EUROPEAN FUSION DEVELOPMENT AGREEMENT

Current Hole Effect on Fast Ion Confinement in JET

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OUTLINE

- **Introduction & motivation**
- **Current hole (CH) model B**
- **FO loss and confinement criteria of fast ions**
- **Neoclassical & cone losses**
  - **i) DT alphas & DD tritons**
  - **ii) NBI tritons**
- **CH effect on the distribution of confined energetic ions**
  - **i) distribution function in COM space**
  - **ii) density, bootstrap-current, bulk plasma heating profiles, NBI triton induced neutron emission**
- **Summary**

• Motivation

Hollow current profiles typical for tokamak experiment scenarios with ITBs ⇒

improved plasma core energy confinement at reduced inductive current
plasma equilibrium states stable over remarkably long periods

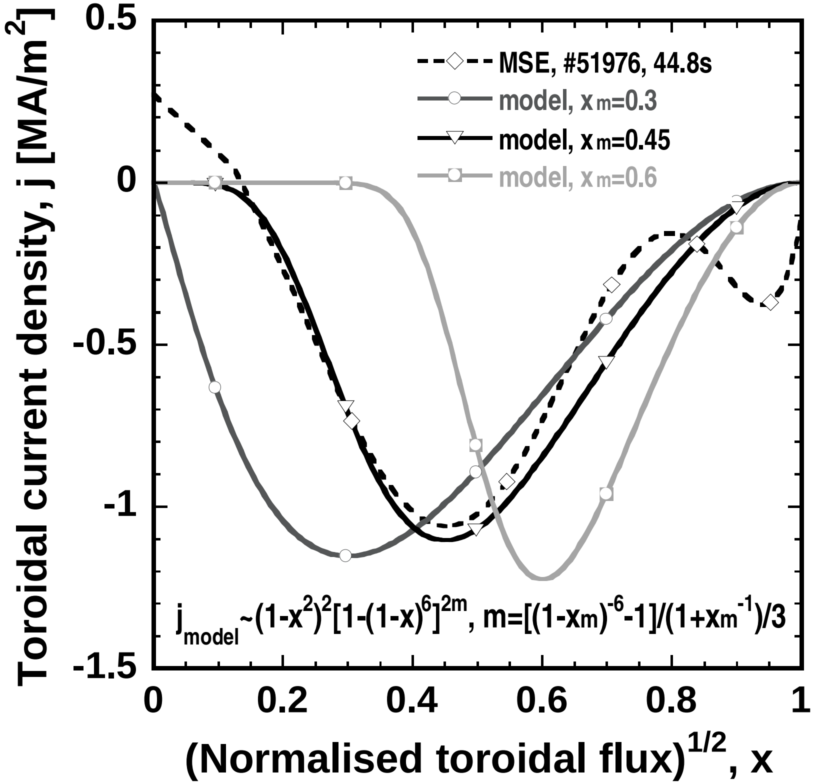
⇒ hollow current configurations could be regarded as serious candidate for stationary operation of a fusion tokamak-reactor

confinement of charged fusion products (CFPs) and NBI ions - ?

Purpose:

- **examine the effect of toroidal current hole on FO loss and on the collisional loss of fast ions,**
- **predictive modelling of distribution function of CFPs (3.5 MeV α's and 1MeV t's) and NBI ions in hollow current JET discharges**

• Model used

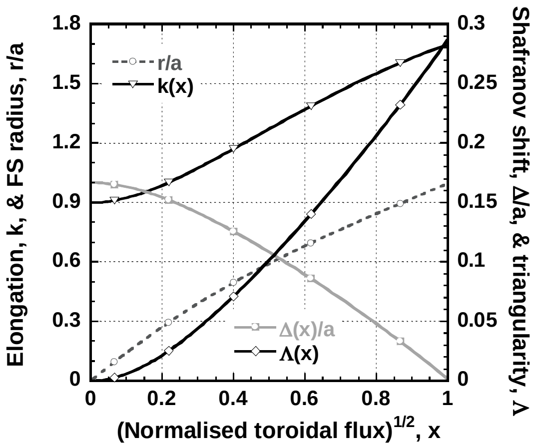


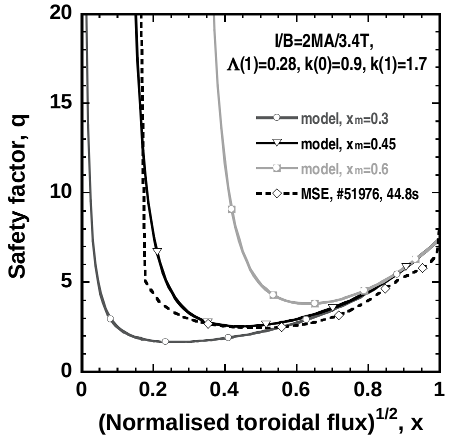
Model B with $j(r)$ and FS shape from MSE measurements for JET (#51976)

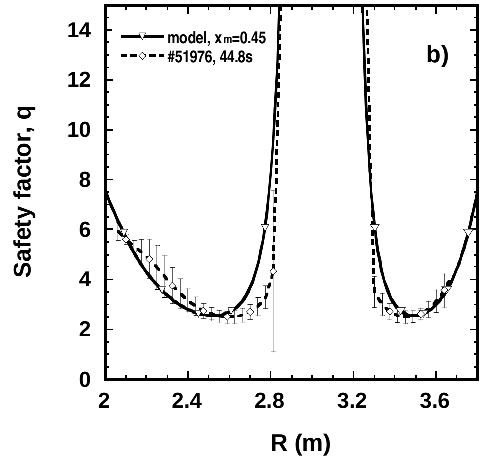
x_m radial position of maximum $j(r)$

reasonable approximation for measured $j(r)$ in JET (x_m=0.45, #51976) and JT-60 (x_m=0.6)

FS shape parameters and *q*-profiles







a) **Shafranov shift $\Delta(r) = \Delta_0[1-(r/a)2]$,**

b) **elongation $k(r) = k_a-[k_a-k_0][1-(r/a)^2]^2-0.5\, k_a'(r/a)^2[1-(r/a)^2]$,**

c) **triangularity $\Lambda(r) = \Lambda_a(r/a)^2$**

with $\Delta_0=0.15m$, $k_a=1.7$, $k_0=0.9$, $\Lambda_a=0.28$, $k_a'=0.8$

Reconstructed q-profiles are in satisfactory agreement with MSE measurements

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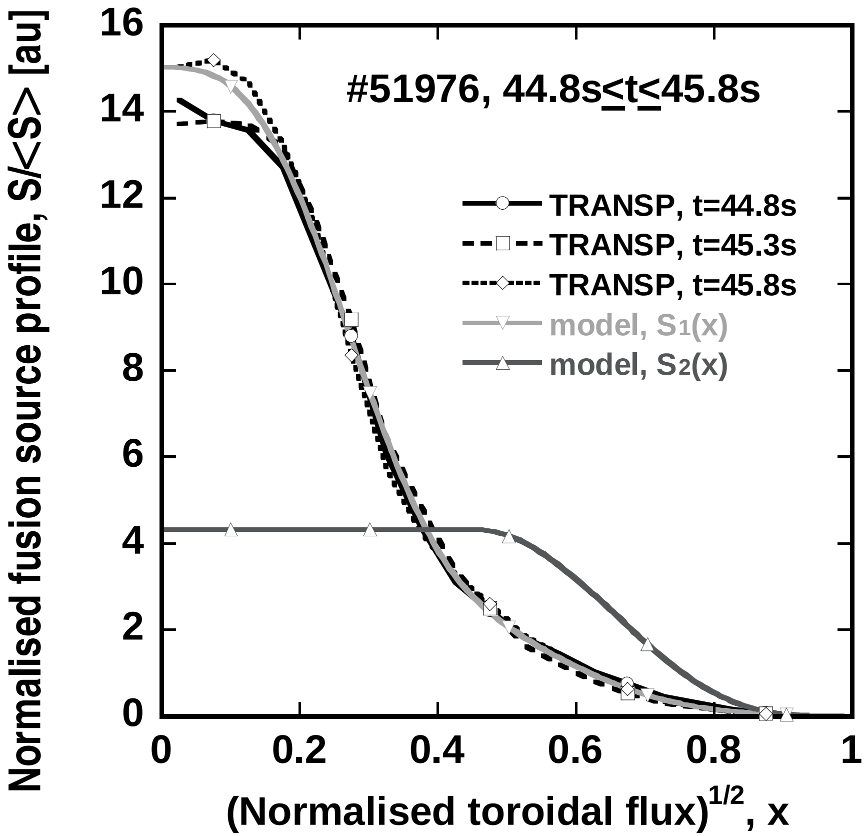
CFPs source term & plasma parameters



$S_1 \sim exp(-33x^3)+30.7x^4 exp(-11x^2)$

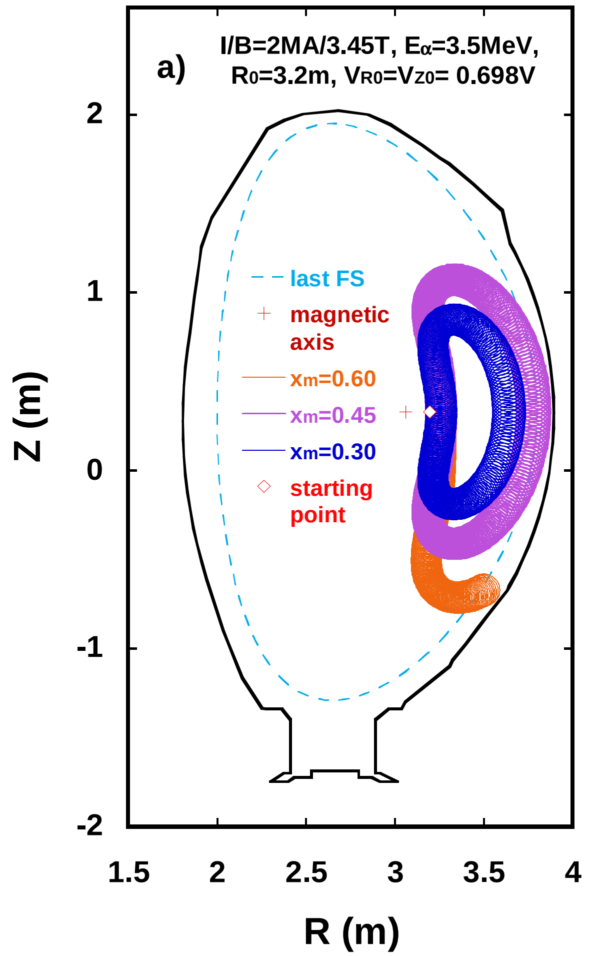
$S_2 \sim n_d n_t \langle \sigma V \rangle$

