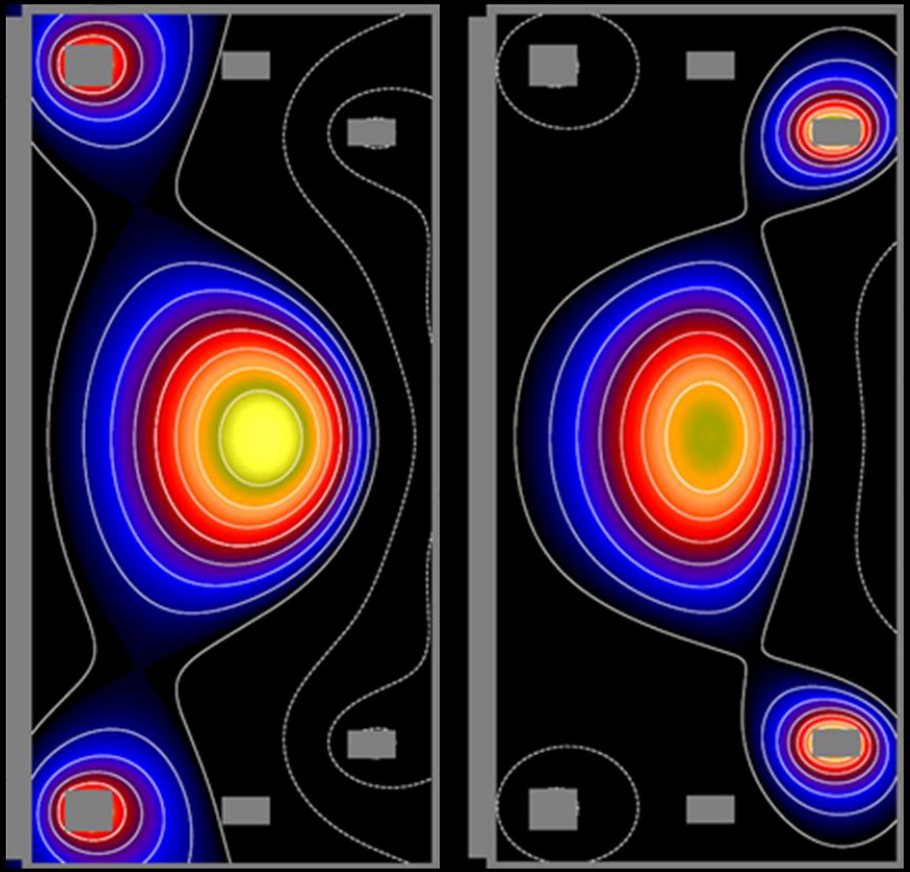


Design and current status of the SMall Aspect Ratio Tokamak – SMART –

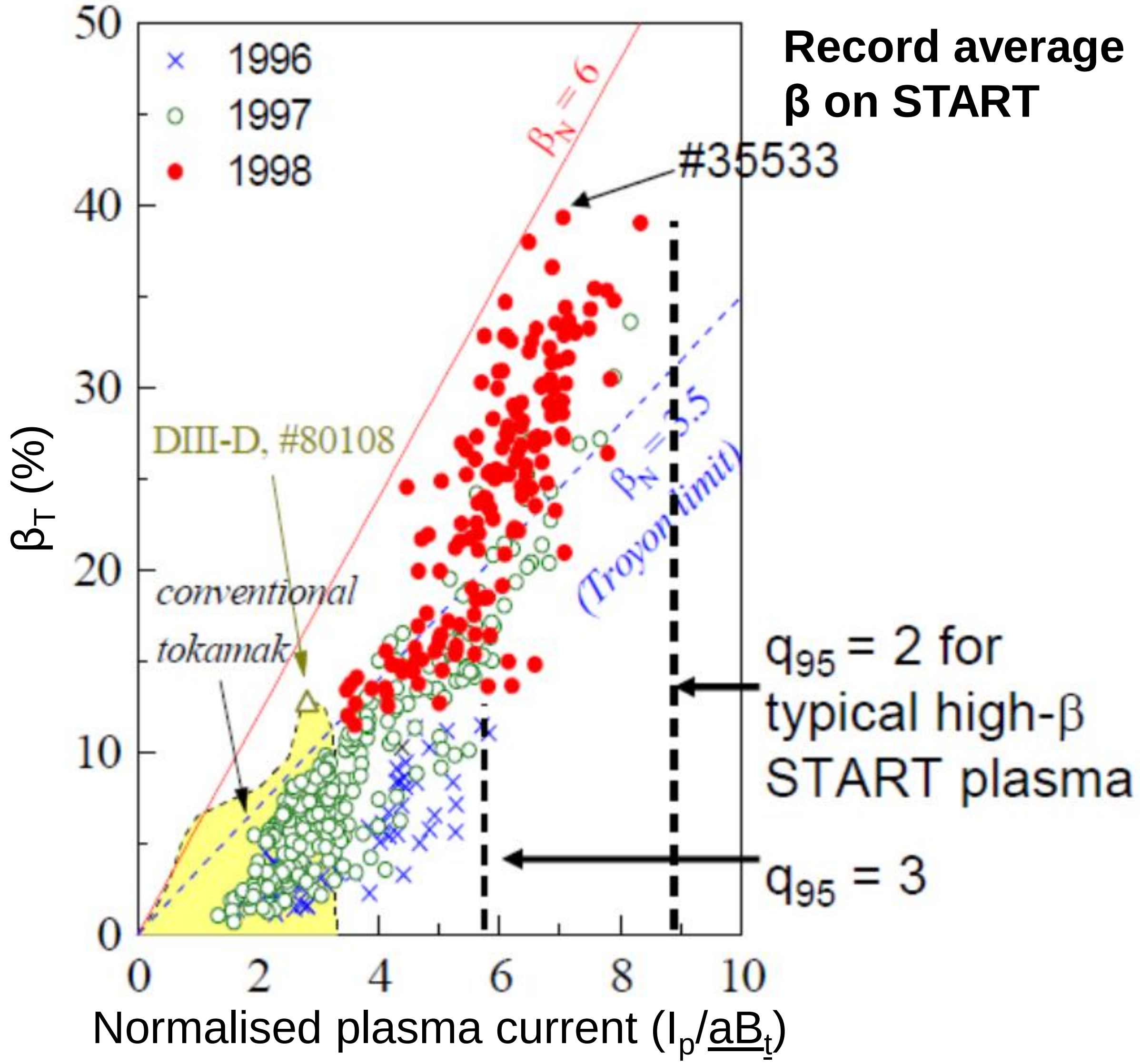
M. Garcia-Munoz

A. Mancini, J. Segado-Fernandez, E. Viezzer,
M. Barragan-Villarejo, S. J. Doyle, M. Agredano-Torres,
J. Ayllon-Guerola, P. F. Buxton, J. Chung, M. Freire-Rosales,
J. Galdon-Quiroga, J. García-Lopez, J. L. Garcia-Sanchez,
M. P. Gryaznevich, S. Hwang, J. M. Maza,
J. F. Rivero-Rodriguez, M. Toscano-Jimenez,
L. Velarde-Gallardo and the PSFT team

