
Thermal Conductivity	**490 W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**	
Density	**1.67**		**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**

Canning Material Properties				
Chemical Formula	**304 Stainless**			
Can Wall Thickness (inches/mm)	**0.012/0.3048**			
Can Dimensions (inches/mm)	**Can Diameter 2.75/69.9 Can Width 0.1815/4.6096**			
Melting Point	**1424**	**^{o}C**	**2600**	**^{o}F**
Thermal Conductivity	**16.2 W.m^{-1}.K^{-1}**	**Temperature dependence**	*(if available)* **16.2@100^{0}C, 21.4@500^{0}C**	
Density	**8.0**	**g/cm^{3}**		
Specific Heat	**500**		**J/kg.K**	

PHASE II

Target Capsule #1 – #4 Molybdenum-Graphite			
Target Name:	*MoGr_LHC*	**Target & Canning No.** *Assign unique no*. (2016-001a)	

Target Material Properties (Molybdenum-Graphite)				
Purity or Grade	99.5%			
Chemical Formula	Mo-GR			
Physical Characteristics at 70 ^{o}F or 21 ^{o}C	**Grey to black metal, odorless, tasteless**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**2.375/60.325**	**Pressed (Torr)**	**n/a**
Elements (%)	**Mo 13.215%, 86.785% Carbon**			
Melting Point	**2505**	**^{o}C**		**^{o}F**
Boiling Point		**^{o}C**		**^{o}F**
Thermal Conductivity	**320 W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* n/a**	
Density	**2.5187 g/cm3**		**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**

Canning Material Properties				
Chemical Formula	**304 Stainless Steel**			
Can Wall Thickness (inches/mm)	**0.012/0.3048**			
Can Dimensions (inches/mm)	**Can Diameter 2.75/69.9 Can Width 0.1815/4.6096**			
Melting Point	**1424**	**^{o}C**	**2600**	**^{o}F**
Thermal Conductivity	**16.2 W.m^{-1}.K^{-1}**	**Temperature dependence**	*(if available)* **16.2@100^{0}C, 21.4@500^{0}C**	
Density	**8**	**g/cm^{3}**		
Specific Heat	**500**		**J/kg.K**	

Target Capsule #8: Vacuum Degrader			
Target Name:	*Degrader_160MeV*	**Target & Canning No.** *Assign unique no*. (2016-003)	

Target Material Properties (N/A)				
Purity or Grade	99.5%			
Chemical Formula				
Physical Characteristics at 70 ^{o}F or 21 ^{o}C	**VACUUM**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**2.375/60.325**	**Pressed (Torr)**	**n/a**
Elements (%)	**N/A**			
Melting Point		**^{o}C**		**^{o}F**
Boiling Point		**^{o}C**		**^{o}F**
Thermal Conductivity		**Temperature dependence**	***(if available)* n/a**	
Density			**g/cm^3**	
Specific Heat			**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**

Canning Material Properties				
Chemical Formula	**304 Stainless**			
Can Wall Thickness (inches/mm)	**0.035/0.889**			
Can Dimensions (inches/mm)	**Can Diameter 2.75/69.9 Can Width 1.728/43.91**			
Melting Point	**1424**	**^{o}C**	**2600**	**^{o}F**
Thermal Conductivity	**16.2 W.m^{-1}.K^{-1}**	**Temperature dependence**	*(if available)* **16.2@100^{0}C, 21.4@500^{0}C**	
Density	**8.0**	**g/cm^3**		
Specific Heat	**500**		**J/kg.K**	

3. Target Canning Process

Blueprints: attached

General considerations:

The target capsules or cans containing the Mo-GR compound and CFC graphite materials are made with 304 stainless steel and it are identical in design with the target cans used for the rubidium chloride targets.

It consists of three parts, the outer rim and the two windows which are welded under vacuum at the outside company EB Industries used for all the isotope-producing target fabrication.

The windows are 0.012" (0.3048mm) thick each and the inside width of the target capsule varies between 0.1575" for all the six the MoGR target capsules to 0.46304" for the CFC graphite containing capsule.

Mo-GR capsules (6 total for 200 MeV Irradiation, 4 total for 160 MeV irradiation):

Can Outside Diameter (in/mm): 2.75/69.9

Can Inside Diameter (in/mm): 2.375/60.325

4mm Can Width (in/mm): 0.1815/4.6096

CFC Graphite capsule (1 total for 200 MeV Irradiation):

Can Outside Diameter (in/mm): 2.75/69.9

Can Inside Diameter (in/mm): 2.375/60.325

13mm Can Width (in/mm): 0.5/12.7

Canning Process:

1. The back window of the target capsule is welded onto the capsule rim
2. The solid specimens of each target material type are arranged in a tight and specific arrangement (see attached Figure) within the volume of the capsule
3. The target capsule containing the target material is sent to the vendor (EB Industries) where the front window is welded under vacuum.
4. Vacuum leak tests are performed at the vendor prior to being shipped back to BNL and also at the BNL shops upon arrival.

   The fabricated and leak checked target capsules are given to the BLIP staff along with instructions of the layout into the irradiation target box. The layout of the array is based on precise proton beam degradation calculations.

4. Beam Characteristics		
Maximum Instantaneous Current Desired	**40**	**mA**
Average Current Desired	**115-150**	**µA**
Total Integrated Current Desired	**40,000 (200 MeV)** **40,000 (160 MeV)**	**µA - hrs**
Maximum Proton Energy on Target Material	**185 (200 MeV irradiation)** **155 (160 MeV irradiation)**	**MeV**
5. Experiment Description		

5.a Procedure for irradiation of target material in BLIP:

BLIP staff shall install and remove target array and degraders in BLIP, as per CAD OPM 19.4.5.2. Irradiations are planned for three ~8-day segments at 200 MeV energy to achieve 20,000µAh during each exposure. After EOB at 200 MeV raise the array into the hot cell, remove the Thorium foil and store the array inside the BLIP hot cell storage box. At the end of the 2nd 200-MeV exposure and during the removal of the Thorium foil, remove MoGR capsules #5 and #6 and the CFC graphite capsule (shown in Figure 5.1) and insert the 160-MeV vacuum degrader shown in Figure 5.2. The remaining four (4) MoGR capsules and the 160-MeV degrader constitute the 160 MeV irradiation array. Install the array into beam for ~3-week irradiation at 160 MeV (the duration of the 160-MeV irradiation will be influenced by the accumulated beam current during the 3-stage 200 MeV irradiation). Upon EOB disassemble array and move degrader to storage.

5.b Target array in Box 1 (upstream) and Box 2 (downstream):

- **200 MeV Irradiation:** Thorium target (position 1), MoGR (positions 2-7), CFC graphite (position 8) in Box 1, cGMP approved RbCl array in Box 2 with 0.220 inch Cu beamstop
- **160 MeV Irradiation:** MoGR (positions 1-4), 160-MeV degrader (position 5) in Box 1, cGMP approved RbCl array in Box 2 with 0.220 inch Cu beamstop

See **Appendix 1** for details of energy loss in these arrays.

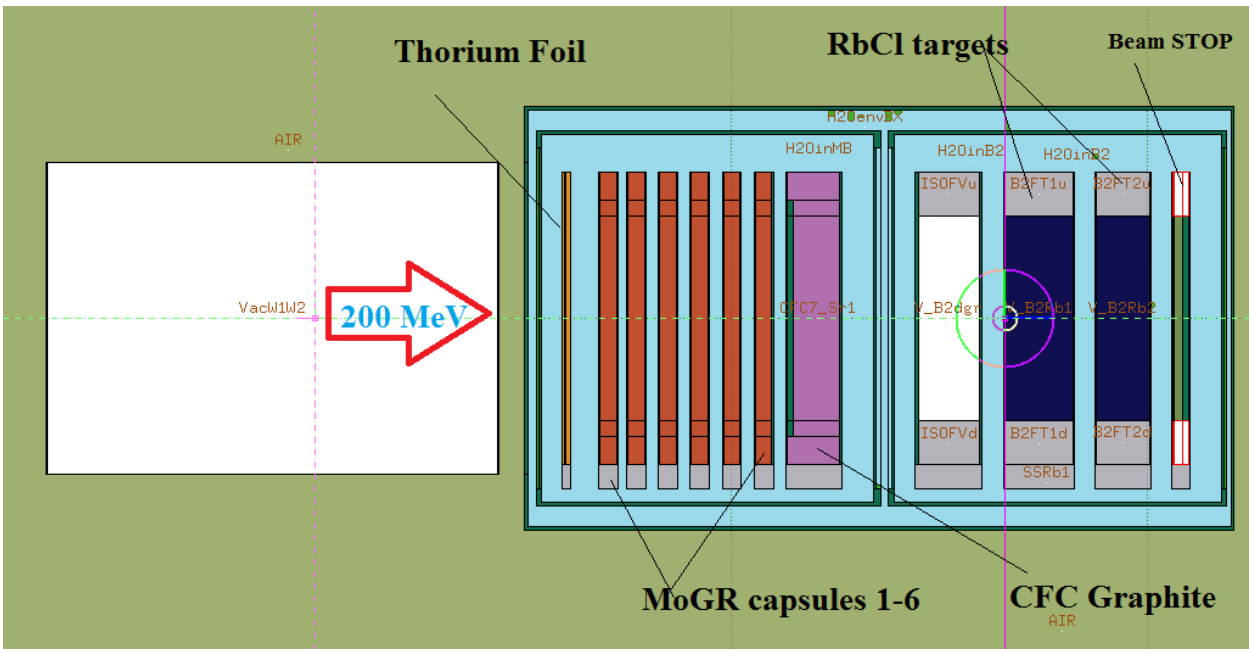


Figure 5.1: 200 MeV irradiation configuration

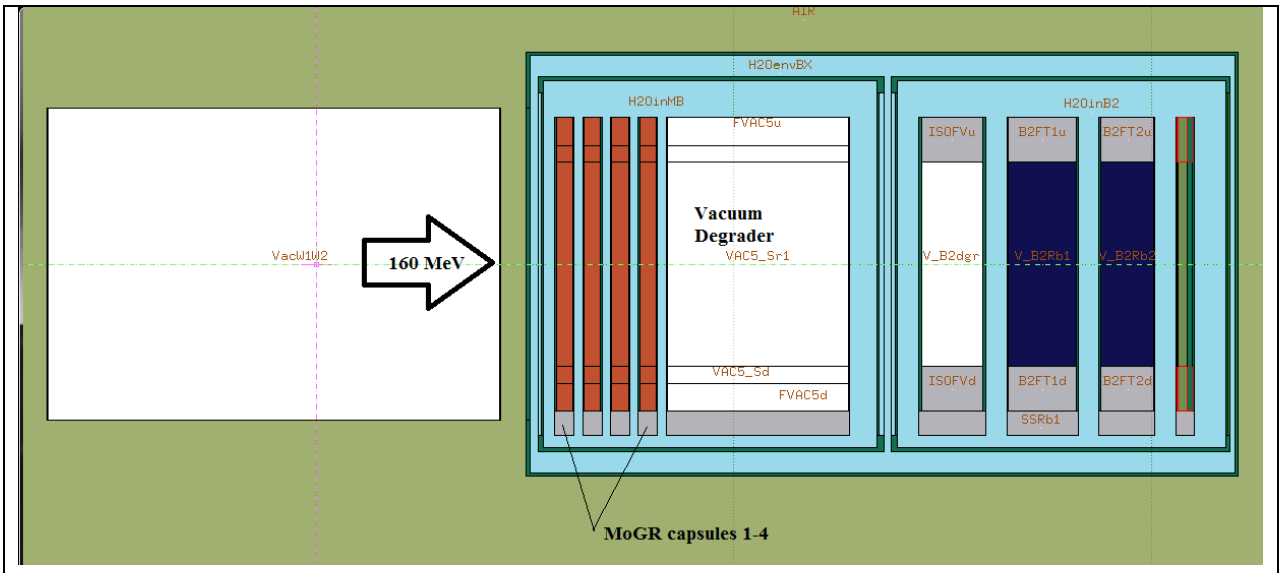


Figure 5.2: 160 MeV irradiation configuration

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

See Appendix 2. No issues.