n_d , n_t - deuteron and triton density

$\langle \sigma V \rangle$ - fusion reaction rate

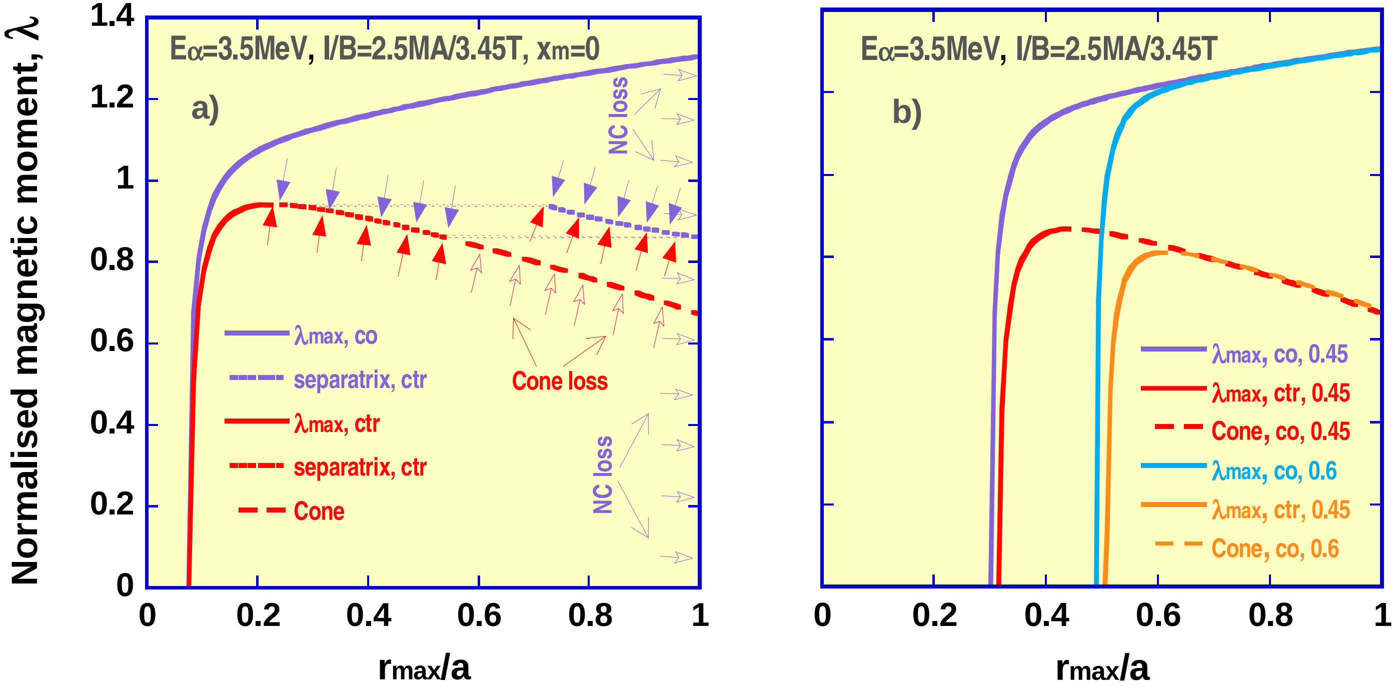
$T_e=10\ p(x)$ keV, $T_d= T_t=20p(x)$ keV,
$n_e=0.5\times 10^{20}\ p(x)\ m^{-3}$, $n_d= n_t$,
$Z_{eff}(x)=1.5+2.4x^2/(1+4x^{20})$
$p(x)=1-((x-x_m^*)/(1-x_m^*))^2 \Theta(x-x_m^*)$,
$x_m^*=0.45$
$\Theta(x)$ - Heaviside step function

3.5MeV alpha gyro-orbits



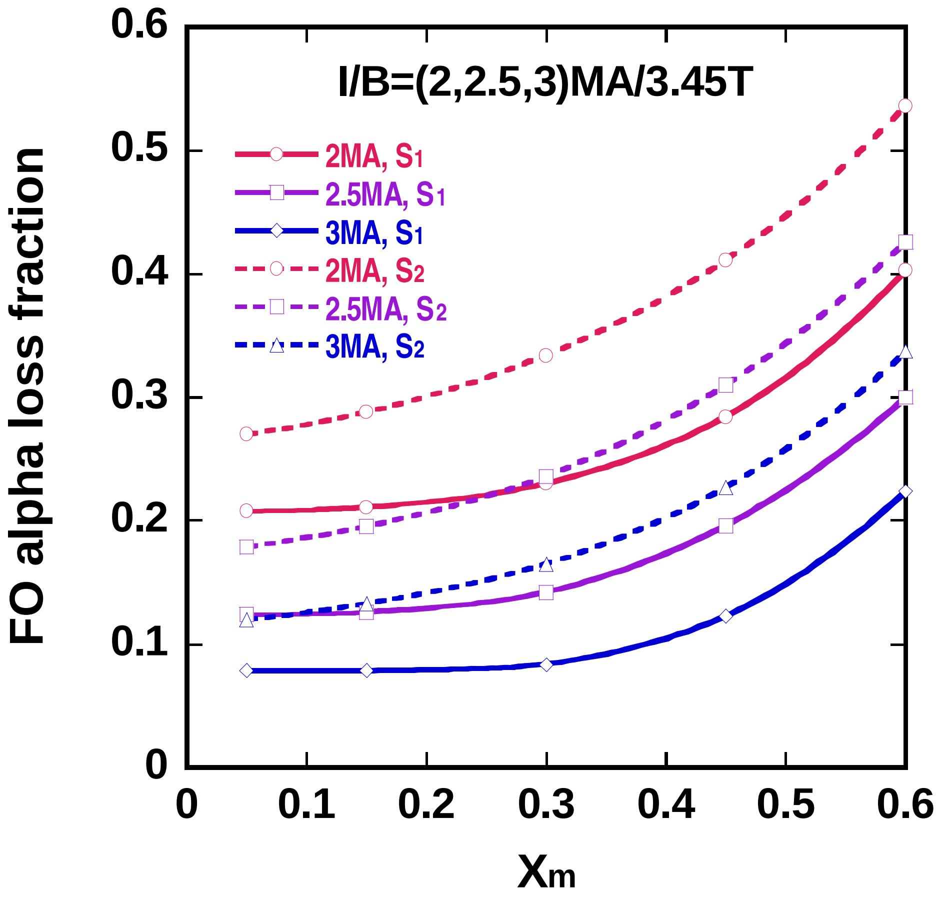
- Fixed FS shape & same initial conditions
- Effect of current hole is rather strong

Confinement domains



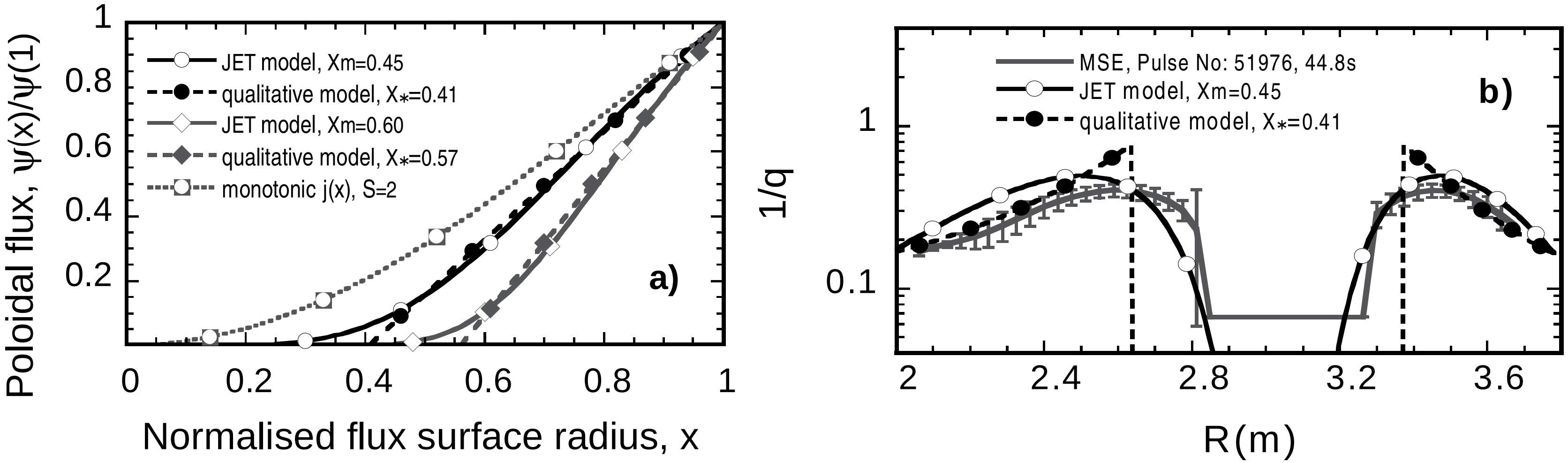
- **substantial reduction of confinement domain of alphas as current hole region is enlarged (increasing x_m)**

First orbit (FO) loss of alphas



- current hole enhances FO loss from (8-25)% at monotonic profile ($x_m \Rightarrow 0$) to (20-50)% at x_m=0.6
- shift of current maximum from 0.45 to 0.6 corresponds to effect of current decrease of about 0.5MA

Confinement criteria (qualitative consideration)



$$\Psi(r) \cong a\Psi_a' \psi(x - x_*), \quad \psi(y) = \begin{cases} 0, & y \le 0 \\ 0, & y > 0 \end{cases}$$

$x_* \cong 0.2 + 1.1x_m^2 - 0.3x_m^4$ - effective size of current hole

Critical currents & energies

- $I>I_{cr1}$; ($E<E_{cr1}$) particles crossing CH, $r<r_*$, are confined
- $I>I_{cr2}$; ($E<E_{cr2}$) particles crossing $r=0$ are confined

$$I_{cr1} \cong F \frac{1}{Z_i}\sqrt{\frac{\mu_i E}{A}}\frac{1}{1-\sqrt{x_*}} = I_{cr2} f$$

