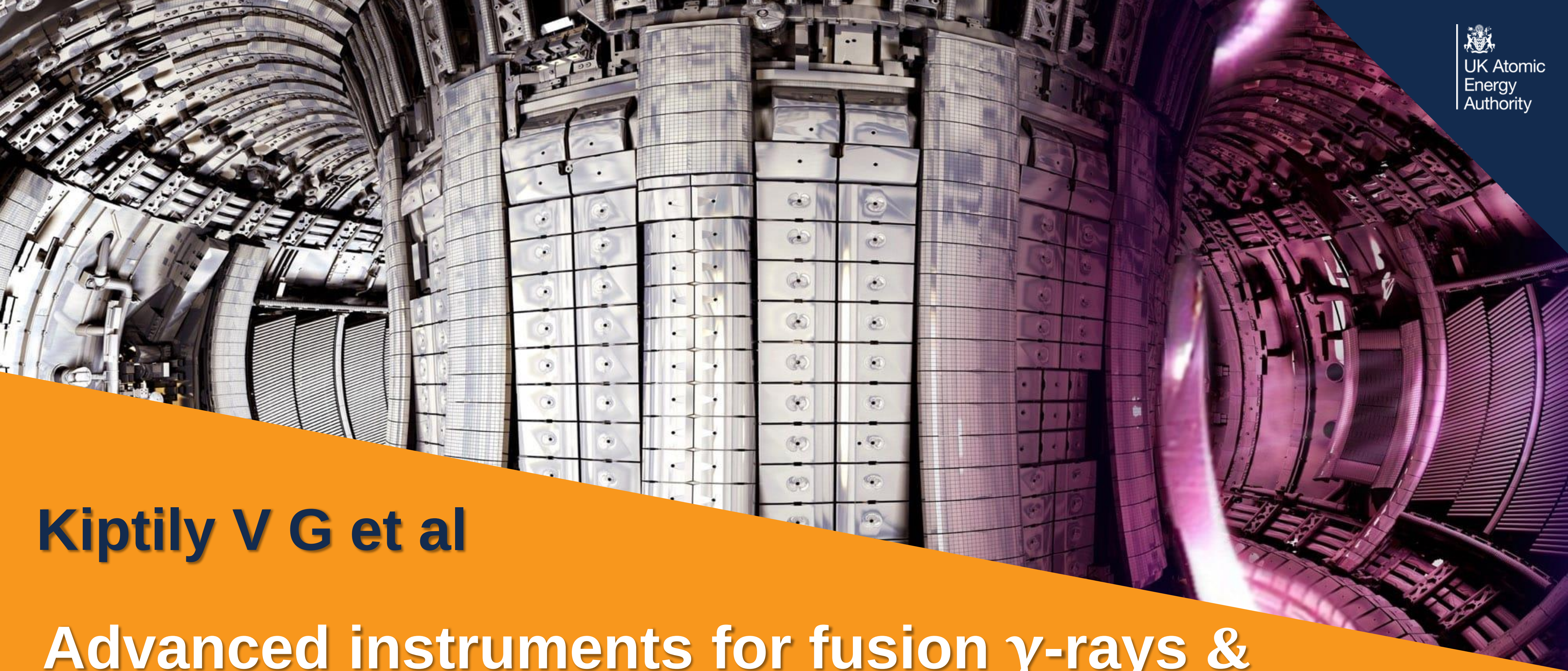


UK Atomic Energy Authority

Kiptily V G et al

Advanced instruments for fusion γ-rays & α-particles monitoring of reactor plasmas

DIAGNOSTICS FOR FUSION REACTORS: THE BURNING PLASMA ERA, Varenna, Italy, 1st – 5th September 2025

European Commission

Contract for the Operation of the JET Facilities Co-Funded by Euratom
This work was funded by the RCUK Energy Programme [Grant number EP/P012450/1]

Acknowledgements

Beaumont P. S., Beldishevski M., Ghani Z., Hussain R., Jones I., Kandan B., Marsh R., Mianowski S., Mianowska Z., Tilley A. & Turner A.,

JET contributors* and the EUROfusion Tokamak Exploitation Team**

UKAEA, Culham Campus, Abingdon, Oxfordshire, OX14 3DB, UK

*See the author list of C.F. Maggi et al 2024 Nucl. Fusion 64 112012
** See the author list of E. Joffrin et al 2024 Nucl. Fusion 64 112019

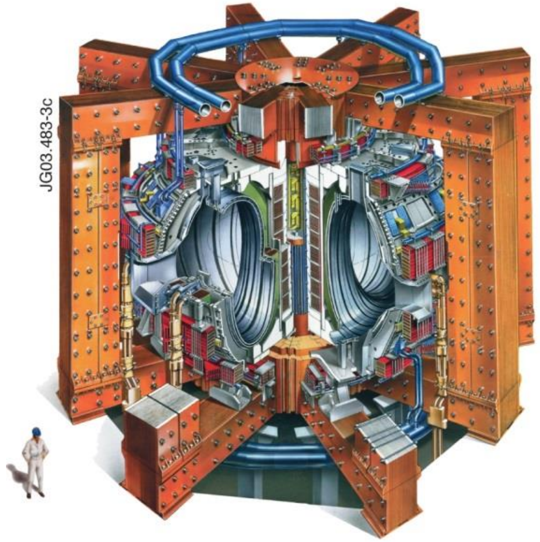
Outline

- JET fusion diagnostics
  - γ-ray spectrometry
    - α-particle studies
    - fusion reaction control
  - α-particle loss detectors
- Fusion γ-ray spectrometer for next step devices
  - FUGAS prototype
  - FUGAS tests
- Alpha-particle loss monitoring in fusion plants
  - α-particle loss monitoring with γ-rays
  - α-particle charge collectors
- Conclusions

