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V G Kiptily

Fusion α-particles diagnostics: from JET to ITER and DEMO

6th EIROforum School on Instrumentation, 13th – 17th May 2019, Noordwijk, The Netherlands

European Commission
EPSRC Engineering and Physical Sciences Research Council
CCFE Culham Centre for Fusion Energy
Contract for the Operation of the JET Facilities Co-Funded by Euratom

Acknowledgements

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P. Beaumont,[1] F.E. Cecil,[2] I.N. Chugunov,[3] S. Conroy,[4] T. Craciunescu,[5] M. Curuia,[6] A.M. Fernandes,[7] M. Garcia-Munoz,[8] L. Giacomelli,[9] D. Gin,[3] V. Goloborodko,[10] G. Gorini,[9] E. Khilkevich,[3] I. Lengar,[11] A. Murari,[12,13] M. Nocente,[9] R.C. Pereira,[7] C. Perez Von Thun,[13] I. Polunovsky,[3] M. Salewski,[14] K. Schöpf,[10] S.E. Sharapov,[1] A. Shevelev,[3] S. Soare,[5] L. Swiderski,[15] Tardocchi,[16] V.L. Zoita,[5] I. Zychor[15] and JET contributors*

[1] CCFE of UKAEA, Culham Science Centre, Abingdon, UK
[2] Colorado School of Mines, 1500 Illinois Street, Golden, Colorado, USA
[3] A.F. Ioffe Institute, Russian Academy of Sciences, St. Petersburg, Russia
[4] Department of Physics and Astronomy, Uppsala University, BOX 516, Uppsala, Sweden
[5] National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania
[6] National Institute for Cryogenics and Isotopic Technology, Bucharest, Romania
[7] IST, Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal
[8] FAMN Department, Faculty of Physics, University of Seville, 41012 Seville, Spain
[9] Dipartimento di Fisica "G. Occhialini" Università di Milano-Bicocca, 20126 Milano, Italy
[10] Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria
[11] MHST, Reactor Physics, Department, Ljubljana, Slovenia
[12] Consorzio RFX -ENEA sulla Fusione, I-35127 Padova, Italy
[13] EUROfusion PMU, Culham Science Centre, Abingdon, OX14 3DB, UK
[14] Technical University of Denmark, Department of Physics, DK-2800 Kgs. Lyngby, Denmark
[15] Narodowe Centrum Badań Jądrowych (NCBJ), 05-400 Otwock-Swierk, Poland
[16] ENEA sulla Fusione, IFP Milano, Italy

* See author list [X. Litaudon et al., 2017 Nuclear Fusion **57** 102001]

Introduction

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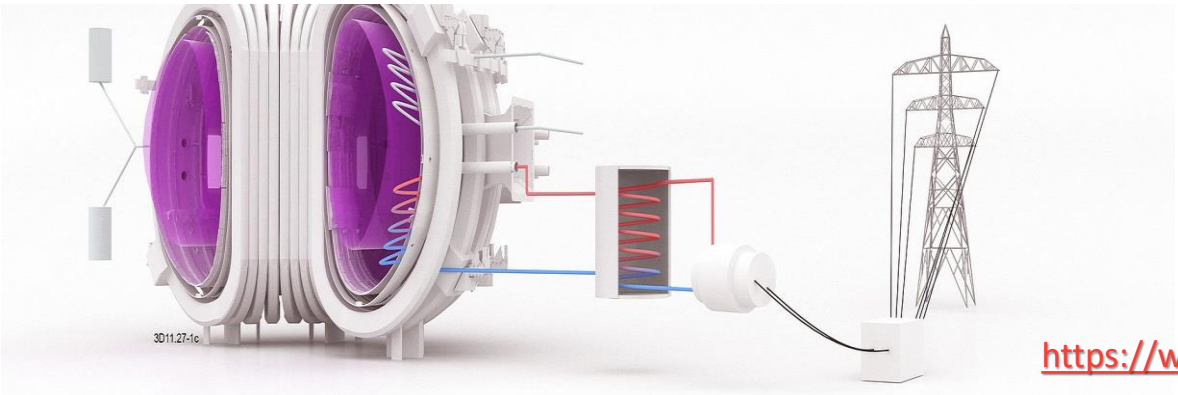
EUROfusion Roadmap

- *Technical demonstration of large scale fusion power – this is the first goal of ITER (500 MW for 400 seconds);*
- *Electricity delivered to the grid via a DEMOnstration Fusion Power Plant (DEMO) hundreds of MW of electricity for several hours*
- *In parallel, a science, technology, innovation and industry basis to allow the transition from the demonstration fusion plant to large-scale commercial deployment*



Visit the site:

https://www.euro-fusion.org/eurofusion/roadmap/

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Introduction

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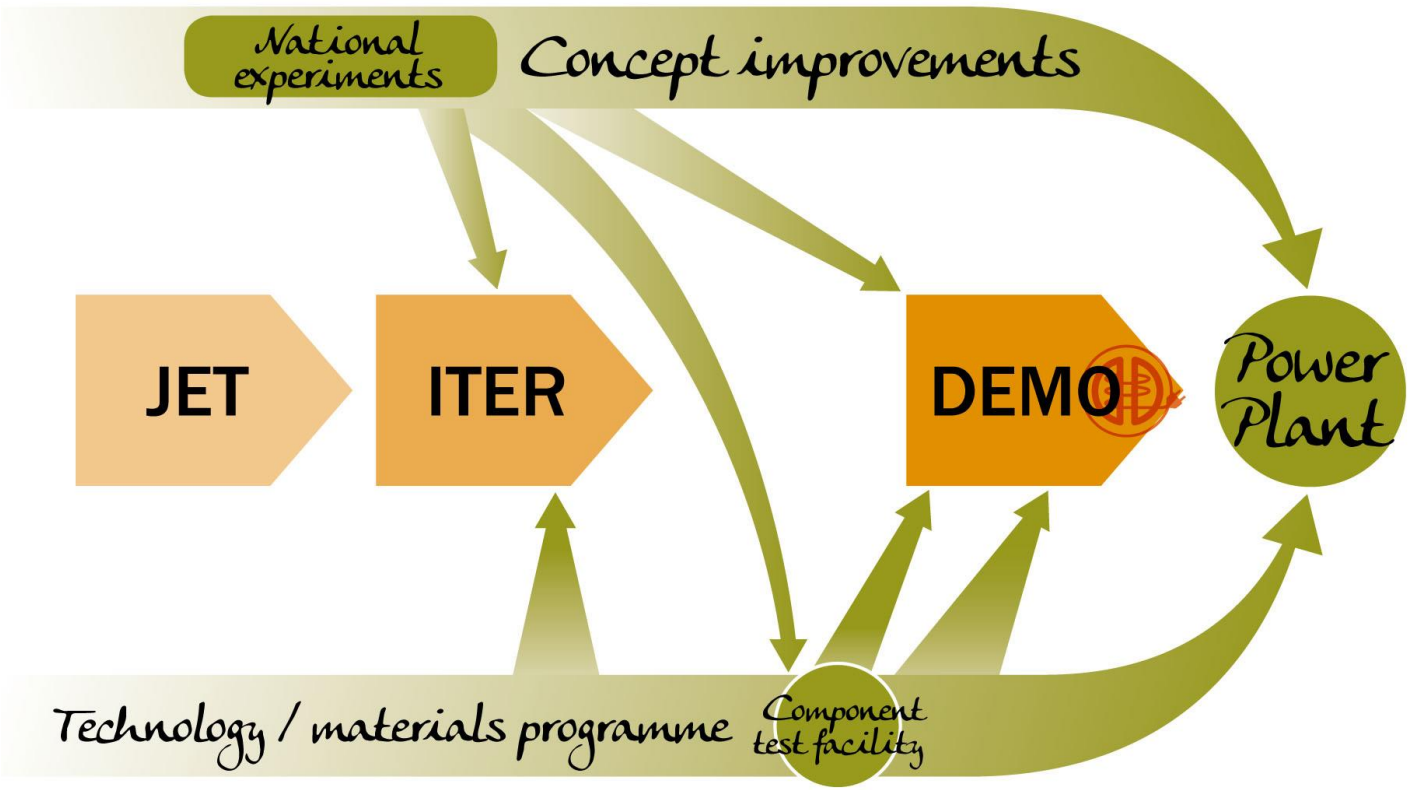
EUROfusion Roadmap



Graphic: EUROfusion/CCFE

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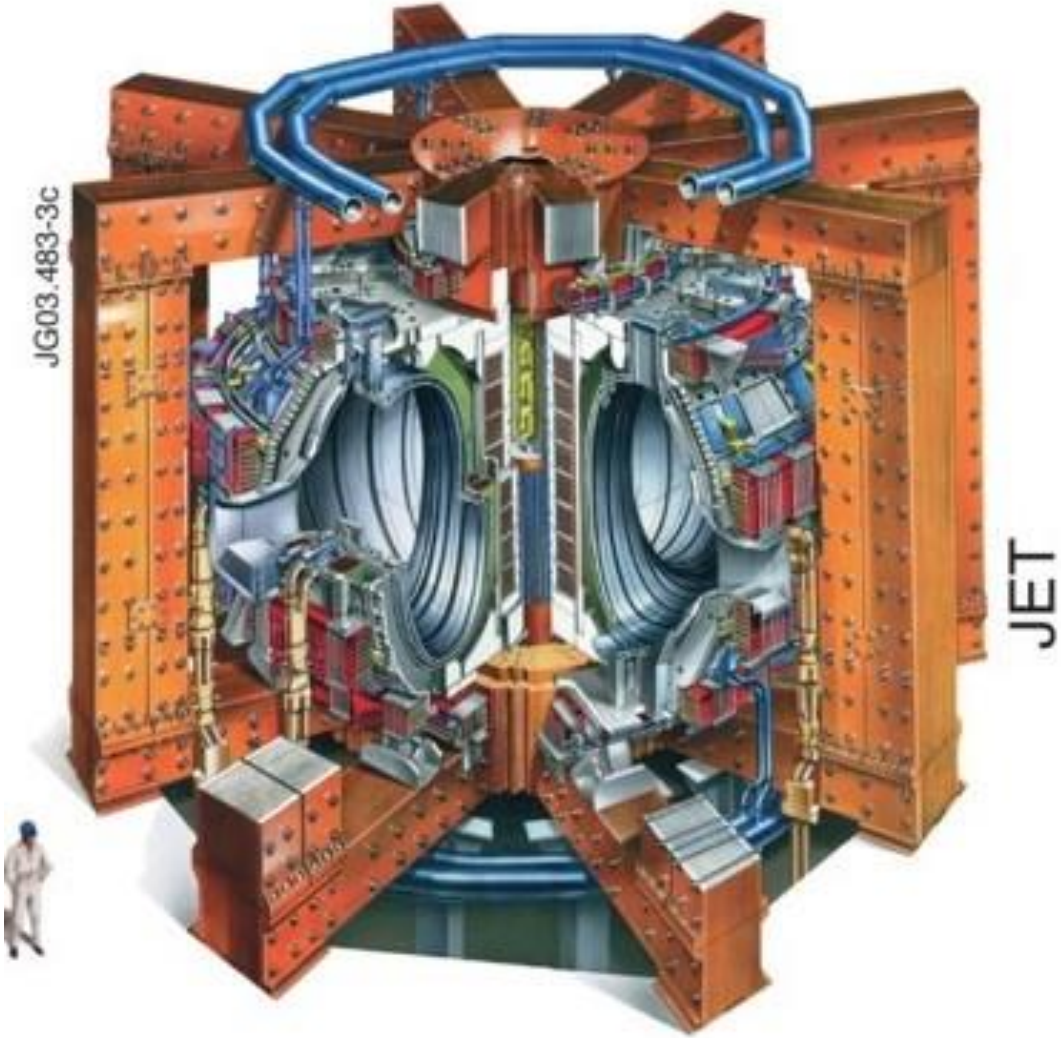
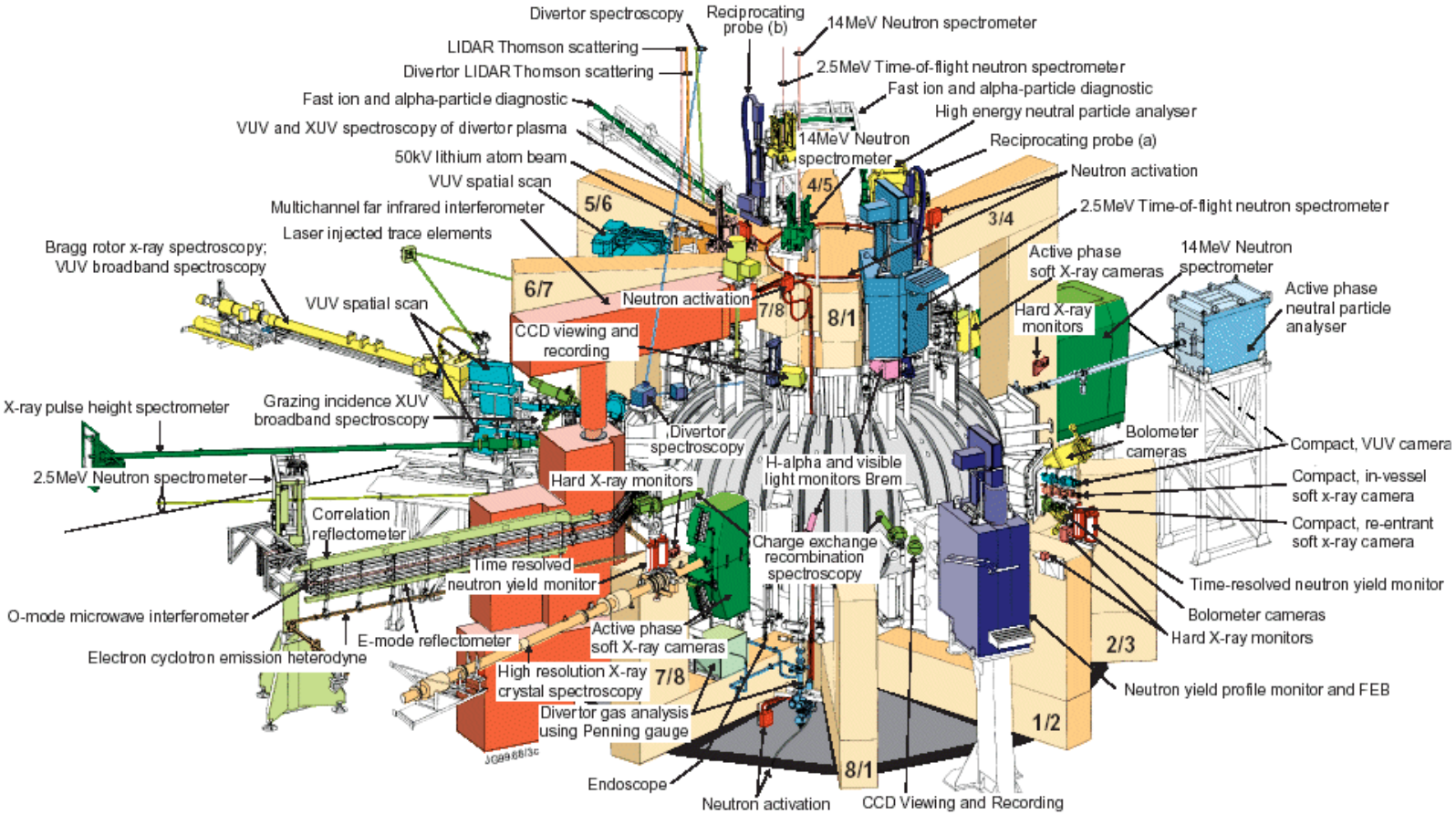
Joint European Torus



