Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

POLITECNICO MILANO 1863

National Physical Laboratory

Bonner sphere spectrometers for neutron stray radiation field characterization

UHDpulse 2nd Stakeholder Meeting
26-27 January 2023

M. Zboril[1], M. Caresana[2], A. Cirillo[2] and N.J. Roberts[3]

[1] Physikalisch-Technische Bundesanstalt (PTB), Germany
[2] Politecnico di Milano (PoliMi), Italy
[3] National Physical Laboratory (NPL), United Kingdom

UHDpulse

Motivation

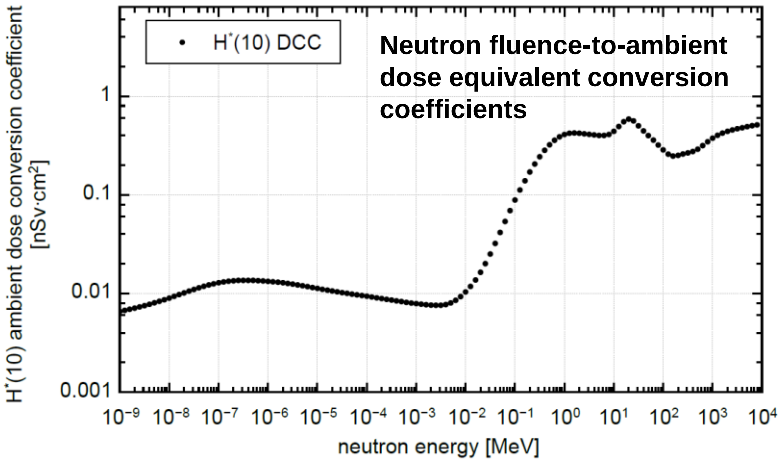
- Interaction of the primary beam with matter ➔ **secondary neutrons**
  ➔ **Unwanted dose** to the patient – must be reliably estimated and minimized
  ➔ Basis for reliable and traceable neutron dosimetry is the **neutron spectrometry**

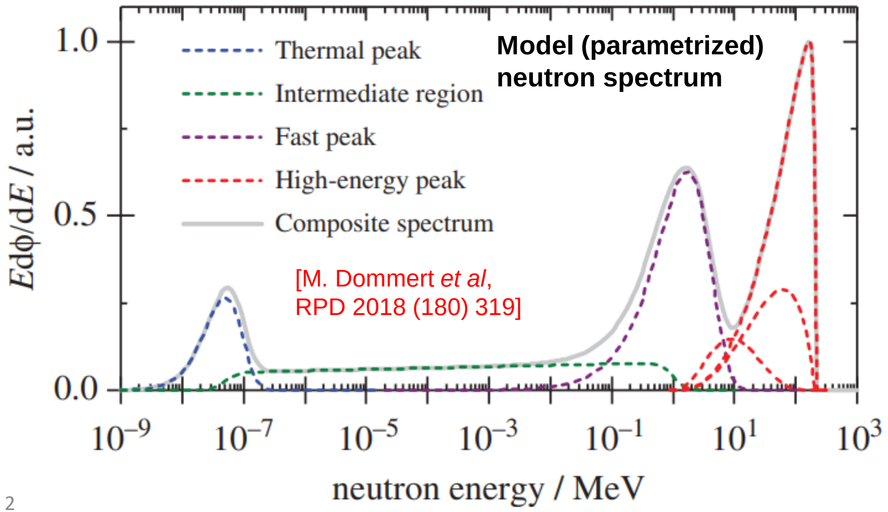
Secondary cancer risk?
Cardiac implants?
Dose to workers?

- Exp. challenges for active spectrometers/dosimeters: pulsed fields

FLASH beam ➔ "FLASH neutrons"?

- Wide energy range – no survey instrument available with good response over the whole range

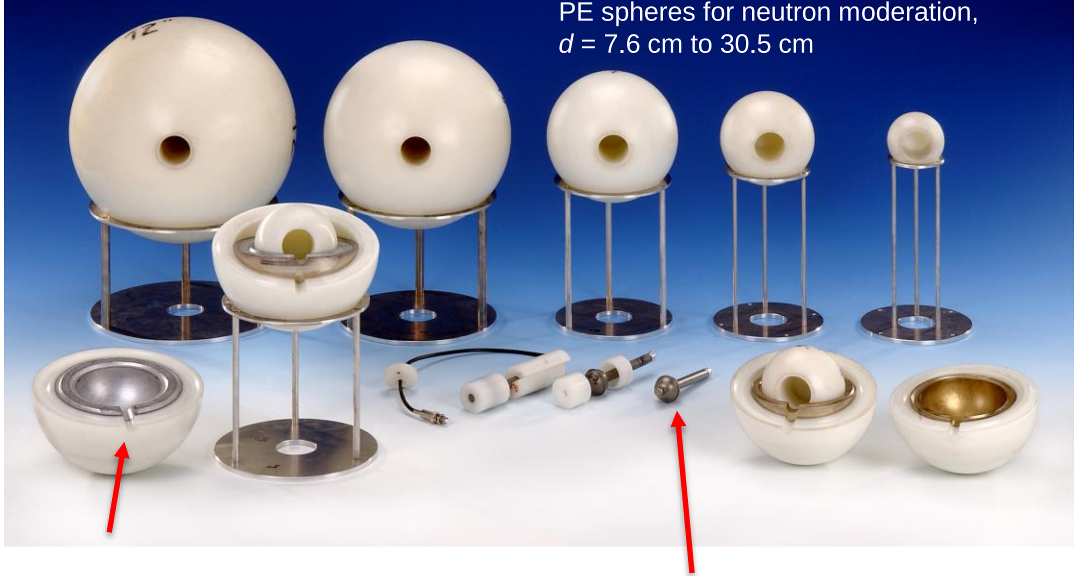




Bonner sphere spectrometry

PTB ERBSS (Extended range Bonner sphere spectrometer) NEMUS
→ From thermal neutrons up to GeV
→ Active detection of neutrons

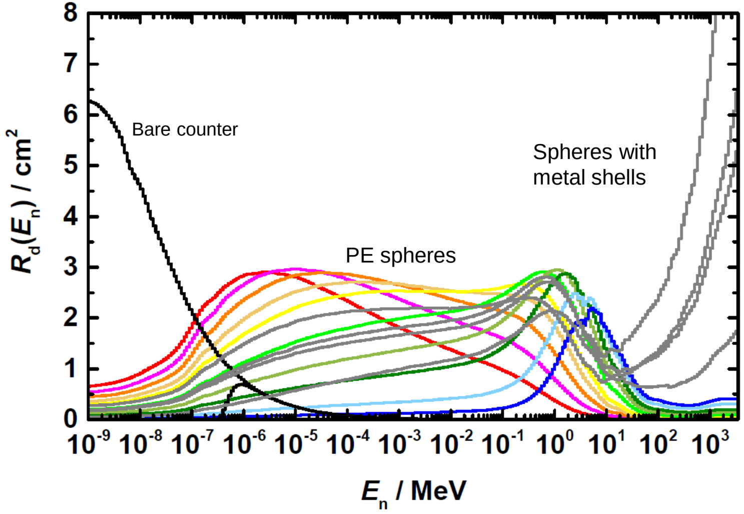
PE spheres for neutron moderation,
d = 7.6 cm to 30.5 cm



Metal shells (Pb, Cu) for spectrometry of high-energy neutrons

Standard sensor of thermalized neutrons:
He-3 proportional counter, type SP9 (Centronic UK)

Validated response functions (MCNP6 model):



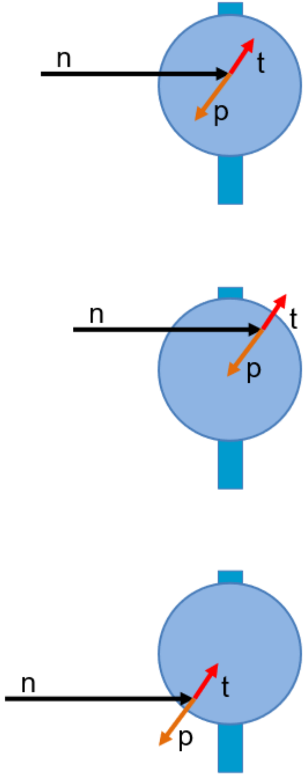
Bonner sphere spectrometry

Detection reaction: $n + {}^{3}He \rightarrow p + t$ $Q = 0.764$ MeV

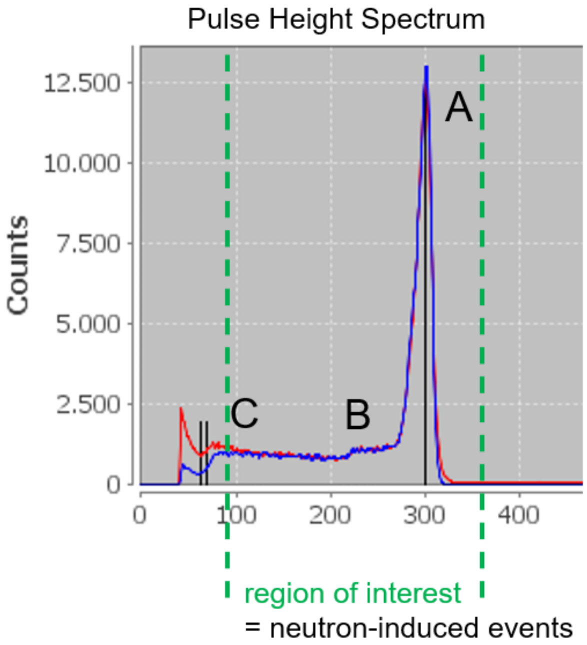
A:

B:

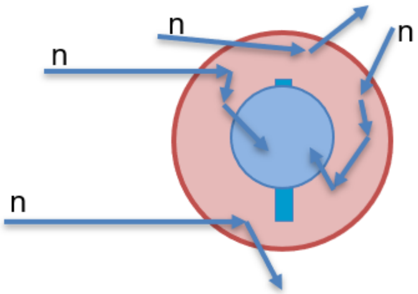
C:



Energy deposition in ^{3}He detector

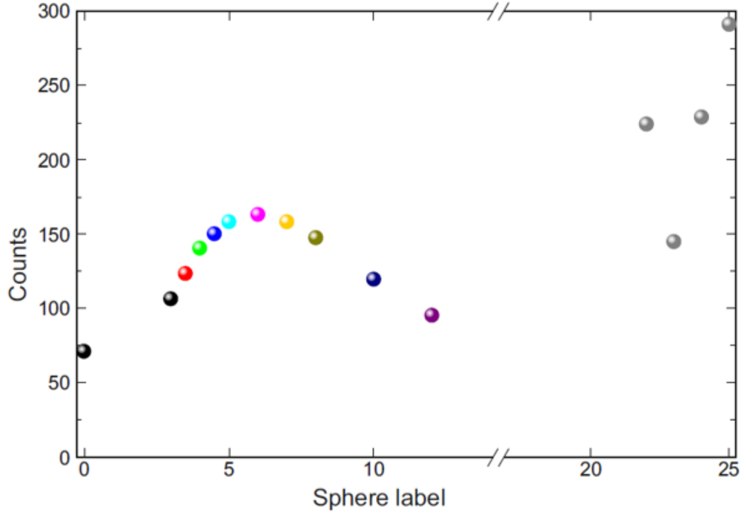


Bonner sphere spectrometry

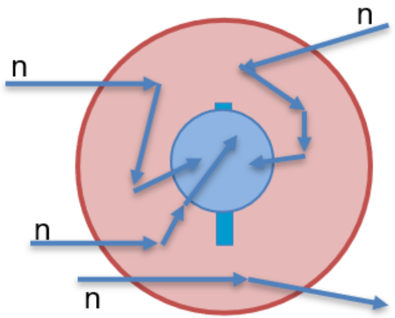


Number of events C_1 in sphere A

Number of neutron-induced events in Bonner spheres of different diameter



This is not a neutron energy distribution!

