APPLICATIONS OF DETECTORS AND TECHNOLOGIES IN THE ENERGY FIELD

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INFN Sezione di Genova

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INFN - LNS

MOTIVATIONS

Nuclear power currently not adopted in Italy, but:

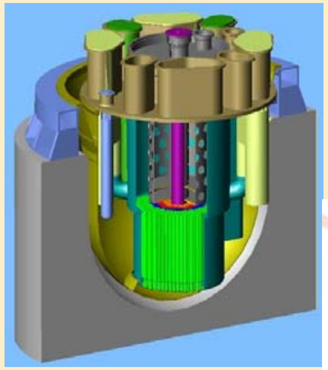
- **Research** on future generation fission and fusion reactors and related technologies continues
- **INFN involved in fusion research** through RFX Consortium (CNR, ENEA, Padova University, INFN joined in 2005) and IFMIF project within Broader Approach
- **Nuclear waste management and nuclear safety/security** are important beyond power plants (e.g. disposal of medical and industrial sources)
- **Knowledge preservation** in nuclear science and technology is a critical issue in the EU
- **INFN can give a contribution** to the above topics based on its historical research fields (fundamental nuclear physics, detectors, accelerators)
- Based on the above considerations, in 2008 a dedicated applied nuclear physics program was started

TOPICS

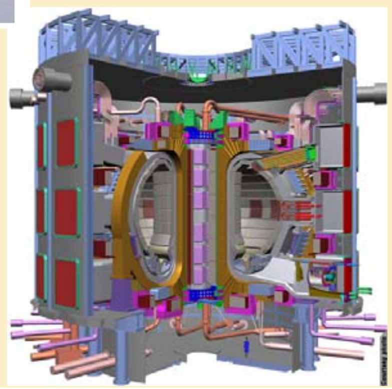
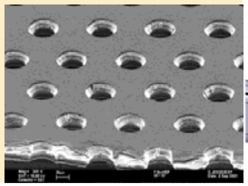
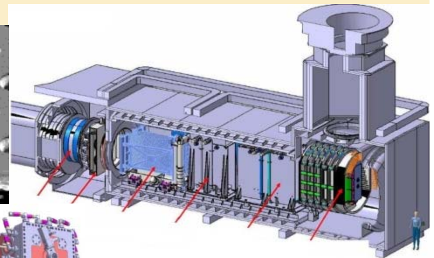
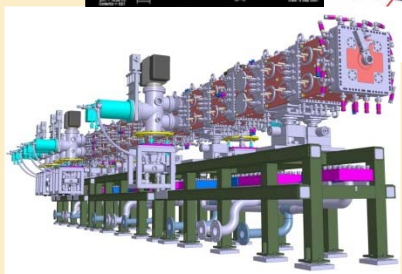
- Nuclear safety and security: innovative systems and instrumentation for radiation monitoring with applications to
  - ✓ Waste storage sites
  - ✓ Port security
  - ✓ Inspections



- Fission
  - ✓ Neutron physics aspects in fast reactors
  - ✓ Accelerator Driven Systems
  - ✓ Transmutation
  - ✓ Diagnostics




- Fusion:
  - ✓ Neutral Beam Injection
  - ✓ Material irradiation
  - ✓ Diagnostics

WORLDWIDE INVENTORY OF RADIOACTIVE WASTE

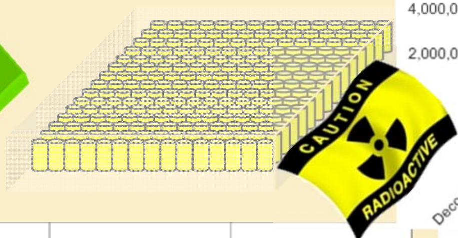
IAEA 2012

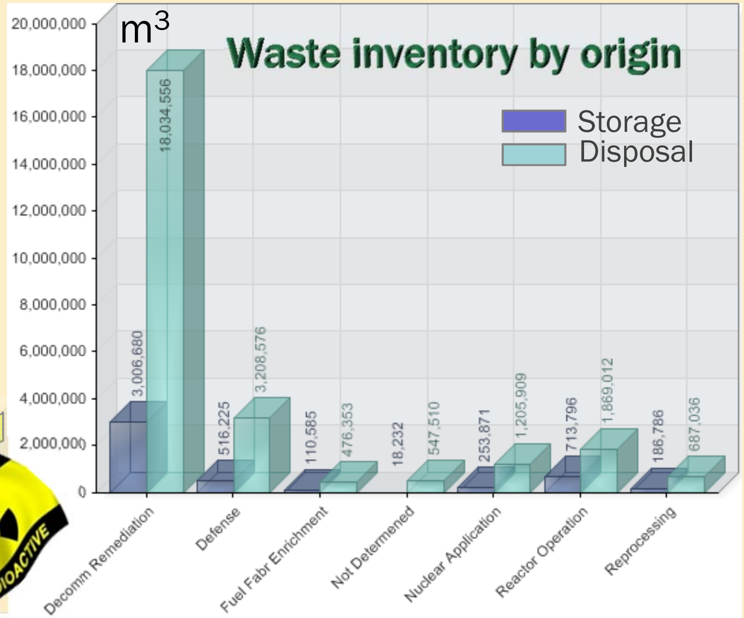
(Net-Enabled radioactive Waste Management DataBase, NEWMDB)

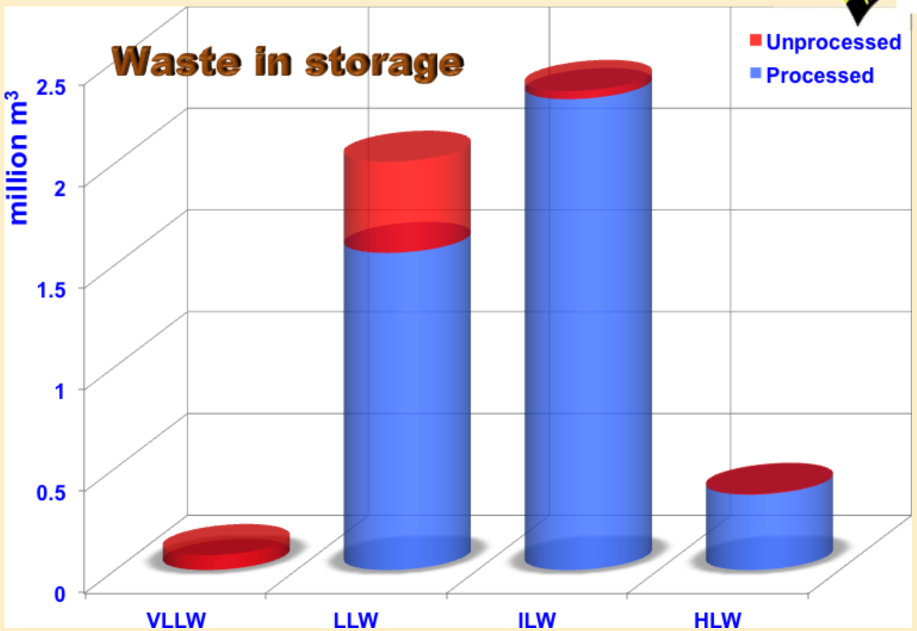
total of > 30 million m³

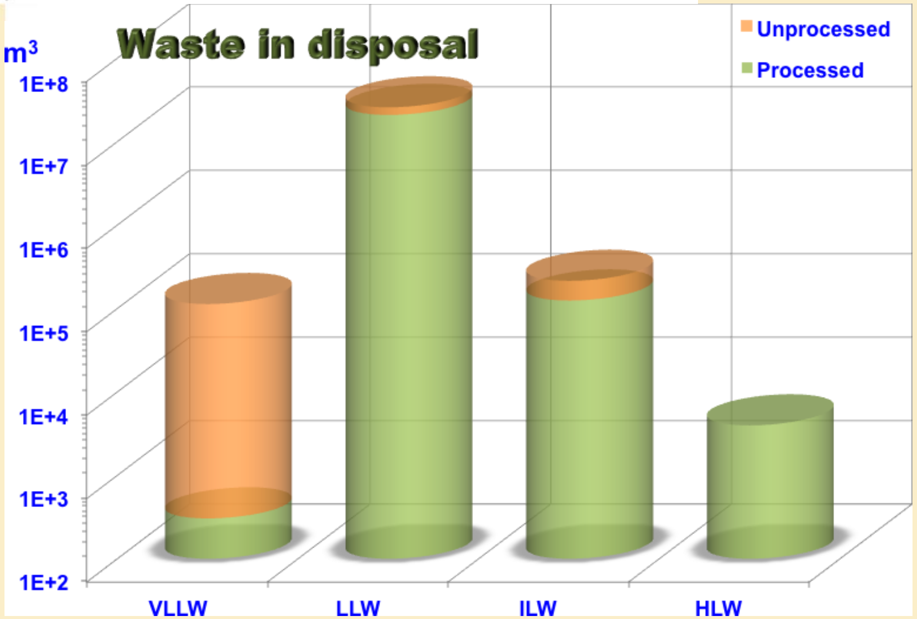
equivalent to

(1 km) x (1 km) x (30 m)



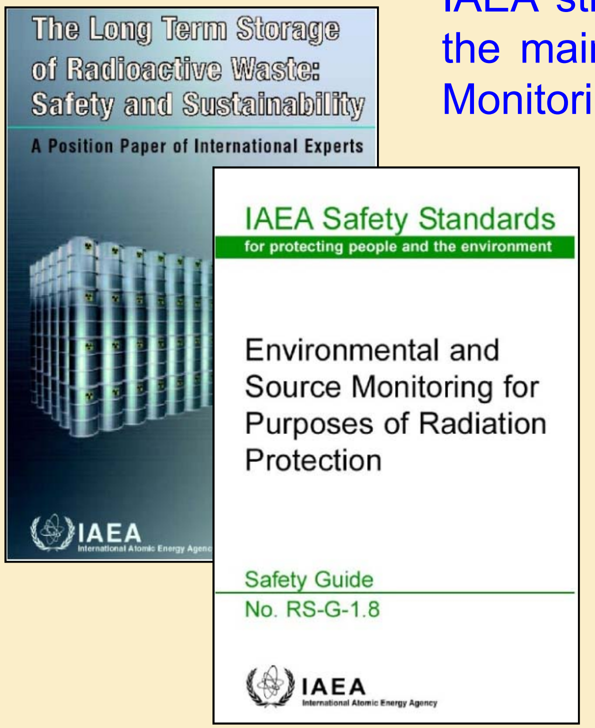




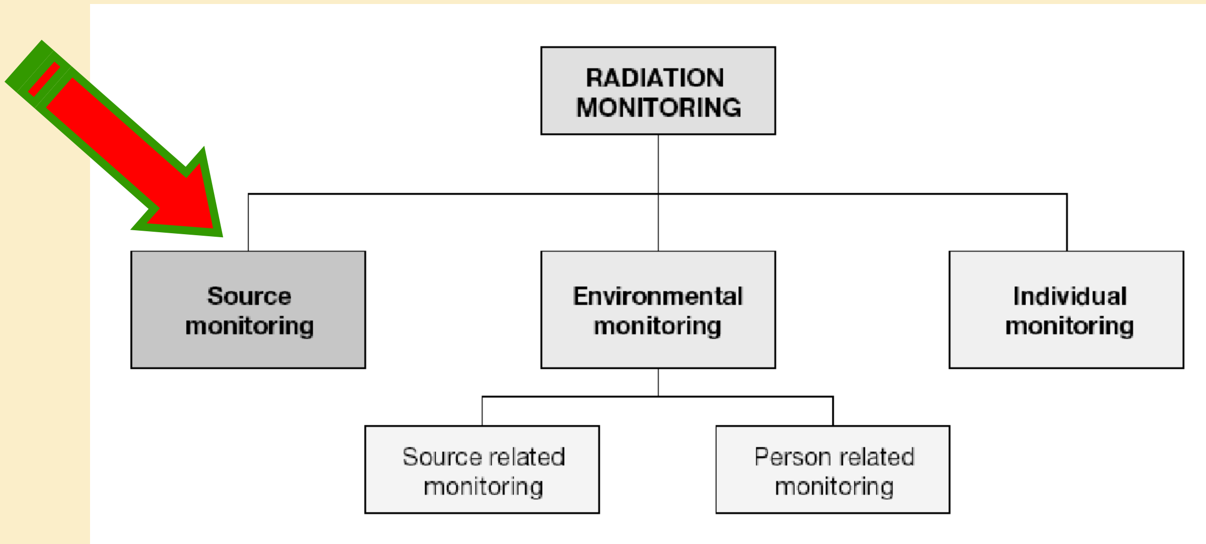


CURRENT SITUATION WORLDWIDE

In the UK, the Nirex Report N/077, Vol.1, par.3.8.6 “Monitoring” the Nuclear Decommissioning Authority (NDA) recommends that **when designing waste repositories care should be taken in order to allow for future implementation of more effective monitoring systems**



IAEA stresses the role of **Source Monitoring**, even though so far the main efforts are directed towards Environmental and Individual Monitoring



ACTIVE INSPECTION OF WASTE DRUMS

- Part of the management of radioactive waste is the so called Passive/Active Waste Assay System (PANWAS)
- It uses **neutron differential die-away technique to quantify the fissile content** (^{235}U, ^{239}Pu etc.)
- Uses a pulsed neutron source (sealed D-T tube, 10^6 n/pulse in 10 μs 100 Hz) and ^3He neutron detector.
- **Present sensitivity** is to about **1 mg of Pu** on a barrel of 400 liters, 1500 kg). **0.1 mg has to be guaranteed for downgrading waste level** (the limit is 0.1 Bq/g, and Pu natural radioactivity is 2 GBq/g, 10^{-10} in mass)

RADIATION PORTAL MONITORS FOR PORT SECURITY

Particle detection systems can be used to detect radioactive sources or materials for the security of the population

- to avoid the illegal transportation of Strategic Nuclear Materials (SNM) across borders
- To detect orphan, lost or not properly shielded sources

Detection devices devoted to gamma and neutron detection and identification.

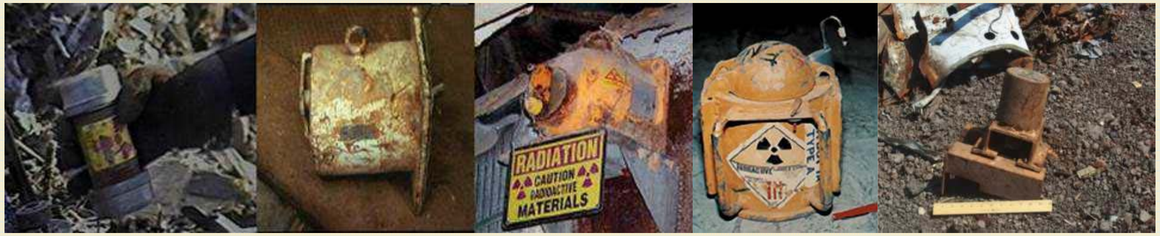
- **Gamma sources:** naturally occurring radioactive materials (NORM), medicals, fertilizers, etc..
- **Neutron sources:** SNM (WGPu, HEU)

INDUSTRIAL SAFETY AND NUCLEAR SECURITY

- Sometimes, radioactive sources are present in recyclable scrap metal. For this reason foundries are equipped with radiation monitors at the material entry point
- However, if the source is shielded it goes undetected and ends up being melted in the furnace, with severe consequences for the workers, the infrastructure and the environment.
- Such sources can be found if there is a method to detect the high-density shielding

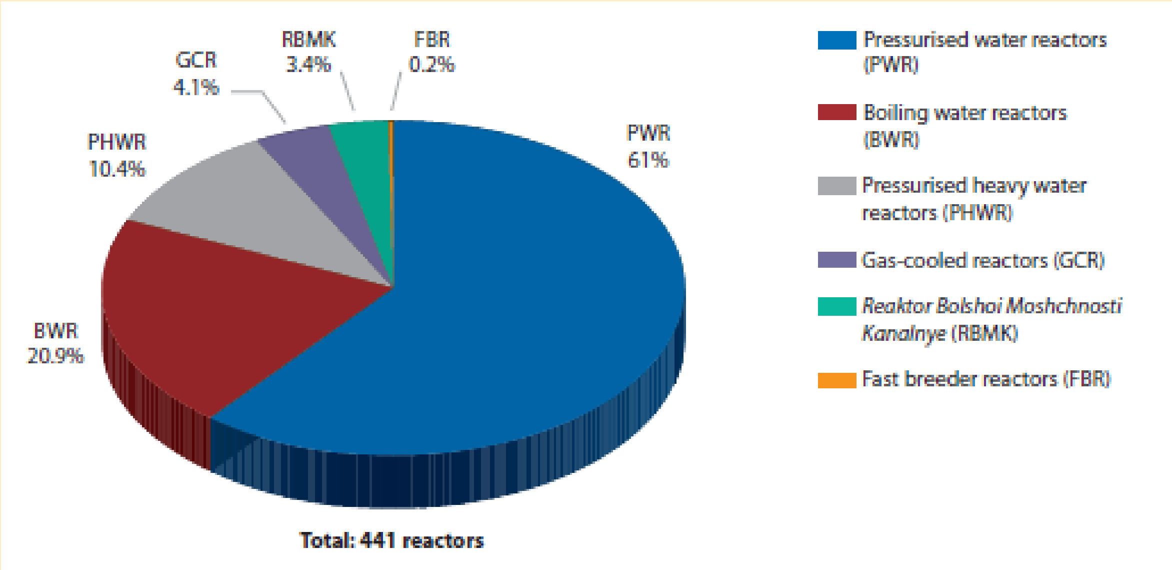
Some known events

Date	Country	Industry	Source	Cost Estimate
1983	Mexico	N.A.	37 GBq 60Co	N.A.
1997	Italy	ALFA ACCIAI	60Co 137Ce	17M€
1998	Spain	ACERINOX	137Cs	26M$
2000	Great Britain	AVESTA STEEL	238Pu	2M£
2004	Italy	AFV BELTRAME	137Cs	13M€



- Sometimes, inspecting legacy containers from old nuclear and decommissioning activities can be necessary; non-invasive inspections from outside are often preferrable
- Another aspect of nuclear security is to prevent tampering with spent fuel assemblies and the possible consequent smuggling of nuclear material

NUCLEAR FISSION AND LONG-LIVED RADIOACTIVE SPECIES



Reactor types in use worldwide (end of 2010)

Source:
Nuclear Energy Today Edition 2012
NEA/OECD

Currently dominant open fuel cycle
→ uranium fuel is irradiated, discharged and replaced with new uranium fuel
→ gradual accumulation of large quantities of highly radioactive or fertile materials in the form of Depleted Uranium, Plutonium, Minor Actinides (MA, Np, Am, Cm,...) and Long-Lived Fission Products (LLFP, Tc, Cs, I,...)

About 2500 tons of spent fuel produced annually in the EU
→ about 25 tons of Pu, 3.5 tons of Mas, 2 tons of LLFP
In Europe spent fuel is reprocessed and some of the separated products are utilized in the form of **MOX (Mixed Pu/U Oxide) fuels**, but **not yet in sufficient quantities** to significantly slow down the steady accumulation of these materials in storage

LONG LIFETIME RADIOACTIVE WASTE PRODUCTION (1 GW_E LWR)

$^{244,\,245}Cm$ 1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

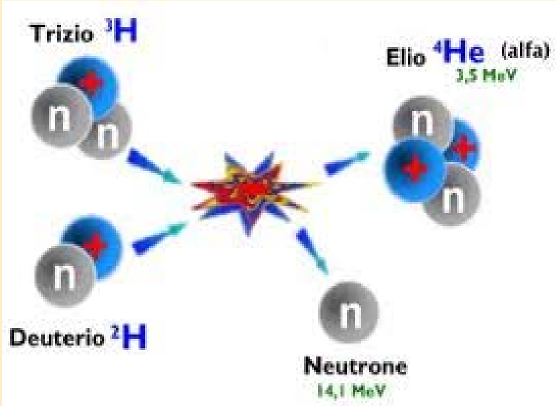
LLFP 76.2 Kg/yr

LLFP=Long Life Fission Products

Transuranics = Minor Actinides + Pu

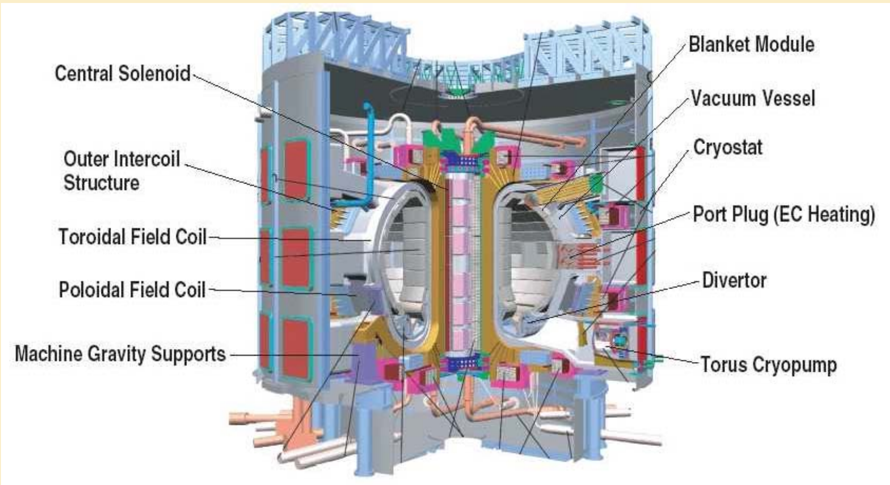
Courtesy of Nicola Colonna, INFN Bari

FUSION RESEARCH



Q_{DT}=17.6 MeV

P_{FUSION}=500 MW



<u>Magnetic confined fusion reactor</u>
- Poloidal field magnets
- Toroidal field magnets

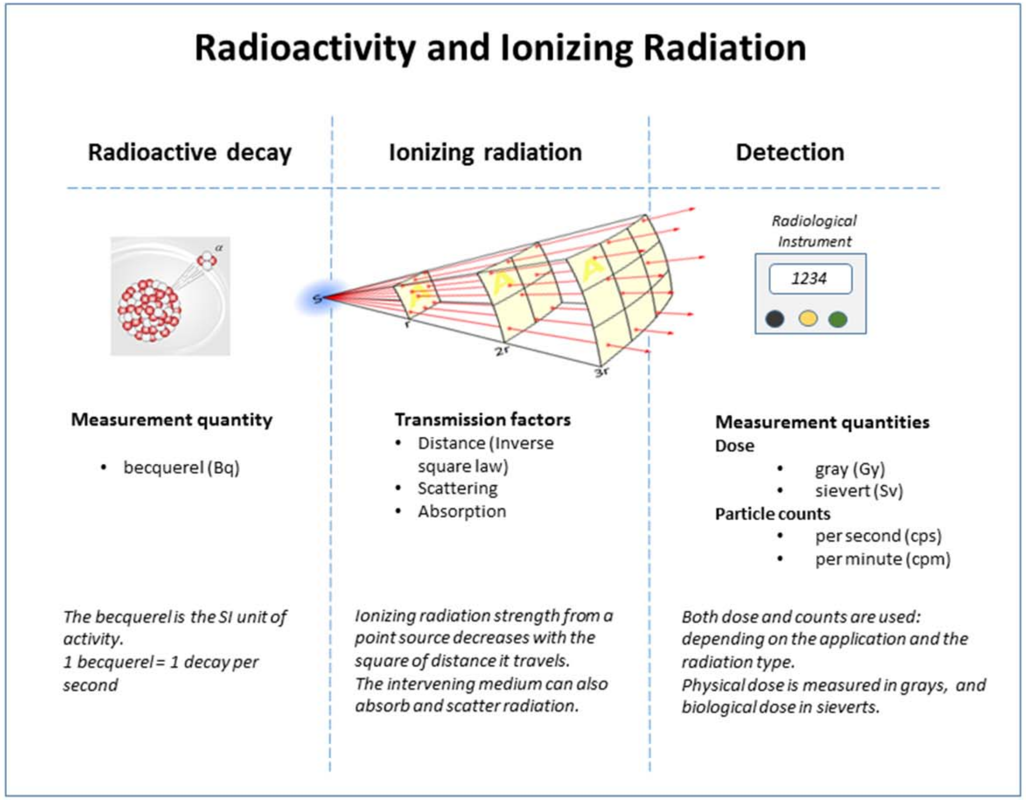
<u>Heating:</u>
- Ohmic heating (Central solenoid)
- Electron/Ion Resonance Cyclotron Heating
- Neutral Beam Injection

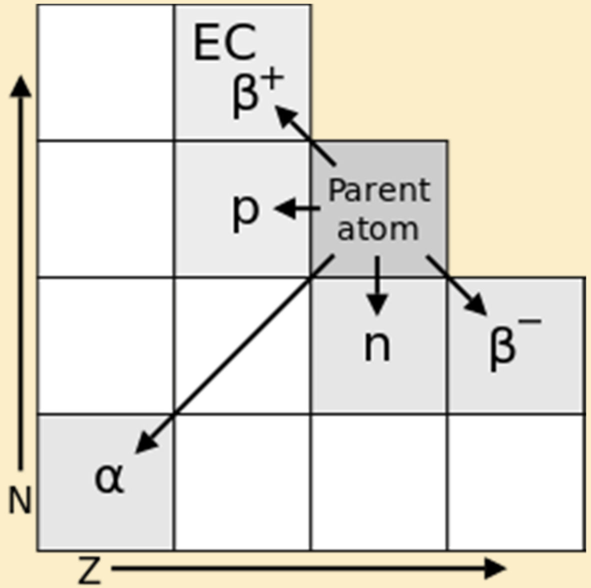
<u>Divertor</u> for the control of the exhaust gas, impurities and heat load

- Heating by Neutral Beam Injection
- $\Phi n=10^{14} n/cm^2 s$ on the First Wall → Materials have to withstand extremely high neutron flux → facilities for material testing
- How much Tritium fuel can be bred ?
- What activation levels in external infrastructure ?

