H2020-MSCA-RISE-2015 – Grant Agreement N° 690835

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The MUSE irradiation network

The concept of the irradiation network

GOAL:

Create an European irradiation network where expertise in
high-flux irradiation beamlines
radiation damage
“frontier” electronics
radiation transport calculations and measurements

are shared and have the possibility to grow

gELBE pELBE and nELBE beamlines at ELBE

(Electron Linear accelerator with high Brilliance and low Emittance)

National Center for High-Power Radiation Sources:

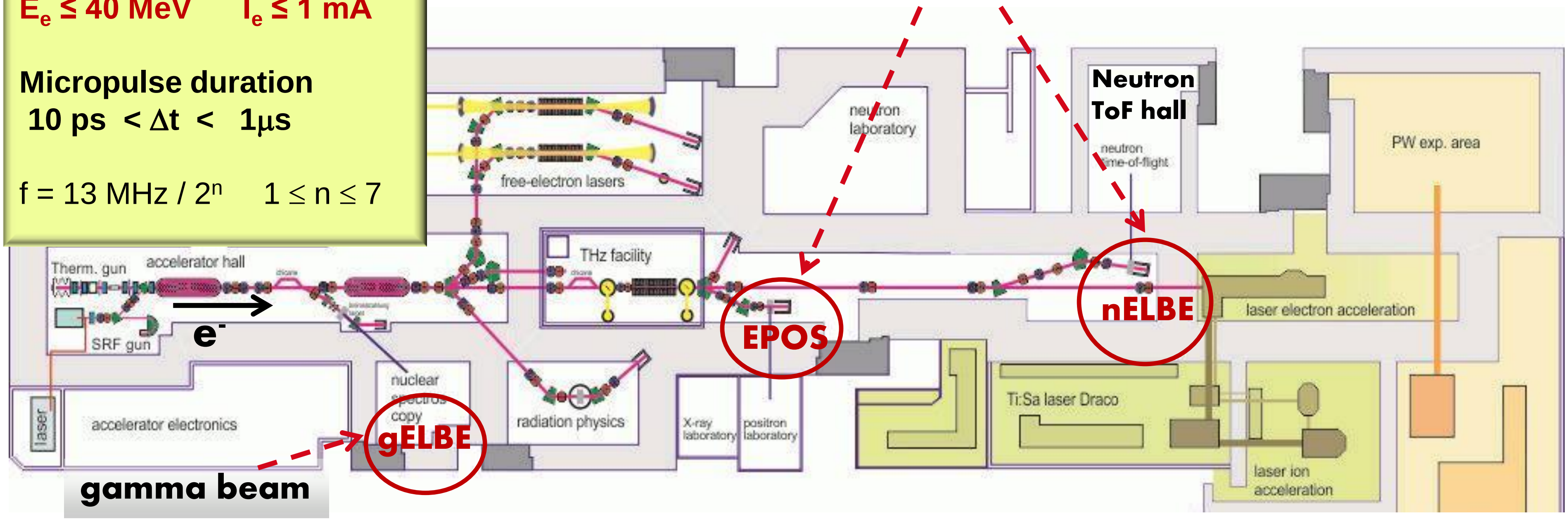
- Multiple secondary beams (neutrons, photons, positrons) & High-Power laser (PW) for electron/ion acceleration
- **nELBE**: Neutron Time-of-Light Facility for Transmutation Studies and Nuclear Physics Exp.
- **gELBE**: gamma beam facility for nuclear spectroscopy and detector tests
- **pELBE** (EPOS)

$E_e \leq 40$ MeV $I_e \leq 1$ mA

Micropulse duration
10 ps $< \Delta t <$ 1 μs

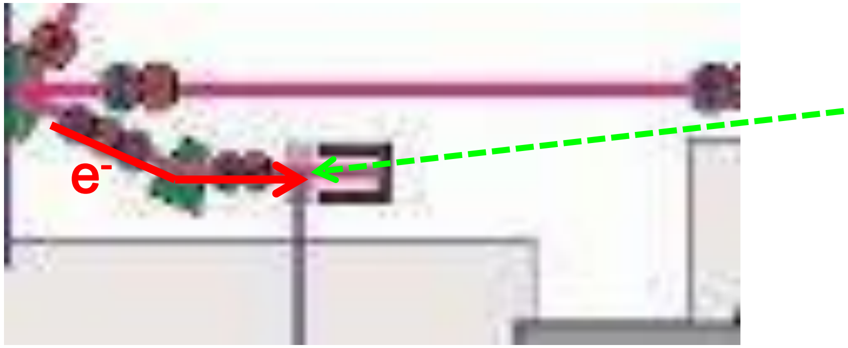
f = 13 MHz / 2^n $1 \leq n \leq 7$

Photo-neutron sources:
neutron production via photo-nuclear reactions

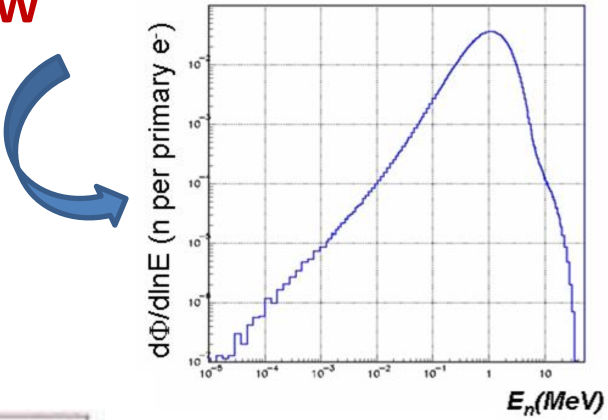


(1) Neutron irradiation

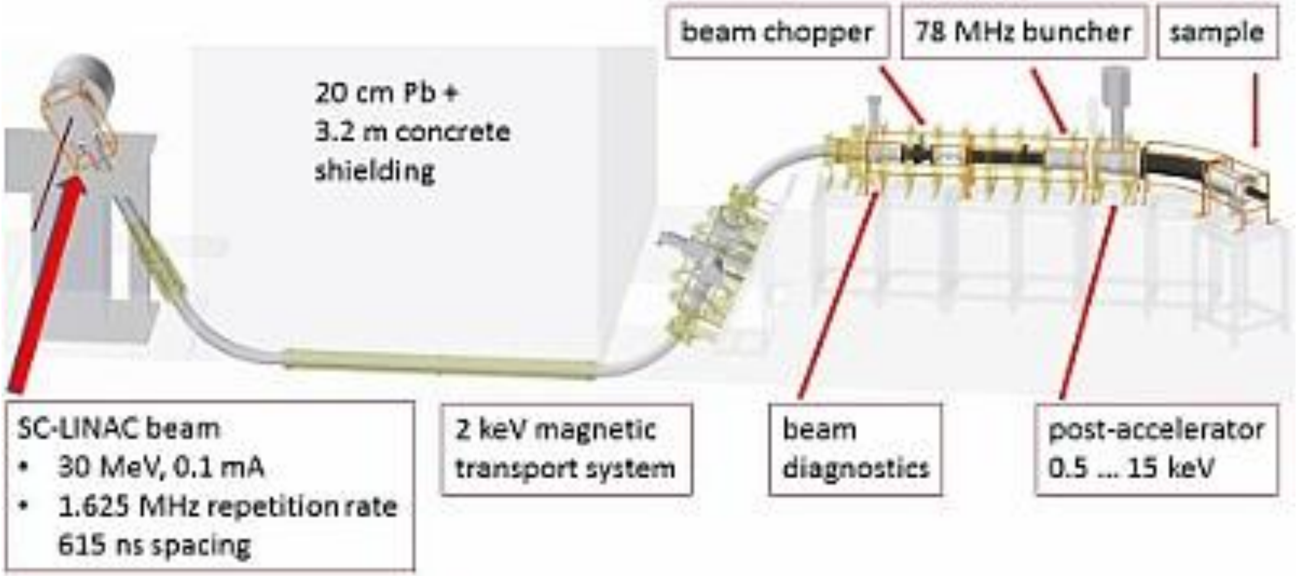
An optimal solution for neutron irradiations: the EPOS source at positron extraction beamline pELBE