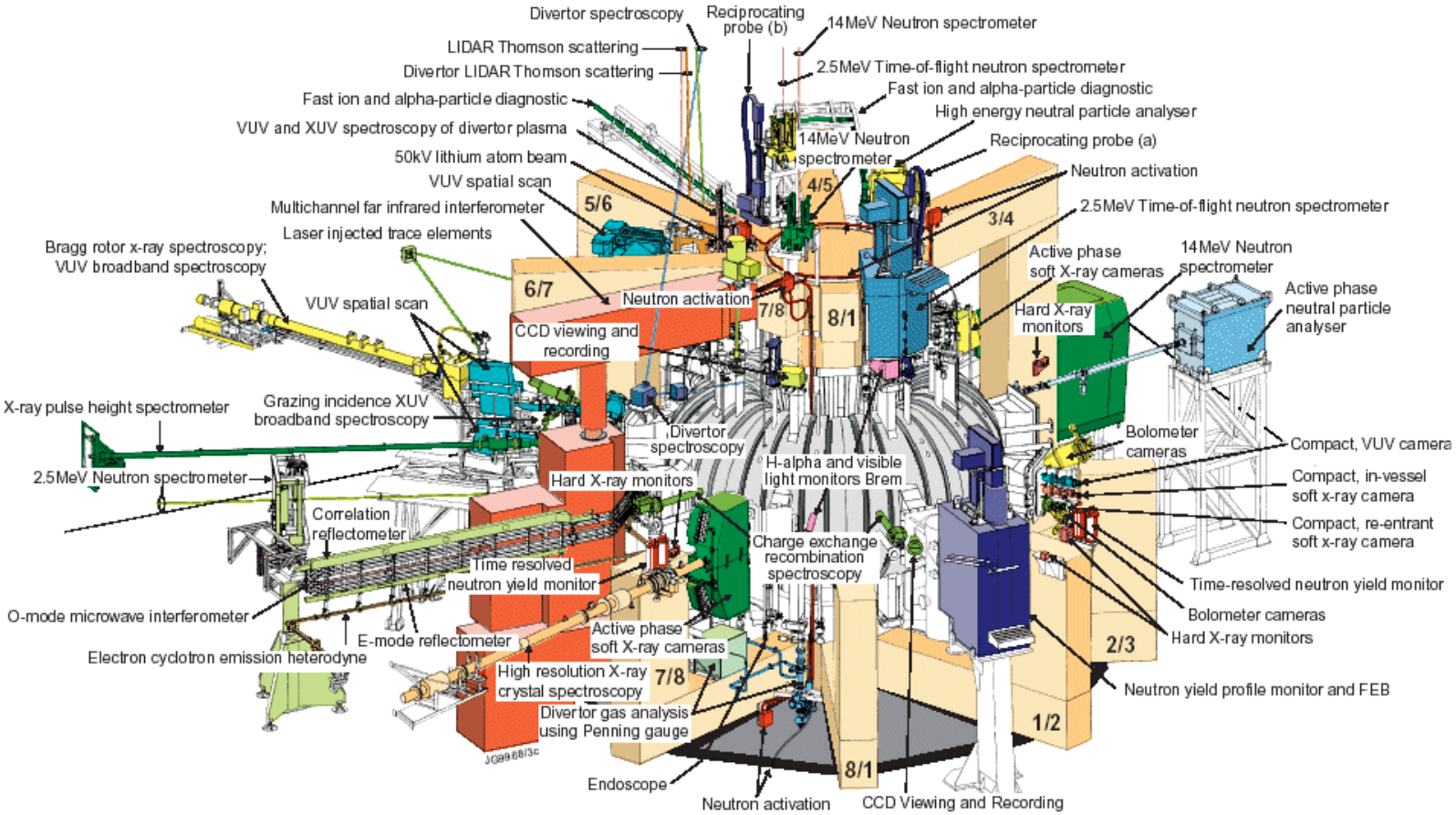
What we measure in JET ?



~ 100 diagnostic instruments

up to 18 GB of raw data per JET pulse

What we measure in JET ?



~ 100 diagnostic instruments

up to 18 GB of raw data per JET pulse

Forthcoming DT experiments

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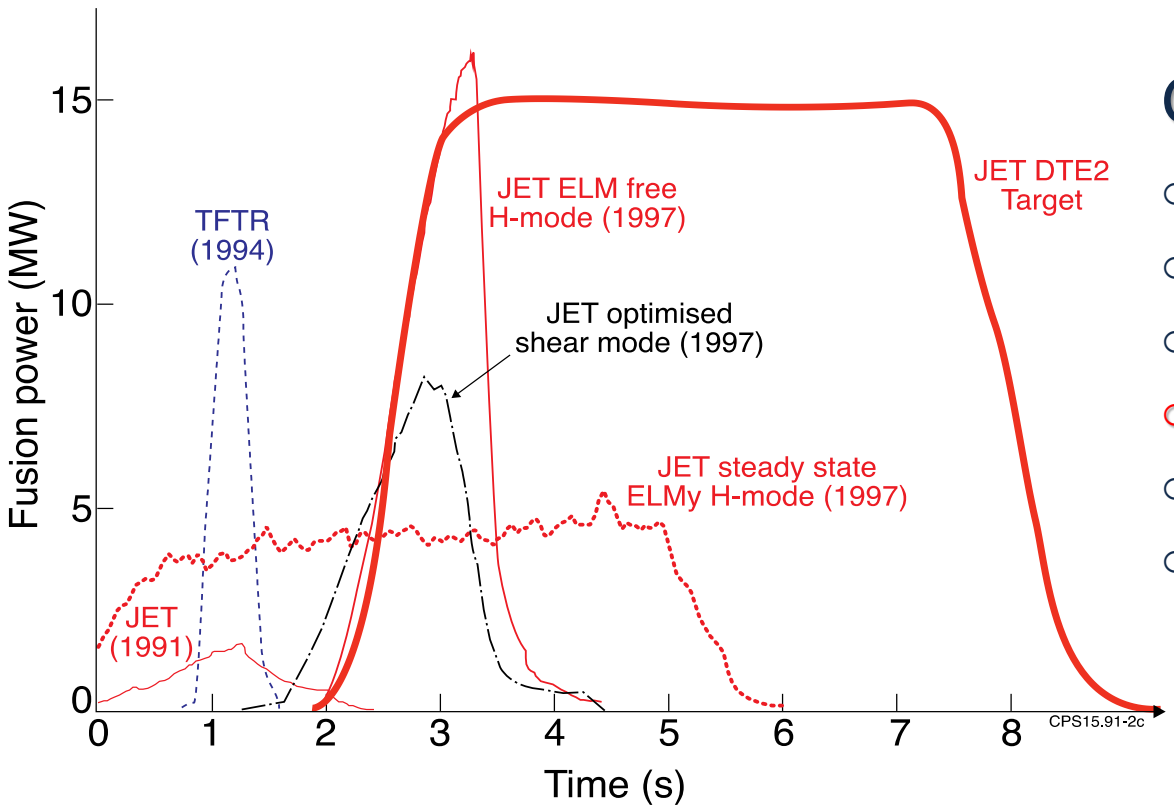
JET towards stationary fusion plasma



W_{fusion} ~ 50-75MJ, P_{fusion} ~ 10-15MW for 5s

Goal:

- Plasma Wall Interaction
- ITER scenarios
- Isotope effect
- α-particle physics
- T-cycle (fuelling, retention etc)
- Fusion technology

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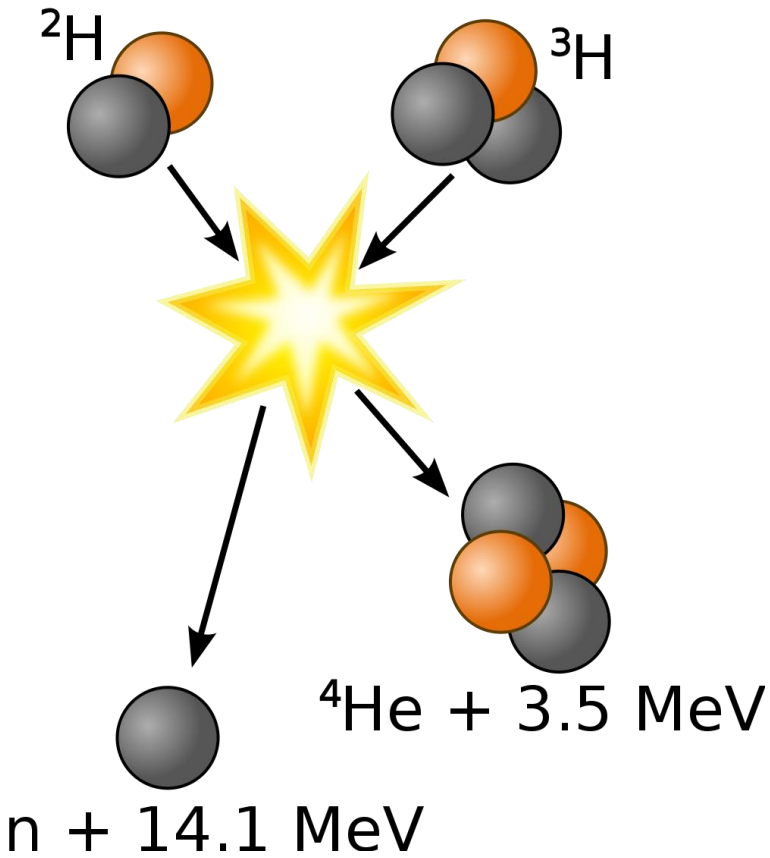
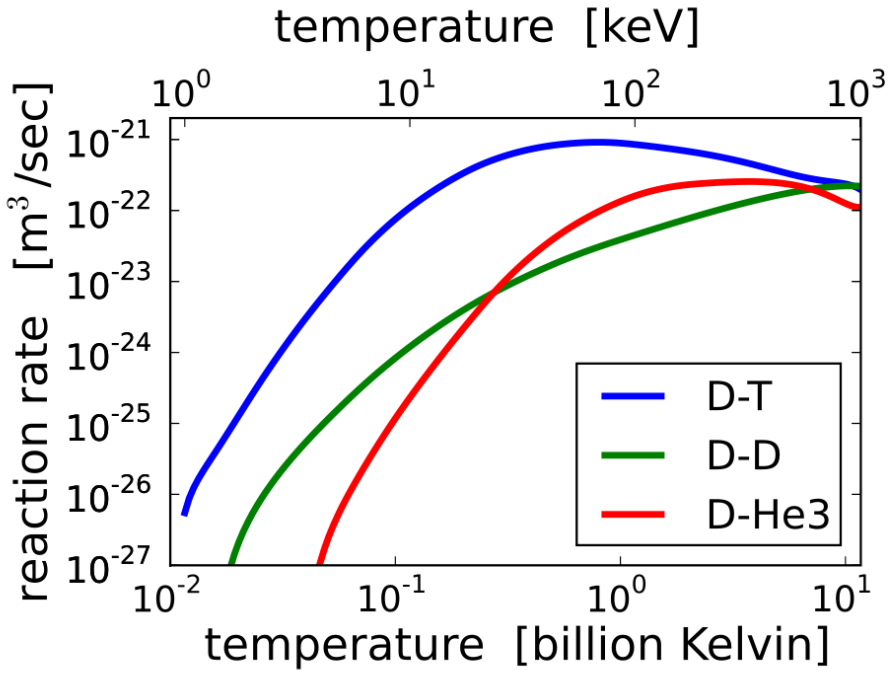
Fusion born α-particles





D + D → T (1.01 MeV) + p (3.02 MeV)
→ ^{3}He (0.82 MeV) + n (2.45 MeV)

D + ^{3}He → α (3.6 MeV) + p (14.7 MeV)

1 MW fusion power ~ 3.6 10^{17} α+n/s

Why should alphas be studied?

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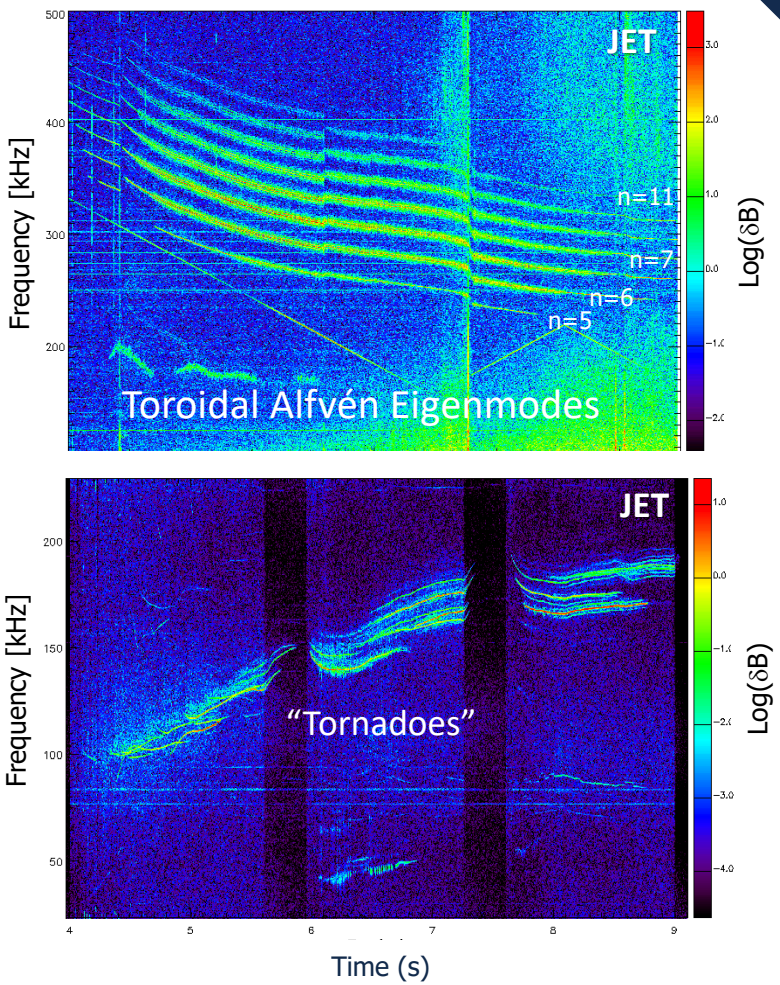
- Reactor plasma is self-heated by α-particles
- But energetic α-particles may drive MagnetoHydroDynamic instabilities and can in turn be re-distributed and, in some cases, lost
- Loss of bulk plasma heating is unacceptable for an efficient power plant
  - May lead to ignition problems
  - Damage to first wall
  - Can only tolerate fast alphas losses of a few % in a reactor



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What to be measured in DT Exp ?

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- α-particle birth profile and spatial distribution
- α-particle energy distribution due to slowing down and losses
- Losses

