Gamma-Ray Spectrometry of Hot Plasmas

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Outline

1. Introduction: basis of γ-ray diagnostics
2. γ-ray spectrometer system:
   - γ-ray detectors
   - DAQ for γ-spectrometry of hot plasma
3. Radiation shielding: ^{6}LiH attenuator
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5. γ-ray diagnostics in ITER
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Introduction

Goals of the diagnosis…

in D-T plasmas:

- ***α*-particle birth profile / *16,7 MeV gammas***
- ***confined 2-MeV α-particle profile / $^{9}Be(\alpha,n\gamma)^{12}C$***
- ***distinguish the 1-MeV deuterons and alphas / $^{9}Be + D$ reactions***
- ***escaping α*-particles / *^{10}B-targets mounted on first wall in detector LOS***

in Zero and Low Activation Phases (*He, H, D*):

- ***ICRF heating optimization***
- ***fast-ion distribution function***
- ***topology of the fast-ion orbits***
- ***the response to plasma instabilities (sawteeth, TAE* modes)**

Basis of the γ-ray Diagnostics

Some diagnostic reactions and associated gamma rays (E_γ, MeV):

Fusion reactions	Reactions with the main plasma impurities	"Pellet" reactions
$D(t,\gamma)^5He$ 16.7	$^9Be(\alpha,n\ \gamma)^{12}C$ 4.44	$^7Li(p,\gamma)^8Be$ 17.6
$D(^3He,\gamma)^5Li$ 17.6	$^{12}C(d,p\ \gamma)^{13}C$ 3.1, 3.7, 3.9	$^{10}B(\alpha,p\ \gamma)^{13}C$ 3.1, 3.7, 3.9
$D(p,\gamma)^3He$ 5.5	$^9Be(d,n\ \gamma)^{10}B$ 2.8, 2.15	$^{19}F(p,\alpha\ \gamma)^{16}O$ 6.1, 6.9, 7.1
$T(p,\gamma)^4He$ 20	$^9Be(p,\alpha\ \gamma)^6Li$ 3.56	
$D(d,\gamma)^4He$ 24	$^9Be(t,n\ \gamma)^{11}B$ 7.3, 4.44	

γ-ray emission in plasma is produced by

- fusion products p(3 MeV, 15 MeV),T (1 MeV), ^3He(0.8 MeV), α (3.5 MeV)
- ICRF-driven ions: **H, D, T, ^3He, ^4He**
- Fast particles NB injected into the plasma (110 kev-in JET, 1MeV – ITER)

α-particle diagnosis

α-particle diagnosis is based on γ-ray emissions from the nuclear reactions **$^{9}Be(\alpha,n\gamma)^{12}C$** and **$T(d,\gamma)^{5}He$**

α-particles source:

16.7 MeV γ's

D+T → $^{4}He+n$

D+T → $^{5}He+\gamma$ (16.7 MeV)

$$\Gamma\gamma/\Gamma n \approx (1.2 \pm 0.3)\times 10^{-4}$$

/J.E.Kammeraad et al 1993 Phys.Rev.C 47,29/

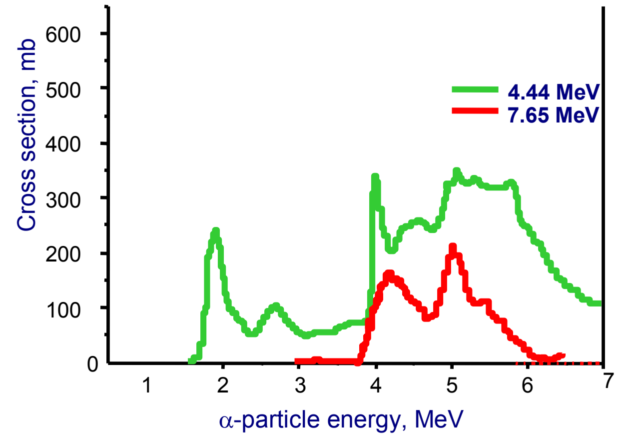
Confined α-particles,

which slowed-down to 2MeV:

