Conclusions on the Energy Deposition and Material Studies for the Cold Powering System

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5th Joint HiLumi LHC-LARP Annual Meeting

CERN 26-30 October 2015

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- Recall of the working program from the first HiLumi LHC Collaboration Meeting (CERN 16-18th November 2011)
- Irradiation test simulations, material comparison and possible SCL routing
- Progress in defining the cable structure, bulk, mixture, real one
- Almost definitive SCL routing
- Neutrons and MgB_2
- P7
- Conclusions

High Luminosity LHC

WP6 – Cold Powering

Task 6.4. Energy deposition and material studies

- To calculate maps of energy deposition from collision debris and beam losses
- To calculate the induced radiation on the cold powering components
- To study the potential effect of radiation on advanced superconducting materials

(Possible) Solution(III)

How to proceed

- Collect and update all the data available in literature

- Perform an irradiation test on the material under study
(maybe useful to reproduce a test reported in literature)

- Benchmark between the simulation code and the test
Correlate the evaluated DPA with the material characteristics (resistivity, thermal conductivity, …)

- Once the reliability of the code has been stated (in most cases it is not necessary, because the most used codes ondergo to continuous comparisons and benchmarking)

- Simulate the irradiation effects with the actual fluencies and parameters to the components

Work Progress

- Simulation of irradiation with different type of beams on MgB_2, BSCCO, YBCCO

(While waiting for the routing of the SCL in the cavern and the cable layout to create the FLUKA geometry

- Evaluation of the different energy neutron beam effects on MgB_2 with ^{10}B, ^{11}B and ^{nat}B composition

(can the n flux damage the B in SCL?)

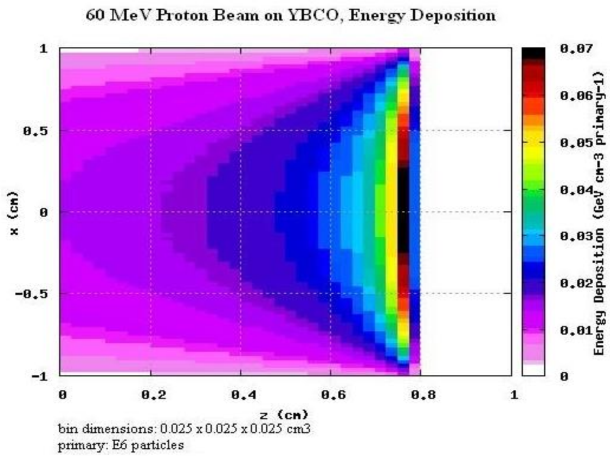
Irradiation Test Simulations

60 MeV p on YBCO and BSCCO

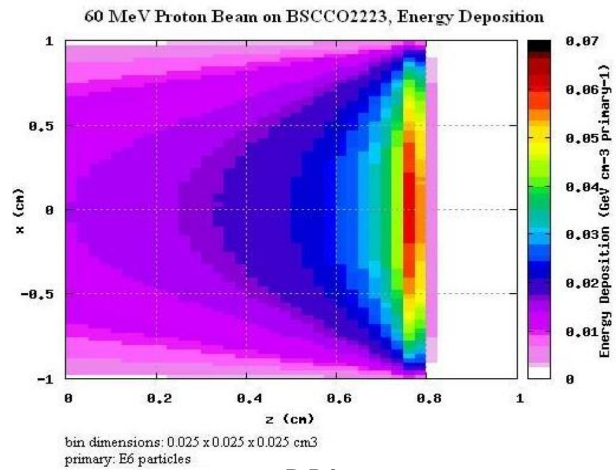
beam spot : 2 cm ; Fluence2x10^9 n/s x 1 d ; target (2x2x1 cm^3)

Energy Deposition

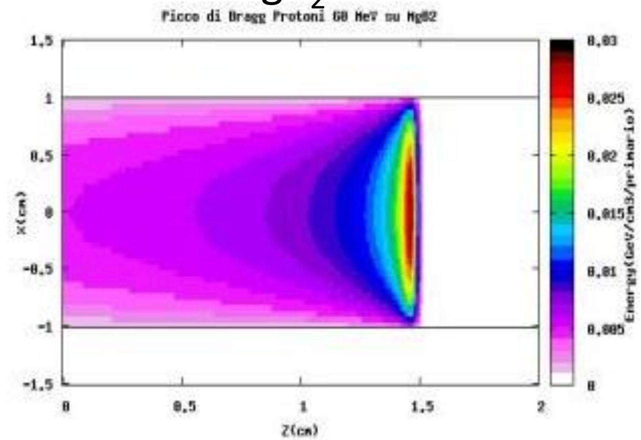
YBCO



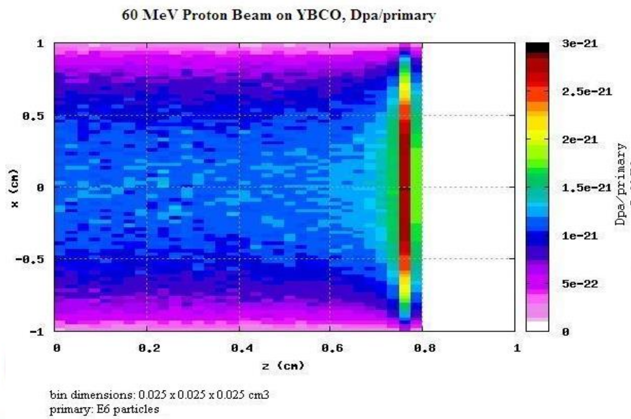
BSCCO2223

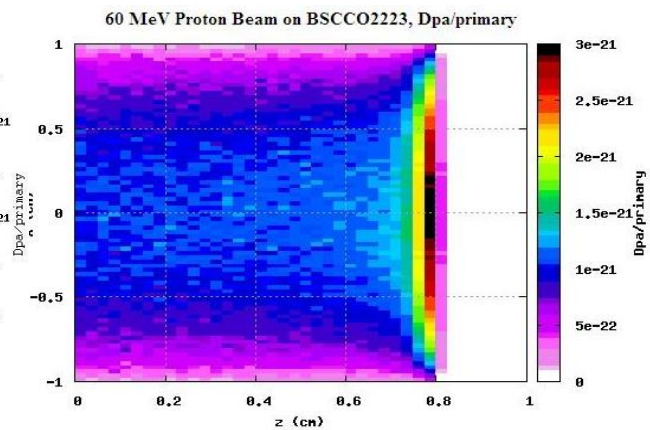


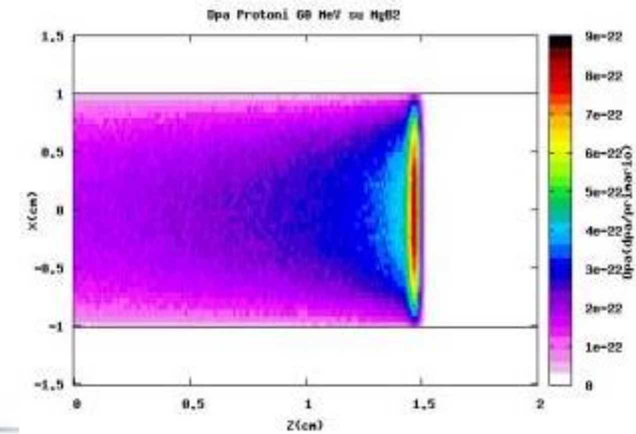
MgB_2



DPA







Irradiation Test Simulations

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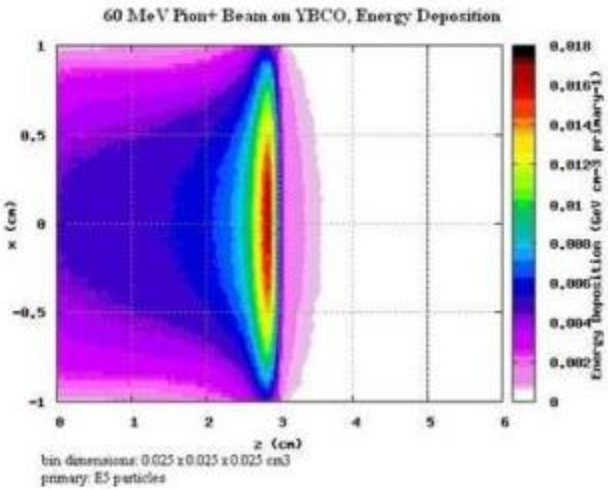
Energy Deposition

YBCO



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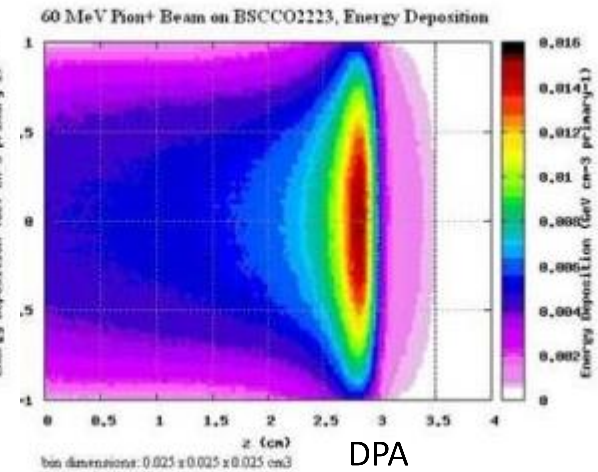
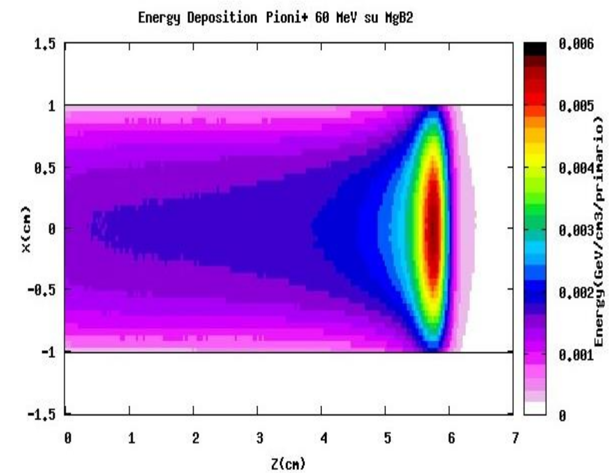
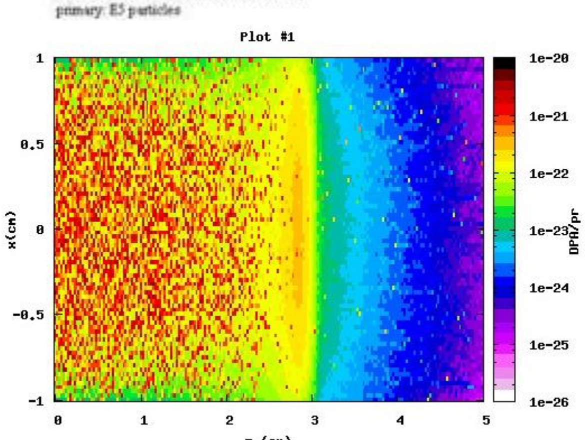
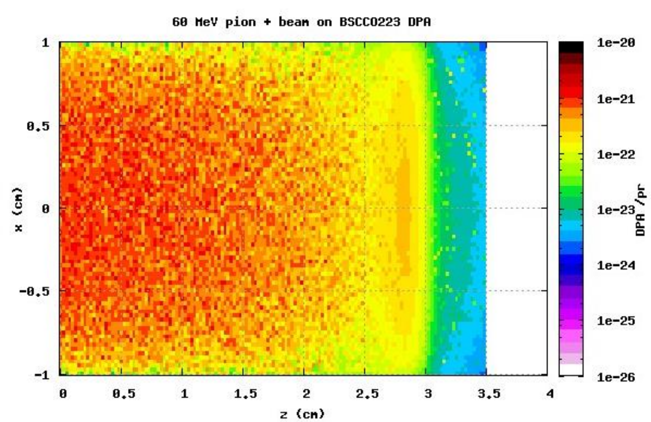


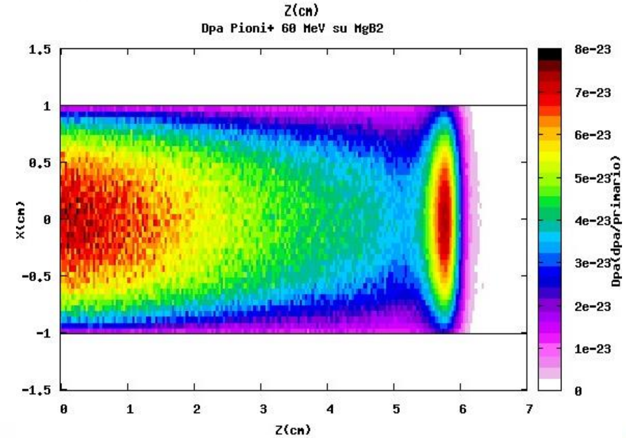
MgB$_2$



DPA







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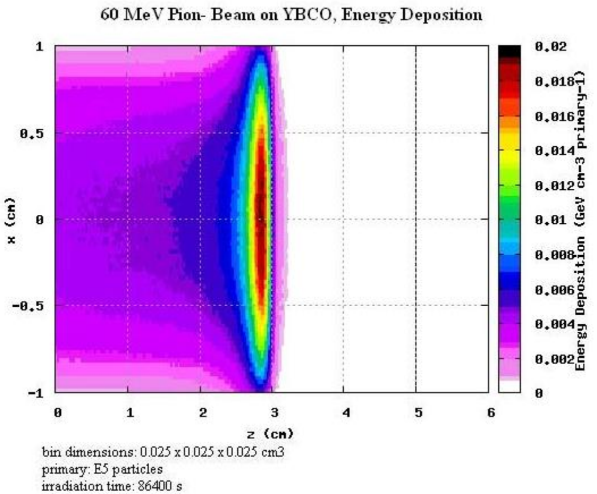
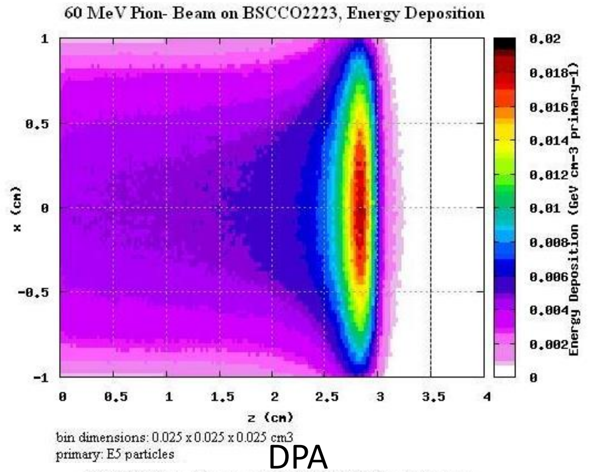
Energy Deposition

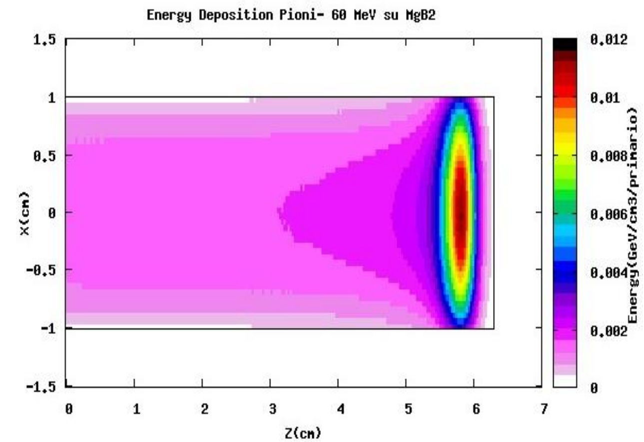
YBCO

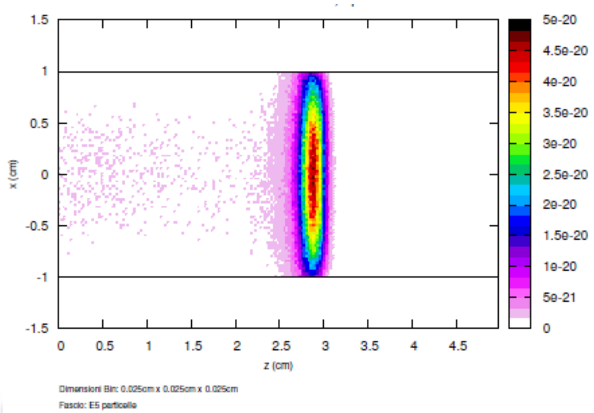


BSCCO2223

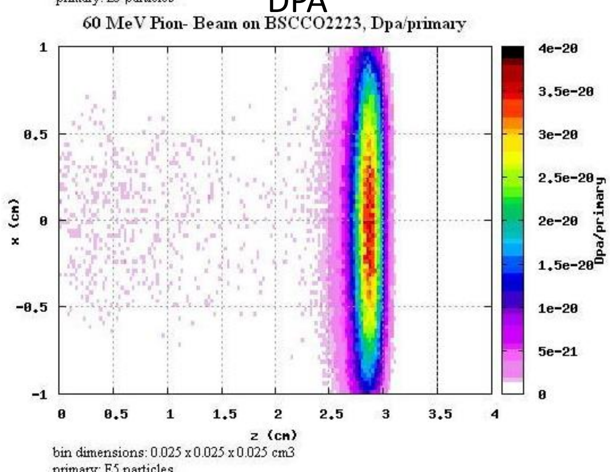


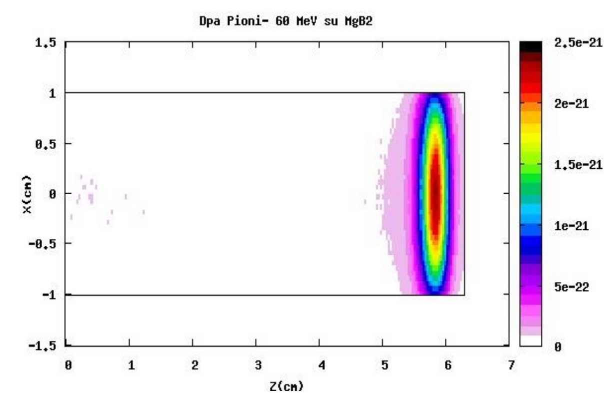
MgB_2





DPA





Irradiation Test Simulations

Many other data are available (Activation, activated elements, decay time etc.)

Other cases have been studied.

