Neutron and gamma ray instrumentation for fusion plasmas and materials science

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Outline

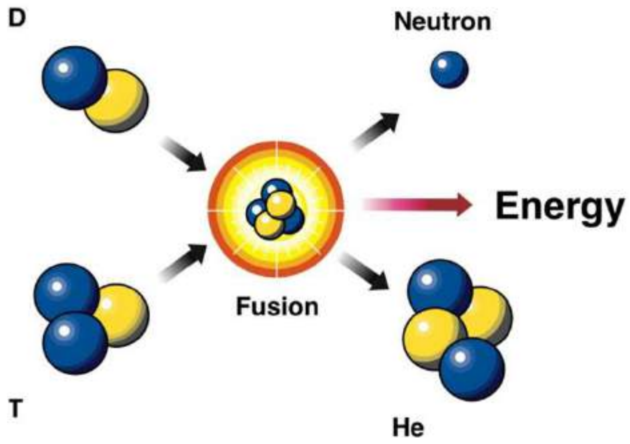
Instrumentation for neutron and gamma ray spectrometers of fusion plasmas

Neutron instrumentation development for ISIS

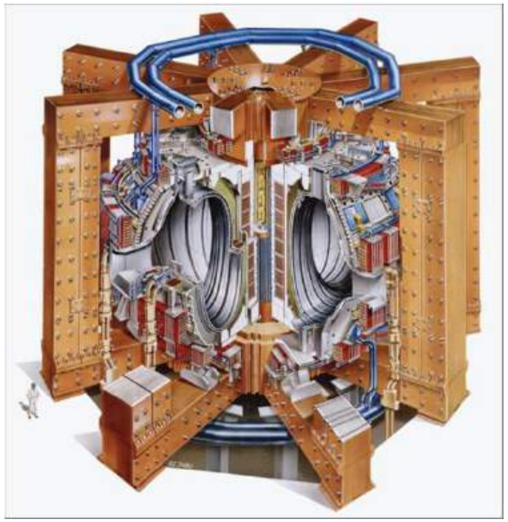
Development of GEM based thermal neutron detector for ESS

Fast ion measurements in a burning plasma

The energy distribution of fast ions needs to be known for reliable operation of a thermonuclear fusion reactor



$D + T \rightarrow \alpha + n + 17.6$ MeV



•α **particles** play a key role in the self sustainment of a fusion reactor

•**fast ion acceleration (NBI or RF)** needs to be assessed in in specific heating schemes to quantify efficiency of auxiliary heating (H, D, T, ^{3}He, ^{4}He accelerated ions)

•fast ions can drive MHD modes that may lead to their **redistribution and losses**

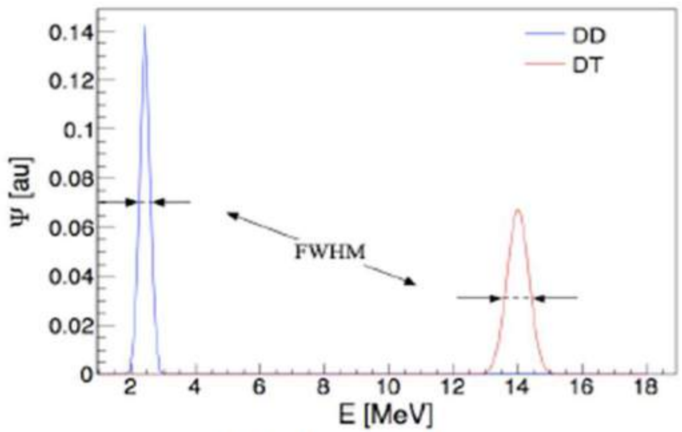
Neutron emission spectroscopy (NES)

In a plasma in thermal equilibrium, the particles are distributed according to a Maxwellian distribution Neutron spectrum is well approximated as a Gaussian centered at 2.45 MeV (or 14.0 MeV) and with FWHM (W)

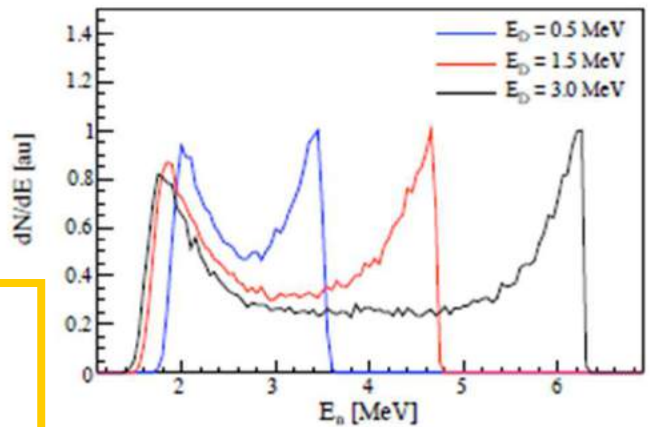
Ion Temperature T_i

$W = 82.5 \cdot \sqrt{T}$ for DD emission

$W = 177 \cdot \sqrt{T}$ for DT emission



σ(E)-spectra



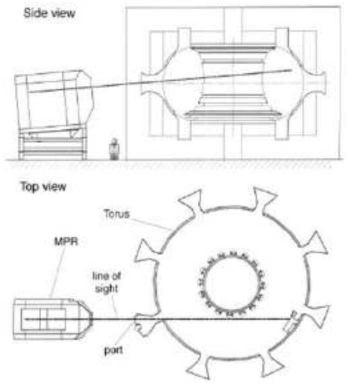
Fast fuel ions can be well diagnosed with NES due the enhanced reactivity

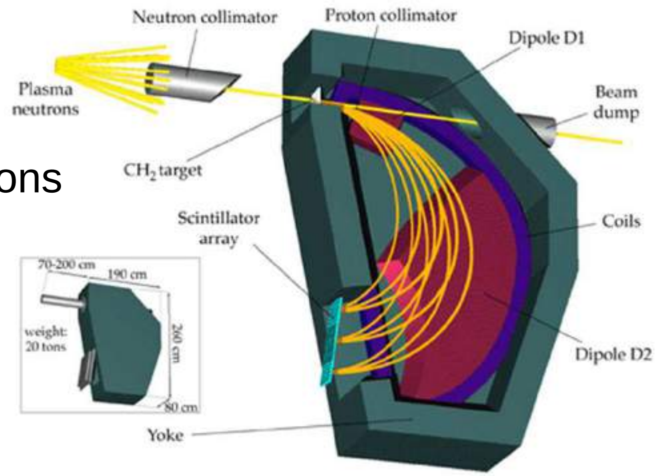
Need for dedicated spectrometers.
Energy resolution ($\Delta E_n/E_n$<5%)
Time resolution (count rate capability, >500 kHZ)

State of the art neutron spectrometers installed at JET (1994-2006)

Magnetic proton recoil

MPR for 14 MeV neutrons
MPRu also for 2.5 MeV neutrons
(DT plasmas)

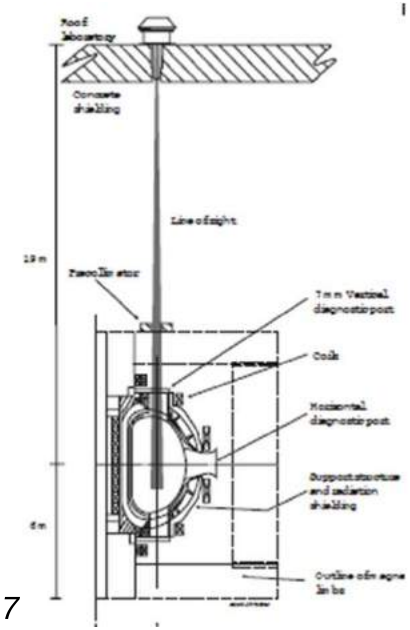




A. Sundén, at al, NIM A610 (2009)6
G. Ericsson, at al, RSI (2006);

Time of flight optimized rate

TOFOR for 2.5 MeV neutrons
(D plasmas)

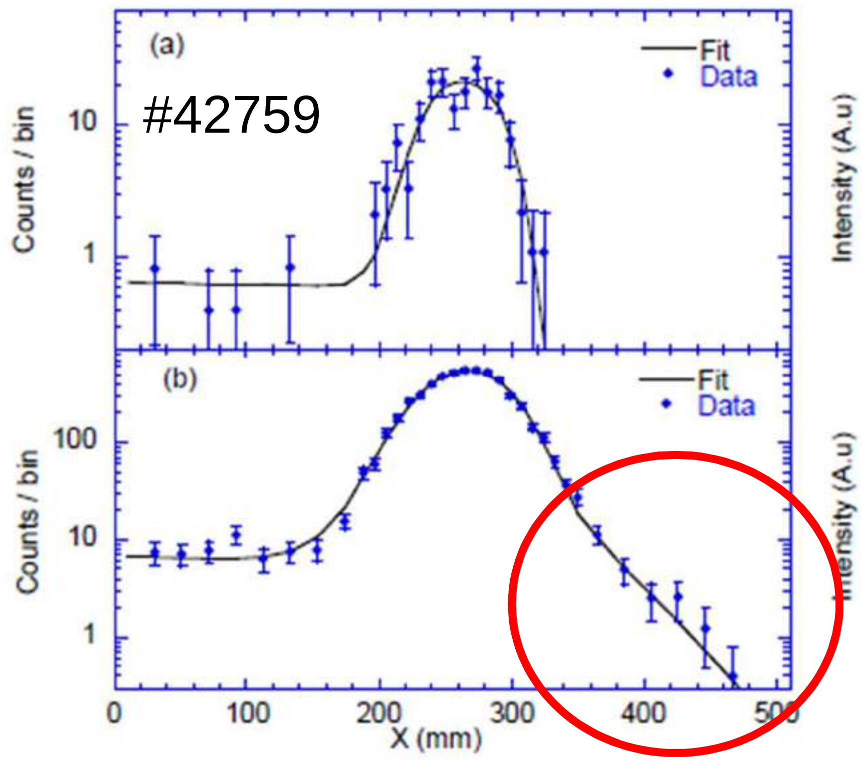


Collaboration between Uppsala University, UNIMIB and CNR

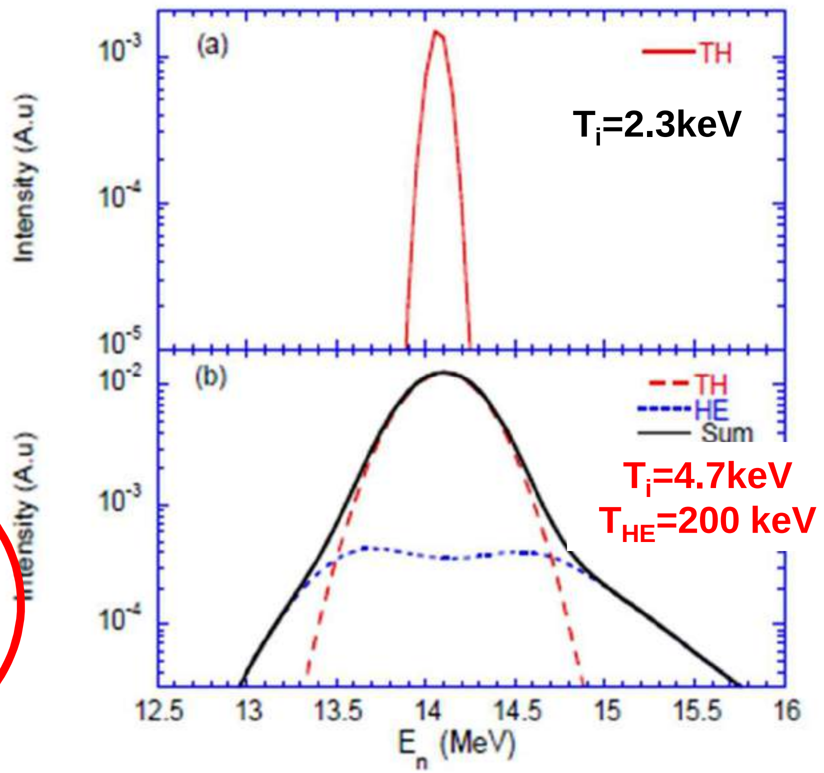
M. Gatu Johnson, NIM A591 (2008)417

NES results on DT plasmas

Ohmic and ICRH at $2\omega_{CD}$



Spectral components inferred from fit



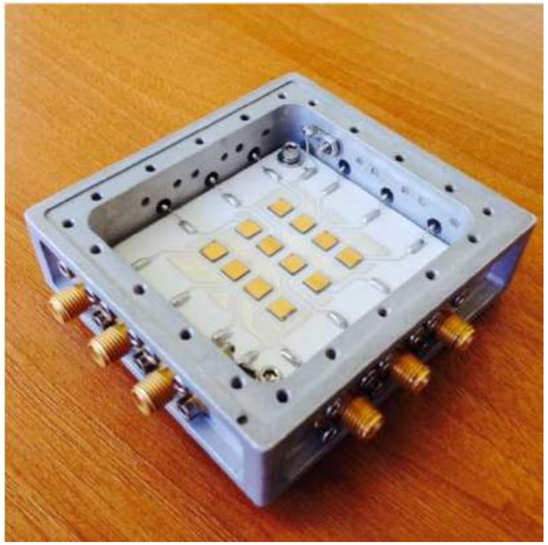
M.Tardocchi, PhD thesis,Uppsala (2000)