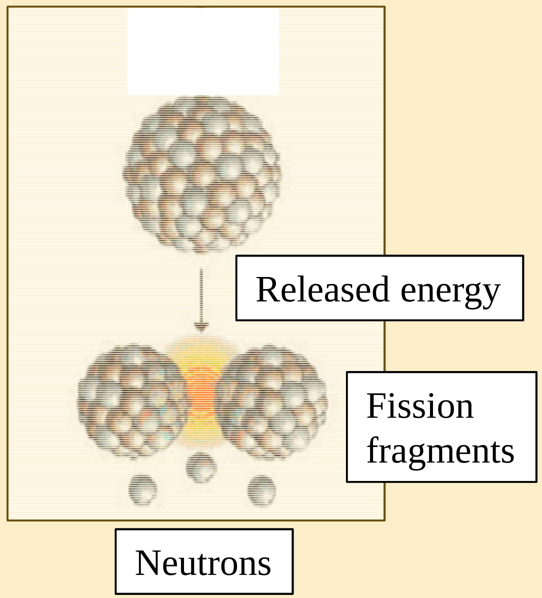
SPECIFIC APPLICATIONS

RADIOACTIVE WASTE: GENERAL ASPECTS

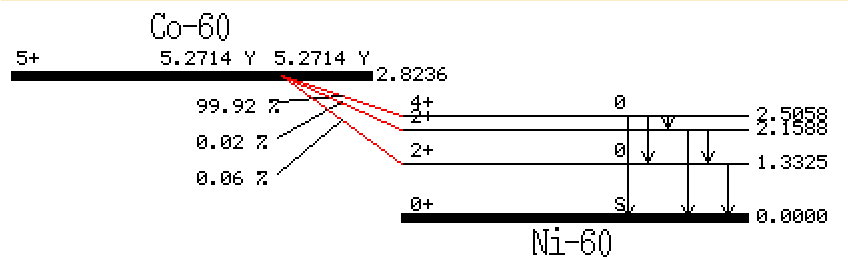


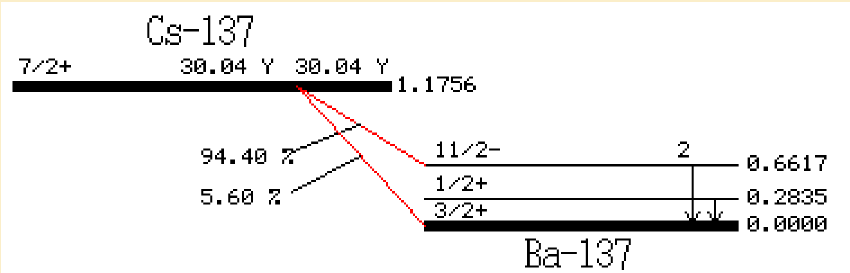


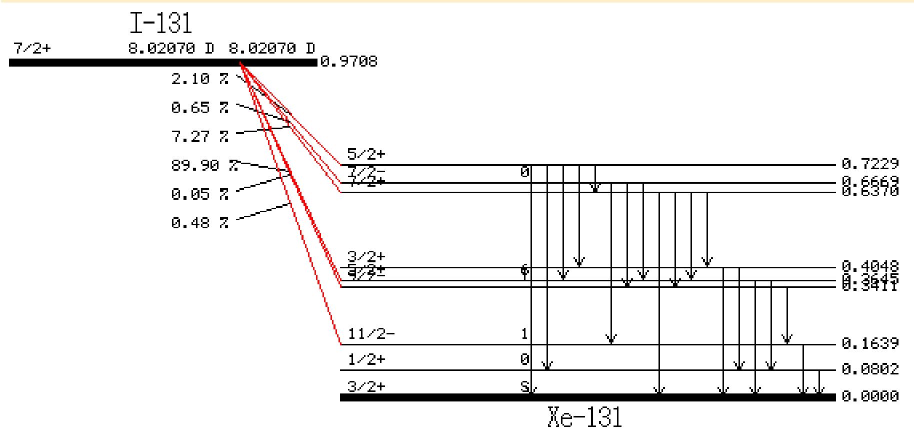
+ spontaneous fission

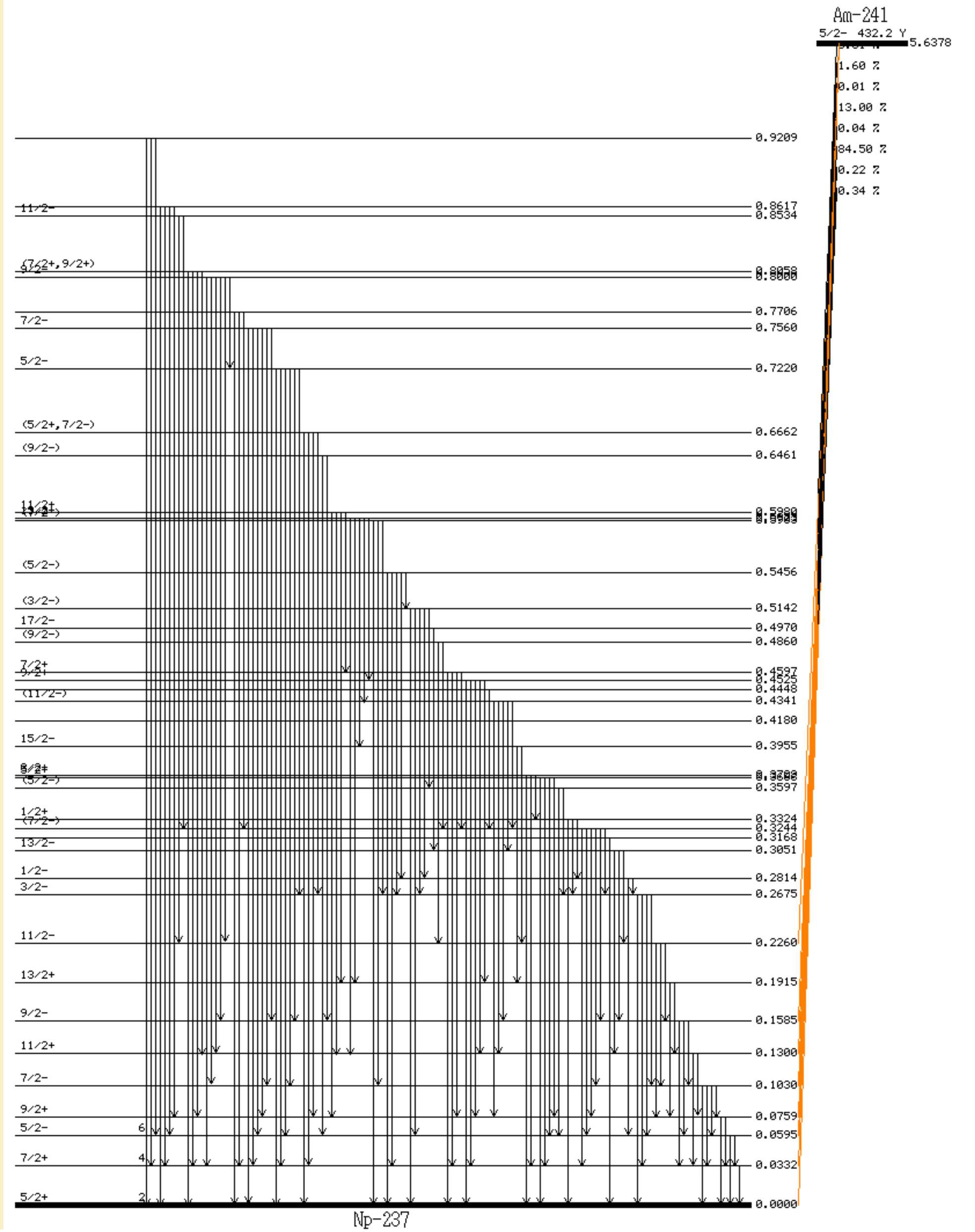


RADIOACTIVE WASTE: GENERAL ASPECTS





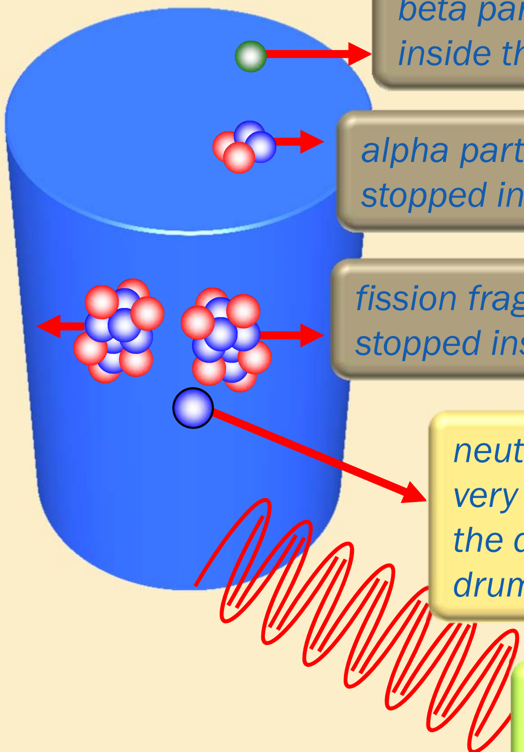




RADIOACTIVITY FROM THE WASTE

What comes out of a waste drum?

Basic radioactivity coming out is gamma rays



beta particles are mostly stopped inside the material and in air

alpha particles are immediately stopped inside the material

fission fragments are immediately stopped inside the material

neutrons (from fission) come out very easily but at very small dose. The amount of fissile material in the drums is small: it is removed before packing the drums (not so for spent fuel rods)

gamma rays are penetrating, therefore they come out easily and abundantly

Rom. Journ. Phys., Vol. 56, Nos. 9–10, P. 1136–1142, Bucharest, 2011

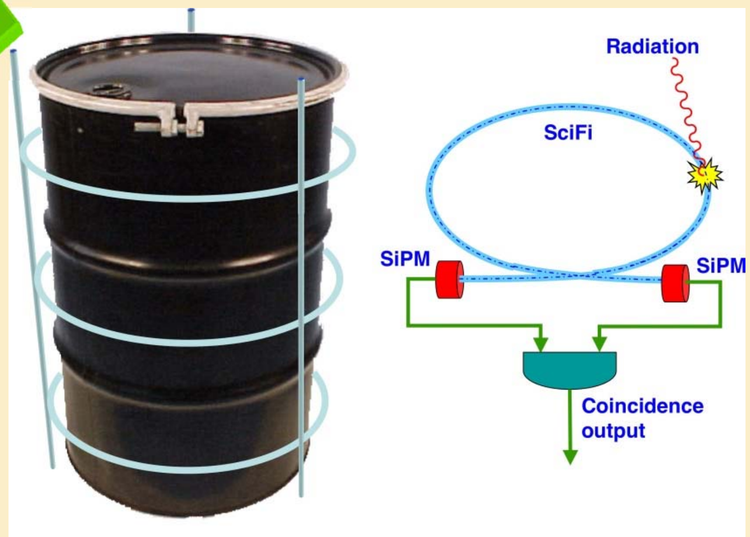
Waste drum #	Nuclide activity (MBq)			Dose rate (mSv/h)		% discrepancy
	Mn-54	Co-58	Co-60	measured	calculated	
1		49	511	2.8	2.7	3
2		41	493	2.8	2.6	8
3	17	35	418	2.4	2.2	7
4	13	42	447	2.28	2.4	-5
5		12	171	0.8	0.9	-10
6		51	588	2.5	3.1	-20
7	13	50	531	2.75	2.9	-4
8	18	40	489	2.4	2.6	-9
9	16	55	638	2.9	3.4	-15
10	11	36	383	2.6	2.1	24
11	7	18	213	1	1.2	-14
12	12	34	394	1.8	2.1	-16
13	13	53	565	1.9	3.0	-37
14	6	17	229	1.5	1.2	22
15	9	27	314	1.48	1.7	-13
16	16	49	503	1.84	2.7	-32
17		46	494	2.23	2.6	-15
18	8	36	348	1.6	1.9	-14
19	11	40	426	1.9	2.3	-19
20	12	34	402	1.62	2.2	-26
21	4	18	196	0.9	1.1	-15
22	15	50	514	1.85	2.8	-33
23		42	456	1.4	2.5	-44

THE DMNR TECHNOLOGY

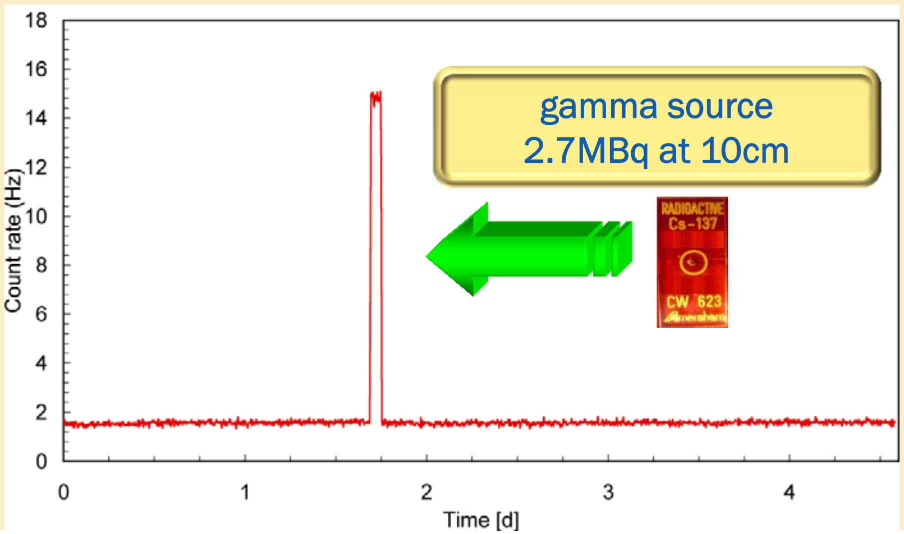
the detector: scintillating fiber + 2 SiPM

- radiation hardness ≈100-1000 years close to a drum with 10-100 mGy/h
- robustness yes, plastic scintillators; SiPM not damaged by ambient light exposure
- low efficiency ≈0.1%
- high sensitivity: few photons
- reliability yes
- (possible position sensitivity) yes
- ease of handling yes
- low cost yes

the left-right coincidence suppresses spurious counts



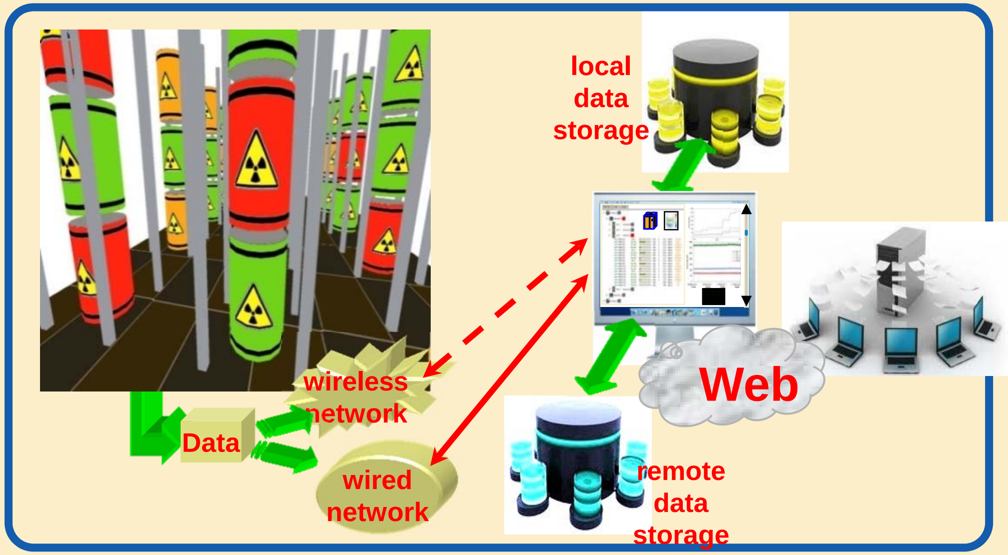
a mesh of scintillating fibers read-out at both ends by means of Silicon PhotoMultipliers (SiPM)

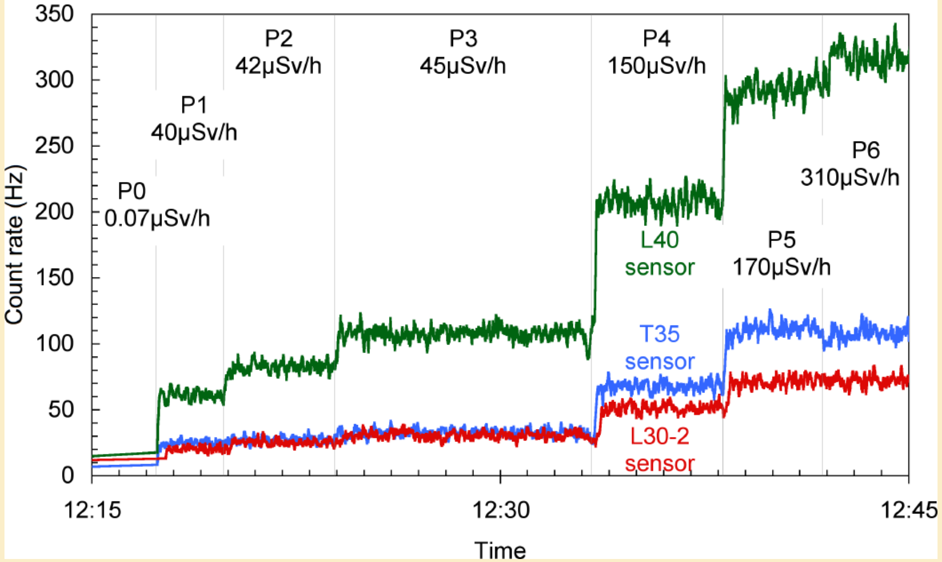


INFN National Southern Laboratory, Catania
in collaboration with Ansaldo Nucleare and Sogin companies

A TOOL FOR REAL-TIME RADIOACTIVE WASTE MONITORING

- radwaste handling by means of advanced tools and procedures suitable for reducing the risks to the local workers and to the population
- real-time continuous activity monitoring & recording
- on-line availability of data to control authorities, fire departments, local and national governments, etc.