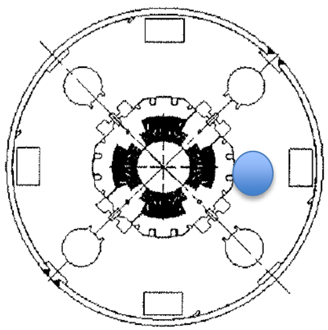
142 MeV protons (Brookhaven energy)

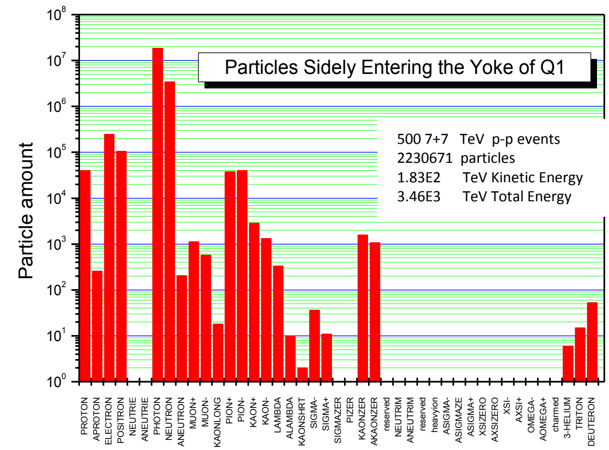
1.5 GeV γ (LHC peak energy photons on low-beta quad coils)

1 GeV $\pi^{\pm}$ (")

Material Comparison in an Almost Real Case

SCL (Homogeneous bulk BSCCO, YBCO, MgB_2)
Inside the Q1 iron yoke

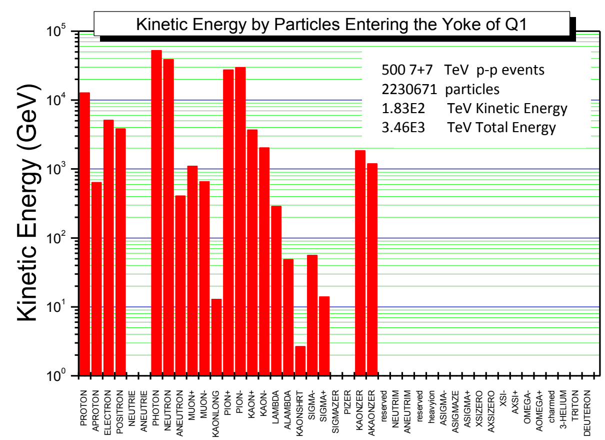




83% of the particles are photons
15% are neutrons

29% of the kinetic energy is from photons
21% from neutrons
31% from pions

1.5% of the total energy is from photons
94% from neutrons



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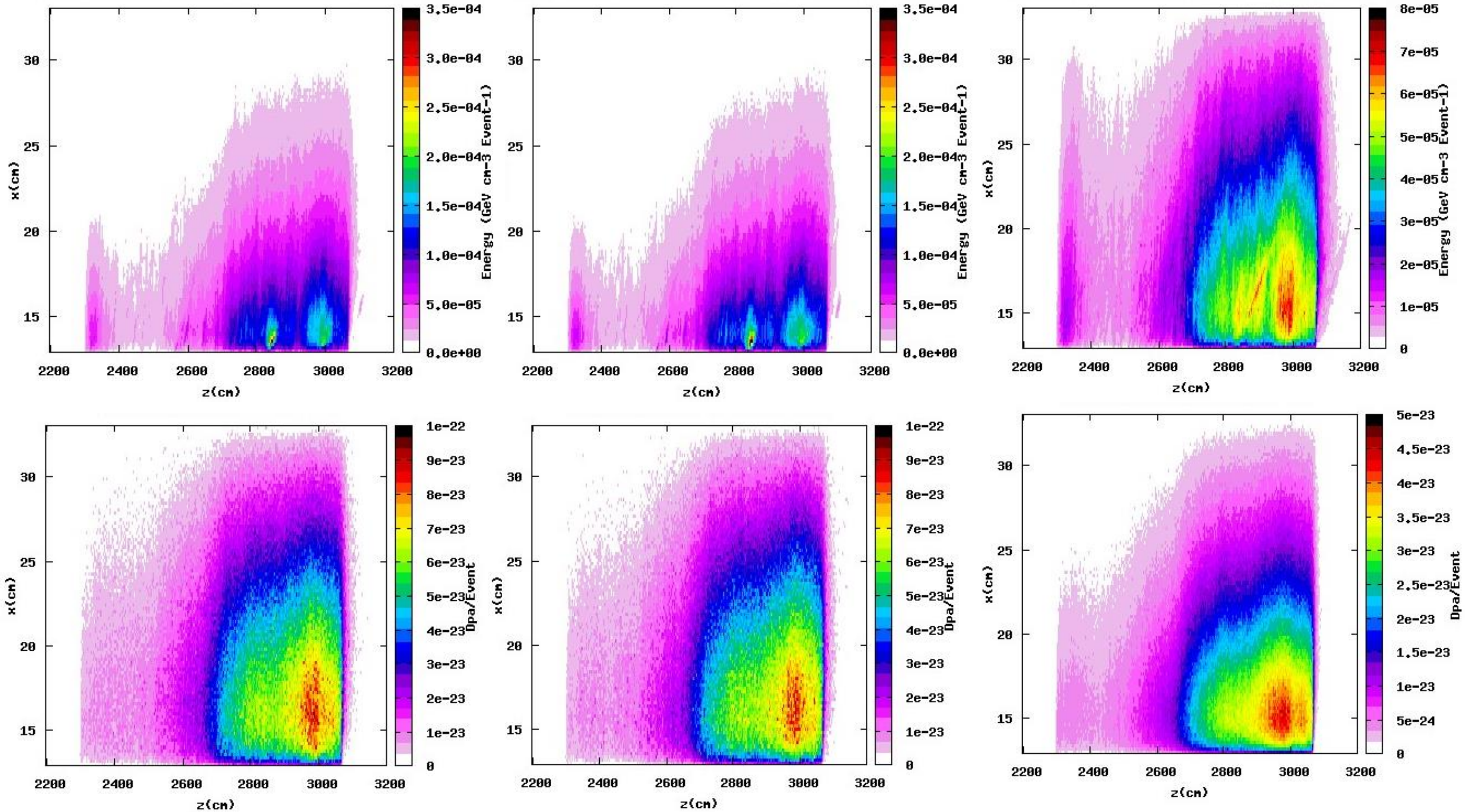
Energy Deposition (top) and DPA (bottom)

YBCO BSCCO MgB_2

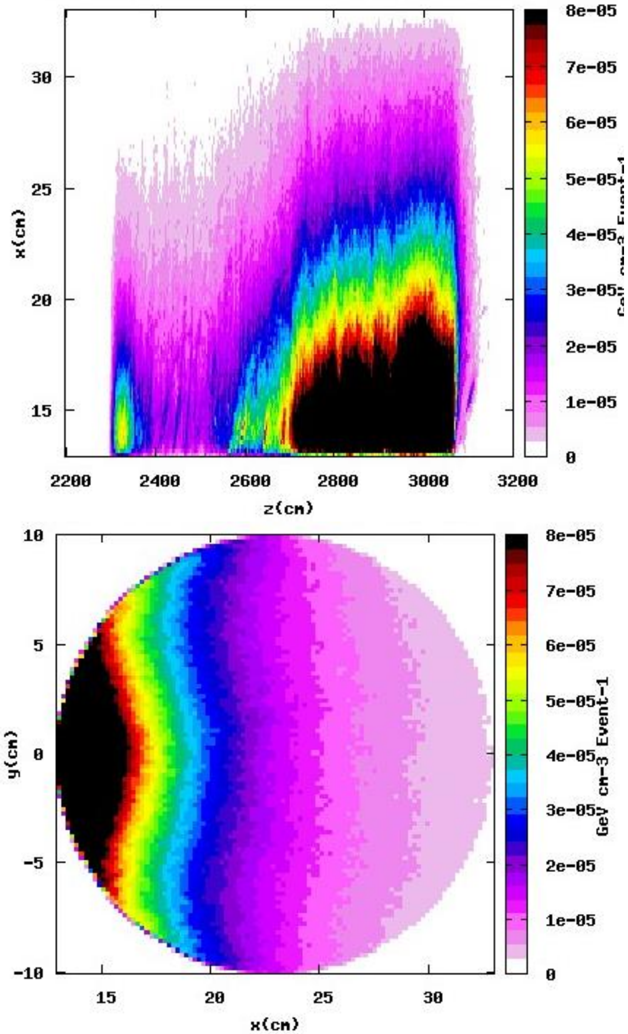


(the scoring bin dimensions are 0.2x0.2x3.3 cm^3).

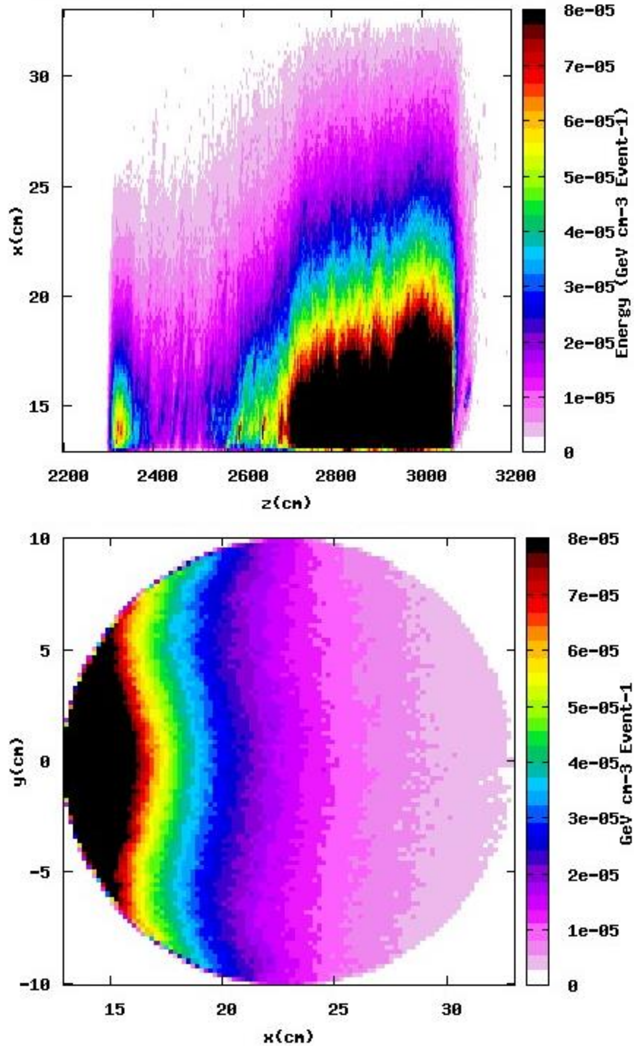
The abscissa is the distance from the IP.

Energy Deposition (same scale)

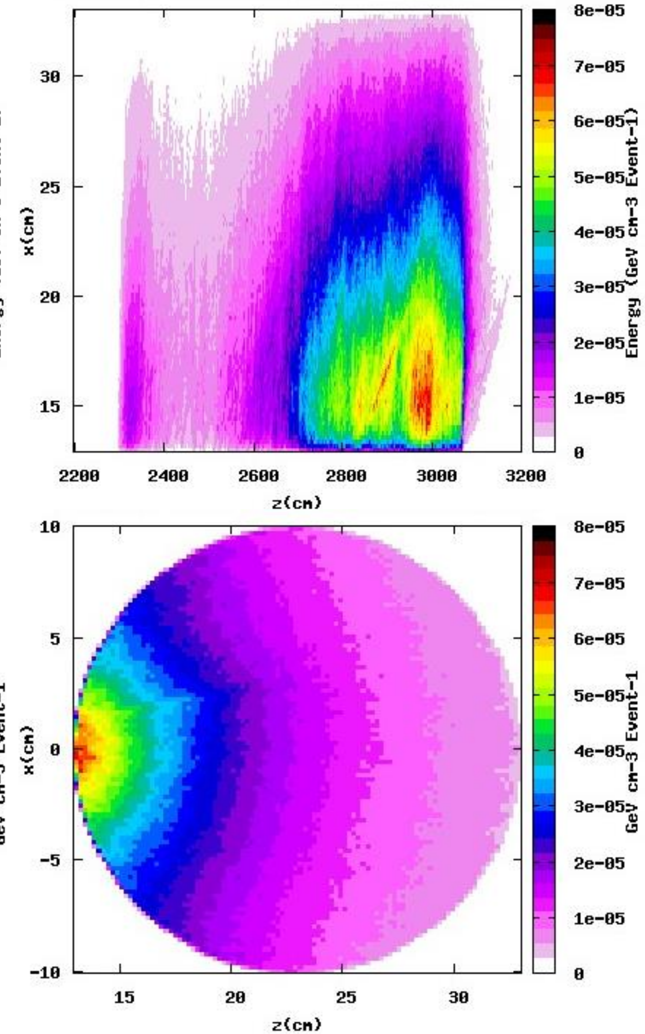
YBCO



BSCCO



MgB_2



Material Comparison

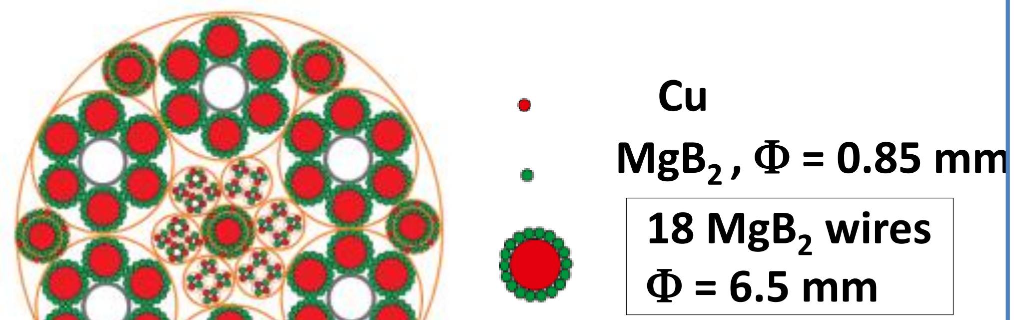
- BSCCO and YBCO are similar
- MgB_2 shows a lower energy deposition and DPA

Simulation progress

- BSCCO and YBCO are similar (for the energy deposition and DPA aspects); MgB_2 has a slightly lower energy deposition

- Definitive definition of the cable geometry and material composition

- Simulation of this cable aside Q1 (P1 geometry), to compare the bulk MgB_2 cable with the composite one



Φext ~ 65 mm

Cable layout
6x20kA , 7x3kA,
4x0.4kA, 8x.12kA

Courtesy A. Ballarino

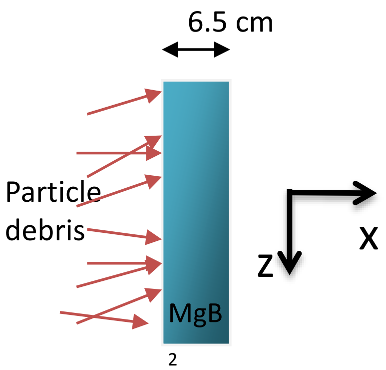
Cable Material Composition

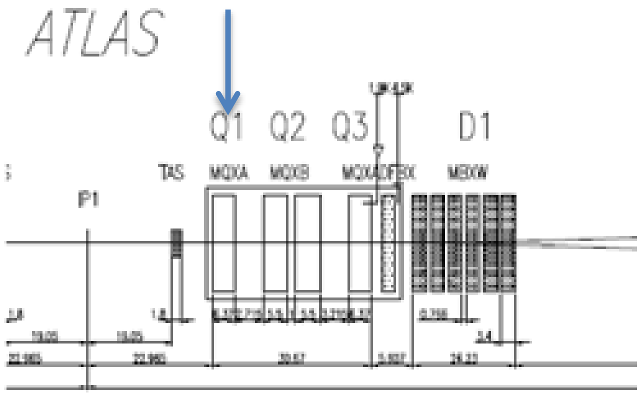
Material composition of the cable for the Monte Carlo simulations

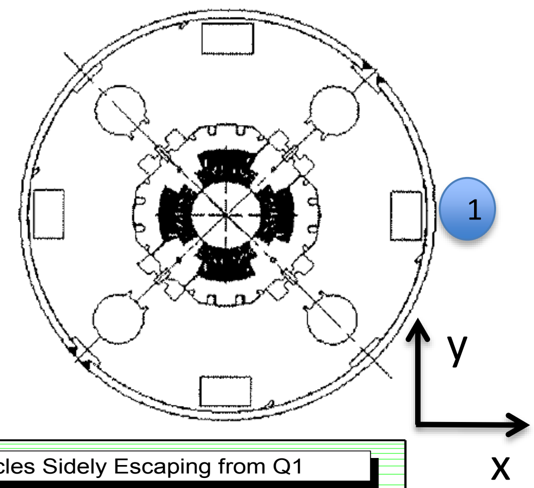
MATERIAL	ATOM CONTENT	PARTIAL DENSITIES (g/cm^3)
MAGNESIUM	0.1225	0.2192
BORON	0.24501	0.195
COPPER	0.48231	2.2563
HYDROGEN	2.03E-02	1.51E-03
CARBON	4.88E-02	4.31E-02
NITROGEN	4.07E-03	4.19E-03
OXYGEN	1.02E-02	1.20E-02
HELIUM	8.89E-03	2.62E-03
IRON	4.05E-02	0.16655
NICKEL	5.55E-03	2.40E-02
CHROMIUM	1.19E-02	4.55E-02

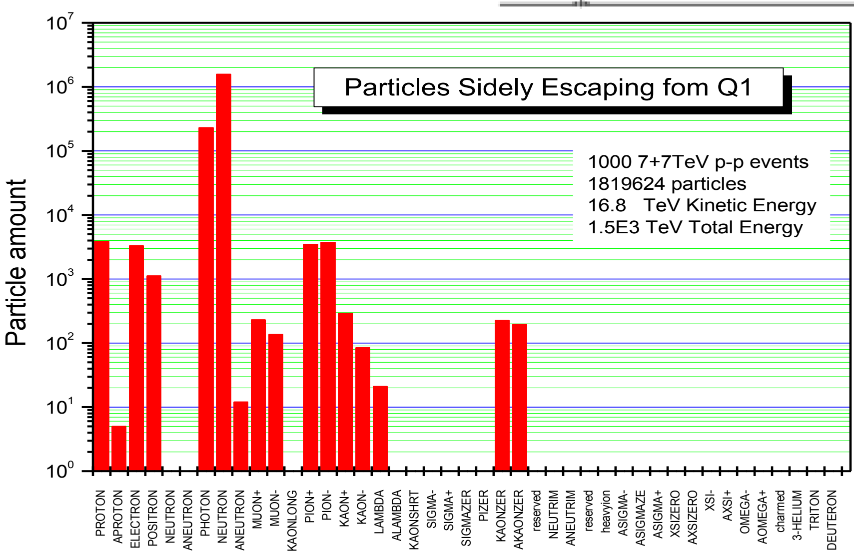
The resulting density of the cable is 2.97 g/cm^3, with a radiation length of 4.846 cm.