Measure high energy tail temperature of fast D

Model describes deuterium velocity distribution with an anisotropic "cut" Maxwellian
-thermal component for the main bulk ions.
-Tail temperature T_{HE} and pitch angle distributed as a Gaussian centred at 90° ±10°

***M. Tardocchi** et al, Nuclear Fusion 42 (2002) 1273.*

Matrix diamond neutron spectrometer for JET DT plasmas
VNS project (2012-today)



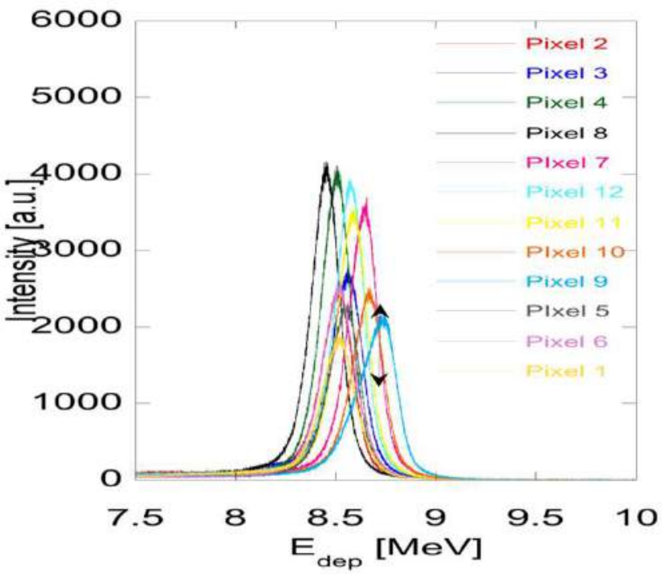
Collaboration with UNIMIB, ENEA, UPPSALA, JET

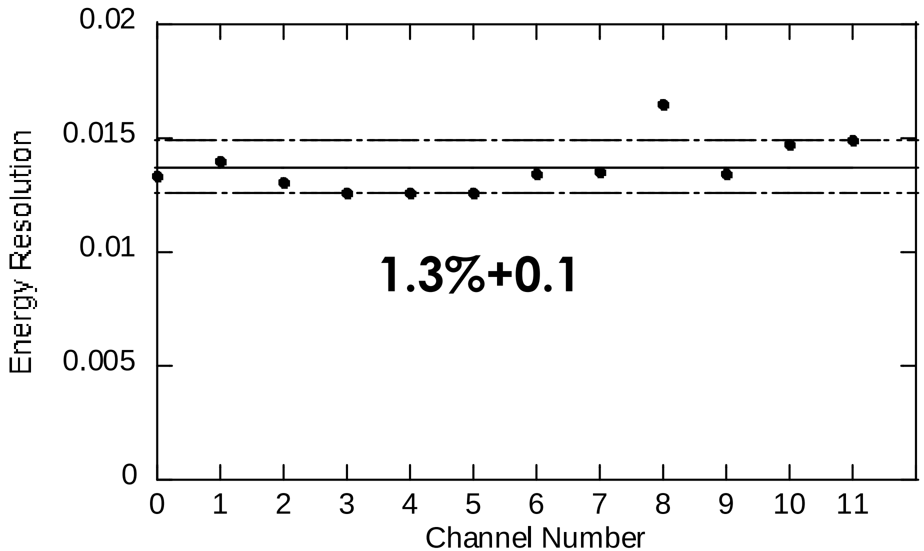
12 indipendent pixel, Detector produced by CNR

Single pixel dimension: 4.5x4.5x0.5 mm^3

Simultaneous measurement of **high energy resolution** (<1%@14 MeV) and **high count rate** capability (>1MHz) in a **compact** device

14 MeV neutrons measured at Frascati FNG





12 pixels response is very uniform!

Gamma-Ray Emission Spectroscopy (GRS)

Gamma are produced by nuclear reactions between fast ions and impurities present in the plasma

They can be produced in fusion reactions (I step reaction) or result from the de-excitation of a nucleus (II step reaction)

An important reaction for the diagnosis of fusion alpha particles in DT plasma is

$\alpha + {}^{9}Be \rightarrow {}^{12}C^{*} + n$, ${}^{12}C^{*} \rightarrow {}^{12}C + \gamma$ (4.44 MeV) (two step reaction)

In general Ions need to be **energetic** for significant γ-ray emission (E > 0.5 MeV typically)

From a high energy resolution measurement of the Doppler broadening of the gamma ray emission spectrum one can infer information on the fast ions responsible for the gamma ray emissions

Need for dedicated gamma ray spectrometers (high energy resolution, high count rate capaility, low neutron damage resistance)

Gamma Ray Spectroscopy (GRS) JET project 2006-2011

Milan UNIMIB-CNR team has coordinated the JET-EP2 **GRS** project on upgrade of the gamma ray spectrometers KM6S and KM6G

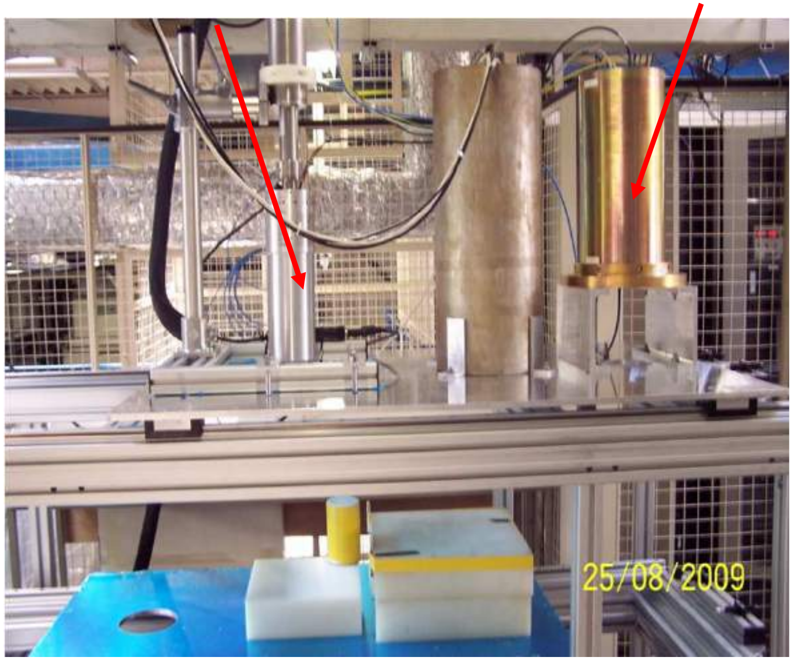
The GRS project was successfully carried out within a consortium (IST Portugal, MEdC Rumenia, CCFE United Kingdom)

New spectrometers for **high energy resolution** and **high rate** operation based on LaBr3 scintillators have been developed.

Doppler Broadening measurements of gamma ray spectra can provide unique information on fast ion in the plasmas (e.g. He4 or He3 ions)

HpGe:very high energy resolution (0.15%@1.3MeV)

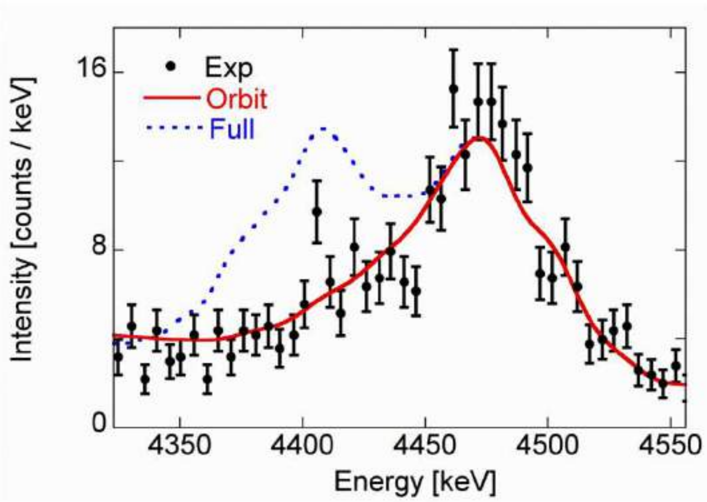
$LaBr_3$: high rate (MHz) at high energy resolution (2%@1.3MeV)

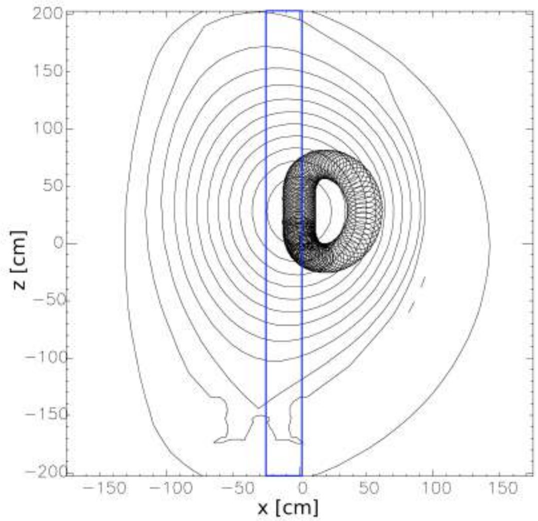


n,gamma

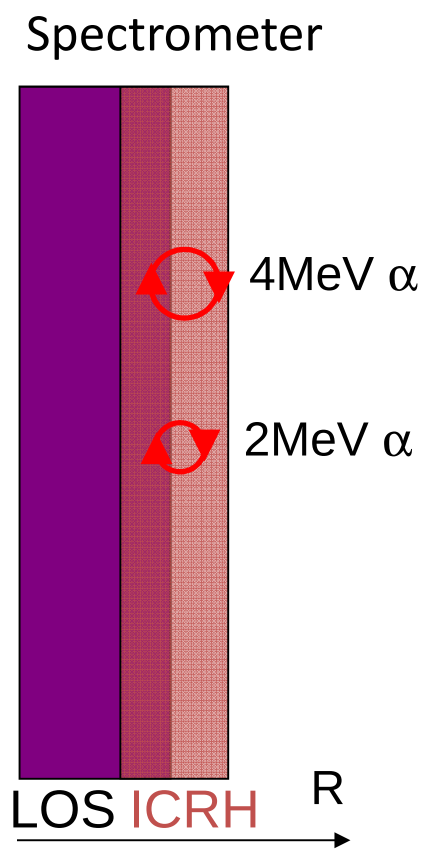
M. Tardocchi et al., Phys. Rev. Lett. 107 205002
M. Nocente et al., Nucl. Fus 52 (2012) 063009