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

Following irradiation the target capsules will be transported to the TPL hot cells by BLIP staff as per CAD OPM 19.4.5.3. MoGR, CFC and 200-MeV Degrader will be transferred to TPL upon the completion of the 200-MeV irradiation. The four (4) MoGR target capsules that will be irradiated with the 160 MeV in addition to 200 MeV (Phase II) will be transferred to TPL at EOB of the 160 MeV irradiation following an estimated 7-8 day decay period within the storage box of the BLIP hot cell.

The 160-MeV beam degrader will remain at BLIP to be available for use in future experiments.

Detailed dose and activity calculations encompassing the irradiation schedule, the decay within the BLIP hot cell and the transport (including the transport container between BLIP and TPL hot cells) have been conducted. The performance of the neutronic analysis model being utilized for dose and activation has been verified during a recent irradiation at BLIP via a blind test with excellent agreement between measurements and predictions.

Shipping target capsules to TPL with the special shipping containers (pigs) will be performed by TPL staff. Dose measurements at cask exterior will be measured. Store containers in storage vault until the exterior contact dose is <200mR/h.

5.e Disposal of waste:

Inconel 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

Activation of the two LHC target array configurations (one for the 200-MeV irradiation and one for the 160-MeV irradiation) has been performed. The first array configuration consists of (a) six MoGR capsules,

and (b) one CFC graphite capsule.

The second array configuration (160-MeV array) consists of (a) four MoGR capsules and the 160- MeV degrader (0.012" thick stainless 304 windows). MCNPX and FLUKA codes have been employed for the activation analyses. The MCNPX code, in conjunction with the CINDER90 library, produced activities and isotopes for a continuous irradiation at 200 MeV encompassing the three exposures at BLIP at the 200-MeV energy.

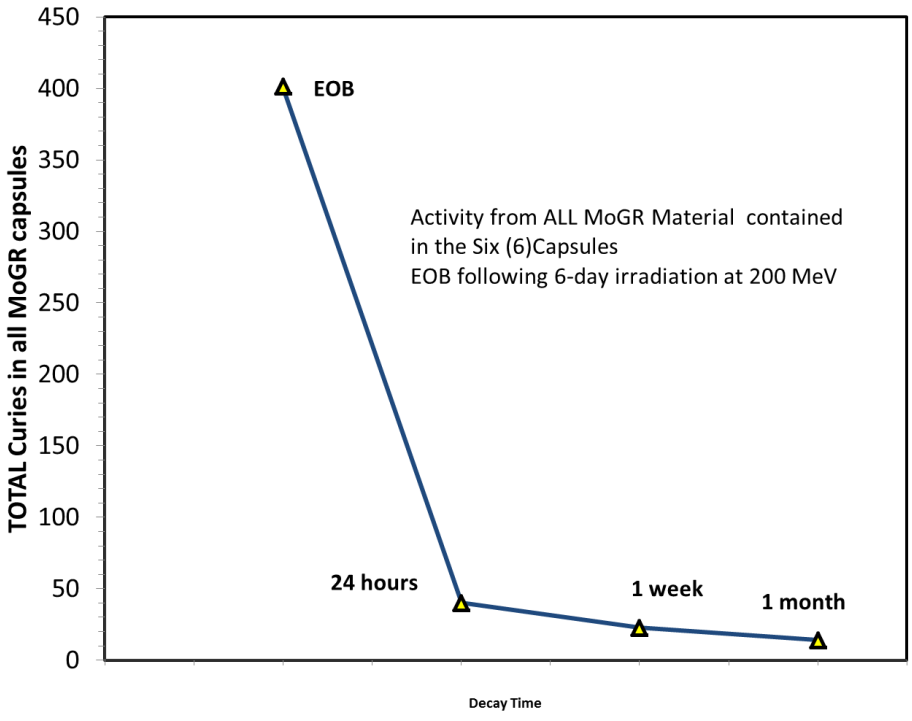
Shown in Figures 6.1 (a,b,c) is the activity decay with time after a 6-day 200 MeV irradiation interval. They depict TOTAL activity in the different materials. Specifically, Fig. 6.1a shows the generated activity in the contents of the first six capsules that contain Mo-GR. Figure 6.1b depicts the total activity in the CFC graphite of capsule 7 and Fig. 6.1c accumulates all the activity from the 304 stainless steel beam windows of the capsules and degrader.

Specifically, at EOB of 6-day bombardment at 200 MeV of the array consisting of 6 MoGR capsules and one CFC graphite capsule the total radioactivity in the array is **601 Ci** in total. The total activity considers (a) the contents of the six MoGR capsules, (b) the contents of the CFC graphite capsule and (c) the activation of the 14 capsules made of 304 stainless. For the latter, the activation of the capsule is contributed almost entirely by the capsule beam windows.

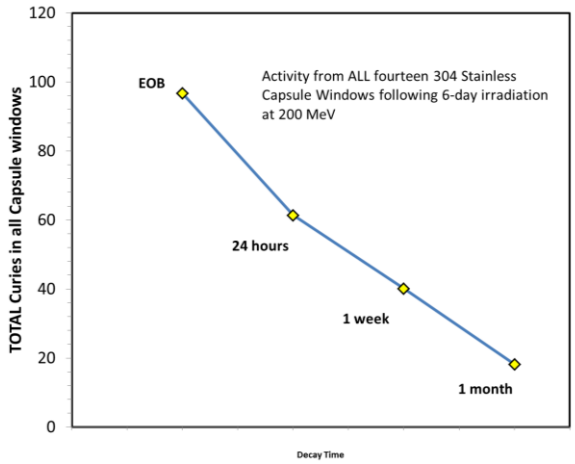
After a week of decay the radioactivity drops to **59.54 Ci** total.

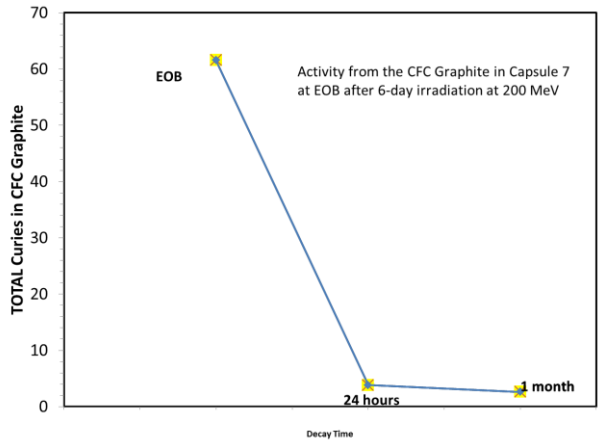
After a month-long decay the radioactivity in the target capsules drops to **15 Ci** total.

More details on the isotopic composition and the corresponding activity for different times during the irradiation segments are provided in detail in Appendix A3



(a)





(b) (c)

Figure 6.1: Generated activity and its evolution with time during the Phase I irradiation following a 6-day long segments at 200 MeV and 150 uA beam

Decay Requirements

Decay at BLIP will be based on the shielding capabilities of the transport pig for transfer to Bldg. 801 Hot Cells.

7. Expected Dose Rate

Dose calculations were performed using FLUKA. During a recent 200-MeV irradiation at BLIP the performance of the model generated to predict dose and activities was verified via a blind test performed at BLIP. The agreement between the predictions and the actual measurements were within 1-2%.

The FLUKA-based calculations considered the exact irradiation pattern for the 200-MeV irradiation segments (3) and the 3-week irradiation at 160 MeV.

Specifically, two 200-MeV irradiation segments of ~6 day duration each are considered separated by ~6-week decay time assuming 150 uA beam. The activity generated and the dose EOB of each irradiation segment as well as its decay is computed taking into account the exact geometry of the BLIP hot cell structure. While dose at 3 feet from the array irradiated in three intervals at 200 MeV is observed for decay (distance of 3 feet assumed inside the BLIP hot cell wall), predictions were made for locations outside the hot cell walls where operators stand. The BLIP hot cell walls include the Pb core and 0.25" lining on either surface. The predictions of dose OUTSIDE the hot cell walls for the irradiation pattern are that there is no recordable dose at the operator locations and so there are NO CONCERNS.

In addition to capturing the irradiation pattern and the resulting dose at BLIP a special model was generated and run that simulates transportation of the irradiated array at the end of Phase II irradiation (160 MeV). Similarly, and based on model verification during the transport of irradiated targets in a recent 200 MeV irradiation, the results indicate that using the 12" thick wall transport pig that is also lined with steel in and out there is no recordable dose outside the transport system.

The following figures describe the results of the complete irradiation pattern in terms of dose while at BLIP and during transport.

7.1 PHASE I – 200 MeV Irradiation (Two 6-day long segments at 150 uA)

In this section the dose rates at (a) 3 feet from the irradiated array after EOB, (b) outside the BLIP hot cell where operators stand to manipulate the array and (c) outside the transport pig that is used to transfer irradiated targets from BLIP to TPL are computed. The 3-foot distance calculations assumed that the irradiated array is located inside the BLIP hot cell. By implementing the shielding geometry of the BLIP hot cell, it is deduced that there is NO added dose outside the hot cell for both irradiation phases, 200 MeV and 160 MeV. This is demonstrated in the following Figures that resulted from a 3D FLUKA analysis.

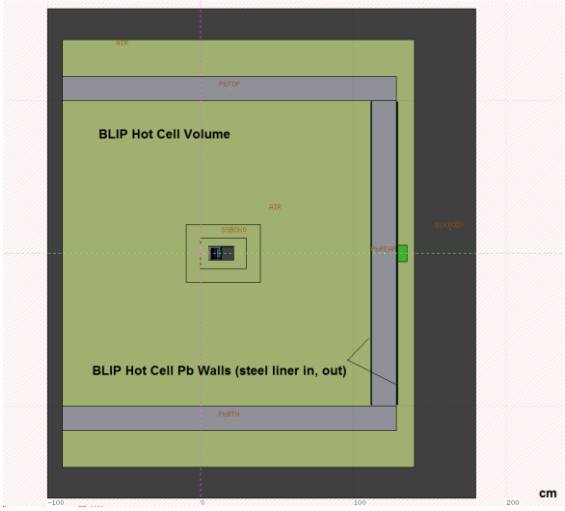


Figure 7.1: Description of the implemented 3D model for decay analysis of the irradiated array at BLIP. The model incorporates the array of Box 1 following irradiation and computes the dose while inside the BLIP hot cell. The Thorium foil irradiated in the first position of the array is removed as well as the cooling water volume during decay and so is the entire volume of Box 2 containing the isotope targets