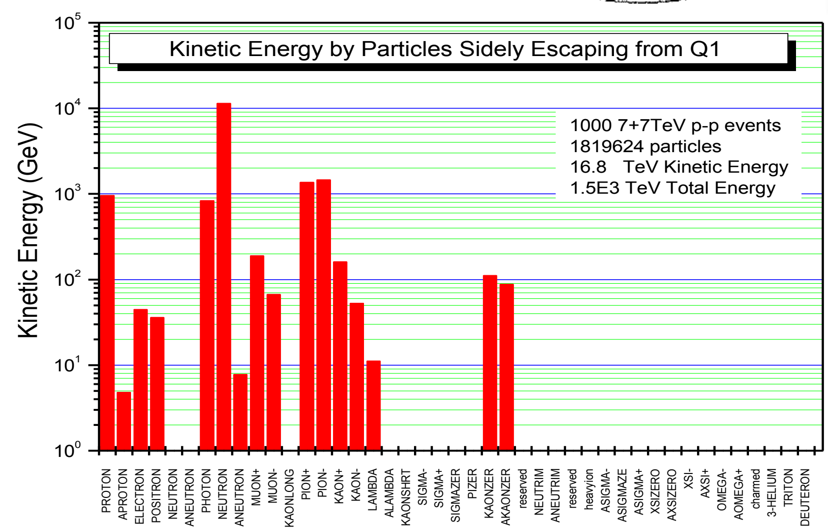
Material (Cable) Comparison











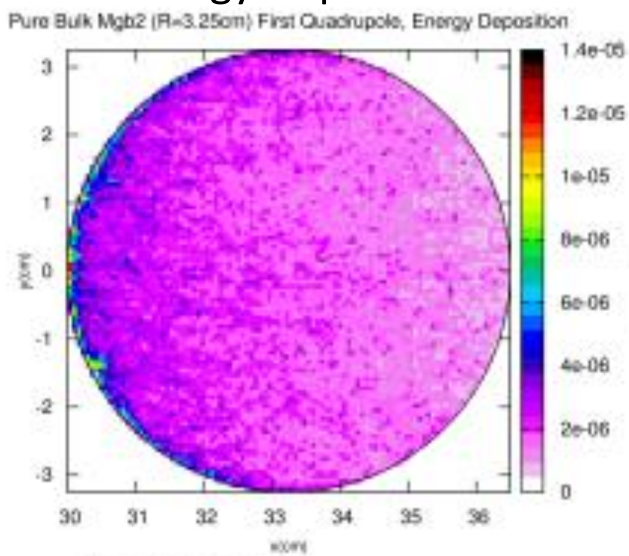
68% of the kinetic energy is from neutrons
17% from pions
6% from protons
5% from photons

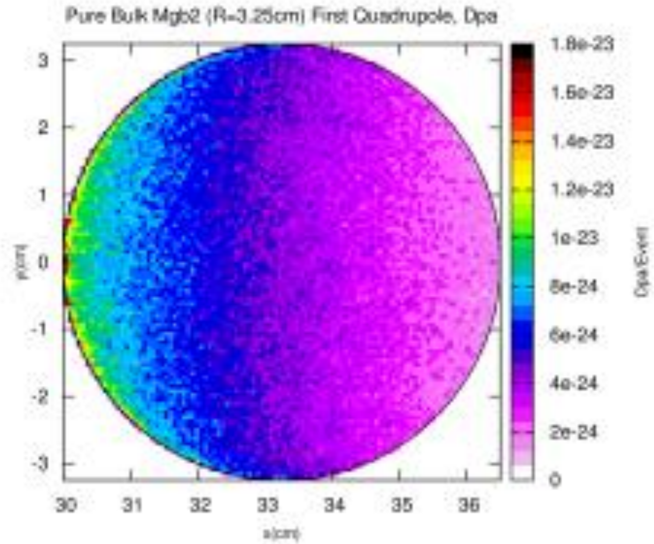
Cable Comparison

Energy Deposition

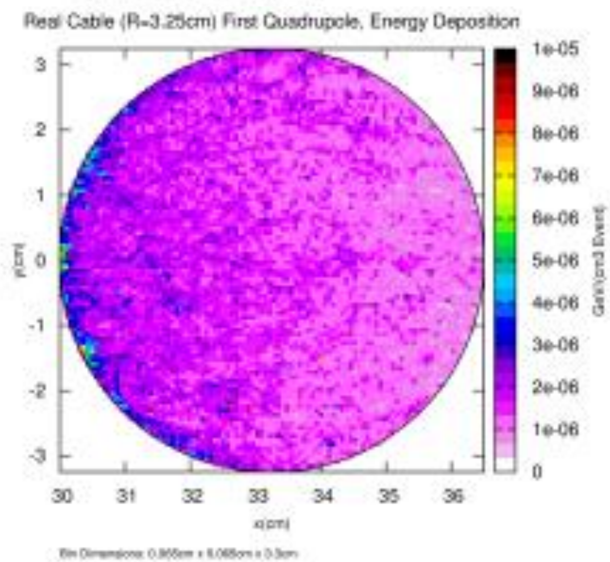
DPA

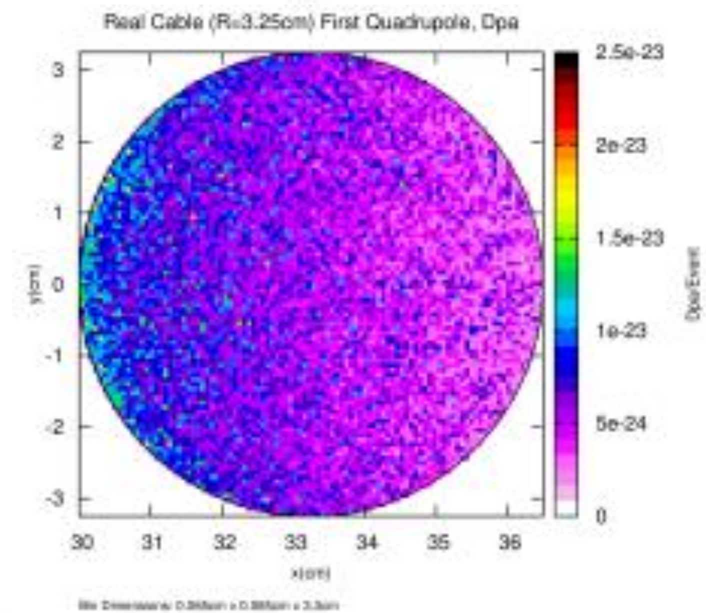
Pure Bulk MgB_2





"Mixture" Cable



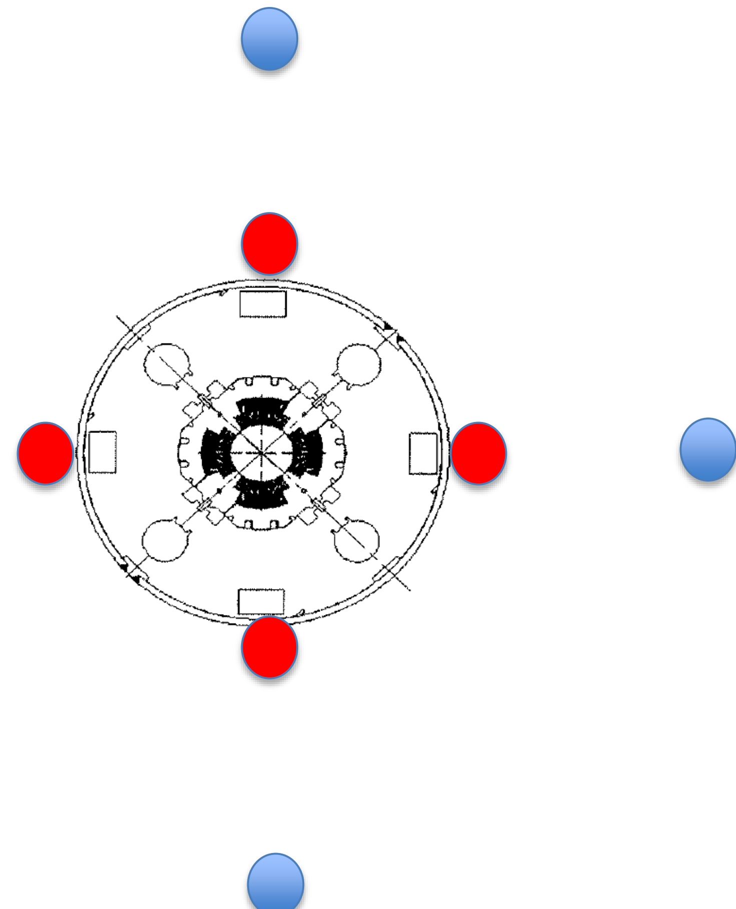


Scaling factor to $3000 fb^{-1} = 3x10^{17}$

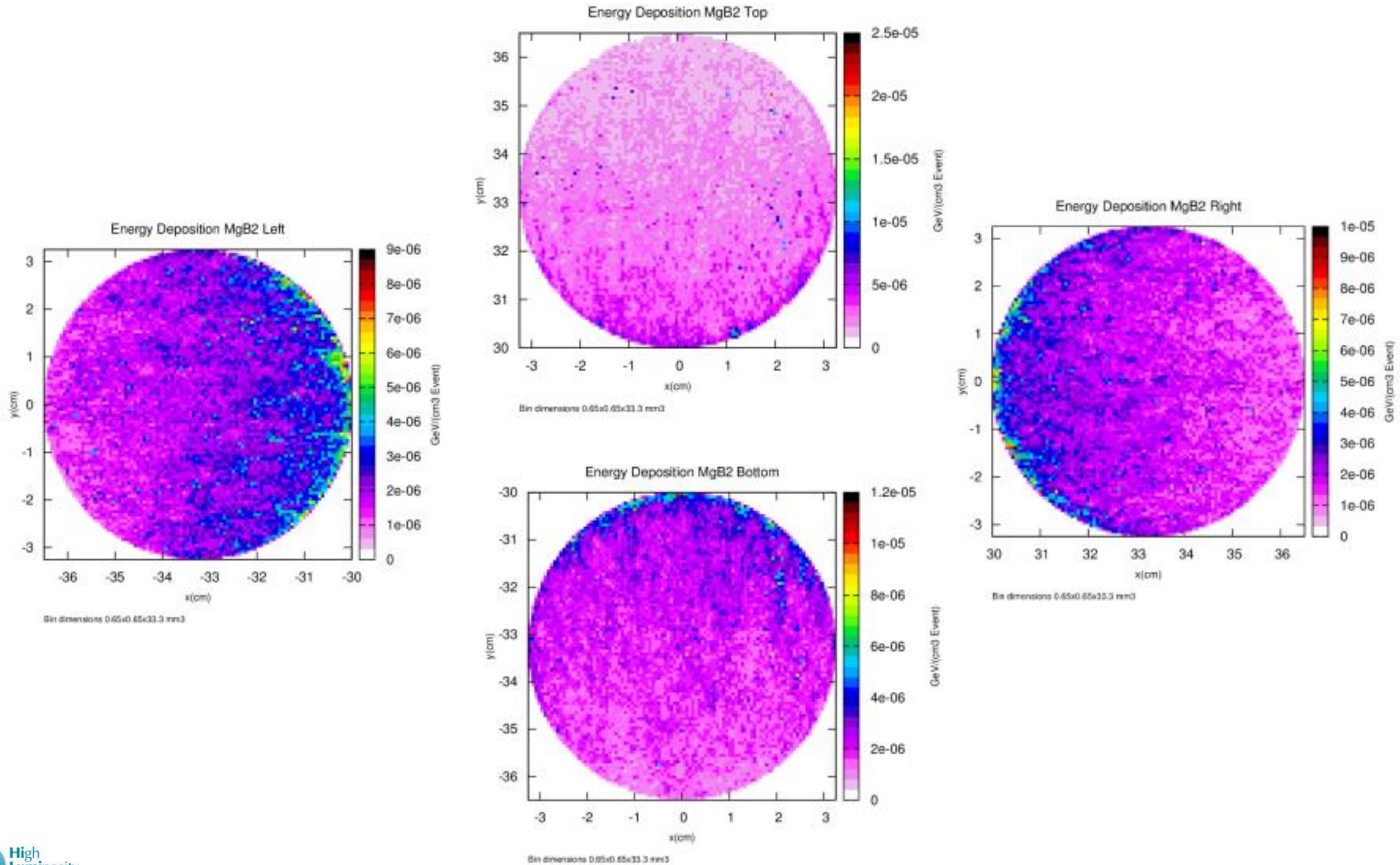
Towards the Final Configuration

The definitive layout was not defined (2013) so we simulated the energy deposition in cables running parallel to Q1 (as done so far) located at different positions.

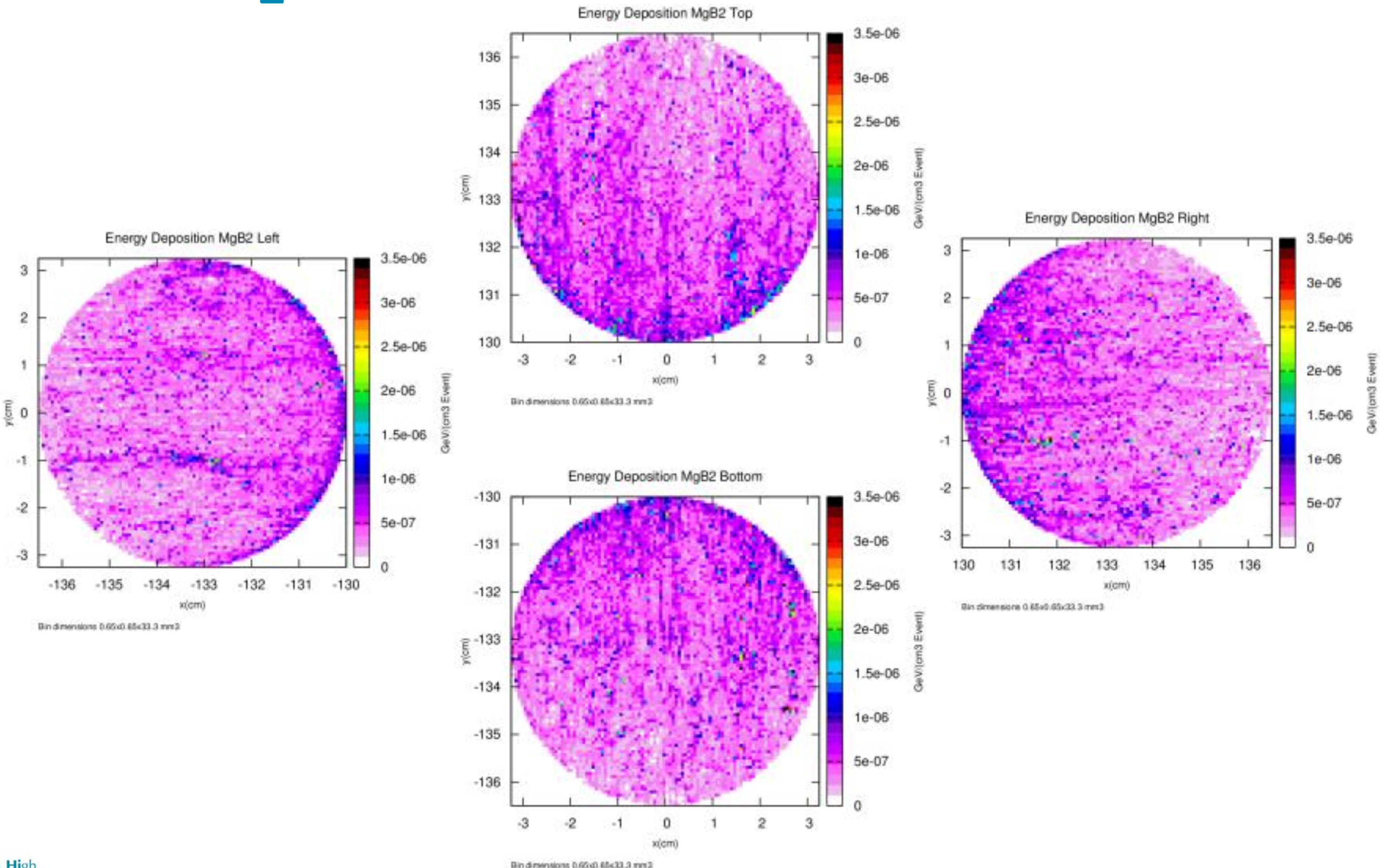
- in contact with Q1 (Near case) at 0°, 90°, 180° and 270°
- at 1 m distance from the magnet (Far case), at the same angular position.



MgB_2 cable aside Q1 (Near case)



MgB_2 cable at 1 m from Q1 (Far case)



Dose and DPA

Total Dose and Average DPA for the examined cases

(Data normalized at 3000 fb^{-1})

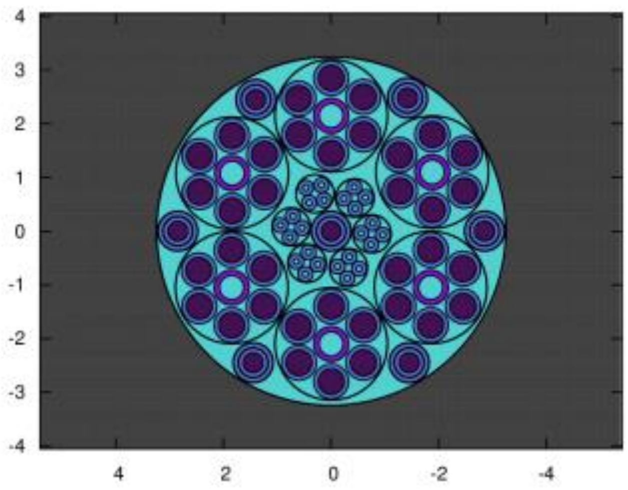
	Near		Far	
Cable	Dose (kGy) ± err%	DPA±err%	Dose (kGy) ± err%	DPA±err%
1 (θ=0°)	32.8 ± 0.5	2.3E-06 ± 0.4	7.1 ± 1.2	4.8E-07 ± 0.8
2 (θ=90°)	38.7 ± 0.3	2.5E-06 ± 0.3	7.6 ± 2.1	5.0E-07 ± 0.7
3 (θ=180°)	35.3 ± 0.6	2.4E-06 ± 0.4	6.5 ± 1.8	4.8E-07 ± 1.0
4 (θ=270°)	34.2 ± 0.5	2.3E-06 ± 0.2	7.4 ± 1.3	4.9E-07 ± 0.6

As we can see the values of dose and DPA should not endanger the cables.
Let’s remind that this configuration is a conservative one, being aside the first quad.

