Modelling Realistic Neutron & Gamma Sources in Fusion Plasma

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Contributing oral

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Outline

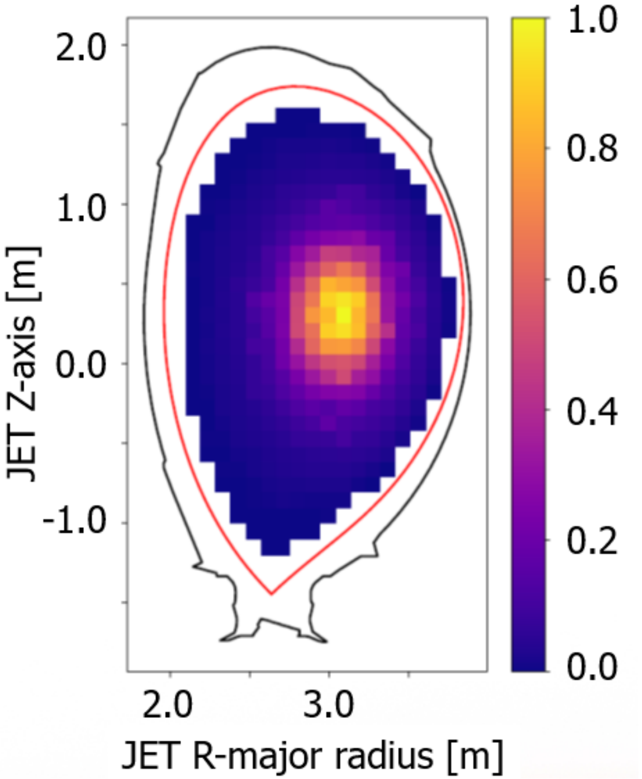
- Introduction - plasma neutron source
- Realistic neutron emission modelling
  - Emissivity profiles
  - Neutron spectra
  - Detector sensitivity study – fission chambers and neutron activation system
- Realistic gamma emission modelling
- ITER PFPO source modelling
- Conclusions

Plasma neutron source

Neutron emission

- Emission position
- Emission vector
- Emission energy

Neutron emissivity profiles

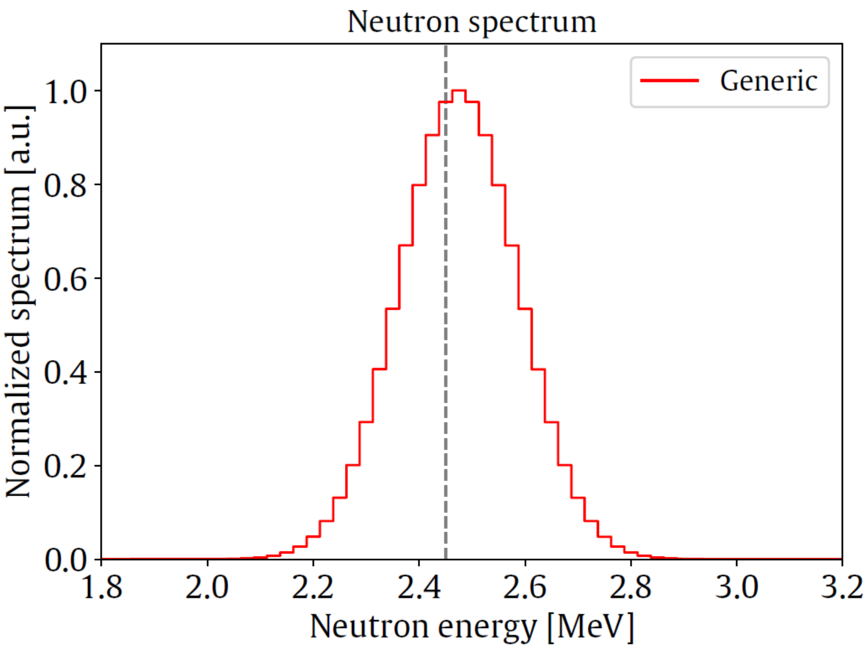


Plasma neutron source

Neutron emission

- Emission position
- Emission vector
- Emission energy

Neutron energy spectra



Realistic neutron emission modelling

JET plasma → JET discharge data = Diagnostics measurements

Plasma simulation = TRANSP/NUBEAM/TORIC

[Breslau J. et al., 2018, doi: 10.11578/dc.20180627.4]

PPPL PRINCETON PLASMA PHYSICS LABORATORY

↓

Neutron spectrum calculation = DRESS

UPPSALA UNIVERSITET

[Eriksson J. et al., Comput. Phys. Commun. 2016]