4.44-MeV γ's

$$^{9}Be + \alpha = {}^{13}C^{*} \xrightarrow{n} {}^{12}C^{*} \xrightarrow{\gamma} {}^{12}C$$

$$Q(Be+\alpha-n) = 5.7\ MeV$$



Experimental equipment: γ-ray detectors

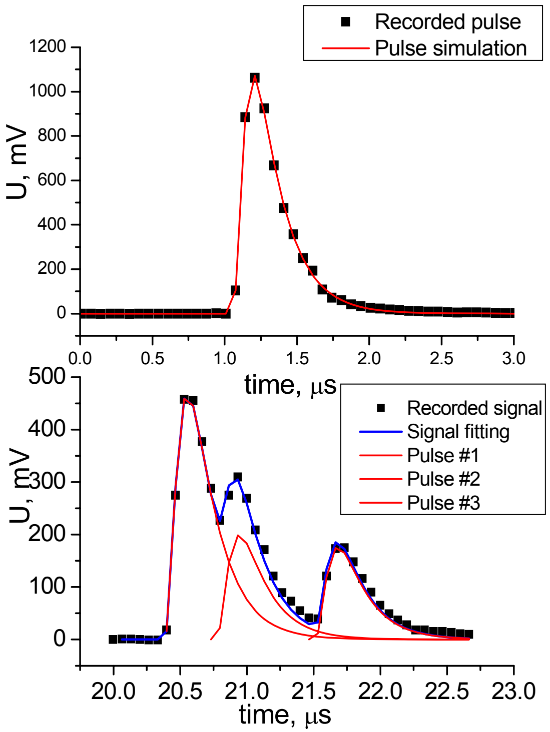
- Scintillation detectors: **Novel fast and heavy scintillates are available (LaBr3, LYSO, LuAP, etc):**

Property	NaI(Tl)	BGO	**$LaBr_3$:Ce**	**LYSO:Ce**	**LuAP**
Density, g/cm^{-3}	3.67	7.13	**5.3**	**7.1**	**8.3**
Attenuation length, cm	2.5	1.04	**2.1**	**1.2**	**1.04**
Energy Resolution @0.662 MeV	7 %	>13%	**3%**	**10%**	**7-9%**
Decay Time, ns	230	300	**16**	**40**	**17**

- Two big size **(Ø3”×6”) $LaBr_3$(Ce)** detectors have been developed under the project of JET spectrometer system upgrade

- **HPGe** detectors can be used in the measurements in the experiments with DD plasmas and in the low activation phase

Data Acquisition System



$$U(E,\ t) = A(E) \times \left(1 - e^{-\frac{t-t_0}{\tau_1}}\right)^P \times e^{-\frac{t-t_0}{\tau_2}}$$

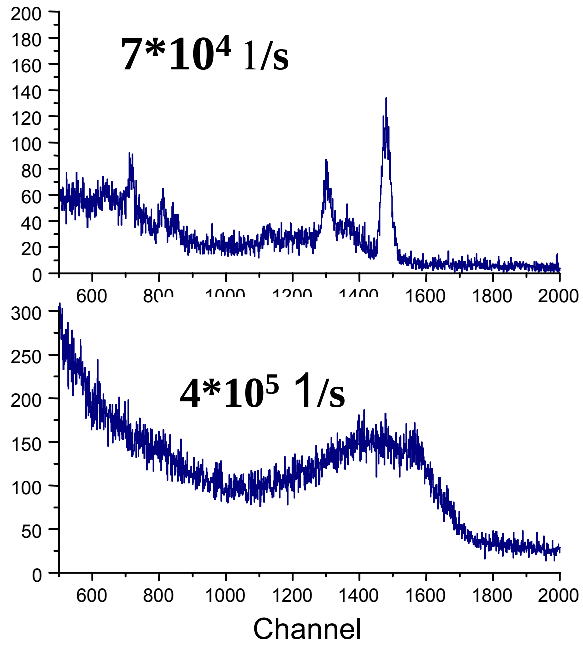
New algorithm for digital signal processing has been developed.