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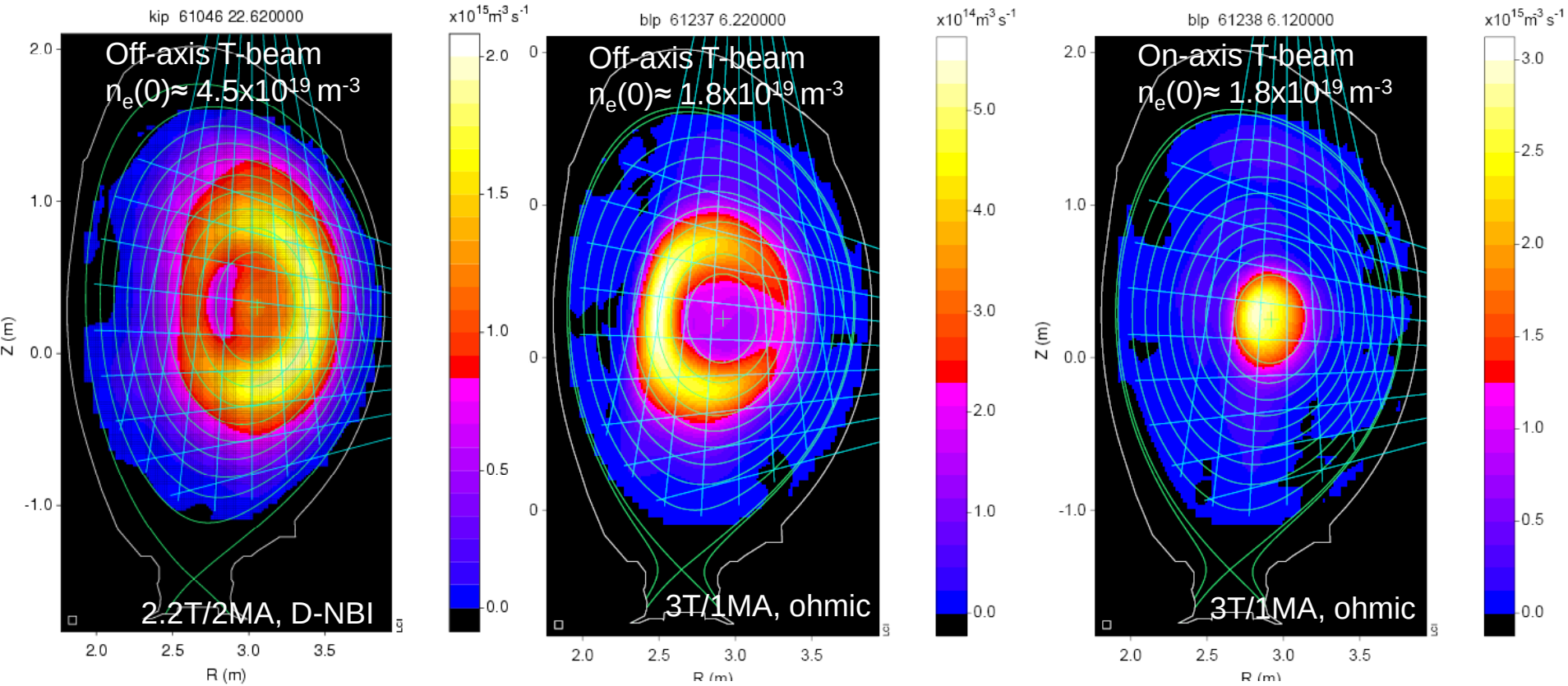
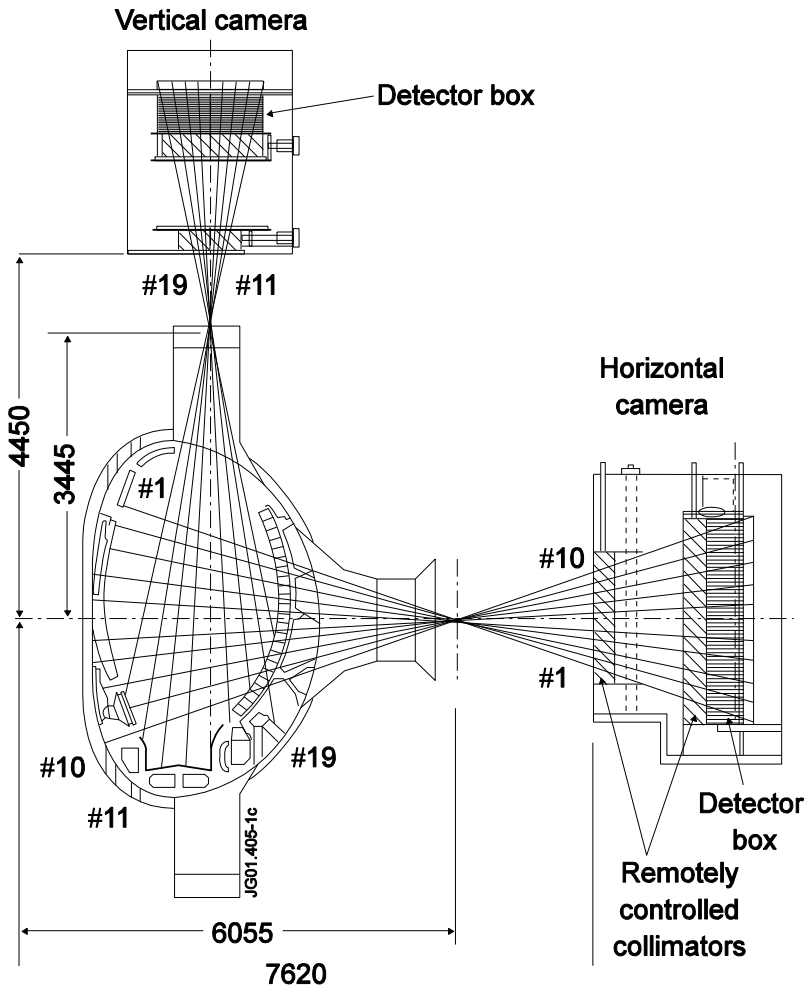
α-particle birth profile

14-MeV neutron profile measurements in discharges with T-NBI blips, during the Trace Tritium Experiments in 2003



D. Stork et al Nucl. Fusion **45** (2005) S181–S194

How it can be measured ?



Neutron & Gamma-ray Cameras

Detectors:

- **NE213** scintillators (DD & DT neutrons)
- **Bicron-418** scintillators (DT neutrons)
- **$LaBr_3$** - γ-ray detectors

Rigamonti D. et al Review of Scientific Instruments **89**, 10I116 (2018)

Fernandes A et al 2014 Fus. Eng. Des. 89 (2014)259

Fast ions and γ-rays

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γ -ray emission is produced due to nuclear reactions of fast ions with fuel and with main impurities Be and C

Protons	Deuterons	Tritons	^{3}He-ions
$D(p,\gamma)^{3}He$	$^{9}Be(d,p\gamma)^{10}Be$	$D(t,\gamma)^{5}He$	$D(^{3}He,\gamma)^{5}Li$
$T(p,\gamma)^{4}He$	$^{9}Be(d,n\gamma)^{10}B$	$^{9}Be(t,n\gamma)^{11}B$	$^{9}Be(^{3}He,p\gamma)^{11}B$
$^{9}Be(p,\gamma)^{10}B$	$^{12}C(d,p\gamma)^{13}C$	$^{12}C(t,\gamma)^{15}N$	$^{9}Be(^{3}He,n\gamma)^{11}C$
$^{9}Be(p,p'\gamma)^{9}Be$		$^{12}C(t,n\gamma)^{14}N$	$^{9}Be(^{3}He,d\gamma)^{10}B$
$^{9}Be(p,\alpha\ \gamma)^{6}Li$		$^{12}C(t,\alpha\gamma)^{11}B$	$^{12}C(^{3}He,p\gamma)^{14}N$
$^{12}C(p,p'\gamma)^{12}C$			

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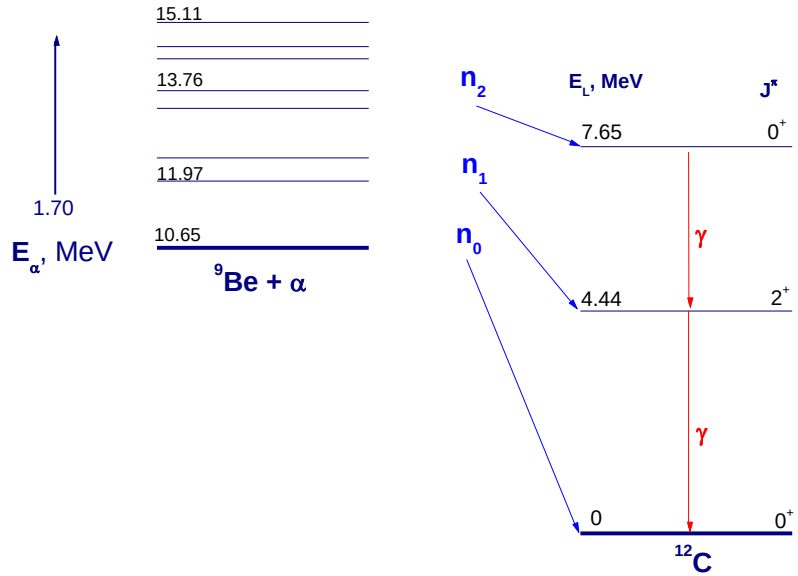
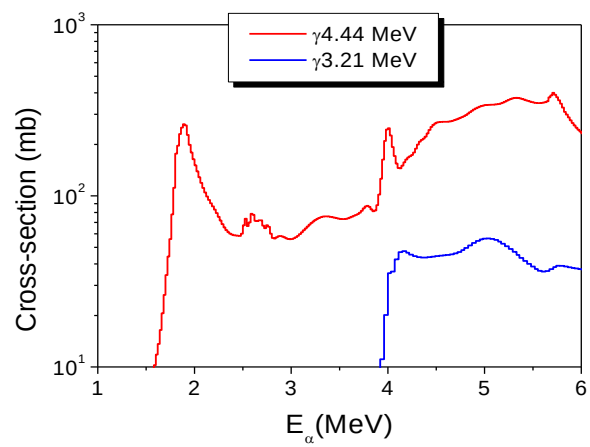
How γ-rays expose alphas ?

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



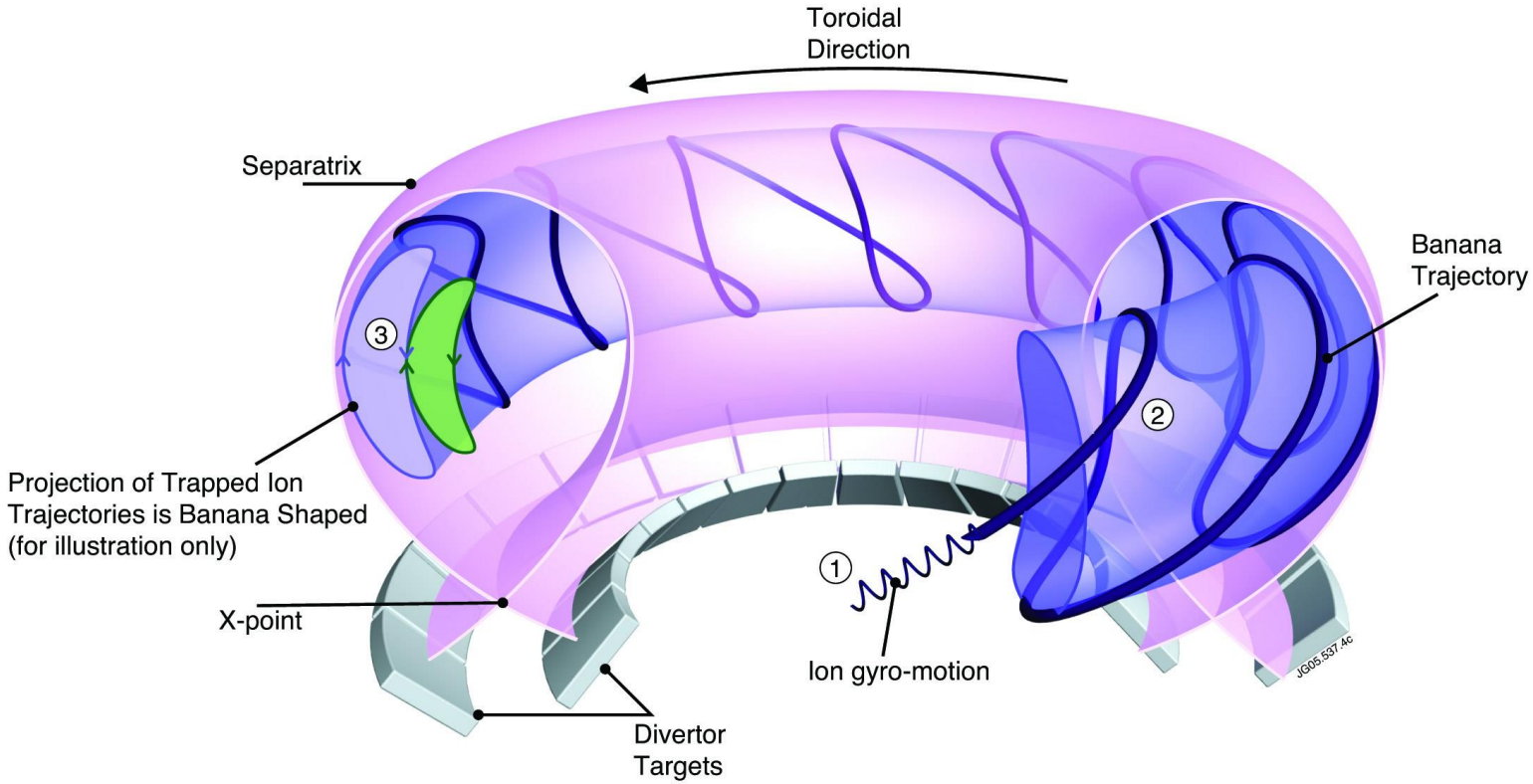
Interaction of α's and Be impurity leads to:

- Excitation of ^{13}C nucleus
- De-excitation by neutrons with excitation of ^{12}C
- Further de-excitation by γ-rays
  - ✓ γ4.44 MeV, $E_\alpha > 1.7$ MeV
  - ✓ γ3.21 MeV, $E_\alpha > 4$ MeV



Kiptily V.G., Fusion Technology **18** (1990) 583

Fast ion- & α-orbits in tokamaks



Trapped and passing trajectories of fast ions in the plasma

Spatial α-particle distribution

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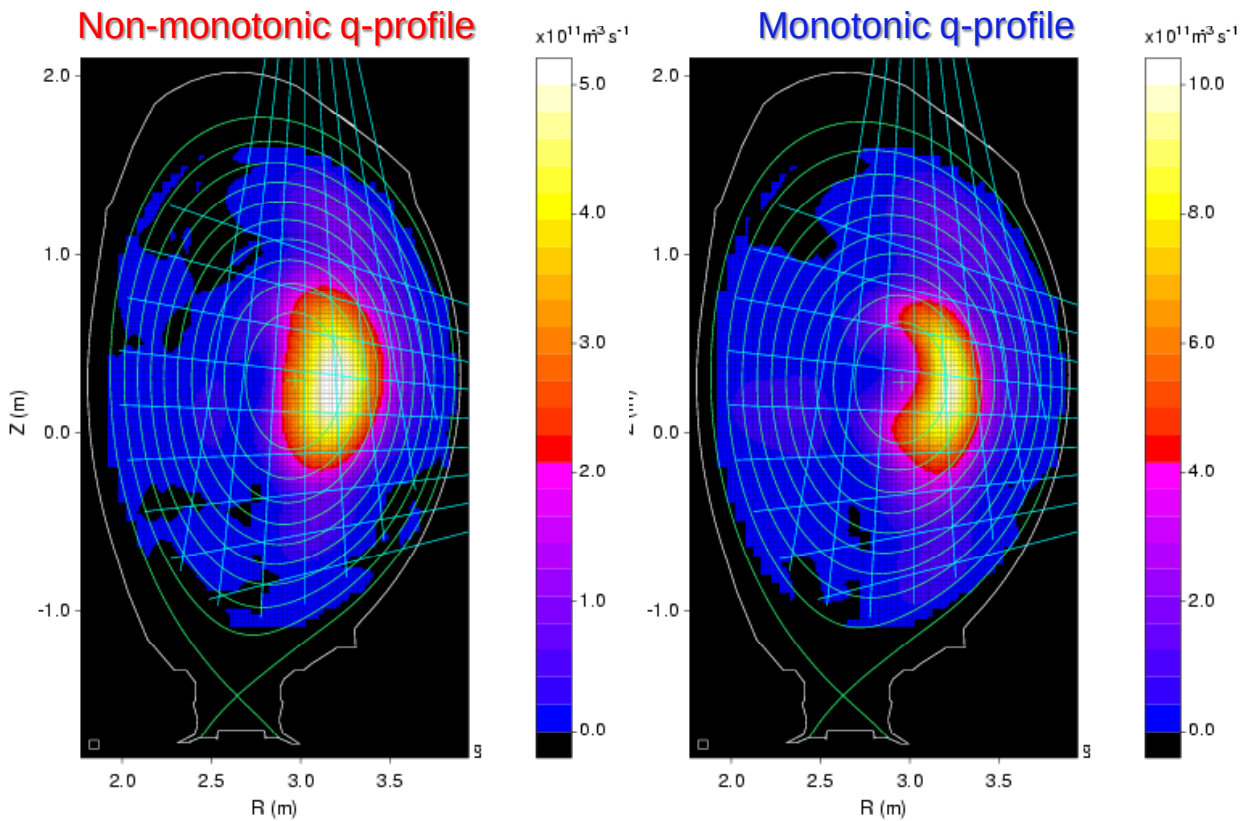
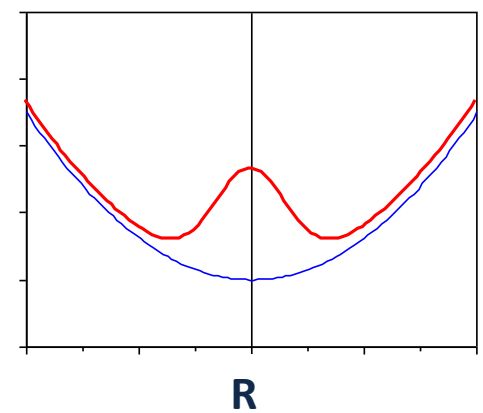
Effect of magnetic field topology on γ-ray image of ^{4}He-ions in α-particle mimicking experiment (^{4}He-ion acceleration)



Safety factor

$q=rB_t/RB_p$



Kiptily et al Nucl. Fusion **45** (2005) L21

Tomographic reconstructions of profiles measured in different q-profile phases of the plasma discharge in JET.

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Is it measurable in DT experiment?

