Impact of Suprathermal Ions on Neutron Yield at Pre-DT Phase of ITER Operation

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ABSTRACT

- An assessment of neutron production has been carried out for the set of scenarios foreseen by the ITER Research Plan [1] for the pre-DT phase, Pre-Fusion Plasma Operation, (PFPO) with the application of H^0-NBI, ECRH and ICRH H minority and 3-ion heating scheme with ^{3}He minority as a function of Be fraction, $f_{Be}= n_{Be}/n_e$.
- Fast deuteron and neutron production by interaction of protons originated from the NBI and hydrogen minority ICRH with Be impurity: $Be^9(p,d)2\alpha$ (1), $Be^9(p,n)X$, (2) is calculated using ASTRA-NBI [2,3] and TORIC+SSFPQL[4] codes
- On the basis of the calculated source (1) of fast deuterons (E_d = 0.56 MeV) neutrons source due to reaction with Be impurity: $Be^9(d,n)X$ (3) is derived
- Neutron sources produced by fast He^3 minority ions accelerated by ICH in the reaction $Be^9(He^3,n)X$ (4) are calculated for the 3-ion heating scheme [5]
- The impact of the synergy between the H^0-NBI ions and hydrogen minority ICH on the fusion products is assessed for full heating mix case [6].
- Stability of the TAE modes is analysed for pre-DT plasmas with high pressure of suprathermal particles and WRS configuration [7,8]
- Possible impact of the saw-tooth oscillations and TAEs on the neutron production is assessed

CROSS SECTIONS OF FUSION REACTIONS [9]

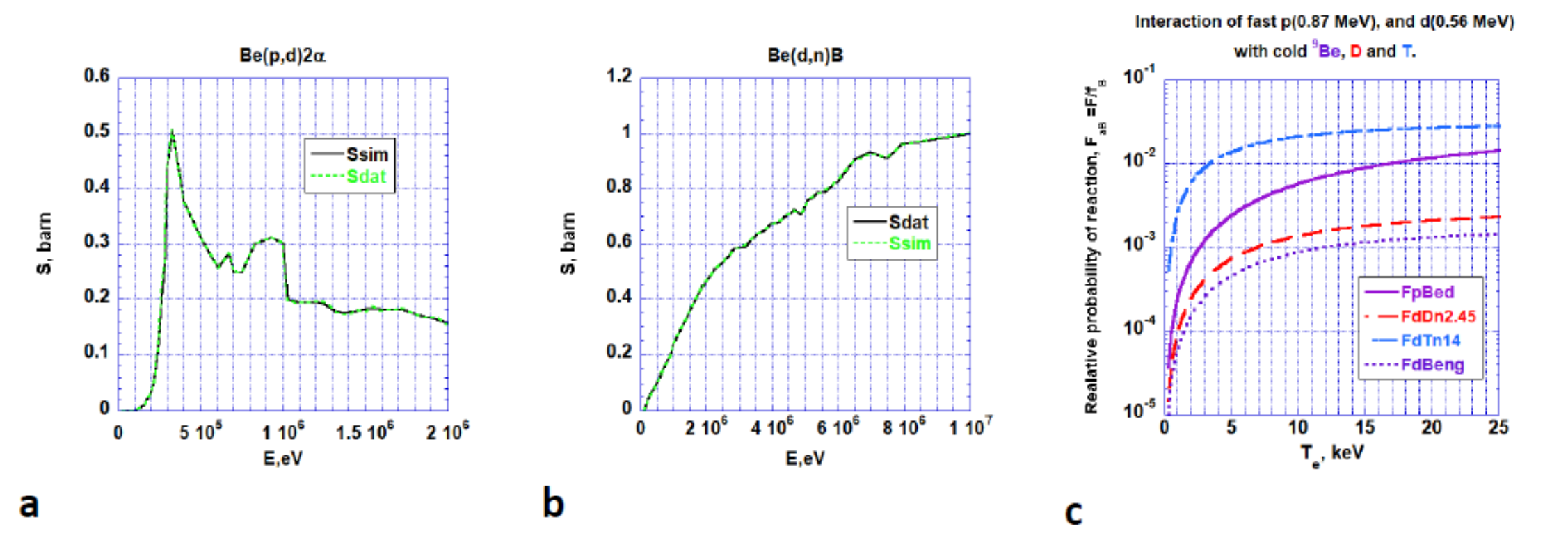


Fig 1 Cross sections of interaction of Be impurity with fast particles:

(a) $Be^9(p,d)2\alpha$, (b) $Be^9(d,n)X$; (c) relative probability to burn out during the slowing down for a fast proton $F_{pBed}(E_p=0.87$ MeV) and fast deuteron $F_{dX}(E_d=0.56$ MeV) due to interaction with Be (F_{dBeng}), T (F_{dTn14}) and D ($F_{dDn2.45}$). In particular for H^0-NBI $S_{p,NBI}$:

$$S_d = S_{Be9(p,d)2\alpha} = f_{Be}\, F_{pBed}\, S_{p,NBI}\ (\sim f_{Be})\ ; \qquad S_{ng} = S_{Be9(d,n)X} = f_{Be}\, F_{dBeng}\, S_d\ (\sim f_{Be}^2)$$

HIGH ENERGY IONS ACCELERATED BY ICRH

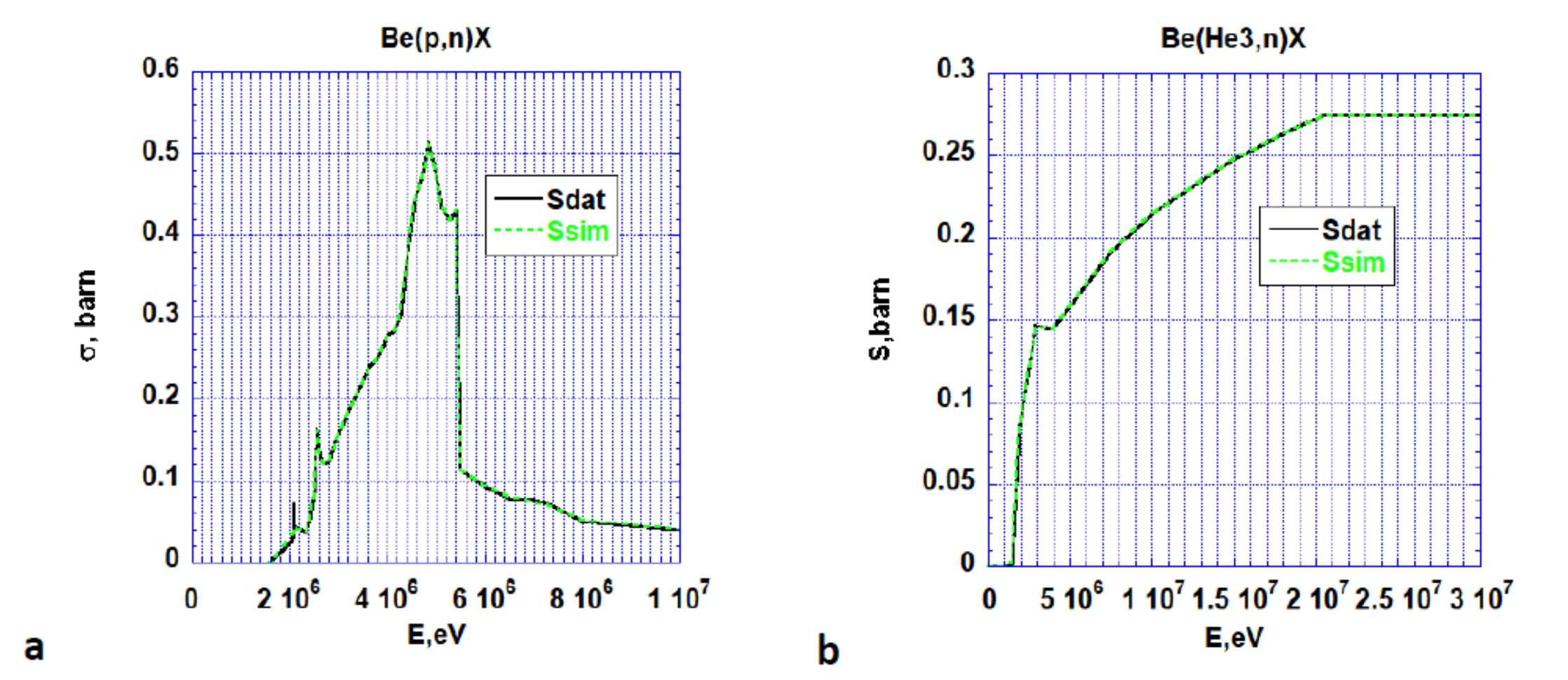


Fig. 2 Cross-sections of interaction of Be impurity with fast ions accelerated by ICRH minority heating:

(a) $Be^9(p,n)X$, (b) $Be^9(He3,n)X$.