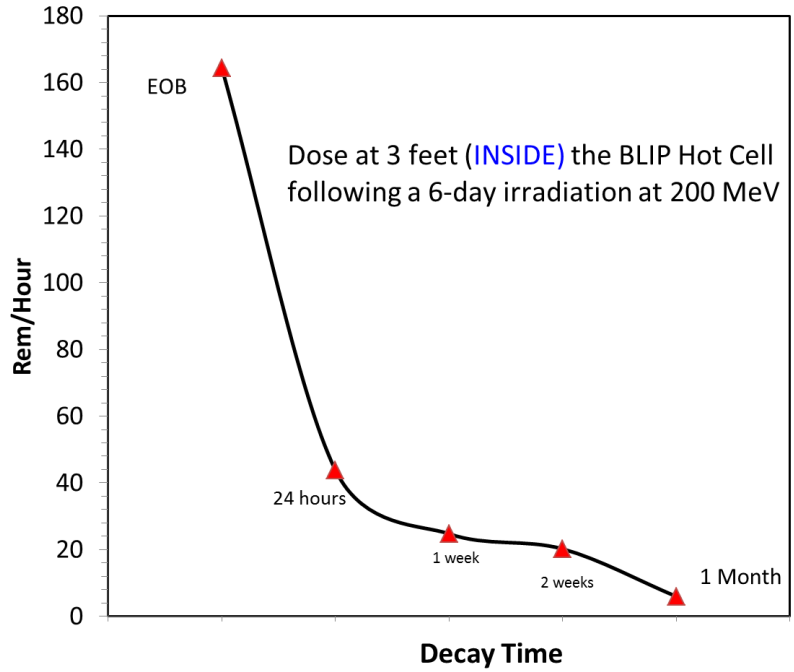
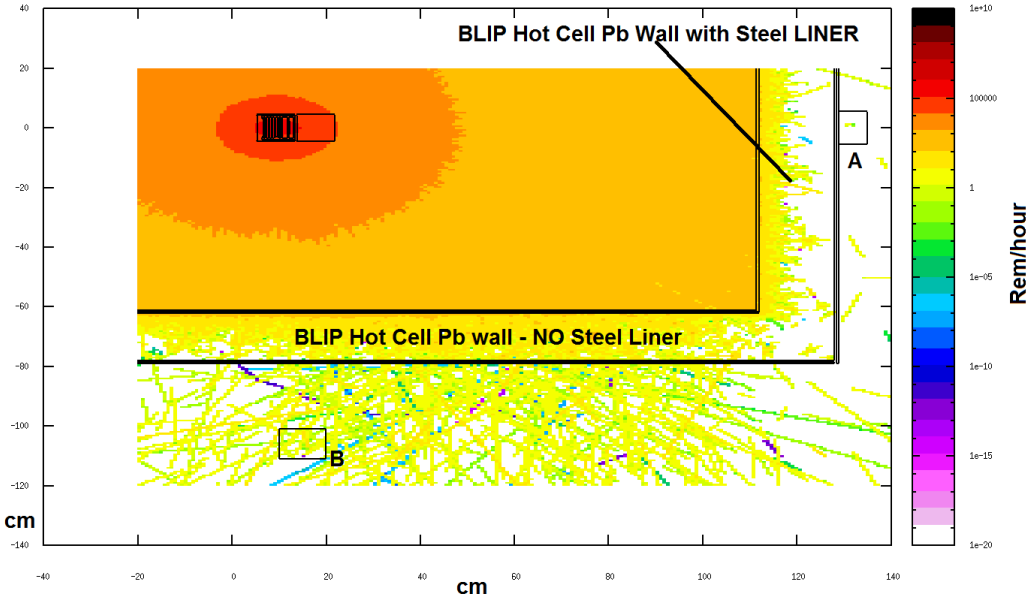


Figure 7.2: Dose evolution with time from the irradiated array at 200 MeV for six days at a distance of 3 feet. NO DETECTABLE dose can be seen outside the BLIB hot cell wall



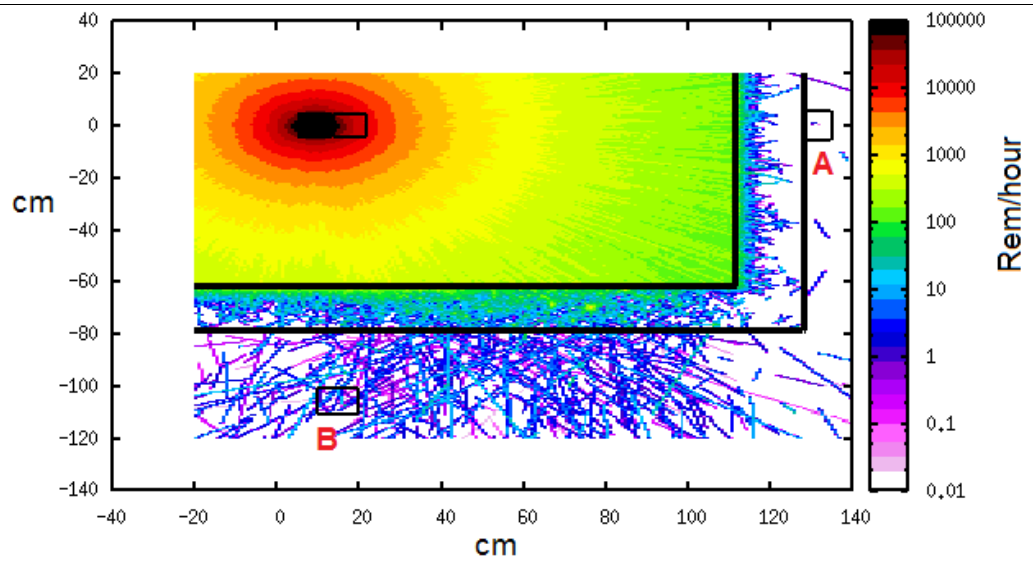


Figure 7.3: Dose profile inside and outside the BLIP hot cell at EOB following the first 200-MeV 6-day irradiation alongside the Thorium foil. Location A is the most representative because of the consideration of steel liner on both sides of the Pb wall at that location. The Thorium foil and its activity are not included in these dose calculations. It has been assumed that the Th foil is removed and the target array remains within the BLIP Hot Cell awaiting the 2nd 200-MeV irradiation. The model incorporates the BLIP Hot Cell walls (Pb) and also the inner and outer steel liners (the forward wall) while the side wall only assume Pb. This was done to evaluate the effectiveness of the steel liner in a single analysis. Location A and B noted represent detector locations where BLIP operators assume to stand outside the hot cell wall.

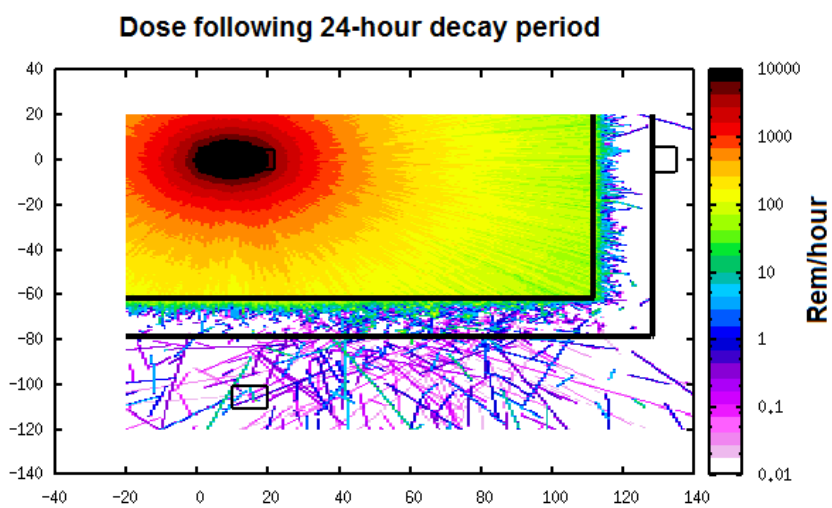


Figure 7.4: Dose profile inside and outside the BLIP hot cell after 24-hour decay time and following the first 200-MeV 6-day irradiation alongside the Thorium foil.

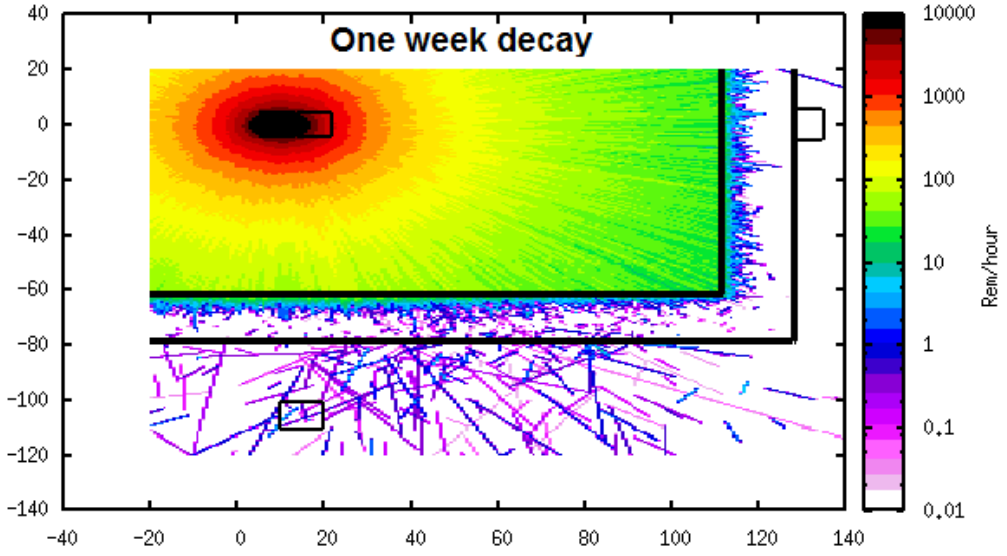


Figure 7.5 Dose profile inside and outside the BLIP hot cell after 1-week decay time and following the first 200-MeV 6-day irradiation alongside the Thorium foil.

7.2 PHASE II – 160 MeV Irradiation (21-day long segment at 150 uA)

Described in the remainder of this section is dose around the BLIP hot cell following the 21-day irradiation at 160 MeV of four (4) of the MoGR target capsules. This phase of irradiation will commence upon completion of the two-segment 200 MeV irradiation. For the set-up and configuration please refer to Figures 5.1 and 5.2.

The irradiation profile which results in the prediction of the doses includes all the two prior 200 MeV irradiations with the decay times in between and it concludes with 21-day irradiation at 160 MeV with 150 uA beam. Figure depicts the LHC 4-MoGR array upon completion of the 21-day 160 MeV irradiation lifted from beam and inside the BLIP hot cell. Box 2 where the isotope target array is irradiated has been replaced with vacuum so there is no contribution of Box 2 to the dose. The cooling water in the channels has also been removed.

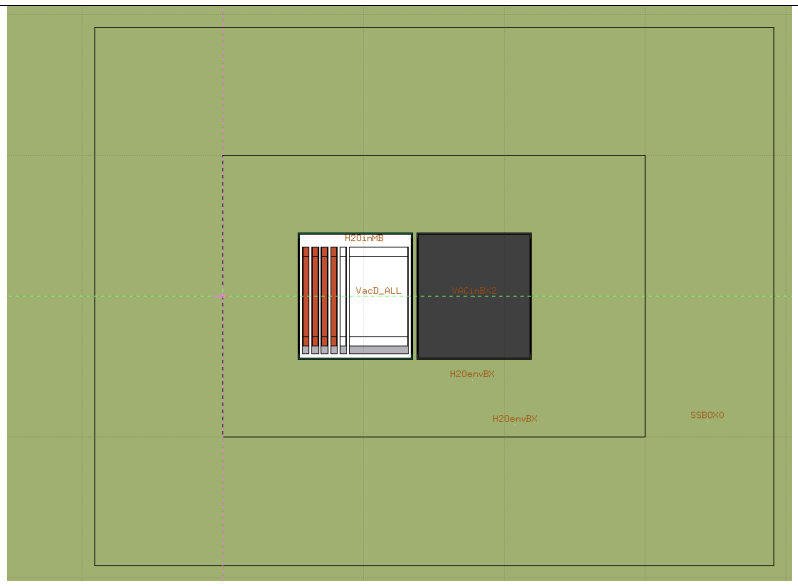


Figure 7.6: Dose model at BLIP hot cell following completion of the 21-day 160 MeV irradiation.