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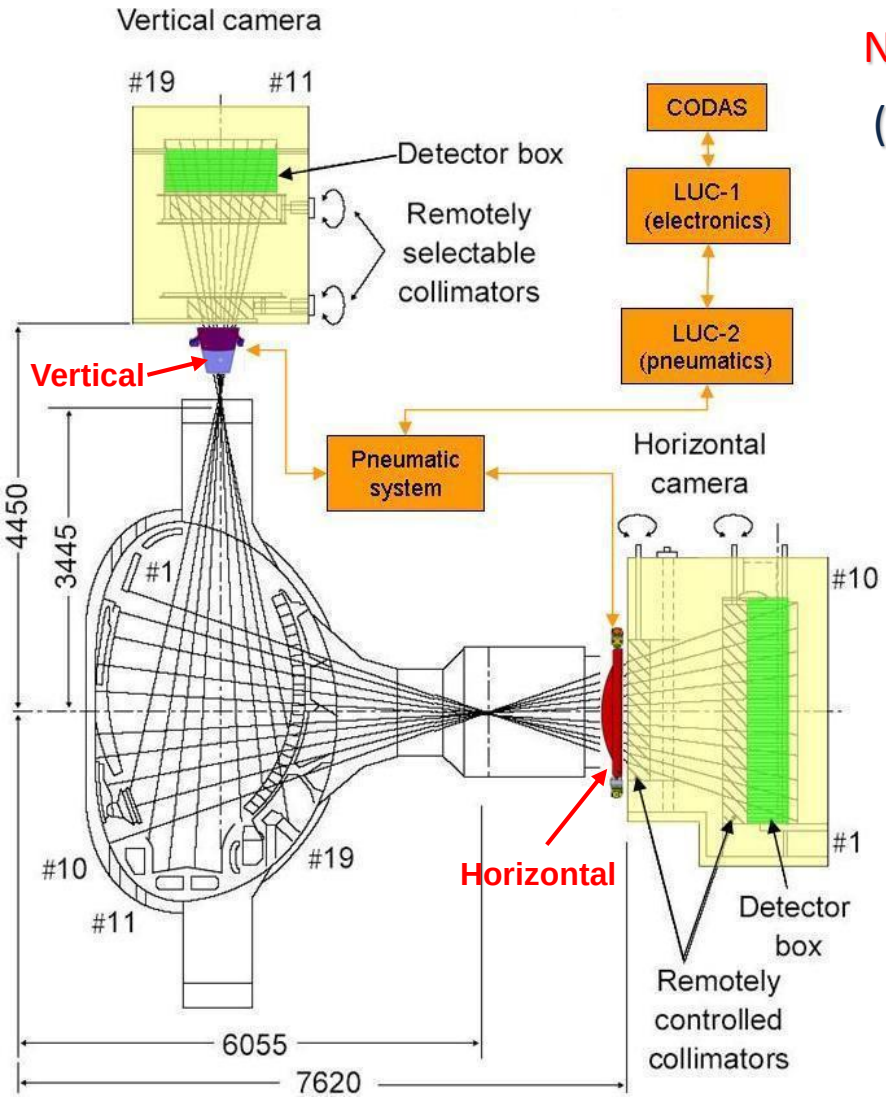
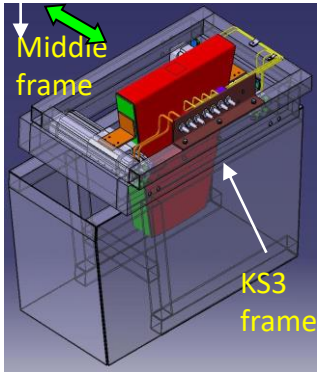
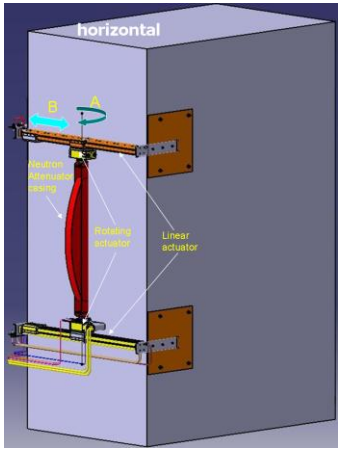


Neutron attenuators for γ-ray measurements

(attenuators are ≈ transparent for MeV γ-rays)





Zoita V. L. et al, Fus. Eng. Des. **84** (2009) 2052

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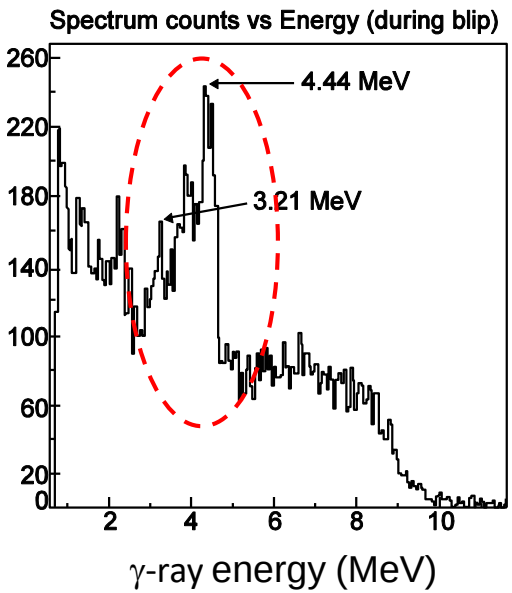
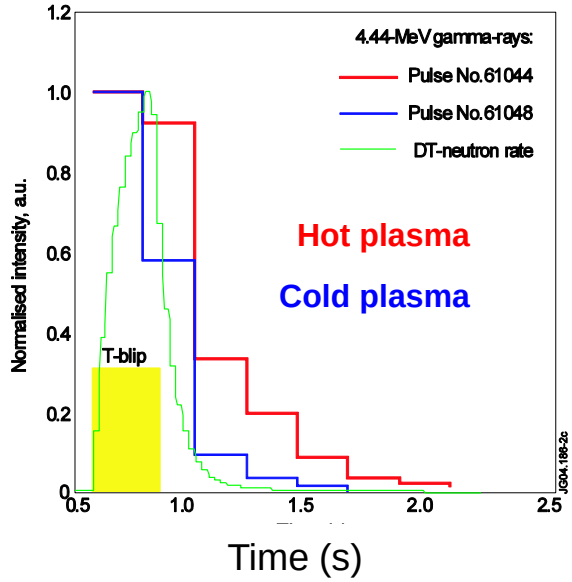
γ-rays from fusion alphas

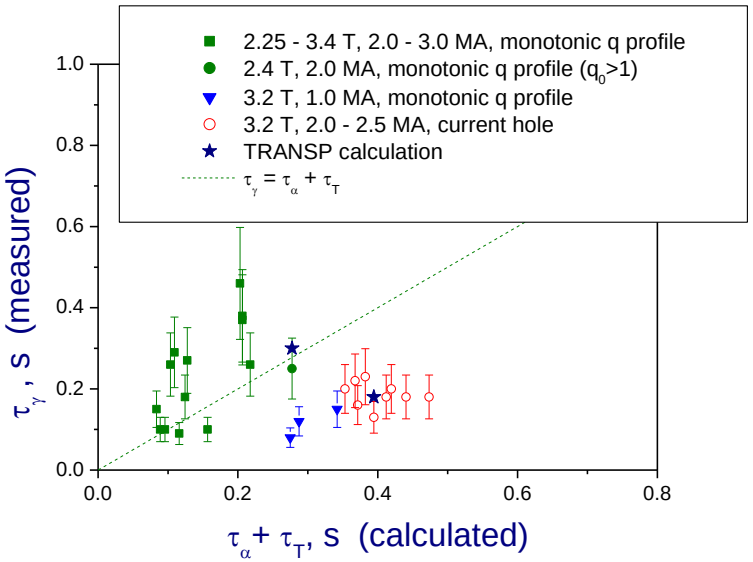
γ-rays afterglow measurements in D-plasma discharges with T-NBI blips

The method used in the first time





Results



γ-ray spectrum recorded just after the T-blip

Relaxation of 4.44-MeV γ-ray intensity in hot and cold plasmas

τ_γ vs $\tau_\alpha + \tau_T$ in discharges with anticipated good and bad confinement

Kiptily et al. Phys Rev Letter **93** (2004) 115001

JET vs ITER

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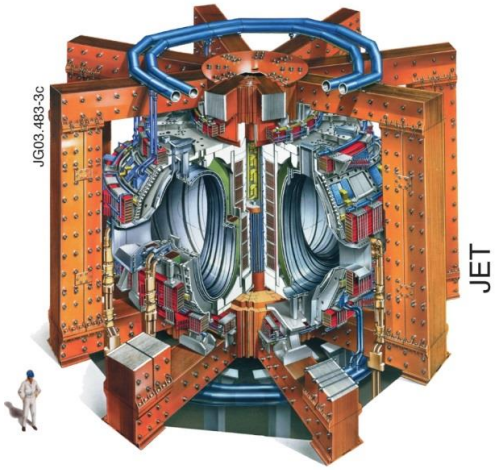
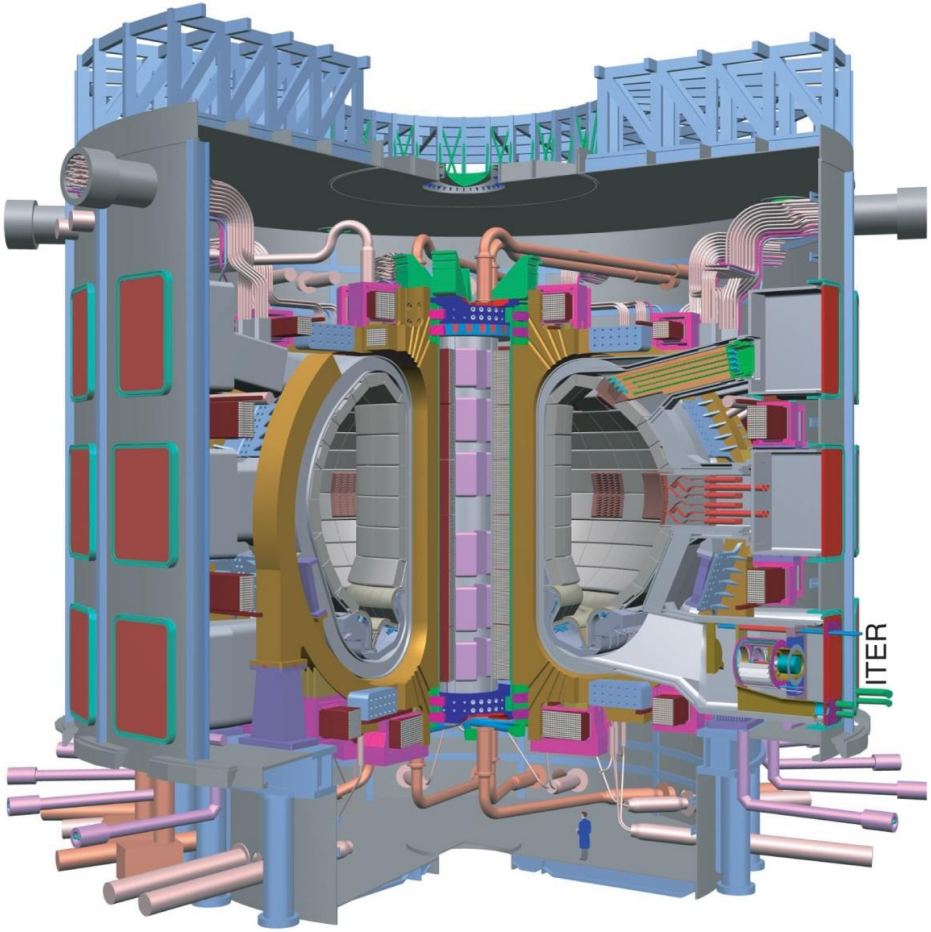
JET is the tokamak closest to the ITER parameters with unique capabilities of tritium operation

	JET	ITER
R, m	3.1	6.2
a, m	1.0	2.0
I_P, MA	up to 5	up to 15
B_T, T	up to 4	up to 5.3

Be-wall & W-divertor

$V_{ITER} / V_{JET} \sim 10$





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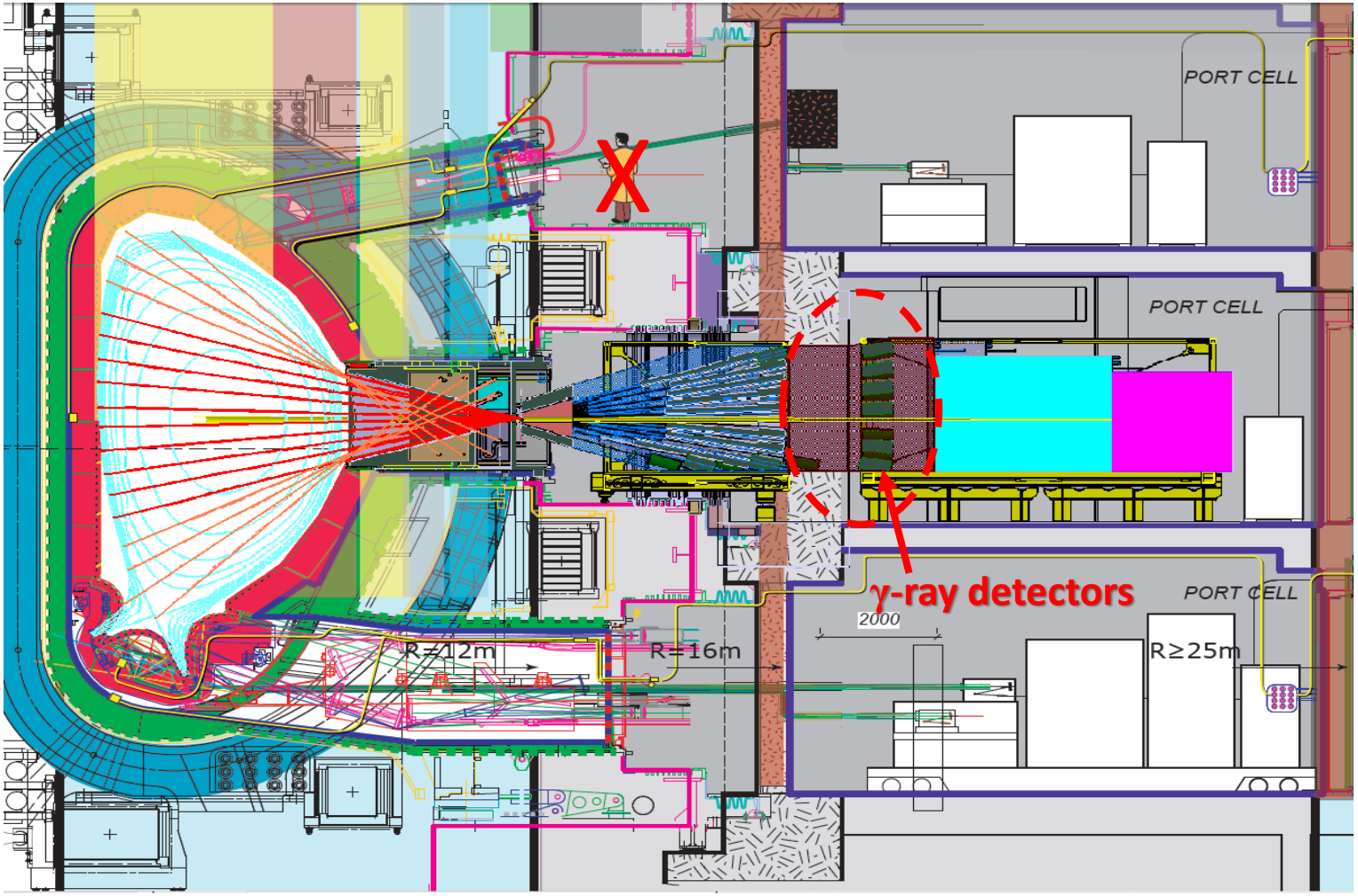
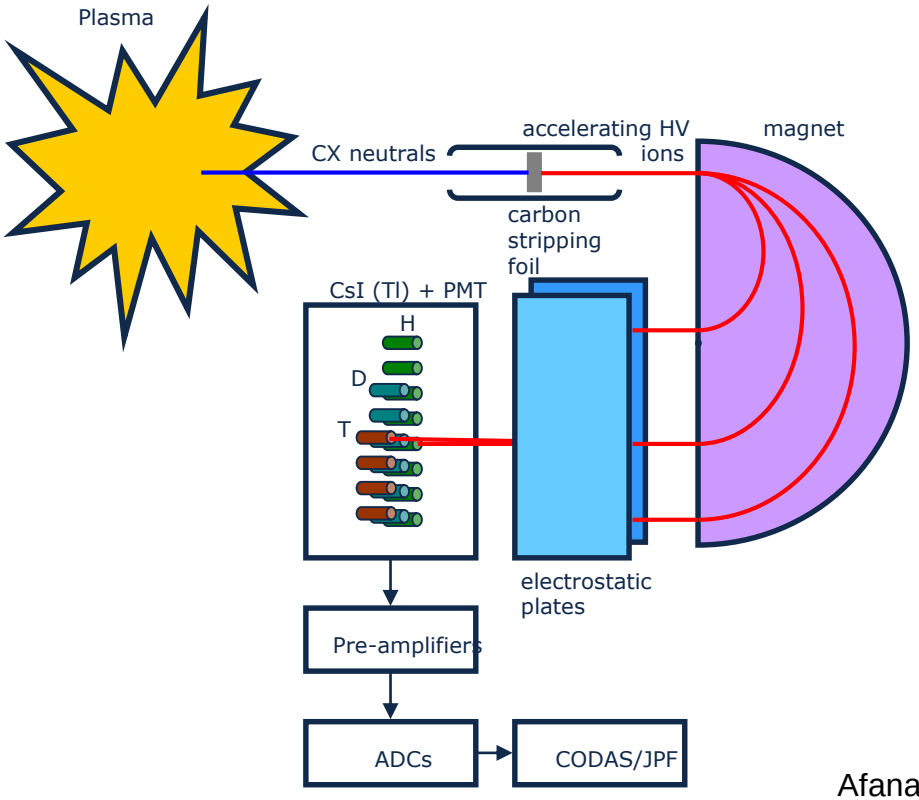
Is it measurable in ITER ?

