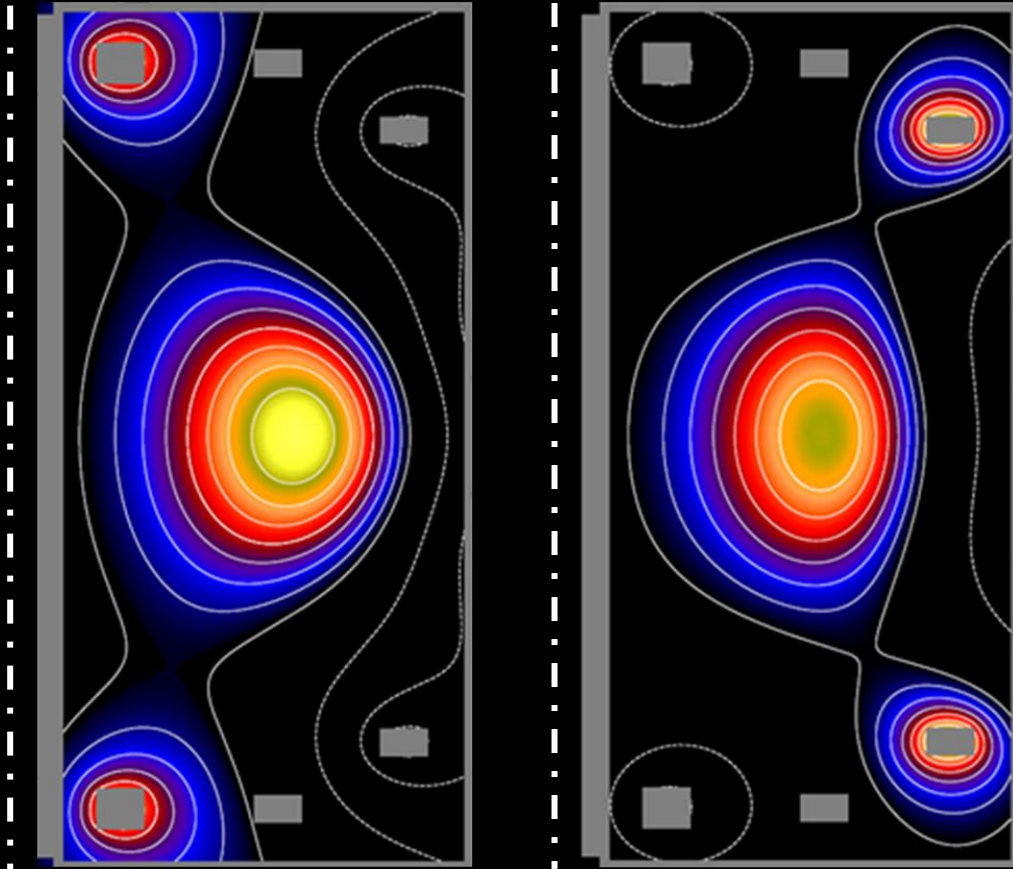


Overview of the Small Aspect Ratio Tokamak - SMART - Project

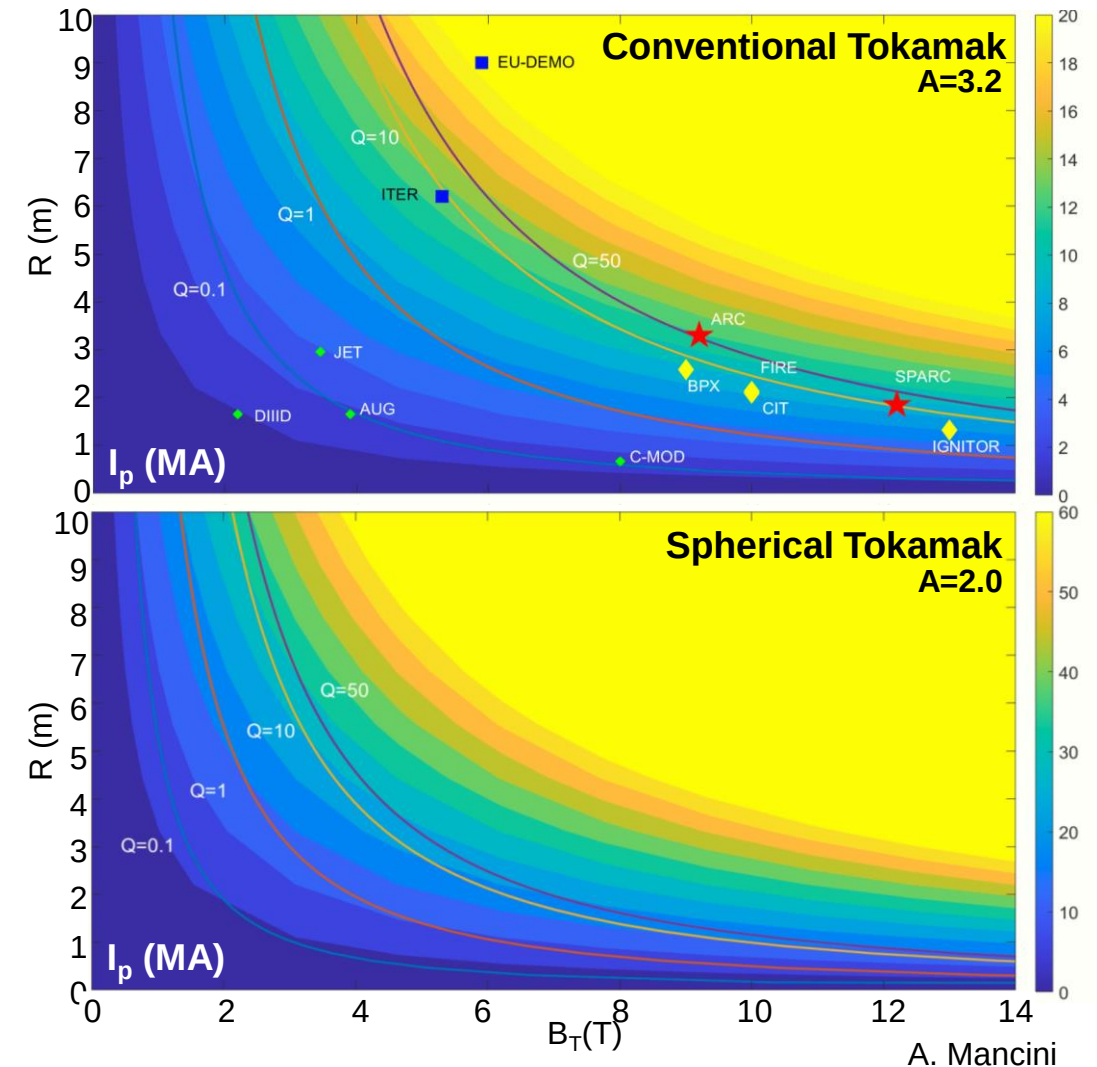
M. Garcia-Munoz

A. Mancini, J. Segado-Fernandez, D. Cruz-Zabala, E. Viezzer, H. Chen, J. Ayllon-Guerola, J. Dominguez-Palacios, J. Berkery, J. Chung, L. Delgado-Aparicio, A. Diallo, M. Freire-Rosales, J. Galdon-Quiroga, J. Garcia-Dominguez, J. García-Lopez, J. L. Garcia-Sanchez, S. Hwang, Y. Liu, R. Maingi, M. Podesta, F. Poli, J. F. Rivero-Rodriguez, M. Toscano-Jimenez, L. Velarde-Gallardo and the PSFT team



Spherical Tokamaks Offer an Attractive Path to a Fusion Power Plant

- Compact configuration
- Natural elongation
- High Beta
- High density limit
- Less major disruptions
- Good energy confinement



Negative Triangularity is a Potential Game Changer



Attractive core confinement and power handling for future fusion reactors

- L-Mode with H-mode like core pressure levels and no pedestal

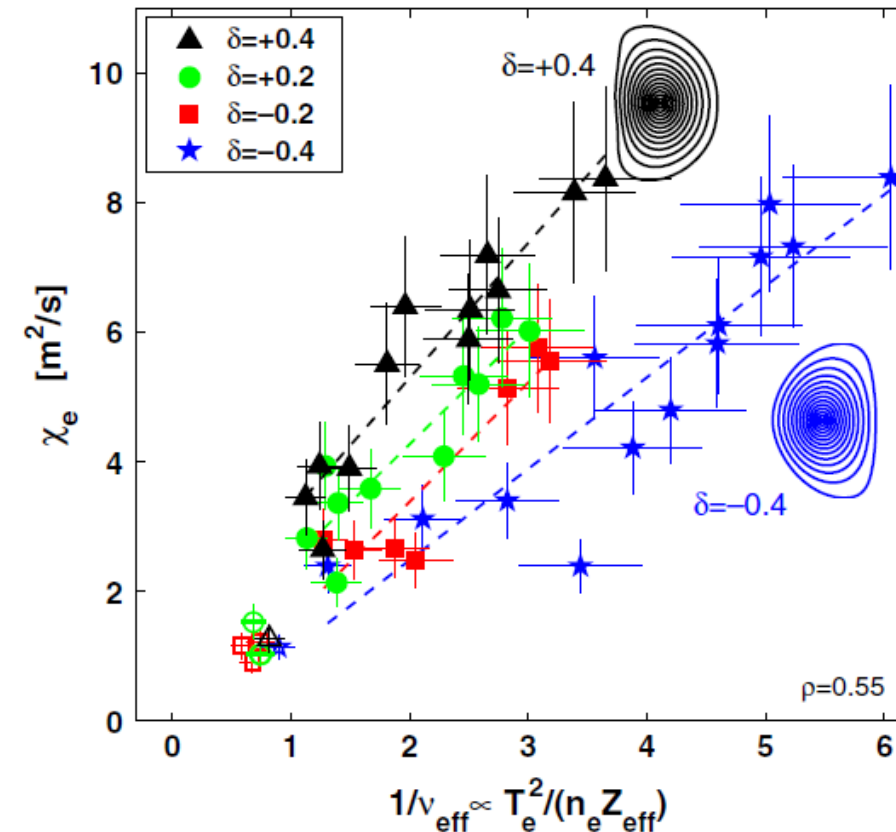
Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

- L-Mode with H-mode like core pressure levels and no pedestal

Core

- Improved thermal plasma transport
 - $-\delta$ features lower **experimental** electron heat diffusivity than similar $+\delta$
 - Reduced ITG and TEM



G. Rewoldt *et al.*, PoF 1982

J.-M. Moret *et al.*, PRL 1997

Y. Camenen *et al.*, NF 2007

A. Marinoni *et al.*, PPCF 2009, PoP 2019, NF 2021

M. E. Austin *et al.*, Phys. Rev. Lett. 2019

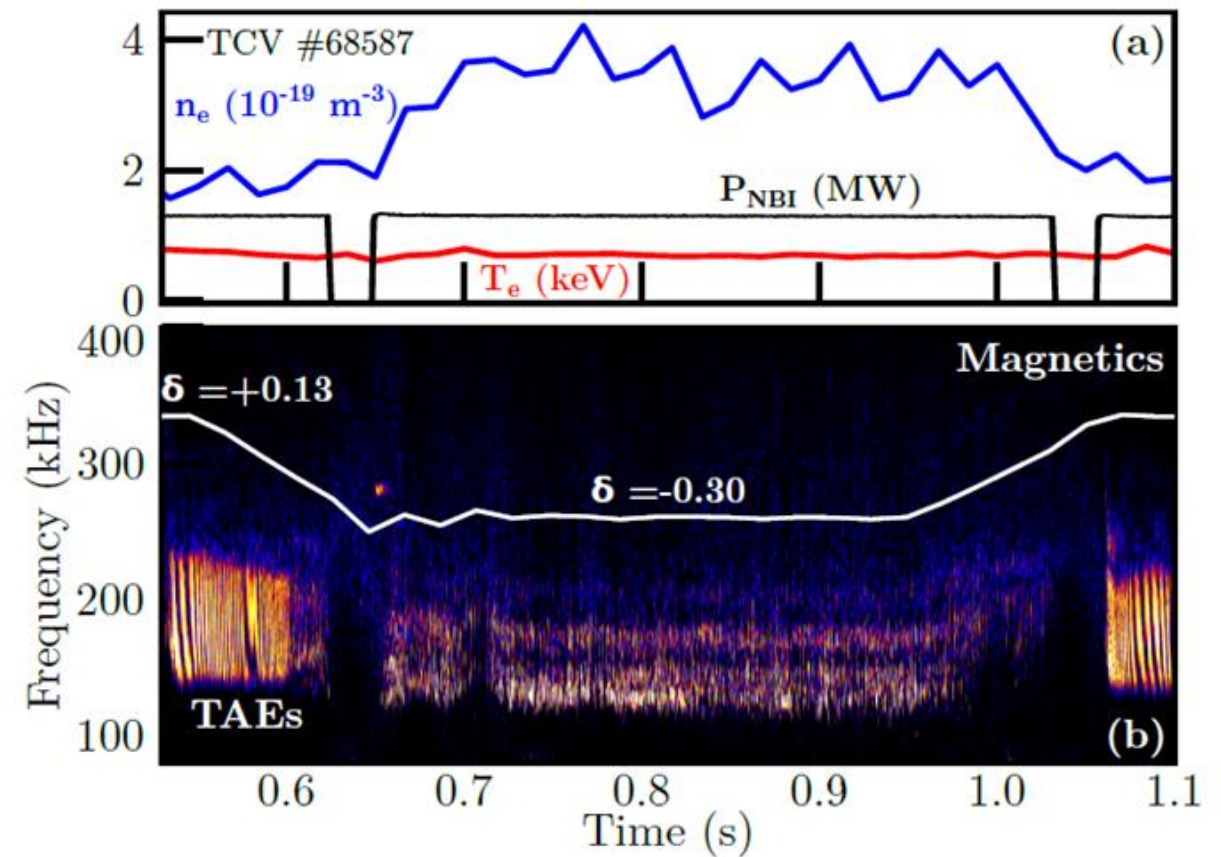
Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

- L-Mode with H-mode like core pressure levels and no pedestal

Core

- Improved core thermal plasma transport
- **Improved fast-ion confinement**
 - Reduced AE activity
 - Larger fast-ion content



Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

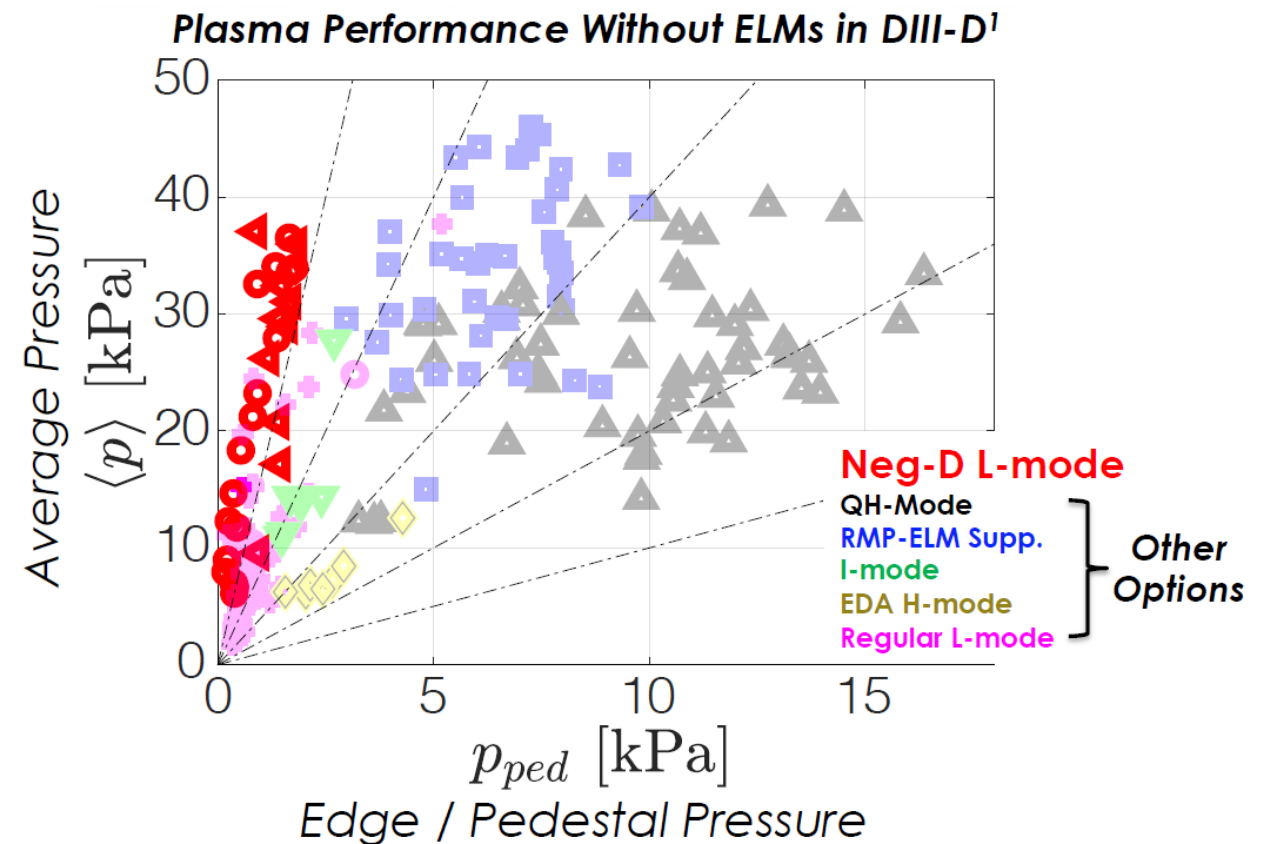
- L-Mode with H-mode like core pressure levels and no pedestal

Core

- Improved core thermal plasma transport
- Improved fast-ion confinement

Edge

- No pedestal > No ELMs



C. Paz-Soldan et al., PPFC 2021

Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

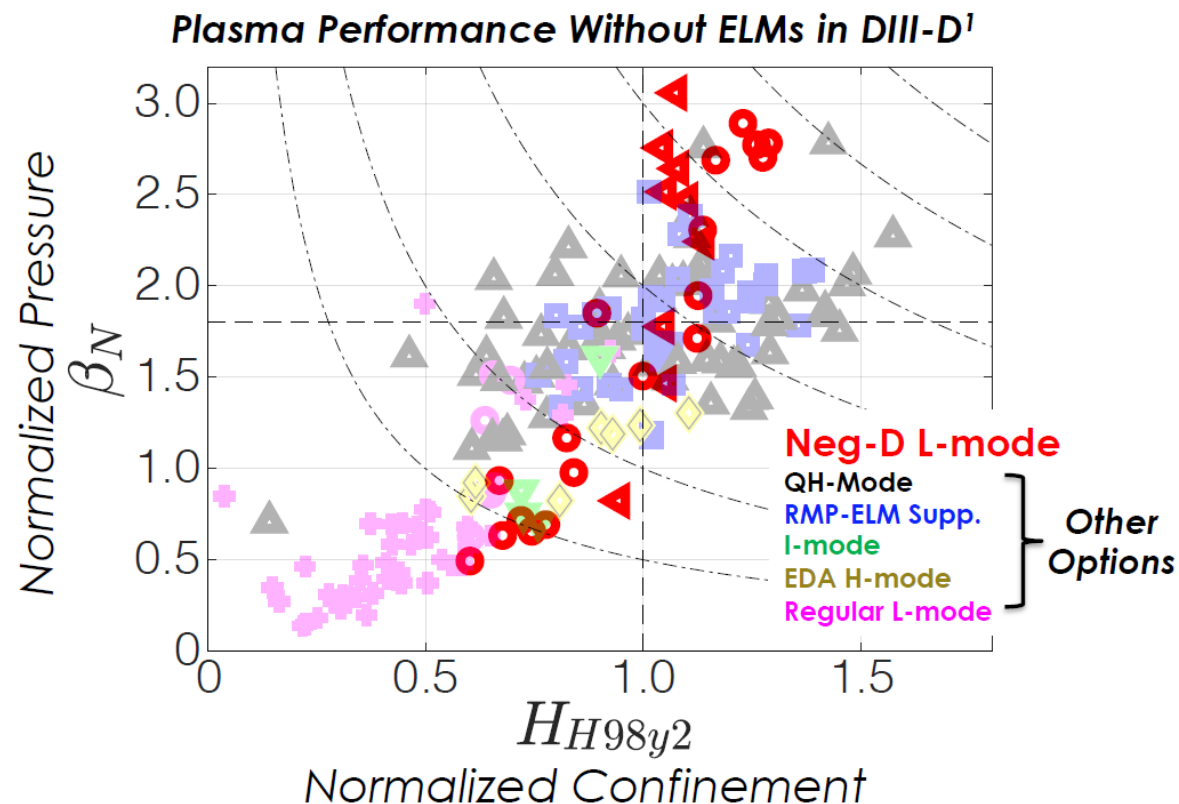
- L-Mode with H-mode like core pressure levels and no pedestal

Core

- Improved core thermal plasma transport
- Improved fast-ion confinement

Edge

- No pedestal > No ELMs



C. Paz-Soldan et al., PPFC 2021

Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

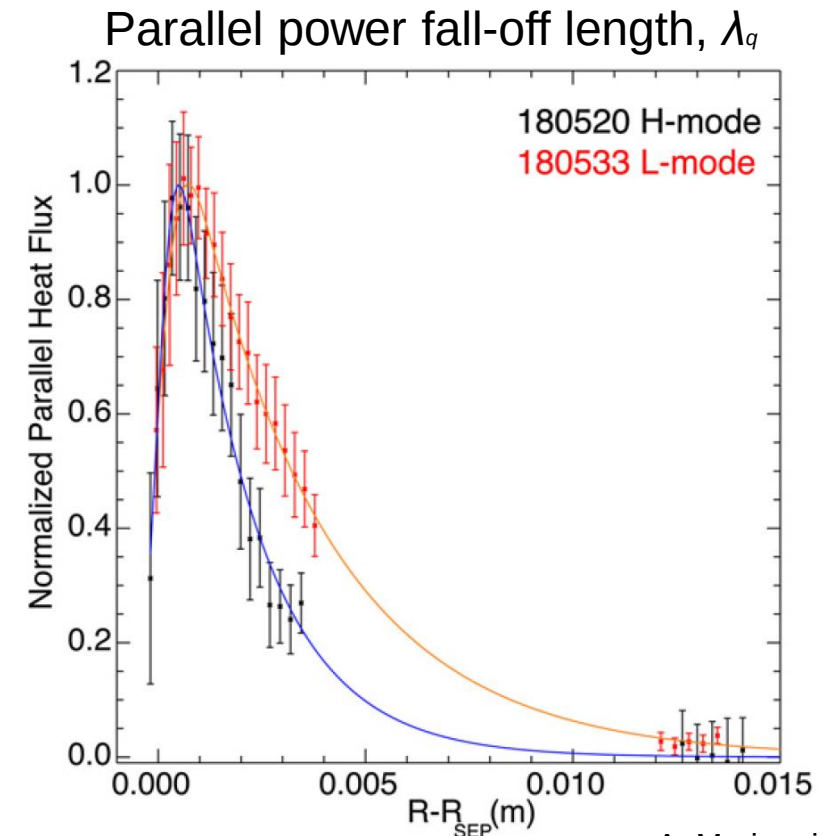
- L-Mode with H-mode like core pressure levels and no pedestal

Core

- Improved core thermal plasma transport
- Improved fast-ion confinement

Edge

- No pedestal > No ELMs
- Low impurity retention
- Wider scrape-off layer heat flux



A. Marinoni *et al.*, NF 2021

Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

- L-Mode with H-mode like core pressure levels and no pedestal

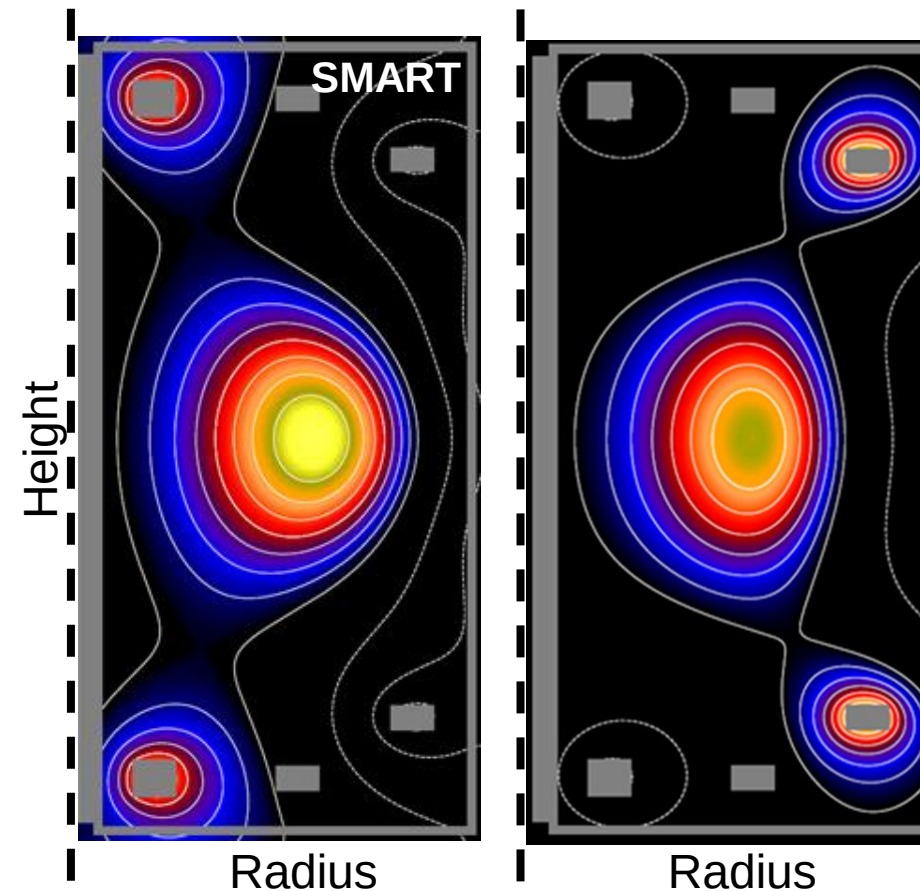
Core

- Improved core thermal plasma transport
- Improved fast-ion confinement

Edge

- No pedestal > No ELMs
- Low impurity retention
- Wider scrape-off layer heat flux

Divertor naturally placed at larger radii



Negative Triangularity is a Potential Game Changer

Attractive core confinement and power handling for future fusion reactors

- L-Mode with H-mode like core pressure levels and no pedestal

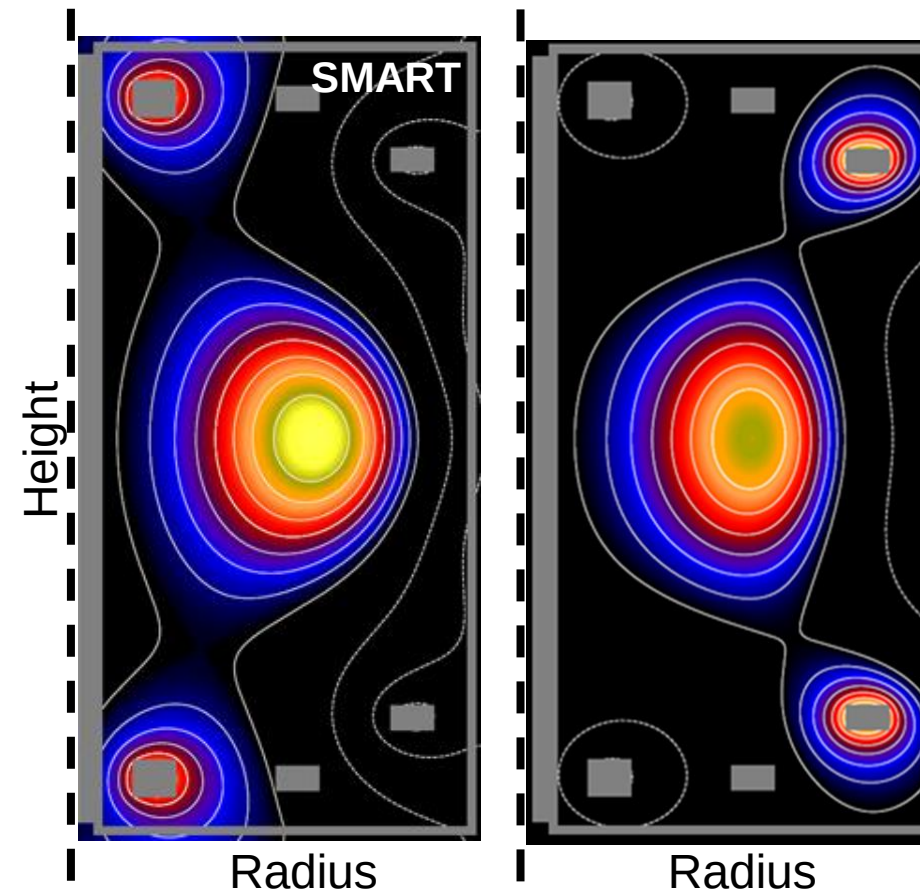
Core

- Improved core thermal plasma transport
- Improved fast-ion confinement

Edge

- No pedestal > No ELMs
- Low impurity retention
- Wider scrape-off layer heat flux

