ICC/P3-47

Single Null Divertor in Negative Triangularity Tokamak

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Outline

- Motivation
  - Negative Triangularity Tokamak (NTT) concept as a prospective Innovative Confinement Concept
  - DN NTT and SN NTT
- Theory and experiment
  - Beta limits, pedestal and ELMs, vertical stability
  - Better core confinement in L-mode
- Technical merits and divertor solutions
  - Reactor perspective: SYSCODE calculations
  - TF coil design and high-Tc superconductors
  - FTE divertor
- Discussion

1. Motivation

- Power handling is a major challenge for magnetic confinement fusion, especially tokamak.
- 600MW/700m^2~1MW/m^2 but actual divertor area is much smaller and peak heat load can be 70MW/m^2 (see. M. Kikuchi, et al., e-conference on energy, 2014, paper E002)

We probably need order of magnitude change to solve this issue.

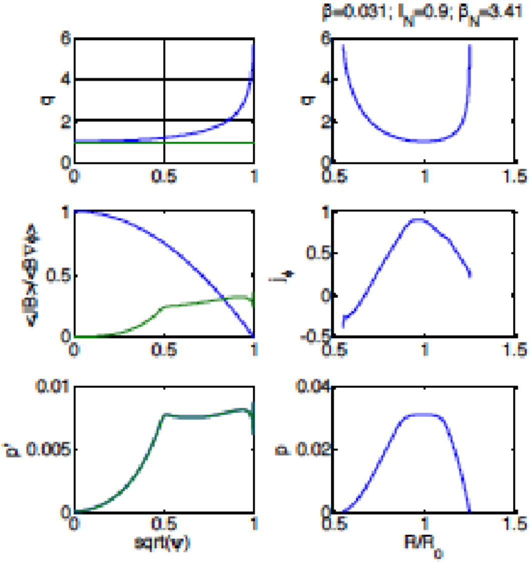
- First step: Divertor priority is higher than core
  - Any fusion energy system must have reliable heat exhaust scenario

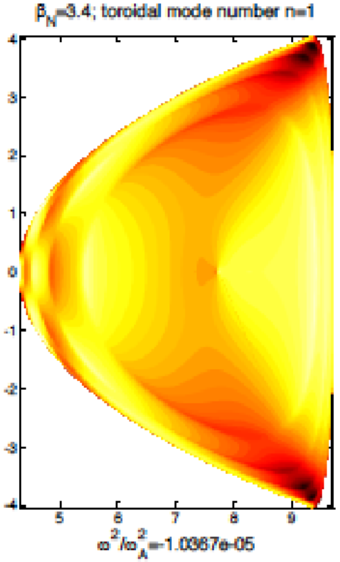
1.1 NTT concept

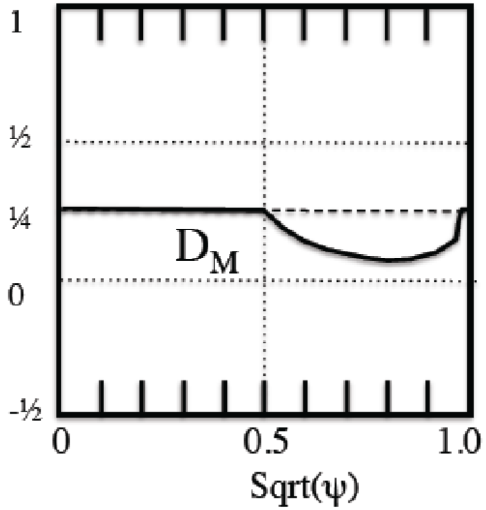
- A choice - negative D
- **X-point toward large R region → geometrically wider wetted area**
- **Make edge pedestal β limit SOFT: not by finite n peeling-ballooning but by Mercier/n=∞ ballooning!**
- **Stay in L-mode edge?**
- **Find new core transport reduction physics**
  - **Experiment TCV → better confinement for δ<0 in L-mode**
  - **Reactor core is more collisionless**
  - **Optimization of TEM**
  - **Trapped electron precession**
  - **Negative delta reduce "stiffening"**
- Beta limits? → $\boldsymbol{\beta}_N$>3 in double null NTT

Medvedev, Kikuchi, et al. NF 2015

1.1 DN-NTT: S. Medvedev NF2015



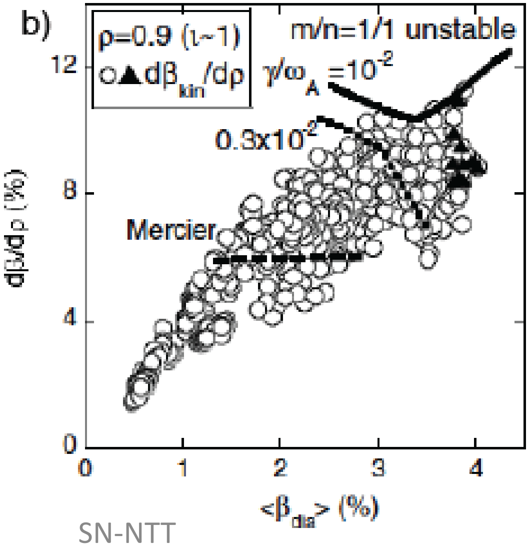




β_N>3 is stable

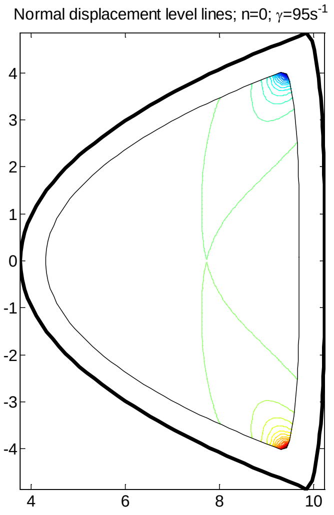
Medvedev, Kikuchi, et al. NF 2015

Can tokamak be OK with magnetic hill?

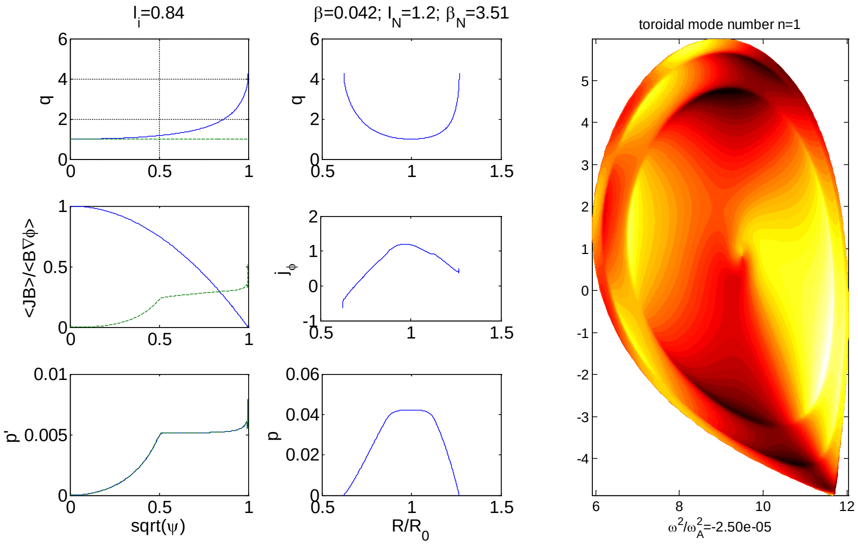


← LHD magnetic hill (Watanabe NF2005)
It can reach above Mercier limit.

