Mu2e CD-2 Calorimeter simulation

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Caltech
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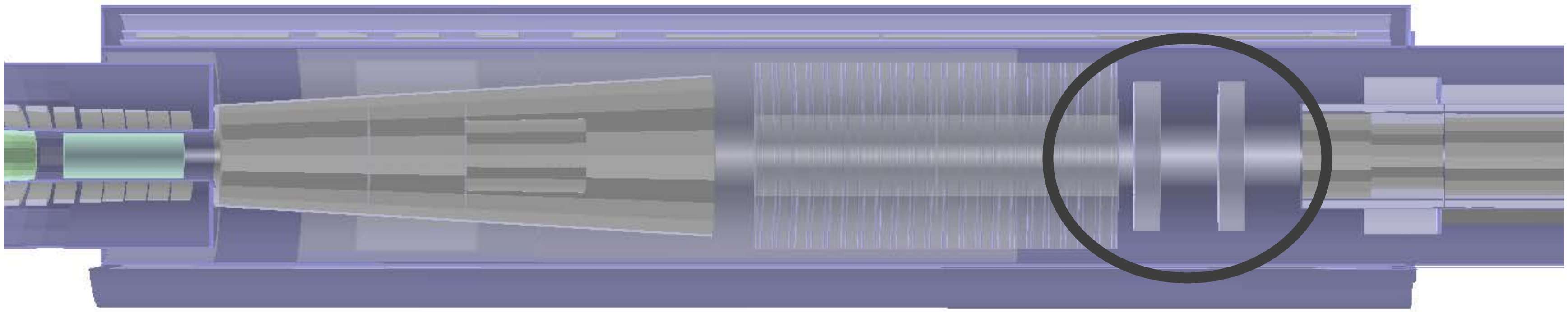
Mu2e disk calorimeter

Disk calorimeter: 2 disks separated by ~1/2 wavelength



Disk dimensions
- inner / outer radii: 351 – 660 mm
- separated by 700 mm (face to face)

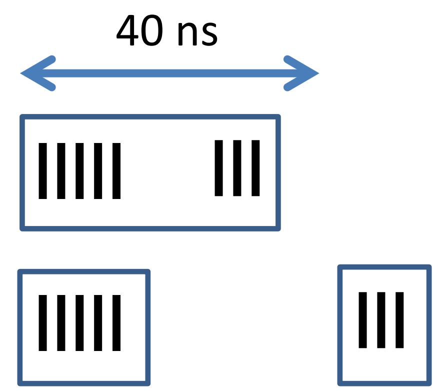
Crystal (hexagonal)
- BaF_2, hexagonal shape
- 3.3 cm across flats x 20 cm
- 2 readouts per crystal
- 65 μm wrapping

Background sources
- Beam flash
- Out of Target (OOT)
- Neutrons
- Photons
- Protons
- DIO

Unless mentioned otherwise, the results shown include all sources of background

Hit creation

Hit creation



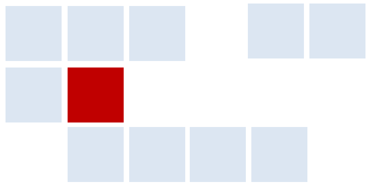
1) Collect energy left in crystal from StepPointMC (Geant4) within a 40 ns window from the first hit to include effect from pile-up (improvement in progress, see below). Might be able to reduce the integration time.

1) Include corrections for
   - longitudinal response non-uniformity
   - non-linear effects in energy deposition (doc-db 1620-1748)
   - photon statistics (30 photo-electron/MeV with RMD APD)
   - electronic noise (300 keV @ 30 p.e./MeV)

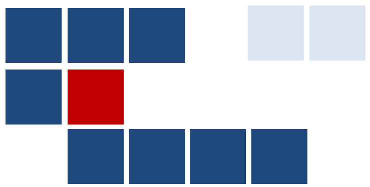
In progress: improve simulation of APD readout: waveform simulation and fitting, better pile-up rejection.

Clustering

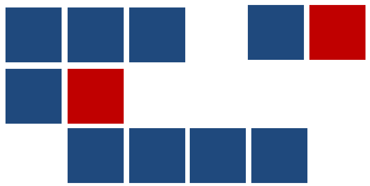
Cluster finding algorithm



1) Start with seed, crystal with largest energy deposit



2) Add all crystals simply connected to the seed in a 10 ns time window around the seed time and with an energy above 900 keV (3σ cut of the electronic noise). Might be able to reduce the time difference to 5 ns.



3) Repeat steps 1 and 2 until there are no more crystal left

In progress:

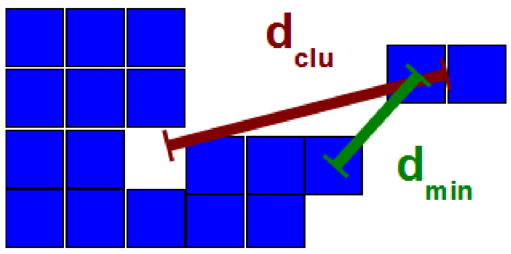
- Multivariate classifier to reject pile-up
- Multivariate regression/ library matching algorithm to improve center-of-gravity determination

Clustering

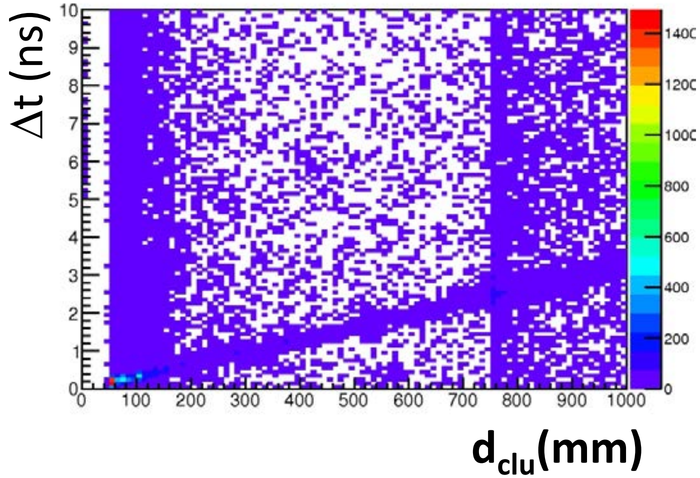
Cluster split-off recovery

1) Split-off selection using distance between clusters' center-of-gravity ($\Delta t_{mes} = \Delta t_{exp} \pm 0.2$ ns), attempting to recover split-off between disks.
   Not optimal, a lot of accidental background is included in the cluster

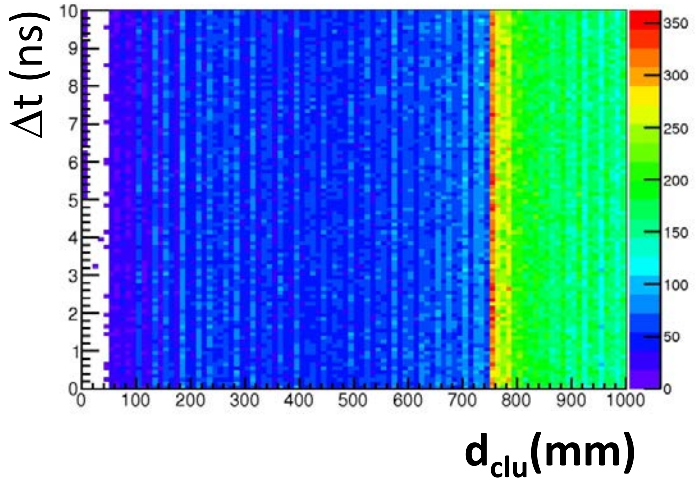
2) Further require the distance d_{min} between the clusters to be less than 60 mm