Neutron & γ-ray Cameras



α-particle energy distribution

Classical method:
Neutral Particle Analysers



NPA provides line integrated energy distribution and fluxes

- Neutrals are generated via CX processes
- Carbon foils (300 Å) re-ionize the neutrals
- Acceleration provide boost to increase detection efficiency
- Momentum separation via B field
  Mass separation via E field.

Afanasyev V. I. et al Review of Scientific Instruments **74**, 2338 (2003)

α-particle energy distribution

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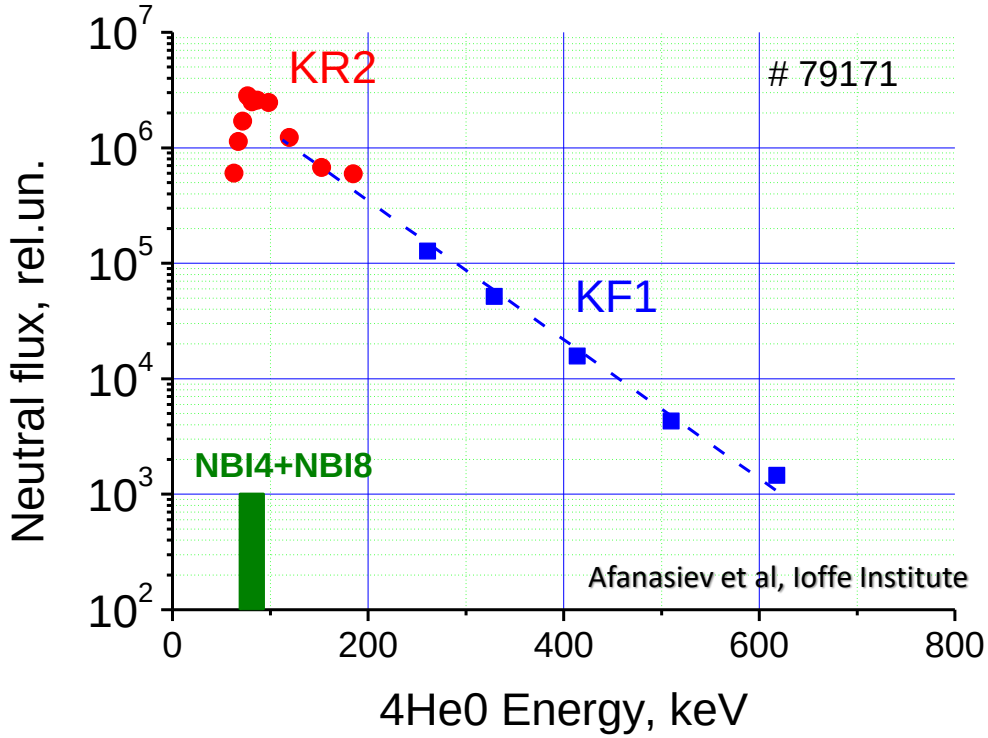
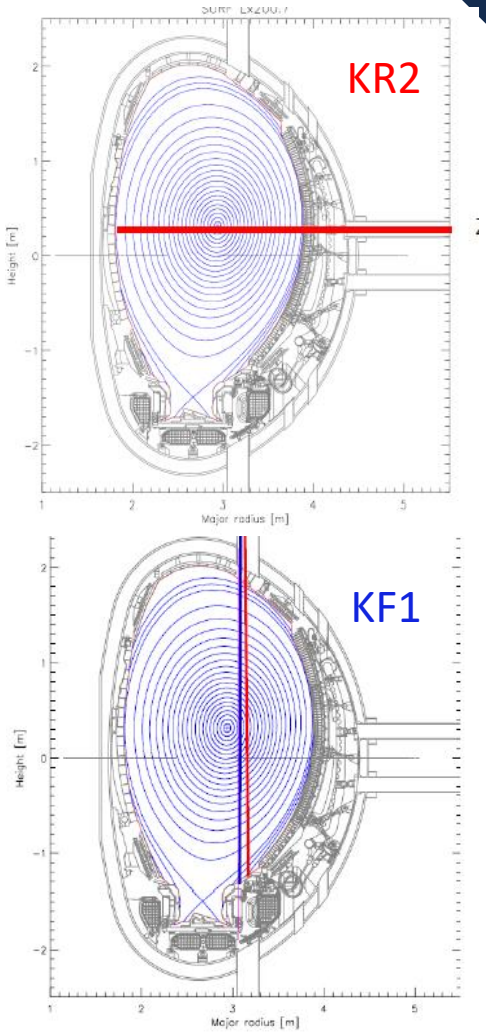
NPA in ^{4}He-ion acceleration experiments

$^4He^0$ neutral has been measured detecting $^4He^+$



High-Energy NPA (KF1) & Low-Energy NPA (KR2) data are normalized at ~ 200 keV



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α-particle energy distribution

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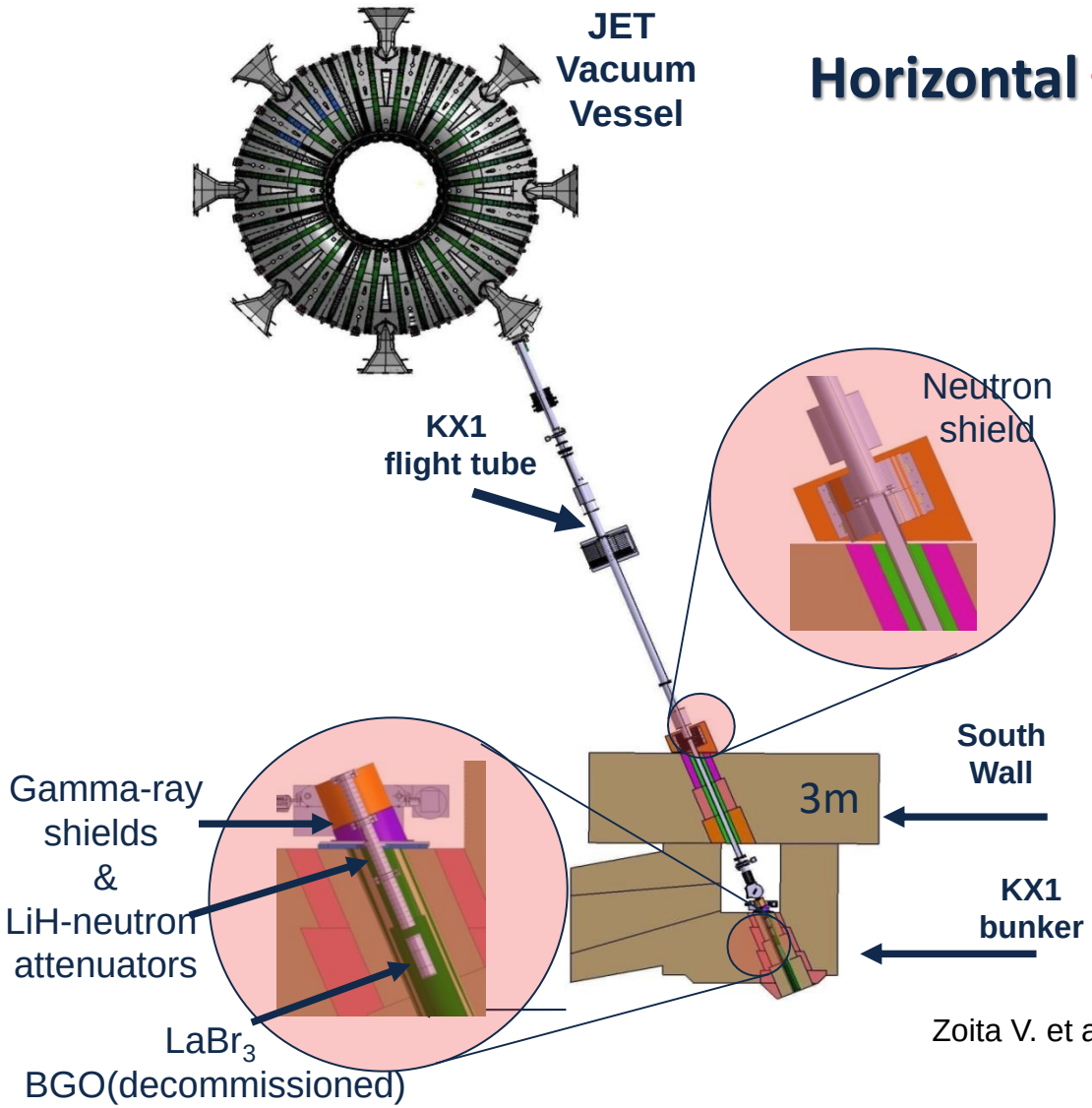
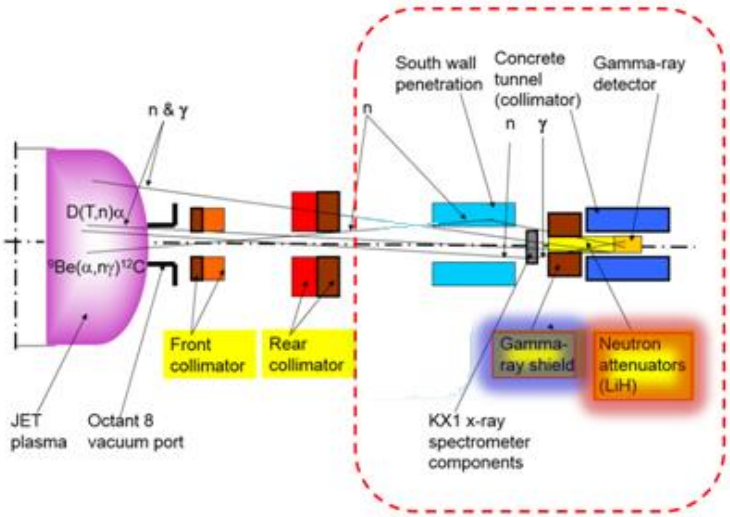
Horizontal γ-ray spectrometer





Zoita V. et al., Fusion Engineering and Design **88** (2013) 1366

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α-particle energy distribution

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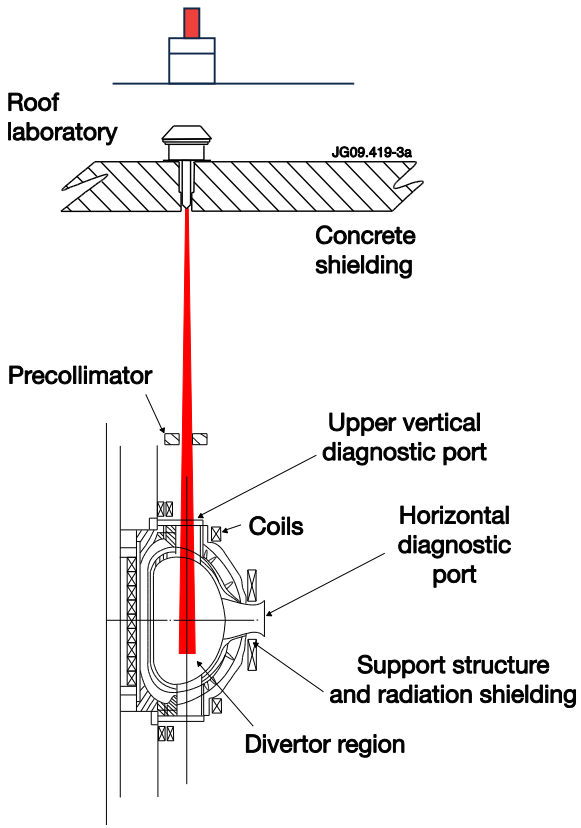
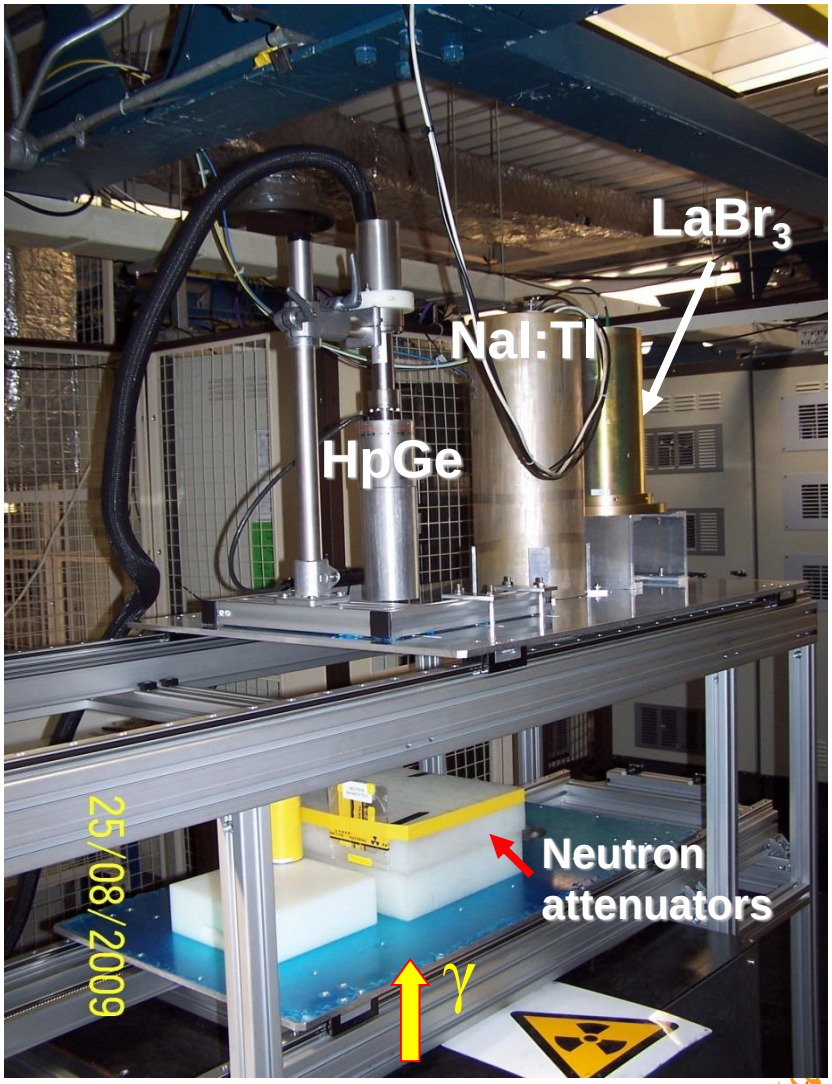
Vertical γ-ray spectrometers

Na(Tl), $LaBr_3$, HpGe





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α-particle energy distribution

