Assessment of Neutron Production during Pre-Fusion Operation of ITER

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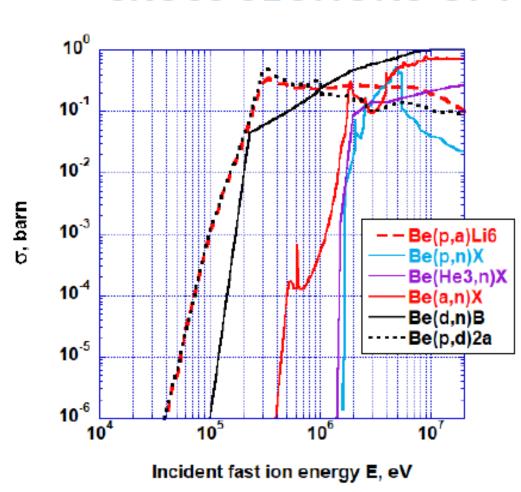
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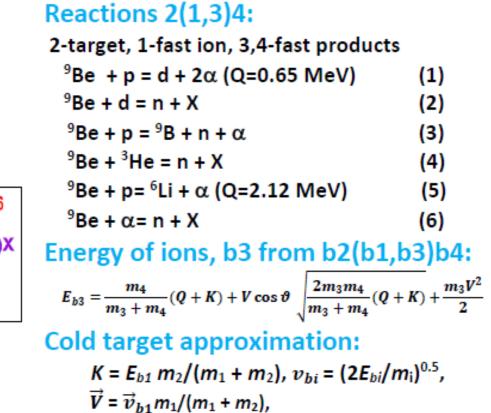
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ABSTRACT

- Importance of fusion reactions due to interaction of Be impurities with fast ions for non DT plasmas has been demonstrated earlier in JET experiments and for some ITER-like plasmas [Kiptily 2012], [Gatu Johnson 2010], [Krasilnikov 2018].
- Here we extended the consideration for a wide range of plasma scenarios foreseen in the ITER Research Plan for the Pre-Fusion Power Operation (PFPO) phase [IRP], for heating scenarios foreseen in the IRP, for a range of Be concentrations, $c_{Be} = n_{Be}/n_e < 10\%$.
- Interaction of Be impurity with fast ions produced by variety of heating schemes: H0-NBI, ECRH, ICRH ^{3}He and H minority heating, and with the 3 ion ICRH heating scheme [Kazakov 2021], is considered.
- We extend the analyses taking account of secondary reactions of Be with fast deutrons and alpha ions, produced in primary reaction of Be with fast protons produced and accelerated by auxiliary heating [Polevoi 2021].
- We assess the impact of synergetic effect between protons produced by NBI and the ICRH in the hydrogen minority heating scheme and transients such as saw-tooth oscillations and TAEs [Bilato 2018].
- We estimate the possible sources that can lead to in-vessel component activation in this phase produced during plasma disruptions should runaway electrons (RE) be formed including bremsstrahlung emission and secondary neutrons.

CROSS SECTIONS OF FUSION REACTIONS

Cross-sections for interaction of fast ions with cold ^{9}Be impurities as a function of the fast particle incident energy in the laboratory frame [Trkov 2019].

Reactions 2(1,3)4:
2-target, 1-fast ion, 3,4-fast products
^{9}Be + p = d + 2α (Q=0.65 MeV) (1)
^{9}Be + d = n + X (2)
^{9}Be + p = ^{9}B + n + α (3)
^{9}Be + ^{3}He = n + X (4)
^{9}Be + p= ^{6}Li + α (Q=2.12 MeV) (5)
^{9}Be + α = n + X (6)

Energy of ions, b3 from b2(b1,b3)b4:
$$E_{b3} = \frac{m_4}{m_3 + m_4}(Q + K) + V\cos\vartheta\sqrt{\frac{2m_3m_4}{m_3+m_4}(Q+K)} + \frac{m_3 V^2}{2}$$