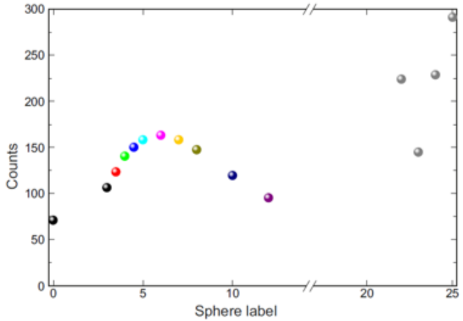


Number of events C_2 in sphere B

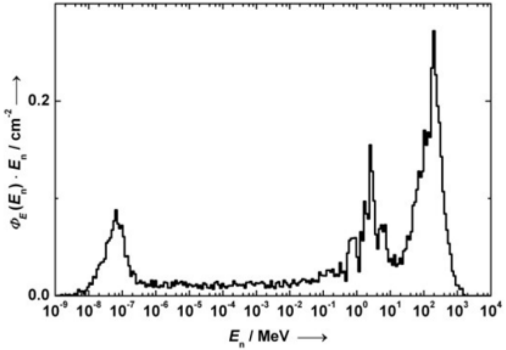
Bonner sphere spectrometry

Measurement
(BSS in unknown neutron field)

→ **Unfolding procedure** → **Neutron energy distribution**



Characterized BSS
(response functions)
&
Additional information about the experiment



- Response functions of the system are needed
  - Computation via Monte Carlo methods
  - Validation in reference neutron fields

Neutron detection systems in UHDpulse

	ACTIVE	ACTIVE	ACTIVE	PASSIVE
System	**PTB BSS with U-235 f.ch.**	**LUPIN-BSS**	**LUPIN-BF_3 REM counter**	**NPL Au-BSS**
Neutron detector	U-235 fission chamber read out in **pulse mode**	He-3 proportional counter read out in **current mode**	BF_3 proportional counter read out in **current mode**	Neutron activation of Au-197 in gold foils
Front-end electronics	Amp CIVIDEC Cx	LogAmp board	LogAmp board	
Digitizer	ADC in list mode	FPGA	FPGA	
Moderator spheres	PE spheres (NEMUS)	Fit into new PE spheres		PE spheres (NPL)
Response functions	Validate in PTB neutron reference fields	Validate at NPL neutron reference fields	Investigated at NPL	Known (NPL)
Validation of method	**Comparison in joint measurement campaign at PTB medical linac and FLASH beamline**			

Neutron detection systems in UHDpulse

	ACTIVE	ACTIVE	ACTIVE	PASSIVE
System	**PTB BSS with U-235 f.ch.**	**LUPIN-BSS**	**LUPIN-BF_3 REM counter**	**NPL Au-BSS**
Neutron detector	U-235 fission chamber read out in **pulse mode**	He-3 proportional counter read out in **current mode**	BF_3 proportional counter read out in **current mode**	Neutron activation of Au-197 in gold foils
Front-end electronics	Amp CIVIDEC Cx	LogAmp board	LogAmp board	
Digitizer	ADC in list mode	FPGA	FPGA	
Moderator spheres	PE spheres (NEMUS)	Fit into new PE spheres		PE spheres (NPL)
Response functions	Validate in PTB neutron reference fields	Validate at NPL neutron reference fields	Investigated at NPL	Known (NPL)
Validation of method	**Comparison in joint measurement campaign at PTB medical linac and FLASH beamline**			

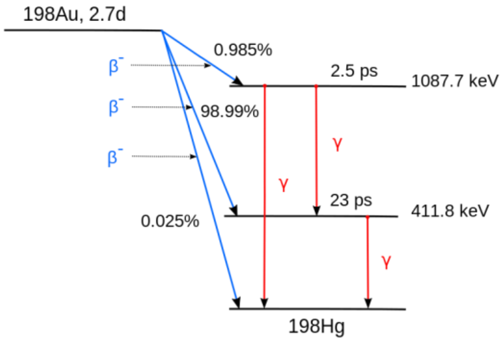
Au foil Bonner spheres

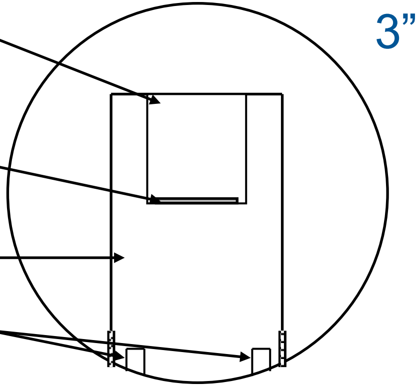
NPL National Physical Laboratory — POLITECNICO MILANO 1863 — PTB

Activation Foils

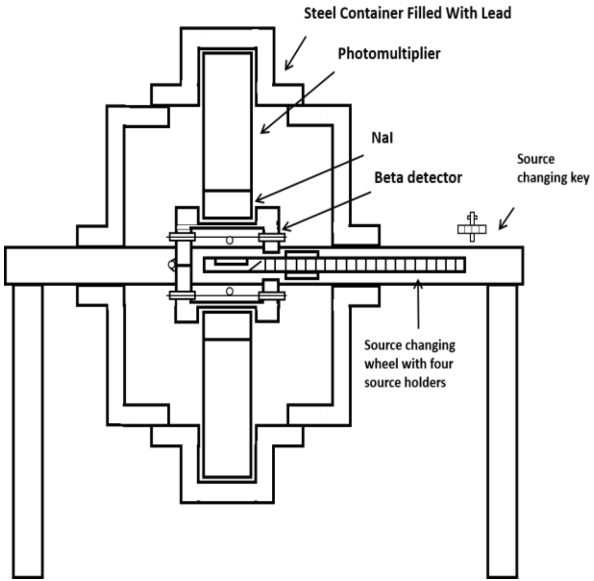
Diameter 22.6 mm
Thickness 0.05 mm
Area = 4 cm^2

- Passive detectors
- Thermal X sec = 99 barn
- Au-198 decay counted in beta-gamma counters

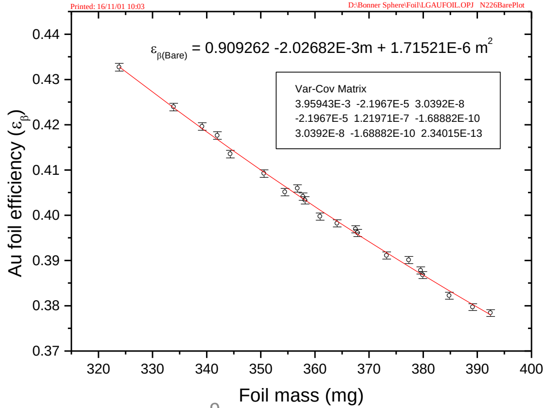




4πβγ coincidence counter



Beta efficiencies from research reactor measurements

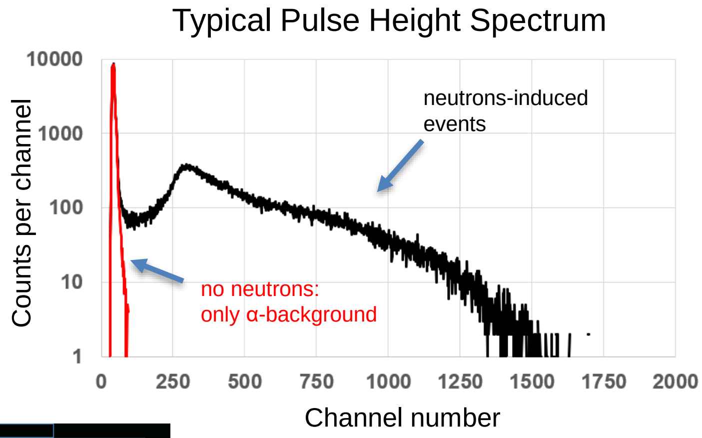


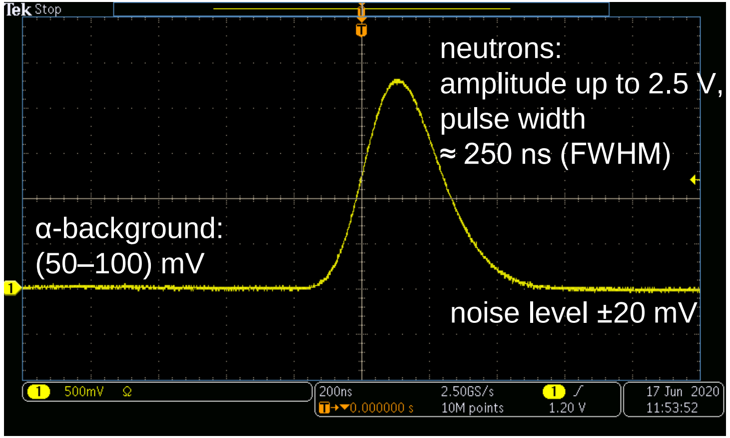
Neutron detection systems in UHDpulse

	ACTIVE	ACTIVE	ACTIVE	PASSIVE
System	**PTB BSS with U-235 f.ch.**	**LUPIN-BSS**	**LUPIN-BF_3 REM counter**	**NPL Au-BSS**
Neutron detector	U-235 fission chamber read out in **pulse mode**	He-3 proportional counter read out in **current mode**	BF_3 proportional counter read out in **current mode**	Neutron activation of Au-197 in gold foils
Front-end electronics	Amp CIVIDEC Cx	LogAmp board	LogAmp board	
Digitizer	ADC in list mode	FPGA	FPGA	
Moderator spheres	PE spheres (NEMUS)	Fit into new PE spheres		PE spheres (NPL)
Response functions	Validate in PTB neutron reference fields	Validate at NPL neutron reference fields	Investigated at NPL	Known (NPL)
Validation of method	**Comparison in joint measurement campaign at PTB medical linac and FLASH beamline**			

PTB BSS NEMUS + U-235 fission chamber

- Neutron-induced fission reaction U-235(n,f), $Q \approx 200$ MeV
- U-235 coated ionization chamber + shaping amplifier CIVIDEC Cx
- ADC (Model 7072 FAST ComTec) with fixed conversion time 500 ns

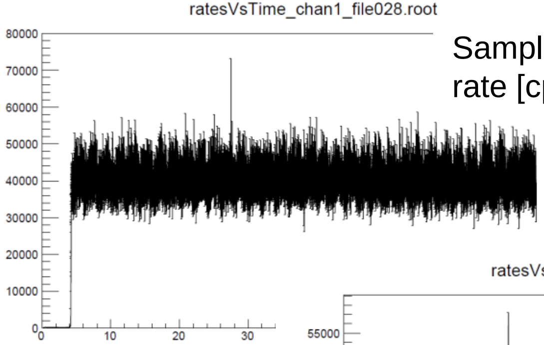




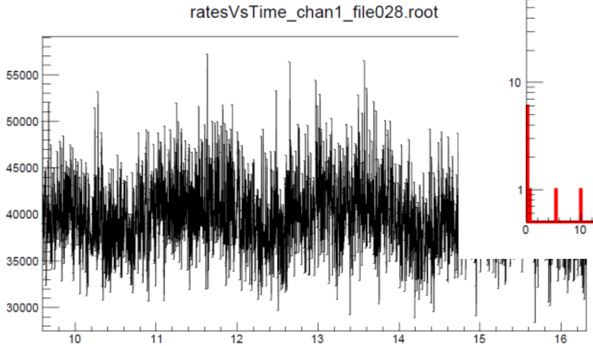
Effective dead time of complete system τ ~ 0.8 microsec.

NEMUS dead time correction

- Sampling of time-resolved data (timestamp, ADC channel)
- Dead time correction carried out every 100 samples
- ADC 7072 (FAST ComTec), fixed conversion time 500 ns



Sampled neutron count rate [cps] as a function of time



JINST

Published by IOP Publishing for Sissa Medialab

Received: December 9, 2020
Revised: February 2, 2021
Accepted: February 2, 2021
Published: March 30, 2021

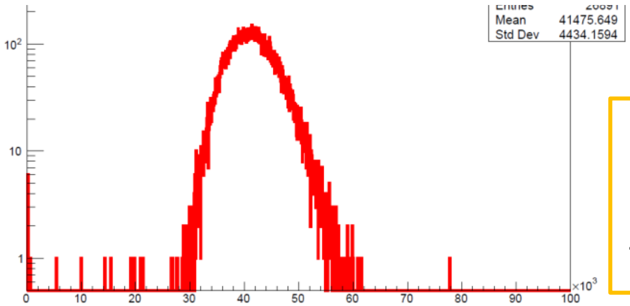
Dead time corrections for Bonner sphere measurements of secondary neutrons at a proton therapy facility

M. Dommert,[a] M. Reginatto,[a] M. Zbořil[a] and B. Lutz[b,*]

[a] *Neutron Radiation Department, Physikalisch-Technische Bundesanstalt, Bundesallee 100, Braunschweig 38116, Germany*

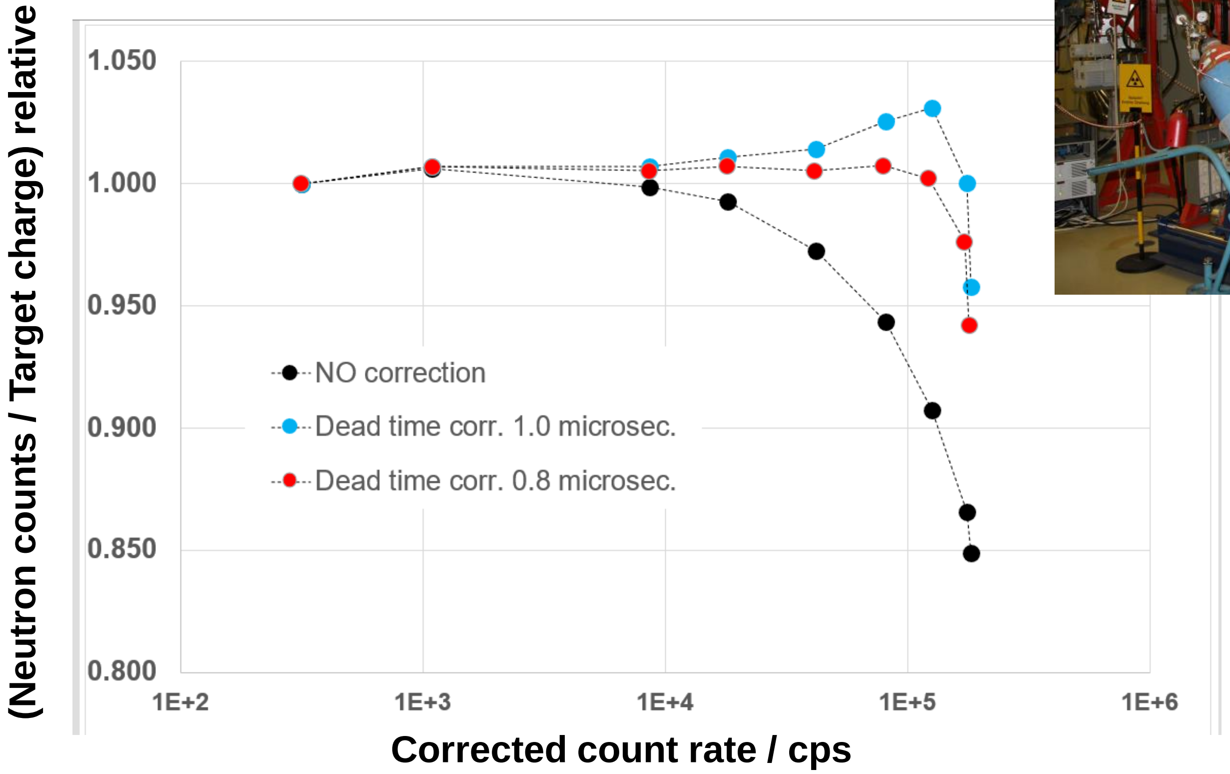
[b] *Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, Dresden 01328, Germany*

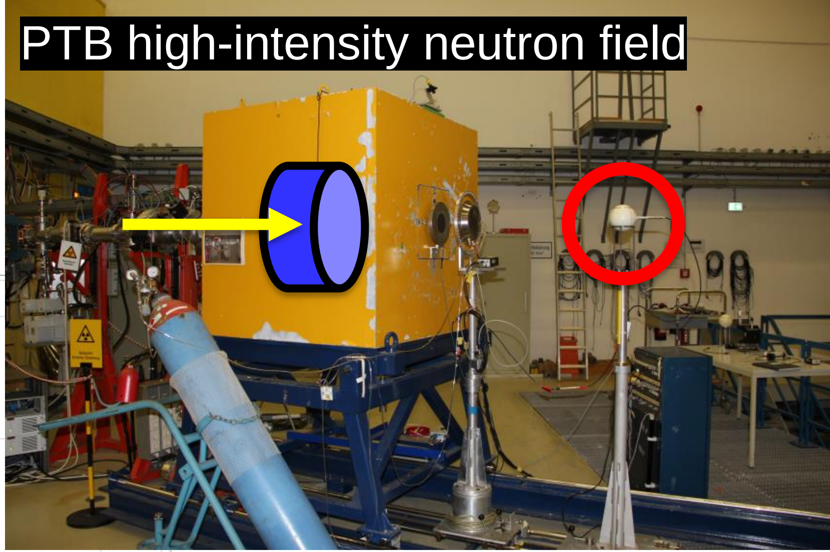
Histogram of sampled count rates



Effective dead time of complete system $\tau \sim 0.8$ microsec.