Signal



Background



Clustering

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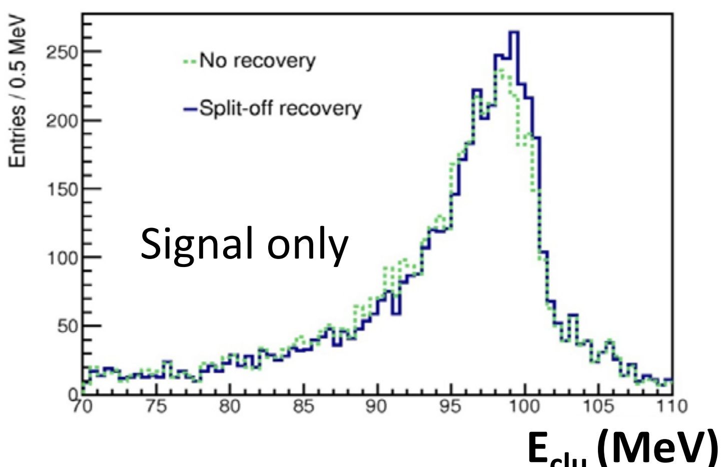
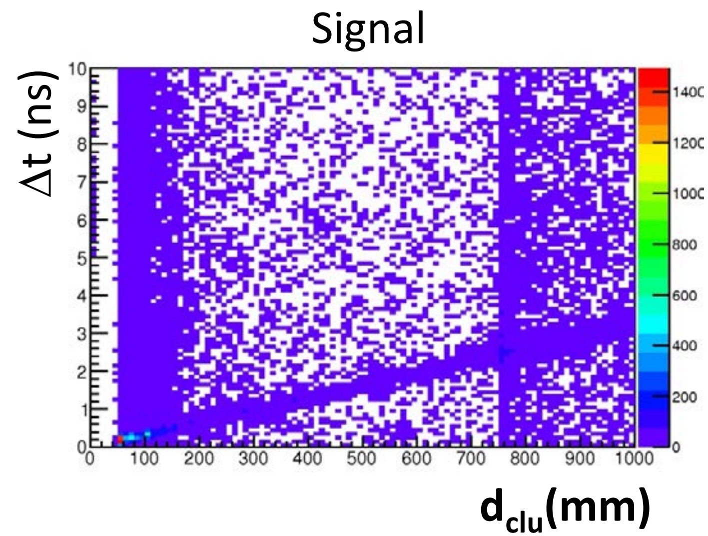
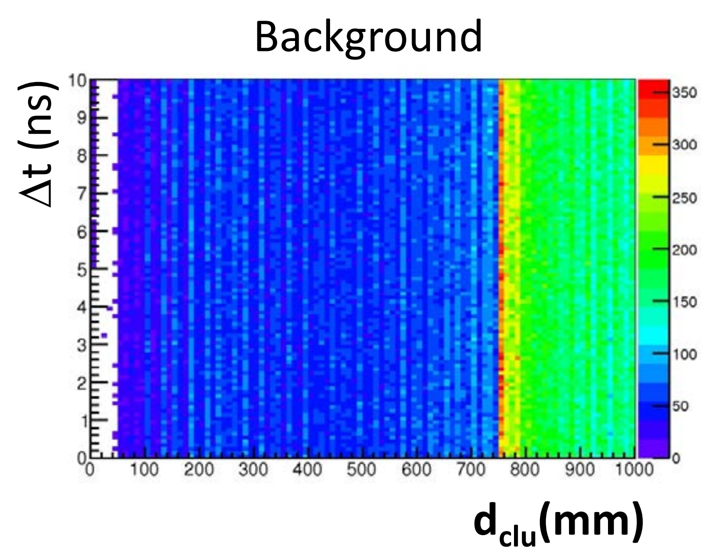


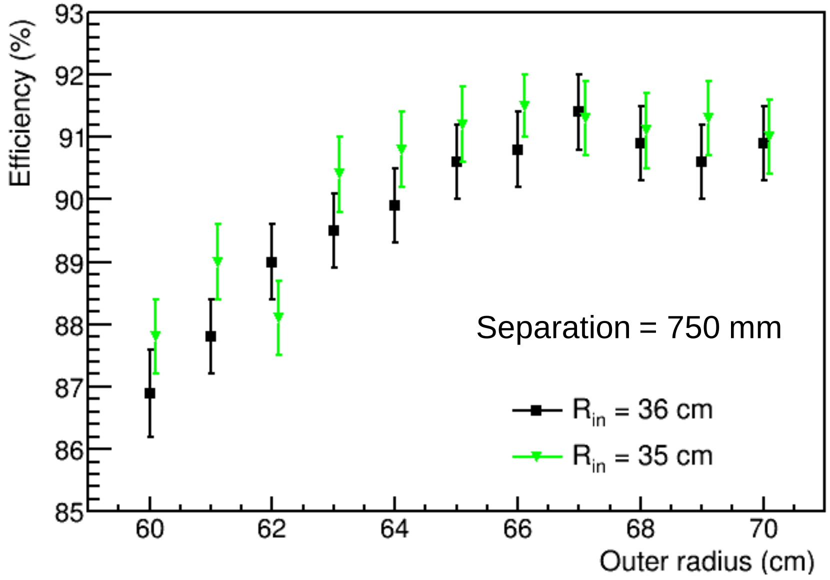




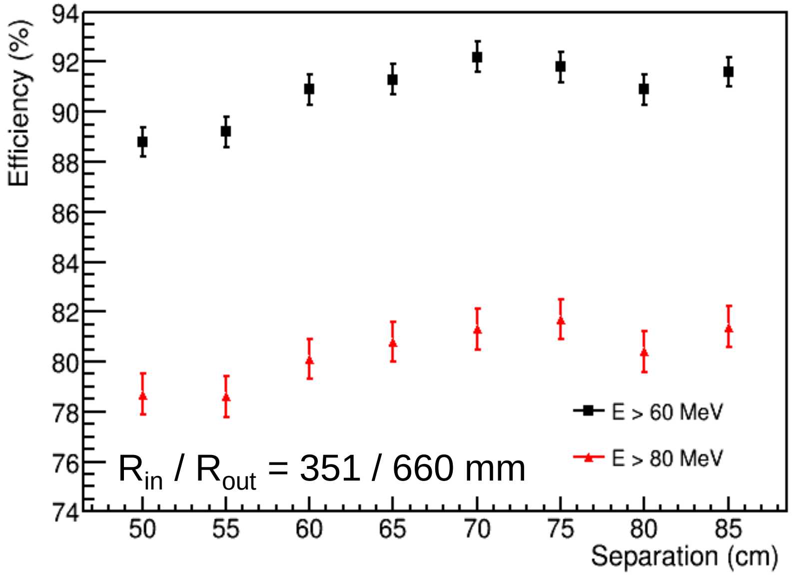
Geometry optimization

Optimize inner / outer radius and distance between disks (signal only)

Disk outer radius



Disk separation



Efficiency = number of cluster with E > 60 MeV / # reconstructed tracks*

Efficiency above ~92% for $E_{cluster}$ > 60 MeV.

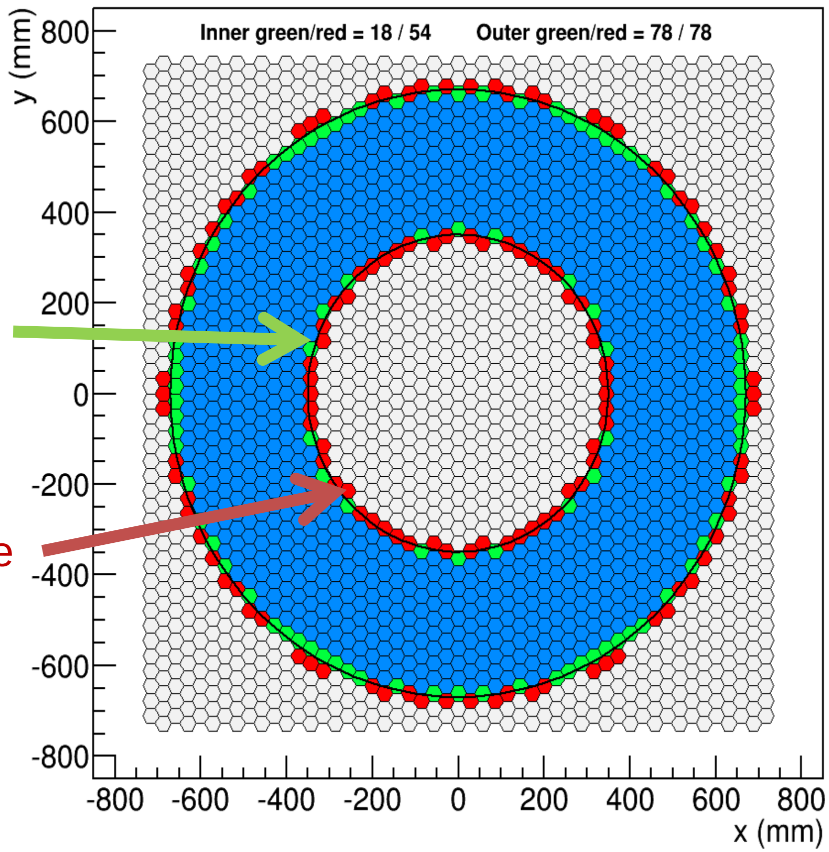
* Not using calorimeter cluster as seed for tracking (see P. Murat talk)

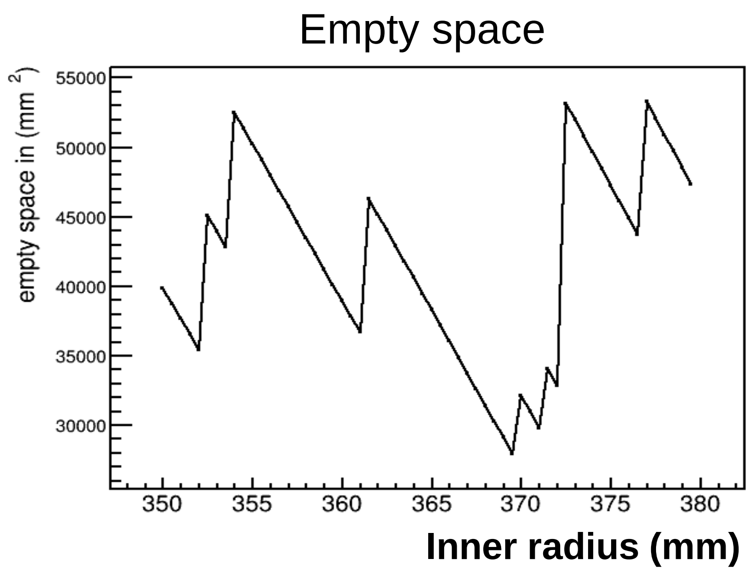
Geometry optimization

Scan to minimize the empty space between the crystals and the disk envelope

Center inside the boundary

Center outside the boundary





Empty space is correlated with the number of “green crystals”