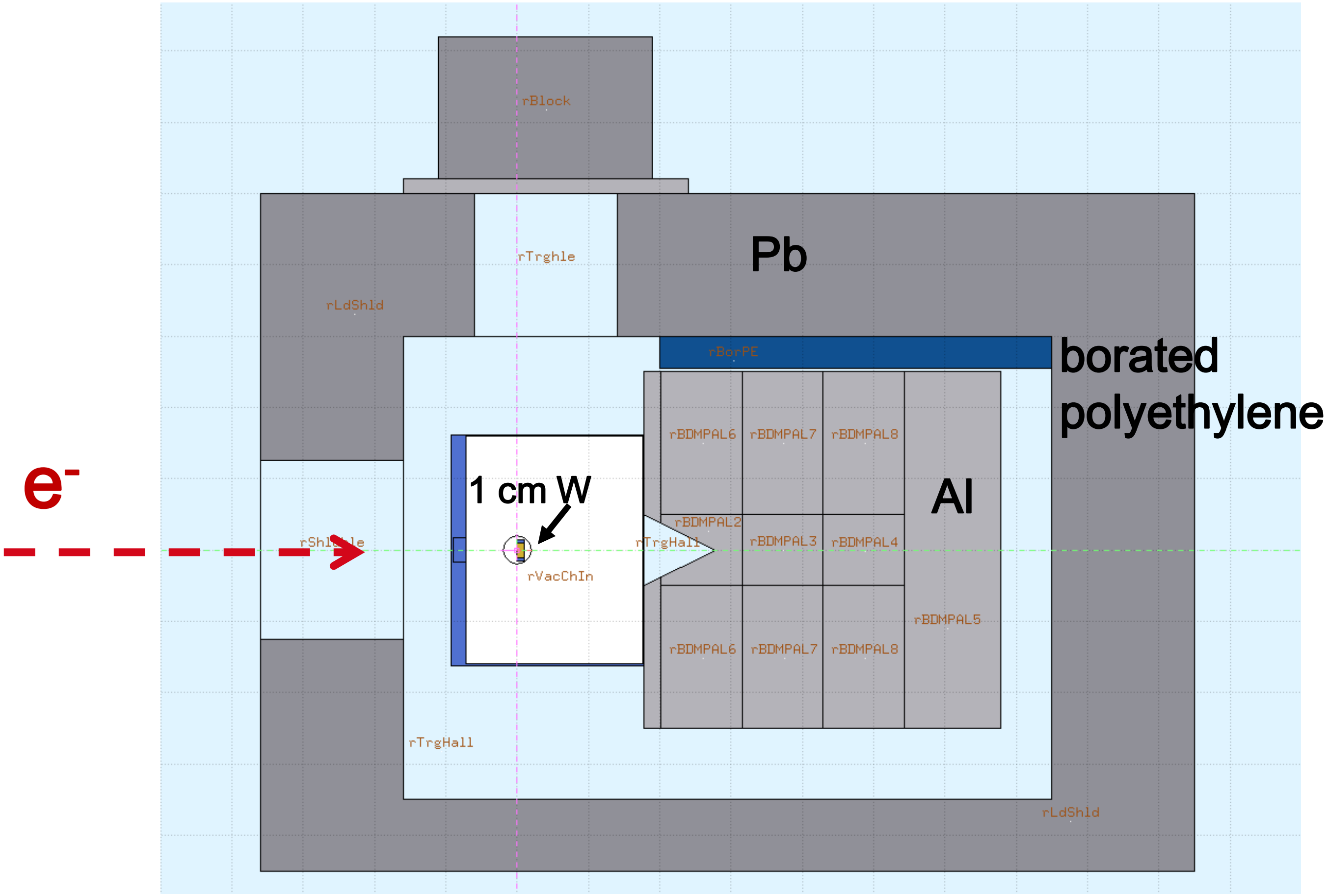
Bremsstrahlung/photoneutron target: 1 cm W



positron extraction beamline



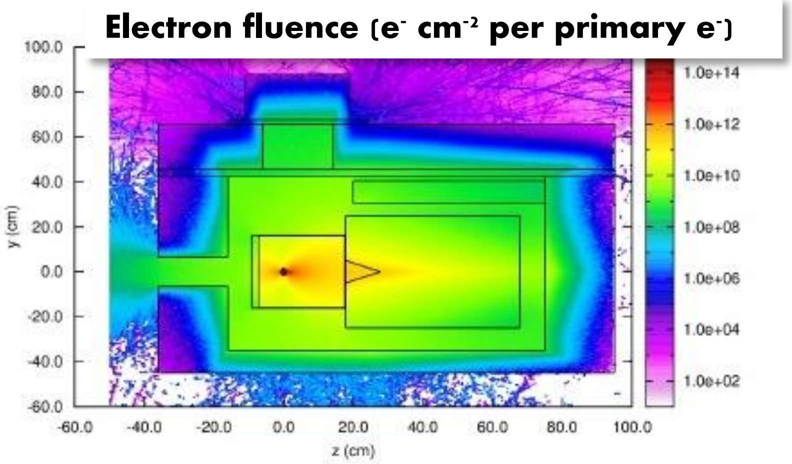
Geometry around the target

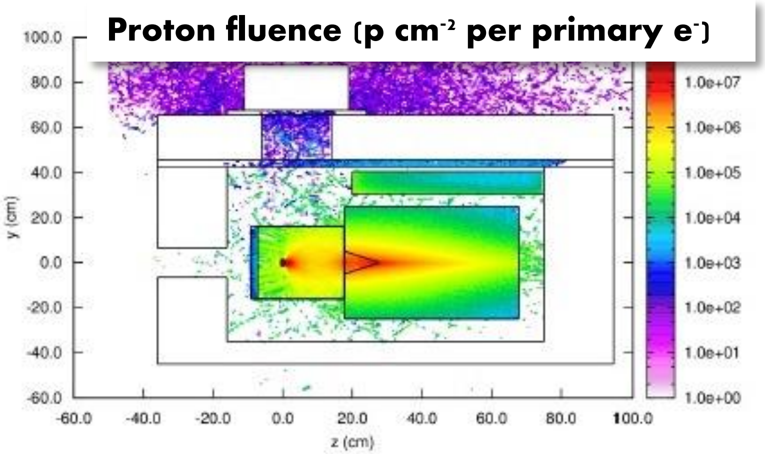


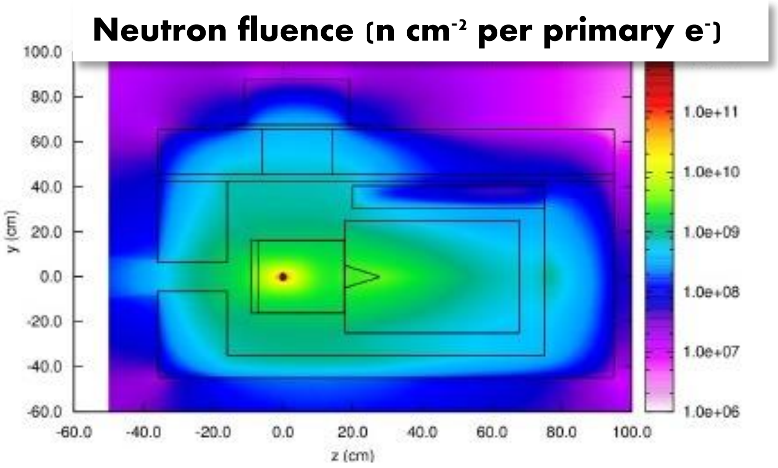
Radiation fields around the target: fluence rates

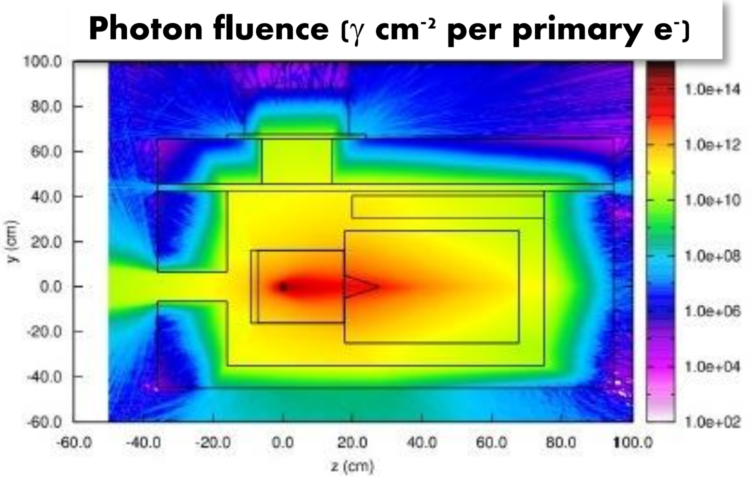
EPOS simulations: Prompt radiation@30 MeV pencil beam ($\sigma_{x,y}$=0.3cm) with 100μA

Total neutron yield coming from target: (2.83e-03 ±8.17e-07) neutrons/primary =(1.767e+12 ±3.979e+08) n/s @100μA


Electron fluence (e$^-$ cm^{-2} per primary e$^-$)


Proton fluence (p cm^{-2} per primary e$^-$)

