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EUROfusion

Feasibility study of a vertical neutron profile monitor and a tangential compact neutron spectrometer for JT-60SA

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FUSION FOR ENERGY

QST

Fast particle physics

- P-NBIs @ 85 keV & N-NBIs at 500 keV resulting in two different FI populations driving different EPs (FBs), BAEs, TAEs, GAEs and CAEs;
- Super-Alfvénic velocity of the N-NBI driving TAEs, GAEs and CAEs; impact on current drive efficency.
- Orbits of MeV D (from NNB) comparable to α-particle orbits in ITER and DEMO;
- Triton burn-up as a proxy for (DT neutrons) to study the transport of 1 MeV tritons which have a Larmor radius similar to that of 3.5 MeV α-particles.
- Verification & validation (V&V) activities of theory-based transport codes for energetic ions through neutron experimental measurements
- ELMs and RMPs impact on fast ions confinement (neutron emissivity profiles).
- Scenarios 2 and 5 used in this study.

Tokamak	TFTR	JET	JET	JT-60U	ITER	Slim CS	JT-60SA Scen#1-#5-1
Fast ion	Alpha	Alpha	Alpha	Deuterium	Alpha	Alpha	Deuterium
Source	Fusion	Fusion	ICRF tail	Co NBI	Fusion	Fusion	Co NBI
τ_s [s]	0.5	1.0	0.4	0.085	0.8	~2	0.5 - 1.6
n_f_max / $n_e(0)$ [%][a]	0.3	0.44	1.5	2	0.85		0.35 - 2.2
β_f_max [%][a]	0.26	0.7	3	0.6	1.2		0.54 – 2.3
$<\beta_f>$ [%)	0.03	0.12	0.3	0.15	0.3	~1.2	0.2 – 0.9
β_f_max / $<\beta_f>$	8.7	5.8	10	4	4		2.5 – 3.2
max $\|R\nabla\beta_f\|$ [%]	2.0	3.5	5	6	3.8		5.2 – 65
v_f_max / v_A	1.6	1.6	1.3	1.9	1.9	~2	1.0 – 1.26

	#1	#2	#3	#4-1	#4-2	#5-1	#5-2	#6[1]
	Full Current Inductive DN, 41MW	Full Current Inductive SN, 41MW	Full Current Inductive High density	ITER-like Inductive	Advanced Inductive (hybrid)	High β_N Full-CD	High β_N High f_{GW} Full-CD	High β_N 300s
Plasma Current (MA)	5.5	5.5	5.5	4.6	3.5	2.3	2.1	2.0
Toroidal field BT (T)	2.25	2.25	2.25	2.28	2.28	1.72	1.62	1.41
q_{95}	~3	~3	~3	~3	~4.4	~5.8	6.0	~4
R/a (m/m)	2.96/1.18	2.96/1.18	2.96/1.18	2.93/1.14	2.93/1.14	2.97/1.11	2.96/1.12	2.97/1.11
Aspect ratio A	2.5	2.5	2.5	2.6	2.6	2.7	2.6	2.7
Elongation κ_x	1.95	1.87	1.86	1.81	1.80	1.90	1.91	1.91
Triangularity δ_x	0.53	0.50	0.50	0.41	0.41	0.47	0.45	0.51
Shape factor S	6.7	6.3	6.2	5.7	5.9	7.0	7.0	6.4
Volume (m^3)	132	131	131	122	122	124	124	124
Cross-section (m^2)	7.4	7.3	7.3	6.9	6.9	6.9	6.9	6.9
Normalised beta β_N	3.1	3.1	2.6	2.8	3.0	4.3	4.3	3.0
Electron density ($10^{19}m^{-3}$) Line-average/volume-average	6.3/5.6	6.3/5.6	10./9	9.1/8.1	6.9/6.2	5.0/4.2	5.3/4.3	2.0/
P_{add} (MW)	41	41	30	34	37	37	30	13.2
$P_{NNB}/P_{PNB}/P_{EC}$ (MW)	10/24/7	10/24/7	10/20/-	10/24/-	10/20/7	10/20/7	6/17/7	3.2/6/4
Neutron production rate, S_n (n/s)	1.3×10^{17}	1.3×10^{17}	7.0×10^{16}	6.7×10^{16}	5.4×10^{16}	4.5×10^{16}	2.9×10^{16}	1.2×10^{16}

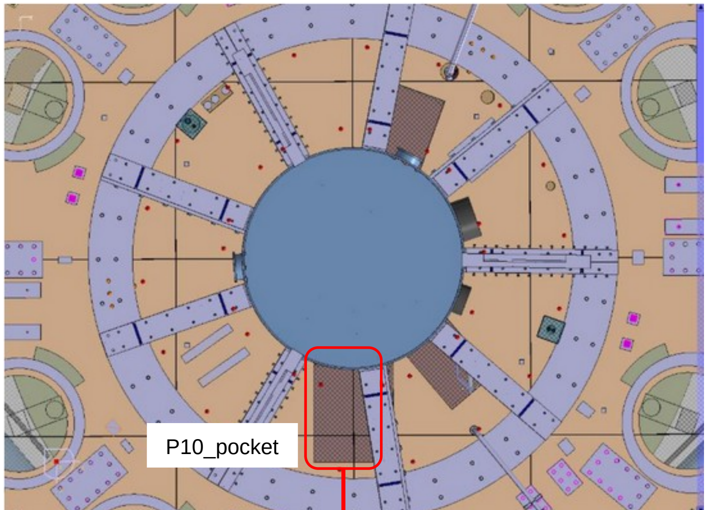
N-NBI (500 keV)
P-NBI (85 keV)

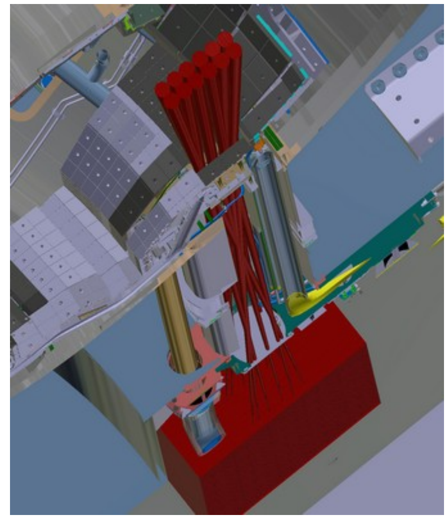
NDs for physics studies

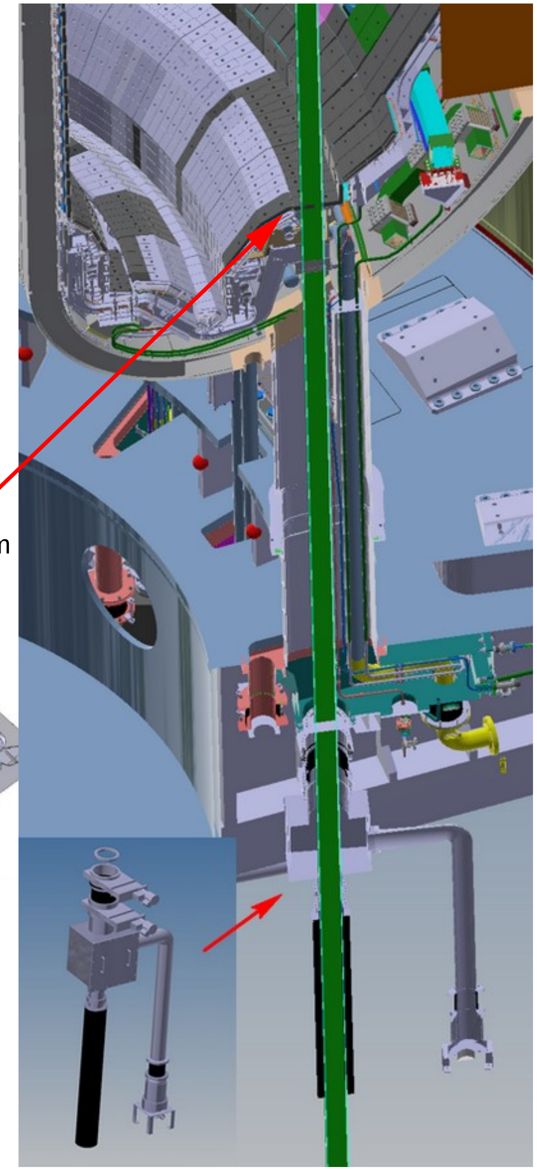
Table 3.11-1 Diagnostic systems and plasma parameters to be measured.