Cold target approximation:
$K = E_{b1} m_2/(m_1 + m_2)$, $v_{b1} = (2E_{b1}/m_1)^{0.5}$,
$\bar{V} = \bar{v}_{b1} m_1/(m_1 + m_2)$,
$\cos\vartheta = (\bar{V}\,\bar{v}_{b3})/V v_{b3}$

Source of fusion products:
$S_{b3,b2b1} = c_{b2}\int n_d \int_{b1}\sigma_{b2b1b3}(E_{b1})\, v_{b1}\, d^3 v_{b1}$

Fusion rate
$<S> = \int S\, dV$

1.5D TRANSPORT SIMULATIONS

Transport model:
- 1.5D transport simulations for n_e, n_D, n_T, T_i, T_e, j by ASTRA [Pereverzev 2002];
- SOLPS boundary conditions and EPED1+SOLPS pedestal [Polevoi 2017];
- ^{9}Be impurity and ICRH minorities are prescribed: c_{Be}, c_{He3}, c_H(in He); c_{He}(in H);
- Main ion densities, n_D or n_{He} are calculated from quasineutrality;
- Heat diffusivities, $\chi_i = \chi_e$, are fitted at the ETP to provide $p_{e,ped}$ by EPED1+SOLPS, and in the core to provide: $\tau_E = \tau_{E,Hy2.98}$ (H-mode) $\tau_{E,L97}$ (L-mode) [IPB];
- Particle transport for n_e, n_D, n_T:
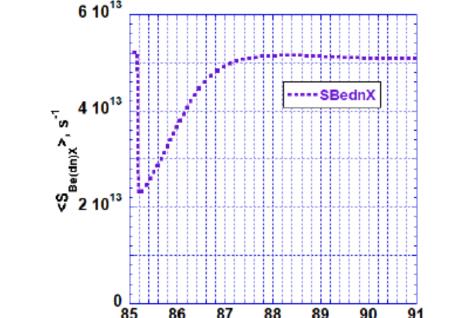 $D_e = (\chi_i + \chi_e)/10$, $V=C_V$ D X/a, $C_v = 0 - 0.3$,
  $D_D = D_T$ are fitted to provide $\tau_{D,T} = 10\ \tau_E$
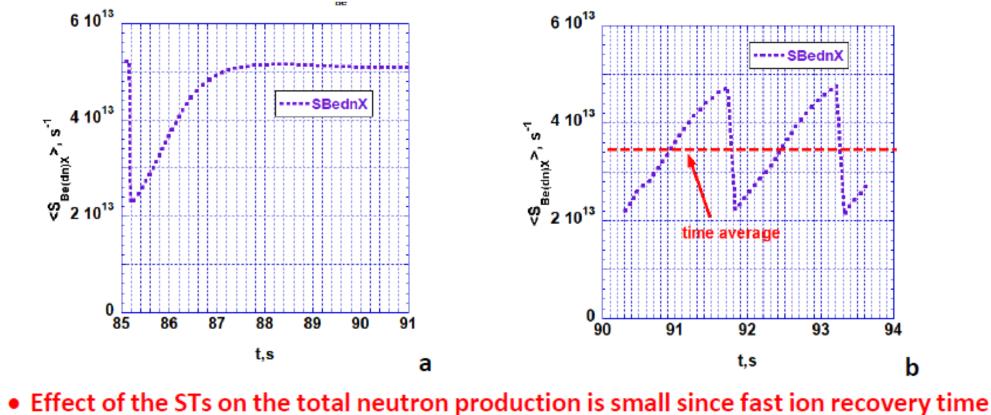- Fuelling is fitted to provide $n \sim 0.5\ n_{GW}$.

