SR Heat Load on FCC-ee Cold SSS

A Deeper Look

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&
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FUTURE CIRCULAR COLLIDER

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Aim of the Presentation

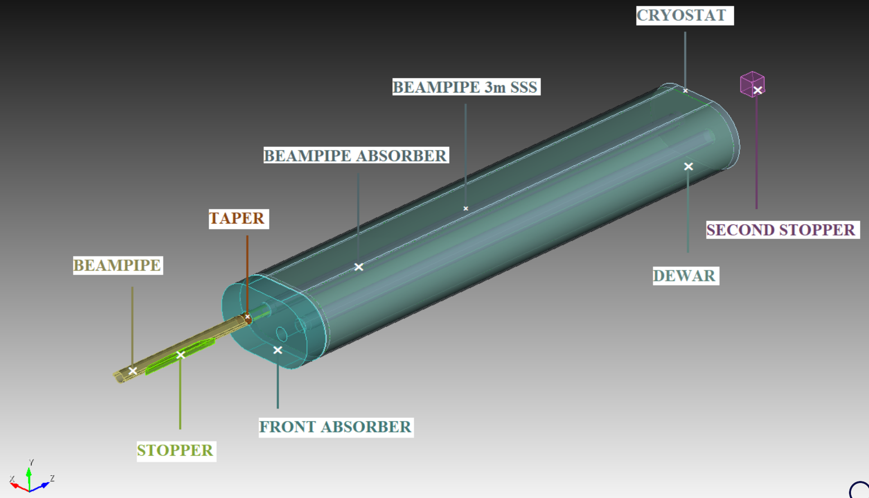
- A question of " *how much heat will creep into the SSS cryostat from the photon stopper upstream?* " was tackled on the 141st FCC-ee Optics Design Meeting by Michael Koratzinos.
- One of the issues raised was the need to verify the presented results using the exact CAD-defined model layout.
- This approach accommodates importing models designed using **CAD** software into **FLUKA** and performing simulations through **FLUKA's** Graphical User Interface called **flair**.
- A specific workflow was followed making good use of **DAGMC** (**D**irect **A**ccelerated **G**eometry **M**onte **C**arlo) tools developed by the University of Wisconsin-Madison.
- The results are preliminary.

CAD Models in MC Simulations

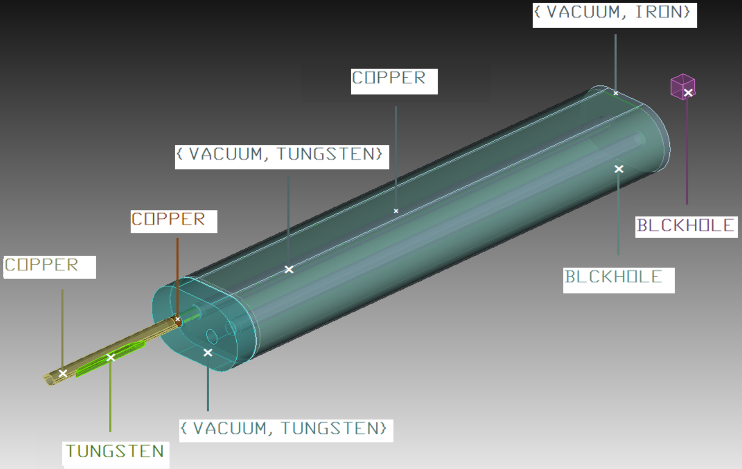
The problem of CAD geometry support in Monte Carlo codes can be broken down in two branches of solution, of which the second approach can be further broken down in two methods.

1. Translation approach (including SuperMC and Geomit).
   - Attempts to decompose the geometry into primitive Combinatorial Solid Geometry (CSG) objects.
   - Issues emerge when the geometry contains spline surfaces which have no analytic representation.
2. Direct use of CAD (including **DAGMC** and OiNC).
   1. High order root finding.
      - Determines the intersection of rays with CAD geometry.
      - High computation time.
   2. High resolution tessellated representation of the CAD surfaces.
      - **DAGMC** geometry is composed entirely of triangular facets.
      - High memory usage.