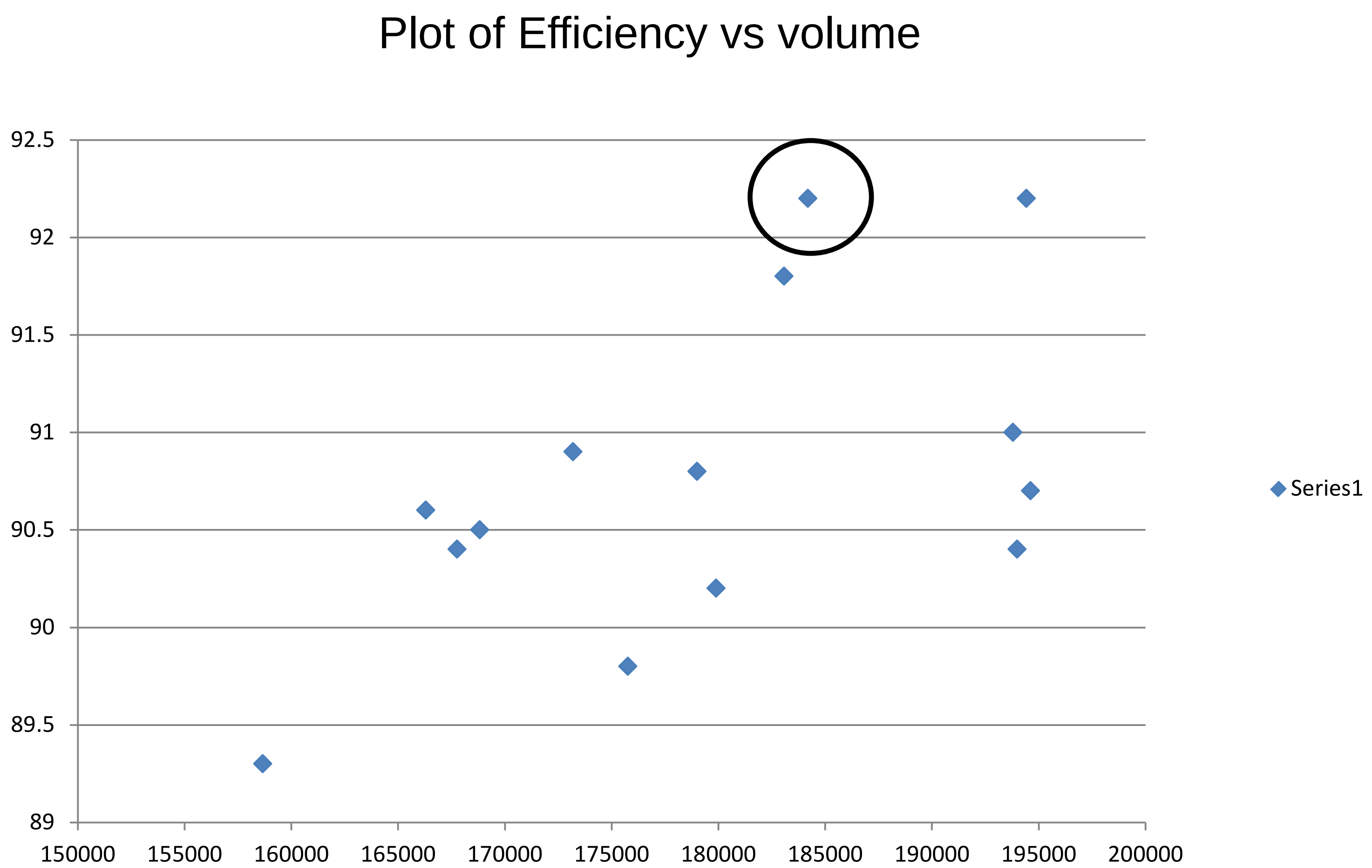
Geometry optimization

Disk Radii	Crystal size	# crystals	empty volume in / out (mm^3)	Volume (cm3)	Eff (%)
350 / 657	32.9	930	41640.2 / 71452.5	183073	91.8 ± 0.6
360 / 674	31.05	1110	28133.8 / 57308.8	194624	90.7 ± 0.6
360 / 645	33.85	798	31826.3 / 70045.9	166292	90.6 ± 0.6
360 / 676	33.85	930	31826.3 / 66704.2	193798	91.0 ± 0.6
370 / 662	31.92	966	29830.0 / 57532.5	179000	90.8 ± 0.6
370 / 662	34.8	798	33780.5 / 69719.4	175756	89.8 ± 0.6

Crystal size	Disk Radii	# crystals	empty volume in / out (mm^3)	Volume (cm3)	Eff (%)
31	359.1 / 643	966	28772.2 / 54288.1	168830	90.5 ± 0.6
31	359.1 / 672.3	1110	28772.2 / 54508.3	193998	90.4 ± 0.6
32	340.1 / 640	930	29098.3 / 62868.4	173194	90.9 ± 0.6
32	340.1 / 663.5	1044	29098.3 / 57184.3	194424	92.2 ± 0.6
32	371 / 640	852	29801.2 / 62869.6	158668	89.3 ± 0.6
32	371 / 663.5	966	29801.2 / 57184.3	179898	90.2 ± 0.6
33	**351 / 660**	**930**	**30243.4 / 67178.5**	**184188**	**92.2 ± 0.6**
34	361.2 / 647.3	798	32992.5 / 68438.1	167769	90.4 ± 0.6

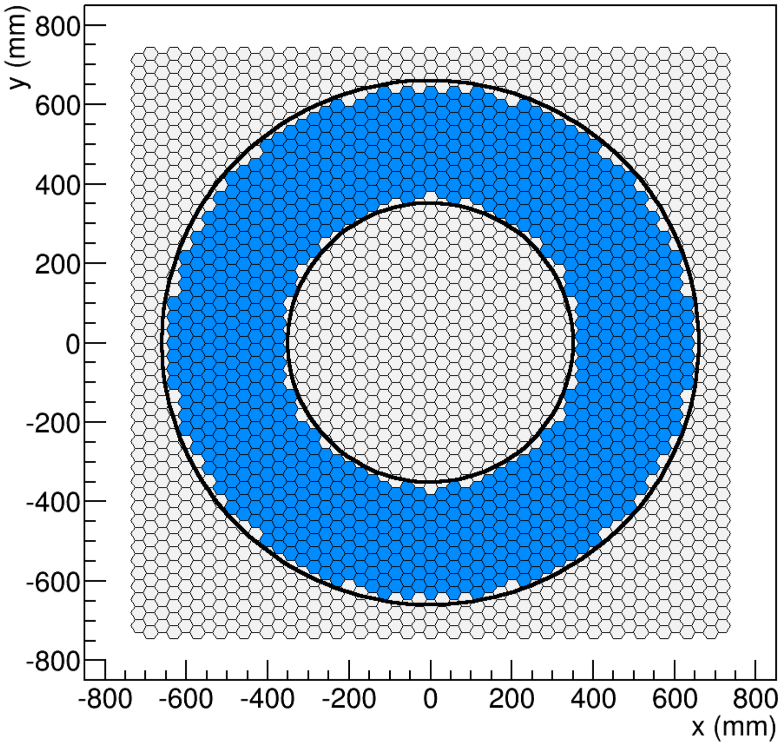
Efficiency = #cluster with E_{clu}> 60 MeV with good track / # good tracks