M. Garcia-Munoz | Seminar at NSTX-U/MFE Monday Meeting | Princeton Plasma Physics Laboratory | November 22 - 2021

Spherical Tokamaks Offer Attractive Path to Fusion Reactor

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



Record average β on START

M. Gryaznevich et al., PRL 1998
D. C. Robinson PPCF 1999

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

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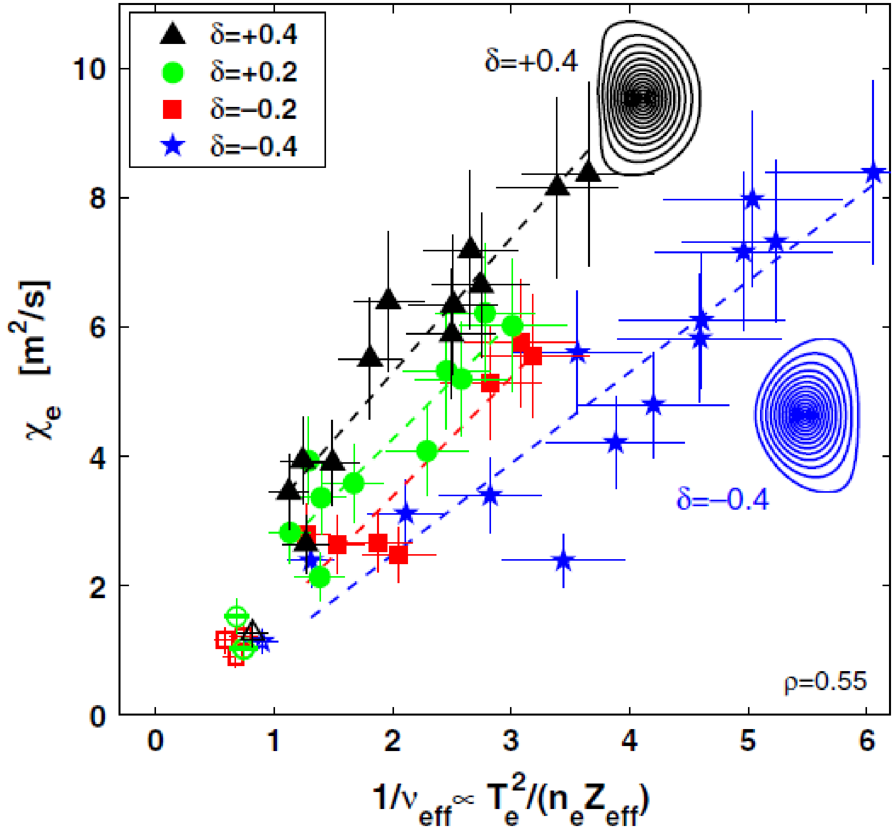
Core

- Improved thermal plasma transport
  - -δ *features lower* **experimental** electron heat diffusivity than similar +δ
    - 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

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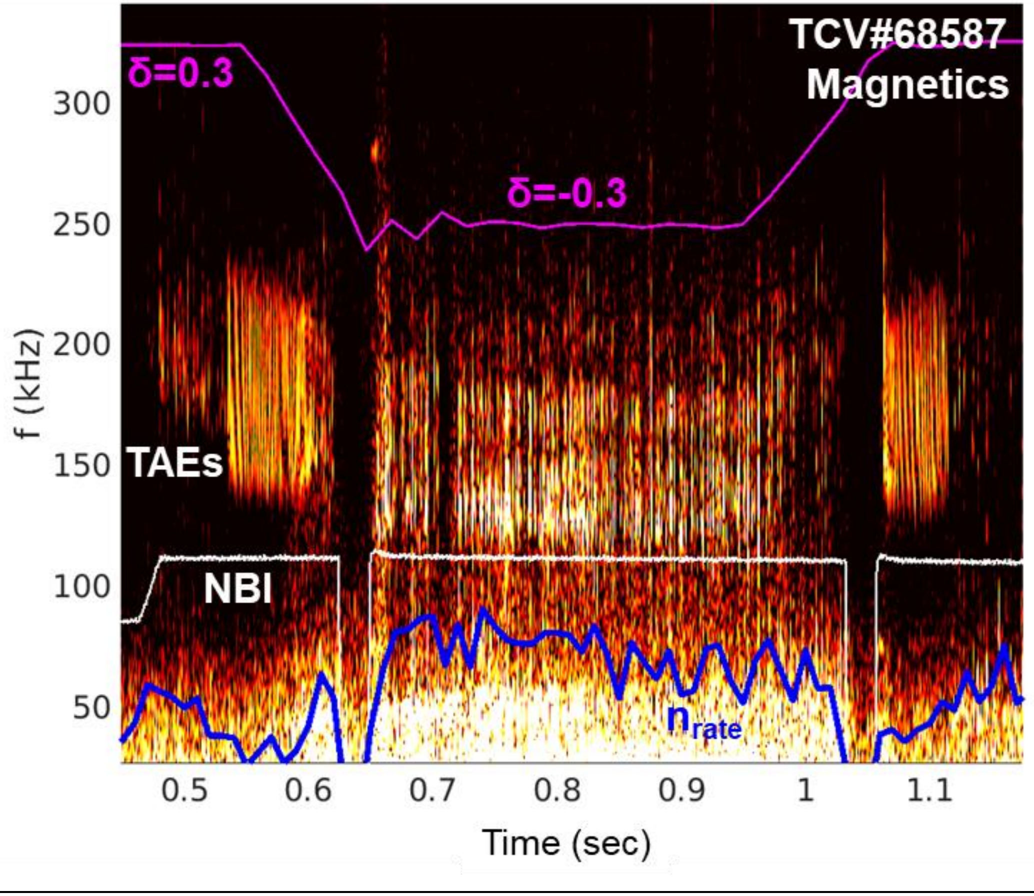
- **Improved fast-ion confinement**
  - Reduced AE activity
  - Larger fast-ion content



