



Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Neutron and runaway electron diagnostics for first plasma DTT operation

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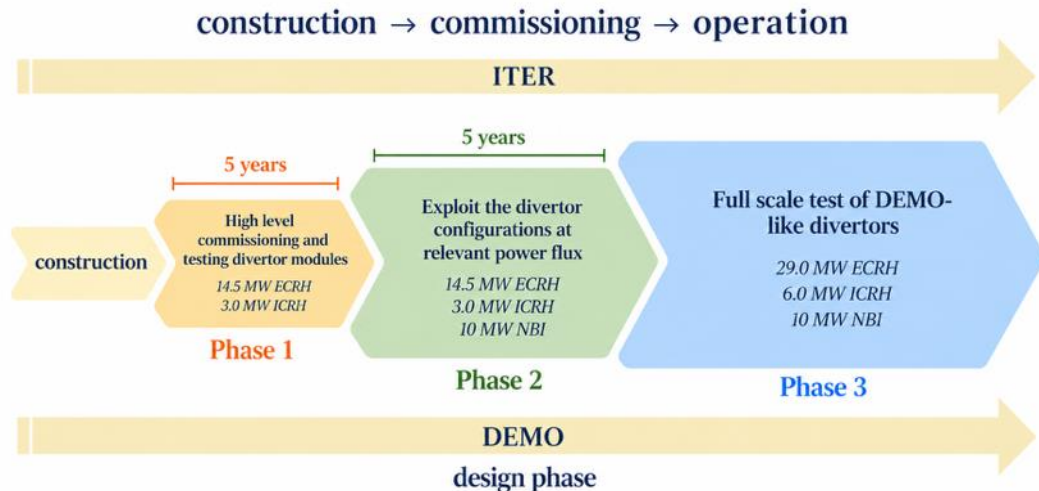
ICFDT8 8th International Conference on Frontier in Diagnostic Technologies



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Introduction: DTT phases & neutron/RE diagnostics



Neutron and runaway electron (RE) generation will be **monitored in DTT from First Plasma** throughout the Early Operational Phase (Phase 1)



Enable assessment of neutron budget

Support early disruption and RE mitigation experiments

Develop interlock and control strategies

Benchmark MCNP models for neutronics studies

Introduction: DTT Phase 1 neutron & RE diagnostics

- Strategy implemented through planned installation of the following set of phase 1 diagnostics:

- Neutron activation system (NAS)
- Neutron Yield monitors (NYM)

} *Time-integrated / time-resolved neutron yield (in-situ calibration)*

- NE213 scintillator
- C₆F₆ scintillators

} *Lost RE*

- Runaway Electron Imaging and Spectroscopy system (REIS)

} *In-flight RE*

- Additional diagnostics foreseen in later operational phases: Time-of-Flight spectrometer, neutron/gamma-ray camera and Cherenkov probe

References

D. Marocco et al., Design status of the neutron and gamma-ray diagnostics for the Divertor Tokamak Test facility, Fusion Engineering and Design 202 (2024) 114308

D. Marocco et al., Neutron Yield Monitors for the Divertor Tokamak Test (DTT) facility: detector set, expected performance and integration, Fusion Engineering and Design, 222 (2026) 115538

V. Anagnostopoulou et al., Preliminary calibration procedure for the Phase1 neutron and gamma-ray diagnostics of the Divertor Tokamak Test (DTT) facility, Fusion Engineering and Design, 222 (2026) 115537

V. Anagnostopoulou et al., Flux-shaping configuration for improved triton burn up detection at the Divertor Tokamak Test facility, Journal of Instrumentation, 20 (2025) C05035

F. Causa et al, Runaway electron imaging spectrometry (REIS) system, Rev. Sci. Instrum.90 (2019) 073501

G. Ghillardi et al., Study of runaway electron dynamics in FTU using synchrotron spectra and imaging measurements, Plasma Phys. Control. Fusion 67 (2025) 055029

