Ion Temperature Diagnostics for the Fusion Demonstration Plant

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Fusion Demonstration Plant Overview

General Fusion (GF) is working towards building the Fusion Demonstration Plant (FDP) in Culham, U.K.. The FDP will use a Magnetized Target Fusion (MTF) scheme [1] to compress a deuterium plasma to fusion conditions.

The FDP will integrate these core technologies:

- Spherical Tokamak plasma,
- Liquid lithium liner,
- Mechanically driven plasma compression.

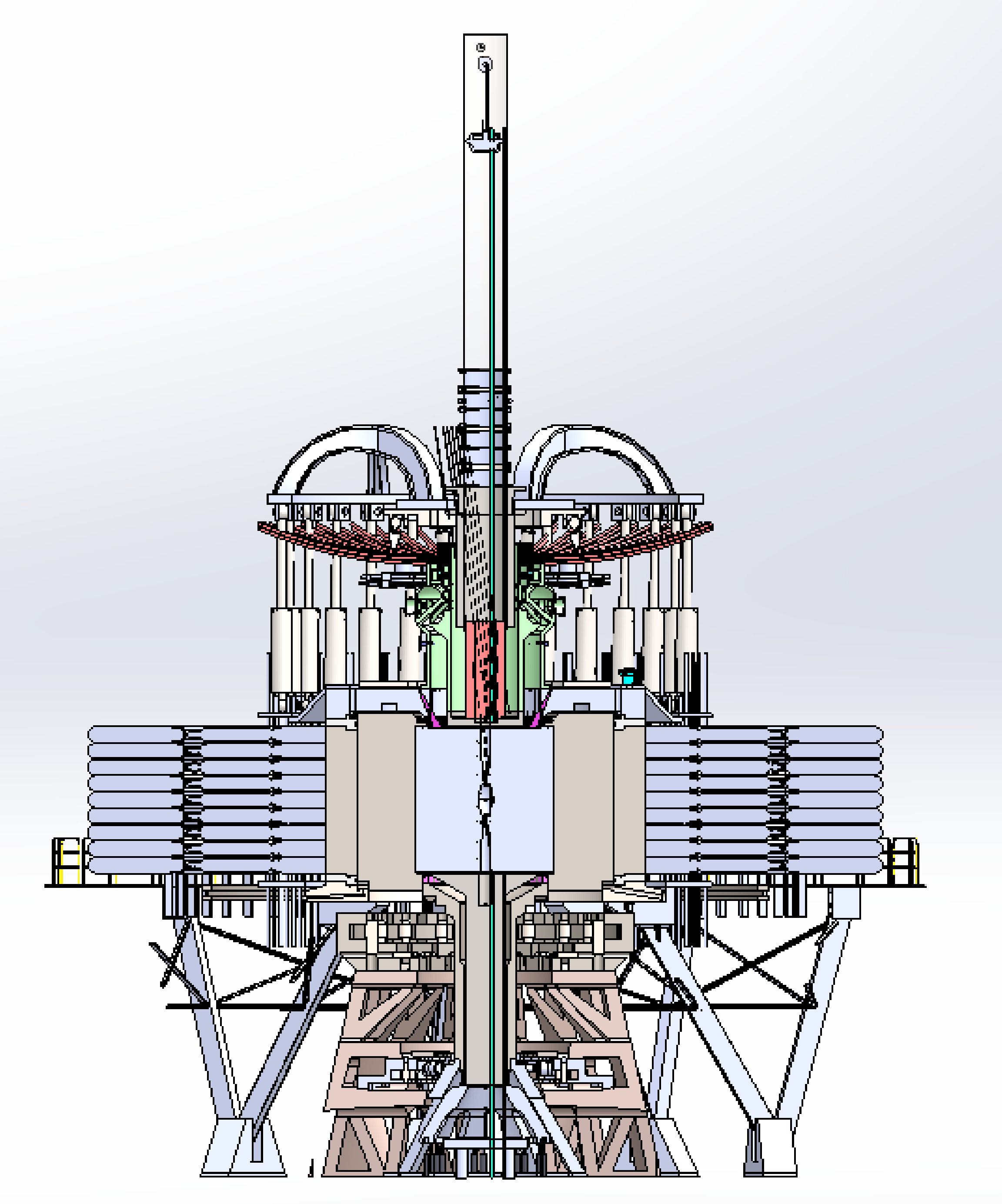
Key machine and plasma parameters:

- Plasma density 5x10^{19} m^{-3} to 3x10^{22} m^{-3},
- Core plasma temperature 200eV to 10 keV,
- Compression time of 5 ms,
- One full compression shot per day.

The FDP program faces several challenges:

- Management of ~250℃ liquid Li liner,
- Extreme pressures from the compressing Li liner, particularly on the centre shaft,
- Limited diagnostic access due to the Li liner.

The ion temperature, T_i , is a key measurement to evaluate the success of a compression.



		PI3	PI4	FDP formation (4.3ms)	FDP full compression (9.43ms)
Plasma major radius, R_0	m	0.57	0.5	0.78	0.11
Plasma minor radius, a	m	0.42	0.35	0.58	0.072
Aspect ratio		1.4	1.5	1.3	1.5
Plasma elongation		1.8	3.2	2.9	3
Plasma volume	m^3	3	4.1	17	0.03
Plasma cross-section area	m^2	0.8	1.3	3.5	0.05
Plasma poloidal flux	Wb	0.15	0.3	0.7	0.5
Max Toroidal Field at R_0	T	0.4	0.7	0.3	8
Max plasma current	MA	0.6	1.5	2.6	4
Normalized beta, β_N (%)		1.7	1.8	0.28	1
Core density	m^{-3}	5x10^{19}	5x10^{19}	5x10^{19}	3x10^{22}
Core temperature	keV	0.2	0.2	0.2	10
Main ion component		Deuterium			
First wall material		Li coated solid Al		Liquid Li	

Plasma parameters for several GF machines. PI3 and PI4 are GF's non-compression spherical tokamak machines used to de-risk the FDP. PI3 is currently operating and PI4 is scheduled to begin operation in early 2023. FDP columns refer to case 24c3-004.

Neutron Emission Spectroscopy

- A time-of-flight (TOF) neutron spectrometer [2] consists of a neutron collimator and two groups of scintillators, S1 and S2. An incoming D-D neutron scatters off S1 with a chance to redirect to S2. The time between a matching S1 and S2 event is related to neutron energy. T_i is calculated from the spread of neutron energies.
- Neutrons should be quasi-monoenergetic since the FDP has no neutral beam or radio-frequency heating, so it is expected a minimum of 300 neutrons is needed to resolve the neutron energy Gaussian distribution.
- The desired time resolution is 100 µs, so the minimum neutron count rate is 3x10^6 counts/s. If the neutron count rate is too high, noise from background neutrons will be excessively high. A shutter is being considered to reduce the neutron count rate late in compression.
- MCNP code was used to calculate the probability of a neutron reaching the neutron spectrometer. The min. required yield was estimated to be ~5x10^{15} neutrons/s.
- A forward model was used to calculate neutron yield for different compression states, current profiles, and for flat and peaked n_i and T_i profiles. The neutron spectrometer is expected to be most effective for $T_i > 5\ \mathrm{keV}$ in the final 300 µs of compression.

$$^2_1\mathrm{D} + {}^2_1\mathrm{D} \rightarrow {}^3_2\mathrm{He}\ (0.82\ \mathrm{MeV}) + \mathrm{n}^0\ (2.45\ \mathrm{MeV})$$