Divertor naturally placed at larger radii



But This Comes with a Price: Reduced Stability Limits



- Current driven (kink) modes: lower safety factor @ same current
- Elongation limits: higher vertical instability growth rates
- Pressure driven (ballooning) modes: lower predicted beta limits

But This Comes with a Price: Reduced Stability Limits



- Current driven (kink) modes: lower safety factor @ same current
- Elongation limits: higher vertical instability growth rates
- Pressure driven (ballooning) modes: lower predicted beta limits

Multi-machine experiments needed to explore stability limits and develop NT scaling laws

- STs with lower toroidal magnetic fields and higher beta limits might be especially attractive
- NT might be attractive for STs power exhaust and CS design

- SMART's missions
- Magnetic equilibrium and prospective discharge scenario
- MHD stability
- Device
 - Vacuum Vessel
 - Coils configuration
 - Diagnostics
- Summary

- SMART's missions
- Magnetic equilibrium and prospective discharge scenario
- MHD stability
- Device
 - Vacuum Vessel
 - Coils configuration
 - Diagnostics
- Summary

A. Mancini et al., Poster, this conference
J. Segado et al., Poster, this conference

- **SMART's missions**

- Magnetic equilibrium and prospective discharge scenario

- MHD stability

- Device

- Vacuum Vessel

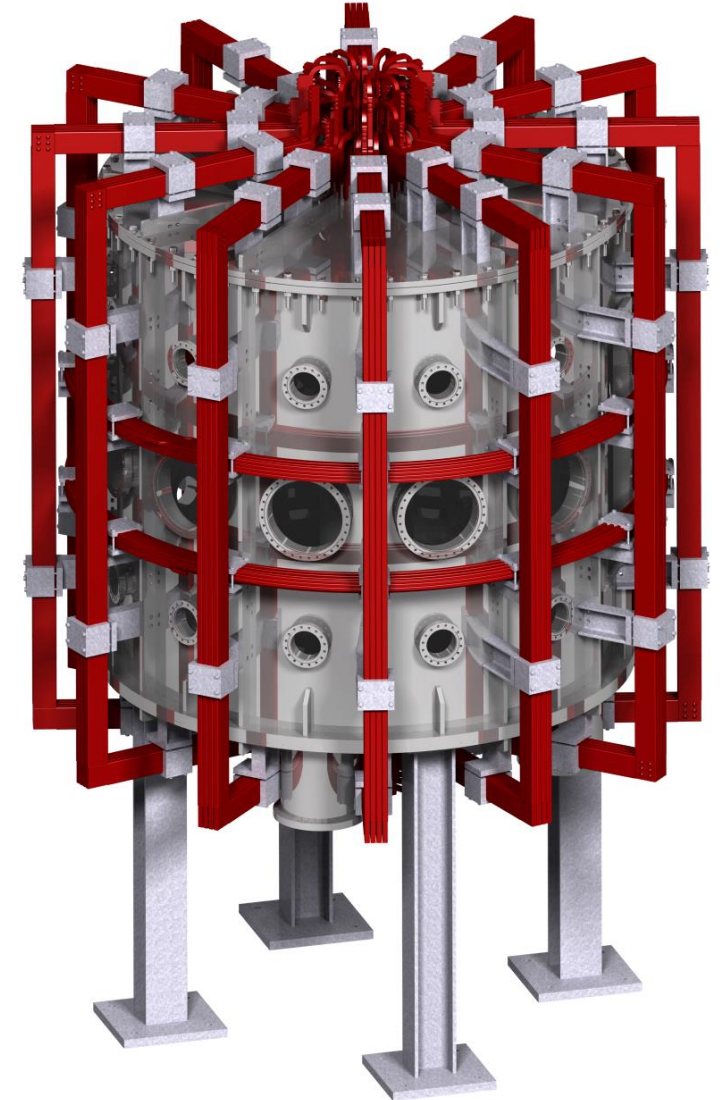
- Coils configuration

- Diagnostics

- Summary

SMART – SMAll Aspect Ratio Tokamak

- SMART: new spherical device currently being assembled at University of Seville as **attractive, fast and economic path** to **compact fusion reactors** with high power densities
- **Mission**
 - Explore high confinement regimes in Spherical Tokamaks (STs) with flexible shaping, high β , and fusion-relevant T_i , T_e , n_e , and collisionalities
 - Develop novel diagnostic and plasma control techniques
 - Develop alternative exhaust techniques
 - Training next generation of fusion physicists and engineers

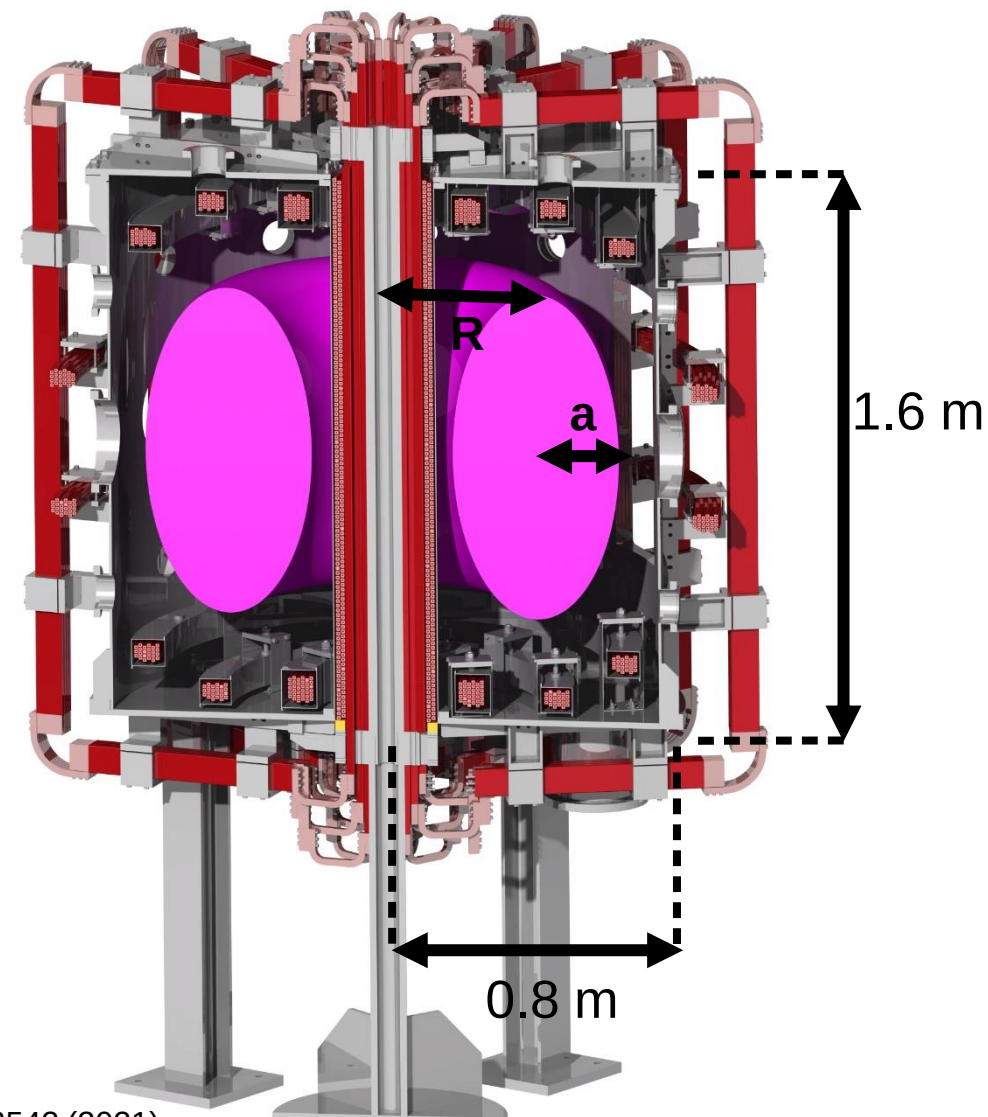


A. Mancini *et al*, Fus. Eng. Des. **171** 112542 (2021)

Main Parameters of SMART

- Vacuum vessel dimensions: 1.6 x 1.6 m
- 12 toroidal field coils, 8 poloidal field coils, 1 solenoid
- Major radius $R = 0.45$ m
- Minor radius $a = 0.25$ m
- $A = [1.4 - 3]$, $\kappa < 3$, $\delta = [-0.6 - 0.6]$
- Operational phases

Parameters	Phase 1	Phase 2	Phase 3
I_p [kA]	100	500	>500
B_t [T]	0.1	0.3	1.0
τ_{pulse} [sec]	0.15	0.5	>1
P_e [kW]	6	6	200
P_{NBI} [MW]	-	1	1

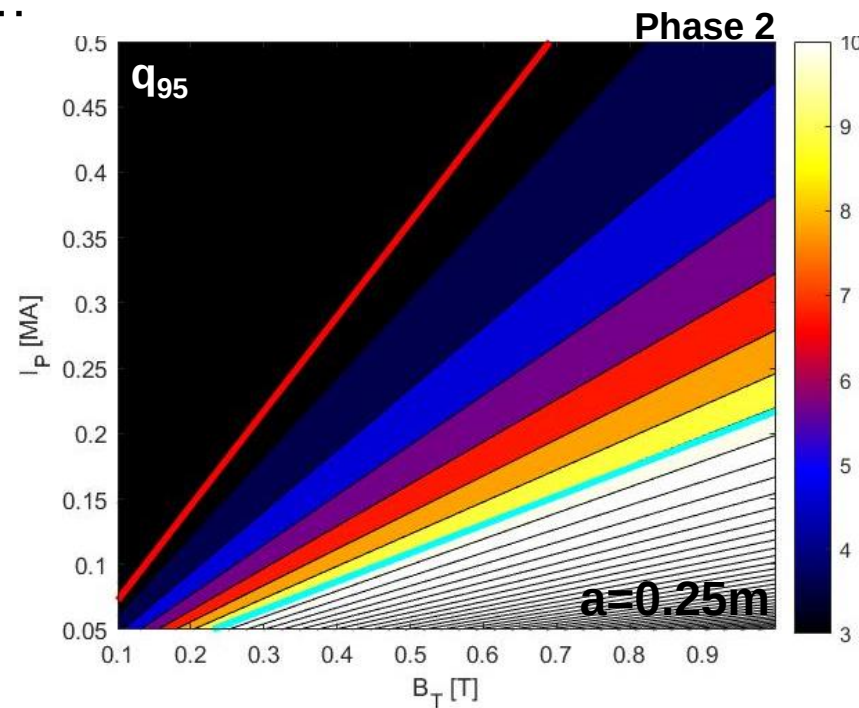
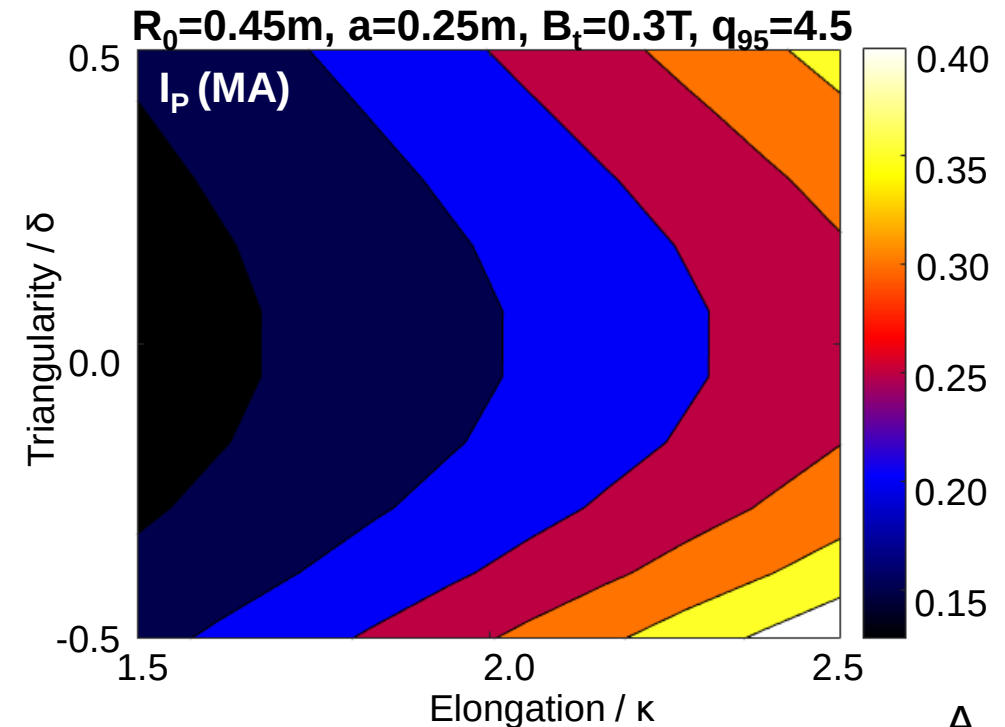


A. Mancini *et al*, Fus. Eng. Des. **171** 112542 (2021)

Design and Operational Regimes Based on Current Empirical Scaling Laws for PT Tokamaks

0D system code + free boundary FIESTA code + ASTRA used to estimate expected performance within basic stability limits, e.g. $q_{95} > 3$

- Minor modifications in plasma volume / aspect ratio enable broad operational regime
 - High I_p
 - Low vs high collisionality
 - ...



