The LHCb ECAL upgrade(s) and ongoing R&D

Outline:

- Limitations of current ECAL
- Requirements for Upgrades Ib and II
- Technological options and overview of ongoing R&D

→ See next talk by Loris on prototype results

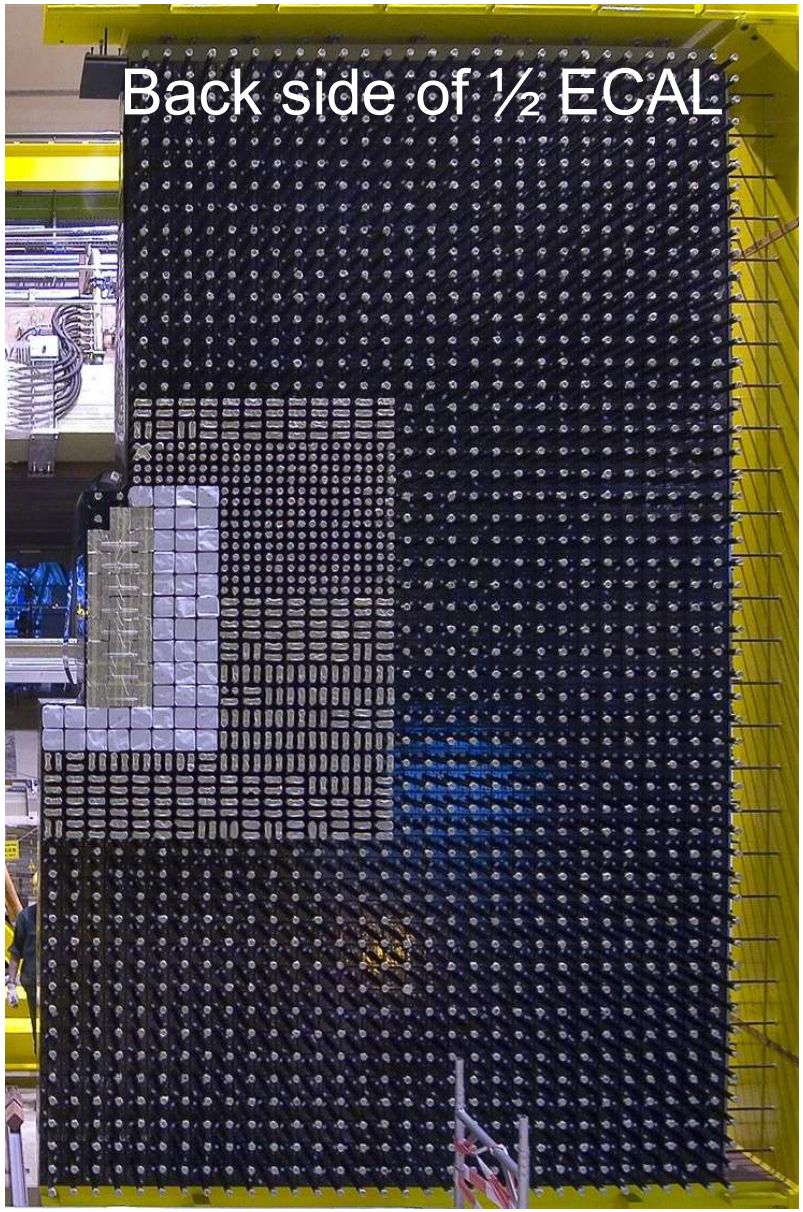
On behalf of the SPACAL R&D group:

- Collaborating institutes
  - ✓ members of LHCb, RD18, CMS, …
  - ✓ CERN, IHEP, ITEP, MISiS, U Barcelona…
- Industrial partners
  - ✓ CRYTUR, FOMOS, Nanocom, …

(1st Miniworkshop with partners last week)

→ New groups most welcome!

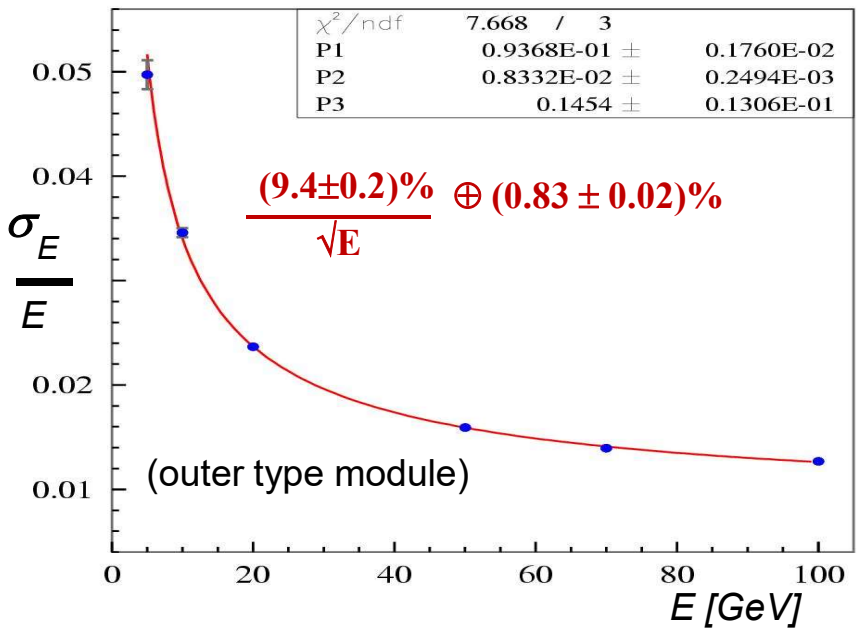
The current LHCb Electromagnetic Calorimeter



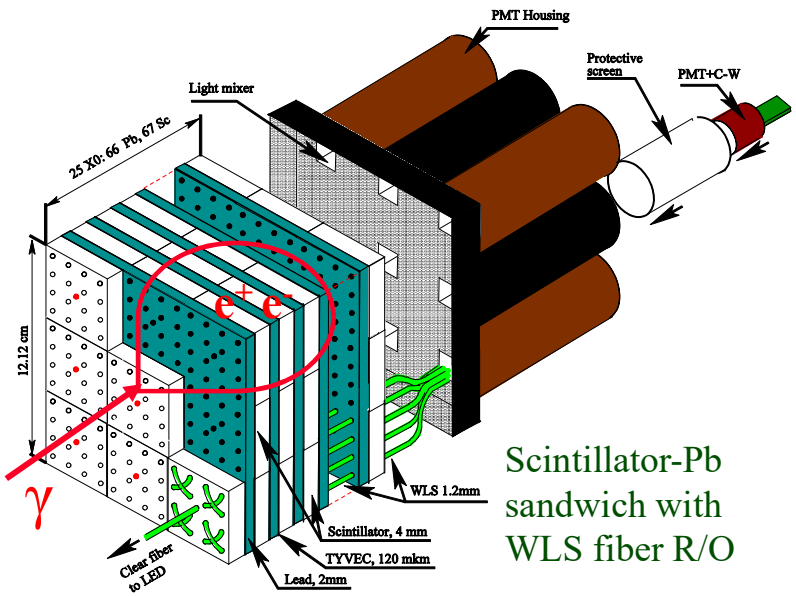
Current LHCb ECAL:

- Large Shashlik array ~50 m^2 with 3312 modules and 6016 channels
- Modular wall-like structure of ~8 x 7 m^2, two halves open laterally within few minutes
- Three sections (Inner, Middle, Outer) of cell size 4x4, 6x6, 12x12 cm^2
- **$\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$**

Energy resolution with electrons



ECAL Shashlik modules



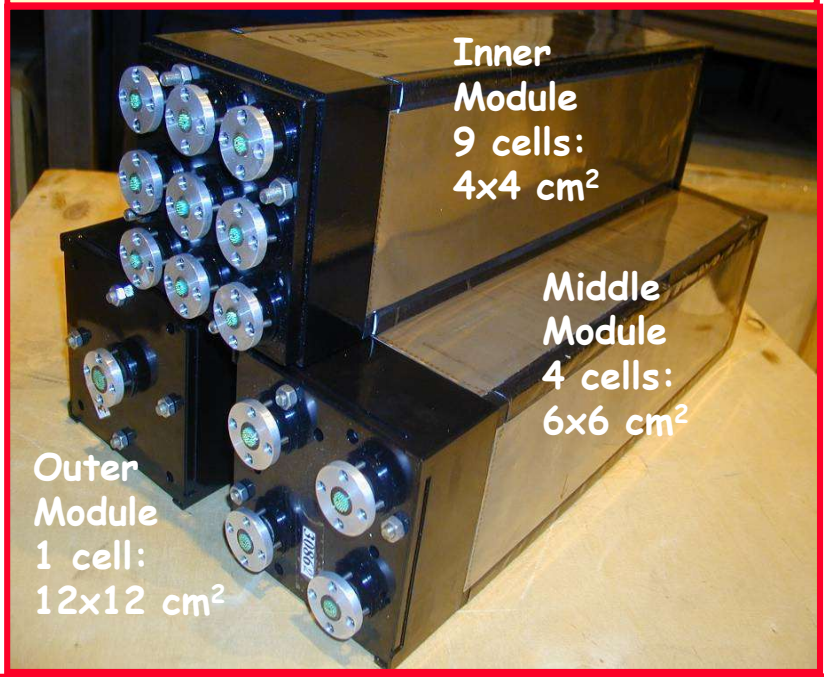
Scintillator-Pb sandwich with WLS fiber R/O

Developed by Russia & CERN (TDR 2000)