Preprocessing

Coupling

OMFIT GENERAL ATOMICS

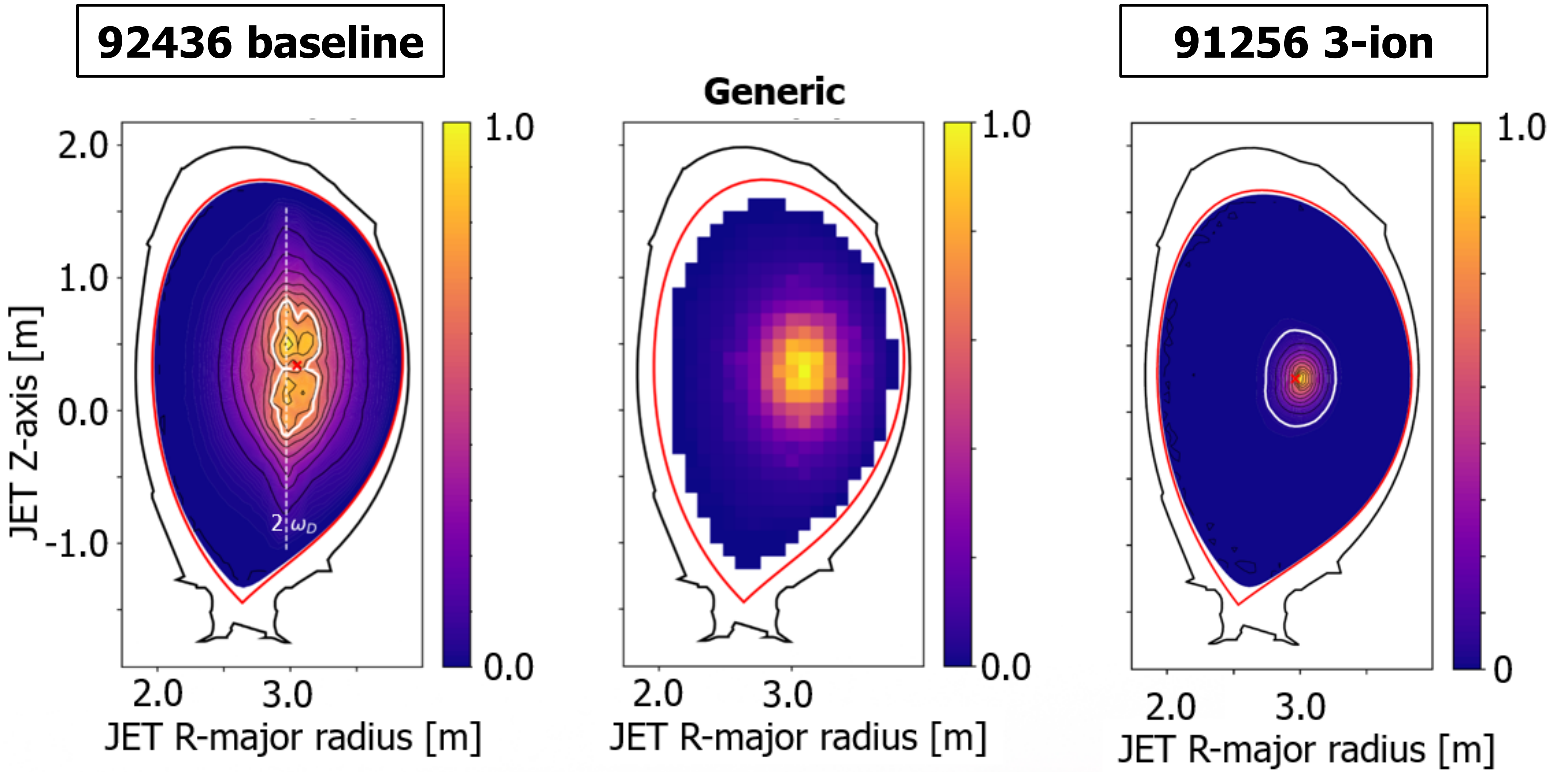
[Meneghini O. et al., Nucl. Fusion 2015]

Neutron transport = MCNP

Los Alamos NATIONAL LABORATORY EST.1943

Ž. Štancar et al 2019 Nucl. Fusion 59 096020

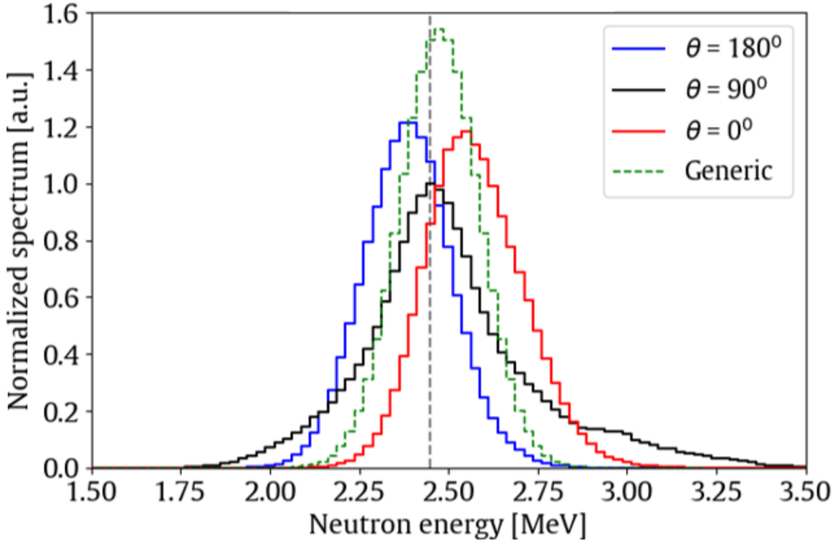
Emissivity profiles (D plasma)



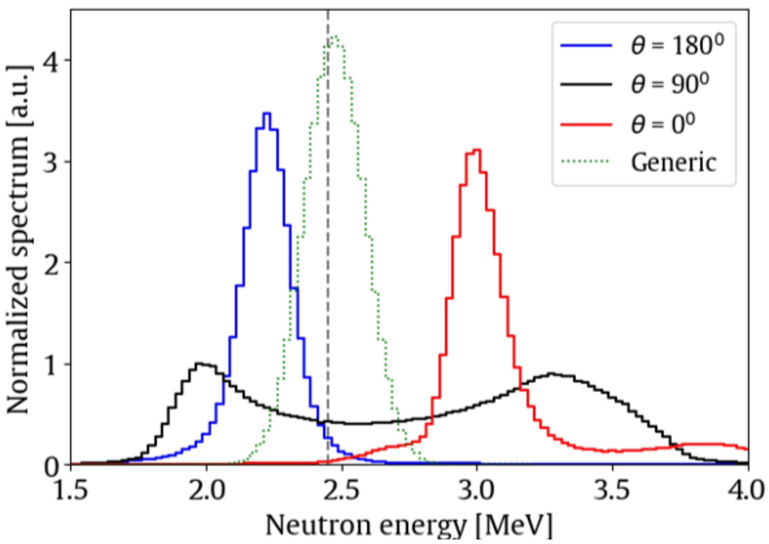
Neutron spectra (D plasma)

