3次元的な構造を持つ周辺磁場配位における プラズマ輸送解析と可視化

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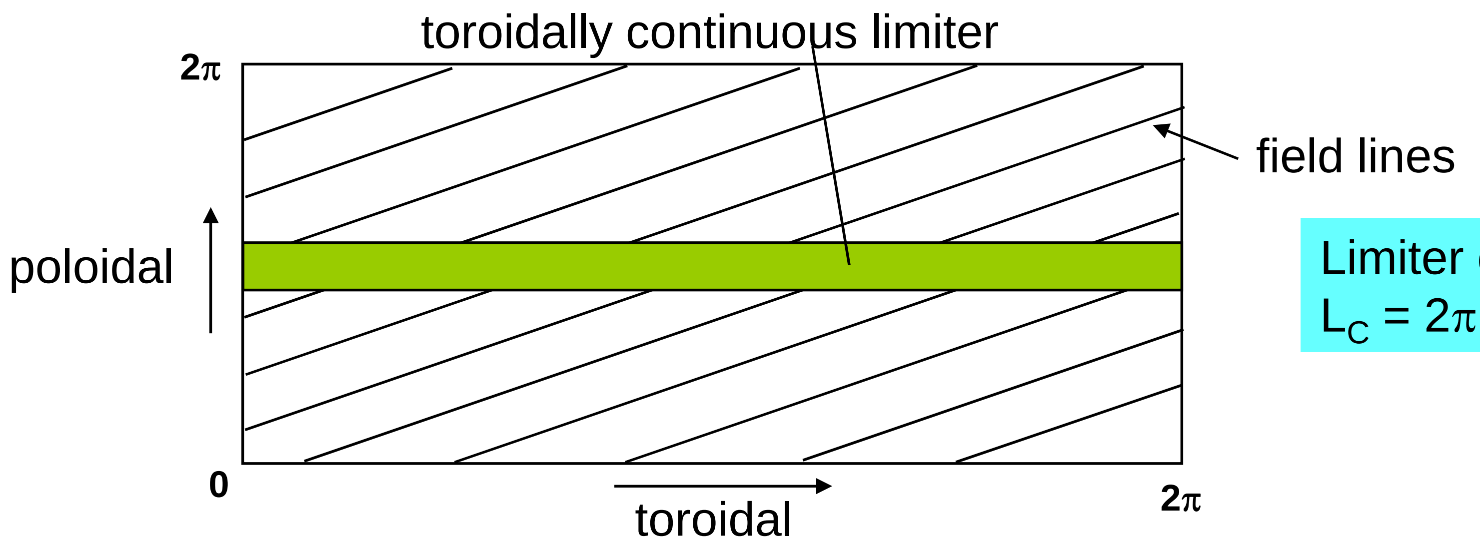
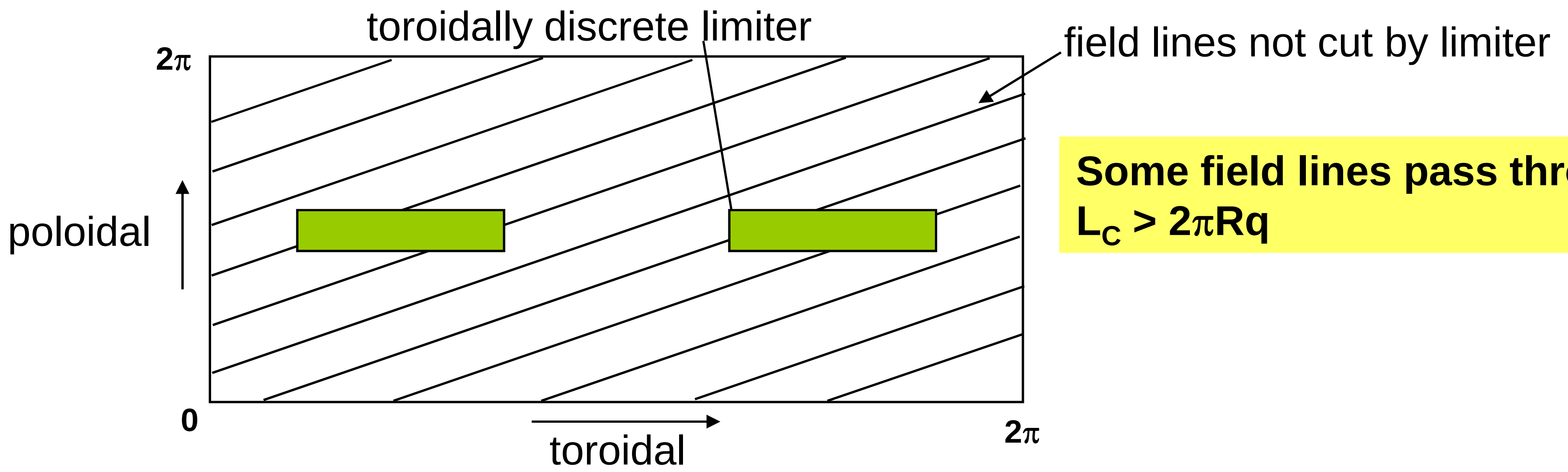
1. 3次元的な周辺磁場配位の例
2. 磁場構造（接続長分布）と予測される輸送
3. 3次元輸送解析
4. 磁場のシアーによる影響：3次元的効果
5. まとめ

3次元的な周辺磁場配位が現れる例:トカマク型装置

トロイダル方向に不連続なリミター配位(プラズマ立ち上げ時など)