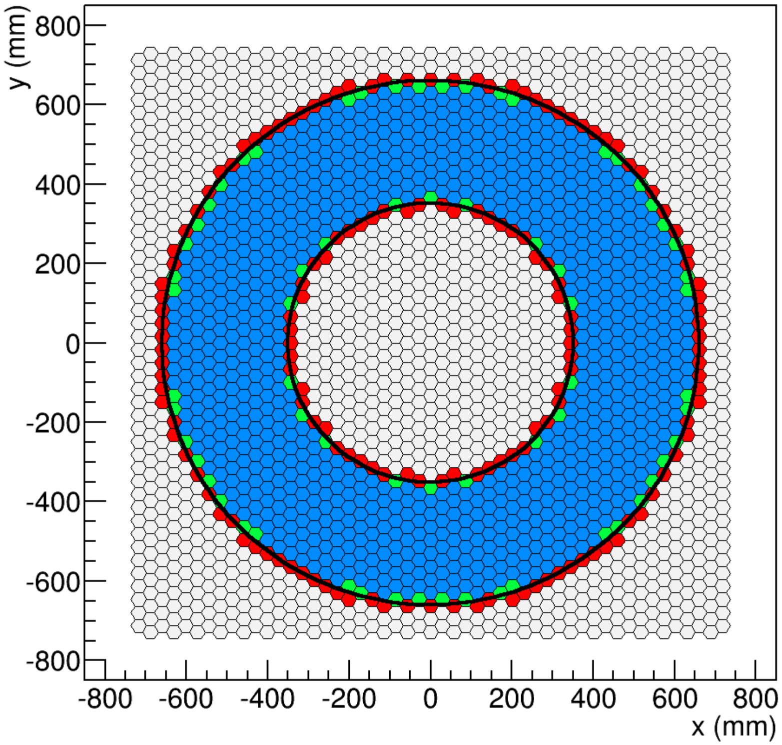
Geometry optimization



Geometry optimization

Disk tessellation for crystals with 33cm across flats,
inner / outer radii of 351 / 660 mm





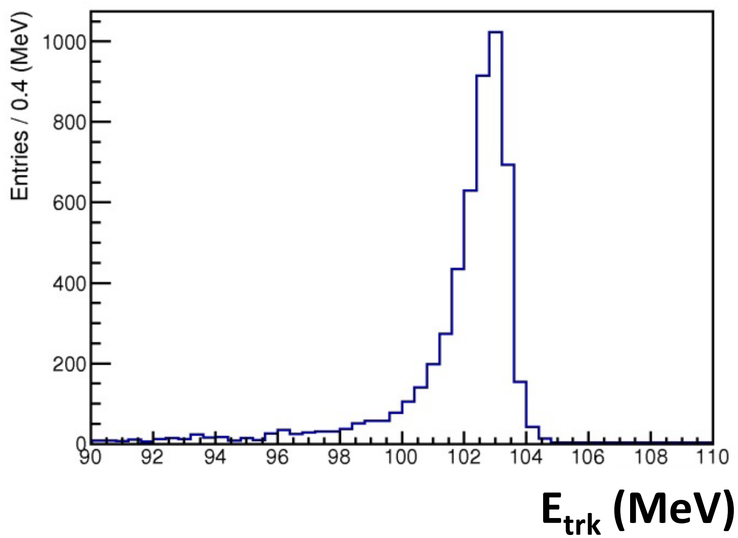
Crystal length set to 20 cm (~10 X_0)

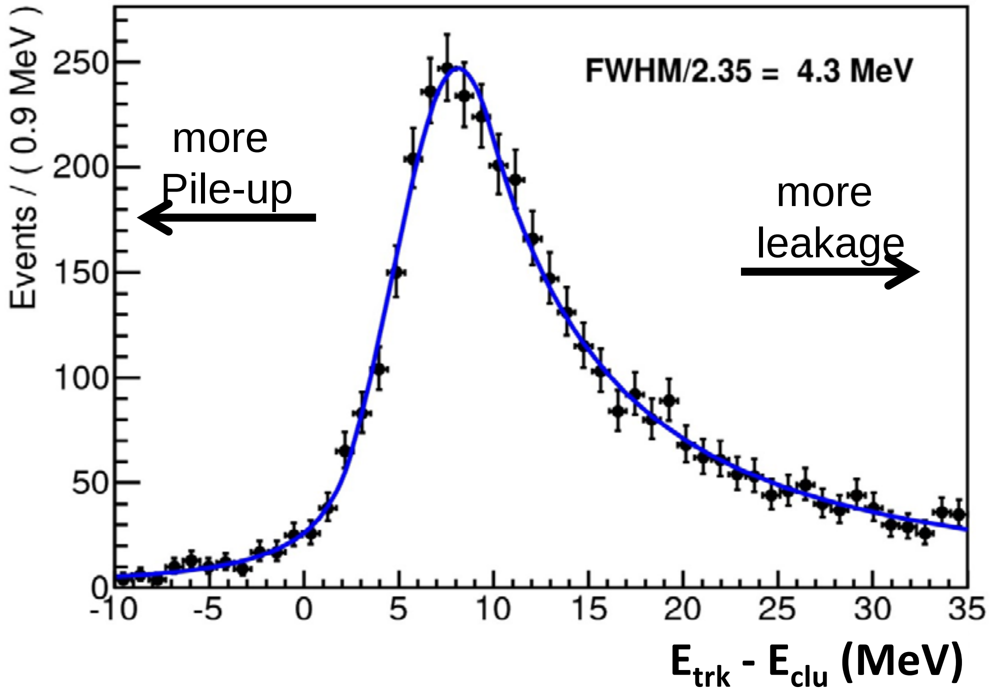
Energy resolution

Resolution given by the difference between the energy of the electron at the entrance of the calorimeter and the cluster energy.

Fit the energy resolution with a double-sided Crystal Ball function.

Electron energy at entrance of the disk





FWHM / 2.35 = 4.3 ± 0.2 MeV

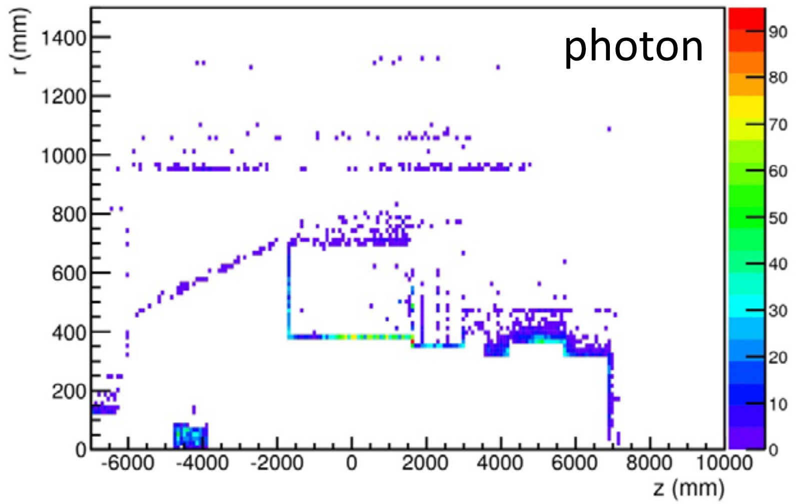
Includes all backgrounds
Signal time window T > 650 ns

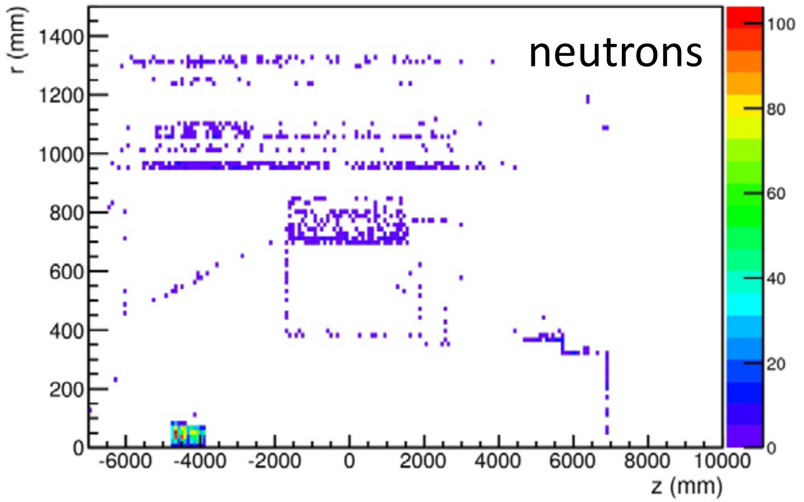
Background sources

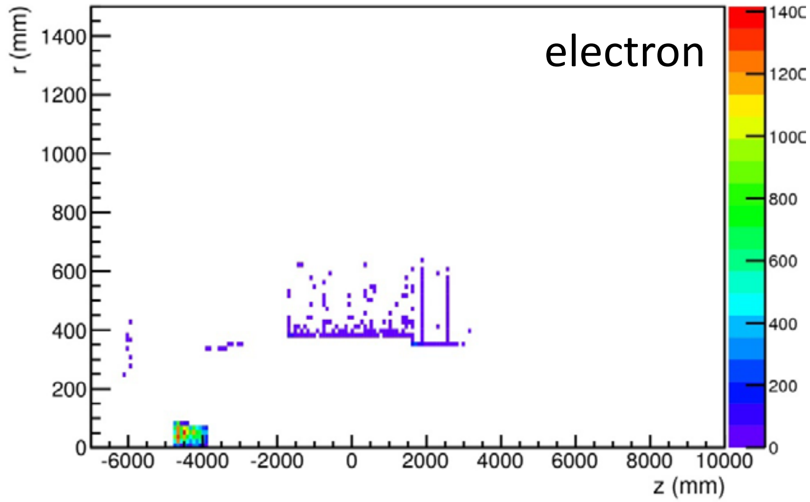
Point of origin of background particles contribution to the clusters

Electrons (DIO) and neutrons mainly from the target

Some photons from the inner side of the tracker and the muon beam stop.