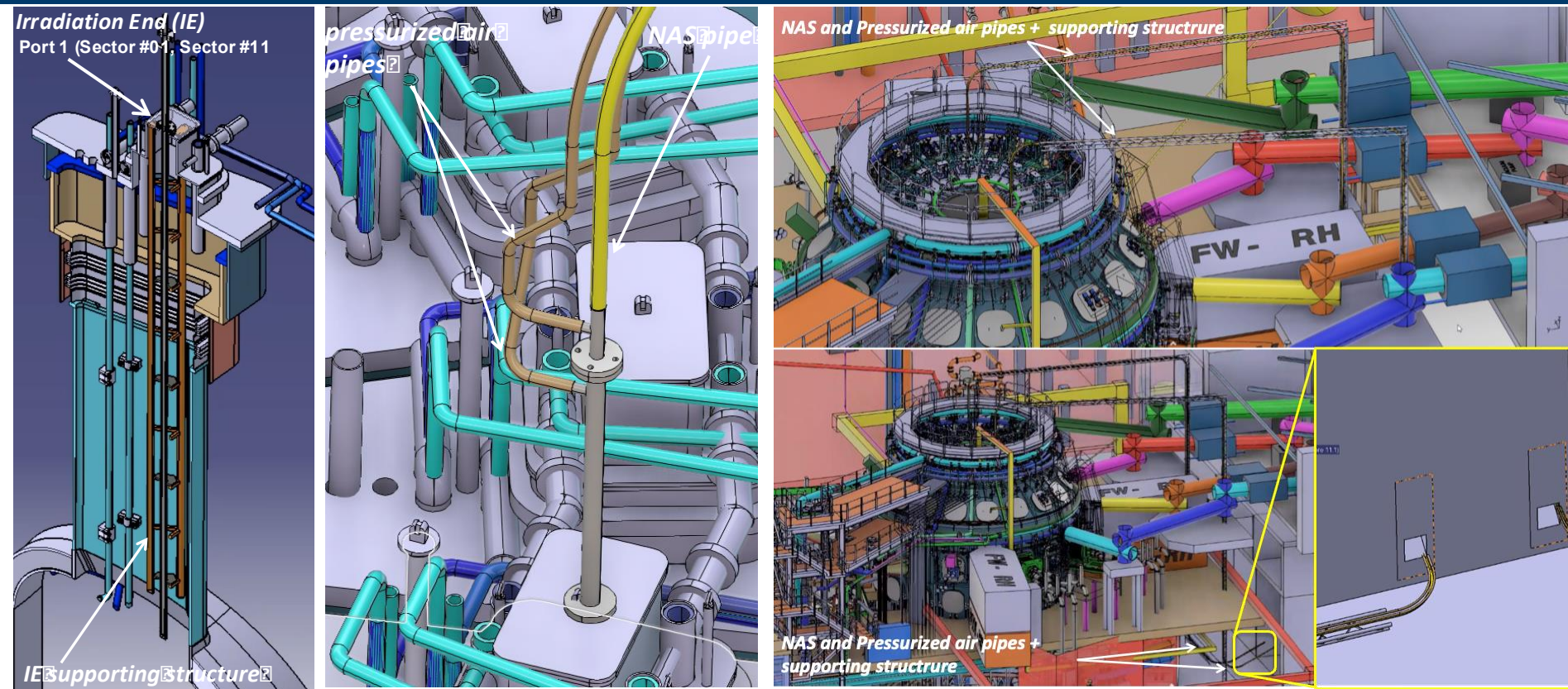
M. Regine et al., Analysis of Runaway Electron Dynamics in WEST based on Synchrotron Radiation Measurements, 52nd EPS Conference on Plasma Physics, Edinburgh, Scotland (<https://indico.ukaea.uk/event/449/contributions/1442/>)

NAS - Overview

- **Metallic foils** moved by **pneumatic system** between **irradiation end** close to plasma and **gamma-ray counting station**.
 - **Foils activated** by (n,γ) reactions
 - **Foils activity measured** by HPGe detector
 - **Neutron Yield determined** combining measured activity and MCNP simulations constrained by in-situ calibration
- Proximity to plasma
→ **unaffected by changes in tokamak hall**
- Thickness-tunable efficiency
→ **suitable for low-yield regime measurements**

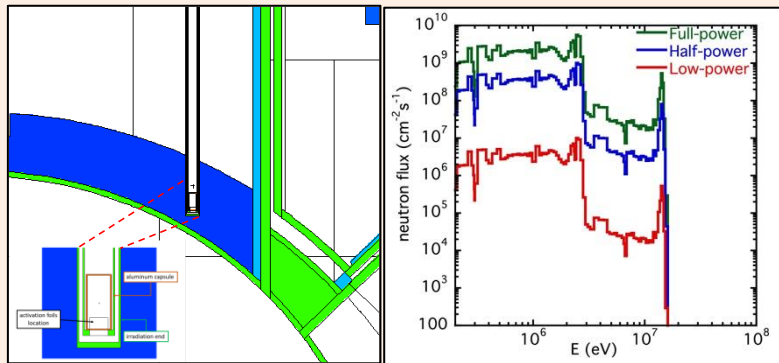
Element	Reaction of interest	Threshold (MeV)	Half Life	γ-ray (keV)	P_γ (%)	D-D	D-T
In	$^{115}\text{In}(n, n')^{115m}\text{In}$	0.6	4.486 h	336.24	45.9	X	–
Al	$^{27}\text{Al}(n, p)^{27}\text{Mg}$	4.3	9.458 min	843.76 1014.52	71.8 28.2	–	X
	$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	6.8	14.956 h	1368.63	99.994	–	X
Nb	$^{93}\text{Nb}(n, 2n)^{92m}\text{Nb}$	9	10.25 days	934.44	99.15	–	X

NAS - Layout



NAS - Performance

MCNP calculation of neutron spectra at foils position



Scenario	DD Yield rate (s^{-1})	TBN fraction (%)	DT Yield rate (s^{-1})
Low-power ¹	2.3×10^{14}	2.8	6.4×10^{12}
Half-power ²	2.3×10^{16}	4.4	9.8×10^{14}
Full-power ³	1.3×10^{17}	5	6.5×10^{15}