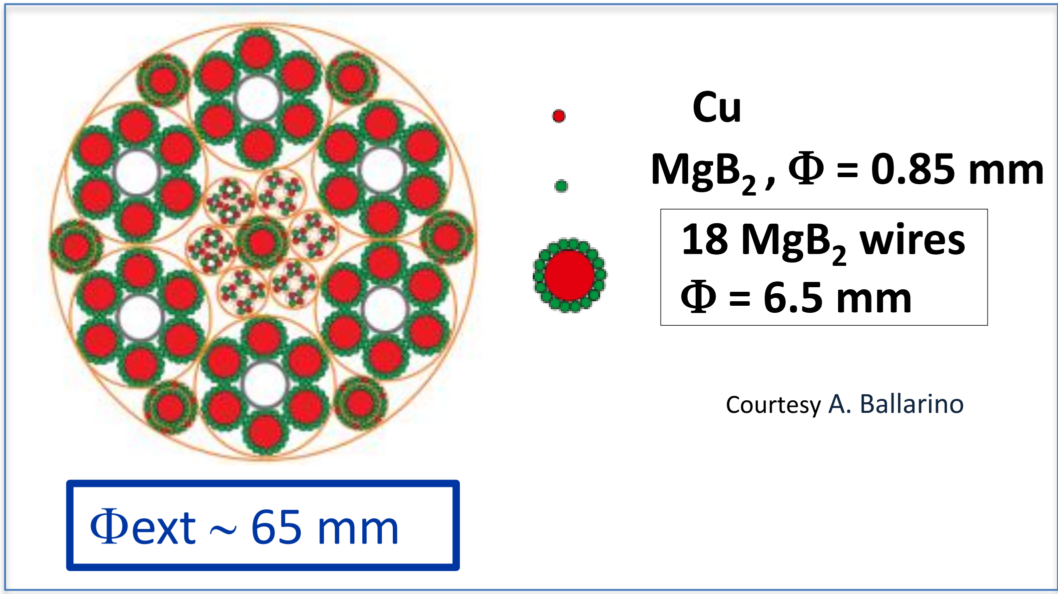
SC Link in FLUKA

- Refinement and definitive definition of the cable geometry

- MgB_2 bulk
- $MgB2+SS+Cu+He$ homogeneous mixture
- Detailed description



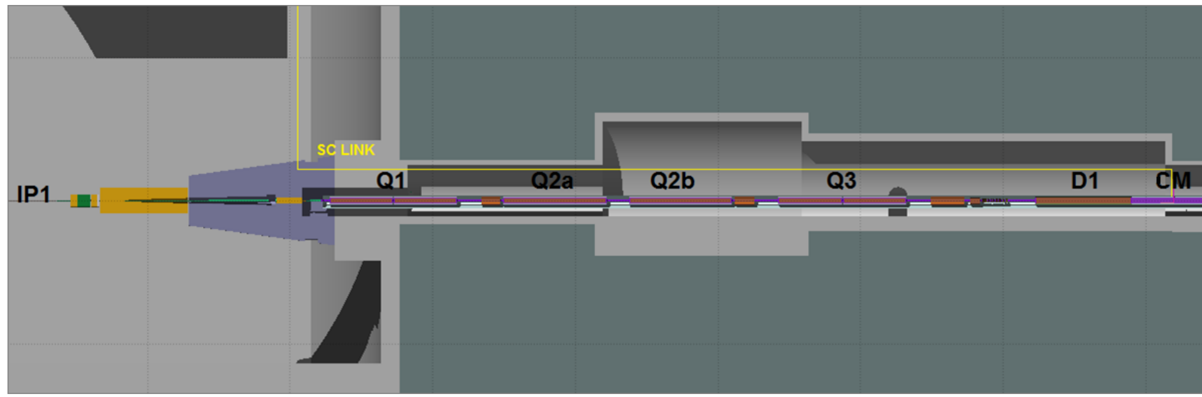
FLUKA geometry



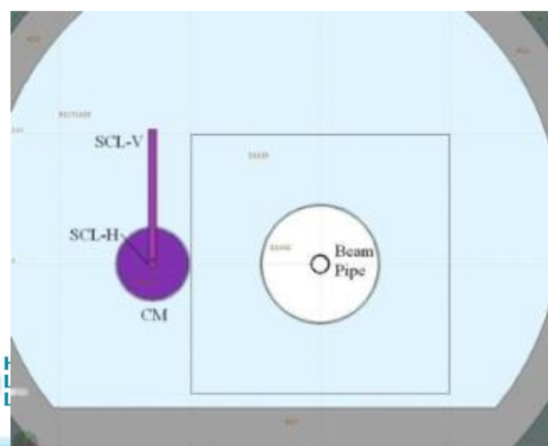
SCL Routing into the tunnel

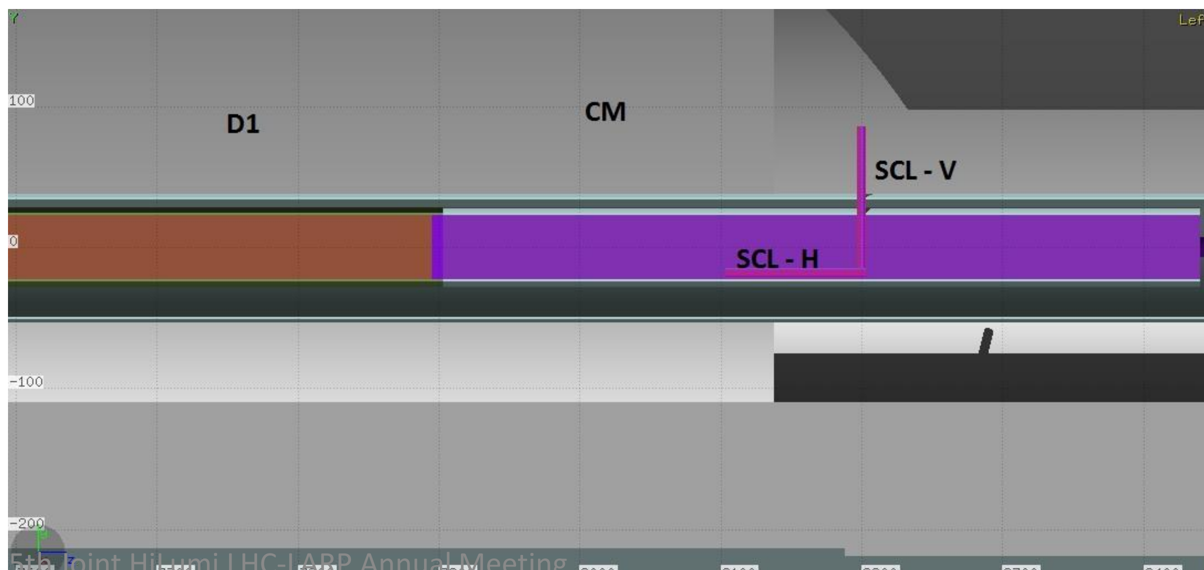
Two possible routings of the SCL have been investigated:

1) Arrive from surface closer to IP1. The SCL runs aside the triplet and then connect to the Connection Module (CM), aside the beam pipe



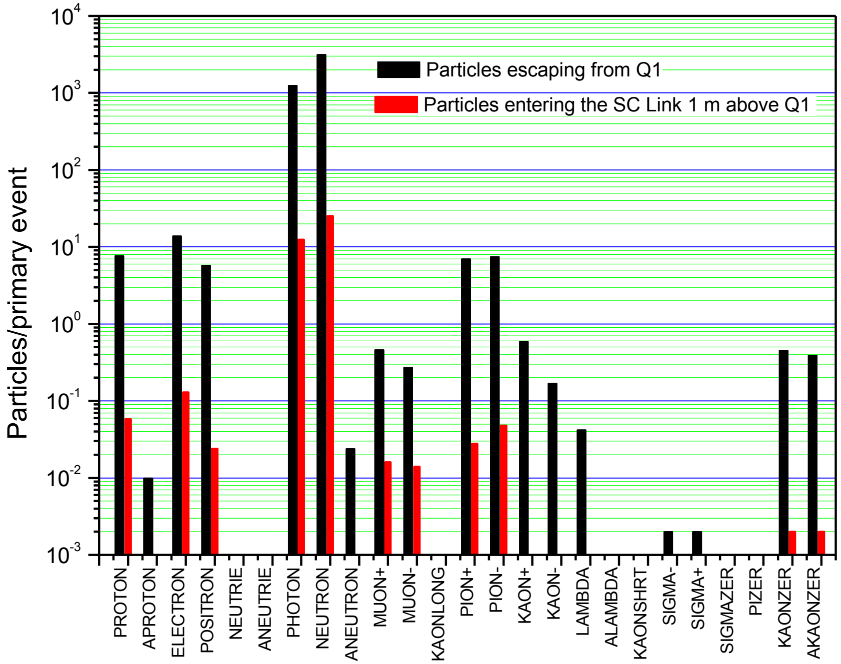
2) Arrive from surface after D1

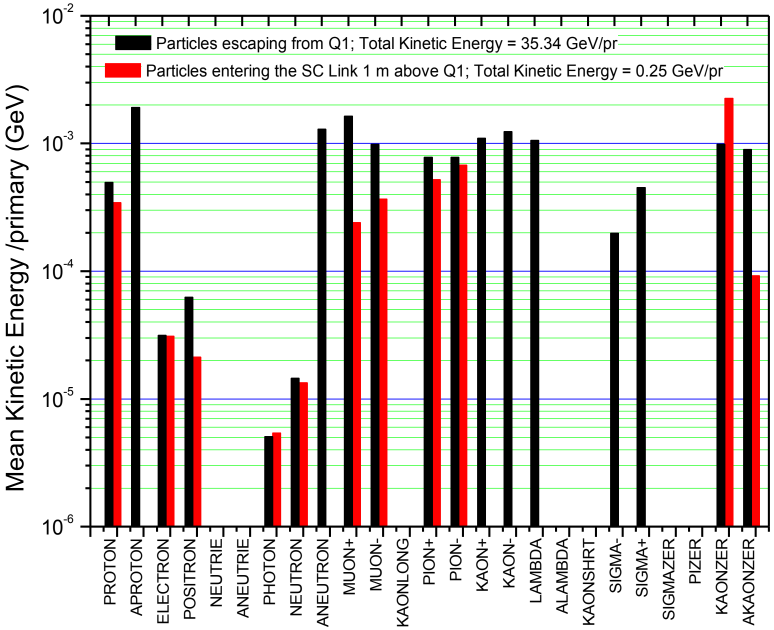




Particle Fluencies (option 1)

(From Q1 to the SCL 1 m above Q1)





Escaping from Q1

28% photons (1250 ph/event)

71% neutrons (3143 n/event)

9% of the kinetic energy is from photons (3.2 GeV/event)

65% from neutrons (22.8 GeV/event)

Entering the SCL

33% photons (12.5 ph/event)

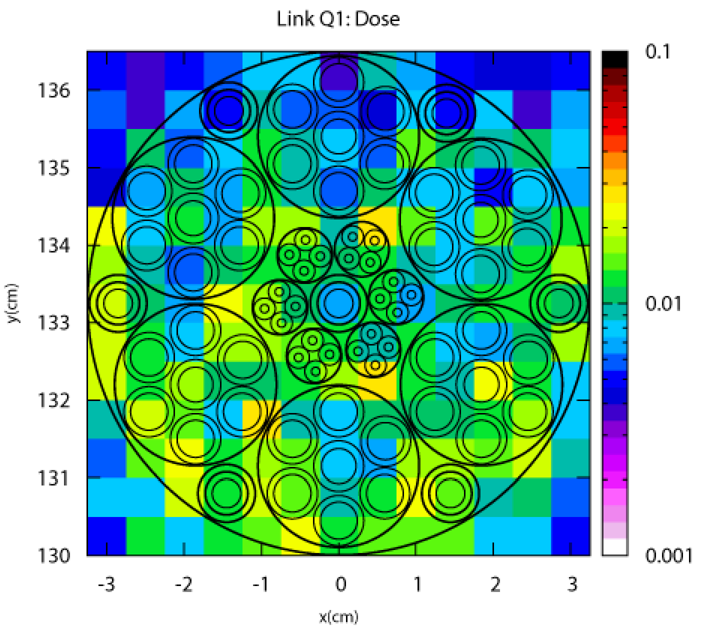
67% are neutrons (25.4 n/event)

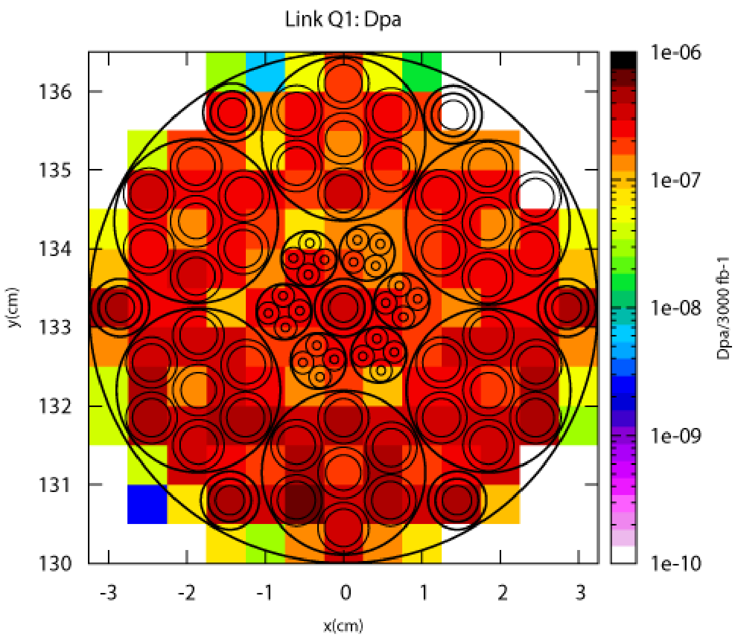
14% of the kinetic energy is from photons (33.8 MeV/event

68% from neutrons (170 MeV/event)

Option 1

(From Q1 to the SCL 1 m above Q1)





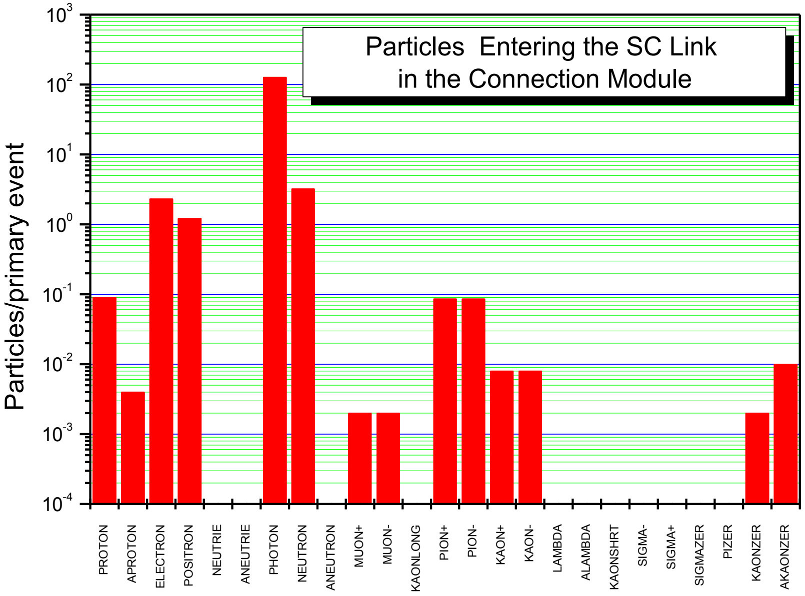
The maximum dose is of the order of some 0.01 MGy (at $3000fb^{-1}$).
The maximum DPA is about 10^{-6}.

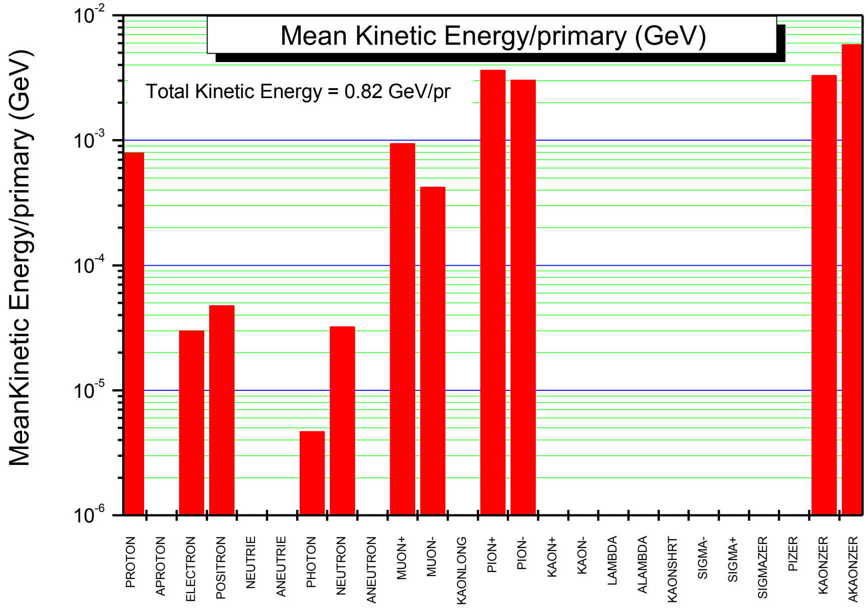
According to literature* a value of $1.1x10^{-2}$ dpa causes a decrease of the critical temperature from 38.3 to 36 K and enhancement of the upper critical field, these values should be not endanger the SCL for all the machine operation.