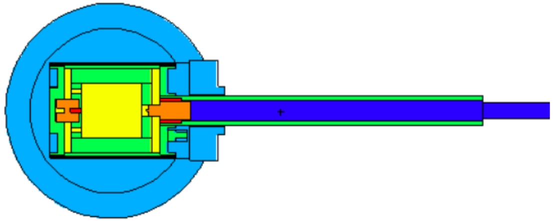
NEMUS dead time correction

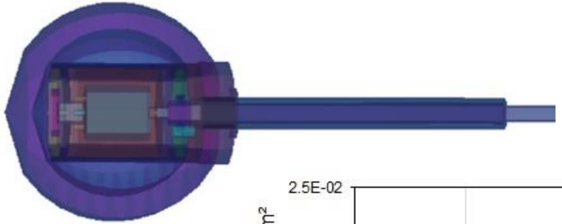


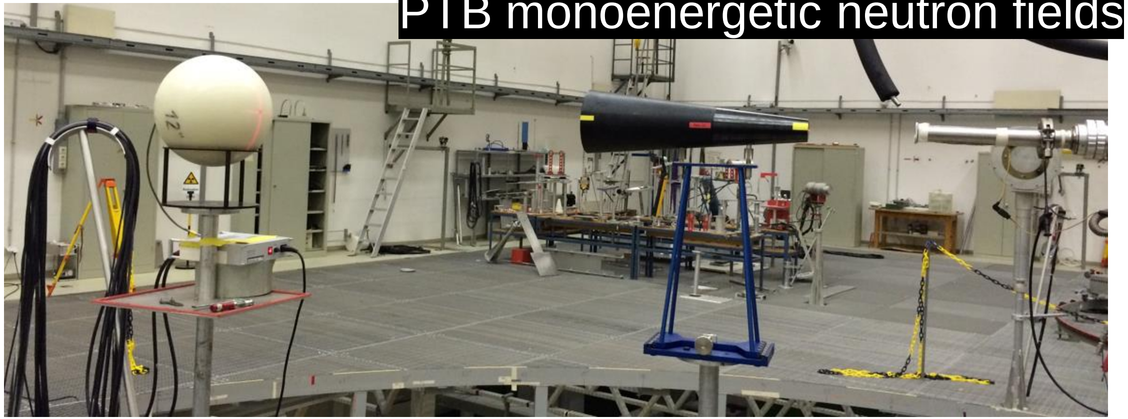


Effective dead time of complete system τ ~ 0.8 microsec.

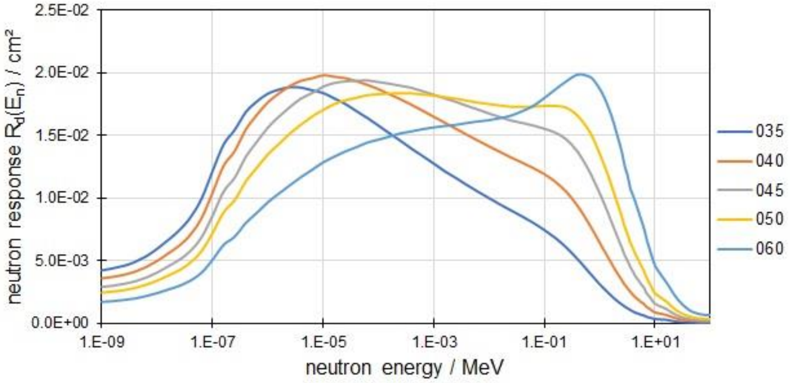
NEMUS + U-235 ➔ new response functions

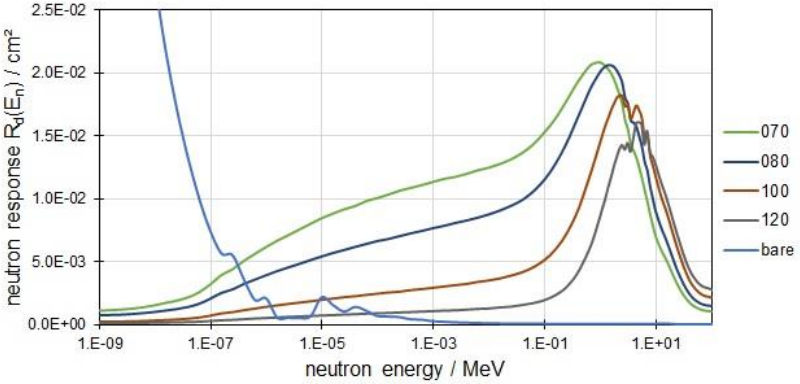






PTB monoenergetic neutron fields





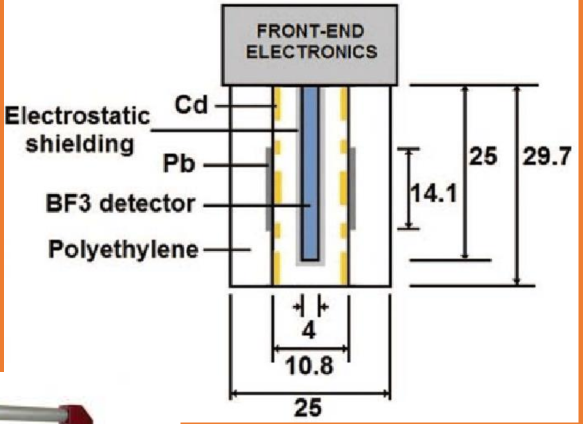
Neutron detection systems in UHDpulse

	ACTIVE	ACTIVE	ACTIVE	PASSIVE
System	**PTB BSS with U-235 f.ch.**	**LUPIN-BSS**	**LUPIN-BF_3 REM counter**	**NPL Au-BSS**
Neutron detector	U-235 fission chamber read out in **pulse mode**	He-3 proportional counter read out in **current mode**	BF_3 proportional counter read out in **current mode**	Neutron activation of Au-197 in gold foils
Front-end electronics	Amp CIVIDEC Cx	LogAmp board	LogAmp board	
Digitizer	ADC in list mode	FPGA	FPGA	
Moderator spheres	PE spheres (NEMUS)	Fit into new PE spheres		PE spheres (NPL)
Response functions	Validate in PTB neutron reference fields	Validate at NPL neutron reference fields	Investigated at NPL	Known (NPL)
Validation of method	**Comparison in joint measurement campaign at PTB medical linac and FLASH beamline**			

The LUPIN

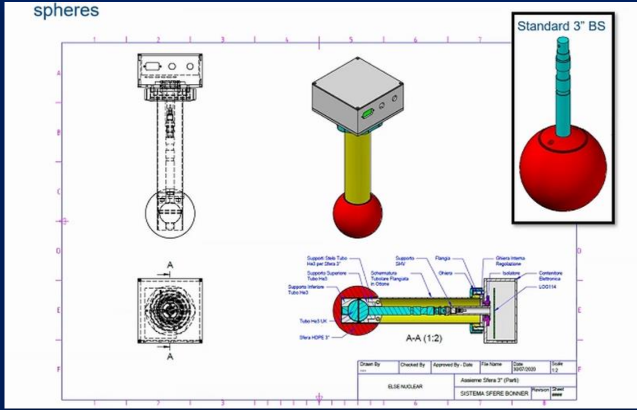
POLITECNICO
MILANO 1863

Long interval, **U**ltra-wide dynamic, **PI**le-up free, **N**eutron rem counter)



LUPIN BF3
REM counter

LUPIN He3
Bonner Sphere
Spectrometer



The Setups

LUPIN BF3
REM counter

- Used for environmental dosimetry
- Based on a BF3 Proportional Counter
- Lower sensitivity
- Linear Response in pulsed fields up to ~ 1000 counts/burst (https://doi.org/10.1016/j.nima.2013.11.073)

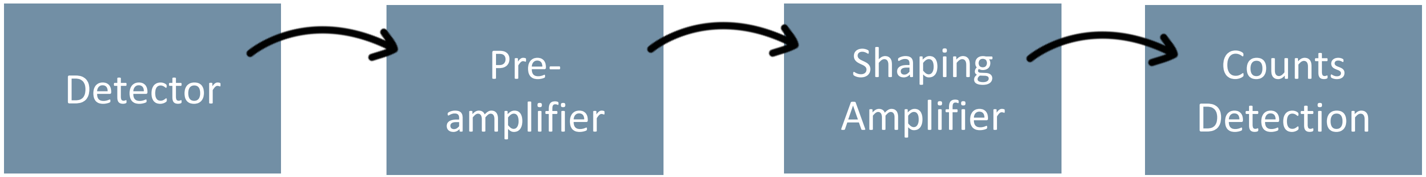
LUPIN He3
Bonner
Spheres
Spectrometer

- Used for neutron spectrometry
- Based on a He3 Proportional Counter
- Higher sensitivity
- The linearity of the response was tested in this work

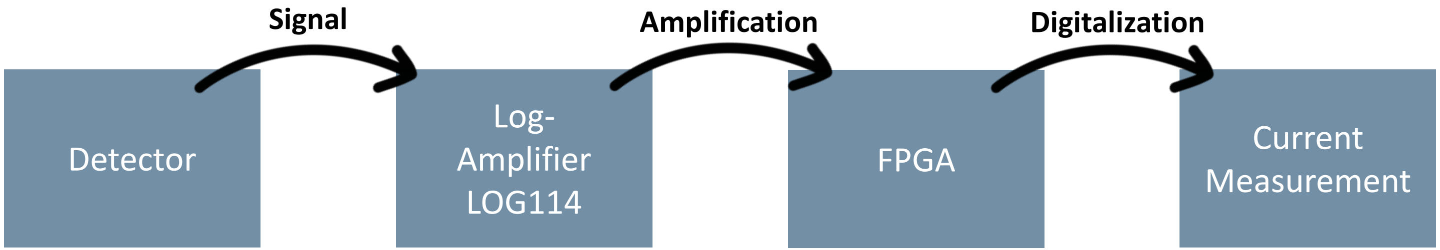
POLITECNICO
MILANO 1863

LUPIN electronics

Conventional Acquisition Chain for a Neutron Counter

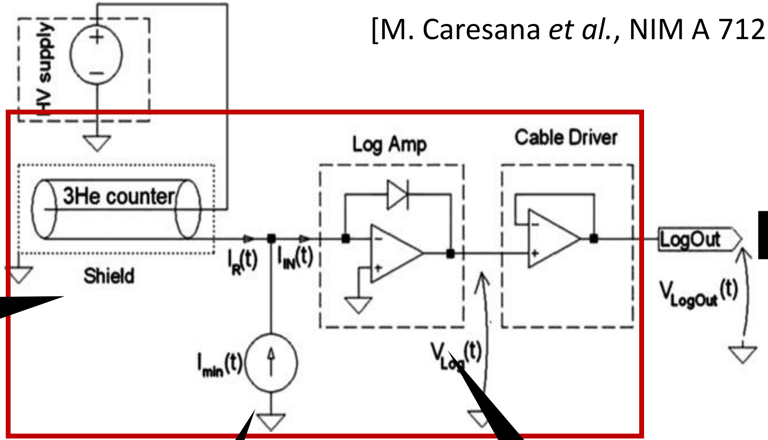


LUPIN Acquisition Chain



LUPIN electronics

[M. Caresana *et al.*, NIM A 712 (2013) 15]



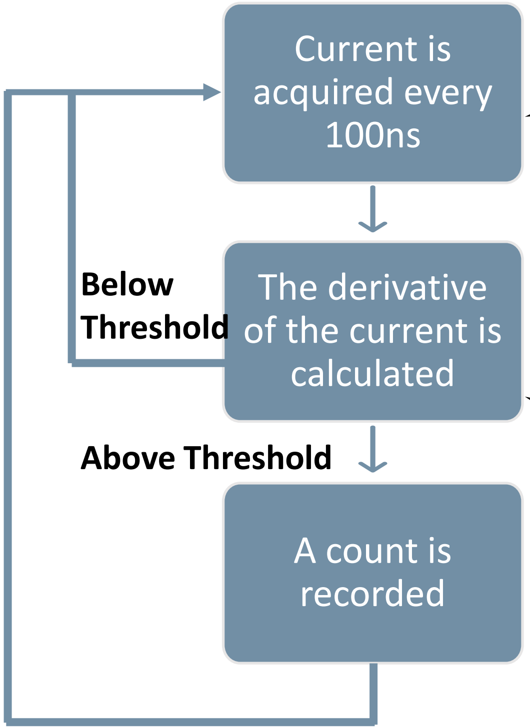
The current signal is collected at the cathode, which is electrostatically shielded with an aluminium cylinder to avoid noise pick up