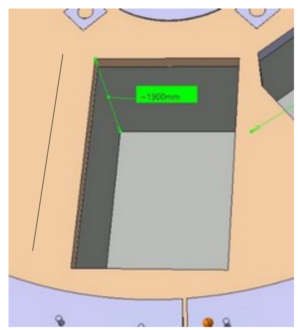
For Machine Protection and Operation	
Neutron monitor	Neutrons
Neutron activation measurement	Neutrons
Visible TV camera	Plasma-wall interaction
Dα emission monitor	Particle recycling
Divertor Langmuir probe	Plasma Configuration, Electron density and temperature
Infrared TV camera (divertor)	Heat load
For Fundamental Parameter Measurement	
YAG laser Thomson scattering system	Electron density and temperature
CO2 laser interferometer / polarimeter (tangential and vertical)	Electron density
Electron cyclotron emission diagnostics (Fourier transform spectrometer, Grating polychoromator, Heterodyne radiometer)	Electron temperature
Charge exchange recombination spectroscopy	Ion temperature, Plasma rotation, Impurity
Z_{eff} monitor (Visible bremsstrahlung emission)	Impurity
VUV spectrometer	Impurity
Motional Stark effect polarimeter	Plasma current profile
Bolometer (main, divertor)	Radiation loss power
For Physics Understanding	
Soft X-ray detector array	Soft X-ray emission
Neutron emission profile monitor	High-energy ions
14 MeV neutron detectors	High-energy ions
Neutron spectrometers	High-energy ions
Infrared TV camera (first wall)	High-energy ions
Li-beam probe	Plasma current profile in the edge
Reflectometer	Perturbations
Reciprocating Mach probe	Plasma flow Electron temperature and density in the SOL
Visible spectrometer for the divertor	Impurity, Recycling
VUV spectrometer for the divertor	Impurity
Neutral gas pressure gauge (Penning gauge, Fast response ionization gauge)	Neutral gas pressure

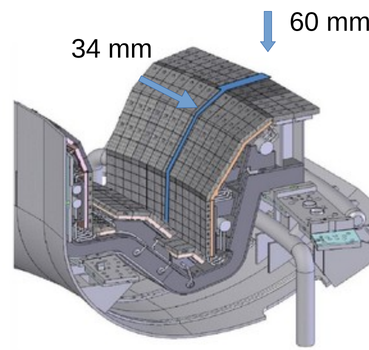
Vertical Neutron Camera Location

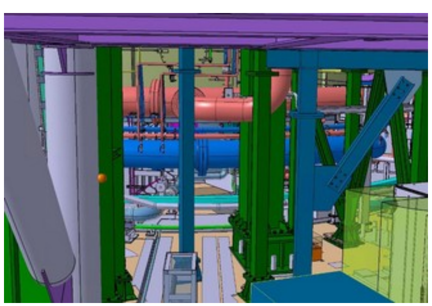


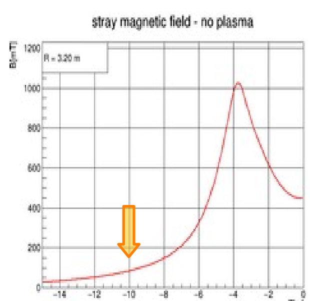






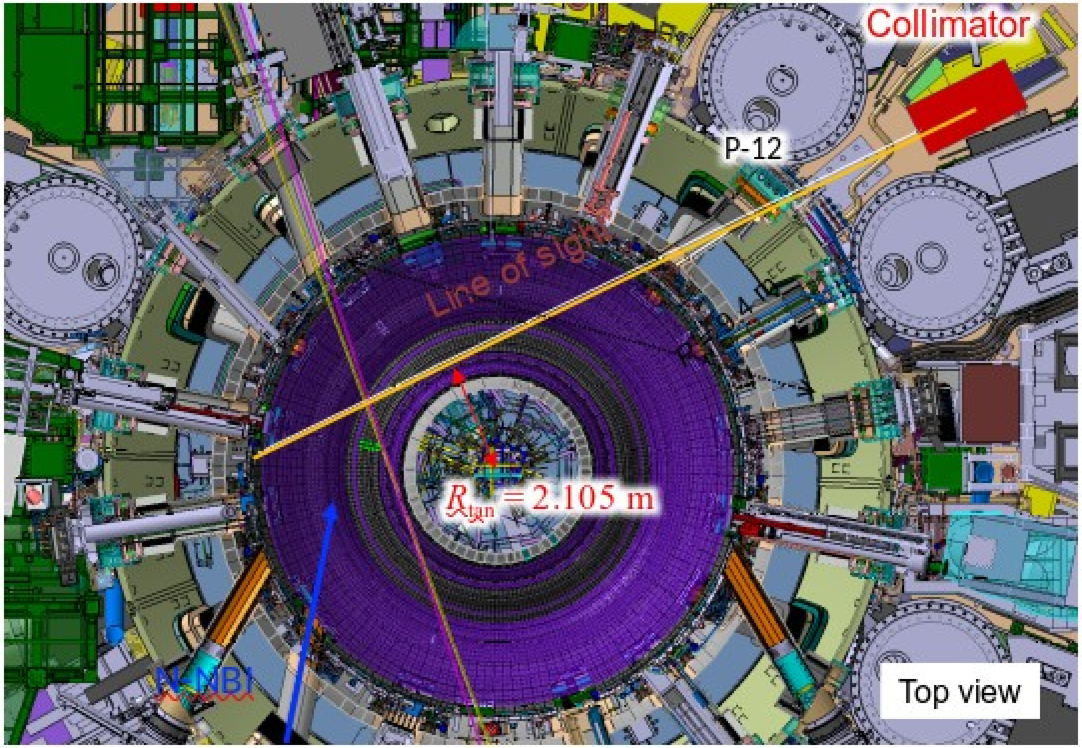




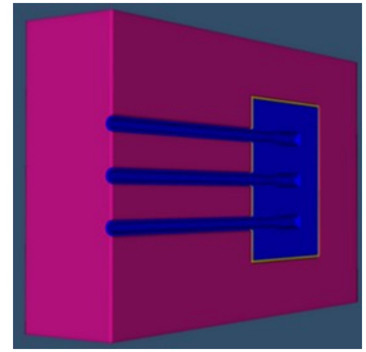


- Stray B field approx 100 mT perpendicular to PMT
- Possible alternatives are Si-PMTs

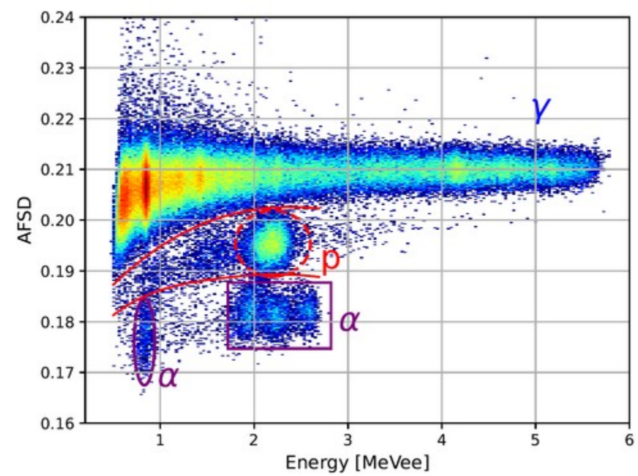
Tangential Compact Neutron Spectrometer

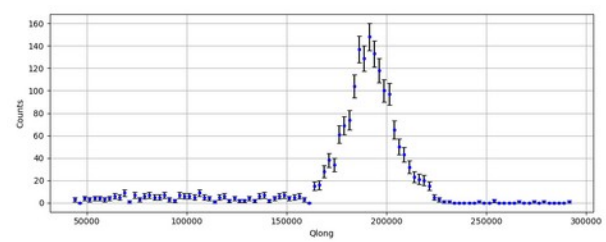


- Detection of DD neutrons mainly based on $LaCl_3$ scintillator $^{35}Cl(n,p)^{35}S$ nuclear reactions coupled to a PMT
- High energy resolution (49000 ph/MeV)
- Fast scintillation (28 ns) -> higher count rates
- n/γ discrimination with enhanced algorithm
- Collimator: 1.4 cm diameter, 95 cm length
- Detector: 1.4 cm diameter, 2.54 cm length, 1.15 % efficiency



NES (JA)
GRS (EU)
NES (EU)