M. Garcia-Munoz *et al.*, EPS 2021
P. Oyola *et al.*, IAEA TM EP 2021

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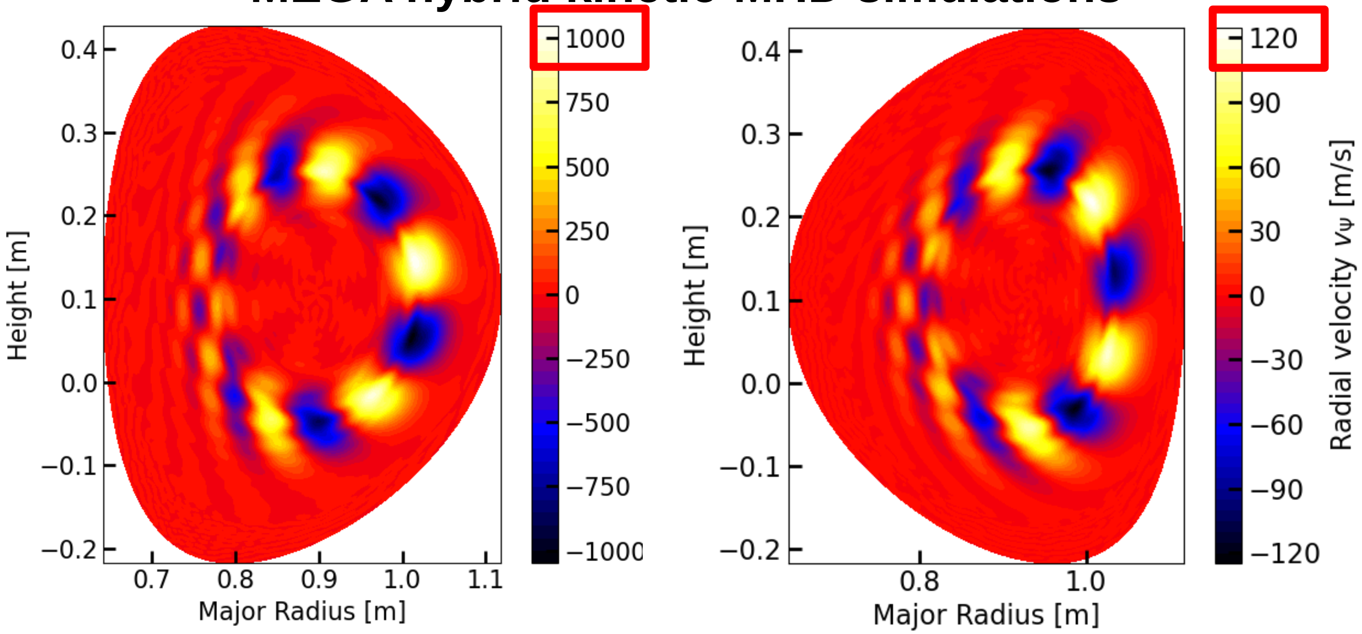
MEGA hybrid kinetic-MHD simulations