H&CD:
- $P_{EC} = 20$ MW (baseline); $P_{EC} = 30$ MW (upgrade) [Zvonkov 1997]
- Fast ions from Fokker-Planck equation: $\frac{\partial f_{bi}}{\partial t} = L_{coll}[f_{bi}] + L_{Qi}[f_{bi}] + S_b(E_{bi,0})$
- Hydrogen NBI, $P_{NBI} = 33$ MW, E_b =870 keV [Polevoi 1997,2020], [Bilato 2011]
- ICRH P_{ICH} =20 MW, f_{IC} = 40-55 MHz, [Bilato 2011]
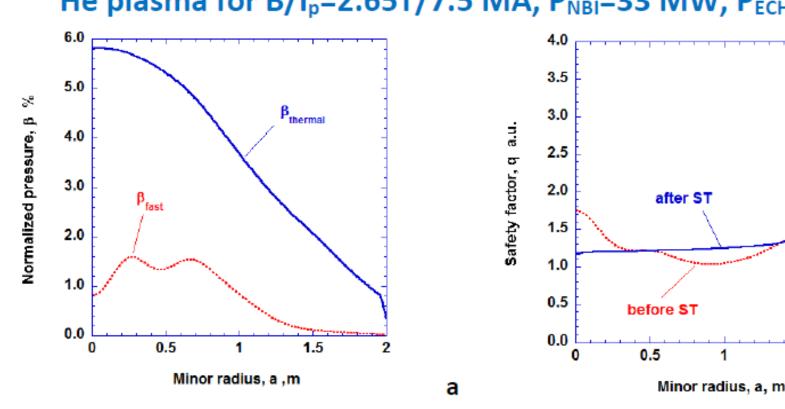
MODELING OF SAW-TEETH AND TAEs

- Saw-tooth and TAE impact is modelled by mixing of plasma parameters (ST) and fast ion redistribution within the area $X_{ST} = 1.4\ X(q=1)$.

- Effect of the STs on the total neutron production is small since fast ion recovery time $\tau_S \sim 1$ s is much smaller than the resistive time, $\tau_{ST} \sim 10$ s. Reduction of the neutron source due to TAEs can exceed 30%. Effect can be higher for ICRH.
- TAE stability is analysed by NOVA-K [Fu 1993], [Gorelenkov 1999].
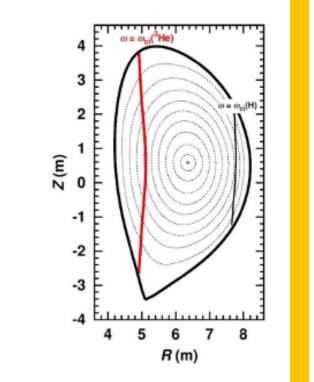
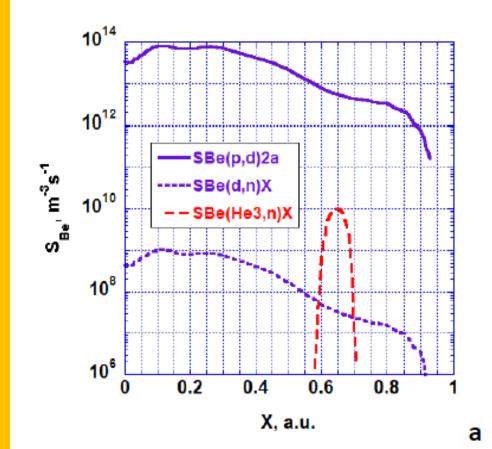### ^{4}He plasma for B/I$_p$=2.65T/7.5 MA, P_{NBI}=33 MW, P_{ECH}=20 MW

- Wide zone of weak or weak reversed magnetic shear together with peaked pressure profile $p_0/<p> \sim 3 - 4$ and significant contribution from NBI fast ions to the total plasma energy, $\beta_{fast}/\beta_{th} \sim 20 - 25\%$ can make the TAEs unstable.
- For He plasmas of the ITER PFPO the H0-NBI with $E_b = 0.87$ MeV is superalfvenic in the whole range of magnetic fields

3-ION MINORITY ICR HEATING SCHEME

- High efficiency 3-ion ICRH scheme H-(^{3}He)-^{4}He enables full power H-mode operation with P_{IC} = 20 MW, P_{EC}=20 MW, P_{NBI}=33 MW in ITER hydrogen plasma with $c_{He4} \sim$ 5-15%, $c_{He3} \leq 1\%$ [Kazakov 2018], [Schneider 2017] in the range of magnetic fields B $\sim$ 3-3.3 T

- In presence of high Be fraction c_{Be} > 2%, 4 ion species has to be considered: H, ^{4}He, ^{9}Be, ^{3}He