To FPGA/ Oscilloscope

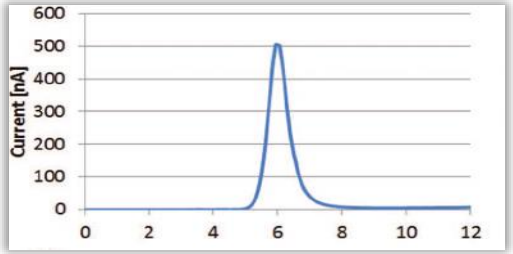
A fixed current is provided to the LogAmp to avoid negative saturation in absence of signal

The high-speed LogAmp LOG114 works over a dynamic range of 8 decades and can **withstand the intense currents generated in pulsed fields**

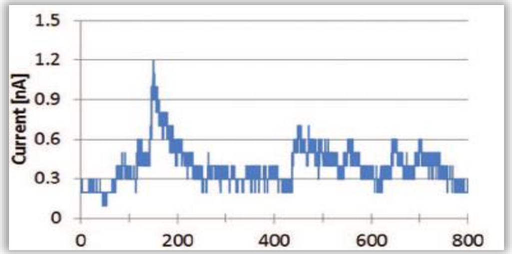
LUPIN: counts detection and n/γ discrimination



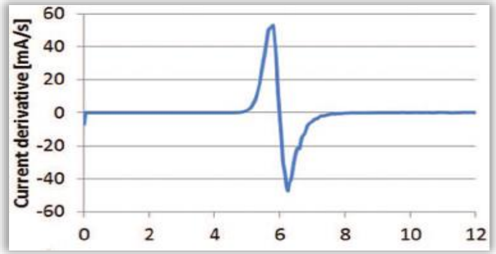
Current from a neutron event



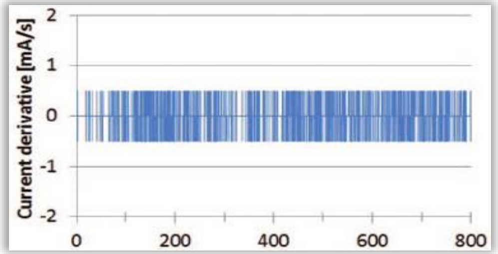
Current from γ events



Neutron Signal Derivative



γ Signal Derivative



The **difference in the derivative** allows to **discriminate** between n and γ events

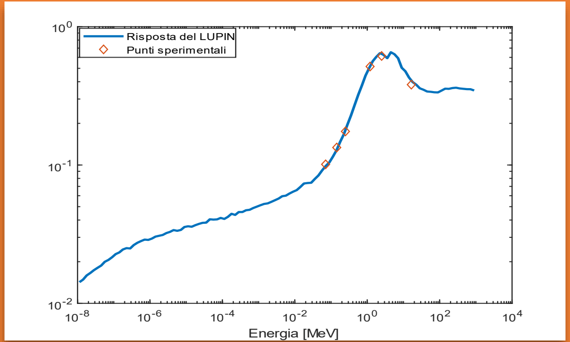
Calibration

National Physical Laboratory

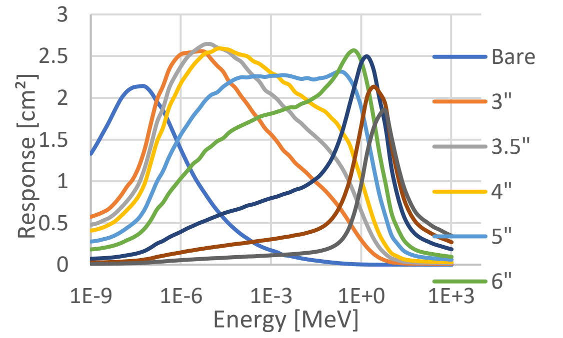
POLITECNICO MILANO 1863

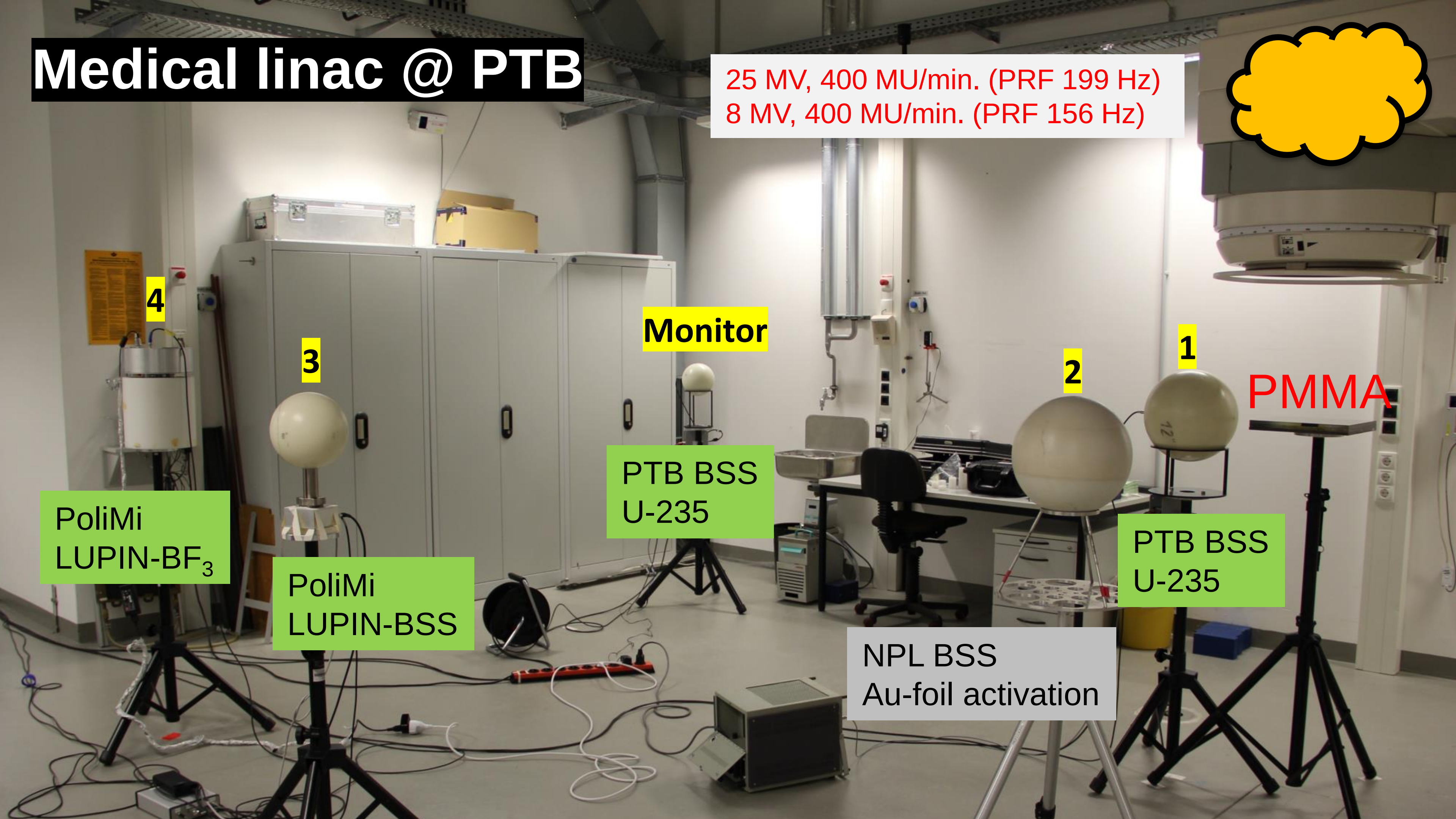
Validation of the **response functions** in the monoenergetic neutron fields at NPL

REM Counter Response



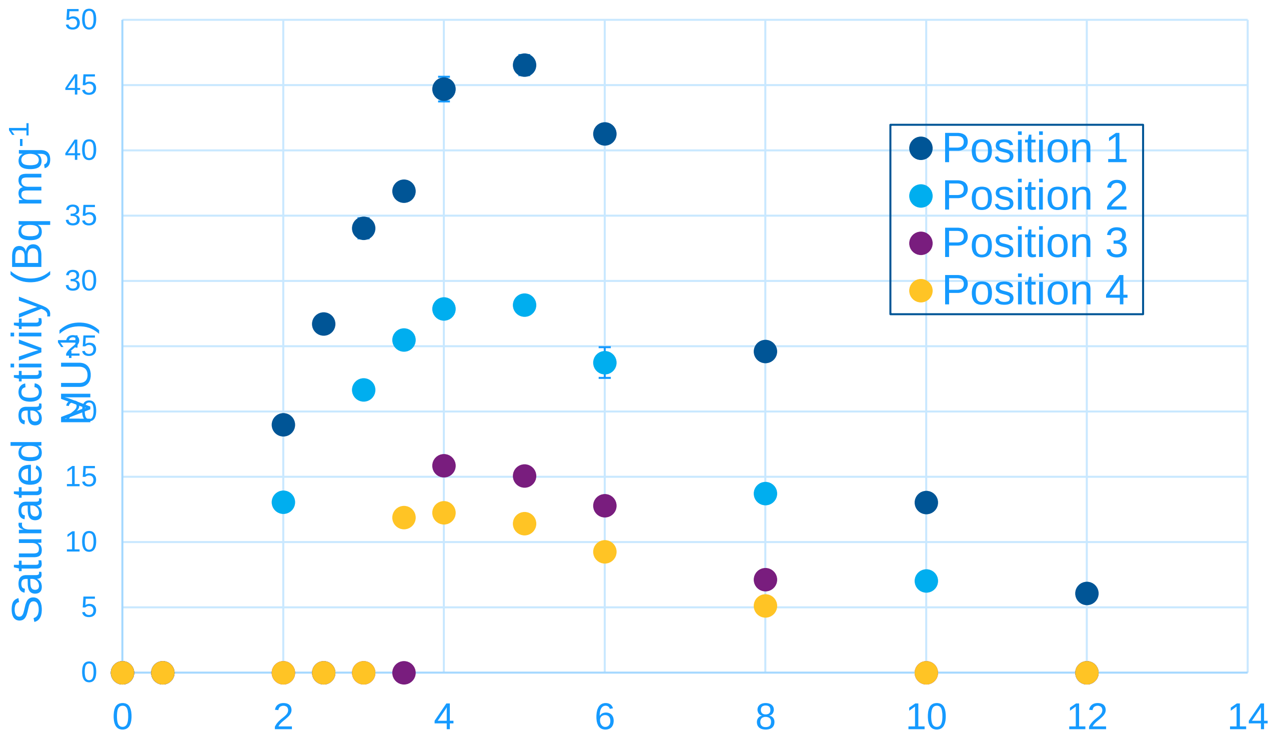
Bonner Sphere Spectrometer Responses




Medical linac @ PTB
25 MV, 400 MU/min. (PRF 199 Hz)
8 MV, 400 MU/min. (PRF 156 Hz)
4
3
Monitor
2
1
PMMA
PoliMi
LUPIN-BF$_3$
PoliMi
LUPIN-BSS
PTB BSS
U-235
PTB BSS
U-235
NPL BSS
Au-foil activation

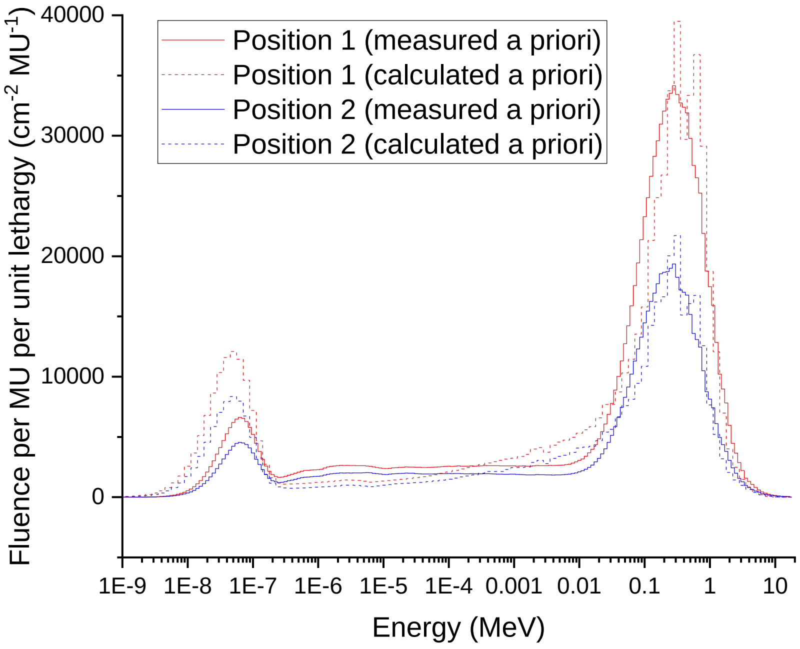
NPL: Au foil analysis

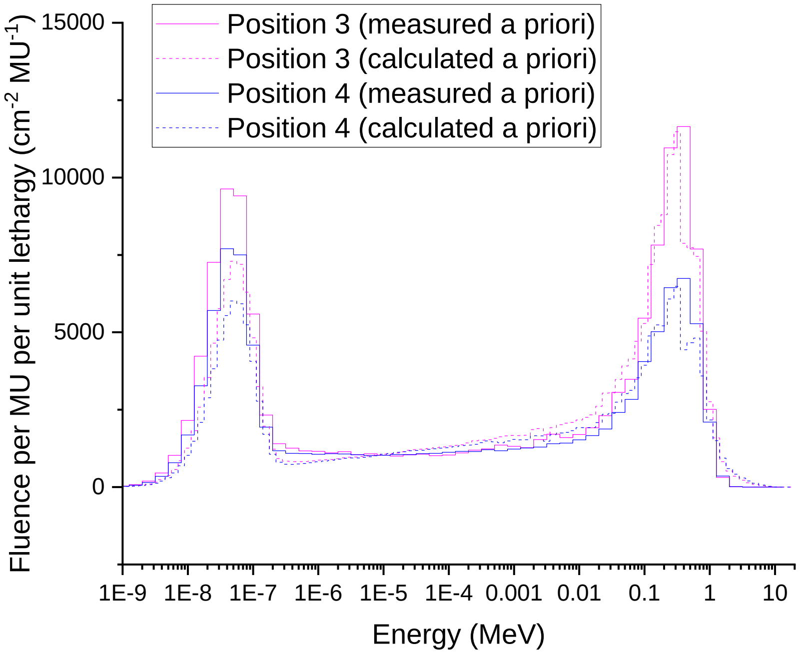
- Measured activities at NPL and evaluated saturated activities per MU for each foil