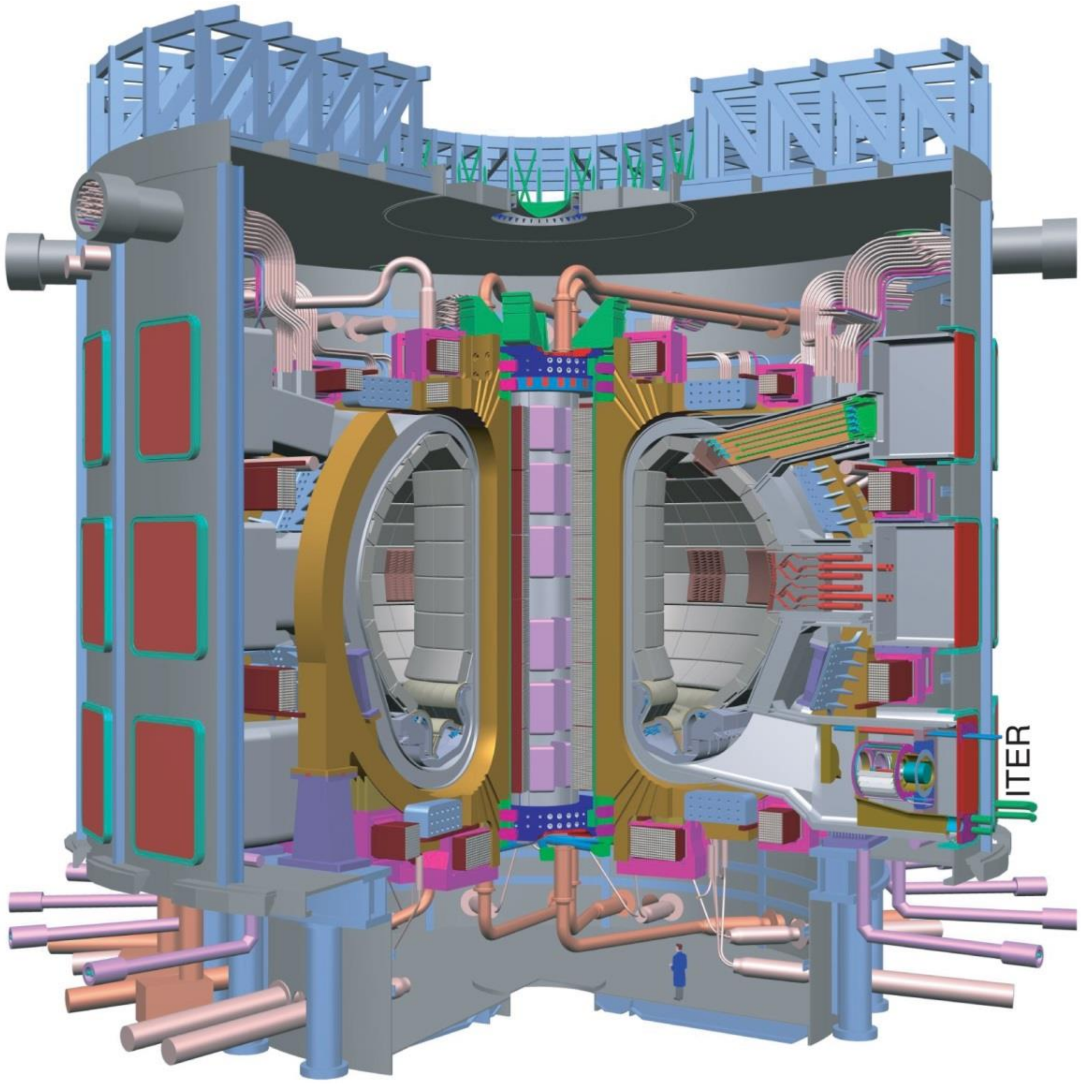
JET *vs* ITER

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

W_{JET} (D-T) = 59 MJ



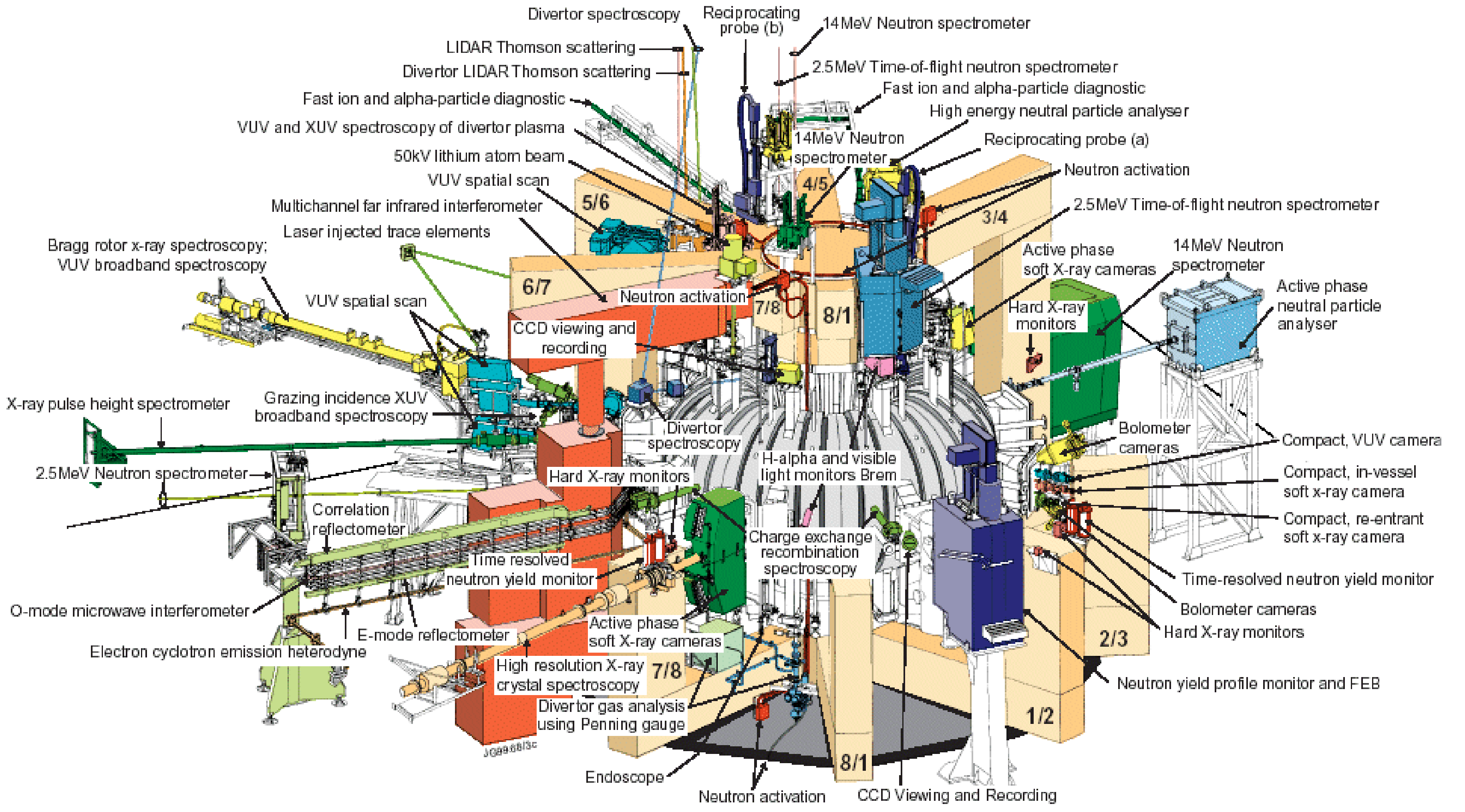
JET



ITER

JET Diagnostics

UK Atomic Energy Authority

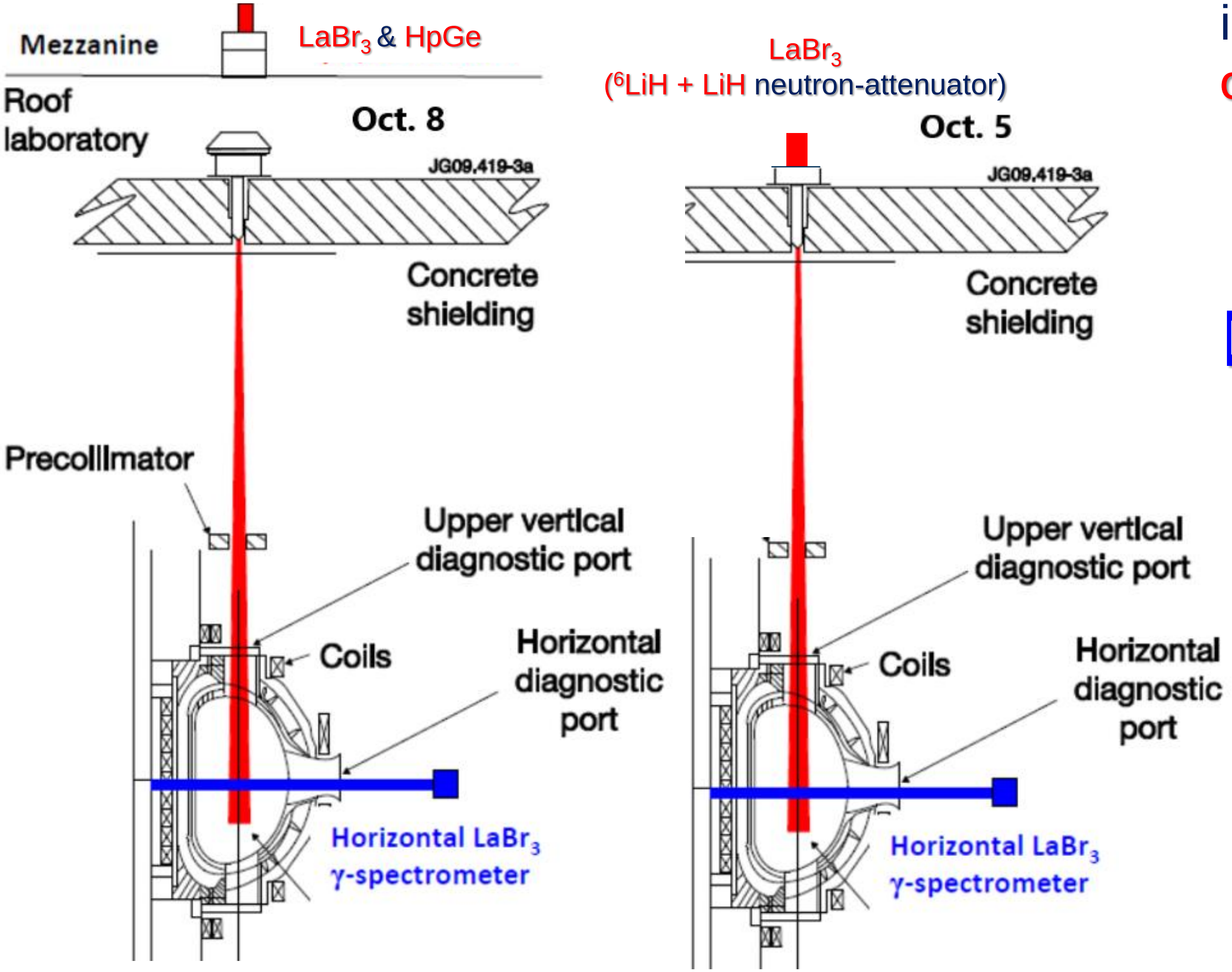


> 100 diagnostic instruments

JET fusion diagnostics experience

Gamma-ray spectrometers

Vertical spectrometers

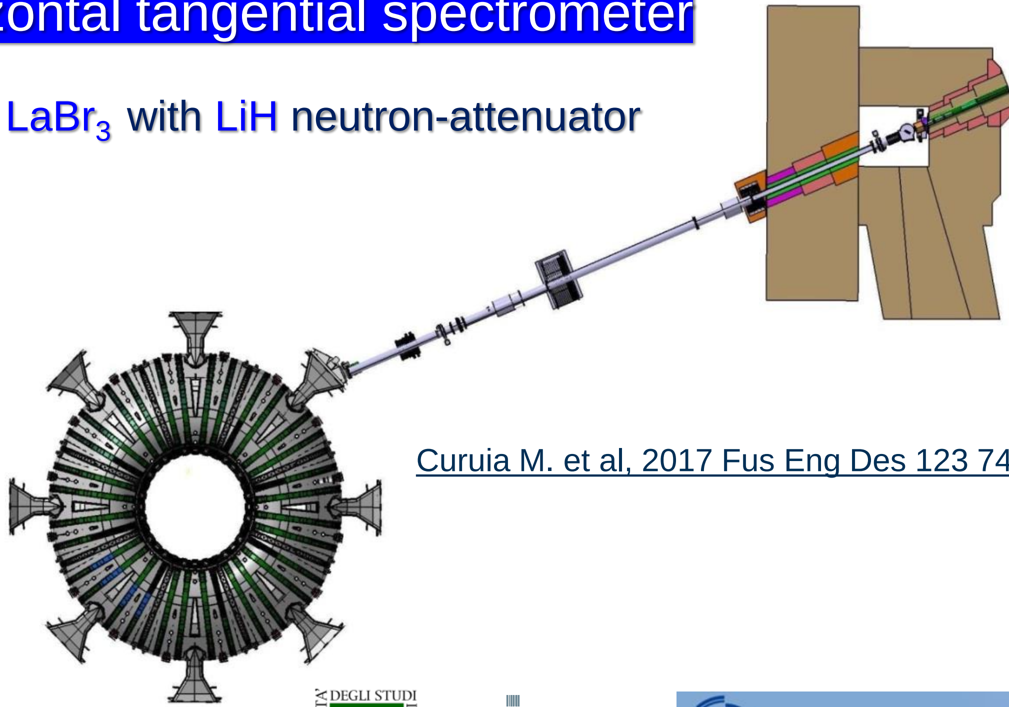


Gamma-ray diagnostics became a routine instrument to study fast-ions and fusion-born α-particles on JET in this century

Kiptily V G et al 2002 NF 999
Kiptily V G, Cecil F E and Medley S S, 2006 PPCF **48** R59
Tardocchi M, Nocente M & Gorini G 2013 PPCF **55** 074014
Nocente N et al 2020 PPCF **62** 014015

Horizontal tangential spectrometer

LaBr$_3$ with LiH neutron-attenuator

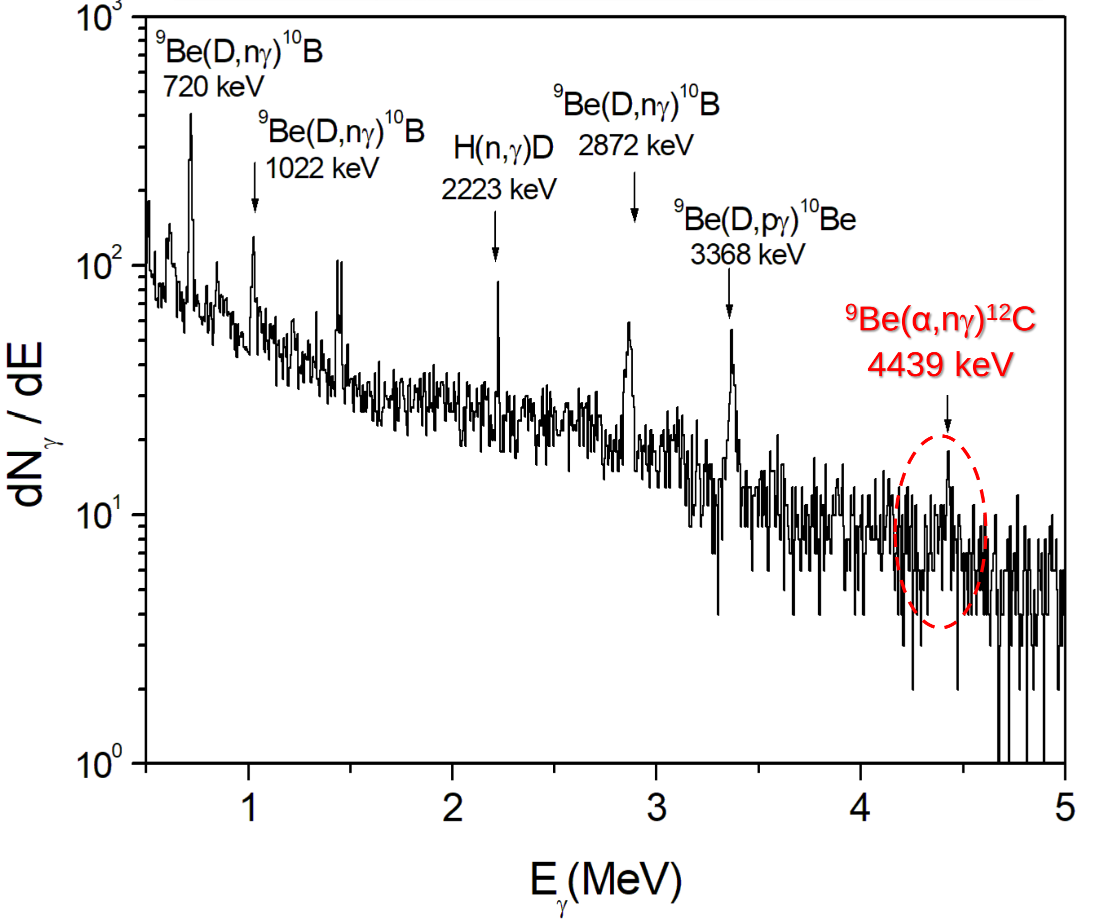


Curuia M. et al, 2017 Fus Eng Des 123 749

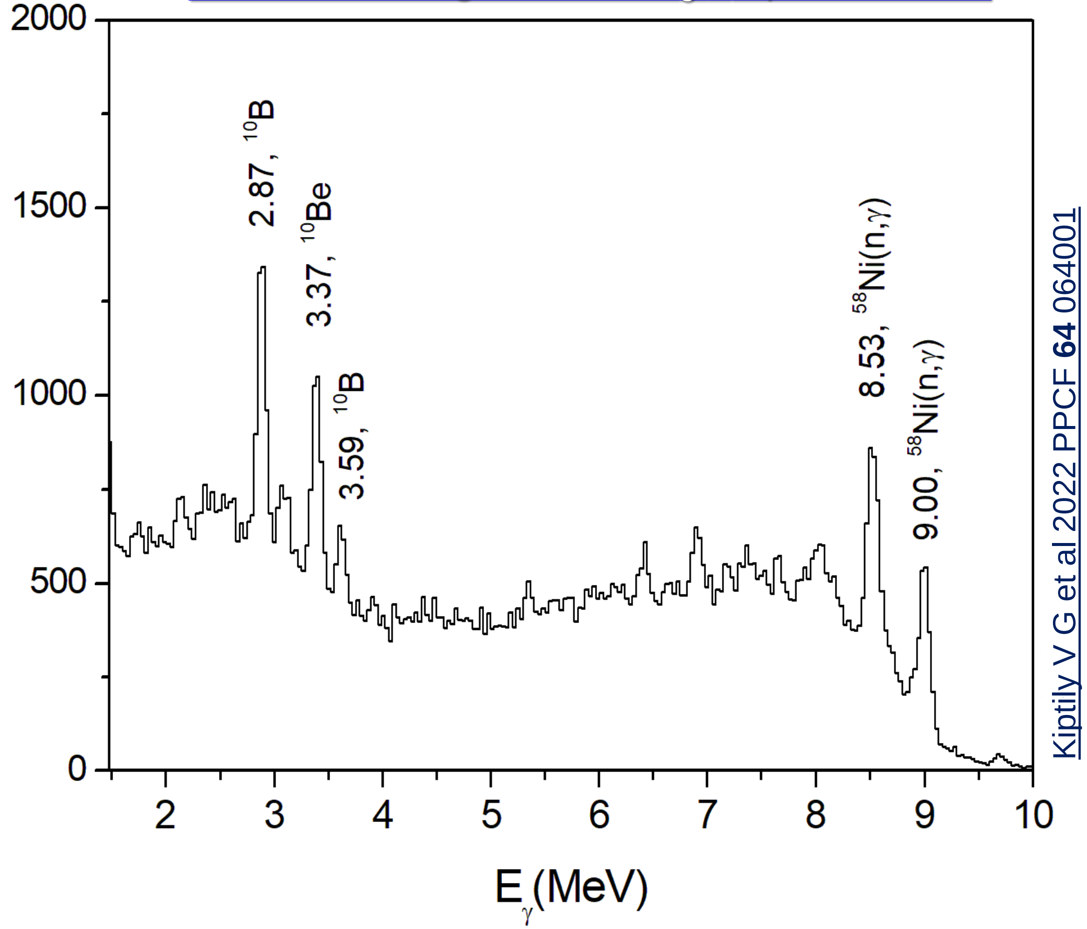
γ-ray spectrometry: **fast-ion studies**

UK Atomic Energy Authority

Vertical High-resolution HpGe – spectrometer



Horizontal tangential $LaBr_3$ – spectrometer



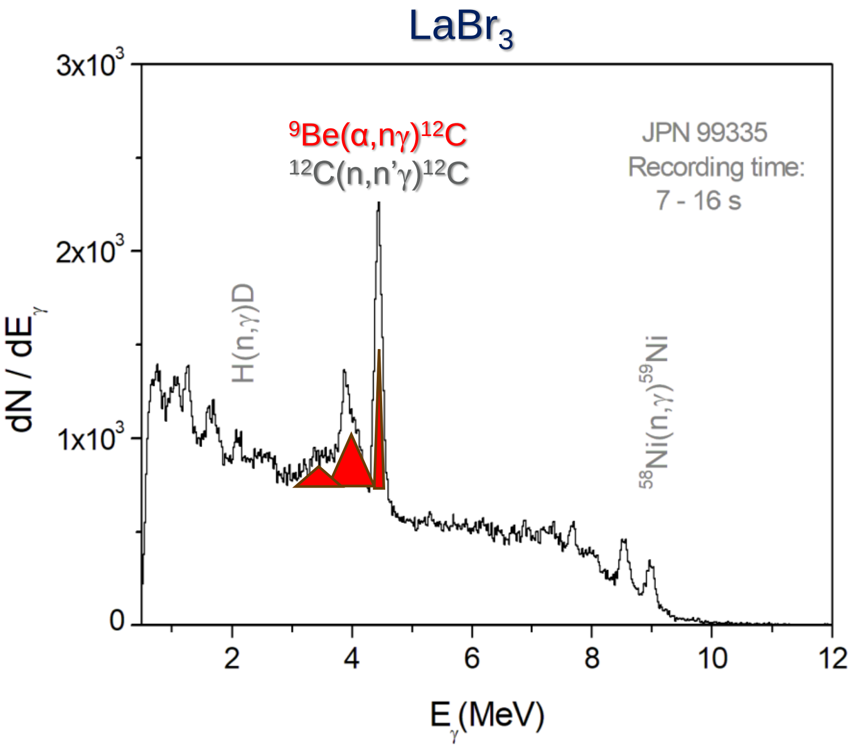
Kiptily V G et al 2022 PPCF **64** 064001

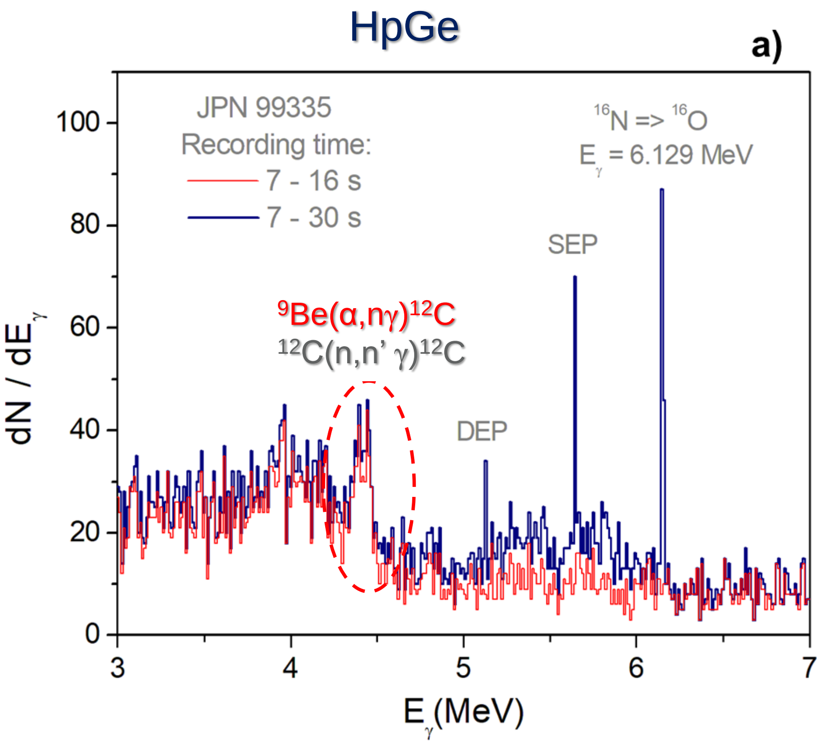
D-ions accelerated by ICRF produce 3.6-MeV **alphas** in **D^{3}He**-plasmas