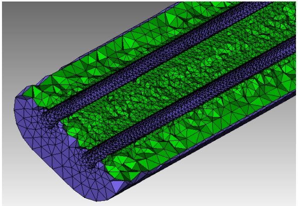
Inspection of the CAD Model



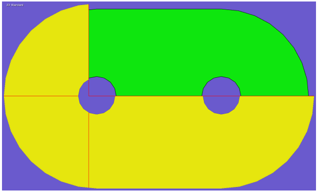
Materials Assigned per Region



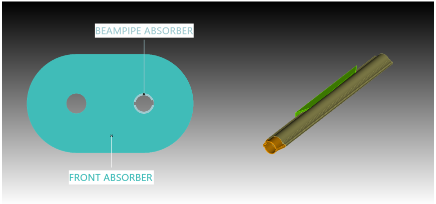
A Closer Look in the Geometry



Internal tetrahedral meshes for DEWAR and CRYOSTAT



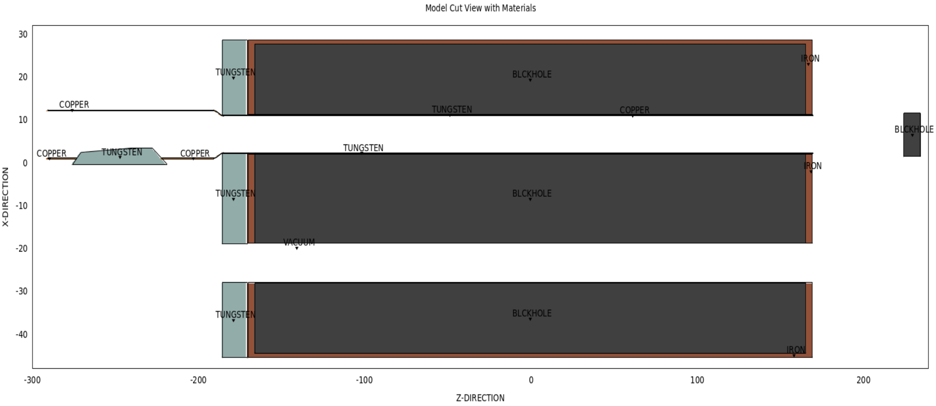
Front face of CRYOSTAT with exposed DEWAR



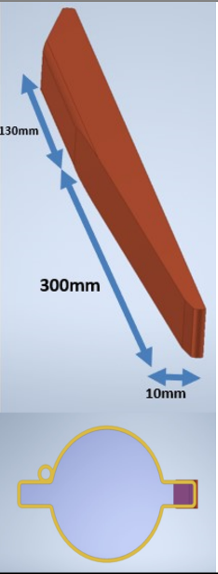
XY projection view of **absorbers**, together they shield the entire **beampipe SSS** within the CRYOSTAT region along with an isometric view of the **beampipe**, the **stopper** and the **taper** outside of the CRYOSTAT region.

A Closer Look in the Geometry

Model Cut View with Materials



Beam Pipe Geometry & Stopper Modifications

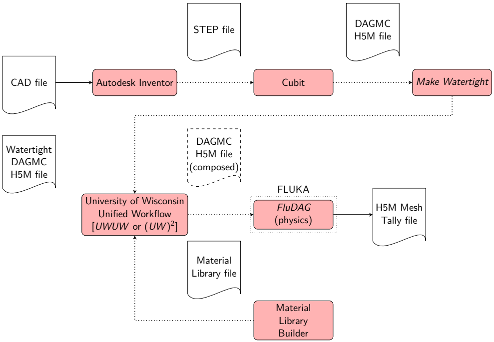


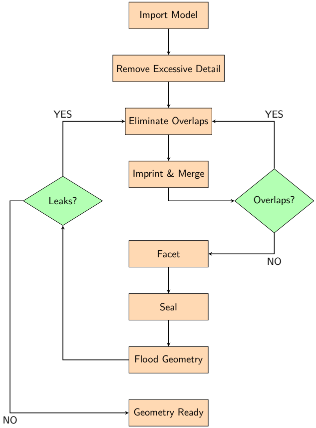
Modifications wrt the CDR stopper [1].