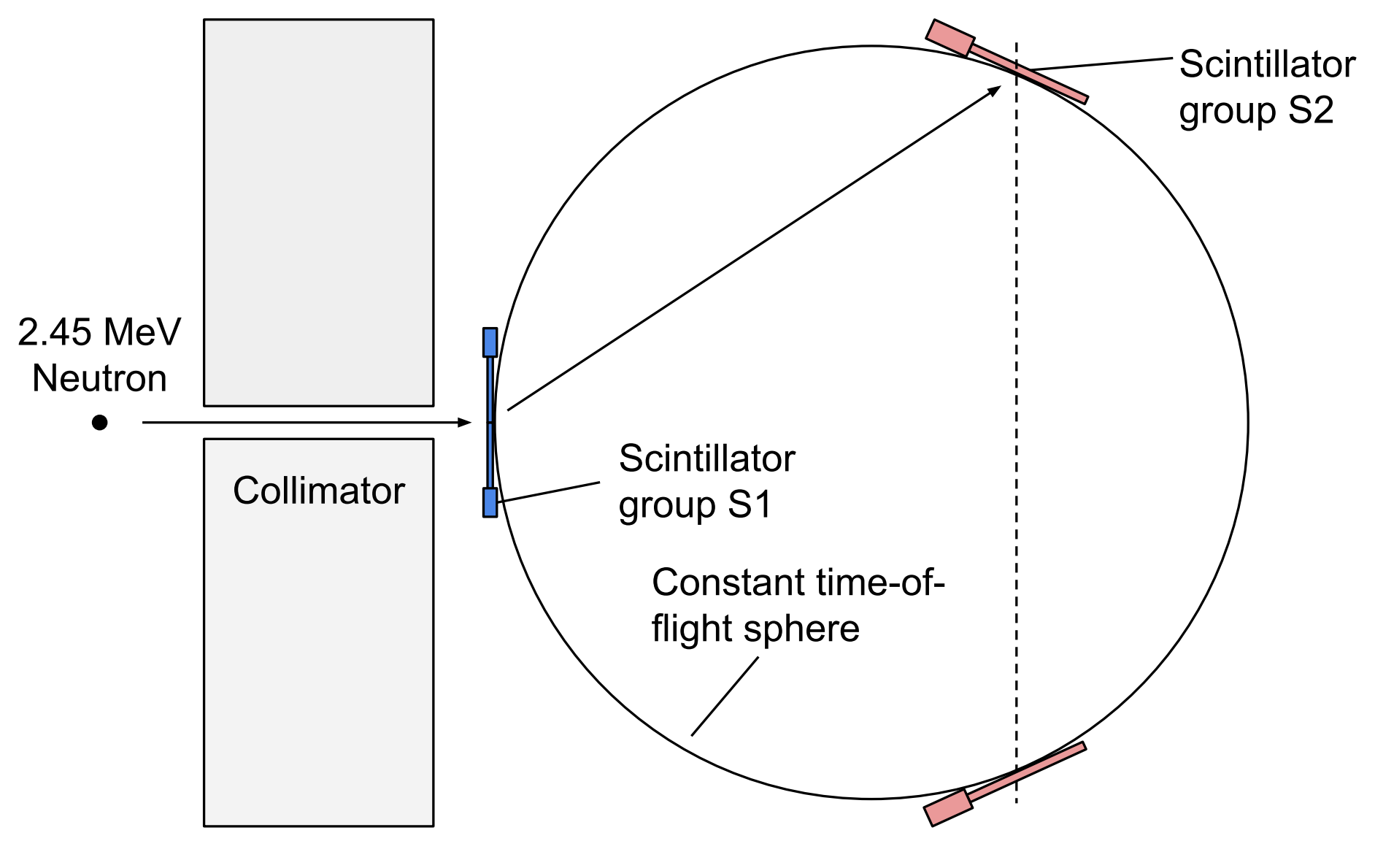
