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Impact of High Field & High Confinement on L-mode-Edge Negative Triangularity Tokamak (NTT) Reactor

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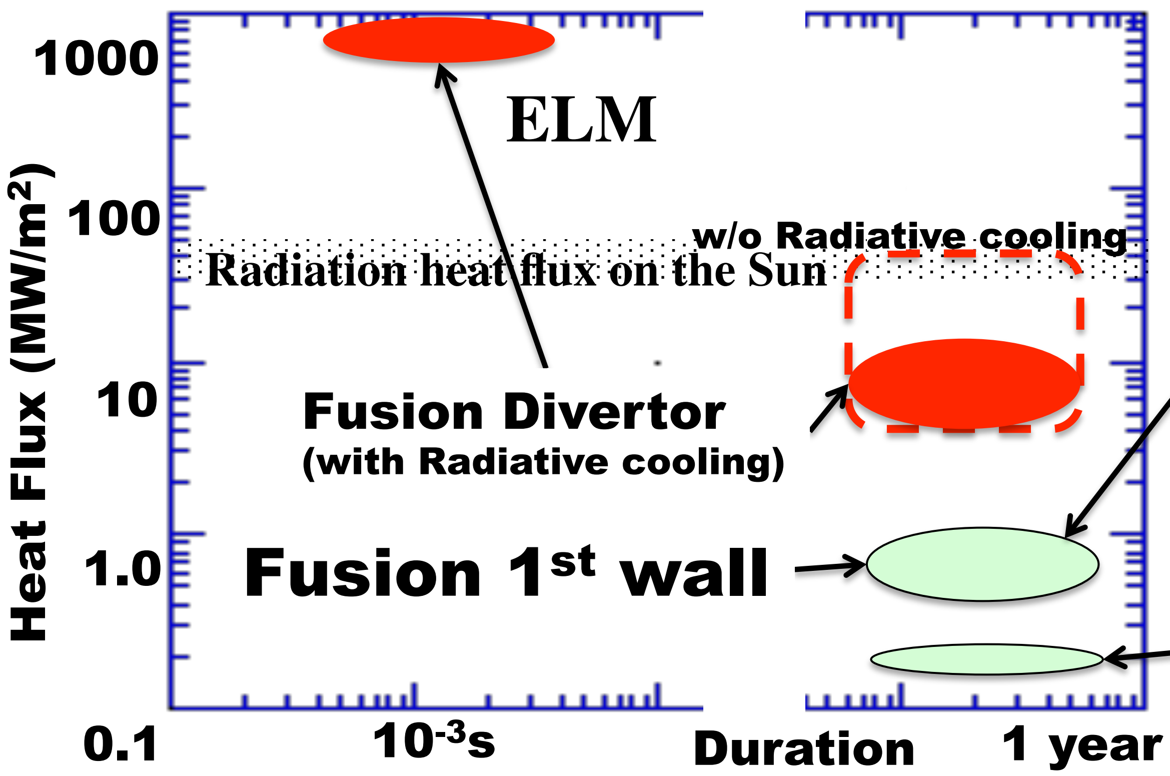
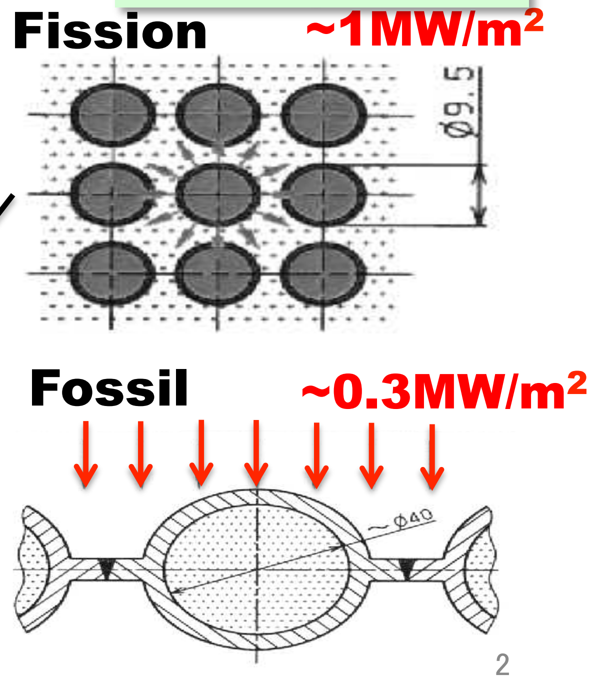
1. Motivation: Fusion Power Handling is quite challenging!