Wave-particle interaction occurs at higher resonance harmonics in –δ than +δ

M. Garcia-Munoz *et al.*, EPS 2021
P. Oyola *et al.*, IAEA TM EP 2021

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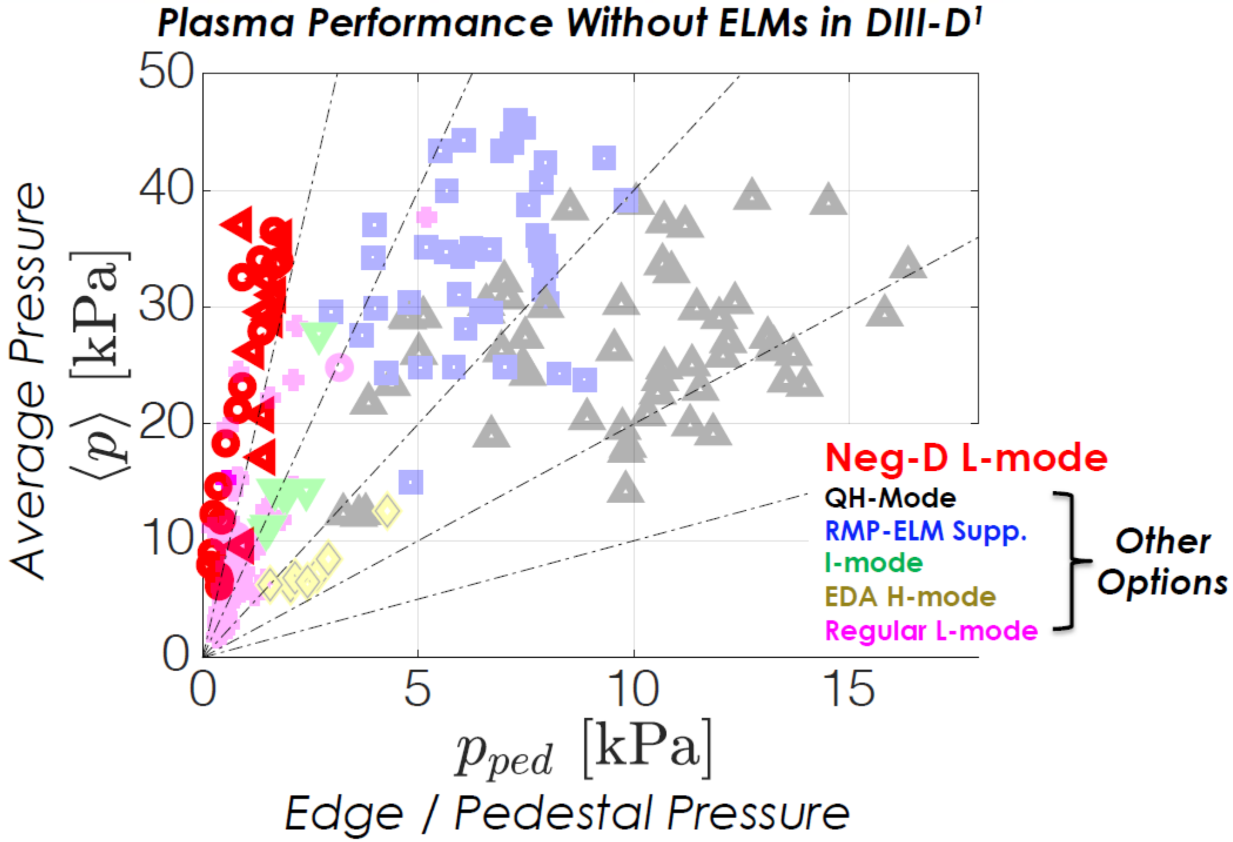
Edge