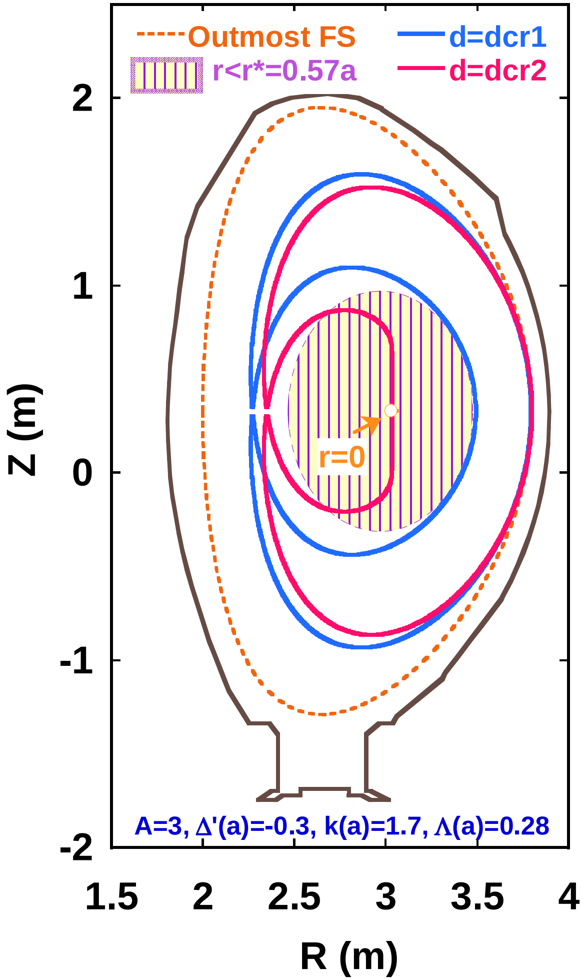
$$E_{cr1} \cong \frac{A}{\mu_i}\left[\frac{Z_i I}{F}\left(1-\sqrt{x_*}\right)\right]^2 = \frac{E_{cr2}}{f^2}$$

E in *MeV*, *I* in *MA*, Z_i and μ_i - *fast ion charge & mass numbers*

1<F<1.5 – geometrical factor

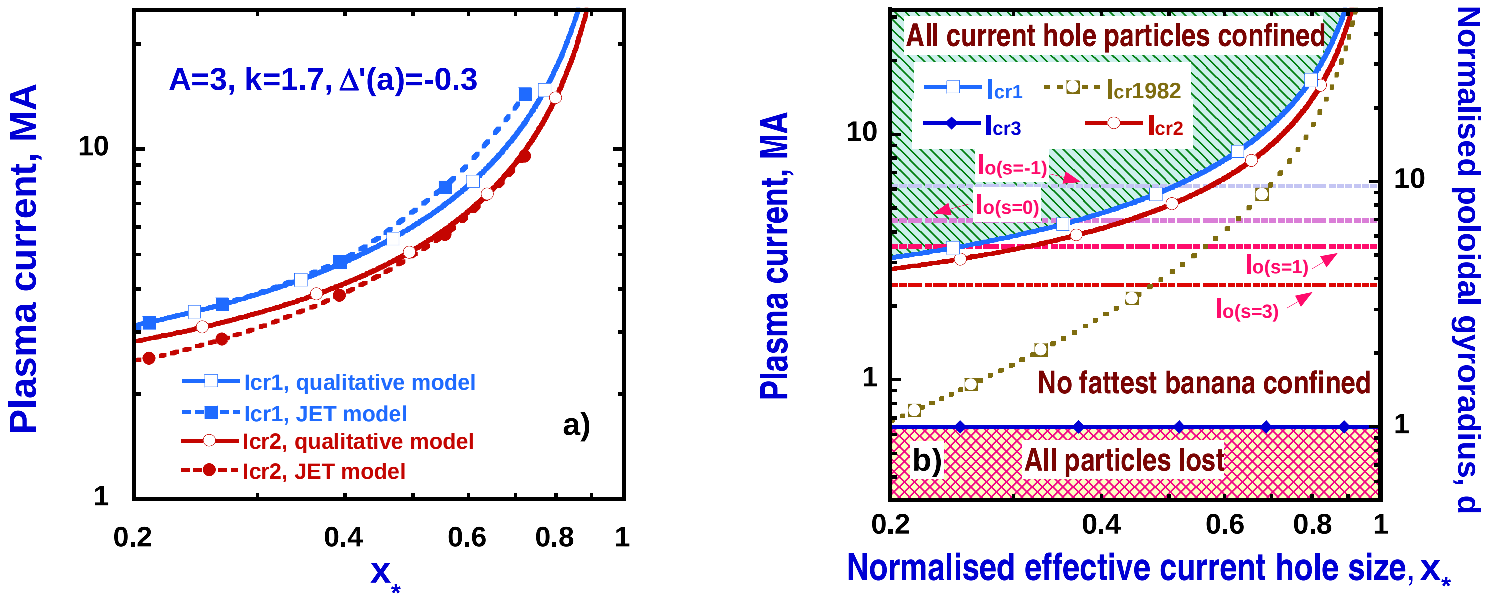
$$1 \le f(x_*) \approx \left(1+0.285\sqrt{x_*}-0.107x_*\right) < 1.2 \quad I > \{I_{cr1}, I_{cr2}\},\ E < \{E_{cr1}, E_{cr2}\}$$

Orbits of marginally confined barely trapped particles for x_* =0.57



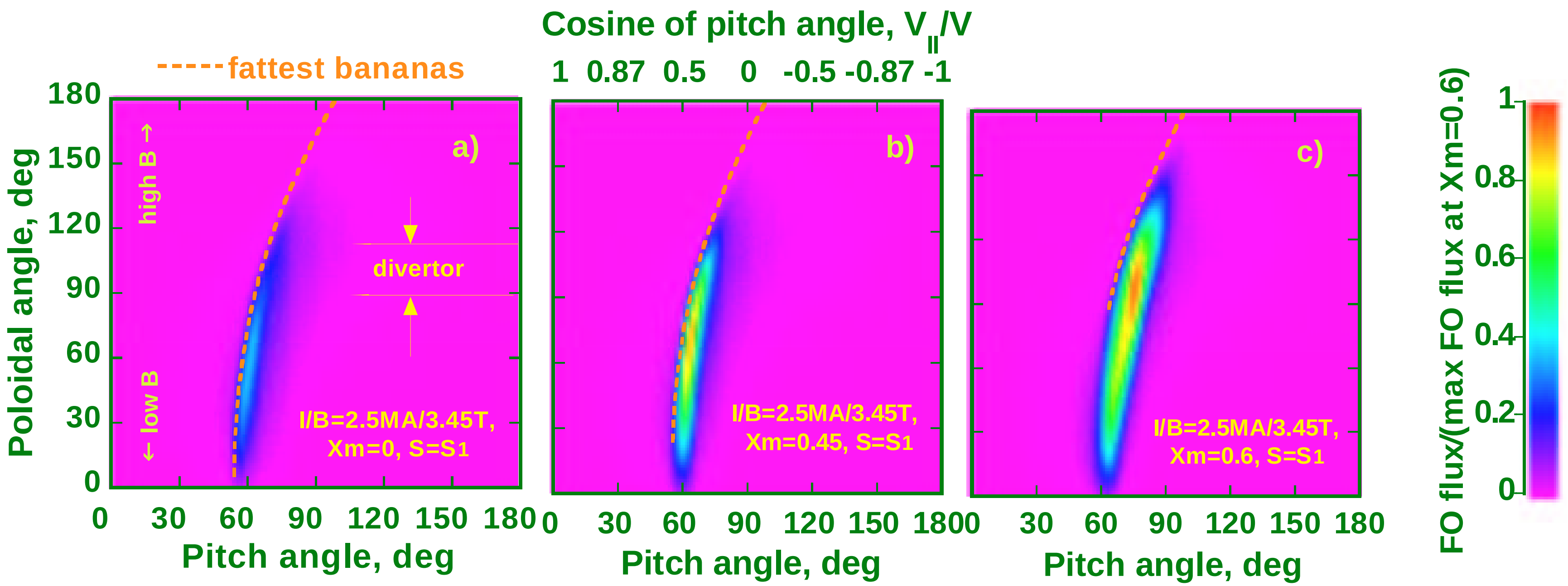
- ***d*** **–** poloidal gyroradius/(plasma major radius)
- at $d<d_{cr1}$ **= 0.08** particles crossing current hole, $r<r_*$, are confined
- at $d<d_{cr2}$ **= 0.108** particles crossing r**=0** are confined
- I_{cr1} **= 7.6MA,** I_{cr1} **= 5.6MA** for alphas
- Essential improvement of confinement requires only **~ 20%** reduction of ***d*** even in the case of rather large CH

Critical currents required to confine fusion alphas passing hollow current plasma core, *Icr1*, & plasma centre, *Icr2*



- in ITER-like tokamak $I \geq$ 10MA will provide a good alpha confinement for hollow current scenarios with x_* up to ~ 0.7
- current hole effect is equivalent to the reduction of total plasma current given by factor $1 - x_*^{1/2}$

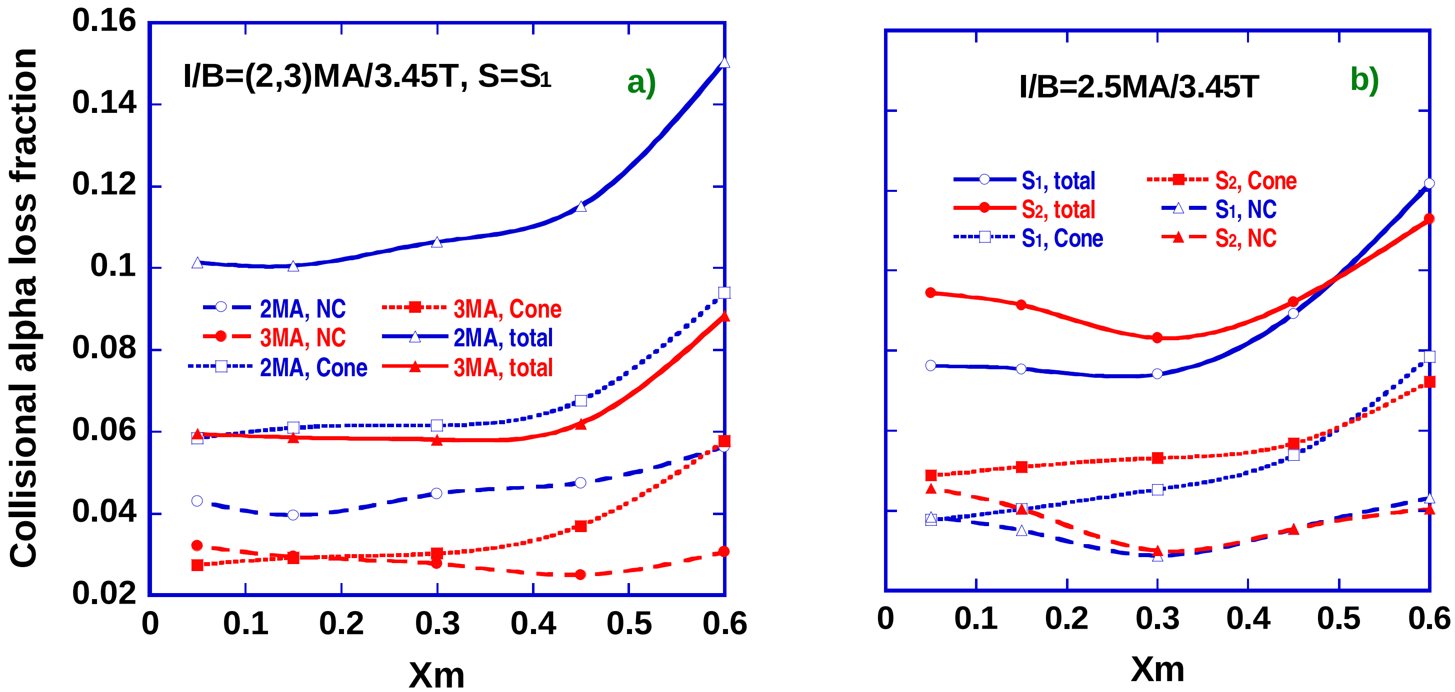
Distribution of FO alpha flux over pitch and poloidal angles