3D virtual navigation tool

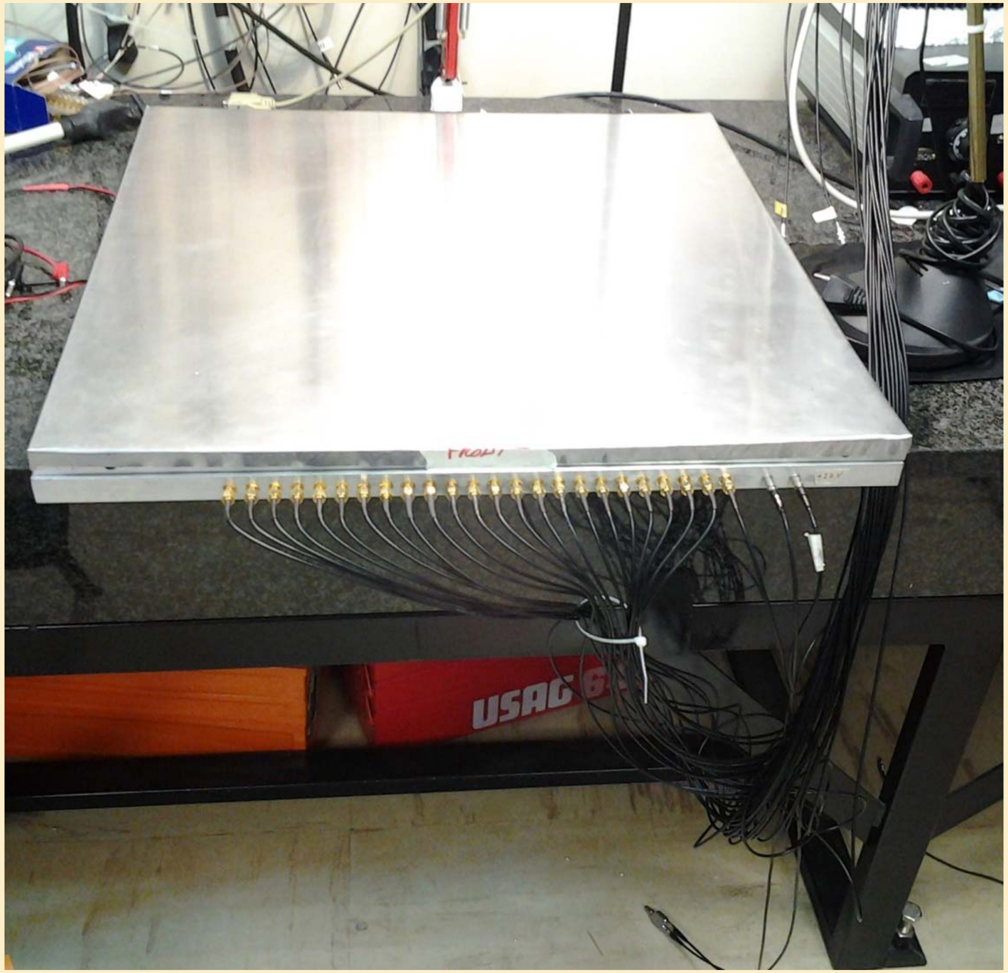
Further developments reported in a patent application

SORTING TABLE FOR RADIOACTIVE WASTE

Sorting table for hot spots detection in decommissioning

INFN National Southern Laboratory, Catania in collaboration with Joint Research Center EURATOM, Ispra (Italy)

PRE-PROTOTYPE



prototype 60cm x 60cm assembled
with dedicated electronics

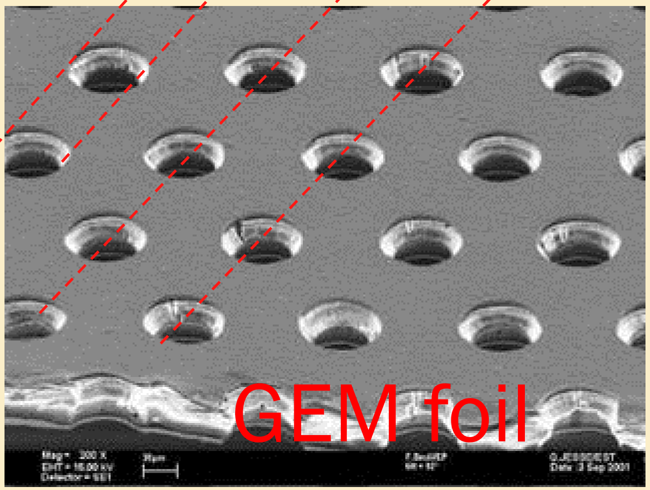
CONFIDENTIAL

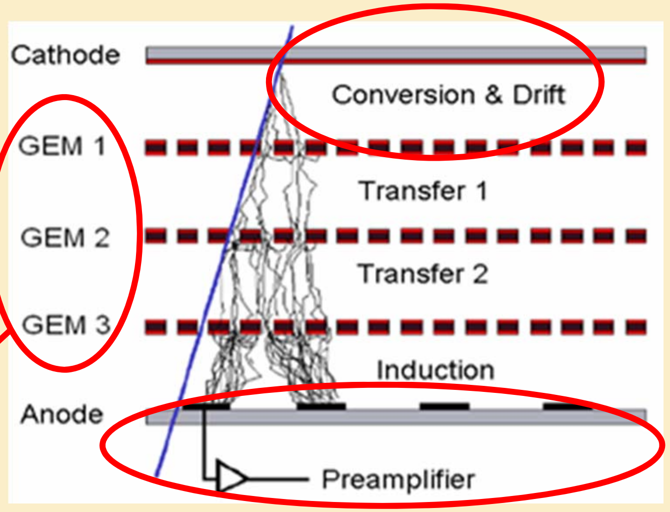
GEM TECHNOLOGY

A Gas Electron Multiplier (F.Sauli, NIM A386 531) is made by 50 μm thick kapton foil, copper clad on each side and perforated by an high surface-density of bi-conical channels;

Several triple GEM chambers have been built in Frascati in the LHCb Muon Chamber framework*

70 μm 140 μm

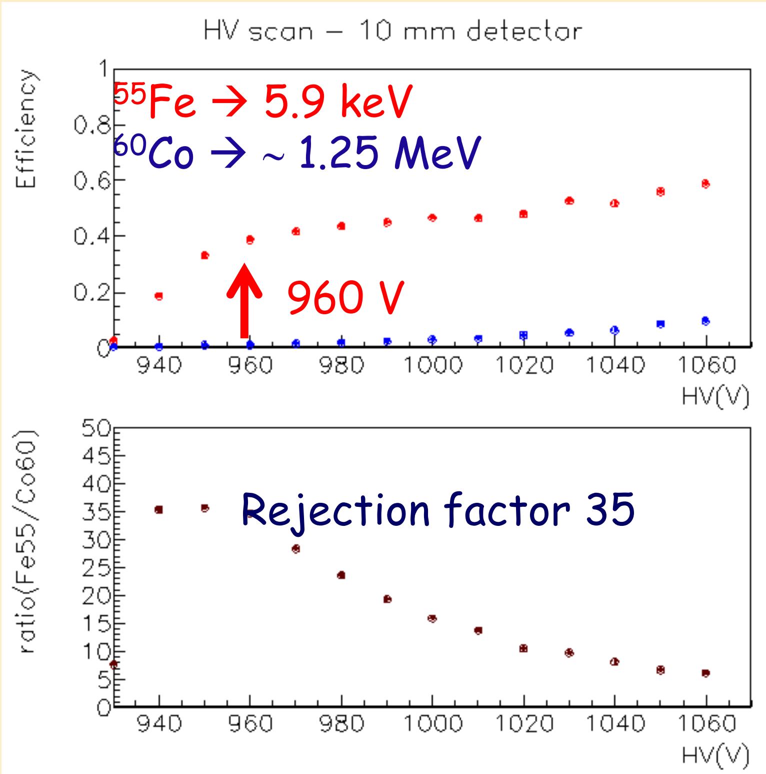


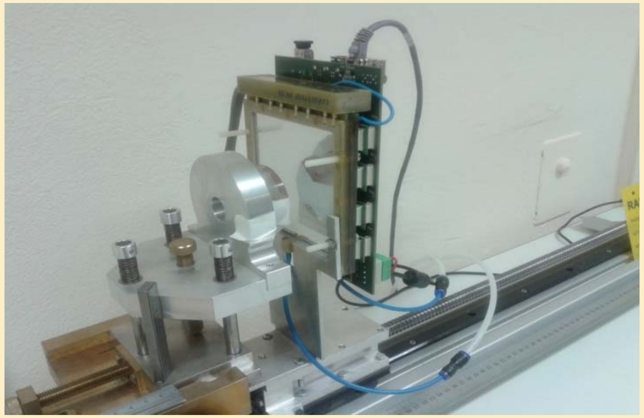


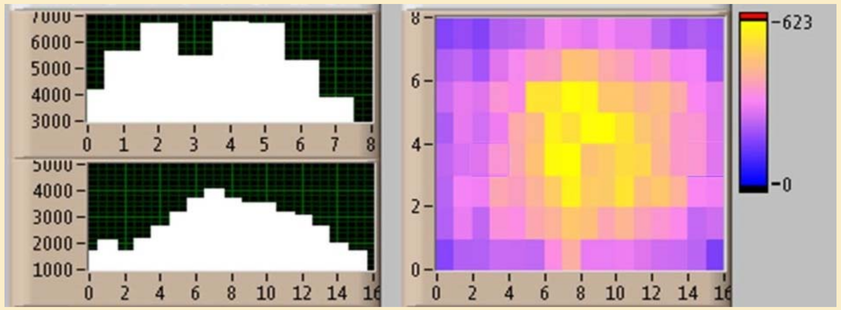
Working with different levels of gain it is possible to obtain high level of gamma- neutron discrimination

HOT SPOT IMAGING

At CERN → cavities and beam pipes from LEP with residual radioactivity
What to release from radiation control ?
→ Stringent limit on ^{55}Fe activity .... Chemical analysis lengthy ...
Gas chambers could be a good monitor for this type of radioactivity



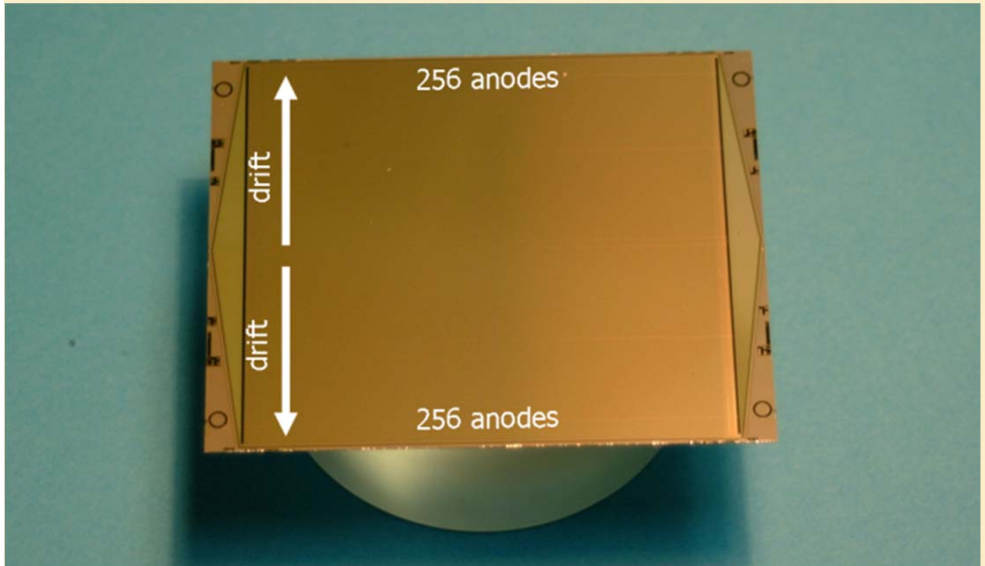




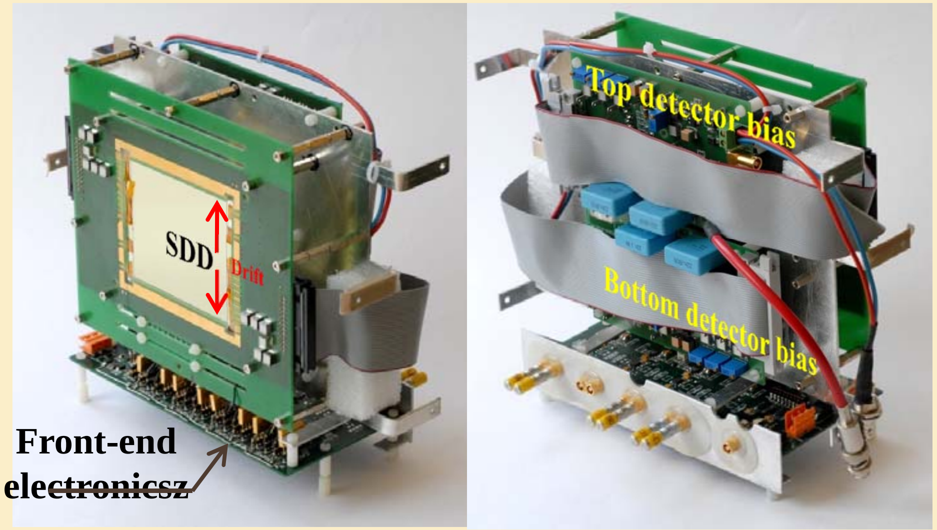
Possibility to find the hot spot

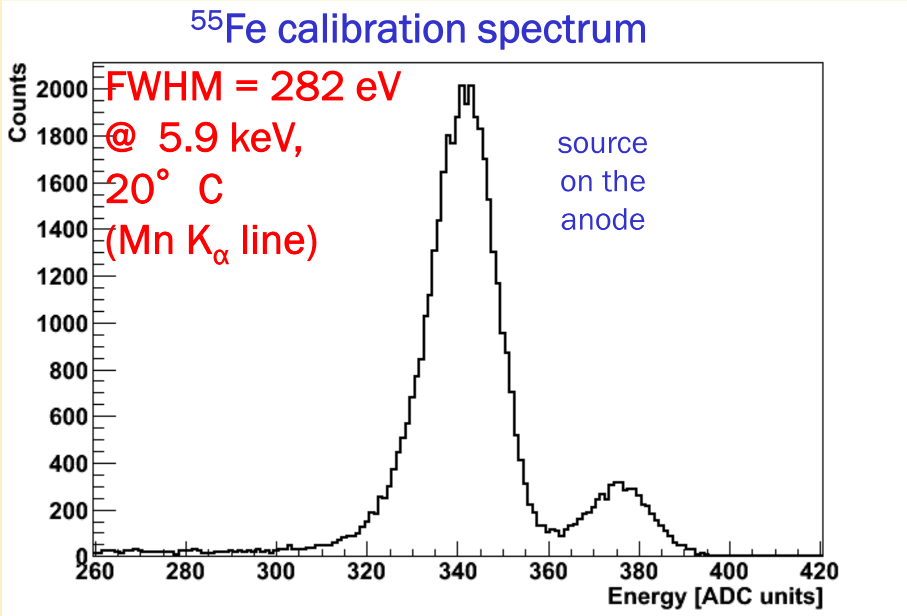
INFN Frascati National Laboratory in collaboration with CERN

LOW-ENERGY X RAYS WITH SILICON DRIFT DETECTORS



5" Wafer, Neutron Transmutation Doped silicon
Resistivity 2 - 4 kΩ·cm, thickness 300 μm
Sensitive area: 7.02 × 7.53 cm² (83% of the total)

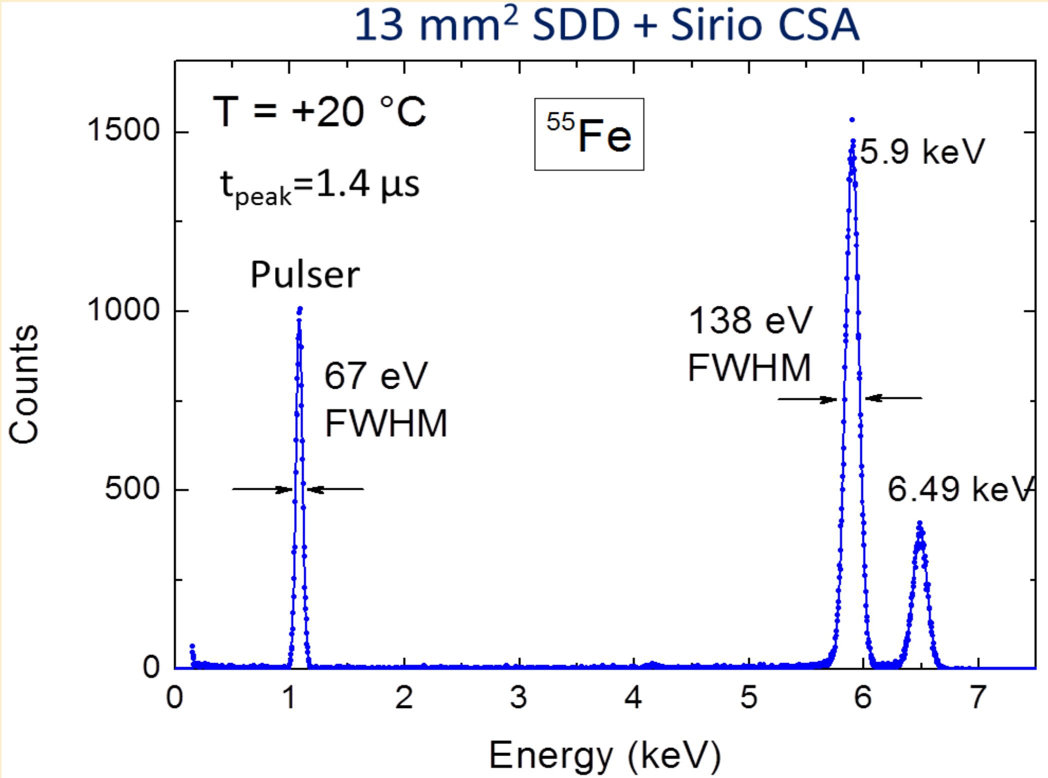




INFN Trieste

LOW-ENERGY X RAYS WITH SILICON DRIFT DETECTORS

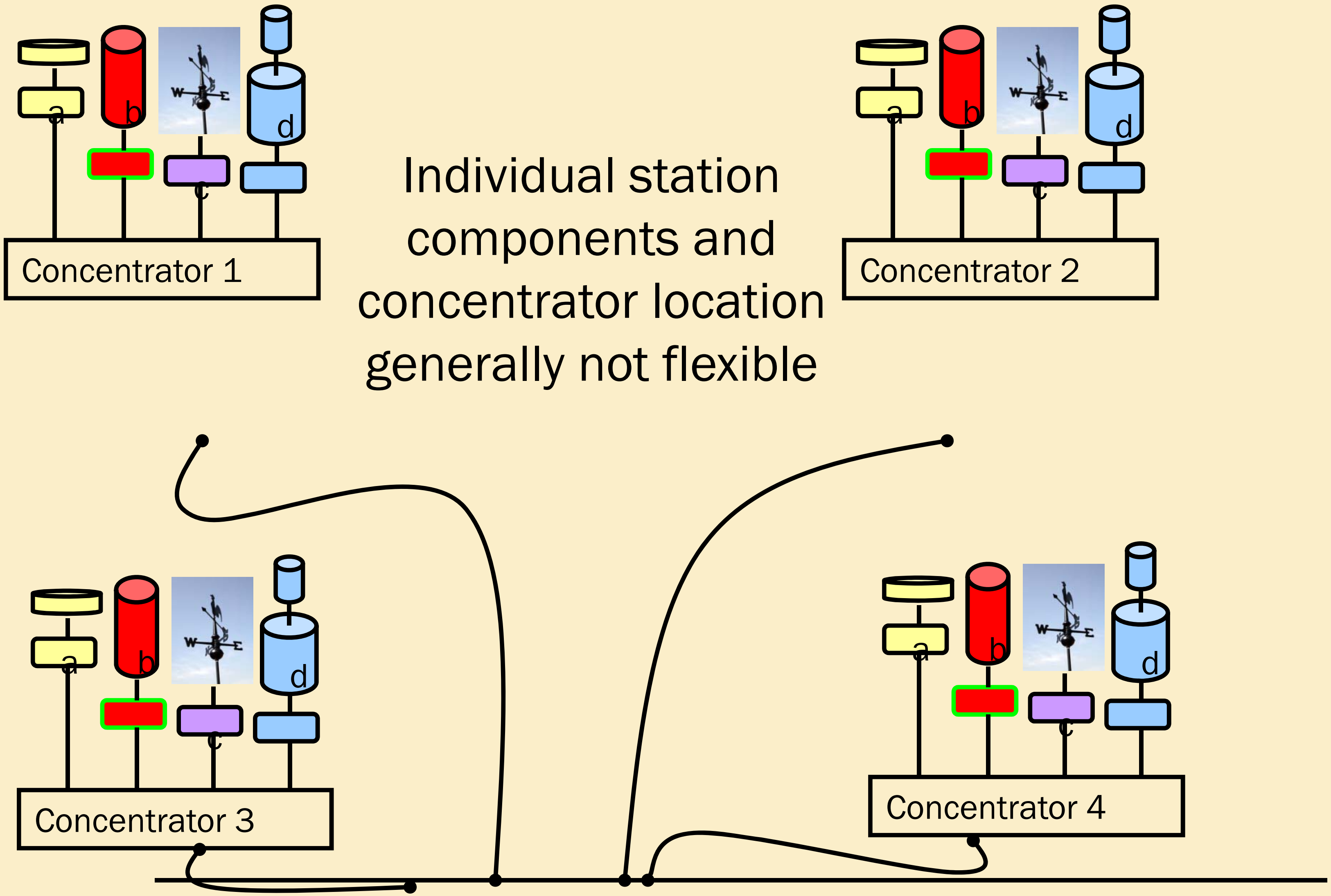
- Detector production process has been optimized → very low leakage currents (as low as 25 pA/cm^2)
- ASIC preamplifier designed to minimize the noise of the first transistor, and make negligible all other noise sources.