DN-NTT problems:
Control of power sharing between upper and lower divertor
Relatively higher growth rate of vertical instability: highly non-rigid with finite j_{sx}
→ Move to SN-NTT



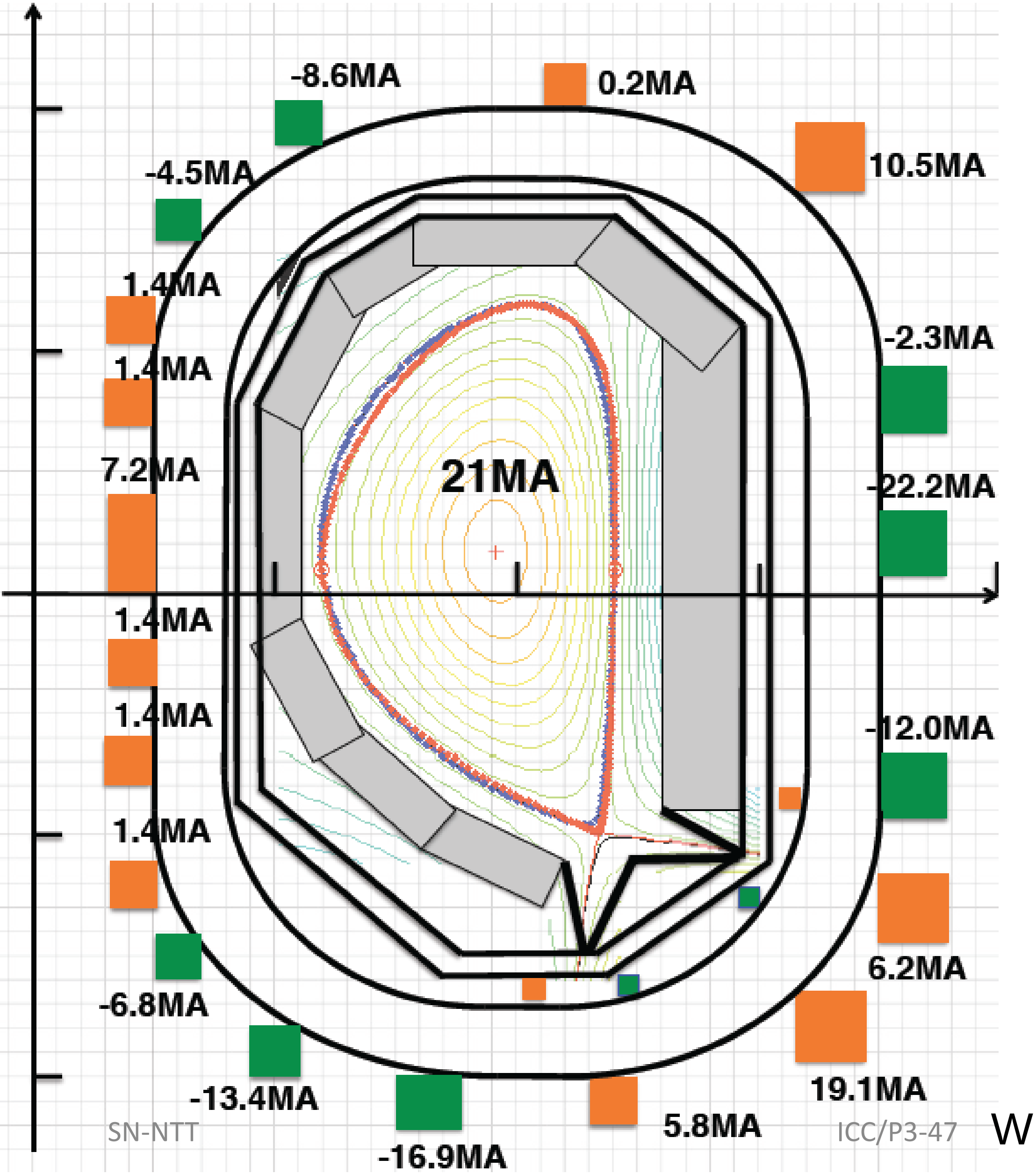
2.1 SN-NTT: M. Kikuchi EPS 2015



- Higher elongation k=1.8 due to better vertical stability
- n=1 external kink mode limit β_N>3 for l_i~0.9 with separatrix at the plasma boundary (KINX)
- Beta limit enhanced for low upper triangularity

- **Free boundary equilibrium calculations with SPIDER code**
  - **PF coil system compatible with racetrack TF coils**
  - **Ratio of PF coil currents to plasma current is close to ITER value $\Sigma|I_{PF}|/I_p = 5.5$**
- **Edge stability is determined by nearly internal Mercier modes as in DN-NTT**

2.1 Single null NTT configuration [Racetrack TF coils



R_p=9m, a_p=3m, I_p=21MA, B_t=5.86T
q_{95}=3.0, κ_{95}=1.73, κ_x=1.8, δ_{Ux}=-0.4, δ_{Lx}=-0.9

Racetrack shaped TF coil is best suited for NTT configuration.
PF coil currents $\Sigma|I_{PF}|/I_p = 6.8$

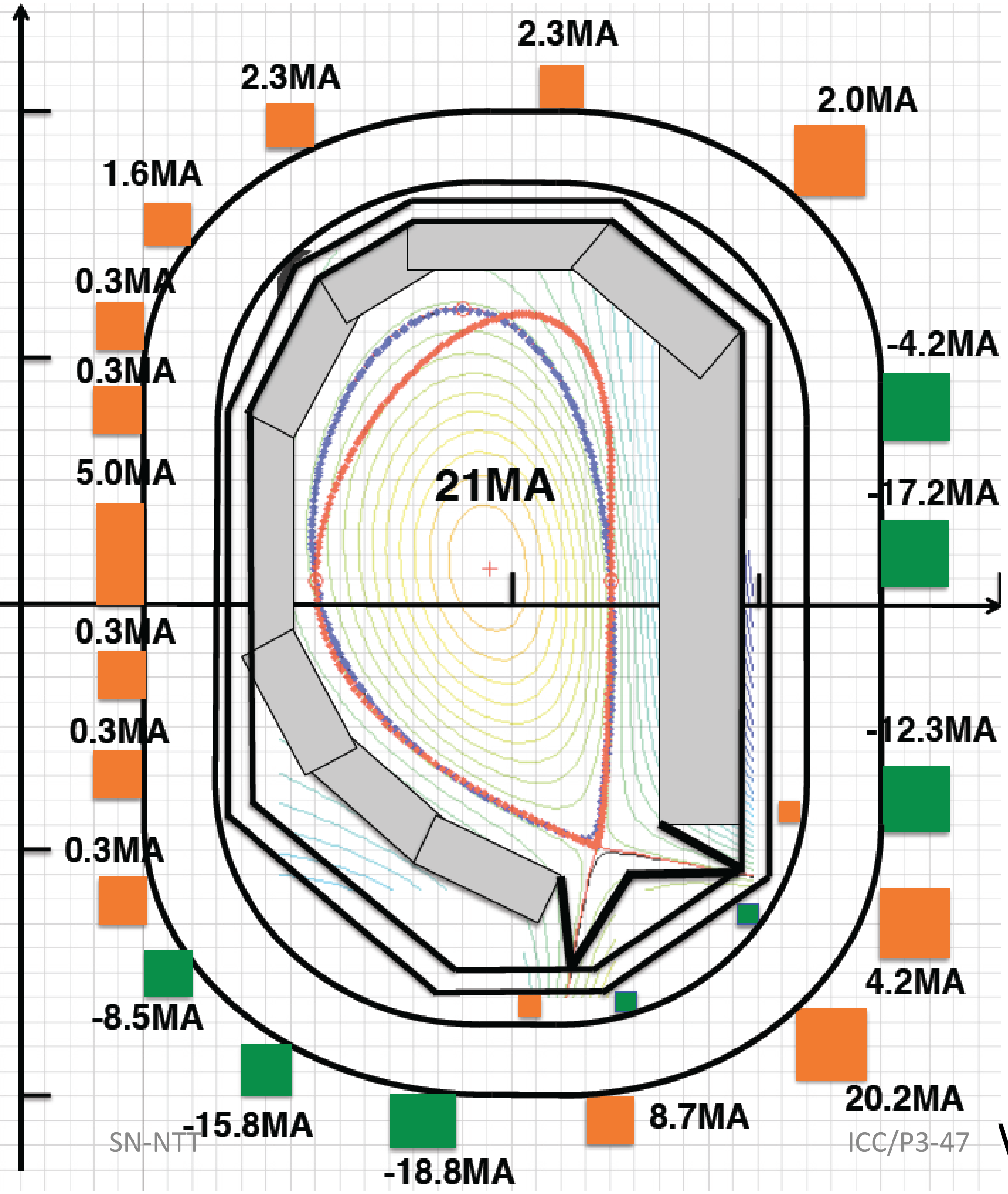
For single null NTT, vertical stability is fairly good. With a_w/a=1.3, the growth rate is ~14s^{-1}, similar to ITER value (6cm thick steel wall).
Beta limit (w/o wall) l_i=0.84