New DAQ realized in ATCA standard with 14 bit ADC, 400 MHz sampling rate, FPGA signal processing provides the count rate range up to **5 MHz** for **$LaBr_3(Ce)$**

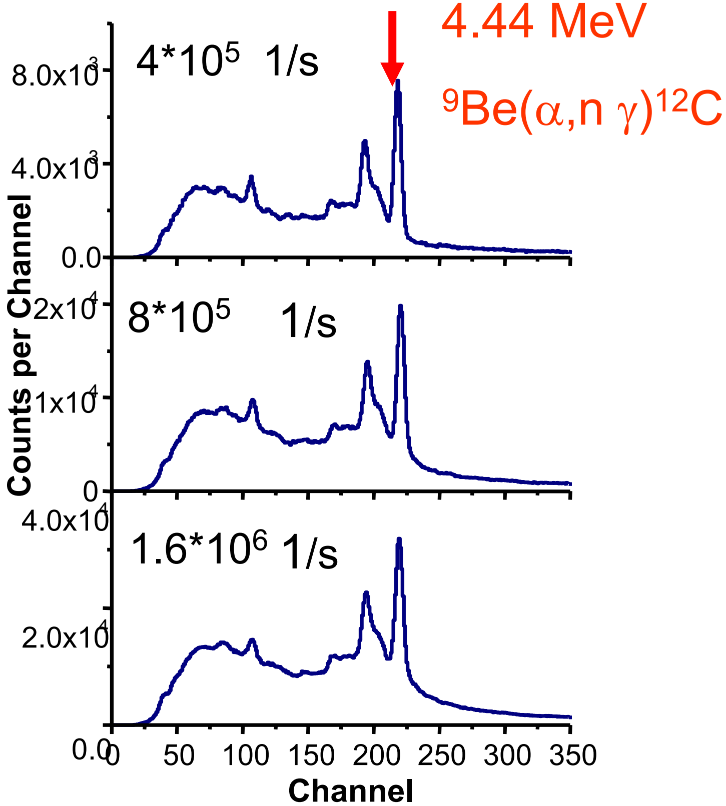
A(E) - the pulse amplitude, **t0** - the pulse start time; τ_1, τ_2, **P** – known parameters

Tests on cyclotron ion beam: LaBr$_3$(Ce) detector (Ø3”×6”) with new DAQ

Conventional DAQ:



new DAQ:



Cyclotron impulse regime: **5 MHz count rate is achieved !**

Neutron shielding: ^{6}LiH attenuators

Calculated attenuation factors are approximately (for attenuator with **1 m** in length):

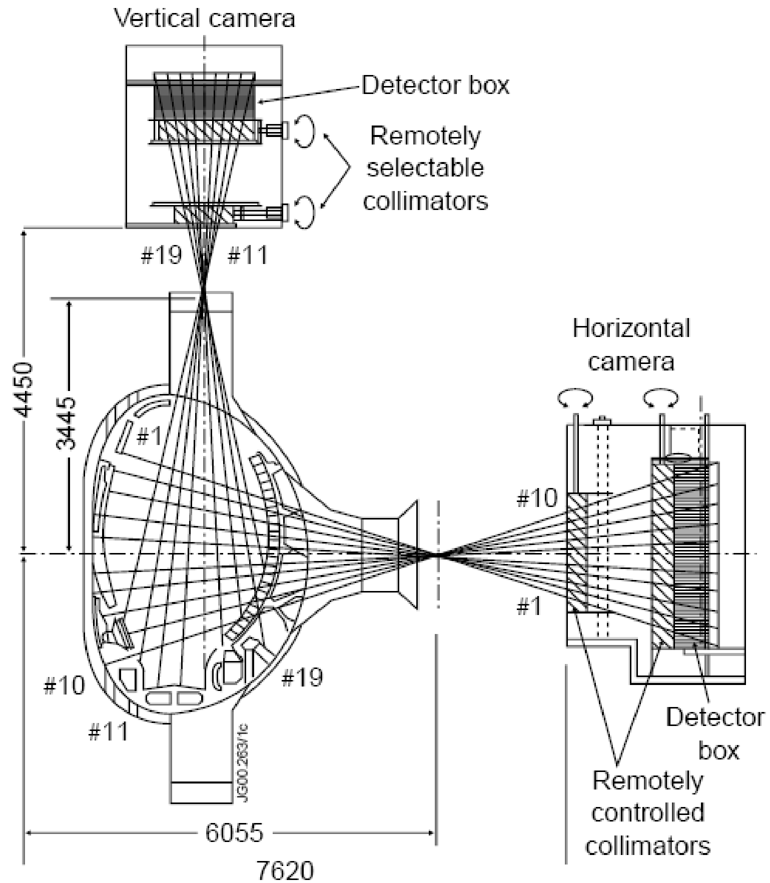
- **10^{5}** (DT- neutrons).
- **10^{10}** (DD-neutrons)