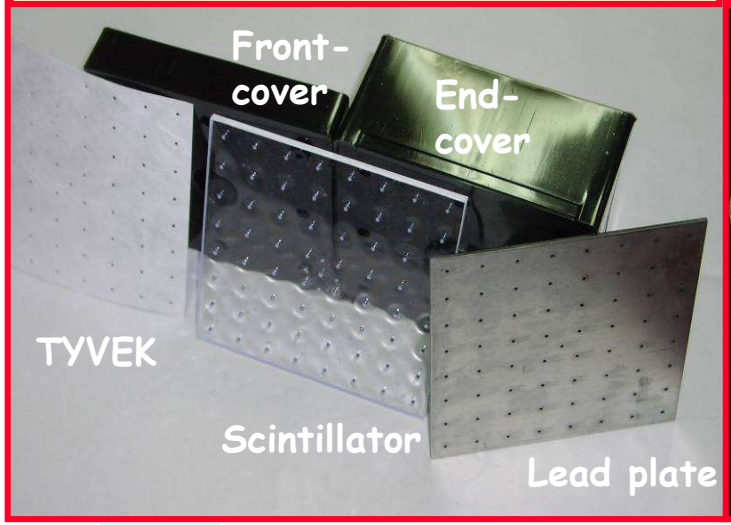
Components:

- Germany
- Japan
- Russia
- …

3312 shashlik modules with 25 X0 Pb

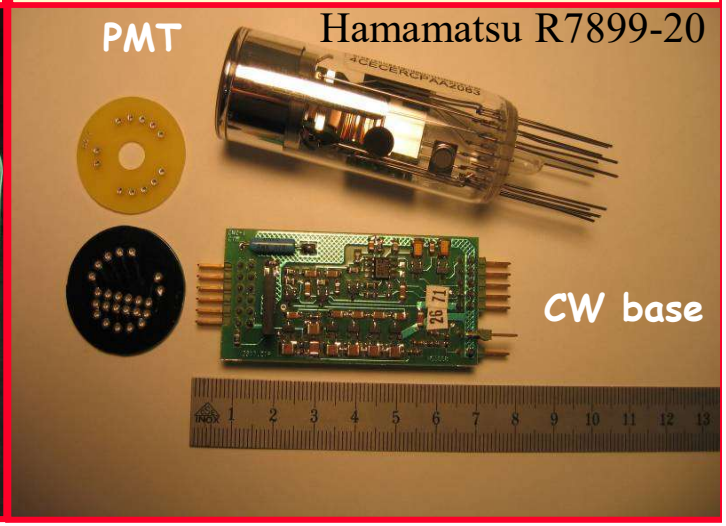


Scintillators, lead-plates, covers

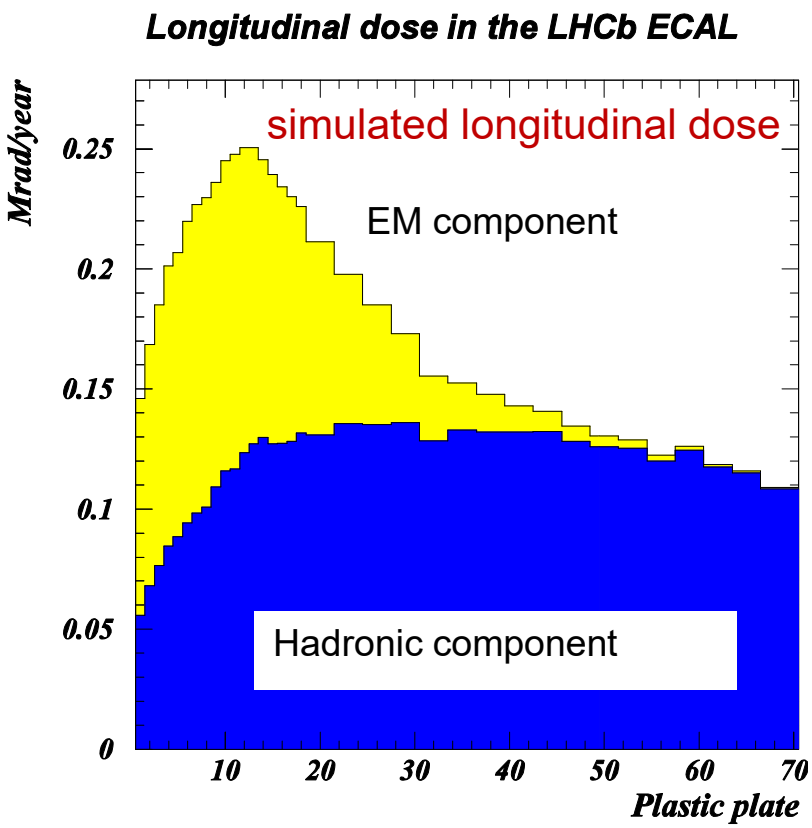


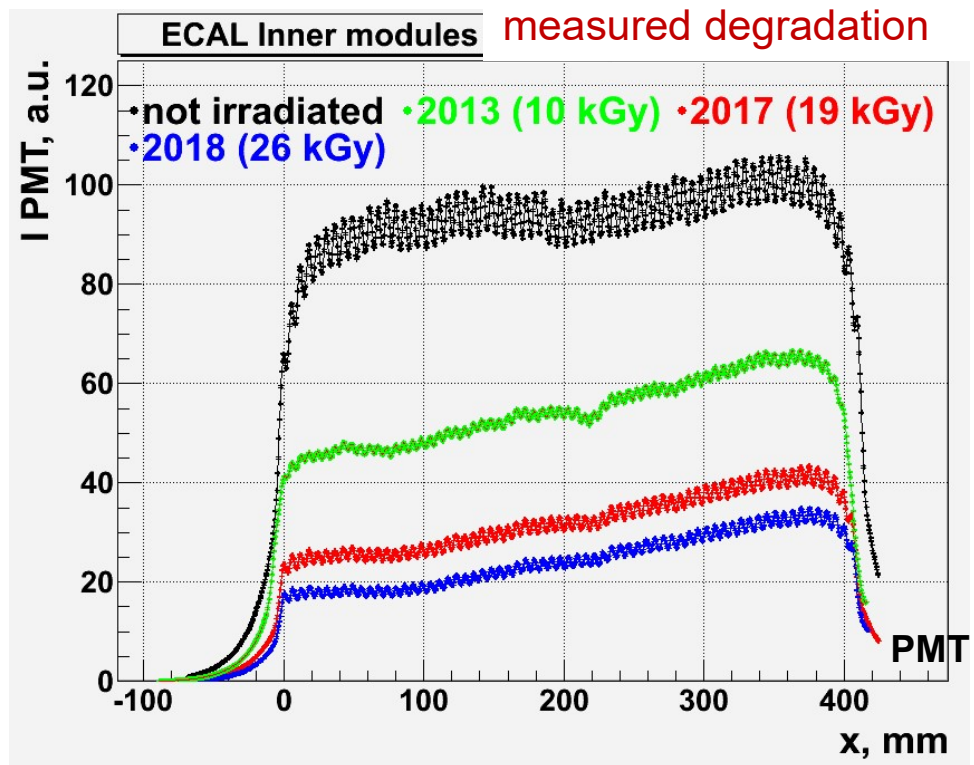
Fibres with loops

PMT and HV base



Radiation environment at $L=2x10^{32}$ $cm^{-2}s^{-1}$

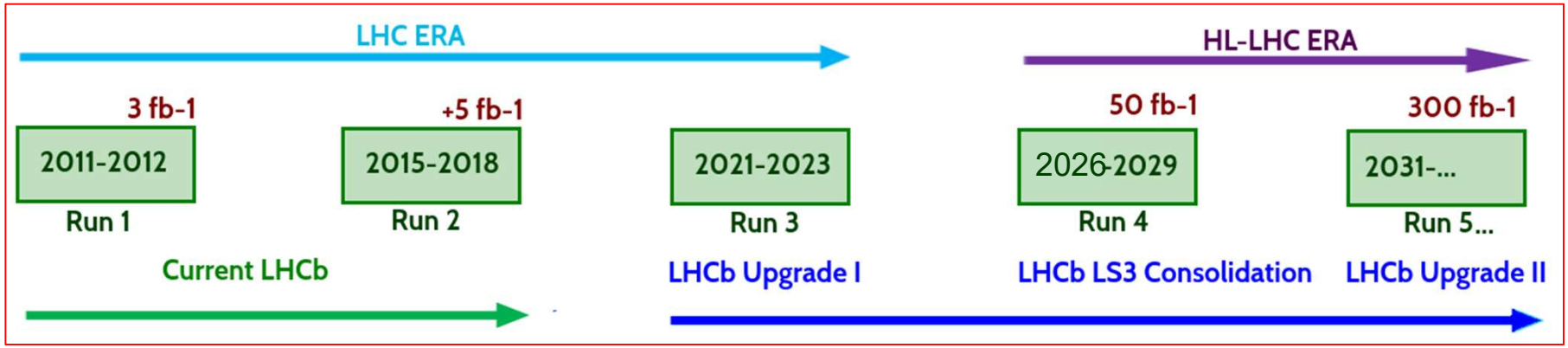




(100rad = 1Gy)

- ✓ radiation dose at shower maximum is ~2-2.5 kGy/fb^{-1}
- ✓ by now accumulated ~10 fb^{-1} in run 1&2 → ~20-25 kGy
- ✓ current Shashlik modules estimated to "survive" ≤ 40 kGy
- ➢ by LS3 ~32 inner modules to be replaced (~50-60 kGy)
- ➢ new modules to sustain much higher radiation doses up to ~1000 kGy (!)