- **n = 1 betaN = 2.79**
- n = 2 betaN = 3.24
- n = 3 betaN = 3.36
- n = 4 betaN = 3.43
- n = 5 betaN = 3.47

n = infty : betaN= 3.41

With a_w/a=1.3 wall, **β_N =3.3** n=1 stable

2.1 Single null NTT configuration [Low upper **δ**]



R_p=9m, a_p=3m, I_p=21MA, B_t=5.86T
q_{95}=3.1, κ_{95}=1.71, κ_x=1.8, δ_{Ux}=-0.1,
δ_{Lx}=-0.9

Racetrack shaped TF coil is best suited for NTT configuration.
PF coil currents $\Sigma|I_{PF}|/I_p = 5.9$

With a_w/a=1.3, the growth rate is ~$11s^{-1}$, similar to ITER value (6cm thick steel wall) and weakly depends on upper triangularity.
Beta limit (w/o wall) l_i=0.84

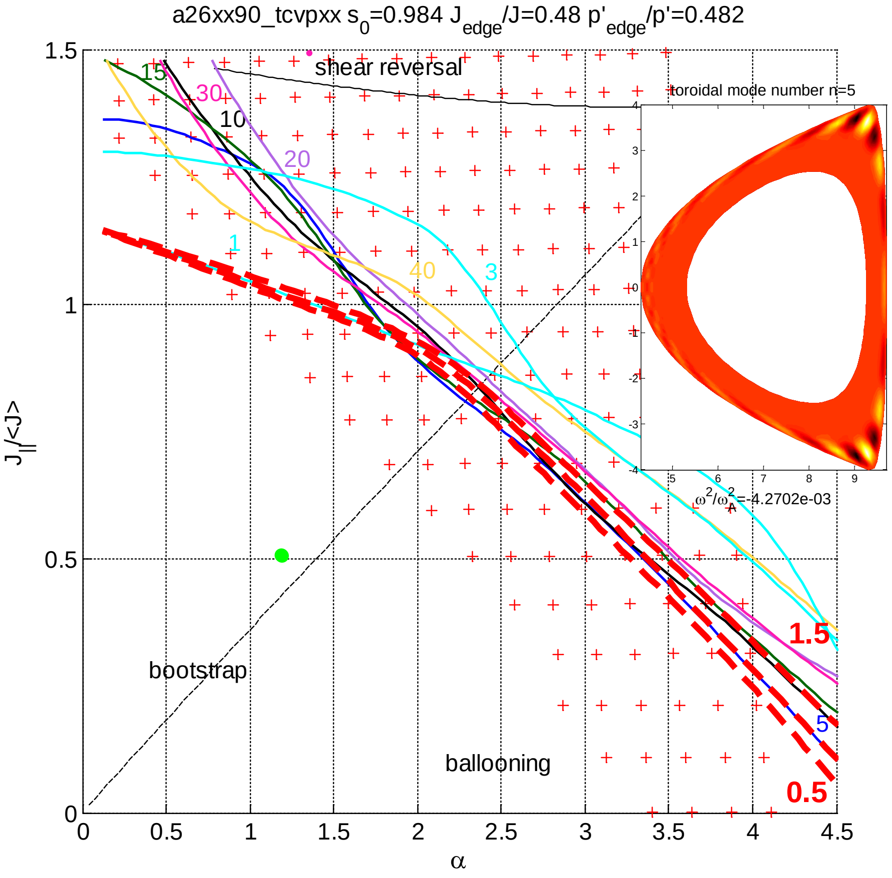
- **n = 1 betaN = 3.14**
- n = 2 betaN = 3.30
- n = 3 betaN = 3.40
- n = 4 betaN = 3.45
- n = 5 betaN = 3.48

n = infty : betaN= 3. 51

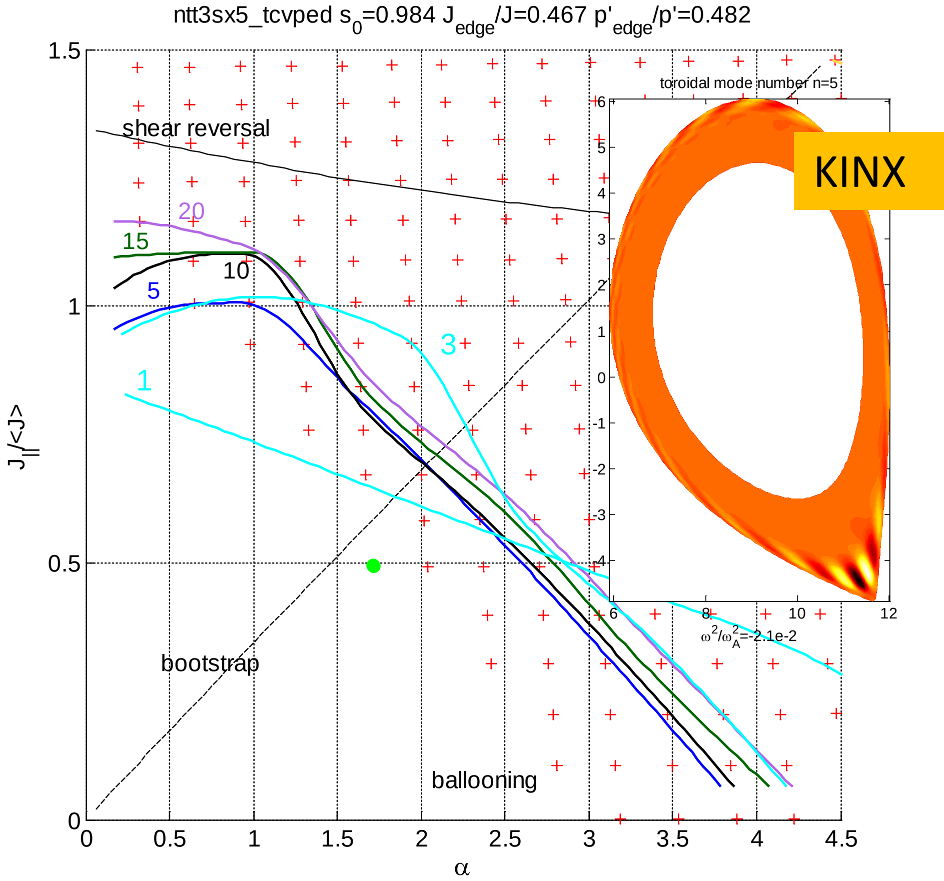
With a_w/a=1.3 wall, **β_N =3.56** n=1 stable