- According to MCNP calculations 35% of 16.7-MeV gamma-rays pass through the filter with 1 m in length without interaction.
- ^{6}LiH attenuator of 30 cm in length was delivered to JET and tested in experiments with DD plasmas: the attenuator suppressed neutron induced background ($E\gamma<3$ MeV) by a factor of $\approx$100
- It is planned to use the attenuator in the T-trace experiments

Gamma-ray Spectrometry at JET

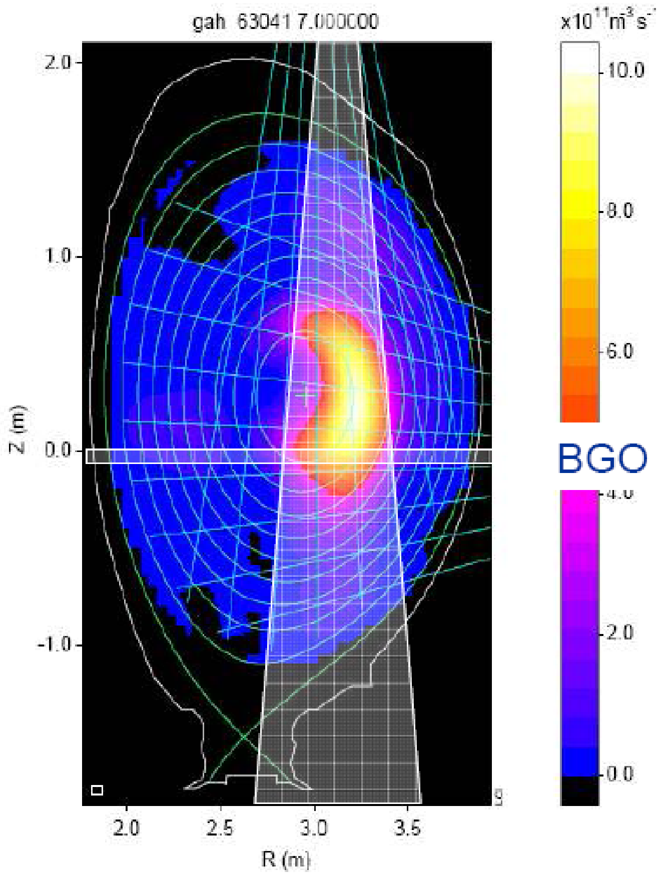
Gamma-ray Camera:
γ -ray emission profile measurements on JET provide information about spatial distribution of fast ions

Vertical camera: **9 lines-of-sight**
Horizontal camera: **10 lines-of-sight**
Collimators: Ø10 and 21 mm
Space resolution: 10 cm in centre
γ-detectors: Ø20x15 mm CsI-diodes
4 energy windows
γ -ray energy range: **2-6 MeV**