- No pedestal > No ELMs



C. Paz-Soldan *et al.*, PPFC 2021

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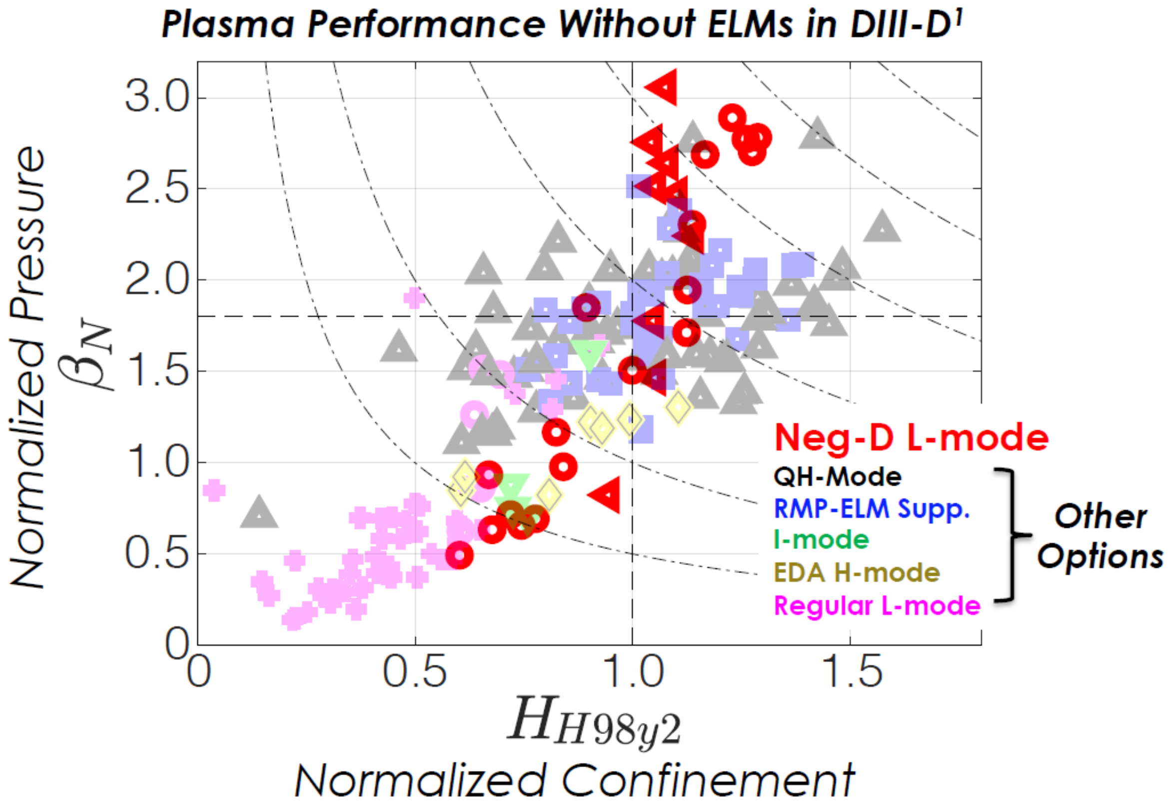

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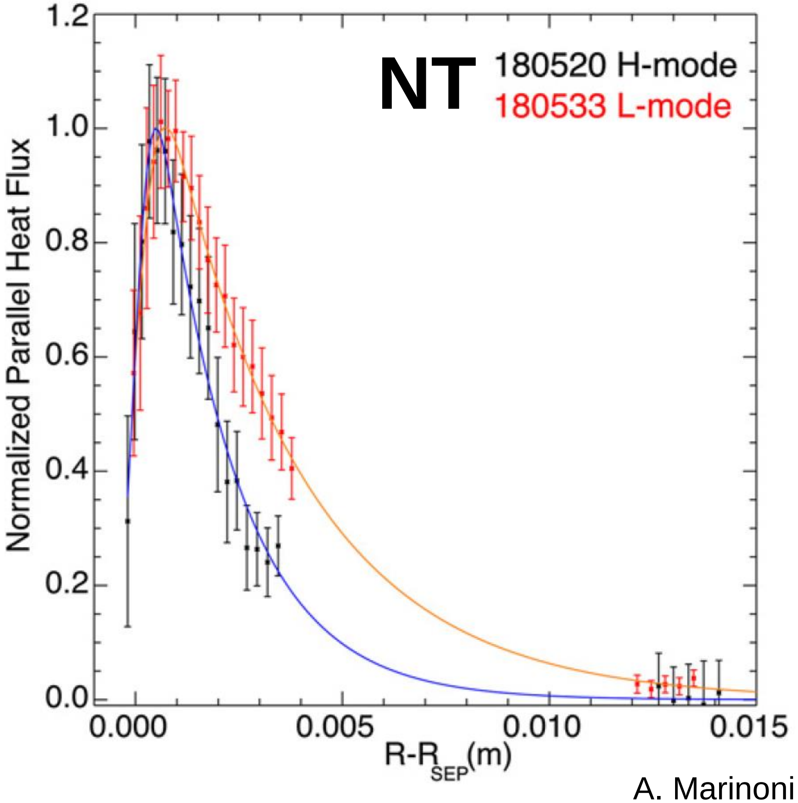
- No pedestal > No ELMs
- Low impurity retention
- Wider scrape-off layer heat flux