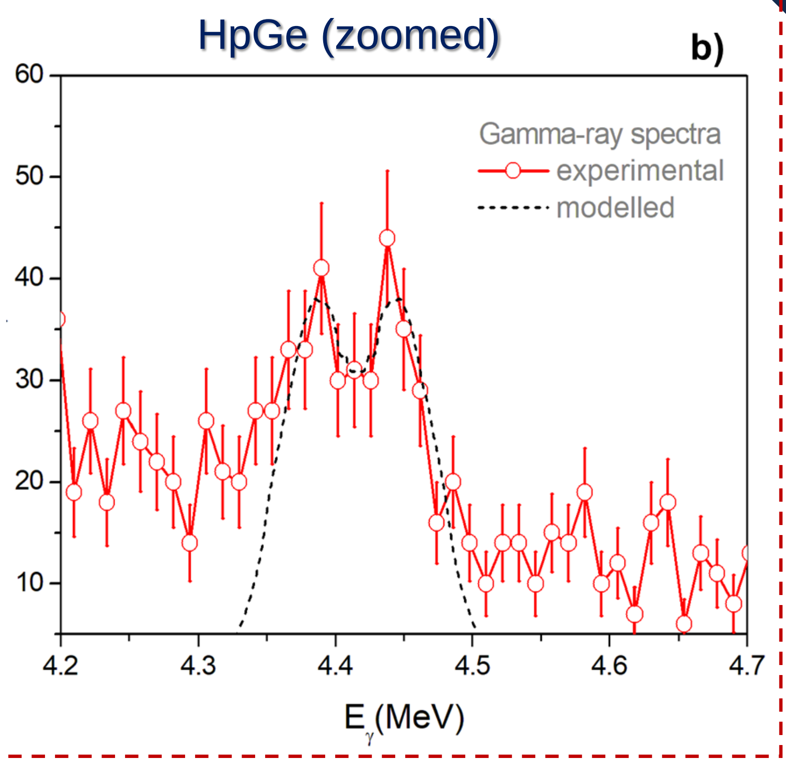
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA | ISTP Consiglio Nazionale delle Ricerche | EUROfusion

γ-ray spectrometry: DT α-particle studies

Vertical spectrometers







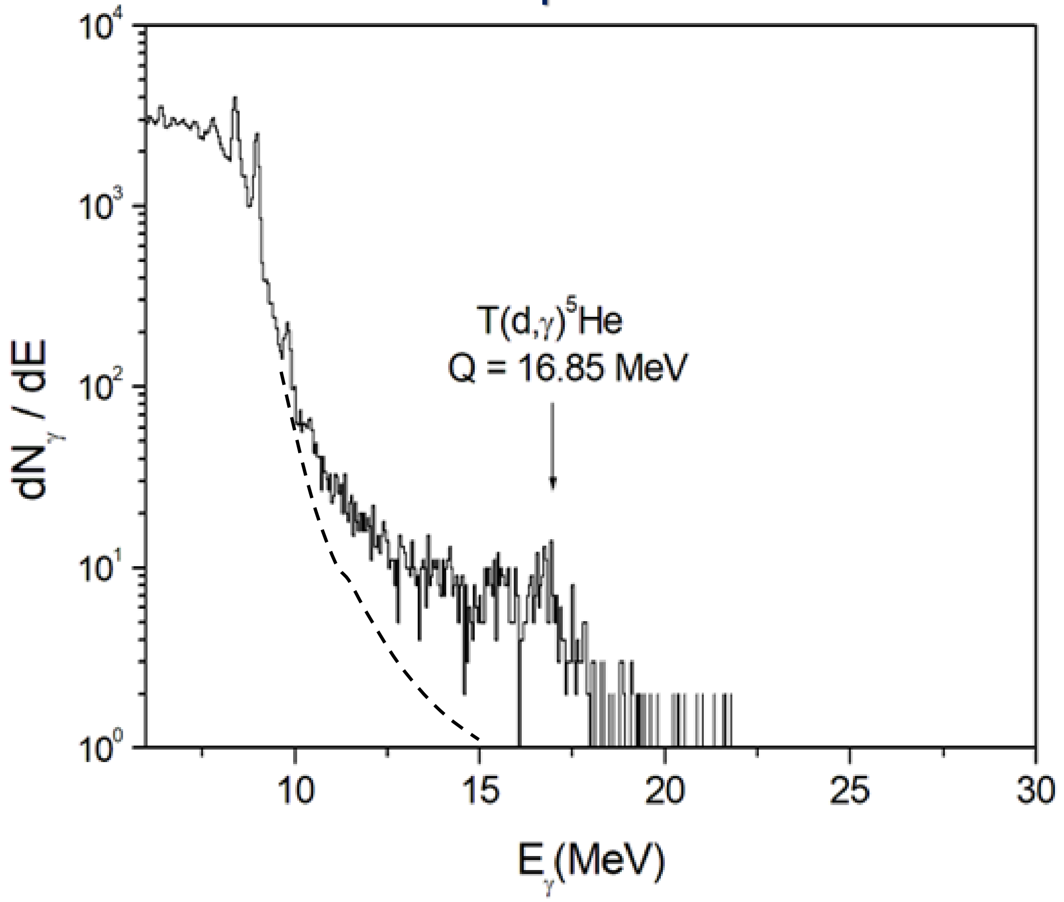
- α-particle related γ-emission from the ^{9}Be(α,nγ)^{12}C reaction ~ 20-30% of total (depends on Be%)
- Background 4.44-MeV γ-emission due to ^{12}C(n,n'γ)^{12}C: W-CFC divertor in LoS

Kiptily V G et al 2024 NF **64** 086059

γ-ray spectrometry: fusion gammas

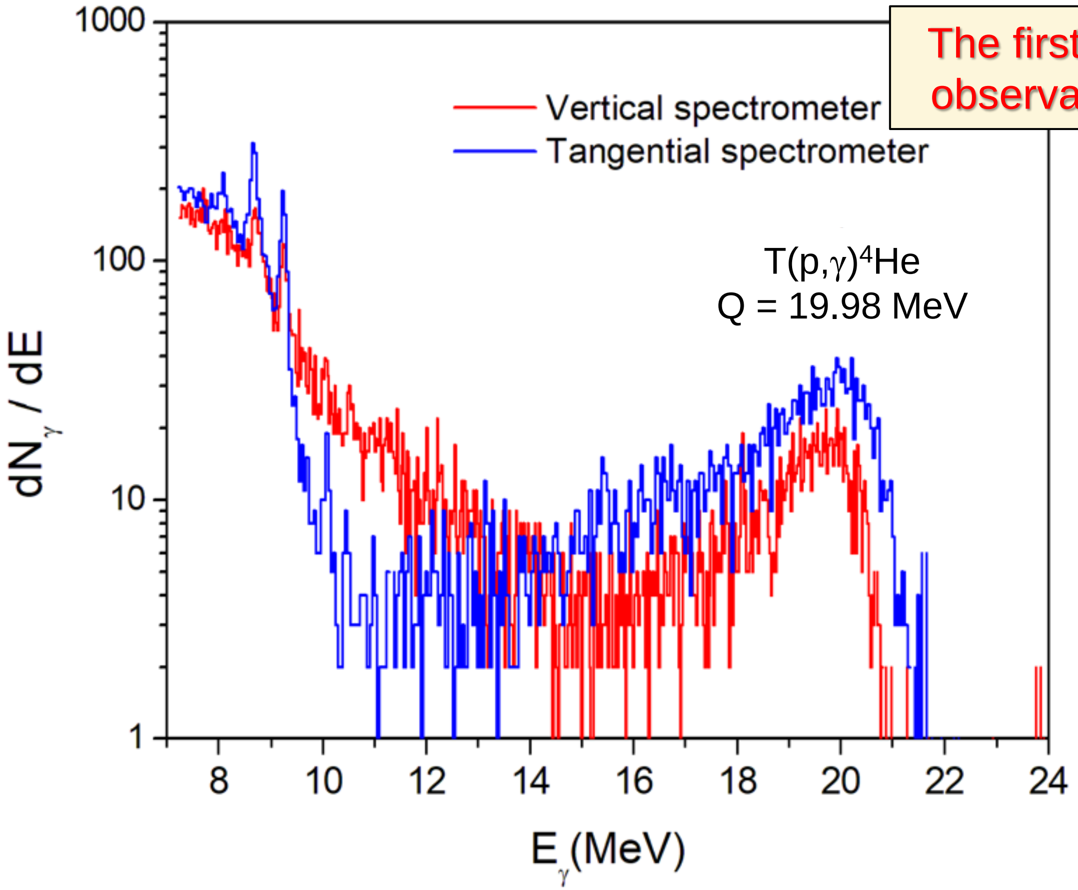
UK Atomic Energy Authority

D-T-plasmas



T-plasmas with H-minority heating

The first ever observation !



Kiptily V G et al 2024 NF **64** 086059

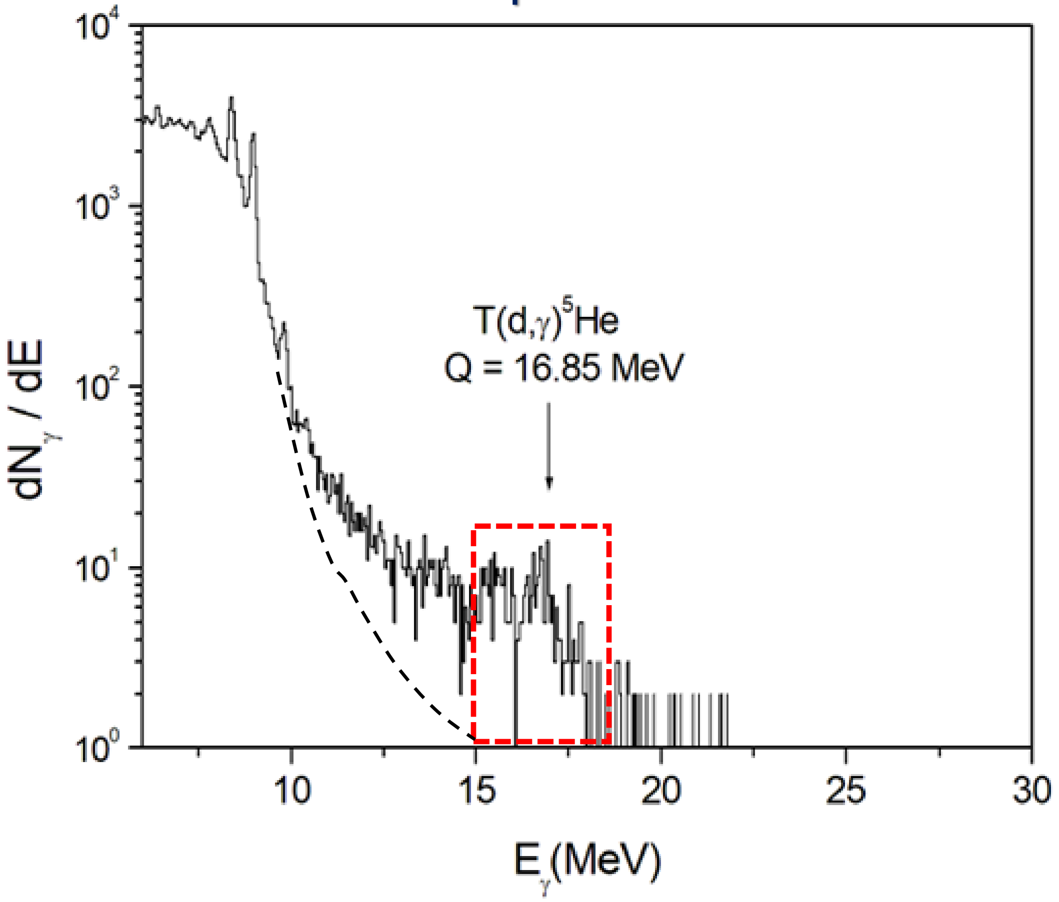
$T(d,\gamma_{17MeV})^5He$ is a weak branch (~10^{-5}) of the $T(d,n)^4He$

$T(p,\gamma_{20MeV})^4He$: $\sigma(E_p=1 \div 3\text{MeV}) \sim 0.03 \div 0.1$ mb

Università degli Studi di Milano Bicocca · ISTP Consiglio Nazionale delle Ricerche · EUROfusion

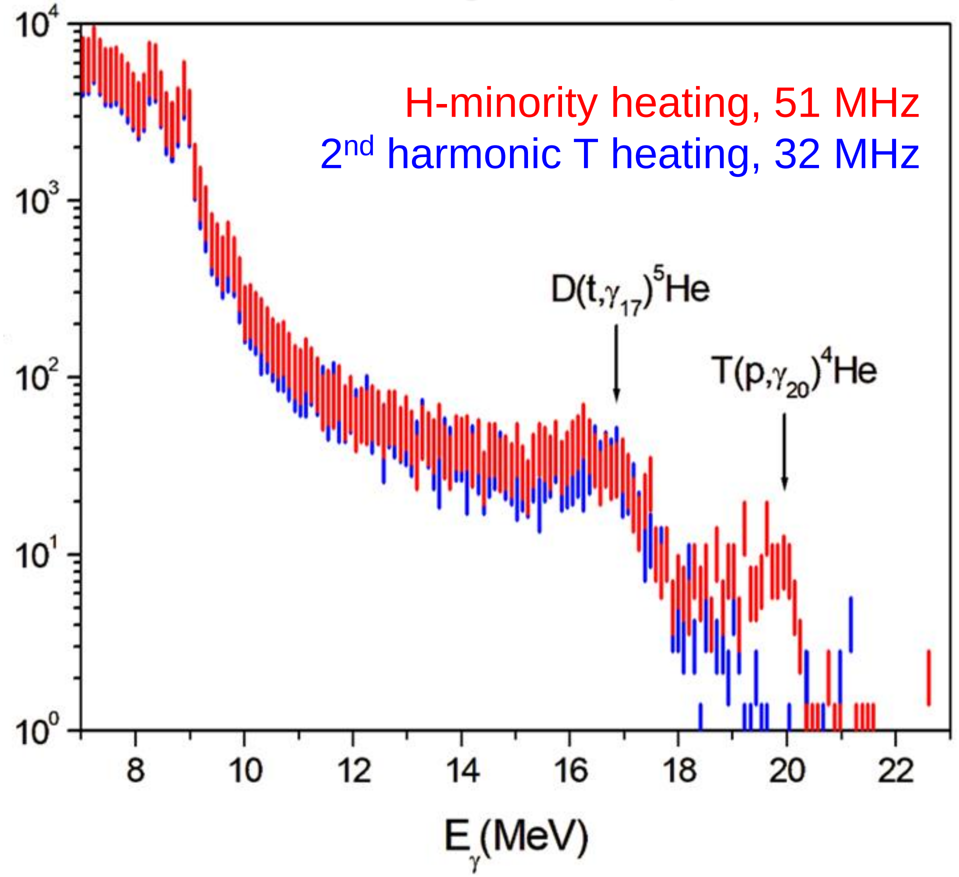
γ-ray spectrometry: fusion gammas cont.