Gamma-ray spectrometers on JET

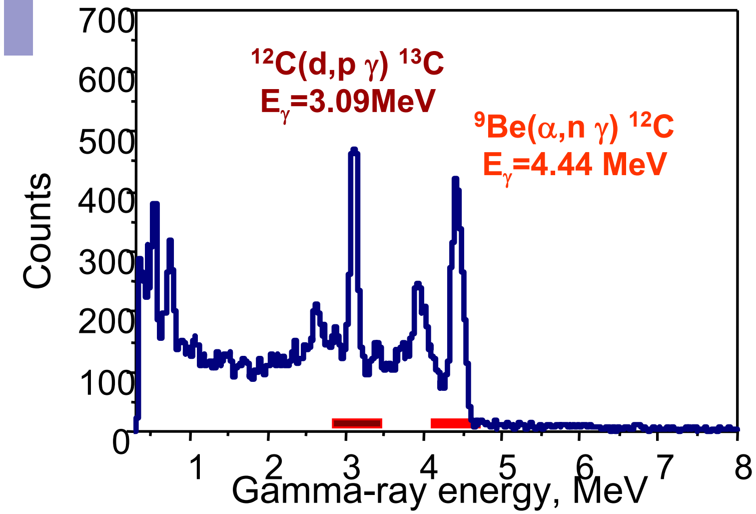
BGO, NaI(Tl), $LaBr_3$, HPGe



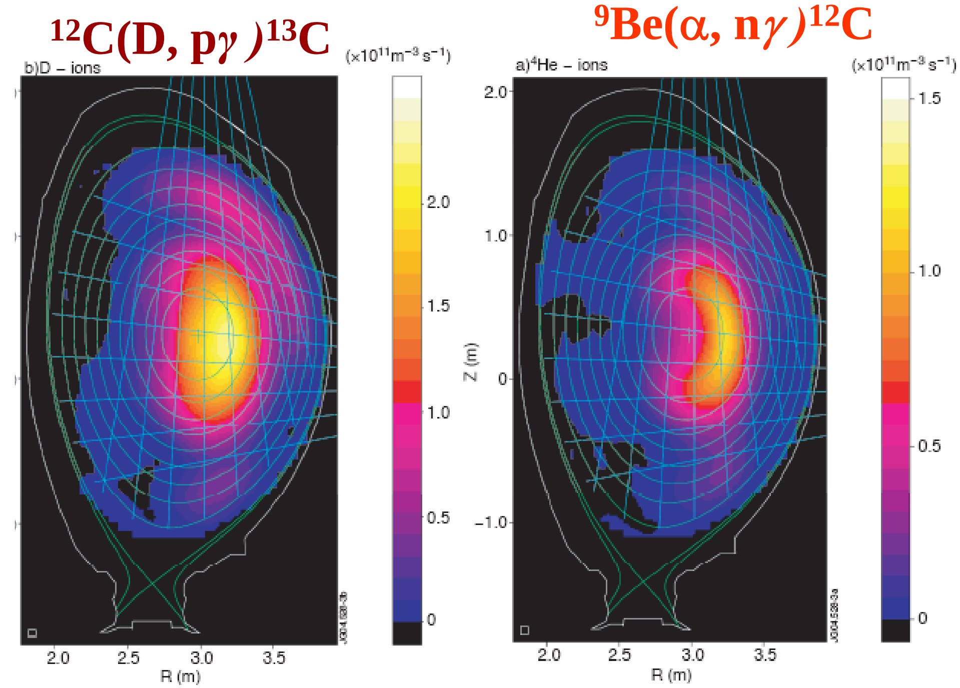
NaI(Tl): δ(662keV) ≈ **8%**
BGO: δ(662keV) ≈ **10%**
Digital Data Acquisition system allows up to **1 MHz** Pulse Height Analysis

$LaBr_3$(Ce) Ø3"×6" (or BrilLanCe):
δ(662keV) ≈ **3%,**
Decay times < **20 ns**
DAQ up to **5 MHz** PHA
HPGe: δ ≈ **0.3%** - the Doppler broadening of γ-lines are measured
DAQ up to **1 MHz** PHA