A. Mancini

- SMART's missions
- **Magnetic equilibrium and prospective discharge scenario**
- MHD stability
- Device
 - Vacuum Vessel
 - Coils configuration
 - Diagnostics
- Summary

Prospective Discharge Scenario

- FIESTA solves time dependent Grad-Shafranov equation accounting for Eddy currents in vacuum vessel

➤ EFIT + RZip

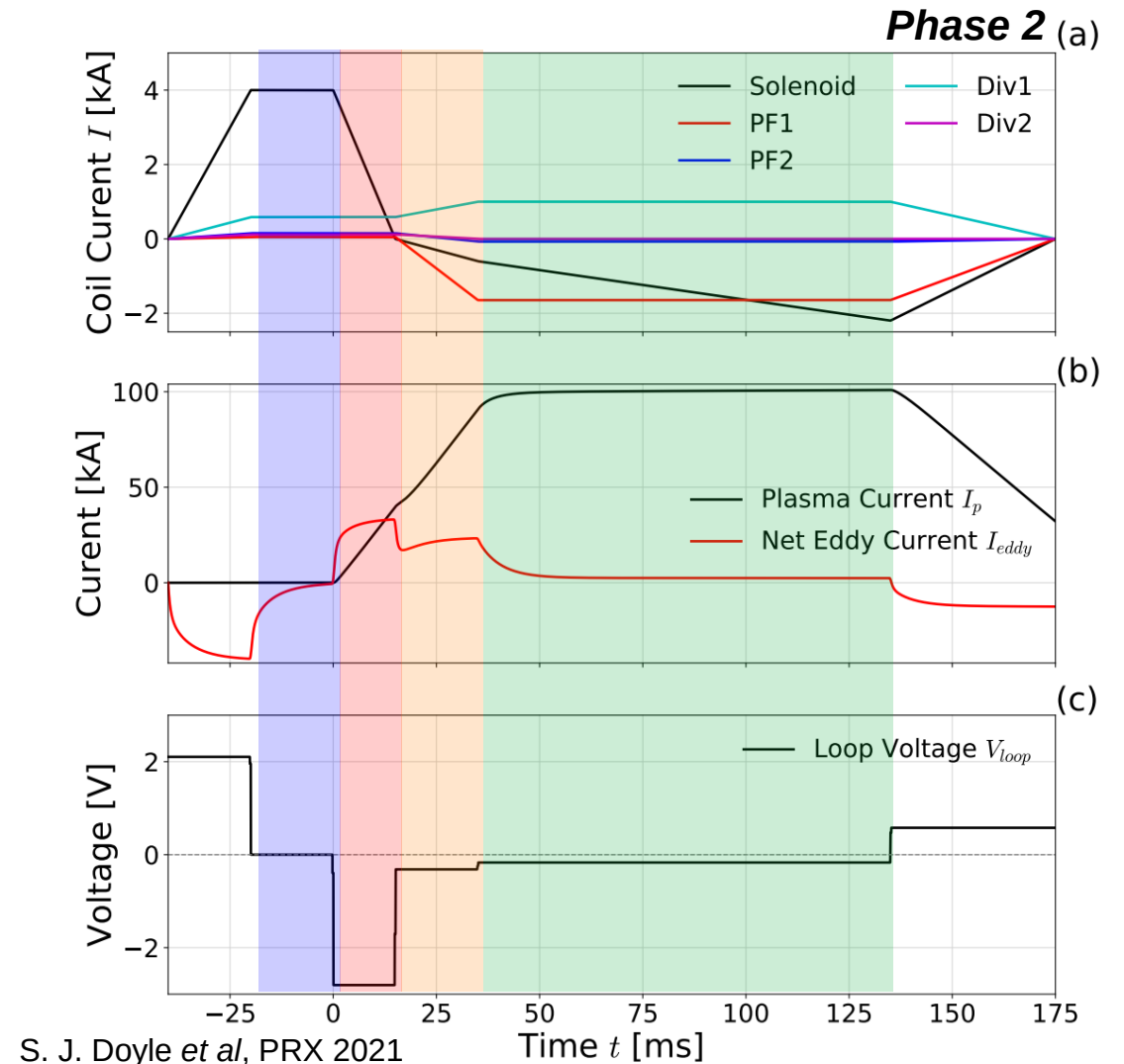
- Optimized solenoid wave form for:

➤ **Formation** of null-field: 16ms

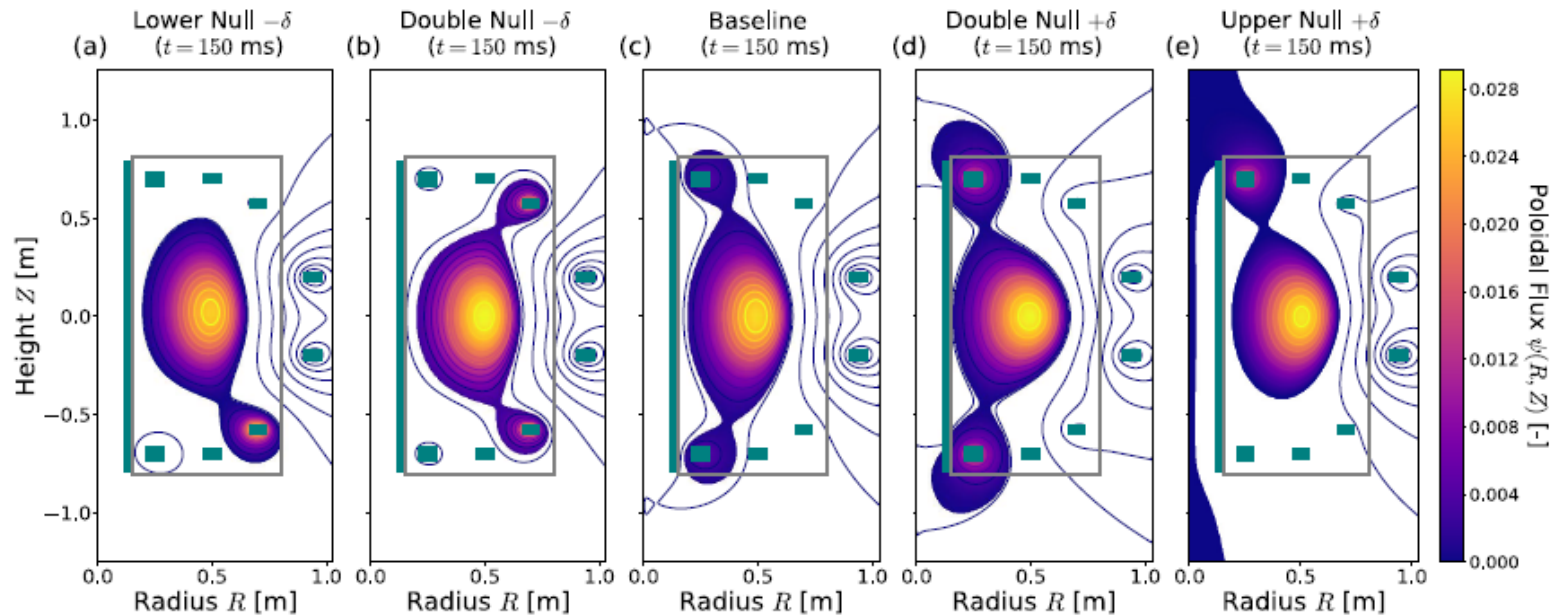
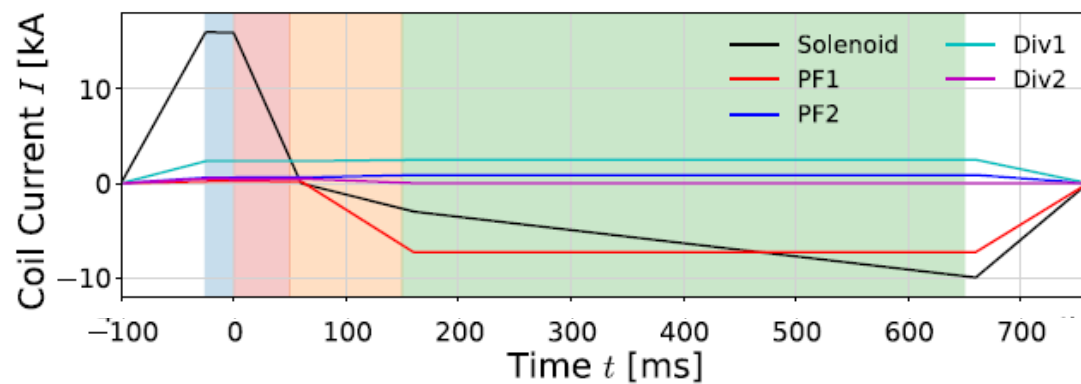
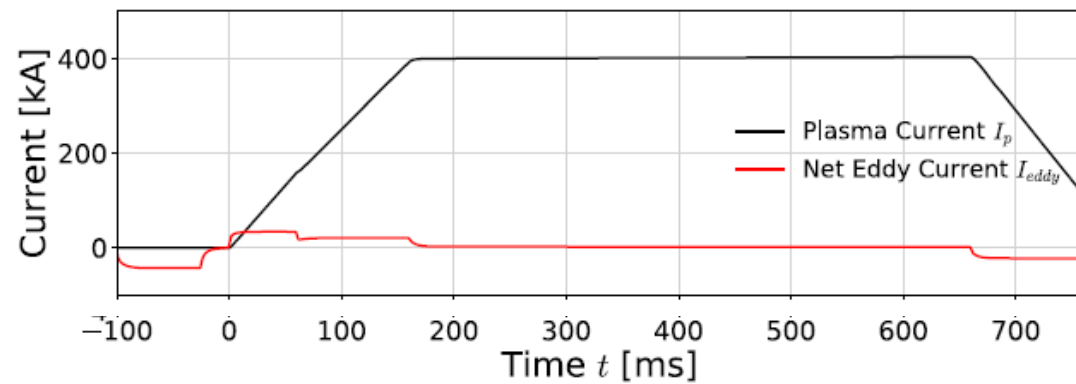
➤ **Breakdown** timescale: 8 ms

➤ **Transition** timescale: 20 ms

➤ **Flat-top** duration: 100 ms



Wide Shaping Range at Relatively High I_p / B_t

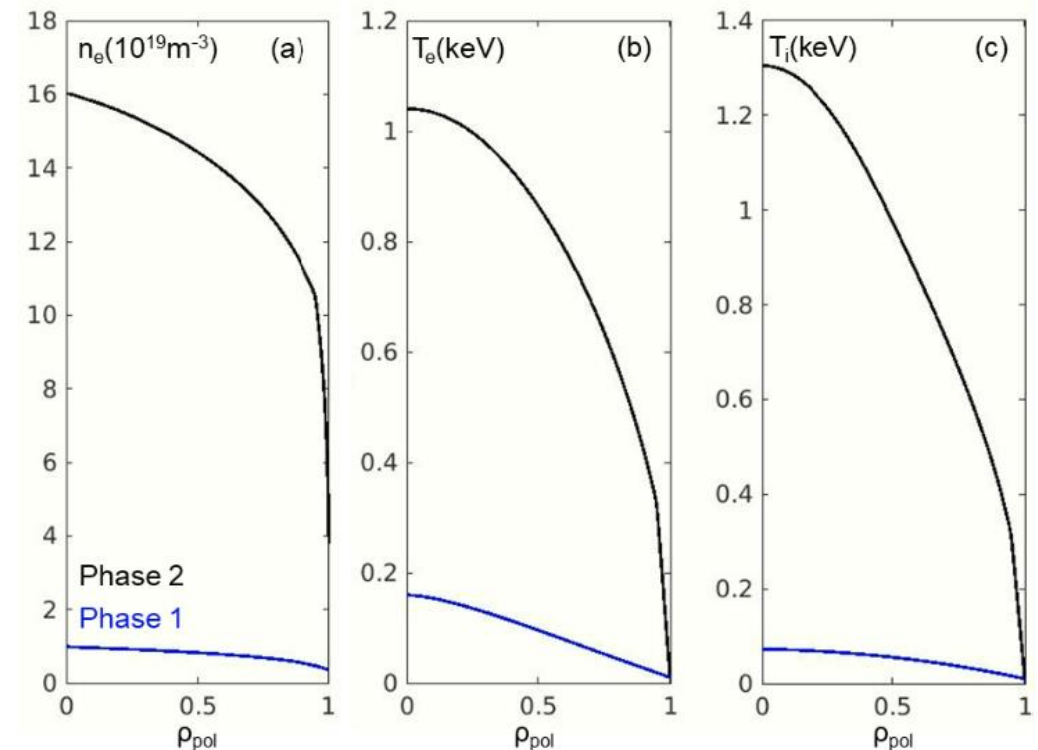


ASTRA Predicts Boost in Confinement From Phase 1 (L-mode) to Phase 2 (H-mode)

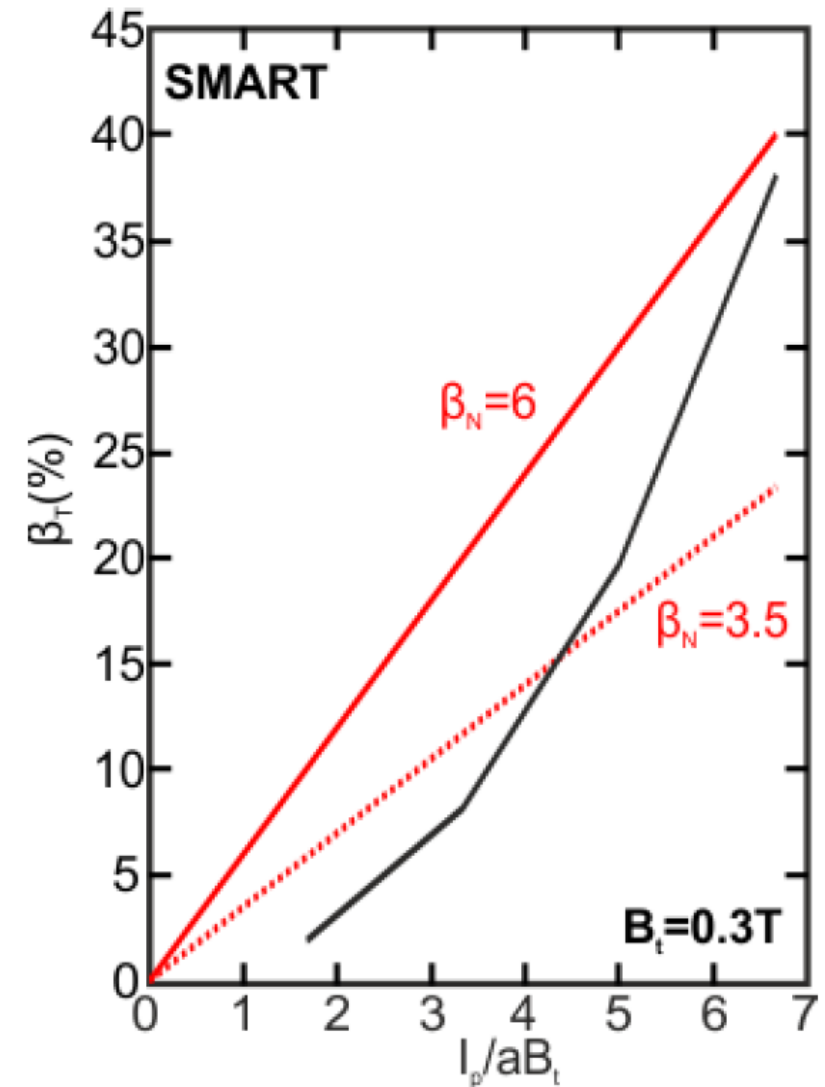
- Transport simulations carried out for most up-to-date baseline scenario
 - Transport coefficients scale with I_p and B_t , no change in pre-factors
 - Expected rise in density and temperature profiles
- Access to ohmic H-mode in phase 1

