Integrated Improved Performance with Negative Triangularity

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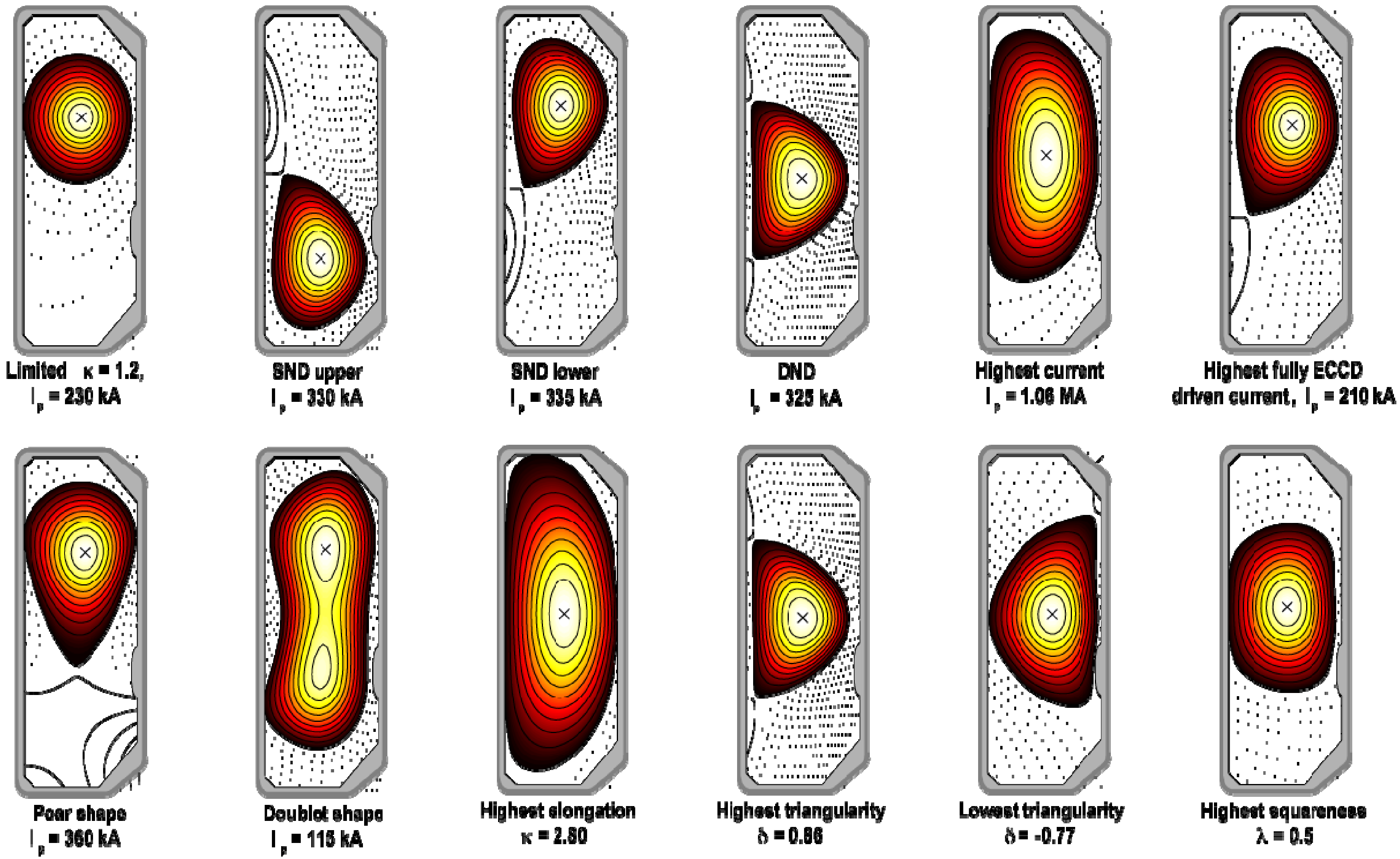
Outline

- Negative triangularity: a long history for TCV
- Effects on core and edge profiles
- Improved confinement
- Gyrokinetic simulations
- Pedestal pressure predictions
- Towards a **NTT**-Demo?

(κ, δ) effects on MHD and confinement



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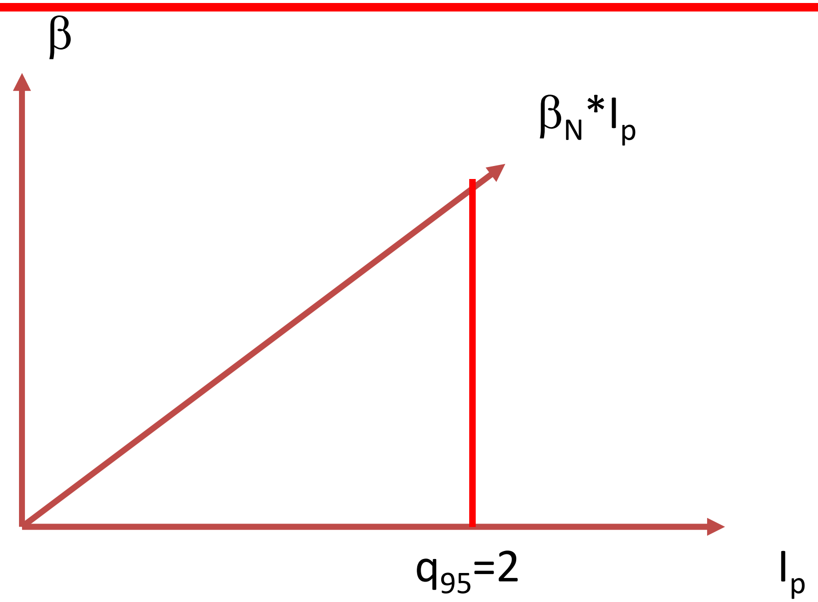
(κ, δ) effects on MHD and confinement

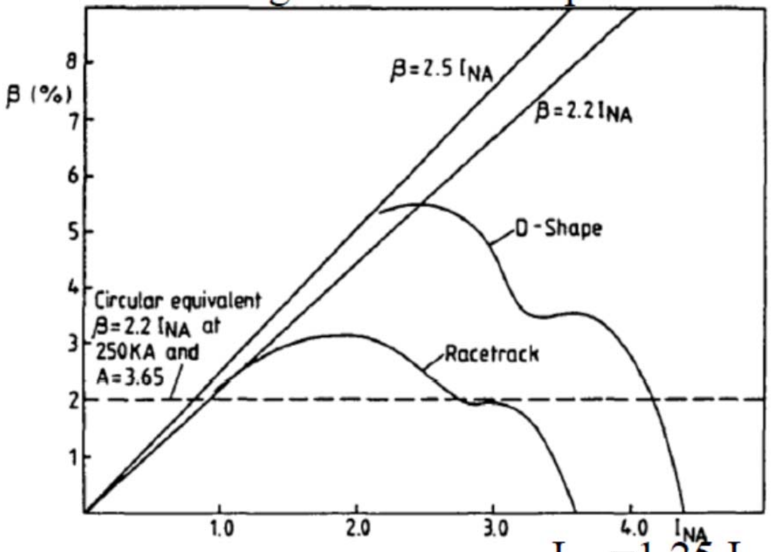


[F. Troyon et al., PPCF (1984)]

• Troyon limit: $$\beta_N = \frac{\beta[\%]}{I_p/aB_0}$$

(κ, δ) effects on MHD and confinement

TCV design calculations: prediction



I_{NA}=1.25 I_N

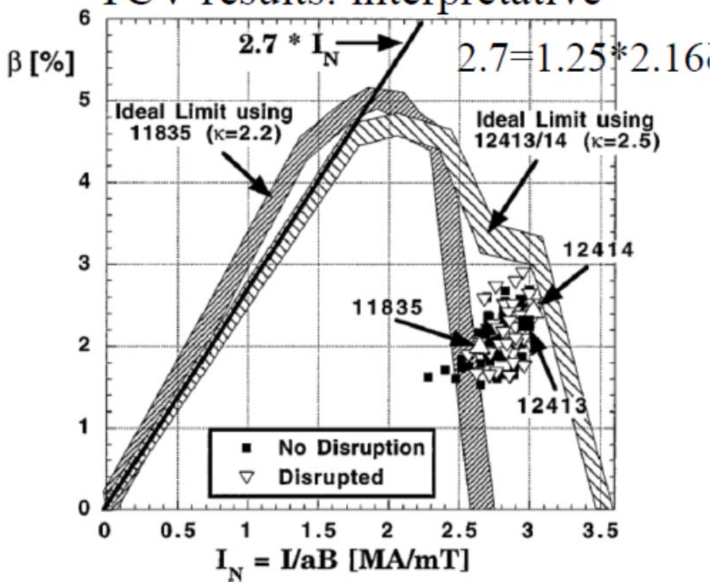
[F. Troyon et al., PPCF (1984)]

[A. Turnbull et al., NF (1988)]

- Troyon limit: $$\beta_N = \frac{\beta[\%]}{I_p/aB_0}$$
- TCV design: β_N decreases for κ>2.5 before q_{95}=2

(κ, δ) effects on MHD and confinement

TCV results: interpretative



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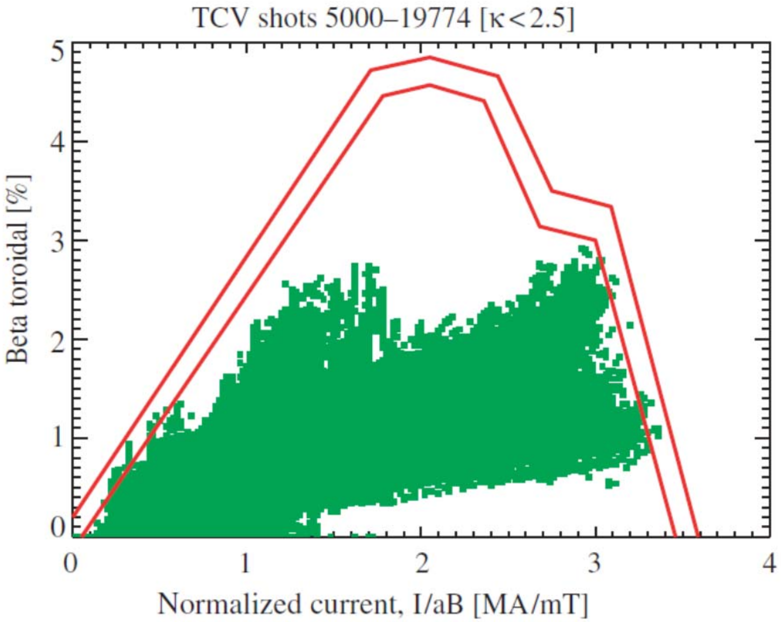

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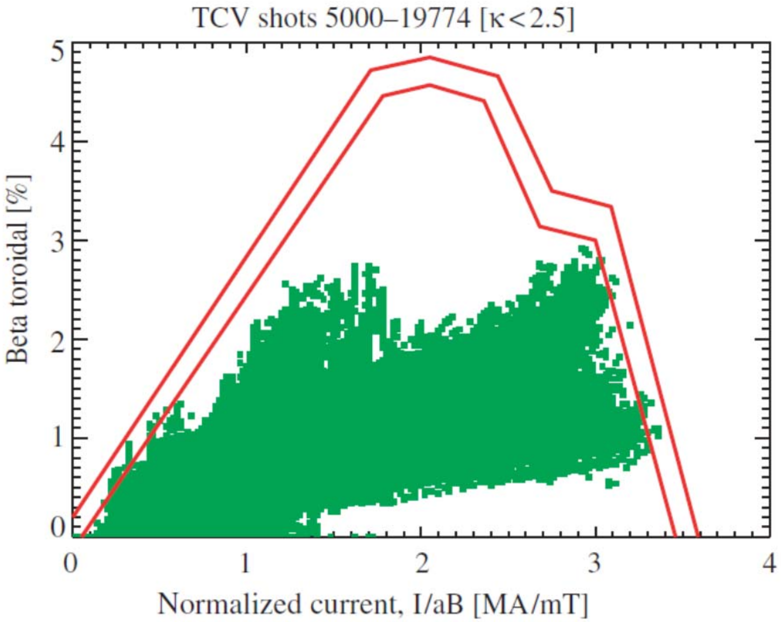

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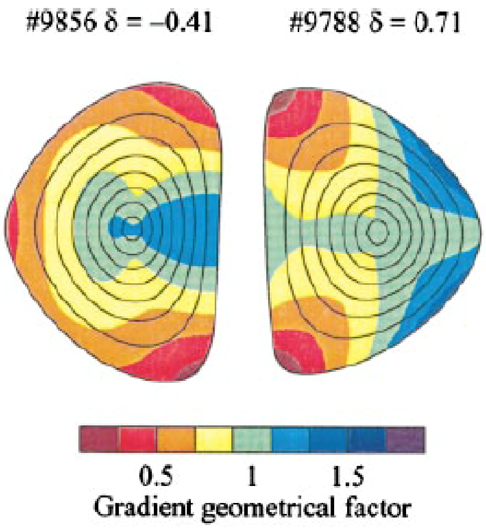
- TCV: Shape enhancement factor explains most confinement improvements at high kappa, negative delta

$$H_s \propto \frac{dr}{d\psi}\nabla\psi$$



[J.-M. Moret, et al., PRL (1997)]

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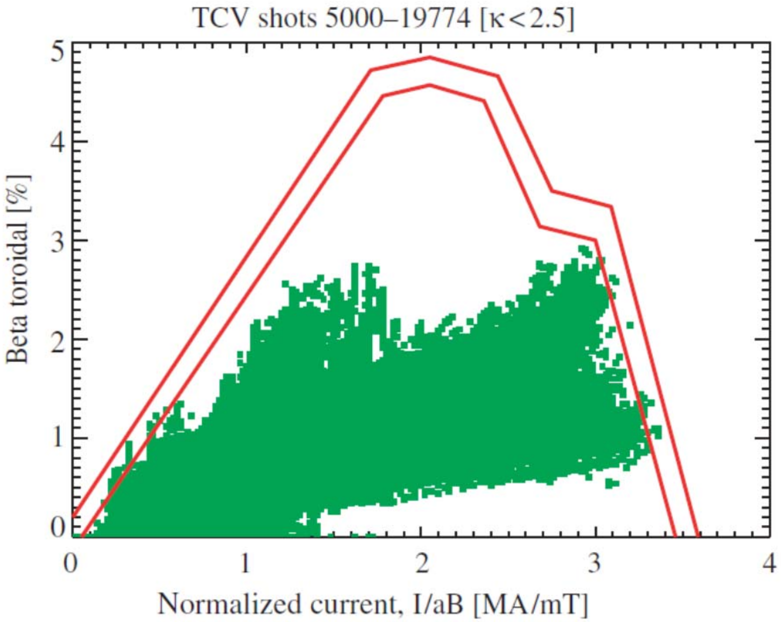