Distinguish signals related to *α-particles and D-ions in JET*

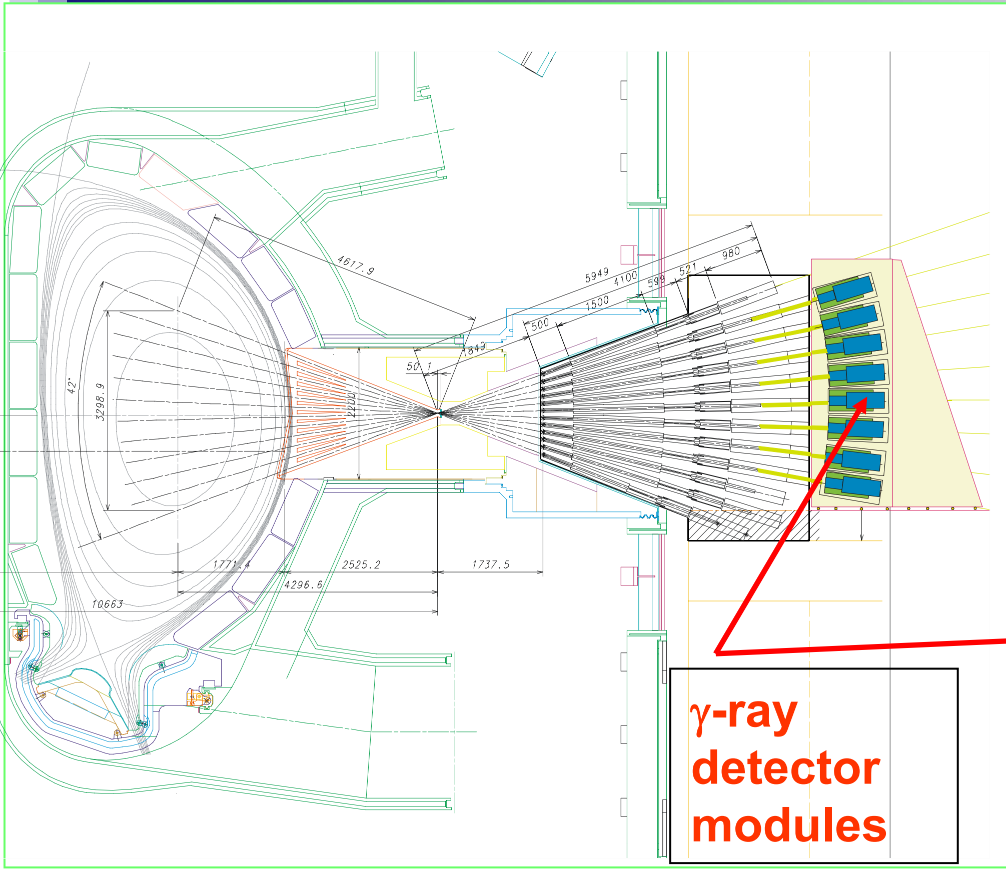


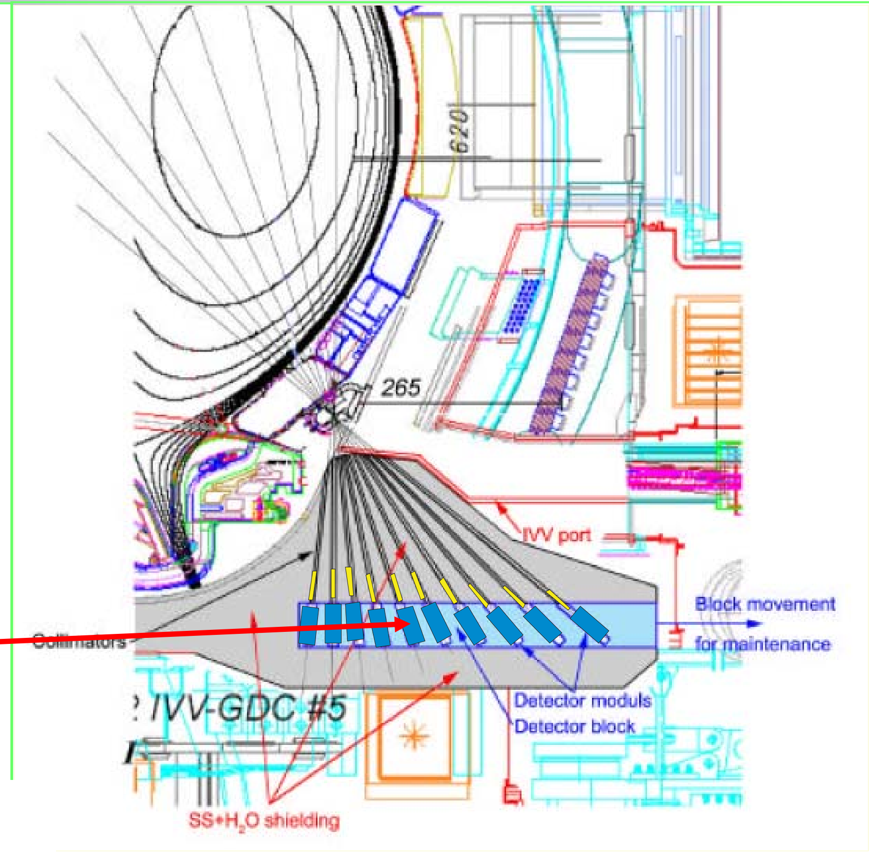
Spectrum recorded by NaI(Tl) spectrometer



Tomographic reconstructions of **4.44MeV γ-ray** emission from the **$^{9}Be(\alpha,n\gamma)^{12}C$** reaction (right) and **3.09MeV** γ-ray emission from the **$^{12}C(d,p\gamma)^{13}C$** reaction (left) deduced from simultaneously measured profiles

γ-ray spectrometry in ITER





Scheme of ITER Radial Neutron Camera's arrangement.