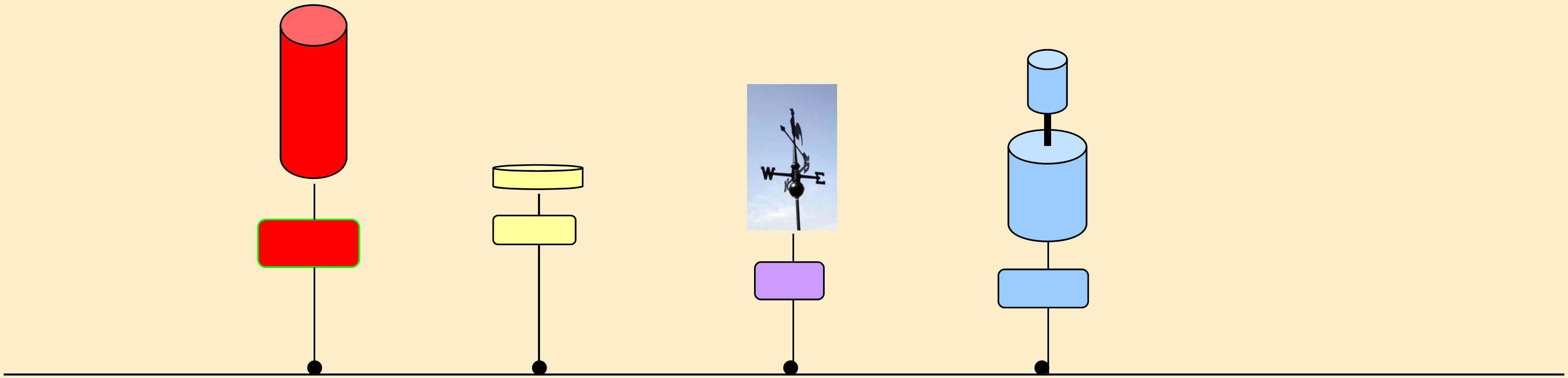
They may be applied e.g. as hot spot detectors: moderate rates, but specific line identification

SMART MONITOR NETWORK

Individual station components and concentrator location generally not flexible



THE NEW CONCEPT



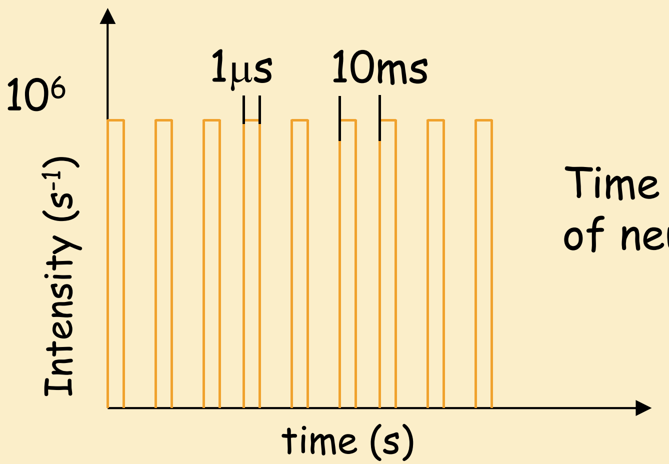
- «Smart» detectors on a network (wired or wireless), operated as virtual clusters according to requirements
- It may be applied e.g. to waste storage sites

TECHNIQUES FOR ASSESSING PU AMOUNT IN WASTE DRUMS

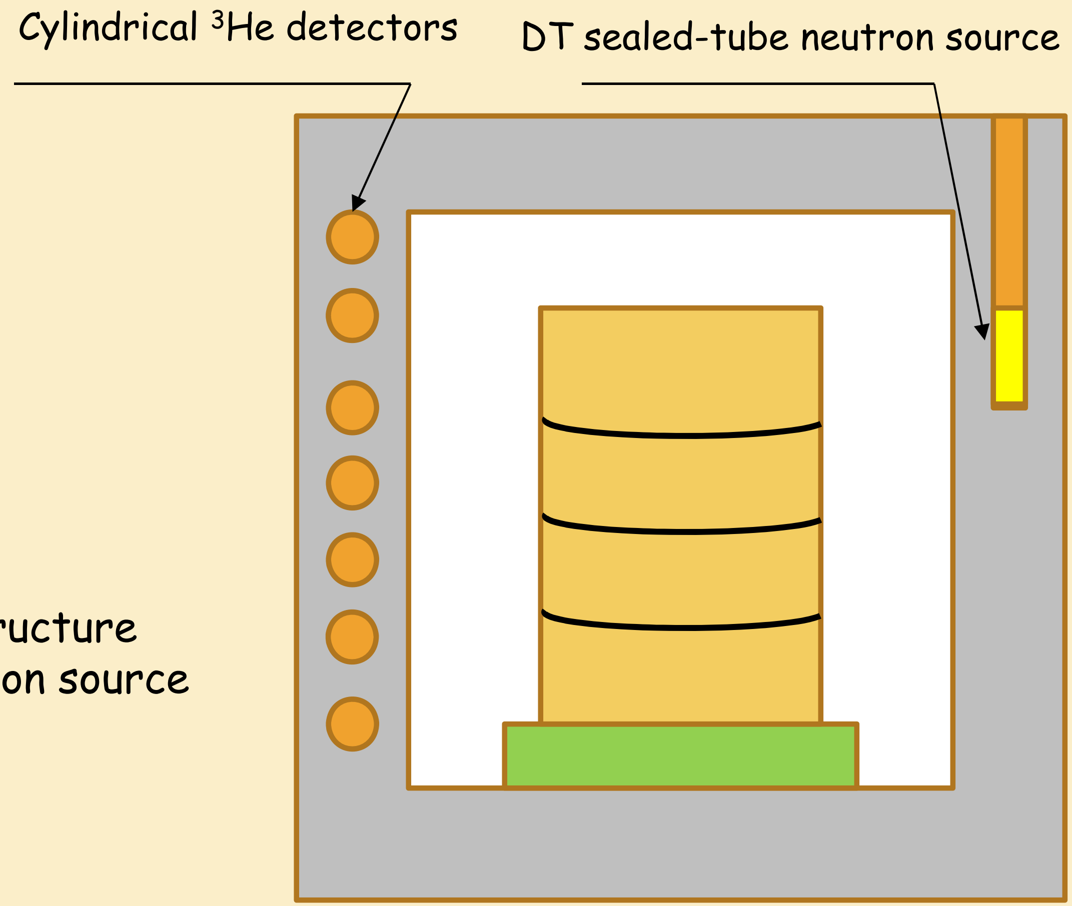
- Apparatus developed at LANL with the addition of technology from Areva
- Commercial technology, no “open-source”
- Technique based on **detection of delayed neutrons from fission**

D+T neutron source

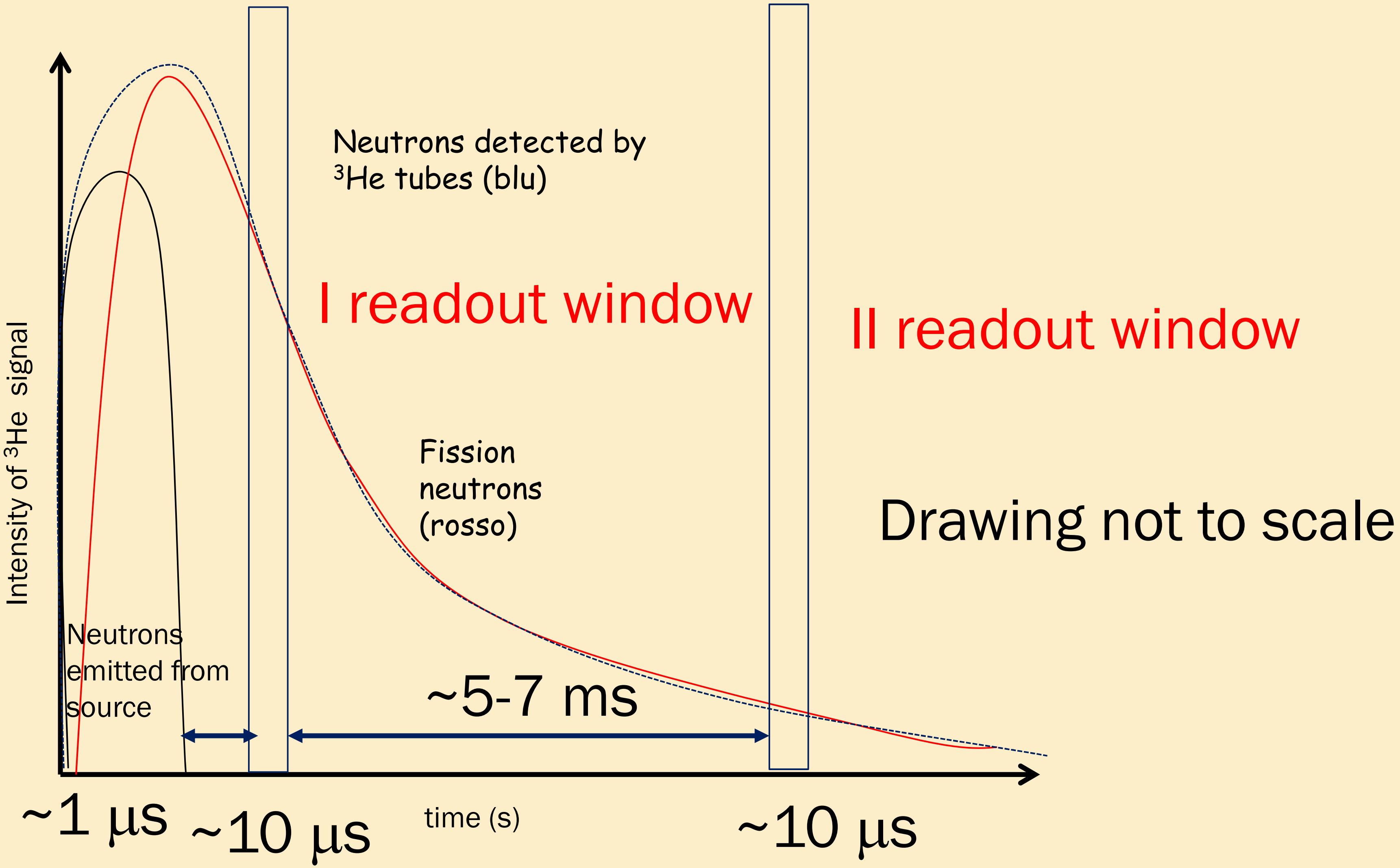
Emitted neutrons:	10^6 /pulse
Energy:	~14 MeV
Pulse duration:	1 μs
Rep rate:	100 Hz
Duty cycle :	10^{-4}
Average intensity:	10^8 s^{-1}
C.W. Intensity	10^{12} s^{-1}



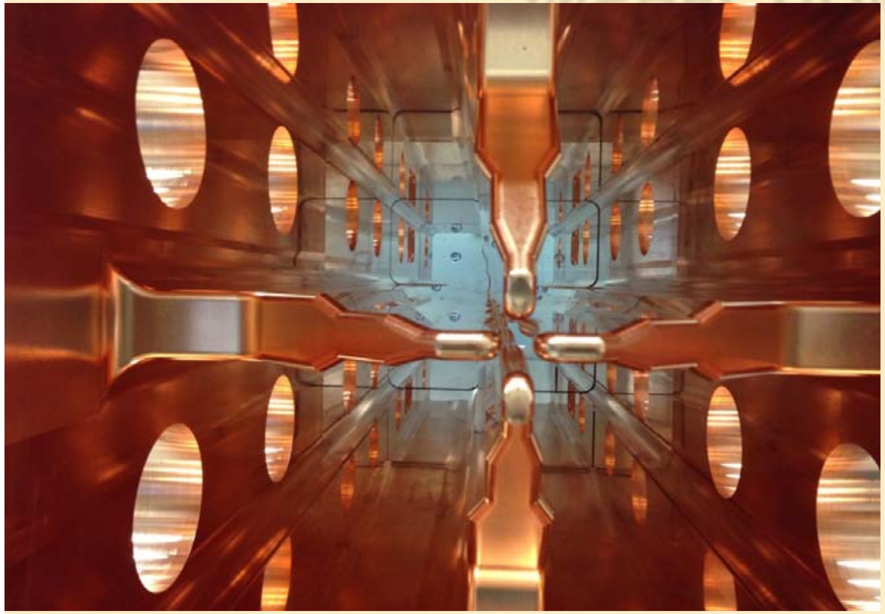
Time structure of neutron source

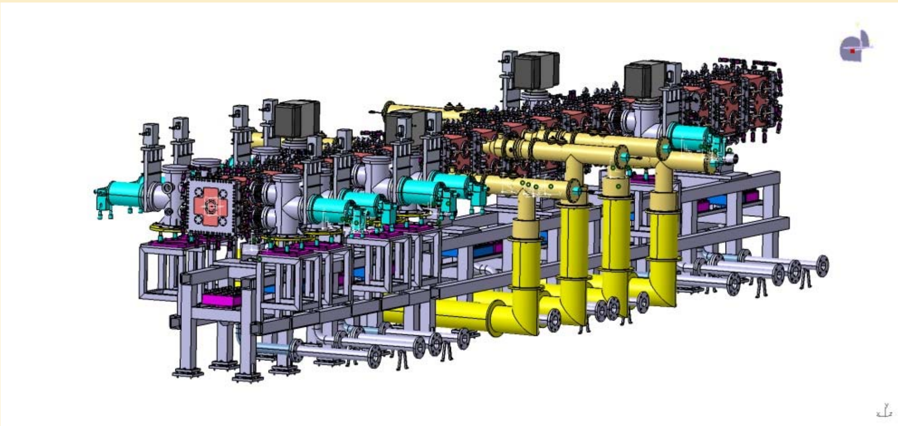


TIME RESPONSE: PROMPT + DELAYED FISSION NEUTRONS



A HIGH-POWER NEUTRON SOURCE FOR ACTIVE INSPECTION OF THE WASTE





IFMIF-EVEDA , prototype accelerator for the IFMIF system devoted to material tests for the fusion program, uses as first stage an RFQ under construction by INFN:
it will be the most powerful RFQ in the world, with a length of 9.8 m, it will provide 130 mA of deuterons at 5 MeV kinetic energy

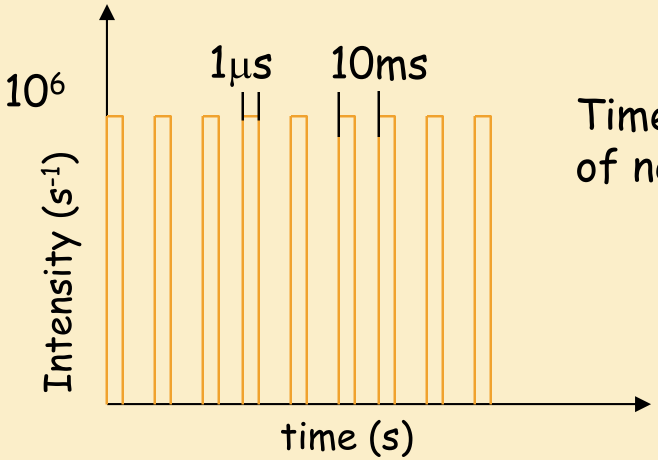
- Main applications:
  - Injectors of multi MW linacs (protons E>1GeV) for multi MW spallation neutron sources (e.g. **ADS** for nuclear waste transmutation, **radioactive nuclear beams**) or neutrino production
  - Injector for deuteron linac (about 40 MeV) for **Fusion Material Irradiation** tests under large neutron fluxes.
- Lower beam power (e.g. 5 MeV 30 mA)
  - Stand alone application as neutron source for **Boron Neutron Capture cancer Therapy**
  - Intense pulsed neutron source for nuclear waste characterization
  - (Part of special grant from Ministry of Education, University and Research, 2012)

INFN Legnaro National Laboratory

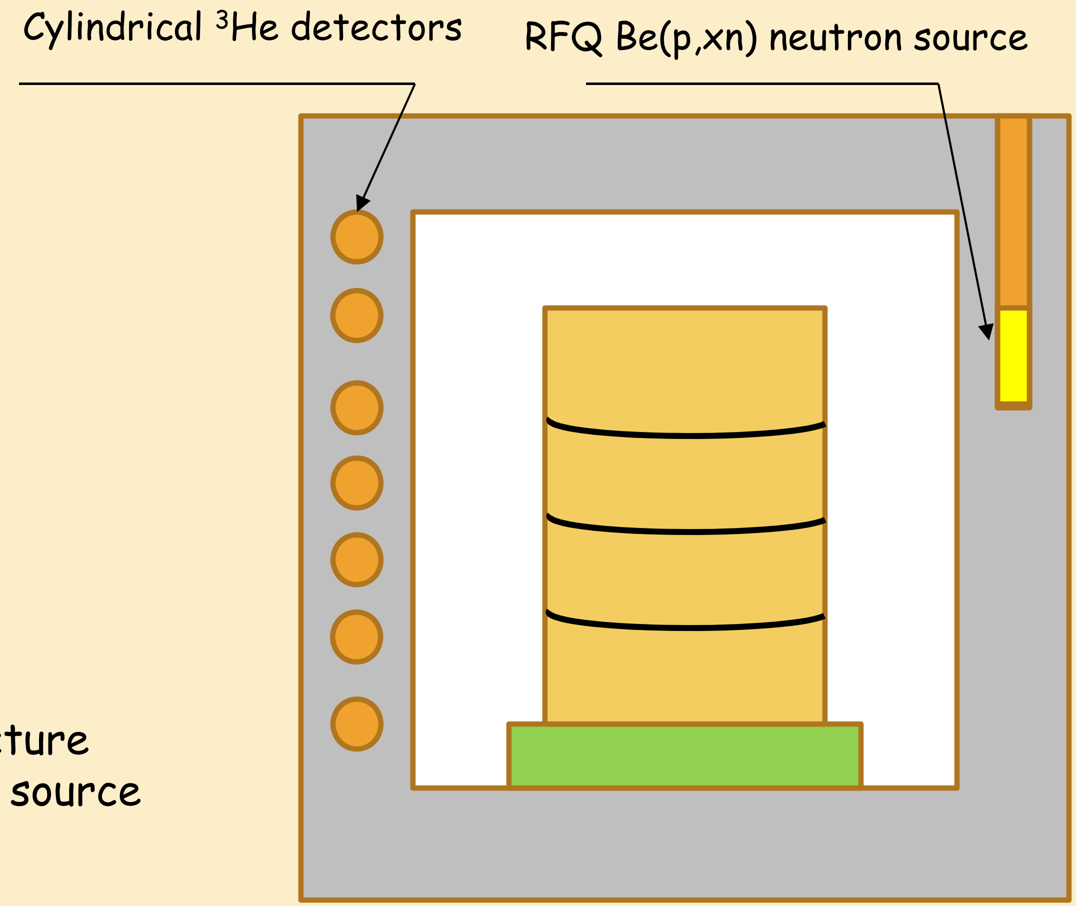
RFQ-BASED NEUTRON SOURCE

Be(p,xn) neutron source
→ 30 mA, 5 MeV proton beam from RFQ

Emitted neutrons:	10^8 /pulse
Max Energy:	~3.2 MeV
Average Energy:	~1.2 MeV
Pulse duration:	1 μs
Rep rate:	100 Hz
Duty cycle:	10^{-4}
Average intensity:	10^{10} s^{-1}
C.W. Intensity:	10^{14} s^{-1}



Time structure of neutron source



With a high-power source (10^9 n/pulse in 10 μs 100 Hz, neutron average energy 1.2 MeV against 14) the sensitivity to Pu contamination can be dramatically improved

WASTE MANAGEMENT IN HORIZON 2020

INFN participates as third party to a Consortium formed to respond to the call EURATOM Fission NFRP-2014-2015

Topic: EU concerted development of Member State research on radioactive waste management

Also, INFN was accepted as a member of the Technology Platform "Integrating Geological Disposal of radioactive waste" (IGD-TP)
P. Finocchiaro (LNS) is INFN contact person

safe solutions for radioactive waste

Courtesy by SKB Photo: Lasse Modin

RADIATION PORTAL MONITORS: STANDARD REQUIREMENTS

There are two main standards for Radiation portal monitors

- The **ANSI** American National Standard
- The **IEC** International Electrotechnical Commission

- **ANSI N42.35** American National Standard for Evaluation and Performance of Radiation Detection Portal Monitors for Use in Homeland Security
- **IEC 62244** Radiation protection instrumentation - Installed radiation monitors for the detection of radioactive and special nuclear materials at national borders

Slight differences between the two standards based on source activities used for testing and test procedures

RPM RADIATION TESTS

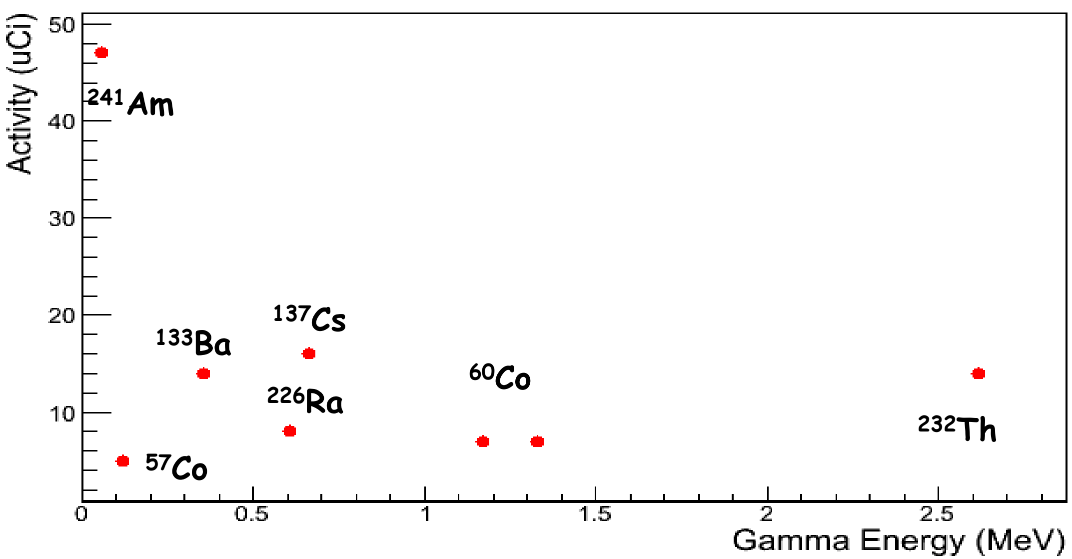
- **Response to gamma radiation:** Gamma sources from ^{241}Am up to ^{232}Th
- **Response to neutron source:** ^{252}Cf
- **Response to shielded neutron source:** ^{252}Cf + HDPe (high density polyethilene) or PMMA (polymethylmethacrylate) moderator
- **Response to masked neutron source:** ^{252}Cf + strong activity gamma source (^{137}Cs)
- **Dynamic tests** (source is moving in front of the system)

	Vehicles**	Pedestrian**
Source distance* from detector surface	2.5m	1m
Source height from ground (center)	~1.2m	~1.2m
Speed	2.2m/s	1.2m/s

* For a system made of 2 pillars
** two examples of RPM usage cases

ANSI: RESPONSE TO GAMMAS AND NEUTRONS

Source	Act(uCi)	Act(MBq)
^{137}Cs	16	0.59
^{241}Am	47	1.74
^{133}Ba	14	0.52
^{57}Co	5	0.19
^{60}Co	7	0.26
^{232}Th	14	0.52
^{226}Ra	8	0.3



The neutron source is a ^{252}Cf source, emitting 20kn/s, gamma-shielded with a 1cm steel + 0.5cm lead

- All tests must be performed at 3 detection points: bottom, center and at the top of the system
- All system has to show at least 59 alarms for 60 transits to consider the test passed

"SCINTILLA" EU PROJECT

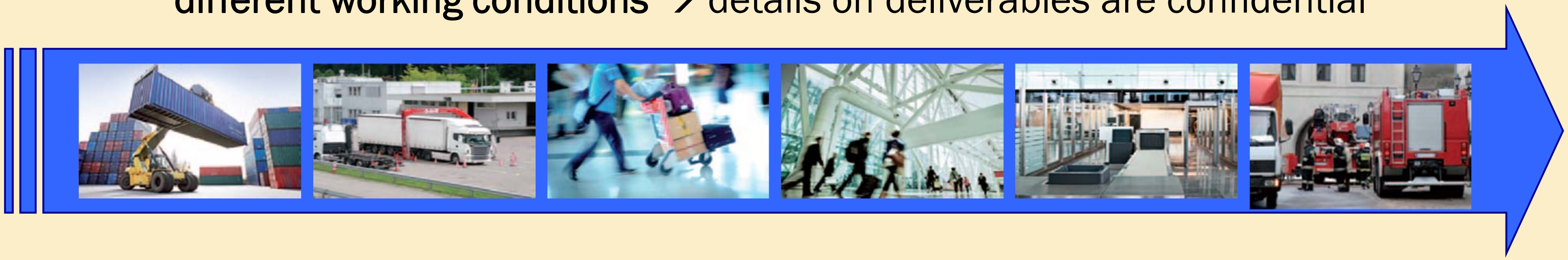
SCINTILLA is a European project within the 7th Framework Program (2007/2014)