* M. Eisterer, M. Zehetmayer, S. Tonies, H. W. Weber, M. Kambara, N. Hari Babu, D. A. Cardwell, L. R. Greenwood, "Neutron Irradiation of MgB2 Bulk Superconductors", Supercond. Sci. Technol. 15 (2002) L9–L12

Particle Fluencies (option 2)

(To the SCL in the CM after D1)



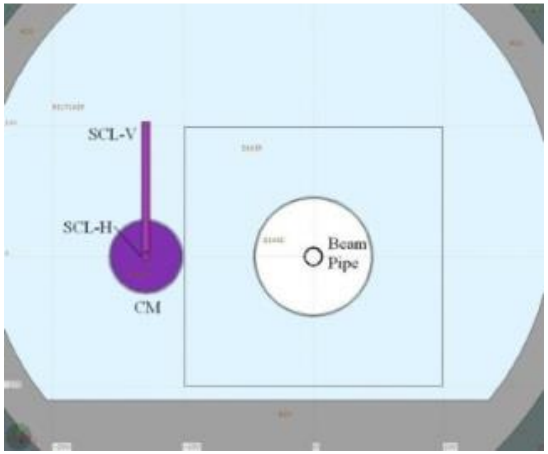


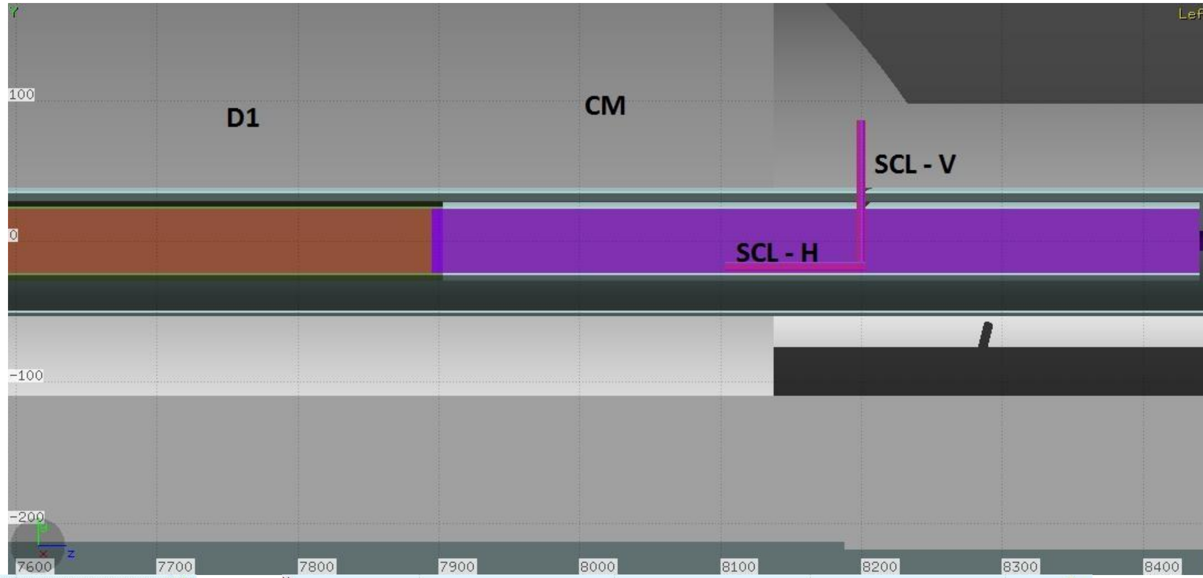
Entering the SCL in the Connection Module

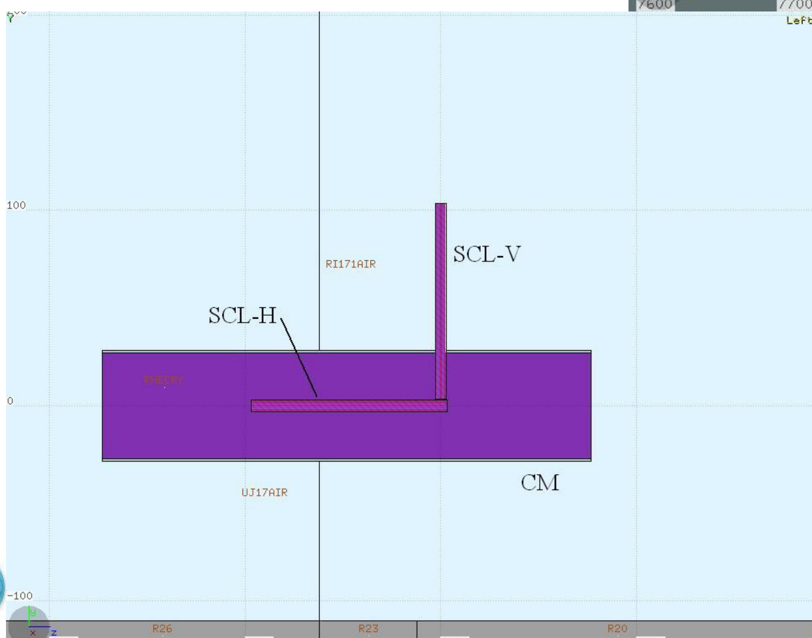
95% photons (126 ph/event)
2.4% neutrons (3.2 n/event)

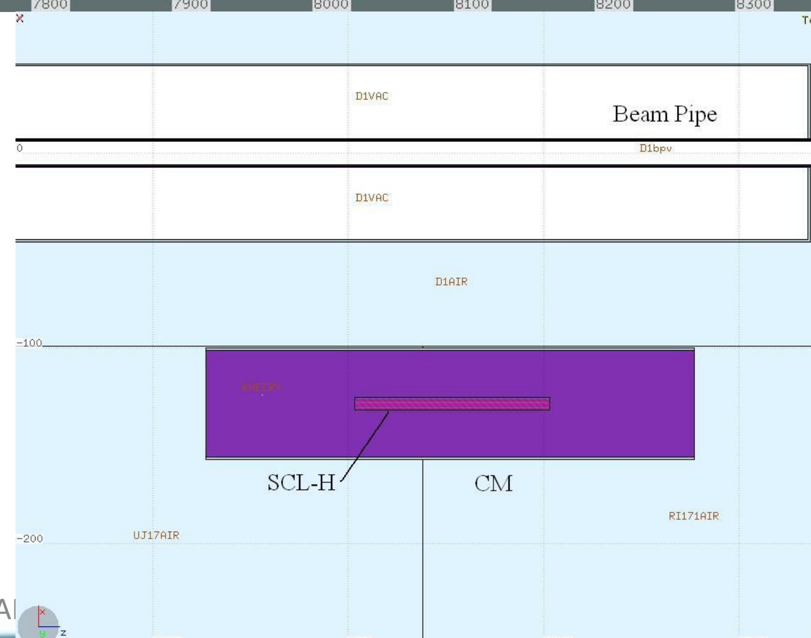
35.8% of the kinetic energy is from photons (295 MeV/event)
6.3% from neutrons (51.6 MeV/event)

Option 2 Fluka Model

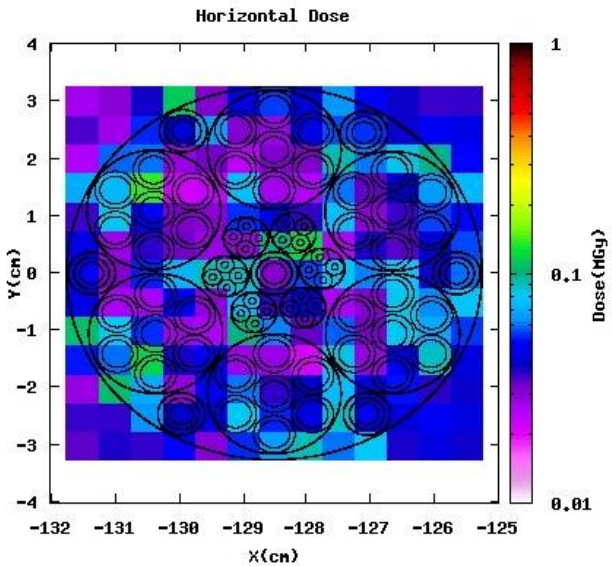


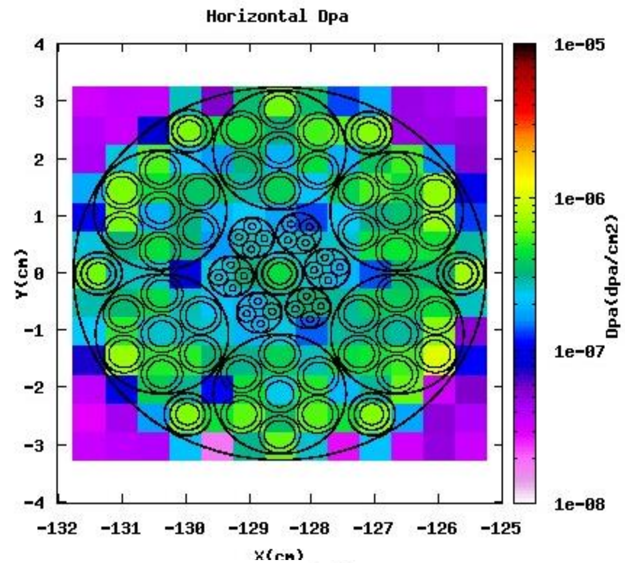


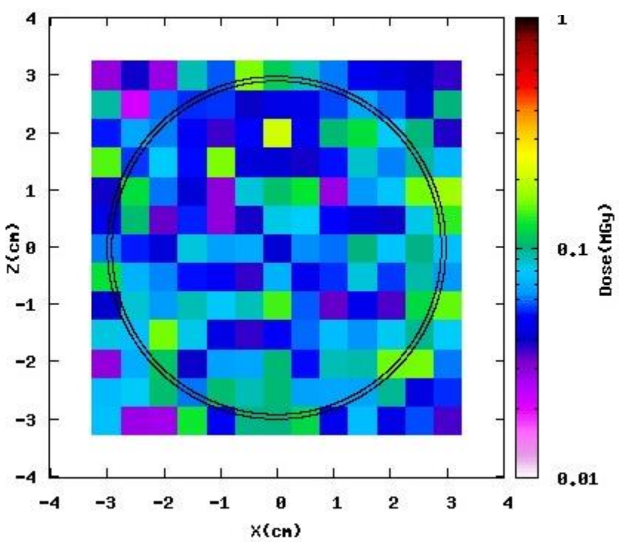




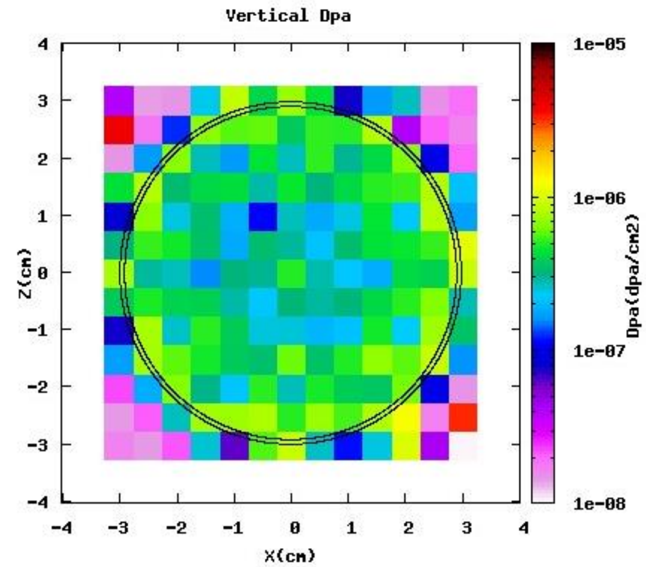
Option 2 Results (definitive)







The internal cable structure is not visible for visualization problems but it is actually implemented



The maximum dose in the SCL is about 0.1 MGy and the maximum DPA is about 10^{-6}

Conclusions on Energy Deposition and DPA

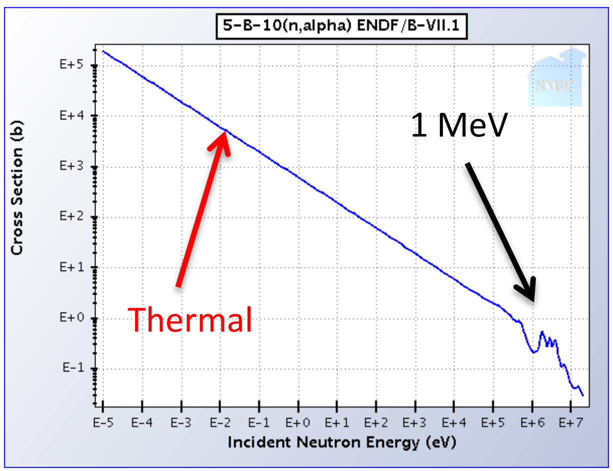
- The SCL configuration used for the simulations so far performed are about definitive. They are in a conservative hypothesis because the external insulation and cryogenic shielding are not take into account.
- The dose and DPA induced into the SCL are well below a critical value that can be assumed as 35 MGy (values at which the kapton start to lose its insulating properties and 10^{-2} DPA as from irradiation tests. Values from literature indicate that the induced DPA increases the pinning effect at the advantage of an increased performance.
- In the future (if necessary), with a detailed layout of the MgB_2 SCL, definitive simulations with the new optics (longer insertion quadrupoles) could be done.
- No big variations are expected so **we can conclude that the energy/dose deposition and the DPA in the MgB_2 cables, with the conservative hypothesis adopted, are not a concern over the whole lifetime of the SC links (3000 fb^{-1}).**
- P5 has not been simulated so far, but we do not expect big differences with P1.

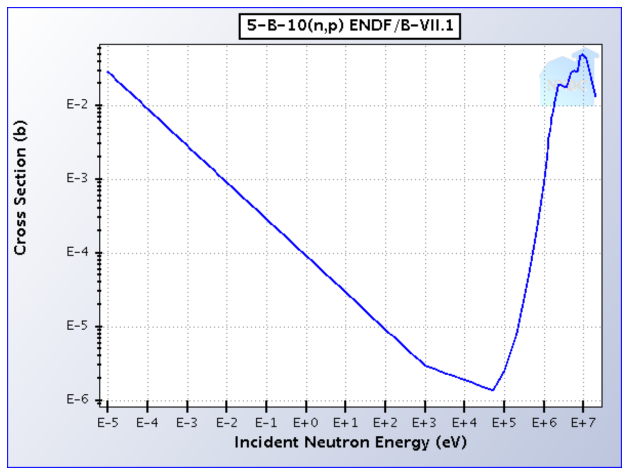
Concerns of Neutrons on MgB_2

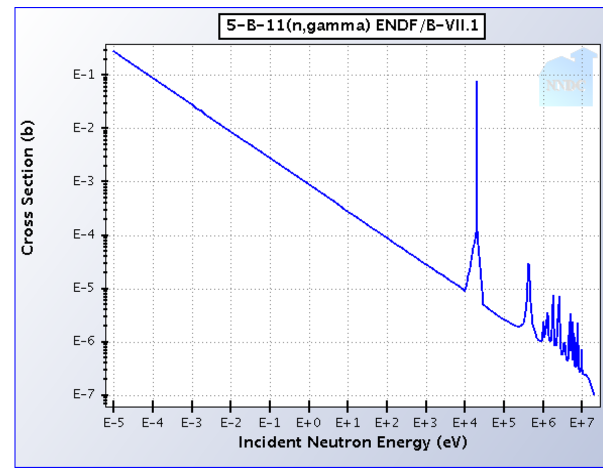
B natural isotopic composition is : 80% ^{11}B - 20% ^{10}B

Mg natural isotopic composition is : 78.99% ^{24}Mg – 10% ^{25}Mg - 11.01% ^{26}Mg

^{10}B has a very high thermal neutron capture cross section for $^{10}B(n,\alpha)^{7}Li$







Data from National Nuclear Data Center
http://www.nndc.bnl.gov/

Reactions occurring

	σ_{term} (b)	σ_{1MeV} (b)	
${}^{24}_{12}Mg + n \rightarrow {}^{25}_{12}Mg + \gamma$	5.7E-2	3.3E-4	
${}^{25}_{12}Mg + n \rightarrow {}^{26}_{12}Mg + \gamma$	2.2E-1	3E-4	
${}^{26}_{12}Mg + n \rightarrow {}^{27}_{12}Mg + \gamma$	4.3E-2	3.7E-4	${}^{27}Mg \rightarrow {}^{27}Al + \beta^- + \nu$ ${}^{27}Mg$ $t_{1/2}$= 9.5 min
${}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + \alpha$	**4.2E3**	**2.2E-1**	
${}^{10}_{5}B + n \rightarrow {}^{10}_{4}Be + p$	6.4E-4	9.6E-4	${}^{10}Be \rightarrow {}^{10}B + \beta^- + \nu$
${}^{10}_{5}B + n \rightarrow {}^{11}_{5}B + \gamma$	5.8E-1	//	${}^{27}Be$ $t_{1/2}$= 1.39 x10^6 y
${}^{11}_{5}B + n \rightarrow {}^{12}_{5}B + \gamma$	6.1E-3	2.2E-6	${}^{12}B \rightarrow {}^{12}C + \beta^- + \nu$ ${}^{12}B$ $t_{1/2}$= 20.2 ms

Data from National Nuclear Data Center
http://www.nndc.bnl.gov/

High Luminosity LHC

Neutrons on MgB_2

In order to evaluate the DPA and radiation damage of this reaction

Cases studied

External Beam and External isotropic n source

Thermal | Epithermal and Fast
0.025 eV | 10 eV | 0.1 MeV

TARGET (2x2x2 cm^3)