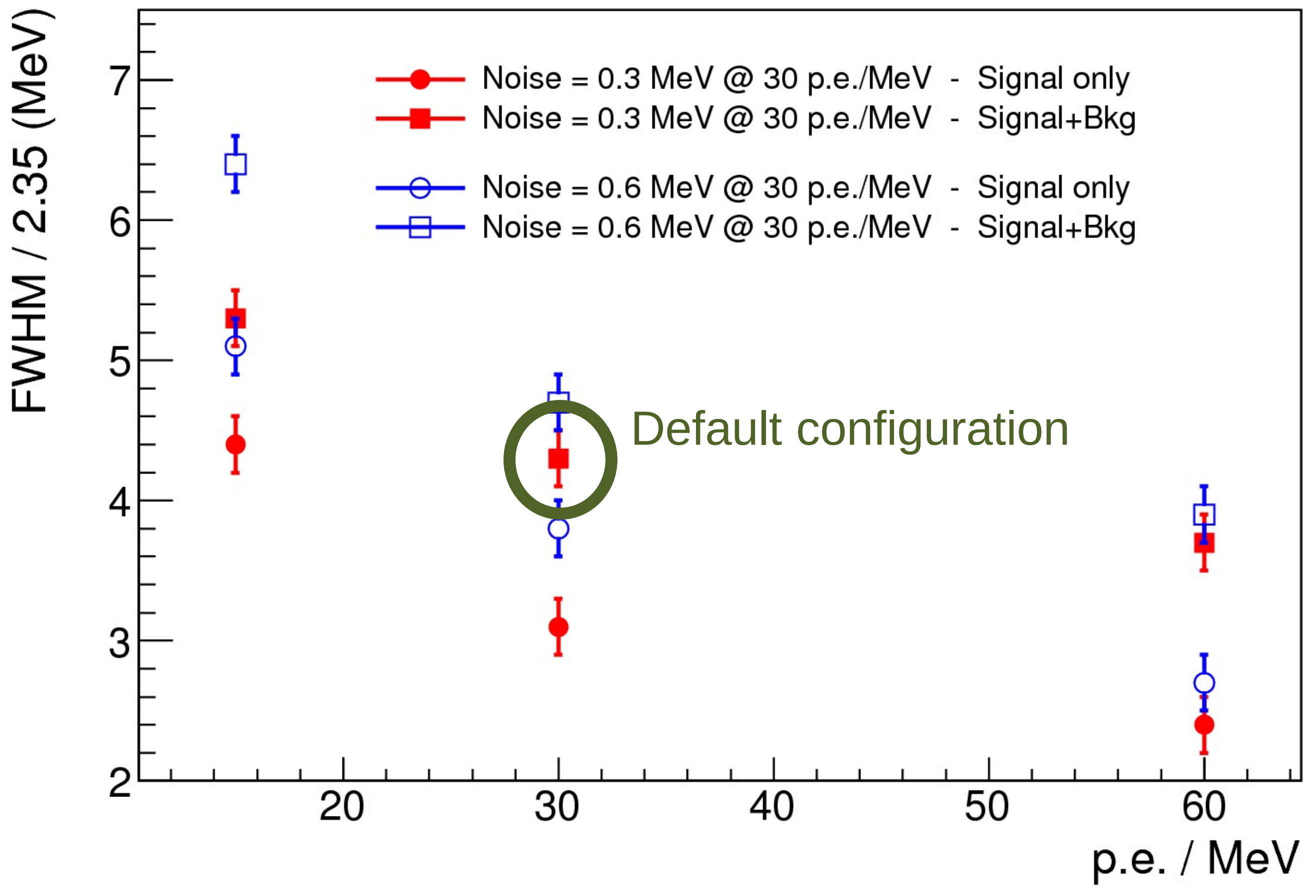






Energy resolution

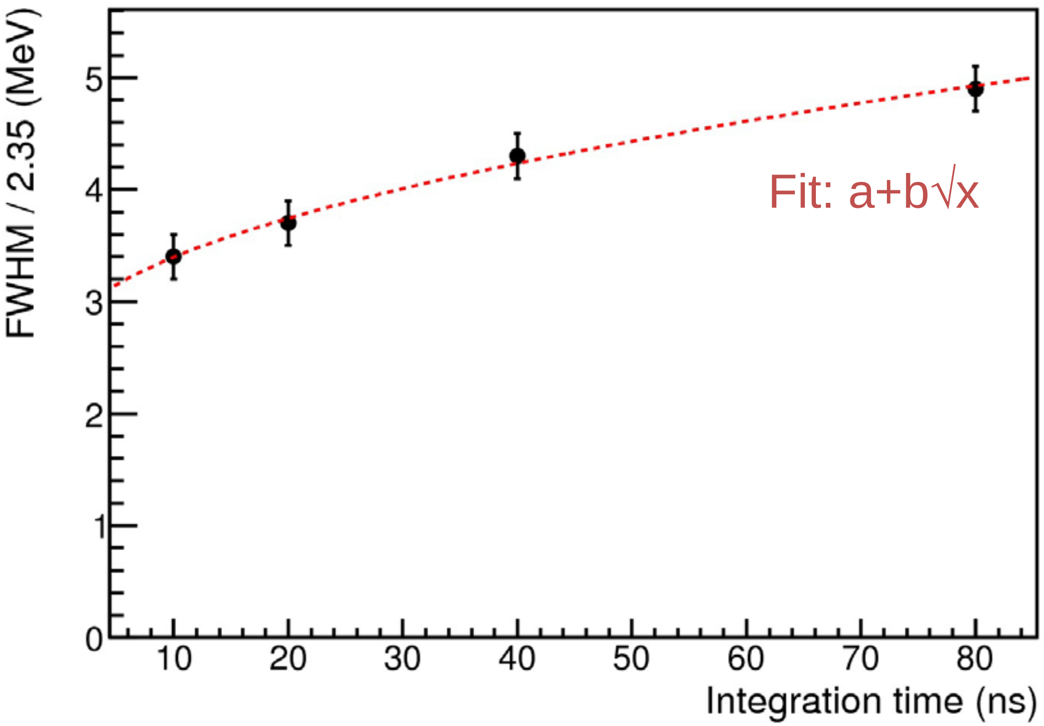
Energy resolution as a function of the number of p.e./MeV and noise level



Resolution using the default configuration is 4.3 MeV for signal electrons

Energy resolution

Effect of the integration time on the resolution – assume a similar amount of light collected (i.e. faster electronics) for shorter integration time



Reducing the integration time by a factor of two brings the resolution down to 3.8 MeV
Background x2 ~ integration time x2 with background x1 → resolution is 4.9 MeV

Position resolution

Calculate the center-of-gravity of the cluster with several algorithms:

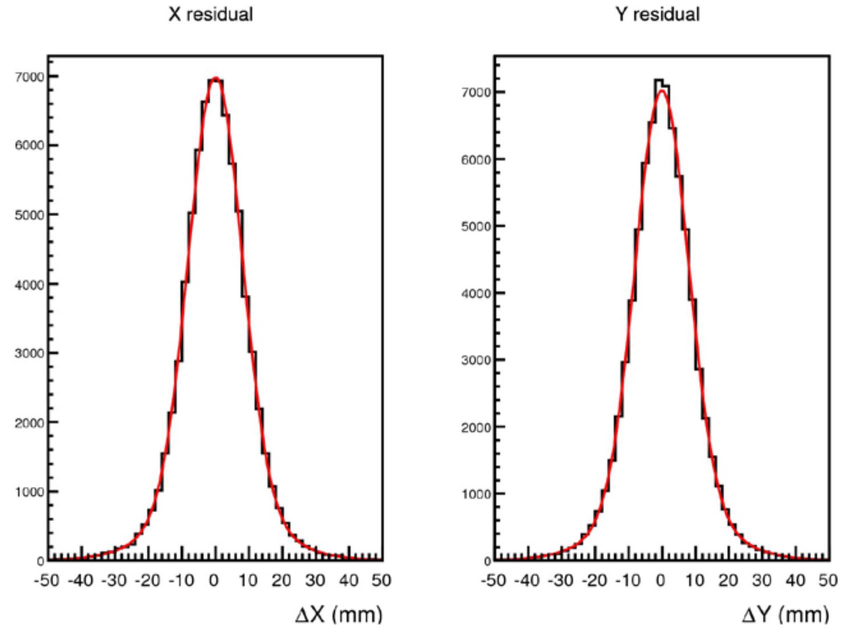
- energy weighted,
- sqrt(energy) weighted,
- log(energy) weighted,
- …

Compare the center-of-gravity with the position of the track (MC level).

All algorithms yield similar results.

In progress: investigate algorithms to determine the direction of the incident particle.