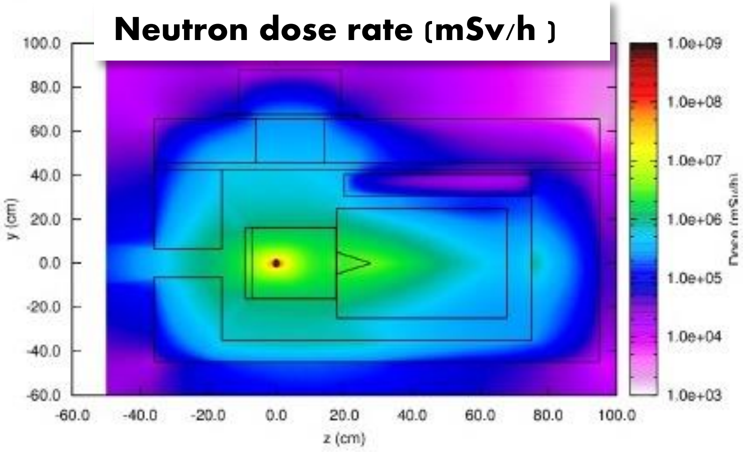

Neutron fluence (n cm^{-2} per primary e$^-$)


Photon fluence (γ cm^{-2} per primary e$^-$)

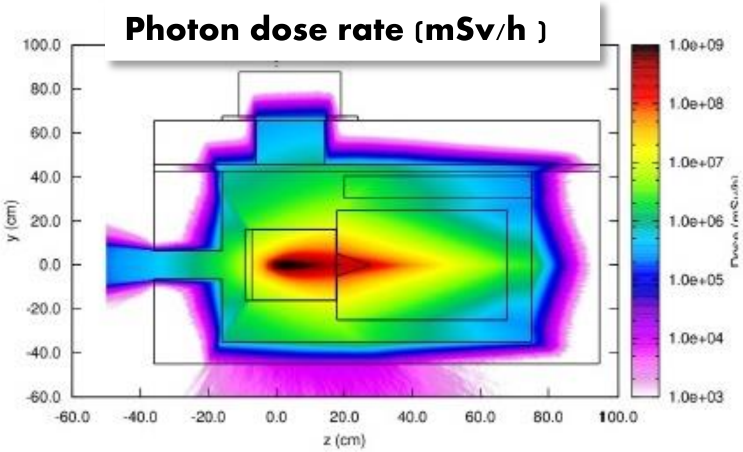
Radiation fields around the target: dose [H(10)] rates*

EPOS simulations: Prompt radiation@30 MeV pencil beam ($\sigma_{x,y}$=0.3cm) with 100µA

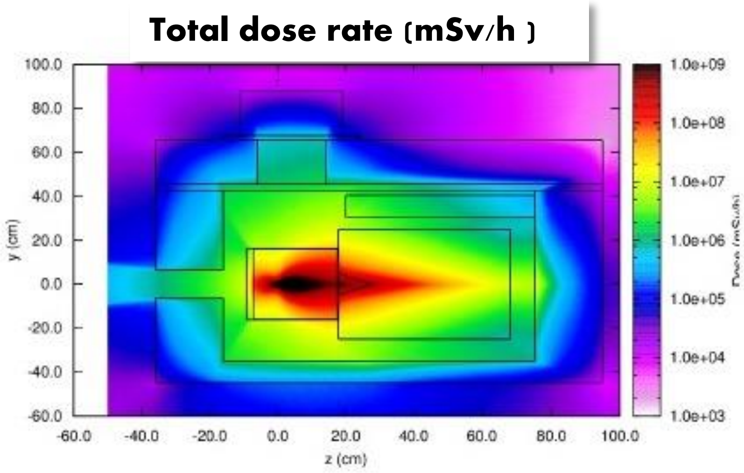
Total neutron yield coming from target: (2.83e-03 ±8.17e-07) neutrons/primary =(1.767e+12 ±3.979e+08) n/s @100µA



Neutron dose rate (mSv/h)

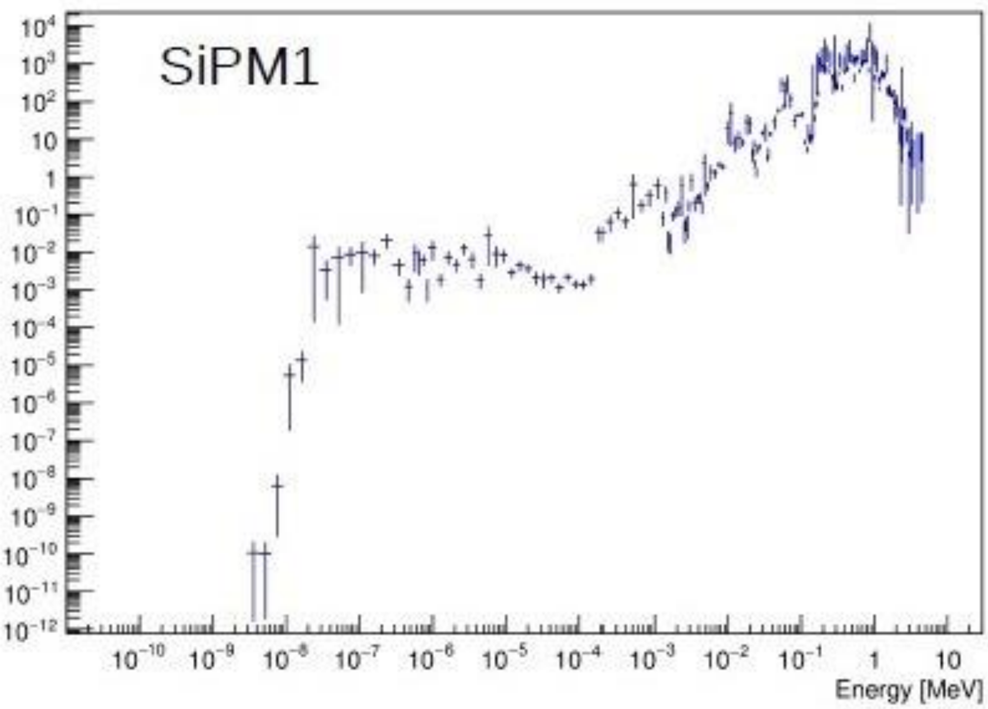


Photon dose rate (mSv/h)



Total dose rate (mSv/h)

1 MeV-equivalent neutron spectra at the irradiation position



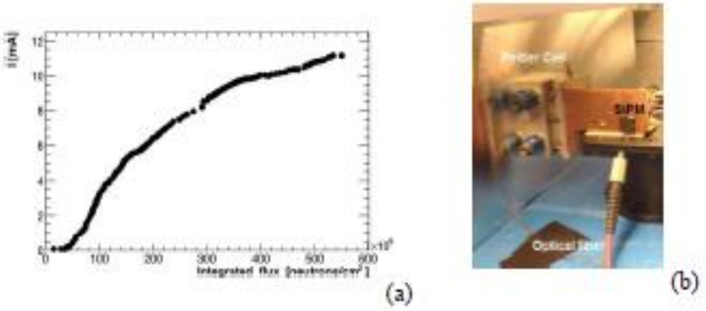
Total 1 MeV-equiv. neutron fluence at 1 µA electron beam: ~ 8 10^4 n cm^{-2} s^{-1}

@ 200 µA electron beam: ~ 1.6 10^7 n cm^{-2} s^{-1} → **in 72 hours: ~ 4.15 10^{12} n cm^{-2}**

Success story in 2016/2017

(1) First irradiation in April 2016: one SiPM tested

Figure 1: (a) Leakage current vs integrated 1 MeV-equivalent neutron fluence, obtained at EPOS during the April 2016 parasitic run. The accumulated statistics corresponds to 6 years Mu2e operation
(b) Photosensor position at the measurement place, at the top of the EPOS shielding cage.

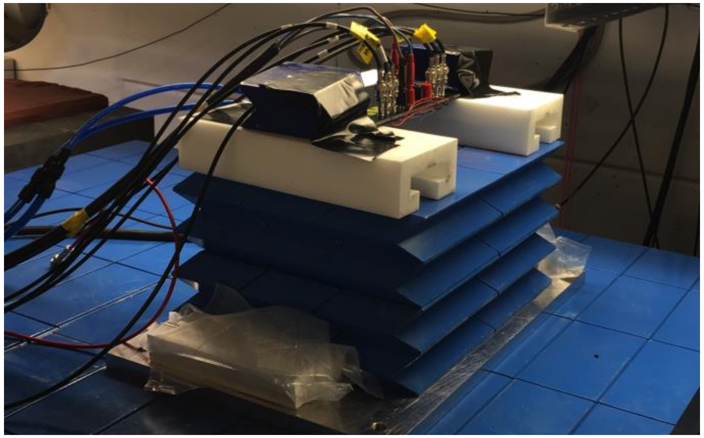


E. Diociaiuti et al.,

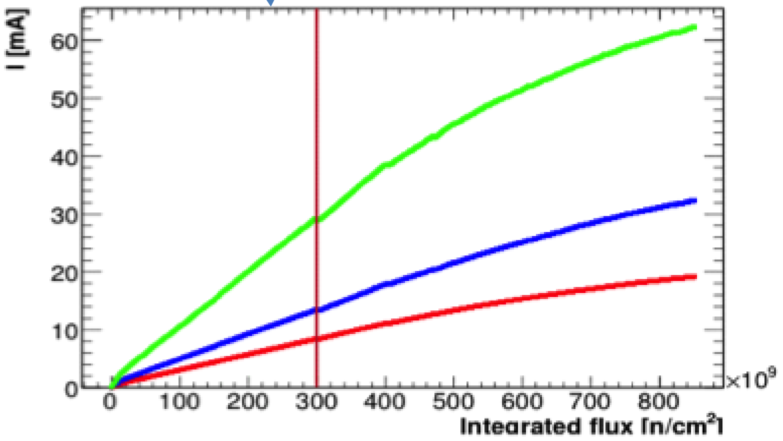
**Irradiation study
of UV Silicon Photomultipliers
for the Mu2e calorimeter**

https://arxiv.org/abs/1701.06464

(2) Second step of the irradiation campaign: 8-10 March 2017
3 different SiPMs tested