- Stopper is thicker.
- Stopper is longer.
- Cooling pipe addition.
- Stopper photon incident slope $= \tan^{-1}(\frac{1}{30})$.

Cubit Software Package

Using Cubit to Produce DAGMC Solid Models





DAGMC model preparation (left) and solid model processing (right) wokrflows (references: [3, 6])

Operations Performed with **Cubit**

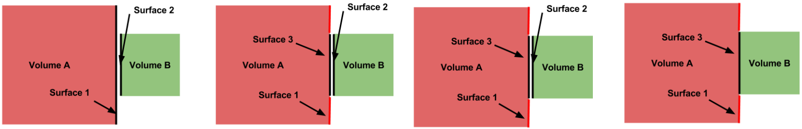
Imprinting & Merging

Imprinting

Imprinting creates a common surface interface between touching volumes.

Merging

Merging then takes the touching surfaces and makes them into one surface.

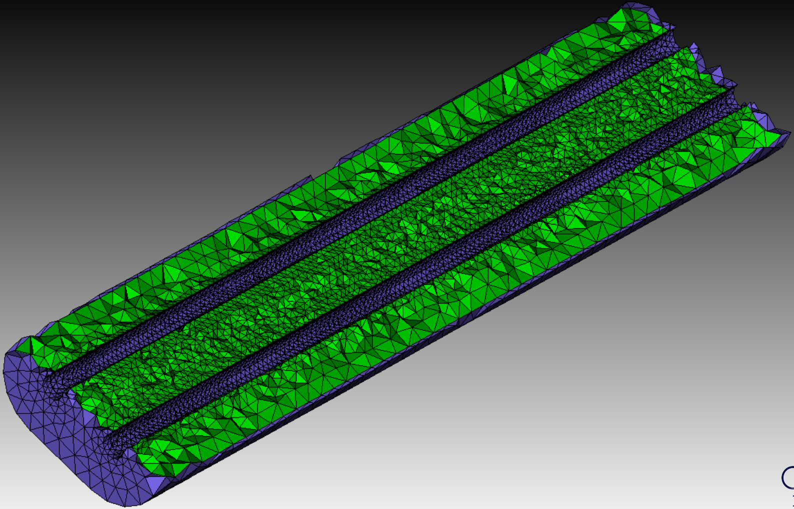


Imprint operation (reference: [6])

Merge operation (reference: [6])

Operations Performed with **Cubit**

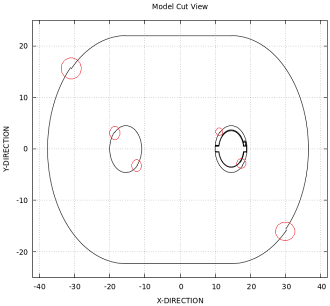
Faceting



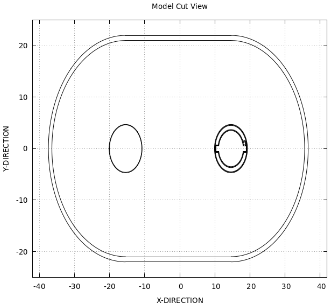
Imperfections Emerging after Processing the Model

Discrepancies Due to Flawed Meshing

Distinct boundaries between the `CRYOSTAT` and the `DEWAR` must be set, in order to avoid flawed meshing which can lead to discontinuities and disruptions in the exported geometry file used by the **FluDAG** executable, in order to run particle simulations with **FLUKA**.



Discontinuous geometry (dimensions in [cm])



Correct geometry (dimensions in [cm])

Misleading results can arise from running simulations with improper tolerance parameter values or if neighbouring faces don't share facet points with the edge they have in common nor with each other. The simulation will run smoothly, but the scoring results and in general the output files will be misleading and untrustworthy.