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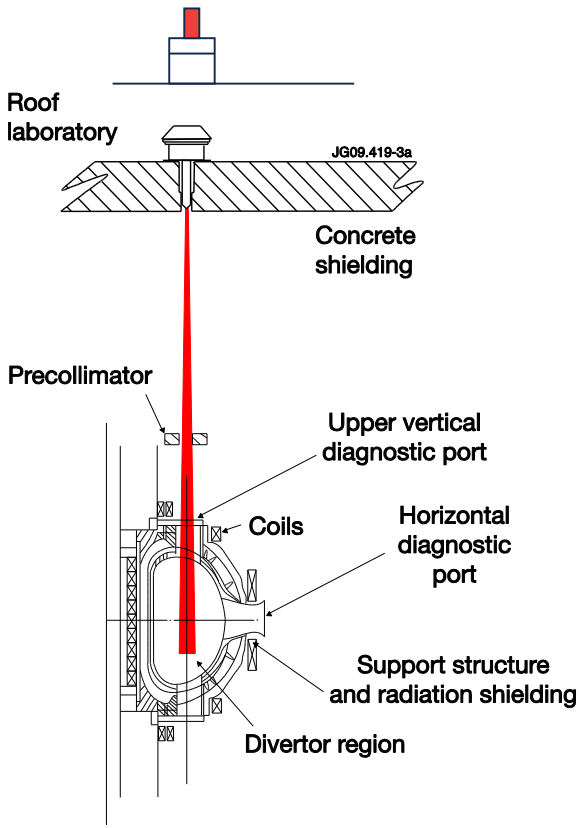
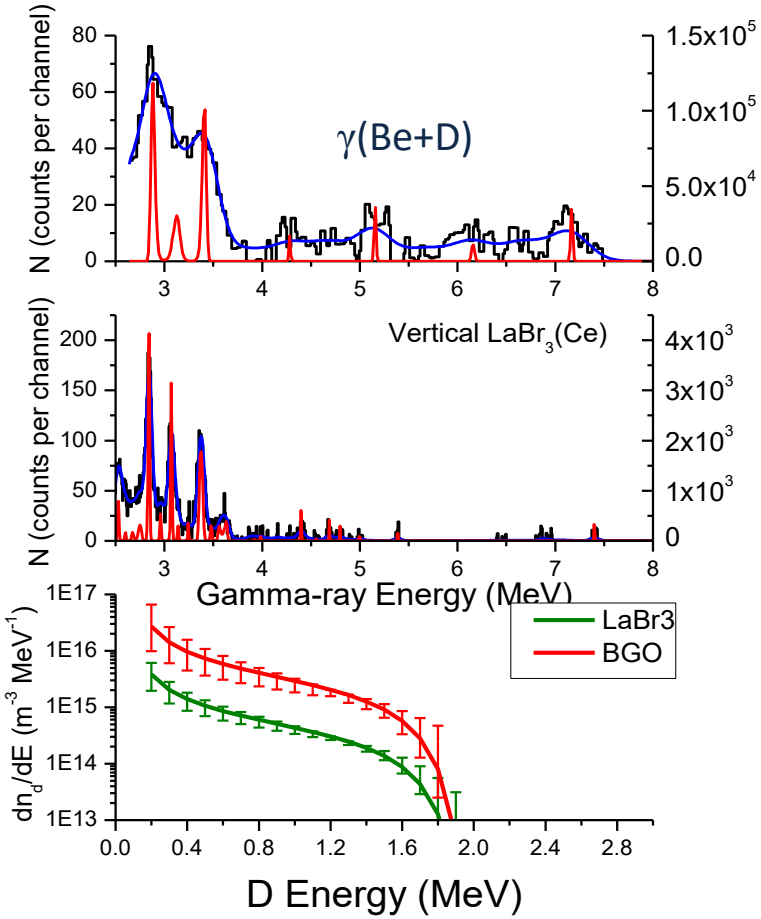
Vertical γ-ray spectrometers

Na(Tl), $LaBr_3$ & HpGe



An example: fast D-ions studies



Shevelev A. et al Nucl. Fusion **53** (2013) 123004

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α-particle energy distribution

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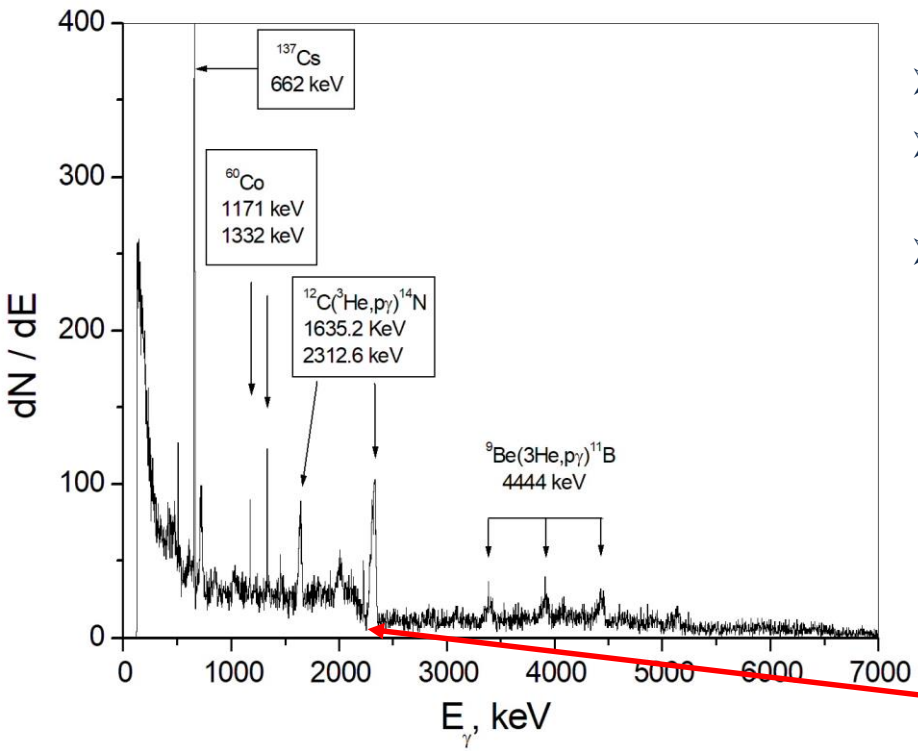
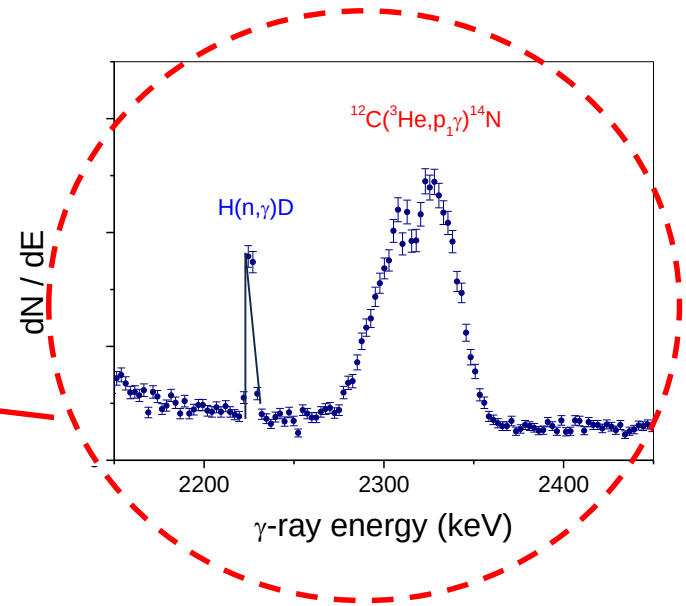
γ-ray Doppler broadening measured with HpGe-detector

This technique used in the first time (developed in 1987)

Kiptily V.G., Fusion Technology **18** (1990) 583



- ^{3}He-ions were accelerated with ICRF
- Doppler broadening due to nuclear reactions of MeV ^{3}He-ions and C and Be impurities
- $\langle T_{3He} \rangle$ has been inferred



Kiptily et al Nucl. Fusion **50** (2010) 084001
Tardocchi et al PRL **107** (2011) 205002
Nocente et al Nucl. Fusion **52** (2012) 063009

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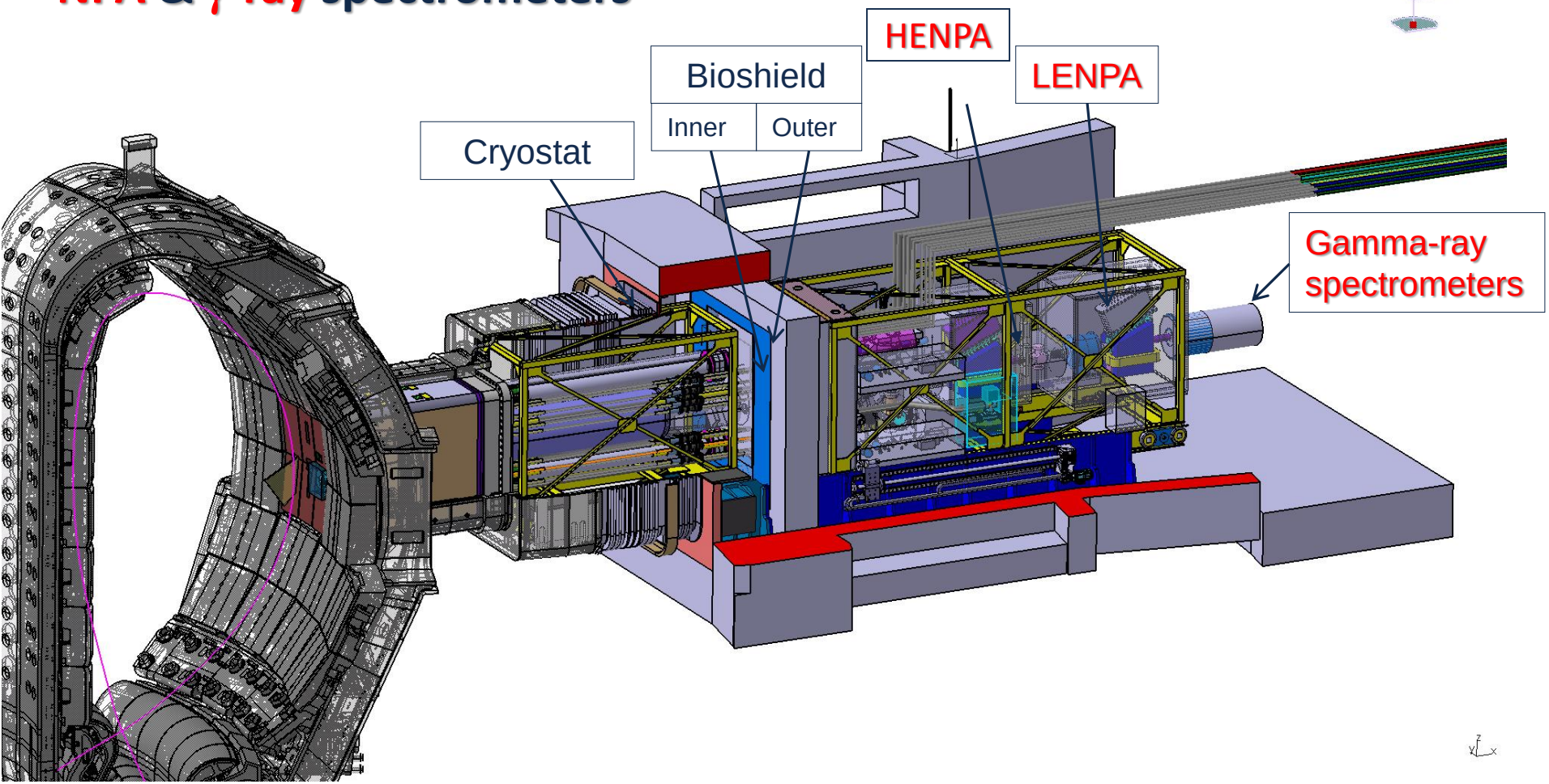
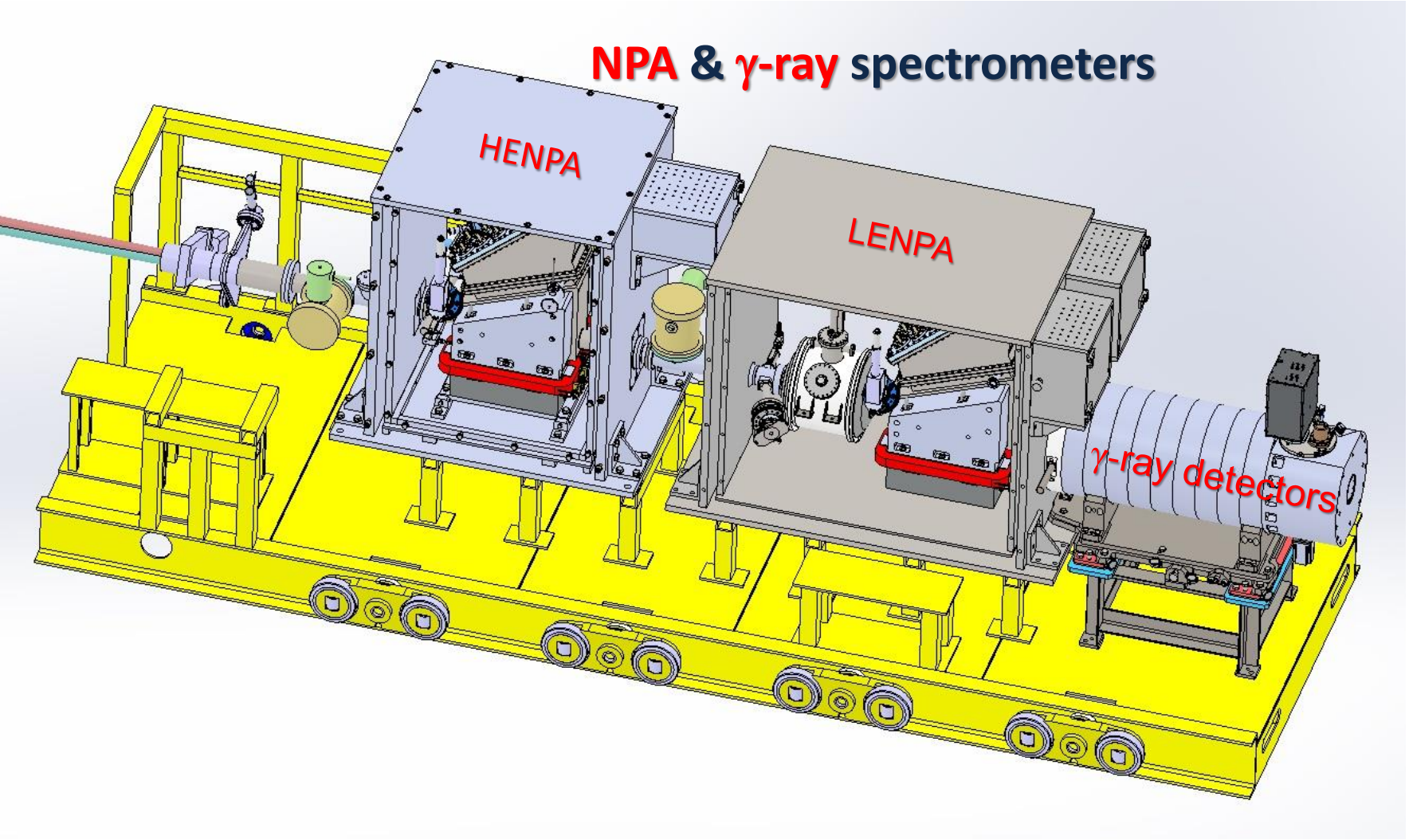
α-particle energy distribution in ITER