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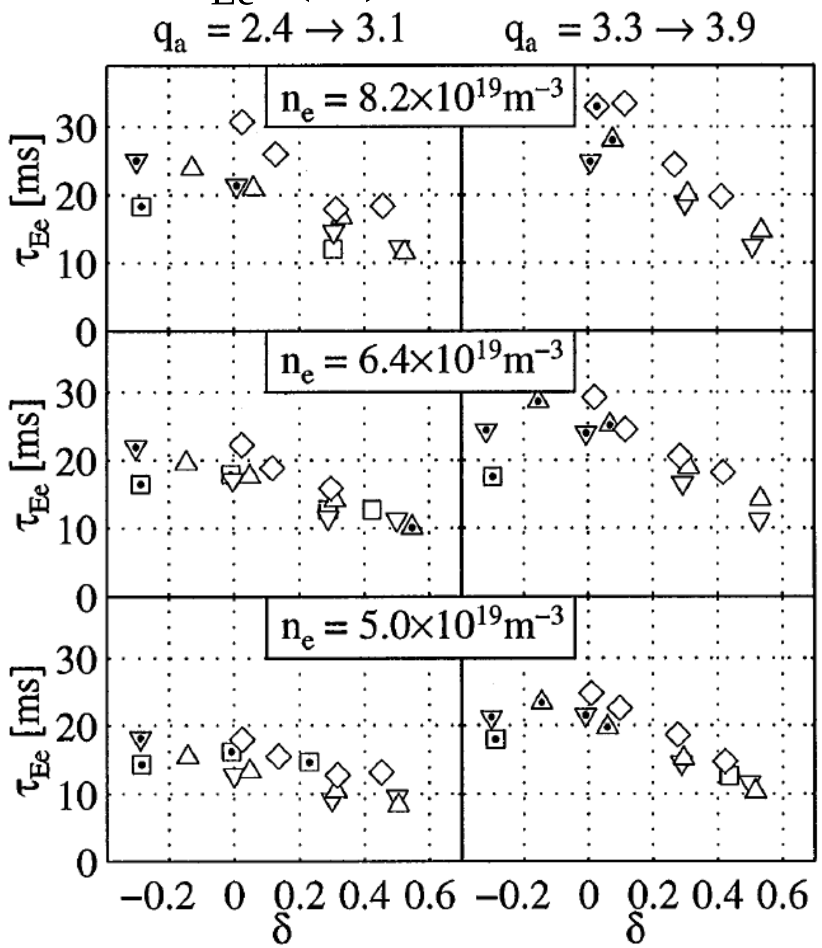
- TCV: τ_{Ee}~(-δ)



- TCV: improv. saturates at high κ

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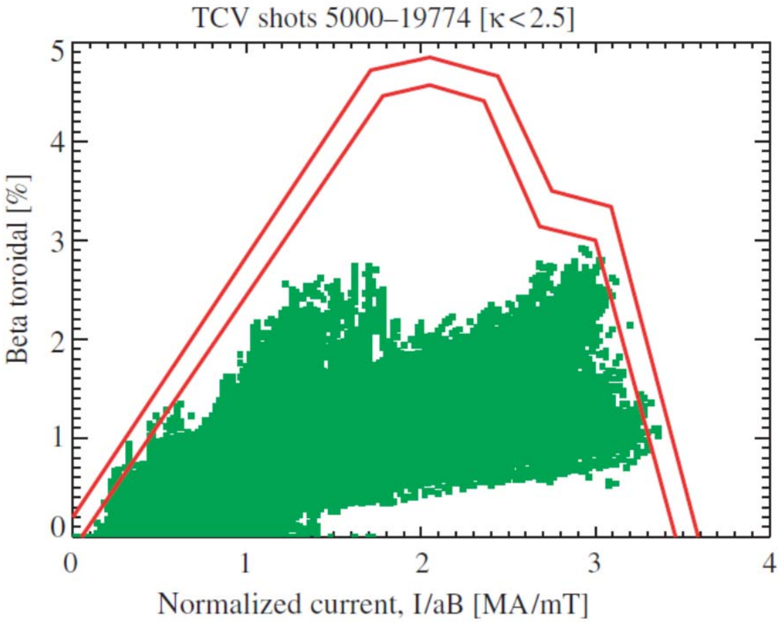
(κ, δ) effects on MHD and confinement



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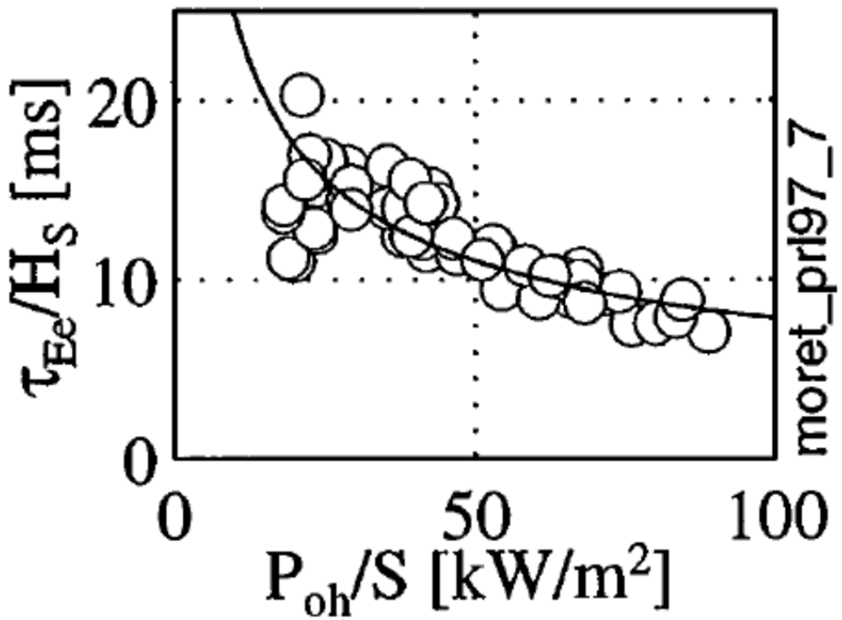


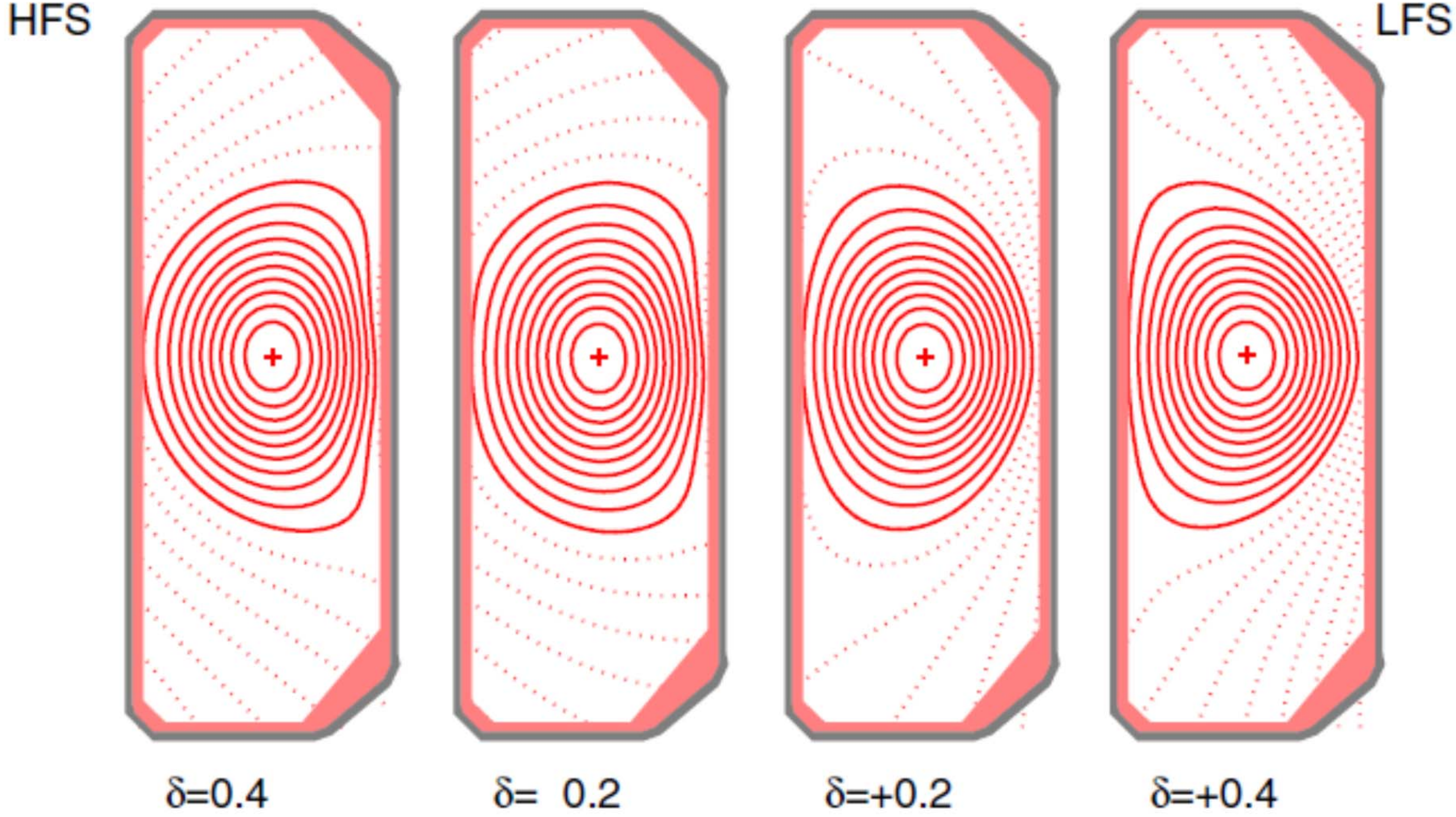
- All shapes overlay essentially

- TCV: improv. saturates at high κ

[J.-M. Moret, et al., PRL (1997)]

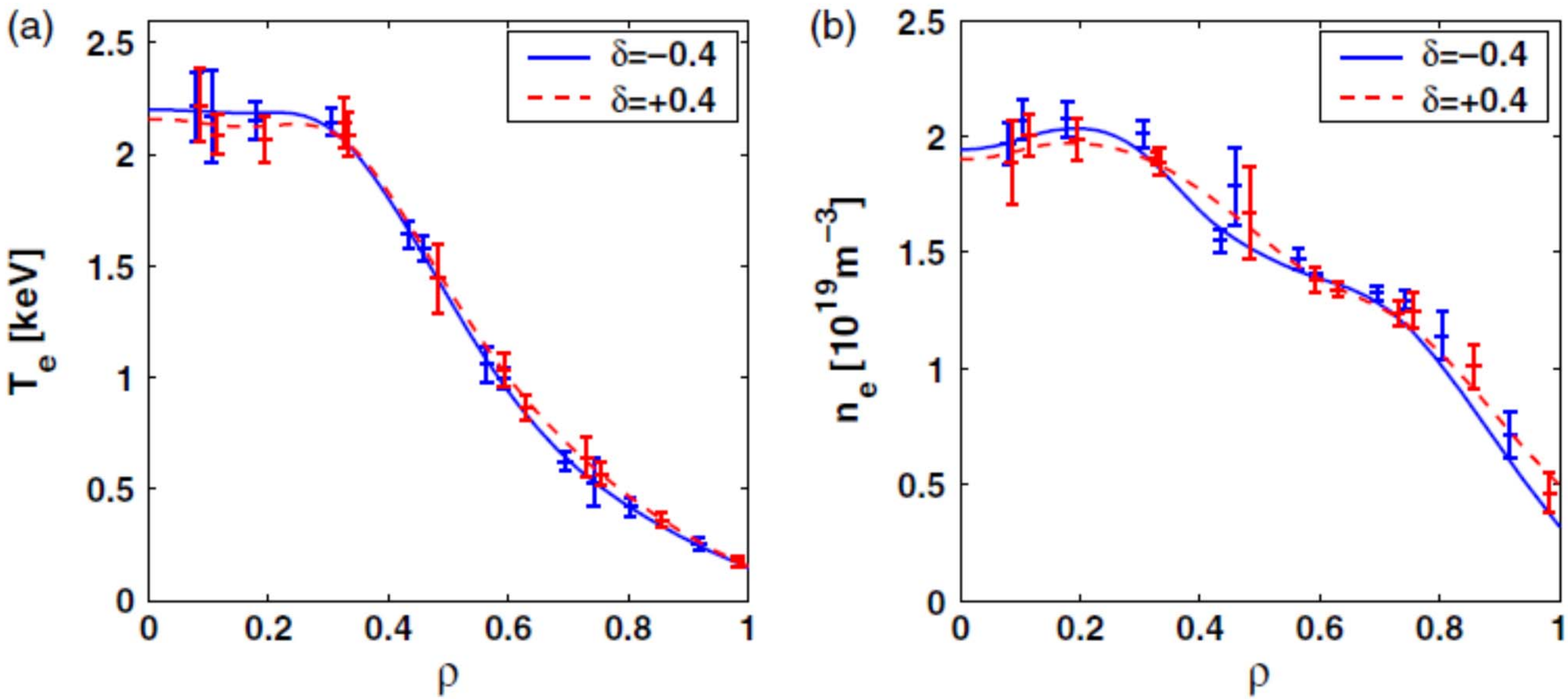
Improved conf. at negative triangularity

- Ohmic and EC heated L-modes show improved conf at high coll.