- $\Gamma(\zeta,\theta)$ =[number of particles lost per 1sm^2·(1*pitch angle deg*)·1*s*]
  Poloidal angle $\theta \Leftrightarrow \sin\theta = -Z/2.9m$ counted clockwise from min *B* at midplane (R=3.9*m*)

- Transition from x_m=0 to x_m=0.6 enlarges maximum FO loss about 2.5 times and shifts it from $\theta \approx 55^0 \div 60^0$ below midplane to rather high $\theta \geq 100^0 \div 105^0$ (divertor area)

Collisional loss fractions L_{NC} and L_{CONE} of alphas with $0.0625<E/E_0<1$

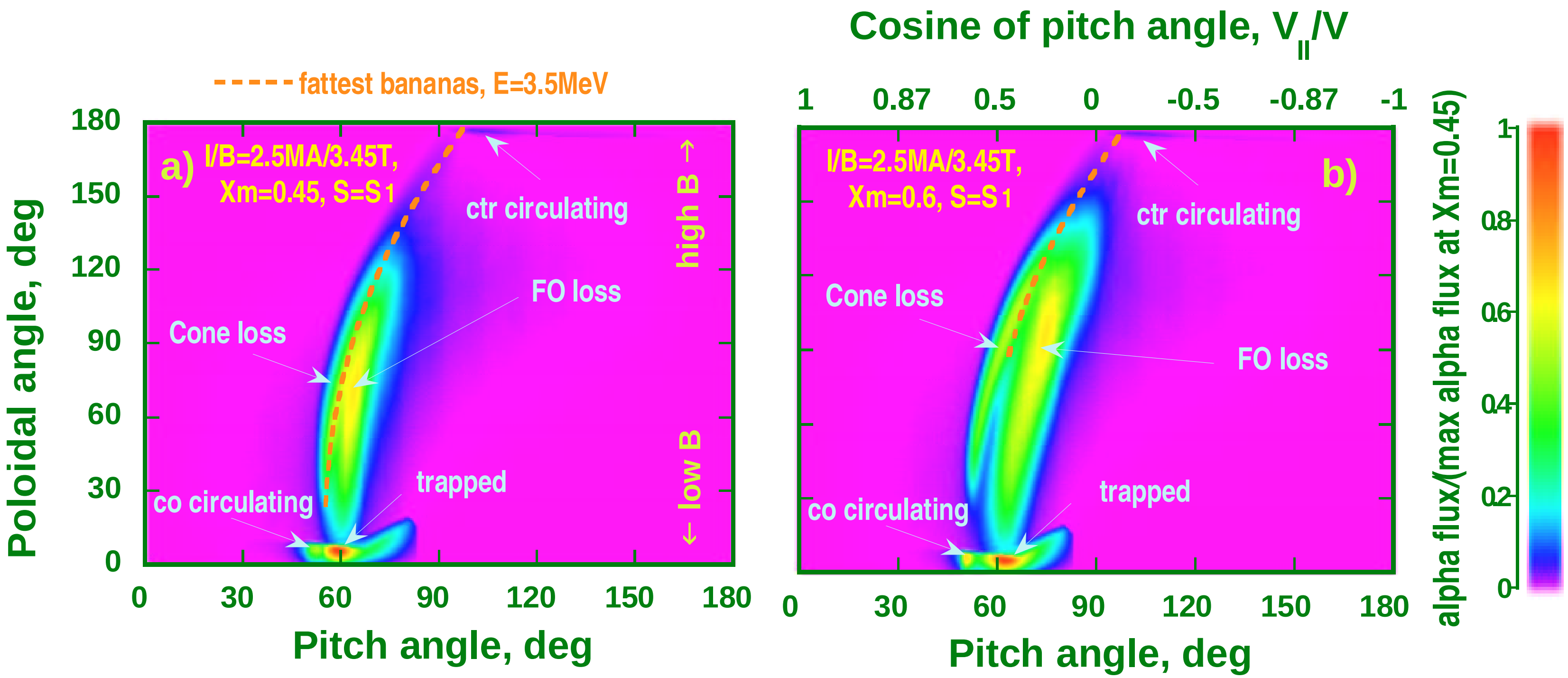


collisional loss fraction of fast alphas

$L_{coll} \sim (D_{\lambda\lambda}/\nu_s)^{1/2} \sim (D_{rr}/[a\text{-}r_{min}(\lambda=0,\sigma)]^2\nu_s)^{1/2} \sim 0.1$ **for** $\nu_\perp/\nu_s \sim 10^{-2}$

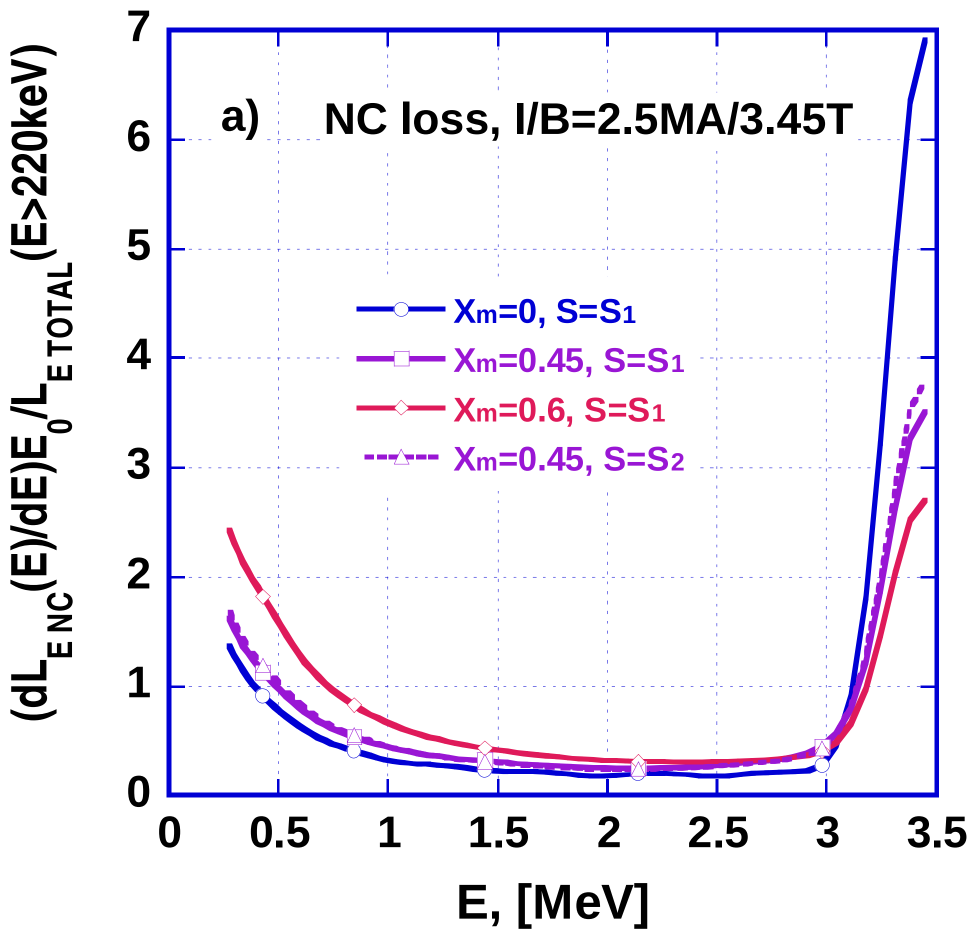
reason - rather steep initial distribution of confined alphas, $|\partial ln f_\alpha/\partial ln c_i| >> 1$

Distribution of collisional + FO alpha flux over the pitch and poloidal angles



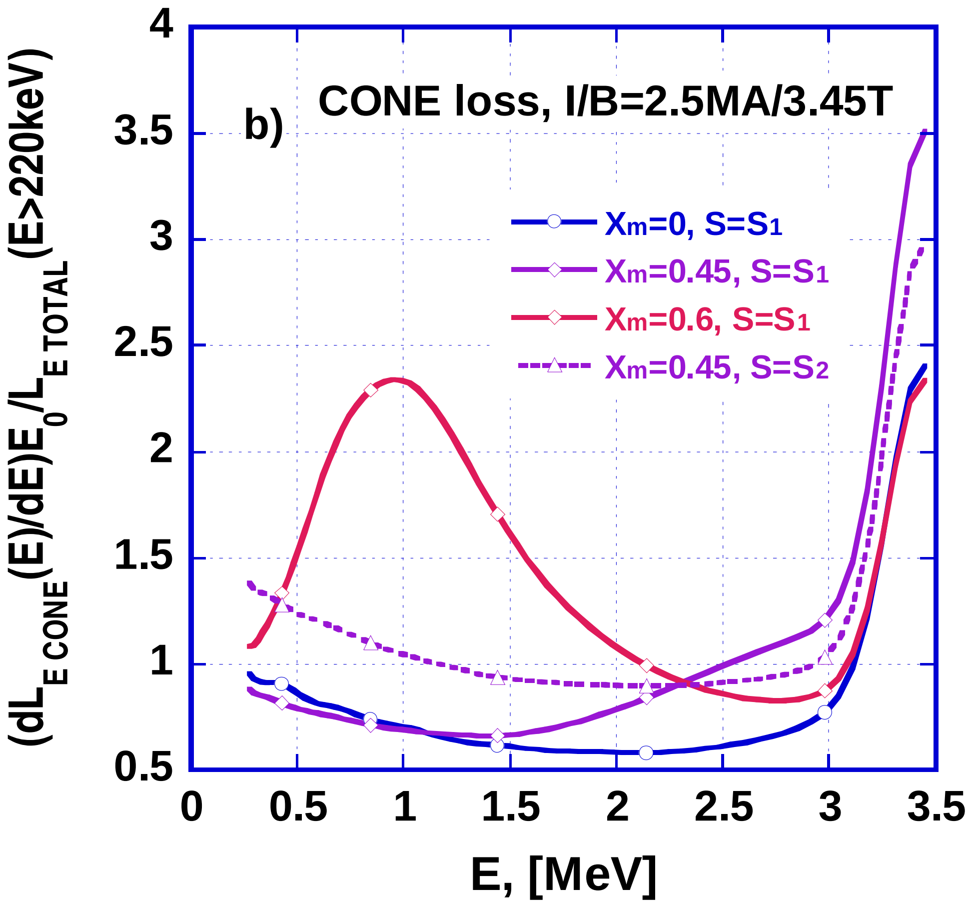
- maximum collisional fluxes result from NC loss of trapped alphas at poloidal angles ~10^0 and pitch angles ~ 60^0 and from cone loss of fattest bananas at pitch-angles ~ 50^0 - 70^0