NPA & γ-ray spectrometers

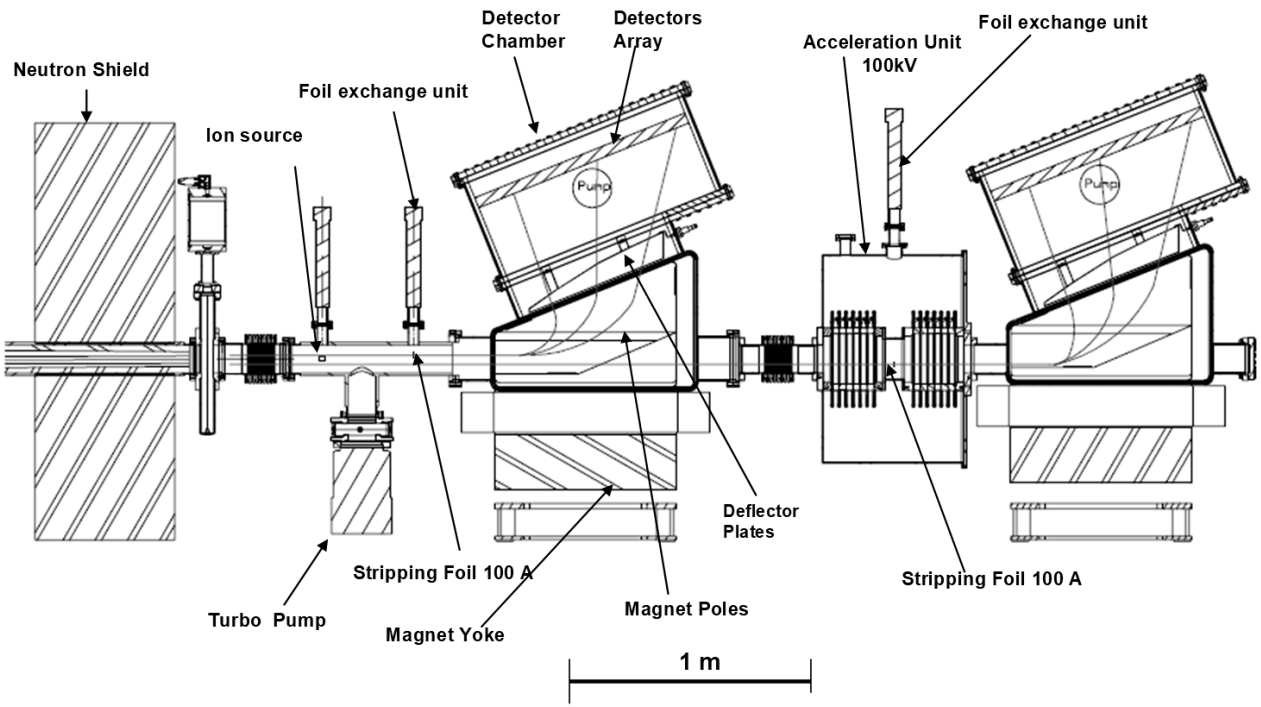


α-particle energy distribution in ITER



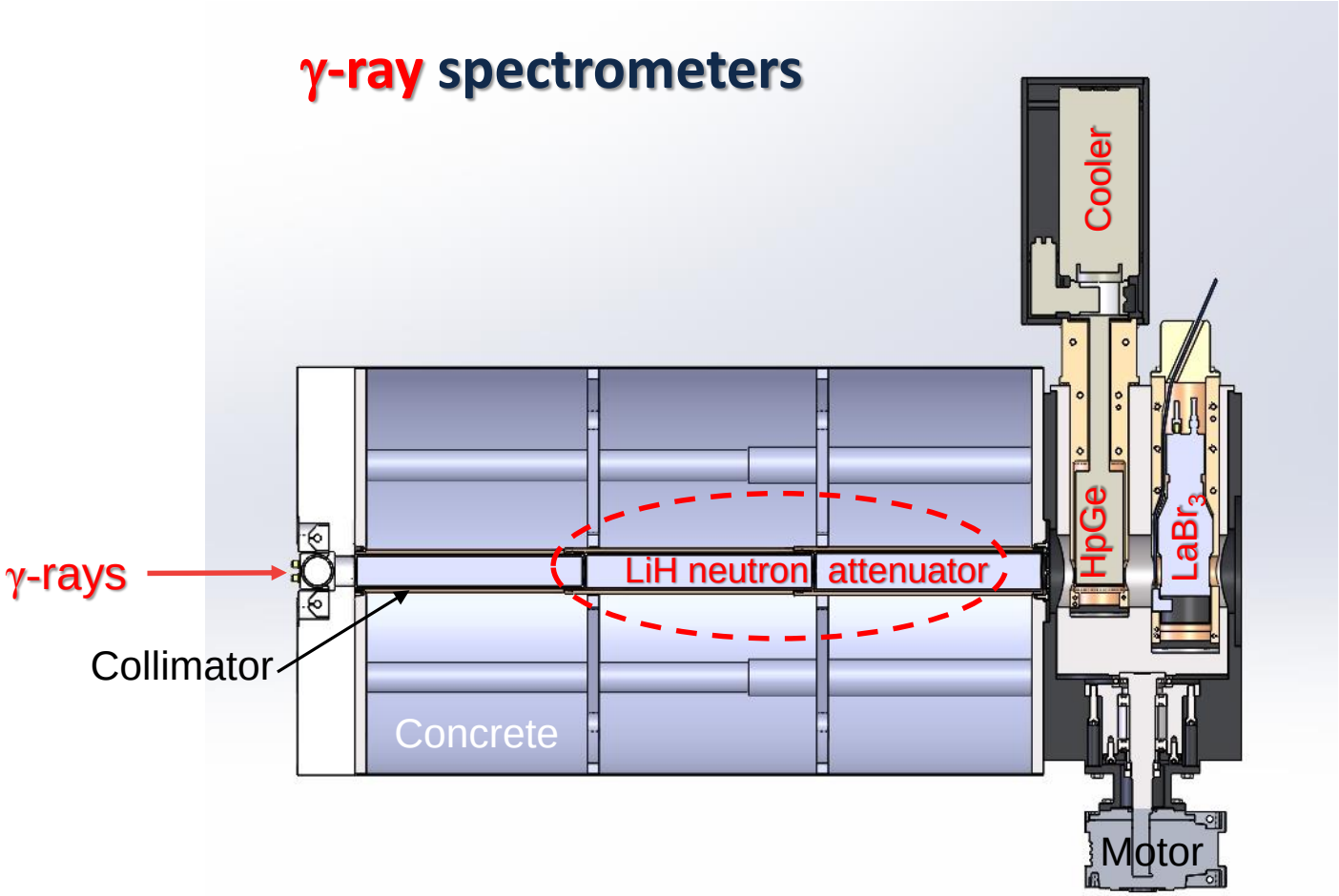
α-particle energy distribution in ITER

HENPA (0.1 – 4 MeV) **LENPA (10 – 200 keV)**



Afanasyev V.I. et al 2010 Nucl. Instrum. Methods Phys. Res. **A62**1 456

α-particle energy distribution in ITER



Chugunov I.N. Et al Nucl. Fusion **51** (2011) 083010

α-particle energy distribution in ITER

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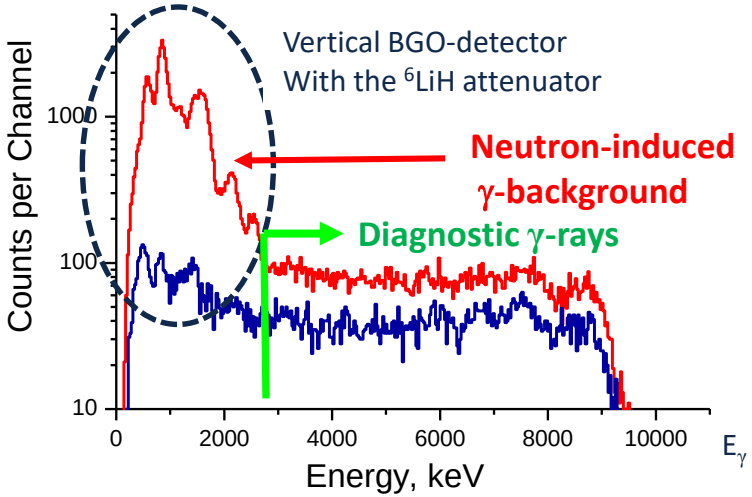
LiH neutron attenuator

Tested on JET (2007):
neutron-induced background (E_γ<3 MeV, inelastic scattering in the detector) suppressed by a factor of ≈ 100



Kiptily V.G. et al Technical Physics **43** (1998) 471
Chugunov I.N. et al Instrum. and Exp. Techniques **51** (2008) 166

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α-particle losses: JET

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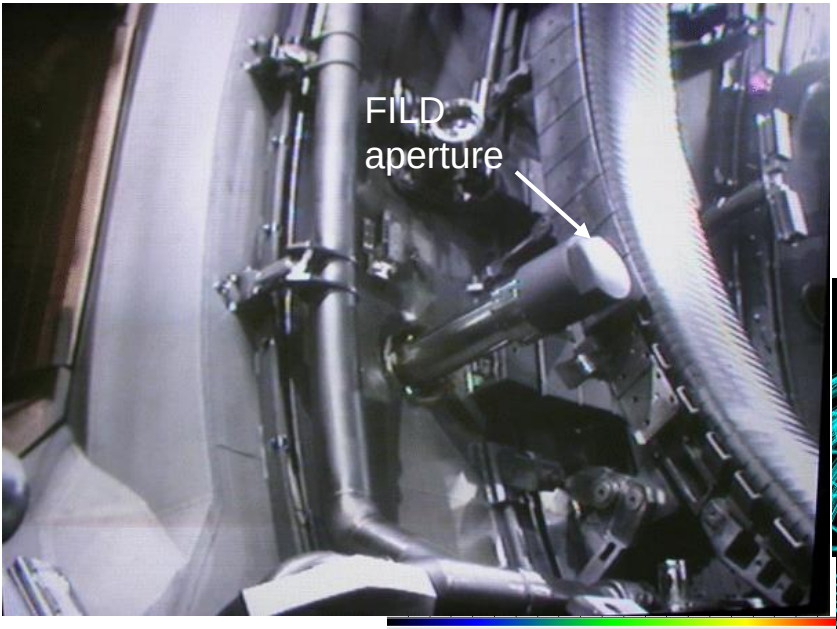
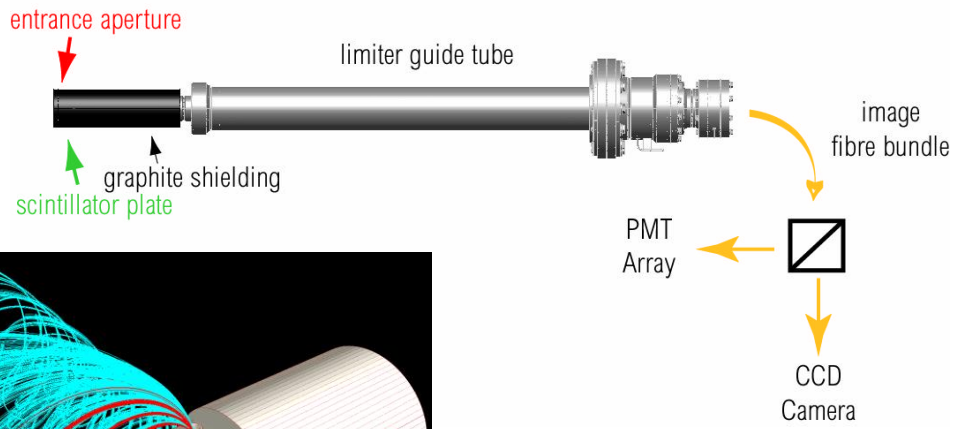
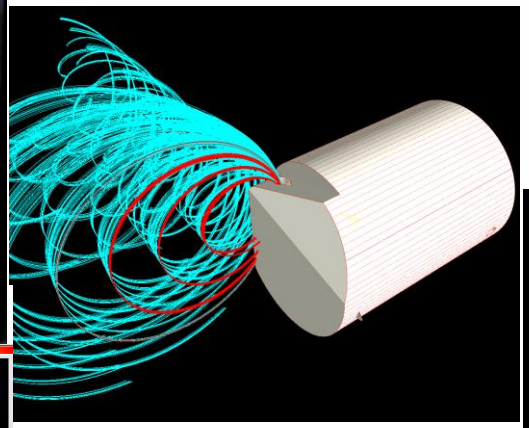
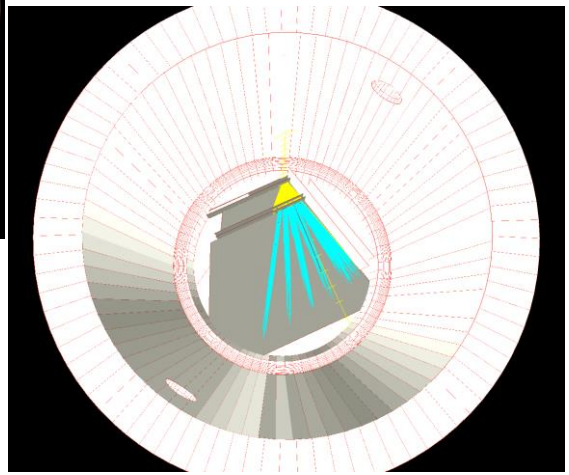
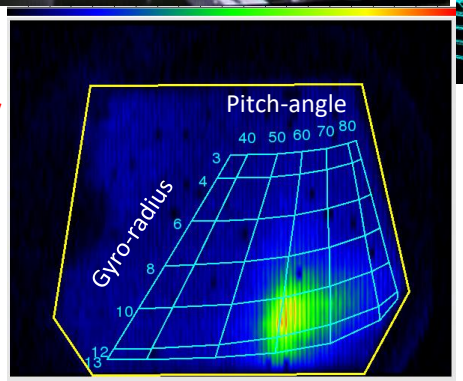
Fast Ion Loss Detector











Footprint of lost 1-MeV tritons & 3-MeV protons (DD fusion product first orbit losses)

- Modelling of lost ions orbits
- Lost ions image on scintillator plate

Darrow D. et al. Rev. Sci. Instrum. **77** (2006) 10E701

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α-particle losses in JET

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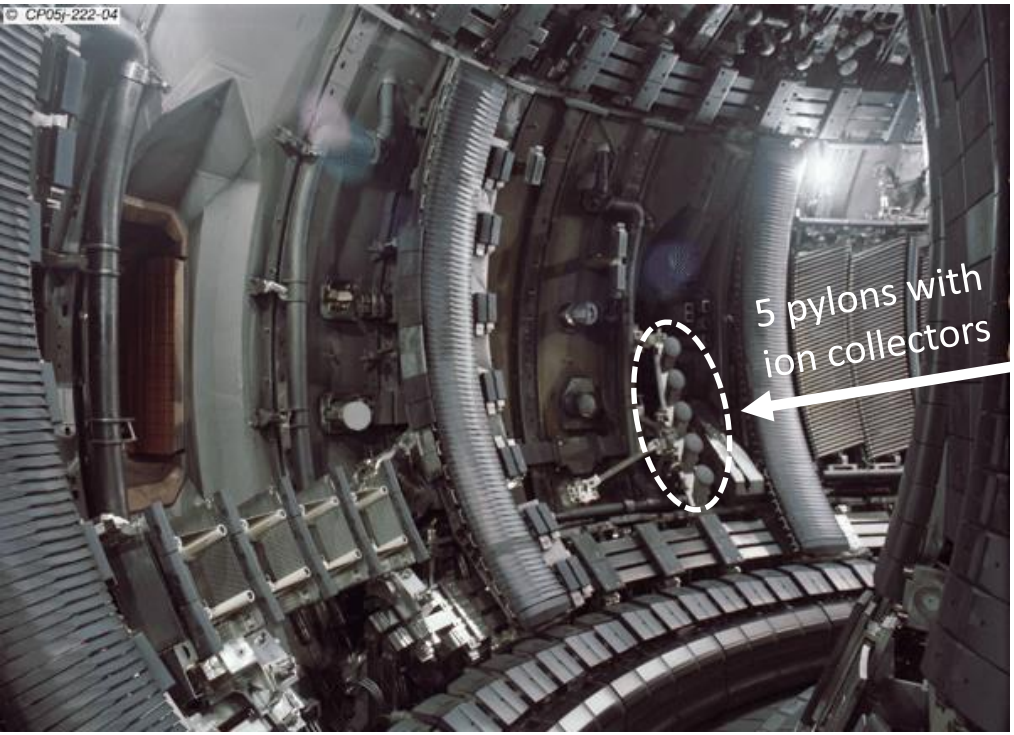
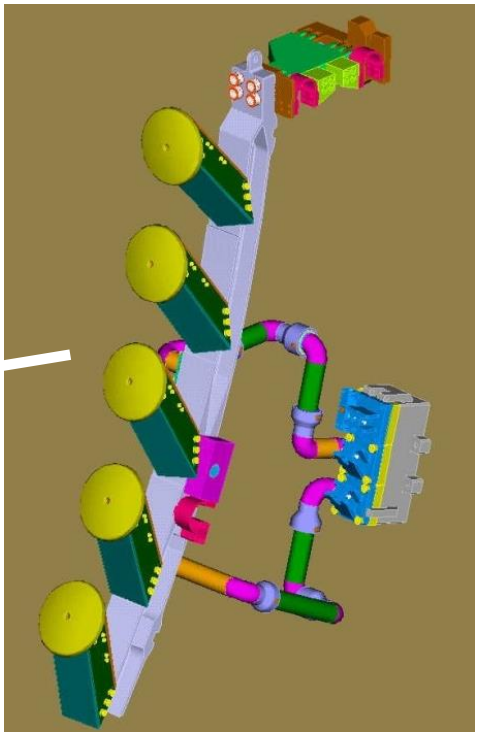
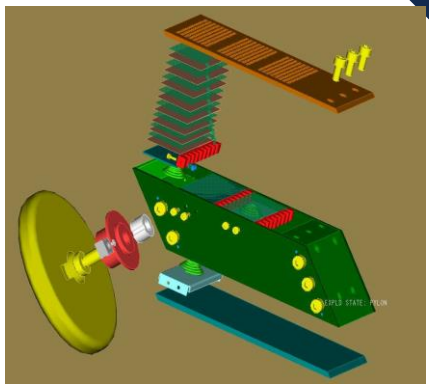
Faraday Cups