1.5D TRANSPORT SIMULATIONS

Transport model:

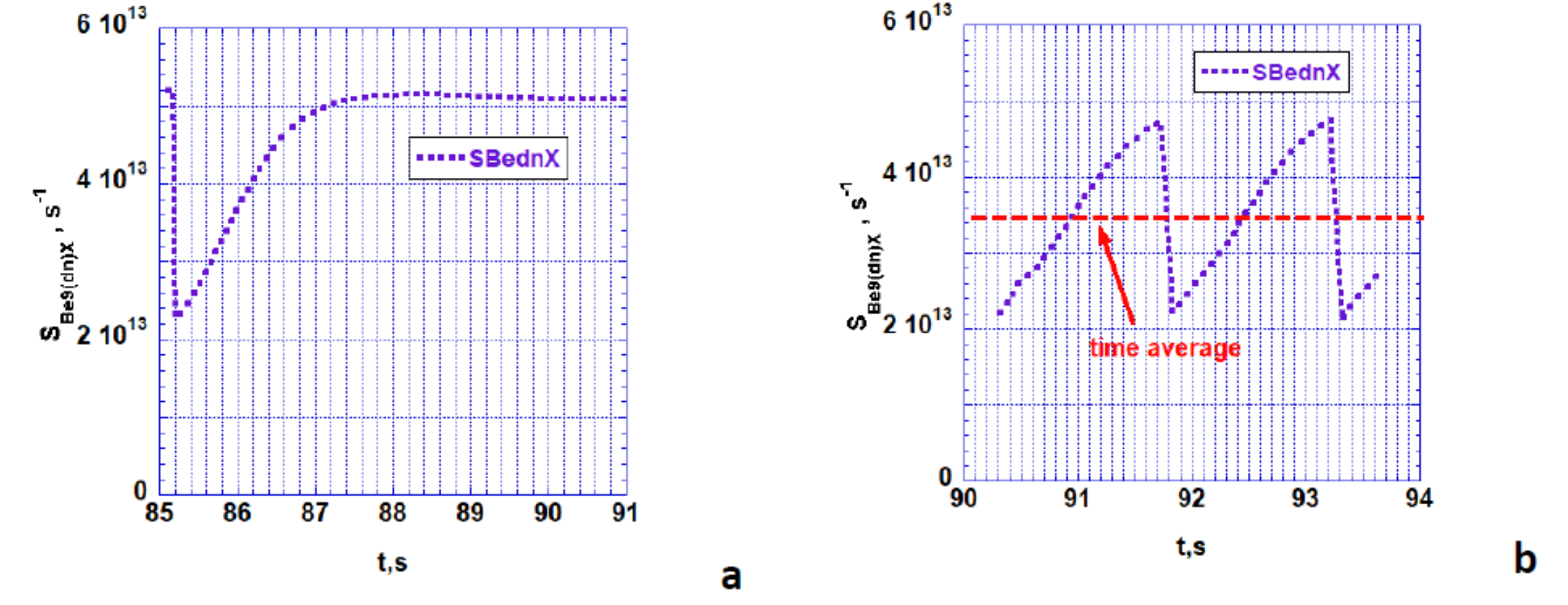
- 1.5D transport simulations for n_e, n_D, n_T, T_i, T_e, j by ASTRA [10];
- SOLPS boundary conditions and EPED1+SOLPS pedestal [11];
- ^{9}Be impurity and ICRH minorities are prescribed: n_{Be}/n_e, n_{He3}/n_e, n_H/n_e(in He), n_{He}/n_e(in H);
- Main ion densities, n_H or n_{He} are calculated from quasineutrality;
- Heat diffusivities, $\chi_i=2\chi_e$, are fitted at the ETP to provide $p_{e,ped}$ by EPED1+SOLPS, and in the core to provide: $\tau_E = 0.75\ \tau_{E,Hy2,98}$ [12];
- Particle diffusivity and particle pinch velocity for n_e, n_D, n_T:
  $D=(\chi_i+\chi_e)/10$, $V=C_v\, Dx/a$ with C_v = 0 - 0.3 for sensitivity studies
- Fuelling is fitted to provide $n\sim0.5\ n_{GW}$;