- Condition for efficient ^{3}He ICRH absorption at $c_{He3} \leq 1\%$
  $6\ c_{He4} + 10\ c_{Be9} \leq 1$

- According to eq. (5), for high fraction of Be impurity ($c_{Be} -> 10\%$), an additional doping of H plasma by He4 is not required, $c_{He4} -> 0$.
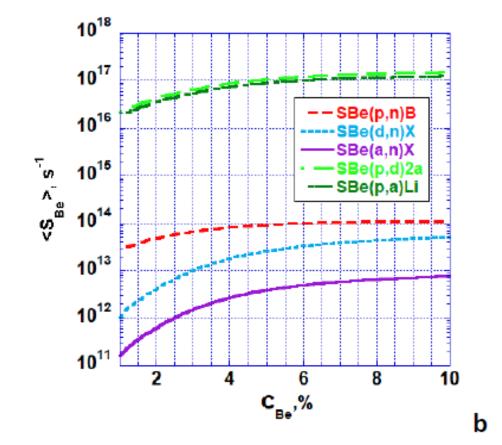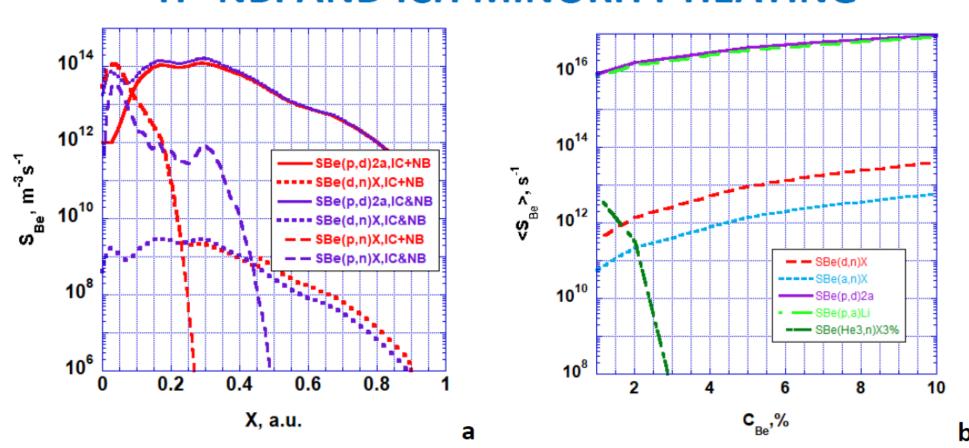

Fig. 3 Fusion sources in the ITER hydrogen plasma for 3-ion ICRH scheme for B/I$_p$=3.12/8.8 [T/MA] with c_{He3} = 0.1%, $6\ c_{He4} + 10\ c_{Be9} \leq 1$

- For low Be fraction < 5 % neutron source from the Be^9(He^3,n)X dominates
- For high Be fraction neutron source from Be^9(p,d)-> Be^9(d,n) becomes dominant
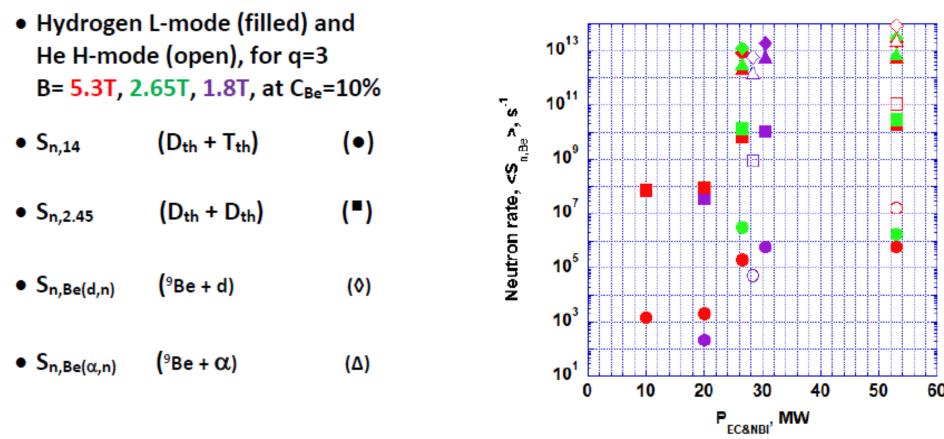
H0-NBI AND ICH MINORITY HEATING