D-T-plasmas



Monitoring of γ17-MeV of T(d,γ)^{5}He as a backup to 14-MeV neutrons of T(d,n)^{4}He

ICRF heating of D-T-plasmas



T(d,γ)^{5}He & T(p,γ)^{4}He: n_D/n_T fuel-ratio & <T> in the plasma core.

Kiptily V G 2015 NF **55** 023008

Kiptily V G et al 2024 NF **64** 086059

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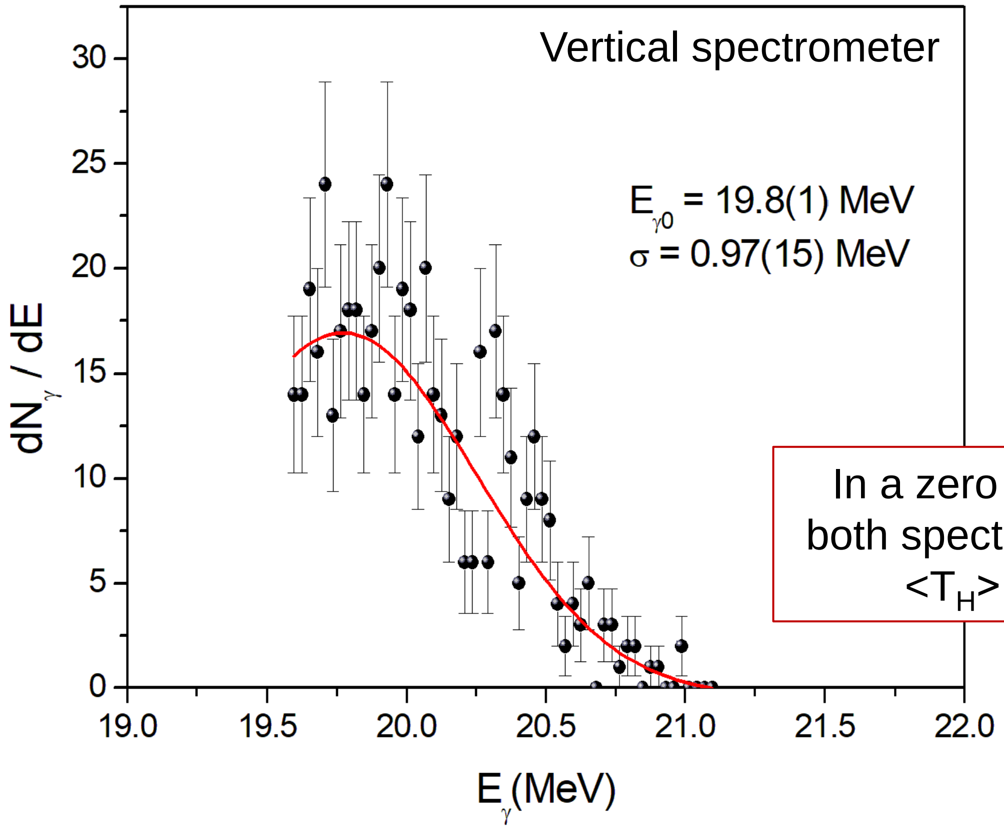
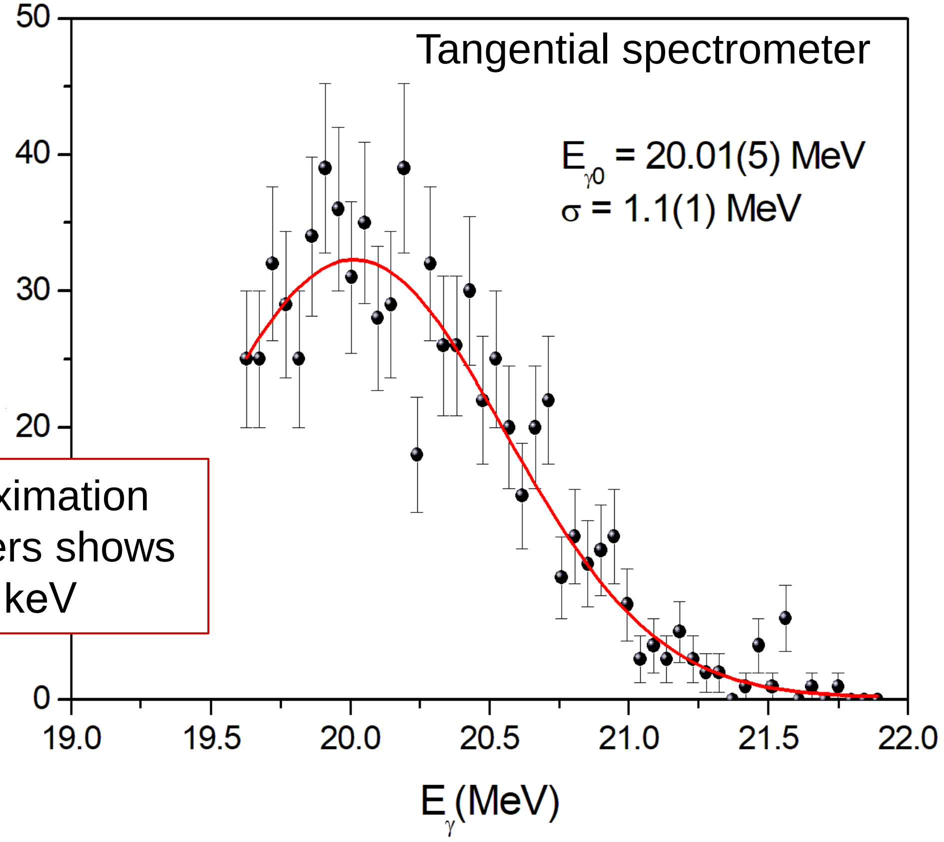
γ-ray spectrometry: fusion gammas cont.

H-minority heating of T-plasmas





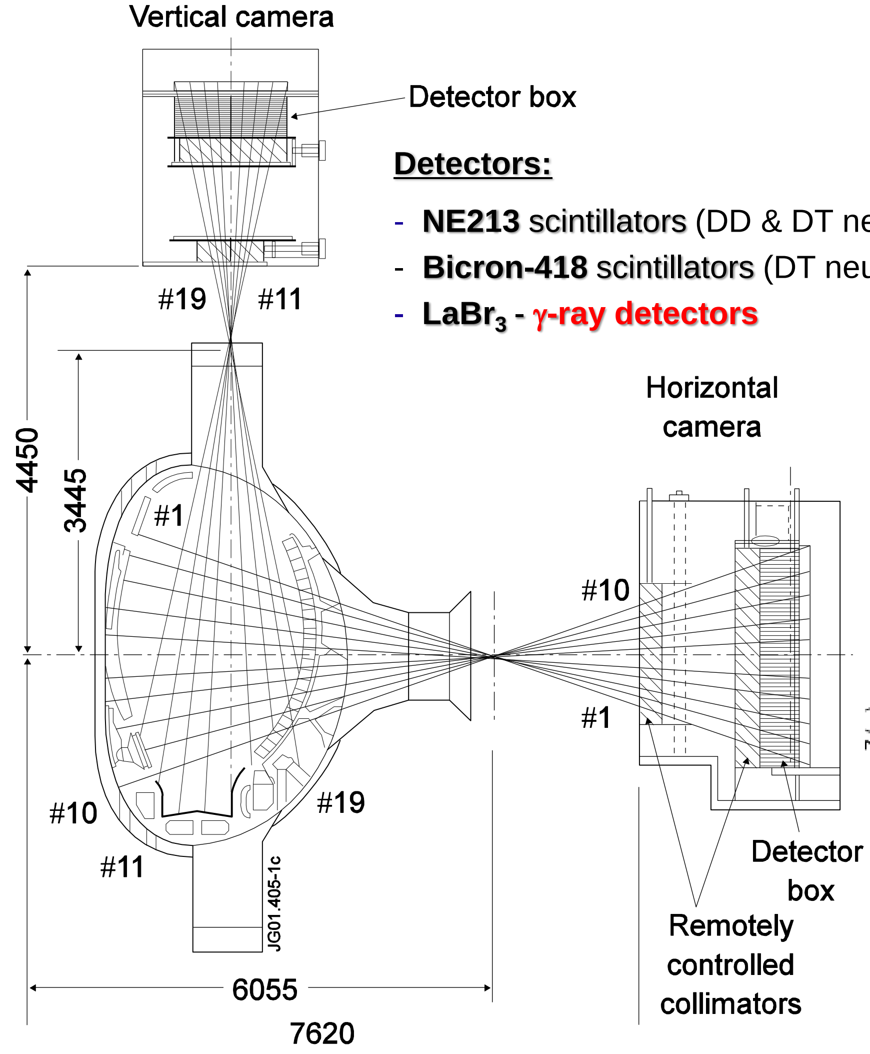
In a zero approximation both spectrometers shows $\langle T_H \rangle \approx$ 400 keV

In burning plasmas, γ20-MeV due to DD-protons can be used to infer the core temperature

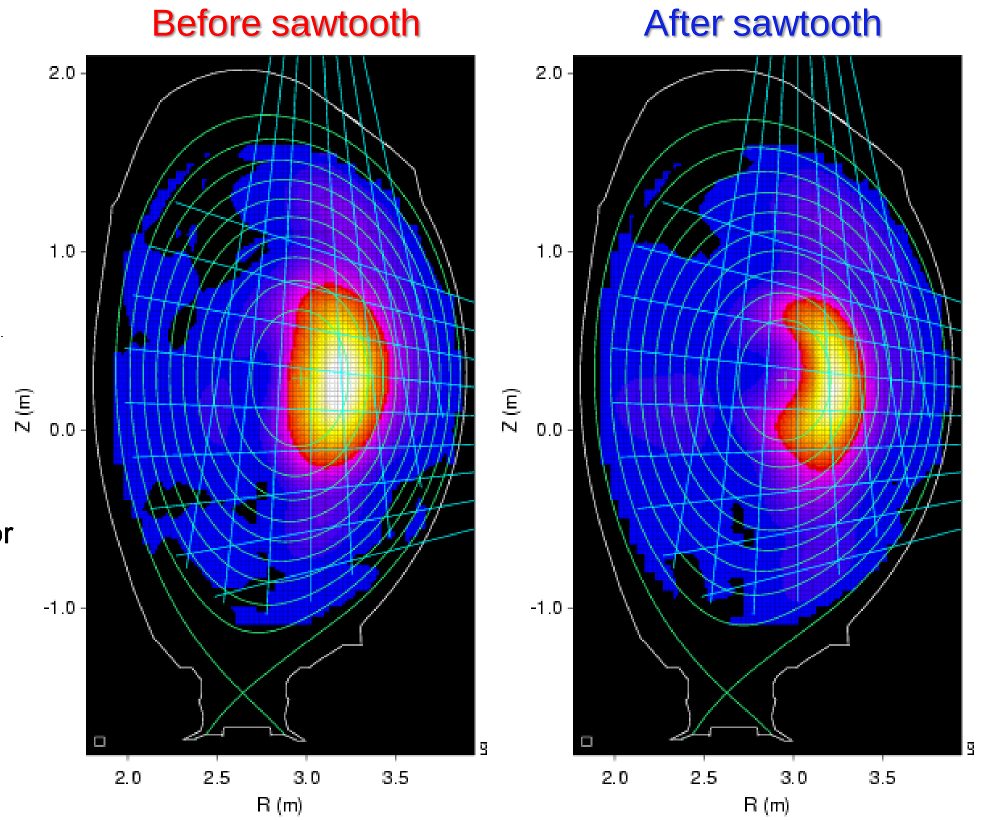
γ-ray tomography: image of confined alphas

Detectors:

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



γ-ray images of accelerated ^{4}He-ions in ICRF heating experiment in He-plasmas



- Detected 4.44MeV γ-ray emission from the reaction $^9Be(\alpha,n\gamma)^{12}C$ (E_α>1.7 MeV)
- Reconstructed γ-ray images of ^{4}He-ions in different phases of the plasma discharge

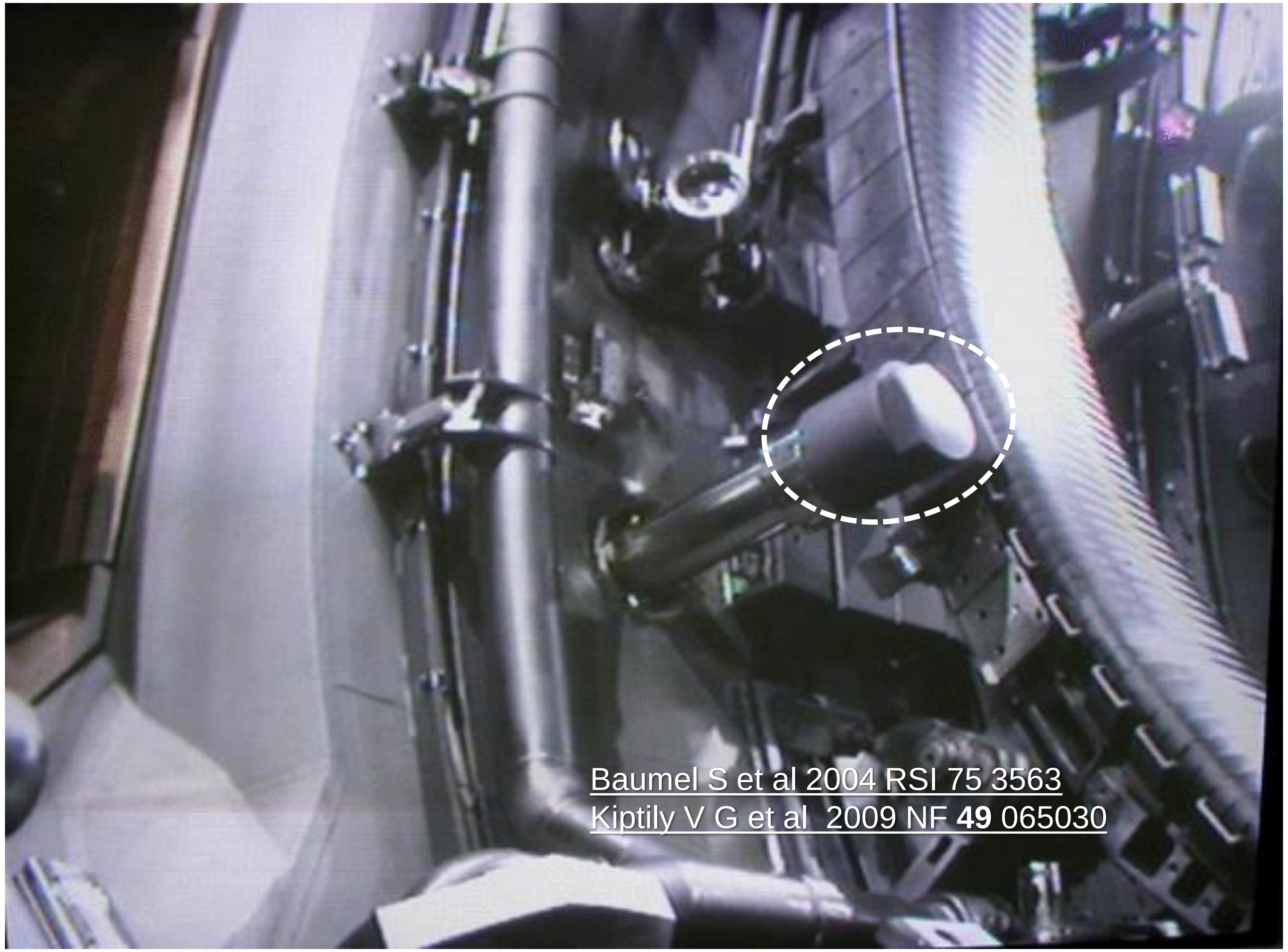
Kiptily V et al 2005 Nucl. Fusion 45 L21