Energy spectra of NC collisional loss



- For NC loss effect of current hole is important only at high, *E*>3*MeV*, and low, *E*<1*MeV*, energies

Energy spectra of cone collisional loss



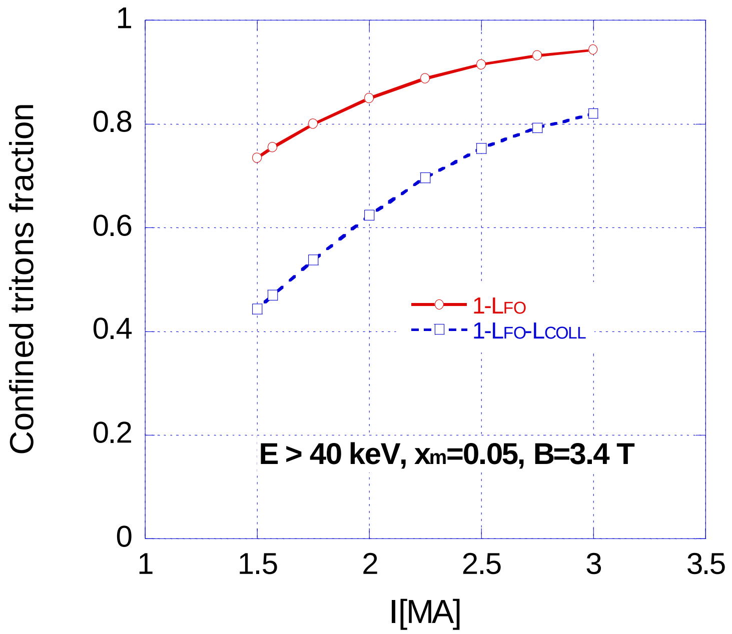
- cone loss is essentially affected by toroidal current shape also in moderate energy range $1 MeV < E < 3 MeV$
- peculiarities of cone loss spectra are due to increase of
  -loss cone size in phase space with enlargement of current hole area and
  -number of alpha particles contributing to loss at plasma periphery

$$\Gamma \sim D(1-L_{FO}) dlnf/dlnc$$

Loss of DD Tritons (40keV<E<1.4MeV) S(*r*) = S_{JET} (#51976)

While $L_{FO\ DD\ tritons} \approx L_{FO\ DT\ alphas}$ (due to gyro radii $\rho_{DD\ tritons} = 0.93\rho_{DT\ alphas}$) the collisional loss L_{coll} of tritons is enhanced because of higher efficiency of pitch-angle scattering

$$\Rightarrow (\nu_\perp/\nu_s)_{DD\ tritons} \sim 7(\nu_\perp/\nu_s)_{DT\ alphas}$$



monotonic *j*(*r*)

$L_{coll\ DD\ tritons} > L_{FO\ DD\ tritons}$

L_{coll}~15-30%

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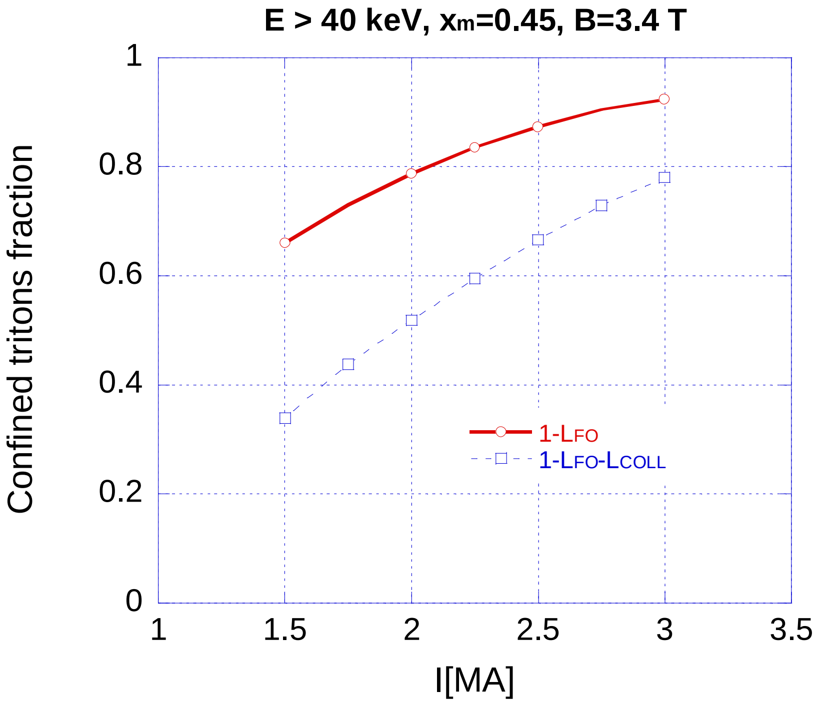
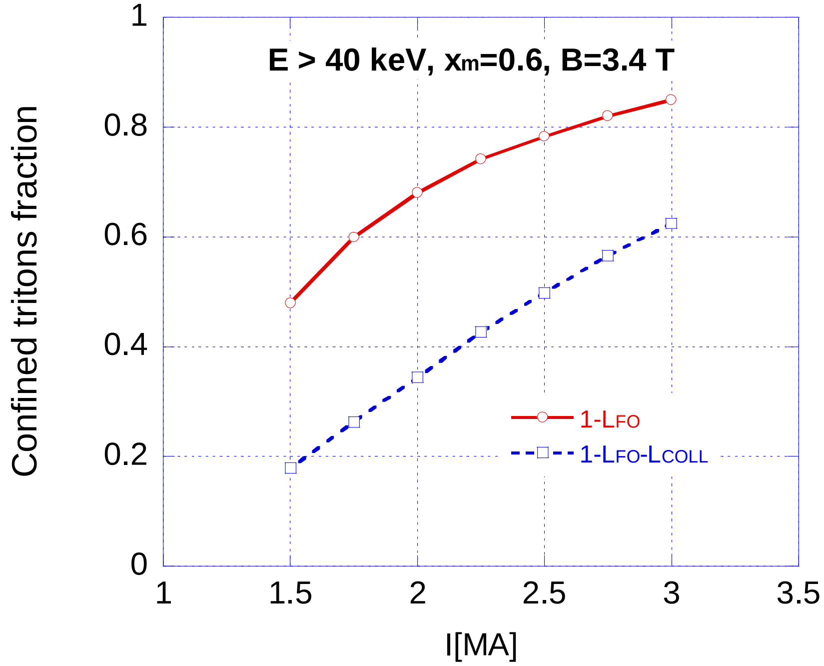
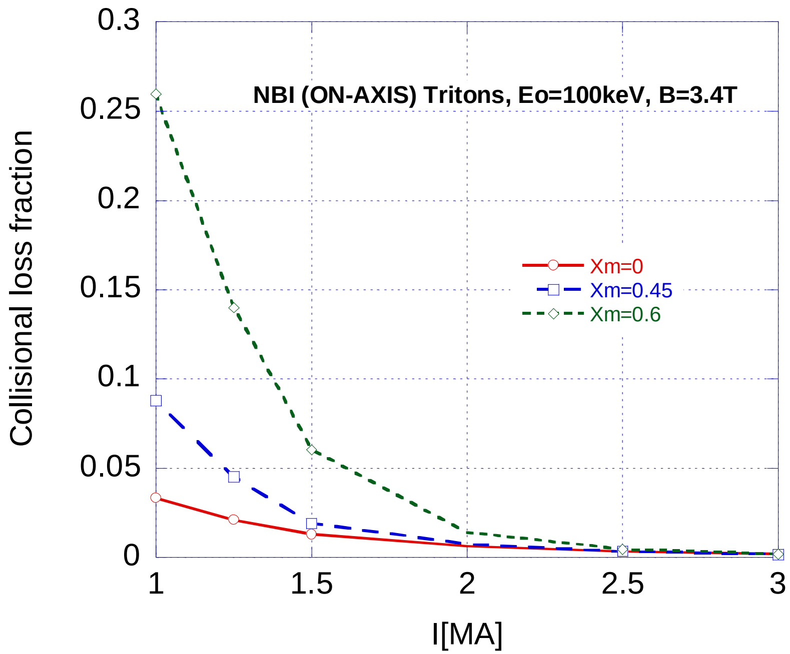
Current hole effect on the confinement of DD tritons

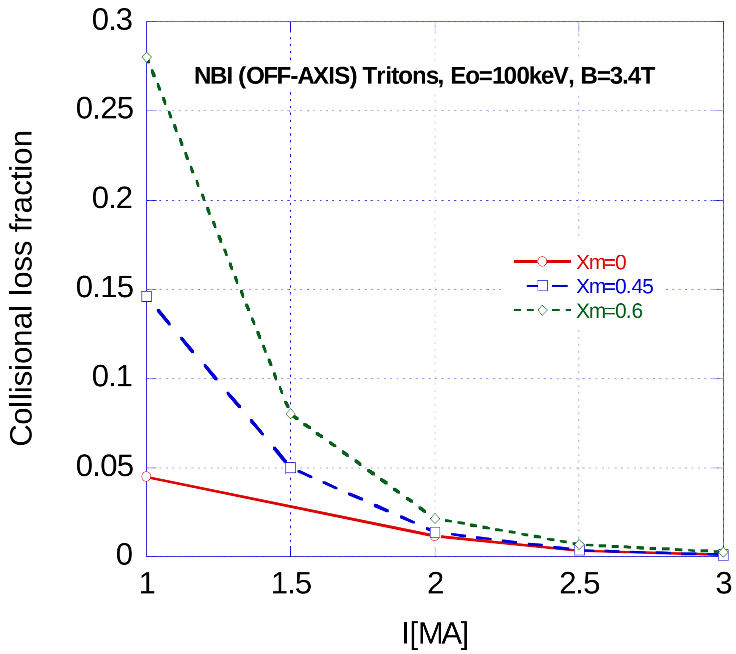




Essential effect of collisional transport on triton burn-up

Collisional loss of 100*keV* co-injected NBI tritons



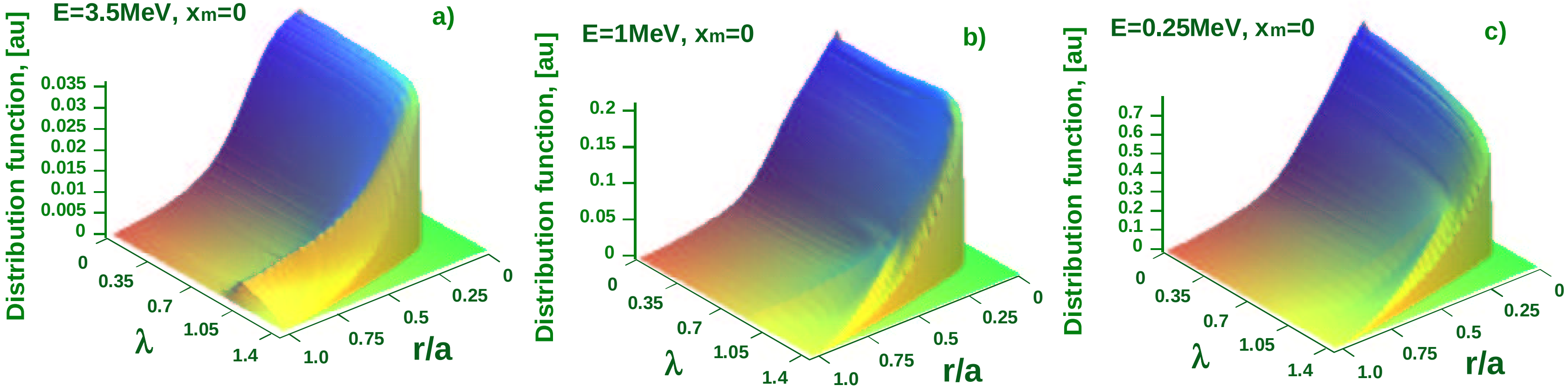


Collisional loss becomes essential (≥ 10%) only at I < 1.5MA and $x_m \geq 0.5$

$I_{cr1}(x_*=0.4)$ =1.5MA!