- Toroidal angle (B-field) anisotropy

92436 baseline



91256 3-ion



Detector sensitivity study

- Monte Carlo neutron transport calculations

  → Each source individually vs. generic

KN1

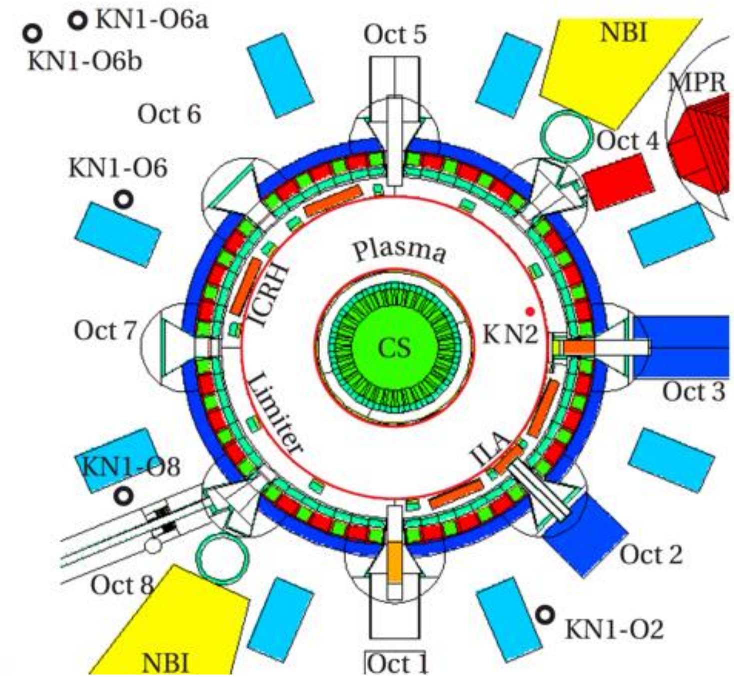
KN2

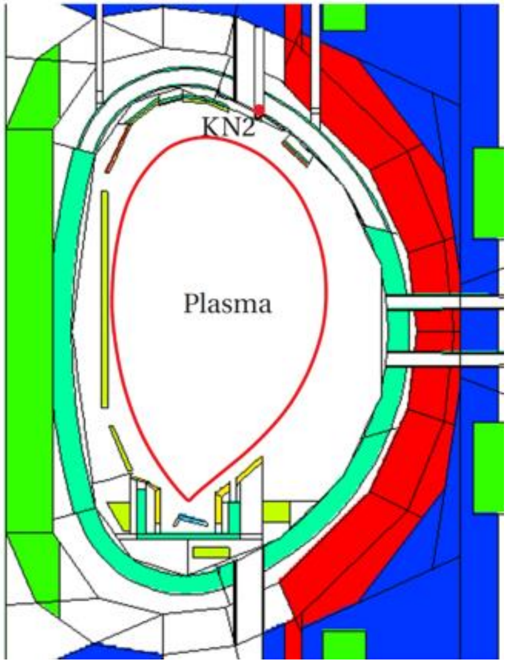
Material activation:

$^{115}In(n,n')^{115m}In$

$^{27}Al(n,p)^{27}Mg$

$^{56}Fe(n,p)^{56}Mn$



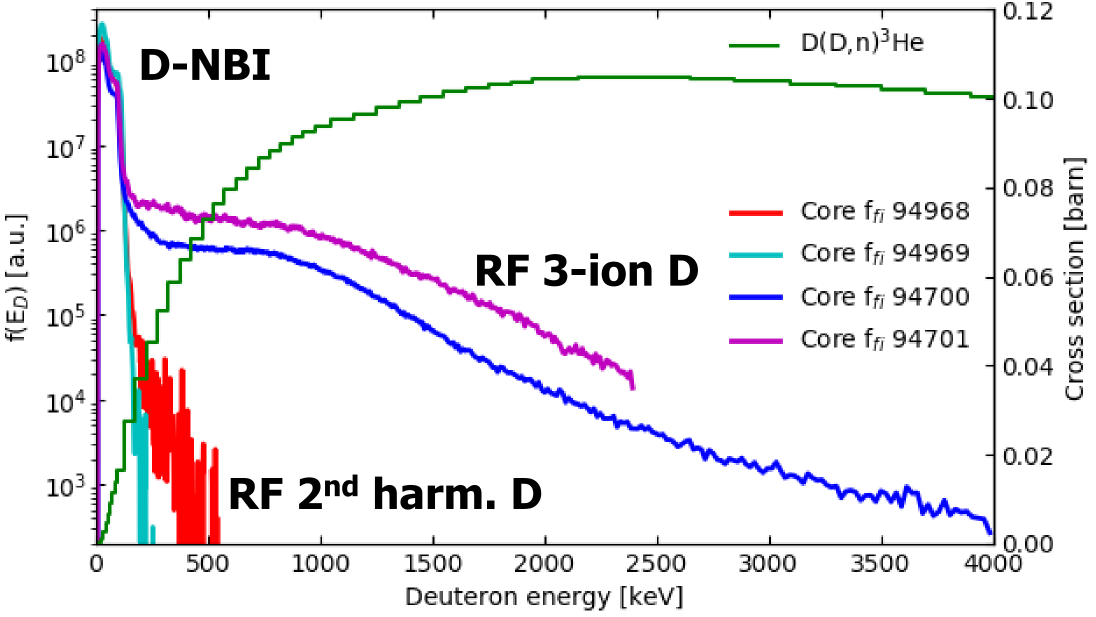


Experimental validation

- Two D plasma scenario with different fusion performance drive
- Neutron diagnostics: fission chambers, neutron camera, time-of-flight spectrometer, activation system