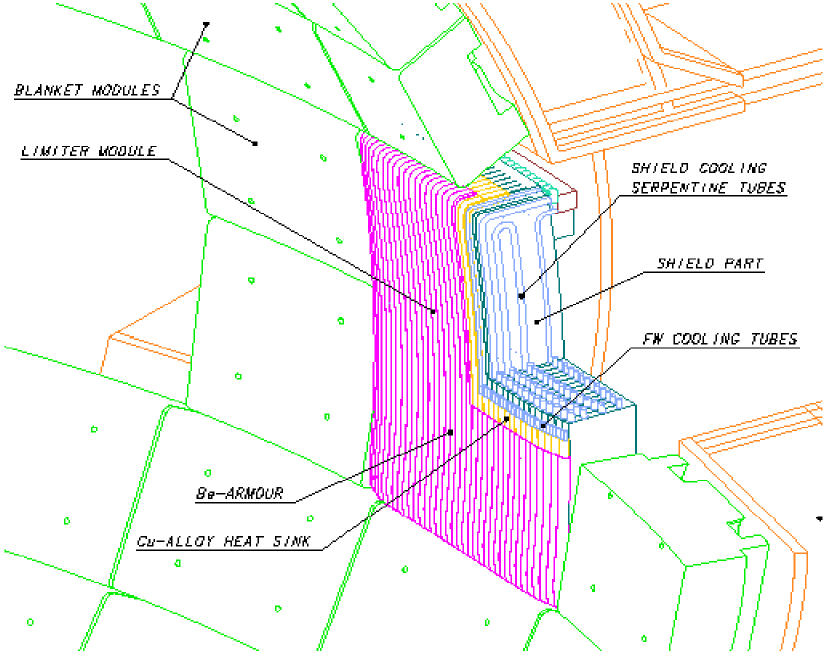


Limiter cut all field lines :
$L_C = 2\pi Rq$

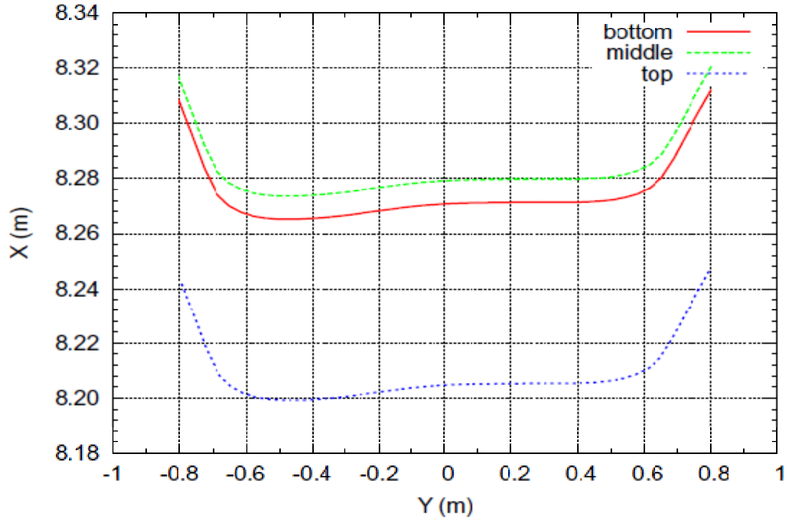


Some field lines pass through:
$L_C > 2\pi Rq$

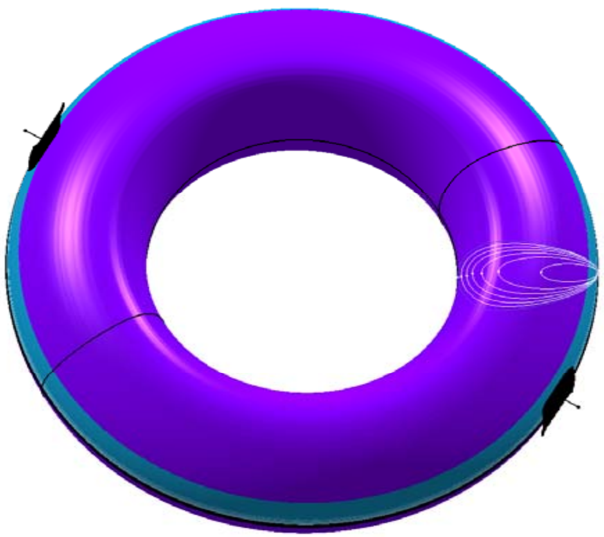
ITERプラズマ立ち上げ時のリミター



horizontal cut of the limiter



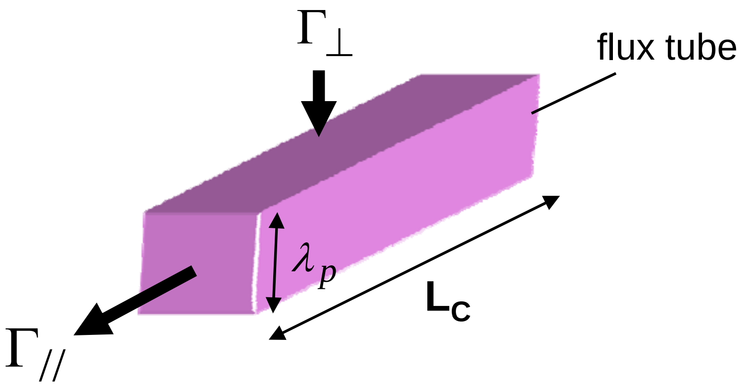
toroidal extent : $\Delta\phi$ ~ 12 deg. (1.6m)
poloidal extent is ~ 2.1 m
Surface area ~ 3 m^2/each (Beryllium)
P_{SOL} ~ several MW



Assumed symmetrically placed
(ϕ=180 deg. apart each other)

Power fall-off length : λ_p

<Simple estimation>



from energy conservation

$$2\Gamma_{//}\lambda_p = \Gamma_\perp L_C$$

⇩

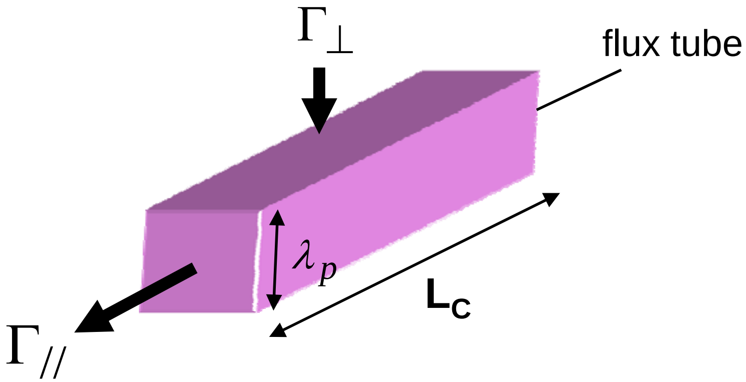
$$\lambda_p \propto \sqrt{\frac{L_C(D_\perp, \chi_\perp)}{c_s}}$$

$D_\perp, \chi_\perp$: cross. trans. coefficients
(assumed to be anomalous)

- For ITER, L_C is long, 2πRq~240m.
- Because of localization of limiter, L_C >> 2πRq, at rational q surfaces.
- D_{perp}, χ_{perp} unknown for ITER.
- Long λ_p -> leading edge, short λ_p -> higher peak power load

Parallel energy flux : $\Gamma_{//}$

<Simple estimation>



$$2\Gamma_{//}\lambda_p = \Gamma_{\perp} L_C$$

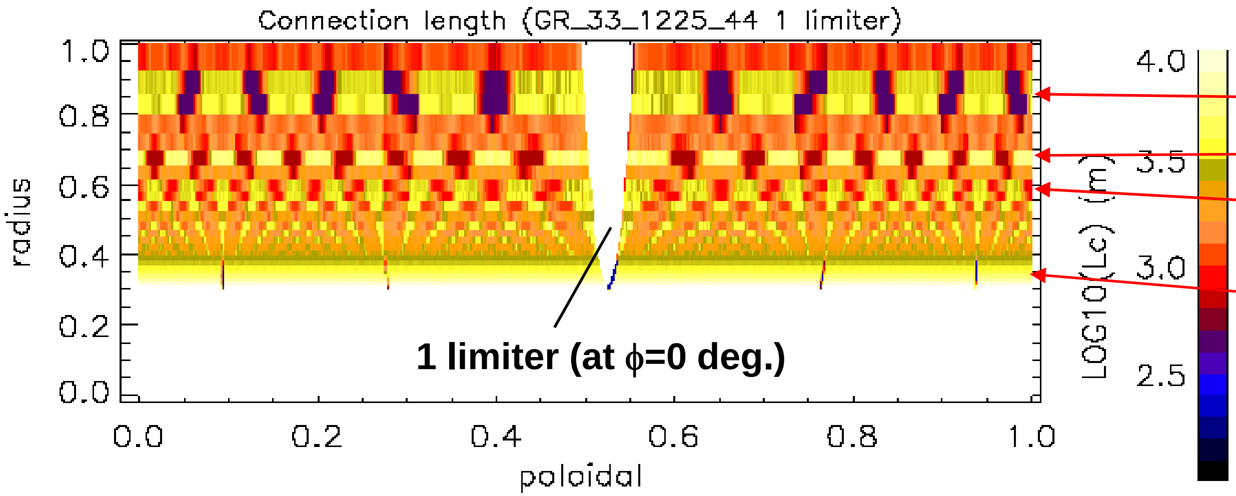
$$\Gamma_{//} = \Gamma_{\perp} L_C / 2\lambda_p \propto \sqrt{L_C}\,\Gamma_{\perp}$$

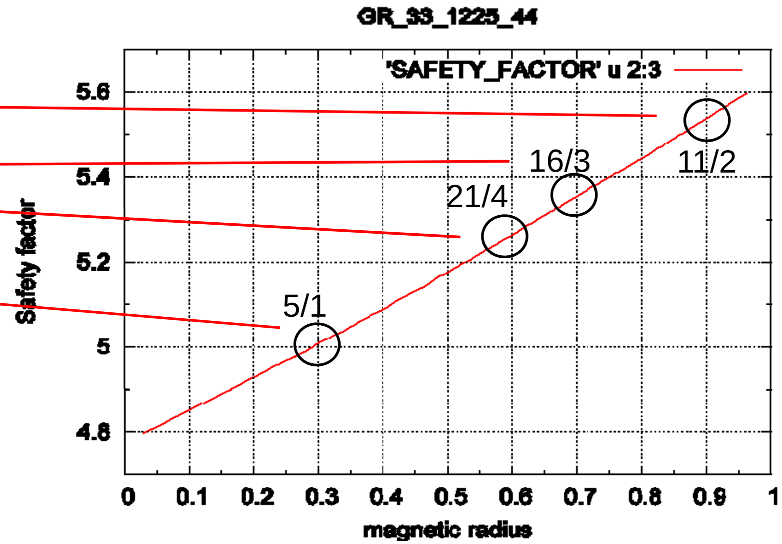
⇩

$$\Gamma_{//} \propto \sqrt{L_C}$$

- Longer flux tubes are fed with more energy.
- Because of localization of limiter, L_C >> $2\pi Rq$, at rational q surfaces.
- When they hit limiter, they cause a hot spot!?
- Cross trans. eases the dependence, $\Gamma_{//} \propto \sqrt{L_C}$. To what extent ?