10MW/m² : short time fusion / **0.3-1MW/m²** : Reliable power syste

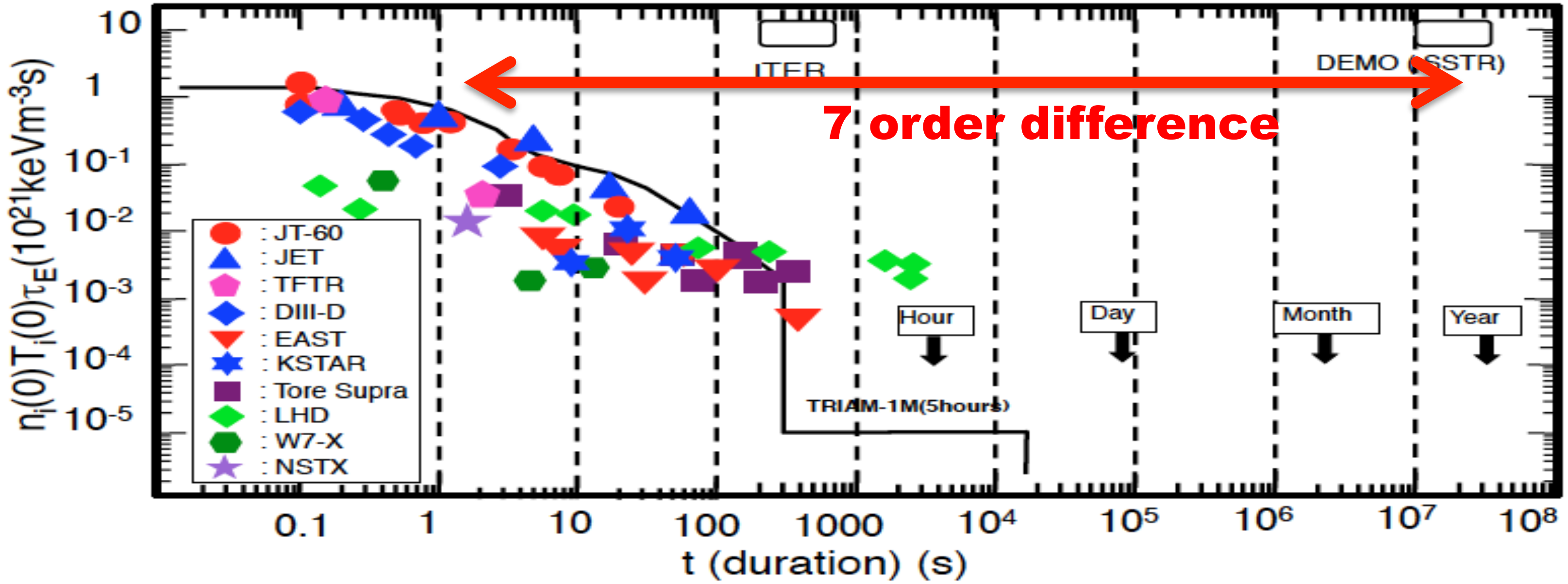


Disruption
Runaway electron



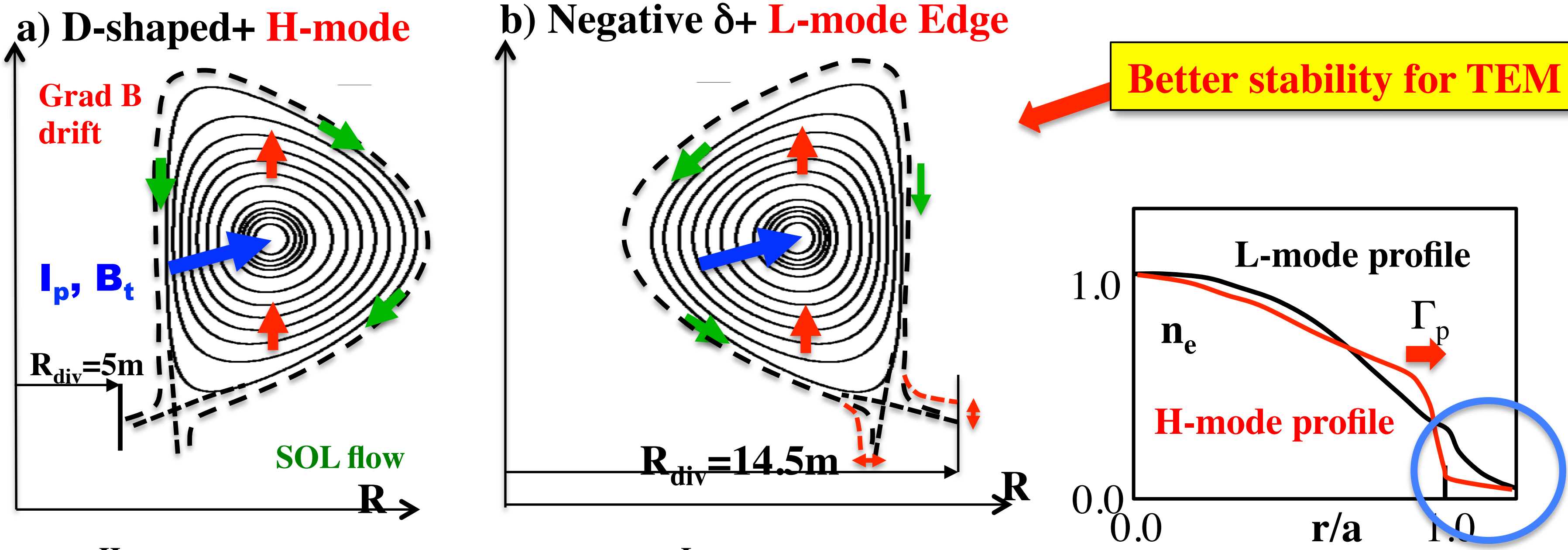
2. Fusion Target to Months of operation

There is 7 order of gap between present-day high performance plasma to DEMO in the power load duration. Most critical is long pulse power handling



3. L-mode Edge Negative Triangularity Tokamak (NTT)

1. **Geometrical Factor ~2.8 @ Grazing angle ~1°**
2. **H-mode edge << L-mode edge (suitable for reactor)**