2.1 DN-NTT vs SN-NTT: edge stability

R=7m, a=2.7m (A=2.6), *k*=1.5, l_N=1.0, l_i=0.77



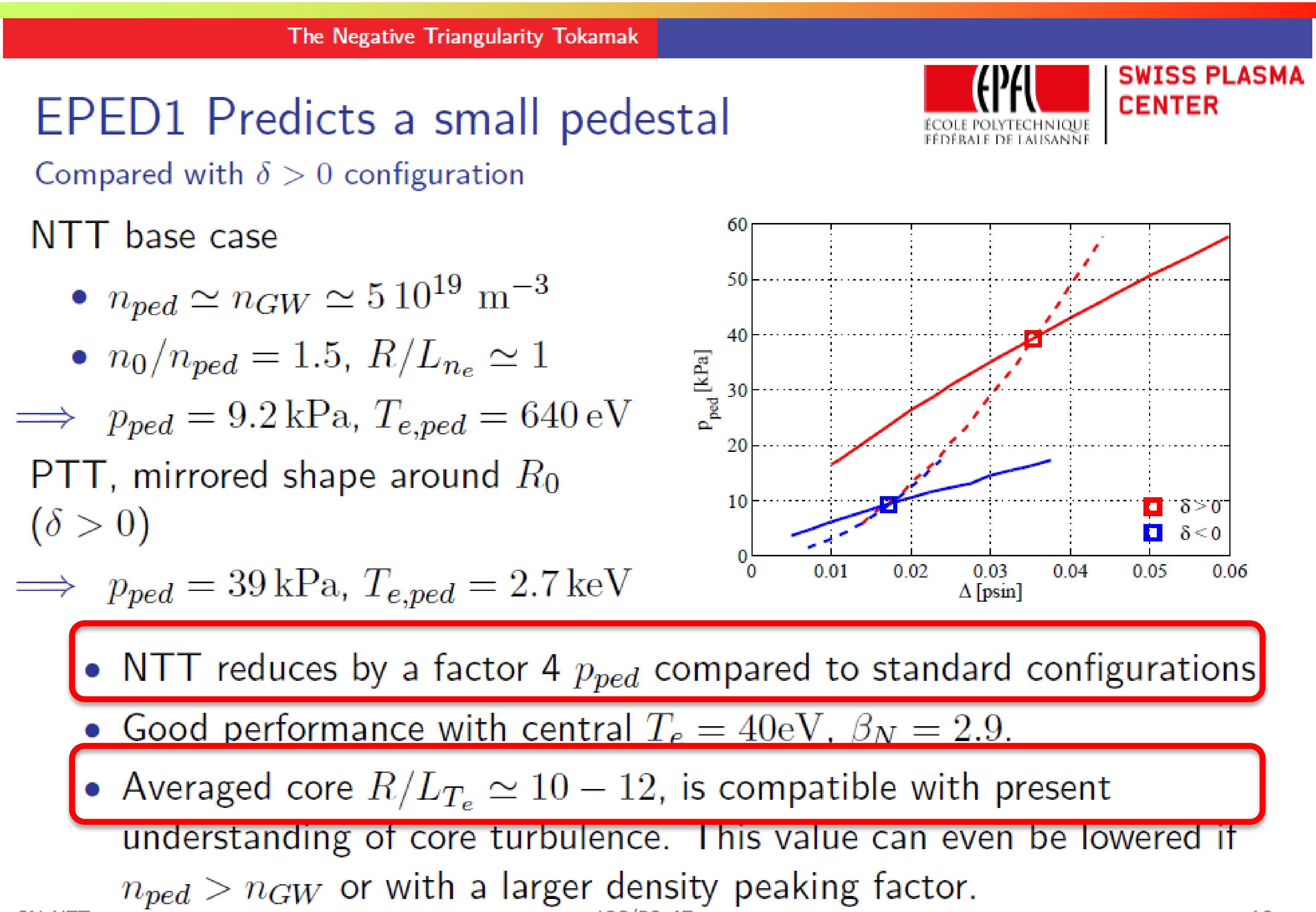
R=9m, a=3m (A=3), *k*=1.8, l_N=1.2, , l_i=0.71



- **red dash: most unstable $\gamma/(\omega_*/2)$=0.5, 1, 1.5 level lines**
- **color solid: individual modes $\gamma/(\omega_*/2)$= 1 level lines**

- **red crosses: Mercier/ballooning unstable**
- **color solid: individual modes $\gamma=0$**

2.1 EPED-CH (Merle 2016) pedestal width and height



The Negative Triangularity Tokamak

EPED1 Predicts a small pedestal

Compared with $\delta > 0$ configuration

NTT base case

- $n_{ped} \simeq n_{GW} \simeq 5\,10^{19}\ \mathrm{m}^{-3}$
- $n_0/n_{ped} = 1.5,\ R/L_{n_e} \simeq 1$

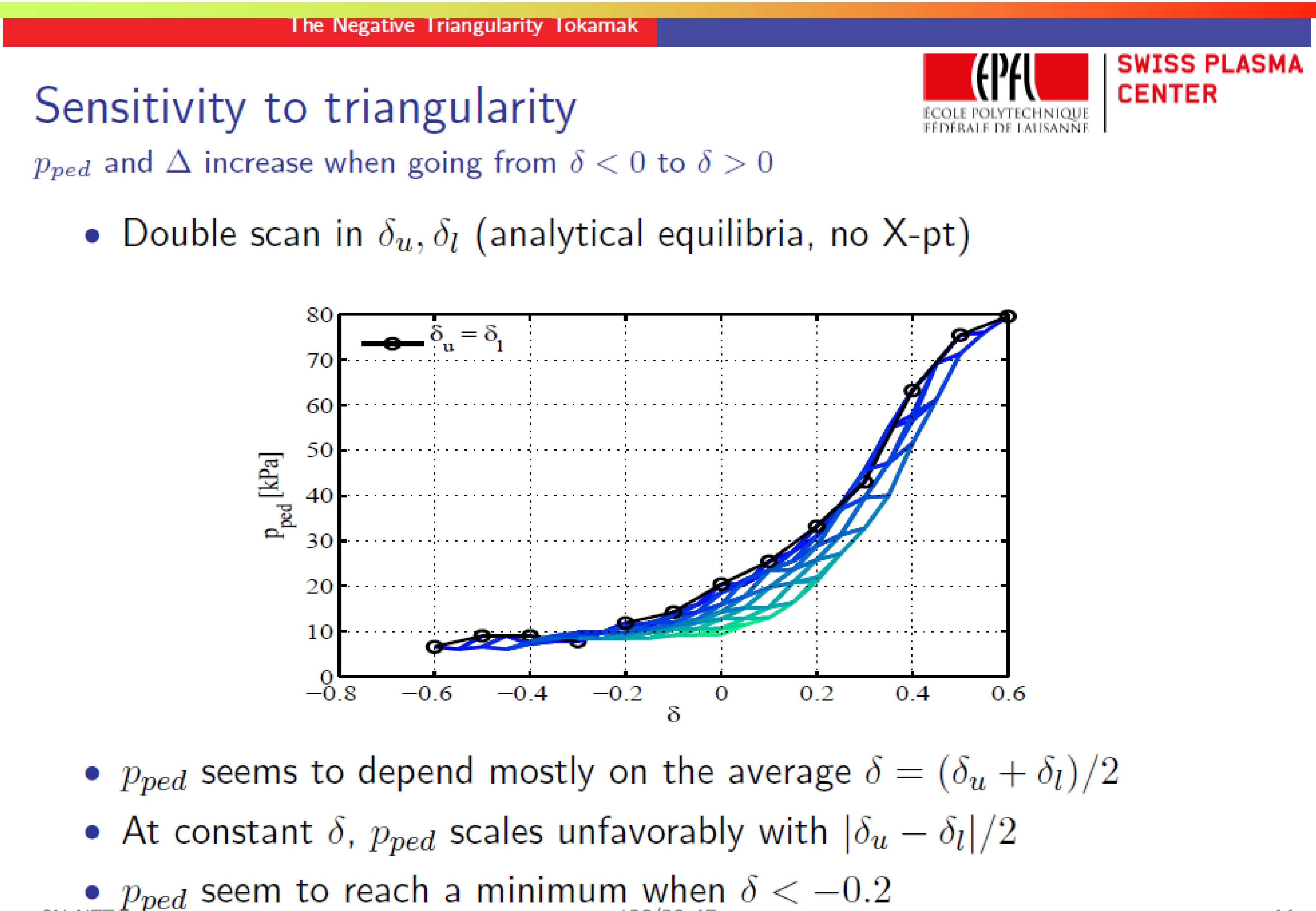
$\Longrightarrow\quad p_{ped} = 9.2\,\mathrm{kPa},\ T_{e,ped} = 640\,\mathrm{eV}$

PTT, mirrored shape around R_0 $(\delta > 0)$

$\Longrightarrow\quad p_{ped} = 39\,\mathrm{kPa},\ T_{e,ped} = 2.7\,\mathrm{keV}$

- NTT reduces by a factor 4 p_{ped} compared to standard configurations
- Good performance with central $T_e = 40\mathrm{eV},\ \beta_N = 2.9$.
- Averaged core $R/L_{T_e} \simeq 10 - 12$, is compatible with present understanding of core turbulence. This value can even be lowered if $n_{ped} > n_{GW}$ or with a larger density peaking factor.