Fixing the Problem

Points of Attention

- Make sure that no shared boundaries between neighbouring volumes of different materials exist. In other words, solids must be **manifold** (they should be able to hold water inside of them).
- Eliminate excessive details in the form of sheet bodies or standalone surfaces not part of any volume, prior to meshing with **Cubit**
- Due to the fact that there is no unit system defined in **Cubit**, models should be scaled appropriately (lengths should take values within the interval [1E-3, 1E+7]).
- Special care is required while adjusting **Cubit's** tolerance values not to be higher than the smallest length in the model's geometry.

Different Material Inspection

Scoring **Energy Deposition** per Region

The **energy deposition** is scored per **region** (see slides: 5 & 6 for a visualised **region** recap) in a number of cases summarised below.

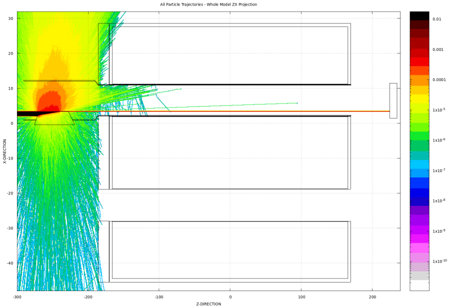
	ID	Name	CASES				
			I	**II**	**III**	**IV**	**V**
Regions	1	DEWAR	*BLCKHOLE*				
	2	CRYOSTAT	*VACUUM*	*IRON*			
	3	BP_SSS_3M	*COPPER*				
	4	ABSORBER_BP	*VACUUM*		*TUNGSTEN*	*VACUUM*	*TUNGSTEN*
	5	ABSORBER_FRONT	*VACUUM*			*TUNGSTEN*	
	6	BP_TAPER	*COPPER*				
	7	BP_32mm	*COPPER*				
	8	STOPPER	*TUNGSTEN*				
	9	GRAVEYARD†	*BLCKHOLE*				
	10	SECOND_STOPPER	*BLCKHOLE*				
	11	VOID	*VACUUM*				

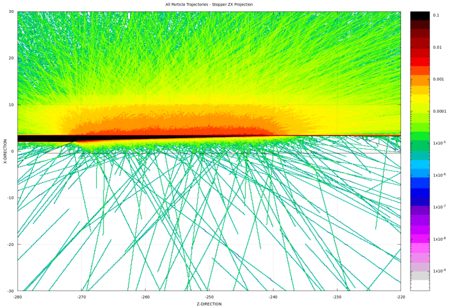
BLCKHOLE is assigned as a material to the DEWAR and SECOND_STOPPER regions for scoring the **deposited energy** therein.

GRAVEYARD†: External area, with an infinite absorption cross section, all particles vanish when they enter.

Running Simulations

Tracing the trajectories of all the particles on the entire model (image on the left) as well as when they hit the stopper (image on the right) projected on the ZX plane.



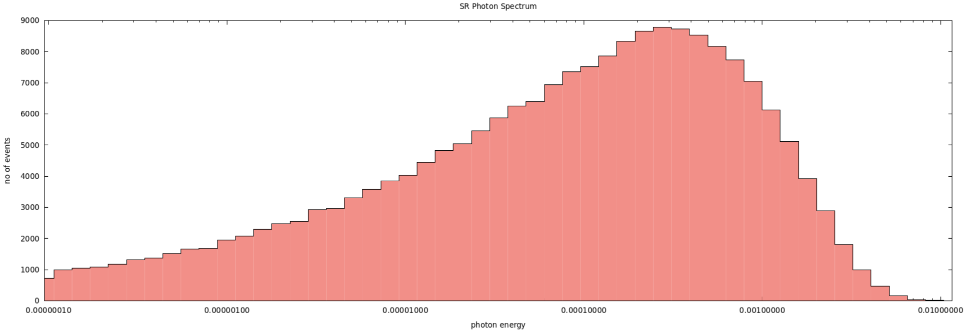


Some of the SR escapes the stopper, to be captured by the next stopper. **FLUKA** gives the average energy absorbed in every region per incident photon. An **energy deposition** analysis per region will follow for each case listed previously.