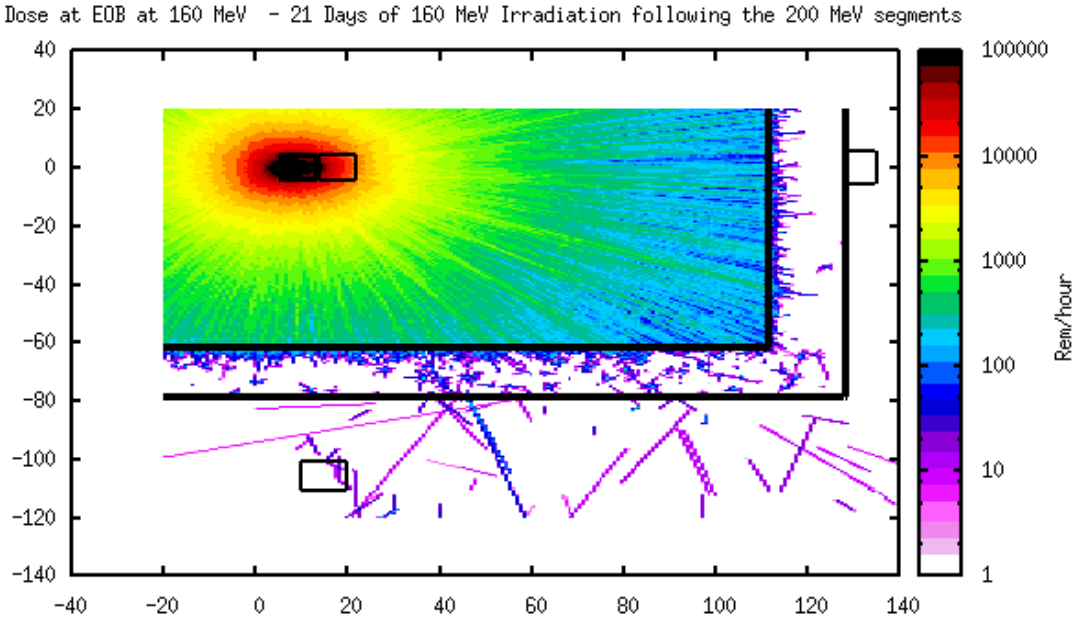


Figure 7.7: Dose at BLIP at EOB following completion of the 21-day 160 MeV irradiation. Array is assumed to have been retrieved from beam and is inside the BLIP hot cell

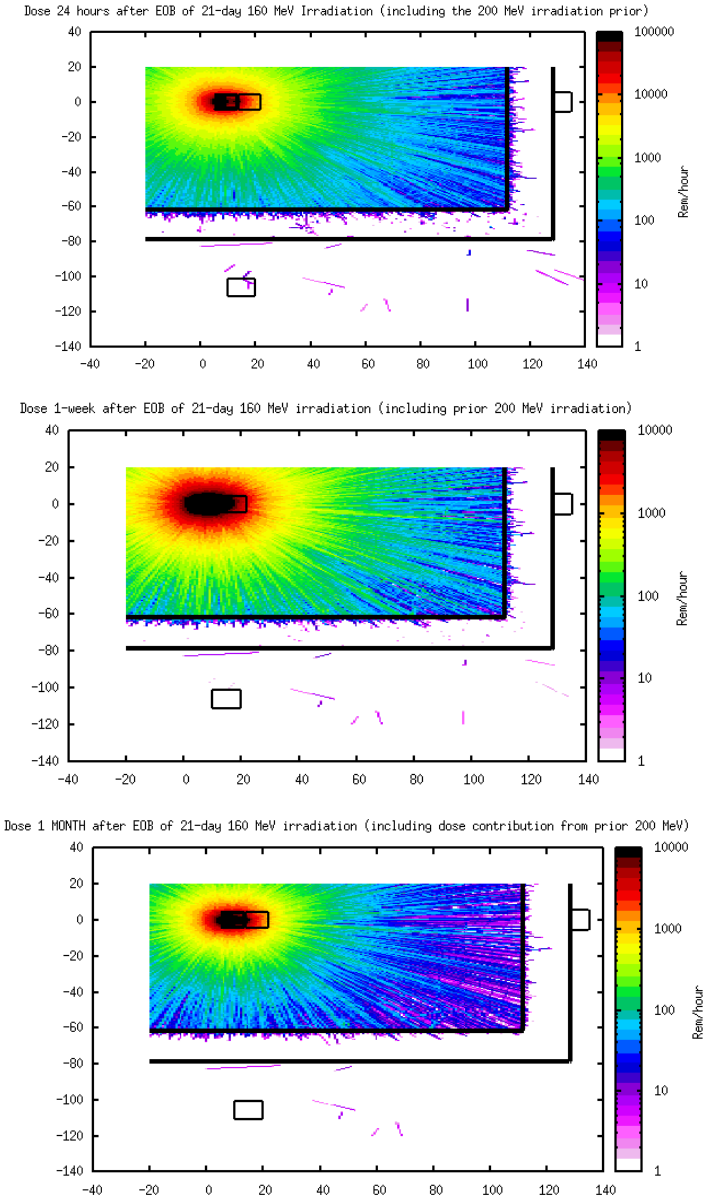
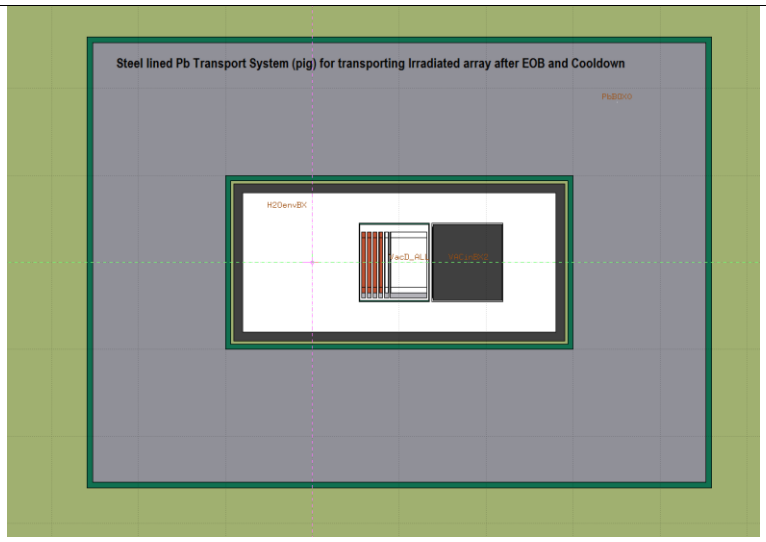


Figure 7.8: Evolution of dose at BLIP at EOB following completion of the 21-day 160 MeV irradiation. Array is assumed to have been retrieved from beam and is inside the BLIP hot cell



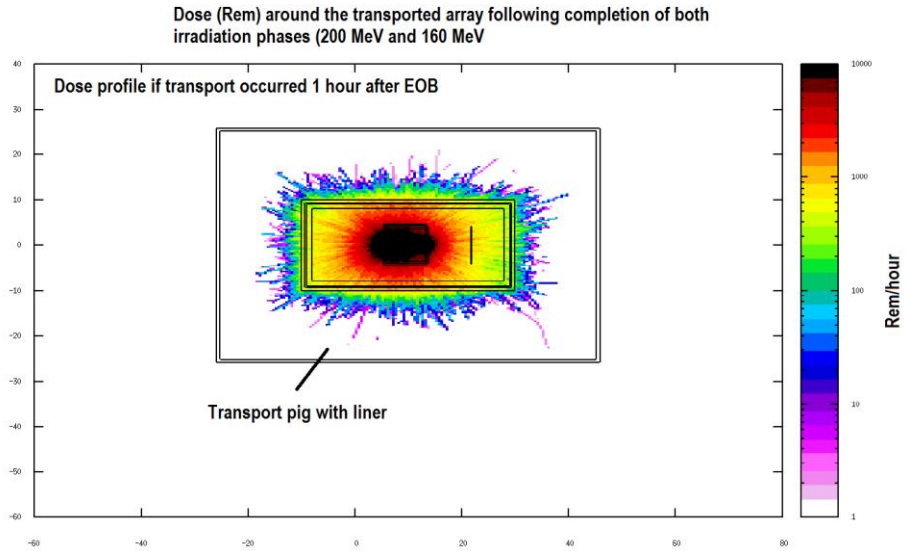


Figure 7.9: Dose profile of the irradiated array encompassing both irradiation phases. Array is placed inside the transport pig to be transferred to TPL (building 801)

8. Additional Safety Requirements

None

9. Special Operating Instructions	
Supporting Documentation	
References	
OPMs	19.2.22, 19.3.5.6, 19.3.5.7, 19.4.5.2, 19.4.5.3.
Drawings	D25-M-3186, 3188; 3452; 3453

Appendix A1

Note: Proton Energy Profile

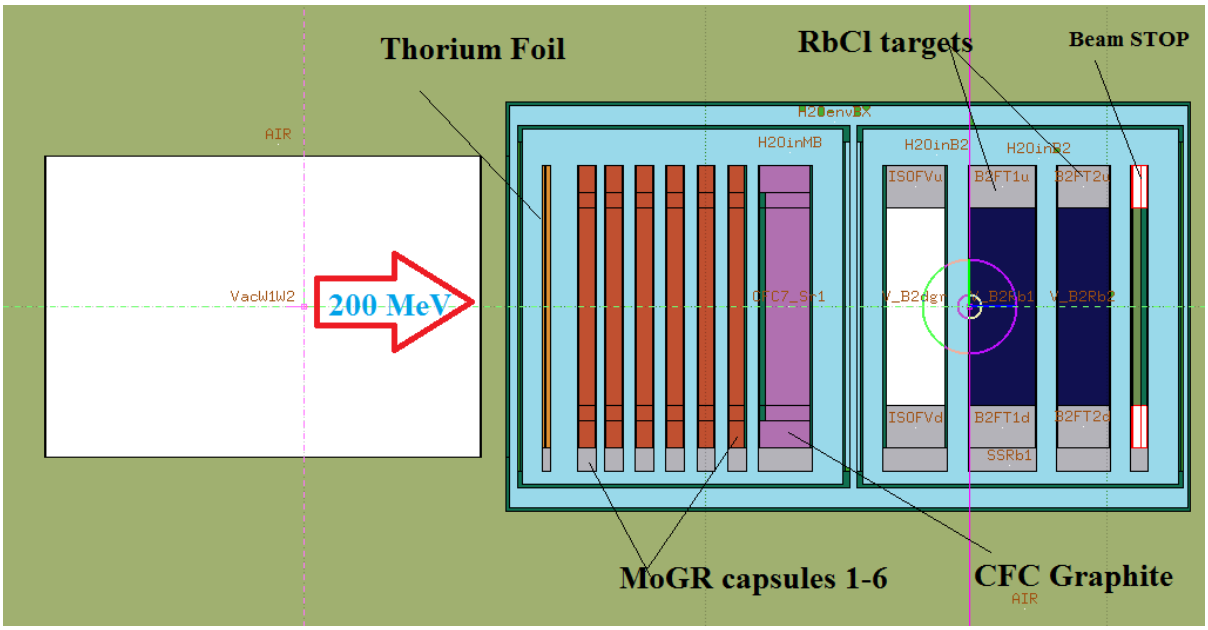


Figure A1.1 Cross section of the experiment configuration for the 200-MeV irradiation including the Thorium foil in the first position of Box 1

Table A1.1 Proton Energy Profile for Thorium-Foil + LHC Array at 200 MeV: RbCl in downstream box

	Energy: 199.05 MeV					
	Layer	Material	density	thickness, inches/mm	Ei, MeV	Eout
	Be window	Beryllium	1.85	0.012 / 0.3048	199.05	198.87
	AlBeMet window	AlBeMet	2.10	0.012 / 0.3048	198.87	198.65
	Beamline window	stainless steel	8.00	0.031 / 0.7874	198.65	196.65
	water gap	water	1.00	0.106 / 2.6924	196.65	195.45
Box 1 (LHC target Array)	upstream box window	stainless steel	8.00	0.020 / 0.508	195.45	194.15
	Water Gap	**water**	**1.0**	**0.2/5.08**	**194.15**	**191.80**
	Thorium Foil	Inconel	8.43	0.02/0.51	191.80	190.35
		Thorium	11.70	0.015/0.3810	190.35	189.34
		Inconel	8.43	0.0435/1.1049	189.34	186.30
	Water Gap	**water**	**1.0**	**0.26476/6.7249**	**186.3**	**183.0**
	MoGR1 Capsule	Stainless MoGR Stainless	8 2.5 8	0.012 /0.3048 0.15748/4.0 0.012/0.3048	183.	177.35
	Water Gap	**water**	**1.0**	**0.08102/2.0579**	**177.35**	**176.25**
	MoGR2 Capsule	Stainless MoGR Stainless	8.0 2.5 8.0	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	176.025	170.35
	Water Gap	**water**	**1.0**	**0.12052/ 3.0612**	**170.35**	**168.77**
	MoGR3 Capsule	Stainless MoGR Stainless	8.0 2.5 8.0	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	168.77	162.70
	Water Gap	**water**	**1.0**	**0.12052/3.0612**	**162.70**	**161.1**
	MoGR4 Capsule	Stainless MoGR Stainless	8.0 2.5 8.9	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	161.1	154.87
	Water Gap	**water**	**1.0**	**0.12052/ 3.0612**	**154.87**	**153.23**
	MoGR5 Capsule	Stainless MoGR Stainless	8.0 2.5 8.0	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	153.23	146.45
	Water Gap	**water**	**1.00**	**0.12052/ 3.0612**	**146.45**	**144.75**
	MoGR 6	Stainless MoGR Stainless	8.0 2.5 8.0	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	144.75	138.05
	Water Gap	**water**	**1.0**	**0.12052/3.0612**	**138.05**	**136.31**