Irradiation time = 25 s

Foil diameter = 9 mm



FISPACT-II calculation of induced activity



Detector counts in ROI based on HPGe response function

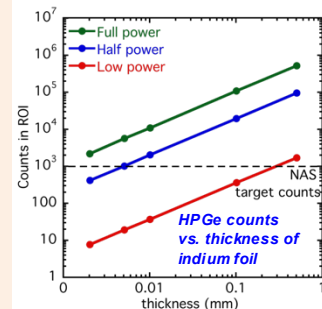
Assumptions

Acquisition time = 3600 s

Foil to HPGe distance = 10 cm

HPGe relative efficiency = 50%

Requirements → 3% statistical error

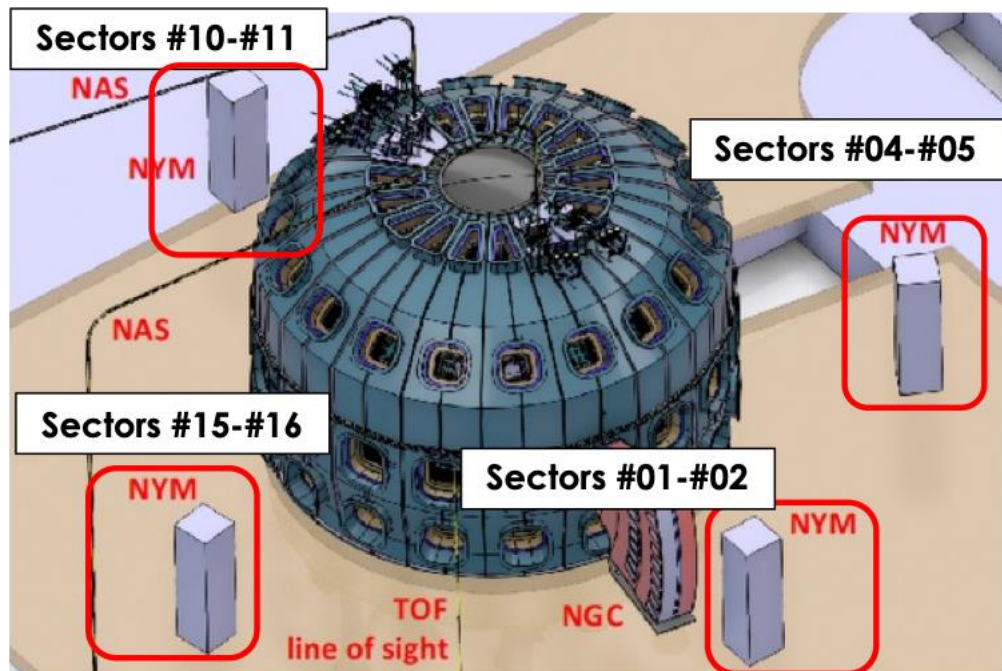


Material	Day0	Half Power	Full Power	Cooling time	D-D	D-T
In	0.5 mm	0.005 mm	0.002 mm	4 h	X	—
Al	> 5 mm*	0.5 mm	0.1 mm	0.5 h	—	X
Nb	> 5 mm*	5 mm	0.5 mm	3 h	—	X

*Note: The 1000-count target is not reached for the available foil thicknesses

NYM - Overview

- **Active detectors working in count mode** located at four positions in the DTT torus hall
- **Time resolved neutron** yield measurement enabled via **in-situ /cross calibration**

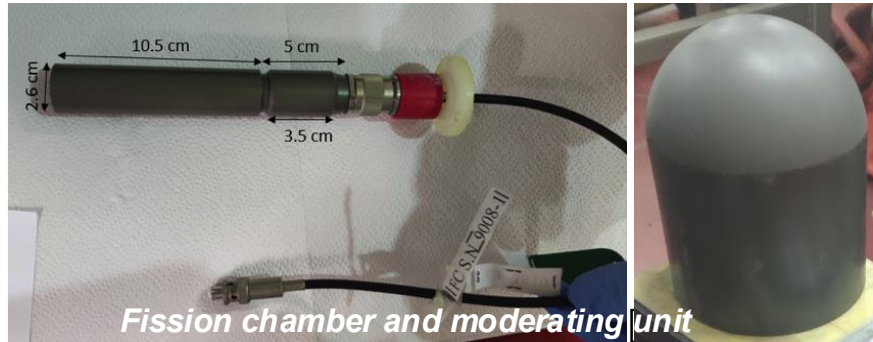


- Measurement of:
 - **DD + DT neutrons (total yield monitor)**
 - **Separate DD and DT neutrons:** designed for DT measurements (**burn up monitors**) but also suitable for **DD**
- **Phase 1 installation:** subset of detectors with **highest efficiency**

NYM - Total yield monitors

- **Former FTU gas detectors embedded in moderating units** exploiting nuclear reactions induced by thermal neutrons:
 - No selectable energy threshold
 - Low sensitivity to gamma/hard x-rays

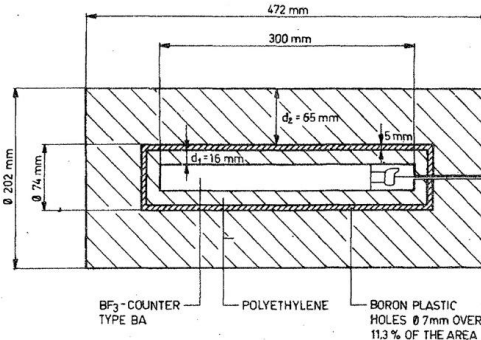
Sixteen ^{235}U Fission chambers $\rightarrow$ ^{235}U (n, f) reaction



- Moderating units: mixture of lead and polyethylene
- 4 detector sets: 4×10^{-2} g; 4×10^{-3} g; 4×10^{-4} g; 4×10^{-5} g

Phase 1

Six BF_3 proportional counters $\rightarrow$ ^{10}B (n, α) reaction



- Moderating units: polyethylene and boron plastic
- 3 low sensitivity + 3 high sensitivity detectors

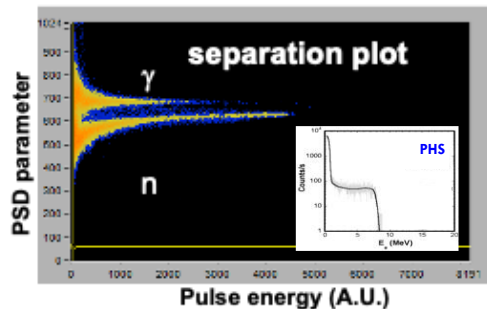
NYM - burn up monitors - Layout

- Liquid/solid state detectors:

- Selectable energy threshold
- Also sensitive to gamma/hard x-rays

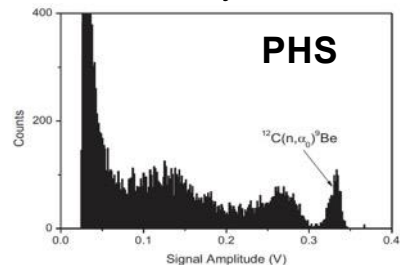
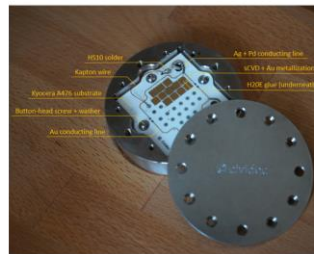
Liquid scintillator

- EJ301 1.5 cm $\varnothing$ $\times$ 1 cm thick
- Neutron elastic scattering on hydrogen nuclei
- DD/DT neutrons discriminated by threshold
- Gamma-rays discriminated by pulse shape



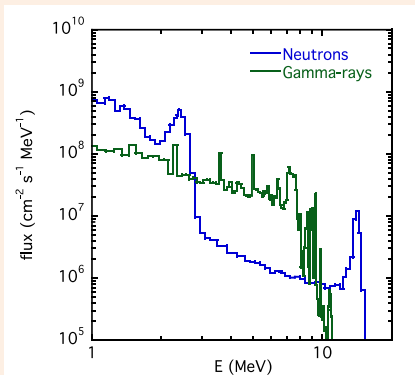
Single crystal diamond (sCD)

- Two 10-pixel matrices:
 - 4.5 mm x 4.5 mm x 200 μ m **Phase 1**
 - 4.5 mm x 4.5 mm x 50 μ m
- DT neutrons: $^{12}\text{C}(n,\alpha)^9\text{Be}$ reaction
- DD neutrons: elastic scattering on ^{12}C nuclei
- DD/DT neutrons/gamma-rays discriminated by threshold



NYM - Performance

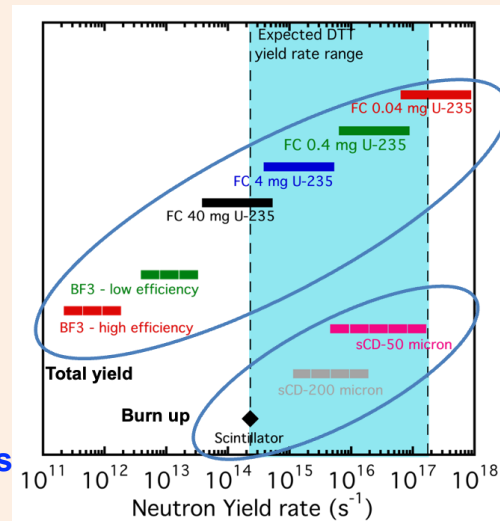
MCNP calculation of n/γ spectra at detector position



Counts at given yield rate/time resolution evaluated by means of detector response functions

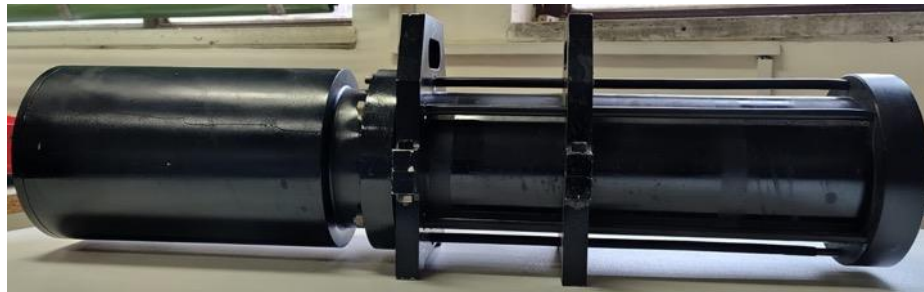
Results checked against requirements

- Time resolution < 100 ms
- Statistical error: < 3%
- Count rate: < 10^5 cps (BF₃/FC);
< 10^6 cps (EJ301/sCD)
- **FCs cover within requirements the full DTT yield rate range.**
- **BF₃s extend performance downwards by three orders of magnitude**
→ Shielding included in the design to shift operating range to higher neutron yield rates
- **EJ301/ sCDs can cover almost uniformly the DTT range but with larger statistical error (10%)** due to sensitivity to DD neutrons
→ Shielding included in the design to reduce DD contribution with minimal impact on DT counts



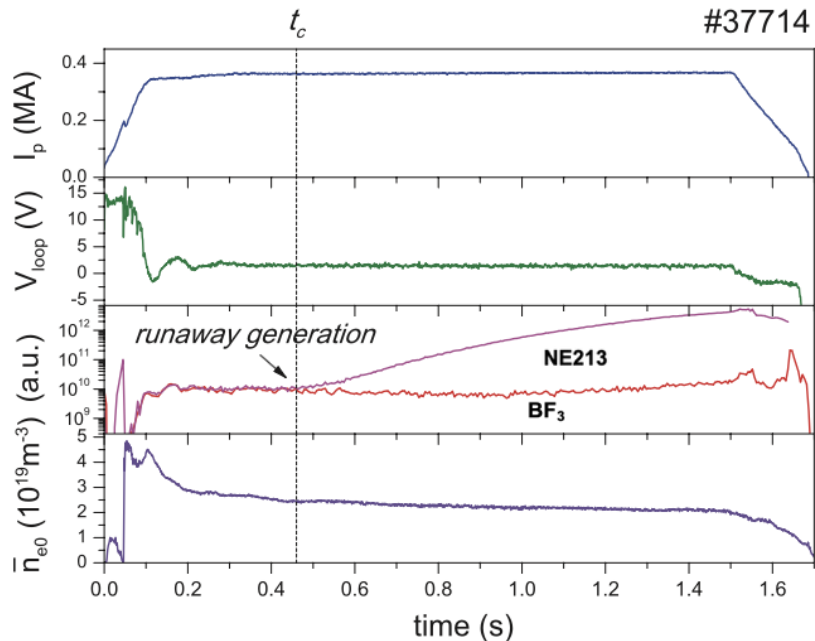
RE monitors - NE213 scintillator - Overview