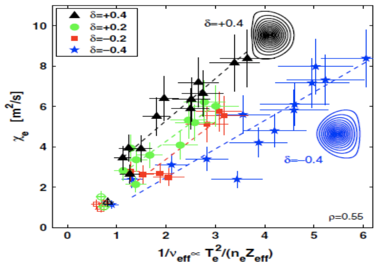
Γ_p^H ~NC level
Difficult to pump

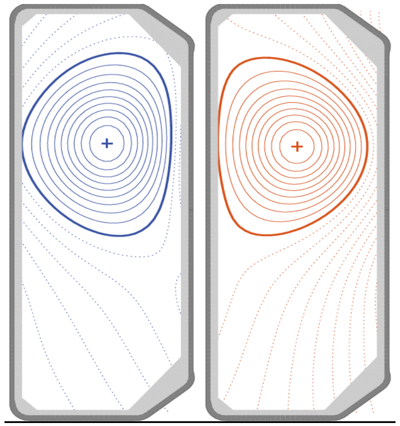
Γ_p^L >>NC level
Easier to pump

4. There are increasing Evidence of L-mode Edge High Confinement

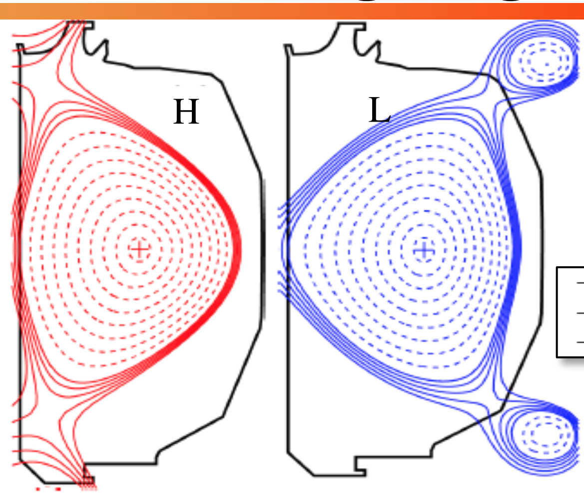
Y. Camenen, NF2007
τ_{Ee} (NTT)~ 2 times (L-mode Edge)

CamenenNF 2007





TCV (a_p=25cm,B_t=1.44T)



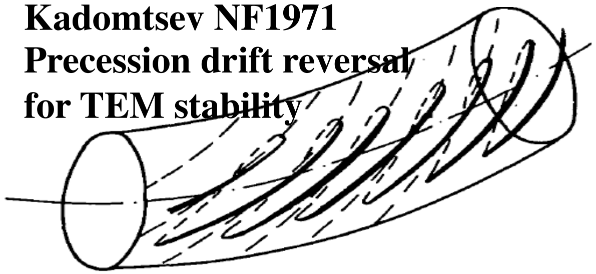
DIII-D (a_p=59cm,B_t=2T)

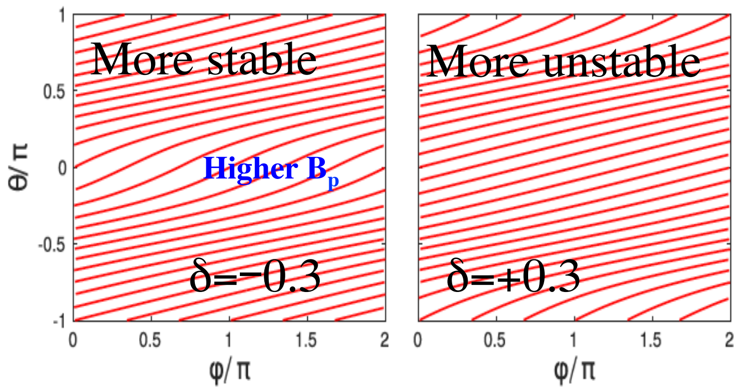
M. Austin, EX/P6-6
High confinement inNegative triangularity discharges in DIII-D