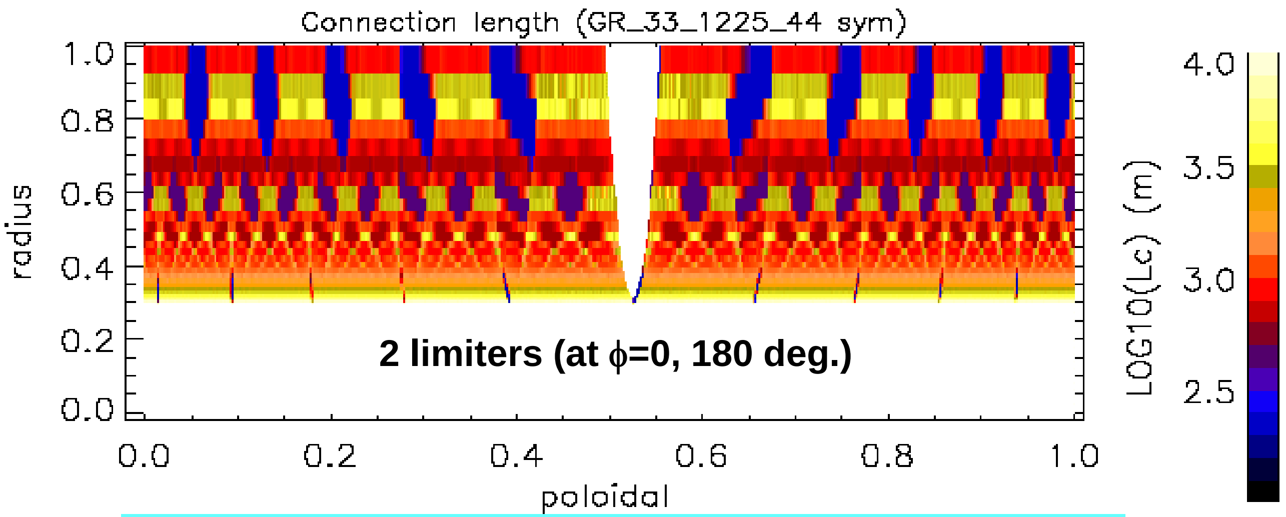
B field structure : connection length profiles

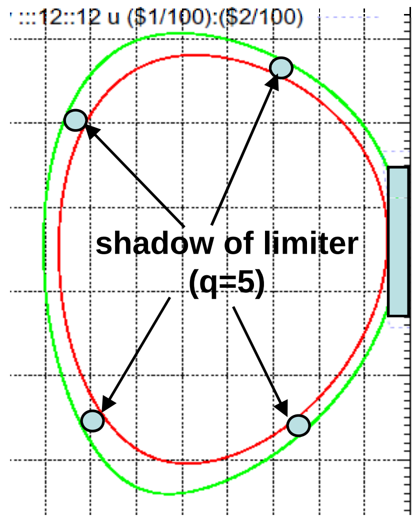




Mode structures identified (resonance)

Resonance at Rational surface :
Long & Short L_C





Resonance from both limiters superposed
Connection length reduced

Fluid equations solved in EMC3

Plasma fluid equations

<density>

$$\nabla_\parallel \cdot (n\boldsymbol{V}_\parallel) + \nabla_\perp \cdot (-D\nabla_\perp n) = S_p,$$

<momentum>

$$\nabla_\parallel \cdot (m_i n \boldsymbol{V}_\parallel \boldsymbol{V}_\parallel - \eta_\parallel \nabla_\parallel \boldsymbol{V}_\parallel) + \nabla_\perp \cdot (-m_i \boldsymbol{V}_\parallel D \nabla_\perp n - \eta_\perp \nabla_\perp \boldsymbol{V}_\parallel) = -\nabla_\parallel p + \boldsymbol{S_m},$$

<ion energy>

$$\nabla_\parallel \cdot (-\kappa_i \nabla_\parallel T_i + \frac{5}{2} n T_i \boldsymbol{V}_\parallel) + \nabla_\perp \cdot (-\chi_i n \nabla_\perp T_i - \frac{5}{2} T_i D \nabla_\perp n) = k(T_e - T_i) + S_{ei},$$

<electron energy>

$$\nabla_\parallel \cdot (-\kappa_e \nabla_\parallel T_e + \frac{5}{2} n T_e \boldsymbol{V}_\parallel) + \nabla_\perp \cdot (-\chi_e n \nabla_\perp T_e - \frac{5}{2} T_e D \nabla_\perp n) = -k(T_e - T_i) + S_{ee},$$