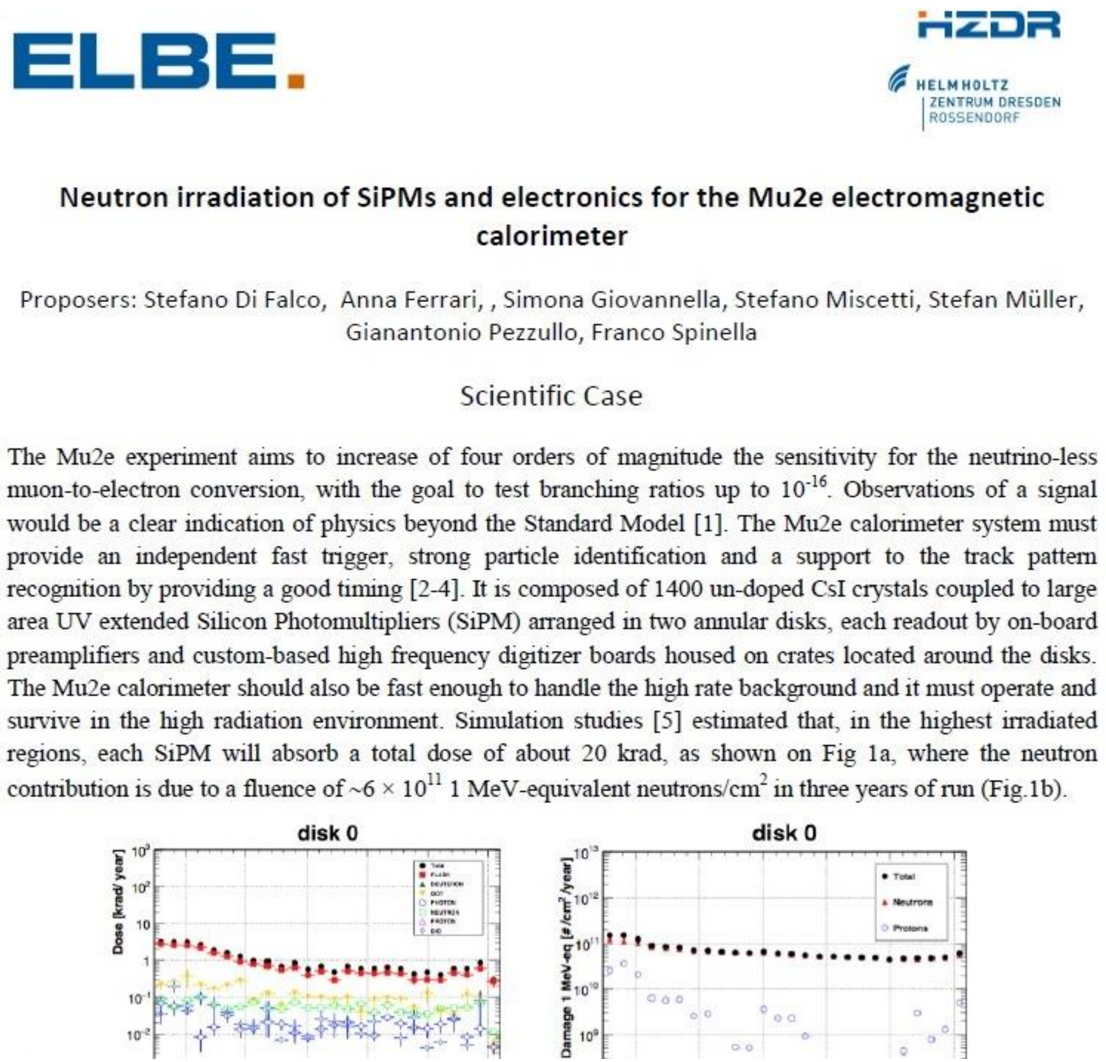


**SIPMs tested
up to 8x10^{11} n_1MeV eq/cm^2**



Submitted proposal for the second semester 2017

Goal:
to continue the campaign, including also the prototypes of the **front-end** and **calorimeter digitizer board**



Neutron irradiation of SiPMs and electronics for the Mu2e electromagnetic calorimeter

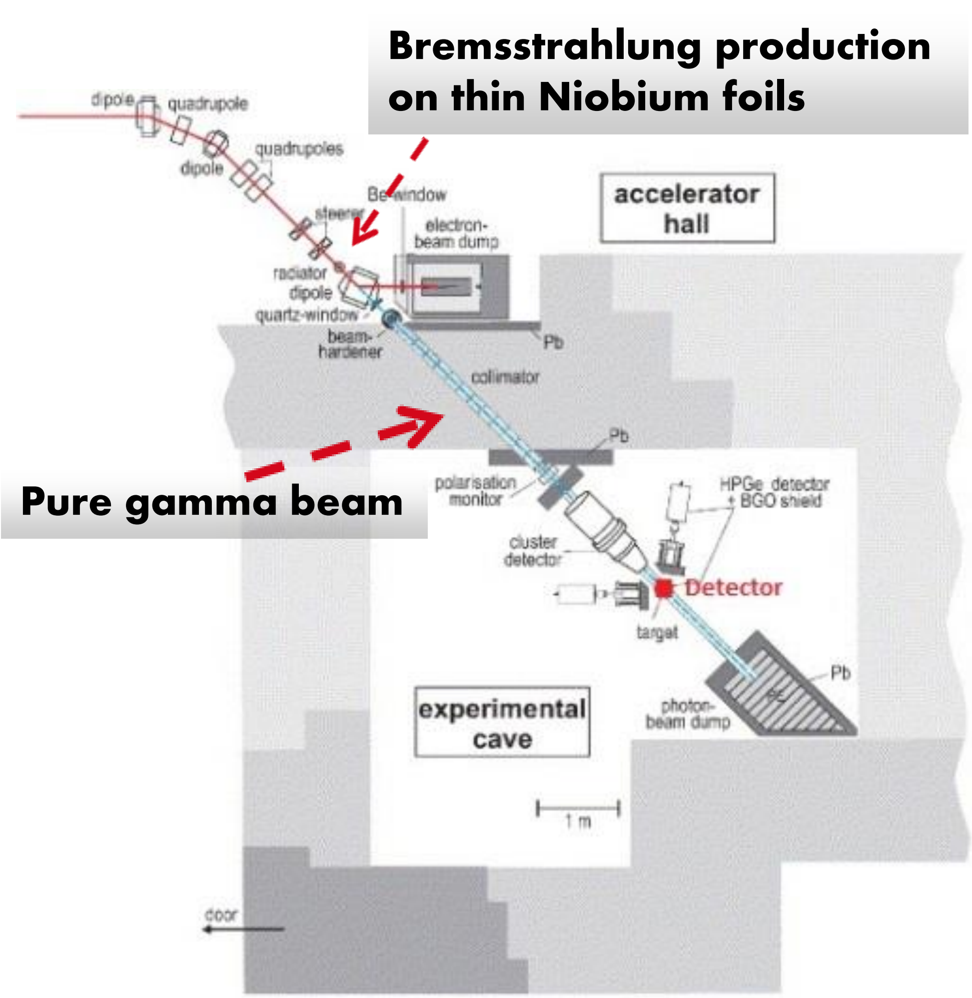
Proposers: Stefano Di Falco, Anna Ferrari, , Simona Giovannella, Stefano Miscetti, Stefan Müller, Gianantonio Pezzullo, Franco Spinella

Scientific Case

The Mu2e experiment aims to increase of four orders of magnitude the sensitivity for the neutrino-less muon-to-electron conversion, with the goal to test branching ratios up to 10^{-16}. Observations of a signal would be a clear indication of physics beyond the Standard Model [1]. The Mu2e calorimeter system must provide an independent fast trigger, strong particle identification and a support to the track pattern recognition by providing a good timing [2-4]. It is composed of 1400 un-doped CsI crystals coupled to large area UV extended Silicon Photomultipliers (SiPM) arranged in two annular disks, each readout by on-board preamplifiers and custom-based high frequency digitizer boards housed on crates located around the disks. The Mu2e calorimeter should also be fast enough to handle the high rate background and it must operate and survive in the high radiation environment. Simulation studies [5] estimated that, in the highest irradiated regions, each SiPM will absorb a total dose of about 20 krad, as shown on Fig 1a, where the neutron contribution is due to a fluence of ~6×10^{11} 1 MeV-equivalent neutrons/cm^2 in three years of run (Fig.1b).