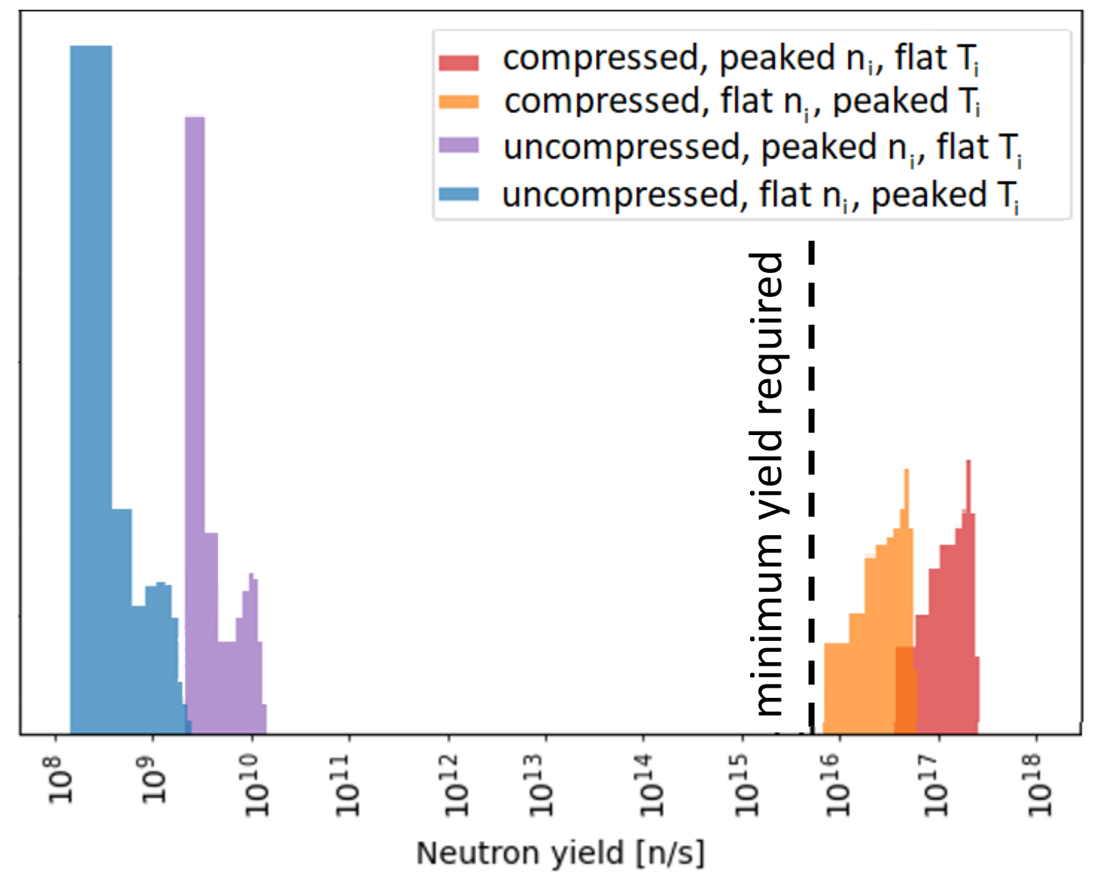