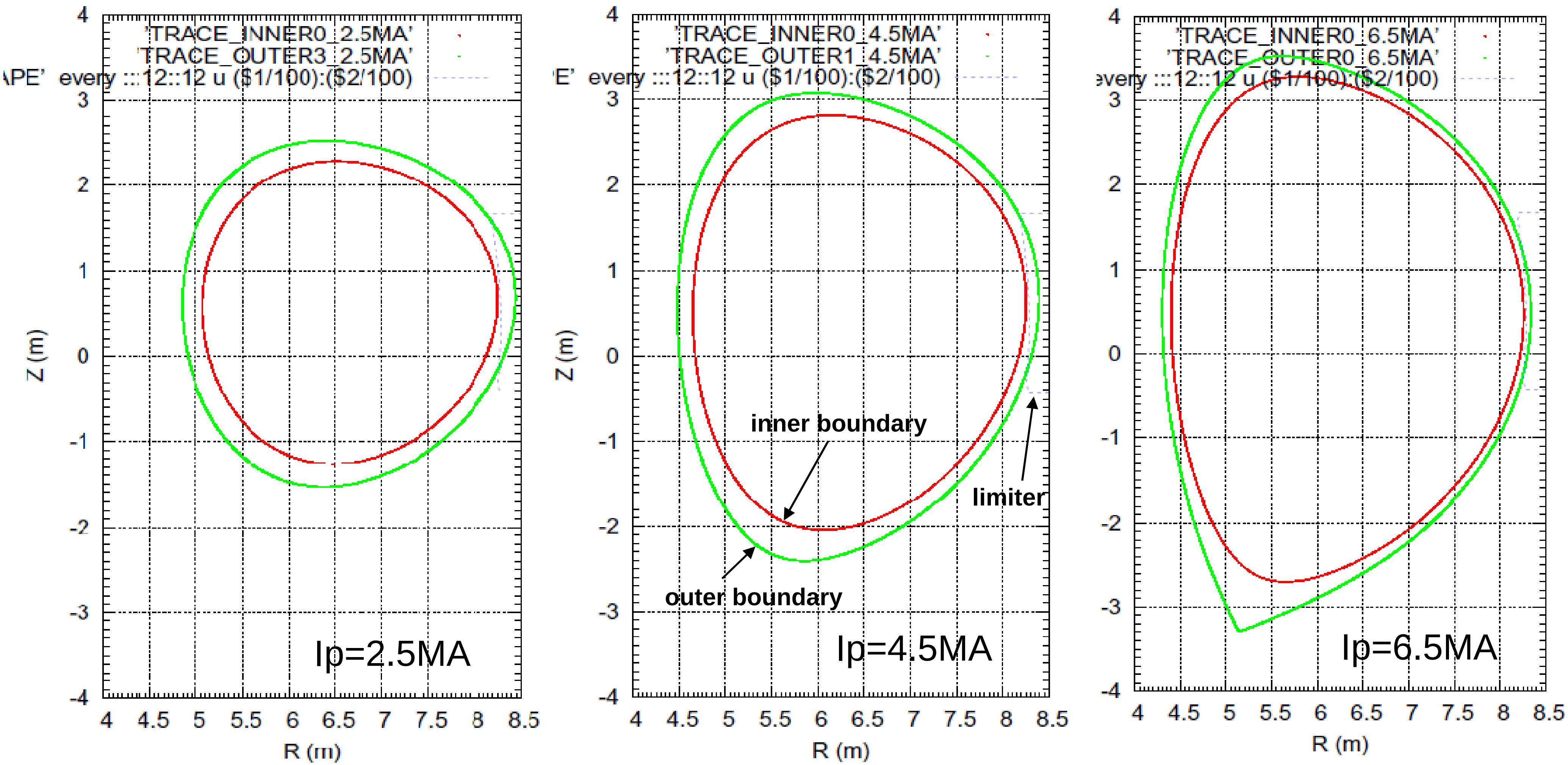
Fokker-Planck equation

$$\nabla_\parallel \cdot [\mathbf{a}_\parallel f - \nabla_\parallel (b_\parallel f)] + \nabla_\perp \cdot [\mathbf{a}_\perp f - \nabla_\perp (b_\perp f)] = S,$$

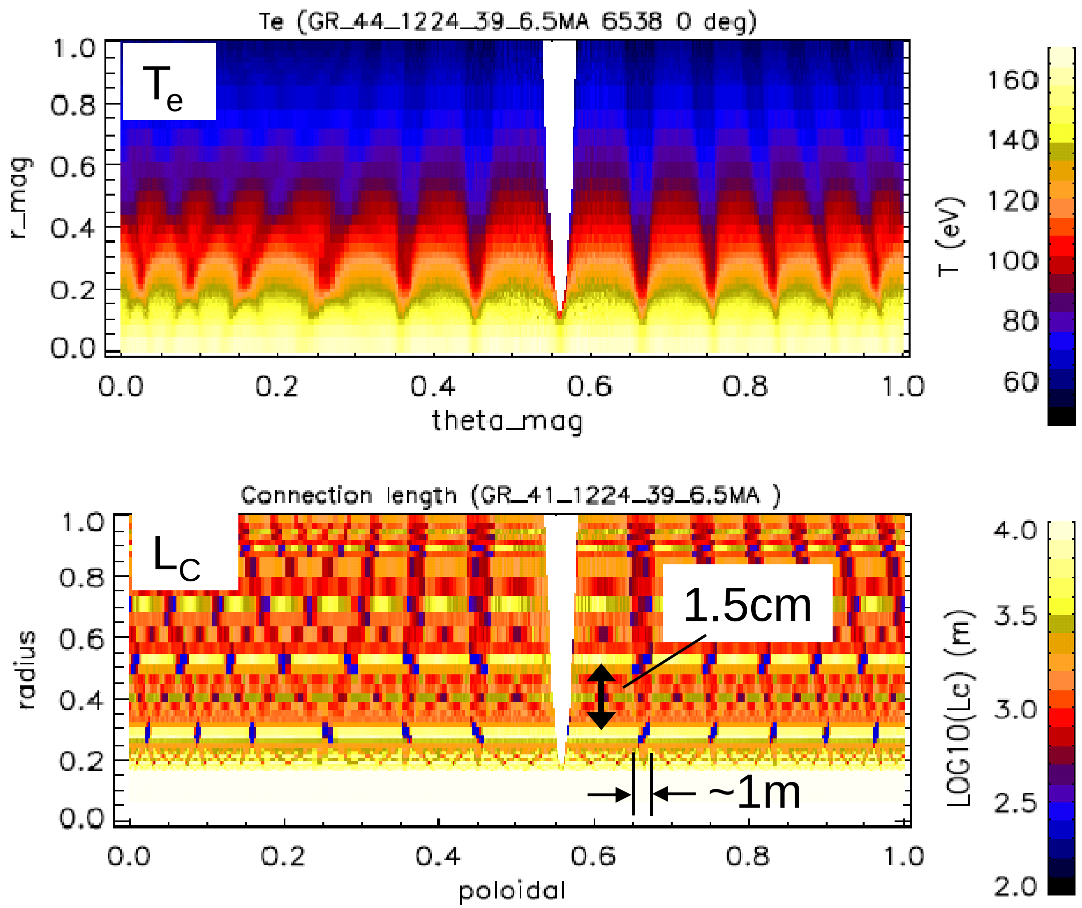
<Coefficients for different f's>

f :	density n	velocity $\mathbf{V}_\parallel$	temperature $T_{i,e}$
$\mathbf{a}_\parallel$:	$\boldsymbol{V}_\parallel$	$m_i n \boldsymbol{V}_\parallel + \nabla_\parallel \eta_\parallel$	$\frac{5}{2} n \boldsymbol{V}_\parallel + \nabla_\parallel \kappa_{i,e}$
$b_\parallel$:	0	$\eta_\parallel$	$\kappa_{i,e}$
$\mathbf{a}_\perp$:	0	0	$(\chi_{i,e} - \frac{5}{2} D) \nabla_\perp n$
$b_\perp$:	D	$m_i n D$	$n \chi_{i,e}$
S :	S_p	$-\nabla_\parallel p + \boldsymbol{S_m}$	$\pm k(T_e - T_i) + S_{ei,ee}$