NPL: Au foil unfolded spectra

- Unfolded using both measured *a priori* spectra and a calculation from EURADOS WG6 unfolding comparison exercise (also for a 25 MV linac)



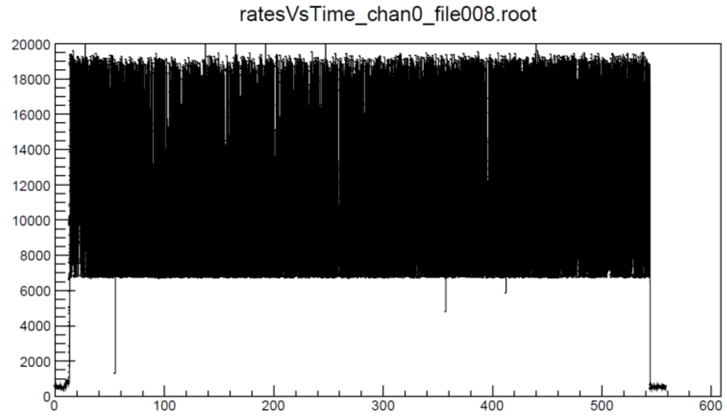


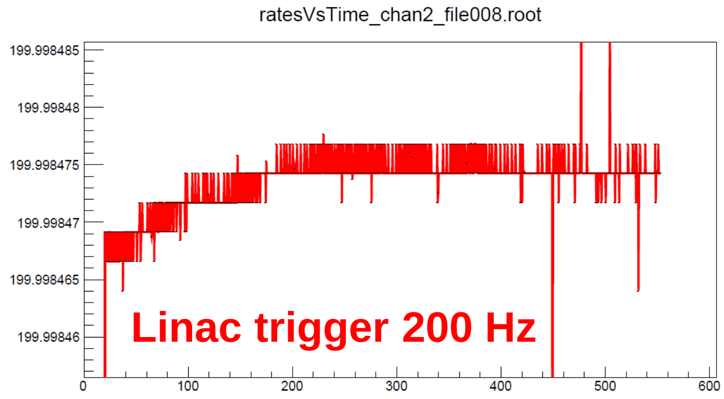
NPL: Au foil dose and fluence

- Integrating spectrum gives neutron fluence
- Folding spectrum with dose conversion coefficients gives neutron dose per MU

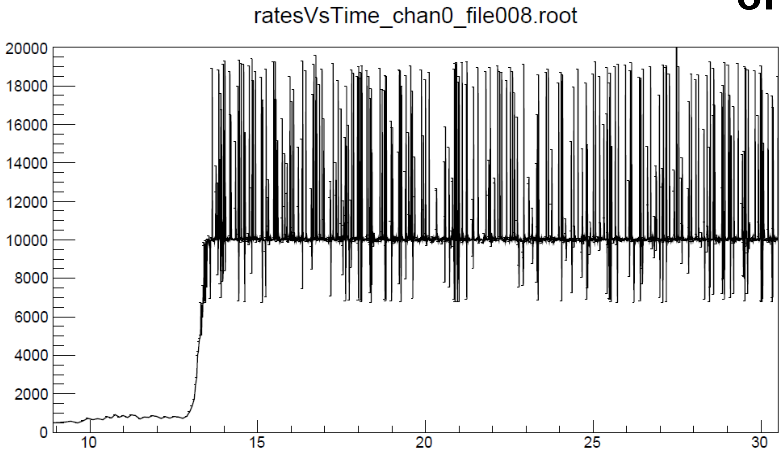
Position	Dose per MU (µSv)			Fluence (cm^{-2} MU^{-1})		
	Measured a priori	Calculated a priori	Difference	Measured a priori	Calculated a priori	Difference
1	21.76	22.35	2.7%	1.37E+05	1.45E+05	5.4%
2	11.61	11.57	-0.4%	8.40E+04	8.93E+04	6.3%
3	5.69	5.40	-5.2%	5.95E+04	5.50E+04	-7.5%
4	3.81	3.65	-4.2%	4.63E+04	4.30E+04	-6.9%

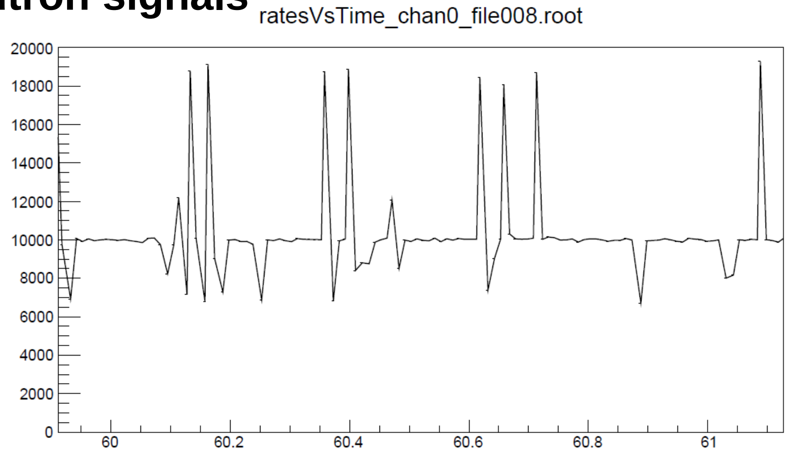
PTB: Time-resolved data



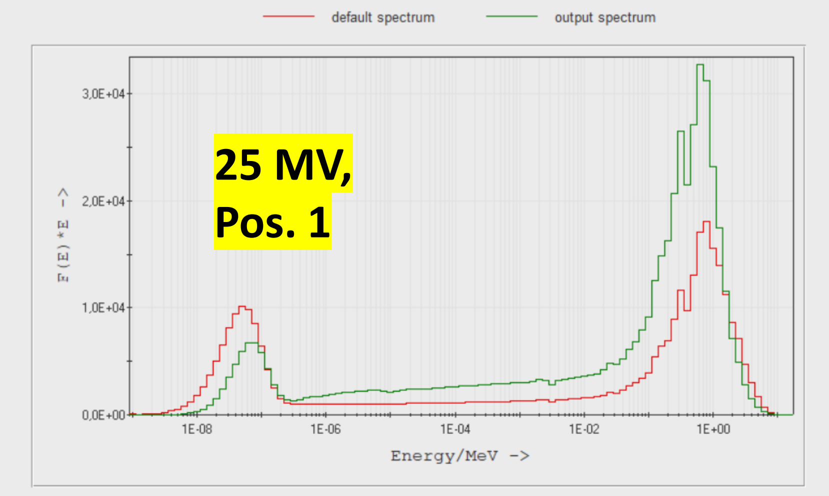


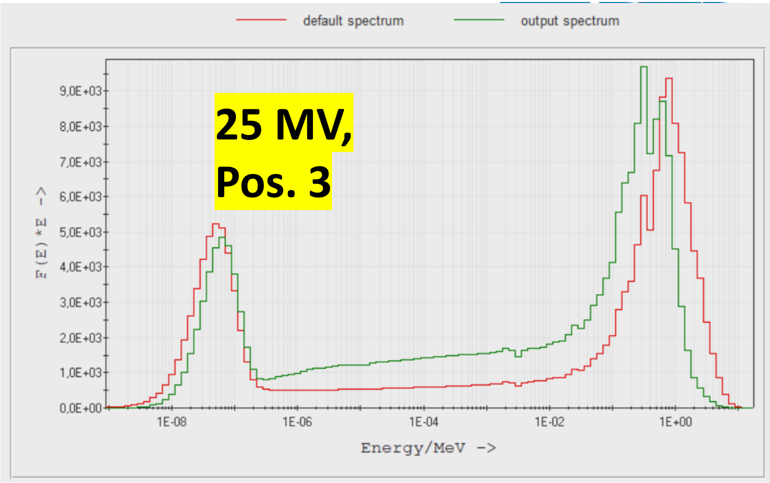
Sampled count rate of neutron signals

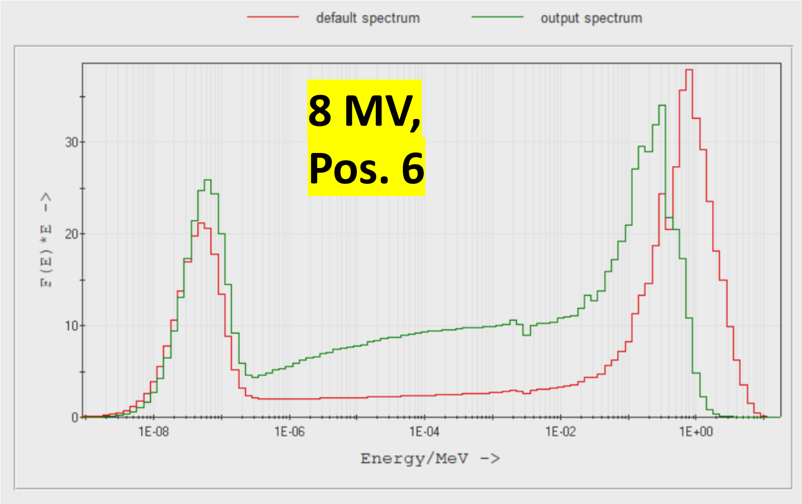




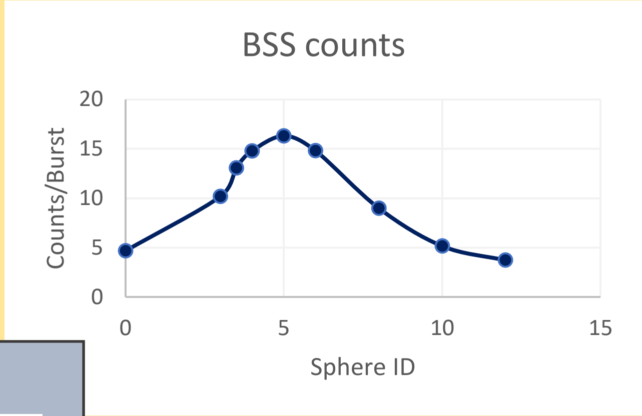
PTB: Unfolded spectra





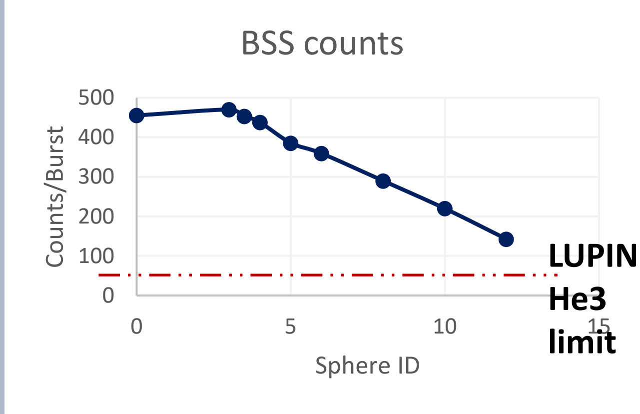


PoliMi: Irradiation at PTB Medical Linac

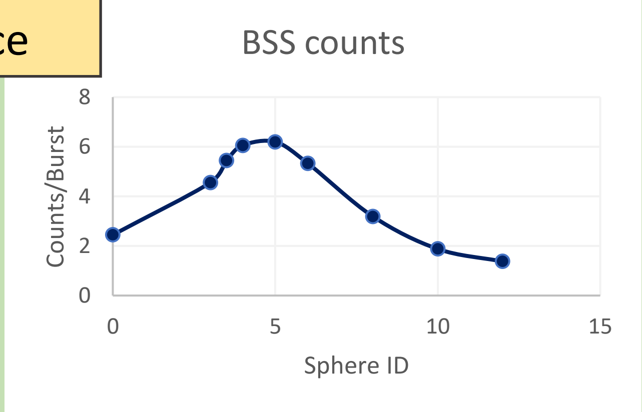


8MV, 1.6 meters distance

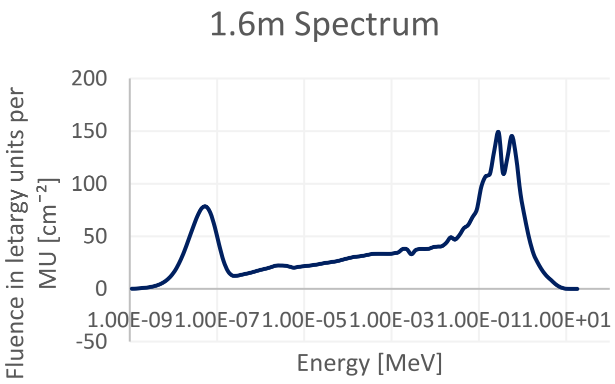
25MV, 4 meters distance

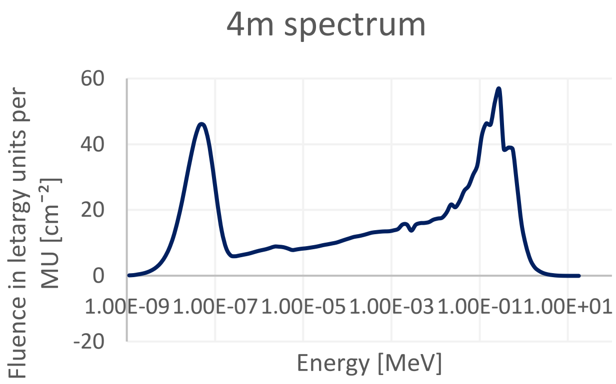


8MV, 4 meters distance



PoliMi: Resulting Spectra and Quantities





Integral Quantities		
	Fluence [$cm^{-2}MU^{-1}$]	H*(10) [nSv MU^{-1}]
1.6 m	882	91
4 m	357	28