[Y. Camenen, et al., NF (2007)]

Improved conf. at negative triangularity



- Same profiles at **half** the power for $\delta<0$

➢ Factor 2 global confinement improvement

[Y. Camenen, et al., NF (2007)]

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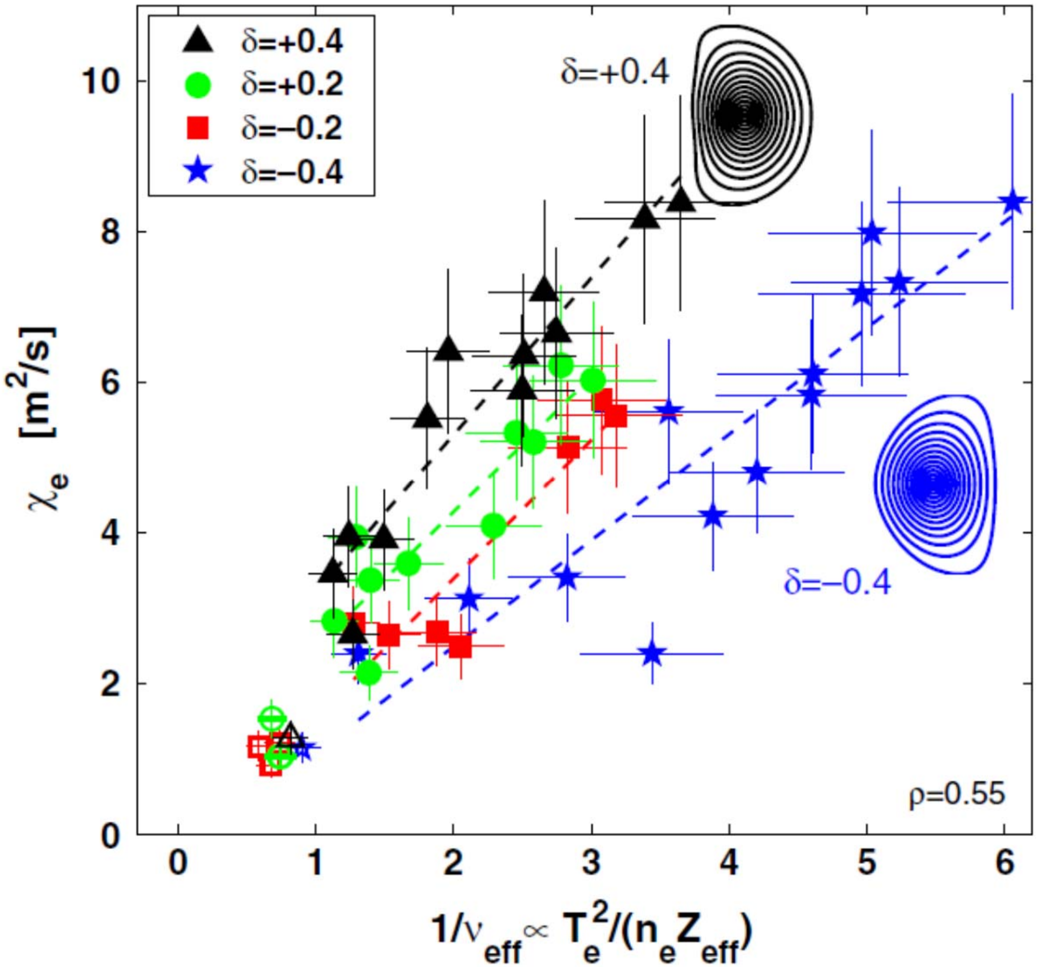
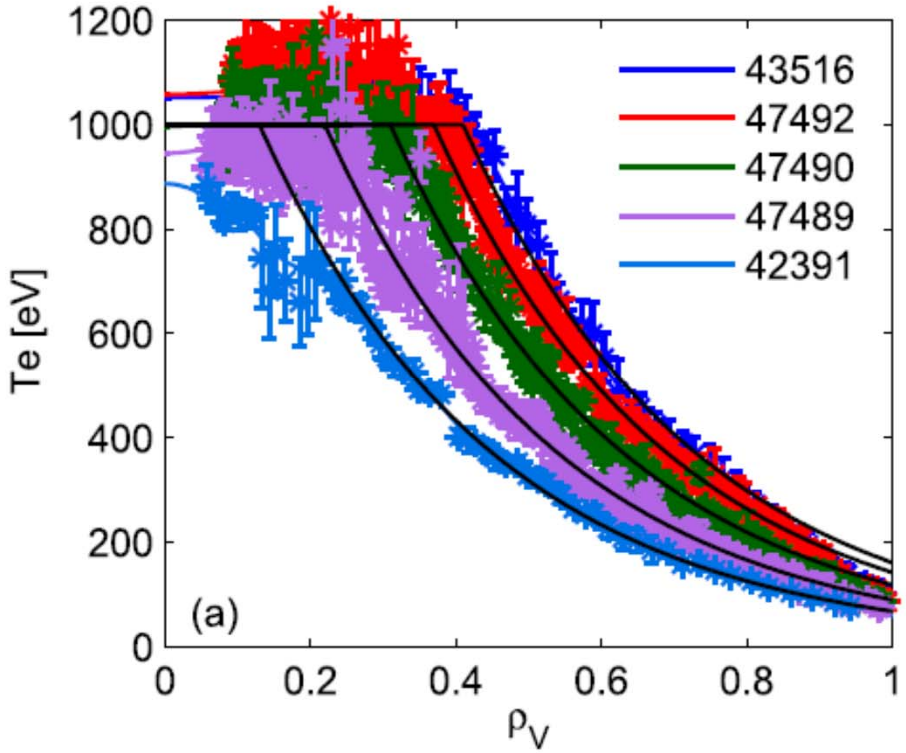
Collisionality dependence

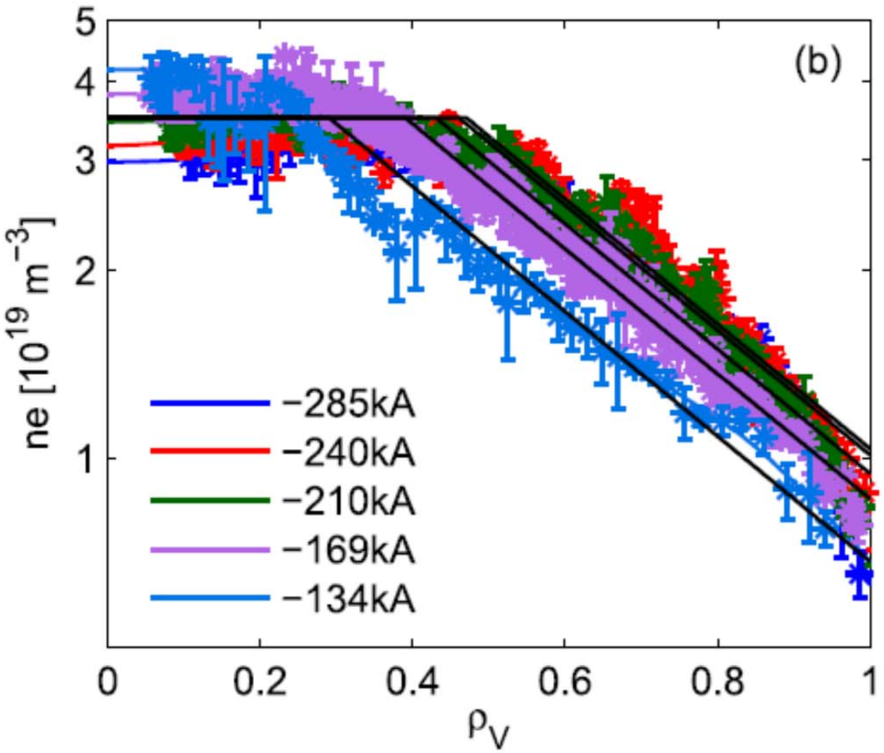


- Main difference at low collisionality (*when TEM more dominant?*)

[Y. Camenen, et al., NF (2007)]

Highly resolved measurements of T_e and n_e profiles localise changes of gradients and scale lengths





- Center dominated by sawtooth
- Core by stiffness
- Edge gradients increase with I_p (P, n_{el}, …)

[O. Sauter, et al., PoP (2014)]

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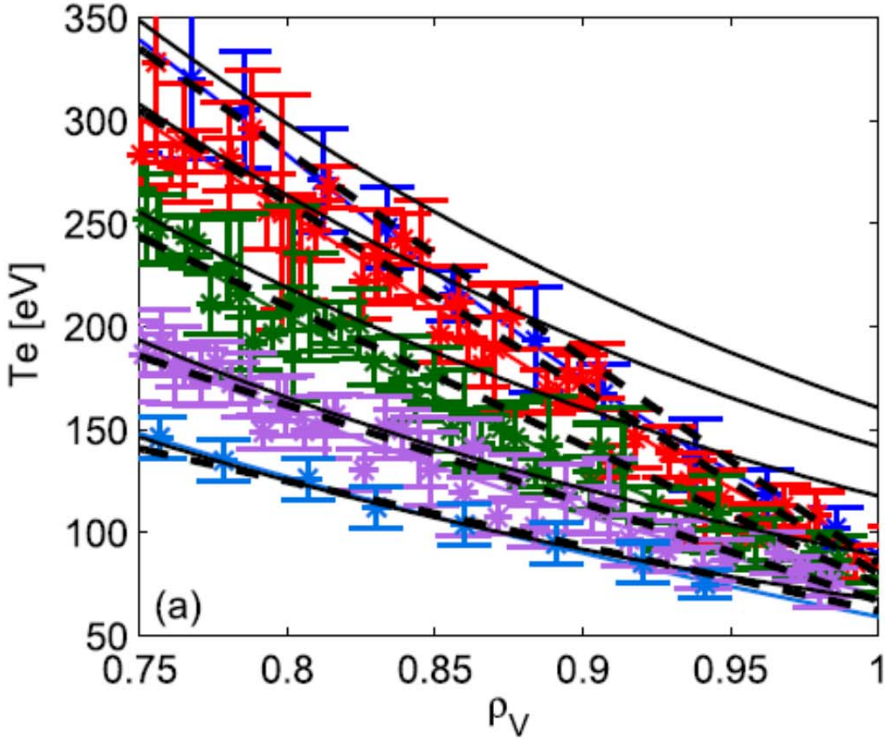
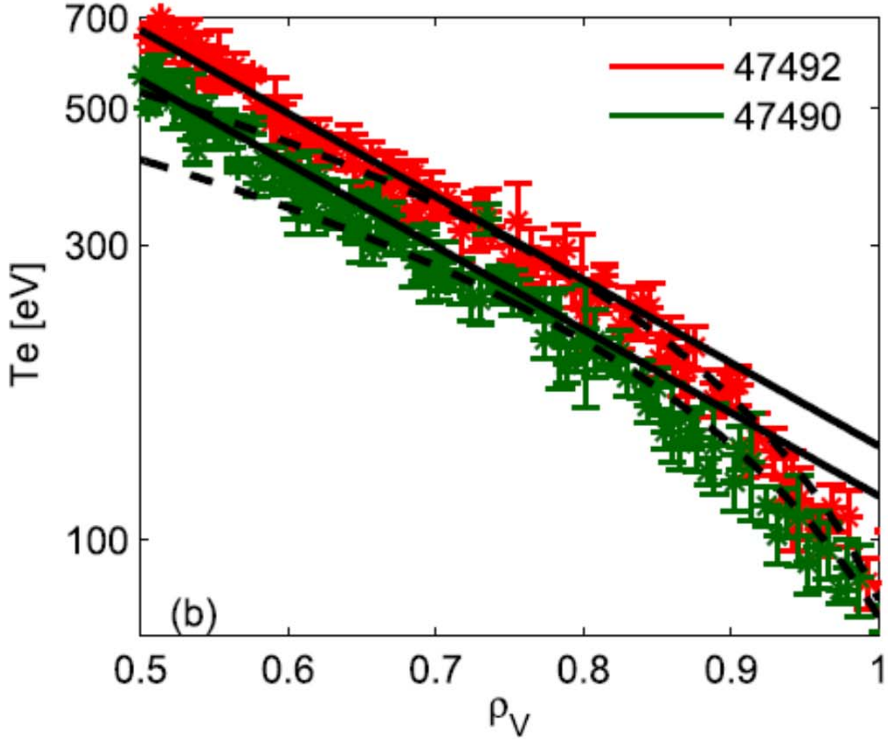
Highly resolved measurements of T_e and n_e profiles localise changes of gradients and scale lengths

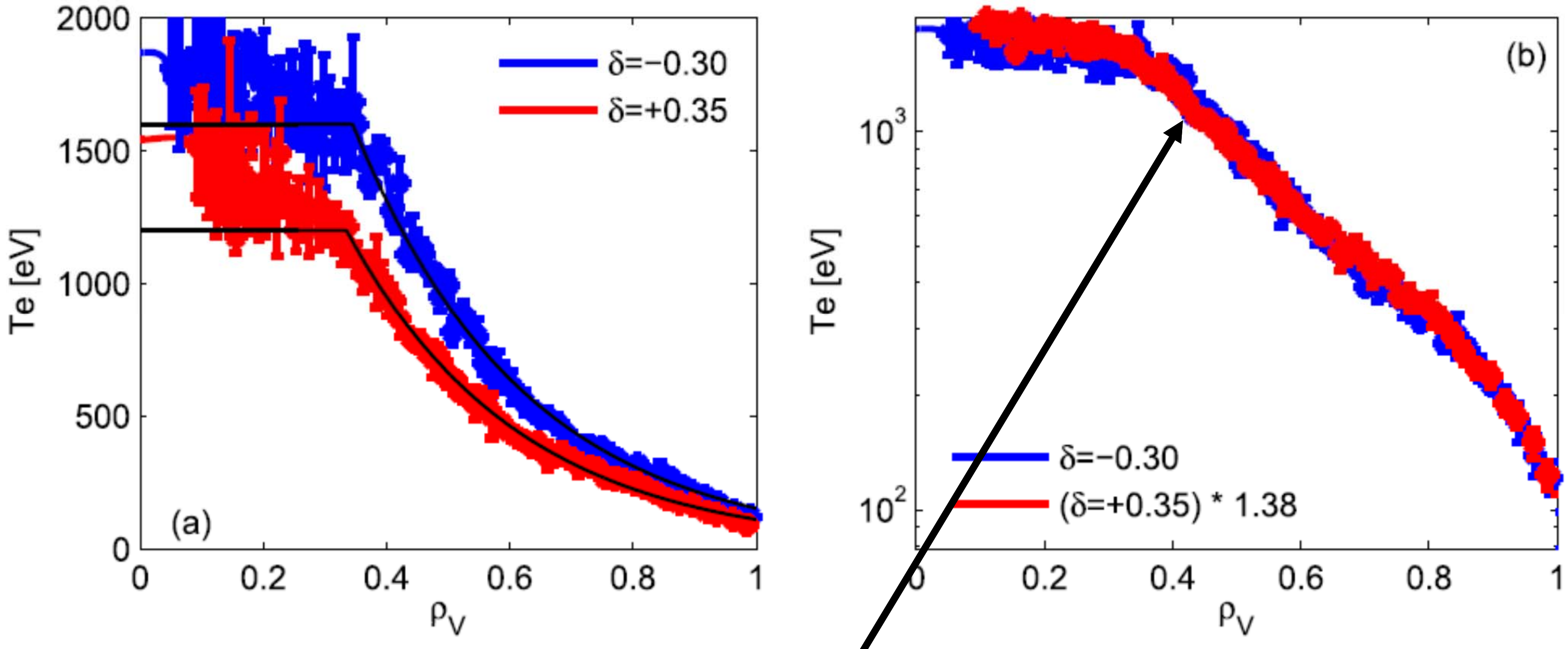




- Linear with ρ_v in edge region
- Gradient increasing with Ip, P, n_{el}, …

[O. Sauter, et al., PoP (2014)]