	CFC Capsule	Stainless Steel CFC Graphite Stainless	8.0 8.0 1.67 8.0	0.012 / 0.3048 0.055/1.4 0.4567/11.6 0.012/0.3048	136.31	119.20
	Water Gap	**water**	**1.0**	**0.3102362/7.88**	**119.20**	**114.05**
	upstream box window	stainless steel	8.00	0.020 / 0.508	114.05	112.2
	water gap between box windows	**water**	**1.00**	**0.150 / 3.81**	**112.2**	**109.3**
	Downstream box front window	stainless steel	8.00	0.020 / 0.508	109.3	107.4
	Water Gap	**water**	**1.00**	**0.200 / 5.08**	**107.4**	**103.85**
	Degrader window	stainless steel	8.00	0.029 / 0.737	103.85	
	vacuum	vacuum	0.00	0.596/15.14		
	Degrader window	stainless steel	8.00	0.029/0.737		98.42
	Water Gap	**water**	**8.00**	**0.200 / 5.08**	**98.42**	**94.63**
	RbCl-1 can window	Inconel	8.43	0.012 / 0.3048	94.63	93.11
	RbCl salt	RbCl	2.38	0.646 / 16.398	93.11	67.75
	can window	Inconel	8.43	0.012 / 0.3048	67.75	66.47
	Water Gap	water	1.00	0.200 / 5.08	66.47	61.57
	RbCl-2 can window	Inconel	8.43	0.012 / 0.3048	61.57	59.42
	RbCl salt	RbCl	2.38	0.500 / 12.701	59.42	28.86
	RbCl-2 can window	Inconel	8.43	0.012 / 0.3048	28.86	25.28
	cooling channel	water	1.00	0.200 / 5.08	25.28	15.6
	Beam stop	Cu	8.96	0.220/ 5.59	15.6	stop
Box 2 (downstre	cooling channel	water	1.00	0.200 / 5.08		
	Box 2 Exit Window					

Figure A1.3 Proton and energy profile during the 200-MeV irradiation

160-MeV Irradiation

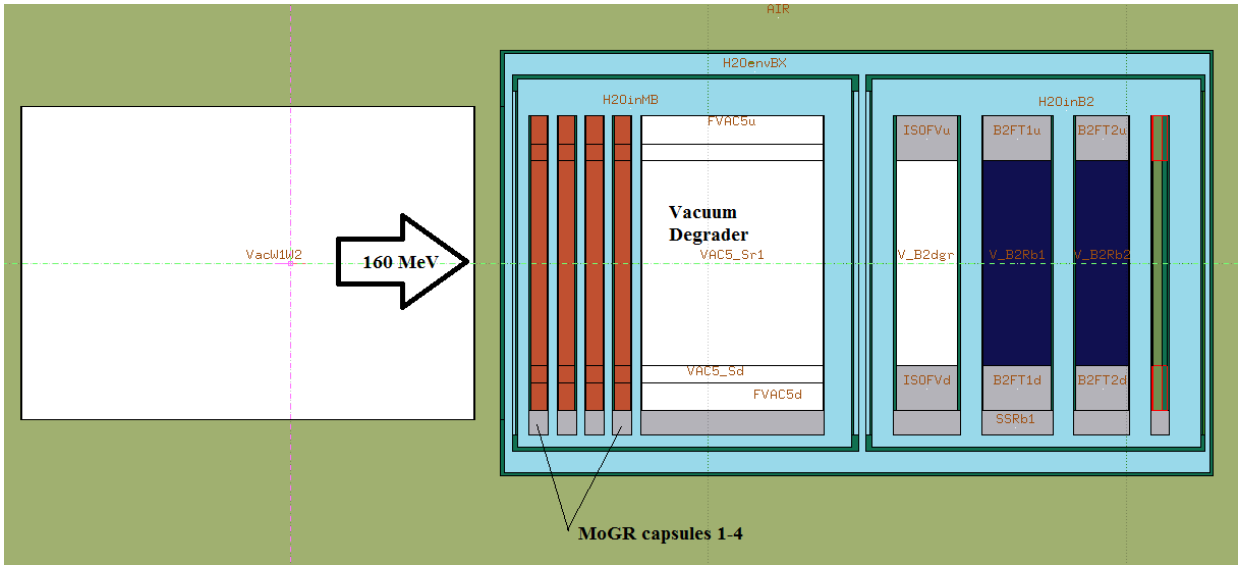


Figure A1.3 Cross section of the experiment configuration for the 160-MeV irradiation which includes four (4) of the MoGR of Phase I (200 MeV irradiation). Note that the CFC graphite capsule is not part of the 160-MeV irradiation.

Table A1.3 Proton Energy Profile for the LHC Array at 160 MeV: RbCl in downstream box

	Energy: 160.5 MeV					
	Layer	Material	density	thickness, inches/mm	**Ei, MeV**	**Eout**
	Be window	Beryllium	1.85	0.012 / 0.3048	160.50	160.27
	AlBeMet window	AlBeMet	2.10	0.012 / 0.3048	160.27	159.95
	Beamline window	stainless steel	8.00	0.031 / 0.7874	159.95	157.75
	water gap	water	1.00	0.106 / 2.6924	157.75	156.35
Box 1 (LHC target Array)	upstream box window	stainless steel	8.00	0.020 / 0.508	156.35	154.8
	water gap	**water**	**1.0**	**0.1105/2.8067**	**154.8**	**153.3**
	MoGR1 Capsule	Stainless MoGR Stainless	8 2.5 8	0.012 /0.3048 0.15748/4.0 0.012/0.3048	153.30	146.75
	Cooling Channel	**water**	**1.0**	**0.0805/2.0447**	**146.75**	**145.55**
	MoGR2 Capsule	Stainless MoGR Stainless	8.0 2.5 8.0	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	145.55	138.85
	Cooling Channel	**water**	**1.0**	**0.0805/ 2.0527**	**138.85**	**137.65**
	MoGR3 Capsule	Stainless MoGR Stainless	8.0	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	137.65	130.47
	Cooling Channel	**water**	**1.0**	**0.0805/2.0527**	**130.47**	**129.25**
	MoGR4 Capsule	Stainless MoGR Stainless	8.0 2.5 8.9	0.012 / 0.3048 0.15748/4.0 0.012/0.3048	129.35	122.01
	Cooling Channel	**water**	**1.00**	**0.02/ 2.0527**	**122.01**	**120.75**
	VACUUM Degrader	Stainless Vacuum Stainless	8.0 0 8.0	0.012 / 0.3048 1.704948/43.3057 0.012/0.3048	120.75	118.45
	Water Gap	**water**	**1**	**0.262/6.6548**	**118.45**	**114.2**
	upstream box window	stainless steel	8.00	0.020 / 0.508	114.2	112.28
	water gap between box windows	water	1.00	0.150 / 3.81	112.28	109.45
	Downstream box front window	stainless steel	8.00	0.020 / 0.508	109.45	107.6
	cooling channel	water	1.00	0.200 / 5.08	107.6	104.3
	Degrader window	stainless steel	8.00	0.029 / 0.737	104.3	
	vacuum	vacuum	0.00	0.596/15.14		
	Degrader window	stainless steel	8.00	0.029/0.737		98.25
	cooling channel	water	8.00	0.200 / 5.08	98.25	94.46

	RbCl-1 can window	Inconel	8.43	0.012 / 0.3048	94.46	93.15
	RbCl salt	RbCl	2.38	0.646 / 16.398	93.15	68.15
	can window	Inconel	8.43	0.012 / 0.3048	68.15	66.7
	cooling channel	water	1.00	0.200 / 5.08	66.7	61.19
	RbCl-2 can window	Inconel	8.43	0.012 / 0.3048	61.19	59.9
	RbCl salt	RbCl	2.38	0.500 / 12.701	59.9	28.44
	RbCl-2 can window	Inconel	8.43	0.012 / 0.3048	28.44	25.9
	cooling channel	water	1.00	0.200 / 5.08	25.9	13.56
	Beam stop	Cu	8.96	0.220/ 5.59	13.56	STOP
Box 2 (downstre	cooling channel	water	1.00	0.200 / 5.08		
	Box 2 Exit Window					

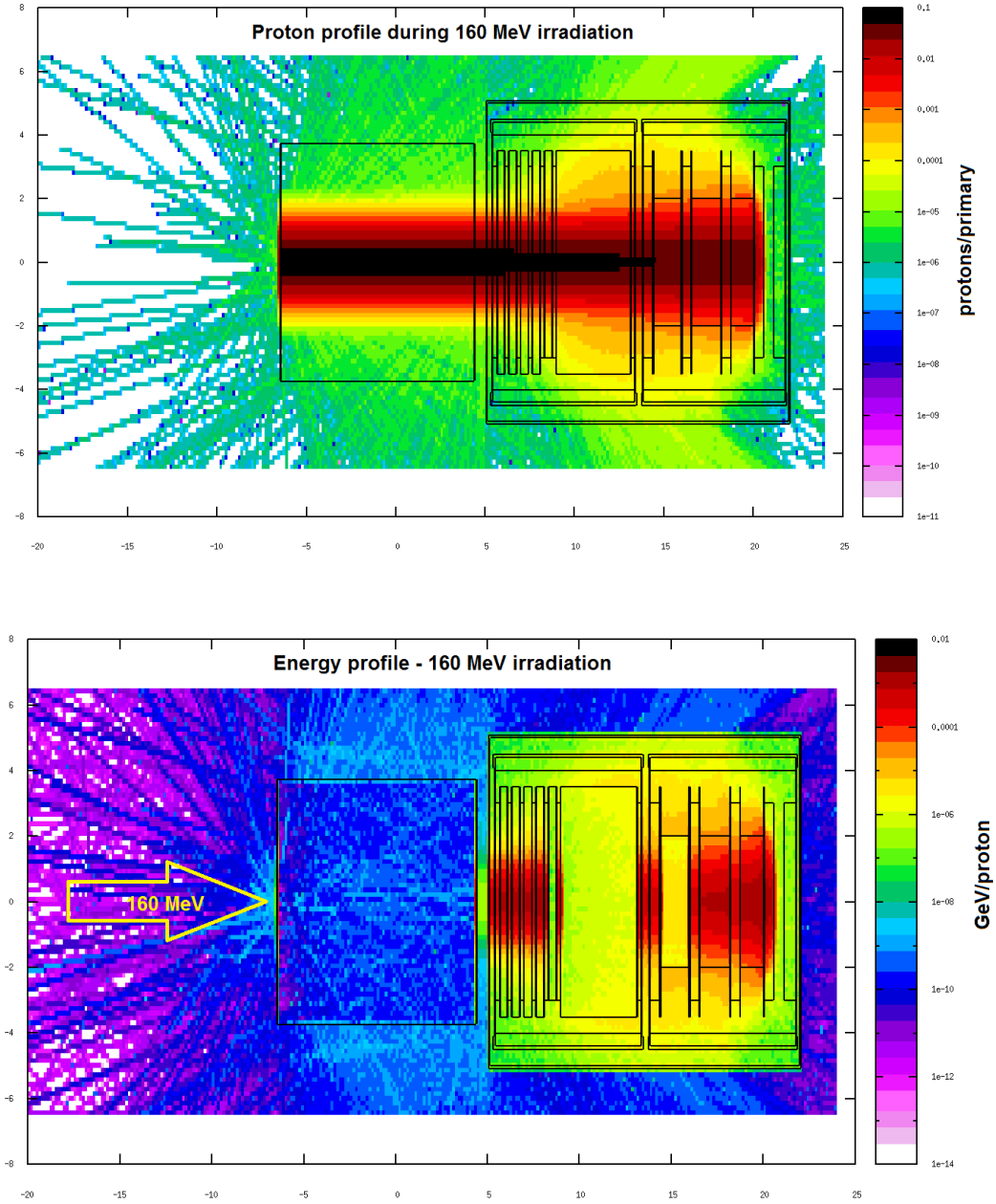


Figure A1.4 Proton and Energy Profiles throughout the irradiation array (including the isotope array in Box 2) for the 160 MeV

Appendix A2

Thermo-mechanical analysis

Analysis Performed on Target Capsules based on estimated by SRIM/MCNPX/FLUKA energy deposition estimates. The estimates of the deposited energy generated by the three (3) different approaches where in excellent agreement Analysis performed by **N. Simos**	Details of the Finite element analysis are in attached file (Thermal-Structural Analysis of LHC Target Array)
Conditions • Instantaneous Current: 40.0 mA • Pulse Width: 0.000425 sec • Number of protons 9.37e+14 p/sec • Pulse Frequency = 6.667 Hz • 200 MeV (Phase II 160 MeV) • 2 condigurations (one per energy) • 100% beam on target	**Summary and Conclusions** Target capsules containing MoGR and CFC graphite are under vacuum (hence 2 atm pressure inward) Temperatures and thermal stresses in the 304 stainlees steel windows for the capsules and the degraders are well within the safety envelope
The results are attached. Please note one significant finding, the water flow through target box 2 is significantly less than through target box 1.	**Summary and Conclusions (cont.)** The temperatures and stresses in the materials inside the capsules depend on the rastering profile. Under the nominal rastering (per design) a large area is effectively heated and therefore the temperatures are well within the safety envelopes. Analyses that assumed a tighter rastering profile with peak beam current were performed leading to higher temperatures. However, the melting point of MoGR and CFC graphite is high and therefore it is expected that even under these conditions the system is safe. Peak temperatures are experienced by the stainless steel layer within the CFC target capsule and the CFC middle layer in the capsule (3 layers of 4mm-thick CFC). Under normal conditions Peak Temp in middle CFC layer <660 ^{o}C. (Melting Temp = 3650 ^{o}C)

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. More detailed/descriptive analysis results of all target capsules are available and can be provided upon request.