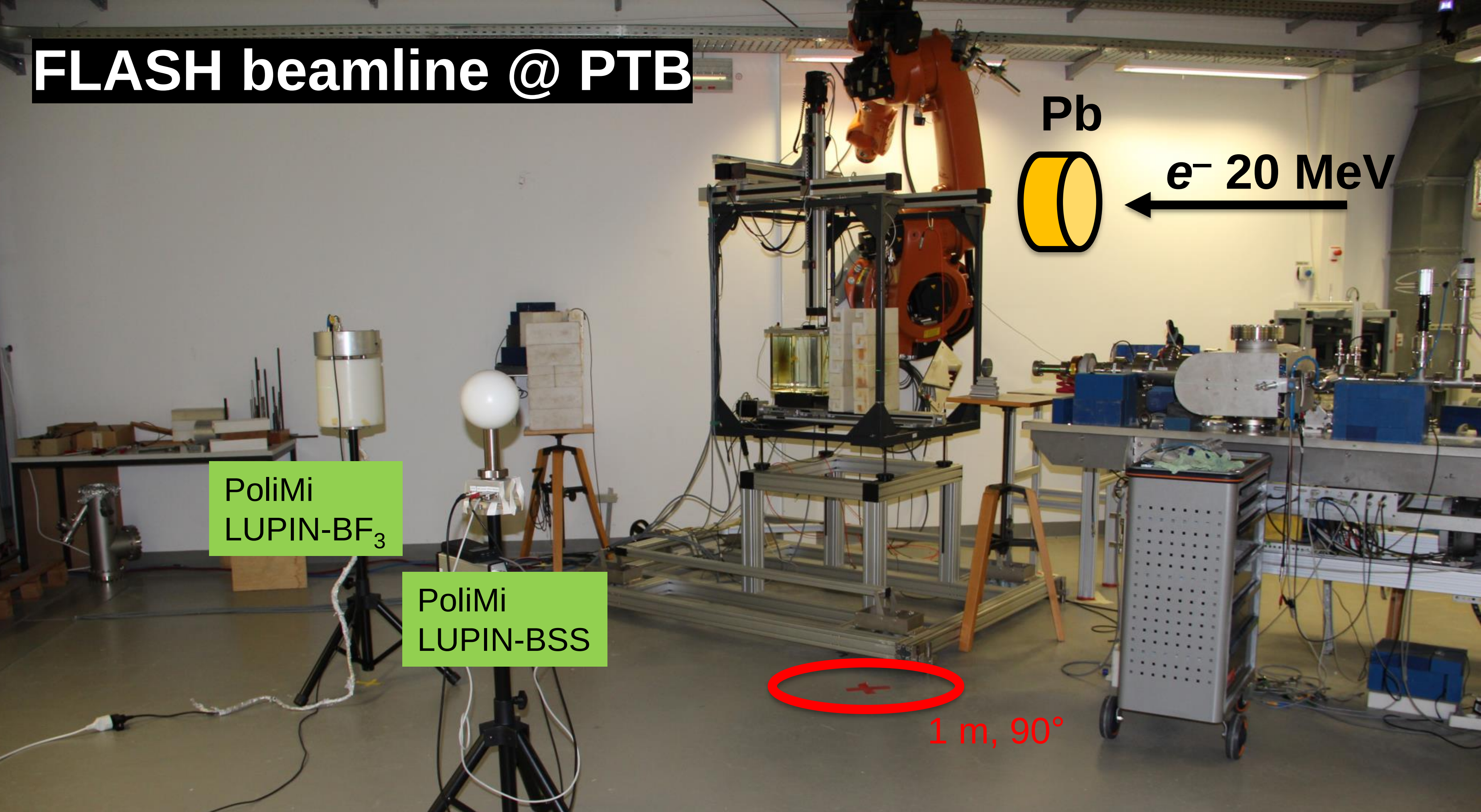
Comparison NPL-PTB-PoliMi

Pos.	Beam settings	[x, y, z] / cm	NPL Fluence	NPL Dose	PTB Fluence	PTB Dose	PoliMi Fluence	PoliMi Dose
1	25 MV, ISO 10x10	[40, 0, 0]	**1.45E+05**	**22.35**	**1.14E+05**	**20.57**		
2	25 MV, ISO 10x10	[0, 160, 0]	**8.93E+04**	**11.57**	**7.62E+04**	**11.75**		
3	25 MV, ISO 10x10	[168, 243, 0] 3.0 m from ISO	**5.50E+04**	**5.40**	**4.73E+04**	**5.57**		
4	25 MV, ISO 10x10	[321, 243, 0] 3.9 m from ISO	**4.30E+04**	**3.65**	**3.80E+04**	**3.91**		
5	25 MV, ISO 10x10	[223, 324, 0] 3.9 m from ISO			**3.94E+04**	**3.91**		
6	8 MV, „closed" 0.5x0.5	[223, 324, 0] 3.9 m from ISO			**224**	**0.015**	**357**	**0.028**
7	8 MV, „closed" 0.5x0.5	[160, 0, 0]			**447**	**0.046**	**882**	**0.091**

Neutron fluence [cm^{-2} MU^{-1}]

Neutron dose *H(10) [μSv MU^{-1}]**

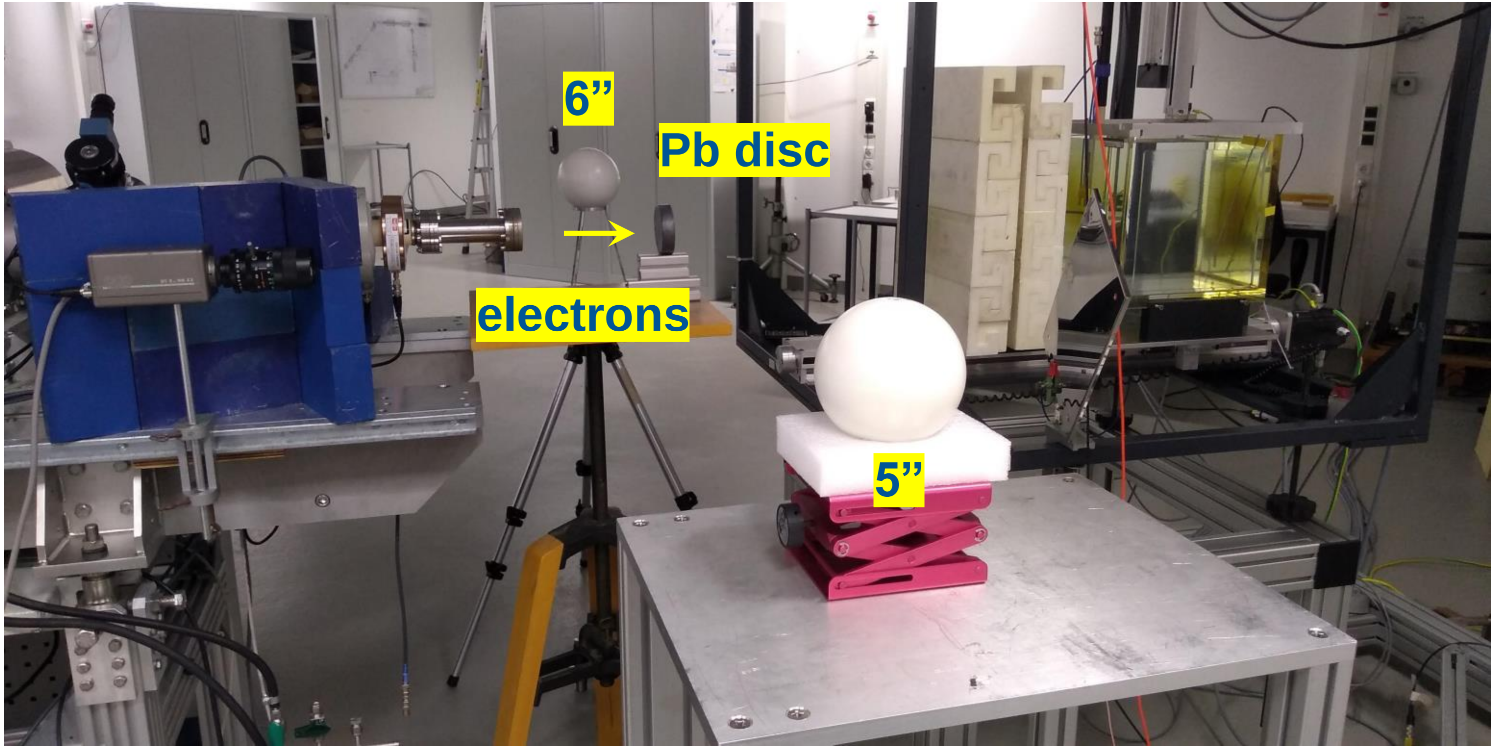
PRELIMINARY RESULTS


FLASH beamline @ PTB
Pb
e^- 20 MeV
PoliMi LUPIN-BF_3
PoliMi LUPIN-BSS
1 m, 90°

NPL: Measurements in FLASH linac

- Au measurements made at ± 90º and 1 m from Pb disc at maximum slit and pulse widths
- Only 5” and 6” spheres used

Expected dose for SSD70-00: 11 Gy/pulse

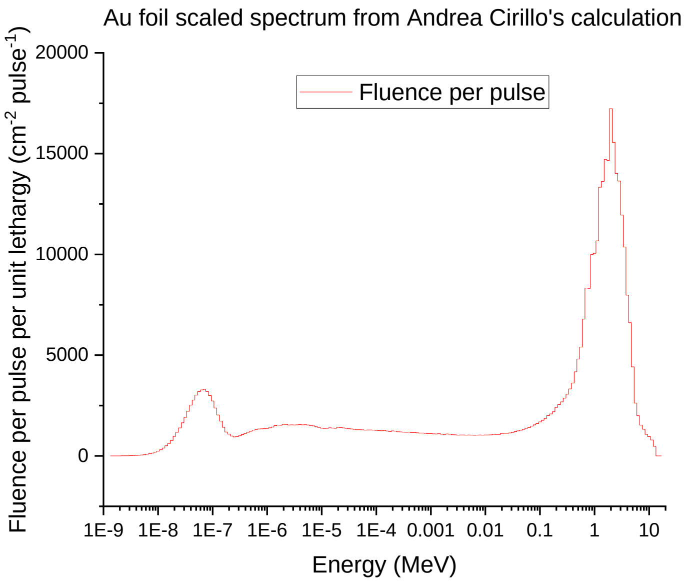


NPL: Au foil dose and fluence

POLITECNICO MILANO 1863 | PTB | NPL National Physical Laboratory

- Used foil results to scale calculated spectrum from Andrea Cirillo/PoliMi
- Integrating spectrum gives neutron fluence
- Folding spectrum with dose conversion coefficients gives neutron dose per linac pulse

Expected dose for SSD70-00: 11 Gy/pulse



Dose per pulse (μSv)	Fluence (cm^{-2} $pulse^{-1}$)
12.14	5.31E+04

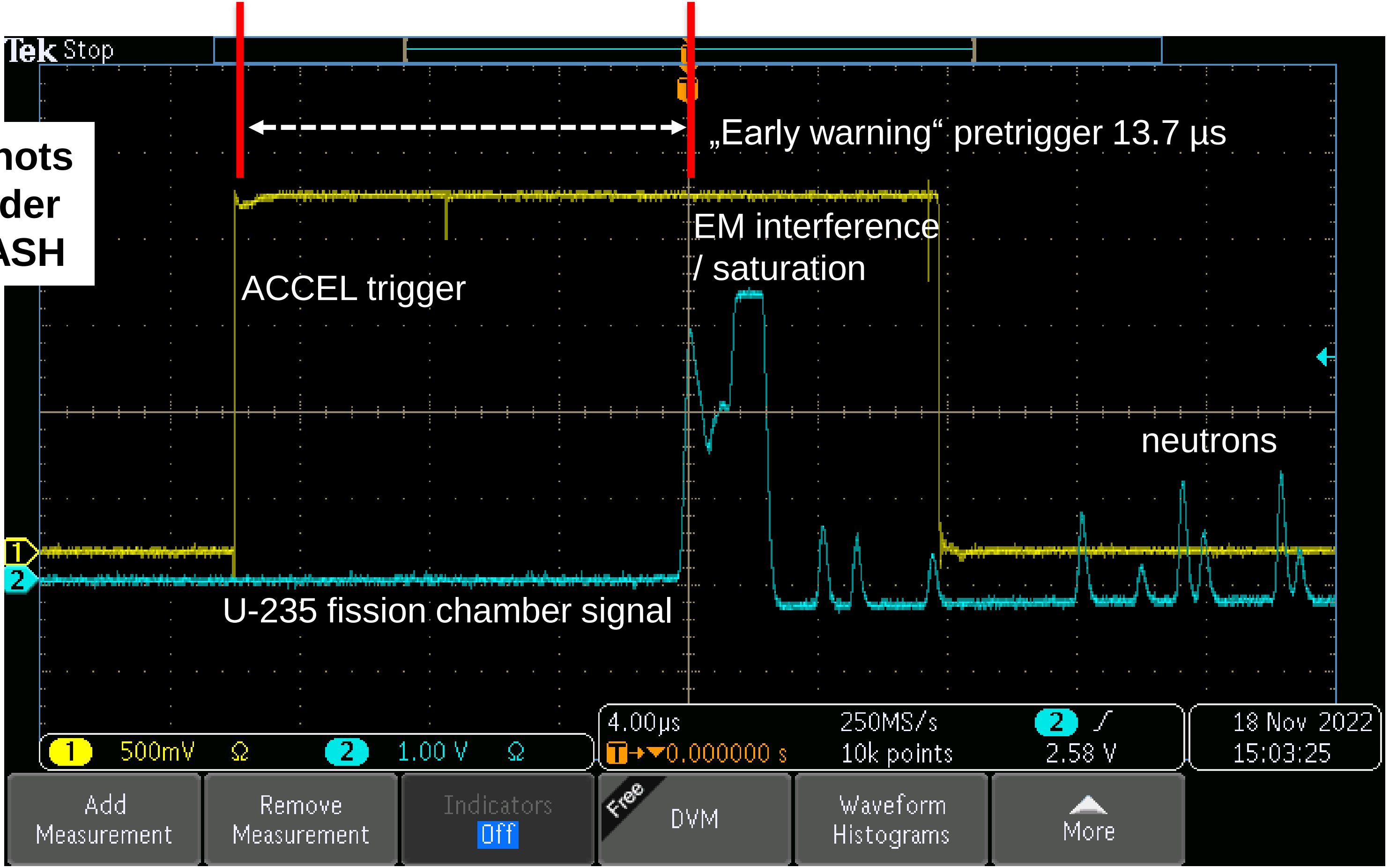
Time averaged dose rate = 219 mSv h^{-1}

cf. Medical linac:
Pos 1 = 397 mSv h^{-1},
Pos 2 = 209 mSv h^{-1}

PRELIMINARY RESULTS!