LHCb ECAL Upgrade II



2020 - 2023: → submit **T**echnical **D**esign **R**eports

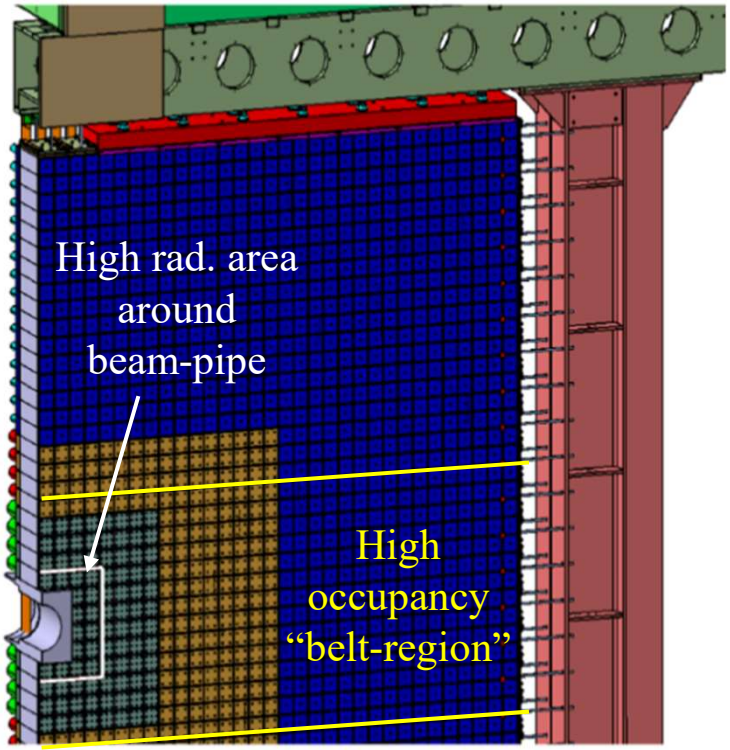
- 2020/21: Framework TDR for Upgrade II including sub-detector **"Consolidation" TDRs**
- 2023/24: Sub-detector **TDRs for Upgrade II**

LS3 in 2024/25: → **Consolidation**

- **Replace modules around beam-pipe** (~32 modules) compatible with $L=2x10^{33}$ $cm^{-2}s^{-1}$

LS4 in 2030/31: → **LHCb Upgrade II**

- **Rebuilt ECAL in high occupancy "belt-region"** compatible with luminosity up to $L \leq 2x10^{34}$ $cm^{-2}s^{-1}$
- Include **timing information** to mitigate multiple interactions/crossing



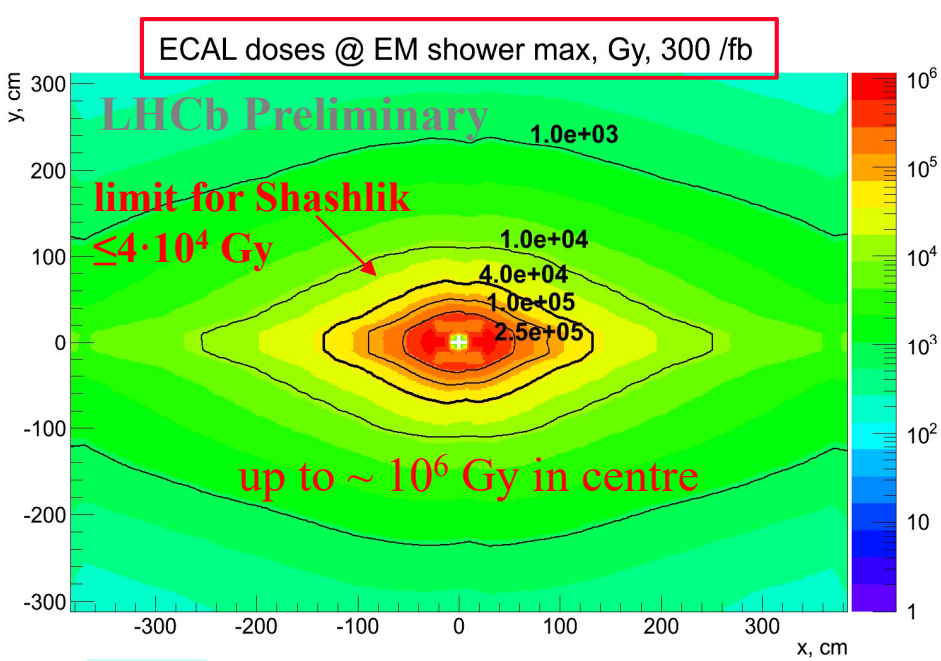
ECAL requirements for Upgrade II

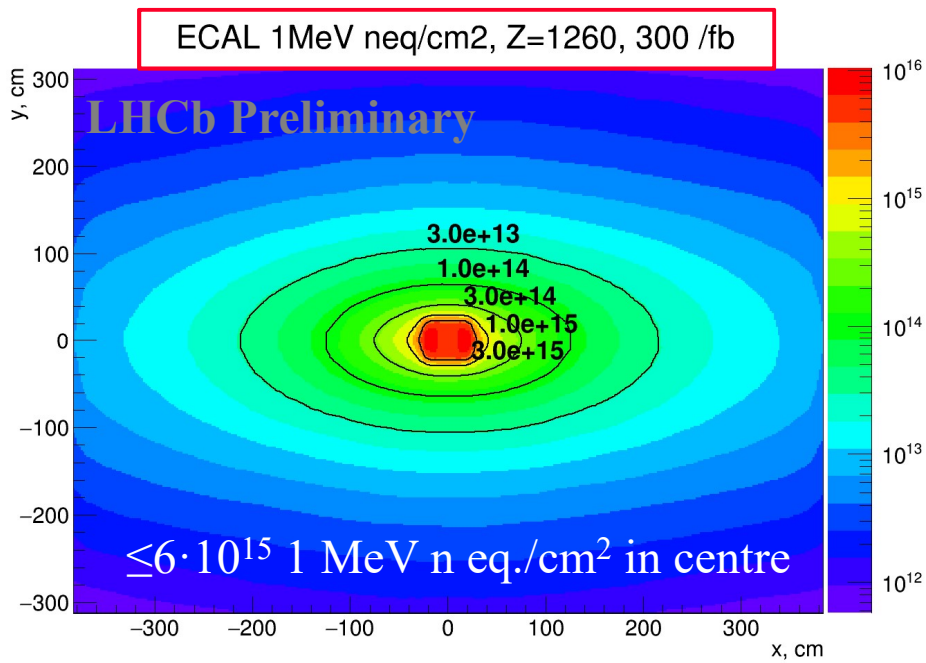
Overall requirements:

- ✓ sustain **radiation doses** of up to ~1MGy and $\leq 6 \cdot 10^{15} cm^{-2}$ for 1MeV neq/cm^2 at 300 fb^{-1}
- ✓ include a **very fast component** ~several 10th ps for pile-up mitigation
  - ➢ into sampling modules or/and
  - ➢ with additional timing preshower

(1MGy = 100Mrad)

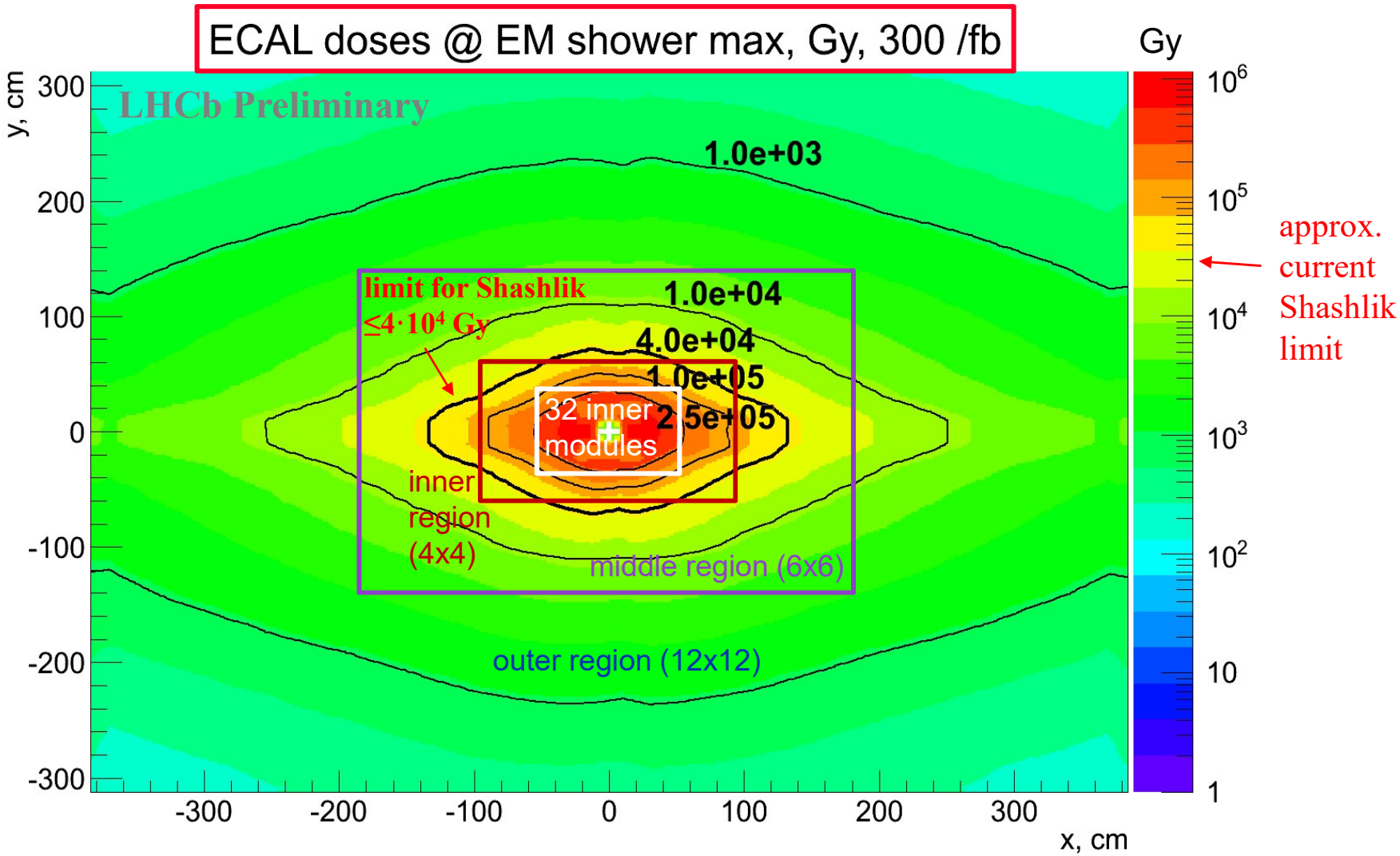
- ✓ keep good **energy resolution** of order $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$
- ✓ handle **increased occupancy** by improving spatial resolution in inner & middle region
- ✓ respect dimensional **constraints of a module**: 12 x 12 cm^2 outer dimension