- **Large NE213 scintillator** (5"× 5", former FTU detector) hosted in one of the torus hall NYM benches
- **RE detected by** measuring the **hard x-rays** produced by RE interactions with tokamak structures (**thick target bremsstrahlung**)
- working in **current mode → continuous signal due to:**
 - Neutrons
 - Neutron-generated gamma-rays
 - **RE-generated hard x-rays**
- The detector will be cross-calibrated with NYM in RE-free discharges → **NE213 & NYM time traces will:**
 - **Overlap when there are no RE**
 - **Deviate from each other when RE are present**

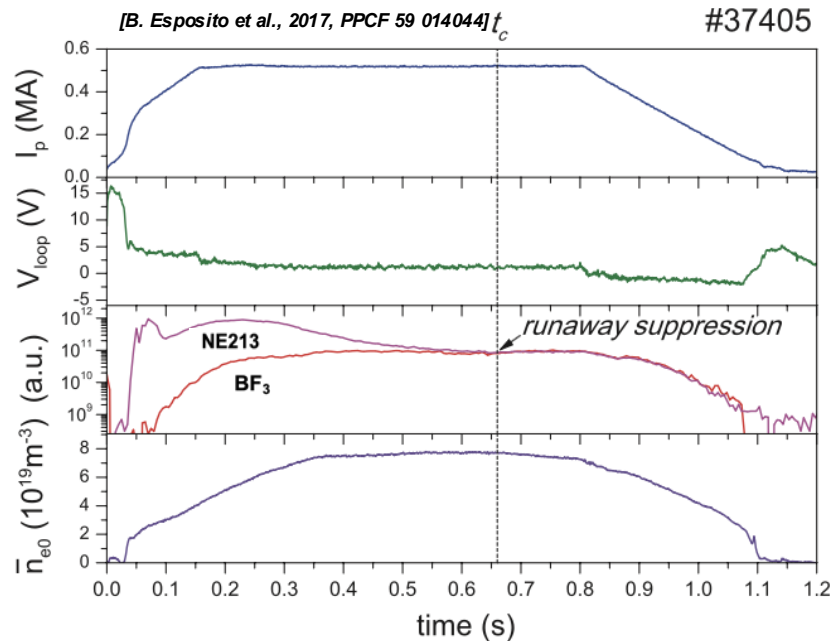


RE monitors - NE213 scintillator - performance

RE detection with BF_3 and NE213 during RE generation/suppression experiments in FTU



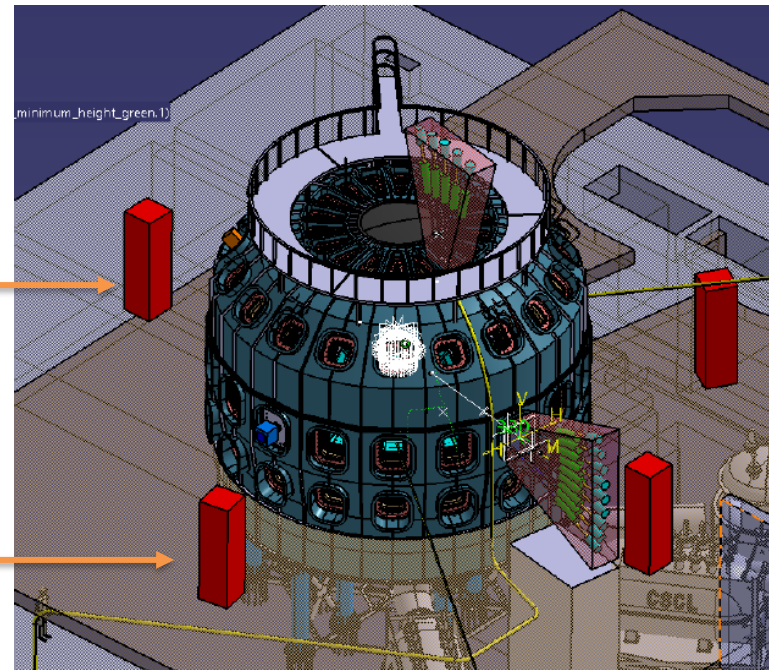
RE generation through decreasing n_e in I_p flat-top



RE suppression via low gas prefill and feedback-controlled constant/increasing n_e

RE monitors - C_6F_6 scintillators - Overview

- **Four detectors** (12.7 mm $\varnothing$ $\times$ 12.7 mm thick) one for each NYM bench, **working in count mode $\rightarrow$ toroidal resolution**
- Almost **Hydrogen-free** $\rightarrow$ **Low neutron sensitivity**
- **10 cm-thick polyethylene attenuator** included in the design to further reduce the neutron flux
- Excess of hard x-rays due to RE detected by comparison with NYM as for NE213