The array of 3D non-linear thermal, thermos-mechanical and CFD analyses performed consisted of:

Steady State Thermal Analysis based on detailed energy deposition produced by the FLUKA code and inserted as heat generation into the materials. The encapsulated materials under vacuum into the capsules were in contact with the inner surface of the capsule (therefore conductance rather than conductivity was used in the thermal and thermos-mechanical analysis). The target capsules and degraders were cooled with the cooling water through the channels. Recent measurements established the volumetric flow for Box1 where the target array is to be irradiated to be 22 gpm. Based on the array with the Thorium target in position 1, 34 mm of total water column/gap is available for the 22 gpm to flow past the targets. The variability of velocity with non-uniform channels was tested using a CFD model (data shown in this section). Based on these findings and the heat transfer analysis based on an analytic study, heat transfer film coefficients were generated and introduced in the analysis. Conservative values of ~7200 W/m^2K were used in the thermal analysis.

Based on the similarity of the different targets in the array (i.e. six MoGR targets in Phase I and 4 MoGR targets in Phase II) the one capsule experiencing the most severe thermal load that is due to the position and thus the beam energy was analysed fully. Thus for Phase I MoGR capsule #6 was analysed and it represented the rest of the MoGR capsules both for the 200 MeV and the 160 MeV.

Considering the rastering scheme of the proton beam which leads to an effective FWHF ~21mm and 150 uA beam the energy density deposited in the target materials is significantly reduced to values of 268 Joules/cc for capsule windows and ~98 Joules/cc for the contents of the MoGR capsules. Based on these reduced thermal loads, the temperature in the 304 stainless capsule windows which are cooled directly by the forced flow does not exceed 347K with nominal temperatures in steady state ~322K. The deformations in the capsule windows are small (<330 microns) and therefore there is no concern for reducing the gap size and thus cooling between the capsules (smallest water gap > 2mm).

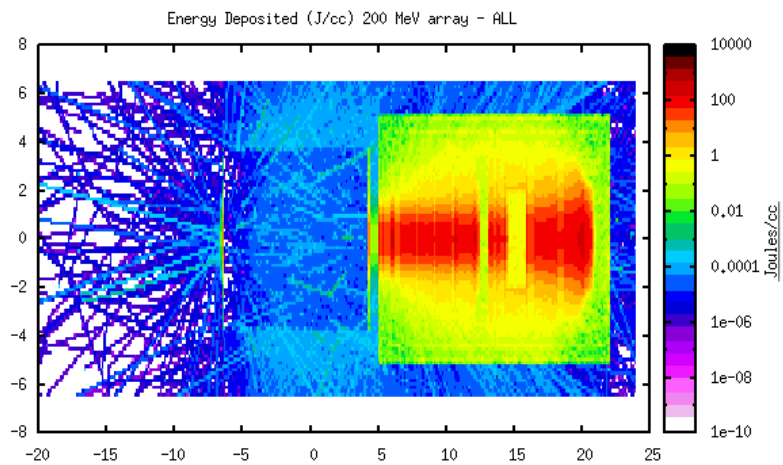


Figure A2.1 Energy deposition through-out the target arrays in Box1 and the isotope targets in Box2

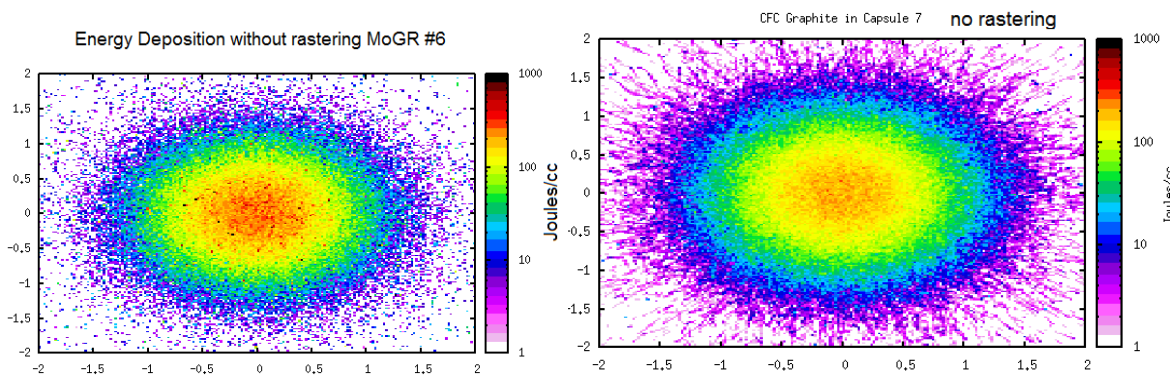


Figure A2.2: Energy deposition profile within each of the Mo-GR capsules (1-4) to be irradiated with 160 MeV protons. Current assumed is 150 uA. The analysis indicates that the four capsules experience similar heat loads.

Based on the findings included in the Memo titled "BLIP Cooling Water Flow Rate Measurement" It was concluded that the volumetric flow is about 22 gpm for target box 1 and 14 gpm for target box 2. The total mass flow into either target box was unaffected by the contents of the other target box.

Analytical Estimation of heat transfer coefficient through the target capsules

Estimation of Reynolds number related to the velocity of flow U_f through the hydraulic diameter (2mm gap between targets),

$N_{Re} = U_f D_e / \nu$

where ν is the dynamic viscosity . Estimate Reynold's number from Nusselt number

$Nu_{De} = 0.023 (R_e)^{0.8} (P_r)^{0.3}$

where P_r is the Prandtl number

By relating the film coefficient to the Nusselt number Nu_{De}

$Nu_{De} = h_f D_e / k$

D_e = hydraulic diameter

A good estimate of the forced convection film coefficient.

To better understand the range of velocities in the gaps between target capsules that would result because of un-evenness resulting from the configuration around the Thorium foil target (5.08mm water front and back vs. 2mm between the capsules in the rest of the array) a CFD-based analysis was performed.

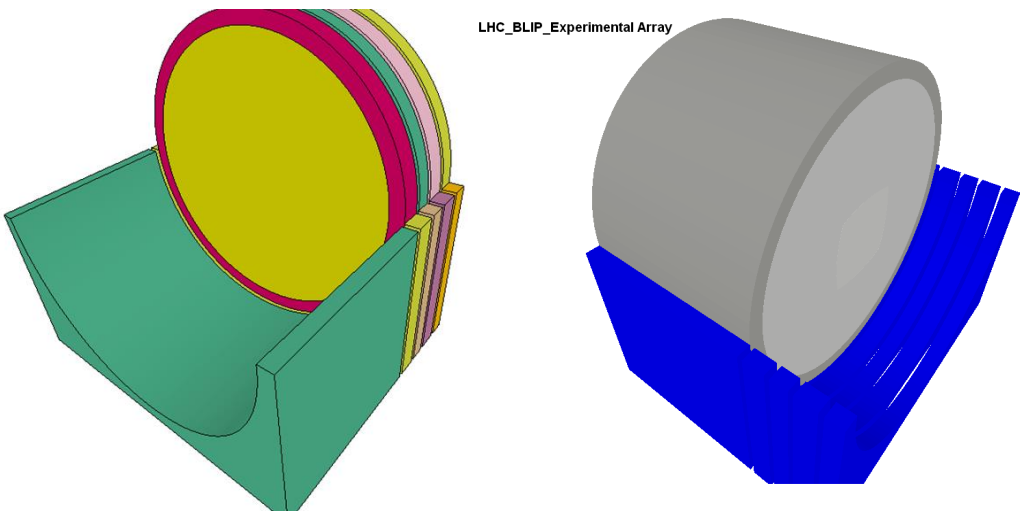
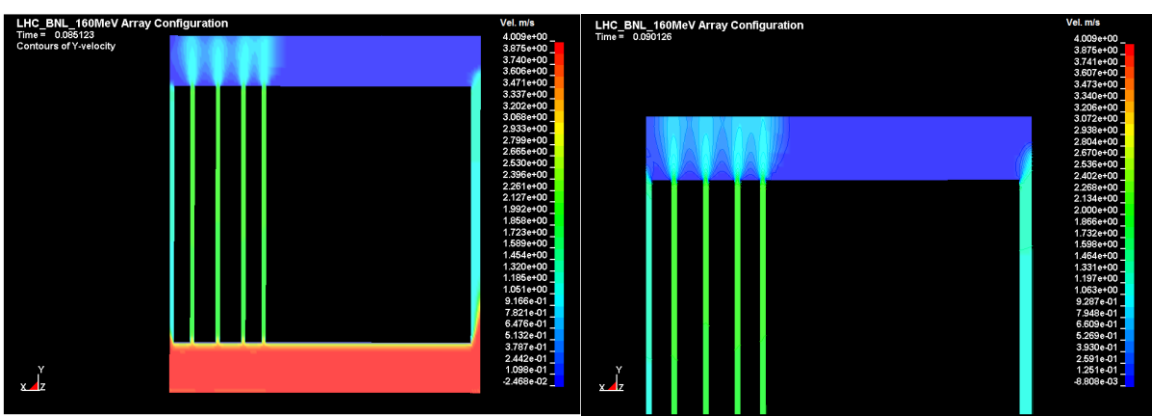


Figure A2.3 Layout of Array of Phase II with the vacuum degrader (right)



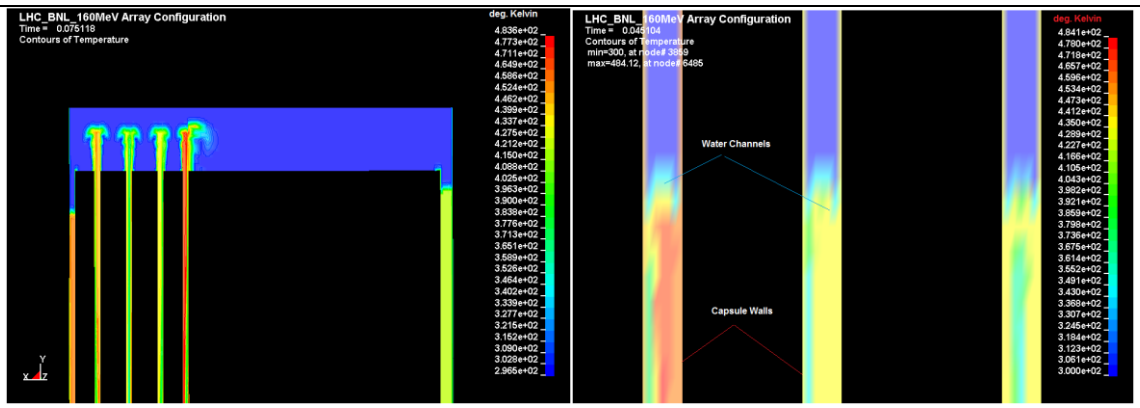


Figure A2.4: CFD analysis with channel width variation shows a difference in the velocity and the temperature of the fluid passing through (that affecting the temperature of the capsule wall)