ECAL requirements for Upgrade II

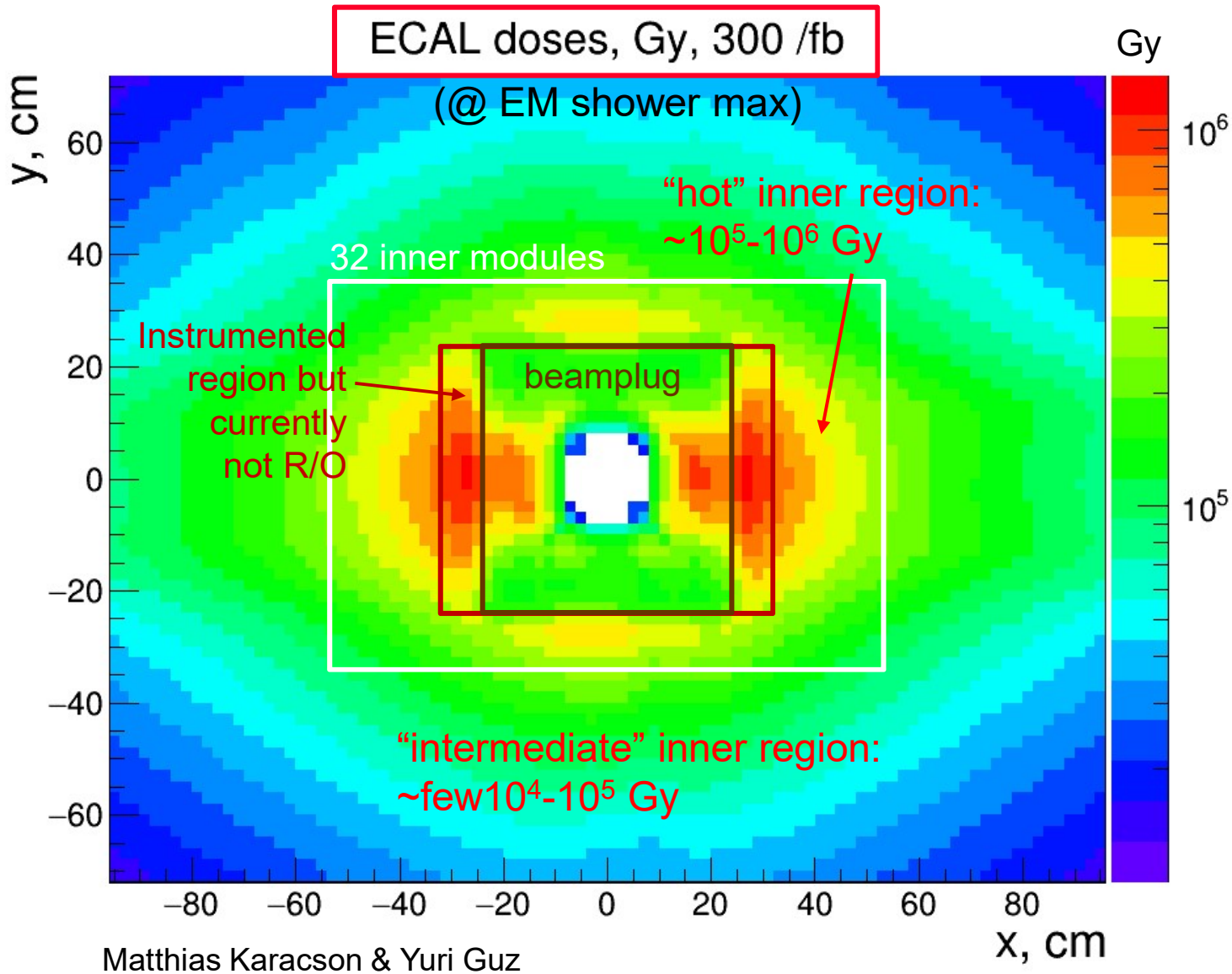
3 regions of ECAL



Matthias Karacson & Yuri Guz

ECAL requirements for Upgrade II

inner region



Matthias Karacson & Yuri Guz

ECAL requirements for Upgrade II

Radiation resistance requirements to modules:

- ✓ in **"hot" inner region** need of very rad. hard modules sustaining up to ~ **1000 kGy**
- ✓ in **"intermediate" inner region** need of modules sustaining between ~50 to **200 kGy**
- ✓ major(?) part of **middle region** and all of **outer region** compatible with current shashlik type modules resisting up to **~40 kGy**

From radiation point of view: (not taking into account cell size requirements due to occupancy)

- ➢ need ≤32 modules for extreme conditions (up to ~1MGy)
- ➢ need another ~150 new modules with "moderate" radiation requirements (up to ~200kGy)
- ➢ can "reshuffle" inner-type modules (176 modules with 4x4cm^2 cells) to middle region
- ➢ can "re-shuffle" middle-type modules (448 modules with 6x6cm^2 cells) to outer region
- ➢ 2688 modules out of a total of 3312 modules are of outer-type with 12x12cm^2 cells

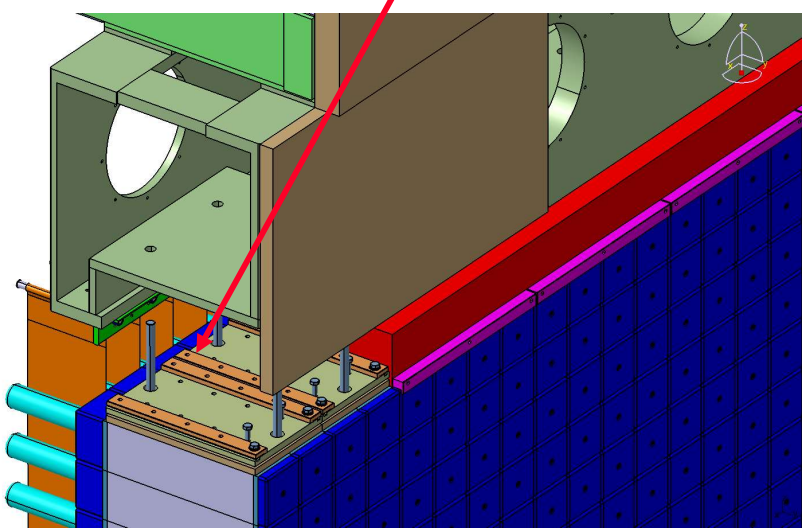
From physics and reconstruction point of view: (→ talk by Zehua and Yasmine)

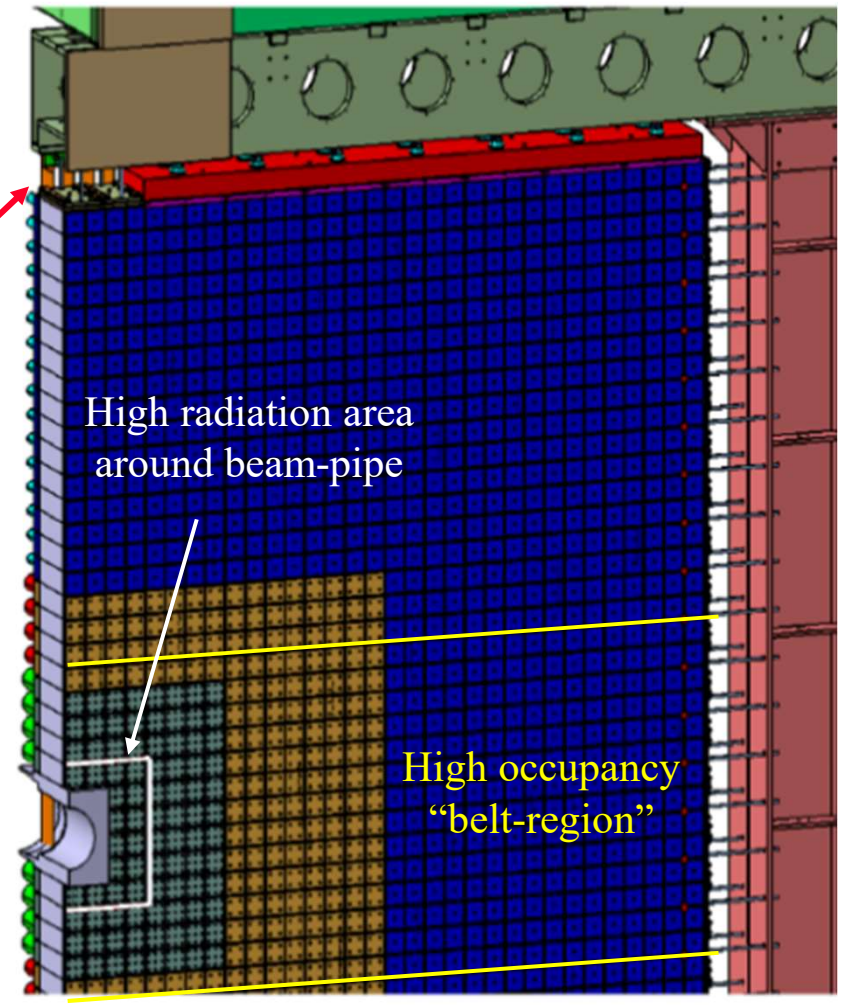
- ✓ 5D ECAL requirements (**E, x, y, z, t**) to be determined from physics performance studies for:
  - ➢ "hottest" and "intermediate" inner region to define E-resol., cell size, Moliere radius…
  - ➢ middle and outer region to optimize "re-shuffling strategy"
  - ➢ note: no need anymore of square regions (no L0) → better match to irradiation map