The GRS peak shape changes with E*

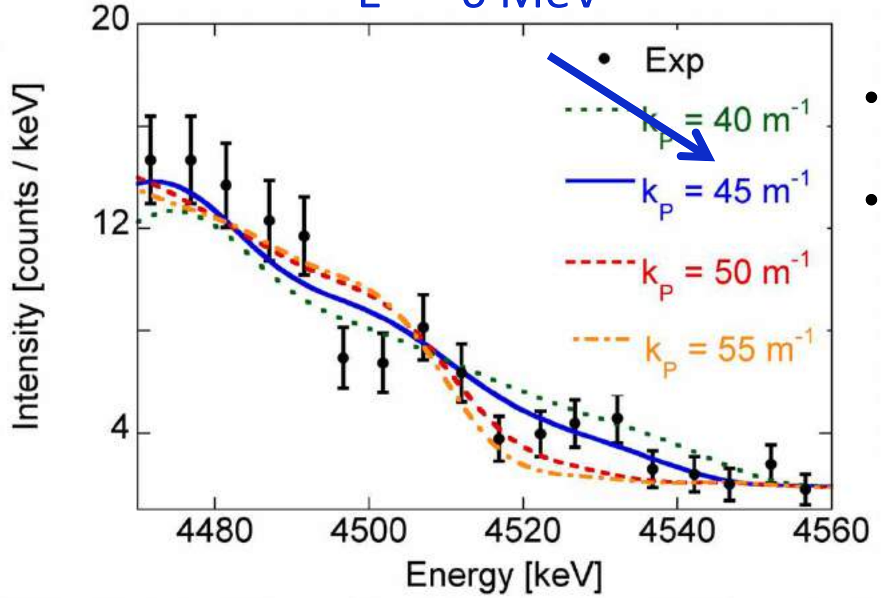




E_α = 3 MeV



E* = 6 MeV



- Shape **does change** with E*
- Limited by **statistics**

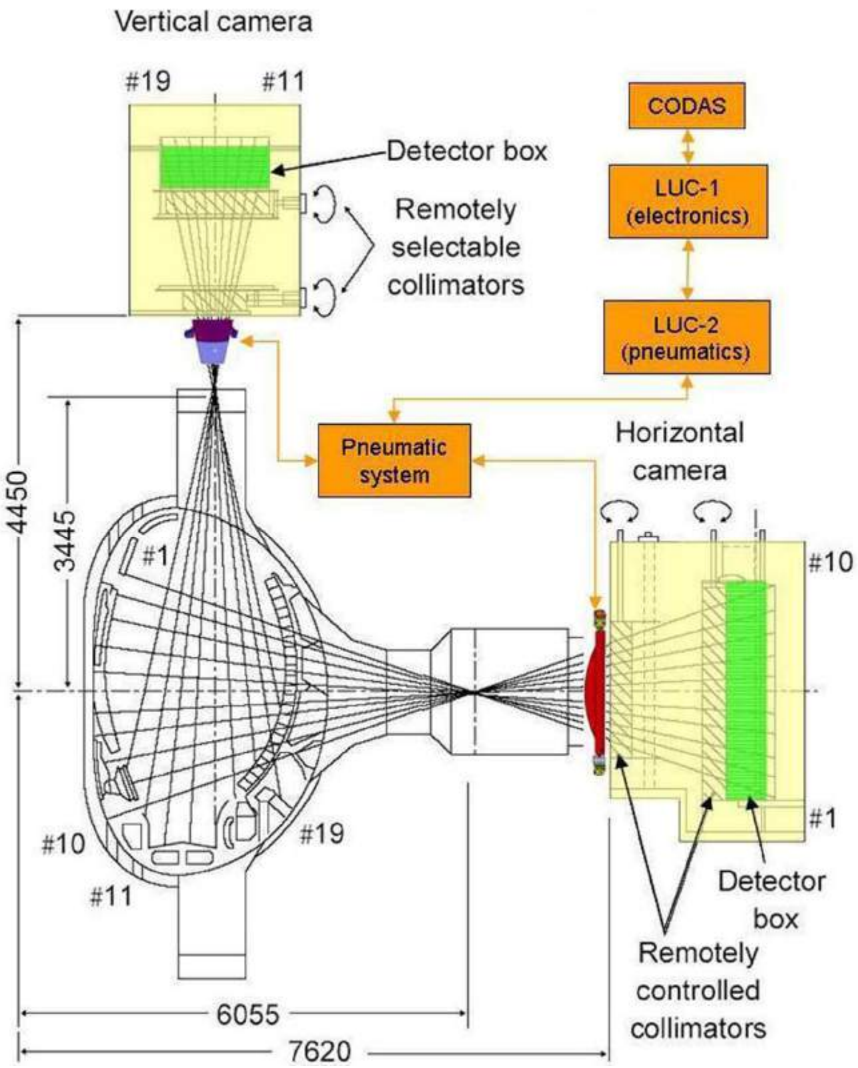
k_p in agreement with values found from analysis of peaks from $^{12}C(d,p\gamma)^{13}C$

M. Tardocchi, M. Nocente et al., proceeding of EPS conference, Dublin, June 2010

M. Nocente et al, Nuclear Fusion 52 (2012)063009

Gamma Ray Camera Upgrade (GCU) 2014-2017

- Two cameras
- Vertical: 9 lines-of-sight
- **Horizontal: 10 lines-of-sight**



Collaboration: Milan, Poland, Portugal, Slovenia, Austria, Uppsala, JET
Coordinated by Milan

upgrade for DT operation

Add **spectroscopic** capability to the existing gamma-ray camera

High Rate operation to be compatible with operation in high flux DT campaign

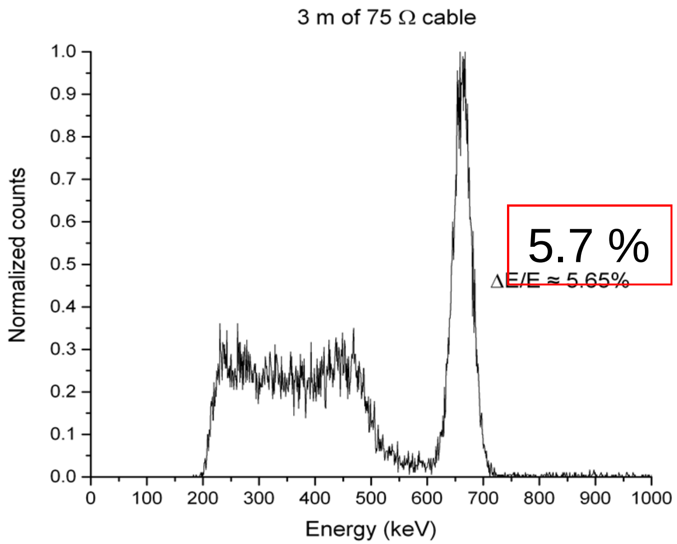
Target values: 5% FWHM at 1.1 MeV and Cn>500kHz

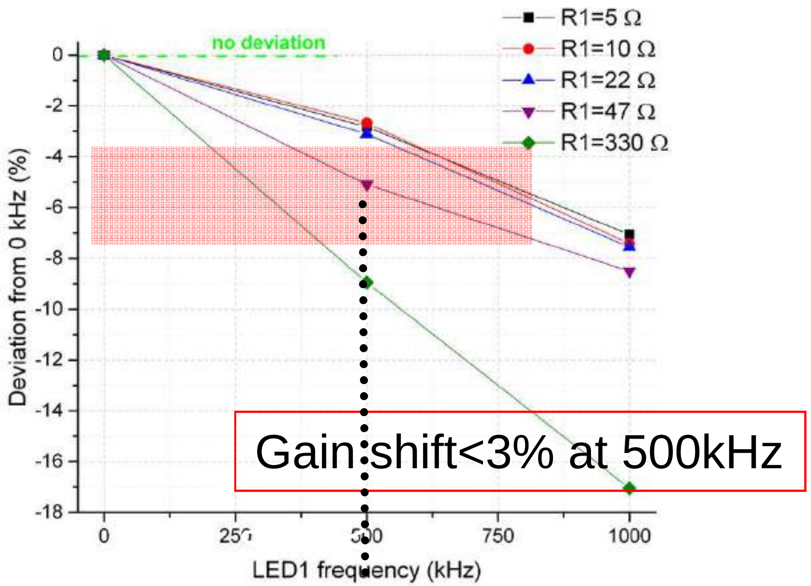
Development of compact gamma ray spectrometers based on LaB3 or CeBr3 coupled to SiPM

Development of a compact Labr3+SIPM gamma spectrometer

Prototype detector based on MPPC+Fast base+LaBr3 crystal

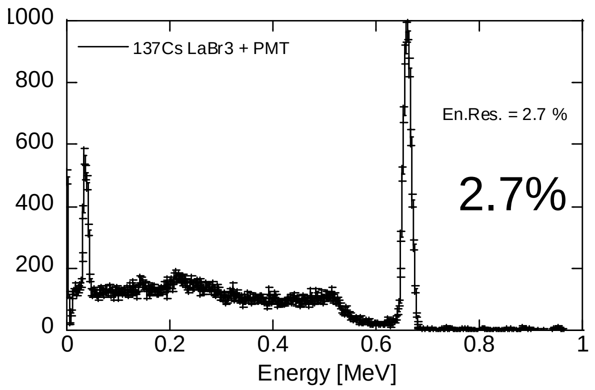
Optimized base that combine **good energy resolution** (5-6%@667keV) with **high counting rate** capability (>500 kHz)

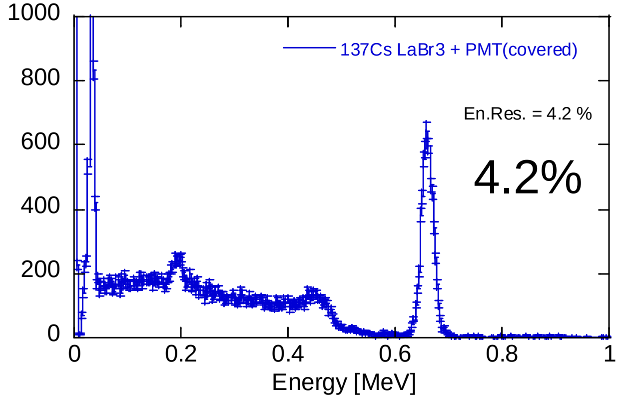


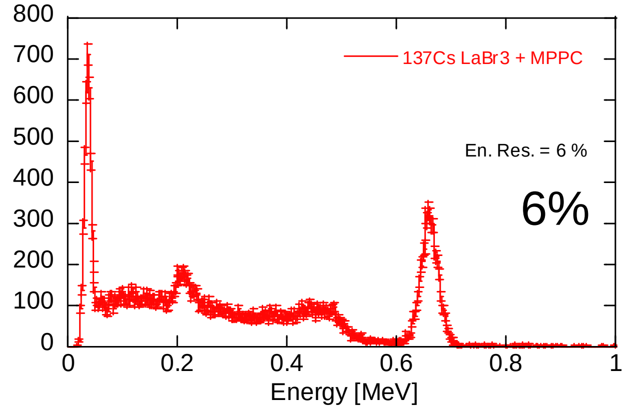


Fast inorganic crystals (Labr3, YAP) coupled to SIPM

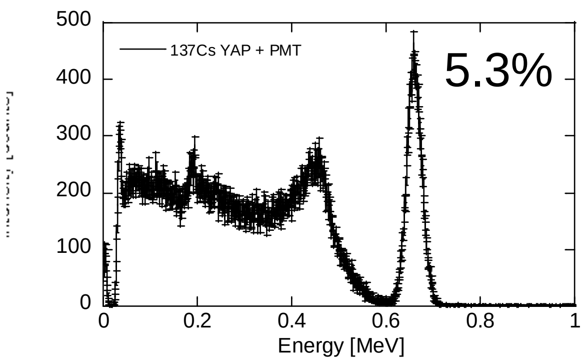
LaBr3 coupled to PMT aand SIPM

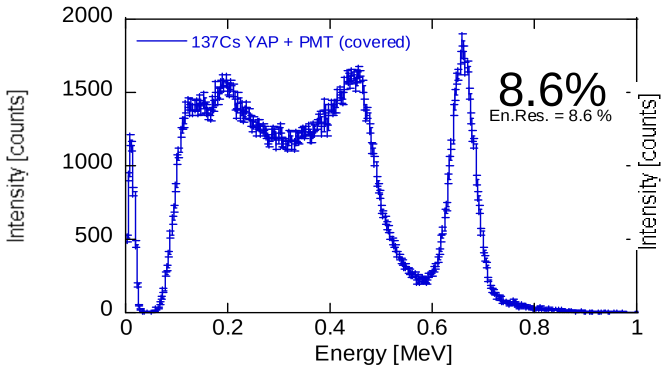


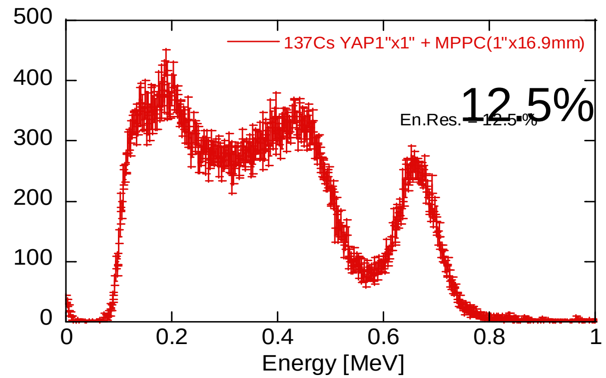




YAP coupled to PMT aand SIPM







Radial Neutron and Gamma ray Camera of ITER 2014-2017

F4E project, Consortium ENEA, CNR, UNIMIB, Portugal, Poland

Milan is responsible for the gamma ray camera

ITER diagnostic to be installed in Equatorial port #1 with the main function of measuring the **neutron spatial emissivity.**