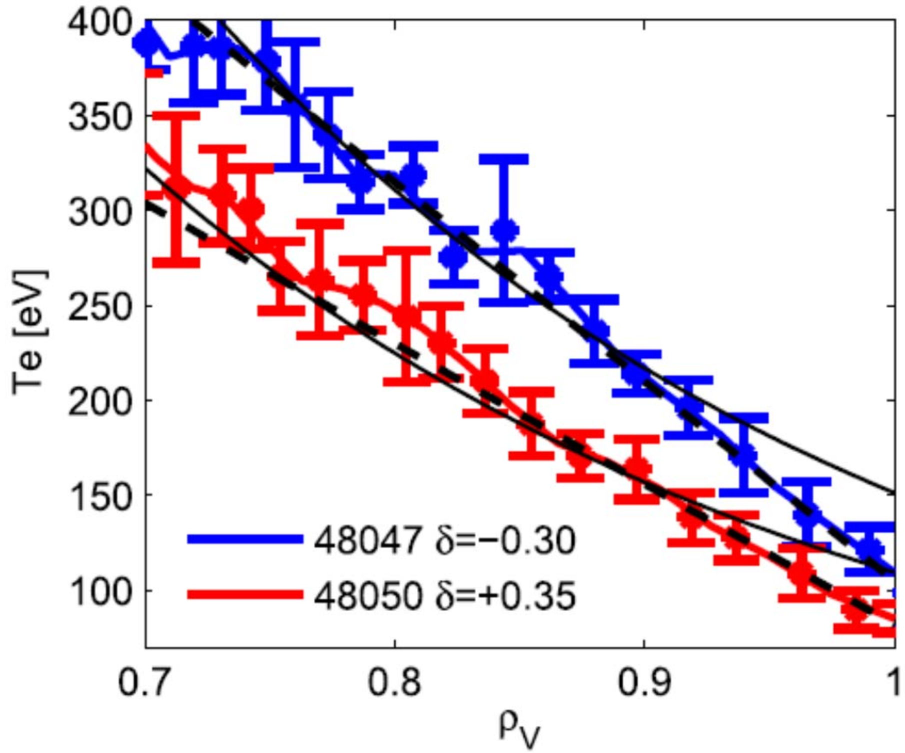
"Core" profiles also remain stiff with δ modifications



- Same input power with positive and negative δ with good radial resolution
- Almost whole profile self-similar…except edge (next VG)

[O. Sauter, et al., PoP (2014)]

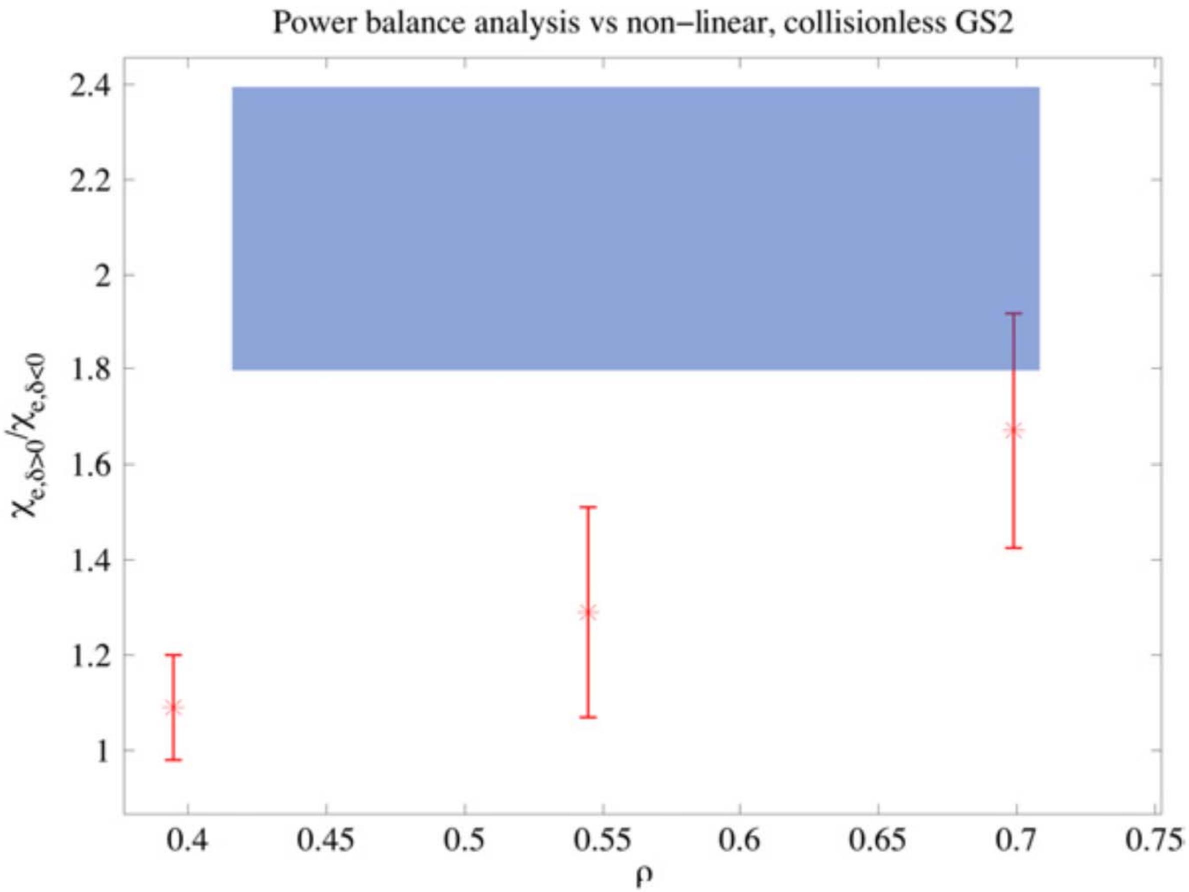
Role of edge for δ effects on transport



- $T_e(\rho_v=0.8)$ increases with negative δ because of increased gradient in edge region 0.8-1.0
- Consistent with previous simulations (**Marinoni** et al)

[O. Sauter, et al., PoP (2014)]

Nonlinear local gyrokinetic simulations at $\delta<0$



- Ratio of χ_e between positive/negative δ explained outside ρ=0.7

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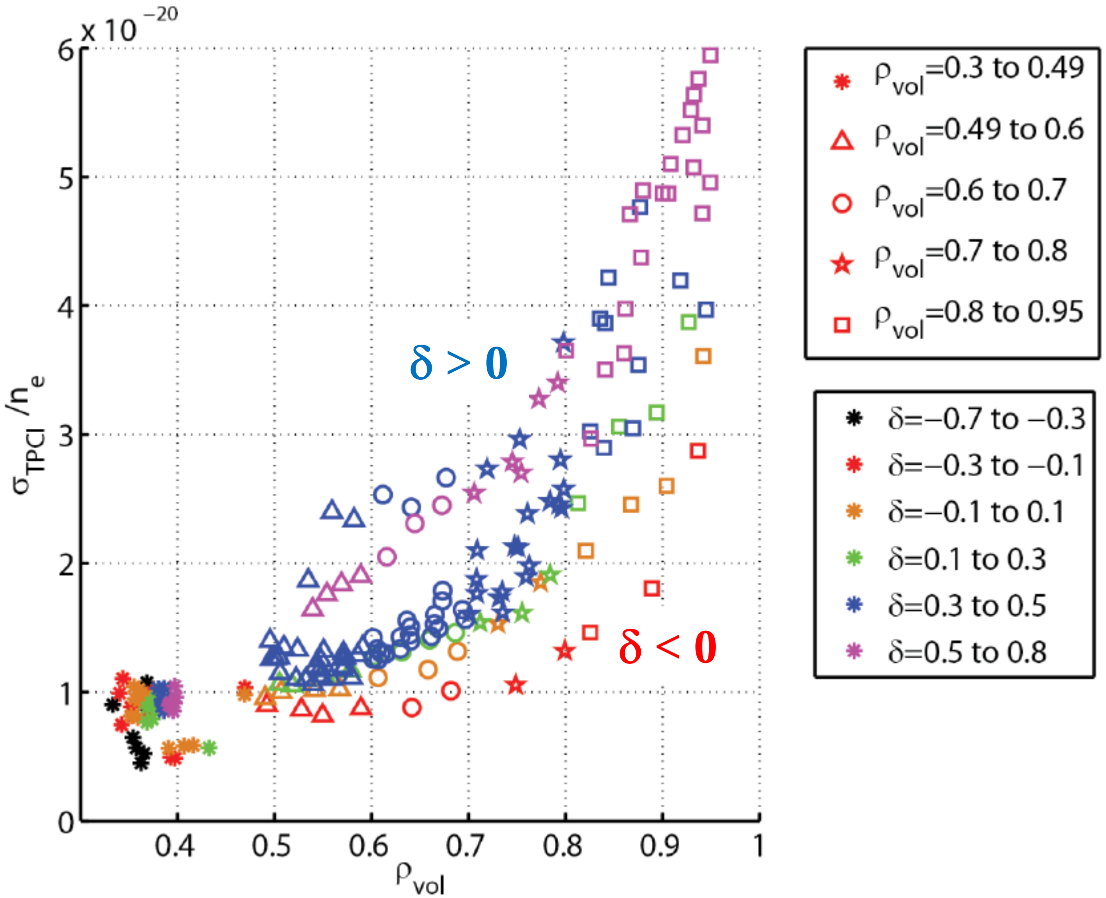
[A. Marinoni, et al., PPCF (2009)]

Relative density fluctuations are lower at negative δ



- Reduction of turbulence with $\delta_{LCFS}<0$, confirmed by extensive Phase Contrast Imaging measurements

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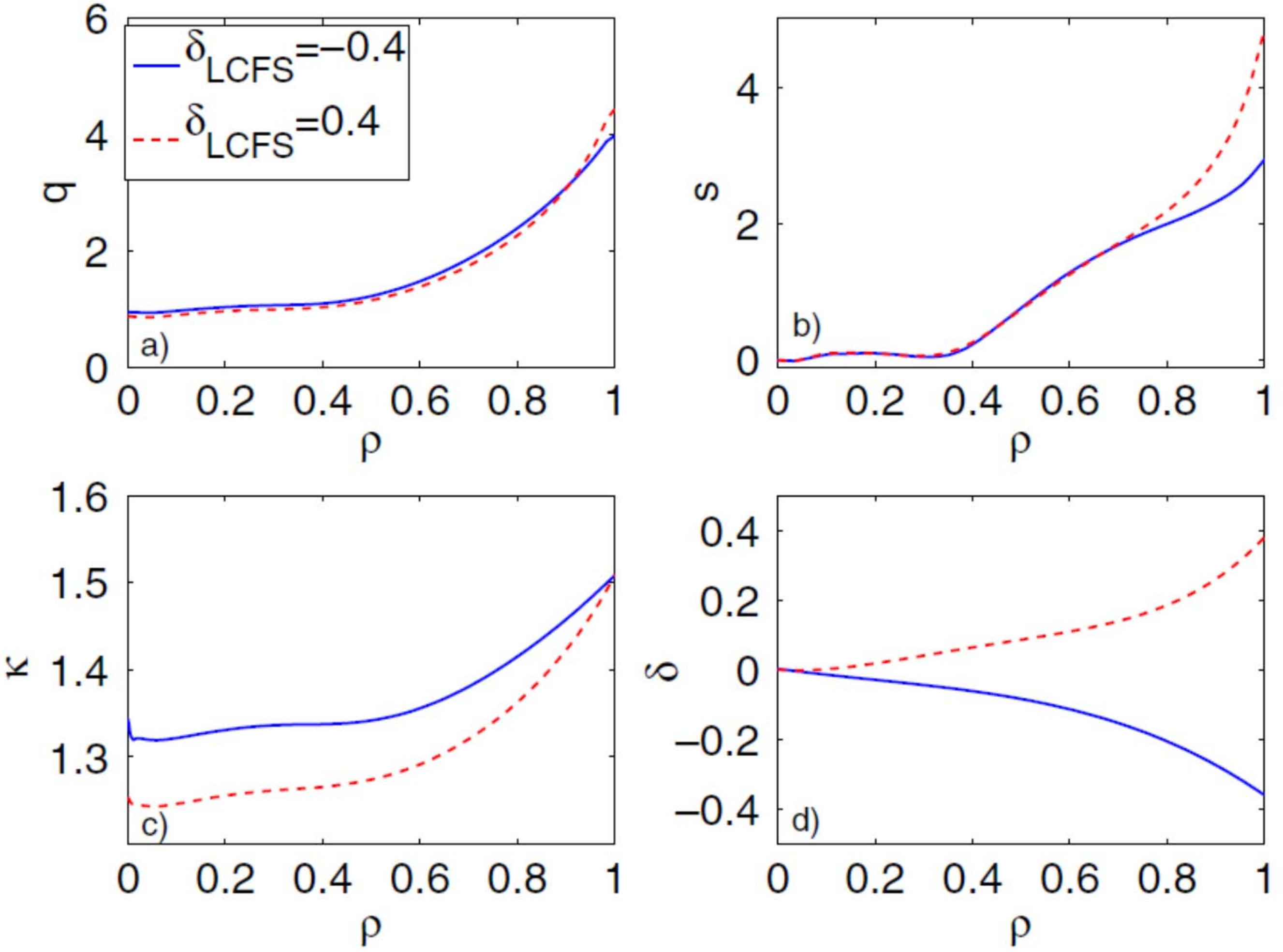
[Z. Huang et al. Proceedings 41th EPS Conf.(2014)]