H&CD:

- P_{EC} = 20 MW (baseline); P_{EC} = 30 MW (upgrade under consideration) [13]
- Hydrogen NBI, P_{NBI} = 33 MW (16.5 MW on-axis+ 16.5 off-axis), E_p =0.87 MeV [2-4]
- ICRH 20 MW, f_{IC} = 40-55 MHz, [4]

MODELING OF SAW-TEETH AND TAEs

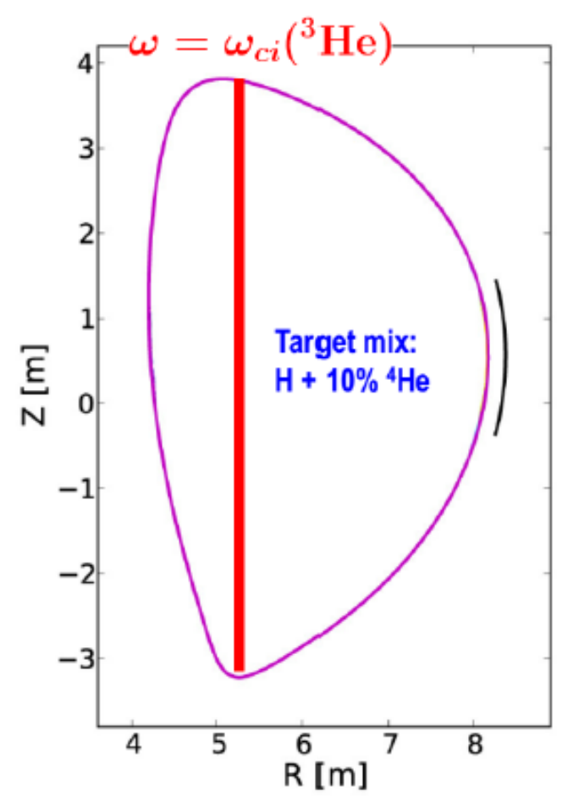
- Saw-tooth and TAE impact is modelled by mixing of plasma parameters (ST) and fast ion redistribution within the area X_{ST} = 1.4 X(q=1).



- Effect of the STs on the total neutron production is small since fast ion recovery time τ_S ~ 1 s is much smaller than the resistive time, τ_{ST} ~ 10 s. Reduction of the neutron source due to TAEs can exceed 30%. Effect can be higher for ICRH.

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 f_{He4} ~ 5-15%, $f_{He3} \le 1\%$ [14], [15] in the range of magnetic fields B ~ 3-3.3 T



- In presence of high Be fraction f_{Be} > 2%,
  4 ion species has to be considered: H, He^4, Be^9, He^3
- Condition for efficient ^{3}He ICRH absorption at $f_{He3} \le 1\%$
  $$6\, f_{He4} + 10\, f_{Be9} \le 1 \qquad (5)$$
- According to eq. (5), for high fraction of Be impurity (f_{Be} -> 10%), an additional doping of H plasma by He^4 is not required, f_{He4} -> 0.