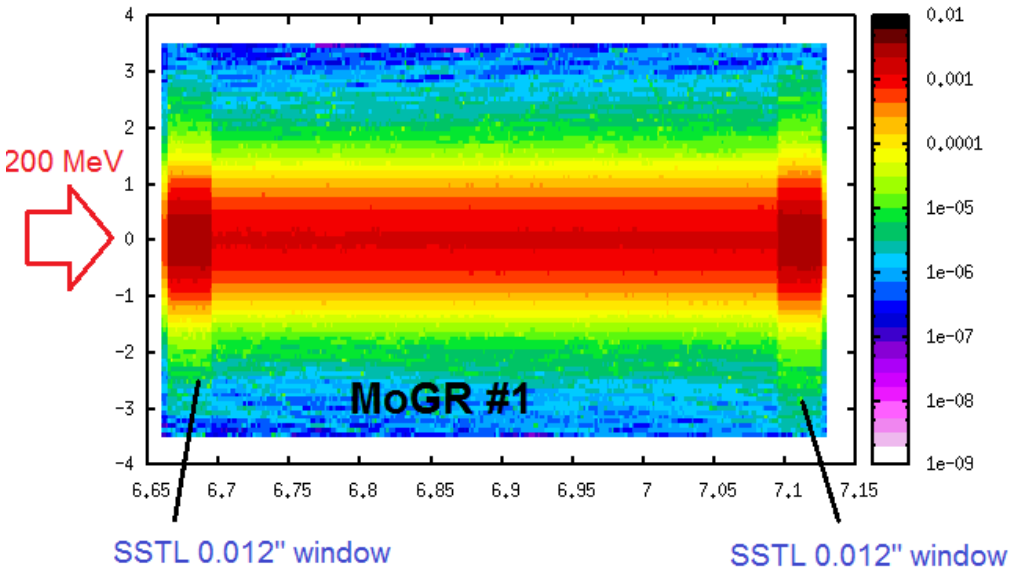


Figure A2.5 Energy profile predicted for the 1st MoGR capsule including the 0.012" thick stainless steel capsule windows during the 200-MeV irradiation. Energy deposition computed for each of the capsules (including the windows) was used in the thermo-mechanical analysis. Specifically, energy deposited in the 304 stainless windows is of the order of 268 Joules/cm^3 and in the MoGR material ~97.8 Joules/cm^3

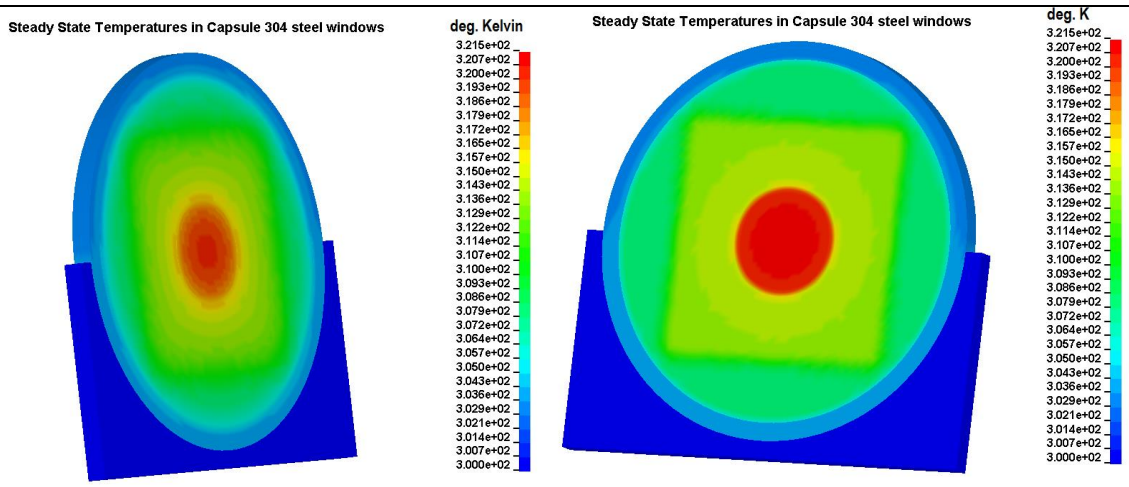


Figure A2.6: Temperature profile in the MoGR capsule windows under steady-state

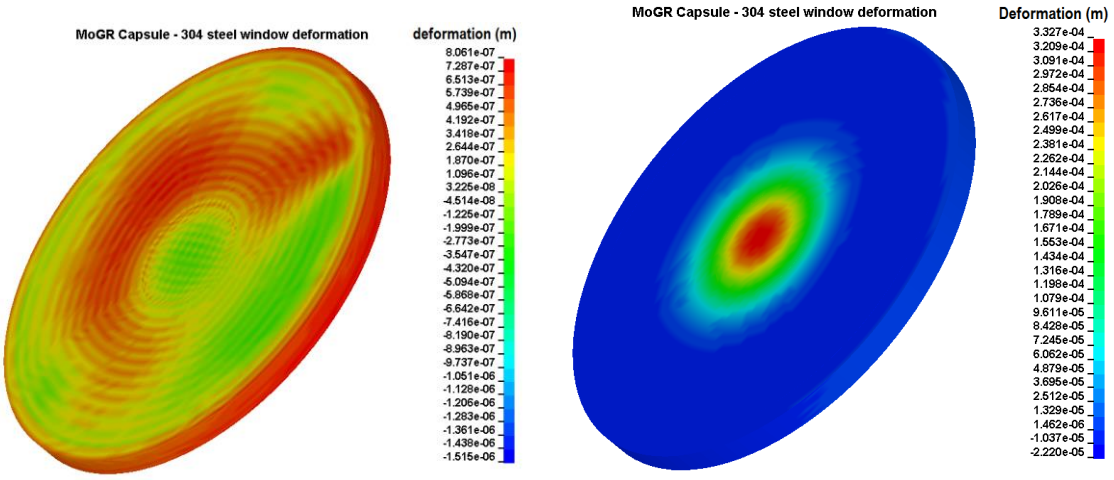


Figure A2.7: Deformation profile in the MoGR capsule windows under steady-state conditions. Nominal steady state conditions (left) and conditions based on increased beam current (right). **Deformations experienced by the windows <330 microns**

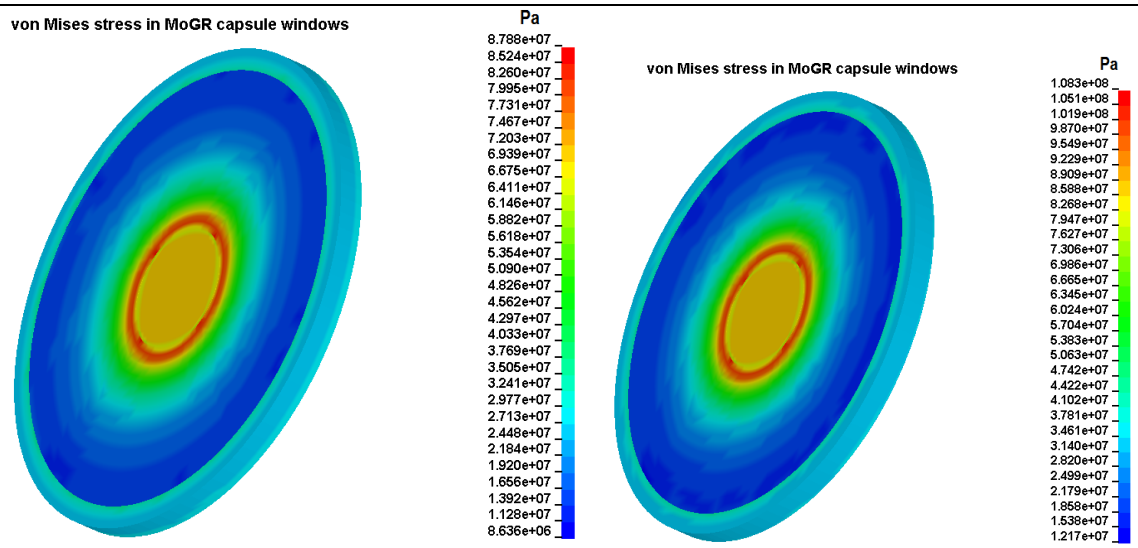
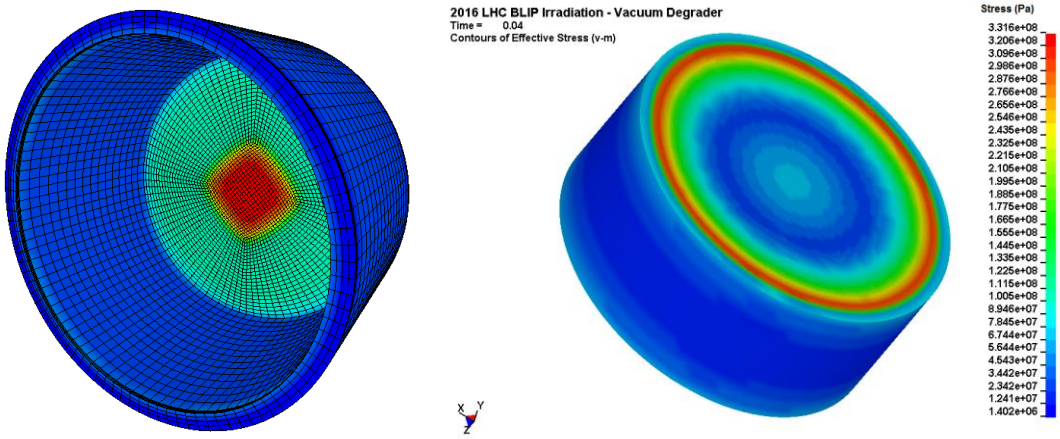


Figure A2. 8: von Mises stress in 304 Stainless Window of MoGR Capsule for nominal beam current of 150uA (left) and increased current (right) with beam rastering.

Vacuum Degrader – 160 MeV Irradiation

No Issue with Temperature in the 0.012" thick 304 window T_{max} ~330 K)



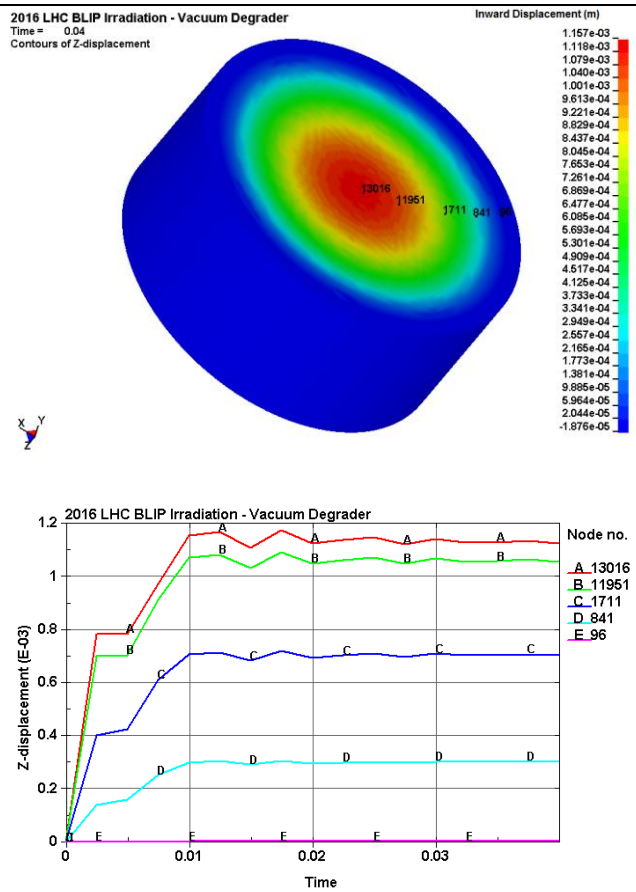


Figure A2.8: Thermo-mechanical study of vacuum degraders with 0.012” thick 304 steel windows.