Gamma ray spectrometers for diagnosing alpha particles via measurements of the 4.5 MeV gamma ray emission form the reaction $\alpha(^9Be,^{12}C)\gamma$

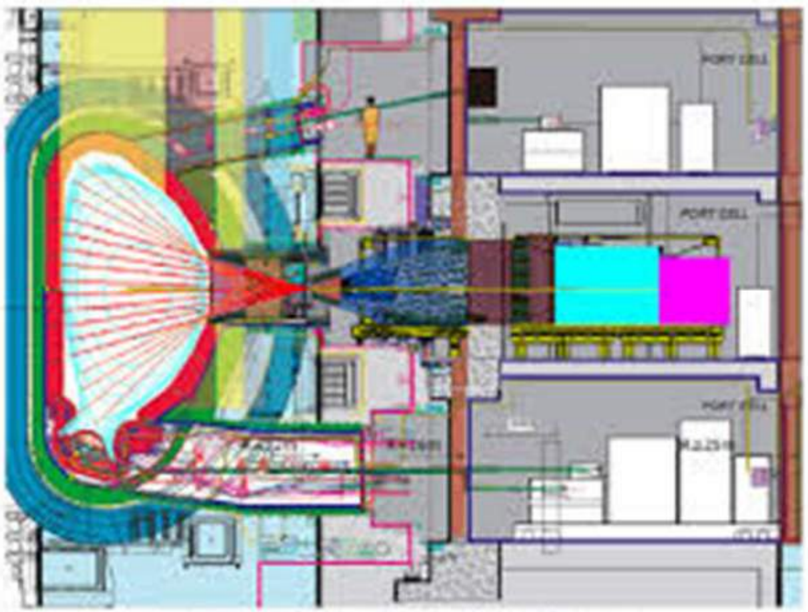
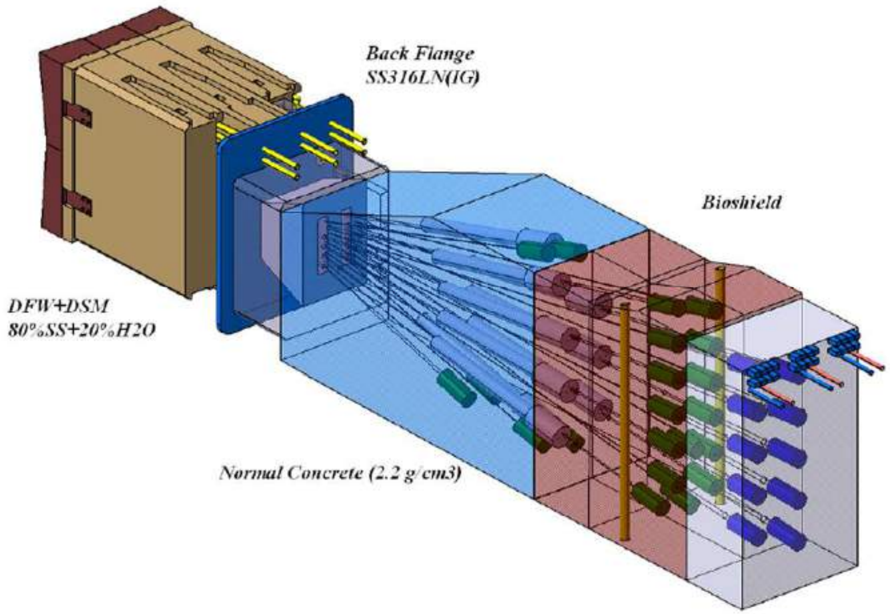
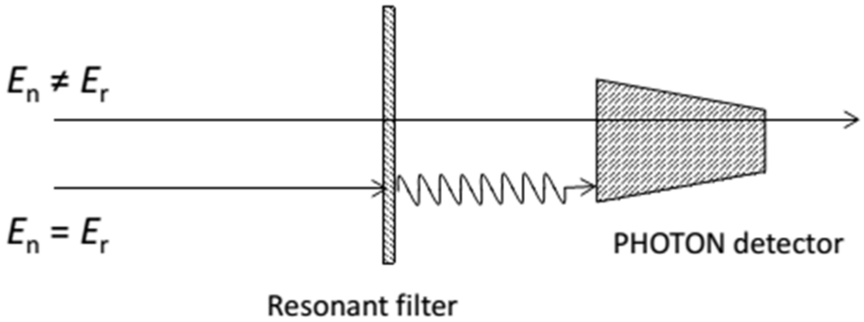


Figure 1.1 RNC locations in the Tokamak Building

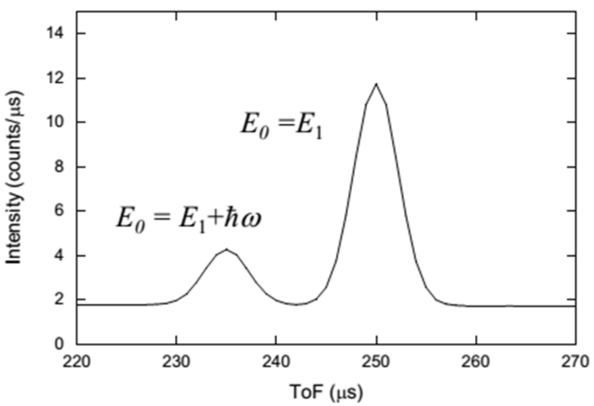


TECHNI and e.VERDI projects 2000-2005

Collaboration between UNIMIB-TorVergata-CNR-ISIS
Coordinated in Milan
Development of a new detector for eVS-VESUVIO (ISIS) based on the *Resonant Detector* (RD)
Epithermal neutron spectroscopy (1 eV< En<1 keV)



Detection of epithermal neutrons necessary for Deep Inelastic Neutron Scattering (DINS) and High-energy Inelastic Neutron Scattering (HINS)

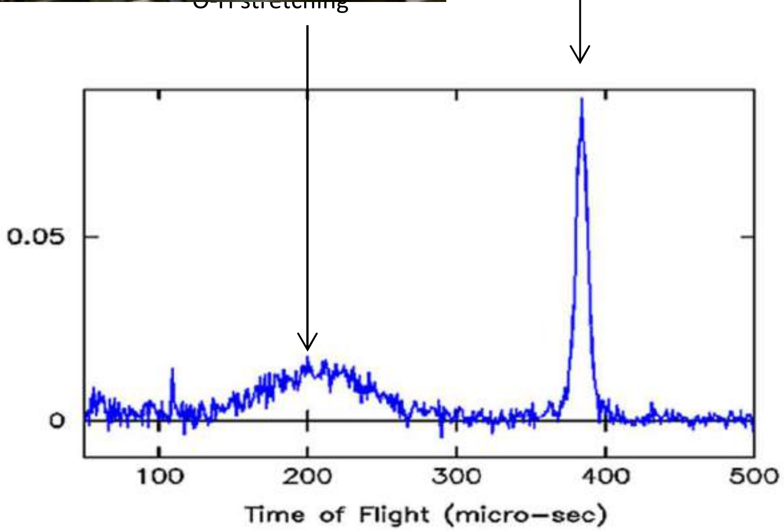


Extending the accessible (*q*, ω) range of INS for the study of high-energy (some eV) interactions in semiconductors and crystals, study of single-particle energy states, momentun distribution etc.

TECHNI and e.VERDI projects 2000-2005

Final configuration (YAP scintillators + gold (or uranium) monochromators chosen for VESUVIO update and low-angle bank.

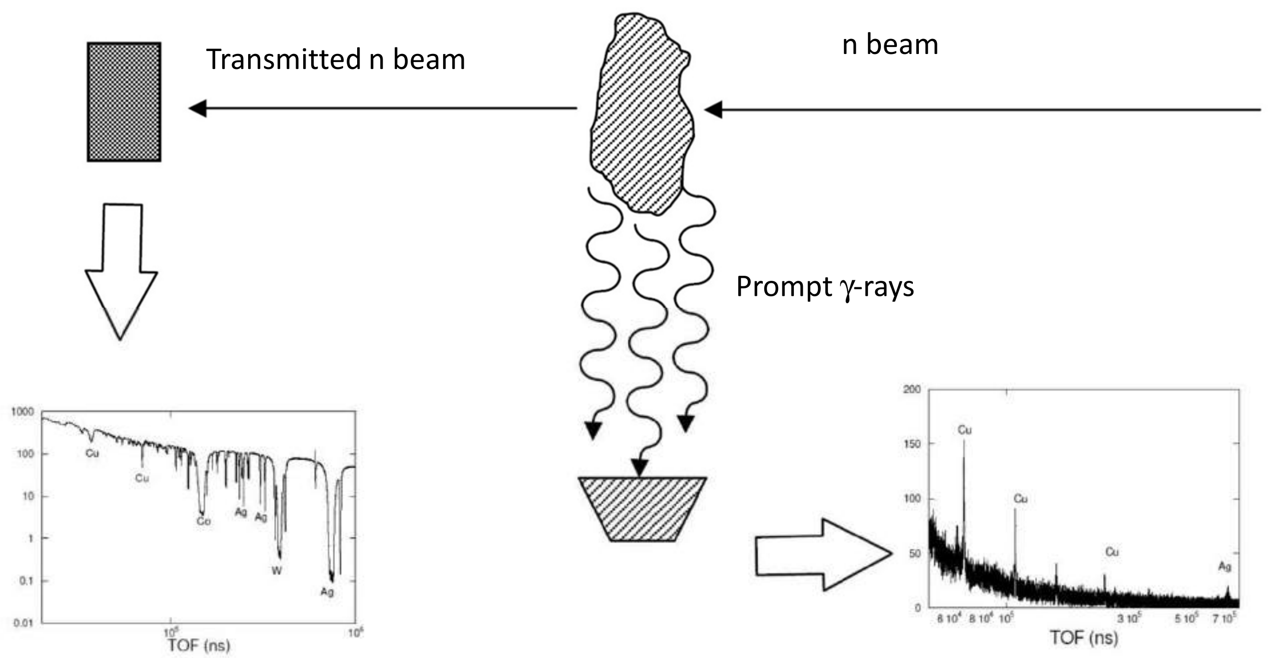
High-energy molecular dynamics (O-H stretching band in ice and water confined in microporous media) studied with DINS and HINS