(a) B/I$_p$=2.65T/7.5MA ^{4}He plasma for ICRH H-minority heating scheme with c_H = 5%, c_{Be} = 1 %. Synergy between H0-NBI and H-minority ICRH: $S_{Be,NBI\&IC} < S_{Be,NBI} + S_{b,IC}$

(b) B/I$_p$=5.3T/15MA H plasma for ICRH ^{3}He-minority heating scheme with c_{He3} = 3%, SPA drops with increase of C_{Be}.

Table 1. Fusion sources for H-mode operation in He plasma with H-minority ICRH with P_{IC}= 20 MW and H0-NBI with E_b=870 keV, P_{NBI}=33 MW for f_{Be}= 1%, f_H= 5% at B/I$_p$=2.65T/7.5MA with the toroidal wave number of the spectrum peak corresponding to the dipole (π) and current-drive (π/2) antenna phasings

N	P_{NBI}/P_{IC}(phase)	$S_{Be(p,n)X}$	$S_{Be(d,n)X}$	$S_{Be(3,n)X}$	$S_{Be(p,d)2β}$	$S_{Be(p,l)Li6}$
1	33/20 MW(π/2)	4.92 10^{14}	1.12 10^{14}	1.76 10^{13}	2.26 10^{17}	1.90 10^{17}
2	33/20 MW(π)	9.68 10^{13}	9.96 10^{13}	1.46 10^{13}	2.09 10^{17}	1.75 10^{17}
3	0/20 MW(π/2)	3.40 10^{15}	3.82 10^{13}	1.10 10^{13}	4.58 10^{16}	4.15 10^{16}
4	0/20 MW(π)	8.20 10^{13}	4.58 10^{15}	4.45 10^{11}	1.04 10^{16}	8.41 10^{15}
5	33/0 MW	<<1	8.29 10^{11}	1.18 10^{13}	1.81 10^{17}	1.51 10^{17}

- Fast hydrogen accelerated by ICRH produces more neutrons for current-drive phasing than for heating phasing (compare 1,2 and 3,4)
- Presence of H0-NBI reduces fast hydrogen tail and neutron production from Be9(p,n)X (compare 1,3 and 2,4)

NBI + ECR HEATING SCHEME

- Hydrogen L-mode (filled) and He H-mode (open) for q=3
  B= 5.3T, 2.65T, 1.8T, at C_{Be}=10%

- $S_{n,14}$ (D$_{th}$ + T$_{th}$)   (●)
- $S_{n,2.45}$ (D$_{th}$ + D$_{th}$)   (■)
- $S_{n,Be(d,n)}$ (^{9}Be + d)   (◊)
- $S_{n,Be(α,n)}$ (^{9}Be + α)   (Δ)

For high Be concentrations C_{Be}=10% neutron sources $S_{n,Be(d,n)}$, $S_{n,Be(α,n)}$ from secondary reactions (^{9}Be + p = d + 2α => ^{9}Be + d = n + X), (^{9}Be + p= ^{6}Li + α => ^{9}Be + α= n + X) dominate, $S_{n,Be,max} \sim 10^{10}s^{-1}$

RUNAWAY ELECTRON EVENTS

(primary activation through bremsstrahlung and secondary activation through neutrons)

Bremsstrahlung photons per energy interval dk can be calculated [Jarvis 1988] from
$$N(k, E_0)dk = 6.8 \times 10^{-34} N_{RE}\frac{Z^2 N_A}{A}\frac{E_0 - k}{S}\frac{dk}{k}$$
$$N_{RE}^0 = \frac{2\pi R}{ec} I_{RE}; \quad N_{RE} = N_{RE}^0\left(1 + \frac{L_{RE}I_{RE}^0}{2\times10^6 eB_0 N_{RE}^0}\right),$$

where N_A = 6x10^{23}, for divertor (W): Z=74, A=184, S = 0.3 MeVm^2/kg, for FW (Be): Z=4, A=9, S = 0.18 MeVm^2/kg, for the first plasma (FP) limiter (Ni), Z=28, A=59, S = 0.25 MeVm^2/kg; L_{RE} = 6 μH, FP: E_0 = 1 MeV, I_{RE} = 1MA, PFPO: E_0 = 15 MeV, $I_{RE,max}$ = I_p x2/3, $I_{RE,no\ melting}$ = 2 MA.