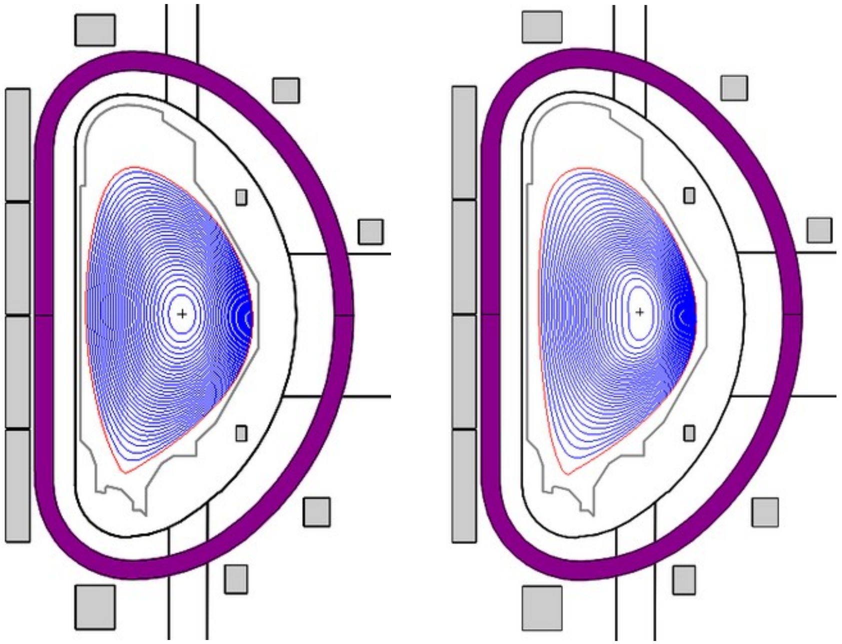




Neutron peak measured with the $LaCl_3$ at MAST-U

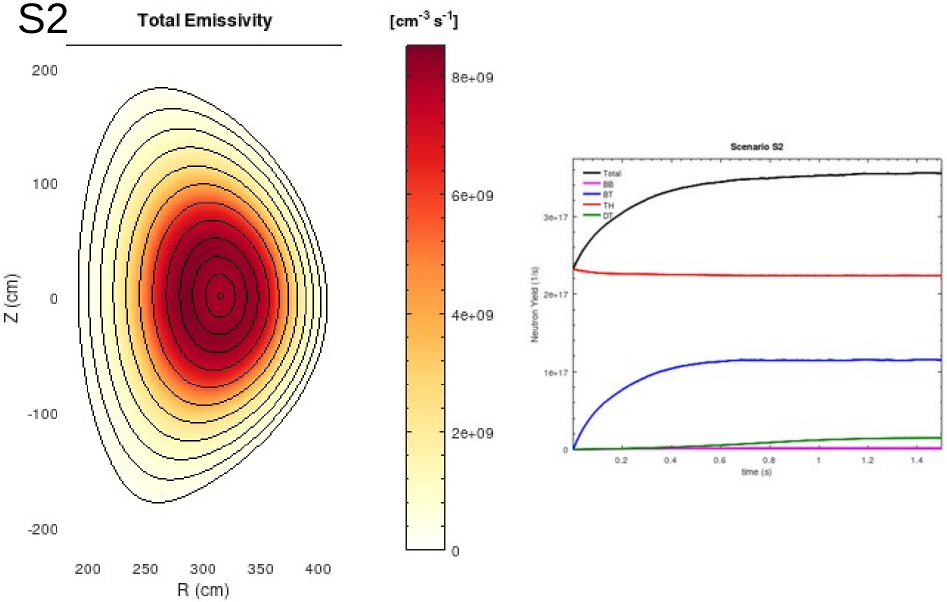
TRANSP/NUBEAM modeling for S2 & S5

- JETTO gEQDSK equilibrium with FI pressure included converted to UFILES via scrunch2
- Kinetic profiles from JINTRAC converted to UFILES
- Profiles and equilibrium frozen
- Scenario:
  - **S2**: Ip = 5.5 MA, RBt = 6.66 mT with R = 2.96 m, Bt = 2.25 T, P-NBI power at 1 MW (Extended Research Phase)
  - **S5**: Ip = 2.36 MA, RBt = 5.11 mT with R = 2.96 m, Bt = 1.72 T, P-NBI power at 0.85 MW (Integrated Research Phase)
- Plasma rotation set to zero
- NLBCCW = NLJCCW = false (correct sign of Ip and Bt)
- NTPCLS = 1 x 10^5, medium fidelity, no FLR/GFLR correction
- Simulation time 1.5 s
- ADAS with JBP for atomic physics
- FI output at 1.45 s (fully slowed down FI)
- Fusion products output
- Without and with Anomalous Fast Ion Diffusion:
  - $D_{\mathrm{FI}} = 5\ \mathrm{m^2/s}$
  - Flat radial profile
  - No energy dependence
  - Applied to all FI (fusion products included)
  - For $t > 0.5\ \mathrm{s}$