ANCIENT CHARM project 2006-2009

10 European Partners, coordinated by UNIMIB, 2 Meuro

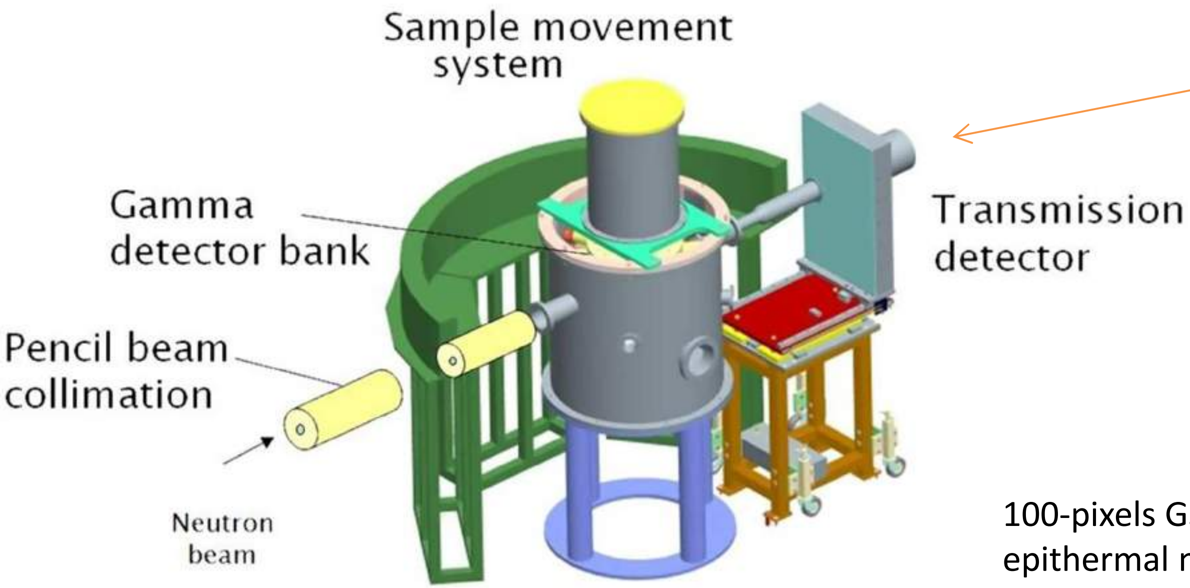
Development of neutron imaging for studies of cultural object.
Neutron Resonance Capture Analysis (NRCA) and *Neutron Resonance Transmission* (NRT) at ISIS and other neutron sources

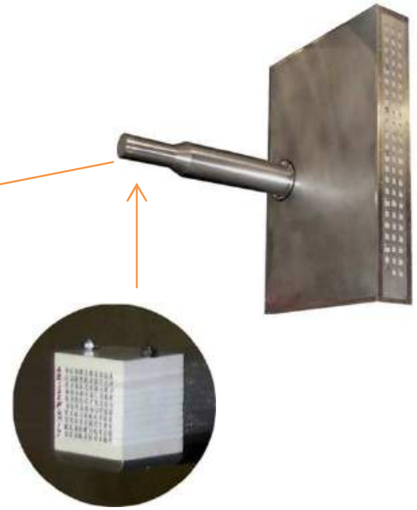


Neutron absorption resonances in the epithermal range can be used for identification and quantification of atoms and isotopes in massive samples, with the added bonus of non-destructivity

NRCA and NRT are the ideal complement of ND, XRF, XRD

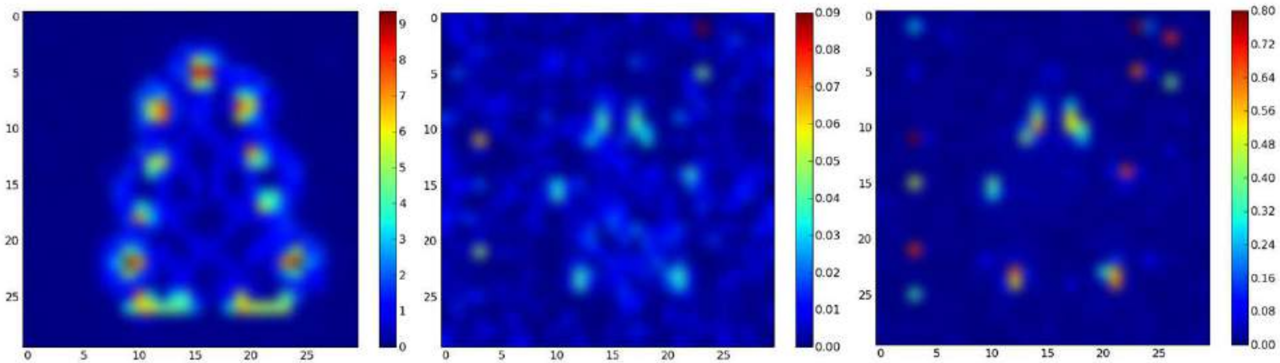
ANCIENT CHARM project 2005-2009





100-pixels GS20 Li-glass detector with high efficiency to epithermal neutrons installed at the INES beamline at ISIS

Element-sensitive radiography of an ancient artifact



Ag (16 eV)

Cu (230 eV)

Zn (514 eV)

PANAREA 2007-today

In kind contribution of ITALY to ISIS spallation neutron sources 0.8Meuro/year

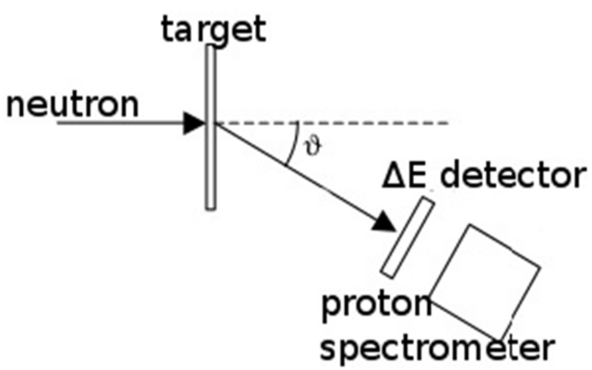
Coordinated by CNR (Giuseppe Gorini)

Construction of the beamline **ChipIr** and **IMAT** on the Target Station 2

Chipir: development of flux monitors and spectrometers for fast neutrons (GEM, diamond detectors, Telescope Proton Recoil TPR)

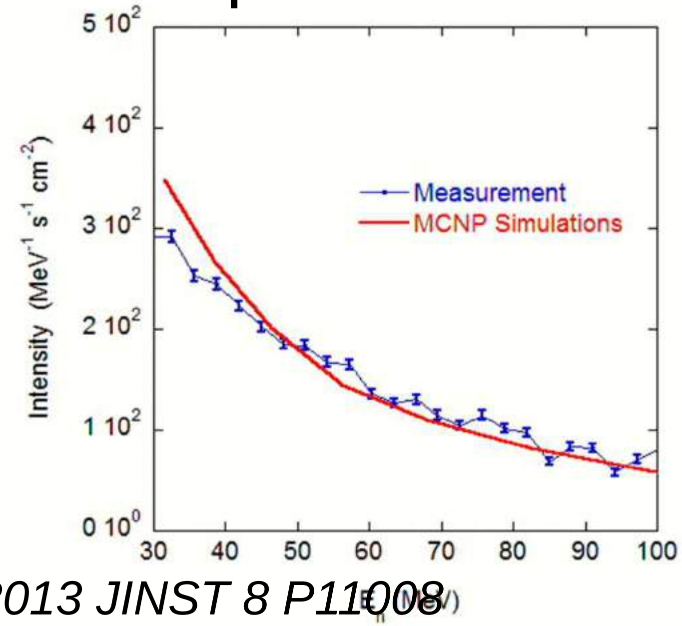
IMAT: imaging with camera for thermal neutrons *CNR-IPCF Messina)

TPR



$$E_p = E_n \cos^2\theta$$

First Measurement of fast neutron spectrum of VESUVIO



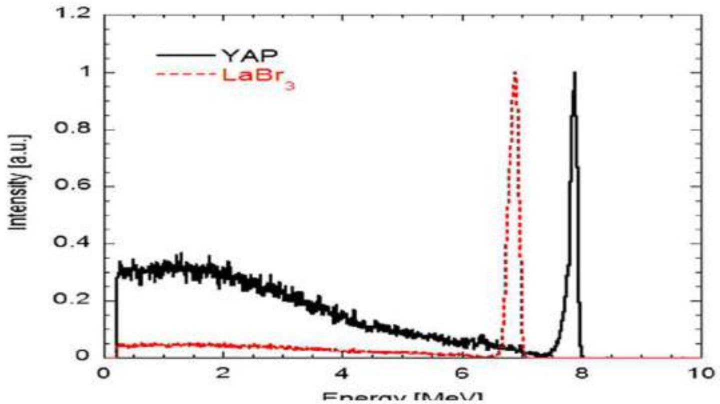
C.Cazzaniga et al, 2013 JINST 8 P11008

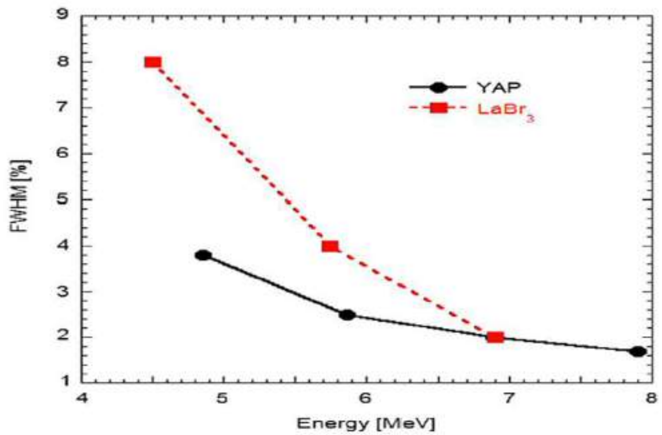
YAP scintillator as TPR proton spectrometer

YAP scintillator is mainly used as X-rays and gamma-rays photon detectors and features a low sensitivity to neutrons

We have measured at LEGNARO tandem accelerator the response of YAP crystals to monoenergetic protons of energies in the range 3-25 MeV

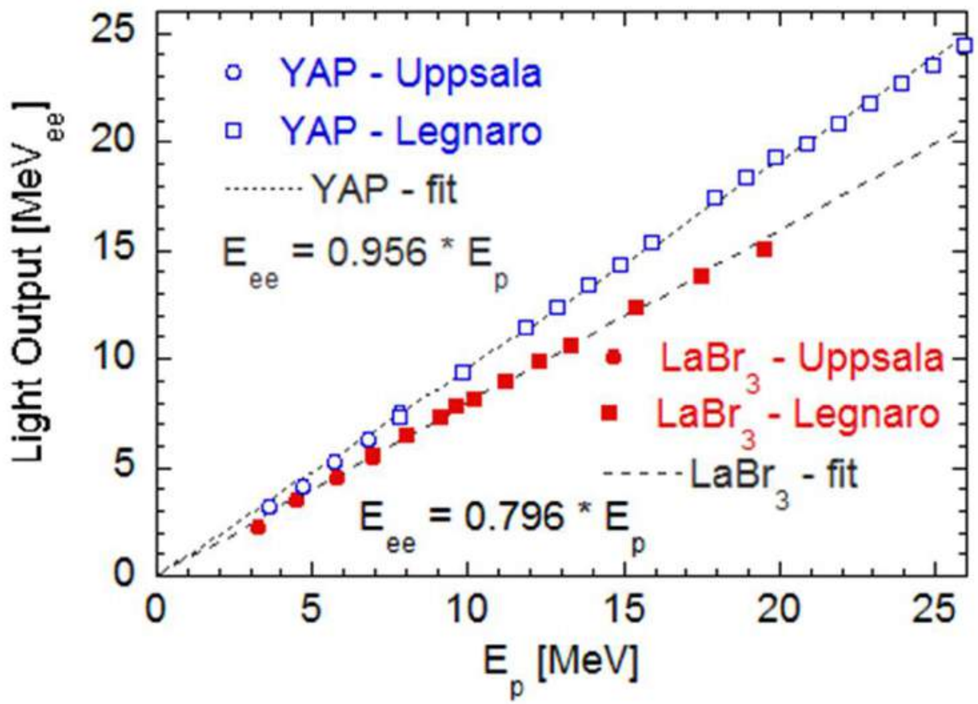
Very good energy resolutions





C. Cazzaniga et al., NIMA, 751 (2014)19

Very good light yield to protons α/β~1

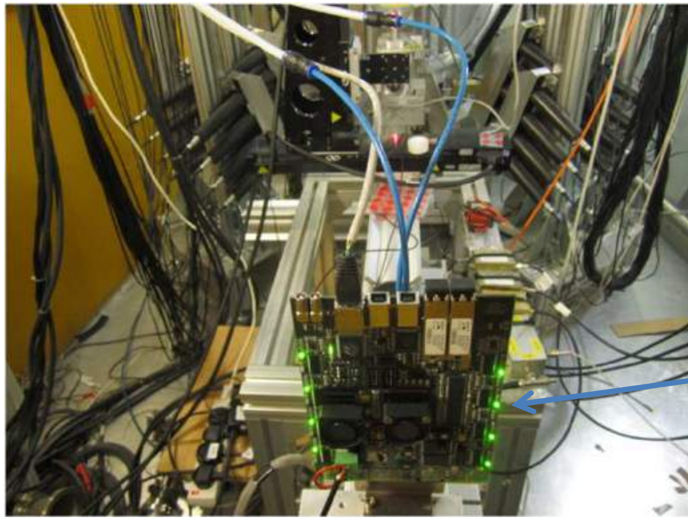


"Light response of YAP:Ce and $LaBr_3$:Ce scintillators to 4-30 MeV protons for applications to Telescope Proton Recoil Neutron Spectrometers", C. Cazzaniga et al., submitted to NIMA