- **H98y2 = 1.2**
- **High beta: β_N > 2.6**
- **No ELMs**

$n_e(0)=6\text{x}10^{19}\text{m}^{-3}$
$T_e(0)$=4keV
P_{heat}=10.5MW

Kadomtsev NF1971
Precession drift reversal for TEM stability



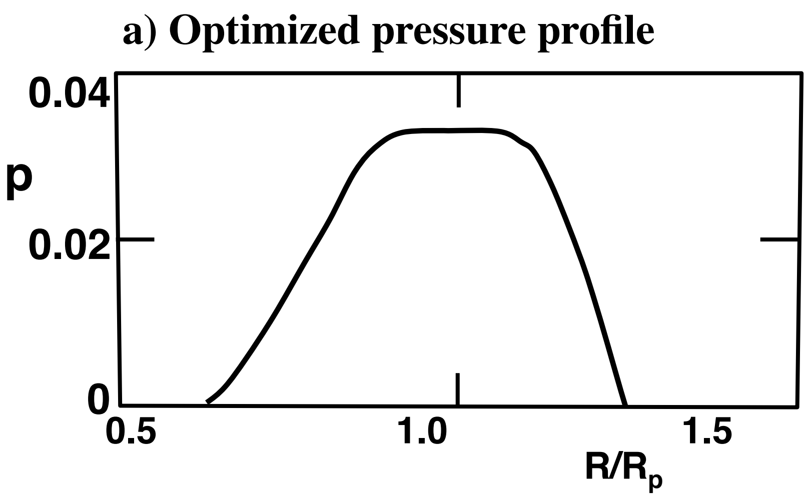


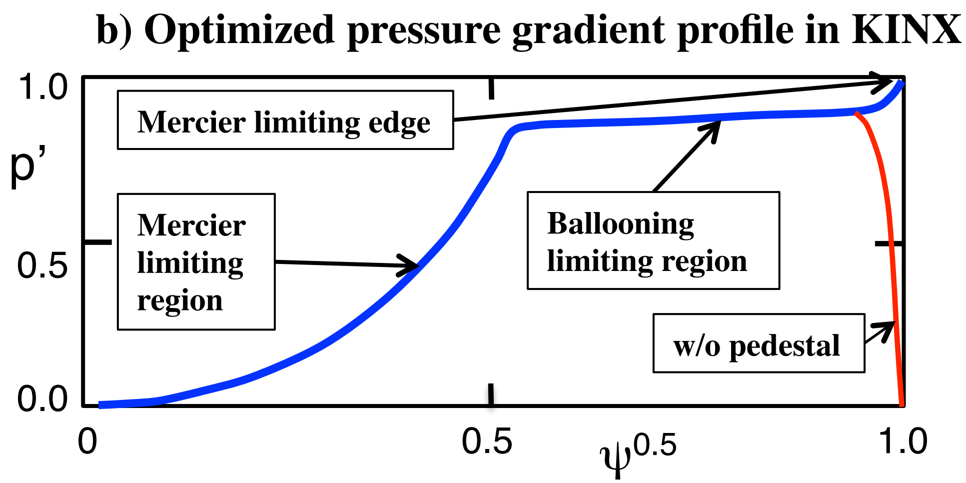
Riva PPCF2017 :
Larger magnetic pitch stabilize resistive ballooning
SauterPoP2014: De-stiffening
MelroPPCF2015: Higher T_{crit}
Fontana2018: smaller turbulence
CodaFEC2018: smaller λ_q??

5. Optimized Pressure Profile in NTT

NTT is magnetic Hill configuration.

- **Central Region limited by Mercier stability.**
- **Outer half limited by Ballooning stability.**