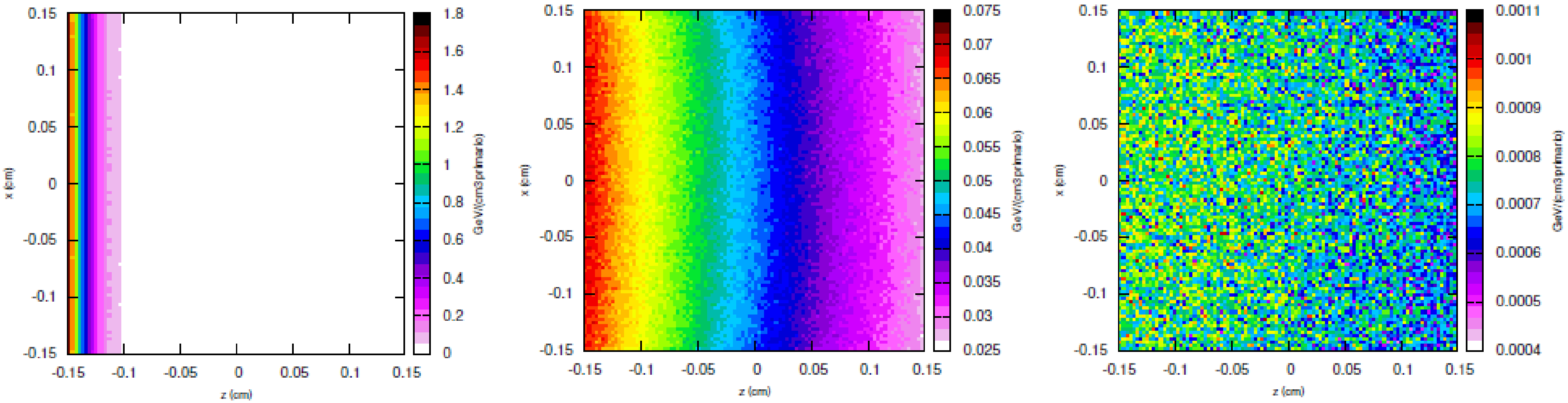
- MgB_2 with only ^{10}B
- MgB_2 with only ^{11}B
- MgB_2 with natural composition of B (80% ^{11}B – 20% ^{10}B)

High Luminosity LHC

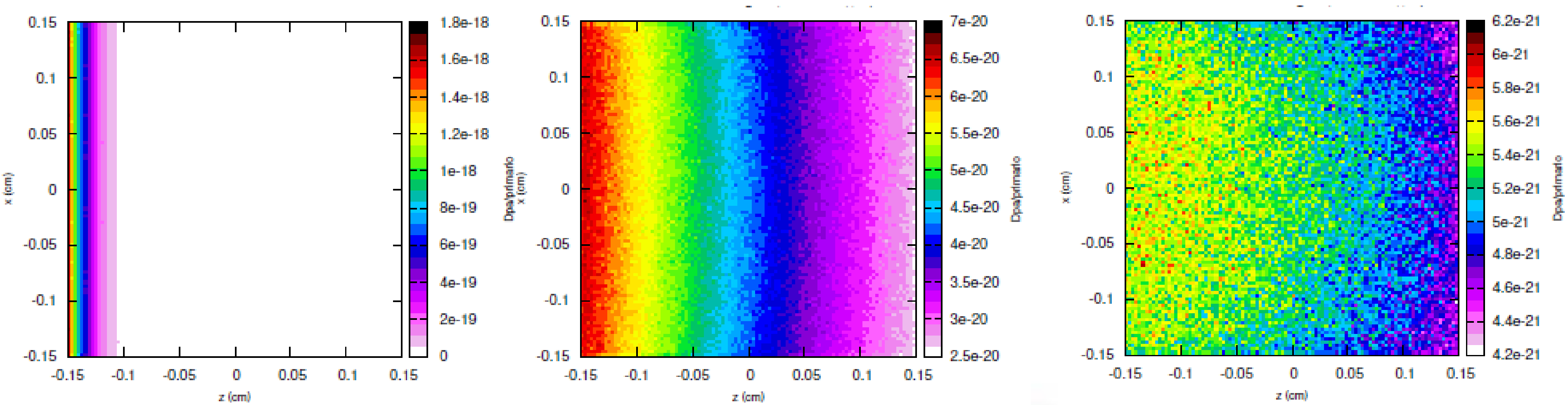
Neutron Beam on Natural B MgB_2

Thermal Epithermal Fast

Energy Deposition



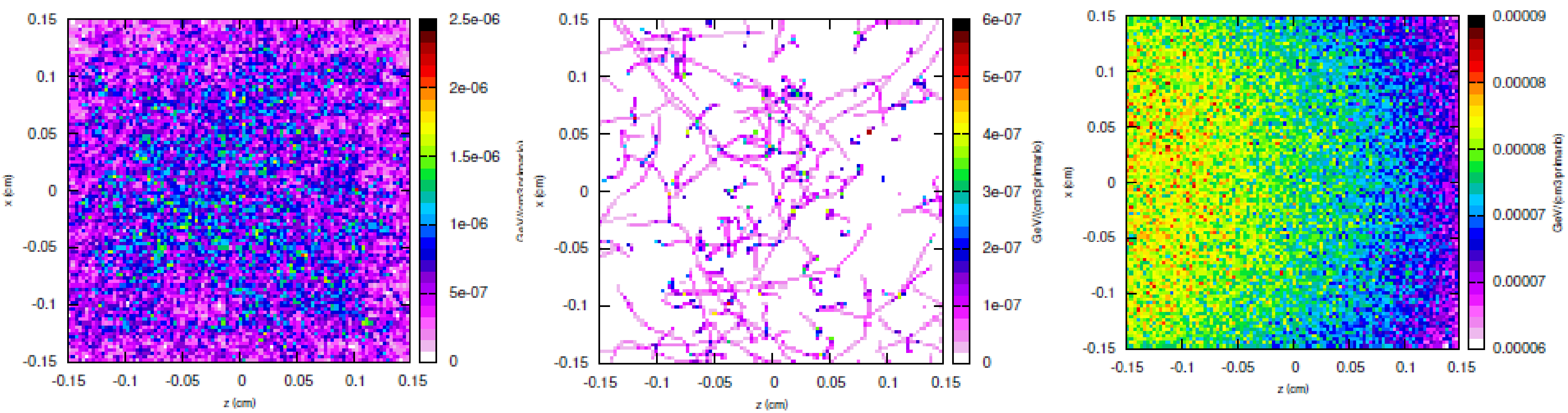
DPA



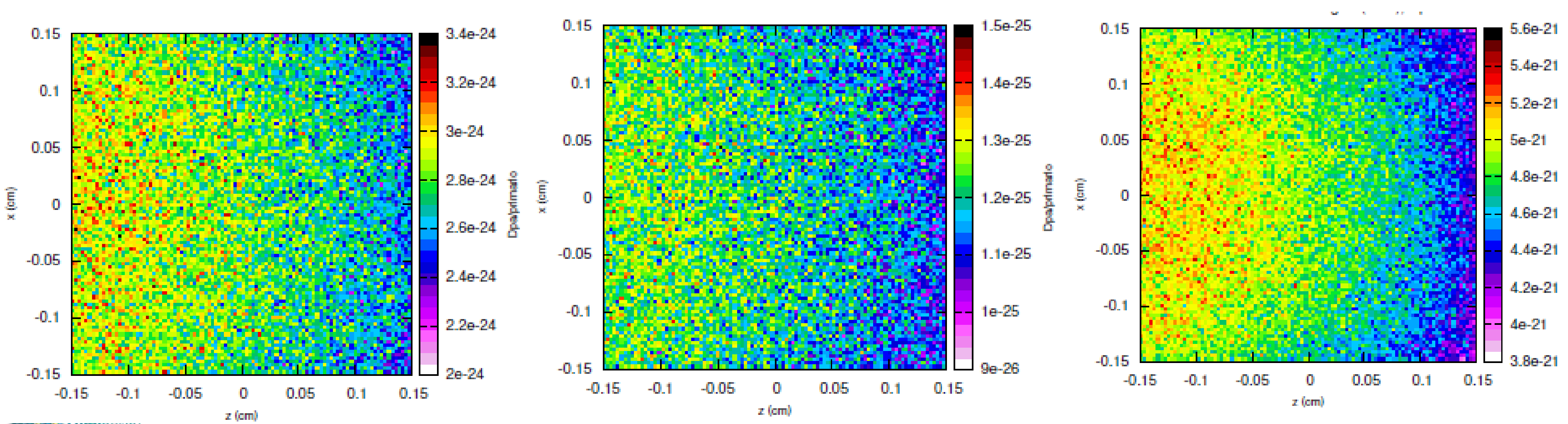
Neutron Beam on ^{11}B Enriched MgB_2

Thermal | Epithermal | Fast

Energy Deposition



DPA



From the previous slides it is evident the effect of th ^{10}B capture reaction for thermal neutrons

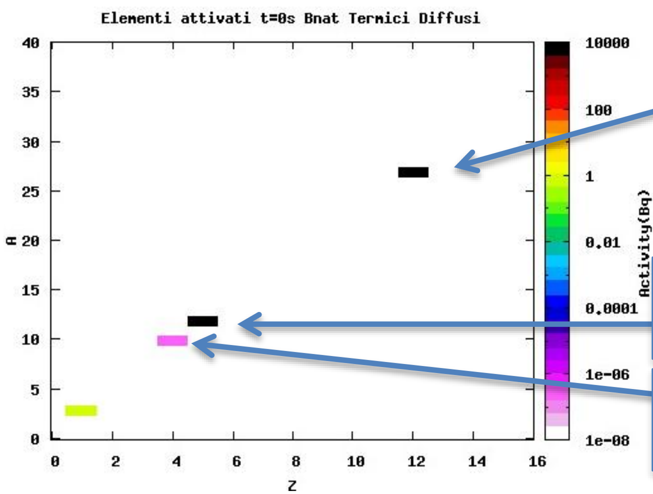
If it is necessary to penetrate the neutrons in the material (for irradiation studies or other needs) it is necessary to use high energy neutrons or ^{10}B depleted target

Residual Nuclei (at t=0 s)

Neutron beam spot : 2 cm
Fluence2x10^9 n/s x 1 d

Thermal n

1 MeV

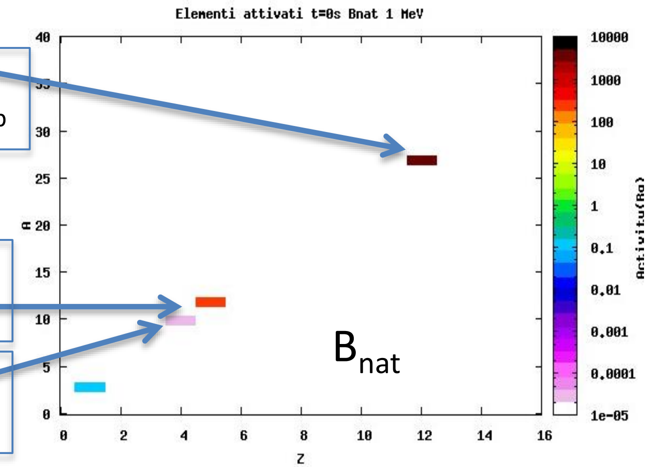


t=0

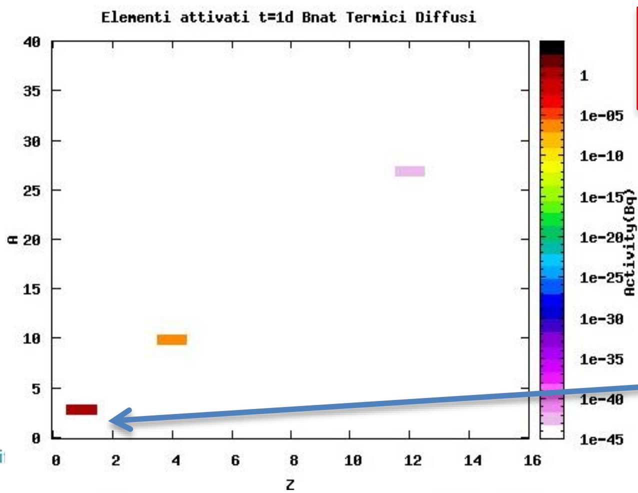
^{26}Mg(n,γ)^{27}Mg
σ_{th}=4.1E-2 b σ_{1MeV}=3.7E-4 b

σ_{th}=5.8E-3 b σ_{1MeV}=1.5E-6 b
^{11}B(n,γ)^{12}B

^{10}B(n,p)^{10}Be
σ_{th}=5.8E-4 b σ_{1MeV}=1.0E-3 b



B_{nat}

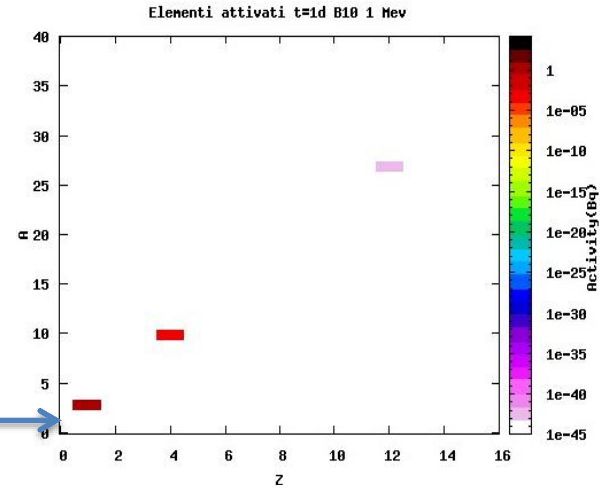


^{10}B(n,α)^{7}Li
σ_{th}=3.8E+3 b σ_{1MeV}=2.1E-1 b

t=1 d

Protons from

$${}^{10}_{5}B + n \rightarrow {}^{10}_{4}Be + p$$



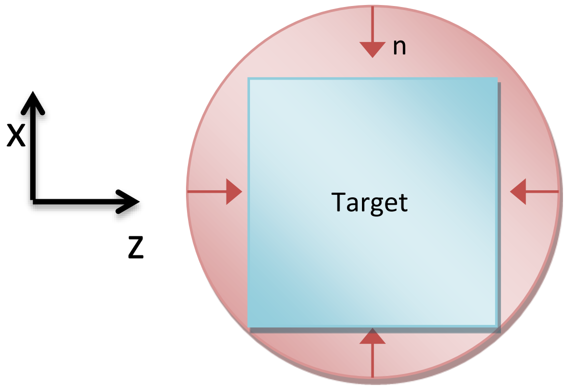
High Luminosity LHC

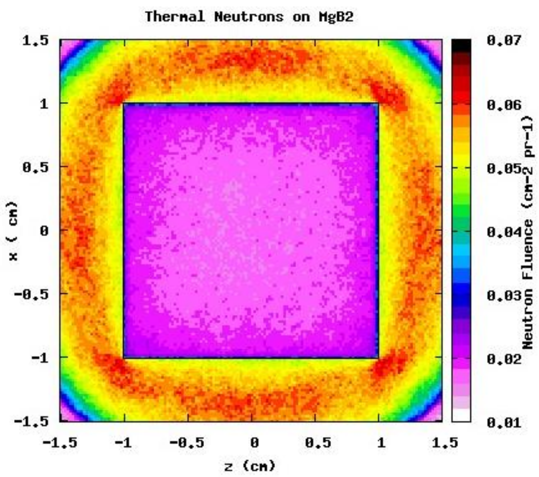
External Isotropic Neutron Source

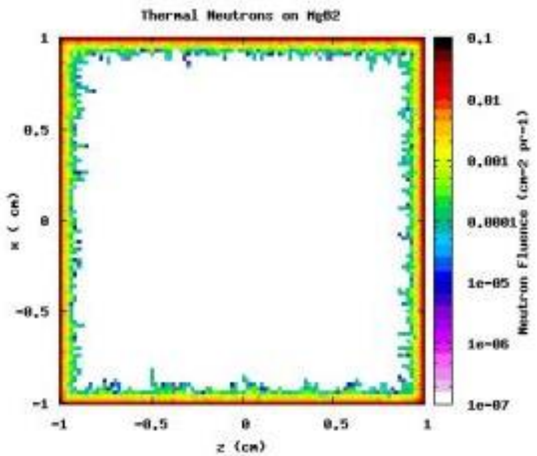
- MgB_2 with natural composition of B (80% ^{11}B – 20% ^{10}B)

Thermal Neutrons (isotropic source)

TARGET (2x2x2 cm³)





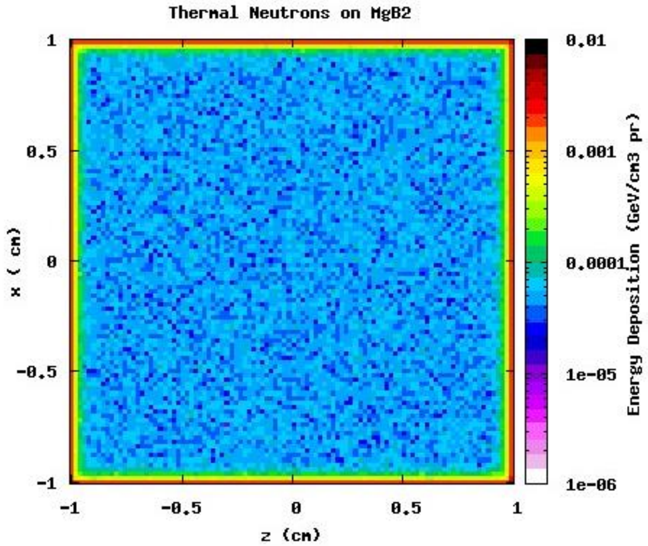


The transport cut-off :
hadrons 10^{-6} GeV
neutrons 10^{-14} GeV

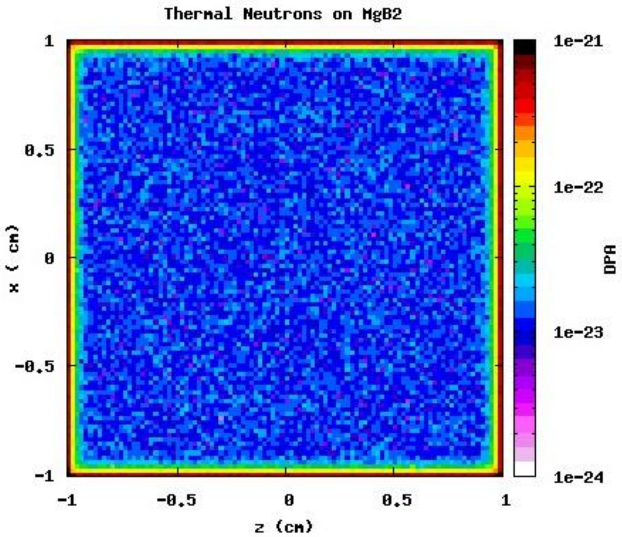
damage energy threshold = 25 eV

Central section: neutrons react at the surface

Energy Deposition and DPA



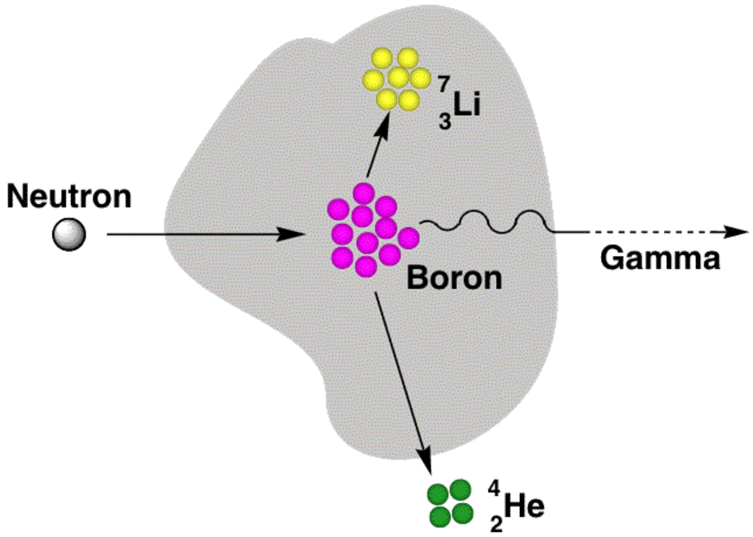
Energy Deposition
1.11E-03(±0.03%) GeV/pr