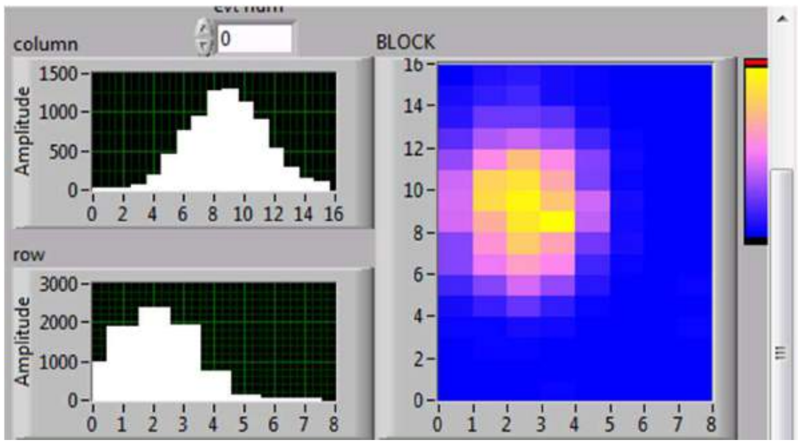
Real-time 2D beam map measurements on VESUVIO

Monitor for a fast neutron beam with energies ranging from a few meV to 800 MeV

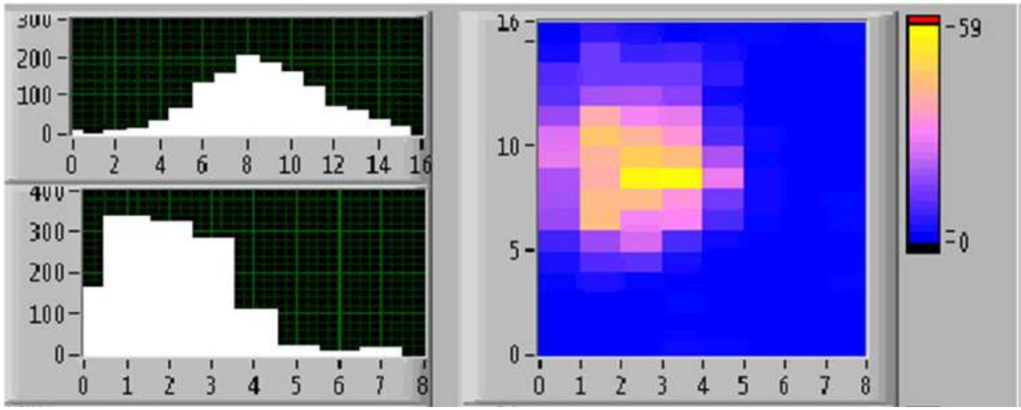
Tested at neutron beam of the Vesuvio facility at RAL-ISIS



nGEM-S-2



2D Beam profiles and intensity in real time



Neutron beam monitorig during the shutter opening

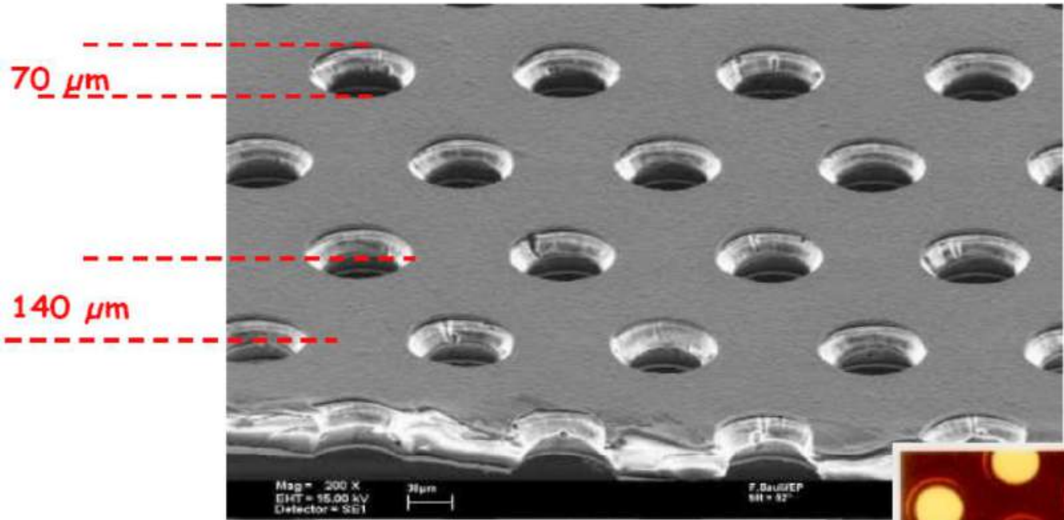
Istituto
di Fisica del Plasma
"Piero Caldirola"
Consiglio Nazionale delle Ricerche

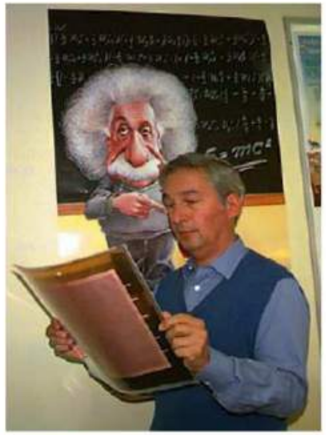
UNIVERSITA' DEGLI STUDI DI MILANO
BICOCCA

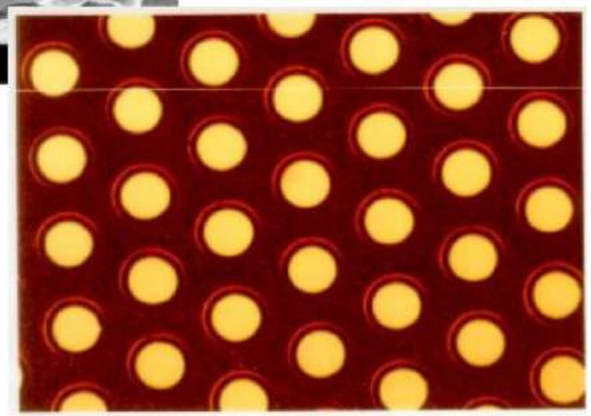
GEM detectors for fast and thermal neutrons

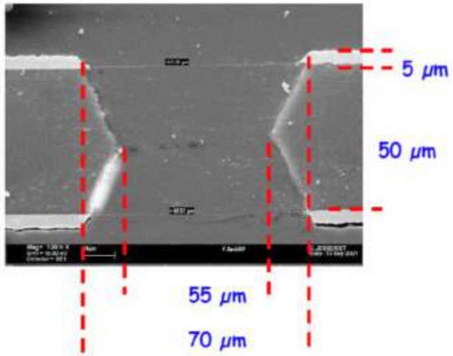
Gas Electron Multiplier

Thin metal-coated polymer foil pierced by a high density of holes (50-100/mm^2).
Typical geometry 5µm Cu on 50µm Kapton, 70µm holes at 140 µm pitch









GEM hole cross section

CNR/UNIMIB/INFN collaboration on GEM detectors

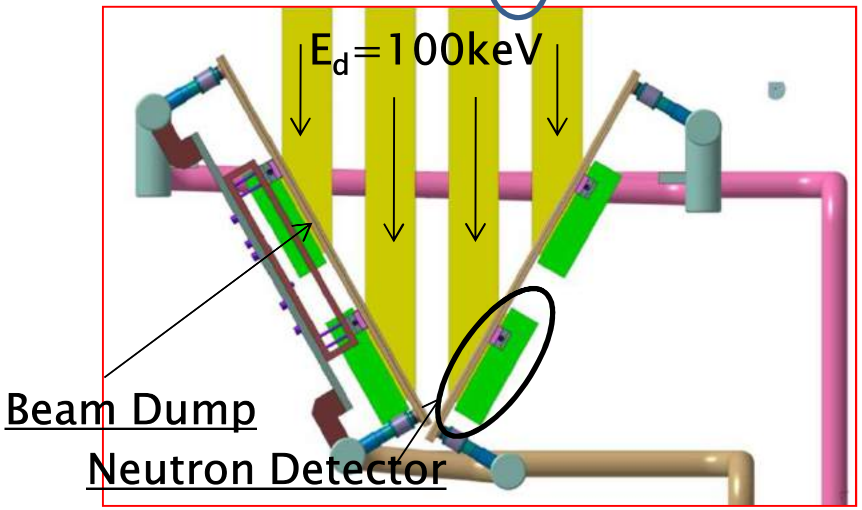
Major leading projects

- CNSEM diagnostic for SPIDER/MITICA (ITER NBI Prototypes)
- Beam monitors for ChipIR beamine at ISIS
- BANDGEM detectors for ESS/LOKI

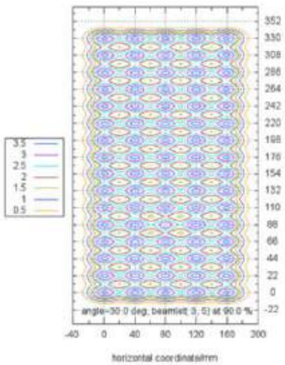
CNESM Diagnostic at SPIDER

Close Contact Neutron Emission Surface Mapping

$$d + d \rightarrow He^3 + n + 3.27\,MeV$$



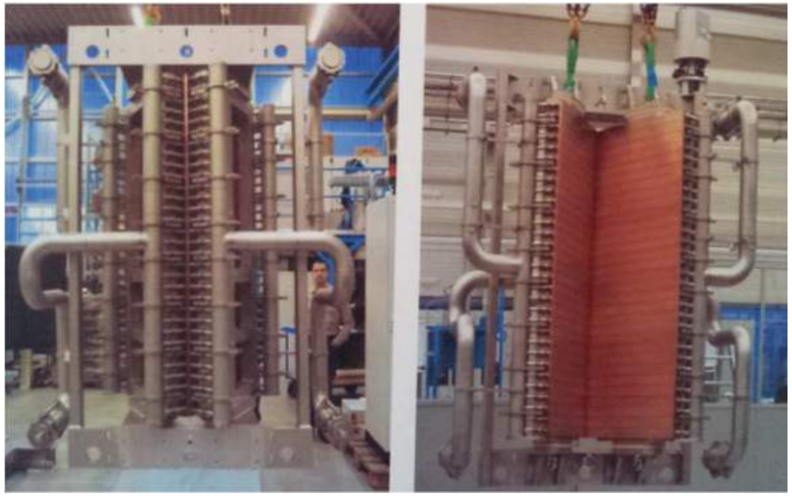
Deuterium Beam composition: 5x16 beamlets



Aim: Reconstruct Deuterium beam profile from neutron beam profile. Angular resolution and directionality property needed