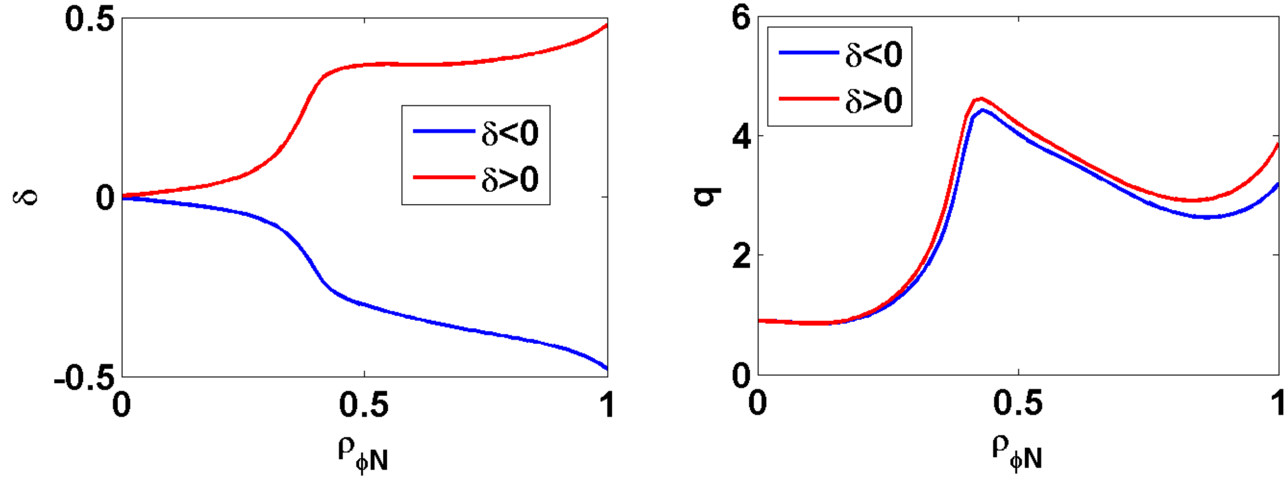
Equilibrium effects with change in delta



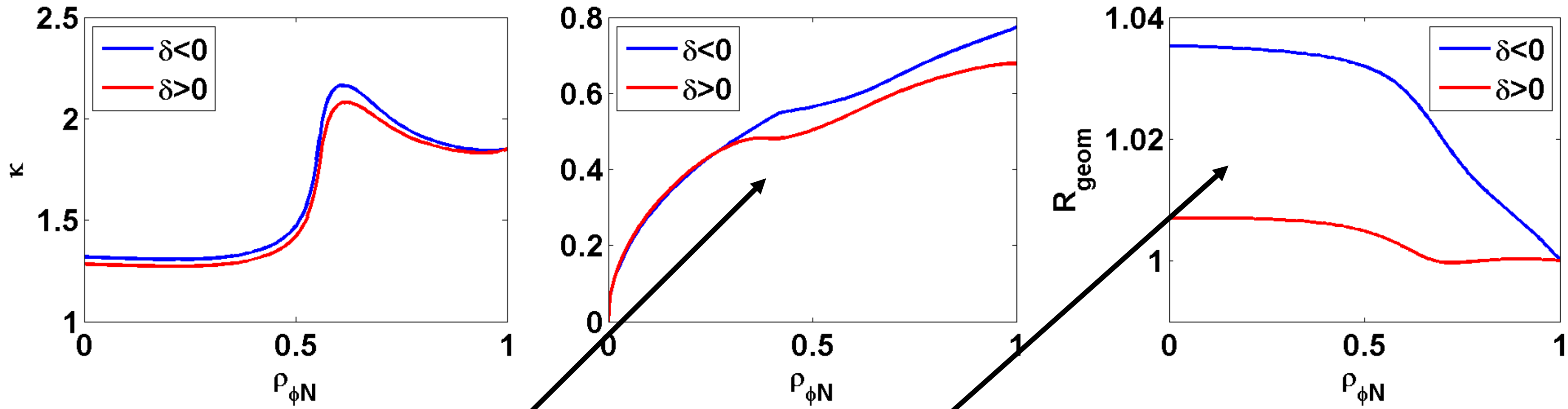
- Elongation “penetration” or shear different for diff. edge δ

[A. Marinoni, et al., PPCF (2009)]

Equilibrium effects with change in delta



- q and δ profiles are related



- Main changes for f_t and Shafranov shift

δ effects on f_t reproduced by new formula in [O. Sauter, FED 2016]

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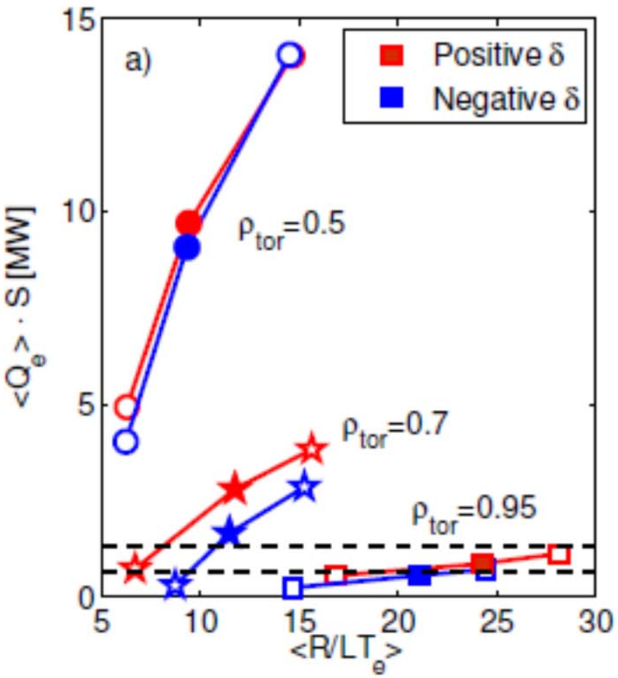
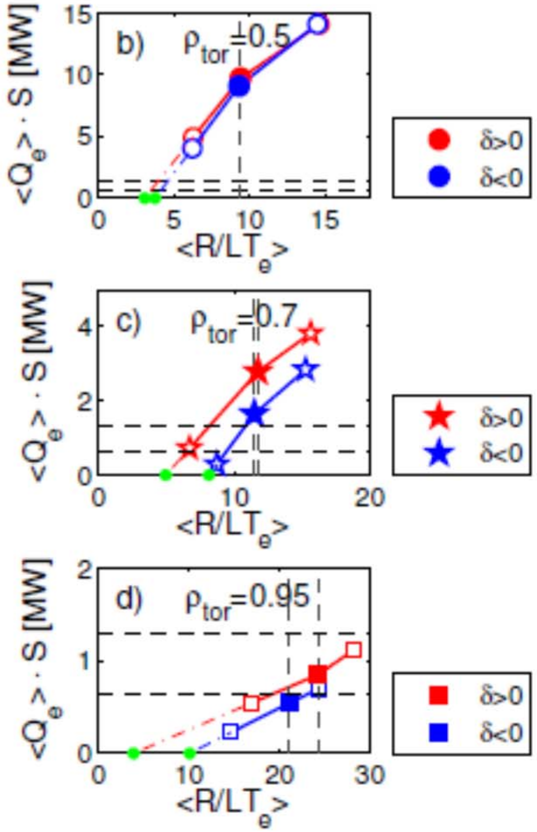
Role of δ revisited with local gyrokinetics





- No change in core
- δ<0 better at outer radii
- Less stiff near edge
- Linear critical gradients increase with decreasing δ

[G. Merlo, et al., PPCF (2015)]

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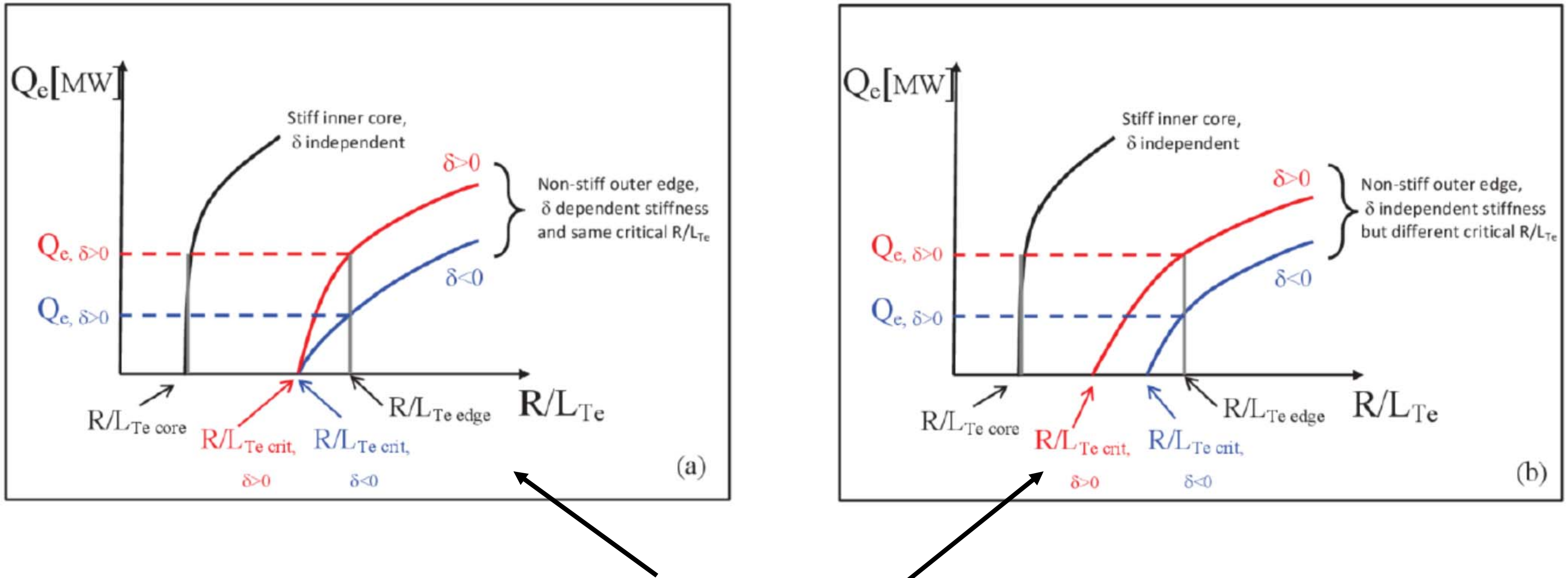
Link between core and edge and stiffness



- How to get same profiles with ½ power with δ<0 ?
- Local runs hint towards change in critical gradients near the edge
- Local runs not sufficient to explain experimental heat fluxes

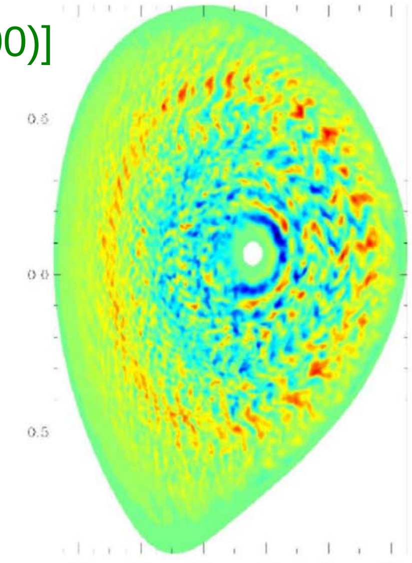
Simulation tool

Inclusion of finite machine size effects appears to be the key missing element.
Finite ρ^* expected to:

1. Capture the effect of negative δ at all radii
2. Reproduce the experimental transport level

Second goal very challenging (profile stiffness vs. computational cost), the first can be met even if the second is not.

[F. Jenko et al., Phys. Plasmas 7, 1904 (2000)]



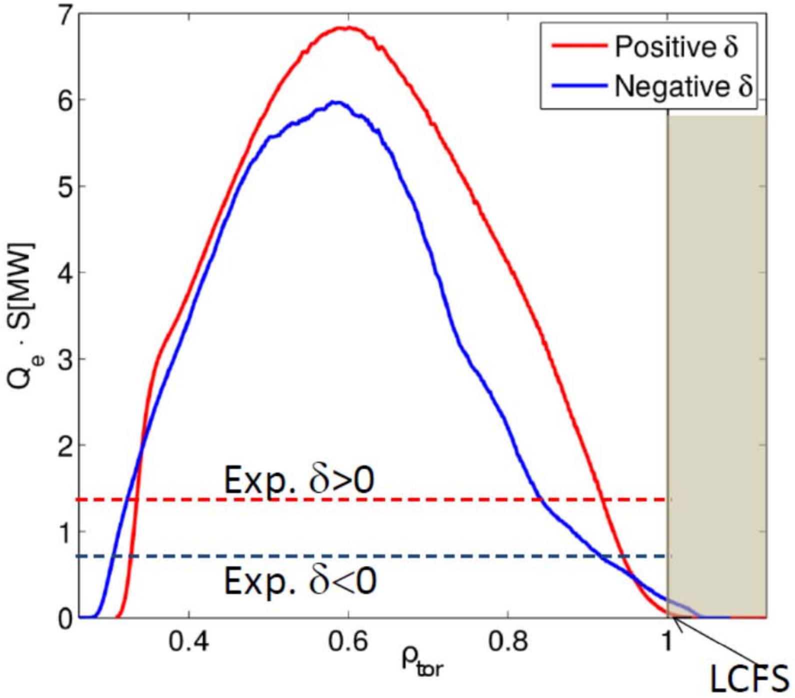
The GENE code (http://genecode.org):

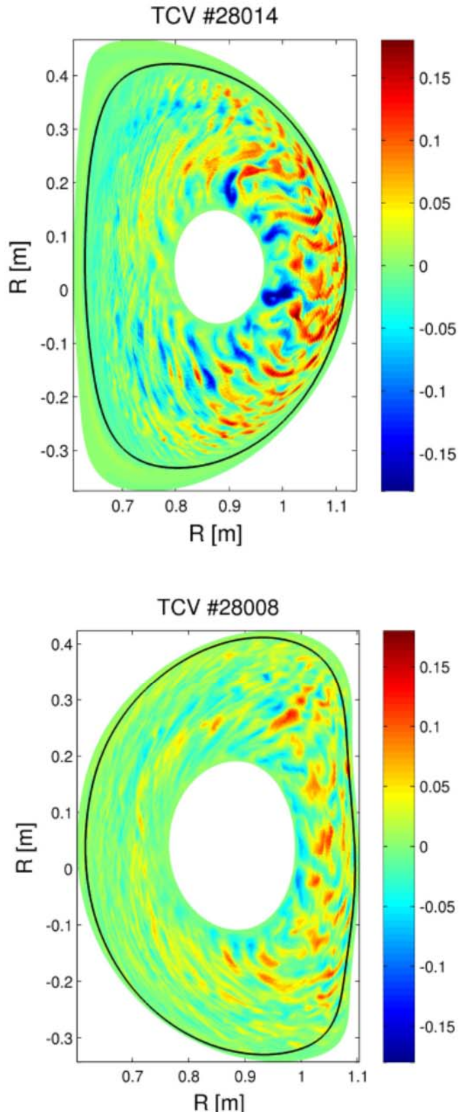
- Eulerian nonlinear gyrokinetic code.
- Arbitrary number of species.
- Radially local and global approaches.
- Electrostatic and electromagnetic fluctuation (here only $A_{//}$).
- Linearized Landau-Boltzmann collision operator.