#94968 & #94969: Baseline-like higher power NBI+RF

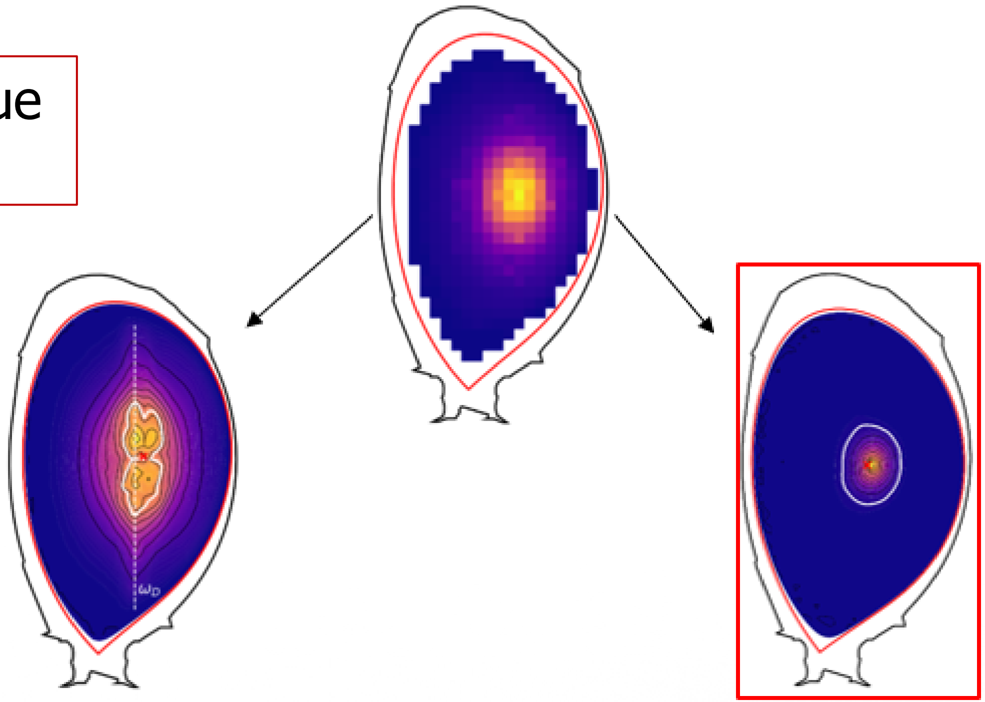
#94700 & #94701: 3-ion scheme RF+NBI synergy



Fission chamber sensitivity

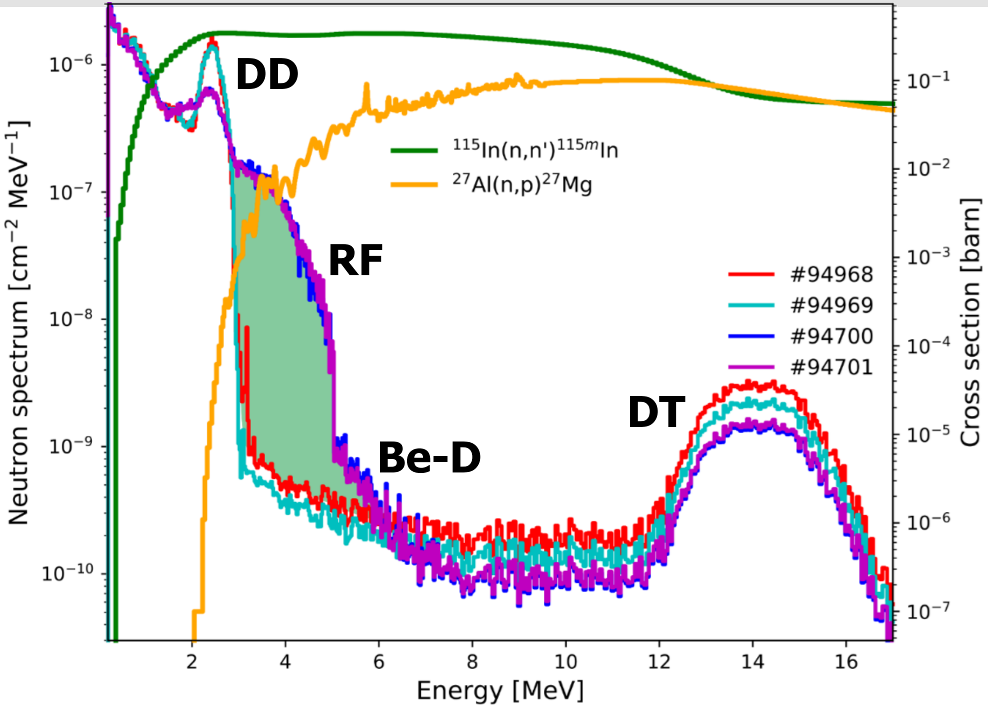
- Relatively low differences between generic and realistic sources

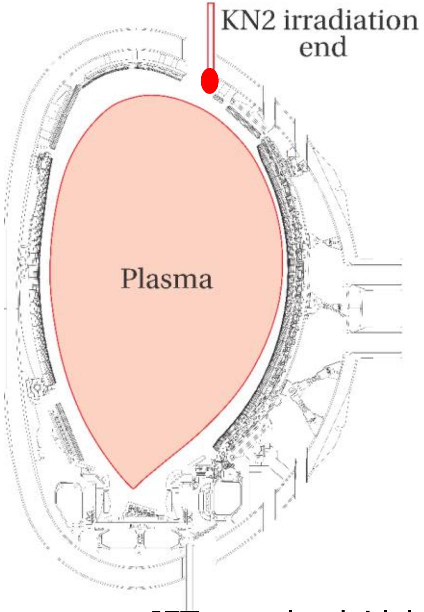
Differences of up to 4-5 % due to profile differences



Differences due to neutron spectra not observable

Activation system sensitivity





JET vessel poloidal cross-section

- Modelling activation of **^{115}In(n,n')^{115m}In** and **^{27}Al(n,p)^{27}Mg**