- γ-ray images of D^3He fusion α-source, see

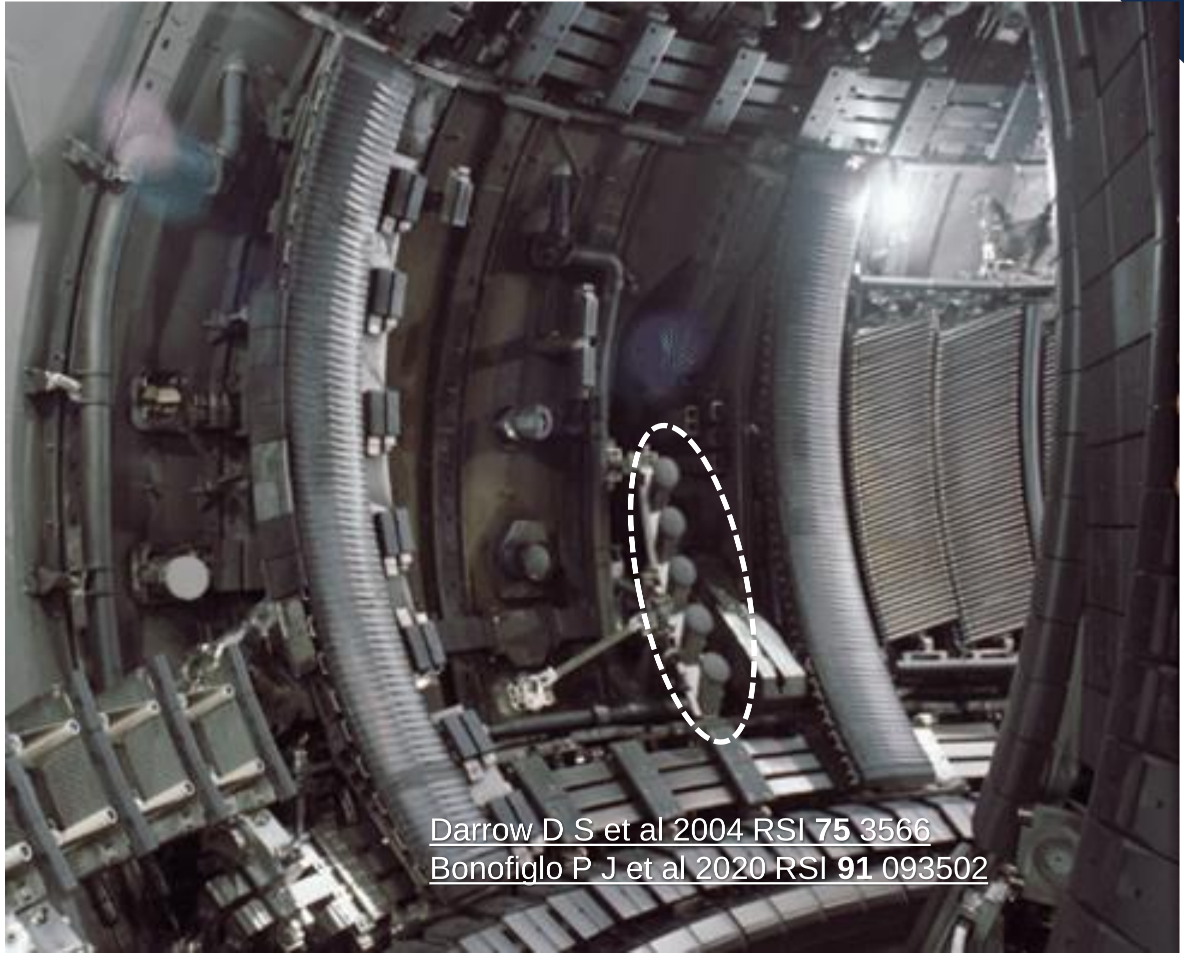
Panontin E. et al, 2021 RSI 92 053529

Fast ion / α-particle loss detection: FILD & FC

Fast Ion Loss Detector



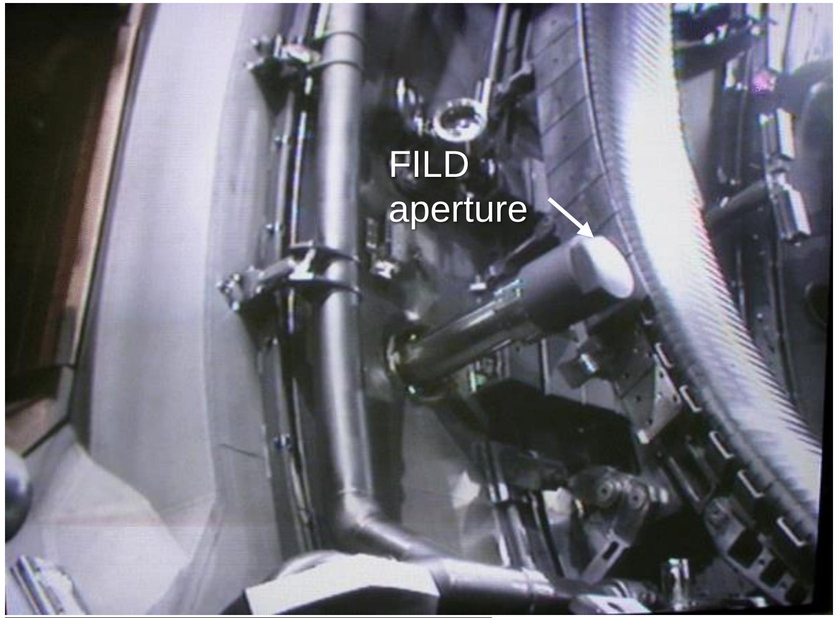
Faraday Cups

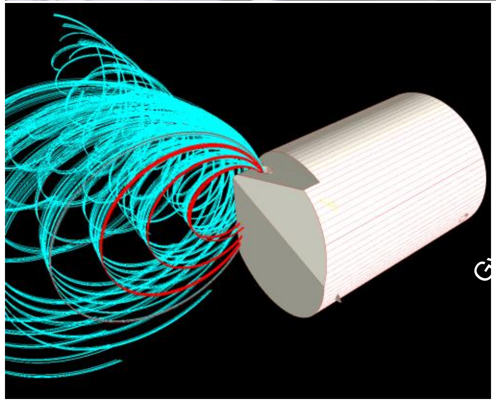


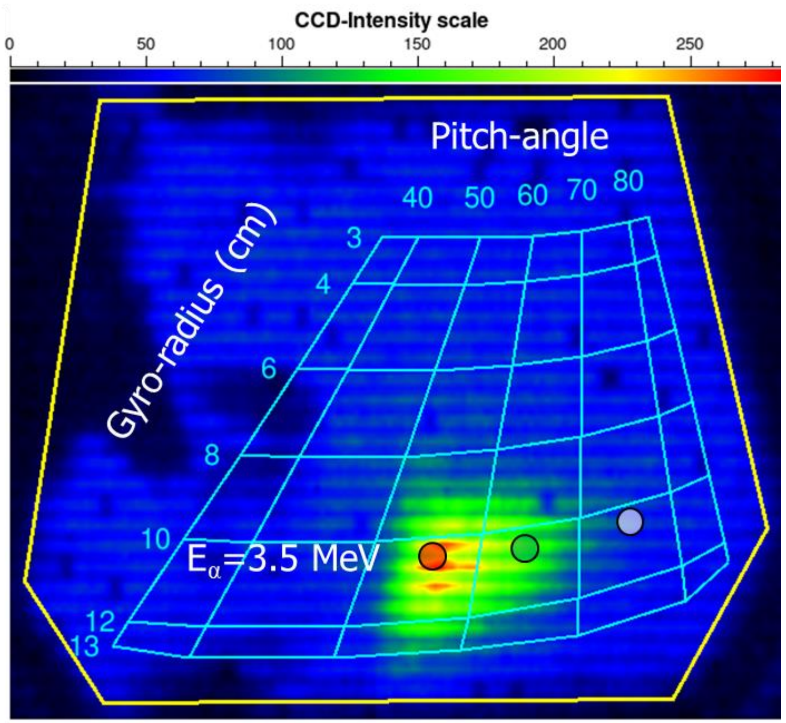
on DTE alpha-particles: Kiptily V G et al 2024 NF **64** 086059 , Bonofiglo P J et al 2024 NF **64** 096038

α-particle loss detection: FILD

Fast Ion Loss Detector

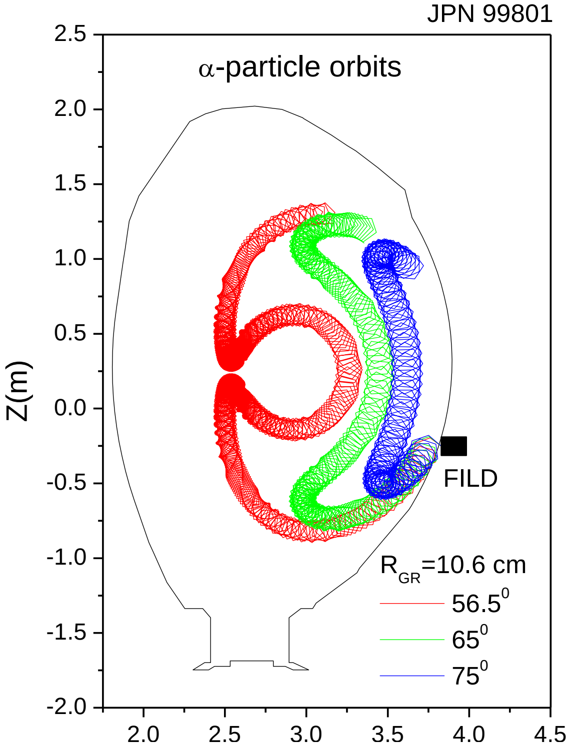






Footprint of D-T fusion alphas first-orbit losses

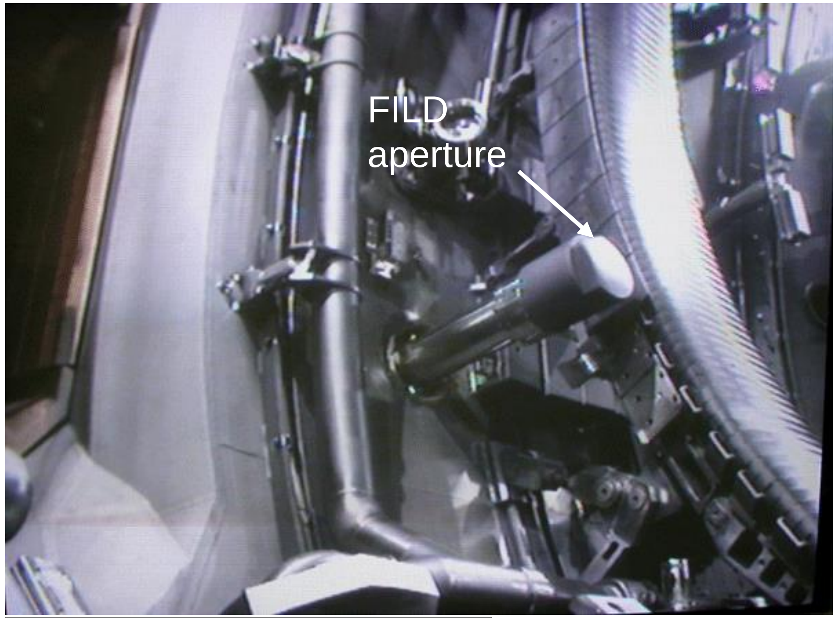
Kiptily V G et al 2024 NF **64** 086059

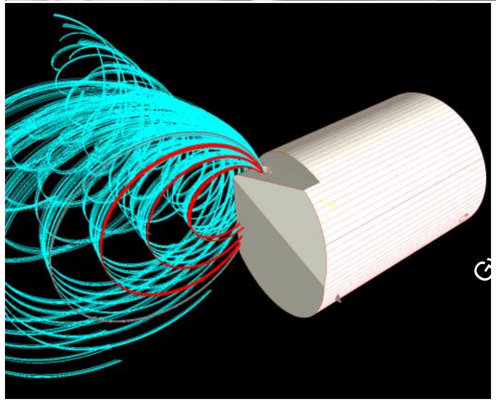


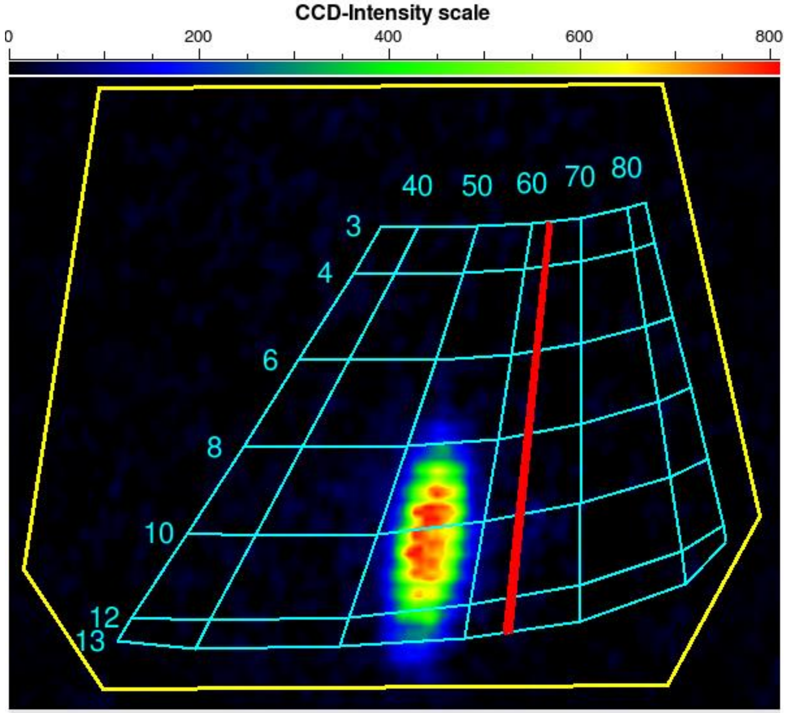
α-particles losses and their orbits related to the different pitch-angles (*a back-in-time calculation from the footprint*)