Fit resolution with two Gaussian:
core + tail resolution



σ_{core} = 8.0 ± 0.1 mm
σ_{tail} = 16.7 ± 0.2 mm
Tail fraction = 10.9%

Core resolution is about 8 mm in x and y coordinates, within the requirements

Position resolution

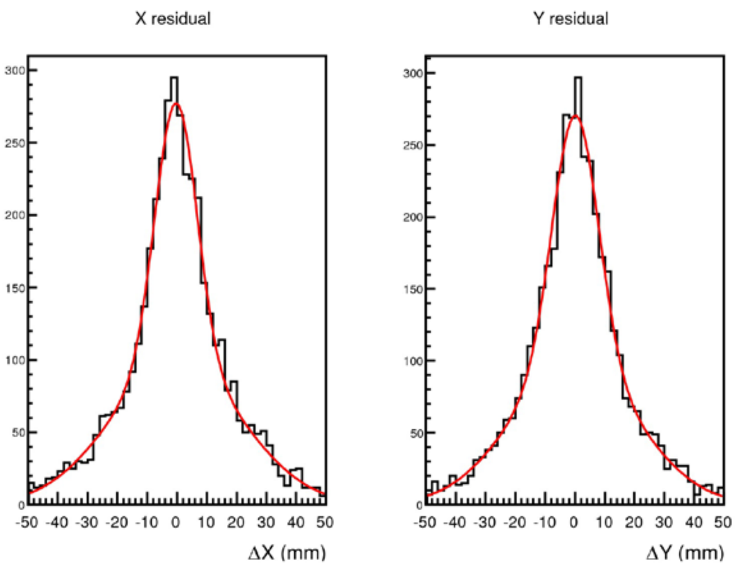
Currently investigation method to improve the determination of the shower parameters (without using tracker information).

Library event matching (LEM):

- generate a library of shower from the MC
- find the N shower closest to the target shower
- estimate the target shower parameters from these N showers

Multivariate regression using BDTs to estimate the shower parameters

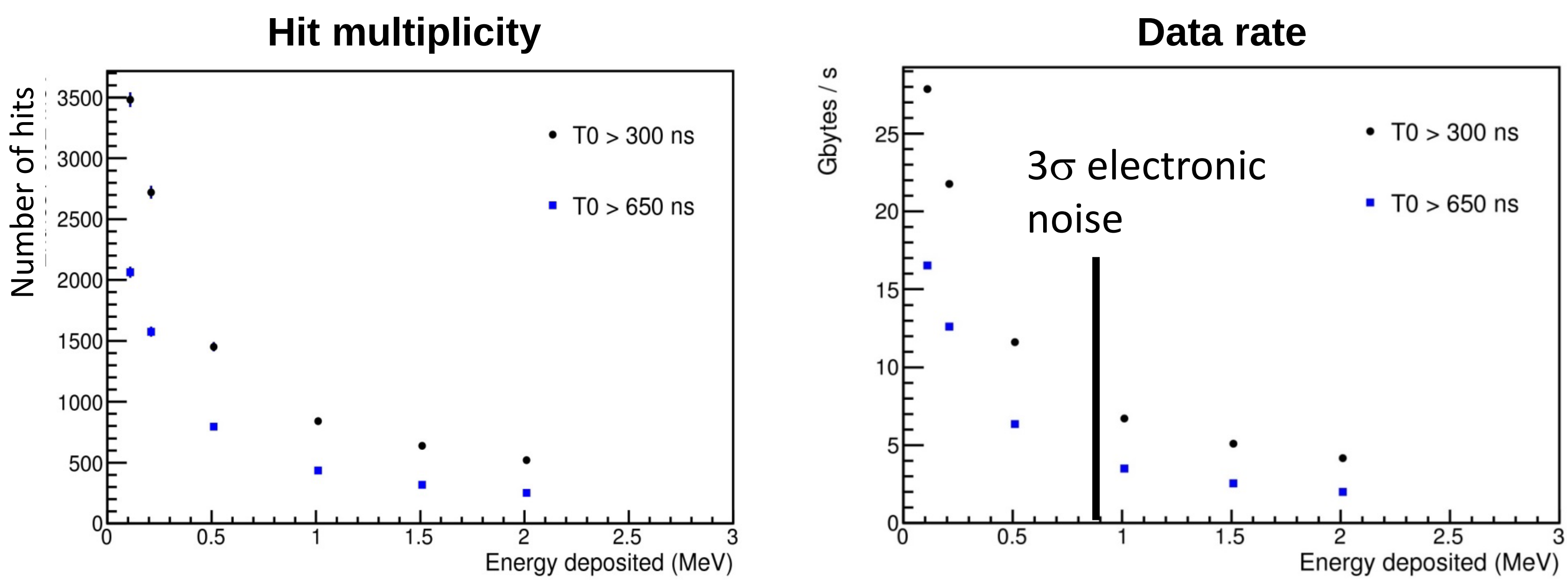
LEM (preliminary)



σ_{core} = 8.1 ± 0.2 mm
σ_{tail} = 23.4 ± 0.7 mm
Tail fraction = 23.9%

Occupancy / data rates

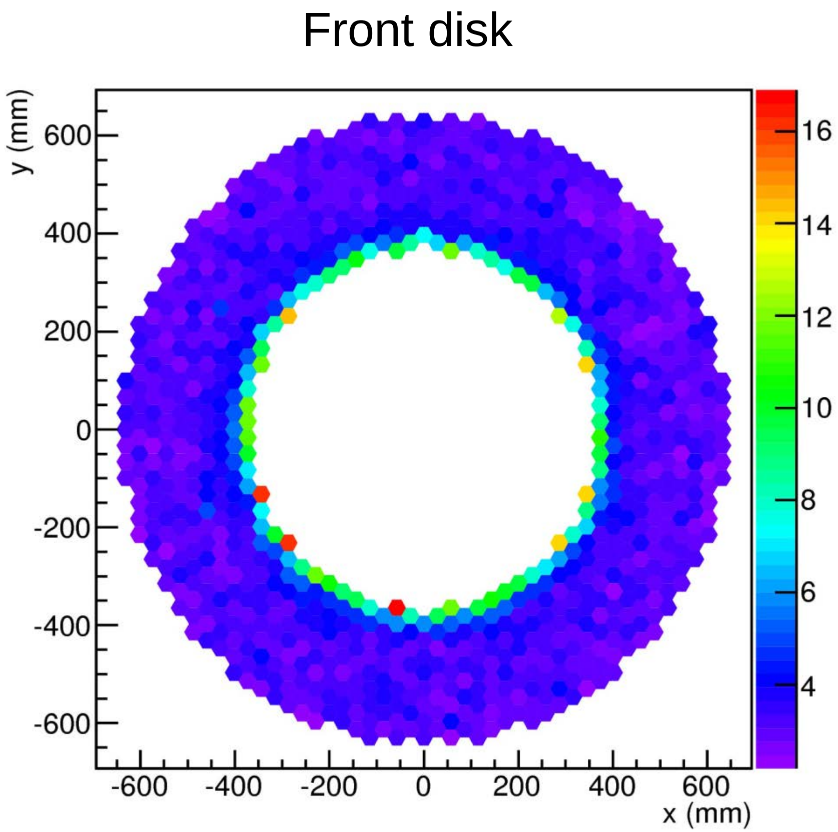
Number of hits / microbunch and data rate as a function of the hit energy with different time cuts (cumulative distribution)

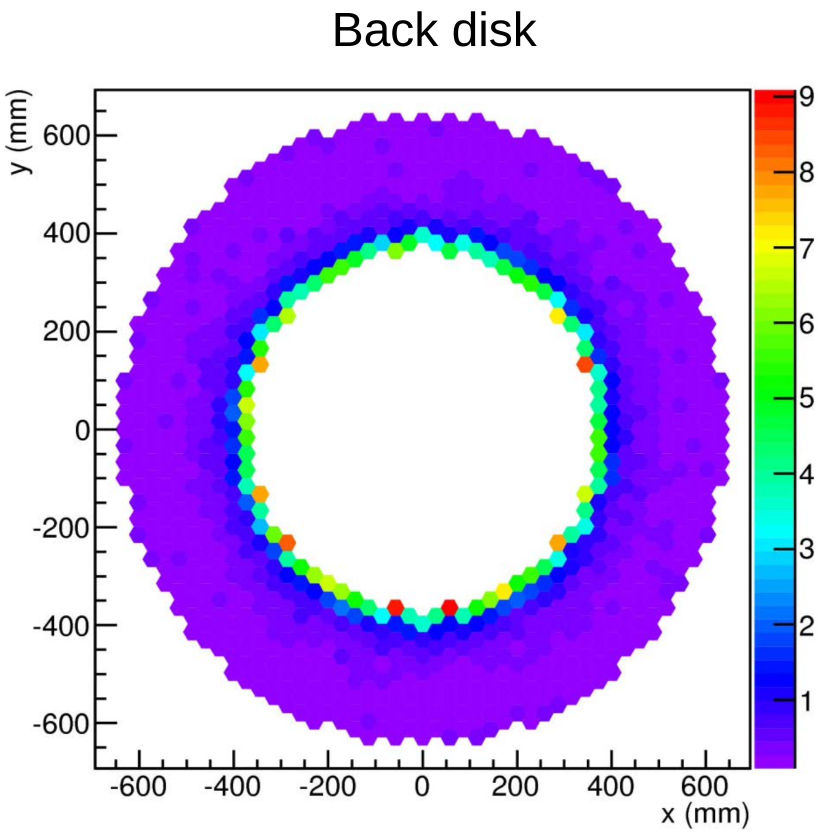


Rate = 20 (bytes / hit) x N(hit / microbunch) x 1.9 x 10^5 (microbunch / sec) x 2 APD