(2) Gamma irradiation

gELBE: the gamma source



Bremsstrahlung production on thin Niobium foils

Pure gamma beam

Bremsstrahlung (Endpoint up to 20 MeV) is available in the nuclear physics cave

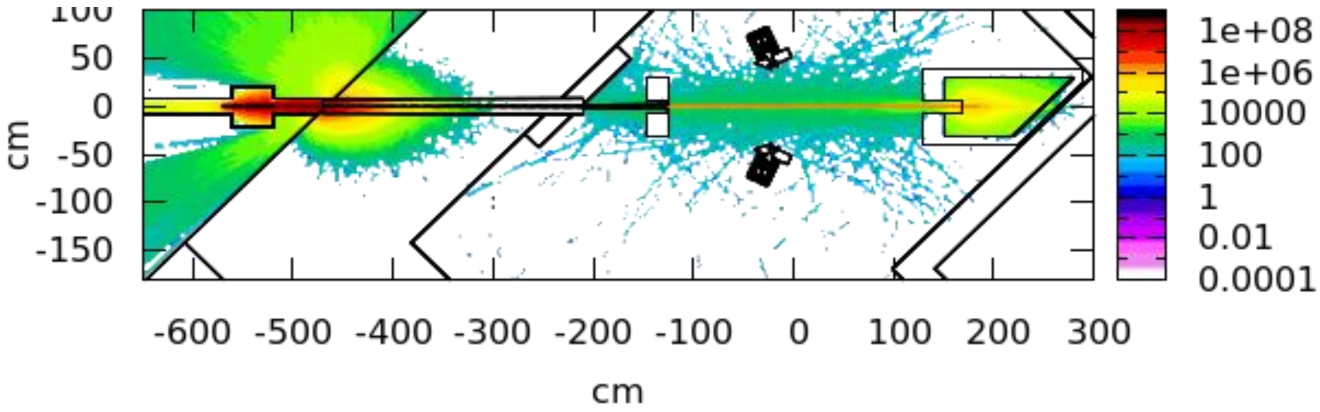
The time structure of the Bremsstrahlung radiation is defined by the electron beam which has to be operated in the micropulse mode.

Typical gamma rates:
up to ~**2 10^7 kHz** **@1μA current**
on the detector position

FLUKA simulation of the gELBE beamline

Elements included as from gELBE design:
Ni target, «volume» with magnetic field, collimator toward the 109 cave, shielding walls, main shielding elements in the experimental room, final beam dump, BGOs (equipment of the cave), with their Pb shielding

Photon fluence rate (γ cm^{-2} s^{-1} @ 1μA e^{-} beam) – E_e = 15 MeV



- Study of the photon yields for different beam energies/thicknesses of the radiator
- Dose distributions (intensity/spatial distribution)

Gamma yields at the measurement position

Ni target thickness: 1.7 mg/cm^2

E_e (MeV)	Gamma yield [γ cm^{-2}per source e$^-$]	Gamma rate @ 1 µA [γ cm^{-2}s^{-1}]
6	$4.40\ 10^{-8}$	$2.75\ 10^{5}$

Ni target thickness: 2.6 mg/cm^2

E_e (MeV)	Gamma yield [γ cm^{-2}per source e$^-$]	Gamma rate @ 1 µA [γ cm^{-2}s^{-1}]
9	$1.96\ 10^{-7}$	$1.22\ 10^{6}$
12	$3.60\ 10^{-7}$	$2.25\ 10^{6}$

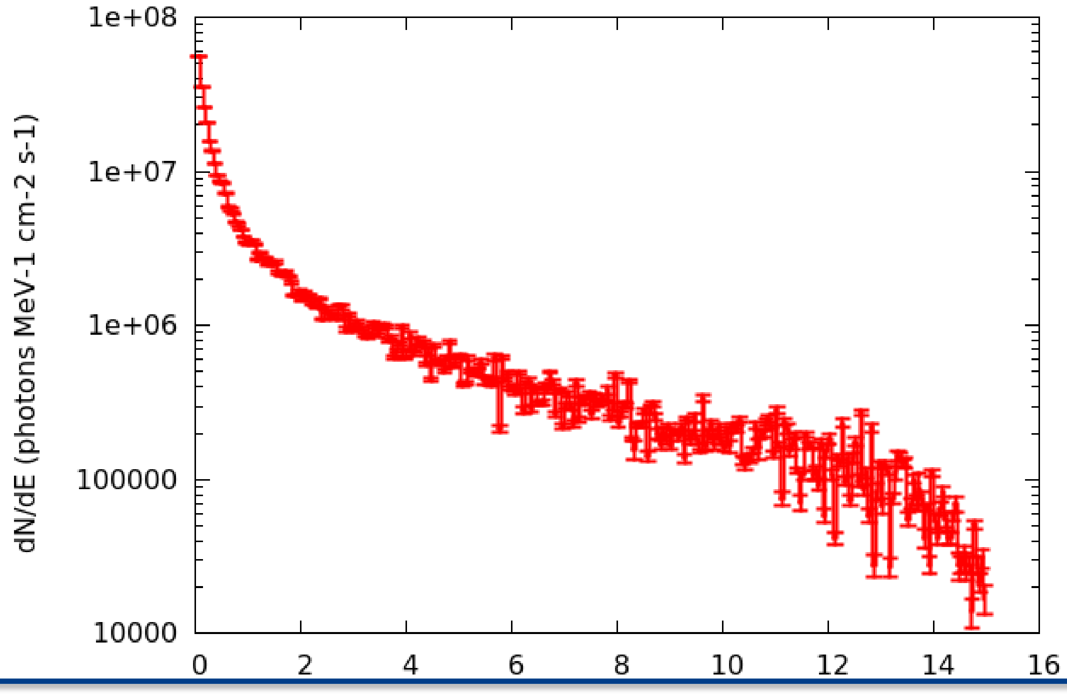
Ni target thickness: 10.6 mg/cm^2

E_e (MeV)	Gamma yield [γ cm^{-2}per source e$^-$]	Gamma rate @ 1 µA [γ cm^{-2}s^{-1}]
12	$8.33\ 10^{-7}$	$5.20\ 10^{6}$
13.5	$1.04\ 10^{-6}$	$6.49\ 10^{6}$
15	$4.17\ 10^{-6}$	$2.60\ 10^{7}$

Beam time request I: dose measurements

E_e (MeV)	Gamma yield [γ cm^{-2}per source e^{-}]	Gamma rate @ 1 μA [γ cm^{-2}s^{-1}]
12	8.33 10^{-7}	5.20 10^{6}
13.5	1.04 10^{-6}	6.49 10^{6}
optimal 15	4.17 10^{-6}	2.60 10^{7}

Photon fluence rate at the Si sample @ 1μA e^- beam - E_e = 15 MeV



Absorbed dose in Si and beam halo

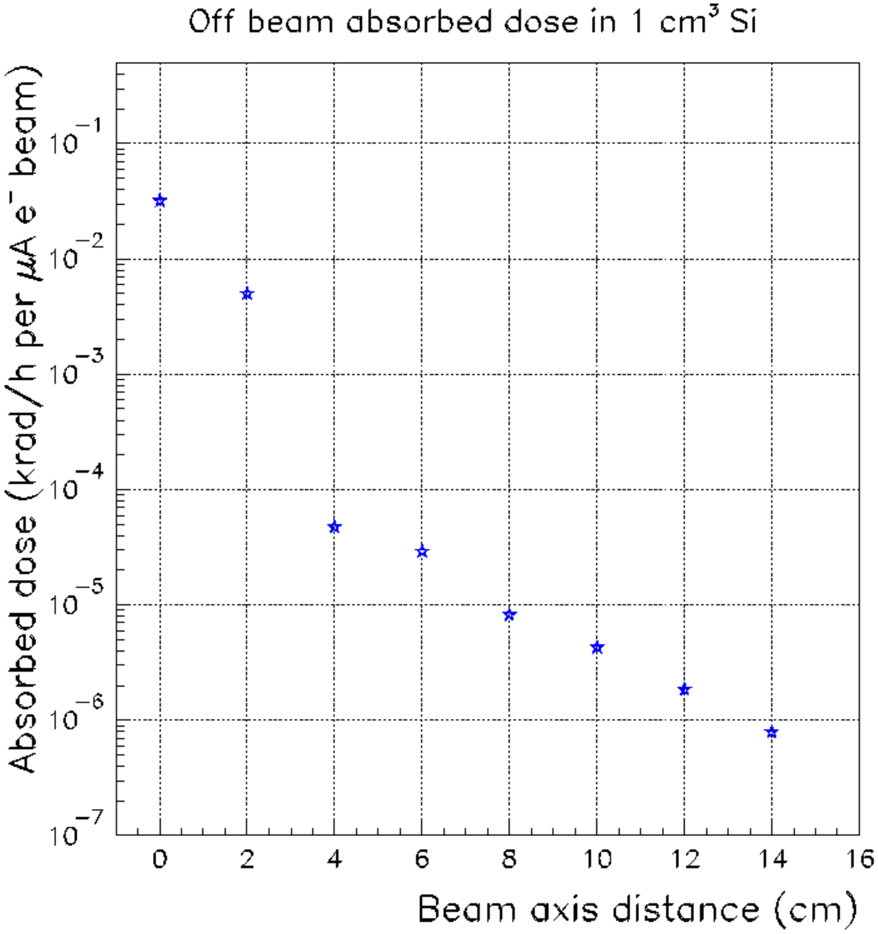
E_e = 15 MeV

Test position: z=50 cm

Absorbed Dose on beam axis at the test position:

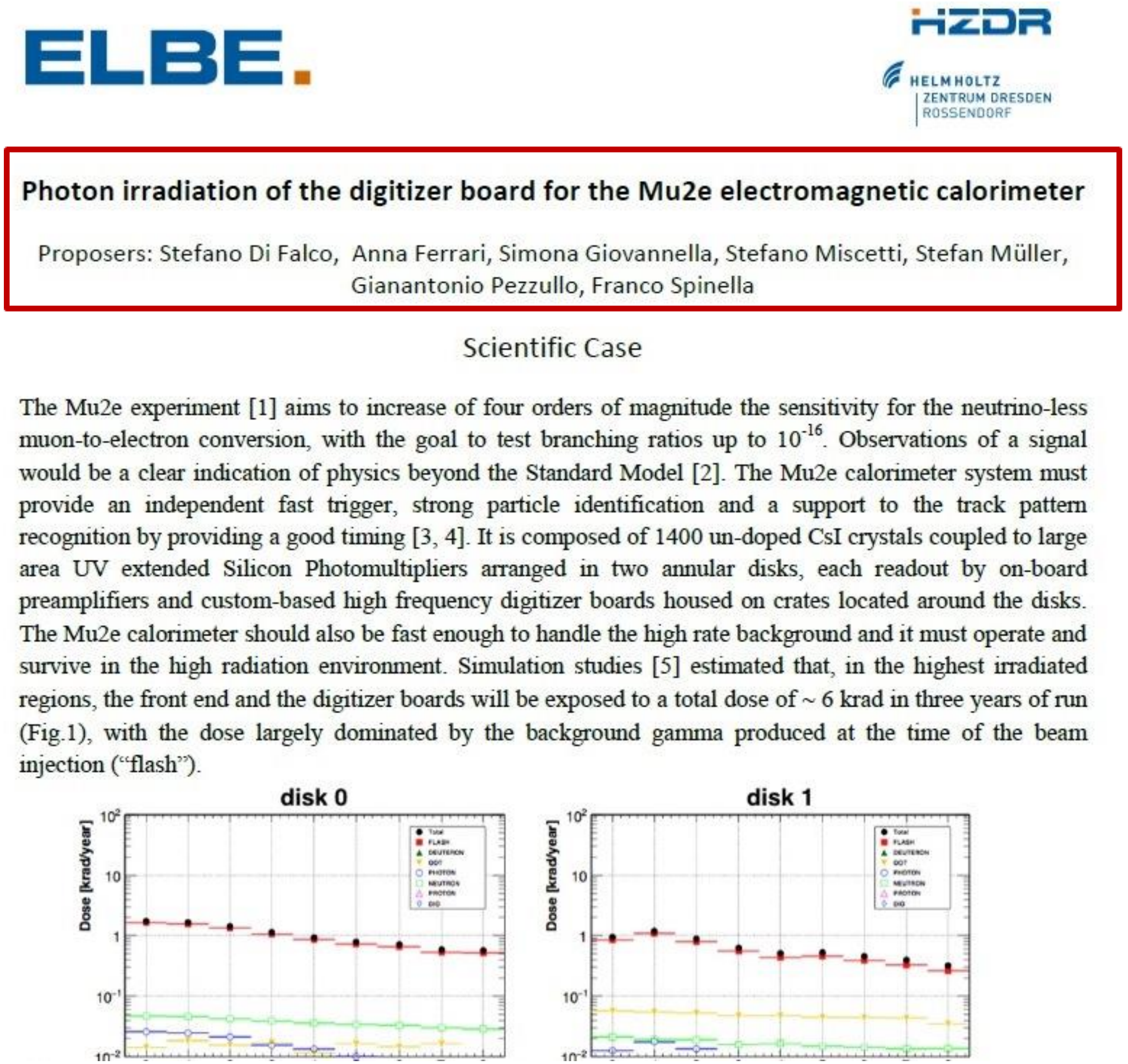
3.2 krad/h @ 100 µA e^- beam

(stat. err. < 5%)



Note that the dose drops down of ~ 1 order of magnitude at 2 cm from the beam axis and ~ 3 order of magnitude at 4 cm. This allows us to minimize the amount of shielding to protect the board around the irradiated element

Submitted proposal for the second semester 2017 (I)



ELBE.

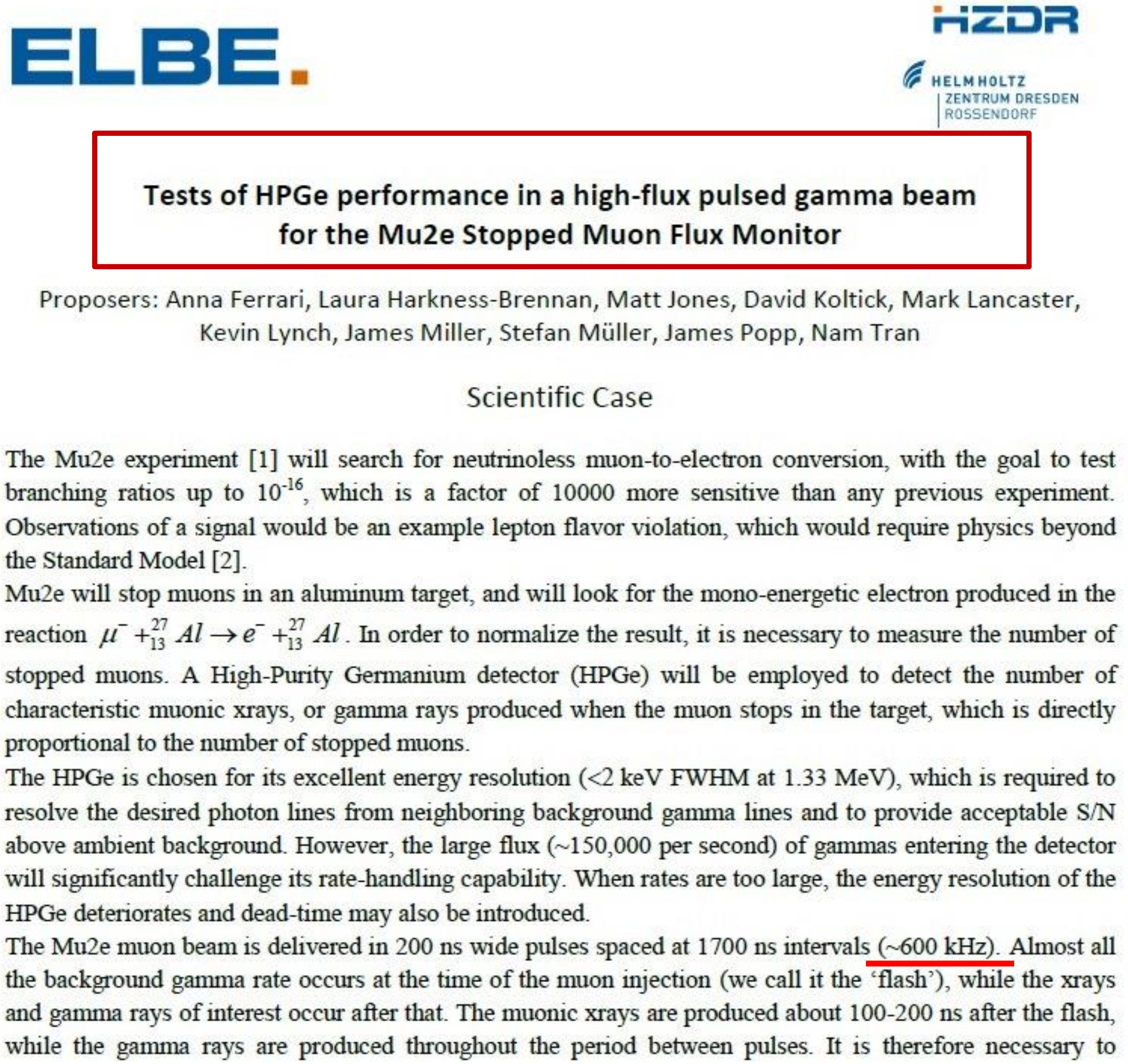
Photon irradiation of the digitizer board for the Mu2e electromagnetic calorimeter