Flat XS
~ Constant response

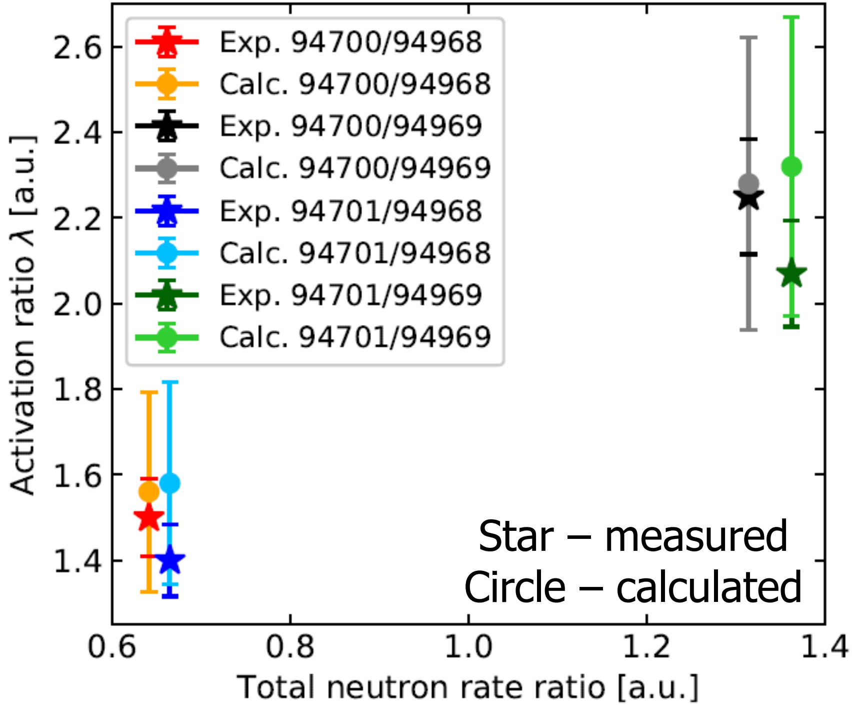
Gradient XS
Sensitive to fast ion effects

Activation system validation

- Comparing measured and calculated activation ratios Al/In
- Detecting fast ions through effect on DD spectrum anisotropy

Baseline Al (↓) / In (~ stable)

3-ion Al (↑) / In (~ stable)



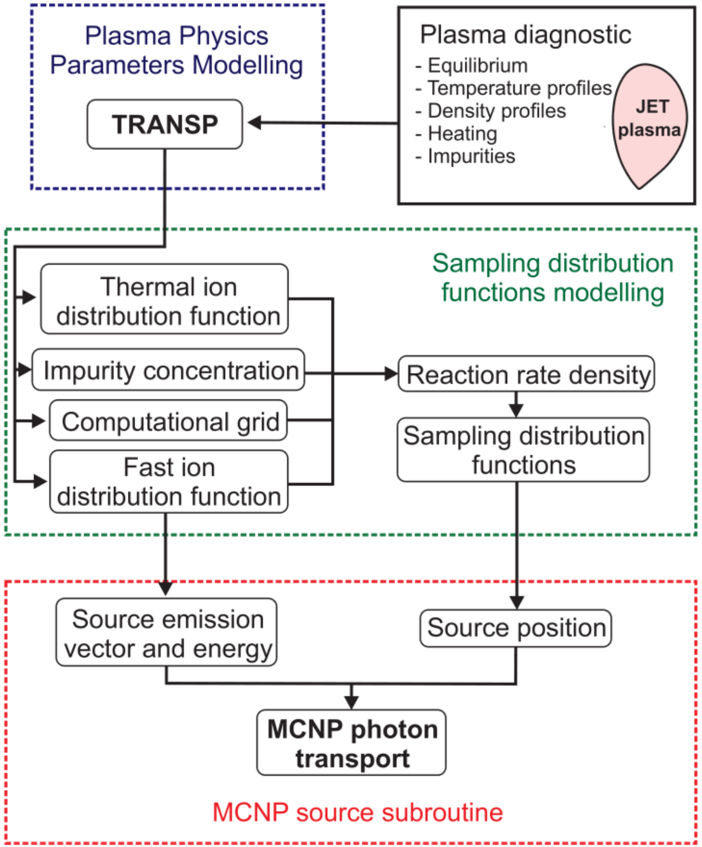
Gamma ray sources in fusion

- Plasma gamma rays from fusion reactions:
  - $D+T \rightarrow {}^{5}He^{*} \rightarrow {}^{5}He+\gamma$ (16.7 MeV)
  - $T+p \rightarrow {}^{4}He^{*} \rightarrow {}^{4}He+\gamma$ (19.8 MeV)
- Plasma gamma rays from reactions with impurities:
  - ^{9}Be, ^{14}N, ^{16}O, ^{12}C
- Neutron produced gamma rays:
  - Reactions: (n,p), (n,γ), (n,α),…
  - Prompt gamma rays (10^{-12} s)
  - Delayed gamma rays (10^{-3} s - years)

Reaction	Gamma ray energy
$^{9}Be(d,n\gamma)^{10}B$	2.9 MeV
$^{9}Be(d,p\gamma)^{10}Be$	3.4 MeV
$^{12}C(d,p\gamma)^{13}C$	3.1 MeV
$^{9}Be(\alpha,n\gamma)^{12}C$	4.4 MeV