RE monitors - C₆F₆ scintillators - Performance

Day 0

Maximum DD neutron yield rate: $3,6 \cdot 10^{14}$ n/s (Villari, 2020)

	Flux	Count Rate	Count Rate (over THR)
X-rays	$0,36 \cdot 10^7 \text{ cm}^{-2}\text{s}^{-1}$	89,58 kcps	12,57 kcps
Neutrons	$1,52 \cdot 10^7 \text{ cm}^{-2}\text{s}^{-1}$	9,33 kcps	1,19 kcps

Threshold counting easily achievable 13,76 kcps

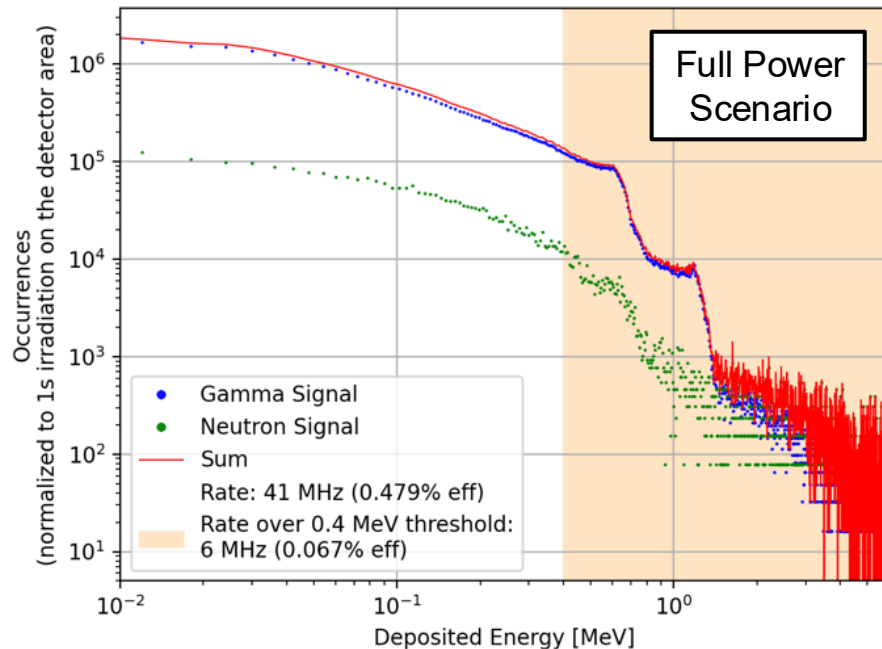
Full Power

Maximum DD neutron yield rate: $1,5 \cdot 10^{17}$ n/s (Villari, 2020)

	Flux	Count Rate	Count Rate (over THR)
X-rays	$1,49 \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$	37,33 Mcps	5,29 Mcps
Neutrons	$6,35 \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$	3,89 Mcps	0,49 Mcps

Significant pile-up 5,78 Mcps

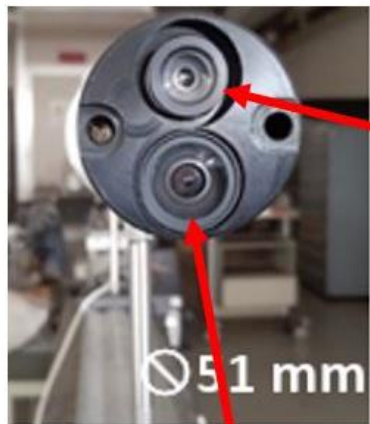
10 cm polyethylene attenuator **can be used from day 0;**
current mode operation can be considered at full power



RE monitors - REIS - Overview

- Infer **RE population parameters** (number, energy, pitch angle) and **RE beam position** from measurements **of synchrotron radiation** emitted by **in-flight RE**

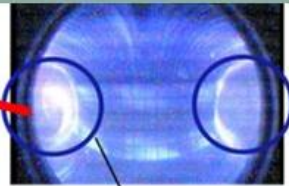
REIS-E HEAD



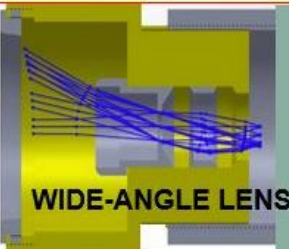
Visible camera

SPECTROMETERS

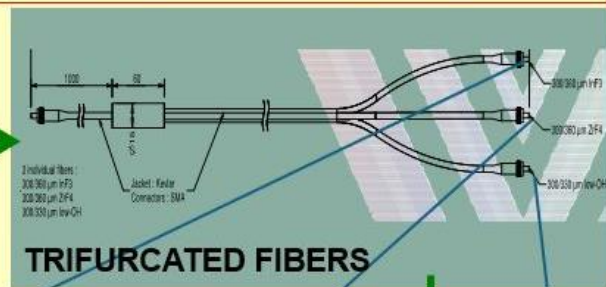
Wide-angle objective lens coupled to 3 spectrometers through fibers



FOV 30° (RE forward view)