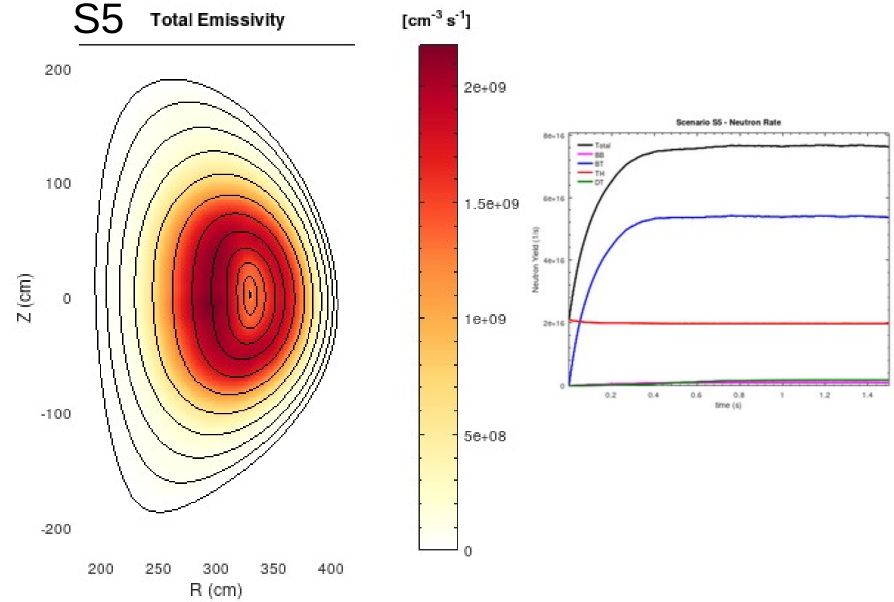


Neutron emissivity with and w/o AFID

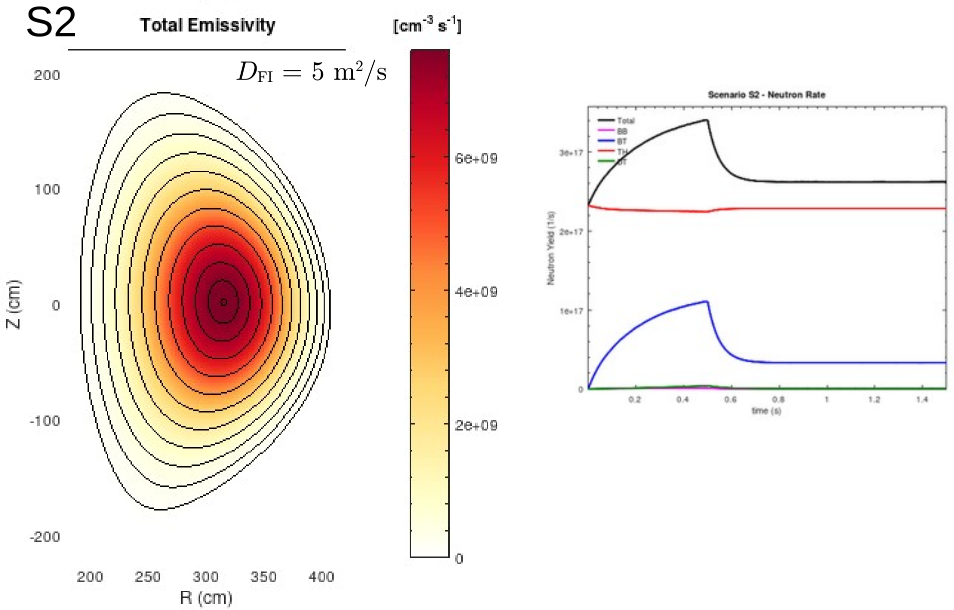
S2



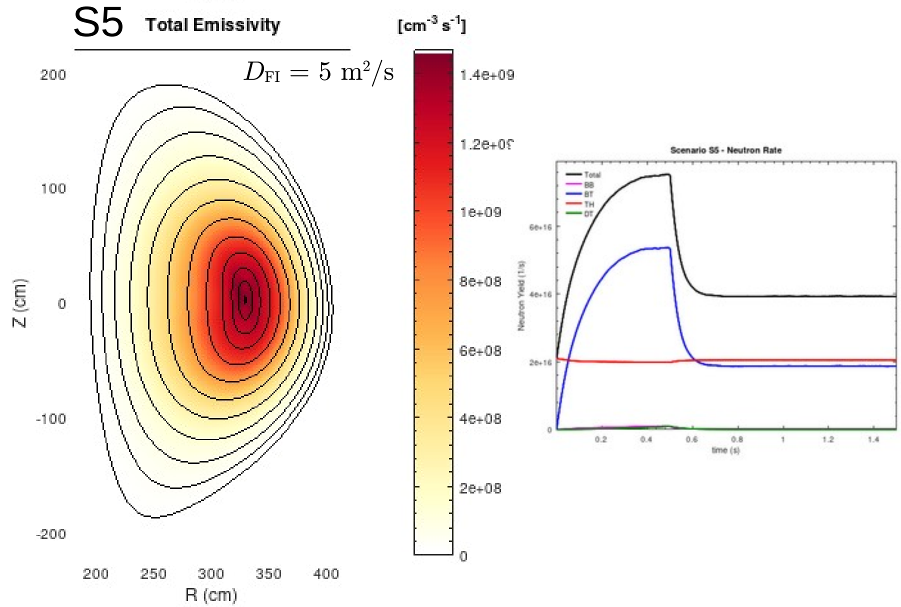
S5



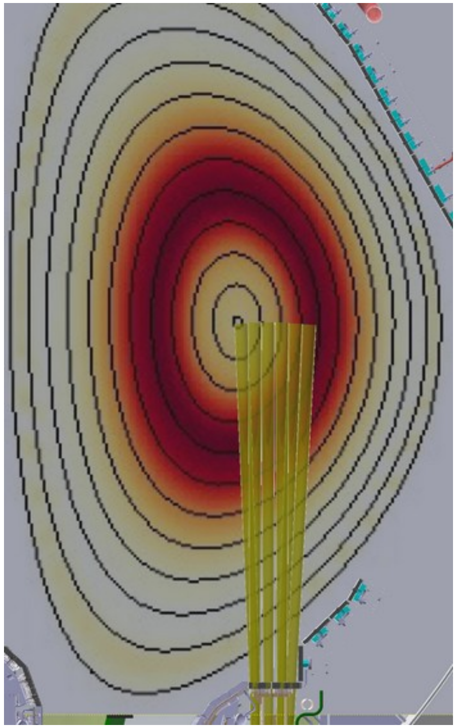
S2

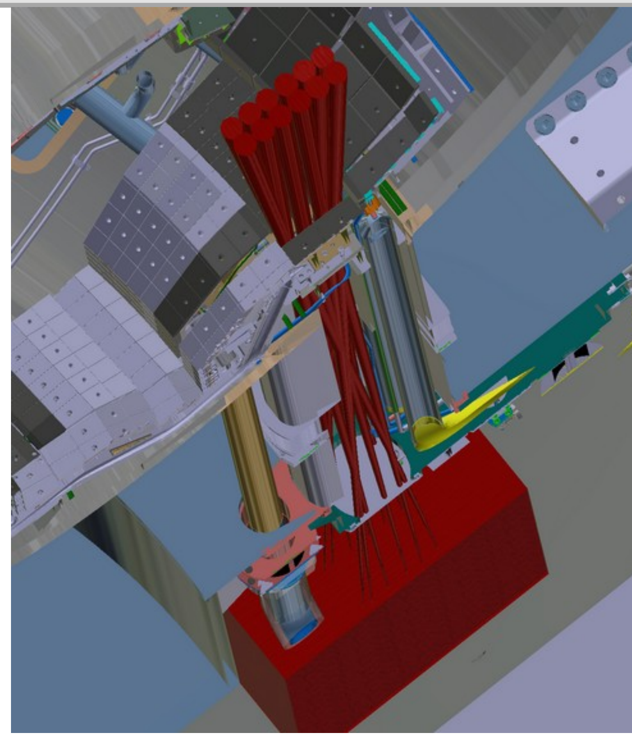


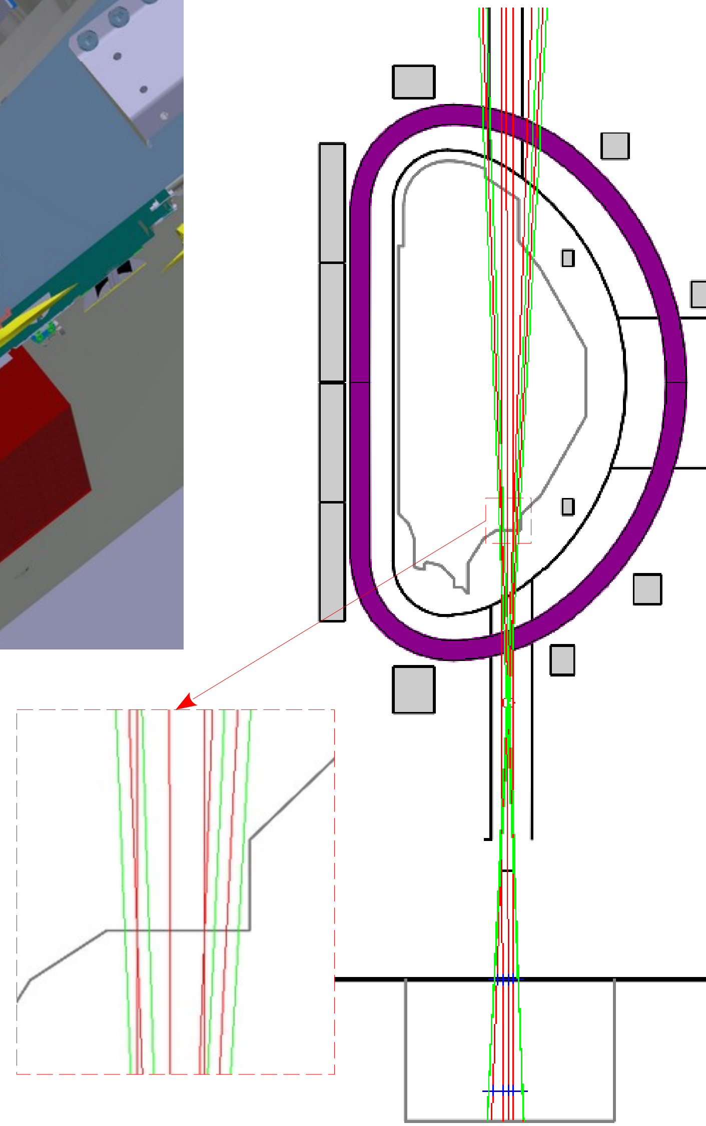
S5



VNC Lines of Sight





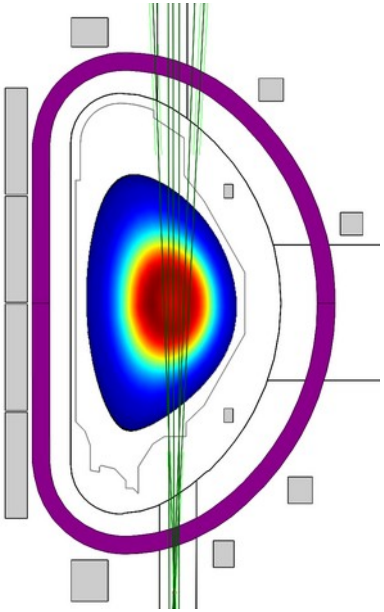


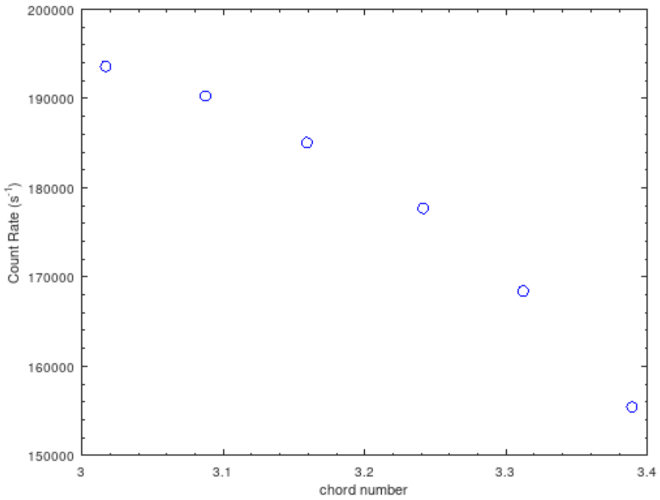
JT-60SA VNC 6 mm diameter collimators

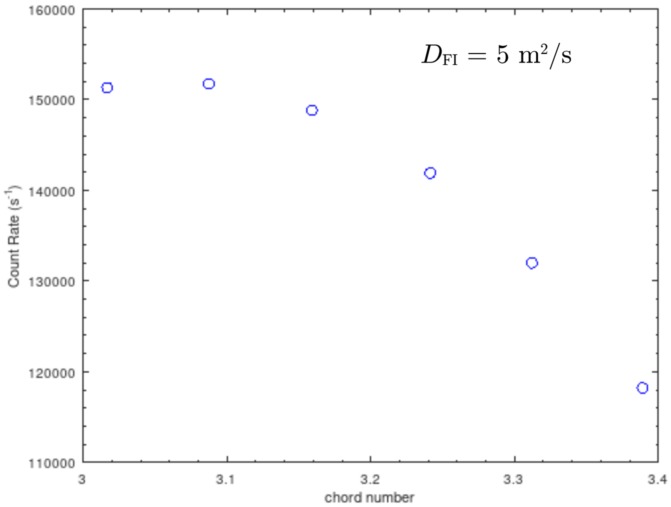
Collimator diameter: 0.006000 (m)

Ch. #	Collimator L(m)	R(m)	Z (m)	Detector R(m)	Z(m)	P P(m)
1	1.502	2.989	-8.000	2.914	-9.500	3.389
2	1.501	3.024	-8.000	2.970	-9.500	3.312
3	1.500	3.098	-8.000	3.100	-9.500	3.087
4	1.500	3.175	-8.000	3.178	-9.500	3.159
5	1.500	3.236	-8.000	3.235	-9.500	3.241
6	1.501	3.310	-8.000	3.365	-9.500	3.017