Computational domain

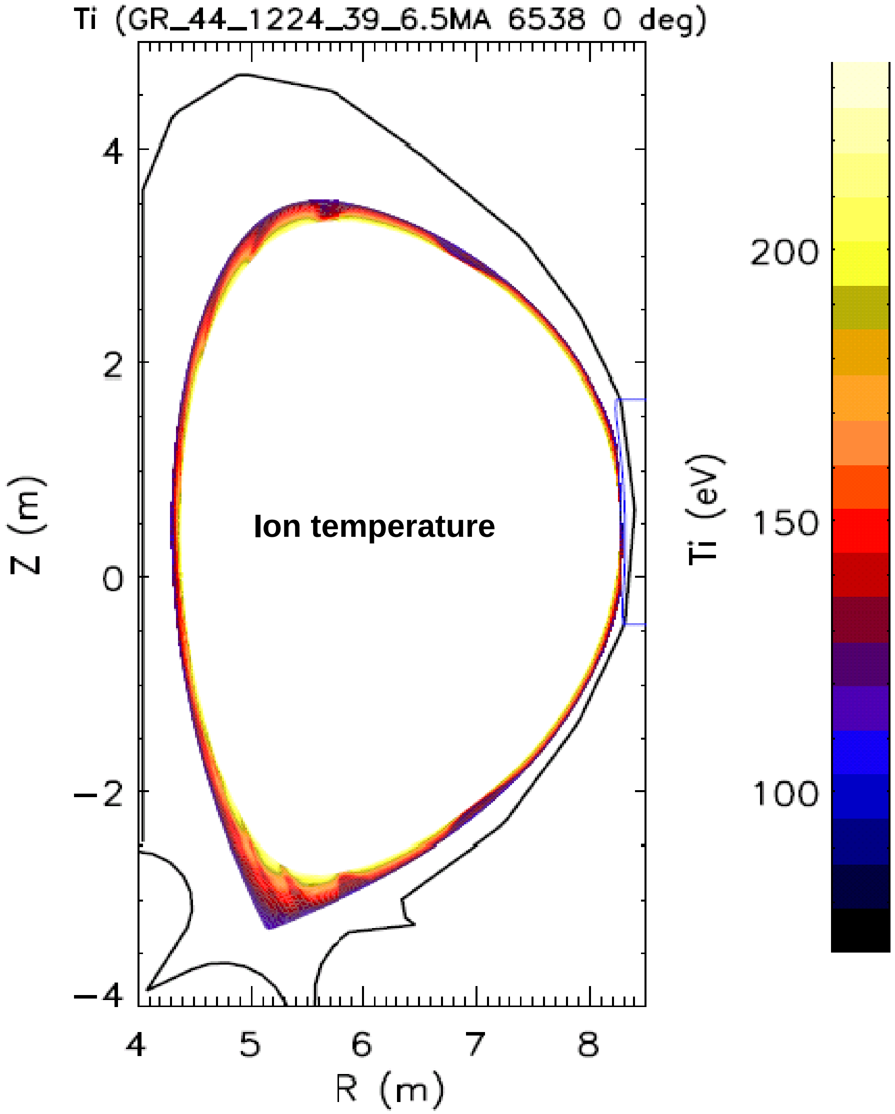


Plasma parameter modulation with Lc profile

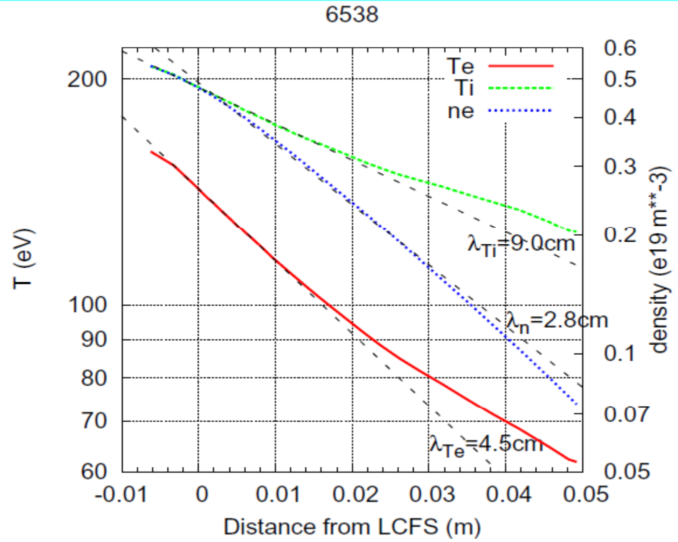


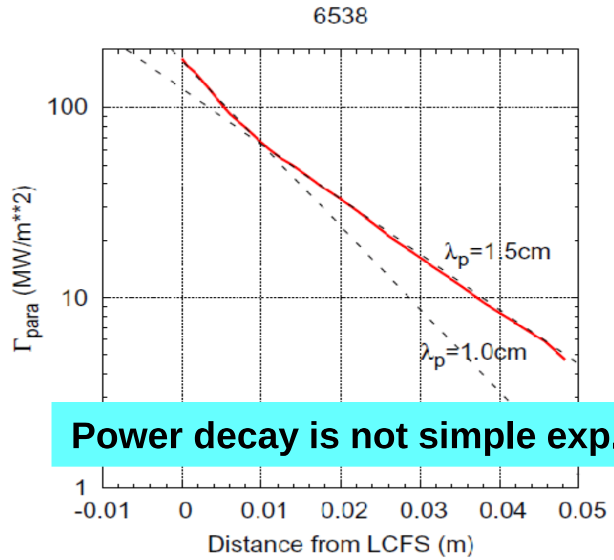
Results of EMC3-EIRENE

Strong poloidal modulation due to limiter shadow



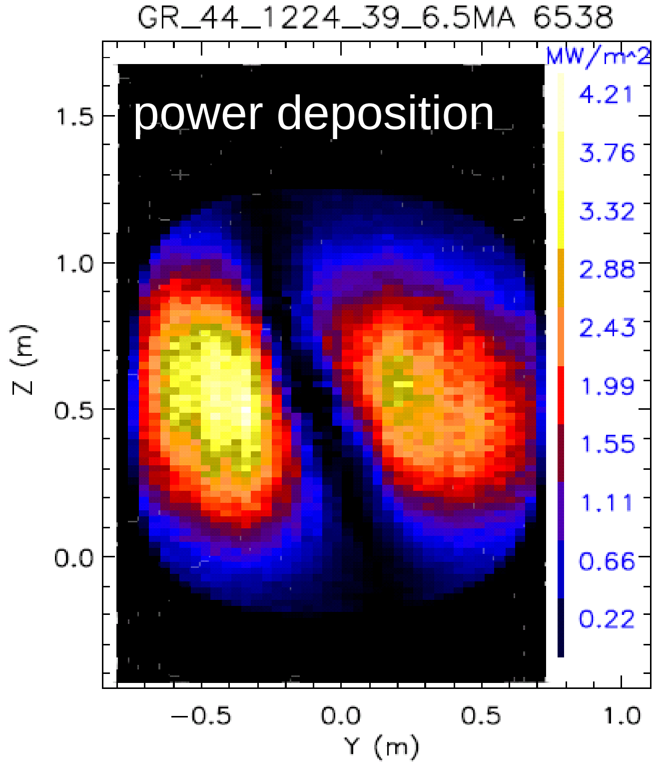
$D_\perp$: scaled from JET data with respect to Ip
$\chi_\perp = 4D_\perp$ => λ_{Te}/λ_n ~1.5, agrees with experiments

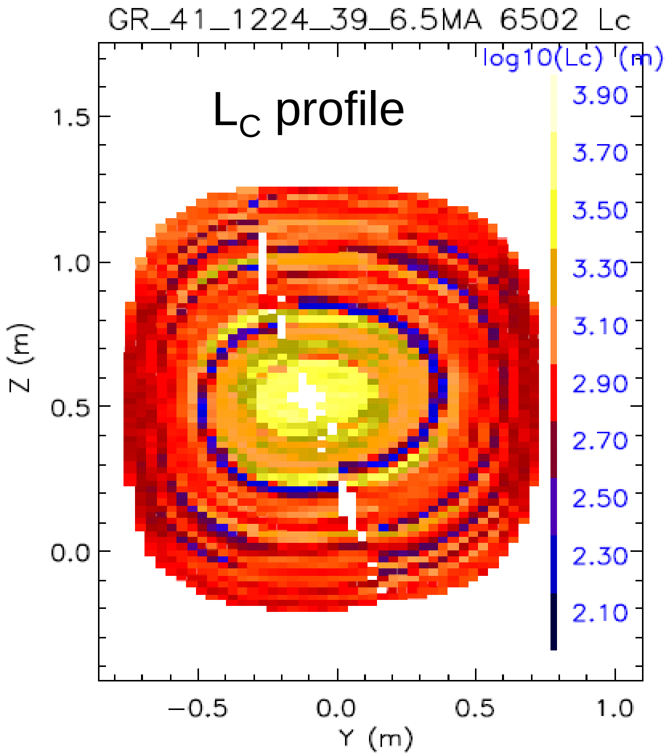




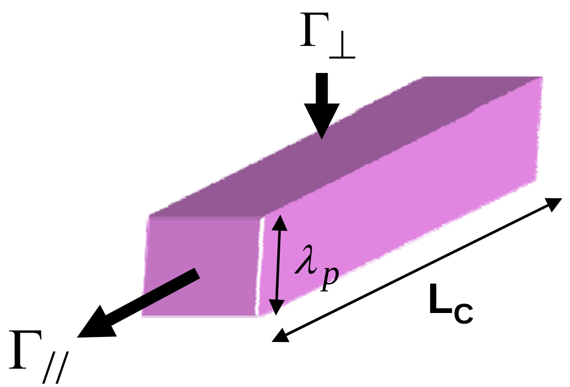
Power decay is not simple exp.