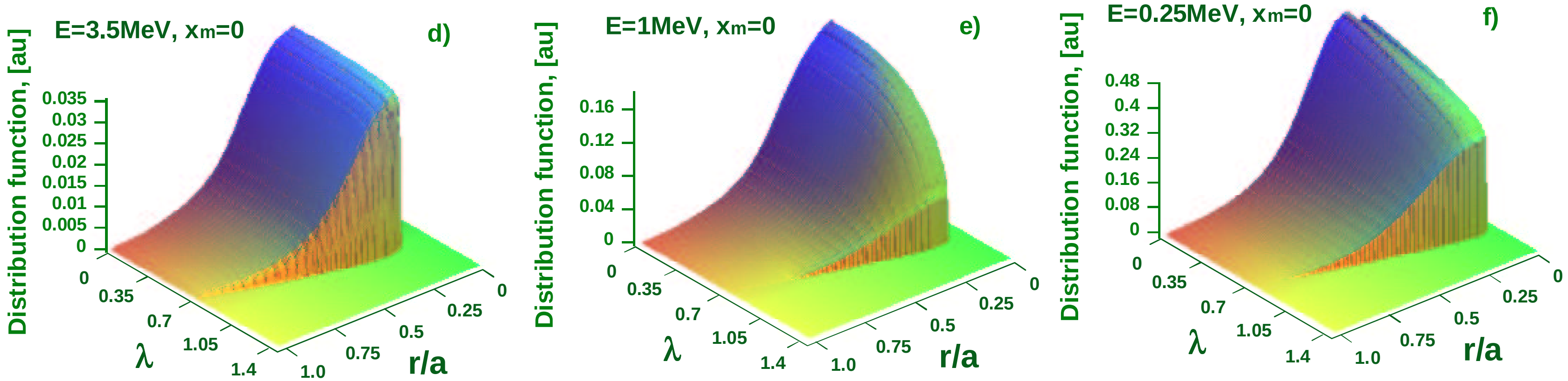
Distribution function of confined alphas at I/B=2.5MA/3.45T for monotonic *j*(*r*)

co-going particles, x_m=0



Normalized to $f_0=S_0/(4\pi V_0^3\nu_0)$, S_0- alpha source rate, V_0=1.3 10^9cm s^{-1}, ν_0=0.03 s^{-1}, $S_{0\,DT} \cong 10^2 S_{0\,DT}$~$10^{11}$cm^{-3}s^{-1}

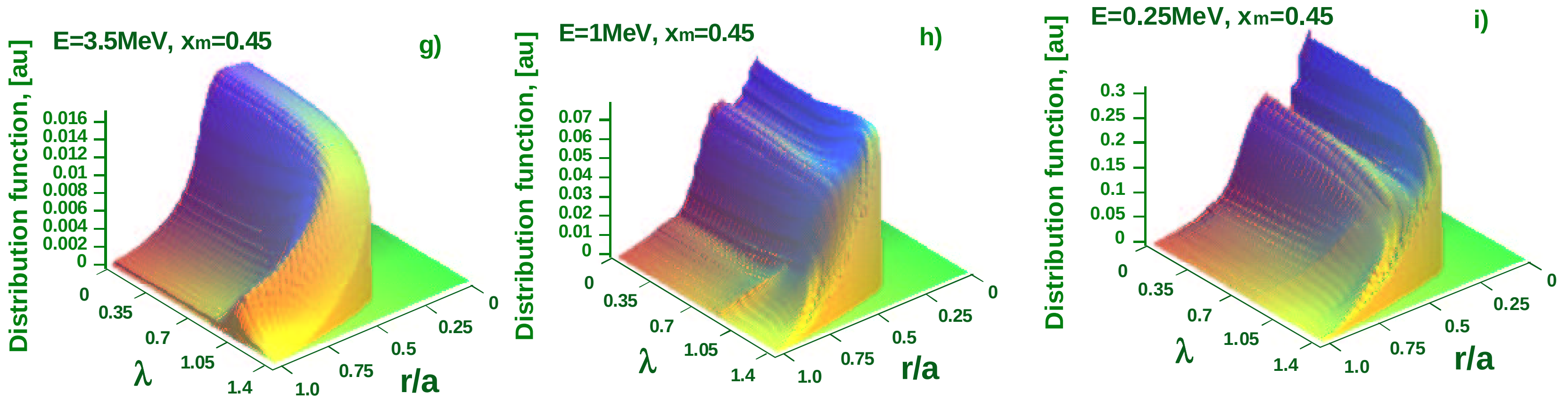
• counter-going particles, x_m=0



$f(r_{max}, \lambda)$ - monotonic in “radial” coordinate with maximum corresponding to stagnation orbits

Distribution function of confined alphas at I/B=2.5MA/3.45T for hollow *j*(*r*)

co-going particles, x_m=0.45



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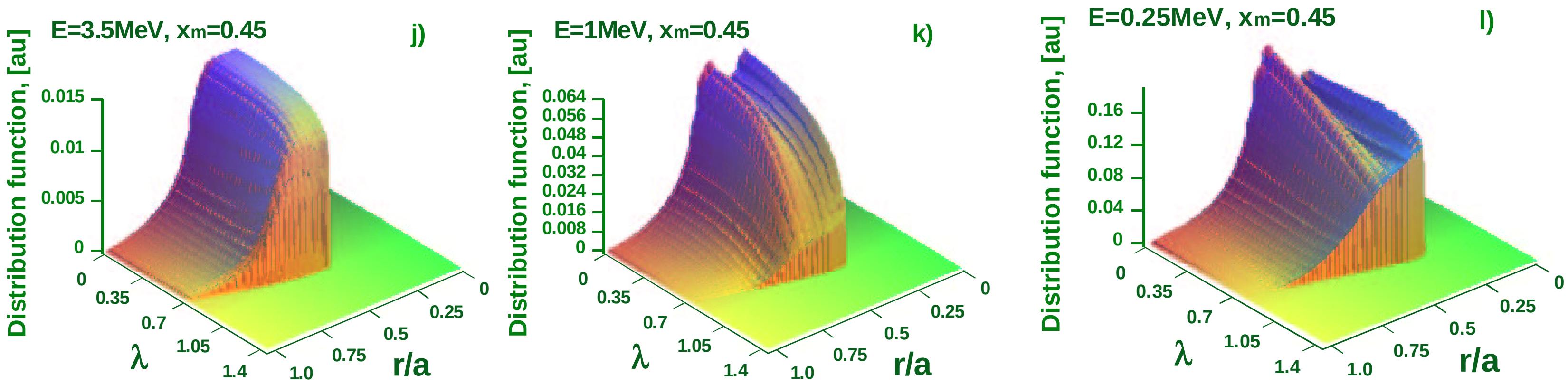
EFDA JET

• counter-going particles, x_m=0.45



$f(r_{max}, \lambda)$ - **nonmonotonic in "radial" coordinate with maximum corresponding to stagnation orbits**

$r_{max}\sim \min\{ r_{max} \}$ **and at** $r_{max}\sim (0.6\text{-}0.7)a$

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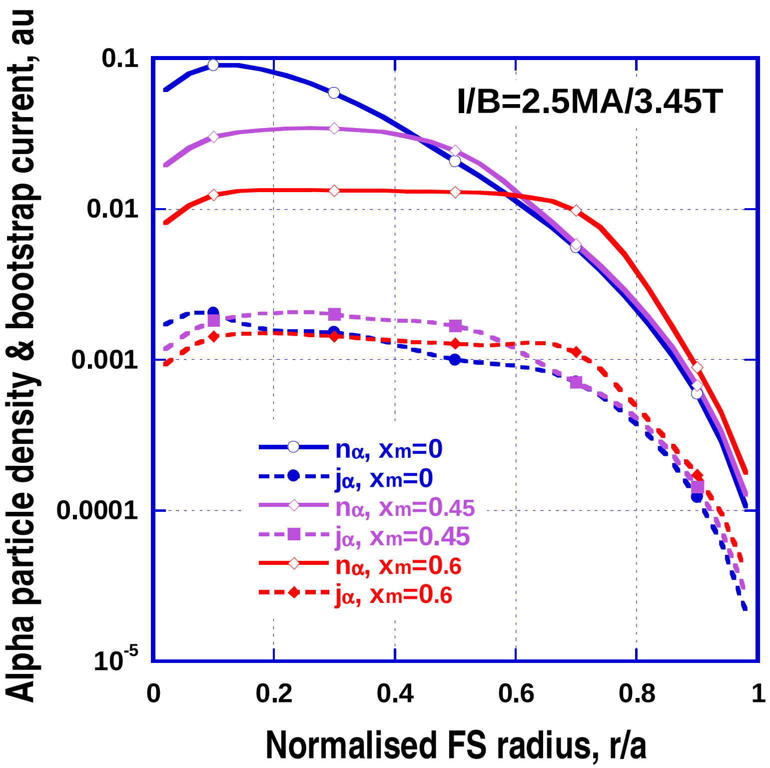
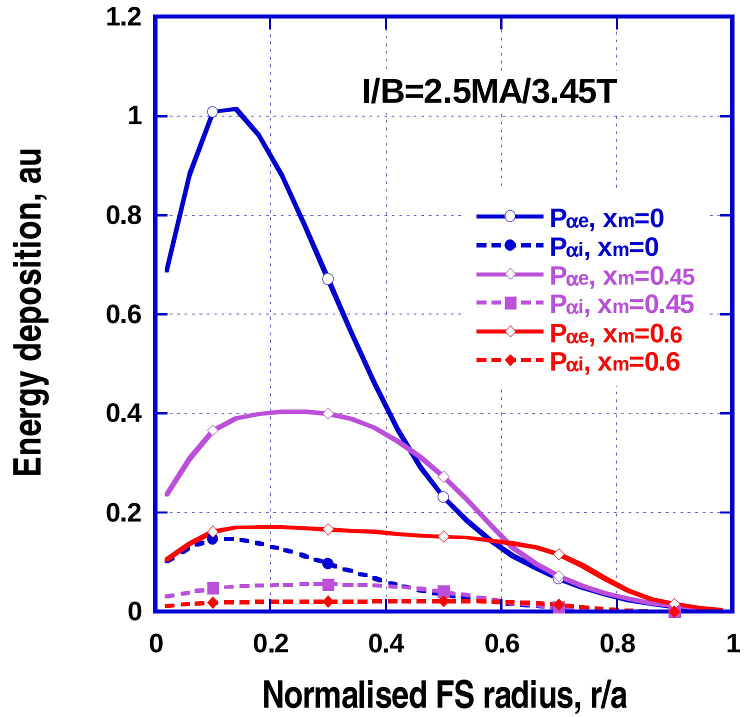
Alpha particle density, bootstrap current and energy deposition