$$P_{LH_ITPA08} = 0.0488 n_{20}^{0.717} B_T^{0.803} S^{0.941}$$

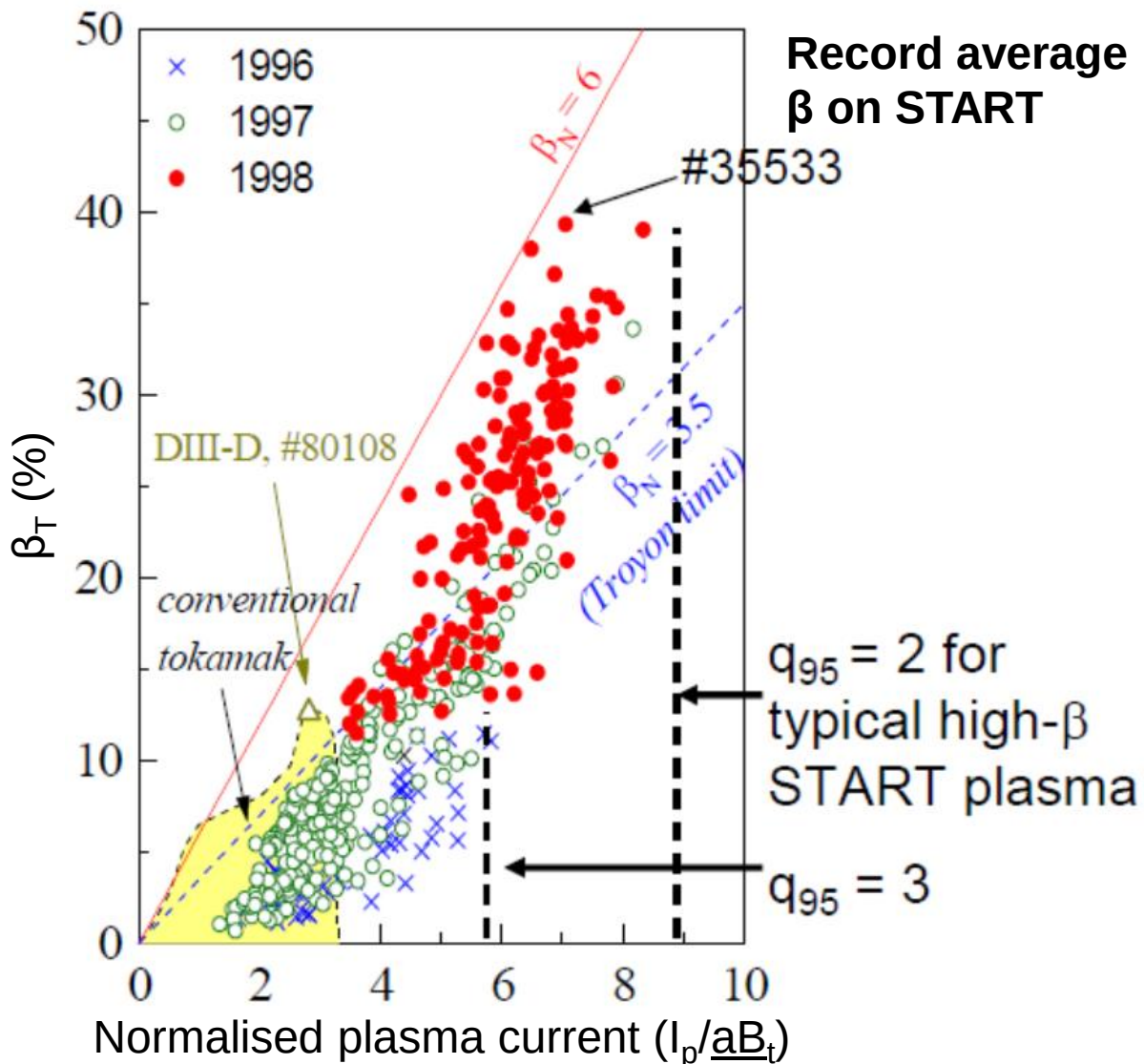
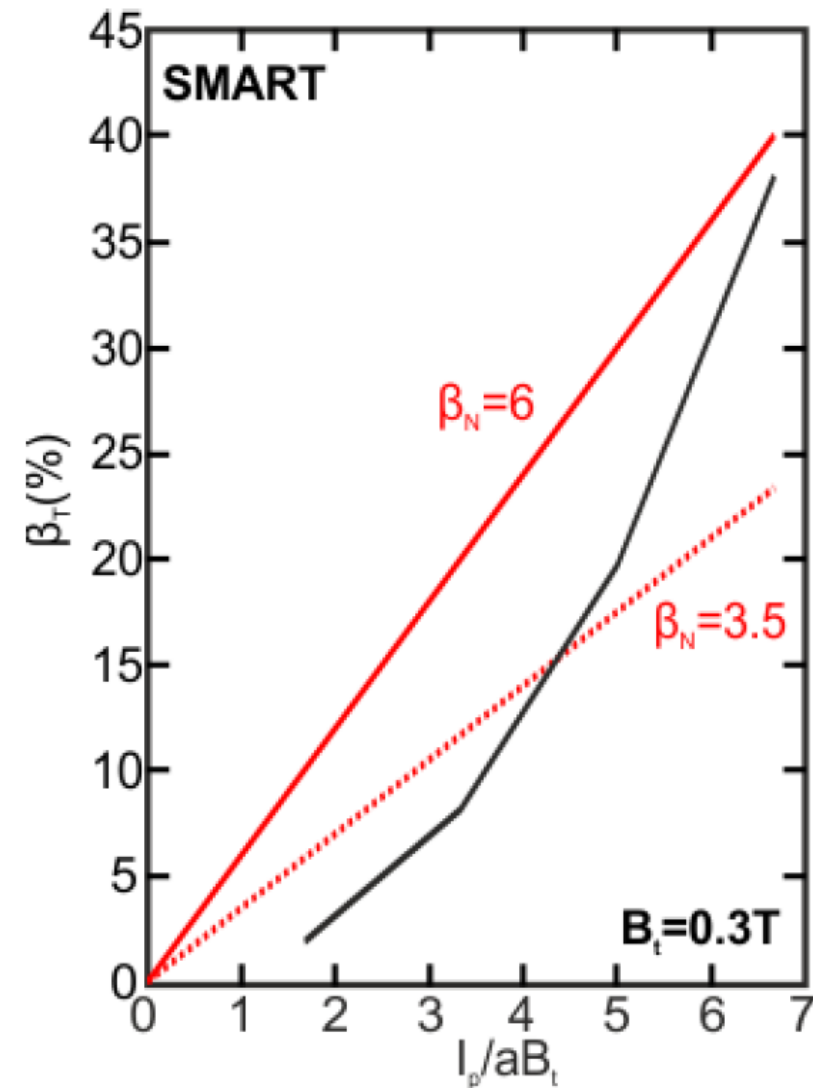
- $B_t = 0.1\text{T}$
 - $I_p = 100\text{ kA}$
 - $n_e = 5 \times 10^{19}\text{ m}^{-3}$
- ➡ $P_{LH} = 20\text{ kW}$
- $P_{OH} = 220\text{ kW} > P_{LH}$



ST High Pressure Plasmas Expected in Phase 2



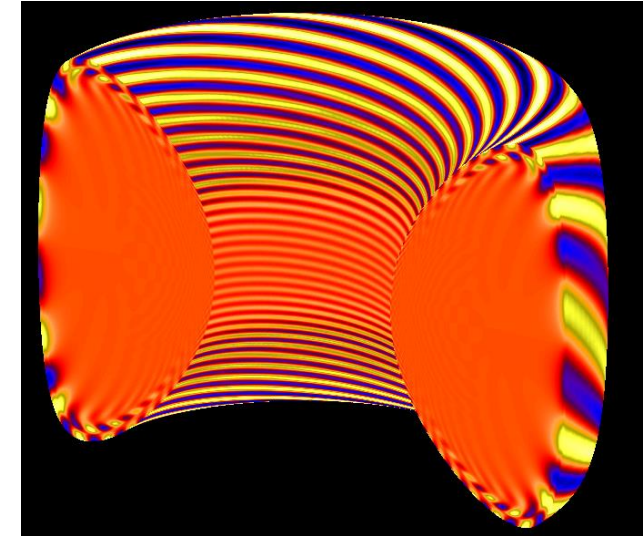
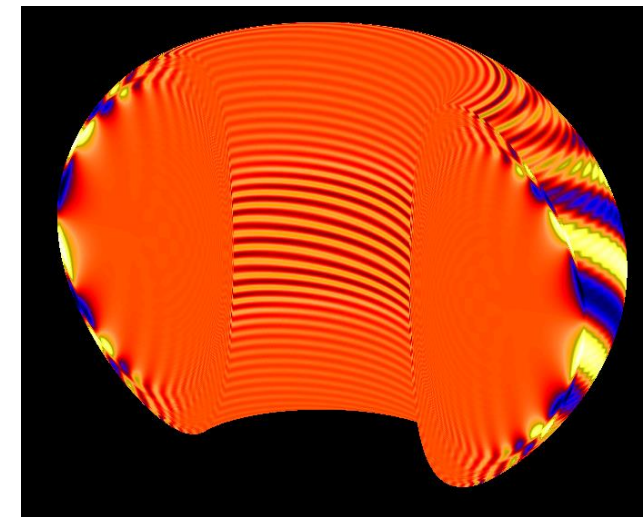
ST High Pressure Plasmas Expected in Phase 2



- SMART's missions
- Magnetic equilibrium and prospective discharge scenario
- **MHD stability**
- Device
 - Vacuum Vessel
 - Coils configuration
 - Diagnostics
- Summary

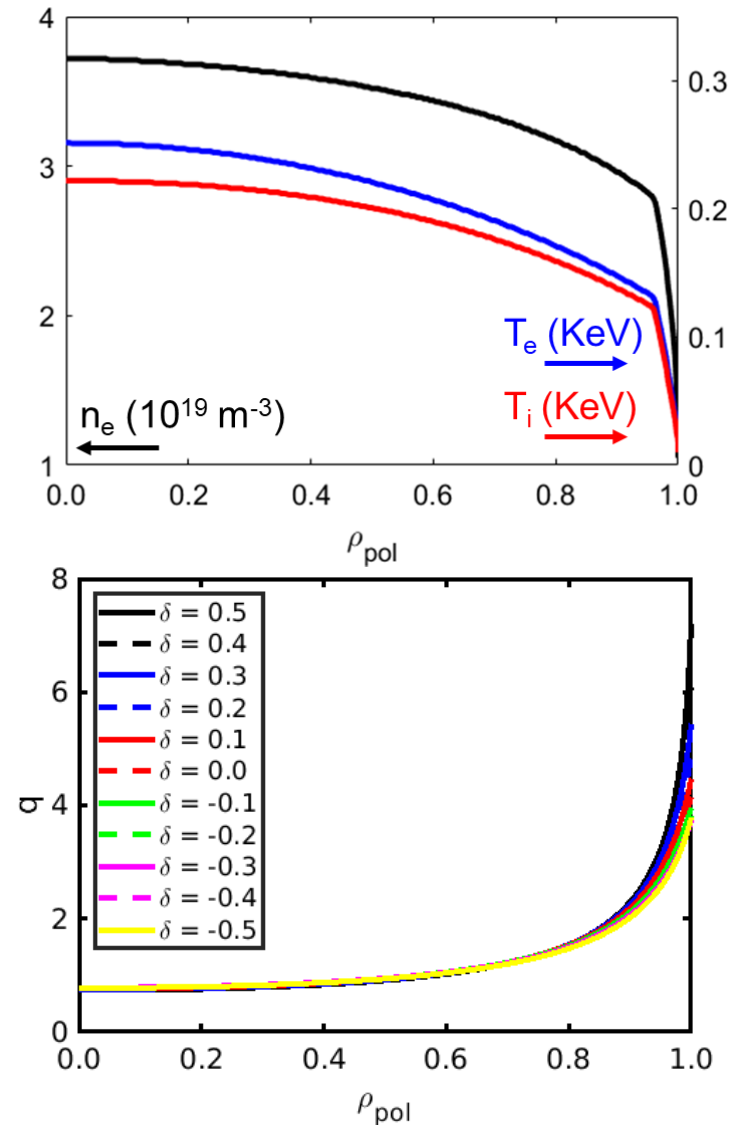
MARS-F Used to Calculate MHD Stability in PT vs NT

- Profiles given by **ASTRA**
- **CHEASE** code used to generate different equilibria
 - **Edge stability** (peeling-ballooning)
 - p' and $I_{||}$ scan with fixed δ
 - δ scan with fixed p' and $I_{||}$
 - **Core stability** with scans in
 - q -profile
 - β_N
 - δ