Version of Vertical Camera's arrangement

Vertical Camera: Operational Conditions

- **High neutron flux:**

  Proposed solutions: neutron shields and using fast detectors with appropriate DAQ

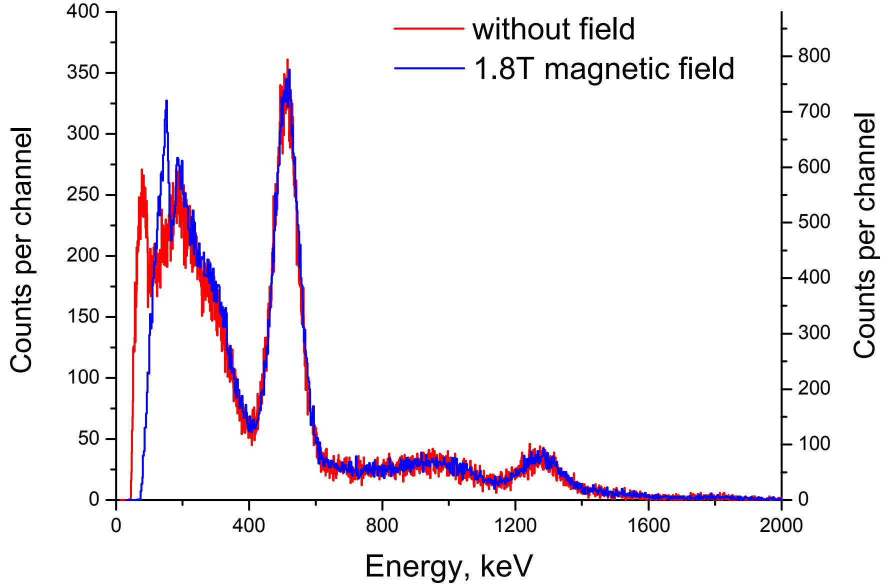
- **High temperature:** **up to 200^0C**

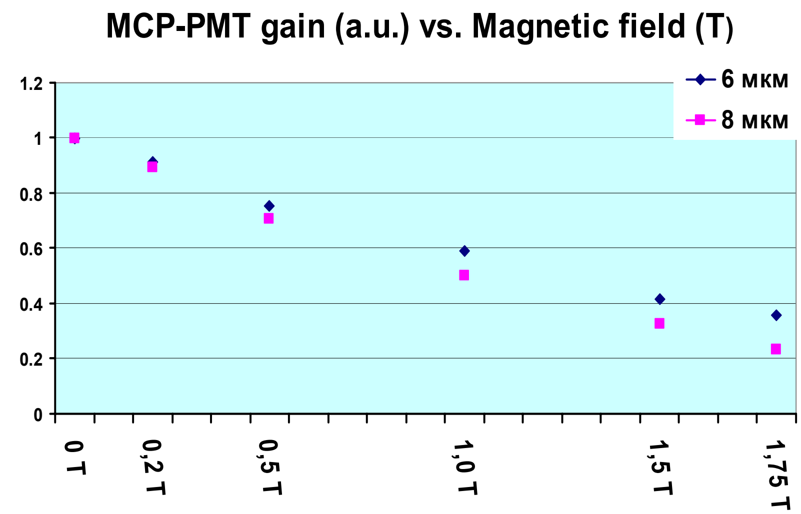
  Cooling the detectors must be applied

- **High magnetic fields:** **~ 2 T**

  Using MCP-PMTs, or optic-fiber light pipe bend

Tests of MCP-PMT in the strong magnetic fields





^{22}Na (511and 1275 keV γ's) spectra measured with and without magnetic field

$LaBr_3$(Ce) crystal (Ø30×30 mm) with MCP-PMT (Ø18mm, channels **Ø6 μm**) in the **1.8 T** magnetic field: PMT gain dropped down by a factor of **~2.5**,

Energy resolution did not change!

Summary

- γ-ray diagnostics more then 20 years is under development in Ioffe Institute, Saint-Petersburg
- γ-ray spectrometry is a routine JET diagnostic used for fast-ion and a-particle studies
- New big size $LaBr_3(Ce)$ spectrometers have been developed and tested
- New DAQ has been developed which allows achieving spectrometric measurements in MHz count rate range
- γ-ray spectrometer system for ITER is under development now

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Thank you!