α-particle loss detection: FILD

Fast Ion Loss Detector

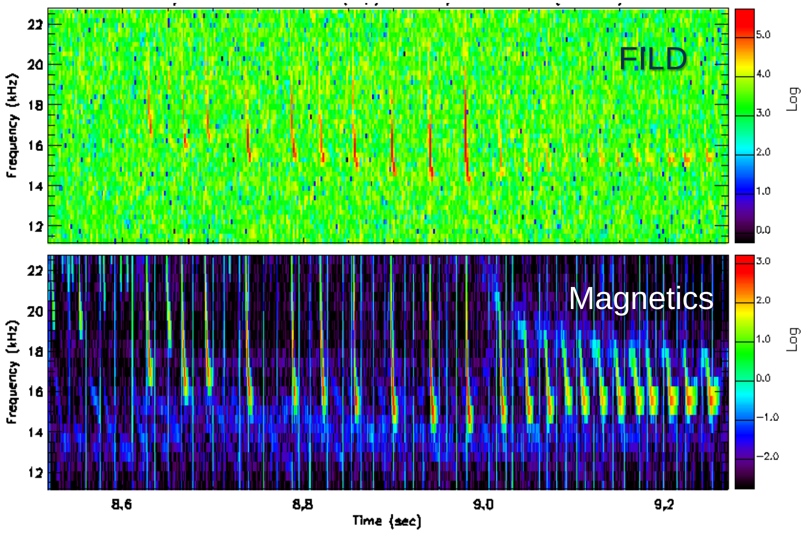






Footprint of D-T fusion alphas fishbone losses

Fishbones induced α-losses



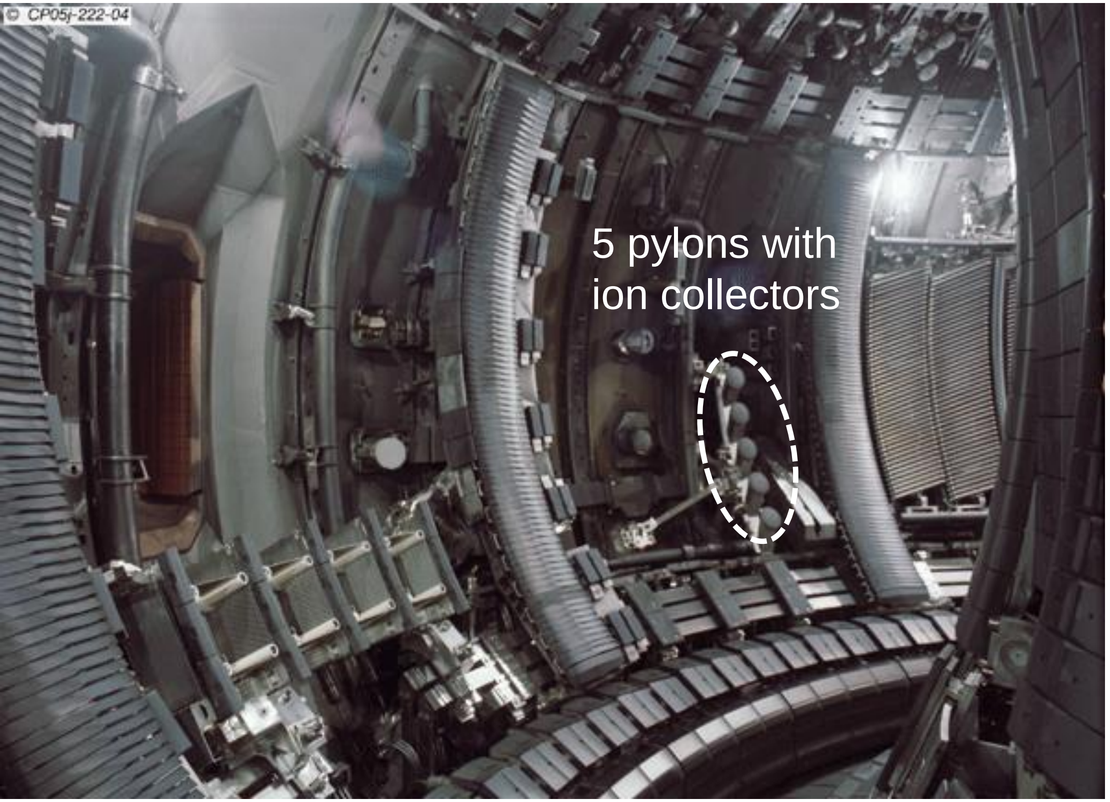
MHD-related α-particle losses were detected and analysed

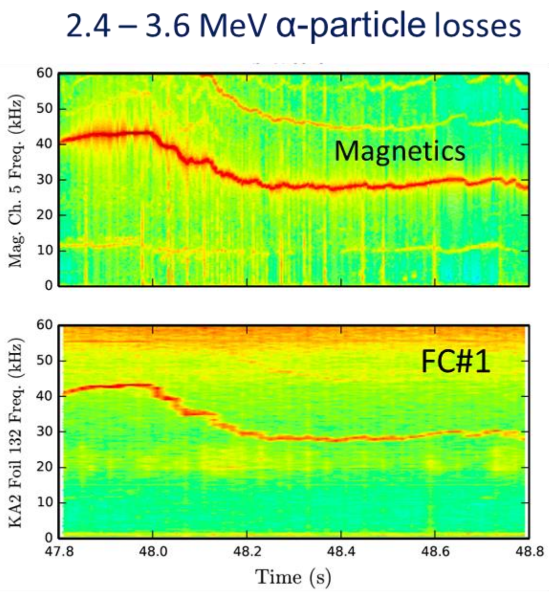
Kiptily V G et al 2024 NF **64** 086059

Bonofiglo P J 2025 NF to be published

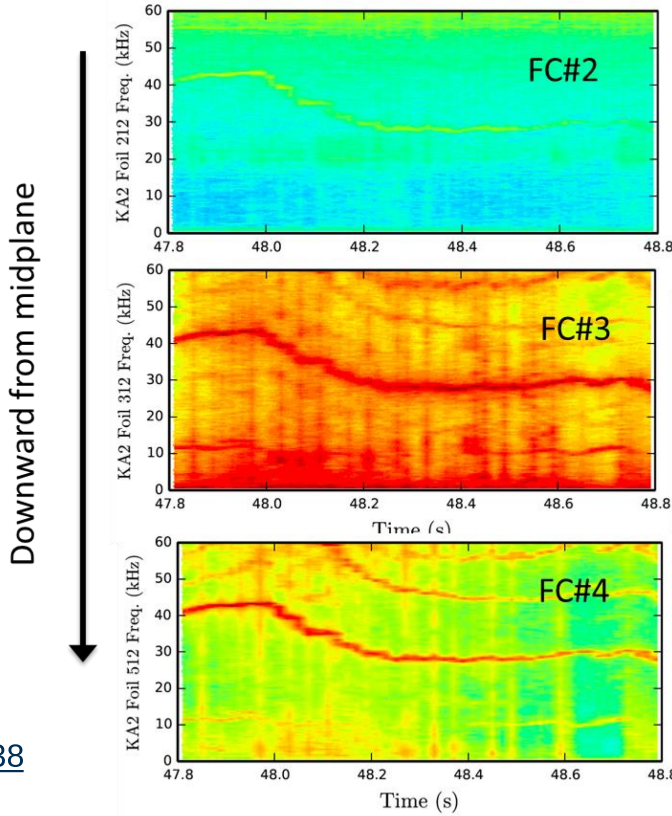
Baumel S et al 2004 RSI 75 3563
Kiptily V G et al 2009 NF **49** 065030

α-particle loss detection: Faraday Cups





Bonofiglo P J et al 2024 NF **64** 096038



Faraday Cups were used for lost α–particle poloidal measurements in DT-plasmas

MHD-related α-particle losses were detected and analysed

JET DTE lessons learnt

UK Atomic Energy Authority

- ❖ JET γ-ray diagnostics led to new and unique observations relevant to burning plasmas
- ❖ Gamma-ray spectrometers can be used as a backup of the DT-neutron monitors
  - ✓ Note: 17-MeV γ-rays & DT-neutrons should be cross-calibrated
- ❖ Measurements of the $T(p,\gamma_{20MeV})^4He$ reaction are feasible in D-T plasmas
  - ✓ Note: in reactors 1) simultaneous measurements of 20-MeV & 17-MeV γ-rays can provide the n_D/n_T fuel-ratio monitoring in the plasma core; 2) 20-MeV γ-rays provide the core temperature.
- ❖ Confined α-particle studies with gammas are possible at least in the pre-burning phase
  - ✓ Note: avoid/supress the background 4.44-MeV γ-rays by selection of LoS and neutron attenuators & shieldings
- ❖ FILD can be used for lost α-particle studies at least in the pre-burning phase

- ❑ **Performance of γ-ray spectrometers should be significantly increased to deliver the feasible scope for reactors**
- ❑ **Robust alternative tools are needed for continuous lost α-particle monitoring in reactors**

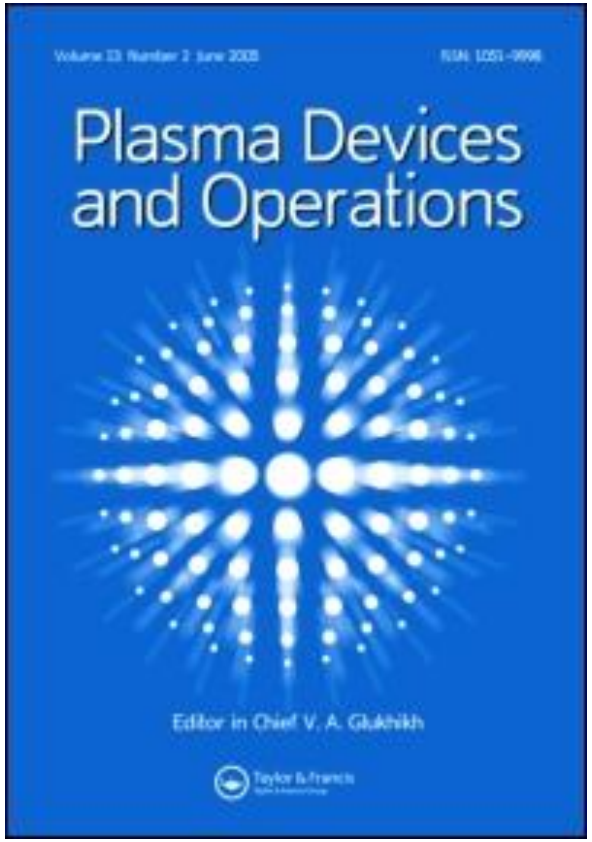
Fusion γ-ray spectrometer for next step devices

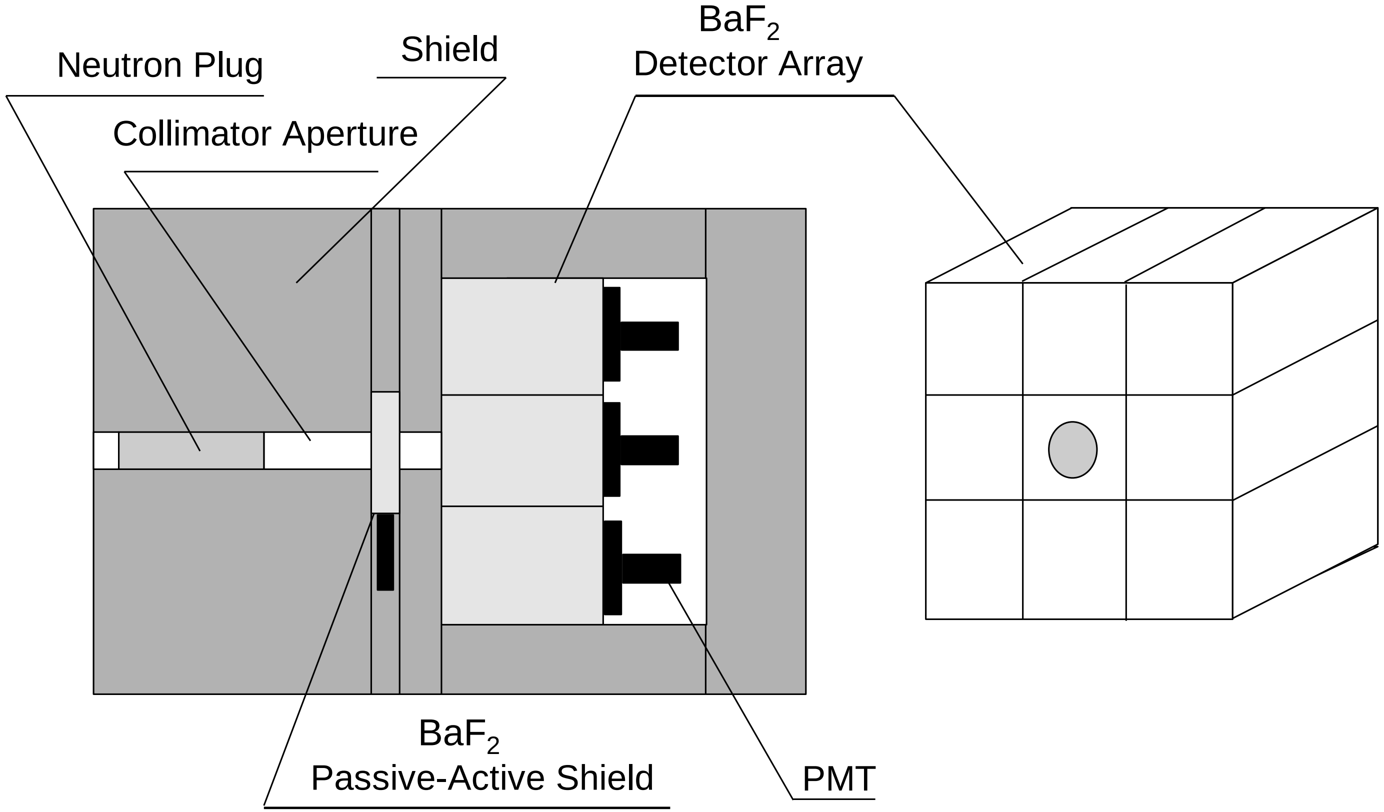
Varenna – 1995: GAMMACELL presented

UK Atomic Energy Authority

Kiptily V.G. et al, "ITER gamma diagnostics: 2-D neutron and gamma camera" // in: Diagnostics for Experimental Thermonuclear Fusion Reactors, p.463. Edited by P. E. Stott et al., Plenum Press, New York, 1996

Fusion Gamma-ray Spectrometer -1995

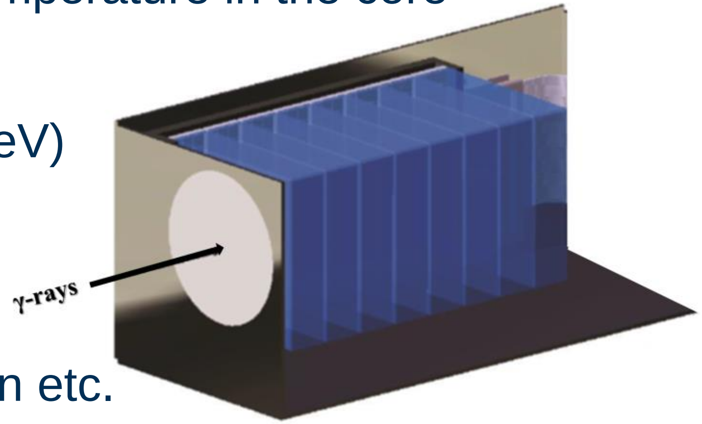




Gamma-ray spectrometer for fusion plasma diagnostics
Kiptily V G et al, 1999 Plasma Devices and Operations **7** 255