Installation: Winter 2016

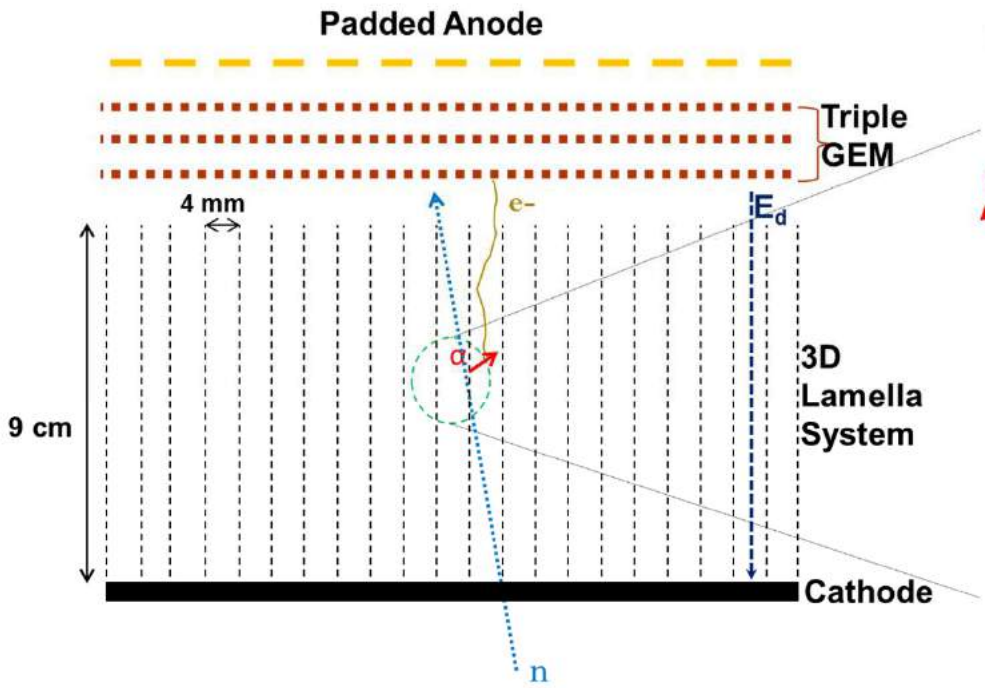
SPIDER Beam Dump

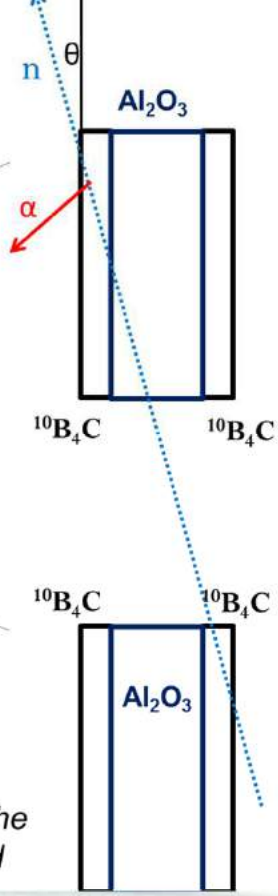


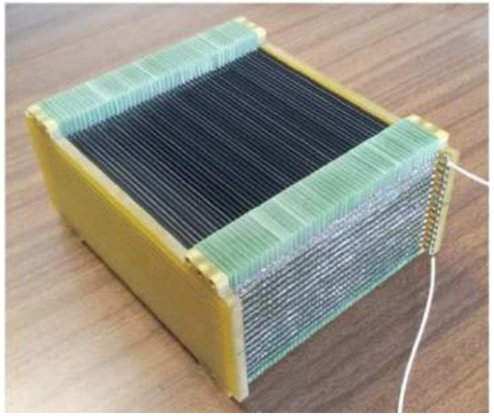
Detector Module to be installed

Boron Array Neutron Detector (BANDGEM)

For thermal neutrons; alternative to He3 detectors

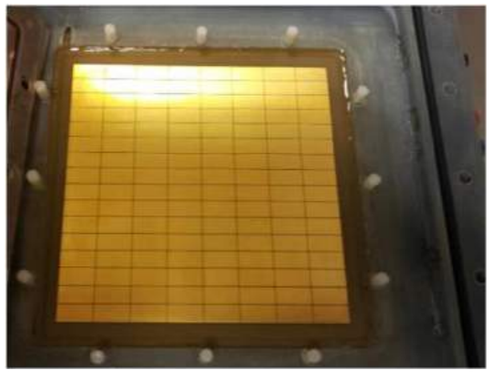




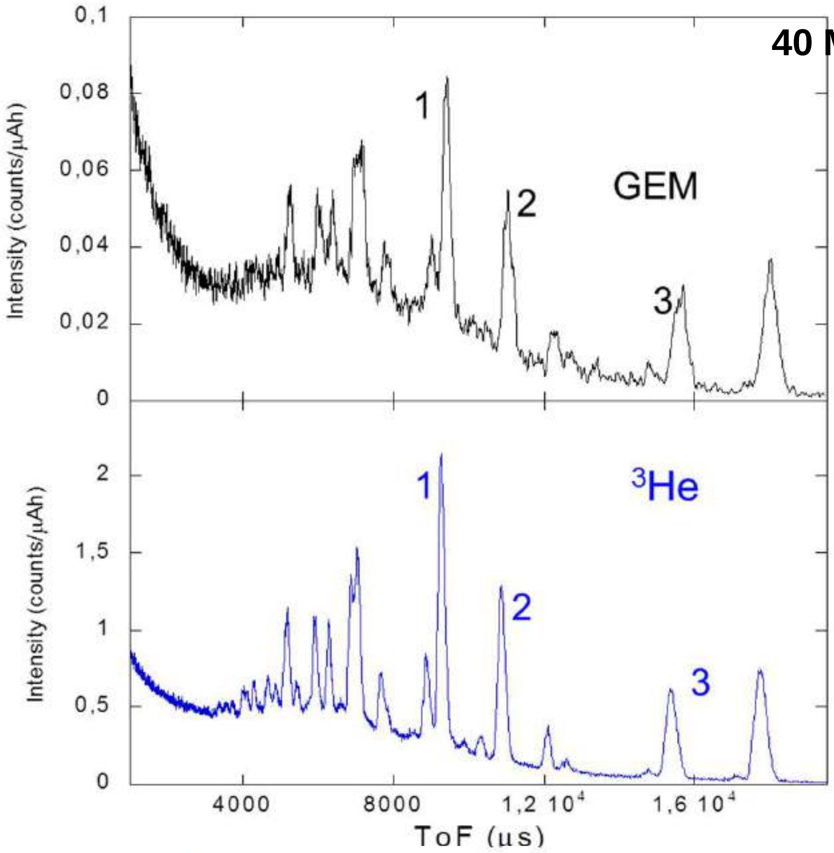


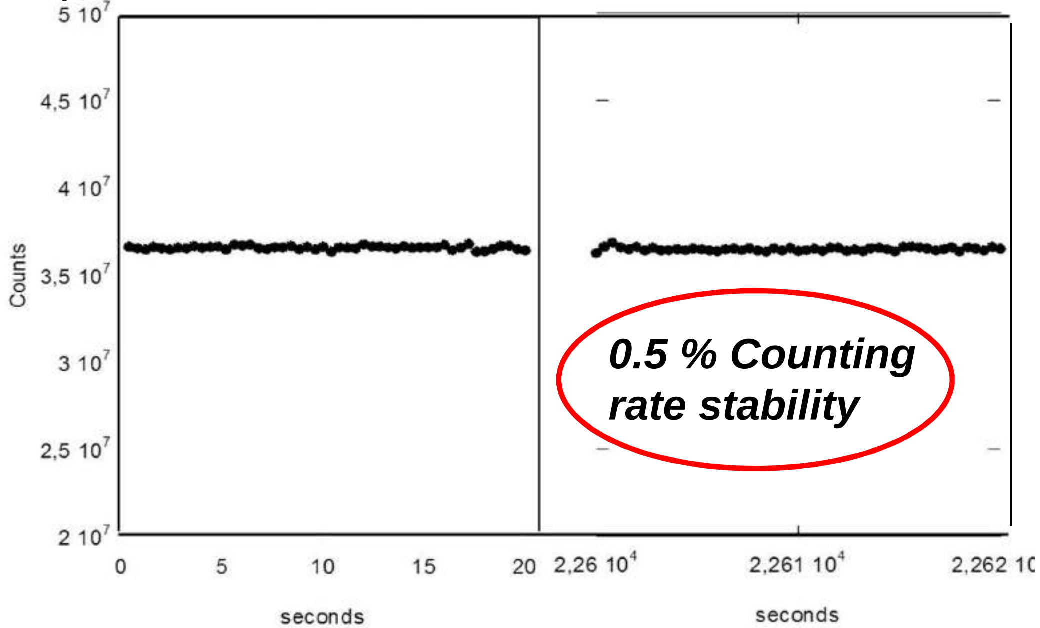
Lamellas coated on both sides with $^{10}B_4C$

Using low θ values (few degs) the path of the neutron inside the B_4C is increased → Higher efficiency when detector is inclined

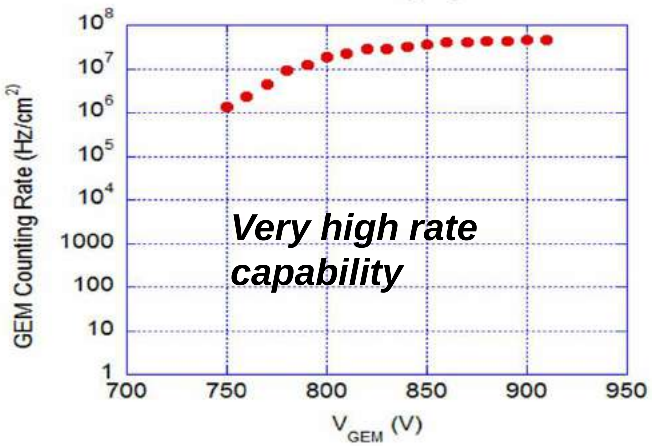


BANDGEM Performance as diffractometer

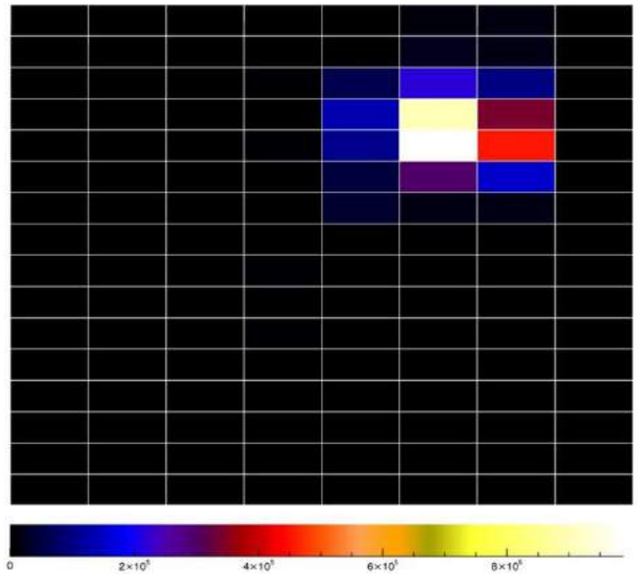




0.5 % Counting rate stability



Very high rate capability



Beam Profile Reconstruction

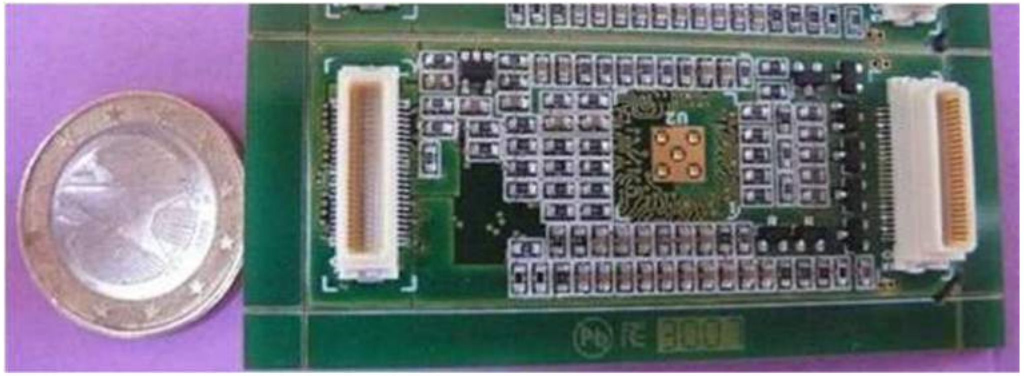
E_d = 230 V/cm
E_{t1}=E_{t2}= 3 kV/cm;
E_i = 5 kV/cm