International consortium of **9 groups:**

- 5 research groups: <u>*CEA, EK, Fraunhofer INT, INFN and JRC*</u>
- 4 companies: <u>*Ansaldo Nucleare (ANN), Arttic, Saphymo and Symetrica*</u>

Seventh Framework Programme (FP7/2007-2013). Grant Agreement n.285204

The aim of the project is to develop of a **toolbox of devices for nuclear safety to monitor and detect nuclear materials, masked and shielded radioactive sources in different working conditions** → details on deliverables are confidential



INFN & ANN developed a Radiation Portal Monitor (RPM) device for the inspection of containers and vehicles

Neutron and gamma radiation detector based on the Gd-lined plastic scintillator technology

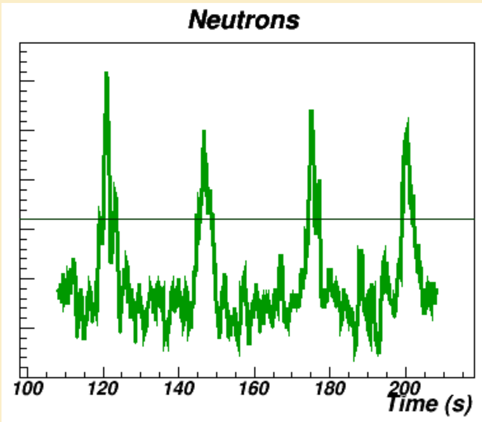
PROTOTYPE TEST

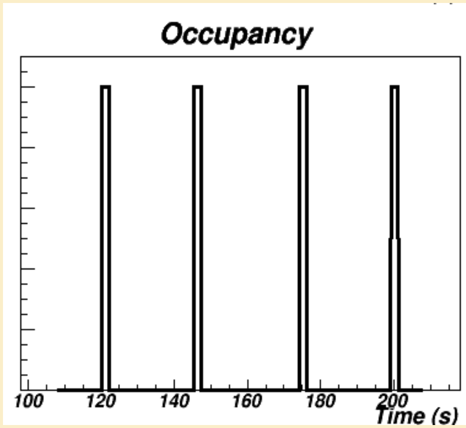
Gd-lined plastic scintillator detector

- Patent request presented in October 2013
- Scintilla Benchmark on February 2014 at the JRC-Ispra facility:

Detector performances comply or exceed the RPM international standards for both gamma and neutron detection

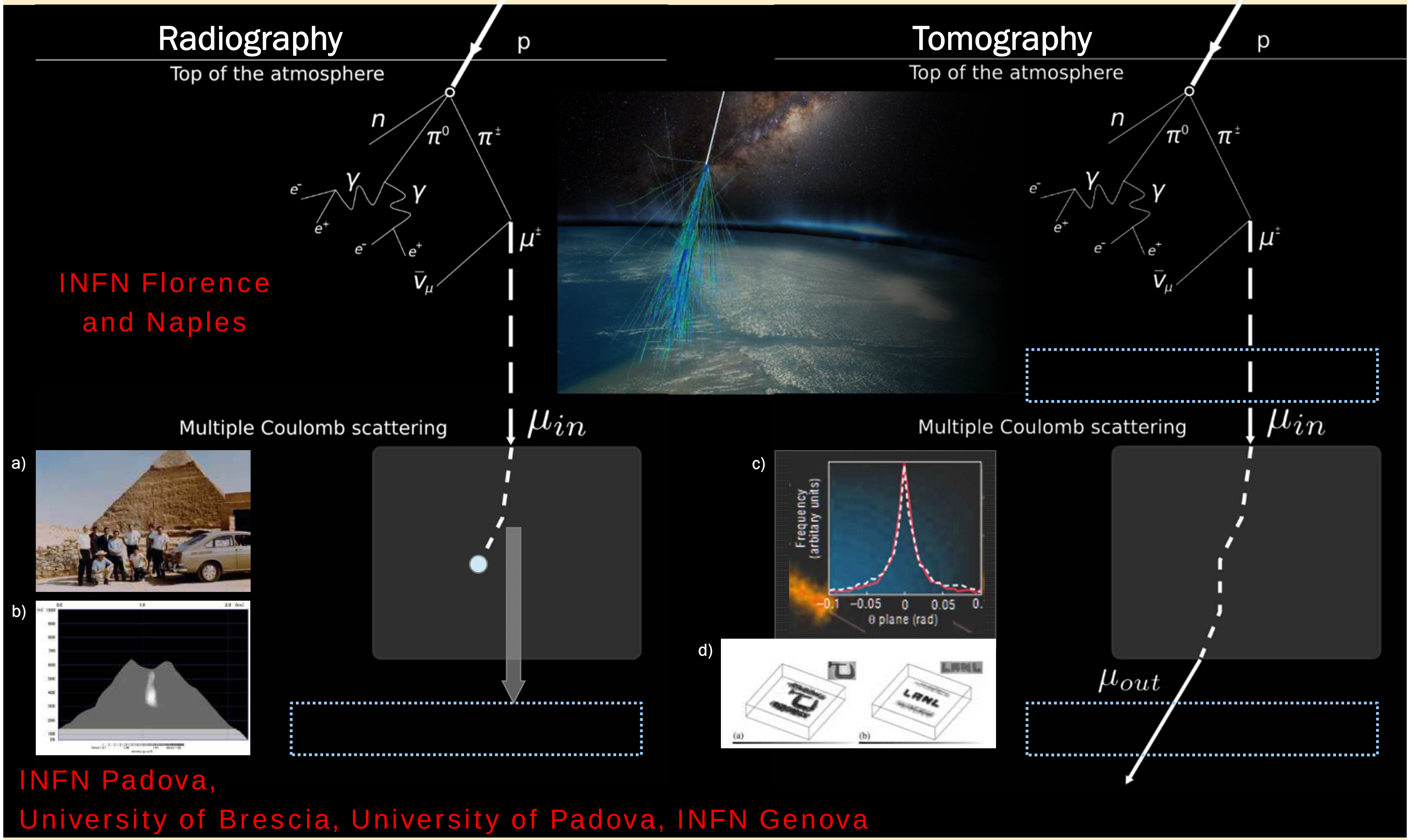
- Final Scintilla benchmark planned in November 2014. It will be performed with a full prototype system based on 2 pillars.





Ex. Of 4 cart transits of a ^{252}Cf neutron source shielded from gammas @1.5 m distance and 1.2 m height from single pillar detector

INSPECTIONS BY COSMIC MUONS



MU-STEEL EU PROJECT

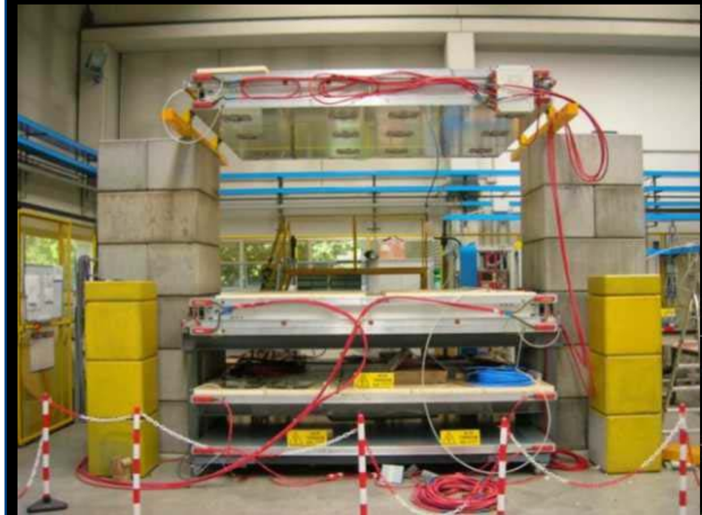
Research Fund
for Coal & Steel

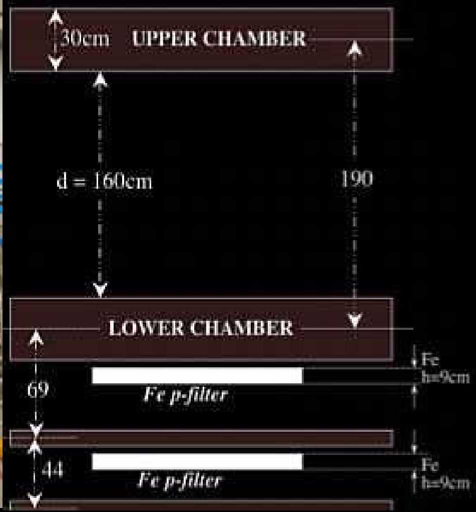
PROJECT TITLE:
"MUONS SCANNER TO DETECT RADIOACTIVE SOURCES HIDDEN IN SCRAP METAL CONTAINERS"

Grant Agreement Number: RFSR-CT-2010-00033

1. TECNOGAMMA
2. PADOVA UNIVERSITY (Physics Dept. & Information Engineering Dept.)
3. INFN
4. BRESCIA UNIVERSITY (Mechanical Engineering Dept.)
5. S.R.B. COSTRUZIONI SRL CONSTRUCTION COMPANY
6. AFV BELTRAME SPA STEELWORKS

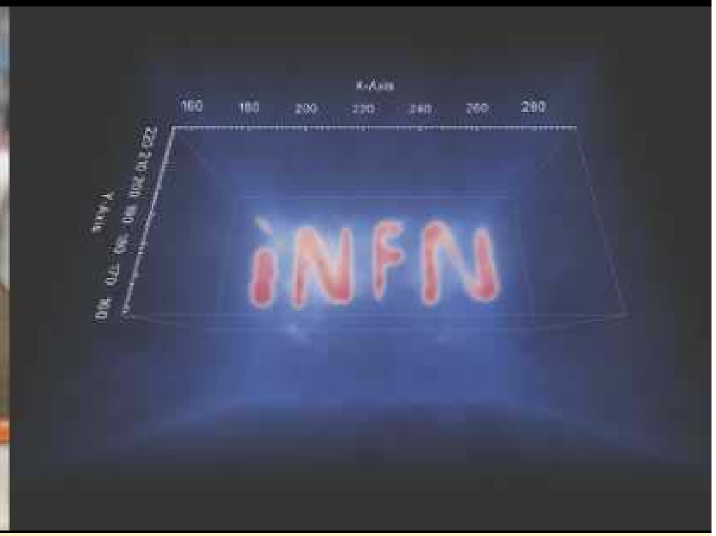
TOMOGRAPHY: THE DEMO





At INFN National Laboratories in Legnaro, a demonstrator based on the technology developed for the CERN experiments has been realized

A system of hardware and software components were developed by the group to test and refine the technique



“ORPHAN SOURCES”: A TEST WITH THE DEMO

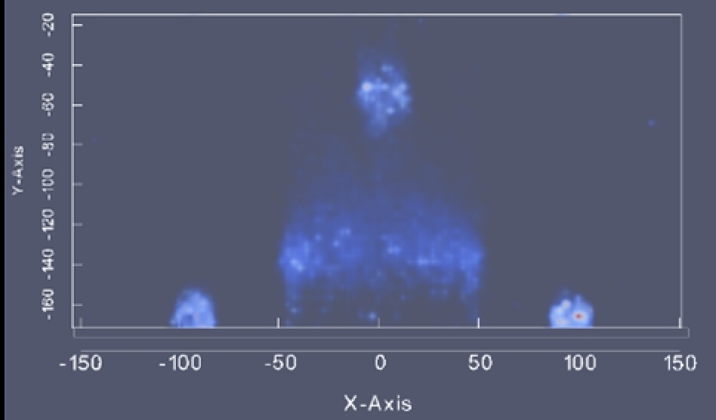
A mockup of a complete portal for the detection of shielded orphan sources has been set up

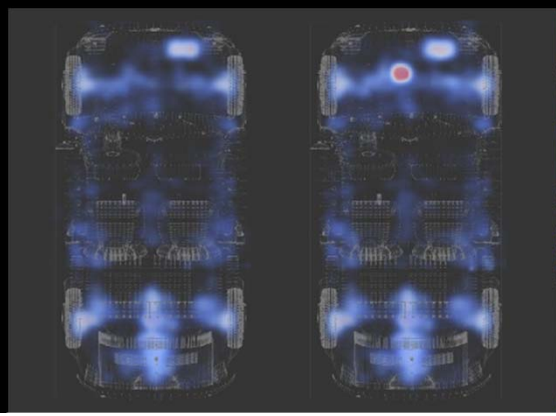
Blocks of various sizes of lead were hidden in baskets of scrap to create a model of the real environment to inspect

12 liters **lead** test

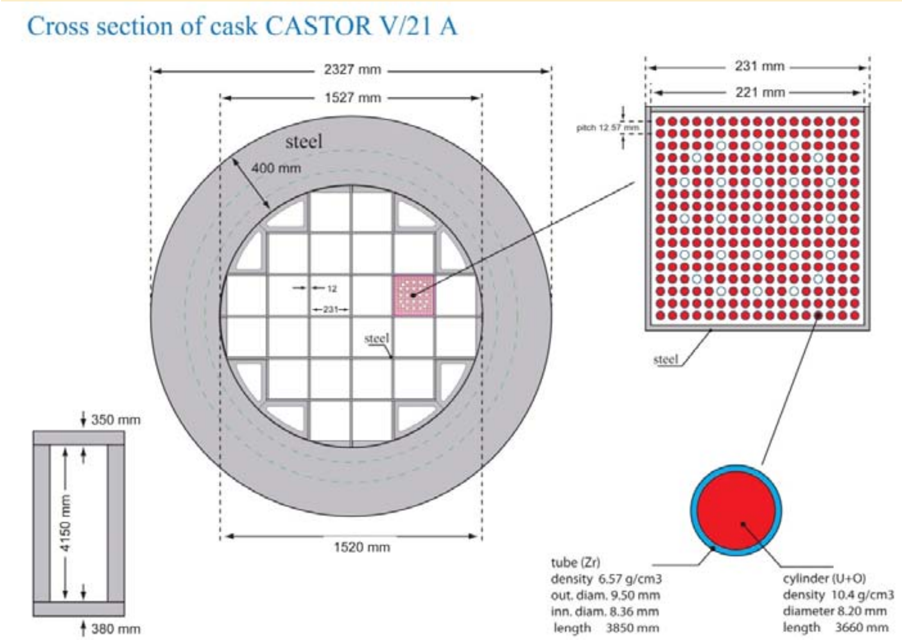
100x100x65 cm
fine scraps metal container

Imaging of the denser structures in 5 min data taking



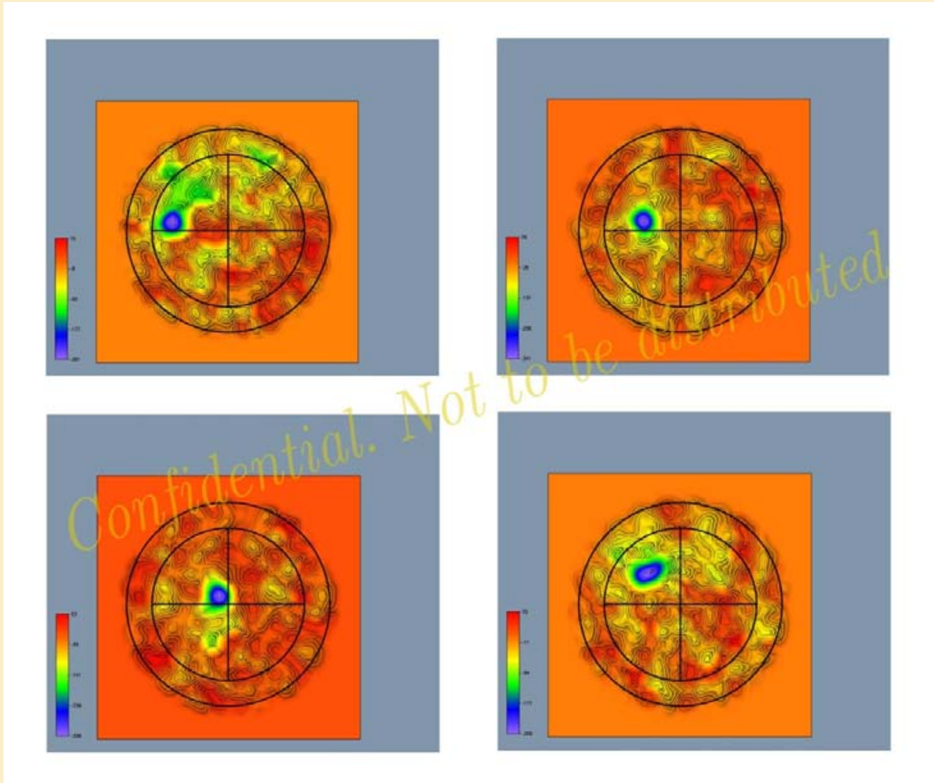


CASTOR® INSPECTIONS



CASTOR®: CAsk for Storage and Transport Of Radioactive material

Simulation of 1 hr exposure



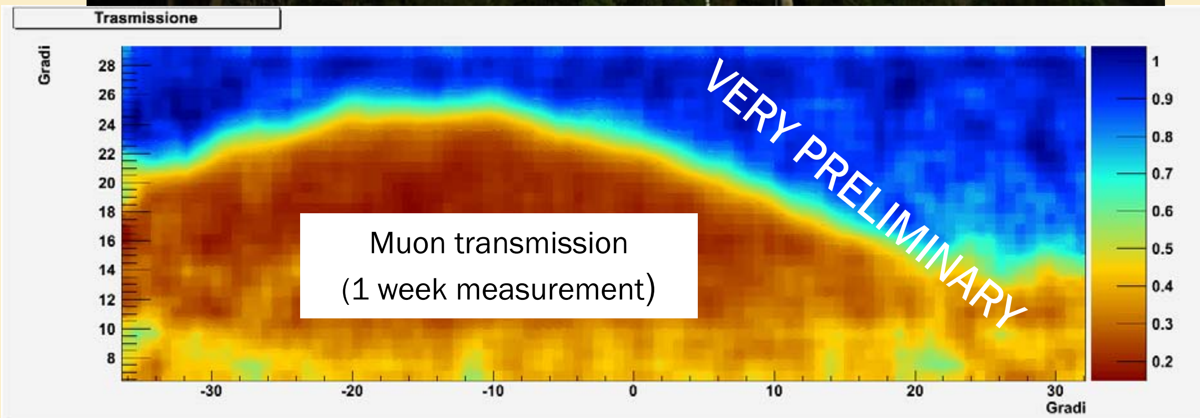
Altre applicazioni

Mu-Blast: characterization of furnaces

Approved EU project

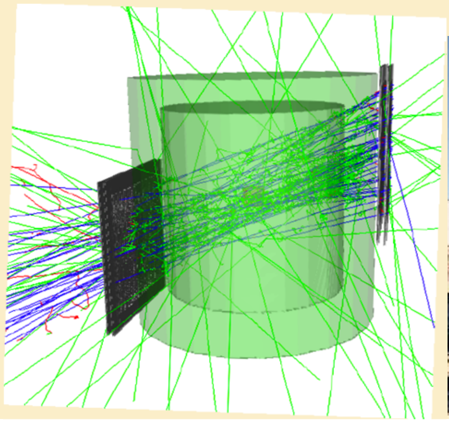
Research Fund for Coal & Steel

RADIOGRAPHY: THE "MU-RAY" DETECTOR



Possible applications at waste storage sites: Sellafield UK Legacy Nuclear Waste Collaboration with University of Glasgow and NNL/Sellafield

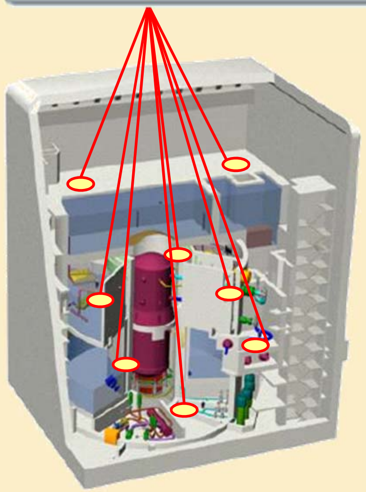
Small silo



Large silo

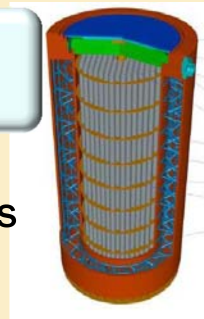
POWER PLANTS, SPENT FUEL AND CASTOR® SURVEILLANCE

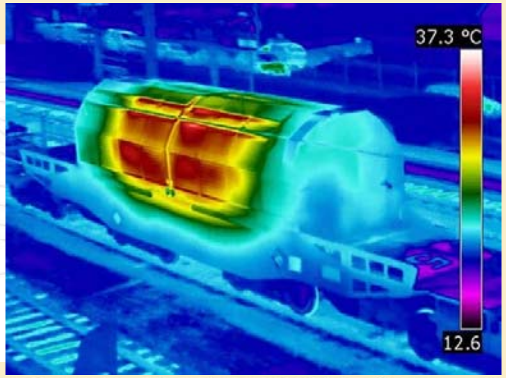
out-of-core monitoring in NPP



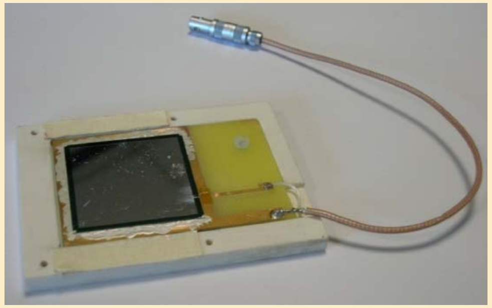
why neutrons?