No clear correlation between deposition & L_C





Simple estimation of $\Gamma_{//}$



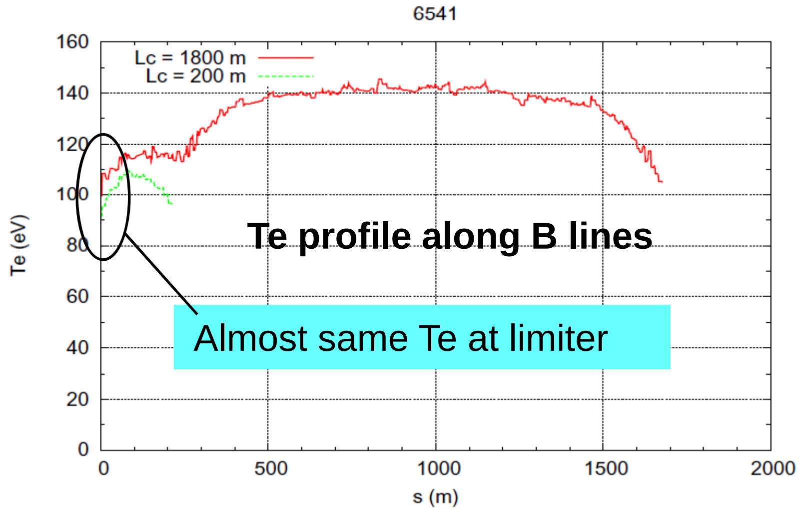
$$2\Gamma_{//}\lambda_p = \Gamma_\perp L_C$$

$$\Gamma_{//} = \Gamma_\perp L_C / 2\lambda_p \propto \sqrt{L_C}\,\Gamma_\perp$$

No clear evidence of

$$\Gamma_{//} \propto \sqrt{L_C}$$

⊥ transport smears out ?!



Parameter scan : D, $\chi_\perp$

n_{up}, P_{SOL} <= core transport simulation

$D_\perp$: scaled from JET data with respect to Ip
$\chi_\perp$ = 2 ~ 4$D_\perp$ => λ_{Te}/λ_n=1 ~1.5

0.2n_G

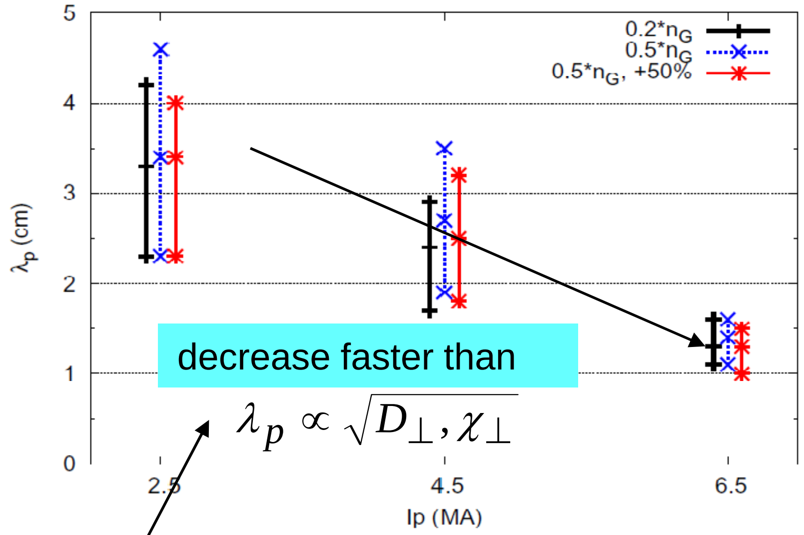
Ip (MA)	Psol (MW)	$D_\perp$ (m**2/s)	λ_{Te}/λ_n	n_{up} (e19m**-3)
2.5	1.0	1.0 ~ 3.0	1	0.12
4.5	2.0	0.3 ~ 1.0	1.5	0.17
6.5	3.0	0.2 ~ 0.4	1.5	0.22

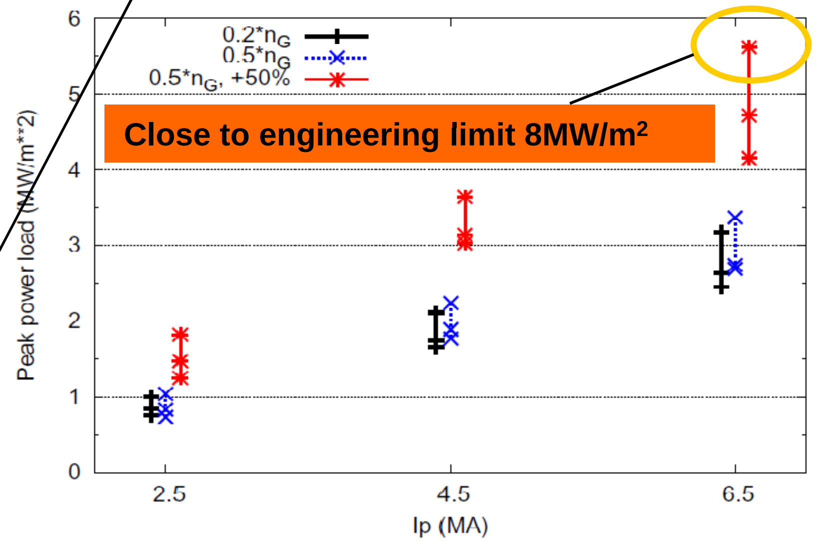
0.5n_G

2.5	1.3	1.0 ~ 3.0	1	0.30
4.5	2.6	0.3 ~ 1.0	1.5	0.44
6.5	4.0	0.2 ~ 0.4	1.5	0.54

0.5n_G, +50% P_{SOL}

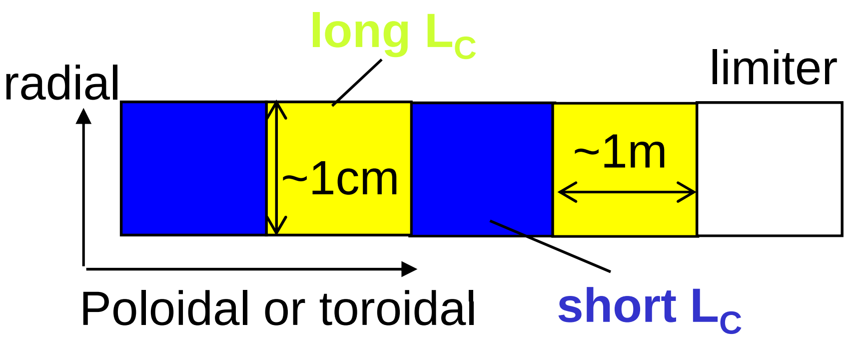
2.5	2.0	1.0 ~ 3.0	1	0.30
4.5	4.0	0.3 ~ 1.0	1.5	0.44
6.5	6.0	0.2 ~ 0.4	1.5	0.54

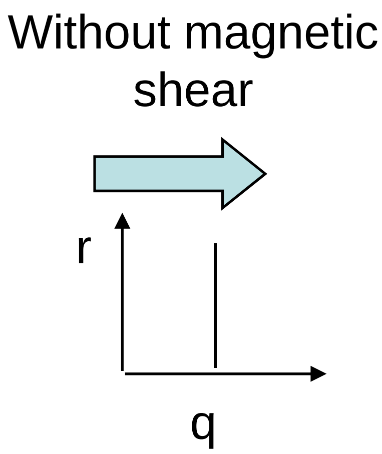


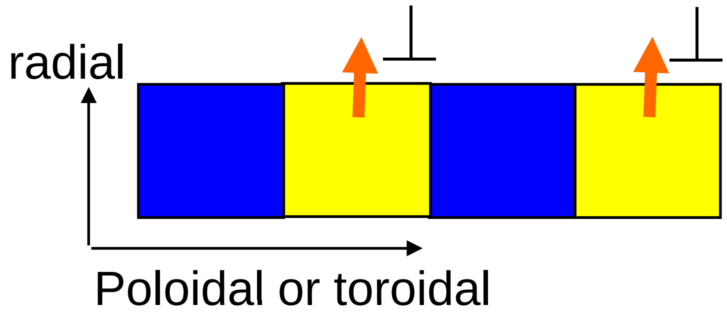


λ_p < a few cm : no dependence of $\lambda_p \propto \sqrt{L_C}$!?
More than 90% of power deposited on limiter!!