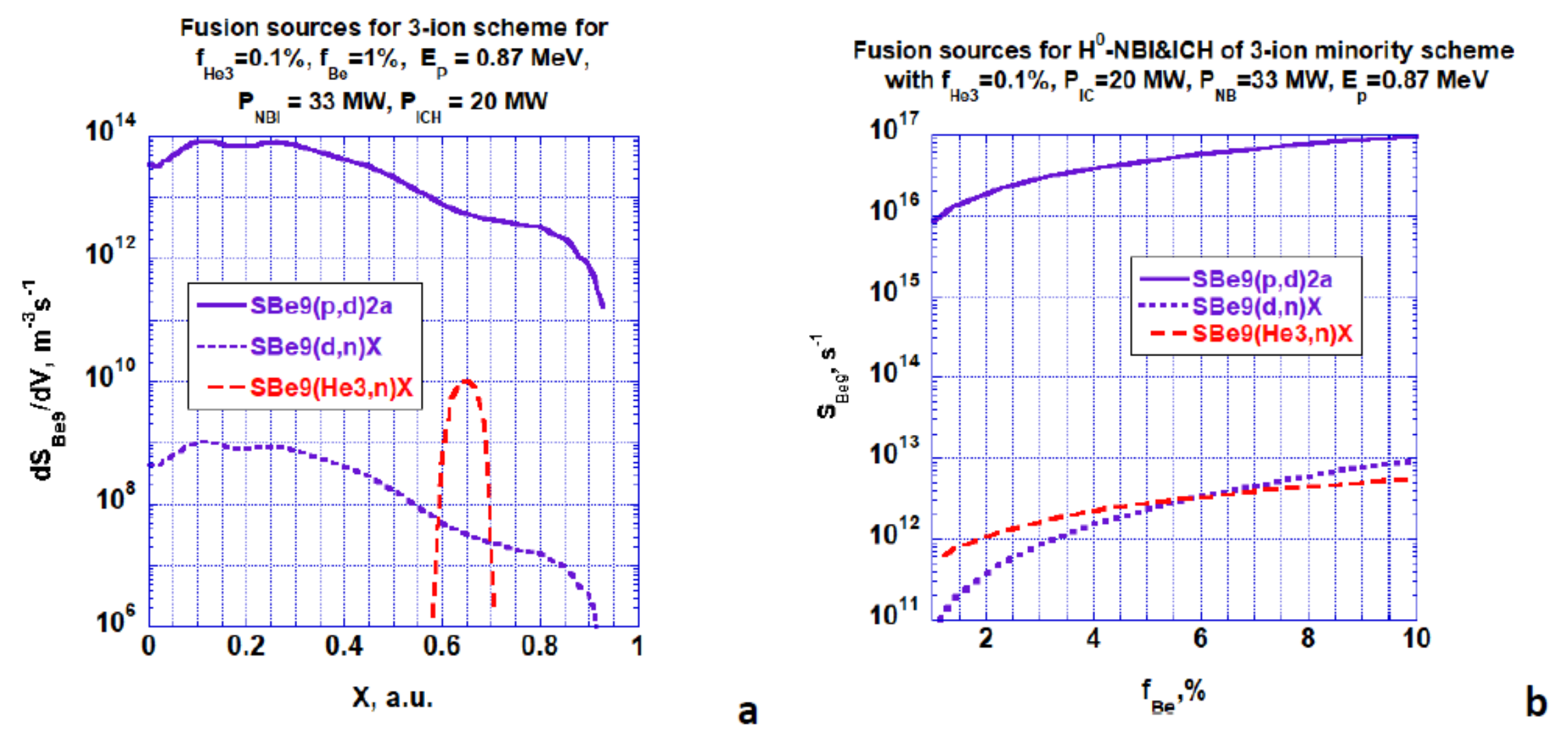


Fig. 3 Fusion sources in the ITER hydrogen plasma for 3-ion ICRH scheme for B/I_p=3.12/8.8 [T/MA] with f_{He3} = 0.1%, $6\, f_{He4} + 10\, f_{Be9} \le 1$