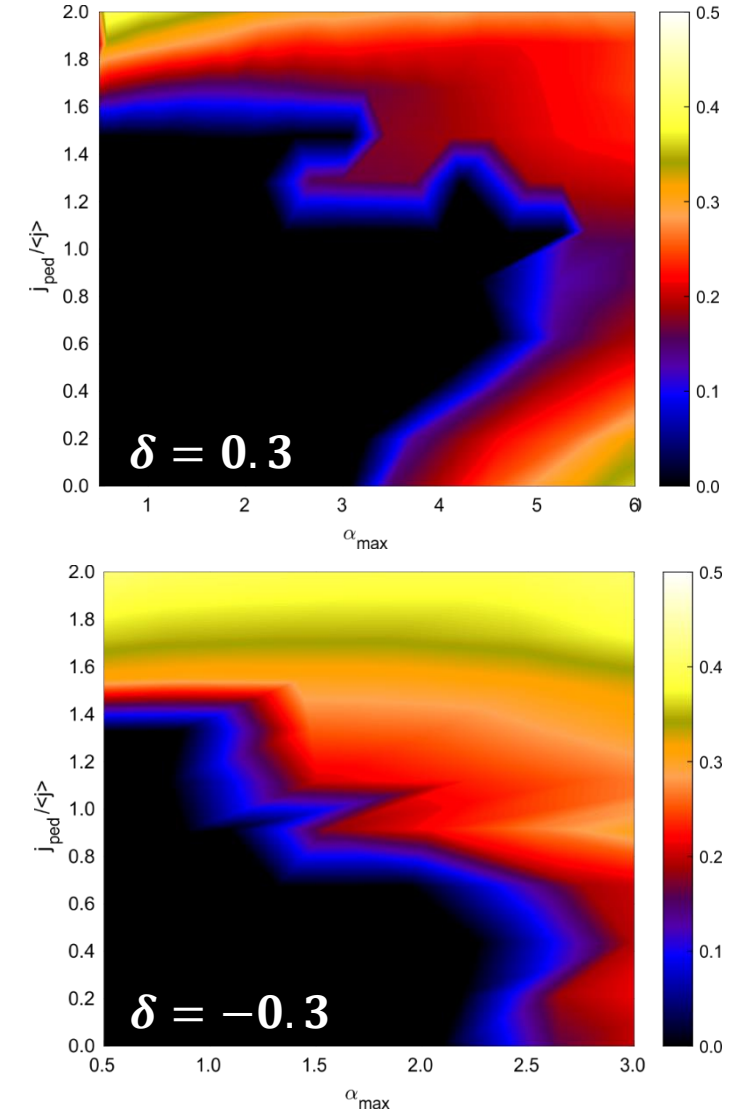
MARS-F Used to Calculate MHD Stability in PT vs NT

- Profiles given by **ASTRA**
- **CHEASE** code used to generate different equilibria
 - **Edge stability** (peeling-ballooning)
 - p' and $I_{||}$ scan with fixed δ
 - δ scan with fixed p' and $I_{||}$
 - **Core stability** with scans in
 - q -profile
 - β_N
 - δ



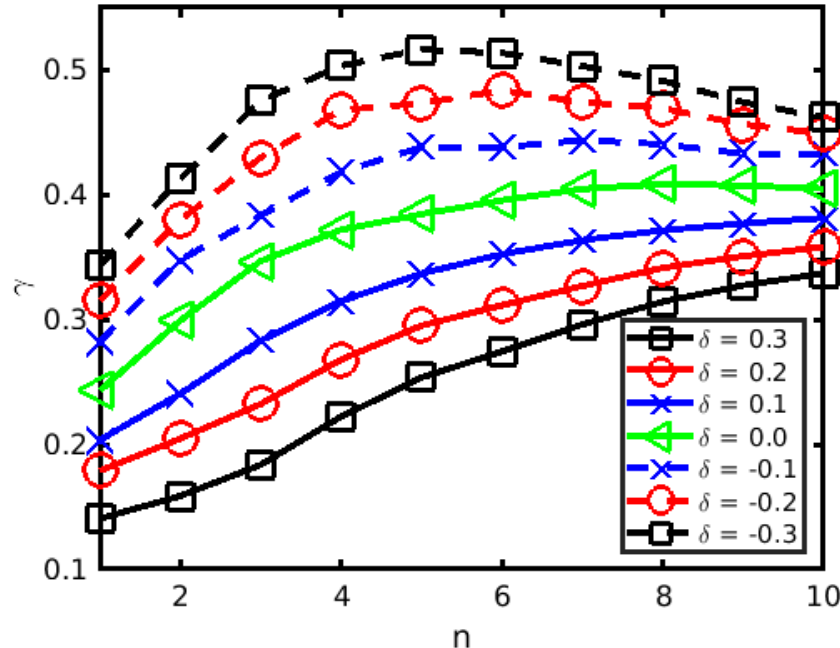
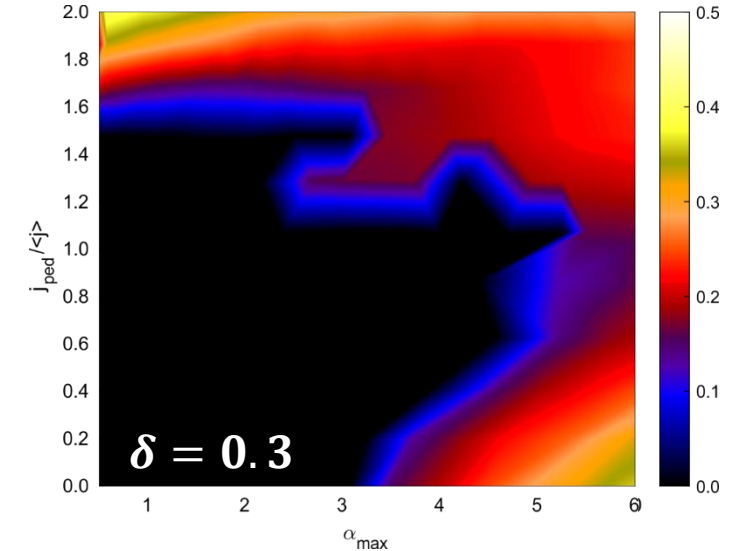
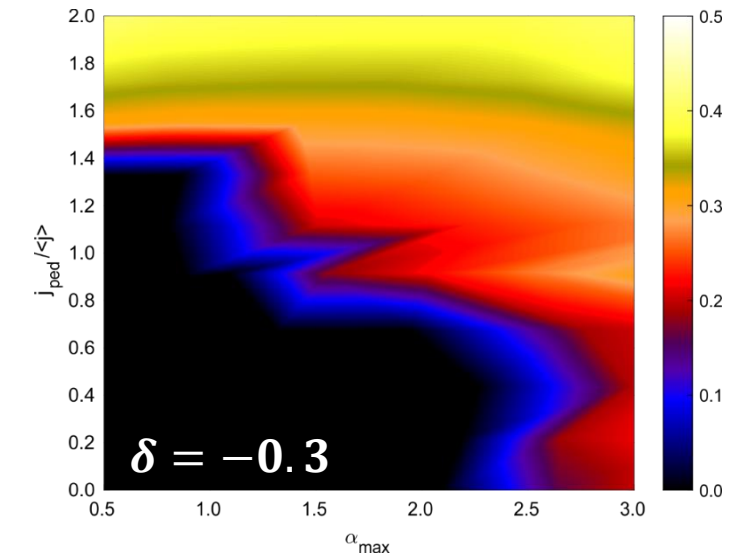
NT is More Unstable to Edge Peeling-Ballooning Perturbations

- As expected NT shaped plasmas show **reduced stability limits** to both edge current and grad-P driven modes



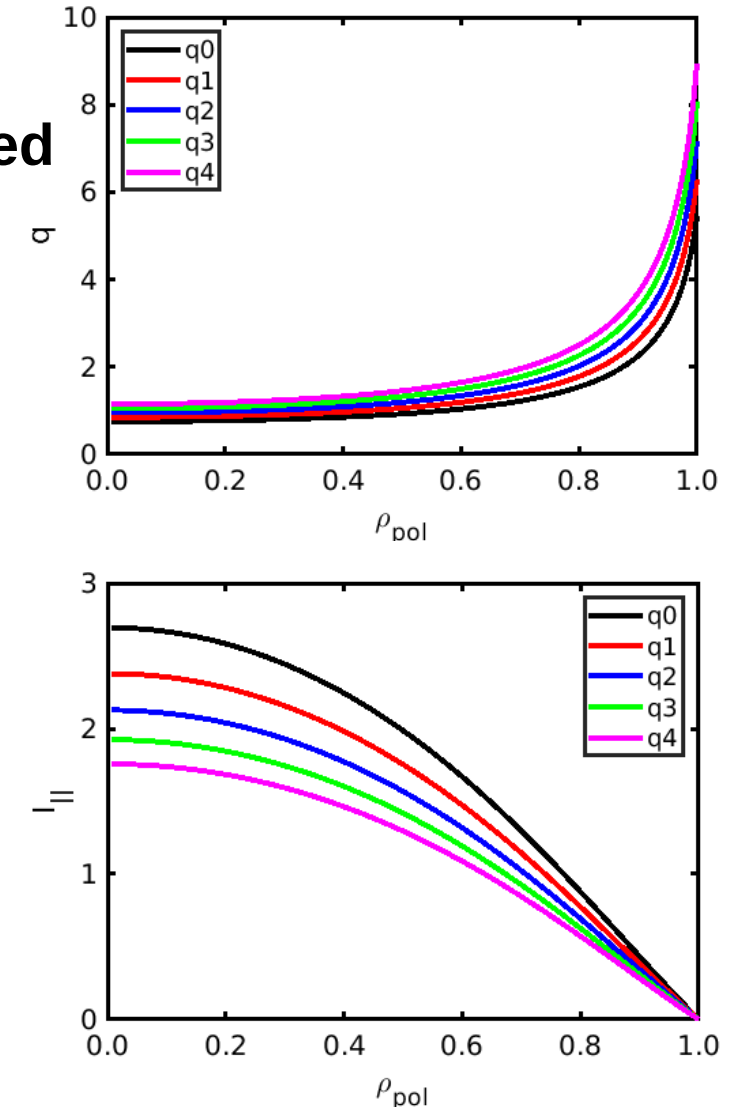
NT is More Unstable to Edge Peeling-Ballooning Perturbations

- As expected NT shaped plasmas show **reduced stability limits** to both edge current and grad-P driven modes
- Dominant n-mode shifts** to mid-numbers (n=5) in strong NT shaped plasma



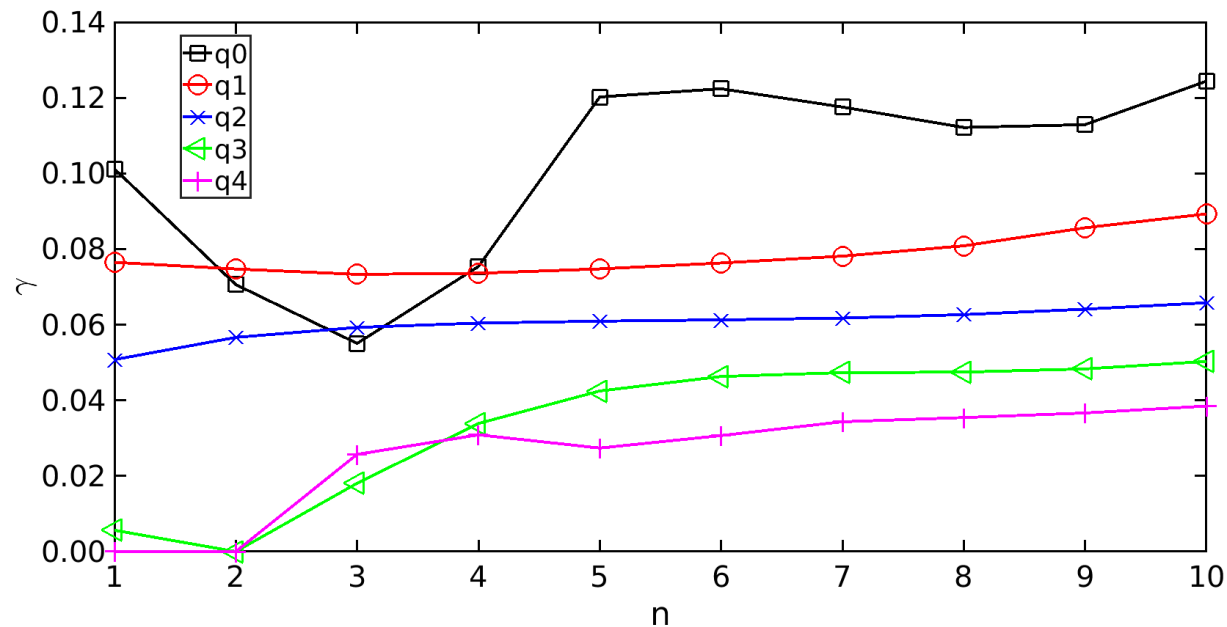
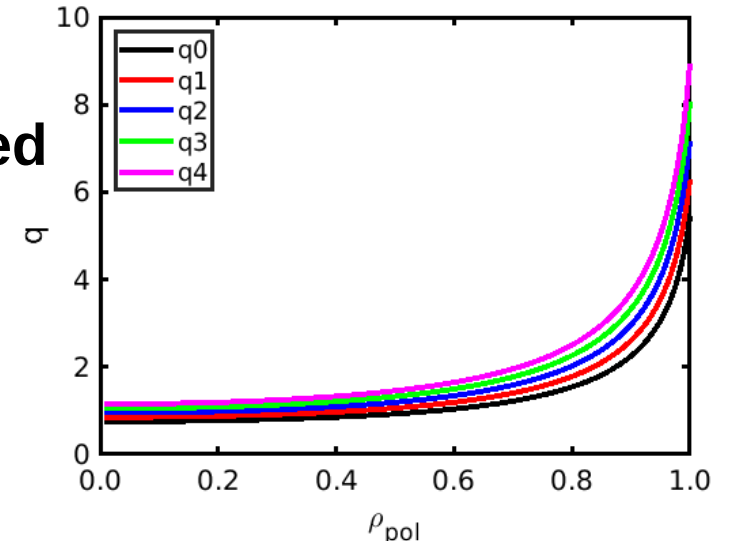
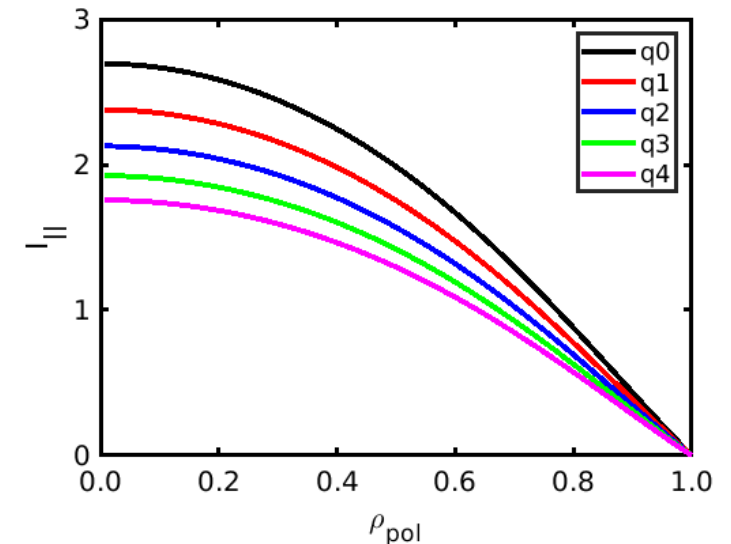
Elevated q-Profiles Tends to Stabilize Plasma Core