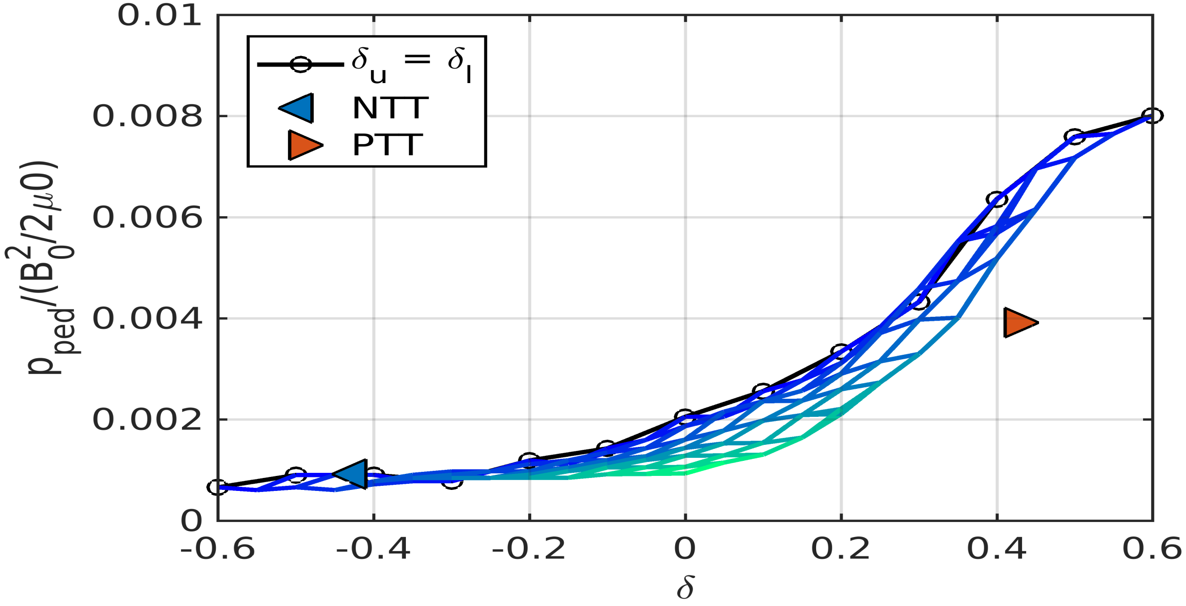


β_N (stability limit) ~3.3

Within this limit, reactor design is possible β_N=2.3.

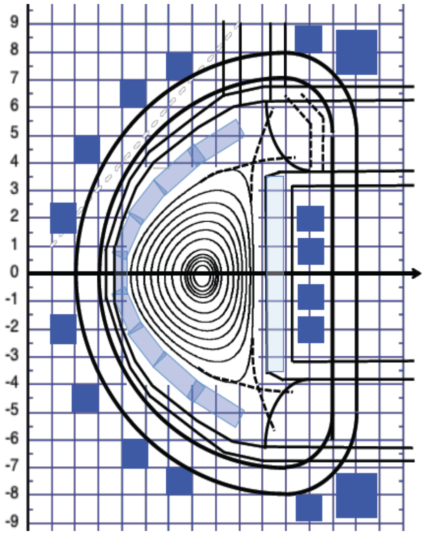
6. Reducing risk for large ELM energy loss

Large pedestal pressure is the source of risk of huge ELM energy loss
NTT tends to stay at L-mode edge but still has risk to be H-mode and ELM.
NTT edge pedestal pressure limit is at least 4 times smaller than D-shaped.
Thus reducing risk of large ELM energy loss.

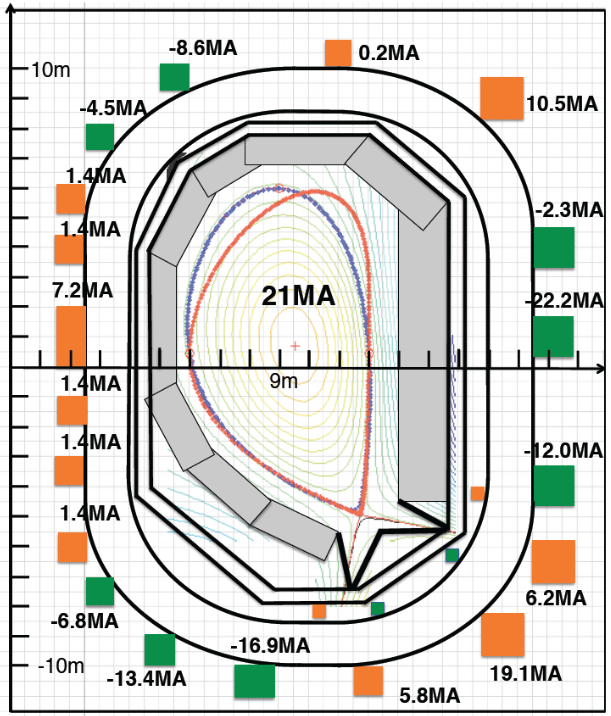


7. Double and Single Null NTT in FEC 2014 and 2016

IAEA FEC 2014 S. Medvedev, M. Kikuchi, et al. R_p=7m, a=2.7m (A=2.6), I_p=15MA, B_t=6.2T, κ_x=1.5,δ_x=-0.9, $\beta_N{}^{lim}$>3, $\gamma_{n=0}$=95/s



IAEA FEC 2016 S. Medvedev, M. Kikuchi, et al. R_p=9m, I_p=21MA, 3GW fusion power at β_N=2.1, B_{max}=13.6T, H_H=1.12