- 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

SYNERGY OF H^0-NBI AND H-MINORITY ICH

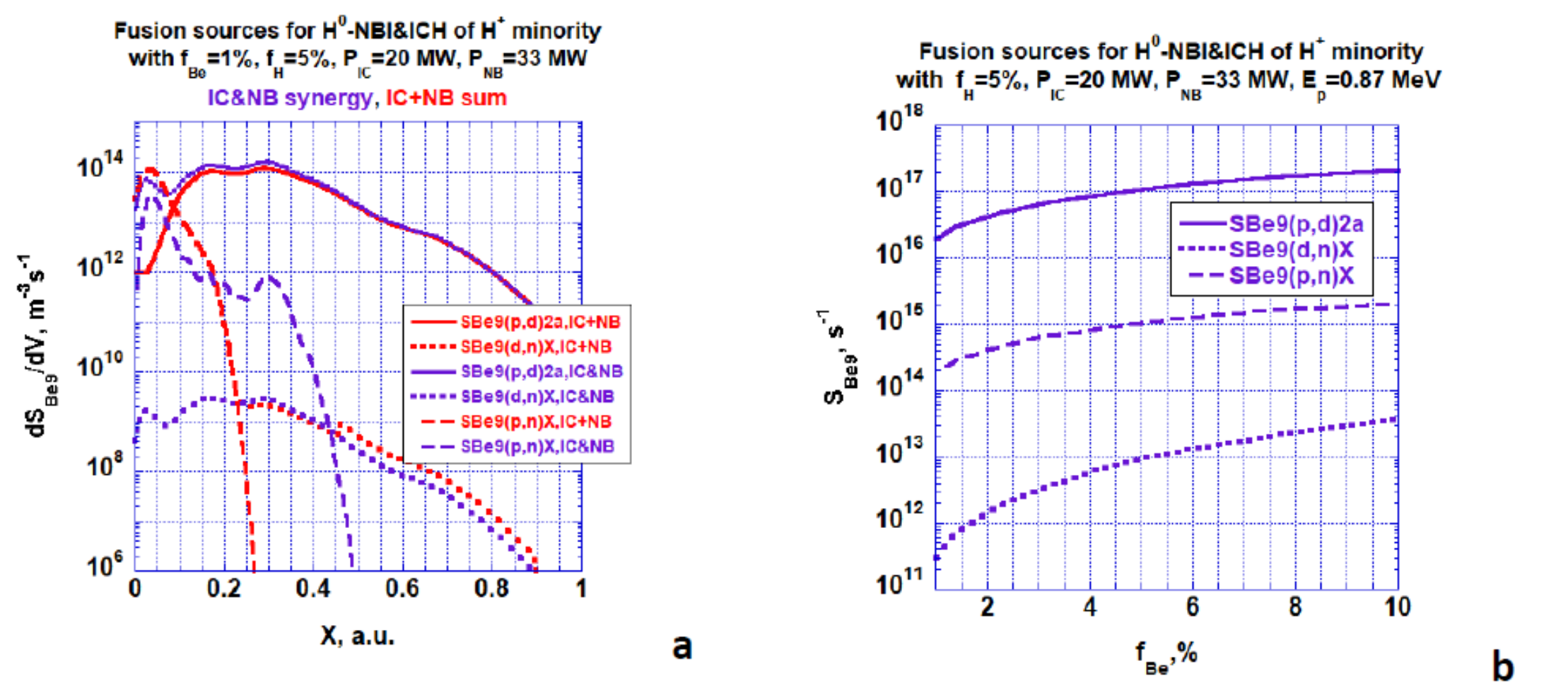


Fig. 4 Fusion sources in the ITER helium plasma for ICRH hydrogen minority heating scheme with f_H = 5%, f_{Be} = 1 -10 % for B/I_p=2.65/7.5 [T/MA]

(a) Impact of synergy between H^0-NBI and H-minority ICRH is strongly nonlinear

(b) Neutron source $S_{Be9(p,n)X}$ caused by H-minority accelerated by ICRH dominates

Table 1. Fusion sources for H-mode operation in He plasma with H-minority ICRH with P_{IC}= 20 MW and H^0-NBI with E_p=870 keV, P_{NBI}=33 MW for f_{Be}= 1%, f_H= 5% at B/I_p=2.65T/7.5MA for different cases of the antenna phasing, (π/2): [0, π/2, π, 3π/2] (current-drive), and (π): [0, π, 0, π] (heating).

N	Heating configuration	$S_{Be9(p,d)2a}$, s^{-1}	$S_{Be9(d,n)X}$, s^{-1}	$S_{Be9(p,n)X}$, s^{-1}
1	(π) P_{ICH}= 20 MW	2.01e+15	4.4e+10	6.5e+14
2	(π/2) P_{ICH}= 20 MW	3.17e+15	6.94e+10	1.35e+15
3	(π) P_{ICH}=20 MW, P_{NBI}=33 MW	2.21e+16	3.61e+11	2.10e+14
4	(π/2) P_{ICH}=20 MW, P_{NBI}=33 MW	2.38e+16	3.90e+11	3.80e+14
5	P_{NBI} = 33 MW	1.81e+16	2.90e+11	negligible

- Fast hydrogen accelerated by ICRH produces more neutrons for current-drive phasing than for heating phasing (compare 1,2 and 3,4)
- Presence of H^0-NBI reduces fast hydrogen tail and neutron production from Be9(p,n)X (compare 1,3 and 2,4)