2.1 EPED-CH: upper/lower triangularity scan



The Negative Triangularity Tokamak

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER

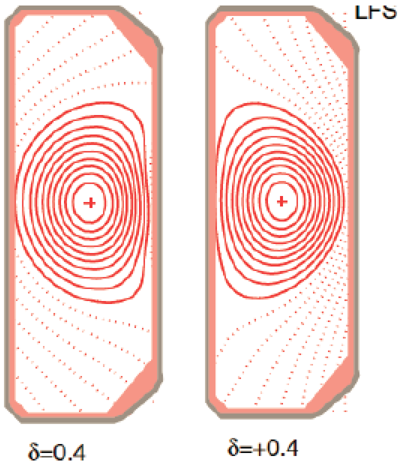
Sensitivity to triangularity

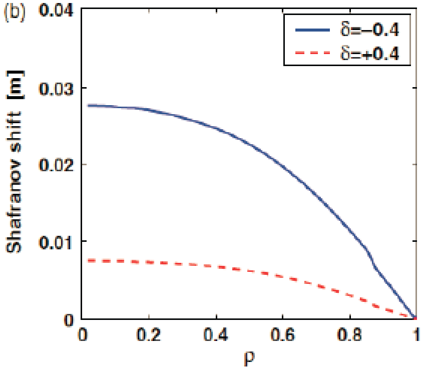
p_{ped} and Δ increase when going from $\delta < 0$ to $\delta > 0$

- 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 $\delta < -0.2$

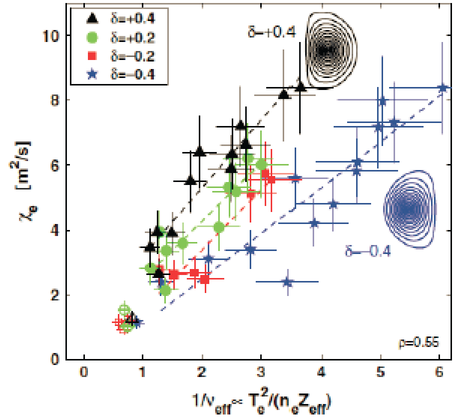
2.2 : TCV negative triangularity L-mode

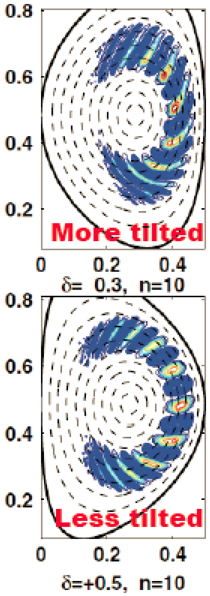




Negative triangularity produces large Shafranov shift, which changes precession drift of trapped electron. This leads to a change in TEM stability.

Large tilting in negative delta
Similar effect like Er' ?





Non-locality will be reduced in Reactor

Camenen NF2007

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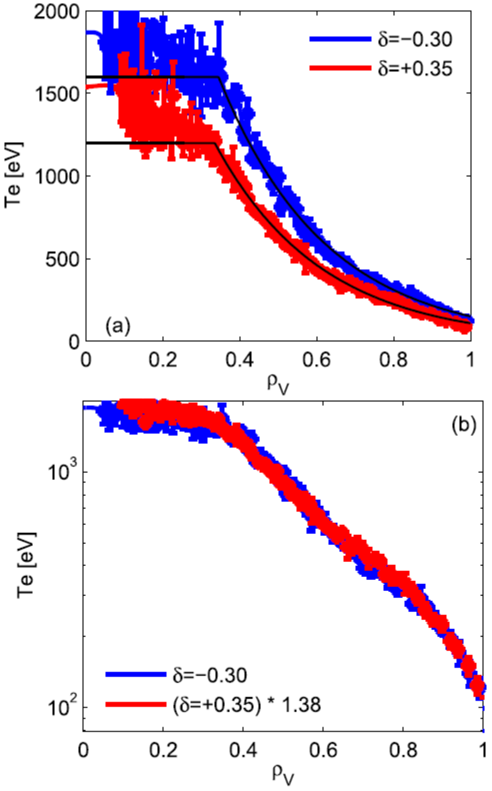
EDGE NON-STIFFNESS RESPONSIBLE FOR THE EFFECT OF TRIANGULARITY ON CONFINEMENT



ECH input power, 0.4 MW

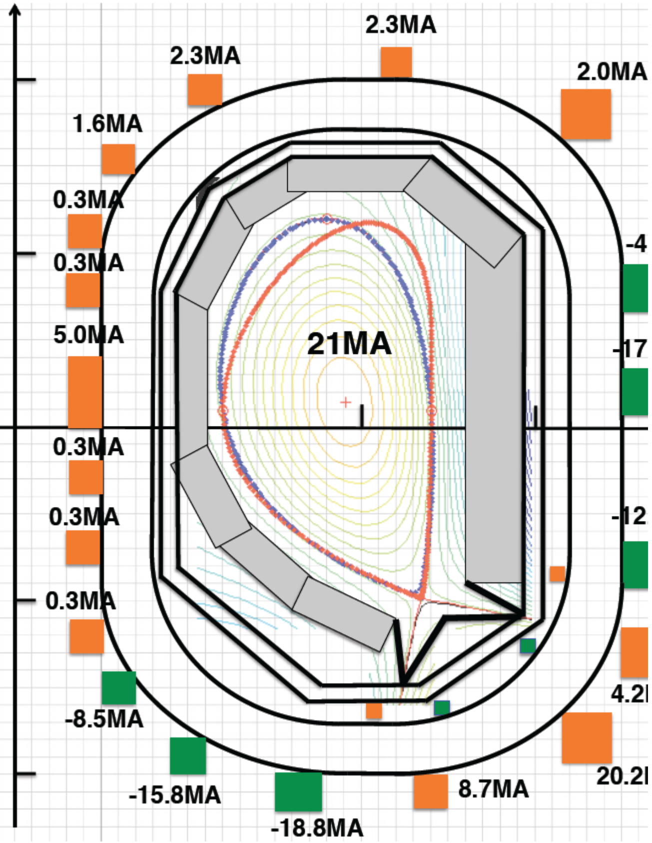
Y. Camenen, et al., Nuclear Fusion 47, 510(2007)

A. Marinoni, et al., PPCF 51,055016 (2009)

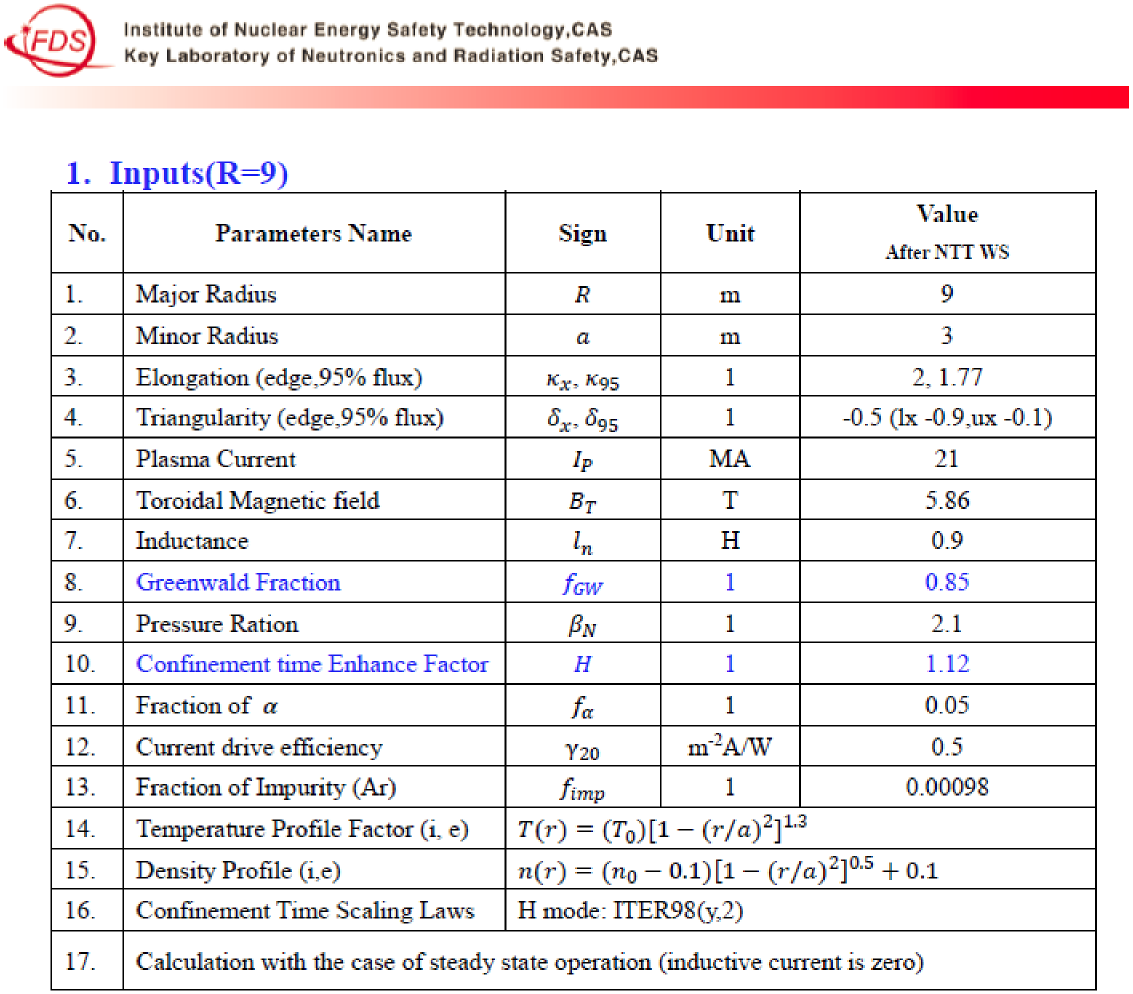
O. Sauter, et al., Physics of Plasmas 21, 055906 (2014)