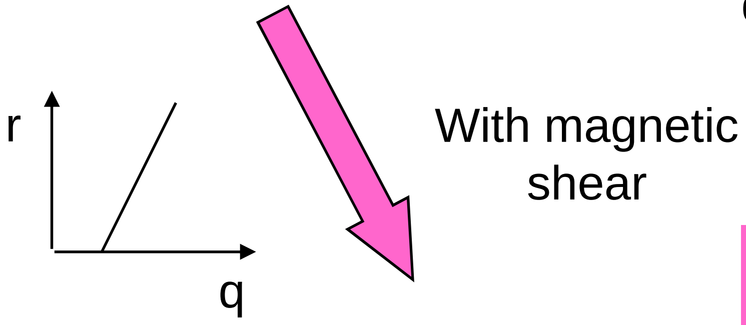
Role of magnetic shear to squeeze short & long flux tubes



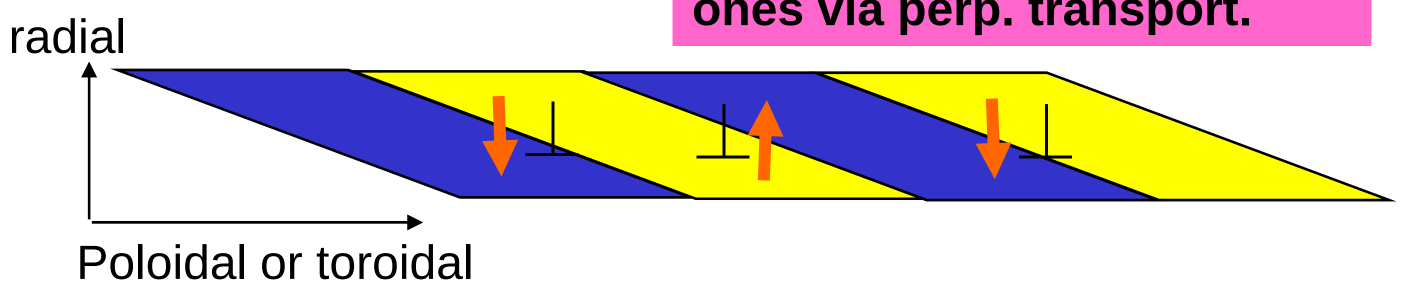




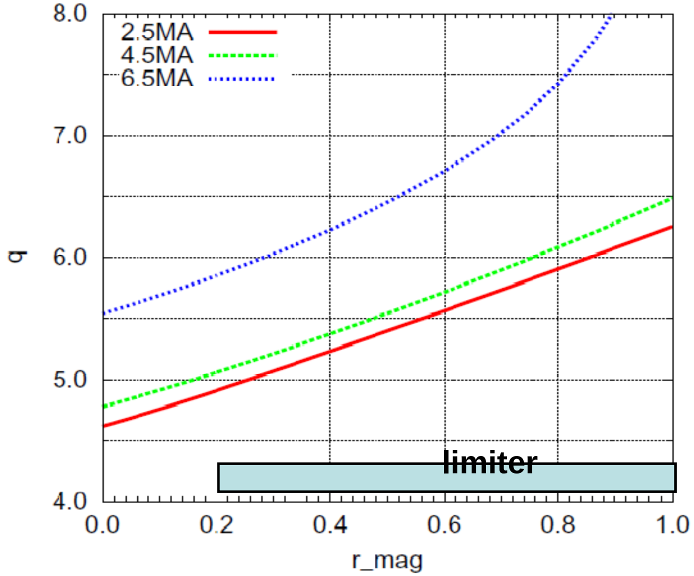
Large energy loss to outside of SOL through long flux tubes via perp. transport.

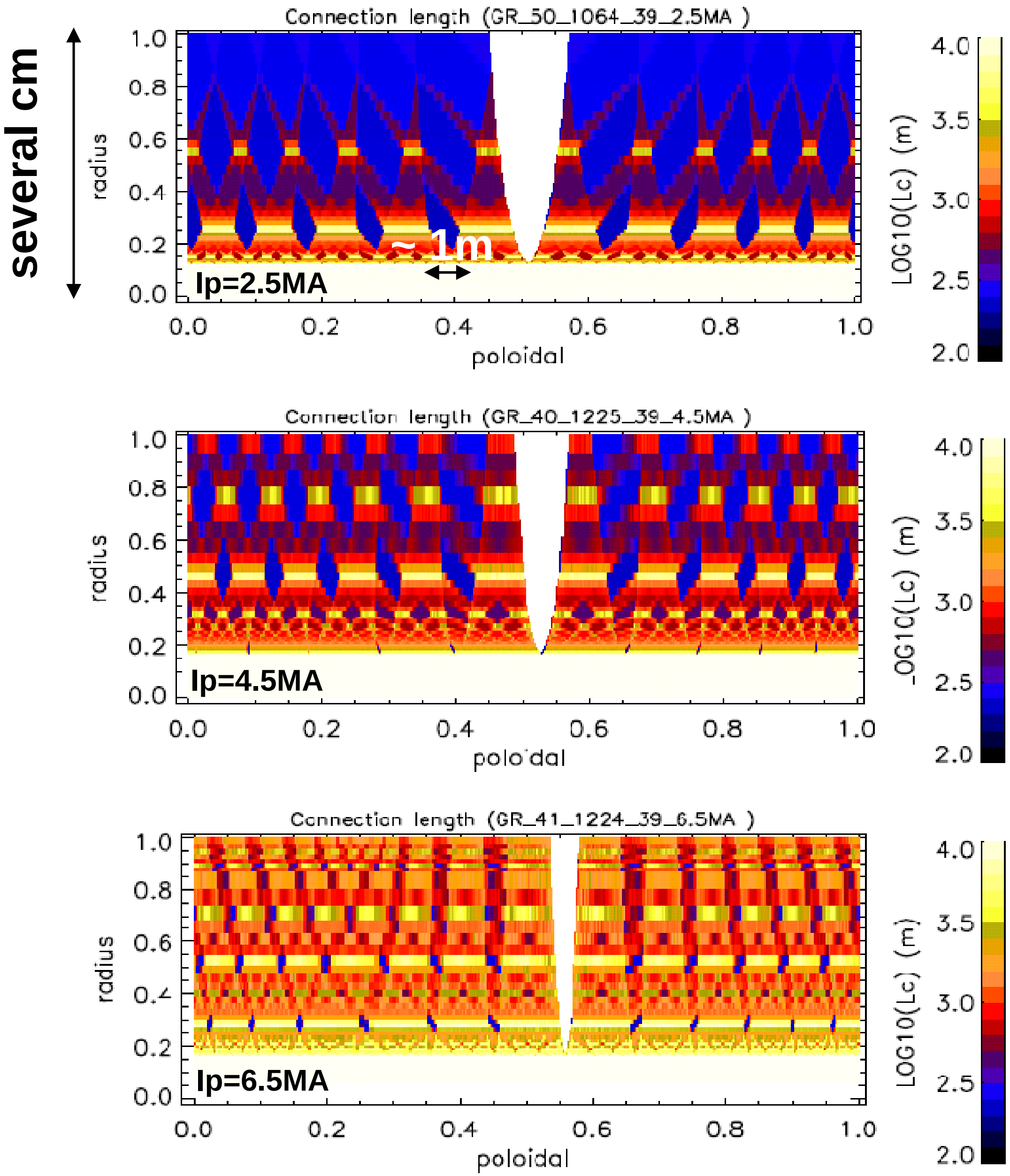


Short flux tubes effectively collect energy from long ones via perp. transport.