Proposers: Stefano Di Falco, Anna Ferrari, Simona Giovannella, Stefano Miscetti, Stefan Müller, Gianantonio Pezzullo, Franco Spinella

Scientific Case

The Mu2e experiment [1] aims to increase of four orders of magnitude the sensitivity for the neutrino-less muon-to-electron conversion, with the goal to test branching ratios up to 10^{-16}. Observations of a signal would be a clear indication of physics beyond the Standard Model [2]. The Mu2e calorimeter system must provide an independent fast trigger, strong particle identification and a support to the track pattern recognition by providing a good timing [3, 4]. It is composed of 1400 un-doped CsI crystals coupled to large area UV extended Silicon Photomultipliers arranged in two annular disks, each readout by on-board preamplifiers and custom-based high frequency digitizer boards housed on crates located around the disks. The Mu2e calorimeter should also be fast enough to handle the high rate background and it must operate and survive in the high radiation environment. Simulation studies [5] estimated that, in the highest irradiated regions, the front end and the digitizer boards will be exposed to a total dose of ~ 6 krad in three years of run (Fig.1), with the dose largely dominated by the background gamma produced at the time of the beam injection ("flash").

Submitted proposal for the second semester 2017 (II)



Tests of HPGe performance in a high-flux pulsed gamma beam for the Mu2e Stopped Muon Flux Monitor

Proposers: Anna Ferrari, Laura Harkness-Brennan, Matt Jones, David Koltick, Mark Lancaster,
Kevin Lynch, James Miller, Stefan Müller, James Popp, Nam Tran

Scientific Case

The Mu2e experiment [1] will search for neutrinoless muon-to-electron conversion, with the goal to test branching ratios up to 10^{-16}, which is a factor of 10000 more sensitive than any previous experiment. Observations of a signal would be an example lepton flavor violation, which would require physics beyond the Standard Model [2].

Mu2e will stop muons in an aluminum target, and will look for the mono-energetic electron produced in the reaction $\mu^- + ^{27}_{13}Al \rightarrow e^- + ^{27}_{13}Al$. In order to normalize the result, it is necessary to measure the number of stopped muons. A High-Purity Germanium detector (HPGe) will be employed to detect the number of characteristic muonic xrays, or gamma rays produced when the muon stops in the target, which is directly proportional to the number of stopped muons.

The HPGe is chosen for its excellent energy resolution (<2 keV FWHM at 1.33 MeV), which is required to resolve the desired photon lines from neighboring background gamma lines and to provide acceptable S/N above ambient background. However, the large flux (~150,000 per second) of gammas entering the detector will significantly challenge its rate-handling capability. When rates are too large, the energy resolution of the HPGe deteriorates and dead-time may also be introduced.

The Mu2e muon beam is delivered in 200 ns wide pulses spaced at 1700 ns intervals (~600 kHz). Almost all the background gamma rate occurs at the time of the muon injection (we call it the 'flash'), while the xrays and gamma rays of interest occur after that. The muonic xrays are produced about 100-200 ns after the flash, while the gamma rays are produced throughout the period between pulses. It is therefore necessary to

Irradiation plan for the HPGe Detector of the STM

gELBE: an ideal time structure

It is driven by the electron beam time structure

The e$^-$ beam can be operated in the micropulse mode (CW mode), with pulse frequency:

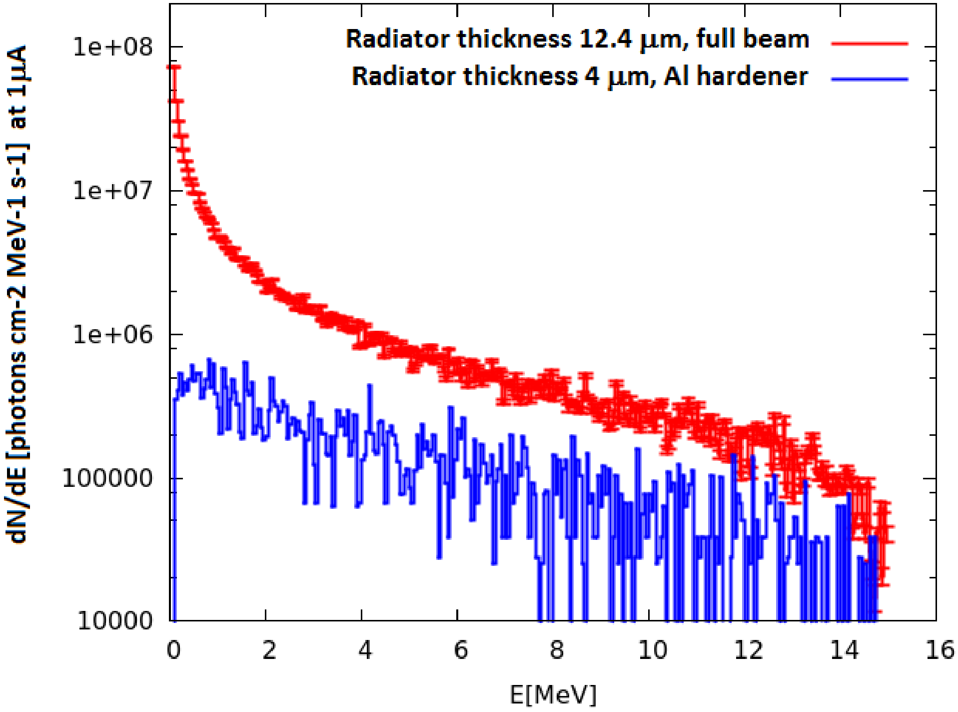
f = 26 MHz/2^n n =1, …,7

In CW mode averaged electron currents can go up to ~ 600 µA

Ideal modes for STM irradiation campaign:

n = 5 -> f = 812.5 kHz, **t = 1.23 µs**

n = 6 -> f = 406 kHz, **t = 2.46 µs**

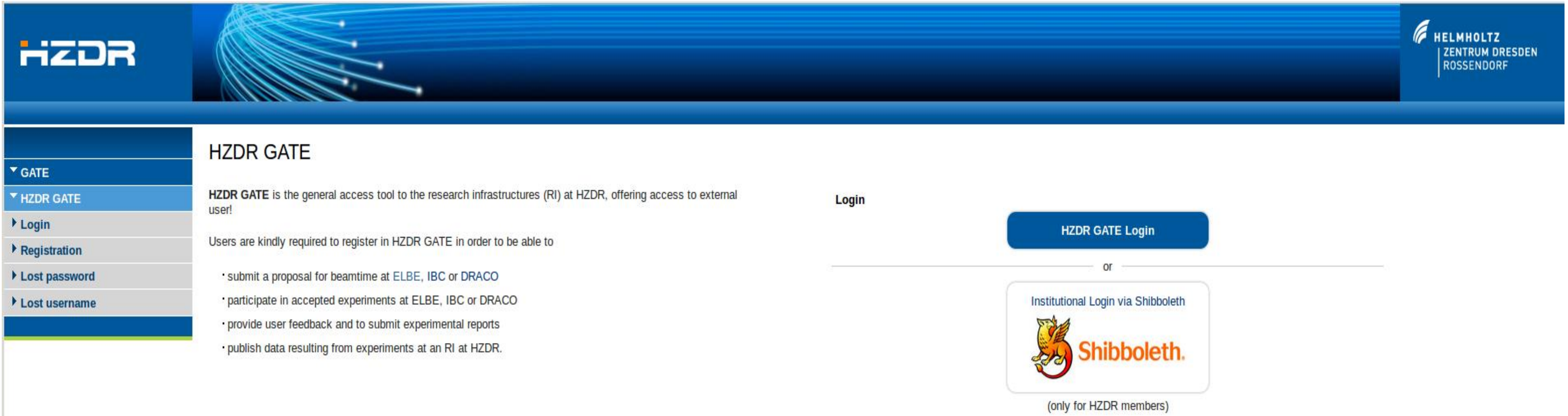


Using a medium/high Z hardener we can lower the photon rate **down to the required 150 kHz**

Summary of the irradiation proposals

- 1 Proposal submitted and approved in 2016
- 3 Proposals submitted 27 april 2017

Dedicated beamtime is asked via the HZDR GATE page:
https://gate.hzdr.de/cgi-bin/gate



HZDR GATE

HZDR GATE is the general access tool to the research infrastructures (RI) at HZDR, offering access to external user!

Users are kindly required to register in HZDR GATE in order to be able to

- submit a proposal for beamtime at ELBE, IBC or DRACO
- participate in accepted experiments at ELBE, IBC or DRACO
- provide user feedback and to submit experimental reports
- publish data resulting from experiments at an RI at HZDR.