DPA
3.66E-23 (±0.03%)

DPA is related to Energy Deposition

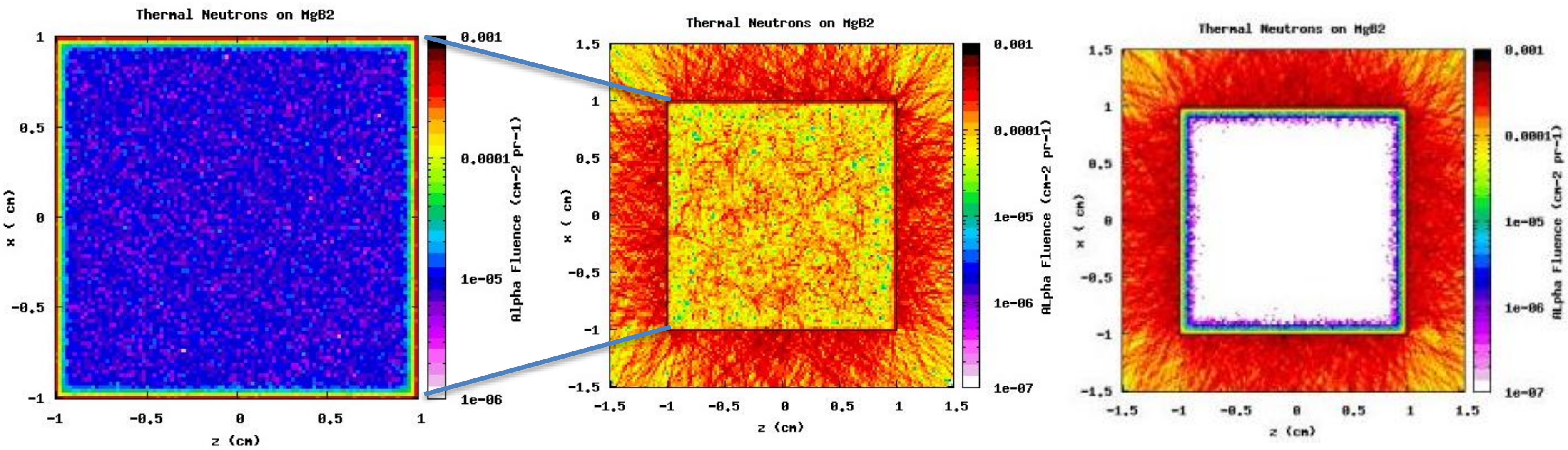
n Boron capture reaction



$$n + {}^{10}_{5}B \rightarrow {}^{11}_{5}B^{*} \begin{cases} \xrightarrow{6\%} {}^{7}_{3}Li + \alpha & 1.015\,MeV + 1.777\,MeV \\ \xrightarrow{94\%} {}^{7}_{3}Li^{*} + \alpha \rightarrow {}^{7}_{3}Li + \gamma + \alpha & 0.84\,MeV + 0.482\,MeV + 1.47\,MeV \end{cases}$$

What is the contribution of alpha particles and of Li ion to the DPA?

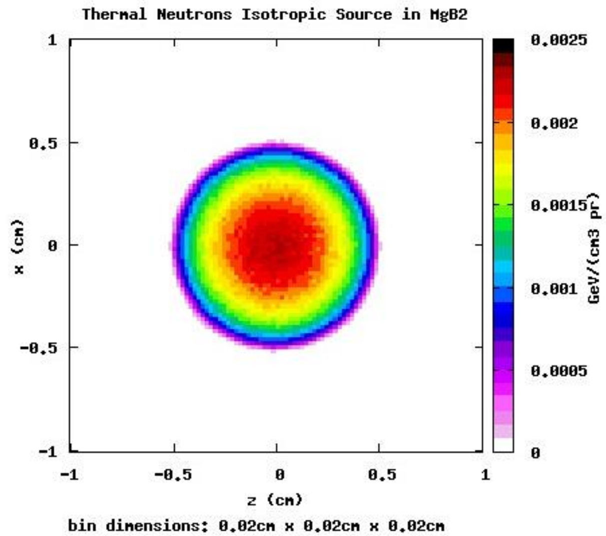
α Fluence

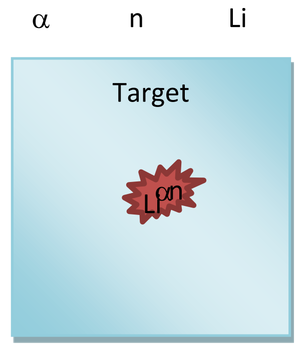


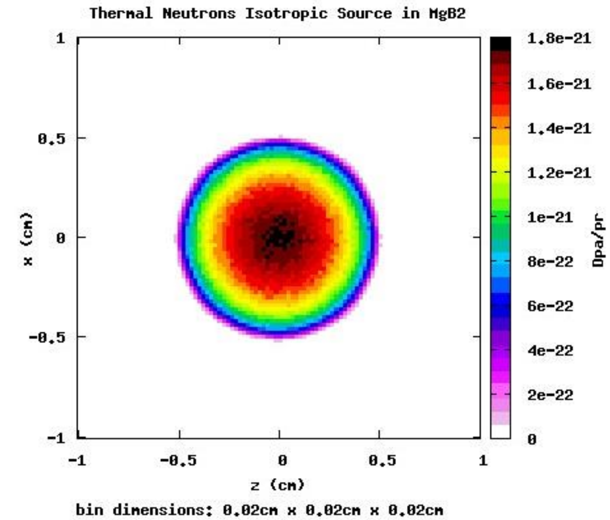
Reactions occurring at the surface cause
a high fluence of alfa particle outside

Single contribution (of α and Li)

Simulation with single internal isotropic source





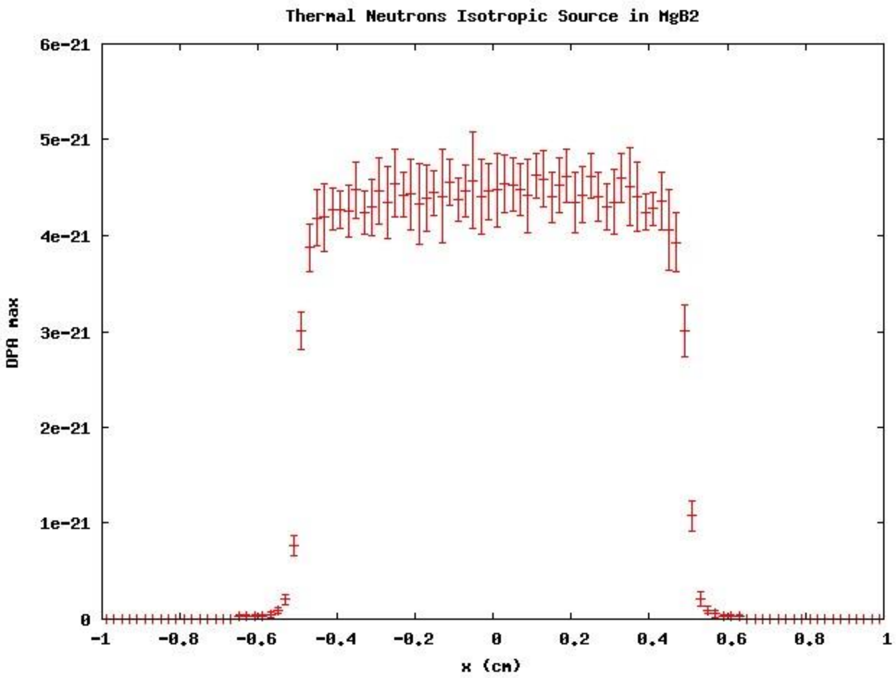


For the other different cases studied (alpha and Li) there are similar plots

These plots have not any absolute meaning, they just show that all the energy is deposed inside the sample (and the corresponding DPA is all provided inside them) and so the results can be compared.

Considerations

The most significant parameter for the DPA is its the peak value. As a matter of fact the mean value of the DPA, as it is defined, indicates that every atom undergoes to the given amount of displacement.



It is evident that it does not happen because from previous figures the energy deposition and DPA occur in a limited part of the target, so it is meaningless to attribute a DPA to the whole region.

Conversely the peak value gives an indication of the localized radiation damage and this can give effects on the material characteristics.

Single contribution (of α and Li)

Maximum and average DPA in the MgB_2 target induced by the reaction products of the boron capture.

Reaction occurrence		Max DPA [DPA/primary]±Err%	Mean DPA [DPA/primary]±Err%
94%	Alpha (1.47 MeV)	$15.911 \cdot 10^{-22} \pm 7.9$	$6.1633 \cdot 10^{-22} \pm 0.001$
	Lithium (0.84 MeV)	$32.968 \cdot 10^{-22} \pm 6.9$	$11.952 \cdot 10^{-22} \pm 0.001$
	Photon (0.482 MeV)	==	==
6%	Alpha (1.777 MeV)	$16.422 \cdot 10^{-22} \pm 6.3$	$6.3141 \cdot 10^{-22} \pm 0.002$
	Lithium (1.015 MeV)	$31.447 \cdot 10^{-22} \pm 6.6$	$12.240 \cdot 10^{-22} \pm 0.001$

DPA Evaluation (of α, Li and n)

Combining the data with the corresponding weight we have

	Max DPA [DPA/primary]±Err%	Mean DPA [DPA/primary]±Err%
Alpha	$15.942 \cdot 10^{-22} \pm 7.8$	$6.1724 \cdot 10^{-22} \pm 0.001$
Lithium	$32.876 \cdot 10^{-22} \pm 6.8$	$11.969 \cdot 10^{-22} \pm 0.001$
Neutron	$46.295 \cdot 10^{-22} \pm 5.0$	$18.345 \cdot 10^{-22} \pm 0.001$

Summing the contribution of the alpha particle with the Lithium one:

$15.942 \cdot 10^{-22} + 32.876 \cdot 10^{-22} = 48.818 \cdot 10^{-22} \pm 0.257$ **max DPA**

$6.1724 \cdot 10^{-22} + 11.969 \cdot 10^{-22} = 18.141 \cdot 10^{-22} \pm 0.001$ **mean DPA**

Internal neutrons

$46.295 \cdot 10^{-22} \pm 2.334 \cdot 10^{-22}$ **max DPA**

$18.345 \cdot 10^{-22} \pm 0.001 \cdot 10^{-22}$ **mean DPA**

The Lithium contribution to DPA is 66-67% of the total (the sum of the alpha and Lithium)

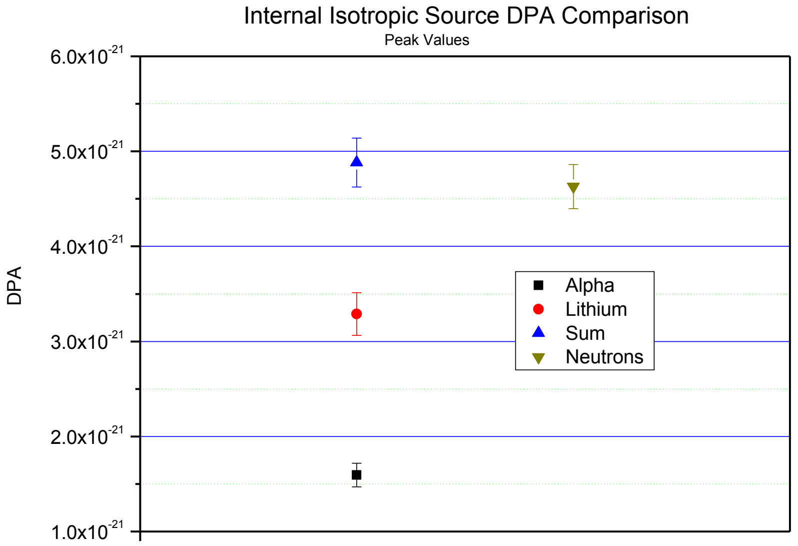
The contribution of the alpha is about 33-34%

Considerations

PEAK VALUES

The peak value calculated by the sum of the alpha and Li contribution is about 6% higher that the values given by the neutrons.

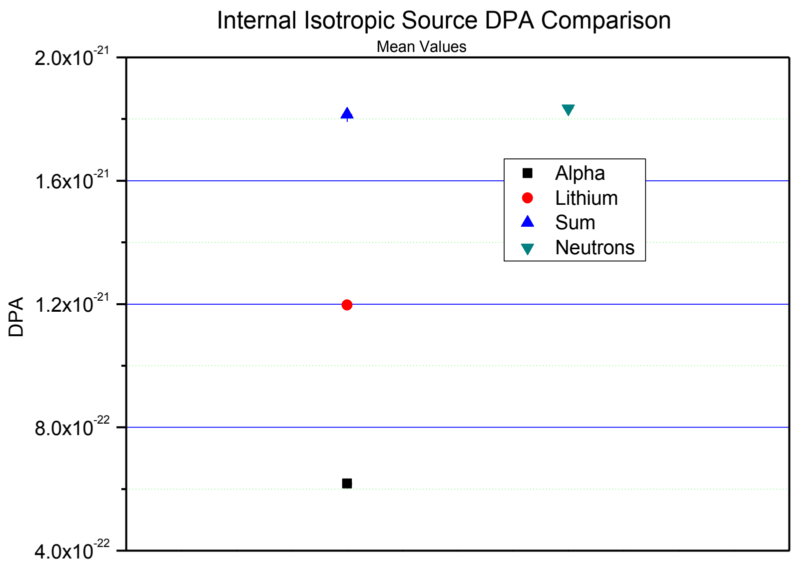
This because we assume that every neutron reacts with ^{10}B realizing one Li and one alpha particle.



MEAN VALUES

For the mean DPA calculated by the sum of the alpha and Li contribution is about 1% lower that the DPA induced by the neutrons.

This is probably due to the statistics, and anyway this value (the mean DPA) in our analysis is less important, as explained before.

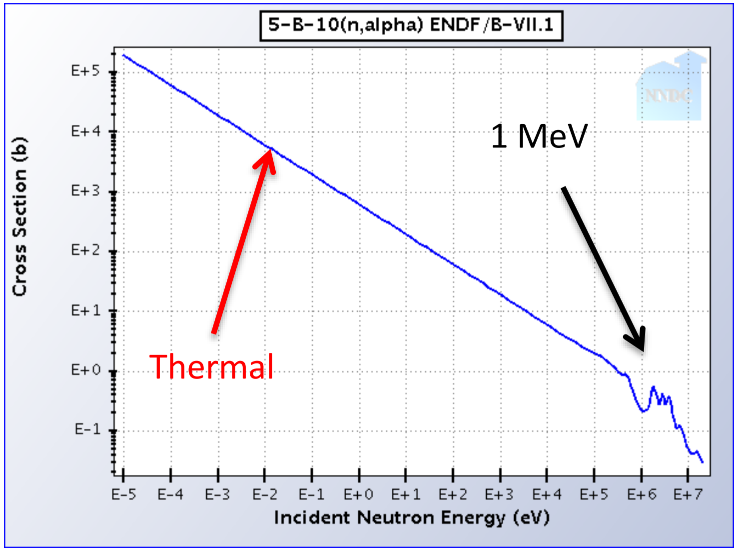


Is the Boron consumpion a worry ?

$$^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + \alpha$$

σ_{term} =4.2 x 10^3 b σ_{1MeV} =2.2 x 10^{-1} b

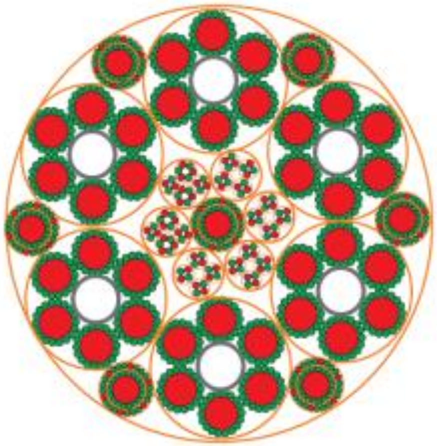
1.5×10^4 b at 20 K (E_n=0.0017 eV)



As from the data before the n entering the SCL inside the CM (Option 2) are about 3.2 n/event. At an integrated luminosity of 3000 fb^{-1} LHC will collect about $3 \cdot 10^{17}$ p-p events, so the

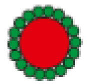
total amount of n in the SCL will be about $1 \cdot 10^{18}$.