Count Rates for S2 with and w/o AFID





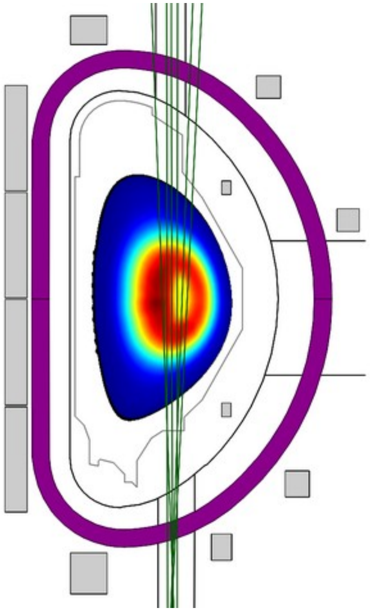


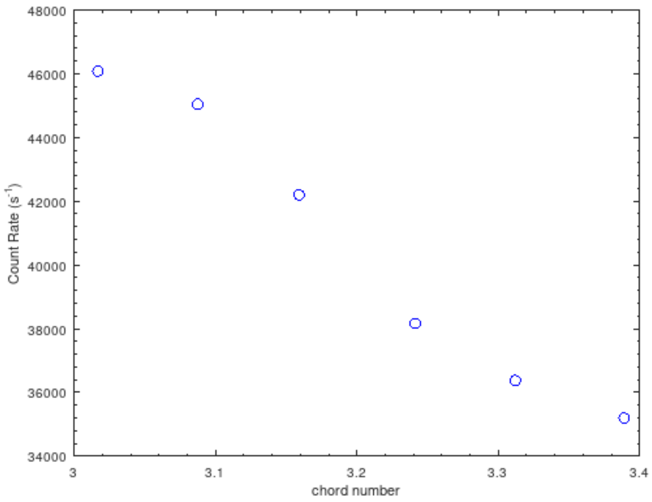
DTT VNC 6 mm diameter collimators

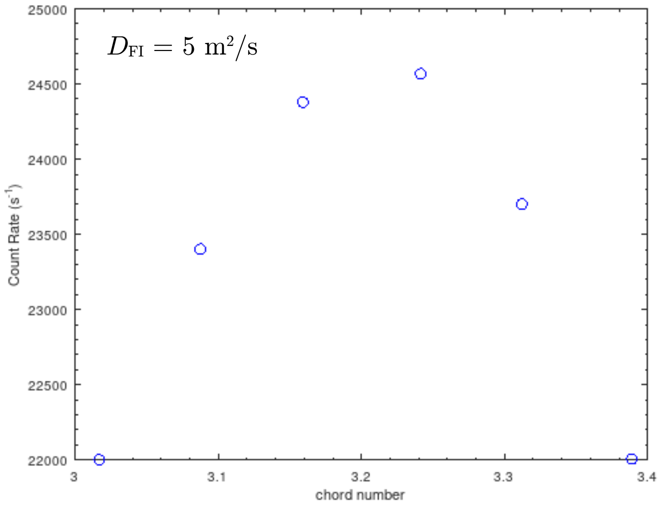
Ch. #	d(cm)	R(cm)	Et(MeV)	Eff	Eff_th	dt(s)	Flux (1/m2/s)	NR(1/s)	Load(1/s)	Det. CR(1/s)	Counts
1	6.00	0.3000	1.80	0.673	0.124	0.001	4.421E+10	1.2499E+06	8.4147E+05	1.5541E+05	1.554E+02
2	6.00	0.3000	1.80	0.673	0.124	0.001	4.790E+10	1.3545E+06	9.1189E+05	1.6841E+05	1.684E+02
3	6.00	0.3000	1.80	0.673	0.124	0.001	5.413E+10	1.5304E+06	1.0303E+06	1.9028E+05	1.903E+02
4	6.00	0.3000	1.80	0.673	0.124	0.001	5.264E+10	1.4882E+06	1.0019E+06	1.8504E+05	1.850E+02
5	6.00	0.3000	1.80	0.673	0.124	0.001	5.055E+10	1.4292E+06	9.6222E+05	1.7771E+05	1.777E+02
6	6.00	0.3000	1.80	0.673	0.124	0.001	5.508E+10	1.5572E+06	1.0484E+06	1.9362E+05	1.936E+02

$$\Delta t \approx 5\ \text{ms for}\ N = 1000\ \text{counts}\ (\Delta t \approx 10\ \text{ms with}\ D_{FI} = 5\ \text{m}^2/\text{s})$$

Count Rates for S5 with and w/o AFID





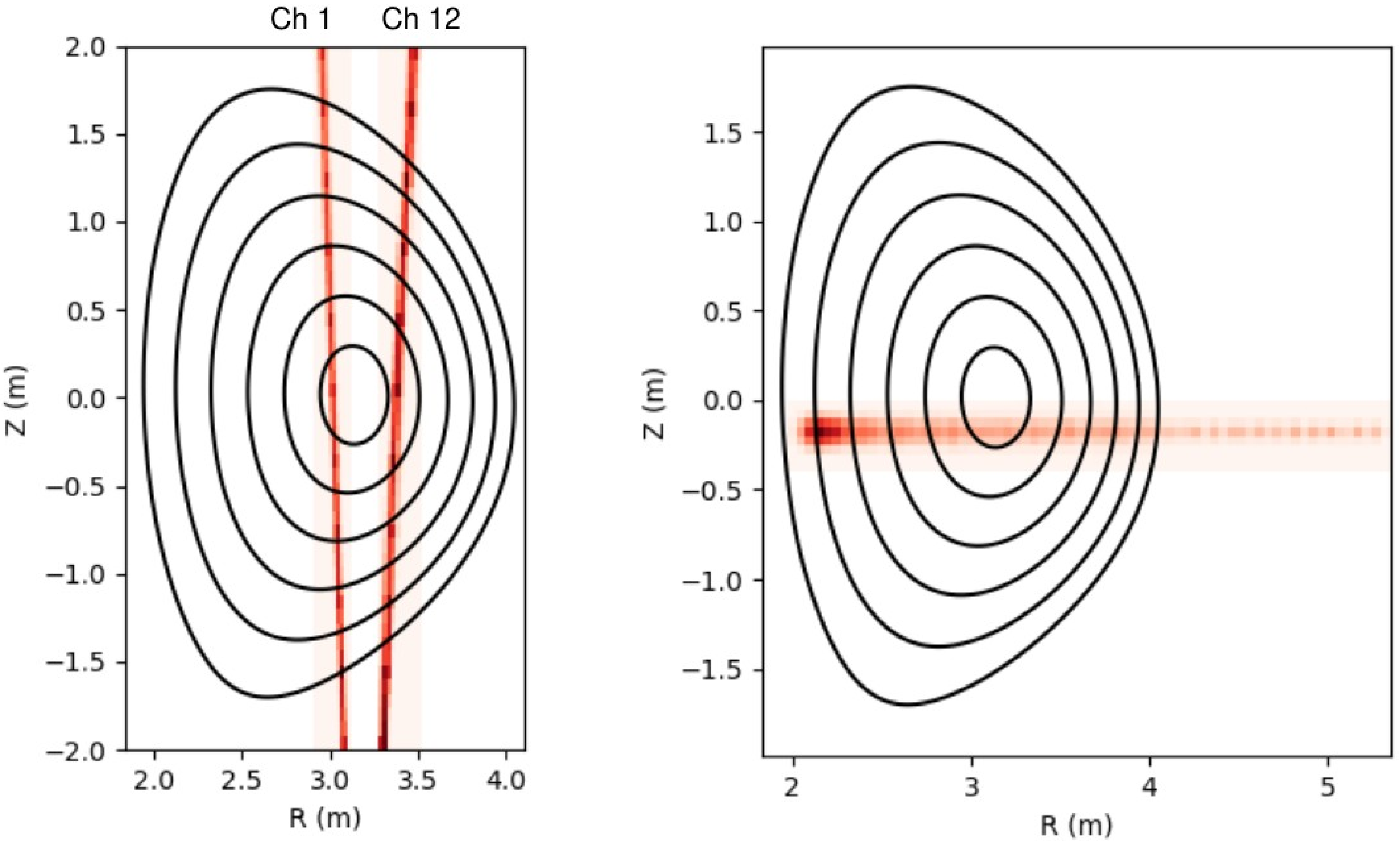


DTT VNC 6 mm diameter collimators

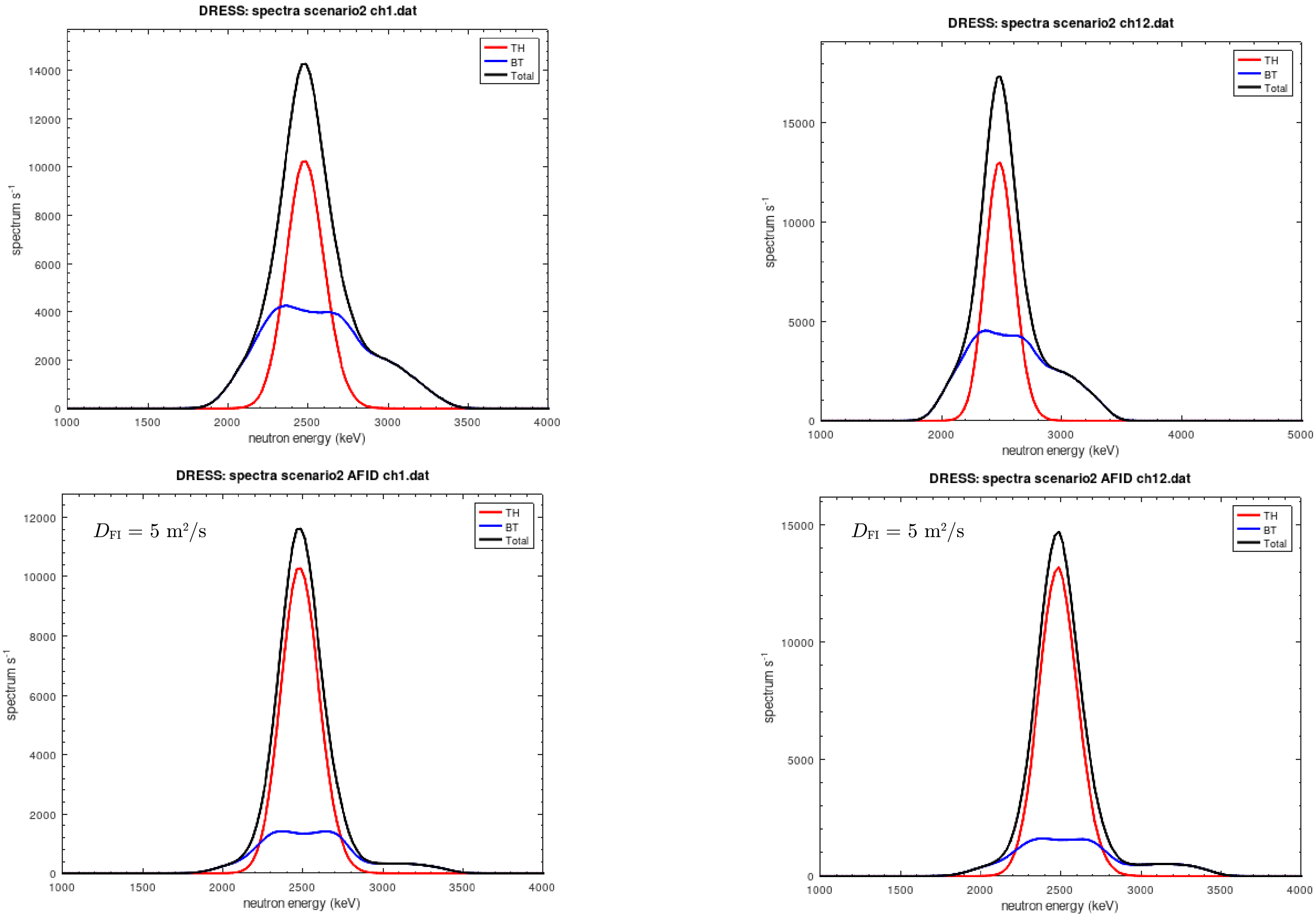
Ch. #	d(cm)	R(cm)	Et(MeV)	Eff	Eff_th	dt(s)	Flux (1/m2/s)	NR(1/s)	Load(1/s)	Det. CR(1/s)	Counts
1	6.00	0.3000	1.80	0.673	0.124	0.001	1.001E+10	2.8303E+05	1.9055E+05	3.5191E+04	3.519E+01
2	6.00	0.3000	1.80	0.673	0.124	0.001	1.035E+10	2.9253E+05	1.9694E+05	3.6372E+04	3.637E+01
3	6.00	0.3000	1.80	0.673	0.124	0.001	1.281E+10	3.6227E+05	2.4389E+05	4.5043E+04	4.504E+01
4	6.00	0.3000	1.80	0.673	0.124	0.001	1.200E+10	3.3938E+05	2.2849E+05	4.2198E+04	4.220E+01
5	6.00	0.3000	1.80	0.673	0.124	0.001	1.086E+10	3.0693E+05	2.0664E+05	3.8163E+04	3.816E+01
6	6.00	0.3000	1.80	0.673	0.124	0.001	1.311E+10	3.7063E+05	2.4952E+05	4.6083E+04	4.608E+01