FLUKA Results

At $182.5 GeV$ *average beam kinetic energy* (top threshold):

- the *critical energy* is $1.25 MeV$,
- average photon energy $\sim 0.4 MeV$,
- SR hits the stopper $\sim 27m$ downstream.



Total energy histogram (source: [7])

Case I

Energy Deposition per Region

CASE I (200000 primaries)				
Region #	ID	**Name**	**Material**	ENERGY Density GeV/cm**3/one beam particle
1	1	DEWAR	**BLCKHOLE**	3.36E-06
2	2	CRYOSTAT	**VACUUM**	0.00E+00
3	3	BP_SSS_3M	**COPPER**	1.81E-07
4	4	ABSORBER_BP	**VACUUM**	0.00E+00
5	5	ABSORBER_FRONT	**VACUUM**	0.00E+00
6	6	BP_TAPER	**COPPER**	2.75E-08
7	7	BP_32mm	**COPPER**	3.25E-05
8	8	STOPPER	**TUNGSTEN**	3.28E-04
9	9	GRAVEYARD	**BLCKHOLE**	4.55E-05
10	10	SECOND_STOPPER	**BLCKHOLE**	1.30E-07
11	11	VOID	**VACUUM**	0.00E+00
Total (integrated over volume):				4.10E-04

Total_SR_Energy	4.10E-04
Total_Incident_SR_Energy	4.10E-04
% of the **Total_Incident_SR_Energy** absorbed by the DEWAR	0.82%
% of the **Total_Incident_SR_Energy** absorbed by the CRYOSTAT	0.00%
% of the **Total_Incident_SR_Energy** absorbed by the BP_SSS_3M	0.04%
% of the **Total_Incident_SR_Energy** absorbed by the ABSORBER_BP	0.00%
% of the **Total_Incident_SR_Energy** absorbed by the ABSORBER_FRONT	0.00%
% of the **Total_Incident_SR_Energy** absorbed by the BP_TAPER	0.01%
% of the **Total_Incident_SR_Energy** absorbed by the BP_32mm	7.95%
% of the **Total_Incident_SR_Energy** absorbed by the STOPPER	80.07%
% of the **Total_Incident_SR_Energy** absorbed by the GRAVEYARD	11.12%
% of the **Total_Incident_SR_Energy** absorbed by the SECOND_STOPPER	0.03%

The formula used for calculating **total incident SR energy** percentages deposited in each region can be parametrized as follows.

$$RelativeEnergyX := \frac{EnergyX}{TotalEnergy - EscapingEnergy}\ \%,$$

where $X \in \{\texttt{DEWAR}, \ \ldots, \ \texttt{SECOND\_STOPPER}\}$

and *EscapingEnergy* = the amount of energy absorbed by the SECOND_STOPPER.

Case II

Energy Deposition per Region

CASE 2 (200000 primaries)				
Region #	ID	Name	Material	ENERGY Density GeV/cm**3/one beam particle
1	1	DEWAR	BLCKHOLE	1.18E-06
2	2	CRYOSTAT	IRON	2.18E-06
3	3	BP_SSS_3M	COPPER	1.96E-07
4	4	ABSORBER_BP	VACUUM	0.00E+00
5	5	ABSORBER_FRONT	VACUUM	0.00E+00
6	6	BP_TAPER	COPPER	3.65E-08
7	7	BP_32mm	COPPER	3.26E-05
8	8	STOPPER	TUNGSTEN	3.28E-04
9	9	GRAVEYARD	BLCKHOLE	4.58E-05
10	10	SECOND_STOPPER	BLCKHOLE	1.12E-07
11	11	VOID	VACUUM	0.00E+00
Total (integrated over volume):				4.10E-04