WIDE-ANGLE LENS



TRIFURCATED FIBERS

SPECTROMETERS

MIR range
1400-5000 nm

Spectral Products SM301-EX



NIR range
900-2500 nm

Ocean Optics NQ256-2.5



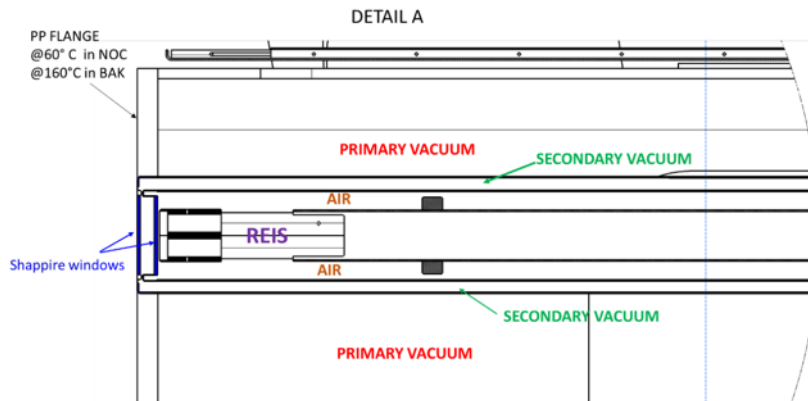
VIS range
400-800 nm

Ocean Optics HR2000+

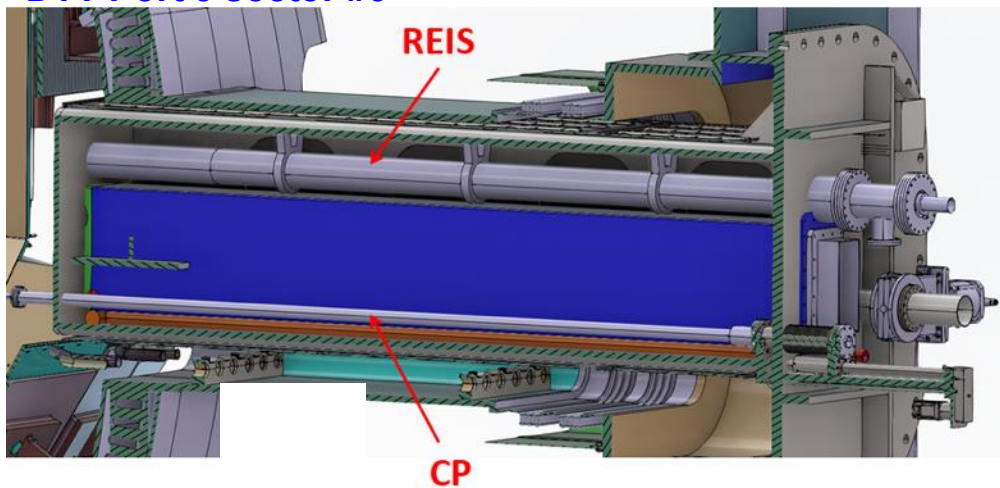


RE monitors - REIS - layout

- A version of the **REIS without visible camera** is **available** and **currently installed in WEST**
- REIS measurements at **WEST used as testbed for overall diagnostic setup**, acquisition and real-time processing
- The current REIS will be adapted **for DTT** with the following new features:
 - **Cooling system**
 - Double **vacuum window**
 - **Real-time** data acquisition system

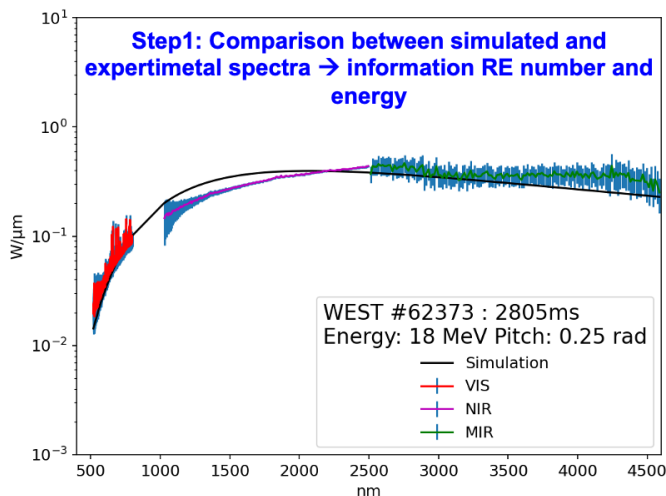


DTT Port 3 sector #9



RE monitors - REIS - Performance - WEST discharge # 62373

Combined analysis of REIS spectra and visible camera images to determine RE number, energy, pitch angle and radial position → **SOFT simulations** (Synchrotron-detecting Orbit Following Toolkit) **constrained by experimental data**



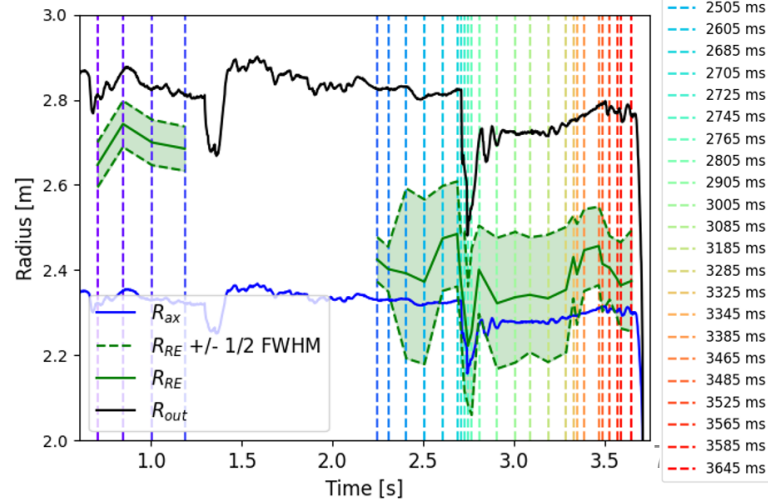
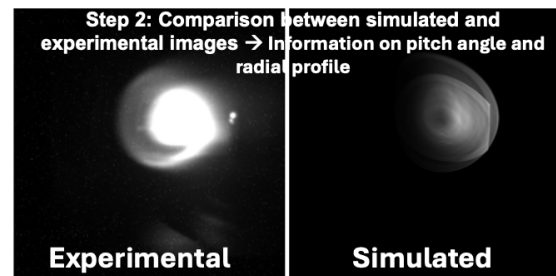
- Fixed pitch angle
- Mono-energetic
- Flat radial distribution