ECAL requirements for Upgrade II

- 32 modules around beam-pipe can be replaced without dismantling of complete structure (special mechanics to lift columns)
- Replacing and re-shuffling modules within "the belt" will require **dismantling of a major part of the calorimeter wall**

Special mechanics to lift columns for replacing modules around beam-pipe





Possible options for new ECAL modules

- ✓ Homogeneous crystal calorimeter (with longitudinal segmentation ?):
  - Fast and **radiation hard crystal** with high light yield
- ✓ Sampling calorimeter:
  - **Converter material:** Lead, Tungsten or various alloys (with typical $R_M \sim$ 1-2cm)
  - **Radiation hard crystal:** as scintillating medium with high light yield and fast response
  - **Fast timing component:** of ~few 10th ps in scintillating crystal for pile-up mitigation
  - **Radiation hard photodetector:** with high efficiency in the required spectral range
  - For Shashlik: **Radiation hard light-guide/fibre** to transport light

Generic R&D is ongoing in collaboration with experts on crystals & absorbers:

- performance studies of sampling calorimeters (energy & timing resolution)
- radiation hard and fast scintillators of garnet type (i.e. YAG and GAGG)
- absorber materials from tungsten alloys with Cu and Pb
- radiation hardness of GaAs photodiodes with epitaxial technology
- determination of specifications for fast readout electronics

Performance studies of sampling calorimeters

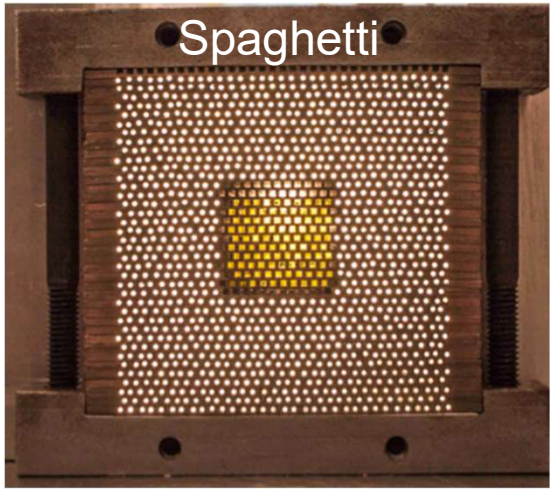
Possible options for new ECAL modules

Pros and cons of different options:

Homogeneous Crystal:

- requires long crystal of ~40cm to contain 25 X_0
- "given" Moliere Radius
- very good homogeneity
- potentially very good E-resolution (<10%)
- large volume of crystal → high cost

Sampling Technologies



Shashlik type module:

- can be made very compact ~15-20cm
- Moliere Radius "tunable"
- **no rad. hard WLS fibers (yet) to transport light!**
- challenging optimization to reach $\sigma(E)/E \leq 10\%/\sqrt{(E)}$
- some cost optimization possible

Spaghetti type module:

- can be made very compact ~15-20cm
- **fibers scintillate AND transports light!**
- Moliere Radius "tunable"
- challenging optimization to reach $\sigma(E)/E \leq 10\%/\sqrt{(E)}$
- some cost optimization possible

Performance optimization of sampling calorimeters

Advantage of sampling calorimeters:

- sampling fraction (ratio of active to inactive material) can be optimized
  - ✓ define fiber dimension (cross section)
  - ✓ define fiber-to-fiber distance and fiber layout
- tunable radiation length (X_0) and shower width (R_M)
  - ✓ R_M should be of same order than cell size
  - ✓ X_0 should be as small as possible (short module = short fibers)

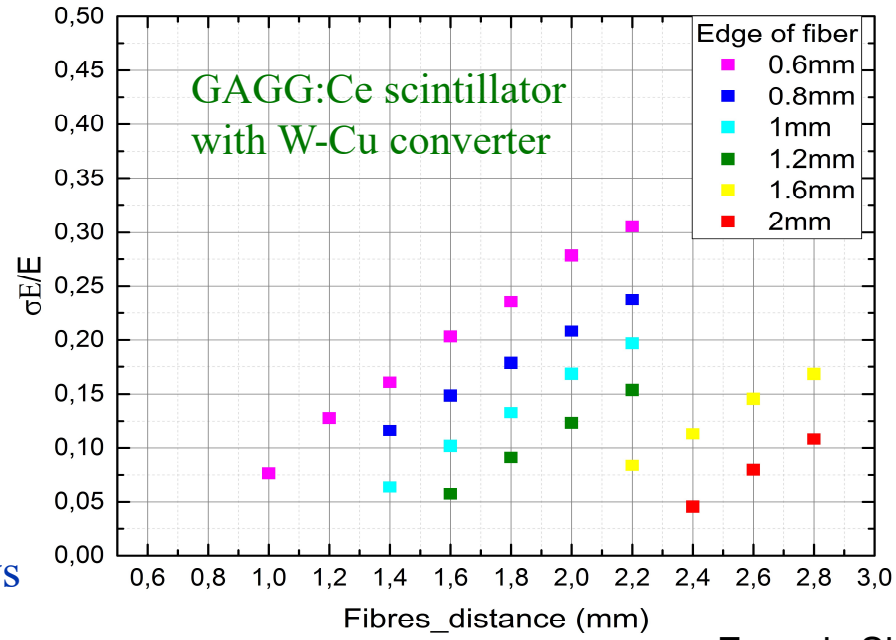
Ongoing R&D:

- for inner region → SPACAL R&D: (no need of rad hard wavelength-shifting fibers)
  - ✓ fiber size and
  - ✓ fiber-to-fiber distance and fiber layout
  - ✓ crystal to absorber ratio
  - ✓ longitudinal segmentation
  - ✓ minimization of module length (X_0)
  - ✓ optimization of Moliere radius (R_M) and cell size
  - ✓ optimization of timing response
- for middle and outer region → Shashlik R&D
  - ✓ performance of timing response (→ see talk by Loris)

Performance optimization of SPACAL

Simulation studies ongoing on dependence of energy resolution on:

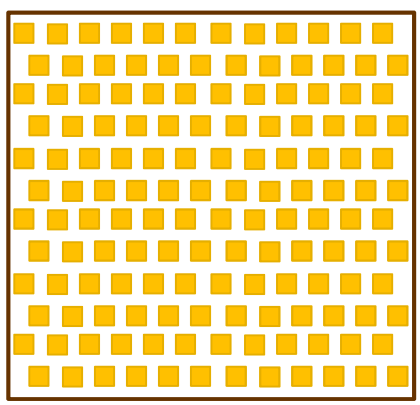
- ✓ fiber dimension
- ✓ fiber-to-fiber distance
- ➢ Current prototype 1x1 mm^2 fibers with 1.8 mm pitch



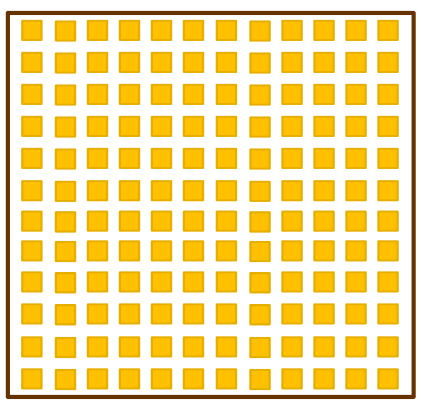
Evgeniy Shmanin

Simulation studies will start on detailed fiber layout with:

- ➢ shifted fiber rows vs. aligned fiber rows
- ➢ possibility of inclined fibers?



current layout



alternative layout

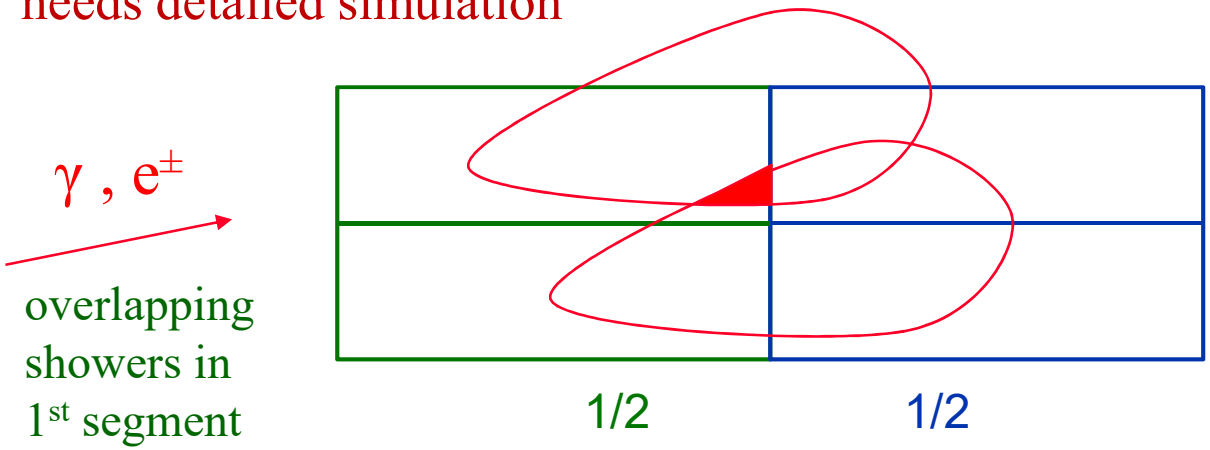
Fiber layout has draw-back on manufacturing technique of absorber!