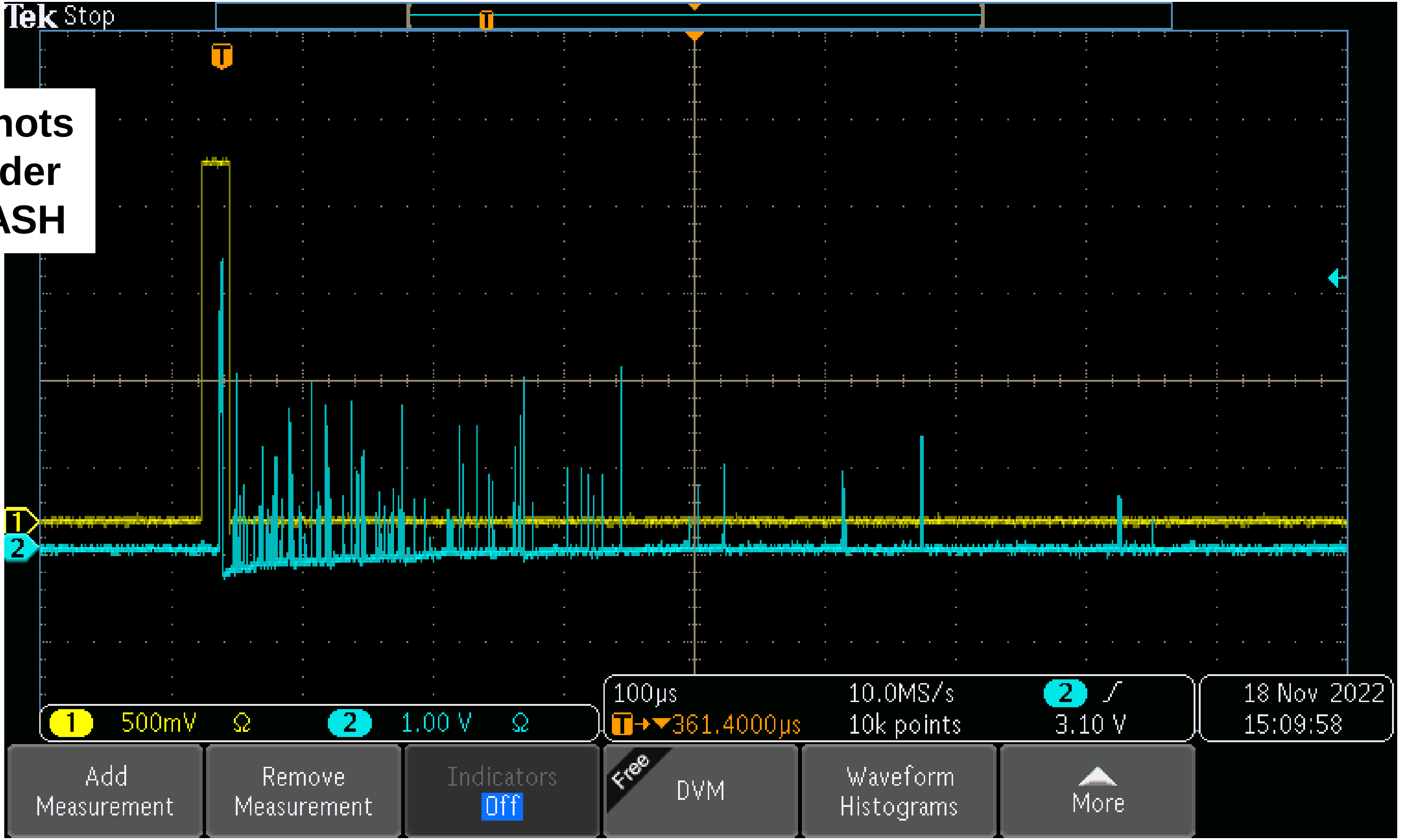
PTB: Time-resolved data

Screenshots taken under MAX FLASH



PTB: Time-resolved data

Screenshots taken under MAX FLASH

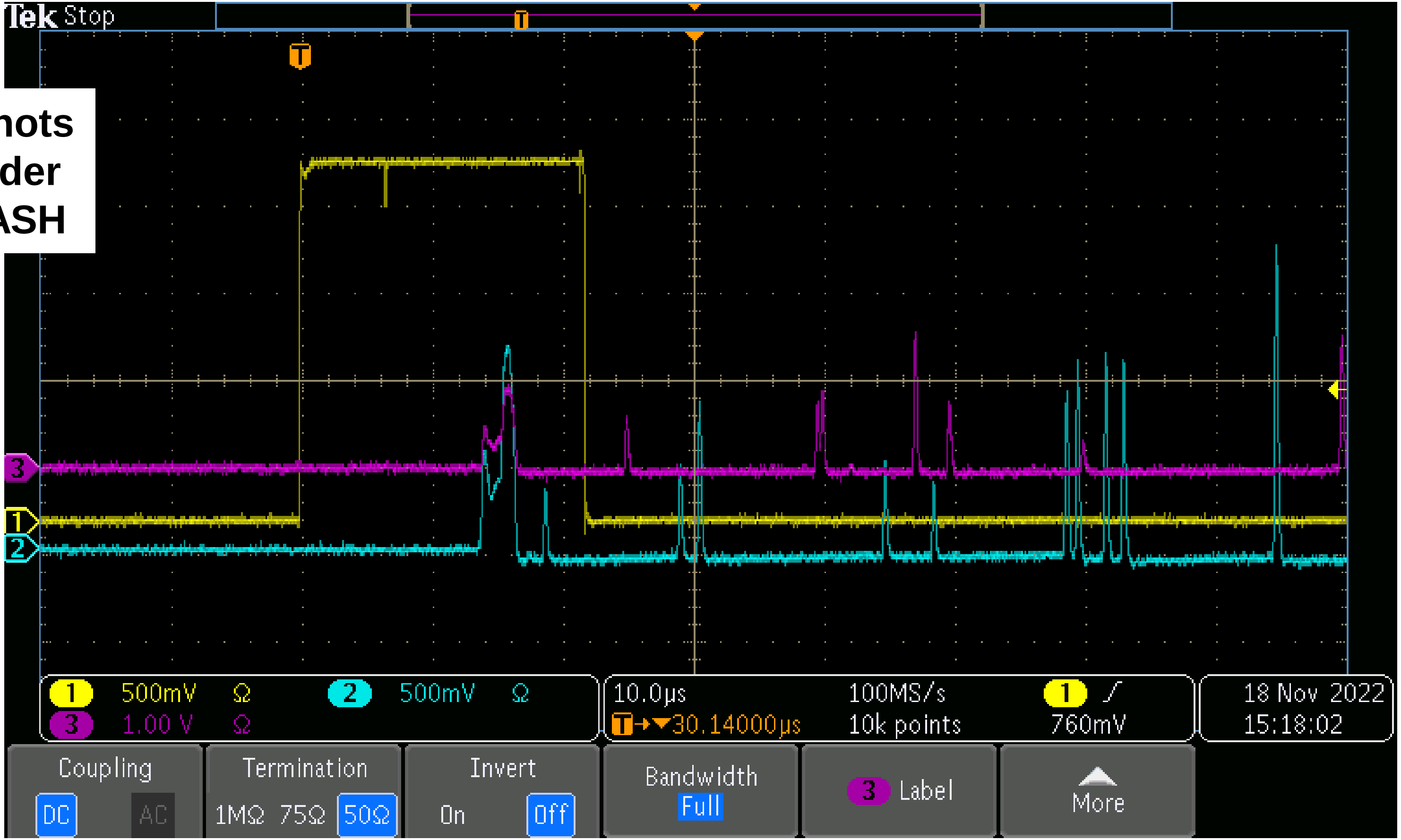


PTB: Time-resolved data

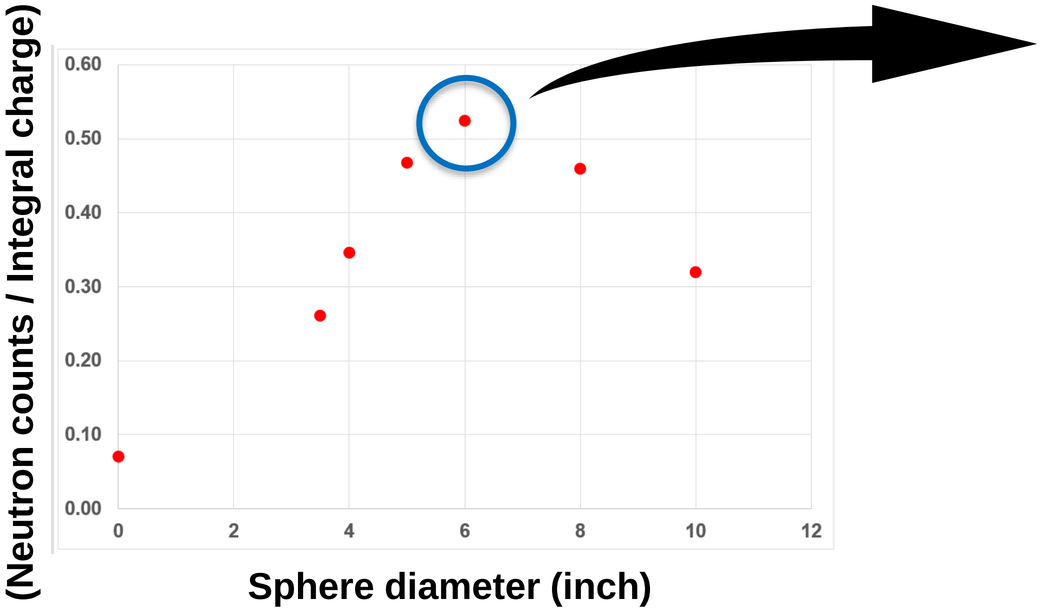
Screenshots taken under MAX FLASH

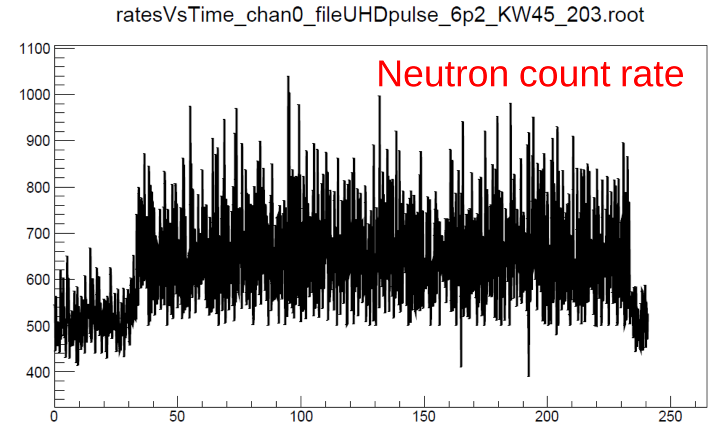
PTB: Time-resolved data

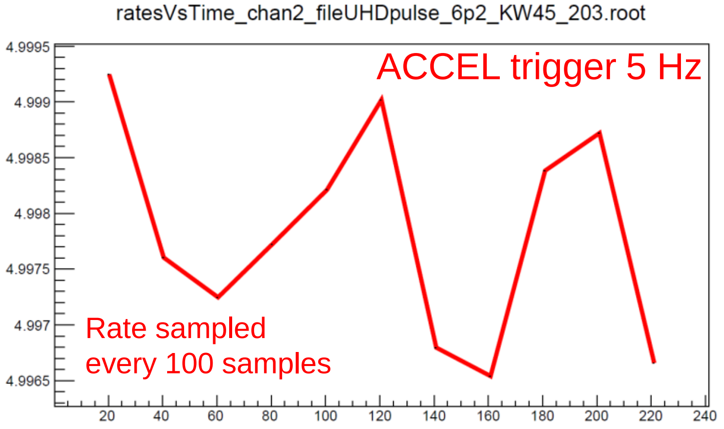
Screenshots taken under MAX FLASH



PTB: BSS in „minimal FLASH“

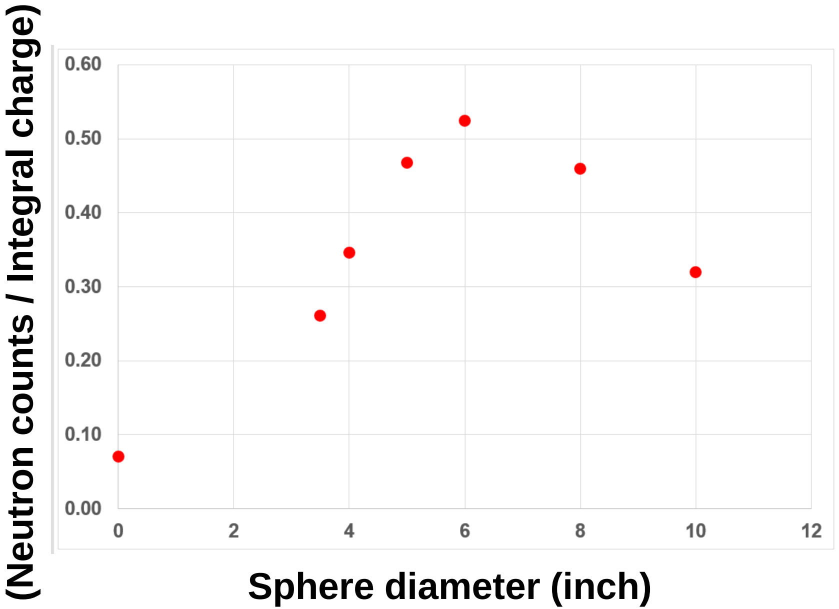


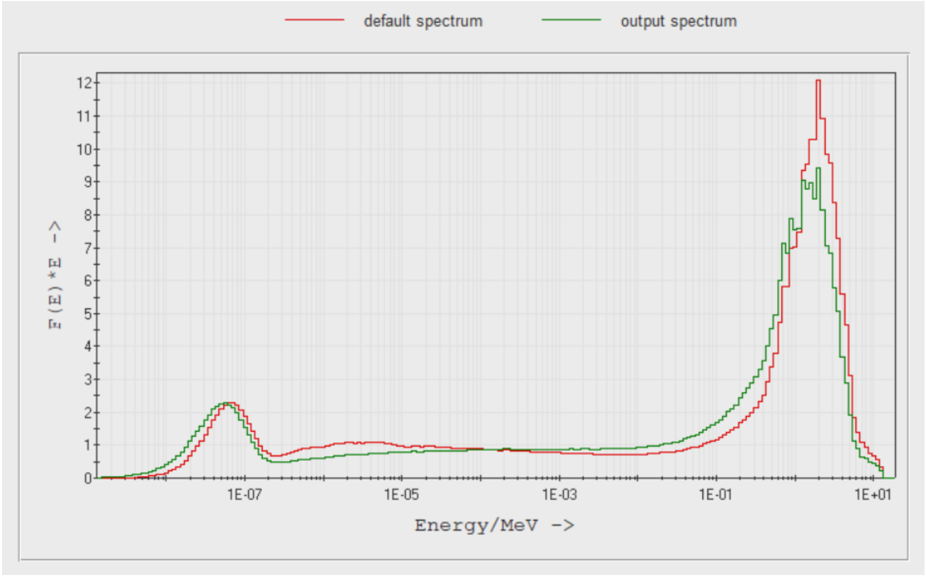




Meas. conditions:
„Minimal FLASH“ … energy slits 0.5, pulse width 84 %
Charge in 1 pulse ~ 45 nC (beam monitor)
Exp. dose for SSD70-00: ~2 Gy per pulse
Neutrons measured at 2.8 m from Pb target

PTB: BSS in „minimal FLASH“





Meas. conditions:
„Minimal FLASH“ … energy slits 0.5, pulse width 84 %
Charge in 1 pulse ~ 45 nC (beam monitor)
Exp. dose for SSD70-00: ~2 Gy per pulse
Neutrons measured at 2.8 m from Pb target

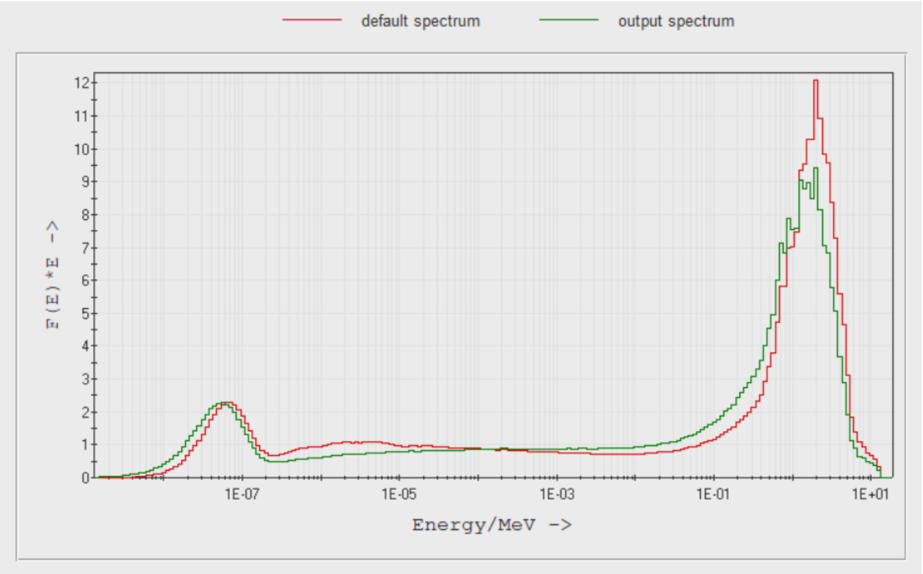
Neutron fluence @ 2.8 m: **36.2**
[cm^{-2} per 1 nC of integral charge]

Neutron dose *H**(10) @ 2.8 m: **0.0078**
[µSv per 1 nC of integral charge]

Comparison PTB-NPL

NPL @ 1.0 m distance in maximal FLASH:
Exp. dose for SSD70-00: ~11 Gy per pulse
Neutron fluence 5.31E+4 cm^{-2} per pulse
9000 pulses, mean charge 310.97 nC/pulse
➔ **171 cm^{-2} per 1 nC of integral charge**