Number of ^{10}B Target in the SC Link



Cu

MgB_2 , Φ = 0.85 mm



18 MgB_2 wires
Φ = 6.5 mm

Φext ~ 65 mm

Considering 1 m Link length
S=33.2 cm^2
Being M=45.93 g/mol the MgB_2 molar mass and
ρ=2.57 g cm^{-3}the density

Material composition of the cable

MATERIAL	ATOM CONTENT	PARTIAL DENSITIES (g/cm^3)
MAGNESIUM	0.1225	0.2192
BORON	0.24501	0.195
COPPER	0.48231	2.2563
HYDROGEN	2.03E-02	1.51E-03
CARBON	4.88E-02	4.31E-02
NITROGEN	4.07E-03	4.19E-03
OXYGEN	1.02E-02	1.20E-02
HELIUM	8.89E-03	2.62E-03
IRON	4.05E-02	0.16655
NICKEL	5.55E-03	2.40E-02
CHROMIUM	1.19E-02	4.55E-02

$$\frac{\rho}{M}A = \frac{2.57}{45.93}6.022 \cdot 10^{23} = 3.37 \cdot 10^{22}$$ Pure MgB_2 atoms cm^{-3}

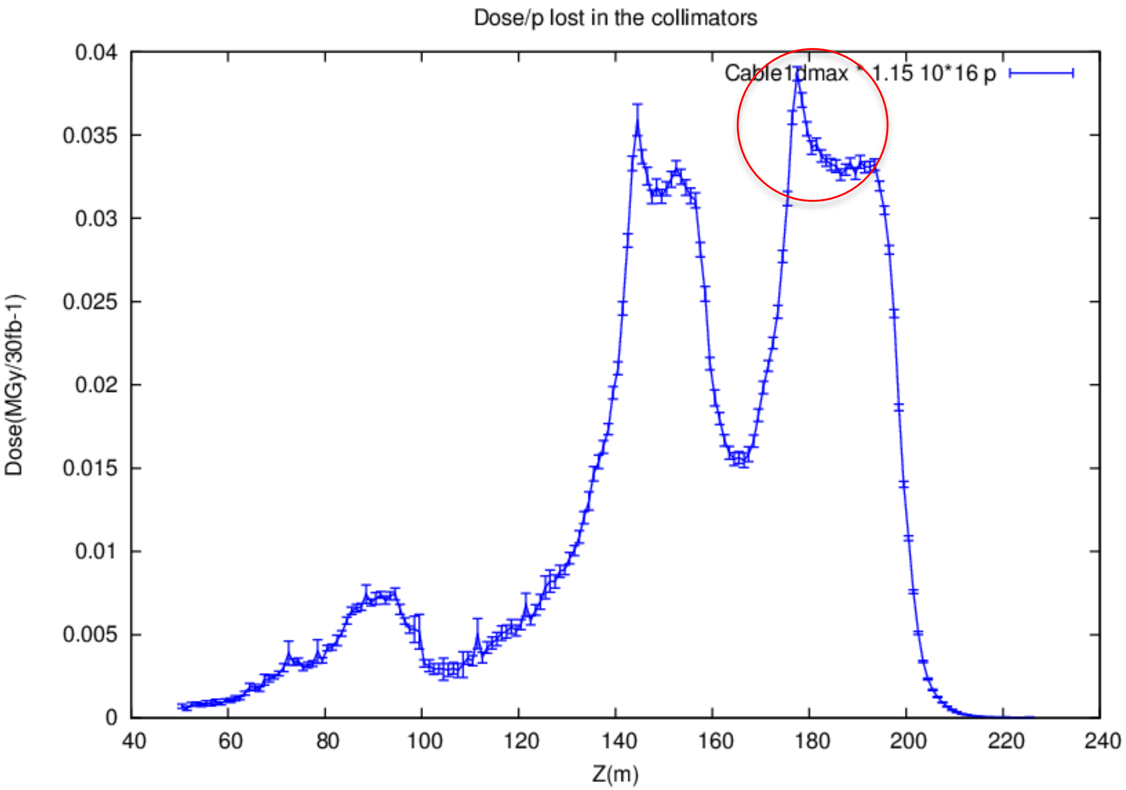
$$3.37 \cdot 10^{22} \times 33.2 \times 100 \times 2 \times 0.245 \times 0.2 = 1.1 \times 10^{25}$$ ^{10}B atoms m^{-1}

Much higher than 1. x 10^{18} and even supposing 1 capture reaction per neutron, the ^{10}B consumption is negligible

P7

(Data presented last year in Tsukuba, no more work on it)

Dose normalized to a number of proton losses in the collimators (10^{16}) in Run 1
Data allows to tentatively correlate to 30-40 fb^{-1}



The maximum proton loss is after the primary collimators of the Beam 2

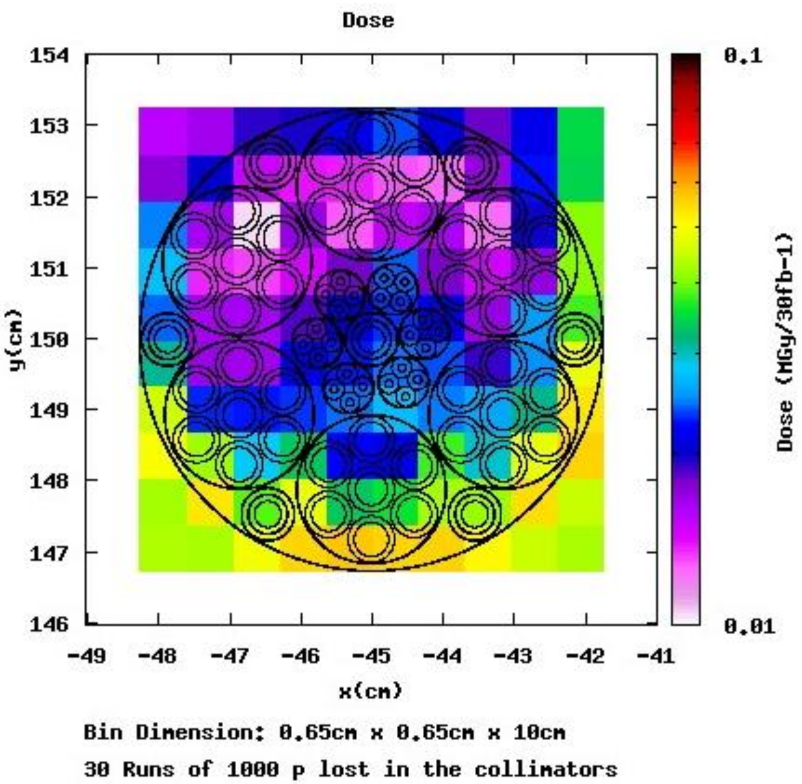
In this region we located the model of the cable

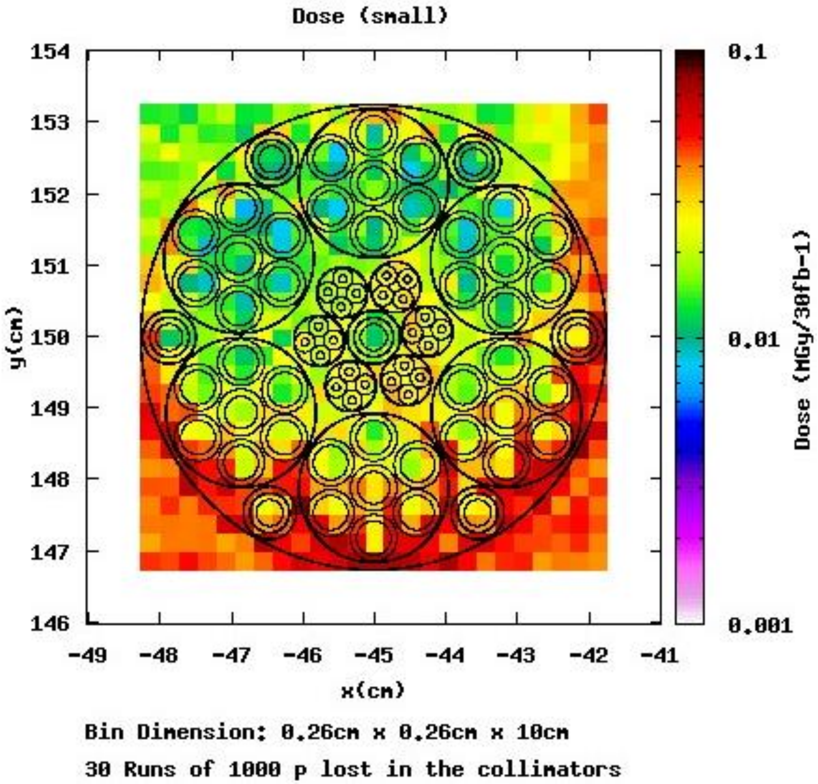
In the maximum point we put 3 meters long SC Link model (the same of IP1).

For the simulation we used 30000 protons lost in the collimators (SixTrack output) and then we normalized the data for 30 fb^{-1}

High Luminosity LHC

Dose



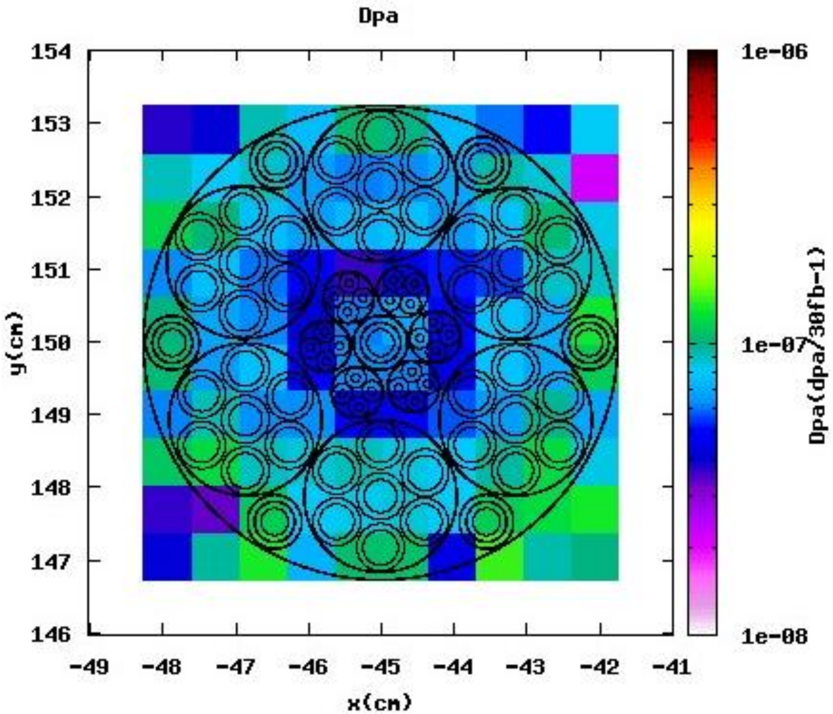


The maximum dose is about 40 kGy integrated over a period of 30 fb^{-1}

If also we extrapolate proportionaly to 3000 fb^{-1} we will obtain only 4 MGy over the whole period of exercise

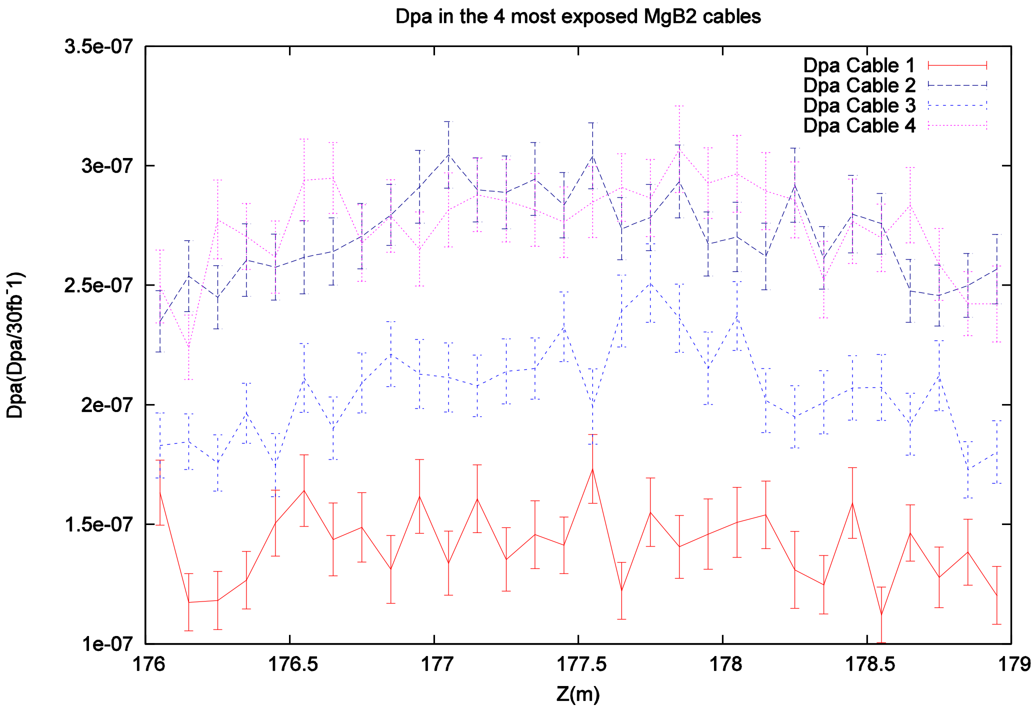
High Luminosity LHC

Dpa



Bin Dimension: 0.65cm x 0.65cm x 10cm

30 Runs of 1000 p lost in the collimators



The dpa is about 10^{-7} over all the cable. This value give us no concern, because it is almost 1 order of magnitude smaller than the one in IP1

Conclusions

- The energy/dose deposition and the DPA in the MgB_2 cables, with the conservative hypothesis adopted, are not a concern over the whole lifetime of the SC links (3000 fb^{-1}).
- The ^{10}B consumption is negligible
- From this work we get more deep knoweledge of the effects of radiations on HTC materials
- In the boron capture reaction the alpha particle and the Lithium nucleus contribute for the 33-34% and 66-67% to the total DPA respectively.
- Maximum dose on MgB_2 SC links is not a concern in P7. It won't be even if we would consider proportional the relation between integrated luminosity and proton losses

Acknowledgments

Thank You for Your attention

- A. Bignami (POLIMI and INFN)
- C.Santini (POLIMI and INFN)

References:

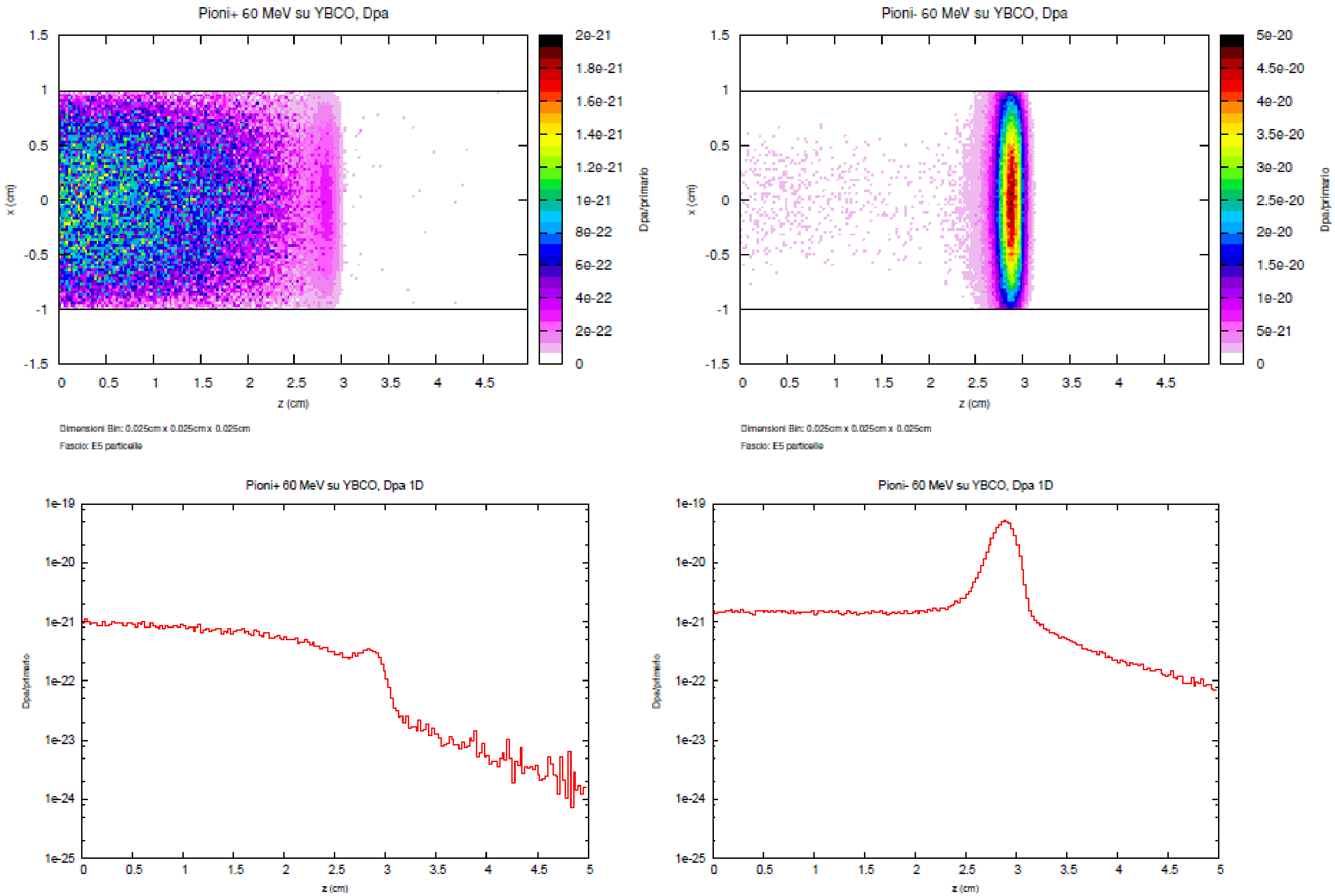
- A. Bignami, “Studio delle Connessioni Superconduttive in MgB2 per il Progetto HiLumi-LHC”, grad. thesys. https://www.politesi.polimi.it/handle/10589/81012

- C. Santini, “Studio degli Effetti del Campo di Radiazione sulle Connessioni Supercondutive per il Progetto HiLumi-LHC”, grad. thesys, https://www.politesi.polimi.it/handle/10589/102125

- Deliverables and Milestone reports

cern.ch

Spare Different interctions of π^+ and π^-



(a) Fascio di π^+ su YBCO. (b) Fascio di π^- su YBCO.

For π^- the dpa peak is higher than for π^+

The different behaviour is due to the absorption of the π^- by the nucleus ($\pi^- + p \to n + \gamma$)

while the π^+ are not absorbed and decay ($\pi^+ \to \mu^+ + \nu_\mu$)

High Luminosity LHC

$^{27}Mg \rightarrow {}^{27}Al + \beta^- + \bar{\nu}$

^{27}Mg $t_{1/2}$=9.5 min