Parallel power fall-off length, λ_q



A. Marinoni *et al.*, NF 2021

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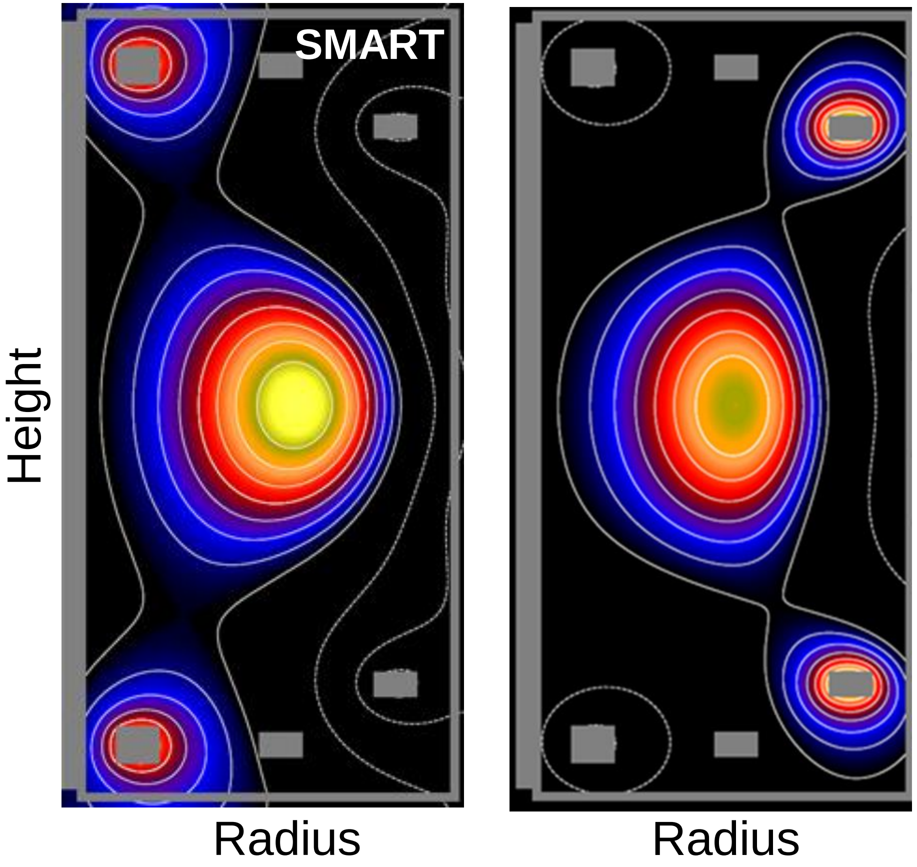
Divertor naturally placed at larger radii



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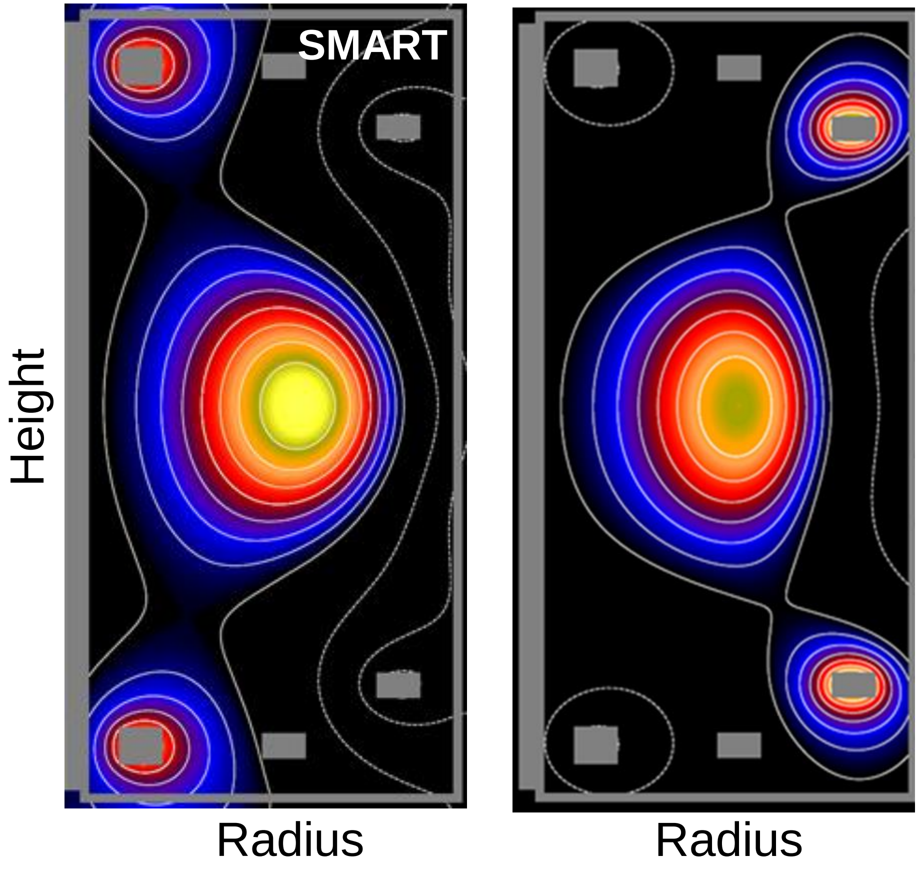