Performance optimization of SPACAL

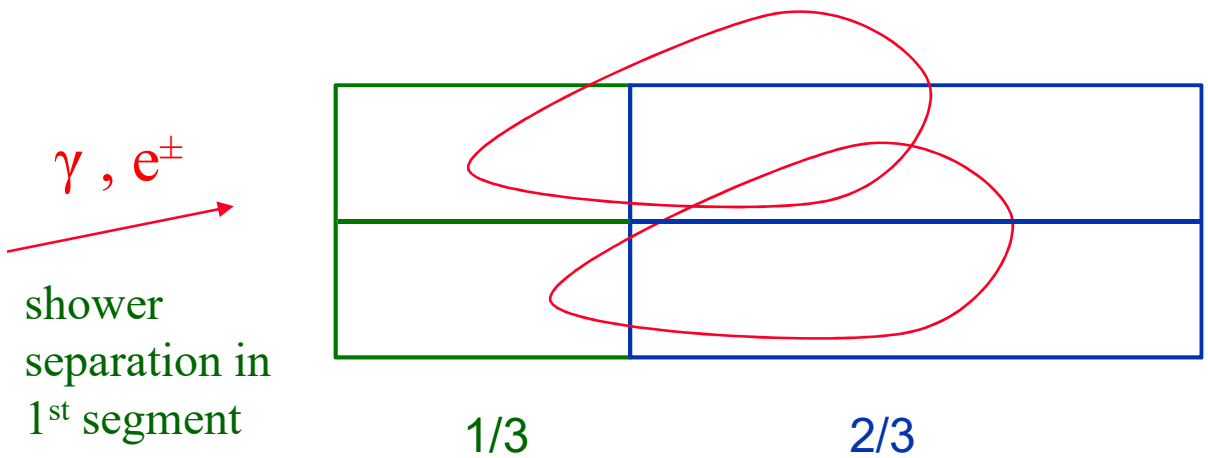
Optimization of longitudinal segmentation:

- reconstruction of overlapping showers
- needs detailed simulation

For illustration only!



present prototype



asymmetric segmentation might be better for overlapping shower separation
→ next prototype

R&D on radiation hard and fast scintillation crystals

Properties of Garnet:Ce doped crystals

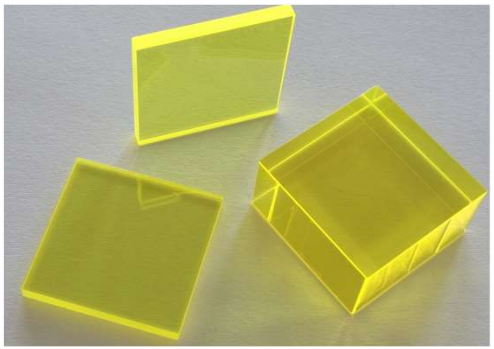
	$Y_3Al_5O_{12}$:Ce (YAG)*	$Lu_3Al_5O_{12}$: Ce (LuAG)*	$Gd_3Al_2Ga_3O_{12}$: Ce (GAGG)**	Lu_2SiO_5:Ce (LSO)
density (g/cm^3)	4.57	6.73	6.63	**7.4**
X_0 (cm)	3.5 cm	1.3	1.59	1.1
Refraction index	1.83	1.84	1.85	1.82
Λ_{max} (nm)	**550**	**535**	**520**	**420**
LY @ RT (ph/MeV)	**35000**	**25000**	**50000**	**30000**
decay time (ns)	70 + slow component	70 + slow component	60 + slow component	**40**
rise time (ps)	**?**	**?**	**?**	**?**

Key requirements:

- radiation hardness up to 1MGy (light yield, attenuation length…)
- good timing properties for both, the decay time component (spill-over, 25ns) and the rise time (pile-up mitigation, ~several 10th of ps)

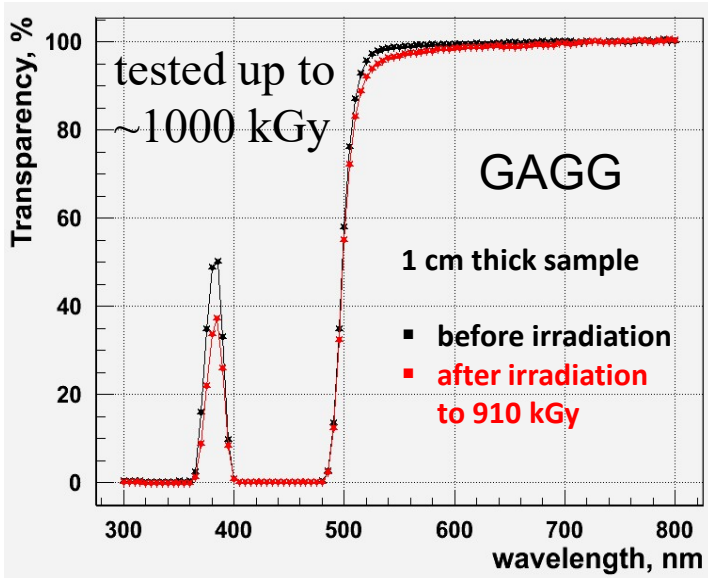
R&D on radiation hardness of Garnet crystals

R&D on radiation hard garnet crystals:



Samples of GAGG crystals irradiated at CERN

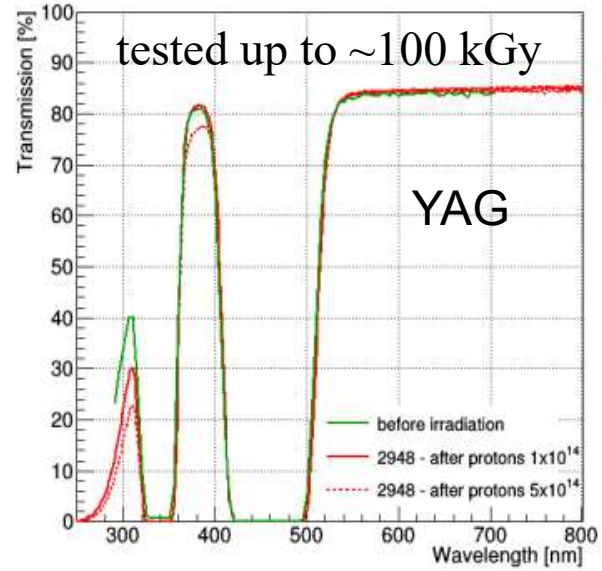
GAGG:Ce,Mg



Irradiation by Yuri Guz

M. Lucchini et al. NIM a 816 (2016) 176-183

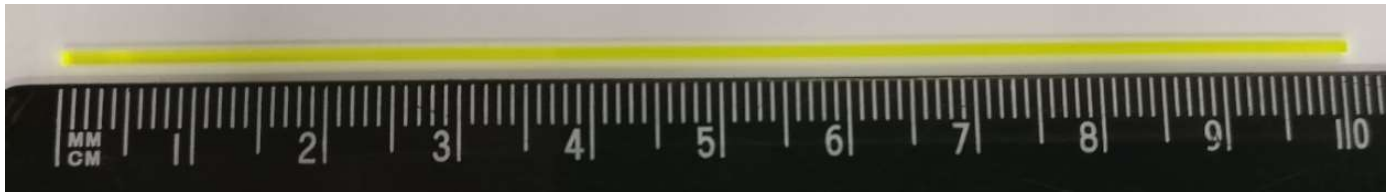
YAG:Ce - sample #2948



Irradiation by CERN RD18 (CCC) group

M. Lucchini,et al., SCINT2015 conference, IEEE TNS 63 (2016) 586-590

Cutting 1mm x 1mm, 10cm long GAGG fiber from ingot

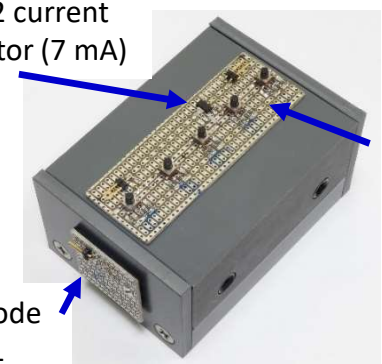


- GAGG crystals resist to radiation of ~1 MGy (100 Mrad)
- Can be cut to 1x1 mm^2 fibers with max length of ~10 cm

R&D on optical performance of GAGG fibers

- ✓ 500 GAGG fibers of 1mm x 1mm x 10 cm produced by FOMOS
- ✓ Quality Assurance (QA) of fibers at CERN and in Moscow
- ✓ Developed portable QA setup, easy and fast to use