Connection length Lc : squeeze of long & short flux tubes





long-Lc reduces ||-to-⊥ transport ratio

||-energy transport time scale:

Collisional:

$$\tau_{E//} = \frac{3n_u T_u\, s}{q_{//}} = \frac{3n_u T_u\, s}{\dfrac{4\kappa_0 T_u^{7/2}}{7s}} = \frac{21 n_u\, s^2}{4\kappa_0 T_u^{5/2}}$$

Collisionless:

$$\tau_{E//} = \frac{3n_u T_u\, s}{q_{//}} = \frac{3n_u T_u\, s}{\gamma \dfrac{n_u}{2} C_s T_u} = \frac{6s}{\gamma C_s}$$

⊥-energy transport time scale:

$$\tau_{E\perp} = \frac{\Delta r^2}{2\chi_\perp} = 1\text{~}2\ \text{ms}$$

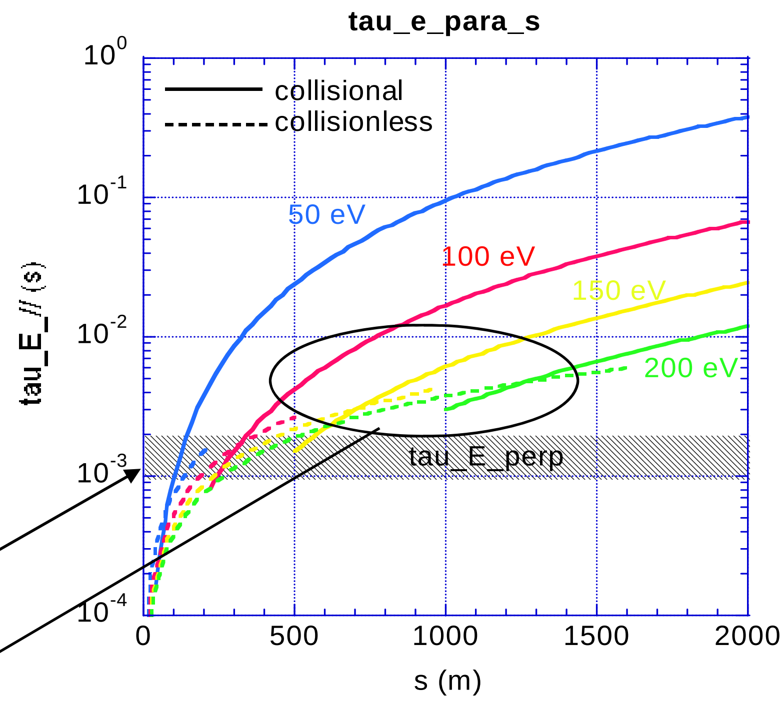
with Δr being SOL width ~ 5 cm.

$$\tau_{E\perp} < \tau_{E//}$$

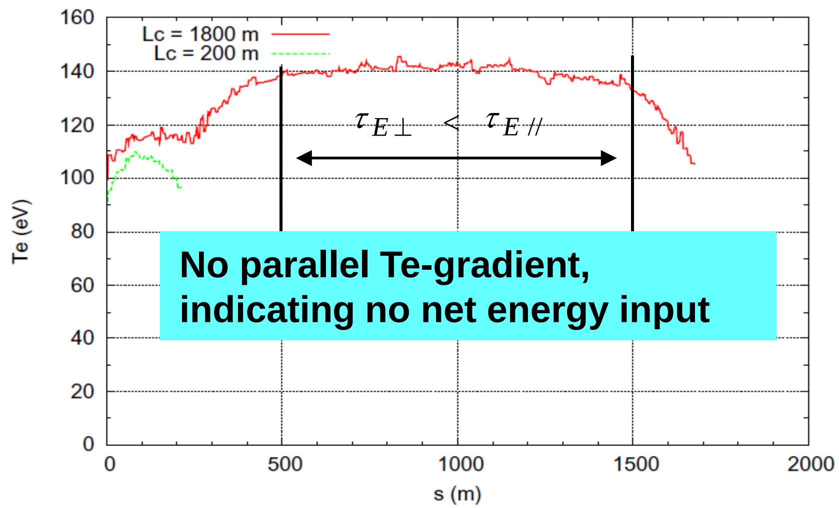
the energy flux is directed radially.
at s > ~500m.

No dependence of

$$\Gamma_{//} \propto \sqrt{L_C}$$



Te profile along flux tubes



Transport process : in poloidal direction

Field line pitch relative to rational surfaces

$$\Theta^* = \frac{r_i a}{R}\frac{d}{dr}\left(\frac{1}{q}\right)$$

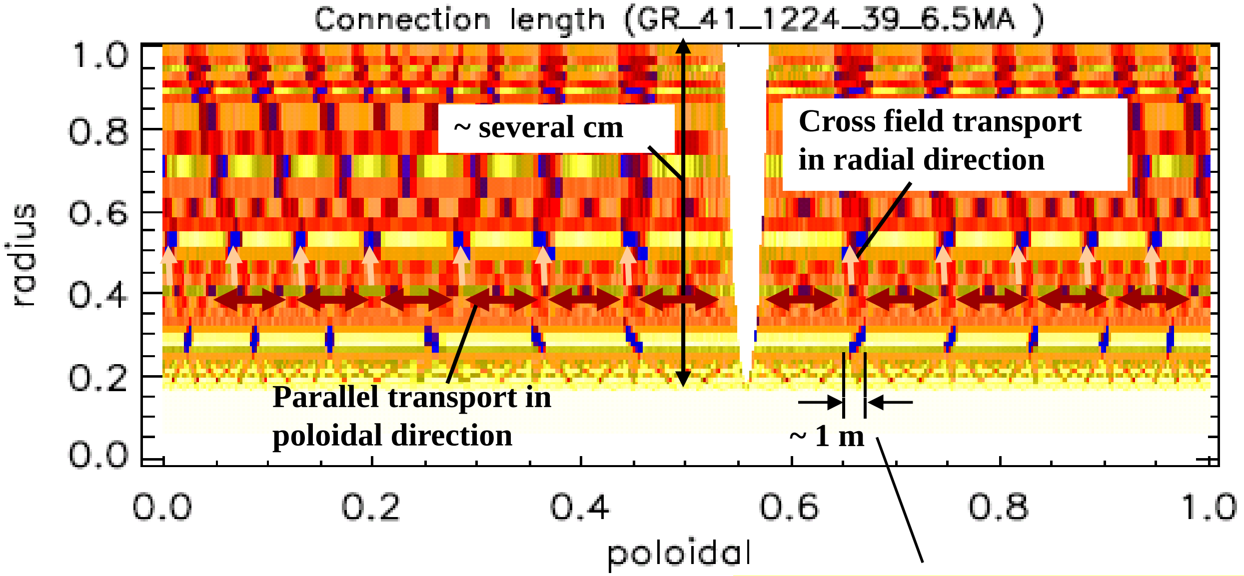
r_i : distance from rational sf.

In ITER start-up,

$$\Theta^* \sim 2\times 10^{-3} >> \sqrt{\frac{\chi_\perp}{\chi_{//}}} \sim 10^{-4}$$

Parallel transport is effective to distribute energy in poloidal direction

Physical picture of energy transport



Remains as shadow of limiter
cross. trans. too small to smear out
(main resonance q=6)

Summary

1. Toroidally discrete limiter introduces non-axisymmetric flux tube structure.
   Resonance feature of flux tube trajectories at rational q surfaces
   => a complex 3D pattern in L_C profile

2. The 3D edge transport code, EMC3-EIRENE, has been implemented on the ITER start-up limiter configuration, in order to analyze 3D transport properties and to investigate the limiter power load.

3. The severity of problem associated with very long flux tubes was mitigated and no significant power loss to outside of SOL.
   → Due to magnetic shear, long & short flux tubes are squeezed and the energy is effectively collected by short ones via radial cross-field transport.