3.1 Reactor perspective: SYSCODE calculations

Dehong Chen (INEST), new system code including O. Sauter's refined formula valid for negative delta (O. Sauter, FED 2016)



Racetrack-shaped TF coil



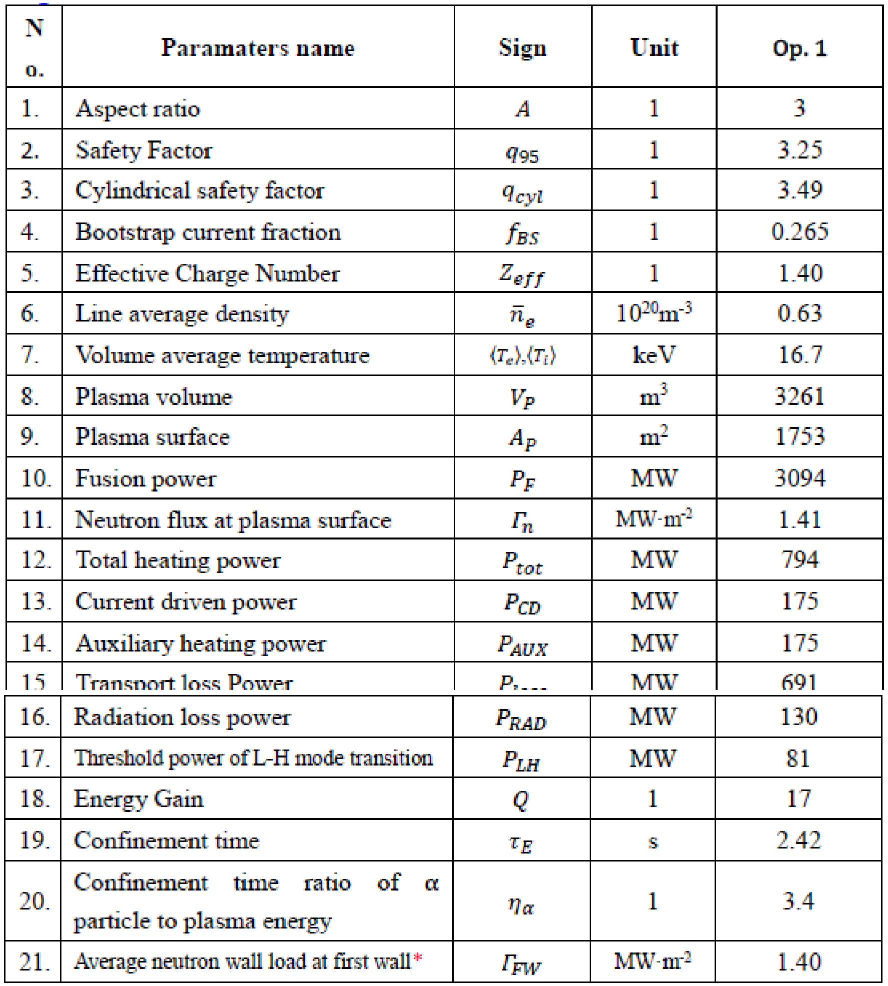
Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

1. Inputs(R=9)

No.	Parameters Name	Sign	Unit	Value After NTT WS
1.	Major Radius	R	m	9
2.	Minor Radius	a	m	3
3.	Elongation (edge,95% flux)	κ_x, κ_{95}	1	2, 1.77
4.	Triangularity (edge,95% flux)	δ_x, δ_{95}	1	-0.5 (lx -0.9,ux -0.1)
5.	Plasma Current	I_P	MA	21
6.	Toroidal Magnetic field	B_T	T	5.86
7.	Inductance	l_n	H	0.9
8.	Greenwald Fraction	f_{GW}	1	0.85
9.	Pressure Ration	β_N	1	2.1
10.	Confinement time Enhance Factor	H	1	1.12
11.	Fraction of α	f_α	1	0.05
12.	Current drive efficiency	γ_{20}	$m^{-2}A/W$	0.5
13.	Fraction of Impurity (Ar)	f_{imp}	1	0.00098
14.	Temperature Profile Factor (i, e)	$T(r) = (T_0)[1-(r/a)^2]^{1.3}$		
15.	Density Profile (i,e)	$n(r) = (n_0 - 0.1)[1-(r/a)^2]^{0.5} + 0.1$		
16.	Confinement Time Scaling Laws	H mode: ITER98(y,2)		
17.	Calculation with the case of steady state operation (inductive current is zero)			

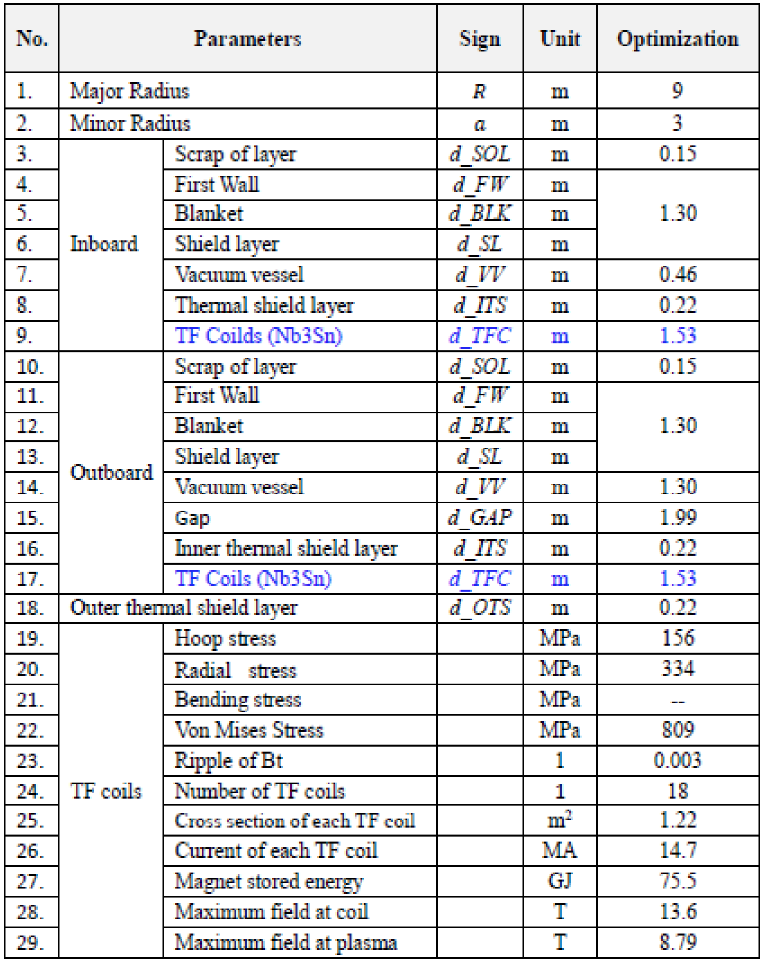
3.1 System code results (continued)