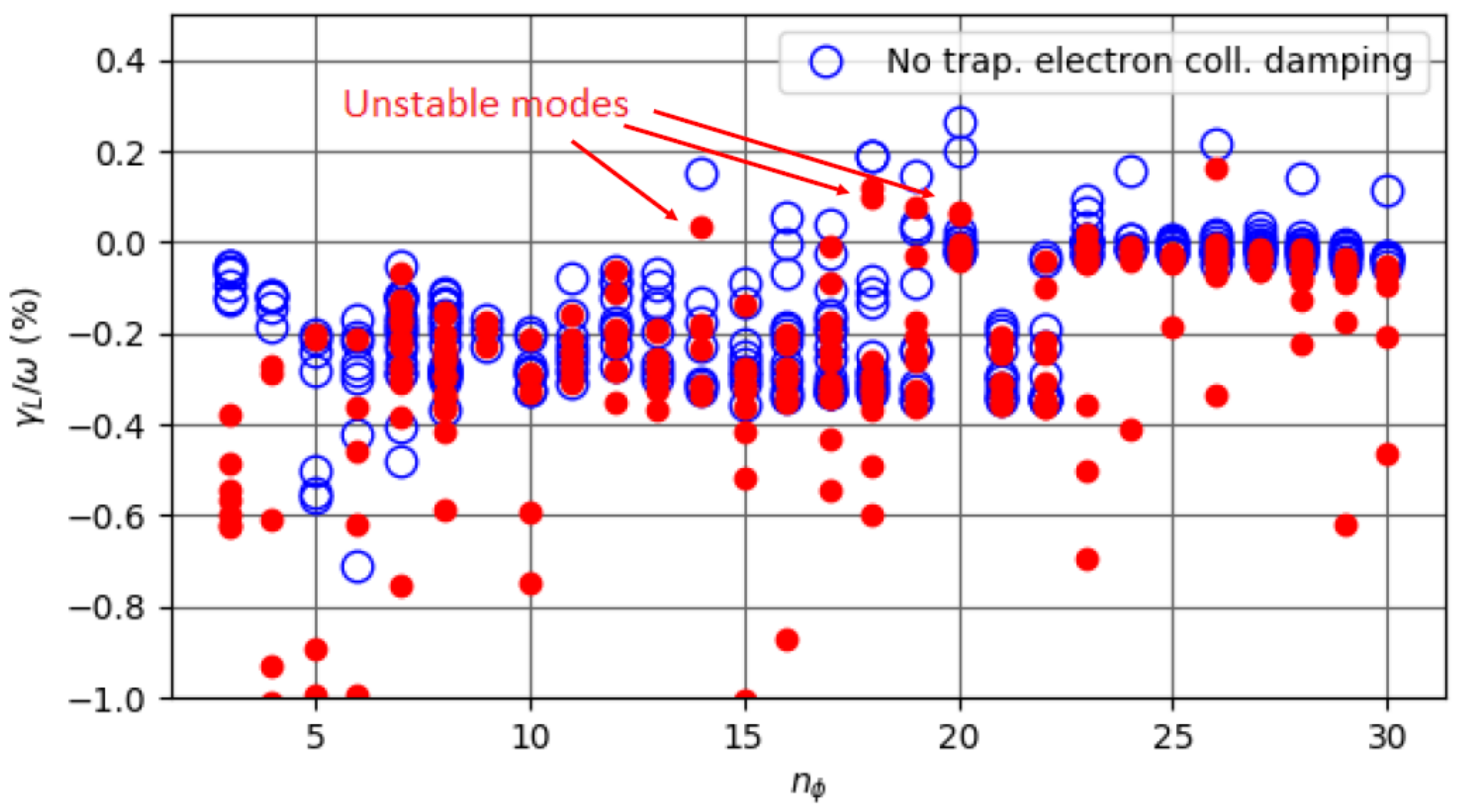
ASSESMENT OF TAE STABILITY

Table 2. Superalfvenic ratio $F_{bA}(g)= V_b/V_A \sim (g(A_i/Z_i)(3/q_{95})(5.3/B))^{0.5}$ for ITER PFPO hydrogen and helium plasmas for H^0-NBI with E_b = 0.87 MeV for q_{95}=3.