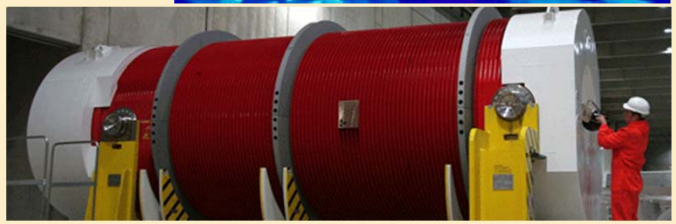
spent fuel monitoring
in place and/or during transportation

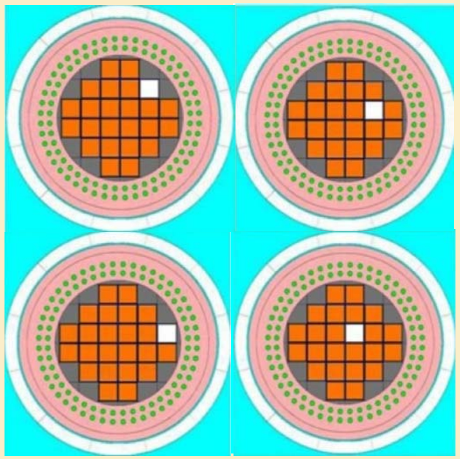




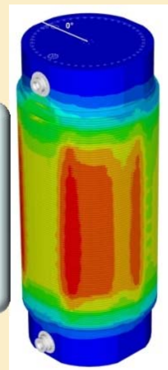
^{3}He-free Lithium-based neutron monitors





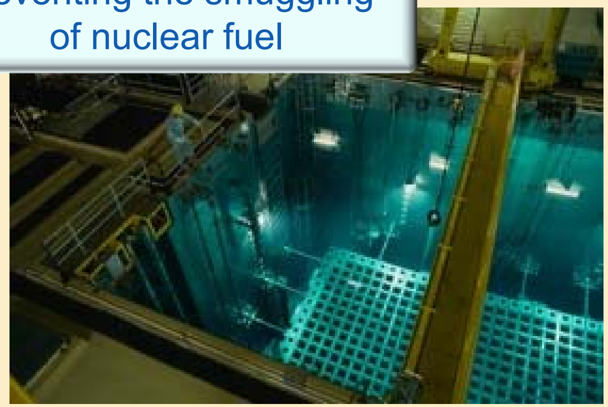


detection of possible diversion of fuel elements from Castor containers



(P.Peerani, M.Galletta, Nuclear Engineering and Design 237 (2007) 94-99)

preventing the smuggling of nuclear fuel



INFN National Southern Laboratory, Catania in collaboration with Joint Research Center EURATOM, Ispra (Italy)

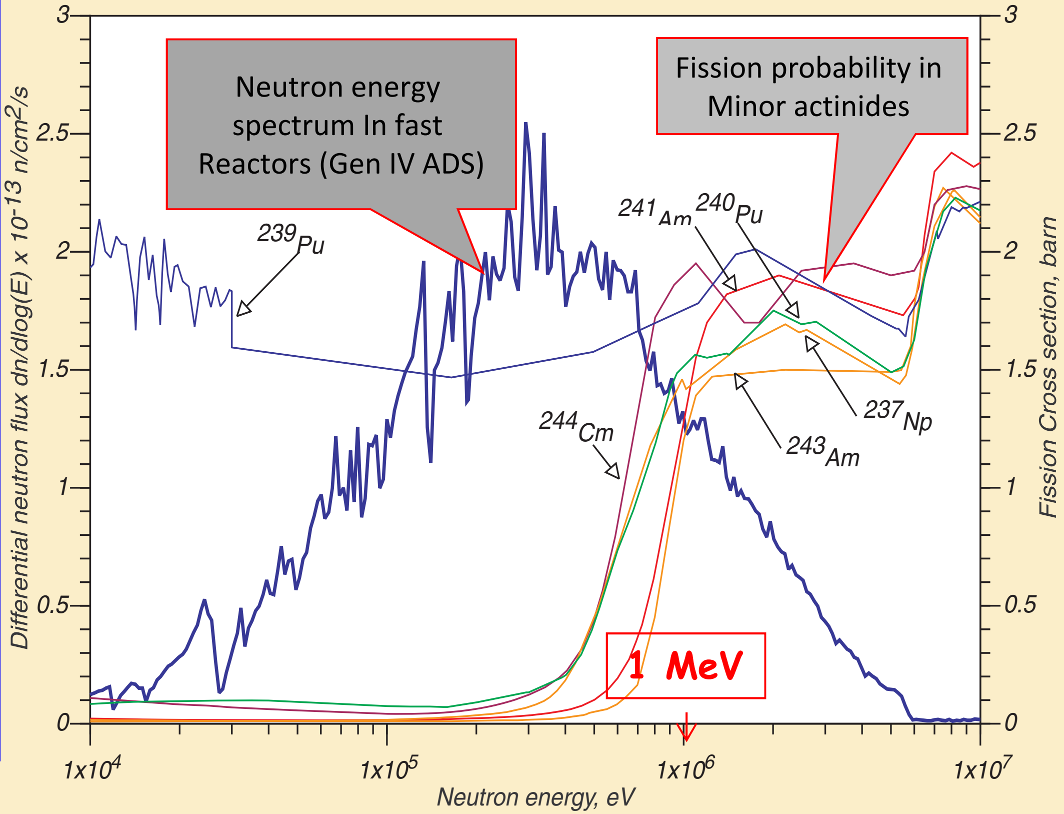
(INFN patent pending RM2013A000254)

INCINERATING LONG-LIVED MINOR ACTINIDES

Apart for ^{245}Cm, minor actinides are characterized by a **fission threshold** around the **MeV.**

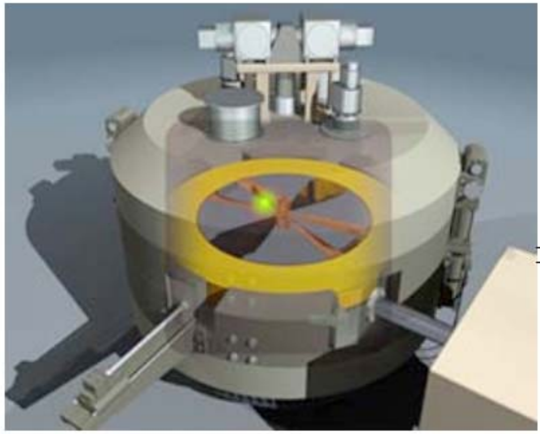
In order to transmute actinides, need **fast neutrons → minimal moderation** in intermediate medium → (cooling) medium must be **gas, sodium, lead,** etc.

➔ Such isotopes can be burnt in **fast reactors or in fast Accelerator Driven Systems (ADS)** (neutron spectrum from 10 keV to 10 MeV)



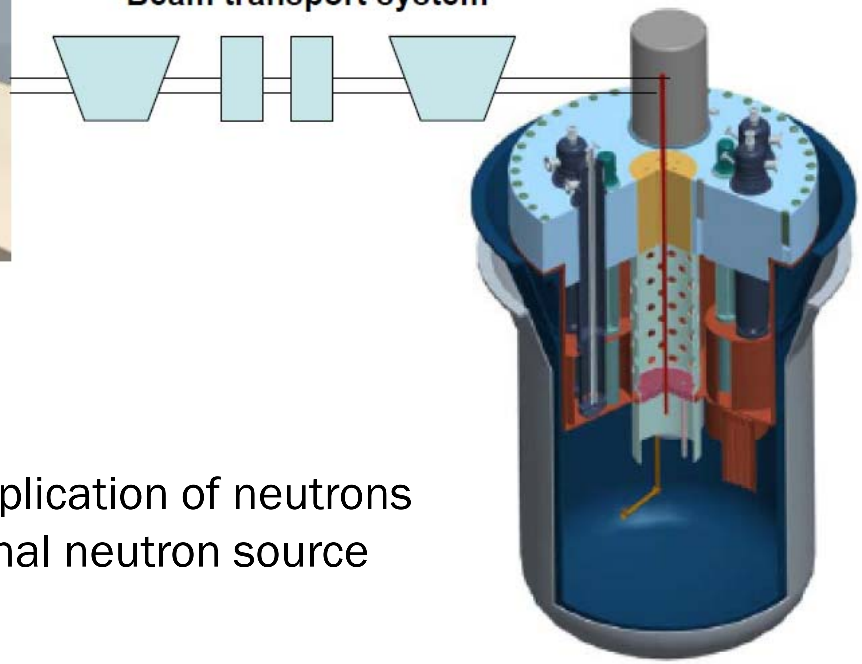
Fast ADS → good candidates as transmuters of high activity and long lifetime (thousands of years) Generation III reactor waste into much shorter lifetime fragments (few hundred years), to be stored in temporary surface storage. But further R&D is still needed

ACCELERATOR-DRIVEN SYSTEM: A 3-COMPONENT INFRASTRUCTURE

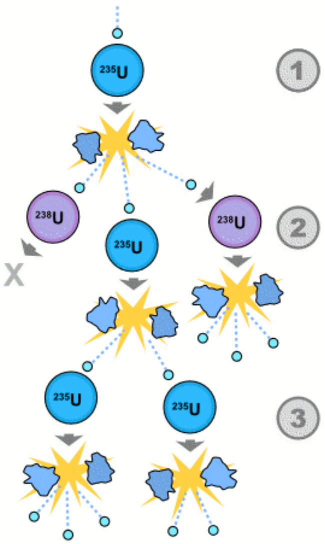


Proton accelerator

Beam transport system



Subcritical reactor



In ADS, effective multiplication of neutrons is < 1→ need an external neutron source → accelerator+target

The maximum thermal power P_{th} from the subcritical reactor is limited (and controlled !) by the input beam power P_{beam}

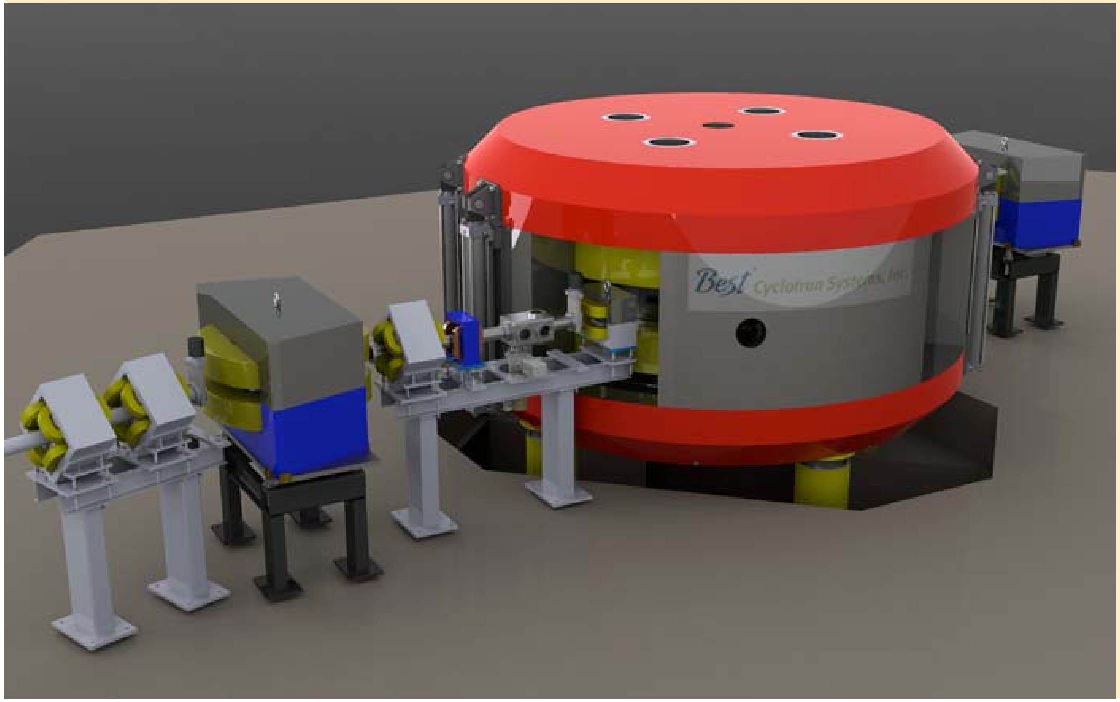
THE PROPOSAL FOR A LOW POWER ADS

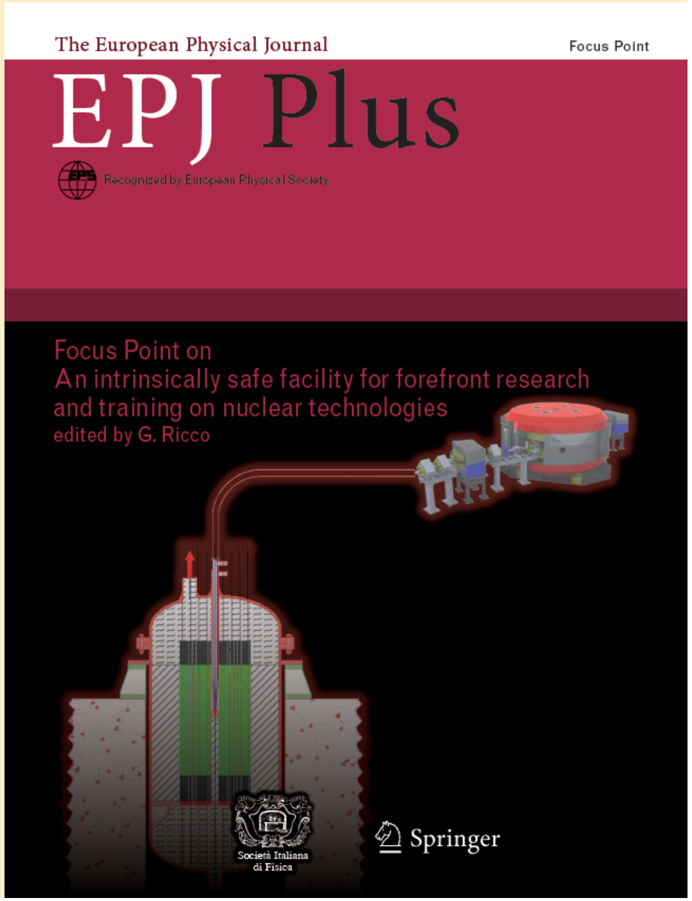
Motivation

- Reference to **70 MeV, 0.5 mA proton** cyclotron purchased by INFN for Legnaro Laboratory as a possible driver
- Collaboration with Ansaldo Nucleare, leader in technology for fast reactors based on **Lead coolant** (also, one of the proposed technologies in the EU)
- Choice of **Pu-free fuel** to minimize security issues → UO_2 w/ 20 % ^{235}U
- **Low thermal power 150-200 kW** to limit safety issues but sufficient to study some aspects of dynamics
- **Temperature < 300 C^{o}** → solid Lead matrix
- k_{eff} **~ 0.95** (limit for storage facil's)
- Relatively low beam energy → Target: Beryllium (weakly bound n)

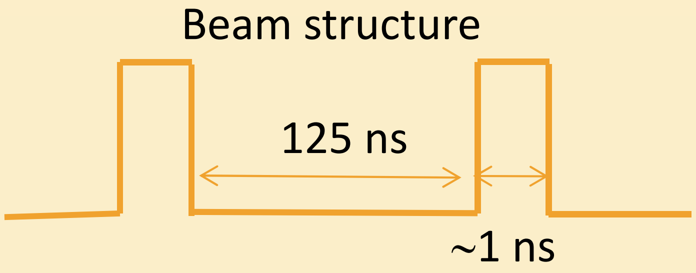
Broad collaboration between

- INFN
- Ansaldo Nucleare
- ENEA
- Milan Polytechnic University
- Turin Polytechnic University,
- LENA-University of Pavia
- University of Genoa





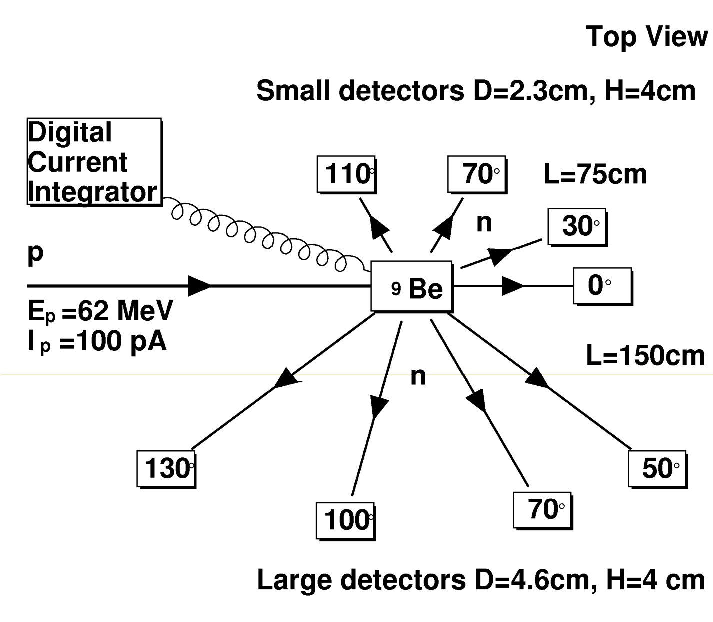
NEUTRON YIELD FROM BE TARGET AT LNS-CS



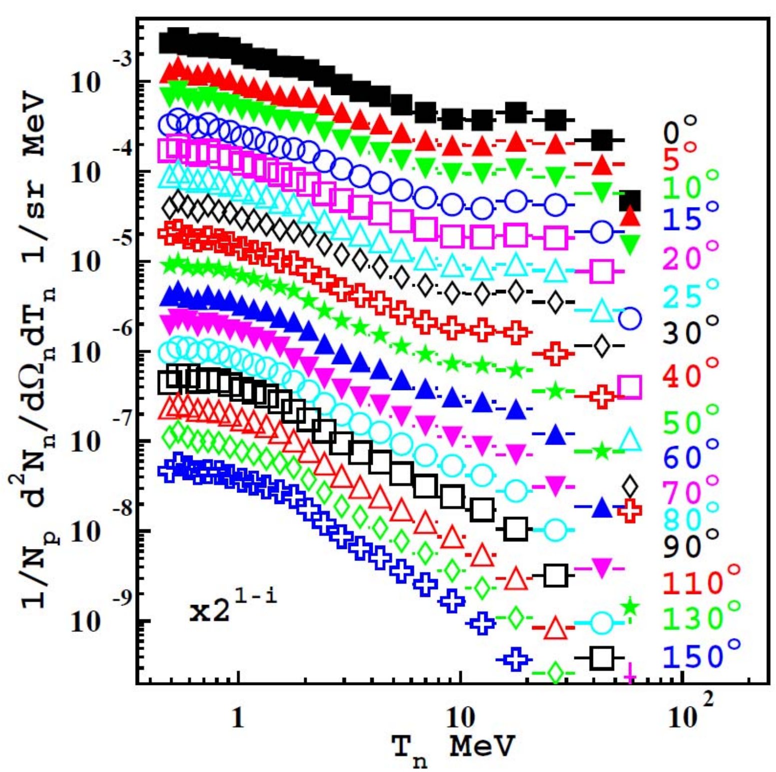
$$T_n = \frac{1}{2} M_n \left(\frac{L}{t_{hit} - t_{RF}} \right)^2 \Rightarrow \frac{1}{N_p} \frac{dN_n}{d\Omega_n dT_n}$$

Experimental setup:

- 8 detectors measured simultaneously
- Two dynamical ranges: T_n=0.5-2 MeV and T_n=2-60 MeV



Nucl. Instrum. Meth. A723 (2013) 8-18

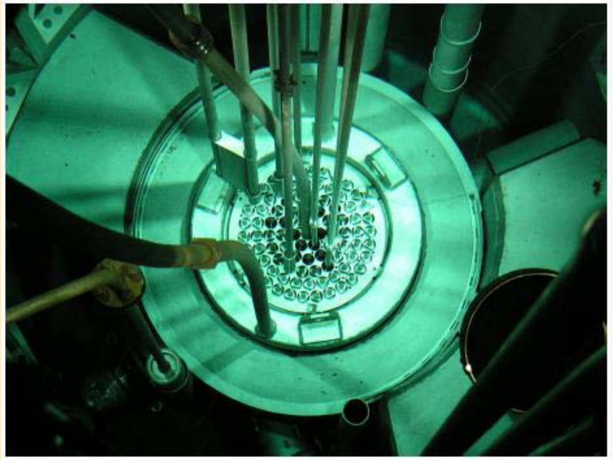


DAEδALUS
A Phased Physics Program Using Decay-at-Rest Neutrino Beams

⇒ Dati utili per
n+^{7}Li→^{8}Li
Progetto ANL
per ν CP violation

KNOWING FISSION REACTORS BETTER

- Systematic study of TRIGA research reactor fast neutron components in various locations
- Identifying fast irradiation channels in the TRIGA
- Study of transmutation of Uranium and Transuranics
- Study of materials for fast reactors



- Complete development of thermohydraulic model
- Implementation of “parametric“ multiphysics model
- System for direct measurement of fuel rod poisoning
- Analysis and validation of computing techniques for multiplying assemblies
- Study and design of a fast neutron facility

Based on the **analysis of 48 yrs of reactory history**, core has been **reconfigured**
→ Reactivity increased by 0.5 \$ without adding fuel
→ Core Excess values simulated: 2.63±0.05 \$, measured: 2.49±0.03 \$

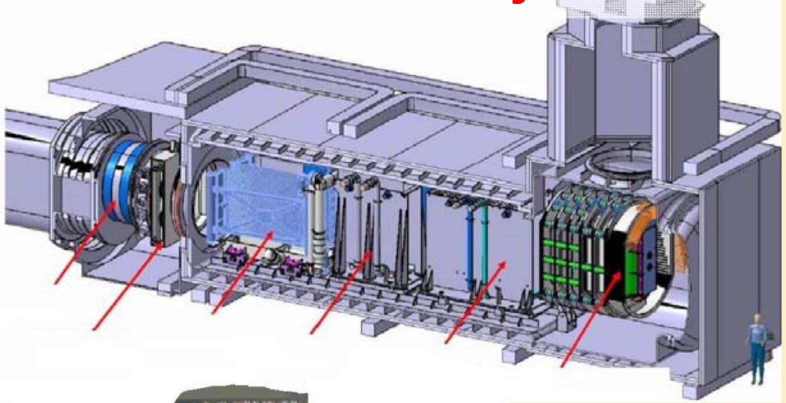
INFN application to become a member of EERA-SET (JP Nuclear Materials)

EERA
European Energy Research Alliance
Coordinating energy research for a low carbon Europe

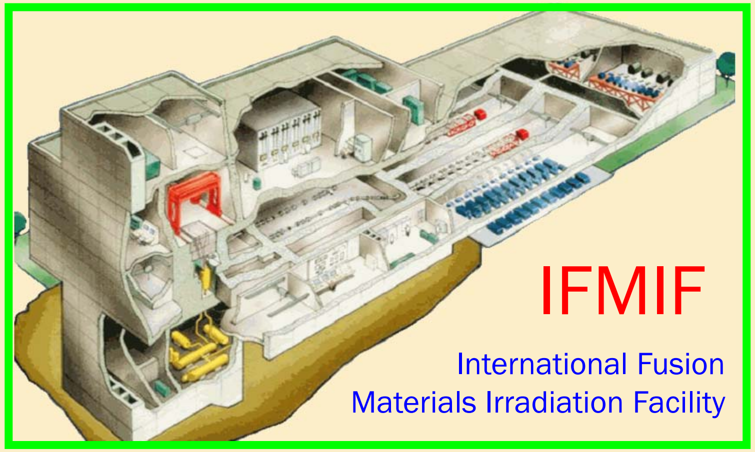
INFN Milano Bicocca
University of Pavia – Laboratory for Applied Nuclear Energy (LENA)