hollow j profiles affect mainly n_α, $P_{\alpha e}$, $P_{\alpha i}$ and less j_α

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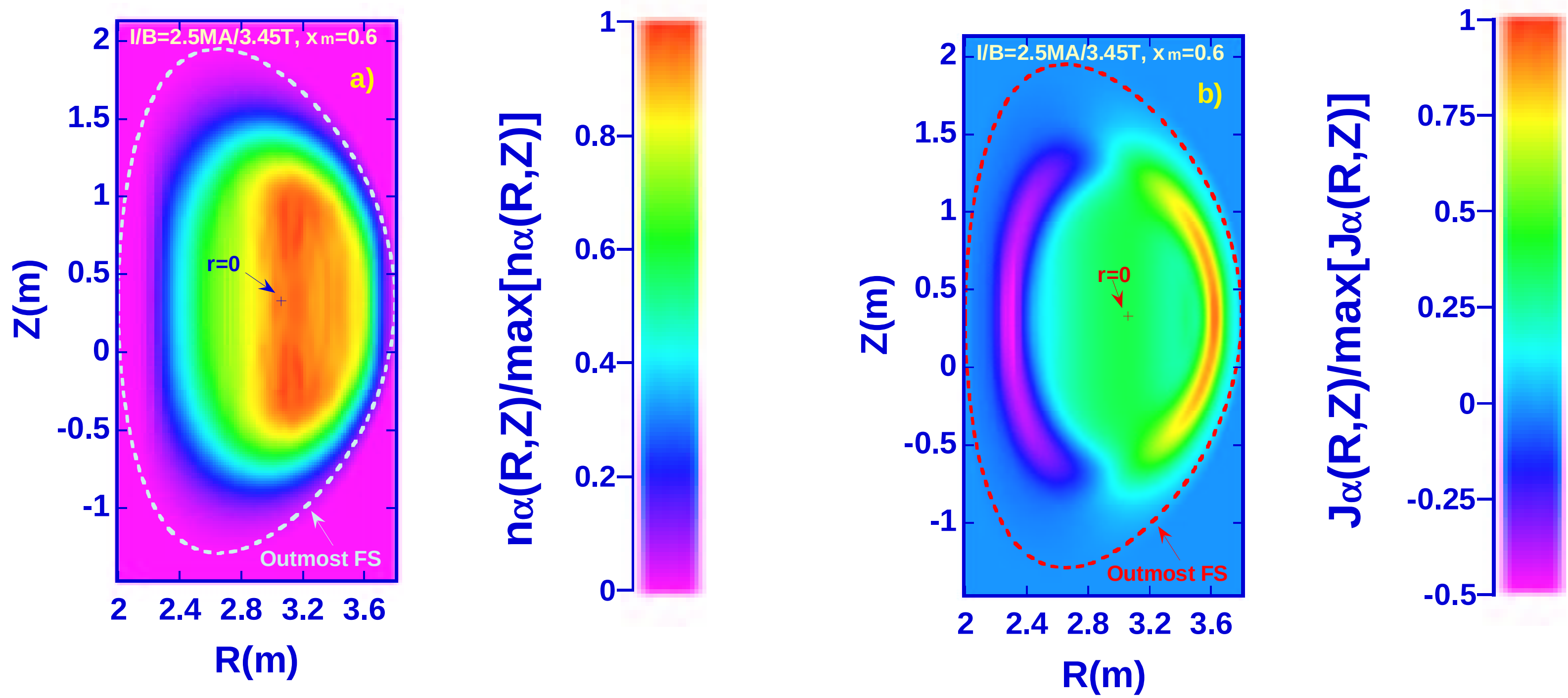
Alpha particle density and alpha driven current, I/B=2.5MA/3.45T, x_m=0.6



$$j_{\alpha\,tot} = j_\alpha\,[1 - (1 - G)Z_\alpha/Z_{eff}]$$

$j_{\alpha\,tot}$ – includes alpha current and electron reversed current;

$G \sim (r/R)^{1/2}$ – trapped electron correction

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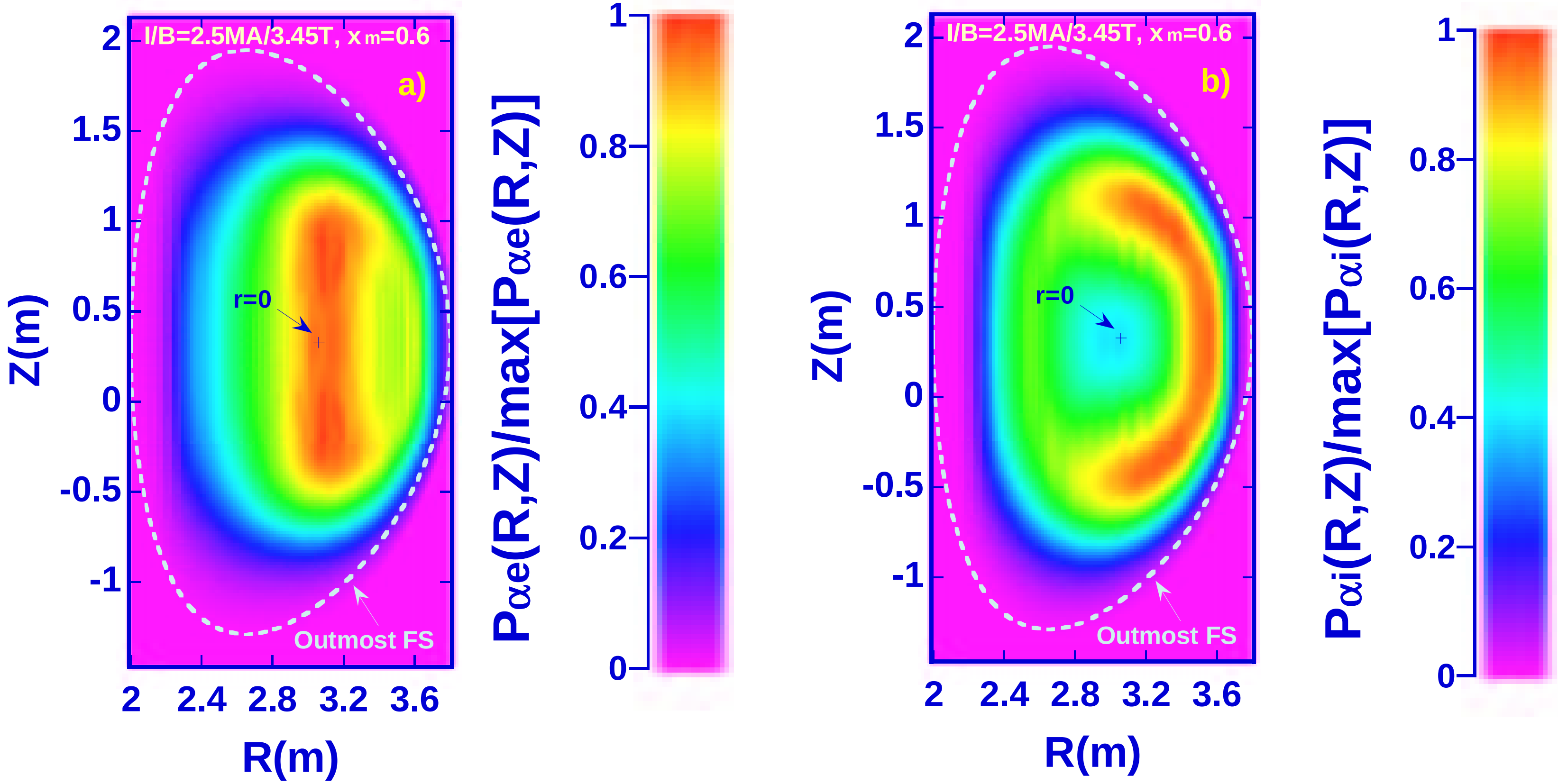
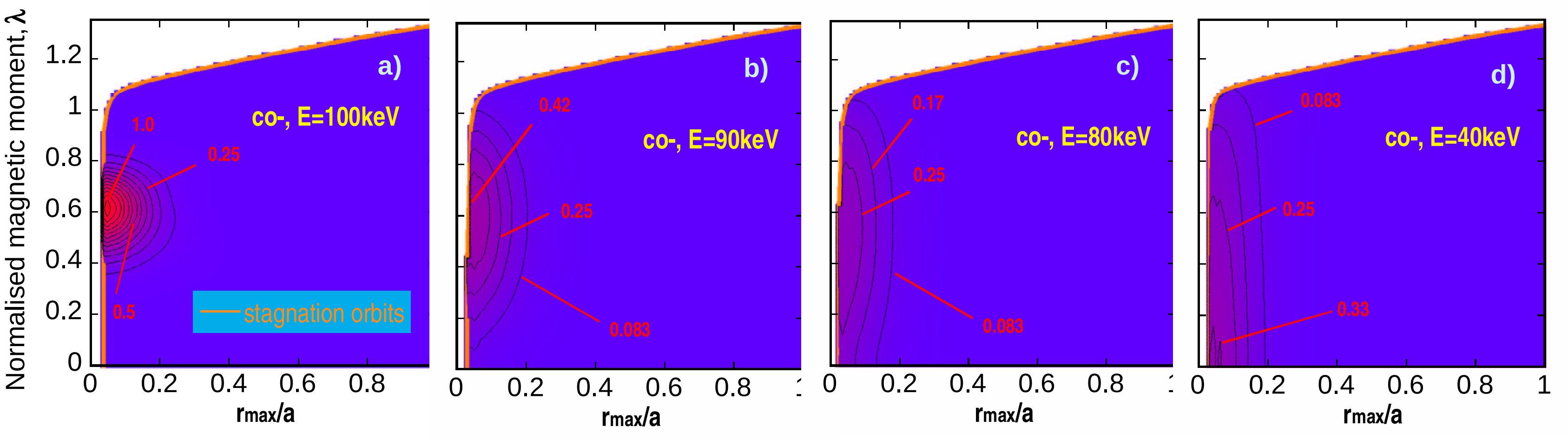
$P_{\alpha e}$ & $P_{\alpha i}$ power depositions, I/B=2.5MA/3.45T, x_m=0.6