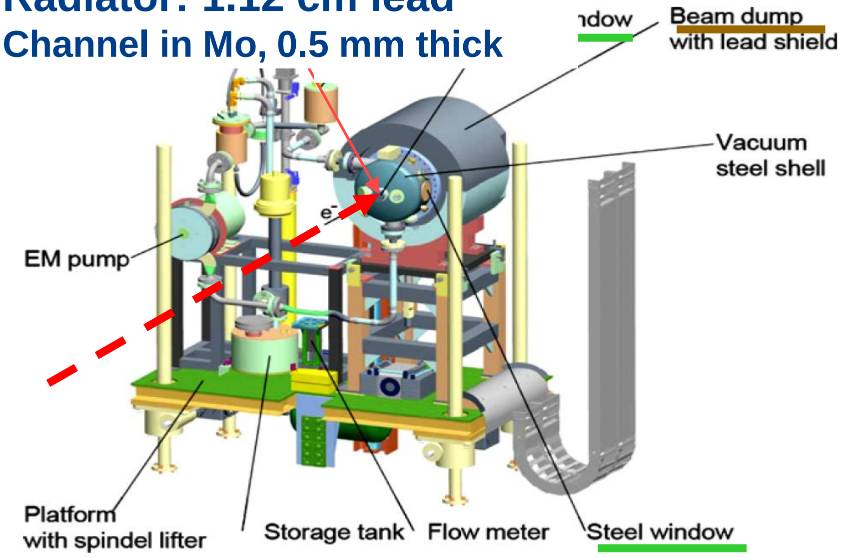
2 documents to be prepared:

- Scientific case (2 pages)
- Experimental plan (1 page)

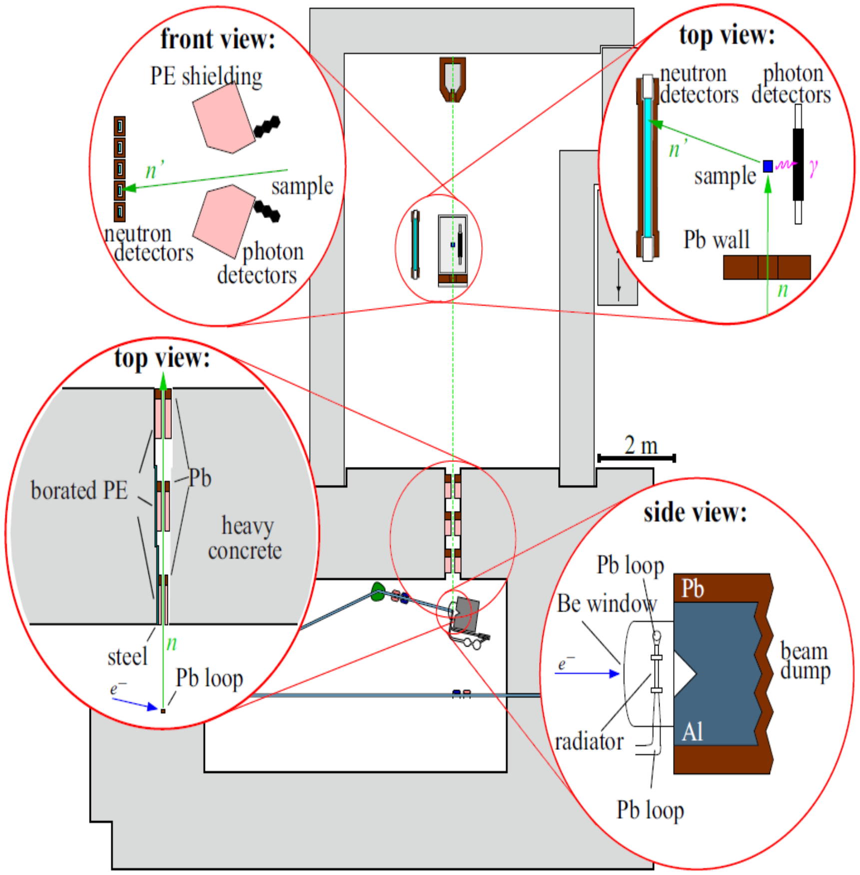
Spares

nELBE: the photo-neutron source

Radiator: 1.12 cm lead
Channel in Mo, 0.5 mm thick

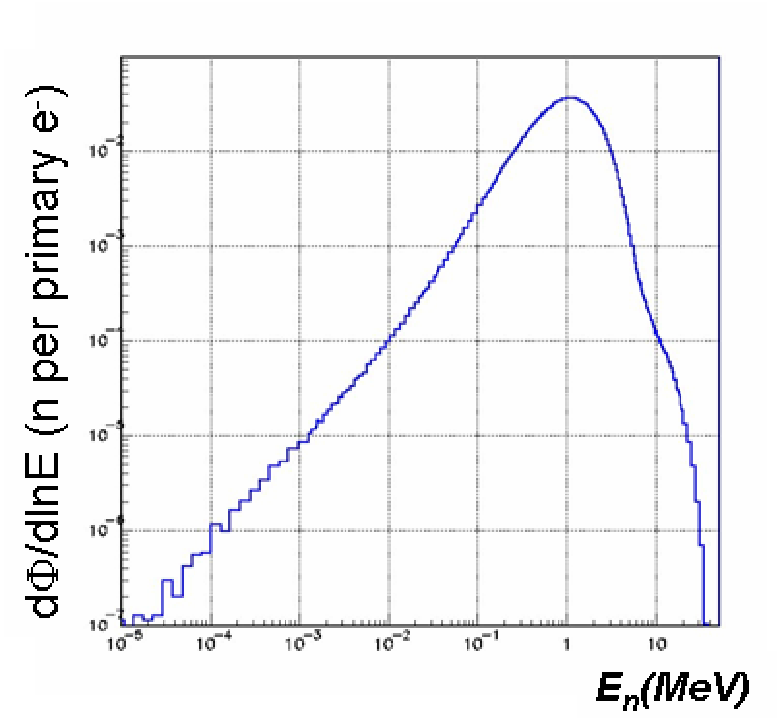


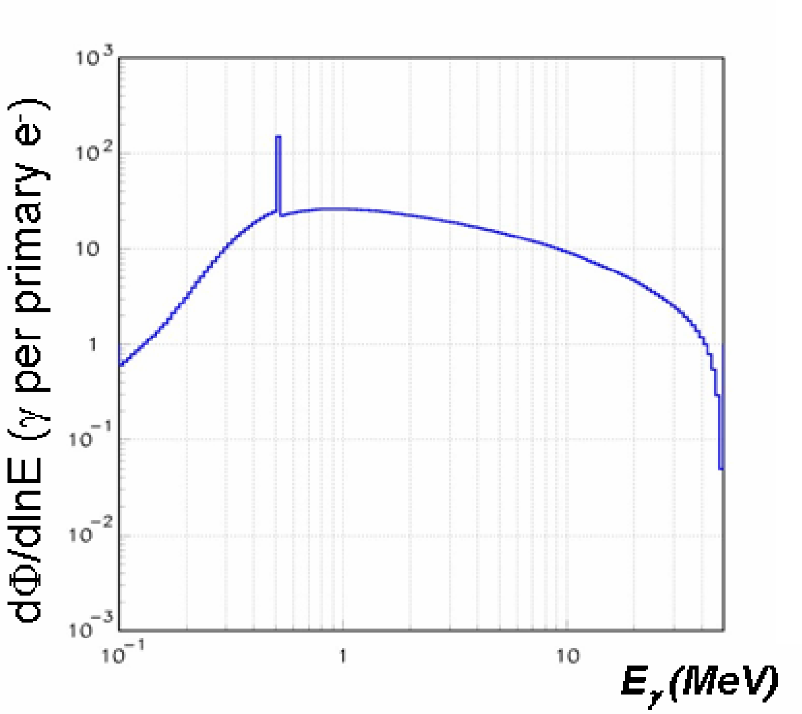
- Electron beam power up to **40 kW**
- Power density in the neutron radiator up to **25 kW/cm³**
- *Liquid lead circuit* for heat transport



Floor plan of the new nELBE neutron source and low scattering experimental hall.

Source strength and photon/neutron yield ratio





Electron Energy (MeV)	Neutron Yield [n/e⁻] (FLUKA sim.)	Source Strength [n/s] @1 mA (FLUKA sim.)	Photon Yield [γ/e-] (FLUKA sim.)
30	$3.108\ 10^{-3}$	$1.94\ 10^{13}$	4.14

Problem: γ/n yield ~ 10^3 !

@ **1 m** , **100μA** e^- current and 30 MeV e^- energy:

$1.54\ 10^7$ n cm^{-2} s^{-1}

To accumulate $3 \cdot 10^{11}$ n/cm^2 only **~5.4 h** are needed

→ To suppress the gamma radiation
a local Pb shielding can be used, without
problematically losing neutron flux