Loop on pitch angle and energy

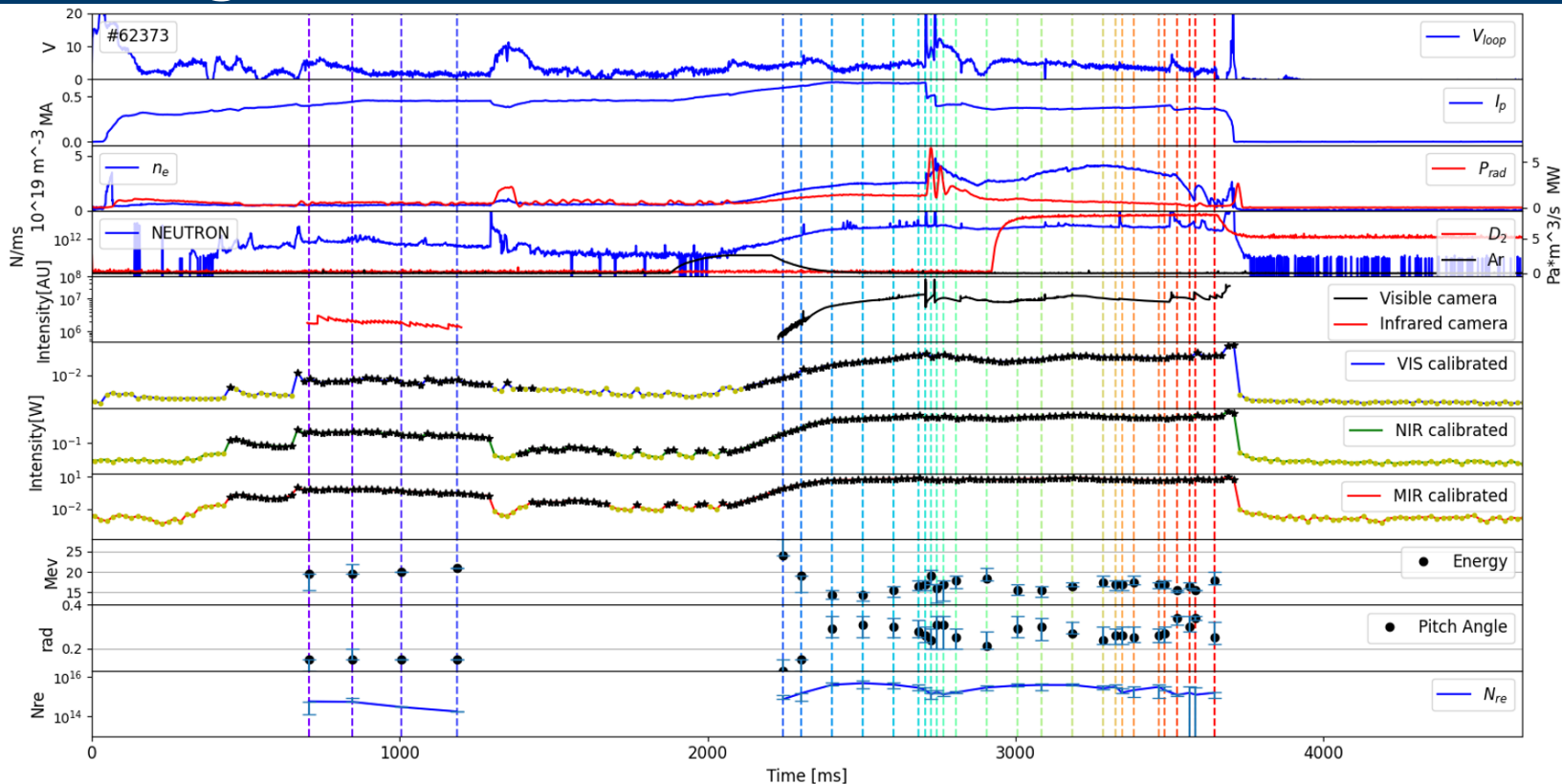


- Exponential pitch angle
- Mono-energetic (selected from spectra)
- Radial distribution function $f_r(r)$
- $f(r, p, \theta_p) = f_r(r) \cdot \delta(p - p^*) \cdot \exp(K^* \cos \theta_p)$

Loop on pitch angle + radial profiles



RE monitors - REIS - Performance - WEST discharge # 62373



Conclusions

- A comprehensive set of neutron and runaway electron diagnostics is planned for installation in DTT from Phase 1 and its desing is on-going
- The diagnostic set includes:
 - **Neutron Activation System (NAS)** for robust and flexible reference neutron-yield measurements, supporting cross-calibration and validation of MCNP models
 - **Neutron Yield Monitors (NYM)** for time-resolved, pulse-by-pulse neutron yield measurements, supporting plasma operations
 - **Scintillators** for monitoring runaway-electron losses through hard X-ray emission
 - **REIS** for measurements of in-flight runaway-electron beam properties and position
- A framework for performance analysis has been established and first results indicate that **the proposed diagnostics can meet the needs of DTT Phase 1 operation**

Thank you for your attention