$$\Delta t \approx 25 \text{ ms for } N = 1000 \text{ counts } (40 \text{ ms with } D_{FI} = 5\ m^2/s)$$

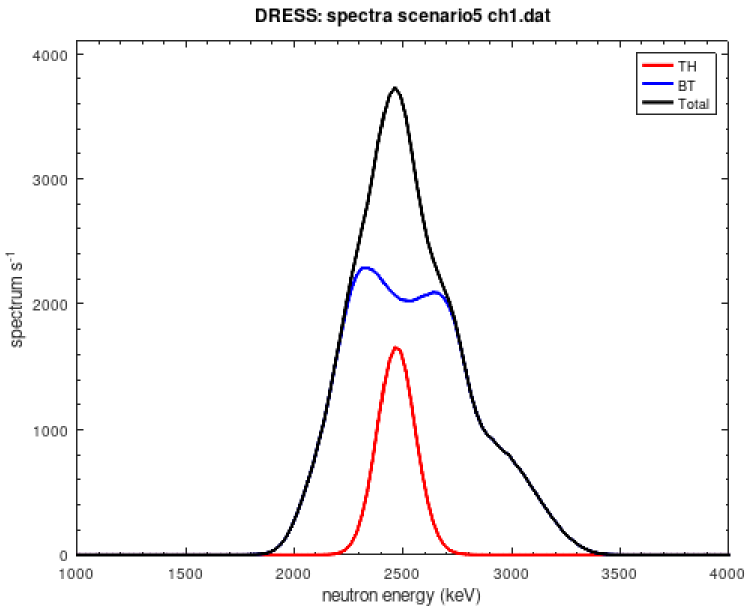
Collimated neutron spectra at the detectors

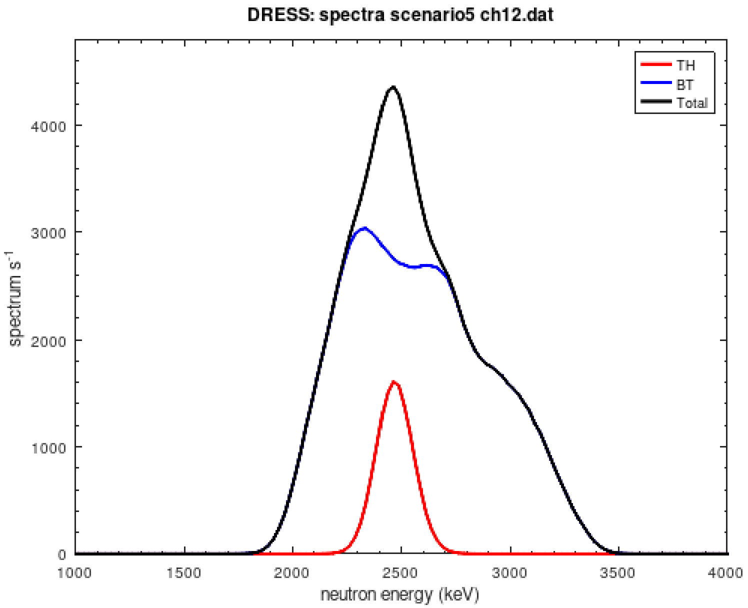


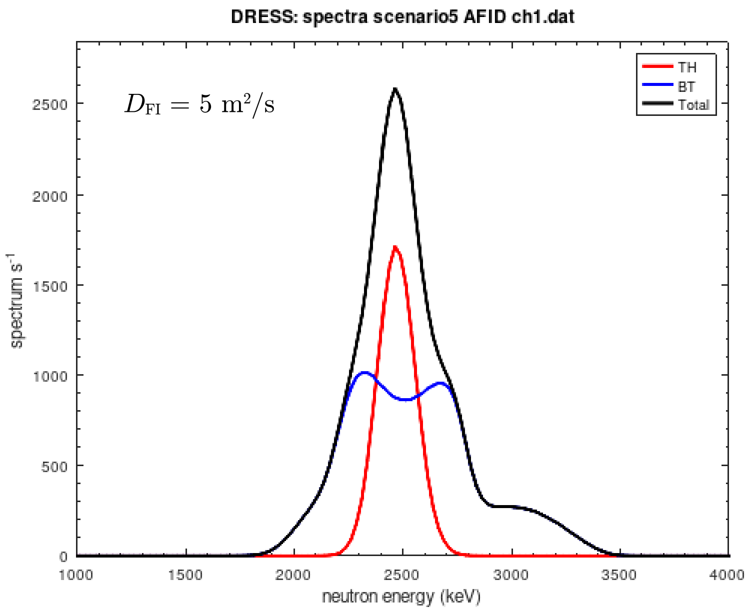
S2 - DD neutron spectra at the VNC detectors