Appendix 3 - Activation analysis of LHC Target Array

RADIONUCLIDES FROM 200 MeV IRRADIATION

Table A3.1 Calculated spectrum of radionuclides and their activity at EOB produced in the first of six (6) Mo-GR target materials after bombardment with 200 MeV protons for 6 days at 150 μA.

Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci
99	42	0.888615	80	37	0.11179
98	41	0.000375	79	36	0.715248
97	41	0.754978	79	37	0.737075
96	41	0.748783	76	36	0.379119
96	43	0.233157	76	35	0.752983
95	41	0.147986	13	7	0.35434
95	43	1.322464	11	6	302.5456
94	43	1.138037	10	6	1.927782
93	43	3.348321	7	4	6.986912
92	43	0.322443	3	1	0.079999
91	41	0.000151			
91	42	3.585402			
90	41	9.101018			**Total= 369 Ci**
90	42	3.032754			
89	40	6.455345			
89	41	2.831673			
88	39	0.004301			
87	40	4.160104			
87	41	0.472459			
86	37	0.075992			
86	39	3.390159			
86	40	1.515015			
86	41	0.236805			
85	38	0.227221			
85	39	2.273511			
85	40	0.872999			
85	41	0.051931			
83	37	0.049644			
83	38	1.449112			
82	37	0.16787			
82	38	0.057062			
81	37	0.379848			
81	38	0.368237			

Table A3.3 Spectrum of radionuclides and their activity remaining after ONE MONTH in the first of six (6) Mo-GR target materials after bombardment with 192 MeV protons for 6 days at 150 μA.

Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci
99	42	9.66E-05	83	37	0.025115			
96	43	0.000455	82	37	0.010124			
95	41	0.049951	82	38	0.010124			
95	43	0.00106	7	4	2.027998			
93	42	1.34E-05	3	1	0.036468			
91	41	7.86E-05						
89	40	0.002539						
88	39	0.019441						
88	40	0.075873						
87	39	0.001967						
86	37	0.009513						
85	38	0.073943						

Table A3.4 FLUKA calculated spectrum of radionuclides and their activity at EOB produced in the CFC material after bombardment with 200 MeV protons for 6 days at 150 μA.

TOTAL = 168.5 Ci

Isotope	Z	Activity, Ci
13	7	0.0644
11	4	0.0034
11	6	163.9
10	6	0.717
7	4	3.8624
3	1	0.04

1-month

Isotope	Z	Activity, Ci
7	4	6.69648
3	1	0.12011

Table A3.9 Calculated spectrum of radionuclides and their activity at EOB produced in all fourteen 0.012" thick capsule windows of the target capsules and degrader four after bombardment with 200 MeV protons for 6 days at 150 μA.

Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci
58	27	0.096585	49	23	0.508691
57	27	0.098666	49	24	8.719343
57	28	4.16178	48	23	5.648427
56	25	0.882377	48	24	0.877232
56	27	0.444443	47	23	5.206103
56	28	0.896642	45	22	2.6491
55	26	0.274294	44	22	0.000412
55	27	3.531137	47	21	2.522457
54	25	0.281566	46	21	0.085839
53	23	0.57627	45	20	0.022221
53	25	1.57E-07	44	21	6.354859
53	26	9.320964	23	12	0.022471
52	23	1.473517	22	11	0.011619
52	25	5.420265	18	9	1.761539
52	26	0.442551	15	8	1.261474
51	24	7.779073	11	6	0.856723
51	25	5.239022	3	1	0.007368
					TOTAL 77.43 Ci

Table A3.6 Calculated spectrum of radionuclides and their activity at **1-month** produced in all the stainless steel capsule shell (windows) material following 6 days of irradiation with 200 MeV protons at 150 μA. (14 TOTAL 0.012"-thick windows)

Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci
58	27	0.028232	48	23	0.194257
57	27	0.029092	47	21	0.000122
56	27	0.047005	46	21	0.012605
56	28	0.001597	45	20	0.003761
55	26	0.04104	44	21	0.000121
54	25	0.091635	22	11	0.001483
52	25	0.029292	3	1	0.00144
51	24	0.57627			
49	23	0.079232			**TOTAL 18.2 Ci**

RADIONUCLIDES FROM 160 MeV IRRADIATION

Irradiation of four (4) MoGR capsules and a vacuum degrader at 160 MeV and 21-day period will result in a total radioactivity at **EOB** of **336.7 Ci** total.

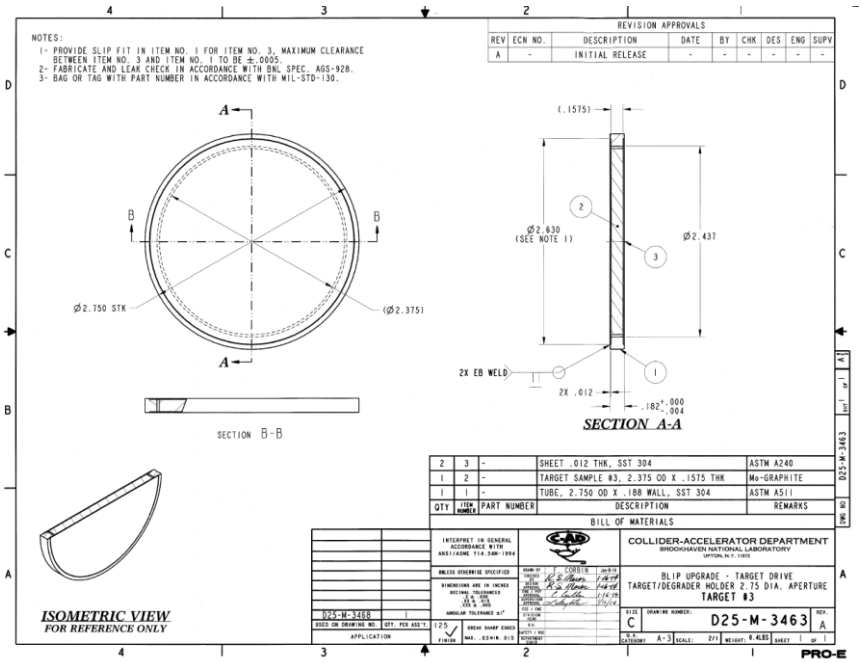
This includes the MoGR contained in the capsules and the stainless steel capsule (including the vacuum degrader). The targets will experience similar decay as those irradiated with 200 MeV protons.

Specifically after just one hour of decay time the radioactivity reduces to **140 Ci** and following a month of decay period to **27.42 Ci**.

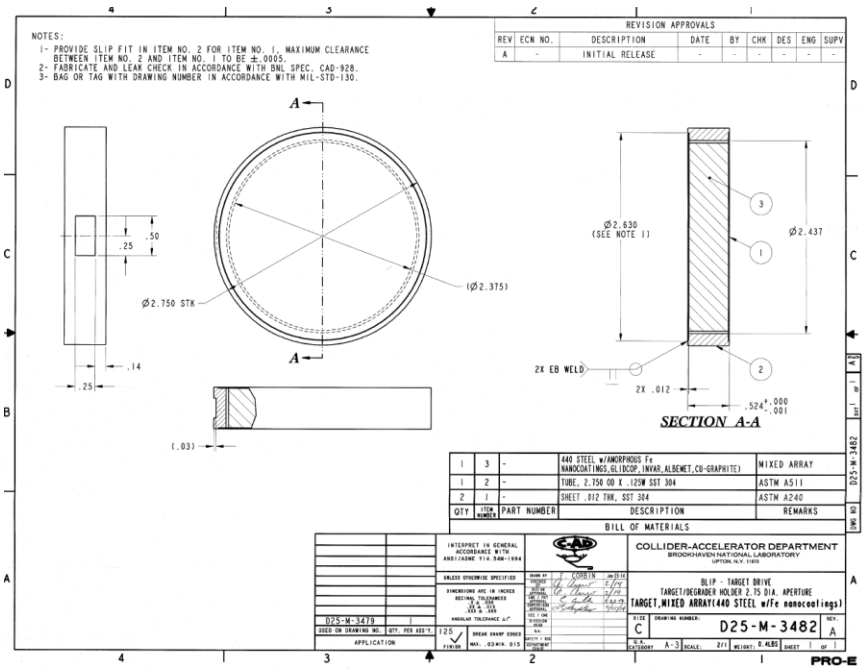
The isotope profile is similar to the one shown for the 200MeV irradiation.

Appendix 4

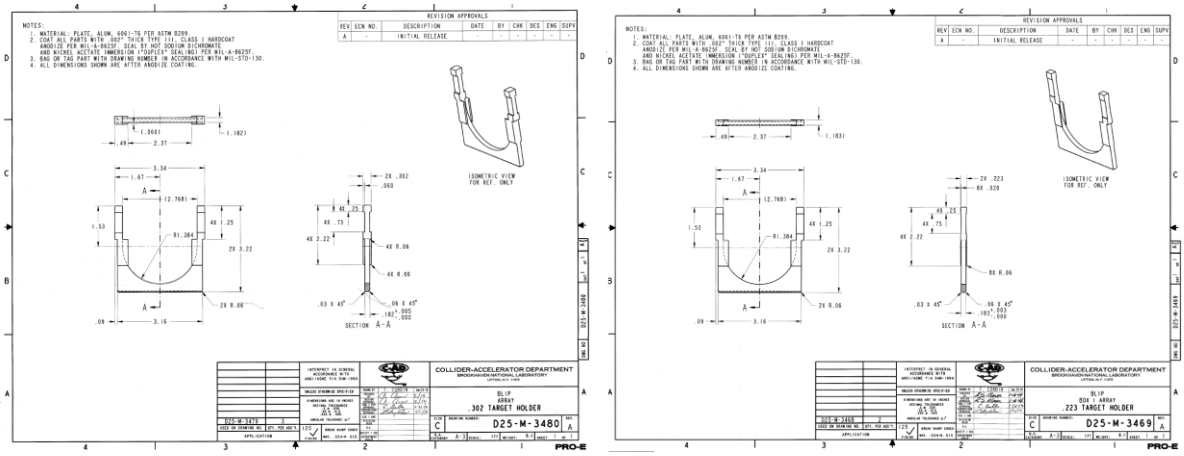
Drawings



Drawing 4.1: MoGR capsule design



Drawing 4.2: CFC graphite containing capsule



Drawing 4.3: Support structures for MoGR capsules

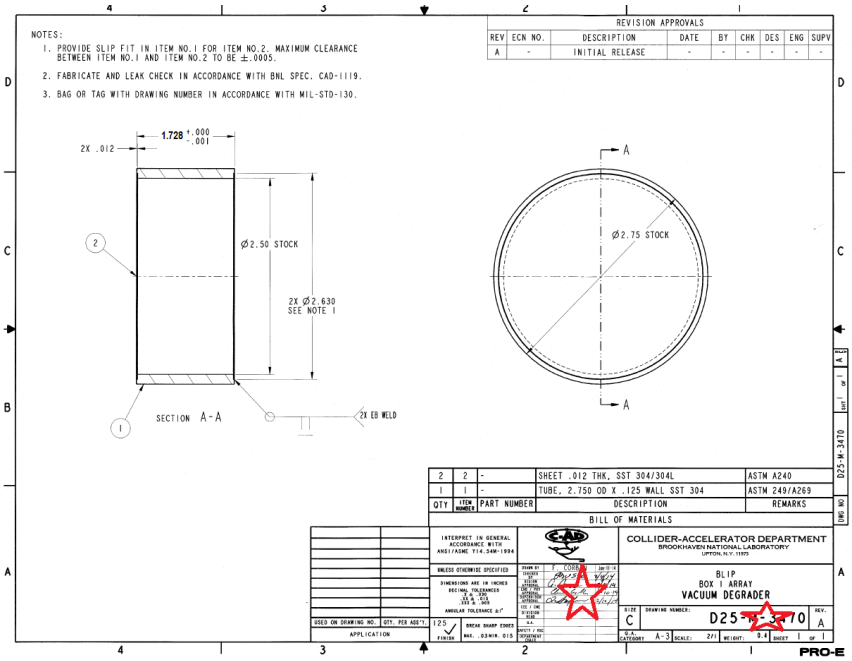


Figure 4.4: Vacuum Degrader utilized in the 160 MeV array irradiation