Data compression not included, might decrease this number

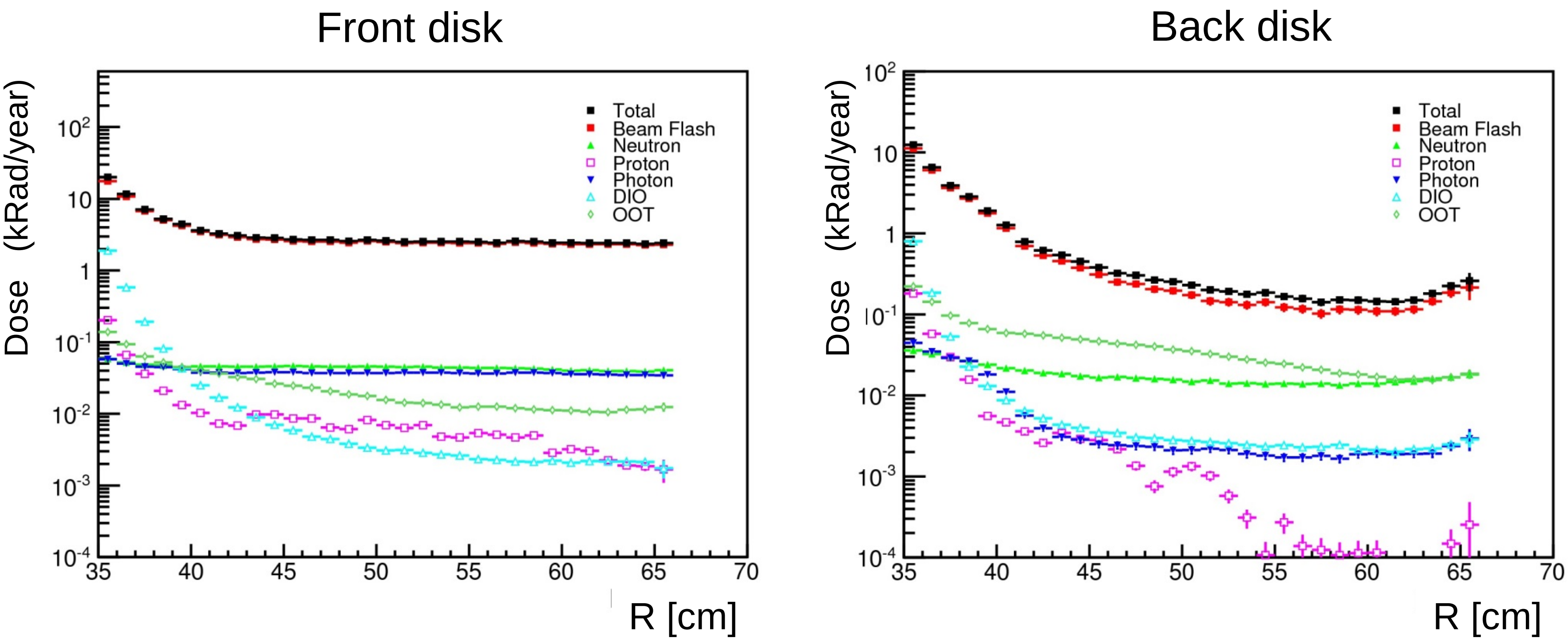
Dose per crystal in kRad / year





The average dose is around 3 (0.5) kRad / year for the front (back) disk, spiking up to 16 (9) kRad / year for the innermost crystals in the front (back) disks

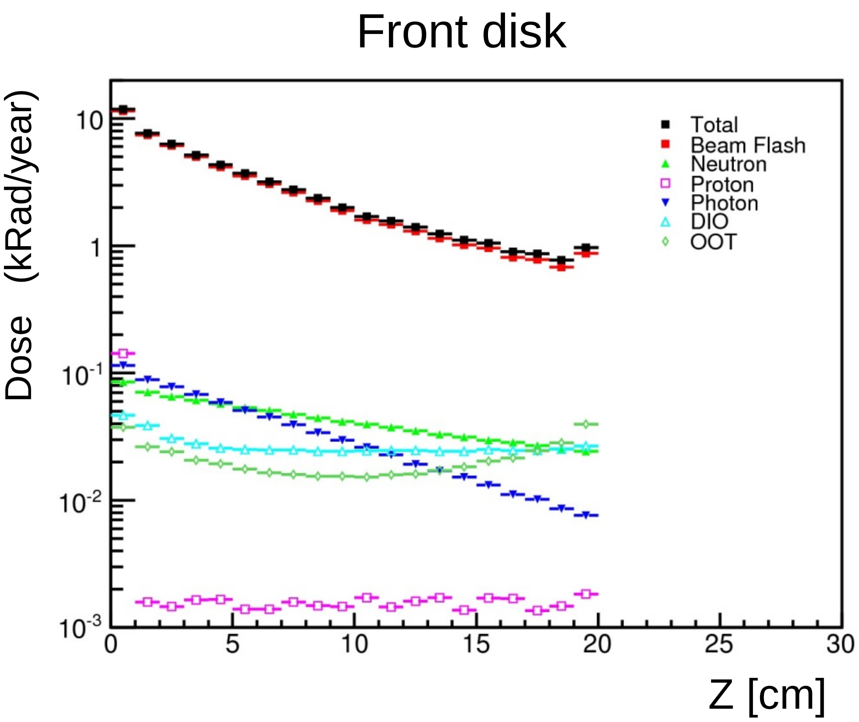
Radial profile of the dose

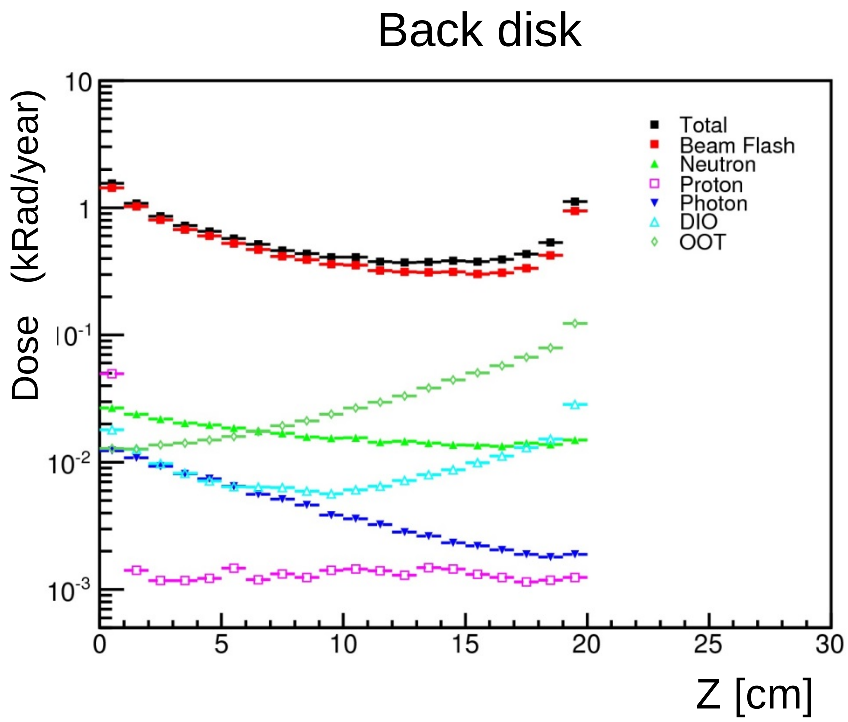


Dose deposited in the amount of crystal present in a ring of 1cm thick (R to R+1 cm), including the fact that only a fraction of crystals are present in the innermost rings.

The beam flash is clearly the dominant contribution; DIO, neutrons and photons follow.

Longitudinal profile of the dose





Dose deposited as a function of crystal depth averaged over the whole disk (R = 351-660 mm).