Number of pulses/Rate of disruptions:
N_{pulse} / F_d = 6000/20% (PFPO-1), N_{pulse} = 7000/10% (PFPO-2).
Rate of RE in disruptions: F_{RE} =10%,
Thus, N_{events} = N_{pulse} N_{events} F_d F_{RE}.

Table 2. Number of RE events N_{events} and neutrons N_n generated in Divertor and FW

	N_{events}	I_{RE},MA	N_{RE}/event	N_n/event(Divertor)	N_n/event(FW)[1]
FP	20	1.0	2 10^{18}		1 10^{12} [2]
	2	0.5	7 10^{17}		2 10^{14} [2]
PFPO-1	1	6.3	5 10^{19}	3 10^{16}	3 10^{15}
	120	2.0	7 10^{18}	3 10^{15}	3 10^{14}
PFPO-2	1	10.0	1 10^{20}	6.5 10^{16}	7 10^{15}
	70	2.0	7 10^{18}	3 10^{15}	3 10^{14}

$N_{j,tot} = \sum N_{events}\ N_j$/event,   j= n, RE

Thus, total amount of RE and neutron production during FP and PFPO can be estimated as:
$N_{n,tot} \approx 4\ 10^{18}$,
$N_{RE,tot} \approx 1.4\ 10^{21}$.

DISCUSSION AND CONCLUSIONS

- It is shown that the main source of neutrons for the plasma parameters expected in PFPO is due to the interaction of Be impurity with suprathermal ions produced by NBI and ICRH, fast deuterium from the Be(p,d)2α reaction and further secondary fusion reactions.
- Production of neutrons strongly increase with local electron temperature and therefore is higher for the central heating and lower density cases
- For H0-NBI heated plasmas w/o the ICRH the dominant neutron source comes from the secondary reaction with Be impurity: Be^9(p,d)-> Be^9(d,n)
- For ICR H- or He^3-minority heating with or w/o H0-NBI the neutron source produced by accelerated minority ions strongly dominates Be^9(p,n)X, Be^9(He^3,n)X
- Neutron production is higher for current-drive (π/2) antenna phasing
- Simultaneous using of the ICR H-minority heating with H0-NBI noticeably reduces neutron production by the fast hydrogen tail due to wider of the ICH absorption
- For the 3-ion heating scheme with ^{3}He minority at B=3.1-3.3 T the ICH absorption is off axis at lower local temperatures and absorbed power density with noticeably
- Local fractions of the NBI and ICRH fast ion pressure and their gradients at PFPO are higher than those of fast alphas in the ITER Q = 10 baseline scenario, making AEs unstable in a wide range of the low magnetic shear, X < 0.5.
- Injection of H0-NBI with E_b=0.87 MeV in helium plasmas is superalfvenic for the whole range of magnetic fields, B=1.8-5.3 T
- The saw-tooth oscillations and excitation of AEs can noticeably reduce the neutron rate, but have little impact on the integral neutron production provided the period of oscillations is less that the fast tail recovery time
- Note that the fusion cross-sections for reactions considered in the ITER relevant range of energies are not accurate. Moreover, the neutron production rate depends nonlinearly on the local electron temperature and Be concentration, which are poorly described by first principle transport models making our estimate more uncertain. The present studies are carried out to refine the estimation of possible neutron production during the PFPO phase of ITER operation taking into account fast particle effects.

Acknowledgement

Disclaimer

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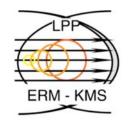[Martín-Solís 2014] J.R. Martín-Solís et al., Nucl. Fusion, vol. 54, p. 083027, 2014

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