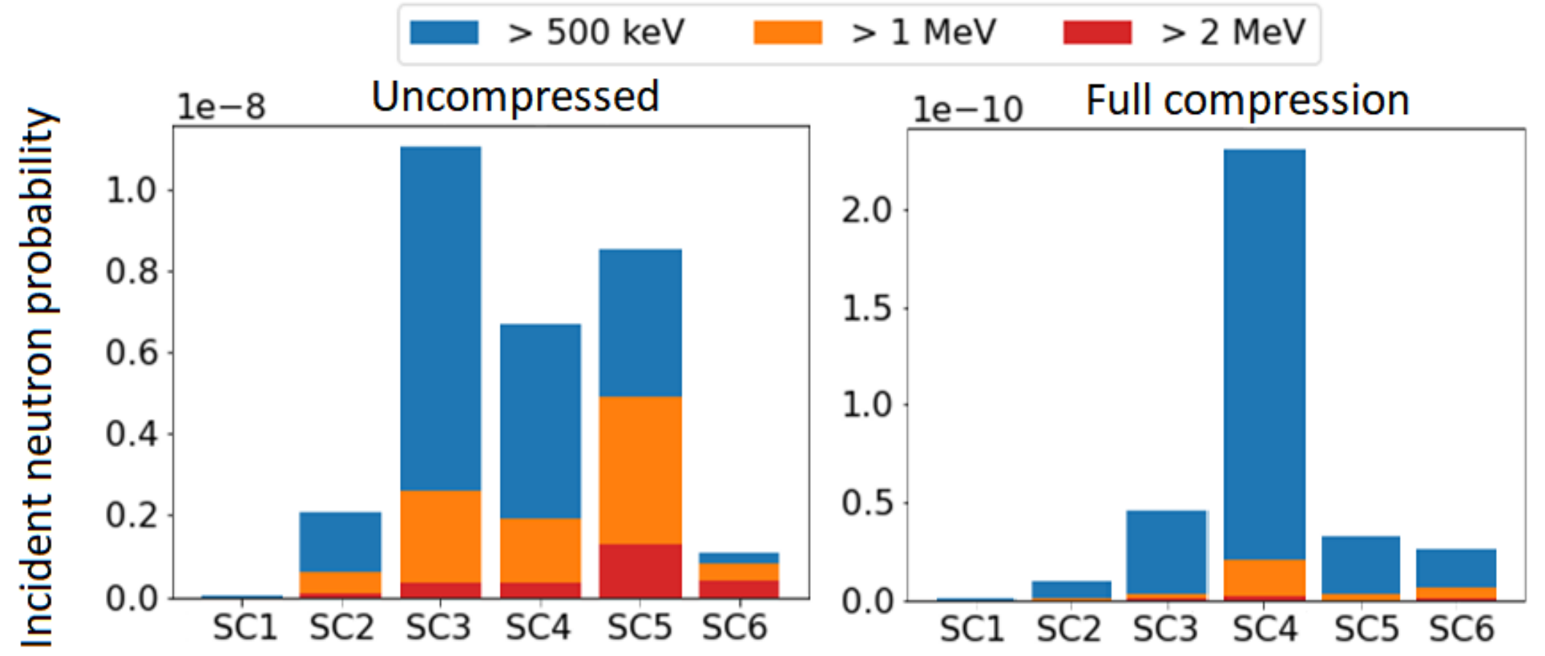
Diagram of a neutron time-of-flight spectrometer [2].