All following simulations are global, electromagnetic (exp. β), collisional, carried out considering fully gyrokinetic ions and electrons with realistic mass ratio and assuming experimental plasma geometry.
Grids up to $n_s \times n_x \times n_{ky} \times n_z \times n_v \times n_\mu$ =3x512x96x32x110x48 points.

- Full study in G. Merlo, et al., PhD thesis No 7065, EPFL, 2016

Global simulations – full radius





416x48x32x140x68= $\sim 10^{10}$ grid-points per species

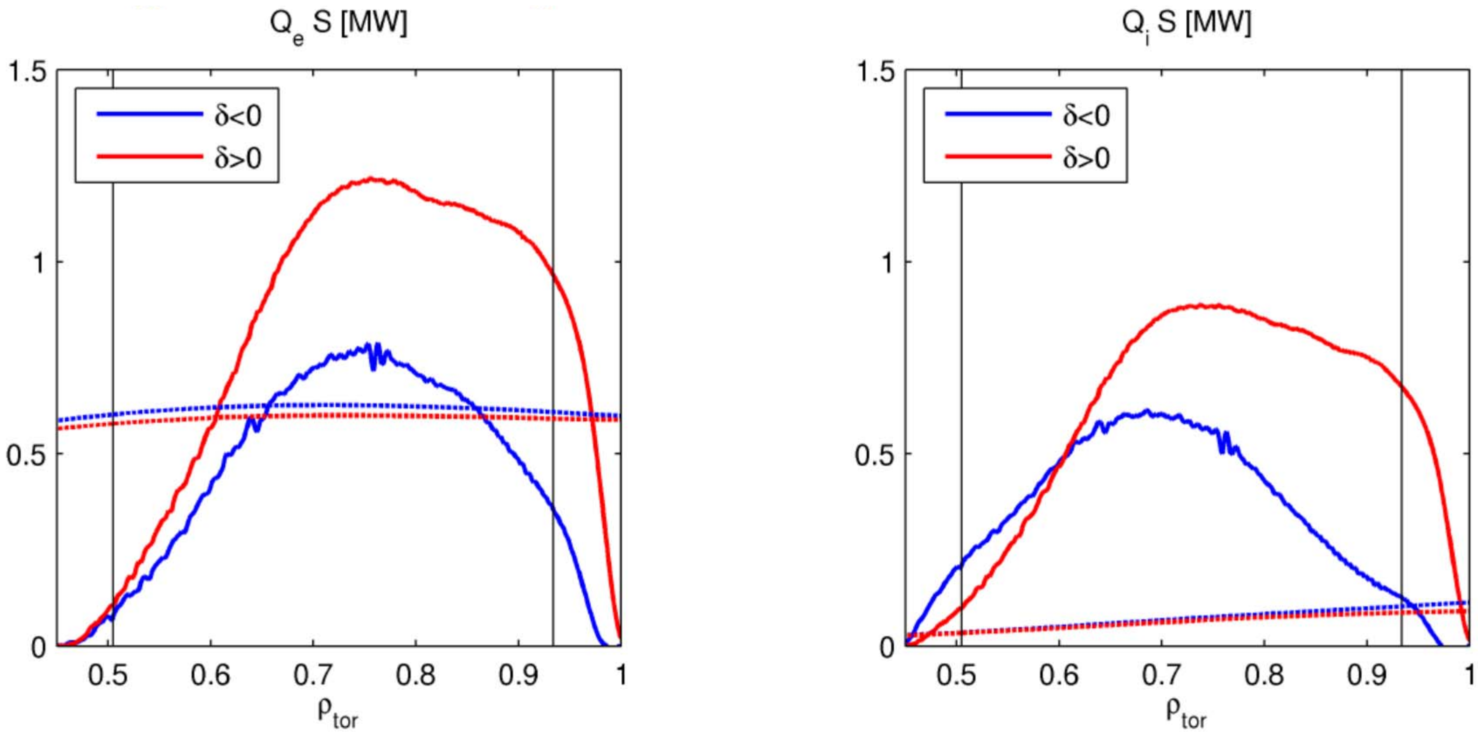
dt= 10^{-4}

- Less agreement than only core results.
- Highly unrealistic deposition profiles.
- Need to include carbon impurities.
- Core very sensitive to electron density gradient.

[G. Merlo, PhD (2016)]

Global simulations – change discharge

- Consider experimentally better diagnosed easier than playing with the profiles. Available only a δ scan carried out at constant power.



- *With C ongoing*

512x64x32x110x60= $\sim 10^{10}$ grid-points per species

dt= 10^{-4}

[G. Merlo, PhD (2016)]

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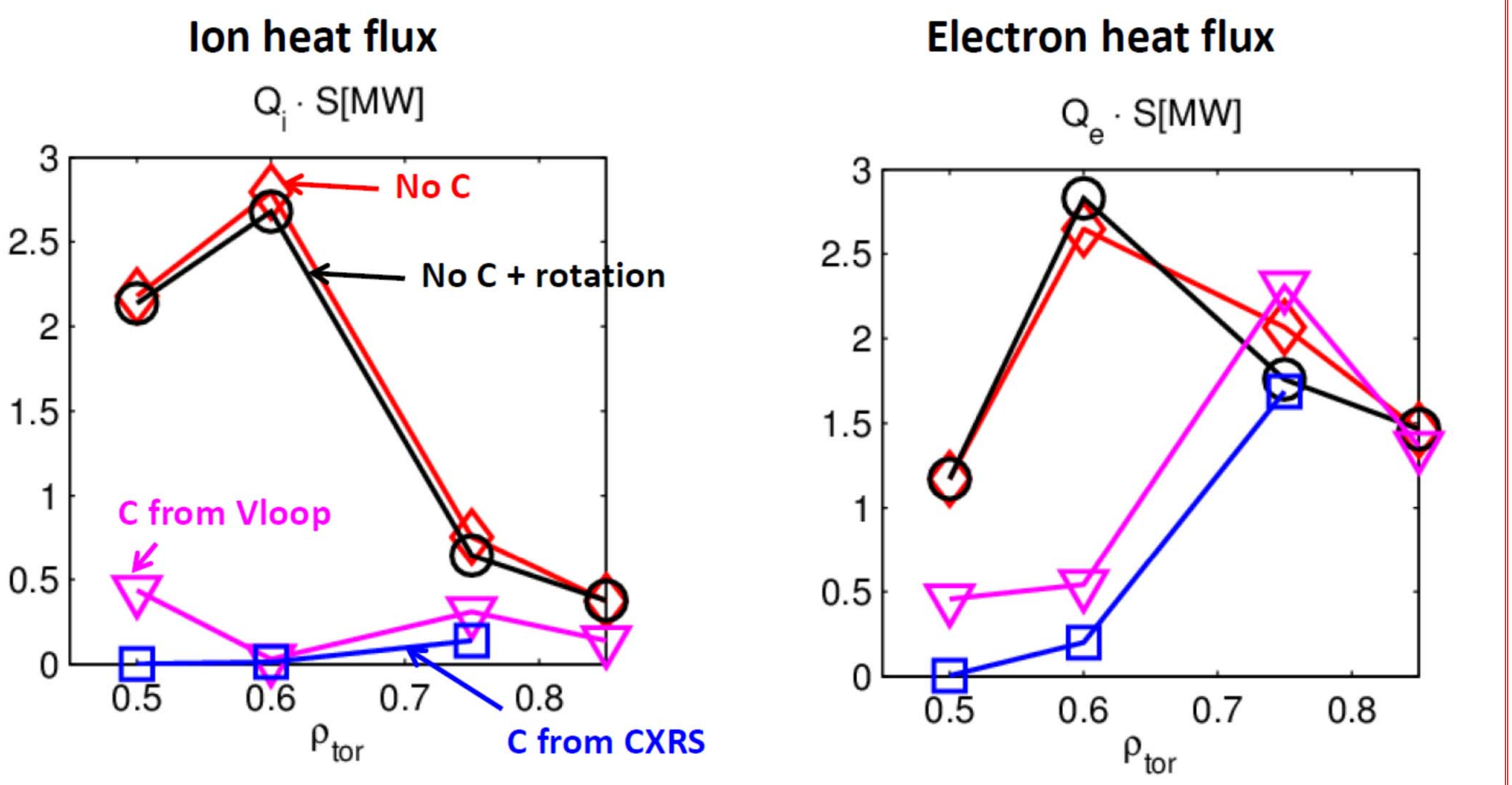
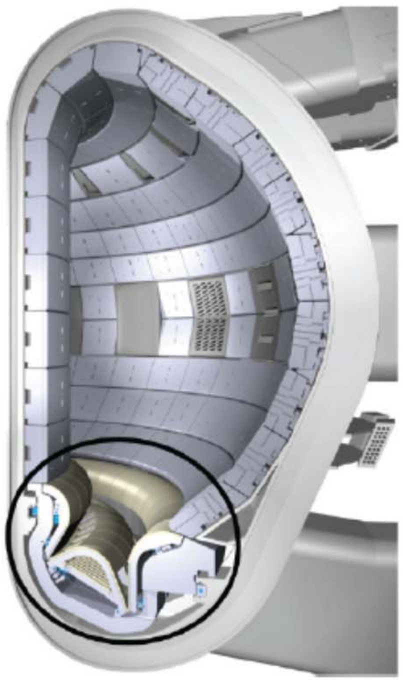
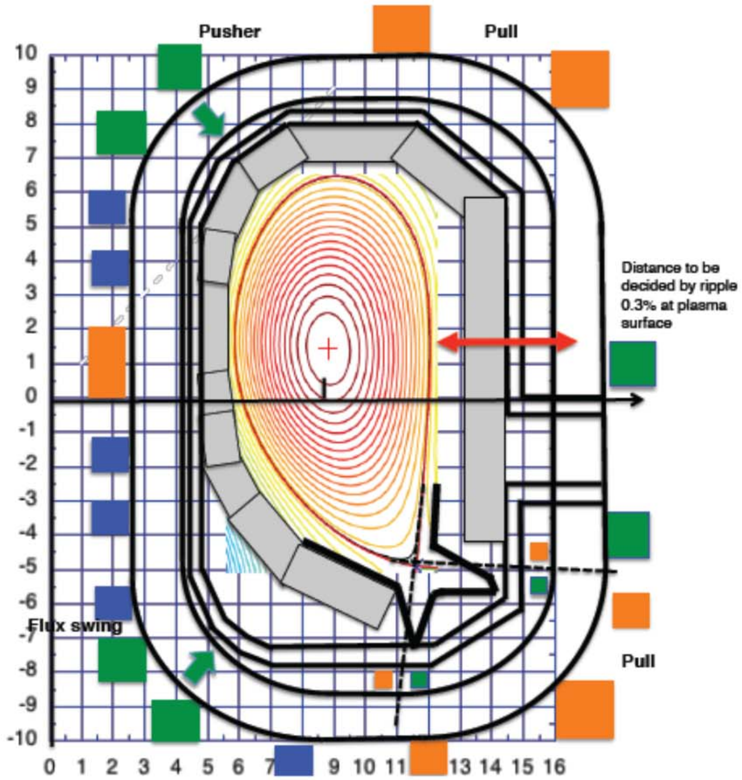
Effect of carbon – local runs



- Inclusion of carbon suppresses ITG (ion channel) and lowers TEM (electron channel)
- Similar behaviour for other shape

Negative Triangularity Tokamak: NTT Demo





- For ITER, $\delta_l > 0$ and $\delta_u > 0$.
- For NTT, $\delta_l < 0$ and $\delta_u \simeq 0$.