System code output



No.	Paramaters name	Sign	Unit	Op. 1
1.	Aspect ratio	A	1	3
2.	Safety Factor	q_{95}	1	3.25
3.	Cylindrical safety factor	q_{cyl}	1	3.49
4.	Bootstrap current fraction	f_{BS}	1	0.265
5.	Effective Charge Number	Z_{eff}	1	1.40
6.	Line average density	$\bar{n}_e$	$10^{20}m^{-3}$	0.63
7.	Volume average temperature	$\langle T_e \rangle, \langle T_i \rangle$	keV	16.7
8.	Plasma volume	V_P	m^3	3261
9.	Plasma surface	A_P	m^2	1753
10.	Fusion power	P_F	MW	3094
11.	Neutron flux at plasma surface	Γ_n	$MW \cdot m^{-2}$	1.41
12.	Total heating power	P_{tot}	MW	794
13.	Current driven power	P_{CD}	MW	175
14.	Auxiliary heating power	P_{AUX}	MW	175
15	Transport loss Power	P	MW	691
16.	Radiation loss power	P_{RAD}	MW	130
17.	Threshold power of L-H mode transition	P_{LH}	MW	81
18.	Energy Gain	Q	1	17
19.	Confinement time	τ_E	s	2.42
20.	Confinement time ratio of α particle to plasma energy	η_α	1	3.4
21.	Average neutron wall load at first wall*	Γ_{FW}	$MW \cdot m^{-2}$	1.40

Radial build



No.	Parameters		Sign	Unit	Optimization
1.	Major Radius		R	m	9
2.	Minor Radius		a	m	3
3.	Inboard	Scrap of layer	d_SOL	m	0.15
4.		First Wall	d_FW	m	1.30
5.		Blanket	d_BLK	m	
6.		Shield layer	d_SL	m	
7.		Vacuum vessel	d_VV	m	0.46
8.		Thermal shield layer	d_ITS	m	0.22
9.		TF Coilds (Nb3Sn)	d_TFC	m	1.53
10.	Outboard	Scrap of layer	d_SOL	m	0.15
11.		First Wall	d_FW	m	1.30
12.		Blanket	d_BLK	m	
13.		Shield layer	d_SL	m	
14.		Vacuum vessel	d_VV	m	1.30
15.		Gap	d_GAP	m	1.99
16.		Inner thermal shield layer	d_ITS	m	0.22
17.		TF Coils (Nb3Sn)	d_TFC	m	1.53
18.	Outer thermal shield layer		d_OTS	m	0.22
19.	TF coils	Hoop stress		MPa	156
20.		Radial stress		MPa	334
21.		Bending stress		MPa	--
22.		Von Mises Stress		MPa	809
23.		Ripple of Bt		1	0.003
24.		Number of TF coils		1	18
25.		Cross section of each TF coil		m^2	1.22
26.		Current of each TF coil		MA	14.7
27.		Magnet stored energy		GJ	75.5
28.		Maximum field at coil		T	13.6
29.		Maximum field at plasma		T	8.79

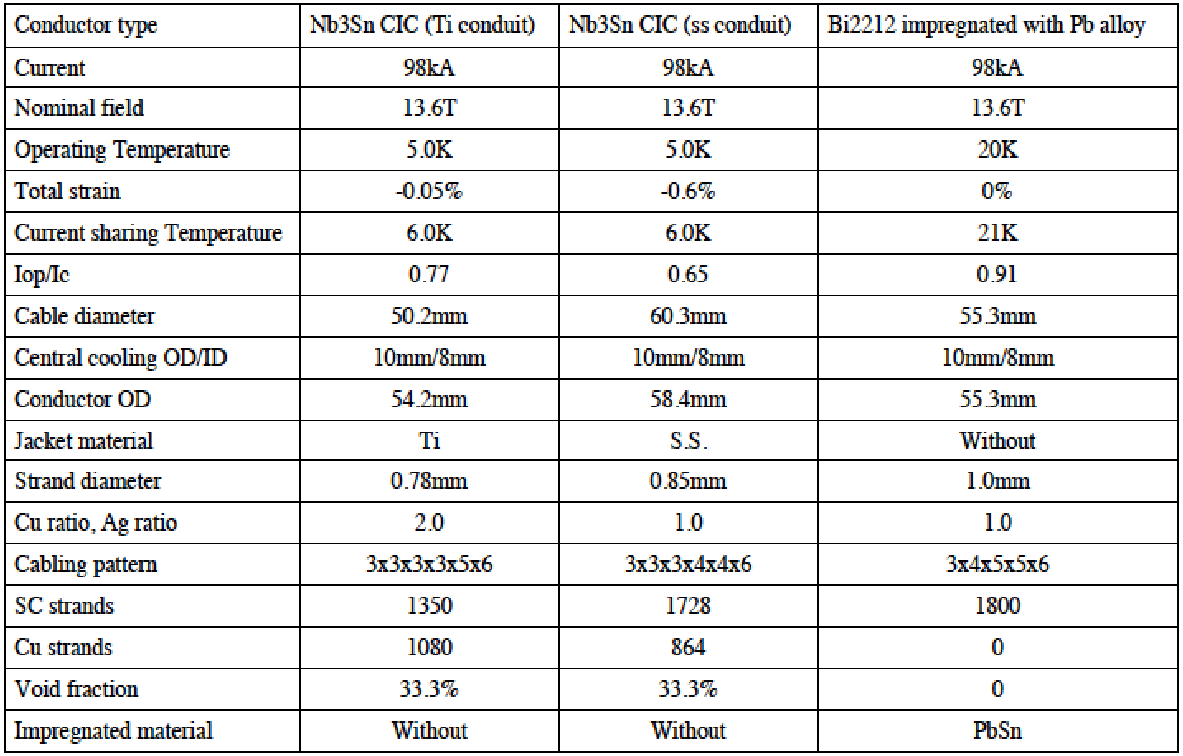
- The required thickness of **Blanket and shield layer is 1.3m** considering the space requirement for fixing, loading and maintaining.
- The thickness of thermal shield layer and vacuum vessel were extrapolated from ITER structure design. In order to ensure the ripple of Bt, the **radius of outboard TF coils should be 17.0m**, so that there will be **a gap 1.99m wide between inner thermal shield layer and vacuum vessel.**
- The stress limit of TF coils is 800MPa, so we get the **thickness requirement of TF coils is 1.53m**.

3.2 TF magnet design (T.Ando)

- Three designs of TF superconductor: racetrack shape TF coils based on Nb3Sn ITER technology and Bi-2212 high-Tc superconductor.
- Since Nb3Sn is sensitive to strain, use of Nb3Sn in such a big magnet (170GJ) is challenging.
- Considering Ti has similar thermal expansion coefficient with Nb3Sn, both SS conduit (ITER type) and Ti conduit designs are explored: the use of Ti conduit will reduce total strain of the Nb3Sn conductor and the expected total strain is -0.05%.

T. ANDO IEEE Trans. Appl. Supercond. 1993, 2004

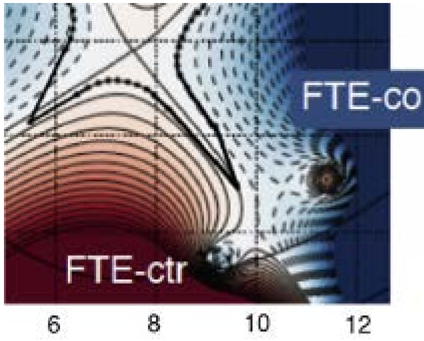
Basic TF parameters:
coil size of 15m x 20m,
number of coils 18,
magnetic energy of 170GJ,
maximum field of 13.6T,
discharge time 15 s,
Turns per coil 152,
coil current of 98kA,
disks per coil 7.