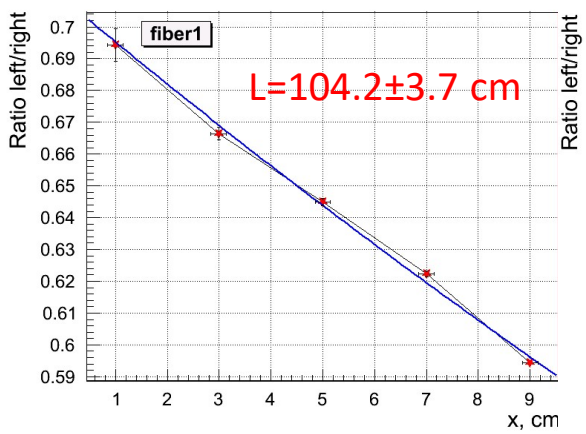
QA setup

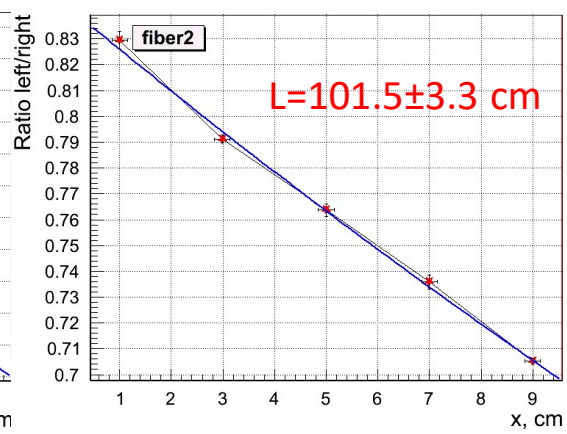


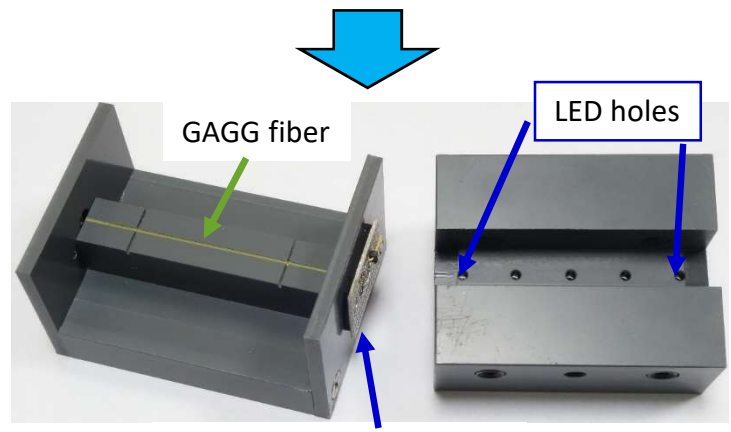
Yuri Guz

- ➢ two measurements:
  - ✓ *effective* attenuation length
  - ✓ relative fiber light yield

- ➢ Preproduction samples measured:



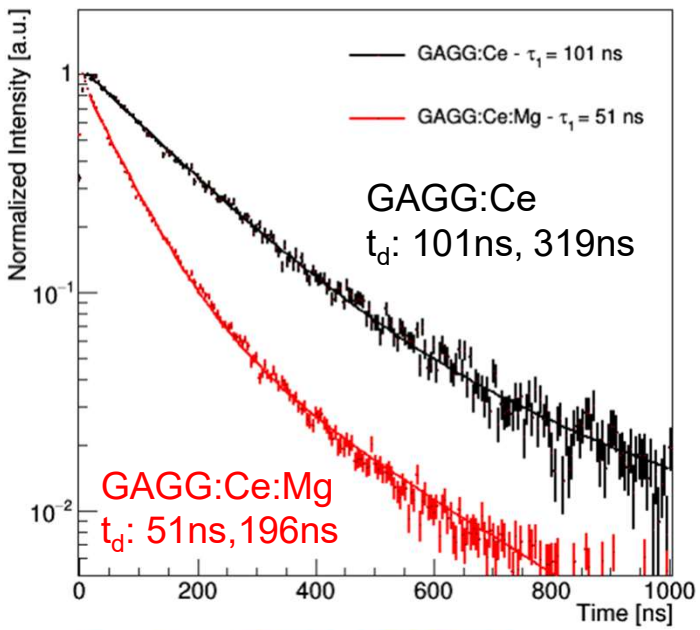




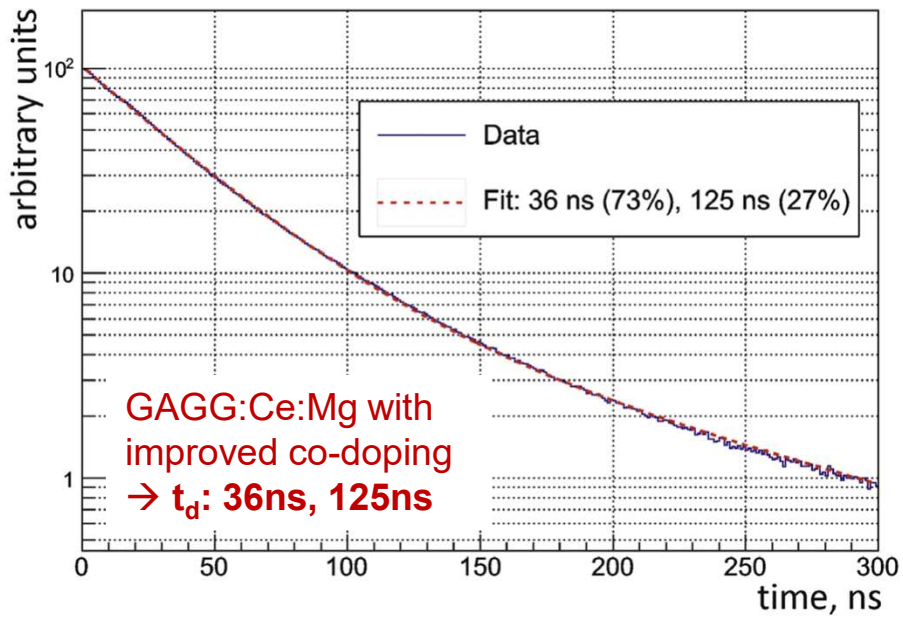
➢ fibers have an excellent effective attenuation length of ~ 1m

R&D on timing properties of Garnet crystals

Decay time properties: t_d



Kamada et al, O-14-3 at SCINT2015
M. Lucchini et al, NIM A Volume 816 (2016), pp 176–183,



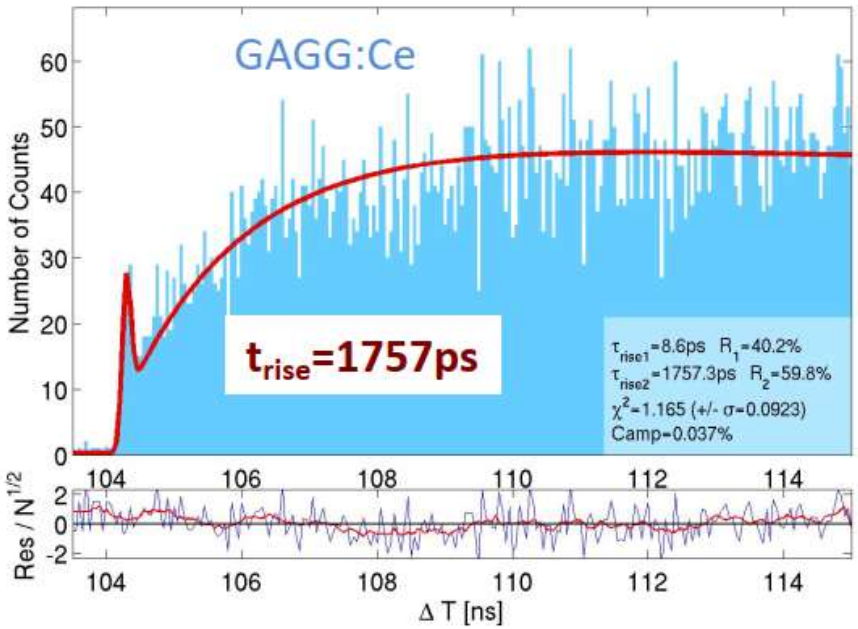
Nuclear Inst. and Methods in Physics Research, A 916 (2019) 226–229

- ✓ minimize spill-over by minimizing pulse length
- ✓ the decay time can be parametrized by two components
- ✓ a shorter decay time and strong decrease of the slow component can be achieved by proper choice of Ce and Mg co-doping

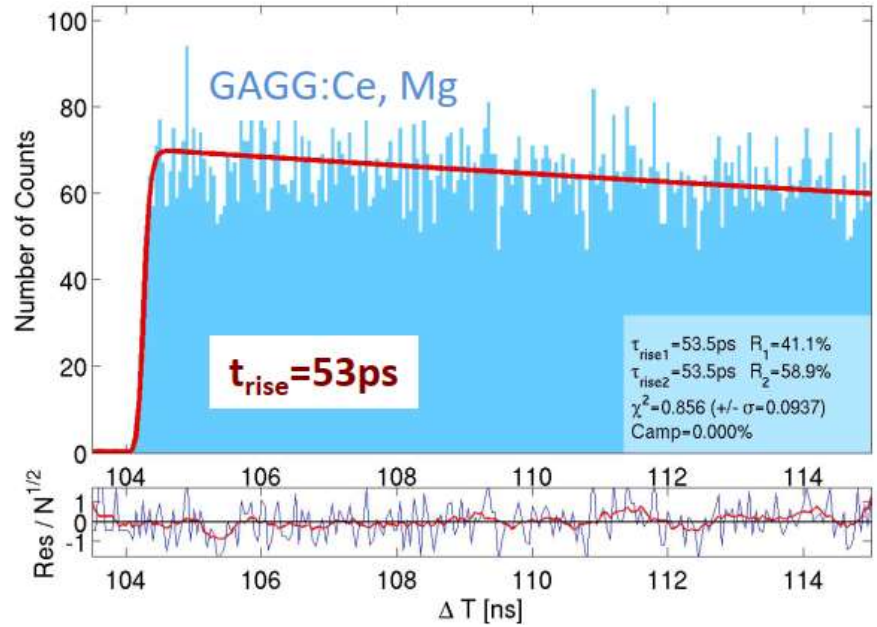
➢ achieved already t_d in the right ballpark, optimization ongoing

R&D on timing properties of Garnet crystals

Rise time properties: t_s



S. Gundacker et al, NIMA A 891 (2018) 42–52



M. Lucchini et al, NIM A Volume 816, (2016) pp 176–183,

- ✓ mitigate pile-up by minimizing rise time
- ✓ the rise time can be parametrized by a single component
- ✓ a fast rise time and strong decrease of slow component can be achieved by proper choice of Mg co-doping