Total_SR_Energy	4.10E-04
Total_Incident_SR_Energy	4.10E-04
% of the Total_Incident_SR_Energy absorbed by the DEWAR	0.29%
% of the Total_Incident_SR_Energy absorbed by the CRYOSTAT	0.53%
% of the Total_Incident_SR_Energy absorbed by the BP_SSS_3M	0.05%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_BP	0.00%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_FRONT	0.00%
% of the Total_Incident_SR_Energy absorbed by the BP_TAPER	0.01%
% of the Total_Incident_SR_Energy absorbed by the BP_32mm	7.96%
% of the Total_Incident_SR_Energy absorbed by the STOPPER	79.99%
% of the Total_Incident_SR_Energy absorbed by the GRAVEYARD	11.17%
% of the Total_Incident_SR_Energy absorbed by the SECOND_STOPPER	0.03%

- The **energy deposition** on the DEWAR has decreased significantly when **IRON** is assigned as a material to the CRYOSTAT (i.e. transitioning from **CASE I** $\rightarrow$ **CASE II**).
- The same trend appears as we advance towards **CASE V**, which is a more **realistic scenario** in terms of material assignment.

Case III

Energy Deposition per Region

The **energy deposition** on the DEWAR is decreasing, but the DEWAR is still receiving a large amount of energy, i.e. 974 *eV* per incident photon.

CASE 3 (200000 primaries)				
Region #	ID	Name	Material	ENERGY Density GeV/cm**3/one beam particle
1	1	DEWAR	**BLCKHOLE**	9.74E-07
2	2	CRYOSTAT	**IRON**	2.17E-06
3	3	BP_SSS_3M	**COPPER**	2.10E-07
4	4	ABSORBER_BP	**TUNGSTEN**	2.59E-07
5	5	ABSORBER_FRONT	**VACUUM**	0.00E+00
6	6	BP_TAPER	**COPPER**	3.78E-08
7	7	BP_32mm	**COPPER**	3.25E-05
8	8	STOPPER	**TUNGSTEN**	3.27E-04
9	9	GRAVEYARD	**BLCKHOLE**	4.57E-05
10	10	SECOND_STOPPER	**BLCKHOLE**	1.09E-07
11	11	VOID	**VACUUM**	0.00E+00
Total (integrated over volume):				4.09E-04

Total_Incident_SR_Energy	4.09E-04
% of the Total_Incident_SR_Energy absorbed by the DEWAR	0.24%
% of the Total_Incident_SR_Energy absorbed by the CRYOSTAT	0.53%
% of the Total_Incident_SR_Energy absorbed by the BP_SSS_3M	0.05%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_BP	0.06%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_FRONT	0.00%
% of the Total_Incident_SR_Energy absorbed by the BP_TAPER	0.01%
% of the Total_Incident_SR_Energy absorbed by the BP_32mm	7.94%
% of the Total_Incident_SR_Energy absorbed by the STOPPER	79.99%
% of the Total_Incident_SR_Energy absorbed by the GRAVEYARD	11.17%
% of the Total_Incident_SR_Energy absorbed by the SECOND_STOPPER	0.03%

Case IV

Energy Deposition per Region

CASE 4 (200000 primaries)				
Region #	ID	**Name**	**Material**	ENERGY Density GeV/cm**3/one beam particle
1	1	DEWAR	**BLCKHOLE**	2.14E-07
2	2	CRYOSTAT	**IRON**	4.02E-08
3	3	BP_SSS_3M	**COPPER**	2.15E-07
4	4	ABSORBER_BP	**VACUUM**	0.00E+00
5	5	ABSORBER_FRONT	**TUNGSTEN**	5.38E-06
6	6	BP_TAPER	**COPPER**	4.28E-08
7	7	BP_32mm	**COPPER**	3.23E-05
8	8	STOPPER	**TUNGSTEN**	3.26E-04
9	9	GRAVEYARD	**BLCKHOLE**	4.29E-05
10	10	SECOND_STOPPER	**BLCKHOLE**	1.09E-07
11	11	VOID	**VACUUM**	0.00E+00
Total (integrated over volume):				4.07E-04