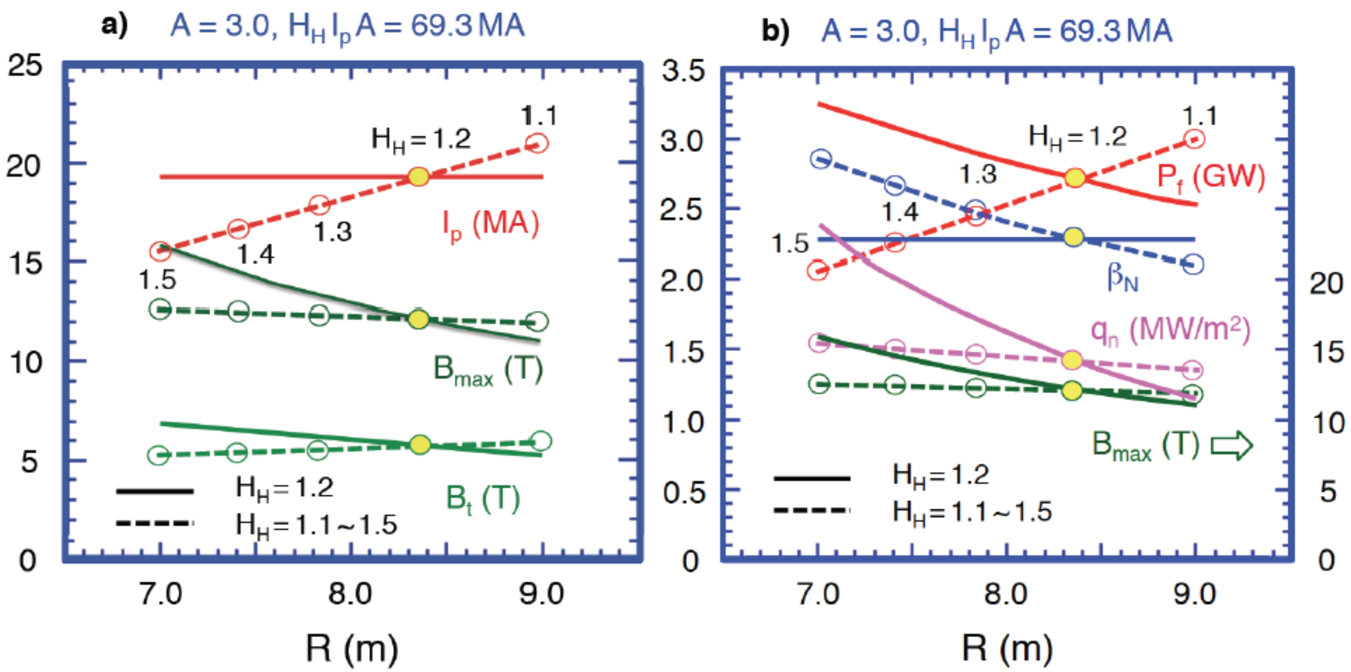


κ_x=2
OK

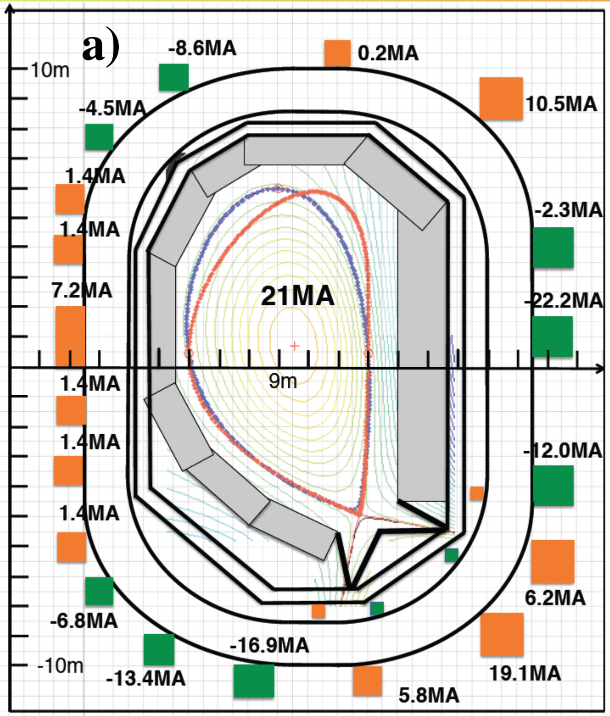
8. Parameter scan of SN-NTT Configuration for compact reactor

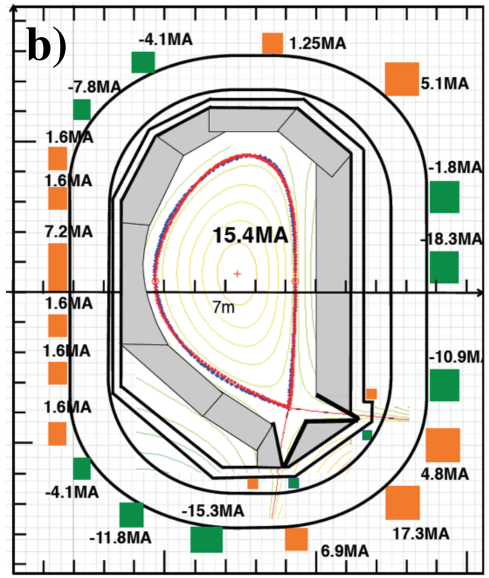
A=3, $H_H I_p A$= 69.3MA : Given

- **Solid line : H_H=1.2 fixed,**
- **Broken line : H_H varied (1.1-1.5) with R_p**