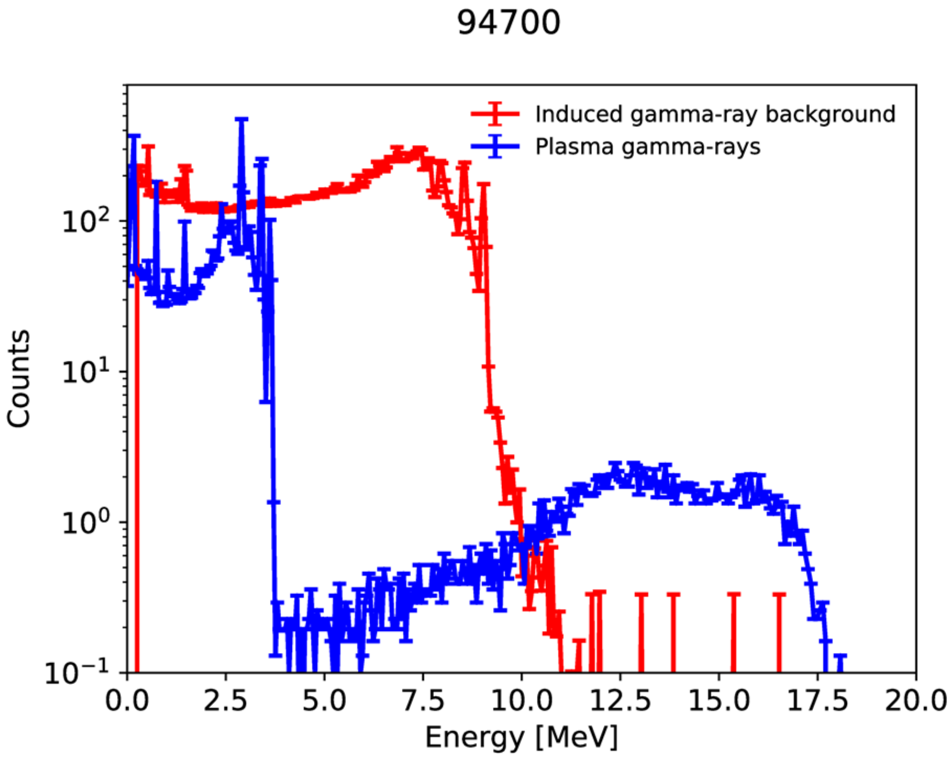
Plasma gamma ray source modelling

- Methodology consists of three steps:
  - Generation of plasma physical parameters
  - Generation of sampling distribution functions
  - Plasma gamma ray source subroutine for Monte Carlo N-particle Transport code (MCNP)
- Computational support for detector measurements
- Methodology validated on JET discharges