➢ achieved already t_s of 53ps, optimization ongoing

R&D on absorber materials with tungsten alloys (Cu, Pb)

R&D on absorber materials

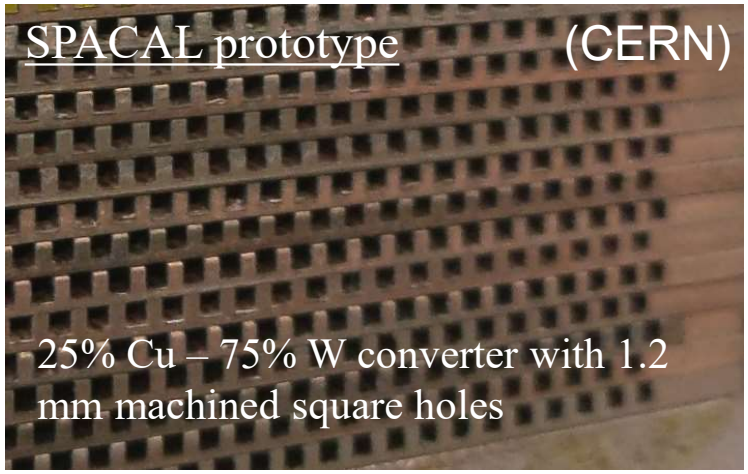
- ✓ tune radiation length (X_0) and shower width (M_R)
  - ➢ M_R should be of same order than cell size
  - ➢ X_0 should be as small as possible (short module = short fibers)

	W	Pb	Cu	GAGG	YAG
Density [g/cm^3]	19.3	11.4	8.96	6.7	4.6
X_0 [cm]	0.35	0.56	1.44	1.59	3.53
M_R [cm]	0.93	1.60	1.57	2.10	2.76

- ✓ pure tungsten has very small Moliere radius and small radiation length but problematic mechanical properties (brittle)
  - ➢ cannot be machined and therefore strongly limits possible absorber shapes
- ✓ Cu-W (25%-75%) alloy is available on the market with good mechanical properties
  - ➢ small Moliere Radius but relatively large radiation length (long module)
- ✓ Pb-W alloy allows for same Moliere radius as Cu-W but with smaller radiation length
  - ➢ shorter module → shorter fibers!

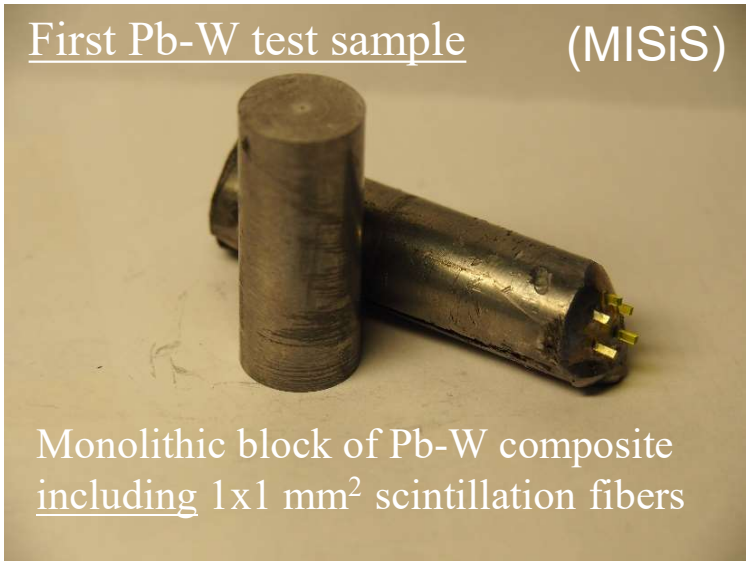
<u>However</u>: lead-tungsten alloys have never been produced!
→ have started R&D on Pb-W alloys

R&D on different alloys for absorber



Technology	Infiltration	Powder metallurgy	Squeeze casting
Rolling	?	☒	☑
Forming (forging)	?	?	☑
Machining	☑	☑	☑

MISiS

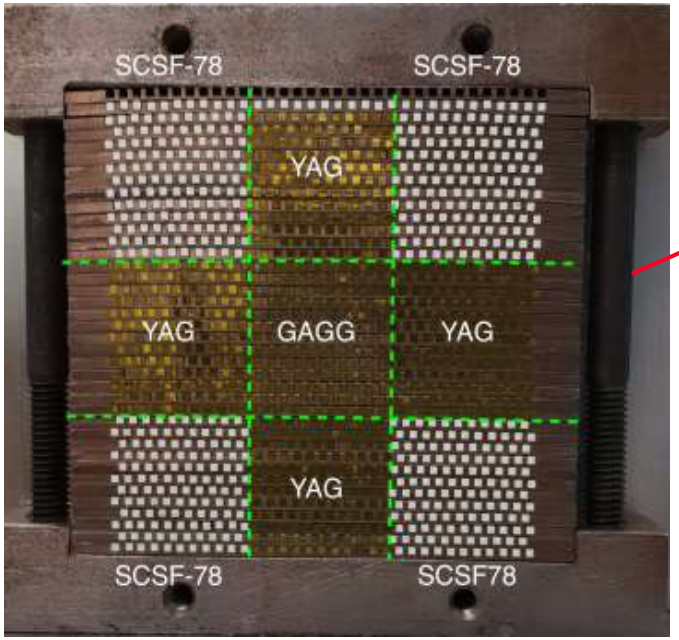


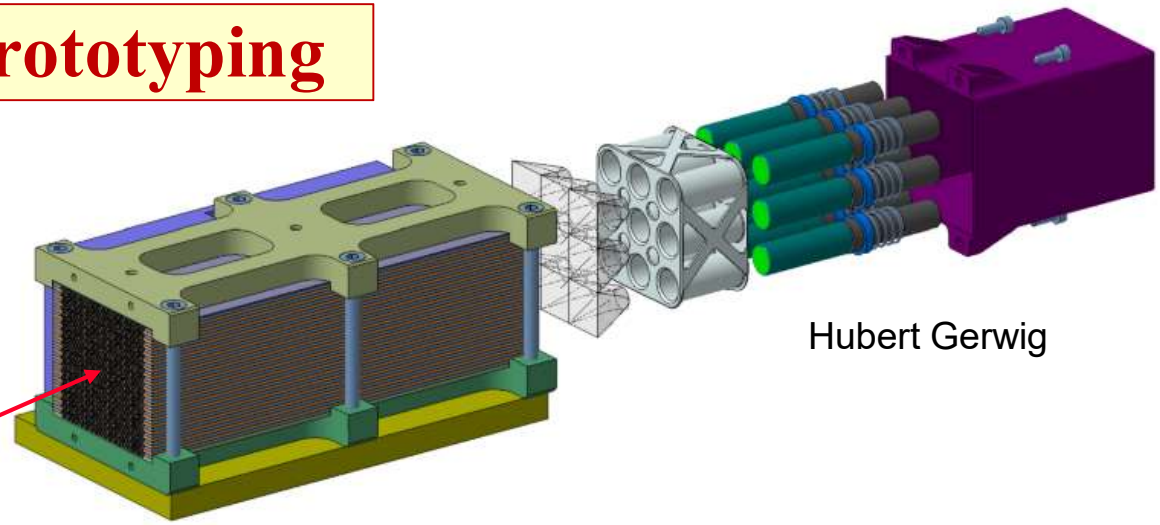
Ongoing activity:

- R&D on reducing Pb content in Pb-W alloy
- developing cost effective manufacturing techniques of absorber!

Prototyping

Current SPACAL prototype





Hubert Gerwig

Current SPACAL prototype:

- ✓ Cu-W alloy with density of 14.9 g/cm^2
- ✓ 20 cm long module to reach 25 X_0
- ✓ longitudinal segmentation: 10 cm + 10 cm
- ✓ 9 cells of 2 x 2 cm^2 with M_R ~1.5 cm
- ✓ 1 cell of GAGG (FOMOS)
- ✓ 4 cells of YAG (CRYTUR)
- ✓ 4 cells of SCSF78 (KURURAY)

New prototype under discussion:

- Pb-W alloy (or pure W) with modified geometry (fiber layout)
- with reduced length (~15 cm)
- longitudinal segmentation: 5 cm + 10 cm
- cell size of 2 x 2 cm^2 or 1.5 x 1.5 cm^2
- equip all cells with GAGG and YAG

- study energy resolution and timing properties as function of alloy, crystal, geometry, cell size, segmentation, …

Summary

- Upgrade II requires R&D on new rad hard ECAL modules for inner region
- Ongoing R&D to develop a SPACAL type sampling calorimeter with:
  - ✓ very good energy resolution of $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$
  - ✓ good spatial granularity with varying cell sizes (1.5x1.5 cm^2, 2x2 cm^2, etc.)
  - ✓ segmentation in depth with readout on both sides (<u>note</u>: segmentation could be 1/3, 2/3 or 1/4, 3/4 etc. and could possibly consist of different materials)
  - ✓ respecting the given modularity of a module with size 12x12 cm^2
  - ✓ scintillators sustaining radiation doses up to 1 MGy and up to a few 10^{15} 1 MeV neq/cm^2
  - ✓ scintillators that have fast rise time (10th of ps) and short decay time (~25 ns)
  - ✓ absorber material that consists of a very dense (~17 kg/dm^3) alloy allowing to "tune" the Moliere Radius (X,Y dim.) and the radiation length (Z dim.)
  - ✓ absorber that fulfills the mechanical specifications to host 1x1 mm^2 fibers
- Need to pursue physics and reconstruction studies to define 5D ECAL requirements (**E, x, y, z, t**) in inner and middle ECAL region

Many thanks to the organizers for hosting us in such an inspiring location!