- $n=1$ internal kink stabilized for $q_0 > 1$
- $n > 1$ internal modes growth rates are significantly reduced



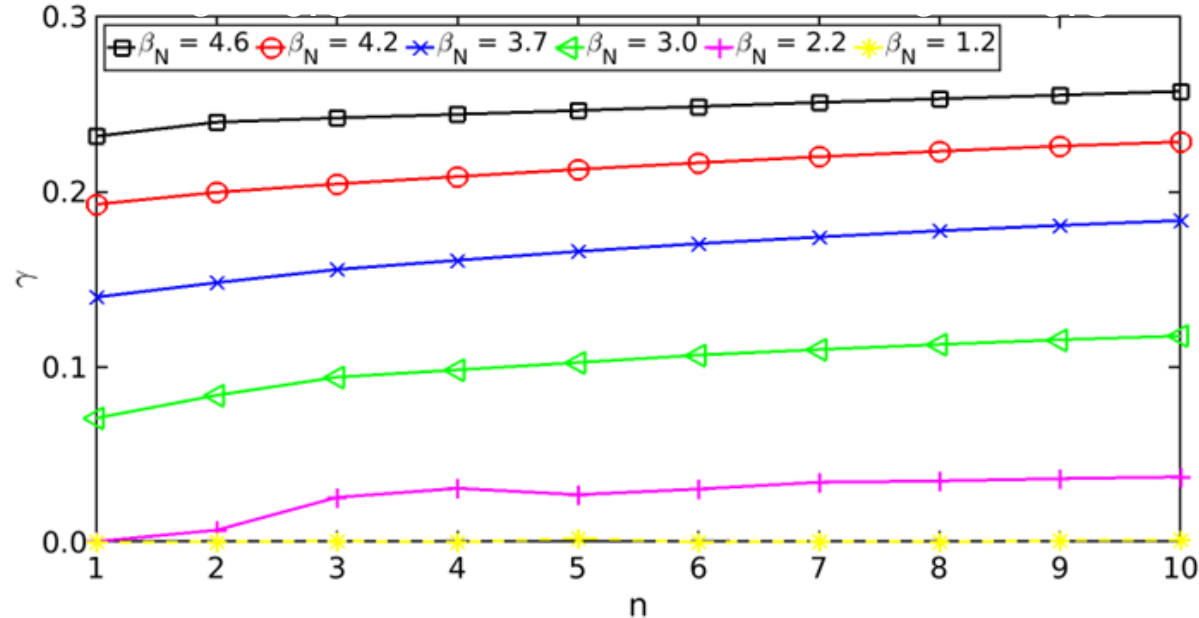
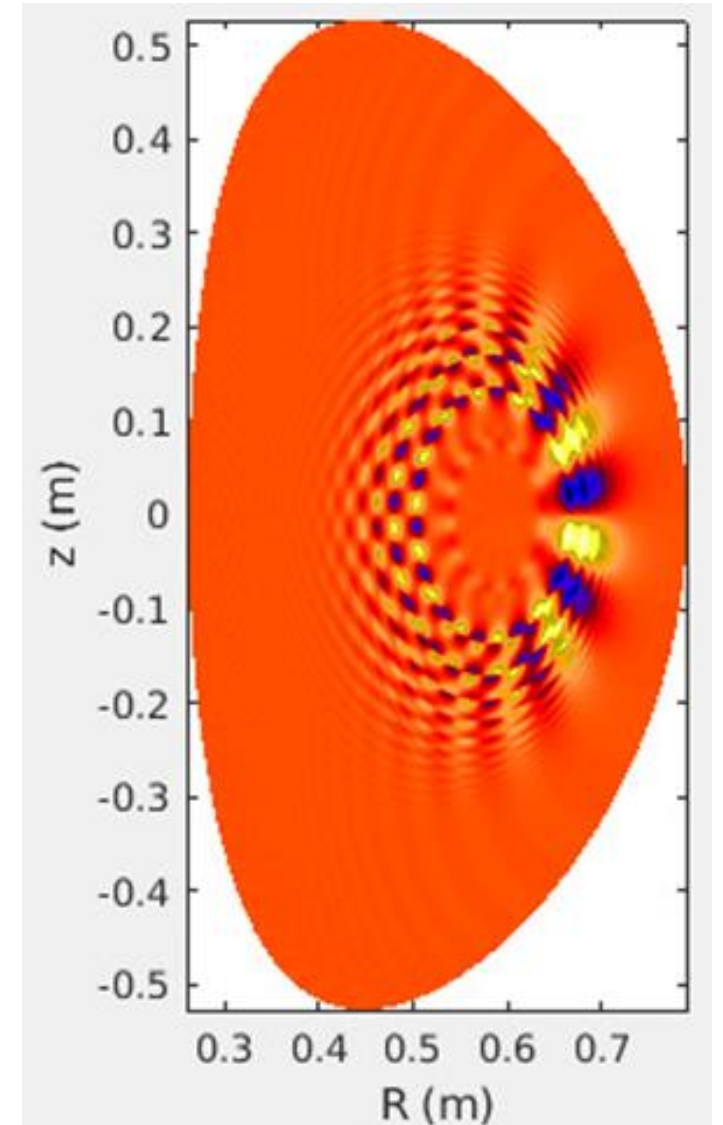
Elevated q-Profiles Tends to Stabilize Plasma Core

- $n=1$ internal kink stabilized for $q_0 > 1$
- $n > 1$ internal modes growth rates are significantly reduced



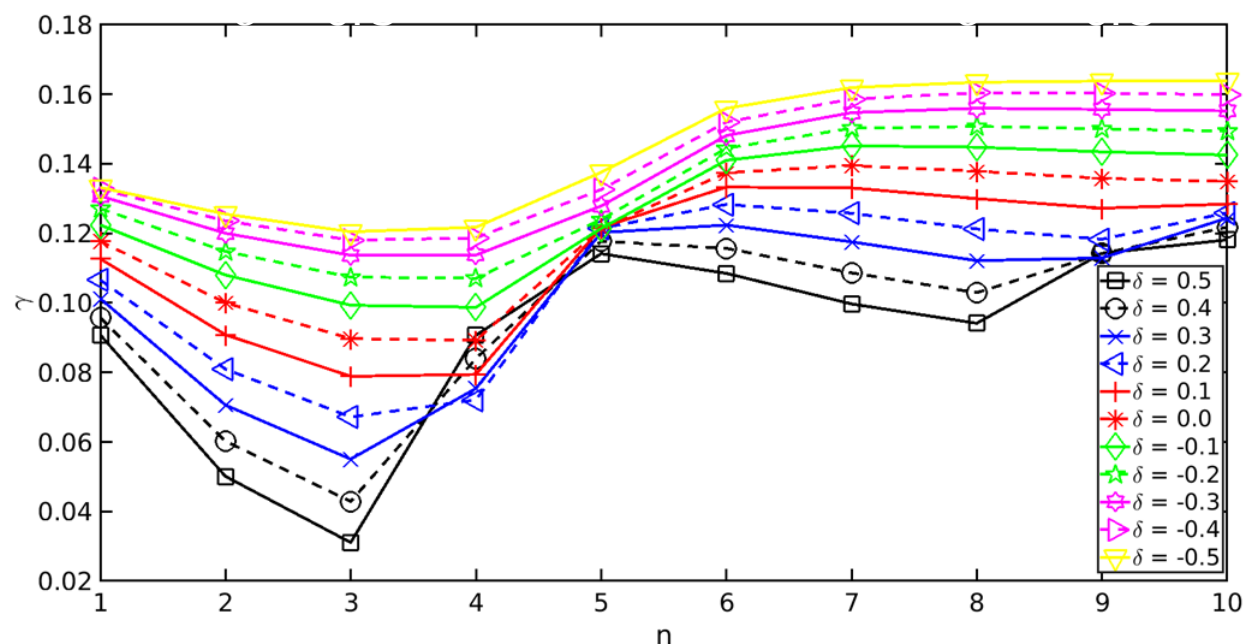
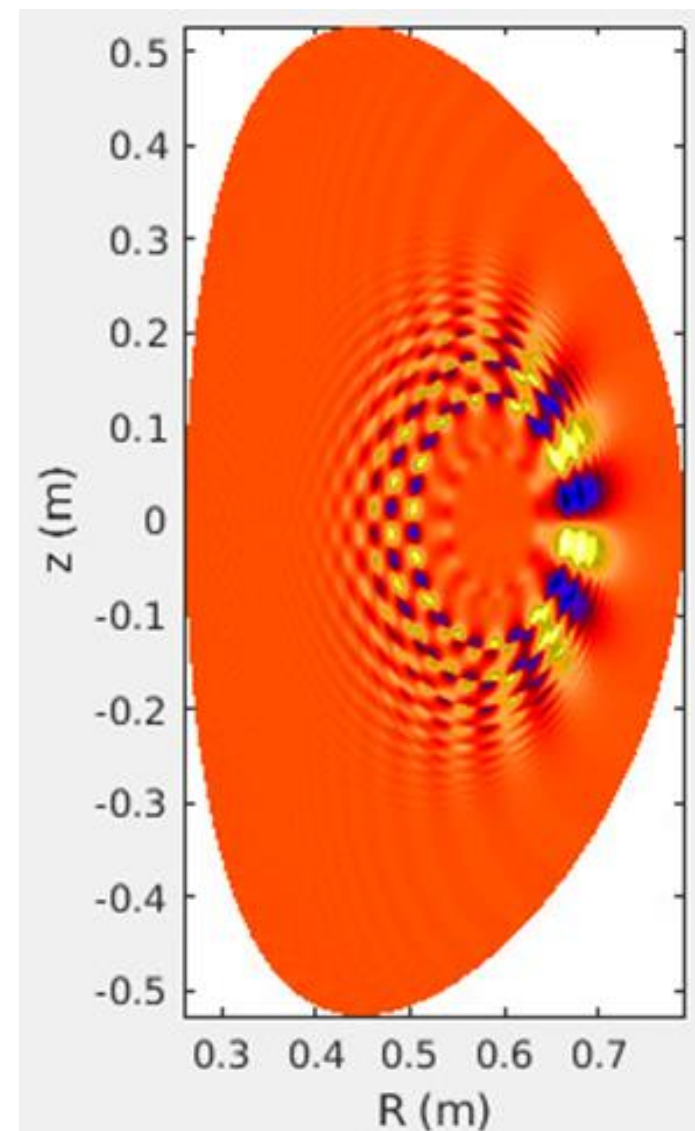
Elevated q-Profiles Tends to Stabilize Plasma Core

- $n=1$ internal kink stabilized for $q_0 > 1$
- $n > 1$ internal modes growth rates are significantly reduced
- **$n=1, 2$ stable up to $\beta_N=3$ in PT shaped plasmas**



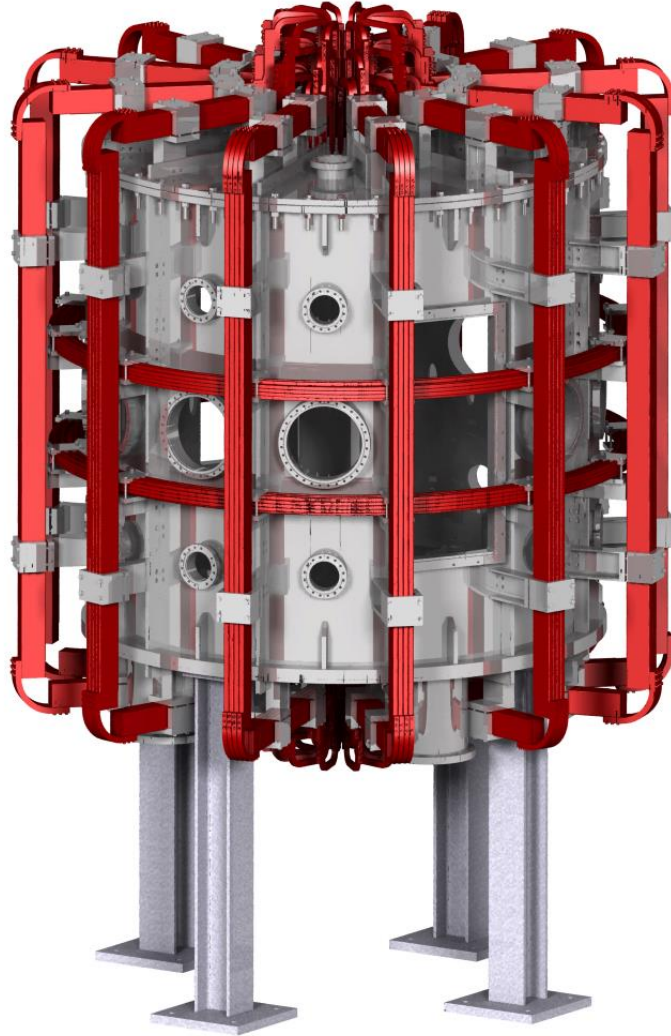
Elevated q-Profiles Tends to Stabilize Plasma Core

- $n=1$ internal kink stabilized for $q_0 > 1$
- $n > 1$ internal modes growth rates are significantly reduced
- $n=1, 2$ stable up to $\beta_N=3$ in PT shaped plasmas
- **Stability scales with δ as expected**



- SMART's missions
- Magnetic equilibrium and prospective discharge scenario
- MHD stability
- **Device**
 - **Vacuum Vessel**
 - **Coils configuration**
 - **Diagnostics**
- Summary