FUSION RESEARCH

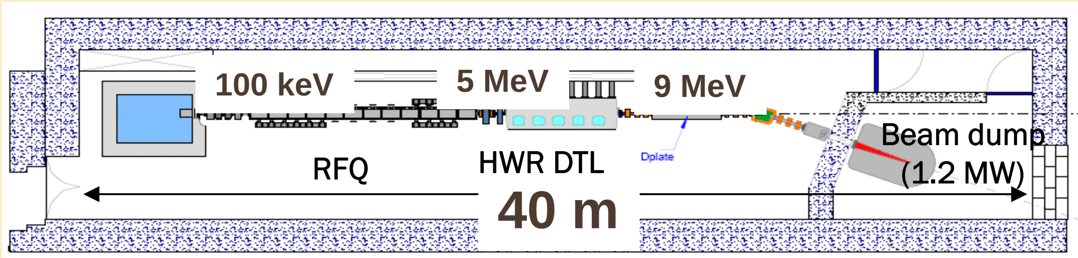
Neutral Beam Injection



Test D2- source:
INFN Legnaro National Laboratory

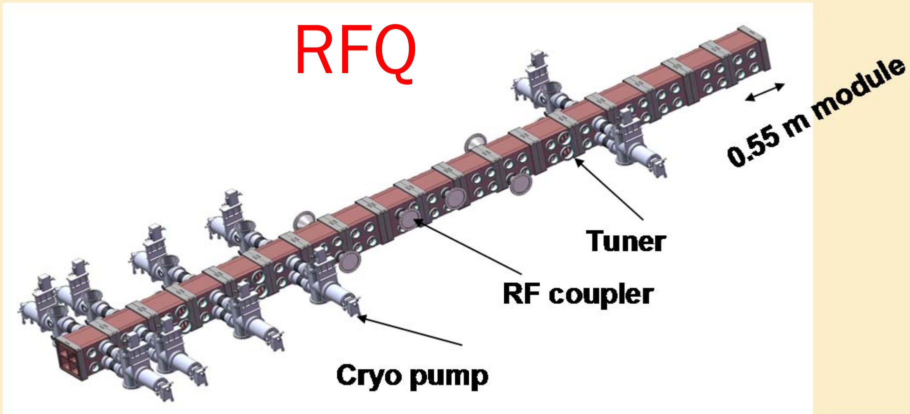


Prototype IFMIF-EVEDA

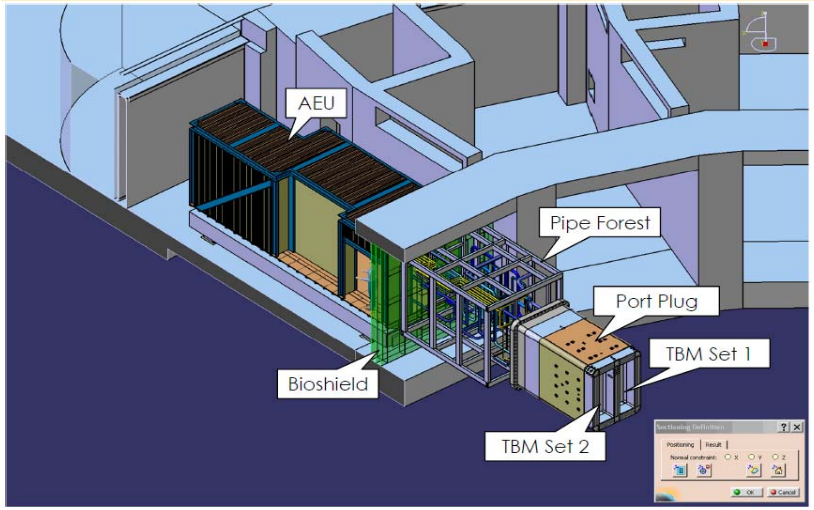


INFN Legnaro
National Laboratory,
Padova, Turin,
Bologna

RFQ



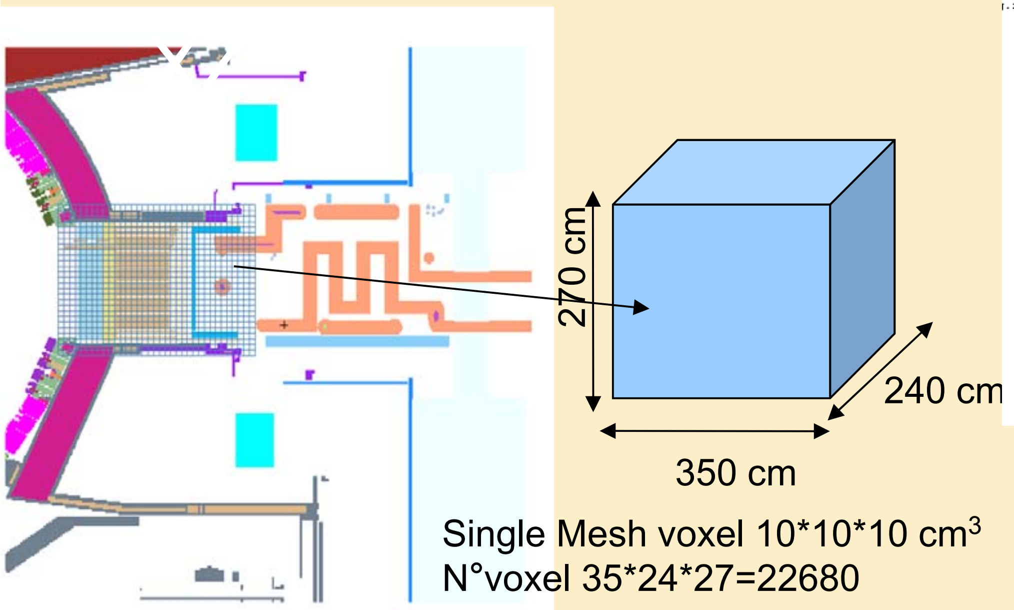
TEST BLANKET MODULES SHUTDOWN DOSE RATES



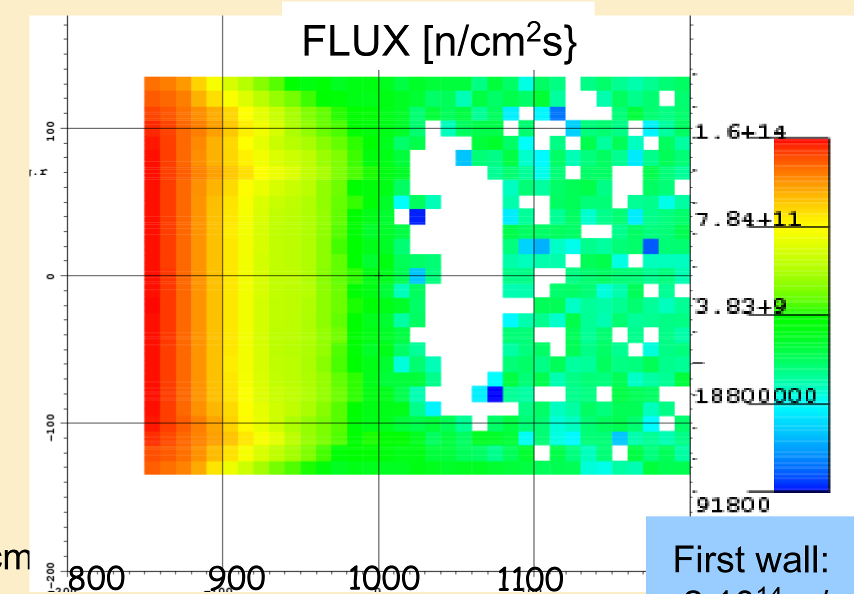
Nuclear Safety Authority limits:

- 100 μSv/h 10^6 s after the shutdown in the Pipe Forest Region [$\phi \sim 10^7$ n/(cm^{2}s)]
- 10 μSv/h 24h after shutdown beyond the bioshield, where the Ancillary Equipment Unit (AEU) is located

PRELIMINARY RESULTS: NEUTRON TRANSPORT
Low statistics → need to reduce variance



Single Mesh voxel 10*10*10 cm^3
N°voxel 35*24*27=22680



First wall:
2 10^{14} n/cm^{2}s
After 1 meter:
~ 5 10^9 n/cm^{2}s

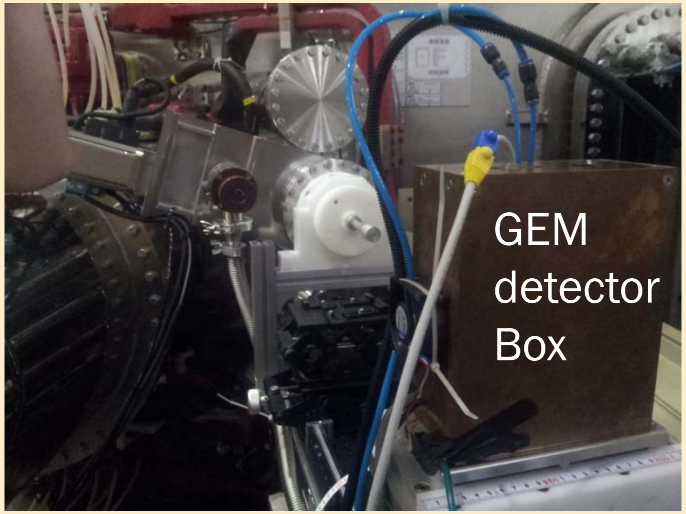
PhD Thesis University of Genova

X-RAY PICTURES OF BURNING PLASMA

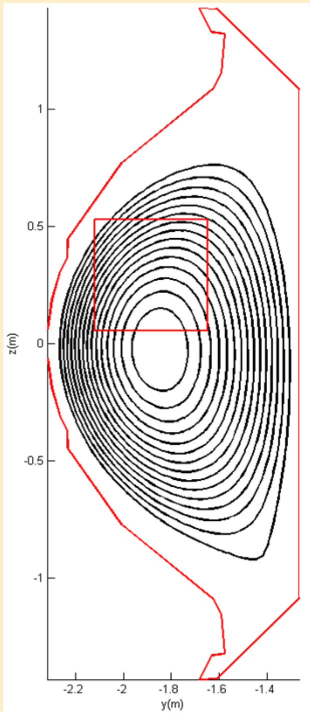
- Soft X-ray (~ 10 keV) diagnostics at present not adequate for a burning plasma experiment, neither in term of hardware nor as diagnostic concept
- Detectors have to be radiation tolerant, easily shielded, with low sensitivity to neutrons and gammas and with energy discrimination
- Layout and viewing capability should be more flexible, thanks to the use also of optical devices, going toward a configuration intermediate between discrete tomography and pure imaging
- The general concept of these diagnostics should therefore evolve in the direction of pattern recognition for a real time feedback

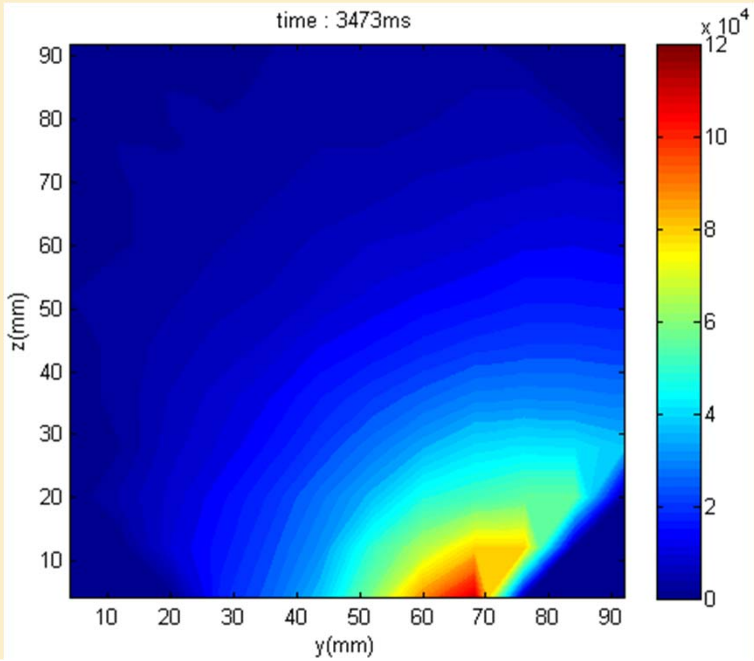
D. Pacella et al., X-ray diagnostic developments in the perspective of DEMO
to be published in Proceedings of the Conference on Diagnostics for DEMO Varenna Italy (2013).

X-RAY IMAGING WITH GEM AT KOREAN TOKAMAK KSTAR



Energy 3÷15 keV





FLUXES AND BACKGROUND

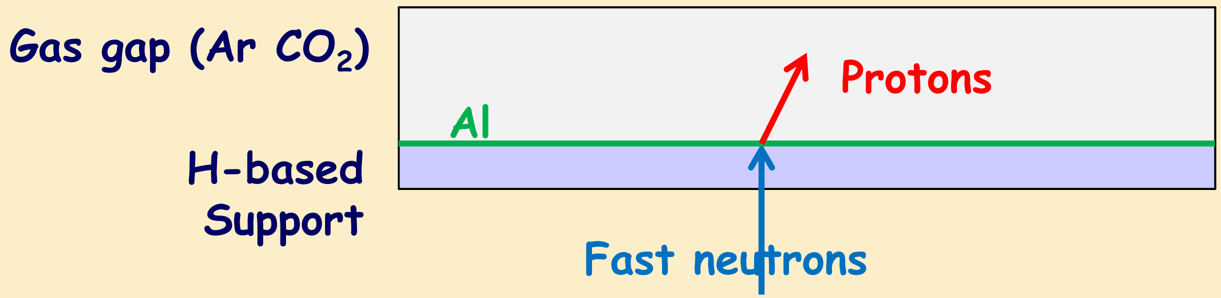
- **Total neutron flux on KSTAR** for these shots having 2 NBI heating, as estimated from neutron diagnostics, is **about 10^{14} n/s**

- **Neutron background** measured with the GEM detector, based on the calibration done at FNG, is 5×10^7 n/s cm^2 (producing about **2×10^3 counts/s pixel**) → coherent with the total neutron yield of KSTAR

- **X-ray signal** produced in the GEM detector **arrives to $7x10^6$ counts/s pixel**, being three-four order of magnitude higher than the neutron background

GEM FOR FAST NEUTRONS

Fast Neutrons interact with H, and protons are emitted entering in the gas volume generating a detectable signal.

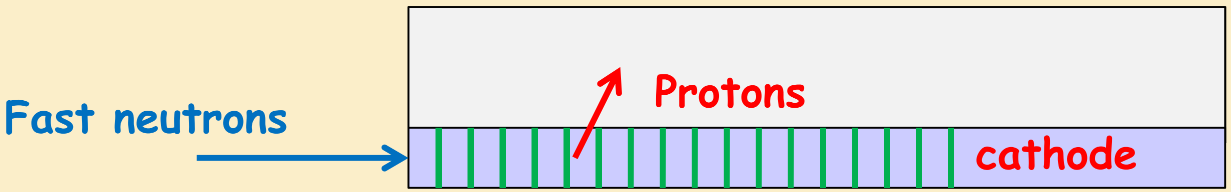


Low Efficiency

Big active area

Beam Monitor and transmission

Side-On detector

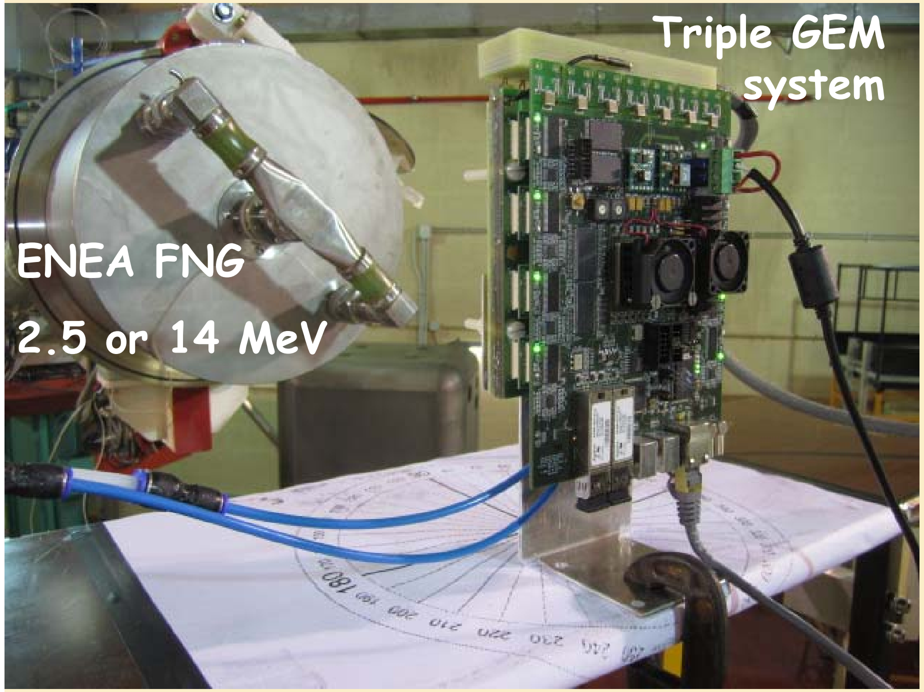


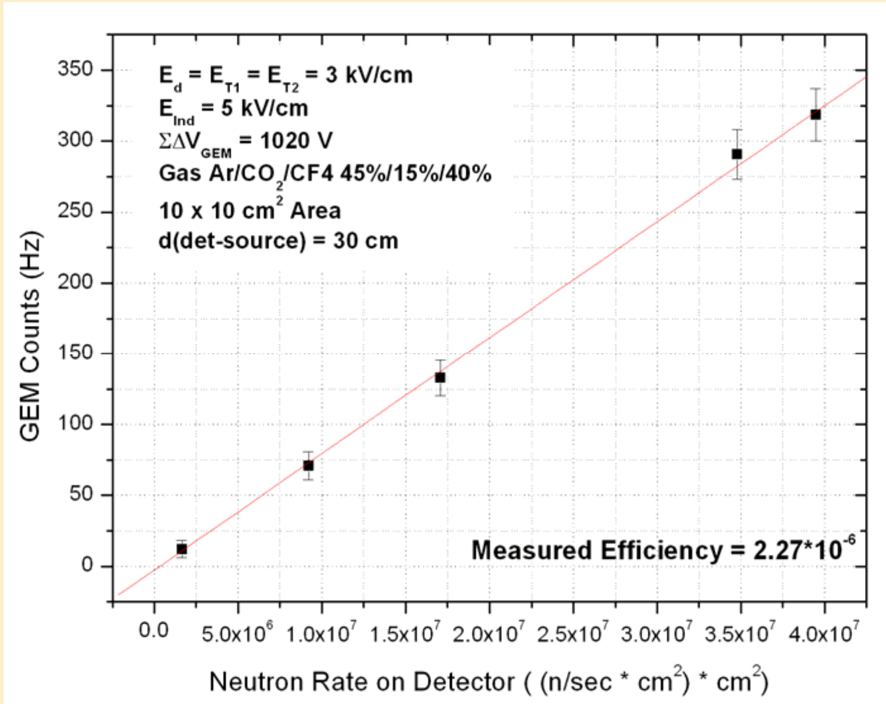
High Efficiency

Small active area

TEST AT FAST NEUTRON GENERATOR

Measurement of the PH spectrum acquired under 2.5 MeV neutron irradiation at different angles with respect to beam direction and comparison with MCNP.
As expected the integrated PH counts decrease when increasing the angle.

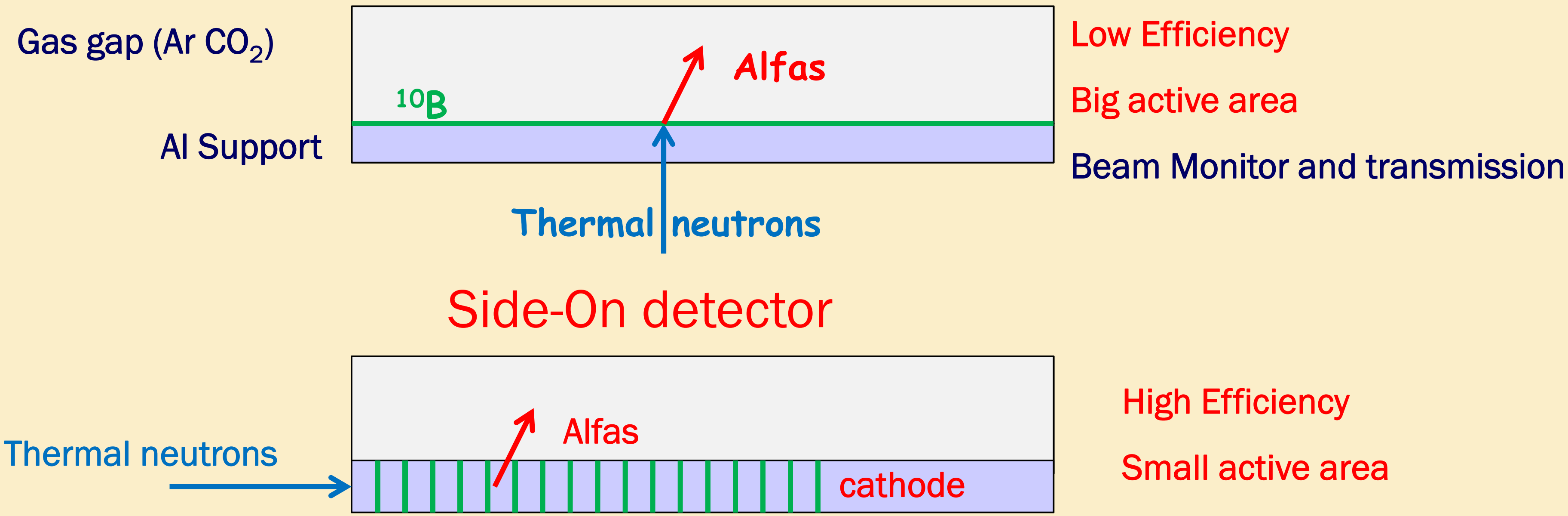




Good linearity measured up to $4x10^7$ neutron/sec cm^2
the maximum rate reached by this facility

^{10}B CATHODE FOR THERMAL NEUTRON

Thermal Neutrons interact with ^{10}B, and alfas are emitted entering in the gas volume generating a detectable signal.