$P_{\alpha e\ max} \sim 10\ P_{\alpha i\ max}$

Distribution function of NBI tritons at monotonic current

(on-axis co-injection, x_m=0, I/B=3MA/3.45T)



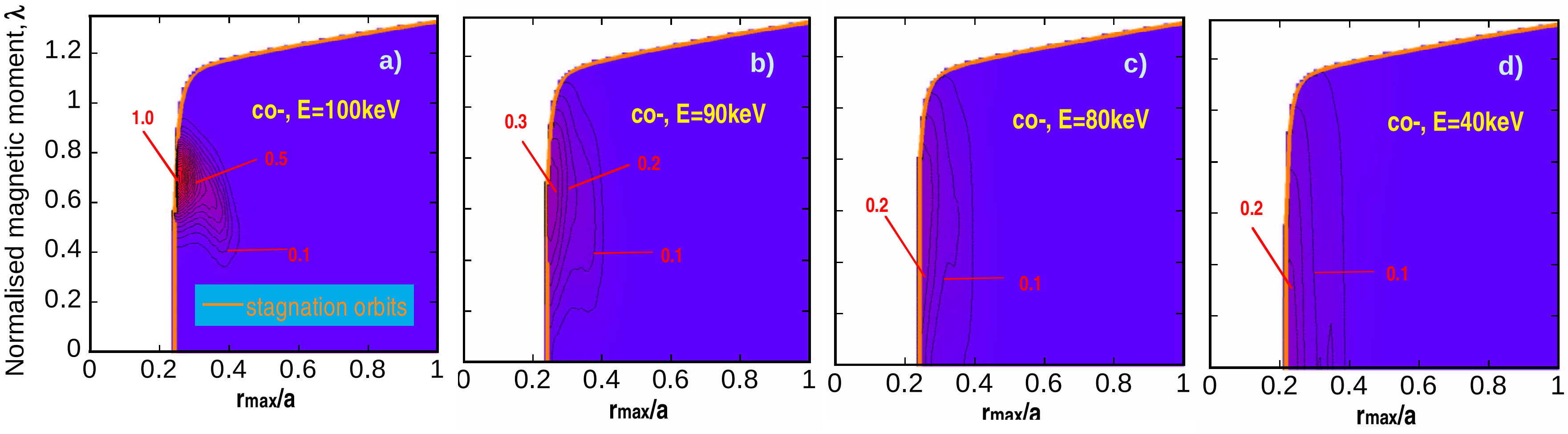
- *f* (40keV<E<100keV) is localized near the confinement domain boundary corresponding to the stagnation orbits with 0.03<r/a <0.1

reason: beam is rather thin and is injected in mid-plane

- at <u>monotonic current</u> the distribution of NBI tritons in plasma cross-section is maximum near magnetic axis

Distribution function of NBI tritons in CH JET equilibrium

(on-axis co-injection, x_m=0.45, I/B=3MA/3.45T)



- ***f*** **(40keV<E<100keV)** at x_m=0.45 is localized near the confinement domain boundary corresponding to the stagnation orbits with **0.25<r/a <0.3**

- **distribution of NBI tritons in plasma cross-section is strongly dependent on poloidal angle with maximum value at r/a~0.3 in midplane**

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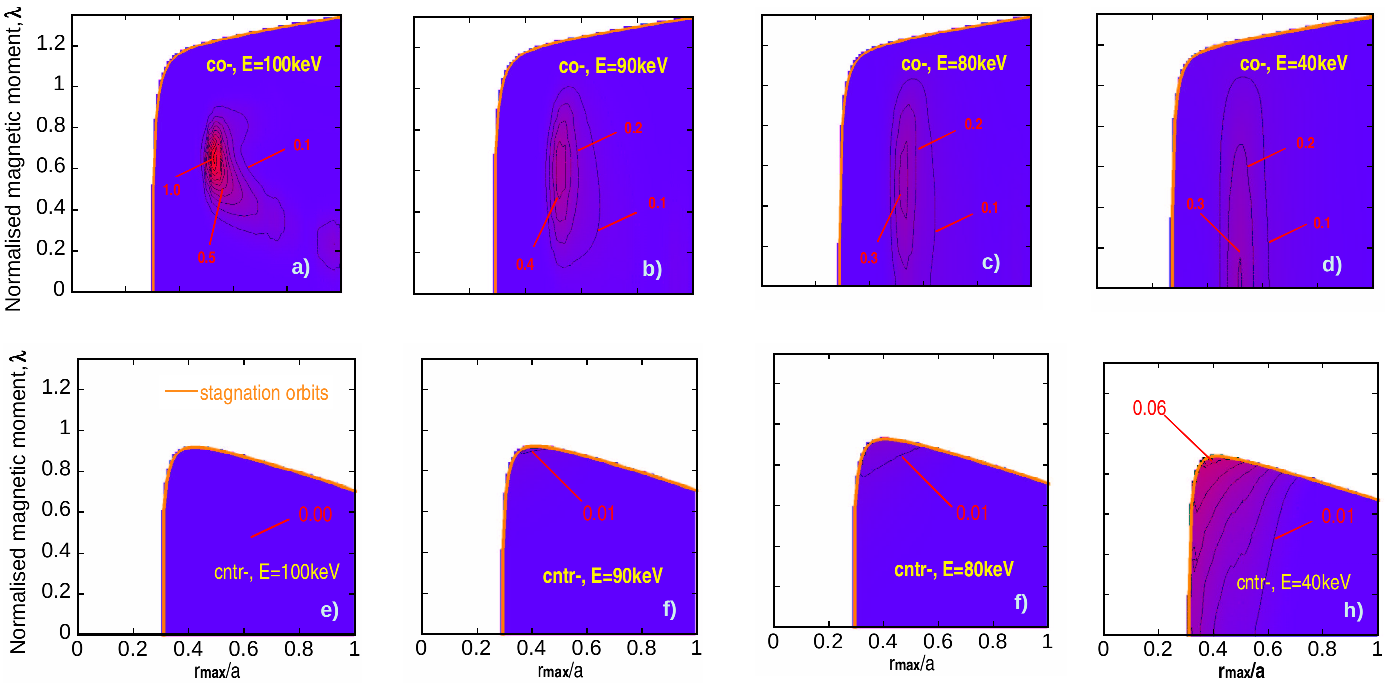
Distribution function of off-axis NBI tritons in CH JET equilibrium

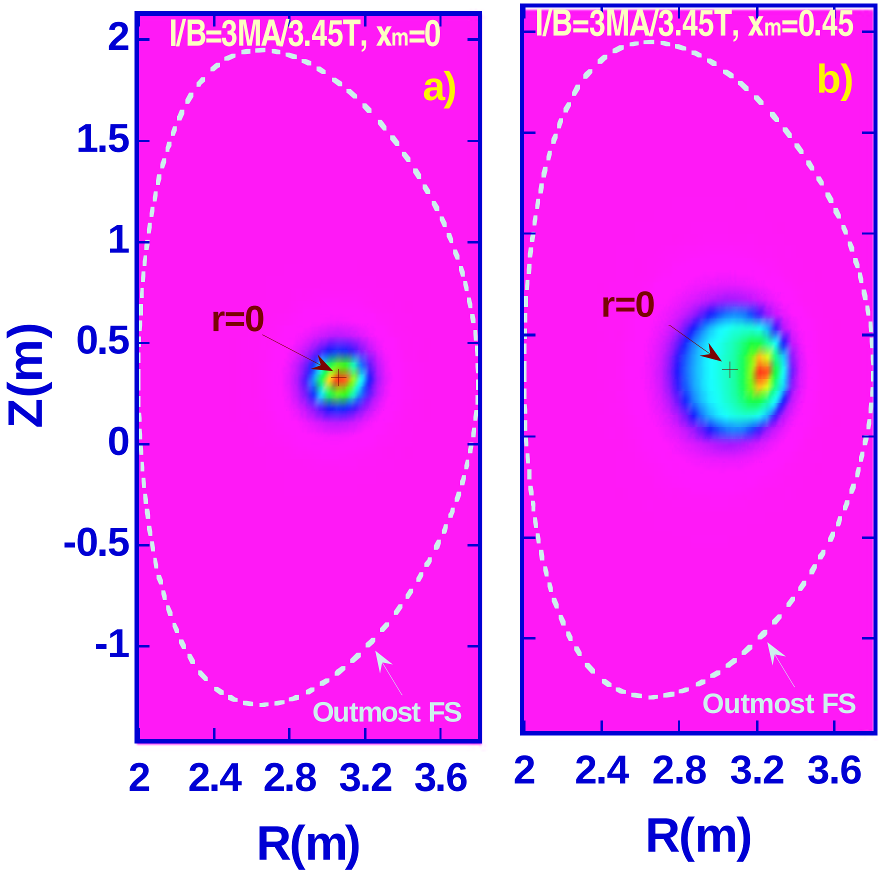
(co-injection, x_m=0.45, I/B=1MA/3.45T)



- **f (40keV<E<100keV) at x_m=0.45 is localized at r/a~0.5**
- **population of coutergoing tritons is small even at E=40keV in spite of rather strong pitch-angle scattering ($\nu_\perp/\nu_s$~0.5-1)**

➢ **distribution of NBI tritons in plasma cross-section is essentially nonmonotonic with maximum value at r/a~0.5**

CH effect on NBI triton induced neutron emission



- distribution of 14MeV neutron emission induced by NBI tritons in JET is expected to be essentially affected by the current hole
- in the case of on-axis injection CH seen to result in i) outward shift (~x_*) of the neutron emission maximum and ii) broadening of emission profile in plasma cross section

• Summary

- hollow current profiles in JET result in a moderate increase of FO & collisional losses of CFPs if current hole region is rather small, $r_m/a<0.5$
- at I>2MA FO loss fraction of CFPs is < 30% and collisional loss fraction is < 10-12% for DT alphas (with E>220keV) and < 20-25% for DD tritons (with E>40keV);

  maximum alpha particle flux is comparable and even exceeds the neutron flux and maximum alpha loss induced heat load is ~ 30-40% of neutron first wall load
- flux of lost CFPs is strongly localised both in poloidal and pitch angle; loss distribution is essentially affected by the current hole
- current hole effect is equivalent to the reduction of total plasma current in accordance with $I \Rightarrow I(1-x_*^{1/2})$
- distribution function of confined CFPs and NBI ions is essentially affected by hollow current profiles ⇒ *affects fast particle density, bootstrap current and energy deposition profiles, distribution of 14MeV neutron emission induced by NBI tritons*