9. Reactor Configurations in NTT with Race-track shaped TF coils





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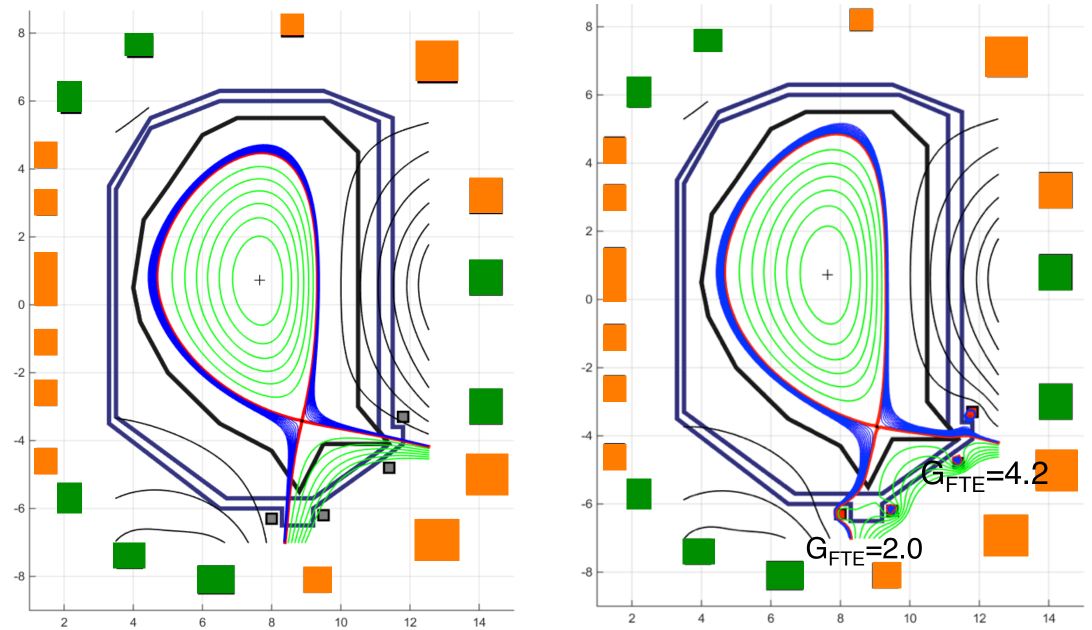
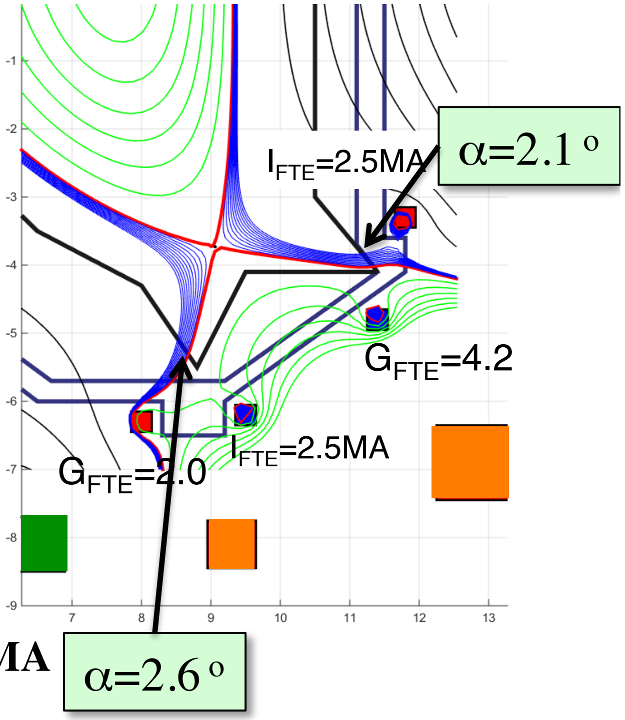
Significant size reduction is possible by enhanced confinement H_H=1.5. R_p=7m, I_p=15.4MA, 2GW fusion power at β_N=2.7, B_{max}=13.5T

10. Flux Tube Expansion Divertor in NTT

15MA equilibrium a) without FTE, b) with FTE, c)Expanded magnetic structure with FTE