- Perforated cover to admit ions
- Stack of alternating Ni foils and mica insulating sheets
- Ion current measured for each foil individually
- Ion energy determines deposition depth

Faraday Cups array was designed for lost α–particle measurements in DT-plasmas

Darrow D. S. et al Rev. Sci. Instrum. **75** (2004) 3566
Kiptily V.G. et al Nucl. Fusion **49** (2009) 065030

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α-particle losses in ITER

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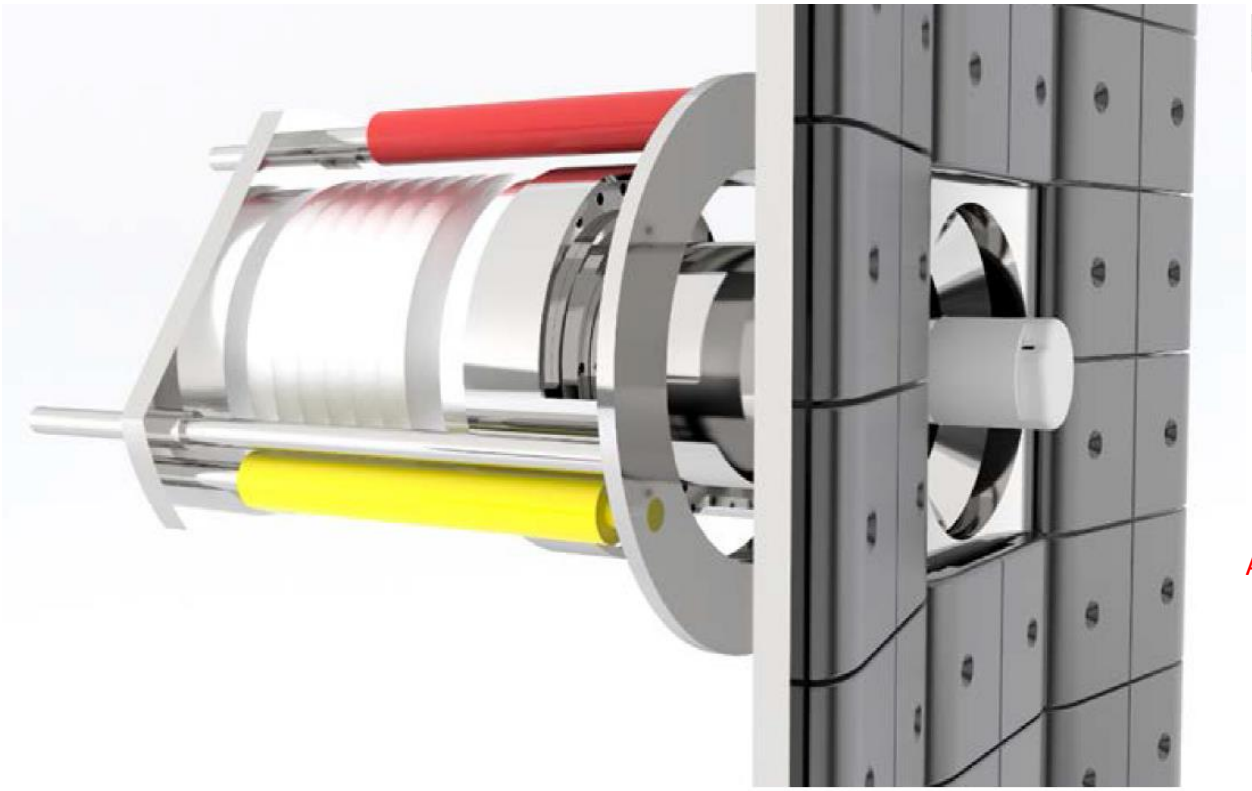
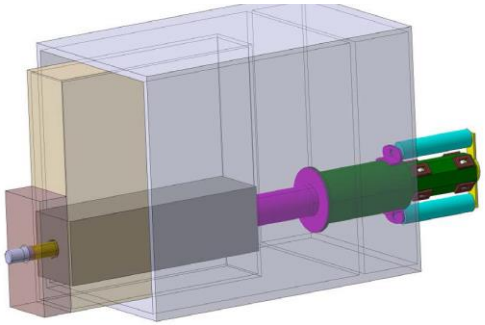
Fast Ion Loss Detector



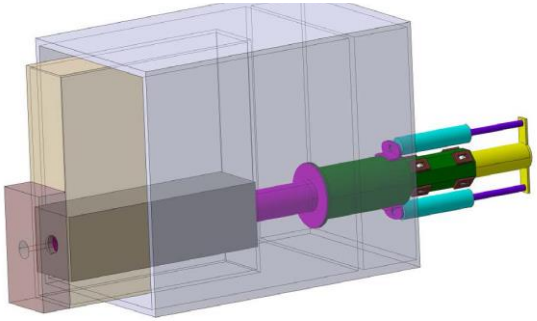
ITER FILD At Measurement Position

FILD based on reciprocating system



ITER FILD At Parking Position

Active cooling is necessary due to nuclear heating



In ITER, lost α-particle measurements are most challenging. However, they are very important for control of fusion plasma performance.

M. Garcia-Munoz et al, ITPA Diag. Meeting 2016

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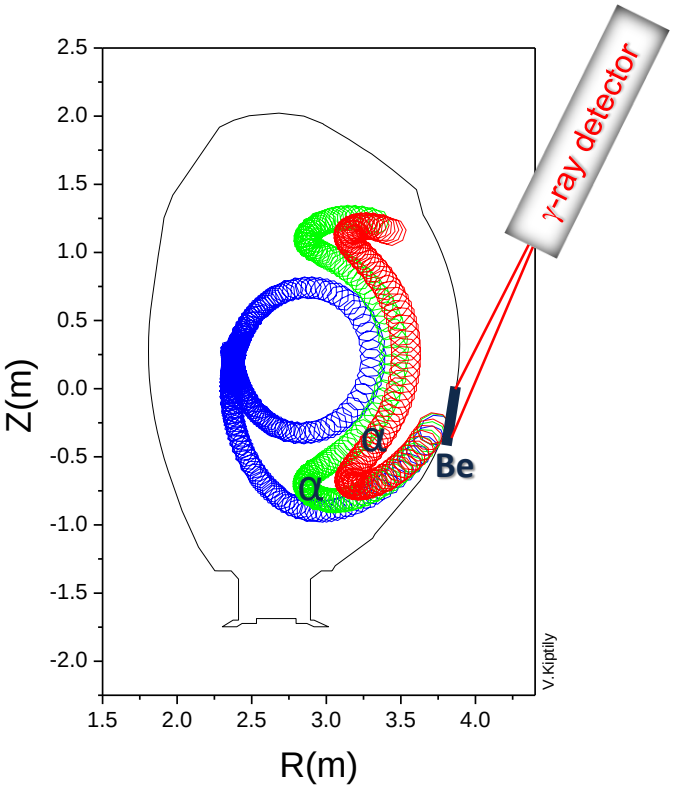
A novel method for α-particle loss measurements



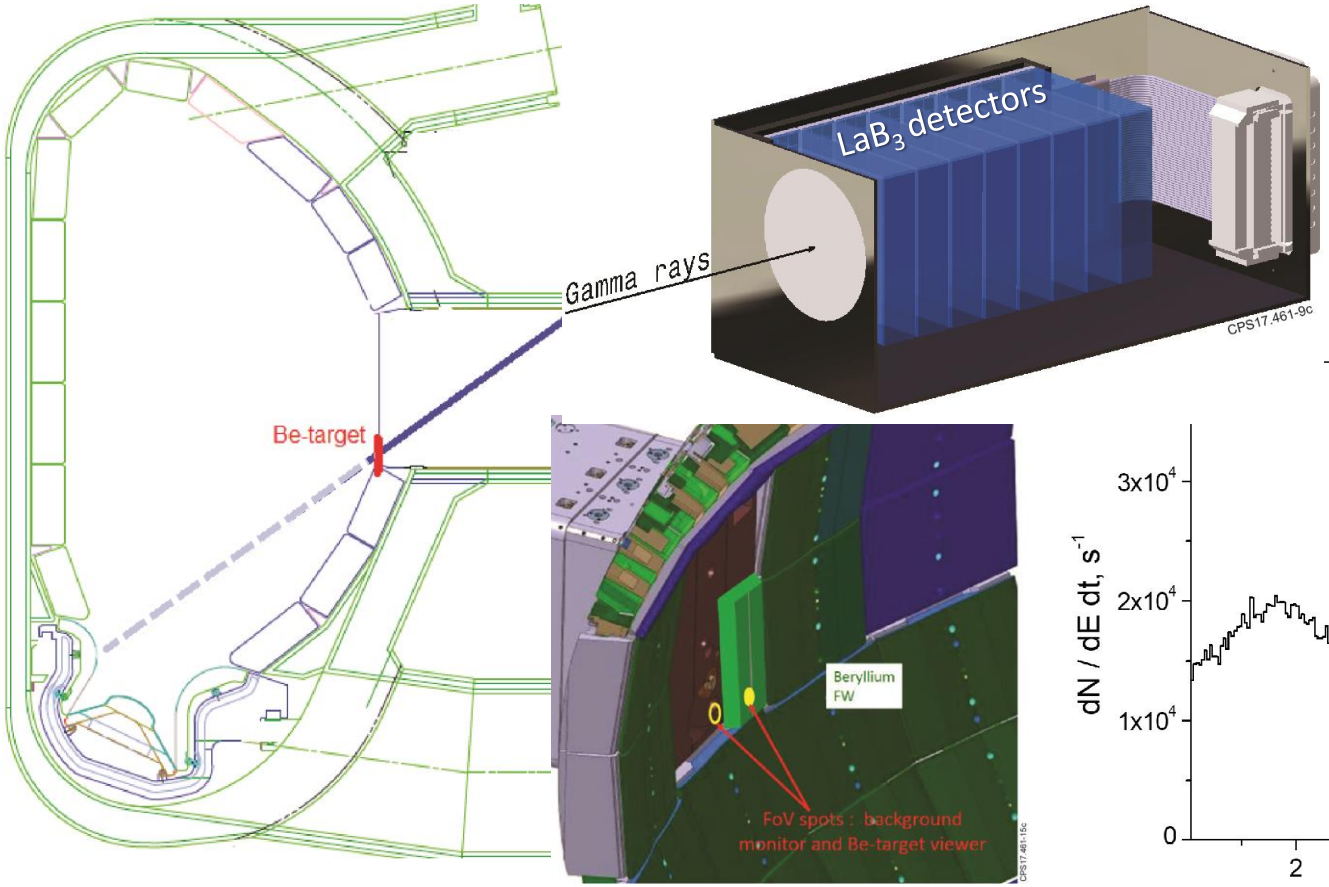
- A thick **Be-target** is in the field of view of a collimated γ-ray spectrometer
- Escaped α-particles strike the Be-target
- Measurements of gammas from the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction:
  $E_\alpha > 1.7$ Me → γ4.44-MeV
  $E_\alpha > 4$ MeV → γ3.21-MeV
- An identical "**blind**" **detector** for the background monitoring is needed.

This robust technique is feasible for monitoring of α-particle losses in DEMO and fusion power plants

Kiptily et al Fusion Technology **22** (1992) 454

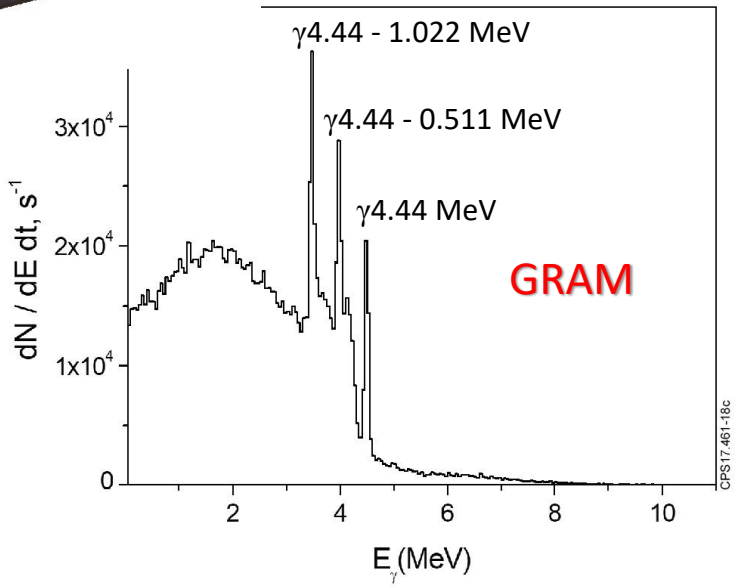
α-particle losses in ITER

Gamma-Ray Alpha-particle Monitor



A high-performance γ-ray spectrometer based on a novel architecture, **GRITER**

Calculated **GRITER spectrum**: 1-MW m^{-2} α-particle losses in 500-MW ITER discharge



Kiptily V et al Nucl. Fusion **58** (2018) 082009

α-particle diagnostics in DEMO

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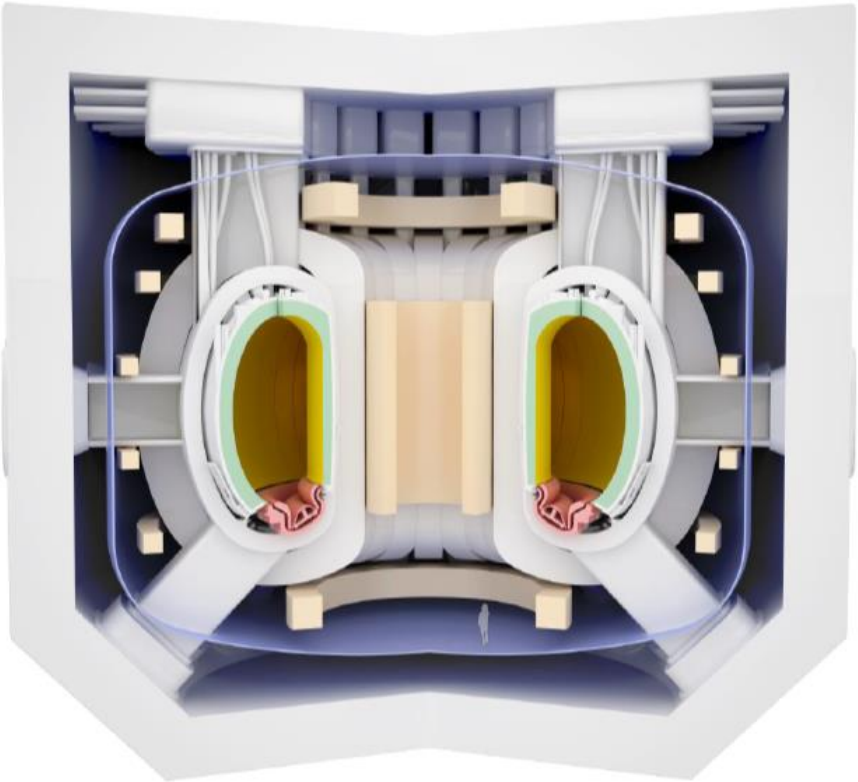
A harsh DEMO environment with a very high level of neutron and γ-ray fluxes will make some conventional diagnostics unfeasible.

Among the restricted set of instruments neutron and γ-ray diagnostics can be used:

- diagnostics do not require a direct access to the vessel
- neutron and γ-ray detectors are placed far away from the plasma.

These diagnostics can provide control of

- Fusion power (neutrons)
- Temperature & fuel ratio in plasma core (γ-rays)
- α-particles losses (GRAM)



Donné A.J.H., Costley A.E. and Morris A.W. 2012 Nucl. Fusion **52** 074015
Kiptily V., Nucl. Fusion **55** (2015) 023008
Kiptily V. et al Nucl. Fusion **58** (2018) 082009

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Conclusions

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- JET, operating with DT plasmas, will provide the opportunity to obtain information on the feasibility and capability of the developed **α-particle diagnostics** for future experiments on ITER
- ITER exploitation will bring a comprehensive information on the restricted set of robust and reliable instruments, which could provide the machine protection and fusion control in DEMO
- Indeed, α-particle diagnostics will be a part of critical control loops in DEMO and future power plants

and

JET contribution to α-particle diagnostics developments is unique

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Thank you for your attention