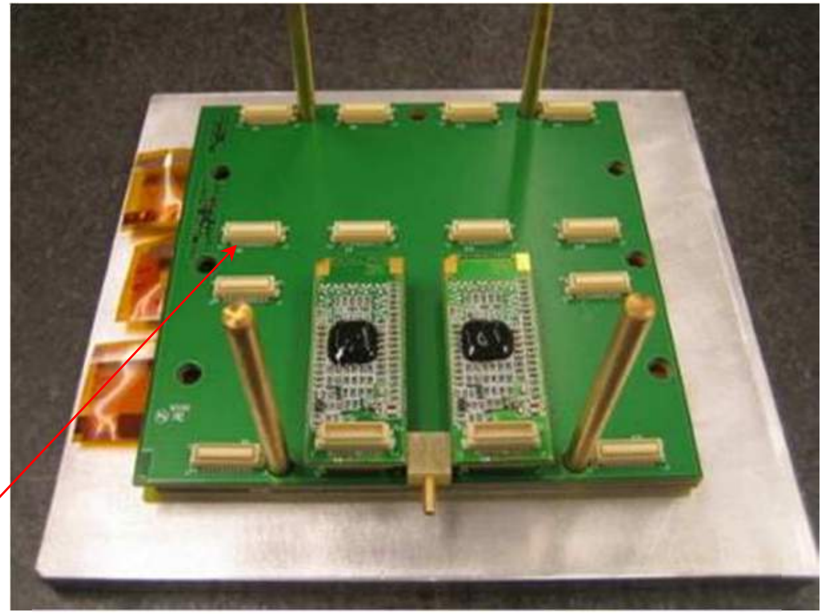
Mixture Ar/CO2 70%/30%
Angle = 10 degrees

END

The Front End Electronics

Collaboration UNIMIB, INFN
The electronics is based on Carioca Chip. Total dimension : 3x6 cm^2



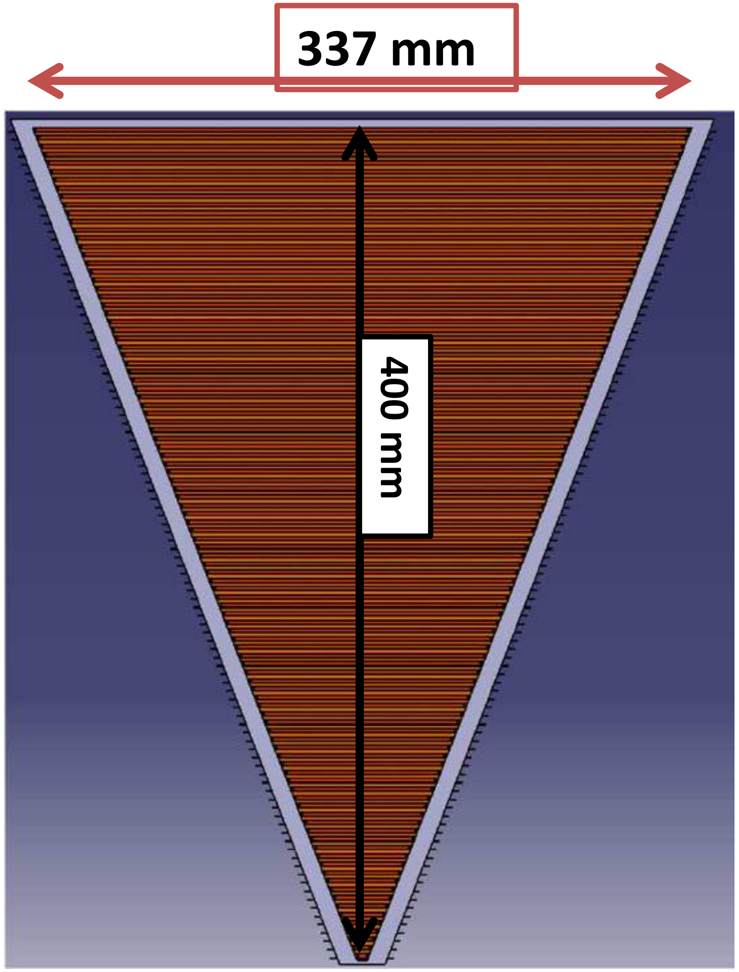


Digital Chip with 8 channels
Equips the LHCb GEM detectors
Fast chip – used for triggering
Adapted from MWPC

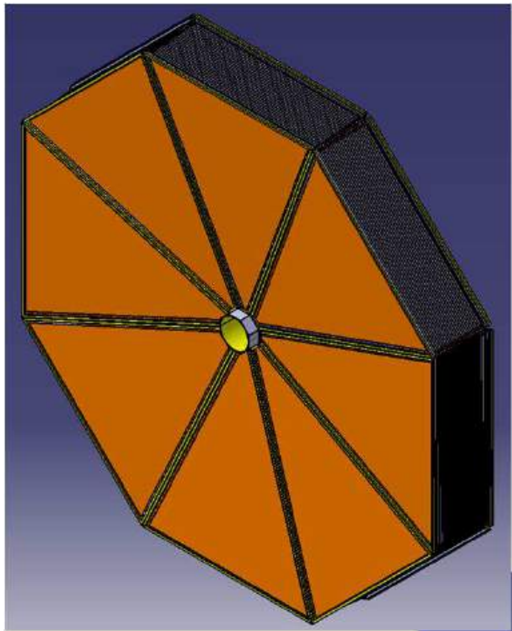
A new chip is being tested: the GEMINI chip.
Mixed analog and digital chip that
Has 16 channels/chip. This is the chip that we would like to use at ESS

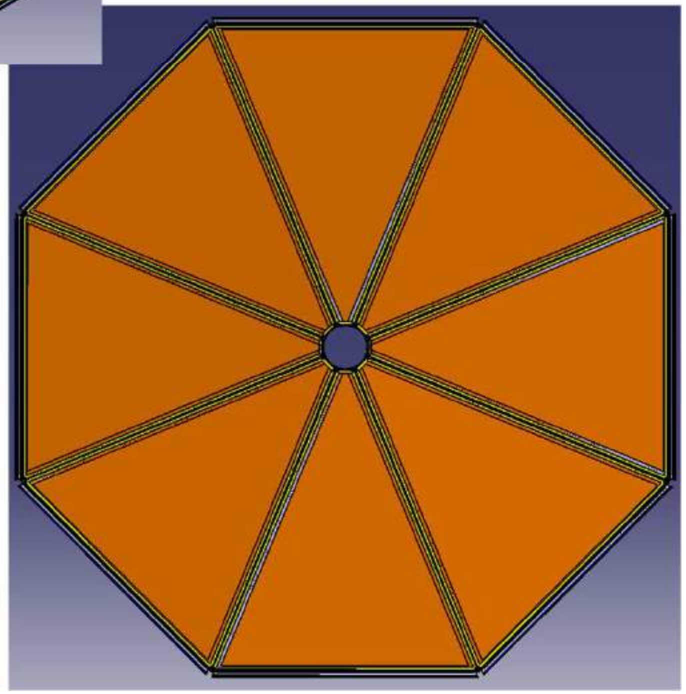
Ad hoc developed for GEM detectors

The BANDGEM umbrella for LOKI

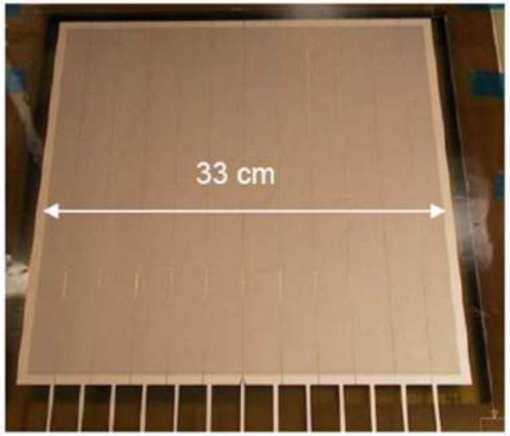


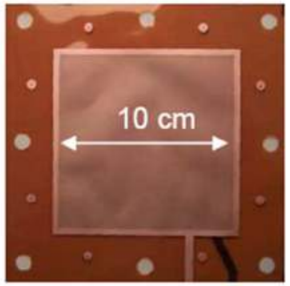
Total active area: 647 cm^2

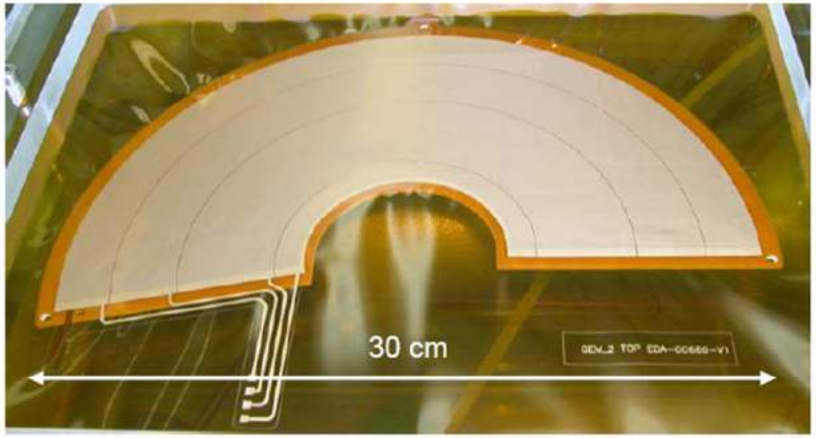


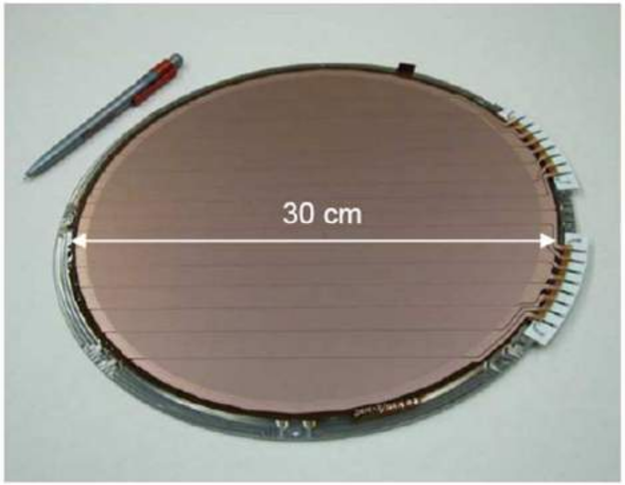


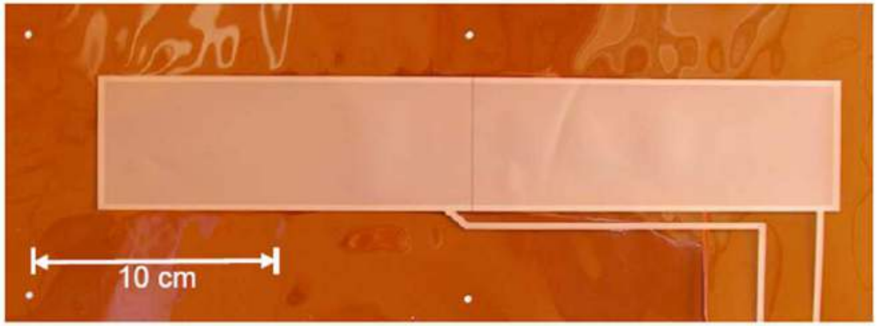
GEM Manufacturing











Wide rage of shapes and sizes

1500÷2000 foils manufactured at CERN
1 cm^2 to 1000 cm^2
30-200 μm holes, 50-300 μm pitch