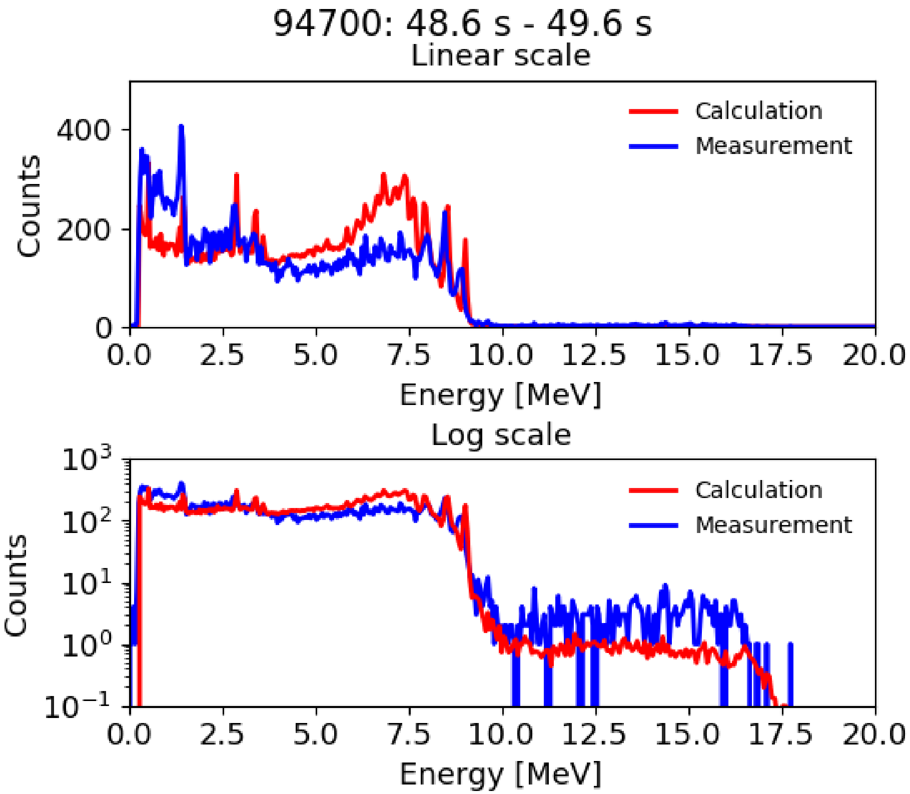


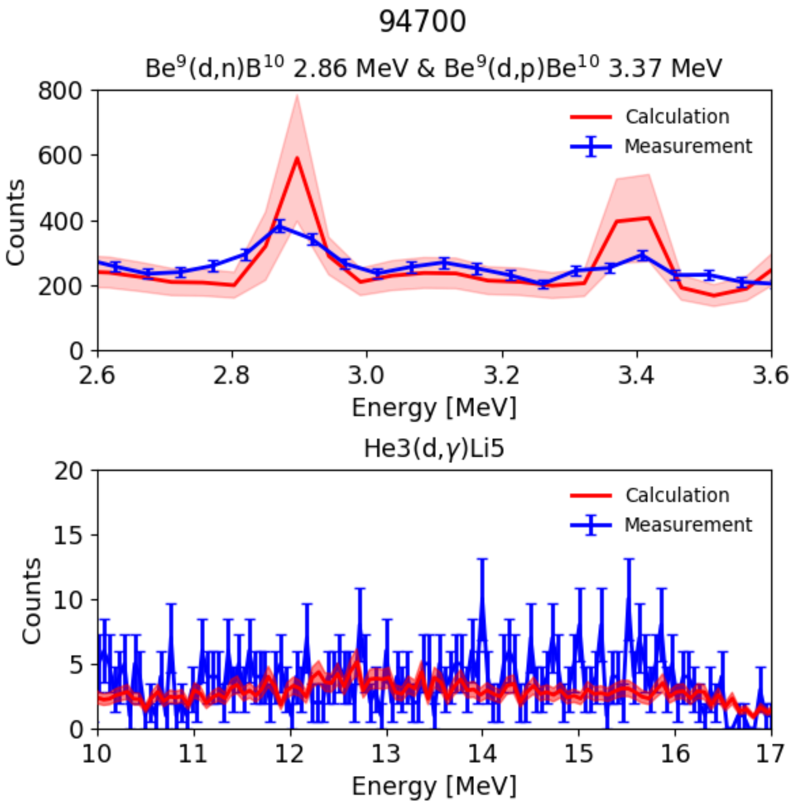
Gamma ray spectra composition

- Plasma gamma rays
  - Reaction rate
- Neutron induced gamma rays
  - Neutron rate
- Uncertainty:
  - ~30 % plasma gamma rays
  - ~15 % neutron induced prompt gamma rays



Gamma ray spectra





Excellent agreement between calculations and measurements

A. Žohar et al, 2022, Nuclear Fusion 62, 066004

ITER PFPO source modelling

[ITER Research Plan 2018]

- ITER Pre-Fusion Power Operation phases a demonstration of plasma control, heating, fueling and diagnostics systems readiness
- PFPO operations aimed at H and He plasmas, heated with a combination of ECRH, ICRH and NBI:
  - Low density He plasmas with fast ion population due to synergy between injected H^0-NBI at 870 keV and RF hydrogen minority heating → MeV range protons
  - Metal wall with intrinsic Be plasma impurities

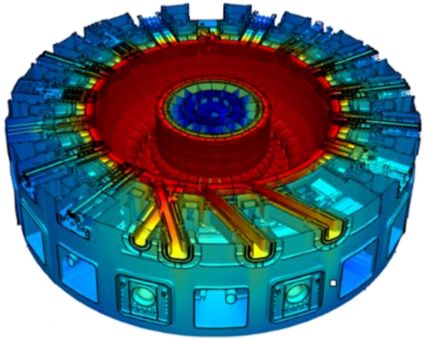
$^{9}Be + p = {}^{9}B + \mathbf{n} + \boldsymbol{\gamma}$

$^{9}Be + p = \mathbf{d} + 2\boldsymbol{\alpha}$

$^{9}Be + \mathbf{d} = {}^{10}B + \mathbf{n} + \boldsymbol{\gamma}$

$^{9}Be + \boldsymbol{\alpha} = {}^{12}C + \mathbf{n} + \boldsymbol{\gamma}$

[Polevoi A. et al., Nucl Fusion 2021]



[Juarez R. et al., Nat Energy 2021]

ITER PFPO source modelling

[ITER Research Plan 2018]

- Relevant plasma scenarios for neutron and gamma production with 33 MW NBI, 20 MW EC, 20 MW RF heating

He plasma in H-mode (7.5 MA/2.65 T) with H RF minority (conc. ~ 5 - 10 % with RF @ 40 MHz)
→ H^0-NBI beams at 870 keV and RF fundamental H resonance with Doppler H^0-NBI synergy

$^9Be + p = {}^9B + \mathbf{n} + \boldsymbol{\gamma}$ (~ 80%)

$^9Be + \mathbf{d} = {}^{10}B + \mathbf{n} + \boldsymbol{\gamma}$ (~ 20 %)

Total neutron rate order of ~ $\mathbf{10^{15}\ s^{-1}}$

H plasma in H-mode (8.8 MA/3.12 T) with mixed ^4He (conc. ~ 15 %) and ^3He RF minority (conc. ~ 0.1 %)
→ H^0-NBI beams at 870 keV and 3-ion ^4He-(^3He)-H RF scenario

$^9Be + {}^3He = {}^{11}C + \mathbf{n} + \boldsymbol{\gamma}$ (~ 80%)

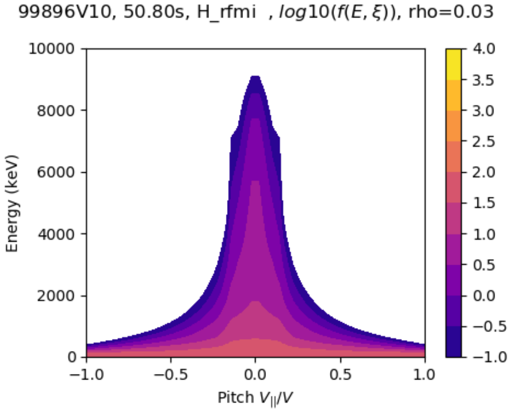
$^9Be + \mathbf{d} = {}^{10}B + \mathbf{n} + \boldsymbol{\gamma}$ (~ 20 %)

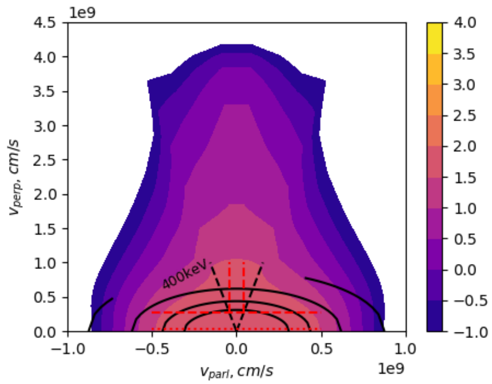
Total neutron rate order of ~ $\mathbf{10^{14}\ s^{-1}}$

JET preliminary results (ITER-like)