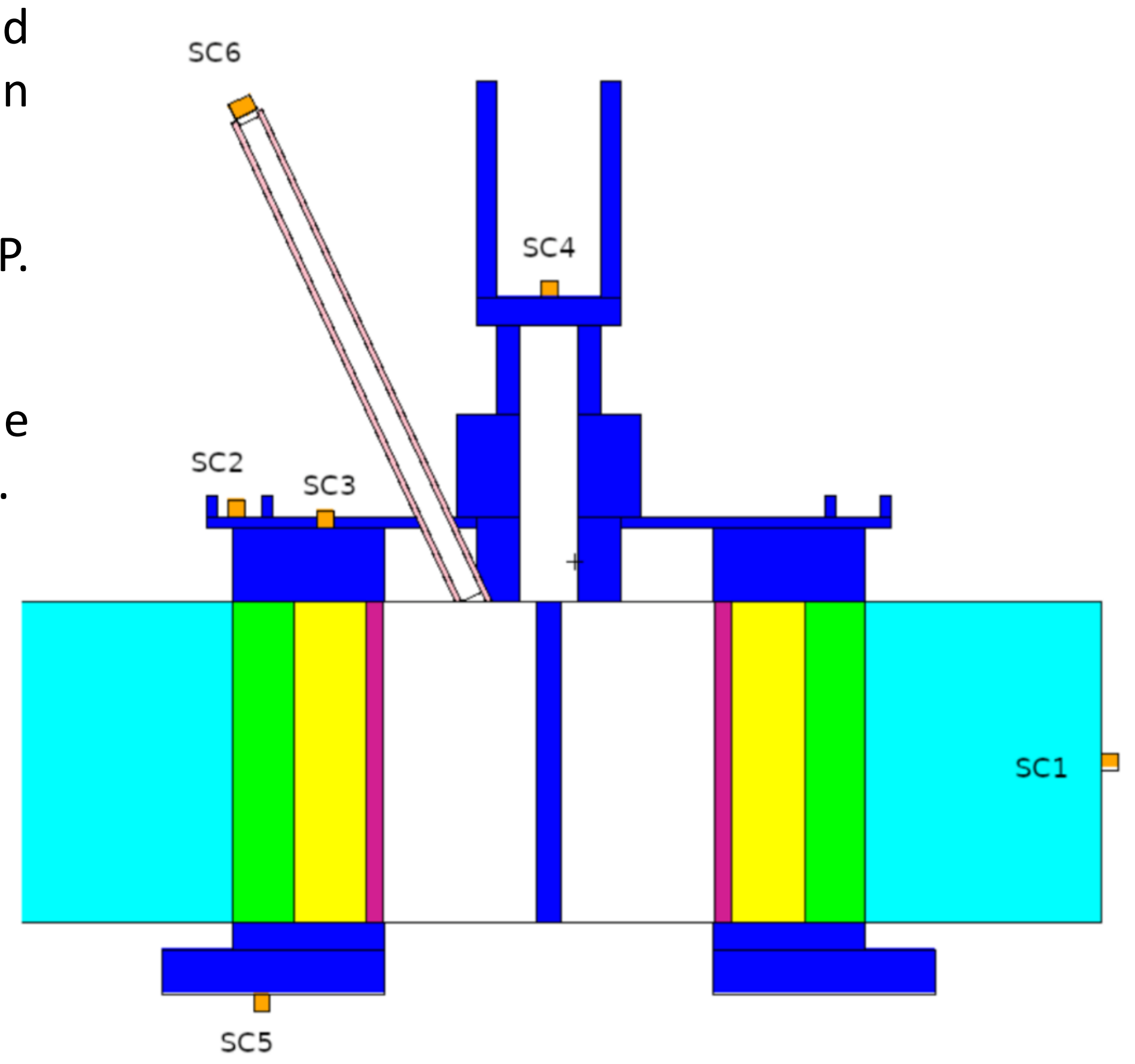
Each neutron yield histogram is composed of many current profiles. Expect to have sufficient yield late in compression.