B, T	5.3		3.3		2.65		1.8	
$g=n/n_G$	0.35	1	0.35	1	0.35	1	0.35	1
F_{bA}, H	0.73	1.22	0.92	1.54	1.03	1.72	1.25	2.11
F_{bA}, He	1.03	1.72	1.3	2.17	1.45	2.53	1.76	2.97

- For ITER $g_{LH} \approx 0.35\ (q_{95}/3)^{2/3}$, where $P_{LH}(g_{LH}) = P_{LH,min}$, thus
  $F_{bA,min}= F_{bA}(g_{LH}) \sim I_p^{0.17}$, $F_{bA,max} = F_{bA}(1) \sim I_p^{0.5}$
- For He plasmas of the ITER PFPO the H^0-NBI with E_b = 0.87 MeV is superalfvenic in the whole range of magnetic fields

TAE STABILITY ANALYSIS BY NOVA CODE



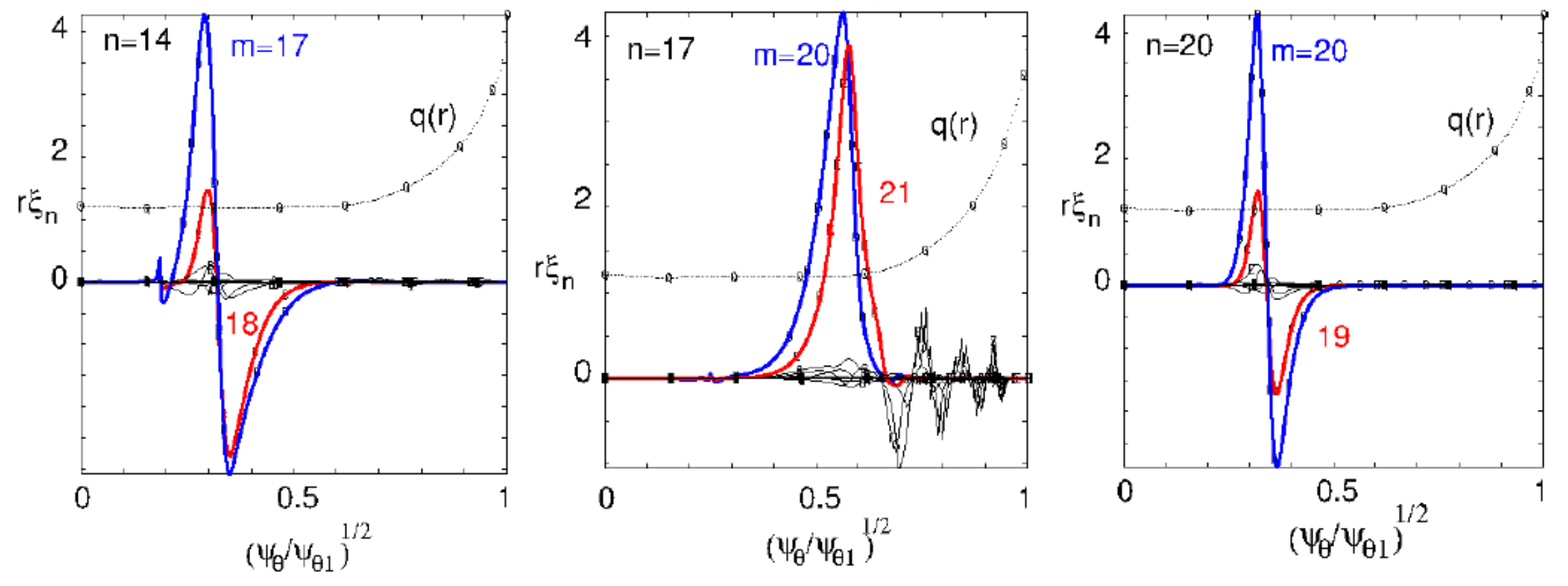


Fig. 7 Unstable TAE modes and their radial structure

- Unstable TAE modes are localized within the low/WRS zone X < 0.5
- Excitation of such modes can affect strongly peaked neutron source caused by central ICH and NBI heating

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 H^0-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 H^0-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 H^0-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 lower production of neutrons caused by ICH
- 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 H^0-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.

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Disclaimer

ITER is the Nuclear Facility INB no. 174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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