JET DTE2 #99896 H RF minority

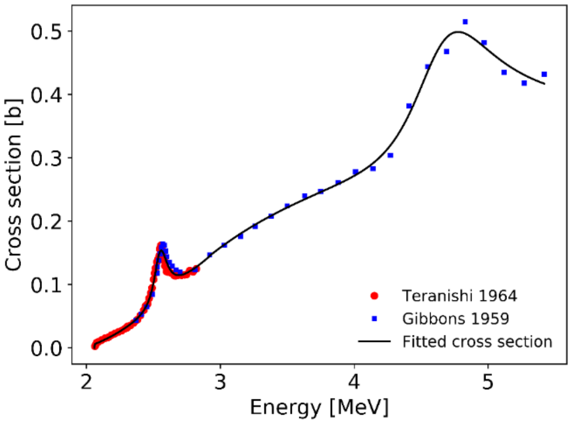
@ 2.8T/1.9MA



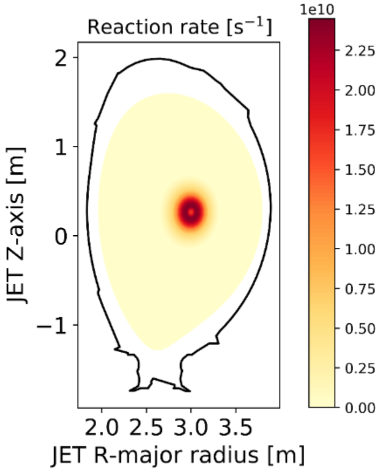


Well-developed highly energetic H RF minority tail in both discharges with large perpendicular velocities

Reaction
$^9Be + p = {}^9B + n + \gamma$
cross section



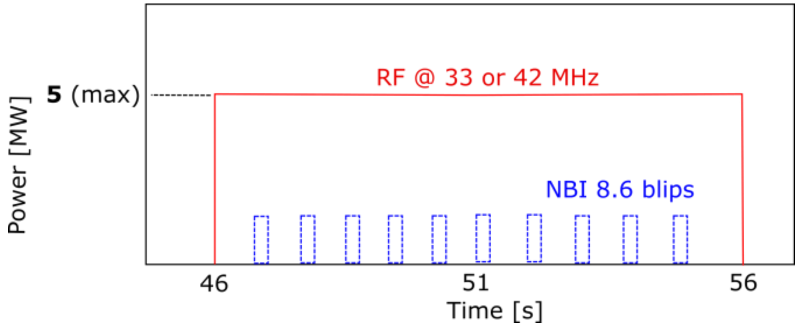
Calculated reaction rate for reaction
$^9Be + p = {}^9B + n + \gamma$

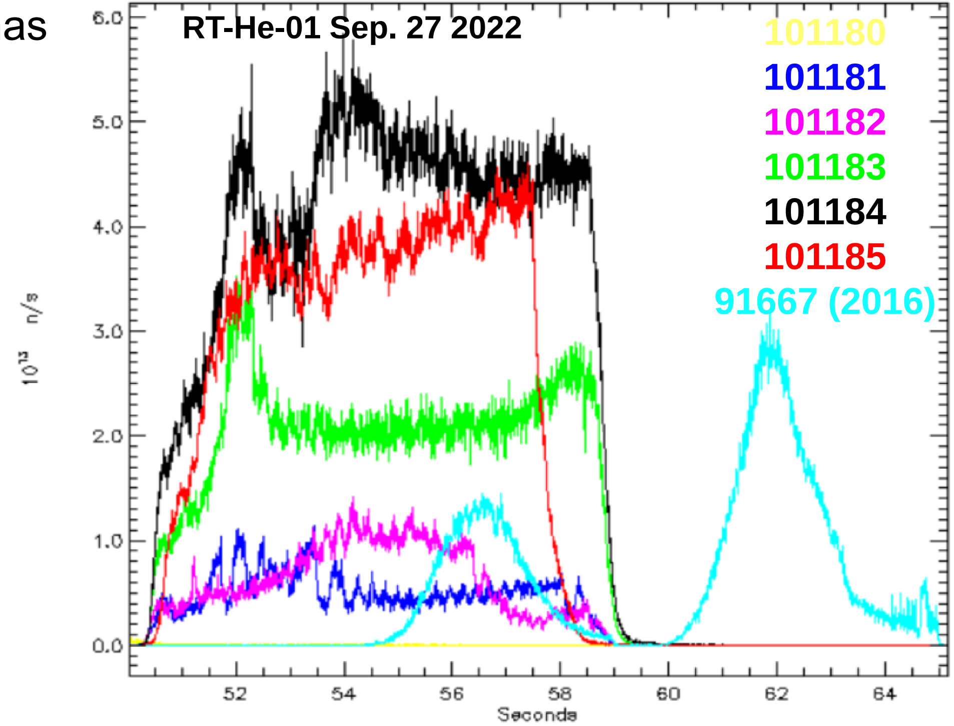


JET He plasma p+Be experiment

Generate MeV-range population of protons in He plasmas, using H RF minority heating at fundamental frequency, and trigger nuclear interactions between fast protons and Be impurities, recording footprints of resulting fusion products

- Support analysis of ITER's PFPO He plasmas with p+Be neutron and gamma production, validate modelling codes and workflows (plasma + neutronics)
- Energetic particle studies in view of ITER, e.g. AE stability in He plasmas





Conclusions

- Plasma → kinematics → neutron transport methodology for creation or realistic plasma neutron and gamma sources developed and applied to JET
- Successfully validated, integrated, and cross-code benchmarked the emission calculation chain
- JET DT and ITER PFPO modelling work in progress, computational support can be offered to ITER FPO calibration, D, and DT plasmas
- Fission chambers response changes due to neutron emissivity profile variations of the order of percent
- Foil activation found to be sensitive to realistic changes in neutron energy spectra – important choice of plasma calibration scenario, excellent for validation

Fusion power measurements in JET plasmas are weakly sensitive to changes in plasma conditions