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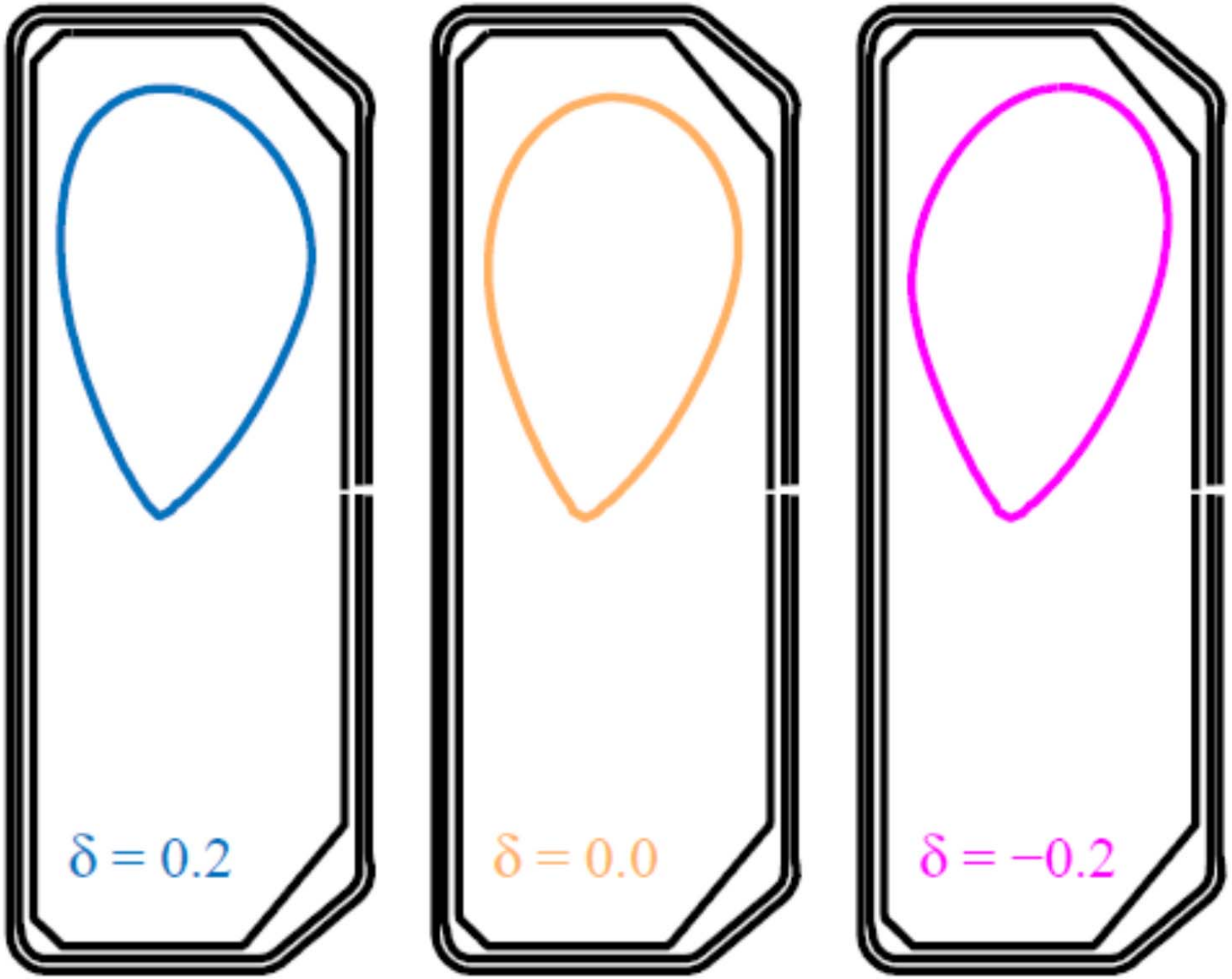
Advantages of NTT Demo

By moving the X-point to the low-field side (LFS) and thus to larger values of R,

- \+ The divertor wetted area is larger $\Longrightarrow$ reduction of the heat flux
- \+ The magnetic field amplitude at the divertor coils is smaller
  $\Longrightarrow$ allows innovative divertor concepts like the snowflake divertor
- \+ [TCV] Confinement is enhanced
- \+ [TCV] individual ELM losses are reduced
- − Plasmas are more vertically unstable
- − Scrape-off layer width is smaller in GBS simulations [Riva et al.]

TCV ELMy H-modes with negative δ_t



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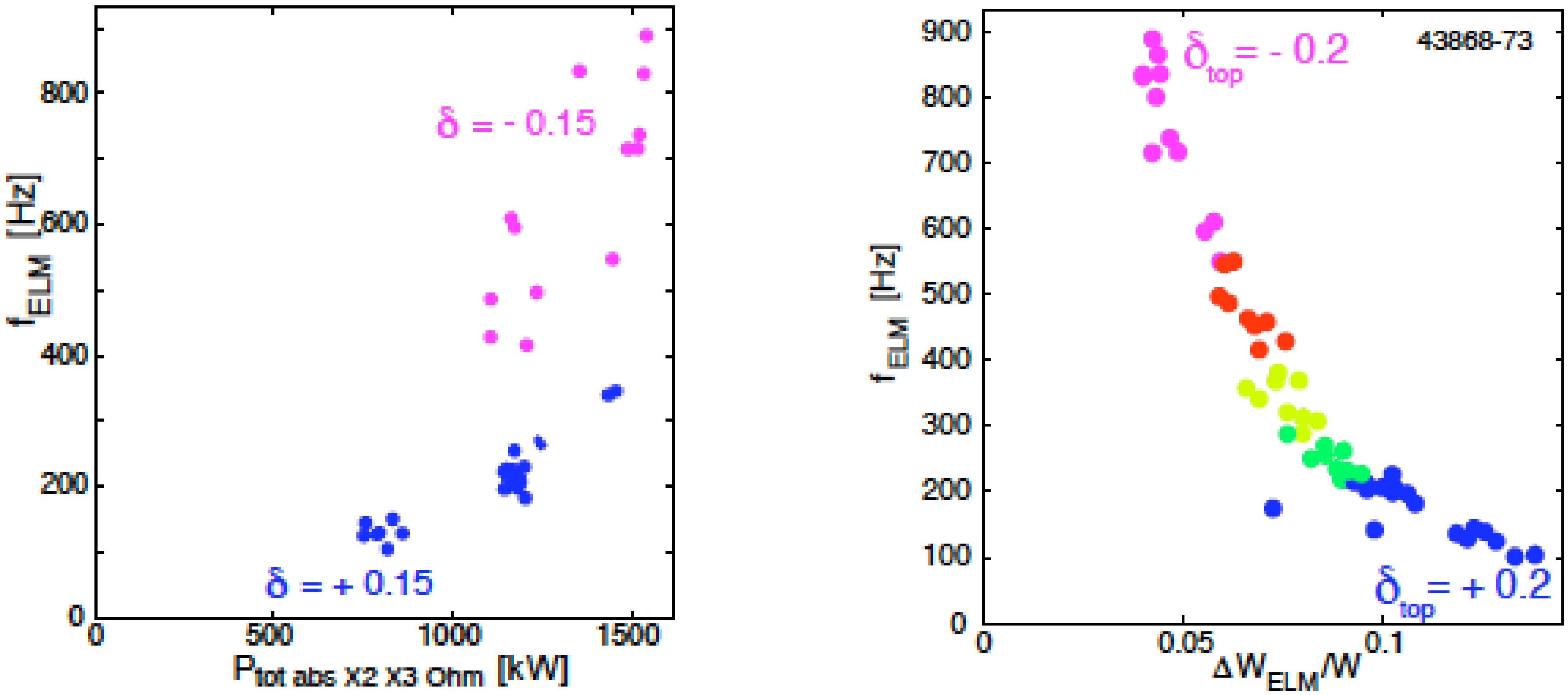

- Type I ELMs from power dependence
- Negative δ increases ELM frequency and decreases relative ELM power loss

[A. Pochelon, et al, PFR (2012)]

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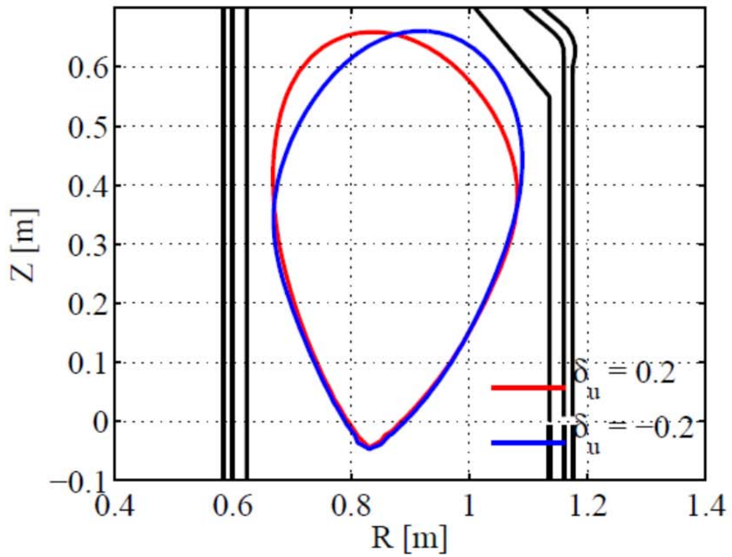
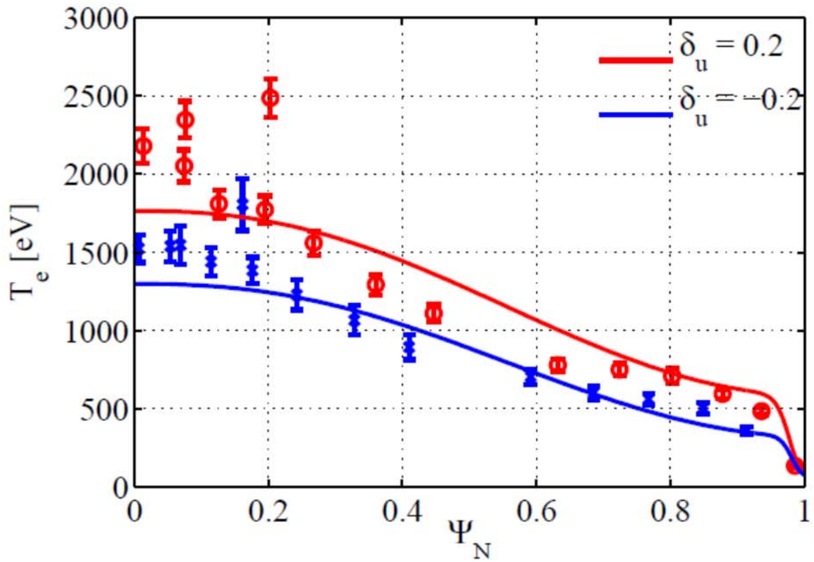
Basic trend of pedestal height recovered by EPED-CH

Experimental data from TCV #43872 at $t = 0.7$ and 1.8 s



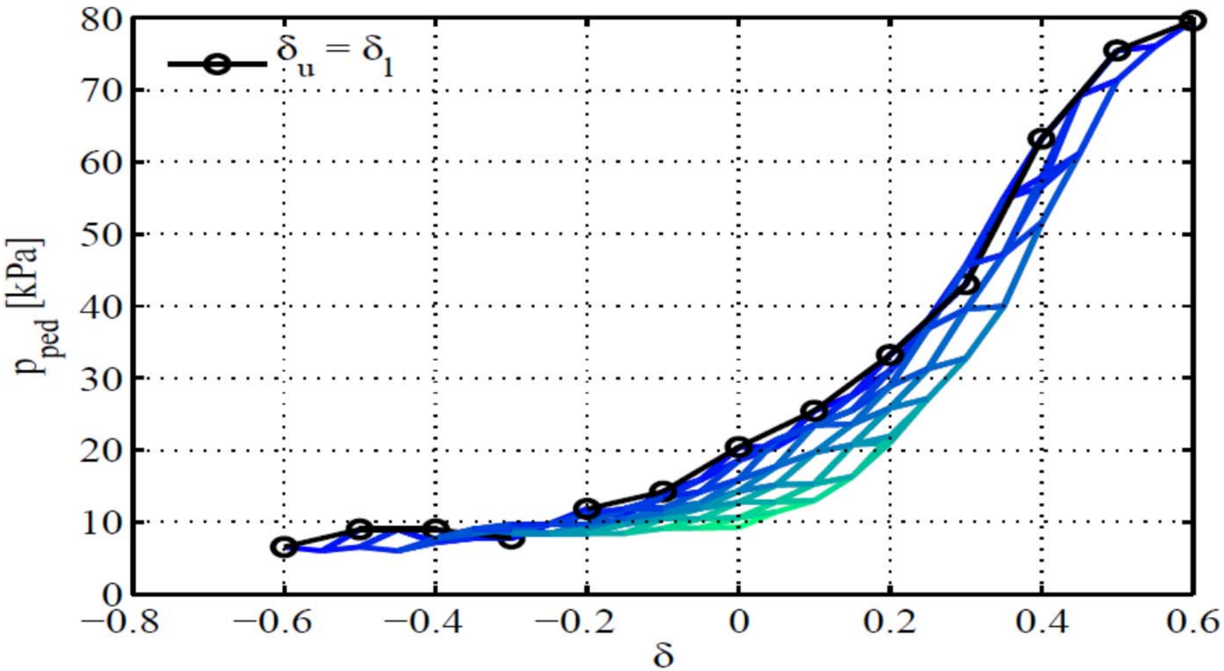


- EPED1 predicts a drop in $T_{e,ped}$ of about 200 eV for $\delta < 0$
- This is in qualitative agreement with the experimental data
- Effect of δ only: both $\overline{n_e}$ and $n_{e,ped}$ are constant during the scan
- No reliable experimental measurement of the pedestal width (Δ)

[A. Merle et al, PPCF submitted, Varenna 2016]

Pedestal height/width versus triangularity

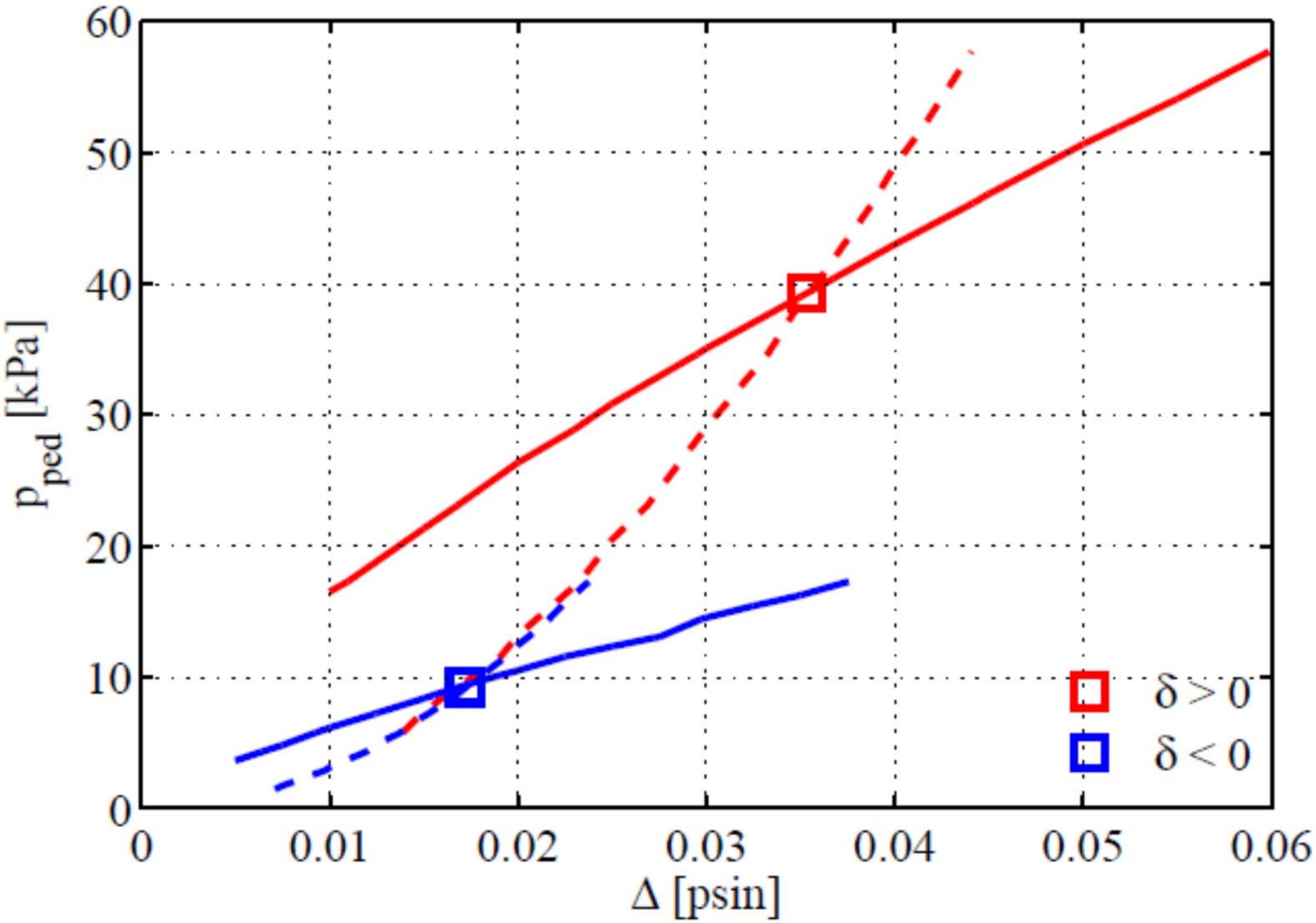
- Double scan in δ_u, δ_l (analytical equilibria, no X-pt)