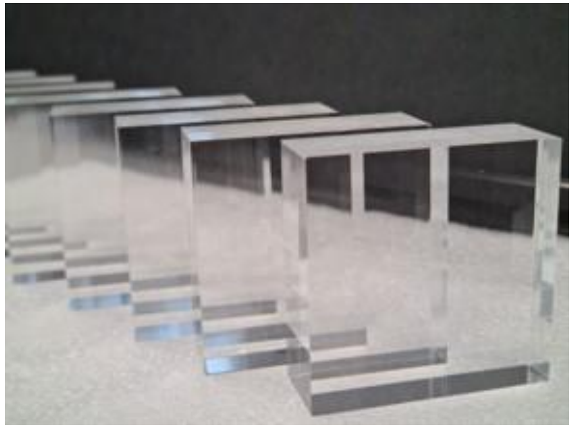
Fusion Gamma-ray Spectrometer

- A high-performance γ-ray spectrometer, FUGAS, is under development in UKAEA
  - it consist of a stack of several fast high-Z scintillators
  - scintillators optically isolated and functioning as γ-ray detectors
  - detectors are equipped with independent signal readouts & fast digitisers
- FUGAS measurement capabilities
  - 17-MeV & 20-MeV γ-rays for monitoring DT-fusion, n_D/n_T -ratio and temperature in the core
  - γ-rays from nuclear reactions for α-particle studies
  - HXR – a bremsstrahlung emission of runaway electrons (up to ~30 MeV)
- Advantages of FUGAS *vs* single-crystal detector
  - **substantial increase of the γ-ray detection performance**
  - **heavy background reduction** with active filtering, Compton suppression etc.
- Drawbacks
  - post-processing time increase
  - cost



FUGAS prototype under development

- ❑ Scintillators were selected



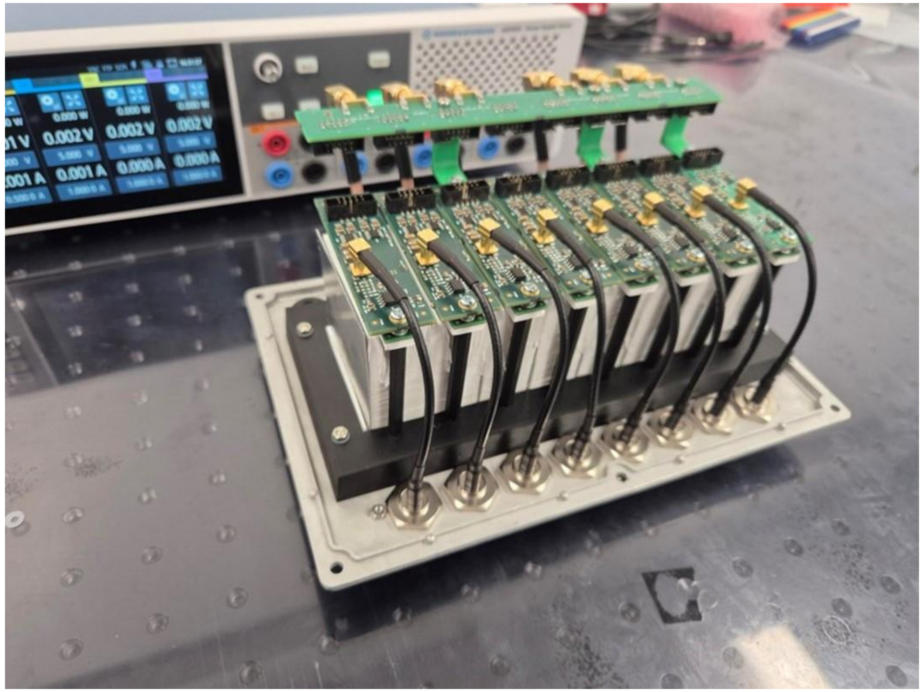
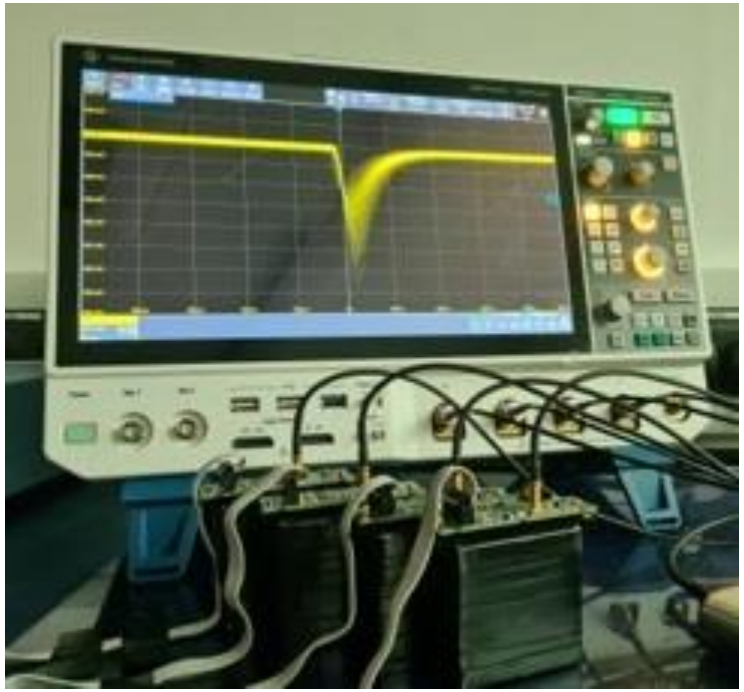
- ❑ Photon detection - Multi-Pixel Photon Counters (MPPC)

- ❑ Data acquisition based on the Teledyne ADQ36-PXIE
  - ✓ a high-end 12-bit quad-channel flexible data acquisition board optimized for high channel-count scientific applications.

FUGAS prototype under development cont.

UK Atomic Energy Authority

- ❑ Assembling and tests in the Lab

- ❑ Prototype housing design & manufacture

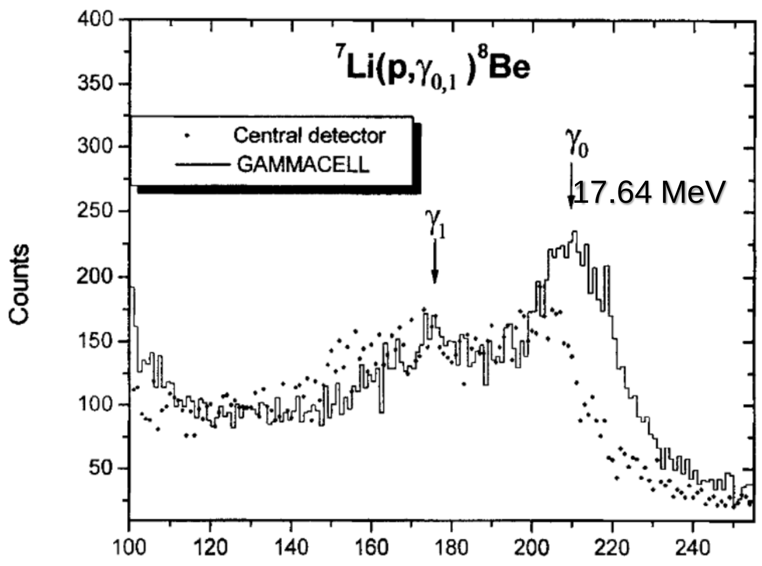
FUGAS prototype tests

- FUGAS is in preparation for tests using beams of the High Flux Accelerator-Driven Neutron Facility in the University of Birmingham :
  - ✓ $I_{protons}$ > 30mA DC / 2.6 MeV
  - ✓ Neutron yield > 2.5 10^{13} primary neutrons

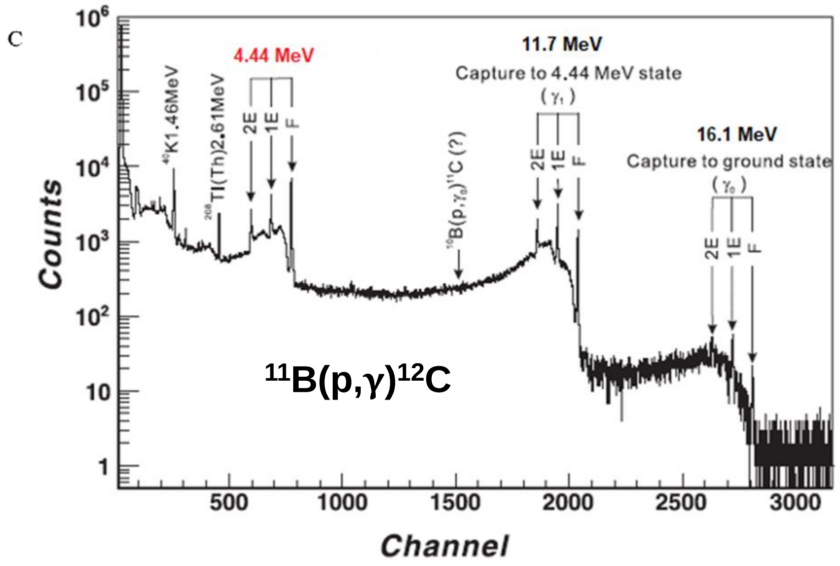
Scope of FUGAS prototype tests

In-beam tests with HFA-DNF will include:

- high-performance γ-ray spectrometry of the reactions
  - $^{7}Li(p,\gamma)^{8}Be$ (up to 20 MeV gammas)
  - $^{11}B(p,\gamma)^{12}C$ (4.44 MeV and higher)
- test of the n- / γ-ray shielding
- etc.



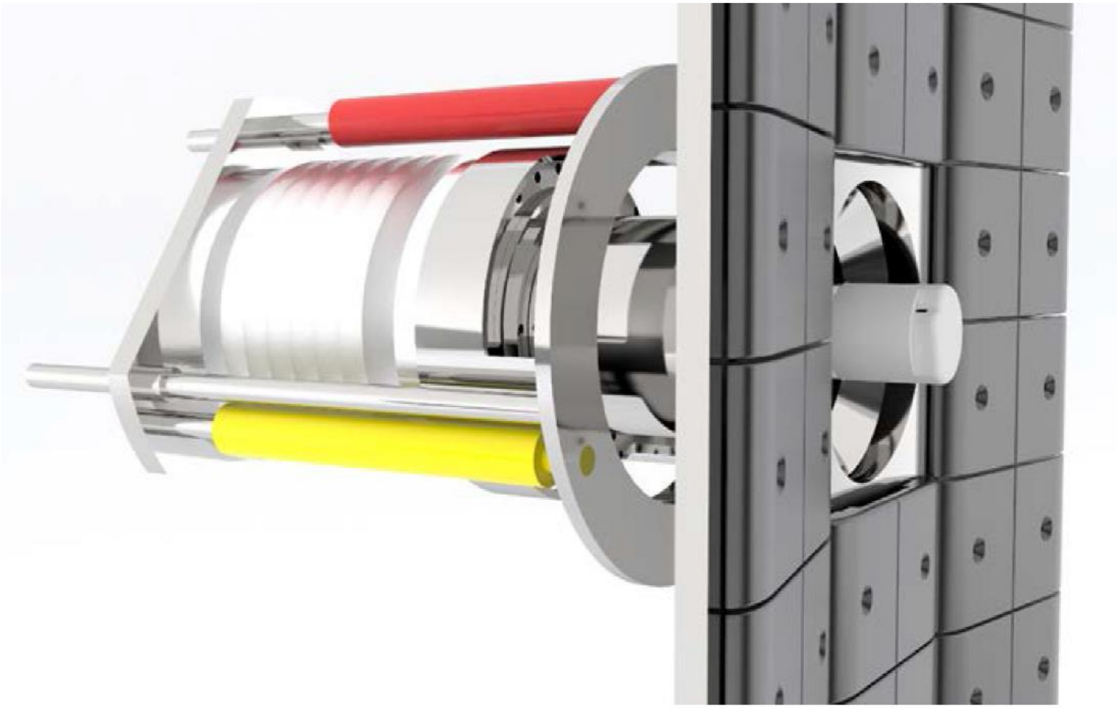
Spectrum recorded by GAMMACEL – predecessor of FUGAS

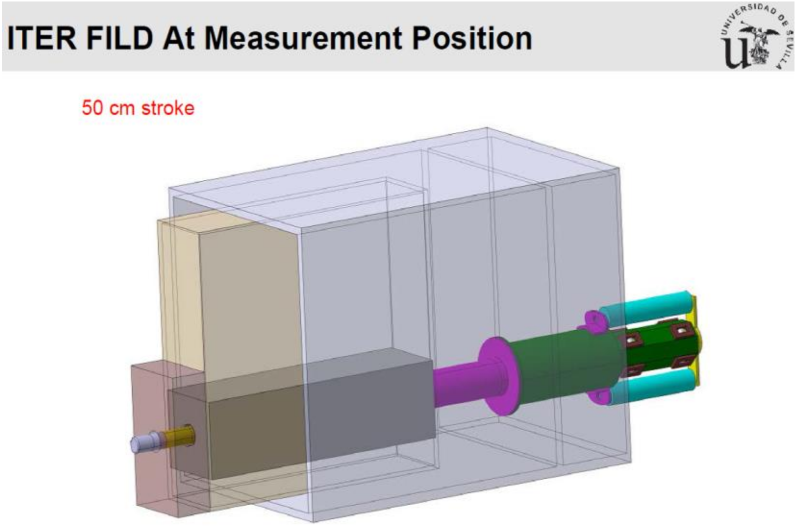


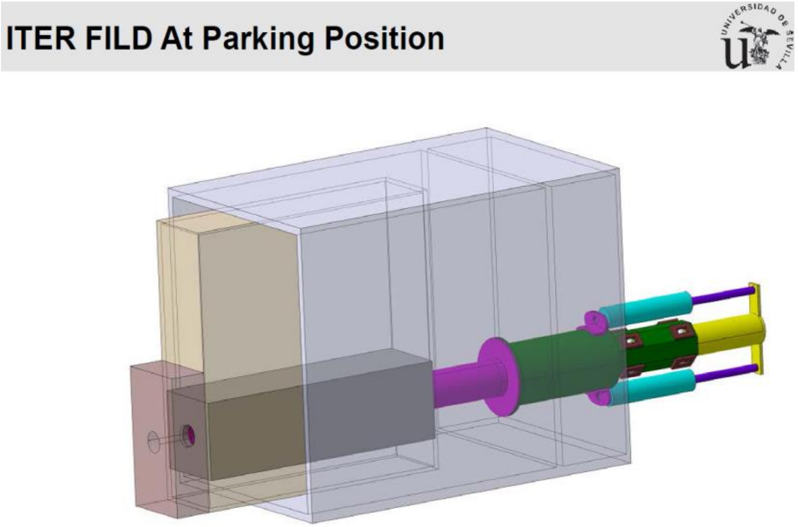
He J.J. et al, Phys. Rev C93 (2016) 055804

Alpha-particle loss monitoring in fusion plants

α-particle loss measurements in ITER







- ✓ ITER FILD (based on scintillator) is reciprocating system
- ✓ Active cooling is necessary because of nuclear heating
- ✓ The FILD exposure to measure lost α-particles < 1s