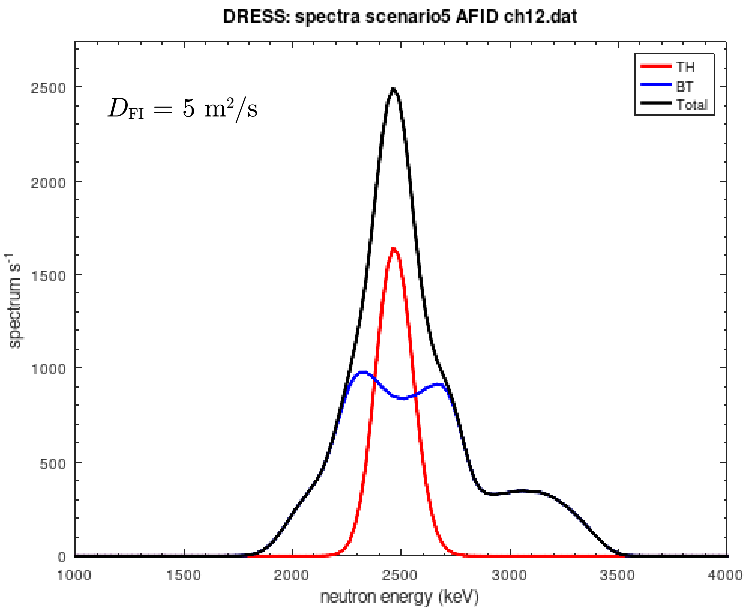


S5 - DD neutron spectra at the VNC detectors

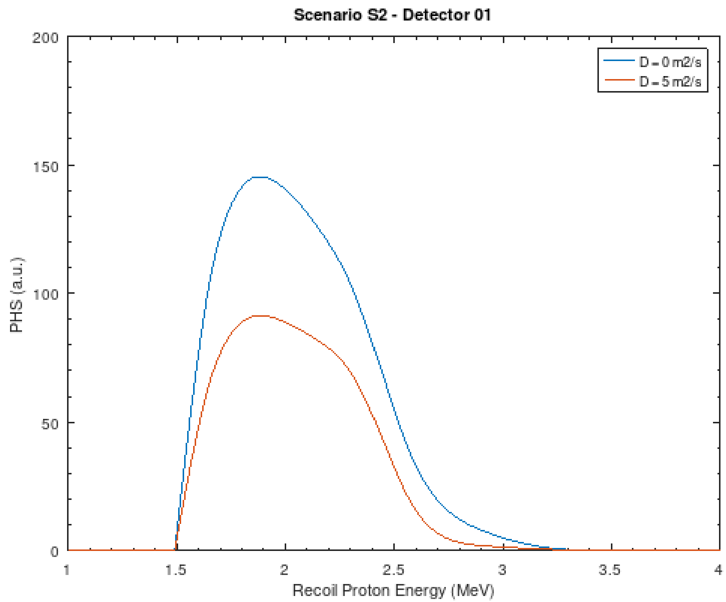


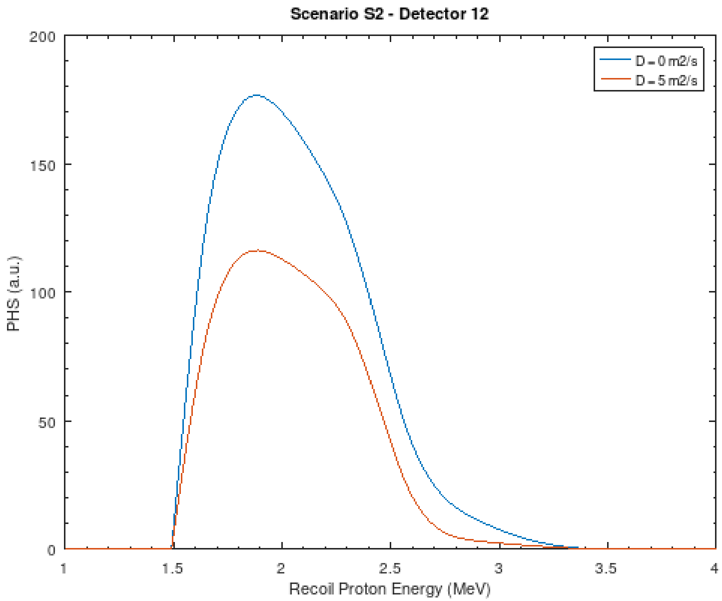


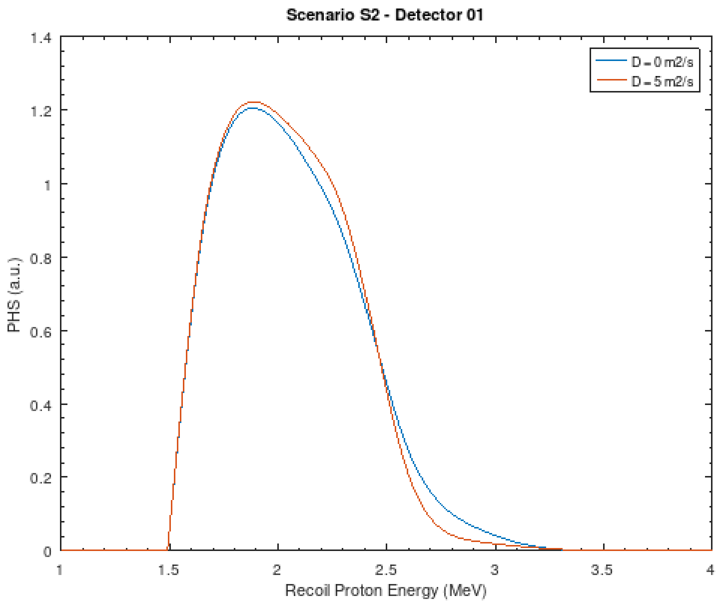


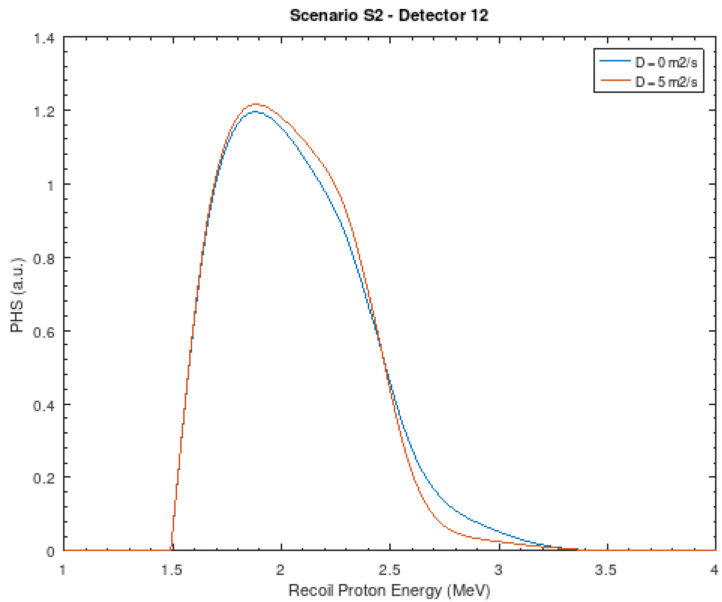


S2 – VNC EJ301 recoil proton PHS

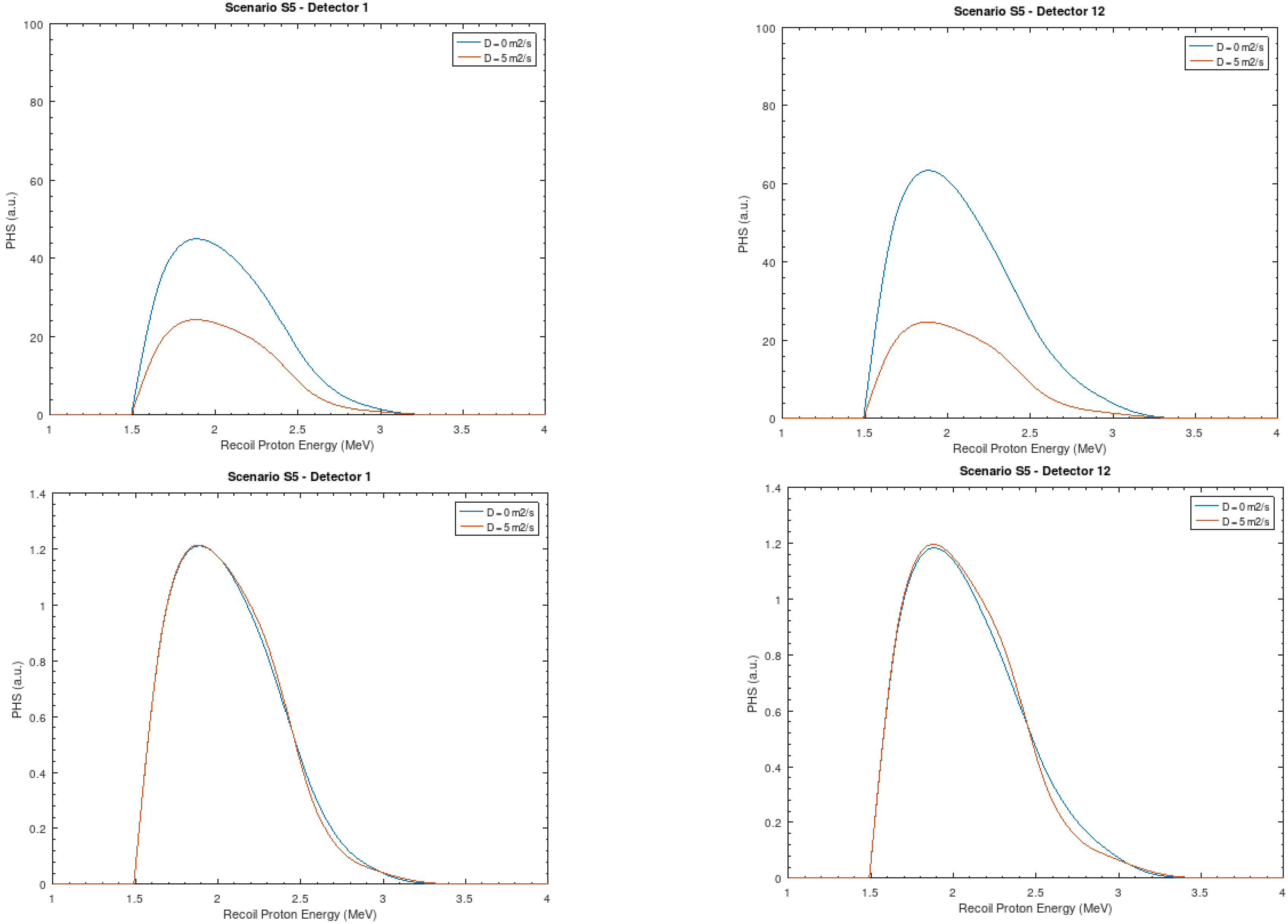




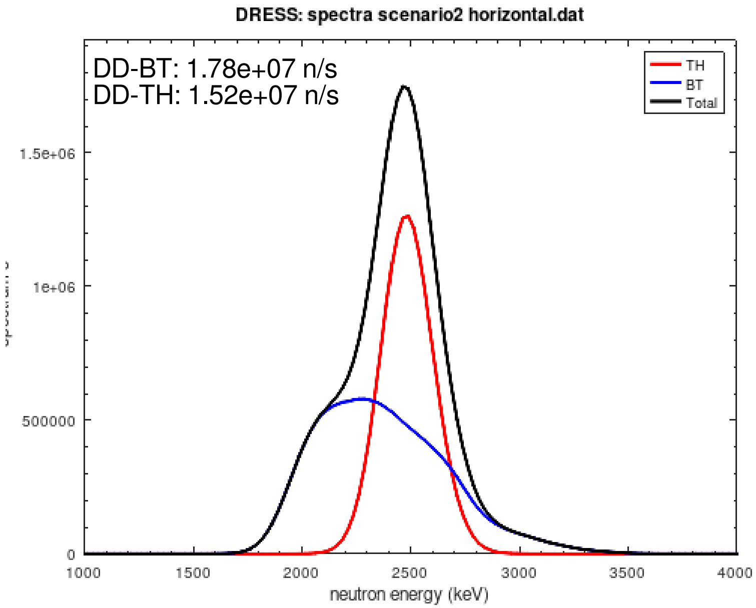


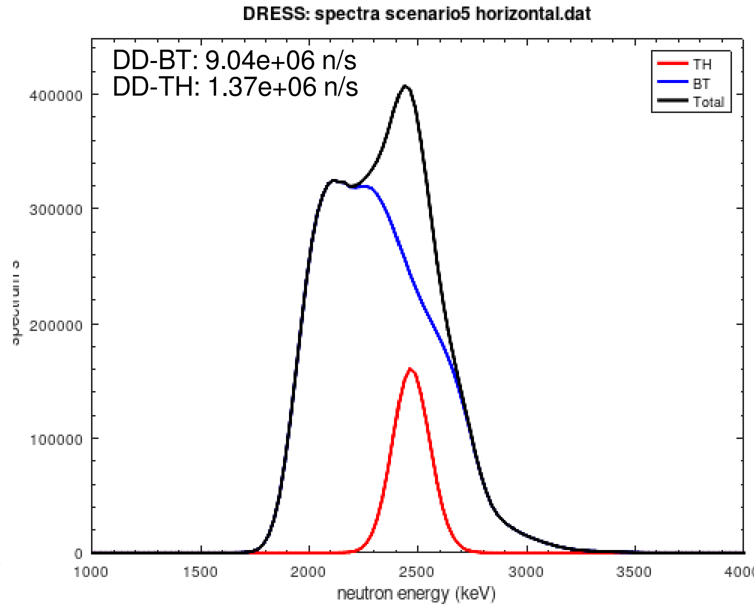


S5 – VNC EJ301 recoil proton PHS



Tangential Compact Neutron DD Spectrum

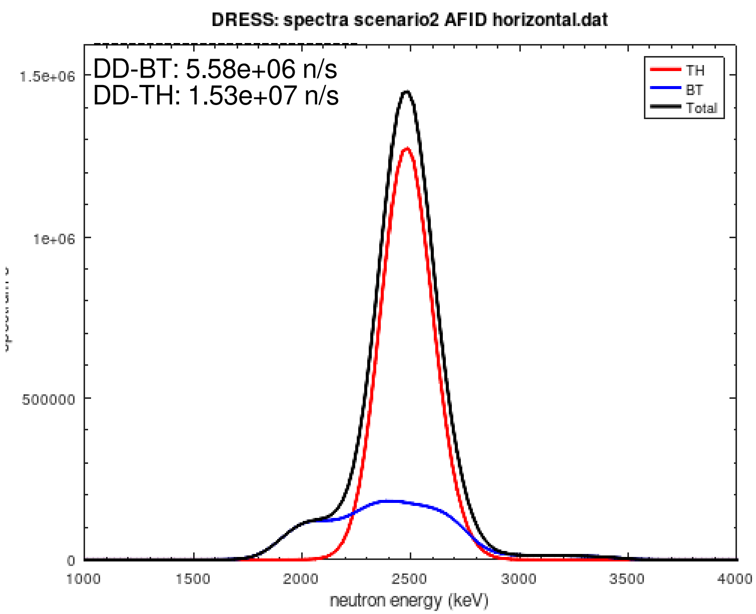


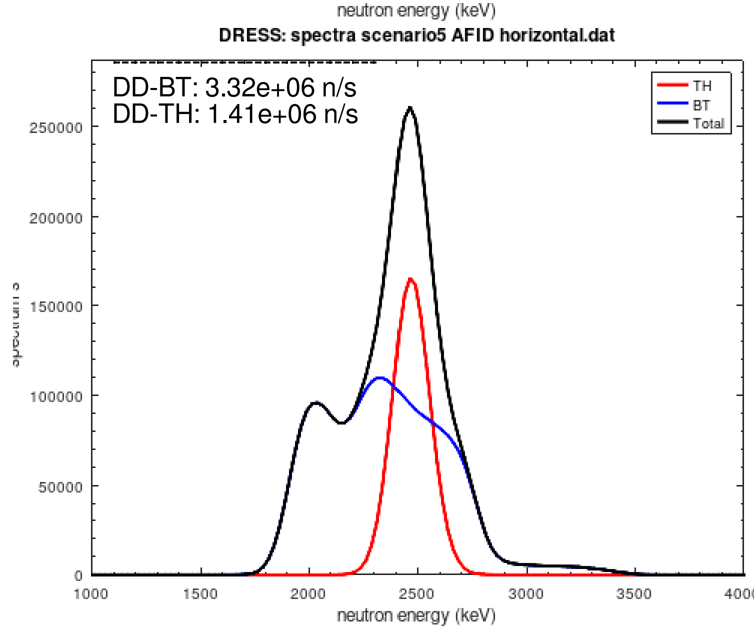


$\Delta t \approx 3$ - 10 ms

for

$N = 1000$ counts



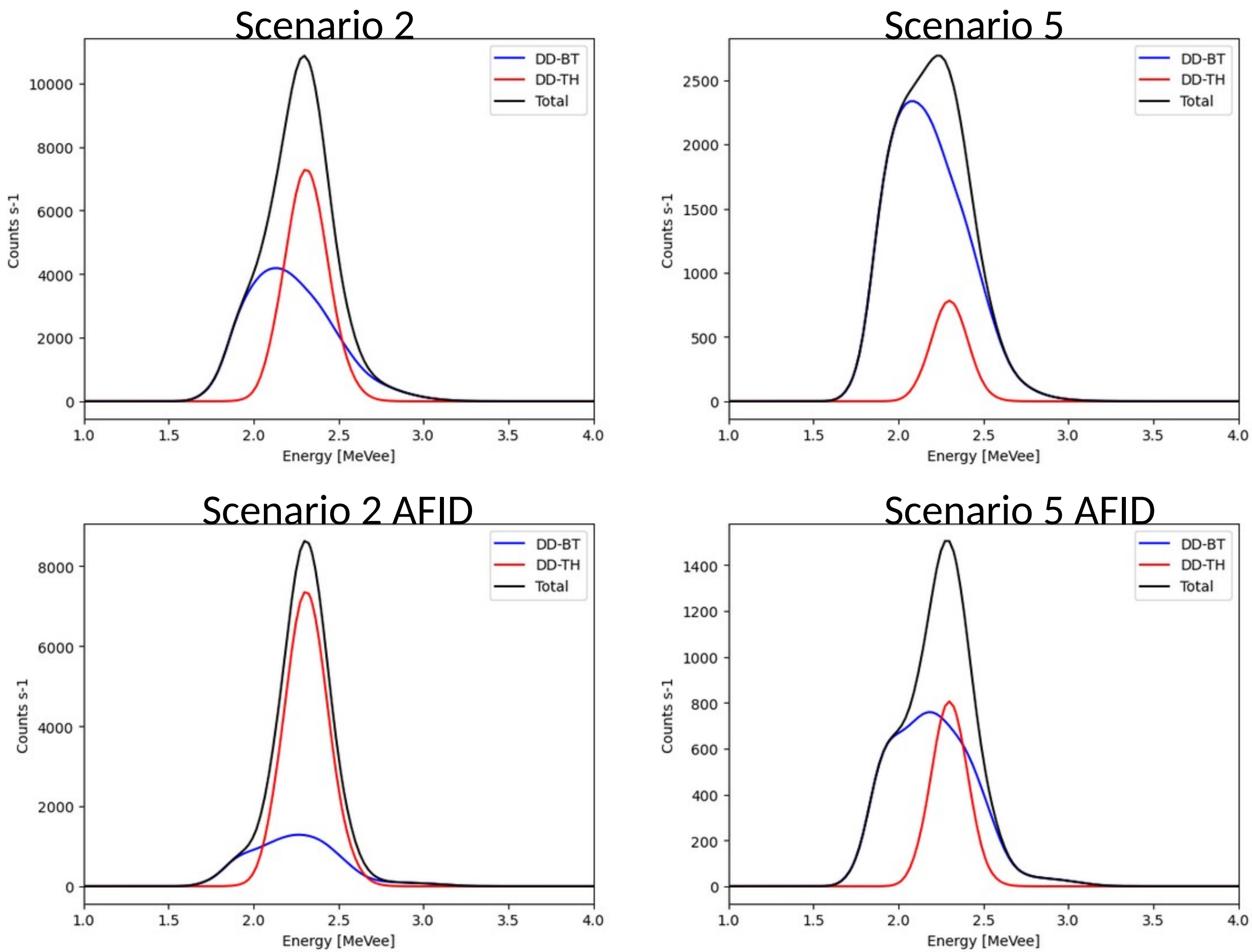


If $D_{\mathrm{FI}} = 5\ \mathrm{m}^2/\mathrm{s}$

$\Delta t \approx 5$ - 50 ms

Expected proton spectra with LaCl3 detectors

- 8% broadening due to “energy resolution”
- Birks law applied for MeVee conversion
- Diameter collimator 1.4 cm
- $LaCl_3$ 1.4cm x 1” dimension, $\varepsilon \approx$ 1.1%
- No background and no other reaction channels have been considered for these calculations.



Conclusion and Future work

- Interfacing constraints severely limits the field of view.
- Changes in the profile due to FI redistribution detectable.
- Count rate sufficiently high for both VNC (particularly with the double array of detectors) and TCNS with time resolution below 50 ms for 10^3 counts.

- More realistic redistribution of fast ions due to MHD instabilities
- Optimization of the neutron shielding for the VNC (MCNP)
- Estimation of scattered neutron spectra and fluxes at detector locations
- DT burn flux and spectrum
- Integration with Horizontal Neutron Camera (JA)
- Final design in 2026
- Aiming at OP3 (2027/28) for installation and comissioning