Dose *H(10): 0.039 µSv per 1 nC of integral charge**

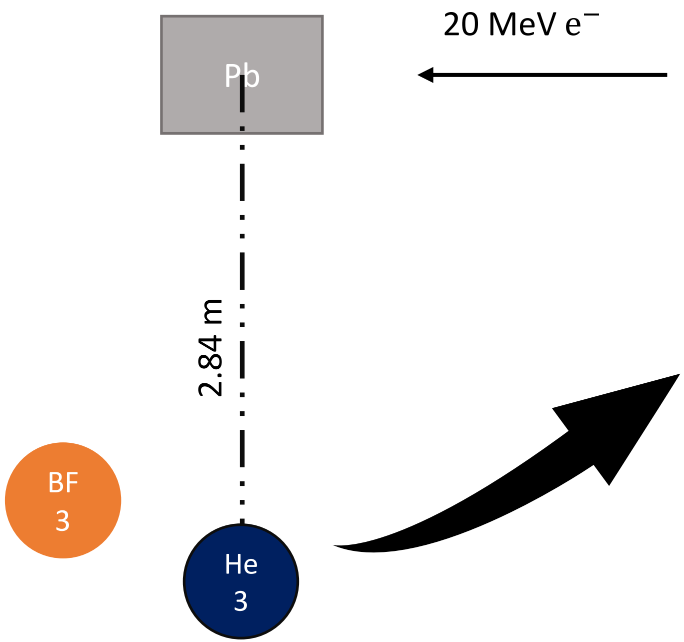


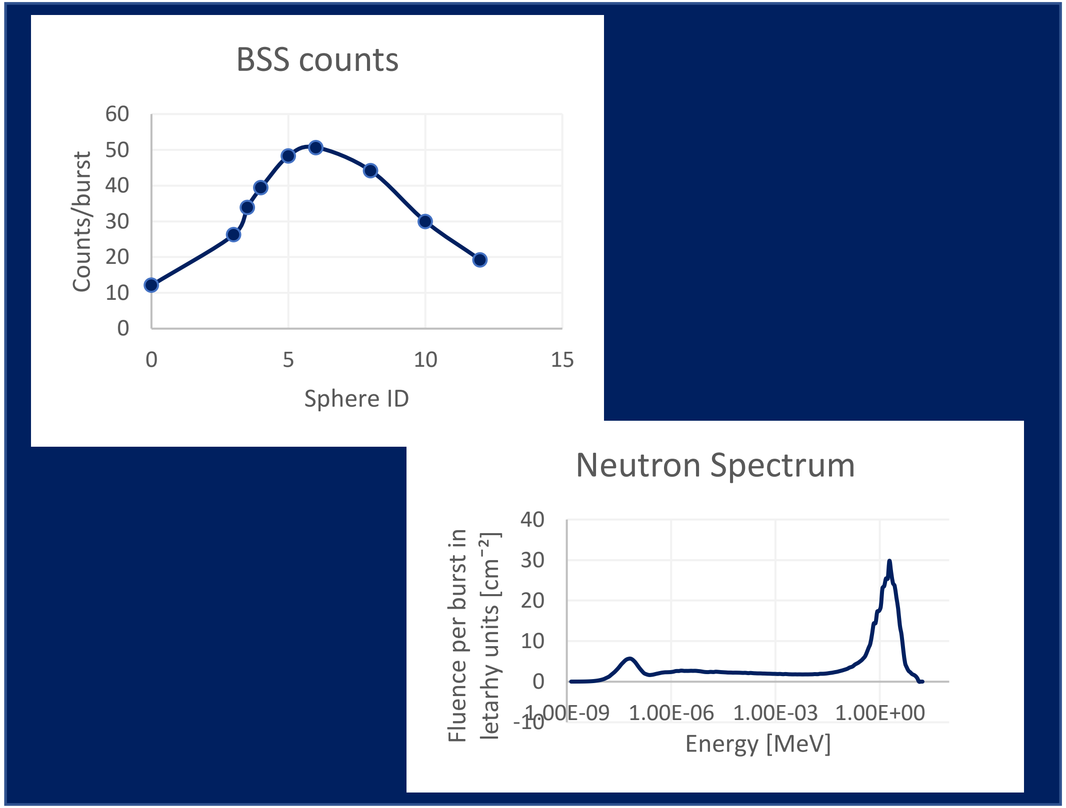
PTB @ 2.8 m distance in minimal FLASH:
Exp. dose for SSD70-00: ~2 Gy per pulse
Neutron fluence 36 cm^{-2} per 1 nC of integral charge
assuming $1/r^2$ dependence
& assuming FLASH regimes scaling via *Q* monitoring
➔ **283 cm^{-2} per 1 nC @ 1.0 m**

Dose *H(10): 0.061 µSv per 1 nC @ 1.0 m**

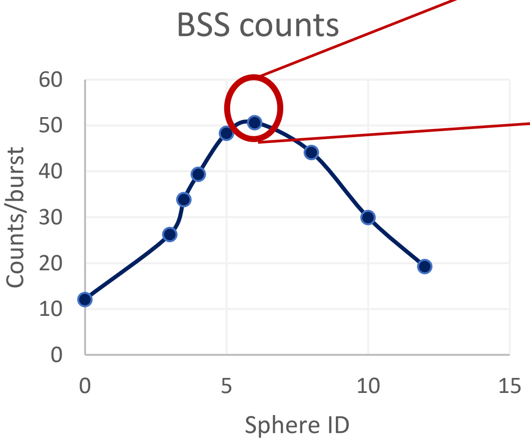
PRELIMINARY RESULTS

Irradiation at PTB research accelerator



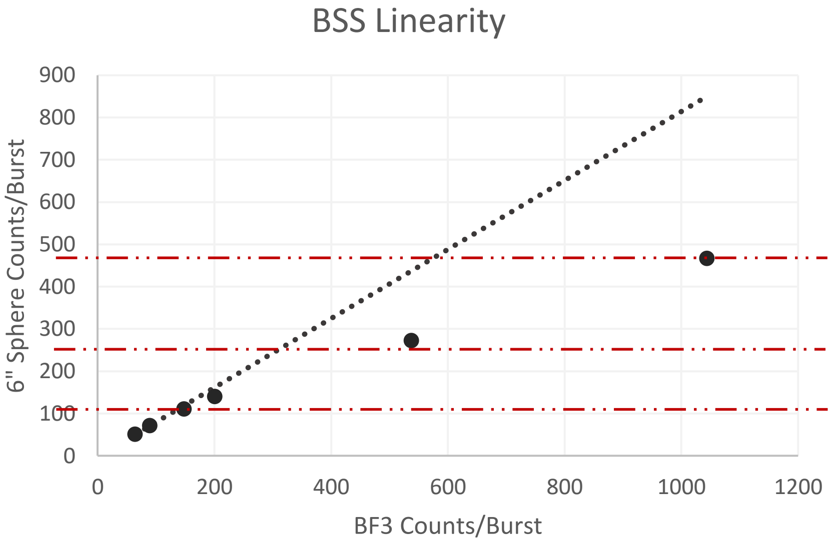


BSS linearity



The **linearity** of the most sensitive sphere was tested against the measurement of the BF3 (linear up to ~1000 counts/burst

LUPIN He3 limit (underestimation of 15% at **150 counts/burst**)



“Mid” flash regime

Beginning of flash regime

Acknowledgement

PTB 6.2 Dosimetry for Radiation Therapy and Diagnostic Radiology
A. Bourgouin, R.P. Kapsch, C. Makowski, M. Schrader, A. Schüller

PTB 6.4 Neutron Radiation
A. Di Chicco, M. Dommert, E. Eggenstein, U. Giesen, T. Klages, B. Lutz,
A. Lücke, R. Nolte, E. Pirovano, M. Reginatto, A. Zimbal

This project 18HLT04 UHDpulse has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

Department for Business, Energy & Industrial Strategy

FUNDED BY BEIS

The National Physical Laboratory is operated by NPL Management Ltd, a wholly-owned company of the Department for Business, Energy and Industrial Strategy (BEIS).