Veshchev E. A. et al 2012 Fusion Sci. Tech. **61** 172

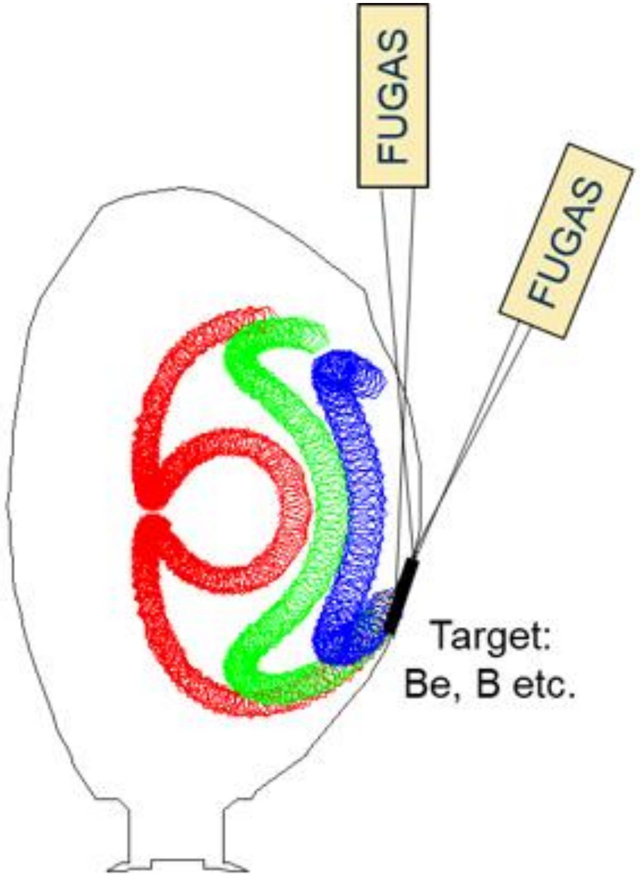
Advanced α-particle loss monitoring

I. GRAM technique (Gamma-Ray Alpha-particle Monitor) with FUGAS as a main detection instrument has been proposed for continuous loss measurements Kiptily V G et al 2018 NF **58** 082009

II. Advanced Faraday Cups for burning fusion plasma reactors are under development in UKAEA (proposed for ITER):

- ✓ Concept SFILD – Strip Film Ion Loss Detector
- ✓ Concept FILCA – Fast Ion Loss Collector Array

I. α-particle loss monitoring: GRAM

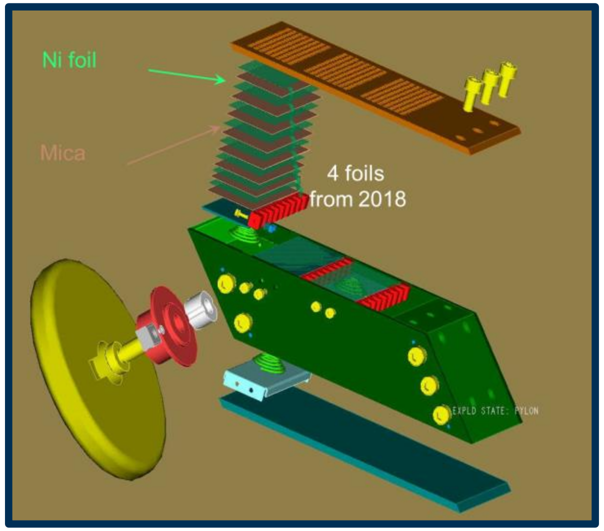


- Be- or B-targets (several μm thick or more) should be in the field of view of collimated γ-ray spectrometer (FUGAS)
- Escaped α-particles strike the target
- Be-target: gammas from $^{9}Be(\alpha,n\gamma)^{12}C$ reaction
  E_α > 1.7 MeV → γ4.44-MeV , γ3.21-MeV
- ^{10}B-target: gammas from $^{10}B(\alpha,p\gamma)^{13}C$ reaction
  E_α > 1 MeV → γ3.08-MeV , γ3.68-MeV, γ3.68-MeV
- An identical "blind" detector for the background monitoring is needed.

- This is a robust technique for continuous monitoring of α-particle losses
- Direct access to the vacuum vessel not required
- It can be used in fusion power plants (it was proposed for ITER)

Kiptily V G et al 2018 NF **58** 082009

II. α-particle loss detector: FC + FILD



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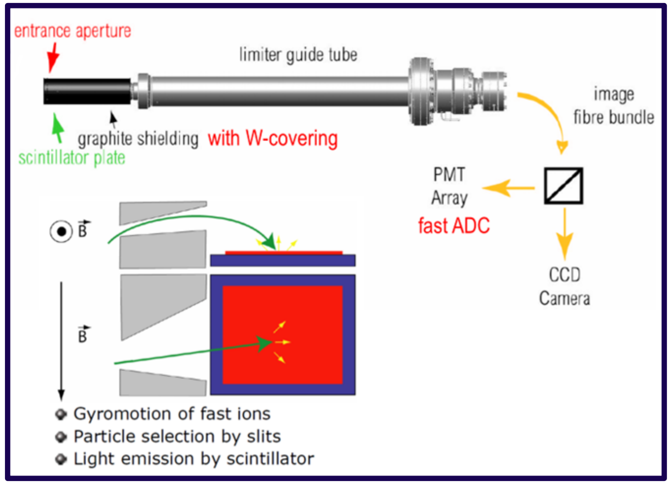
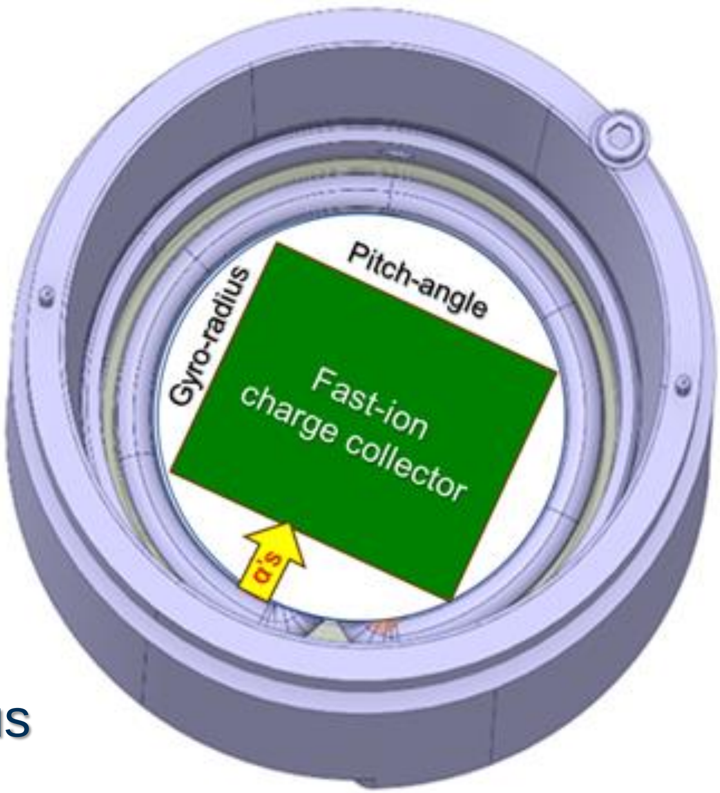


FC is feasible for continuous monitoring losses in reactors

Synergy



FILD provides the gyro-radius & pitch-angle distributions

This concept of FC can provide continuous monitoring pitch-angle & gyro-radius distributions of lost alphas in reactors

α-particle loss detector #1: SFILD

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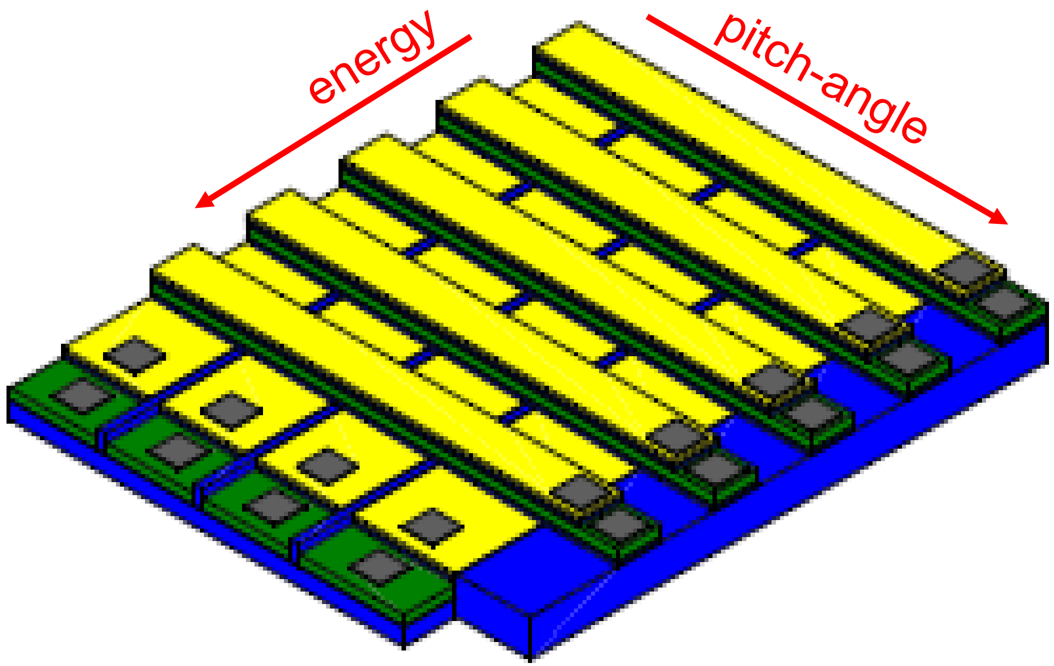
Strip Film Ion Loss Detector

Stack of

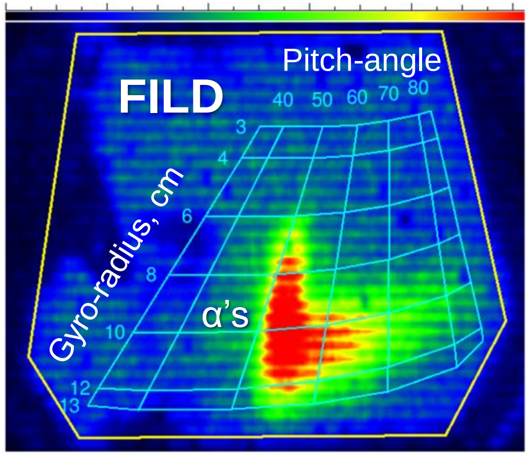
- ➢ Protection layers
- ➢ Dielectric / insulator layers
- ➢ Thin strip FC layers for collection of lost MeV-alphas & 1-MeV tritons
- ➢ Dielectric substrate

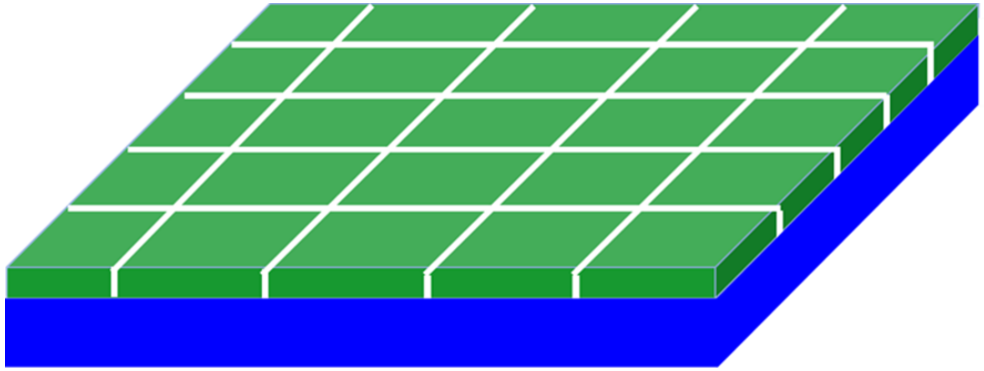


FC material selection: Ni, Mo, W etc.

α-particle loss detector #2: FILCA

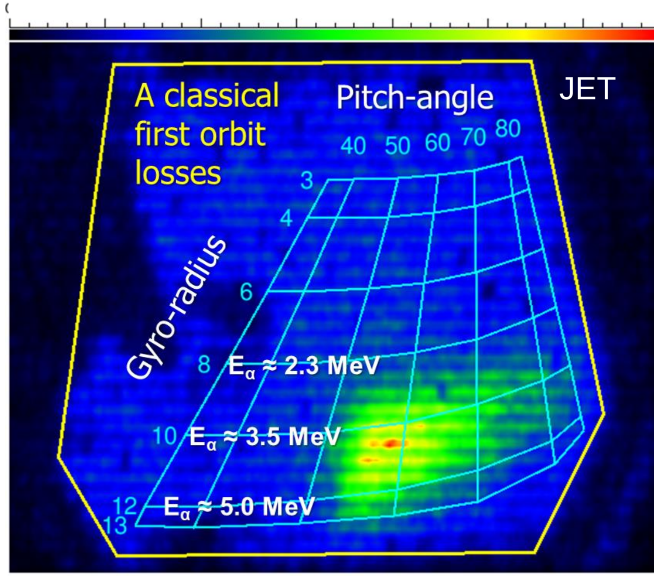
Fast Ion Loss Collector Array





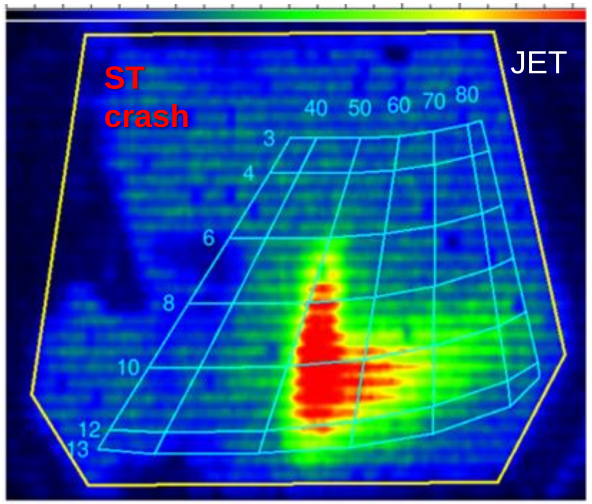
α-particle loss signal assessments

- n-/γ-induced currents in collectors:
  - SFILD: < 3 nA
  - FILCA: < 0.6 nA



- Prompt α-particle losses (as for 500MW ITER)
  - collector current due to prompt alphas ~ 30 nA

- MHD induced α-particle losses (footprint is brighter ~100 times)
  - collector current ~ 3 μA



Note: these assessments are based on ITER plasma parameters, modelling data and ITER FILD head design

Conclusions

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- JET experience shows that γ-ray diagnostics can provide unique and useful information in *all reactor plasma phases* for
  - ✓ initial setup of plasma discharges (start-up REs, disruptions)
  - ✓ ICRH and NBI heating characterisation
  - ✓ scenarios development
  - ✓ α-particle studies
  - ✓ burning plasma monitoring
- Presented diagnostic techniques are being developed for reactor conditions
- High-performance FUGAS is an advanced instrument for burning plasma monitoring: fusion rate, fuel ratio, temperature and α-particle losses
- Alpha-particle loss detectors SFILD & FILCA are robust to be used in fusion reactors providing
  - ✓ continuous measurements of lost alphas
  - ✓ *pitch-angle* & *gyro-radius* distributions of losses
- These advanced instruments can be used in ITER, SPARC, BEST, STEP etc.

Thank you for your attention

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