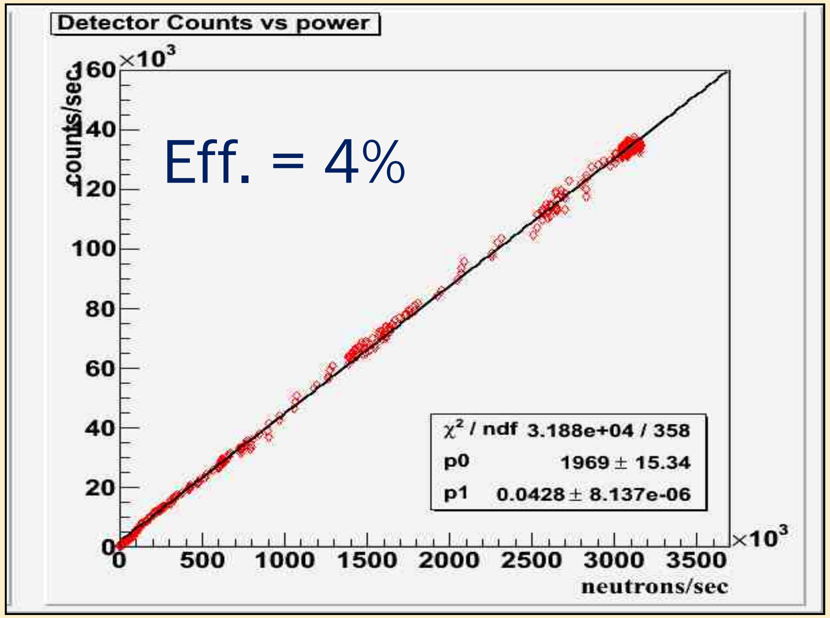
Actually 4% efficiency ... working to obtain 70%.
Good candidate as ^{3}He replacement detector

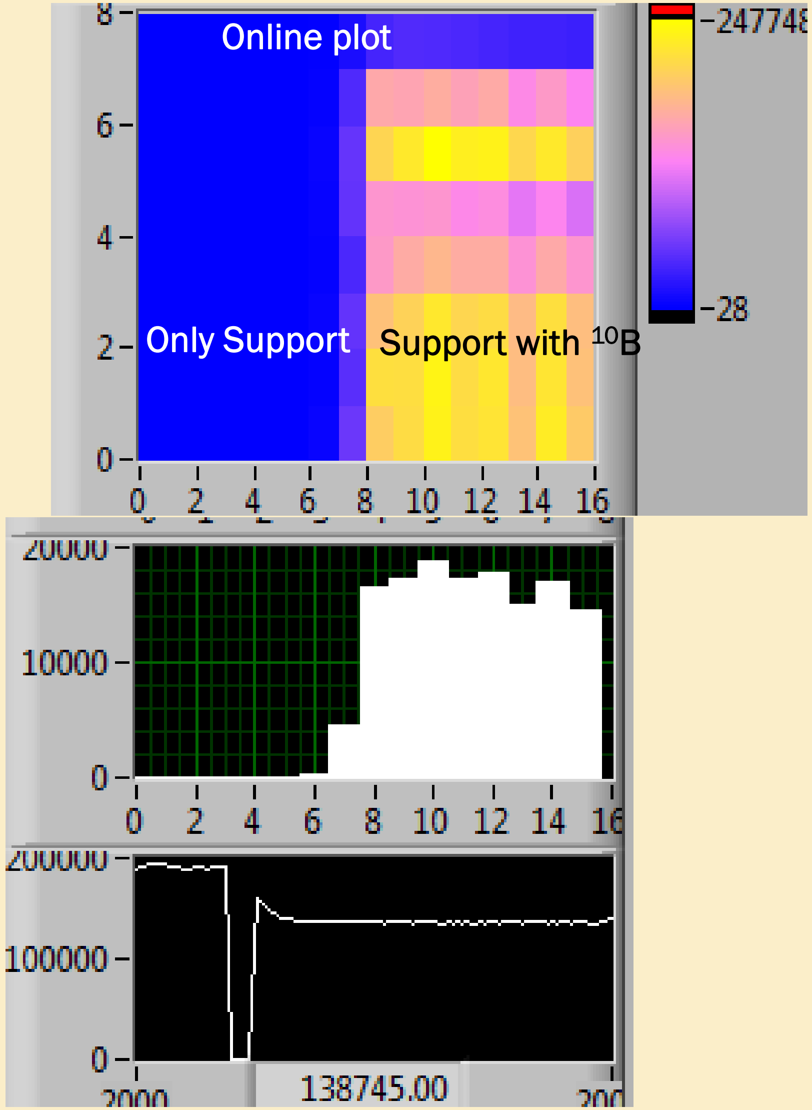
MONITOR FOR FISSION REACTORS

Measurements at Triga (ENEA)

Gamma background free
Without electronic noise

Good linearity up to 1 MW
6 order of magnitude





DIAMOND DETECTORS

Property	Diamond	Silicon
Band-Gap Energy (eV)	5.47	1.12
Intrinsic Electric Resistivity (Ω·cm)	$>10^{15}$	3.2×10^{5}
Thermal Conductivity ($W\cdot cm^{-1}\cdot K^{-1}$)	20	1.12
Breakdown Electric Field ($V\cdot cm^{-1}$)	$>10^{7}$	3×10^{5}
Electron Mobility ($cm^{2}\cdot V^{-1}\cdot s^{-1}$)	2100	1500
Hole Mobility ($cm^{2}\cdot V^{-1}\cdot s^{-1}$)	2500	600
Dielectric Constant (ε_r)	5.7	11.9
Ionization Energy (eV)	13	3.6
Energy to remove an atom from lattice (eV)	80	28
Lifetime under intense irradiation (a.u.)	10^{2}	1
Atomic number (Human Tissue = 6.5)	6	14

Wide Band-Gap Semiconductor

Electrically Insulating & Thermally Conductive

Excellent electrical properties

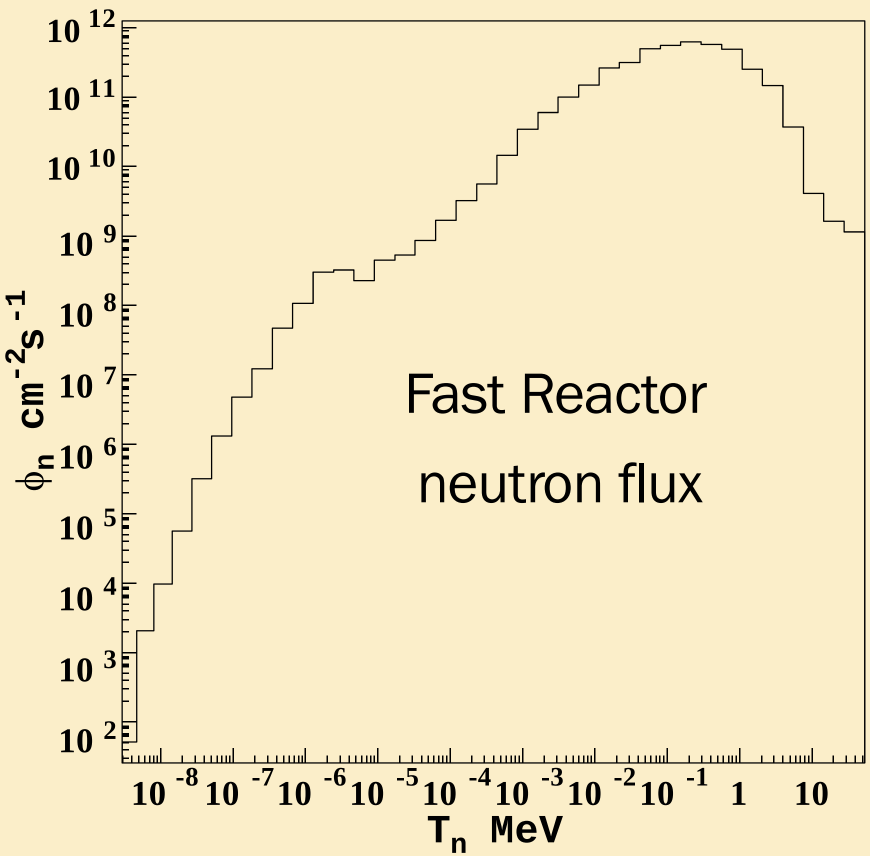
High Radiation Damage Resistance: Applications concerning use of high-energy radiation

Tissue-equivalent behavior

DIAMONDS FOR HIGH FLUX NEUTRON DIAGNOSTICS

Goal: to monitor neutron spectrum inside (fast) reactor core.

Our Solution: single crystal CVD diamond detectors.



Features:

- radiation hard
- insensitive to γ
- fast response
- compact size

Problems:

- small signals

Aim:

- measure neutron energy
- range < 10 MeV
- resolution < 300 keV

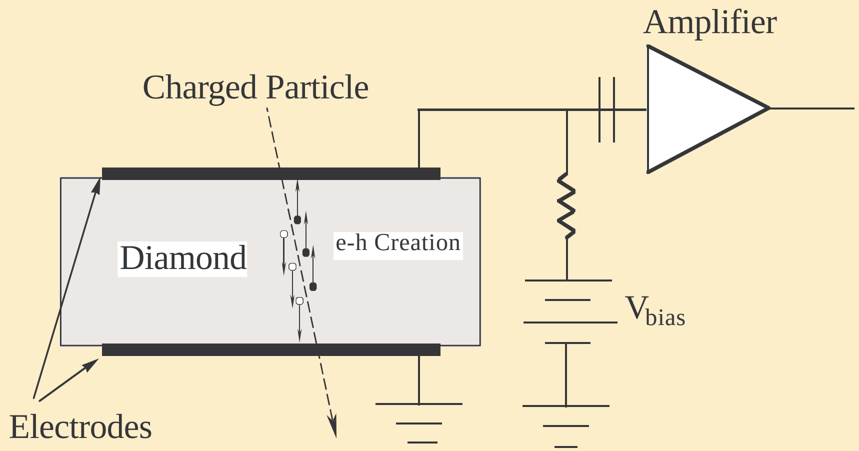
DIAMONDS FOR HIGH FLUX NEUTRON DIAGNOSTICS

In **fluxes <10^{12} n/cm^2/s** Diamond detector can substitute Fission Chamber as active monitor

	Fission Chamber	Diamond Detector
Charge Mobility	0.3-0.4 cm^2/V/s	2000 cm^2/V/s
Charge Collection time	5-7 μs	2-10 ns
Counting Rate	~ 10 kHz	DAQ limited
Size	4×10 mm^2	2×2 mm^2
Converter	U,Th,Pu	H, Li, B
Efficiency at 0.5 MeV	1.1 barn	0.4 barn (^{6}Li)
Signal Size	200 fC	60 fC (^{6}Li)
Spectroscopy	unfolding	direct (^{6}Li)
Energy Range	entire	<7 MeV (^{6}Li)

DIAMOND DETECTOR

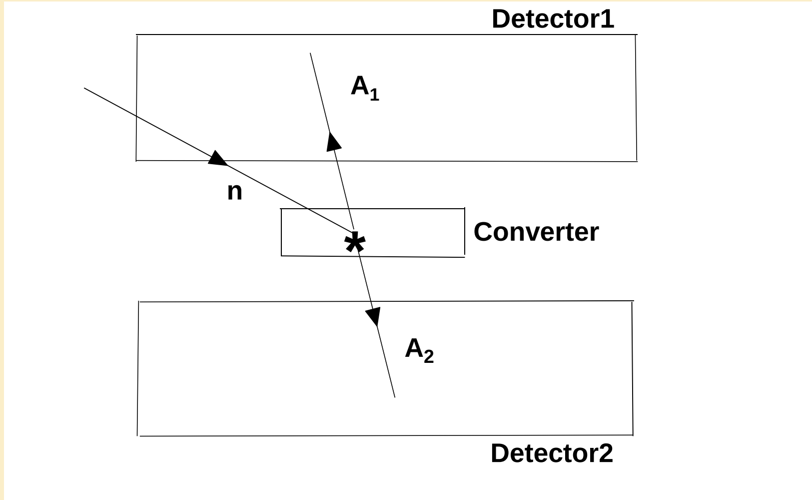
- Charged particle crossing diamond creates e-h pairs
- To collect pairs a bias voltage has to be applied across the diamond
- Current pulses are generated on electrodes
- To become measurable the signals have to be amplified



NEUTRON ENERGY MEASUREMENT

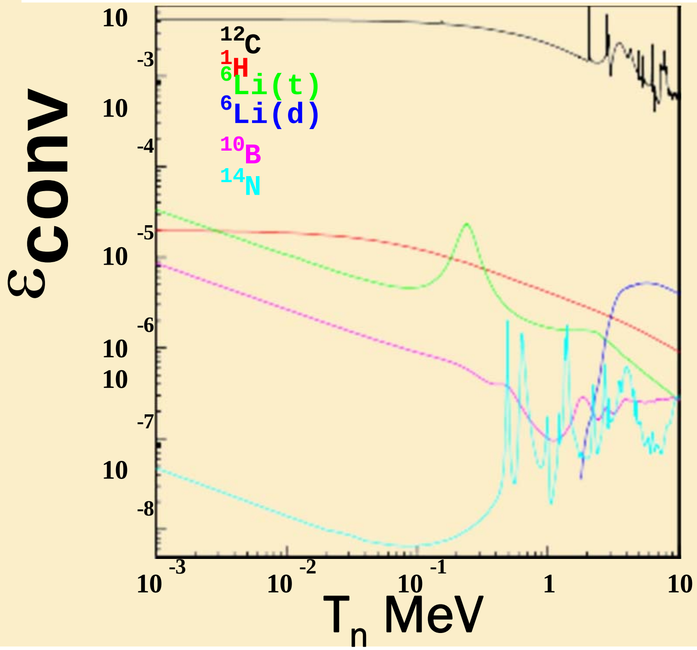
Use exothermic reactions with complete neutron energy conversion:

- $n + ^3He \rightarrow t(0.191 MeV) + p(0.573 MeV)$
- $n + ^6Li \rightarrow t(2.73 MeV) + \alpha(2.06 MeV)$
- $n + ^{10}B \rightarrow \alpha(1.47 MeV) + ^6Li(0.84 MeV)$
- $n + ^{14}N \rightarrow p(0.6 MeV) + ^{14}C(0.025 MeV)$

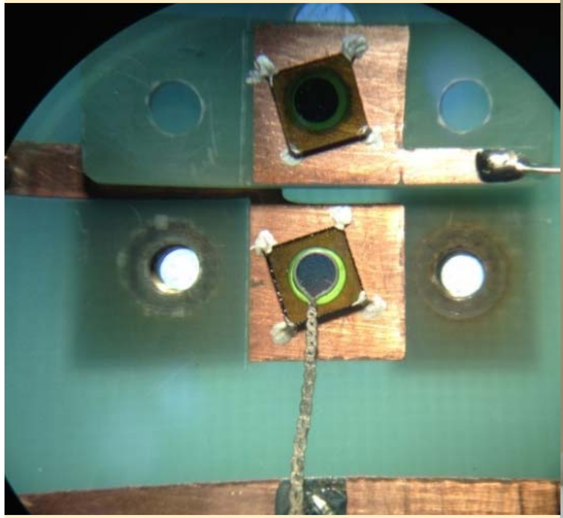


OK for energies below ~ 10 MeV (above that competition from other processes)

→ For higher energies (e.g. in fusion) system with H-based converter under study (PhD thesis Genova)



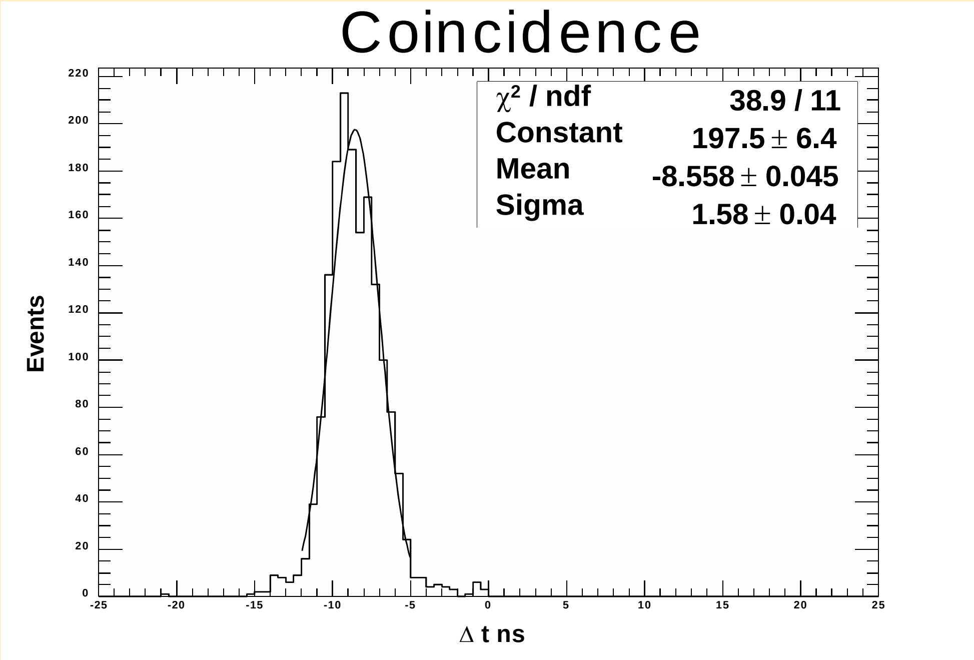
FIRST TEST AT ENEA FRASCATI NEUTRON GENERATOR

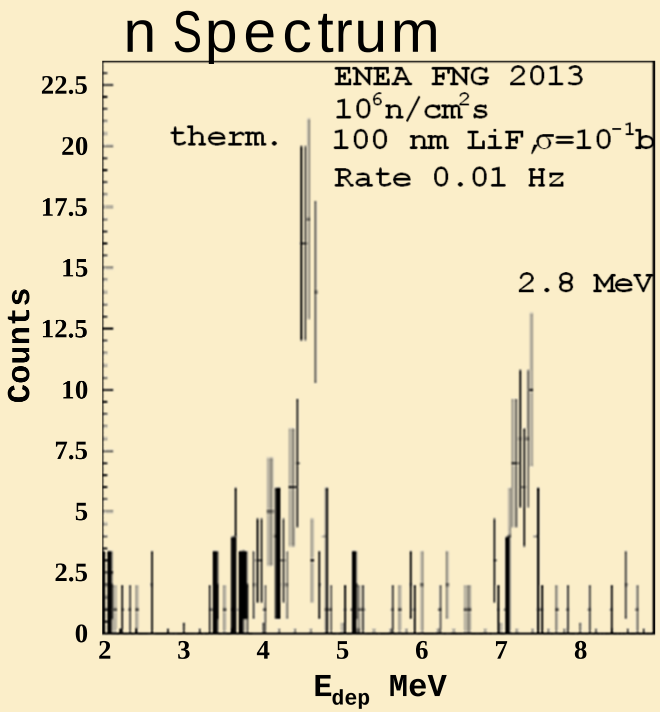


INFN Genova, INFN Rome 2, INFN Turin, CNR, ENEA Frascati, University of Tor Vergata

EXPERIMENTAL RESULTS

- ✓ FNG in D-D mode (2.5 MeV neutrons)
- ✓ neutron flux of ~ 10^6 n/cm^2/s
- ✓ two 50 μm CVD crystals with 100 nm ^{6}Li converter
- ✓ fast amplifiers connected trough 5 m cable
- ✓ coincidence between two crystals

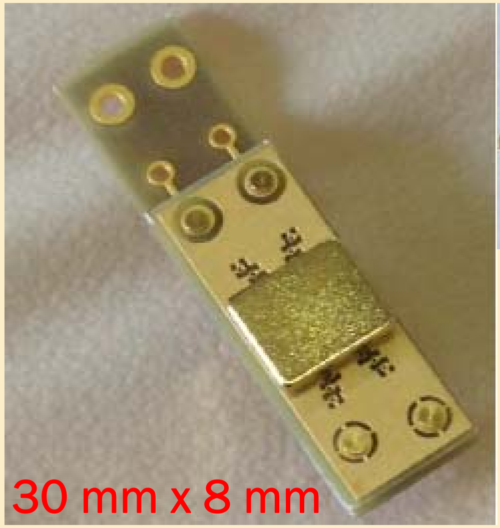




Resolution > ~200 keV FWHM

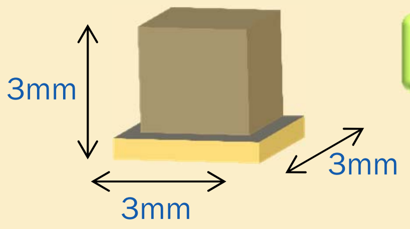
TEST AT TAPIRO FAST REACTOR (ENEA CASACCIA)

New Detector Design

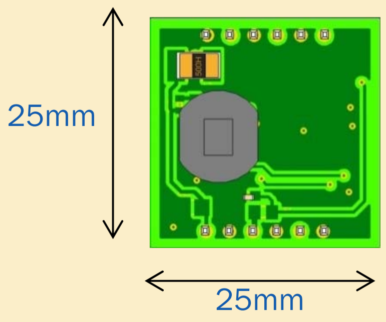


- Measured neutron spectrum in position close to the core is considerably slower than expected
- Fraction of neutrons > 0.4 MeV is > 4 times less than expected
- Also, signal drift observed attributed to space charge accumulation (diamond and electrical contact quality ?)
- New calibrations in progress
- Different diamonds in preparation

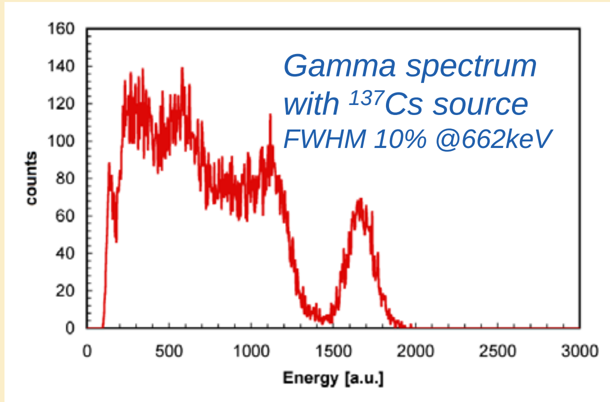
MINIRADMETER: A CHEAP AND PERFORMING PERSONAL DETECTOR



scintillator



sensor electronics



spectrum obtained in ≈5min with a source 20kBq @1cm and 2x2 mm scintillator (30K events)

minimum overall sensitive volume 3mm x 3mm x 3mm could be integrated inside a mobile phone or tablet: there are educational and dissemination aspects → show to the public that radioactivity is a natural phenomenon

20kBq (tiny lab) source @10cm doubles the natural background: gives rise to additional 1cps

Dose at 10sigma in 2min
(30s with a 3x3x3 mm scint.)

INFN National Southern Laboratory and Milano

CONCLUSIONS

- INFN mission is to carry on programs in fundamental science

- However, the broad competences on
  - ✓ basic theoretical aspects
  - ✓ accelerator design, construction and operation
  - ✓ radiation/particle detector design, construction and operation

  can be applied to

- ✓ Waste storage sites
- ✓ Industrial and public safety, port security
- ✓ Reactor monitoring
- ✓ New generation fission systems (ADS and fast reactors)
- ✓ Nuclear fusion program

- Several successful examples (besides INFN contributions to the medical field and the study of the cultural heritage)