As expected, most of the energy is deposited in the front of the crystal

Summary

On-going effort to simulate the calorimeter:

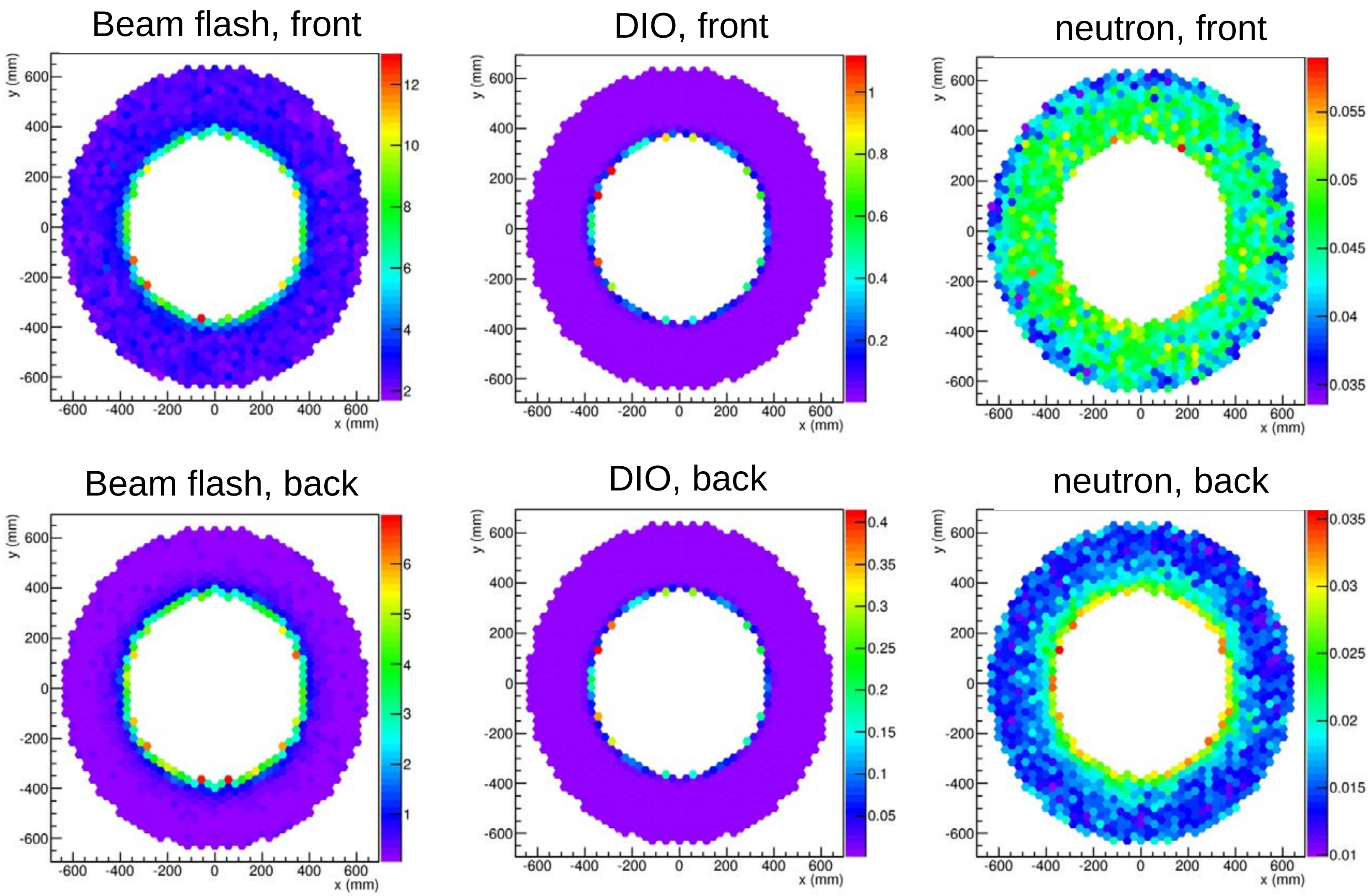
- Dimensions have been optimized
- Energy resolution is around 4.3 MeV for 105 MeV electrons
- Position resolution is around 8 mm in x and y coordinates
- Average dose per crystal is ~ 3 / 0.5 kRad / year for the front / back disk
- Particle identification (P. Murat talk)
- Track reconstruction (P. Murat talk)

Many efforts to improve the simulation in progress:

- Simulation of light propagation / collection
- Electronics simulation / signal extraction
- Pile-up estimation / rejection (multivariate classifier)
- Shower parameter determination (multivariate regression, LEM)
- Particle identification
- Track / cluster matching and track reconstruction

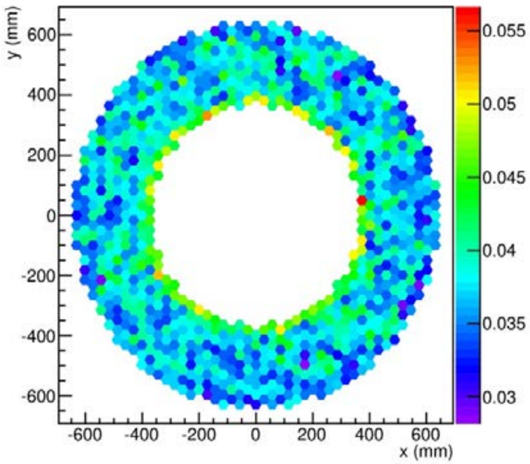
Extra material

Dose (kRad/year) – component breakdown

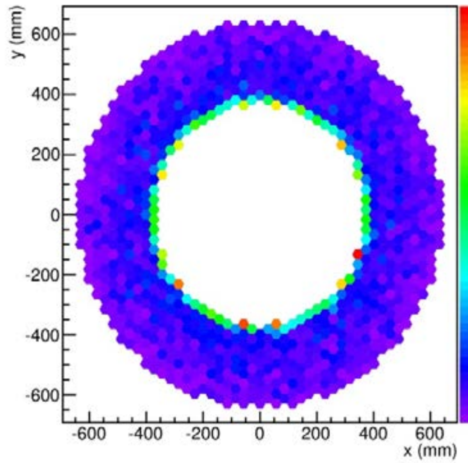


Dose (kRad/year) – component breakdown

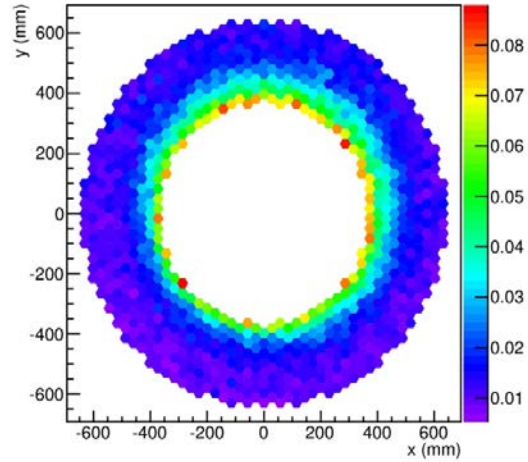
Photon , front



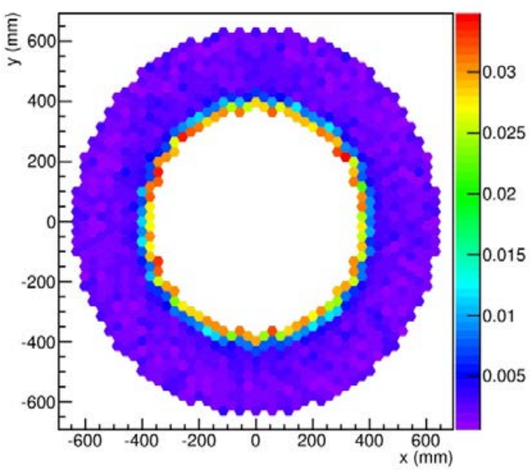
Proton , front



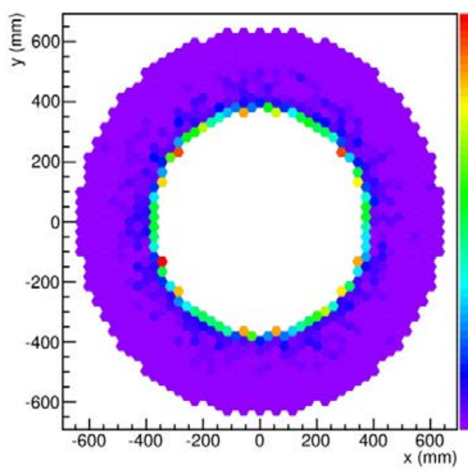
OOT, front



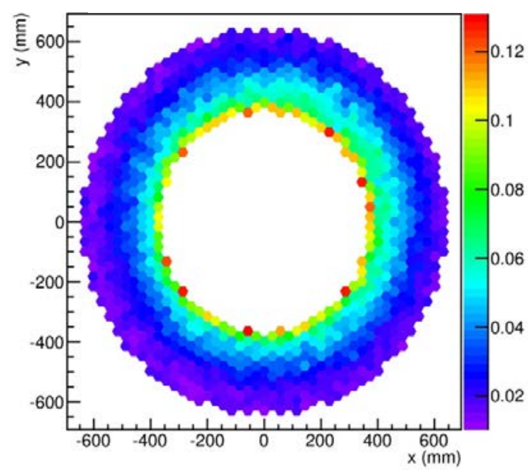
Photon , back



Proton, back



OOT, back



Effect of the radiation