Conductor type	Nb3Sn CIC (Ti conduit)	Nb3Sn CIC (ss conduit)	Bi2212 impregnated with Pb alloy
Current	98kA	98kA	98kA
Nominal field	13.6T	13.6T	13.6T
Operating Temperature	5.0K	5.0K	20K
Total strain	-0.05%	-0.6%	0%
Current sharing Temperature	6.0K	6.0K	21K
Iop/Ic	0.77	0.65	0.91
Cable diameter	50.2mm	60.3mm	55.3mm
Central cooling OD/ID	10mm/8mm	10mm/8mm	10mm/8mm
Conductor OD	54.2mm	58.4mm	55.3mm
Jacket material	Ti	S.S.	Without
Strand diameter	0.78mm	0.85mm	1.0mm
Cu ratio, Ag ratio	2.0	1.0	1.0
Cabling pattern	3x3x3x3x5x6	3x3x3x4x4x6	3x4x5x5x6
SC strands	1350	1728	1800
Cu strands	1080	864	0
Void fraction	33.3%	33.3%	0
Impregnated material	Without	Without	PbSn

3.3 Flux tube expansion (FTE) coils

Ways to enlarge wetted area at the divertor plates.

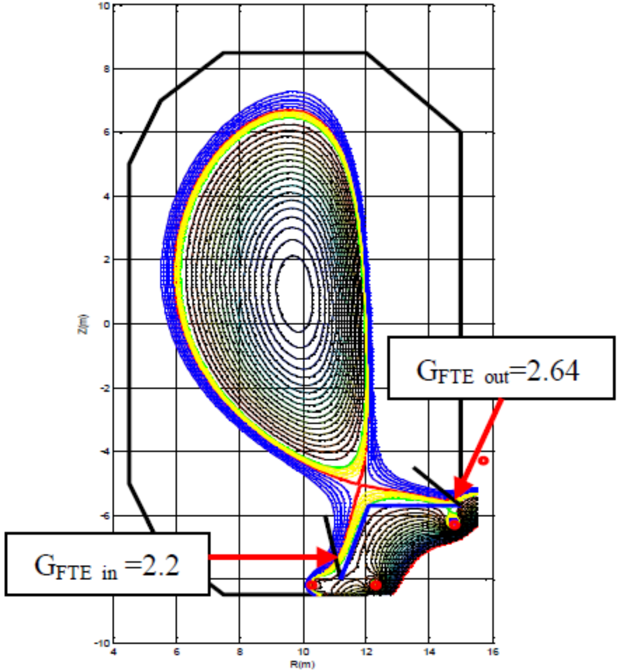


1. Snowflake divertor : Ryutov PoP2007

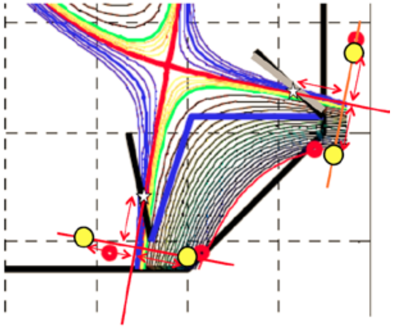
Snowflake : higher order X point subject to more sensitivity to perturbation.

2. Flux tube expansion divertor Takizuka JNM 2015

Flux tube expansion: More robust to perturbation and needs only ~4MA*turn



- **EFIT free boundary equilibrium calculations** (J.X.Li)
- **I_p = 21 MA $|I_{FTE}|$ =3MA; adjust divertor PF currents to maintain the X-point and separatrix leg position**
- **Heat load on the plate is expected over the factor 1/G_{FTE} (FTE rate $G_{FTE} = B_{p0}/B_p$)**
- **Grazing angle outer/inner divertor α = 7.2°/2.7° → 2.7°/1.3°**



Factor 2.7 can be obtained for relatively long leg divertor with FTE coil optimization

4 Discussion

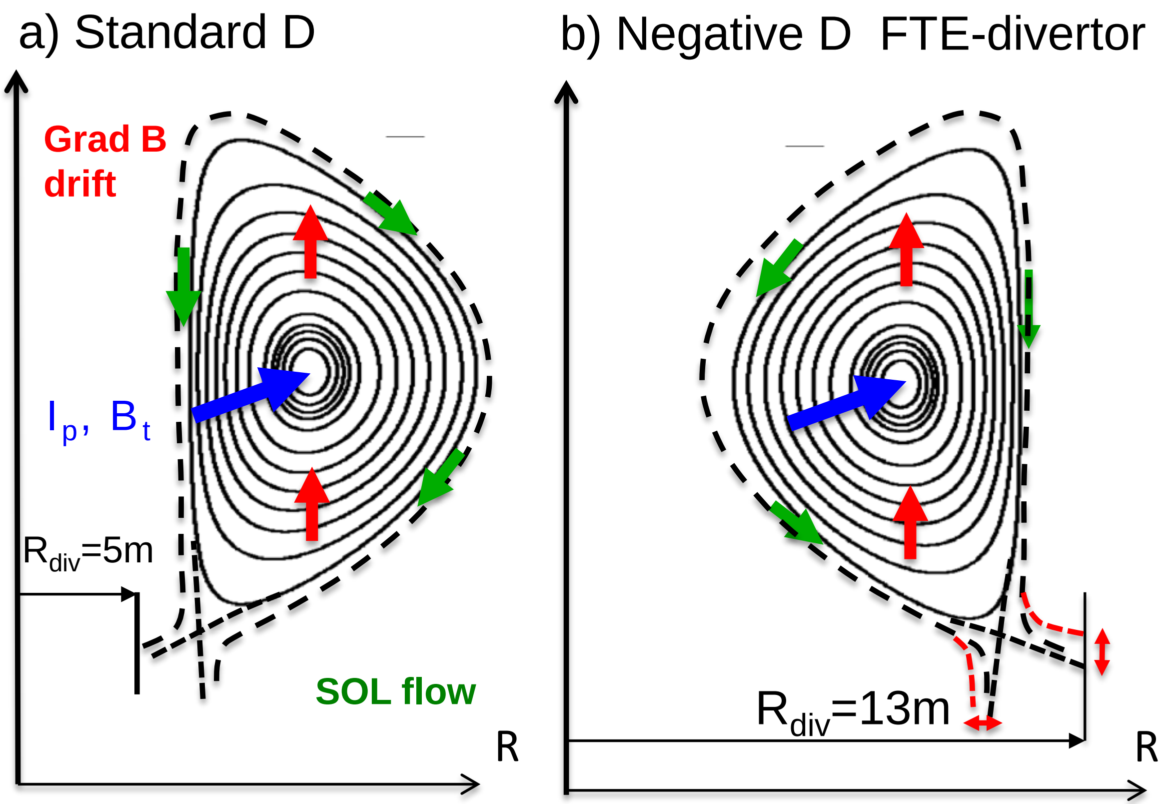
- SN-NTT configurations with optimized pressure gradient profiles can be stable against external kink modes for reactor relevant values of normalized beta β_N ~3.1.
  - Low upper triangularity SN-NTT configurations seems to be a good candidate for the reactor design being better compatible with the racetrack TF coils and featuring both higher beta limits and better $n = 0$ stability compared to the DN-NTT.
- Internal Mercier/ballooning modes set the pedestal height limit, which is much less sensitive to diamagnetic stabilization and pedestal profile variations than conventional peeling-ballooning modes → Mercier mode turbulence for a soft edge limit?
  - The predicted pedestal height in the NTT is a factor of 4 lower compared to the standard positive triangularity configurations. The averaged core scale length of the electron temperature gradient R/L_{Te} ~10–12 corresponding to β_N ~ 3 is compatible with present understanding of core turbulence.
- The NTT with FTE divertor makes power handling easier by a large factor in reactor relevant configuration
  - 3GW fusion power, racetrack superconducting TF coil design
- Improved confinement in the core of negative triangularity tokamaks still needs to be confirmed in large devices.

Make power handling easier by a Large Factor

Simple geometrical

Negative D
+ Flux tube
expansion

Note: Outboard is much easier to modify.



a) Standard D

b) Negative D FTE-divertor

R=9m, a=3m (A=3)

Standard D shape : R_{div}=5m, Negative D shape : R_{div}=13m

Factor of 2.6 for R_{div}

Flux tube expansion at R_{div} : Factor of 2.7

Factors : 2.6 x 2.7 = 7