SMART Vacuum Vessel

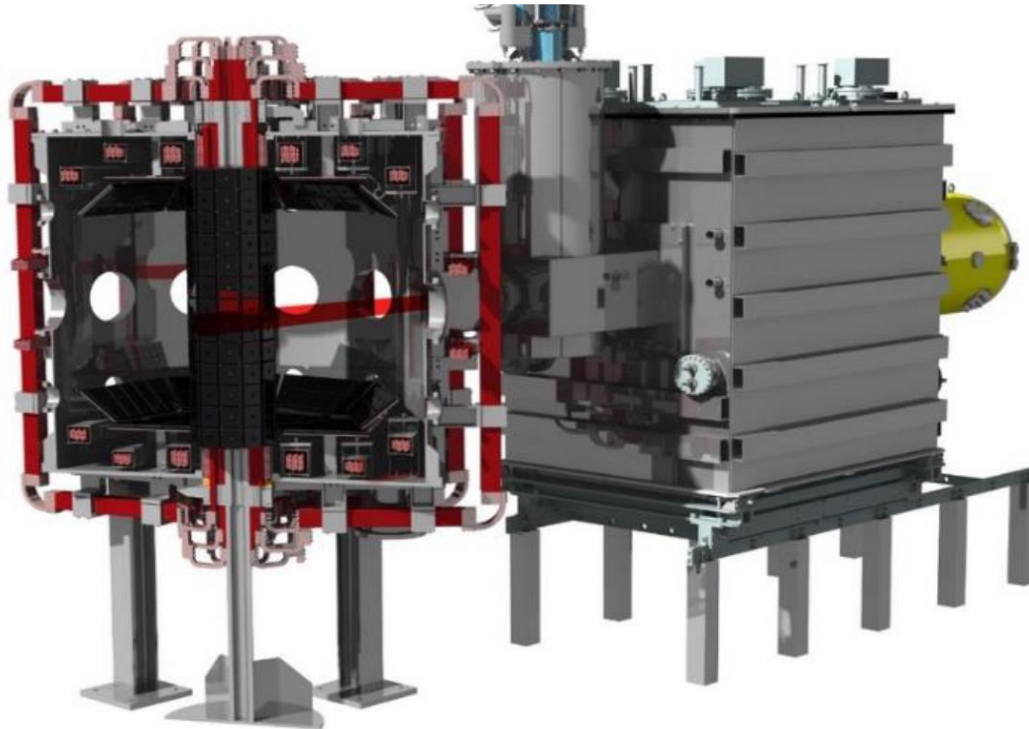
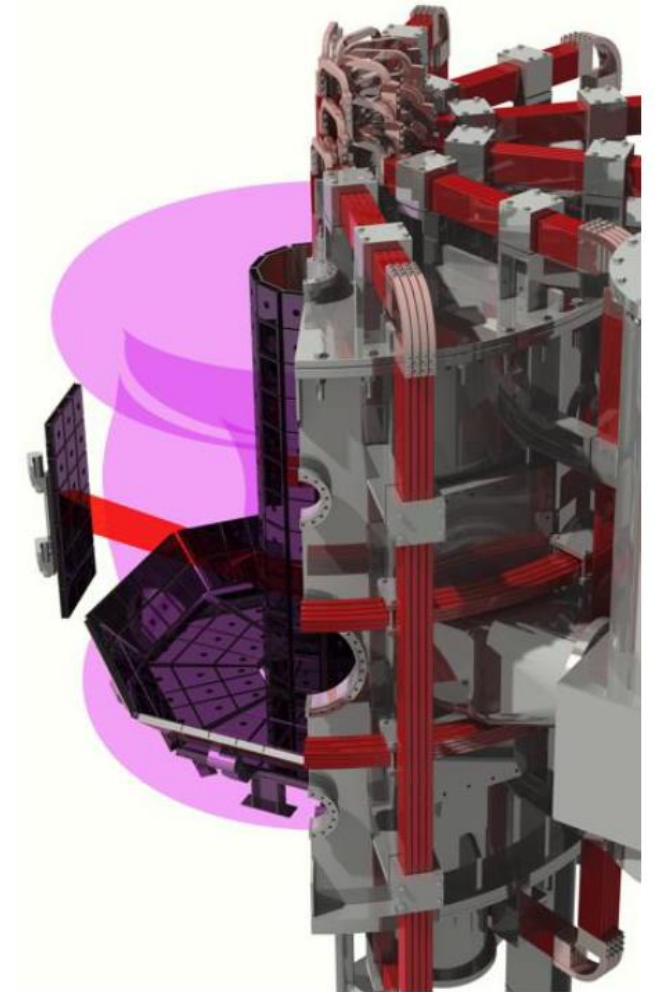


- Overall height of 2,6 m
- Diameter of 2,1 m
- Upper Lid **bolted** and Lower Lid **welded**
- 2 rectangular ports 30×80 cm for NBI and maintenance purposes (customized one)
- 6 lateral ports with CF 300 DN and 24 CF 100 DN
- 6 upper ports & 4 lower ports CF 100 DN
- 4 lower ports CF 250 DN for vacuum
- Mixed thickness (18 mm, 8 mm and 3 mm)
- 12 body ribs and 12 upper and lower lid ribs (15 mm thick)
- Material stainless steel AISI 316 L
- Vacuum 10^{-8} mbar
- Leak rate 10^{-8} mbar*lt/s

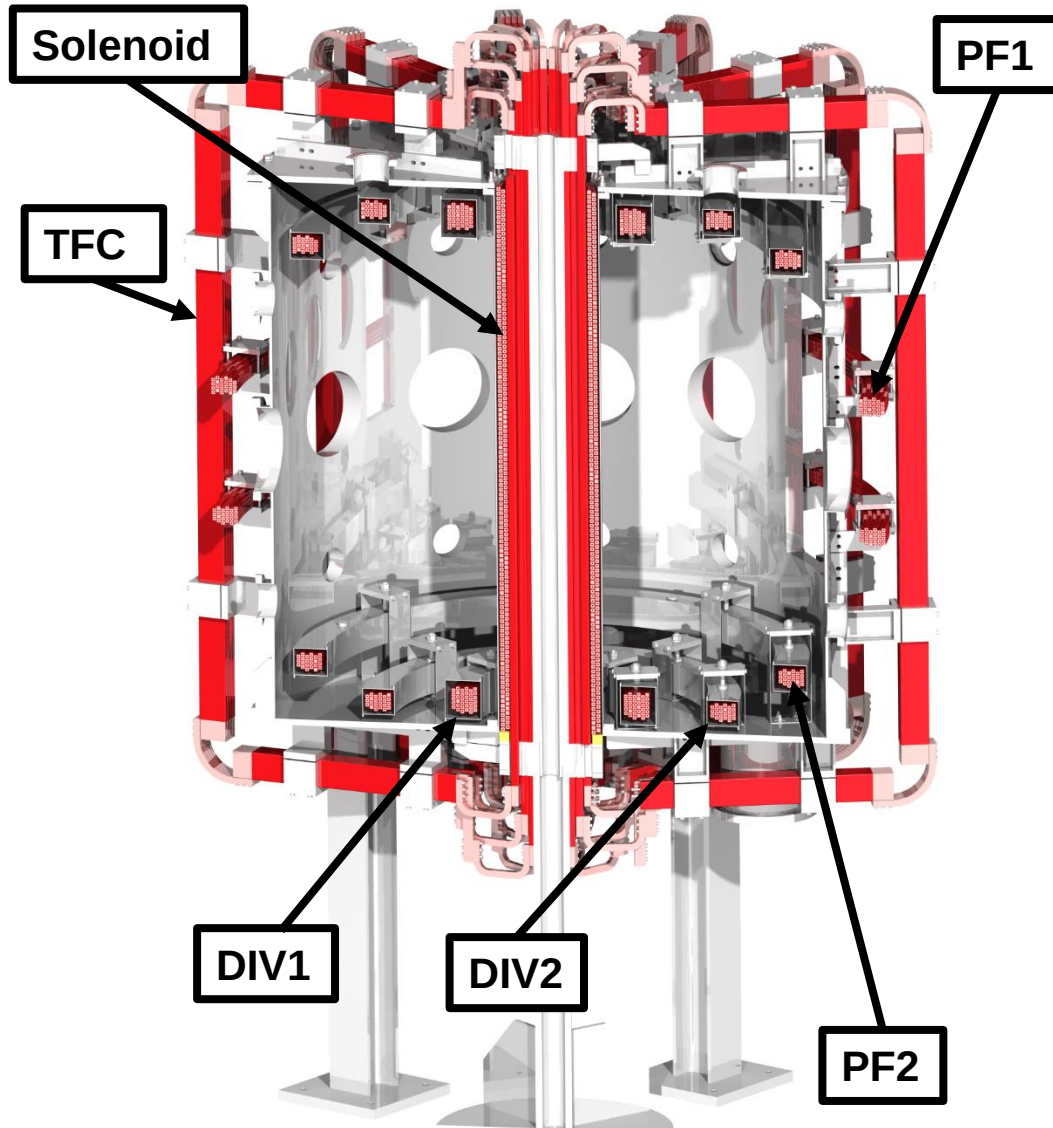
Vacuum Vessel Will Be Equipped with Heat Shield to Protect Exposed PFCs to Excessive Heat Load

High volumetric power density $P_{\text{NBI}}/V = 1/0.31 = 3.2 \text{ MW/m}^3$ to achieve high confinement / temperatures and study power exhaust techniques

- Similar volume-normalized NBI heating to that in e.g. AUG or TCV
 - **AUG** ($R=1.7\text{m}$, $a=0.5\text{m}$) with $P_{\text{NBI}}/V=20\text{MW}/8.4\text{m}^3 = 2.3 \text{ MW/m}^3$
 - **TCV** ($R=0.9\text{m}$ and $a=0.28\text{m}$) with $P_{\text{NBI}}/V=2.2\text{MW}/1.4\text{m}^3 = 1.6 \text{ MW/m}^3$.



SMART Coils

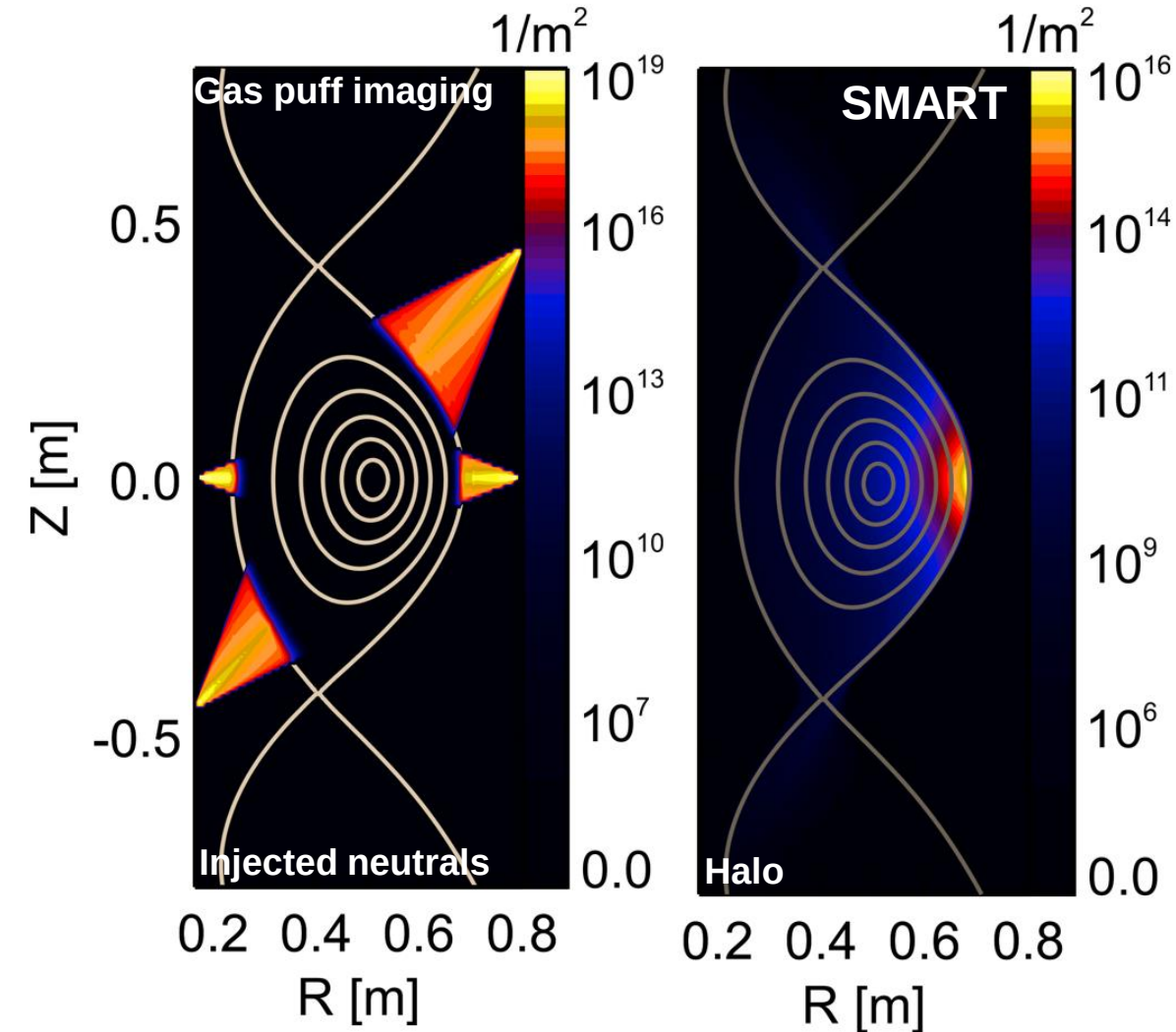


Coil dimensions obtained by iterative process including target plasma parameters and technical restrictions

- DIV1, DIV2 and PF2 coils are placed inside for improving physics performance (control) and reducing coils current
- PF1 and TFC are left outside
- Supports of TFC and PF1 are attached to VV ribs
- Inner coils support attached to lids through welded bolts
- Coils supports and joints accommodate deformation during baking and operation

Diagnostics

Diagnostic Method		Remark
Magnetic Diagnostics	Rogowski Coil	2 out-vessel 2 in-vessel
	Pick-up Coil	48 pick-up coils
	Flux Loop	10 loops
Optical Diagnostics	Gas puffing CXRS	n_i and T_i profiles
	Interferometer	Line integrated n_e
	Fast camera (Phantom v2512)	< 1MHz
	Soft X-ray array	PPPL-DOE
	Thomson Scattering	PPPL-DOE
Particles	Langmuir probes	Midplane and separatrix strike points



- SMART's missions
- Magnetic equilibrium and prospective discharge scenario
- MHD stability
- Device
 - Vacuum Vessel
 - Coils configuration
 - Diagnostics
- **Summary**

Summary

- **Negative Triangularity in a Spherical Tokamak might be an attractive (core-edge-power exhaust) compromise for a compact fusion power plant**
- **SMART – a new and exciting, compact spherical tokamak will be coming online soon to**
 - Train next generation of fusion physicists and engineers
 - Study plasma confinement and stability in PT and NT
 - Develop novel diagnostic and plasma control techniques
 - Develop alternative exhaust techniques
- Please, contact us for potential collaborations!

mgm@us.es
eviezzzer@us.es