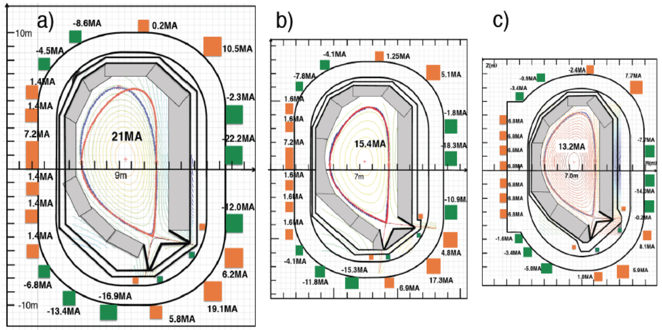




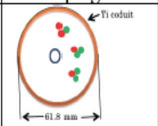
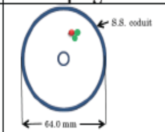
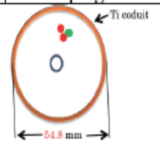
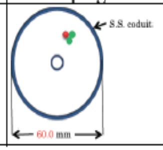
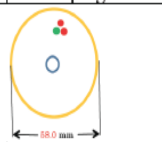
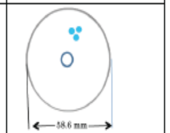
- **FTE coil current to expand flux tube to satisfy a=1-1.5° is only 2.5MA**
- **Active control of flux expansion for both legs are possible.**
- **Coils can be sector coils by NbTi wires**
- **L-mode edge ay enable power handling more easier than H-mode edge.**

11. Magnet Designs in NTT

Magnet design of NTT is technically feasible (J_c=1000A/mm^2)



	A=3, R_p=9m	A=3, R_p=7m	A=3.5, R_p=7m
Coil shape	Racetrack	Racetrack	Racetrack
Coil size	15m x 20m	12m x 16m	11m x 14m
Number of coils	18	18	18
Magnetic Energy	170GJ	86.5GJ	104GJ
Maximum field	13.6T	13.5T	15.5T
Ampere Turn	263MAT	207MAT	263MAT
Discharge constant	12 s	10 s	12 s
Quench detection	2 s	2 s	2 s
Temperature rise	150K	150K	150K
Number of Turn/coil	116	116	146
Conductor current	126kA	100kA	100kA
Winding structure	ITER-like	ITER-like	ITER-like
Disk per coils	6	6	7
Terminal voltage	12.5kV	10kV	10kV

	A=3, R_p=9m		A=3, R_p=7m		A=3.5, R_p=7m	
Conductor type	Nb3Sn CIC (Ti)	Nb3Sn CIC (SS)	Nb3Sn CIC (Ti)	Nb3Sn CIC (SS)	Nb3Sn CIC	Bi2212
Operating current	126kA	126kA	100kA	100kA	100kA	100kA
Nominal field	13.6T	13.6T	13.5T	13.5T	15.5T	15.5T
Operating Temperature	5.0K	5.0K	5.0K	5.0K	5.0K	20K
Total operating strain	-0.05%	-0.6%	-0.05%	-0.6%	-0.05%	0.2%
Current sharing Temp.	6.2K	6.1K	6.1K	6.1K	6.2K	21.2K
Operating curr./Crit. curr.	0.56	0.64	0.56	0.61	0.72	0.89
Cable diameter	57.8mm	62.0mm	50.8mm	56.0mm	54.0mm	54.6mm
Central cooling (ID/OD)	11mm/ 9mm	11mm/ 9mm	11mm/ 9mm	11mm/ 9mm	11mm/ 9mm	11mm/ 9mm
Central coolant	Supercritical He	Supercritical He	Supercritical He	Supercritical He	Supercritical He	Gas He
Conductor outer diameter	61.8mm	66.0mm	54.8mm	60.0mm	58.0mm	58.6mm
Jacket material	Ti	SS	Ti	SS	Ti	No jacket
SC and Cu strand diameter	0.87mm	0.84mm	0.76mm	0.84mm	0.81mm	0.82mm
Cu/Non Cu, Ag/ non Ag	2.0	1.0	2.0	1.0	1.6	0.82
Cabling pattern	3x3x3x4x4x6	3x3x4x4x4x6	3x3x3x4x4x6	3x3x3x4x4x6	3x3x3x4x4x6	3x3x3x4x4x6
SC strand number	1440	2304	1728	1728	1728	864
Cu, Ag strand number	1152	1152	864	864	864	1728
Void fraction(%) in bundle	33.3%	33.3%	33.3%	33.3%	33.3%	0%
Impregnated material	No impregnation	No impregnation	No impregnation	No impregnation	No impregnation	PbSn
Conductor shape						

12. Summary

1. **D-shaped H-mode is the standard operation mode in tokamak.**
2. **It brings many critical issues (ELM, narrow heat channel, small particle flux, heat and particle exhaust at small R)**
3. **Efforts has been made to resolve these issues but still challenging.**
4. **Divertor for Negative triangularity provides maximum wetted surface with flux tube expansion.**
5. **L-mode edge observed in NTT experiments enhances its merit much further.**
6. **Low edge pedestal beta limit is safer for ELM damage.**
7. **Long-pulse power handling is 1st priority for 1st generation tokamak reactor.**
8. **L-mode edge NTT may provide possible solution.**
9. **We are ready for medium to large test NT tokamak.**