Total_SR_Energy	4.07E-04
Total_Incident_SR_Energy	4.07E-04
% of the Total_Incident_SR_Energy absorbed by the DEWAR	0.05%
% of the Total_Incident_SR_Energy absorbed by the CRYOSTAT	0.01%
% of the Total_Incident_SR_Energy absorbed by the BP_SSS_3M	0.05%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_BP	0.00%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_FRONT	1.32%
% of the Total_Incident_SR_Energy absorbed by the BP_TAPER	0.01%
% of the Total_Incident_SR_Energy absorbed by the BP_32mm	7.94%
% of the Total_Incident_SR_Energy absorbed by the STOPPER	80.07%
% of the Total_Incident_SR_Energy absorbed by the GRAVEYARD	10.54%
% of the Total_Incident_SR_Energy absorbed by the SECOND_STOPPER	0.03%

Assigning only the material of ABSORBER_BP to **VACUUM** and having the rest of the regions with their corresponding materials yields, that 0.5‰ of the **incident SR energy** reaches the DEWAR, which is comparable to the results obtained by M. Koratzinos (0.3‰ of the **incident SR energy** was estimated to reach the DEWAR).

Case V

Energy Deposition per Region

Shielding the DEWAR to the full extent yields a remarkable 0.1‰ of the **incident SR energy** reaching the DEWAR, that is 41.3 *eV* per incident photon, according to the simulations.

CASE 5 (200000 primaries)				
Region #	ID	**Name**	**Material**	ENERGY Density GeV/cm**3/one beam particle
1	1	DEWAR	**BLCKHOLE**	4.13E-08
2	2	CRYOSTAT	**IRON**	9.18E-09
3	3	BP_SSS_3M	**COPPER**	2.23E-07
4	4	ABSORBER_BP	**TUNGSTEN**	2.07E-07
5	5	ABSORBER_FRONT	**TUNGSTEN**	5.39E-06
6	6	BP_TAPER	**COPPER**	4.24E-08
7	7	BP_32mm	**COPPER**	3.22E-05
8	8	STOPPER	**TUNGSTEN**	3.26E-04
9	9	GRAVEYARD	**BLCKHOLE**	4.29E-05
10	10	SECOND_STOPPER	**BLCKHOLE**	1.13E-07
11	11	VOID	**VACUUM**	0.00E+00
Total (integrated over volume):				4.07E-04

Total_SR_Energy	4.07E-04
Total_Incident_SR_Energy	4.07E-04
% of Total_Incident_SR_Energy absorbed by the DEWAR	0.01%
% of the Total_Incident_SR_Energy absorbed by the CRYOSTAT	0.00%
% of the Total_Incident_SR_Energy absorbed by the BP_SSS_3M	0.05%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_BP	0.05%
% of the Total_Incident_SR_Energy absorbed by the ABSORBER_FRONT	1.32%
% of the Total_Incident_SR_Energy absorbed by the BP_TAPER	0.01%
% of the Total_Incident_SR_Energy absorbed by the BP_32mm	7.91%
% of the Total_Incident_SR_Energy absorbed by the STOPPER	80.11%
% of the Total_Incident_SR_Energy absorbed by the GRAVEYARD	10.53%
% of the Total_Incident_SR_Energy absorbed by the SECOND_STOPPER	0.03%

Remarks

- Results presented on the [141st FCC-ee Optics Design Meeting] by Michael Koratzinos, have been verified by performing simulations using the **exact layout** as it was exported by Inventor 2020, bypassing completely **FLUKA's** boolean geometry definition.
- A variety of cases has been simulated with **FLUKA** and the arrangement examined on the final case is remarkably efficient, enabling $< 1W$ of heat load to get deposited to the `DEWAR`.
- The precise heat load calculation, taking into account the **total radiation power per arc length** (in accordance with **table 2.2** of the CDR [1]), is given by the expression:

$$
\begin{aligned}
HeatLoad_{DEWAR} &:= RelativeEnergy_{DEWAR} \times PowerArcLength \times LengthSSS \\
&= 0.0001 \times 1.2 \frac{\text{kW}}{\text{m}} \times 4.6 \text{ m} \\
&\approx 0.55 \text{ W}.
\end{aligned}
$$

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