Neutron Yield Diagnostics

- Neutron yield diagnostics: liquid scintillators with lead shielding and pulse shape discrimination, micro fission chambers and activation counters.
- Neutron flux was estimated at several locations with MCNP. A high neutron flux is expected at SC4 at full compression.
- Estimating T_i from neutron flux is very sensitive to the current profile. Accurate magnetic reconstruction is needed.



MCNP probability for a neutron to reach a given detector. Coloured by energy of the neutron at the detector. Shielding was not considered for the neutron spectrometer.



MCNP simplified FDP geometry. Neutron spectrometer location is SC6.

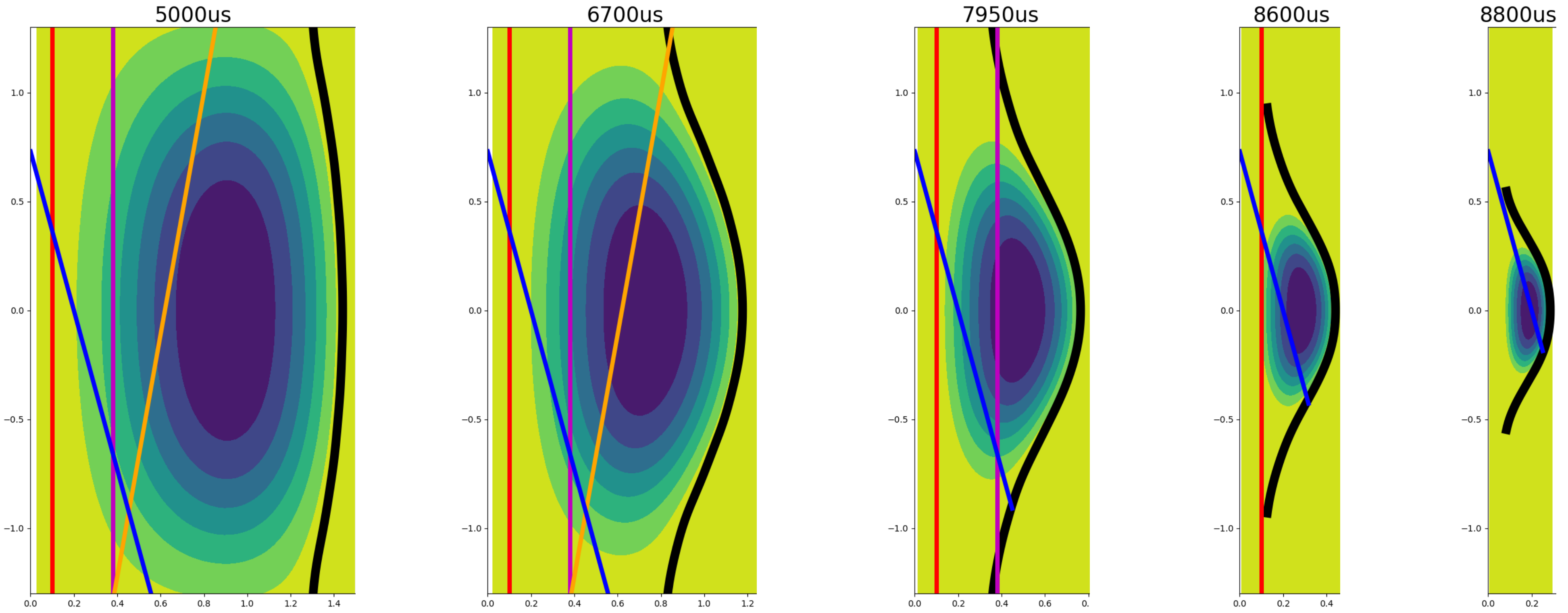
Ion Doppler Spectroscopy

- Ion Doppler Spectroscopy (IDS) [3] measures T_i from the wavelength spread of Doppler broadened impurity line radiation. The plasma fluid velocity can also be measured from the wavelength shift of the impurity line.
- Impurity lines will burn out as T_i increases during compression, so the FDP will be equipped with multiple IDS systems measuring ultraviolet and x-ray line radiation.

T_i range (keV)	Impurity	Dispersion optic	Detector	# of chords	Time resolution (µs)
0.2 – 1	C	Grating	Photomultiplier	12	1
1 – 5	Ar	Crystal	X-ray CCD	4	100

Ion Doppler spectrometer systems for the FDP.

- Access to view chords will be a challenge. The light for the lower energy lines can be fiber coupled and the light-analysis equipment placed away from the machine. High energy lines requires a vacuum path from the plasma to the detector so the equipment must be located on the machine and the field of view will be limited.



Several proposed ion Doppler spectroscopy chords shown for early to late compression times for FDP case 22a.

Other Ion Temperature Diagnostics

- Several other diagnostics are being considered to measure T_i but it is not yet clear if they will be feasible. As with many of the diagnostics on the FDP, access to ports will be a major challenge.
- Collective Thomson scattering (CTS) is the scattering of electromagnetic waves off fluctuations in the plasma when the laser wavelength is comparable to the Debye length. The spectral shape of the scattered light is a function of T_i among other parameters.
- A neutral particle analyzer can measure T_i from the energy spread of neutrals leaving the plasma.
- A neutral beam can be used for charge-exchange spectroscopy to give impurity T_i. However, the plasma density might be too high for the beam to penetrate to the core.

References

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3. R. J. Hu et al., "Upgrade of X-ray crystal spectrometer for high temperature measurement using neon-like xenon lines on EAST," Review of Scientific Instruments, 89, 10F110 (2018).