- p_{ped} seems to depend mostly on the average $\delta = (\delta_u + \delta_l)/2$
- At constant δ, p_{ped} scales unfavorably with $|\delta_u - \delta_l|/2$
- p_{ped} seem to reach a minimum when $\delta < -0.2$

[A. Merle et al, PPCF submitted, Varenna 2016]

Ideal limit is very different

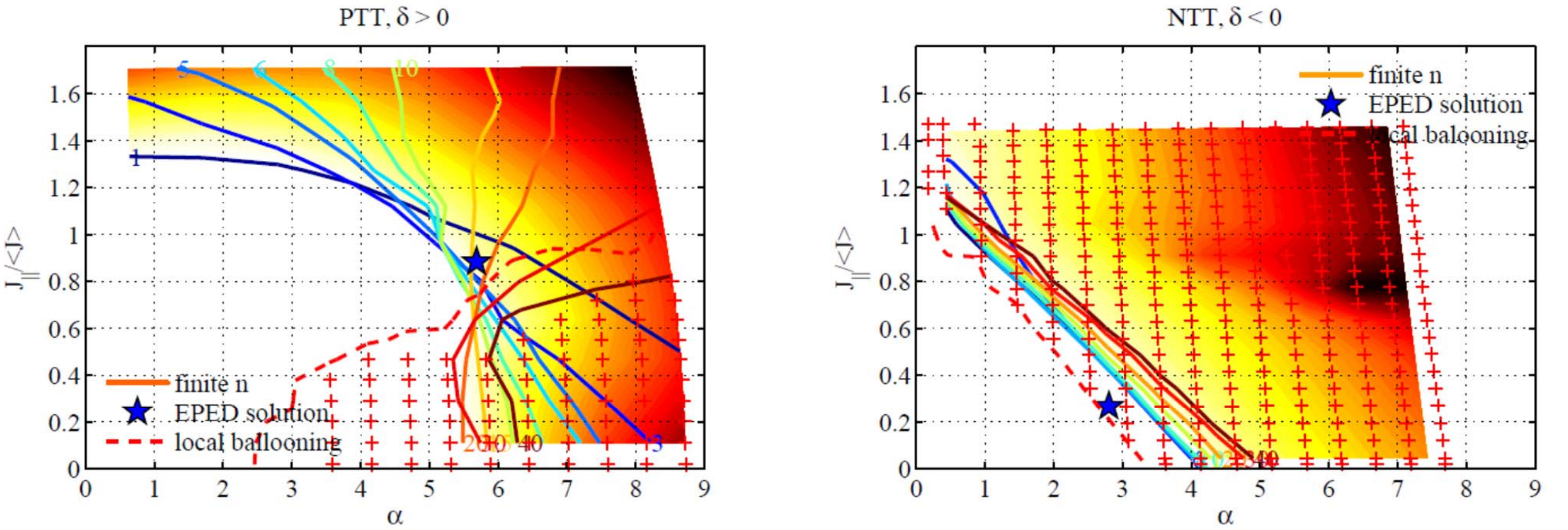


[A. Merle et al, PPCF submitted, Varenna 2016]

No 2^nd stability region with negative δ

Using standard pedestal stability analysis (fixed Δ)

- Scale p' and $I_{||}$ indepently in the pedestal region
- Compute finite-n and infinite-n stability boundaries



- The "nose" disappears for negative δ, preventing access to the high α region. Linked with the absence of the second stability region for ballooning modes. [S. Medvedev, *NF* 2015]

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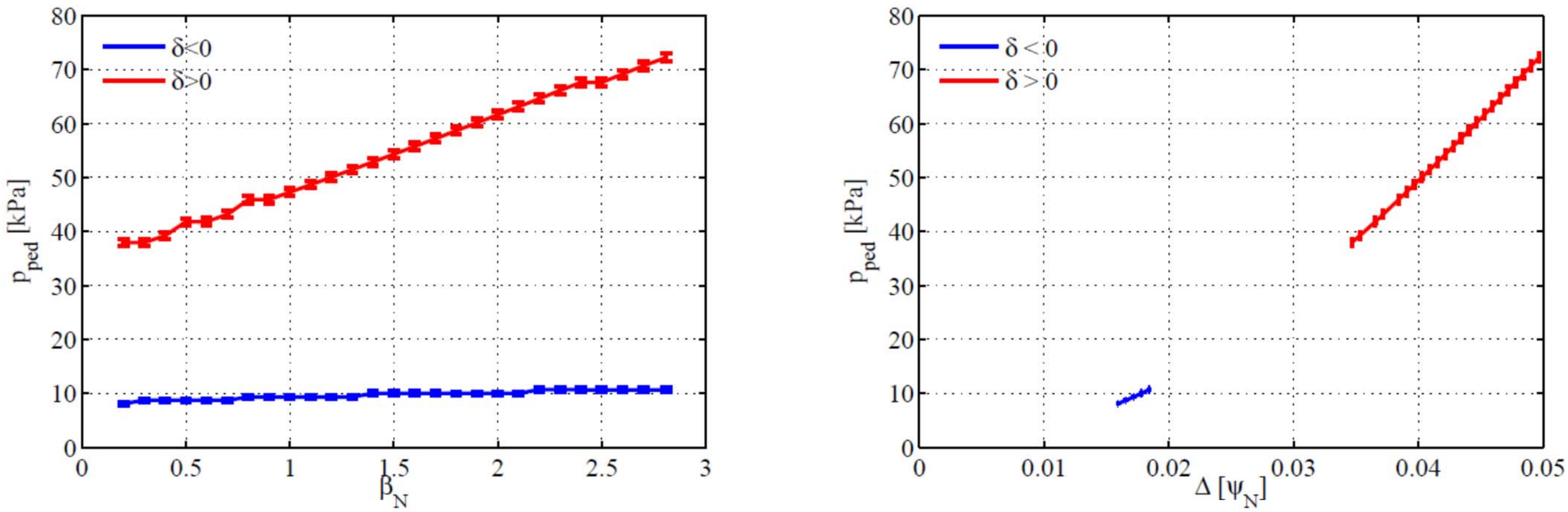
Thus little effect of beta on $p_{ped}(\delta<0)$



- Large beneficial effect of β on p_{ped} for $\delta > 0$

  $\Longrightarrow$ linked with easier access to 2nd stability and "longer nose"

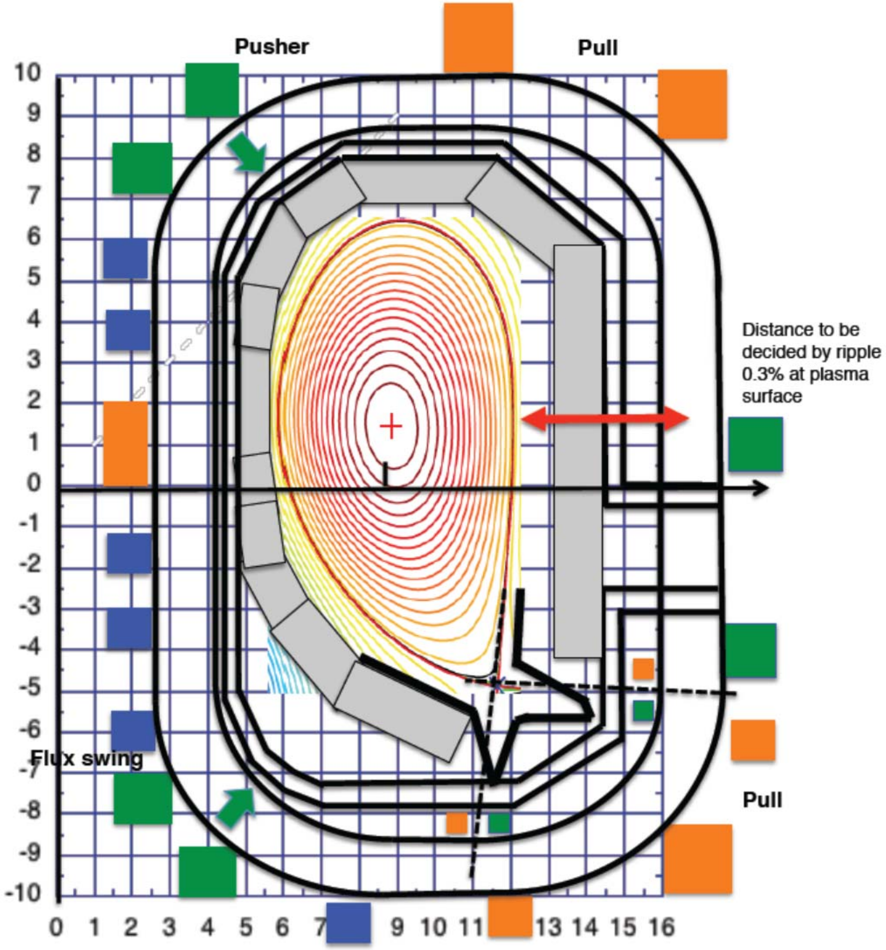
- $p_{e,ped}$ only weakly increasing with β for $\delta < 0$

[A. Merle et al, PPCF submitted, Varenna 2016]

Conclusion: Integrated solution NTT demo

[M. Kikuchi et al., JPS Conf. Proc. 1 (2014)]

[S. Medvedev et al., IAEA (2016) ICC/P3-47]



- R_0=9m, a=3m, B_0=5T, I_p=15MA δ_l=-0.85, δ_u=0, κ=1.8
- Stable up to β_N =2.9
- Compatible with low p_{ped} (δ<0) and R/L_{Te}~10

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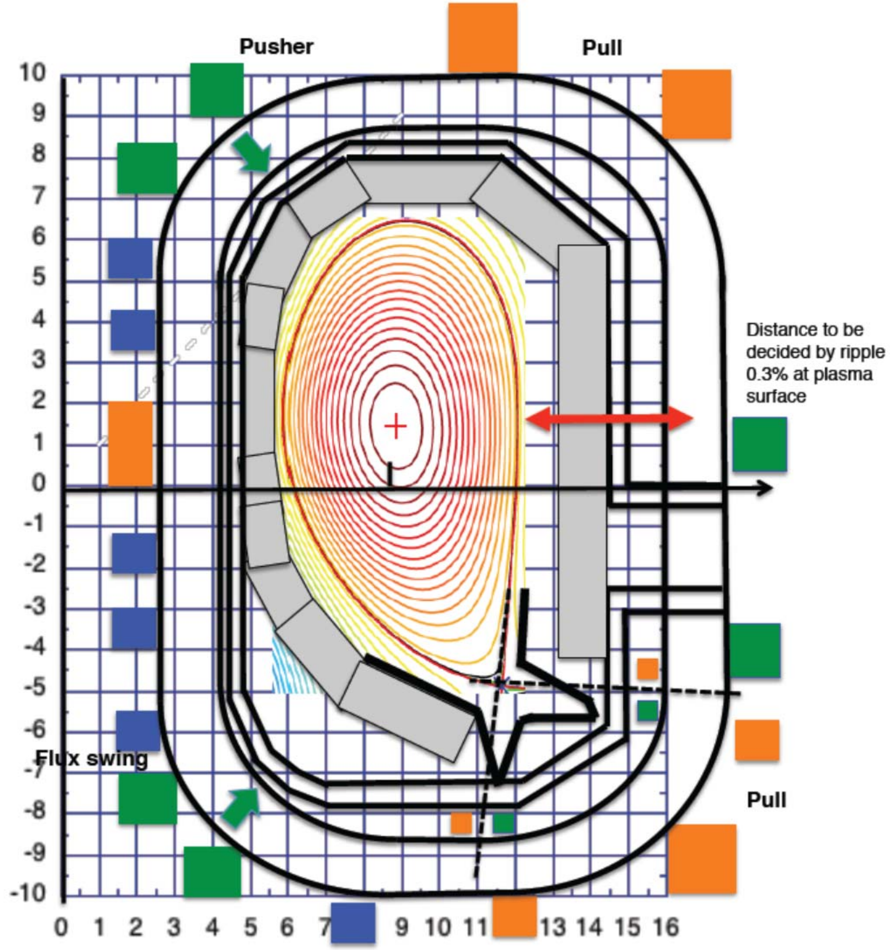
Conclusion: Integrated solution NTT demo

- Potential for improved core transport with $\delta<0$
- Use "MHD" to limit upper bound => no single large events



- R_0=9m, a=3m, B_0=5T, I_p=15MA δ_l=-0.85, δ_u=0, κ=1.8
- Stable up to β_N =2.9
- Compatible with low p_{ped} ($\delta<0$) and R/L_{Te}~10

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