But This Comes with a Price: Reduced Stability Limits

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

S.Yu. Medvedev *et al.,* Nucl. Fusion **55** 063013 (2015)

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

S.Yu. Medvedev *et al.*, Nucl. Fusion **55** 063013 (2015)

Outline

- SMART's missions

- Magnetic equilibrium and prospective discharge scenario

- Device
  - Vacuum Vessel
  - Coils configuration
  - Power supply
  - Diagnostics

- Timeline

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Outline

- **SMART’s missions**

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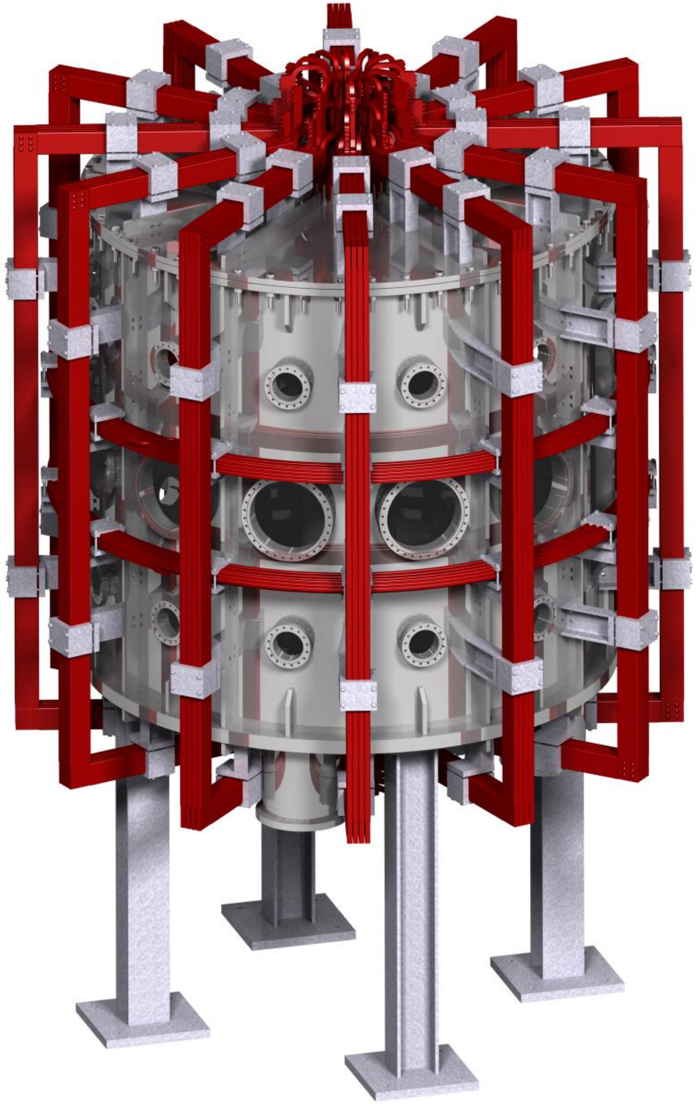
SMART – SMall Aspect Ratio Tokamak

- 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

- **SMART's missions include:**
    - Training of next generation of fusion physicists and engineers
    - Study plasma confinement and stability in positive vs. negative triangularity
    - Develop novel diagnostic and plasma control techniques
    - Develop alternative exhaust techniques



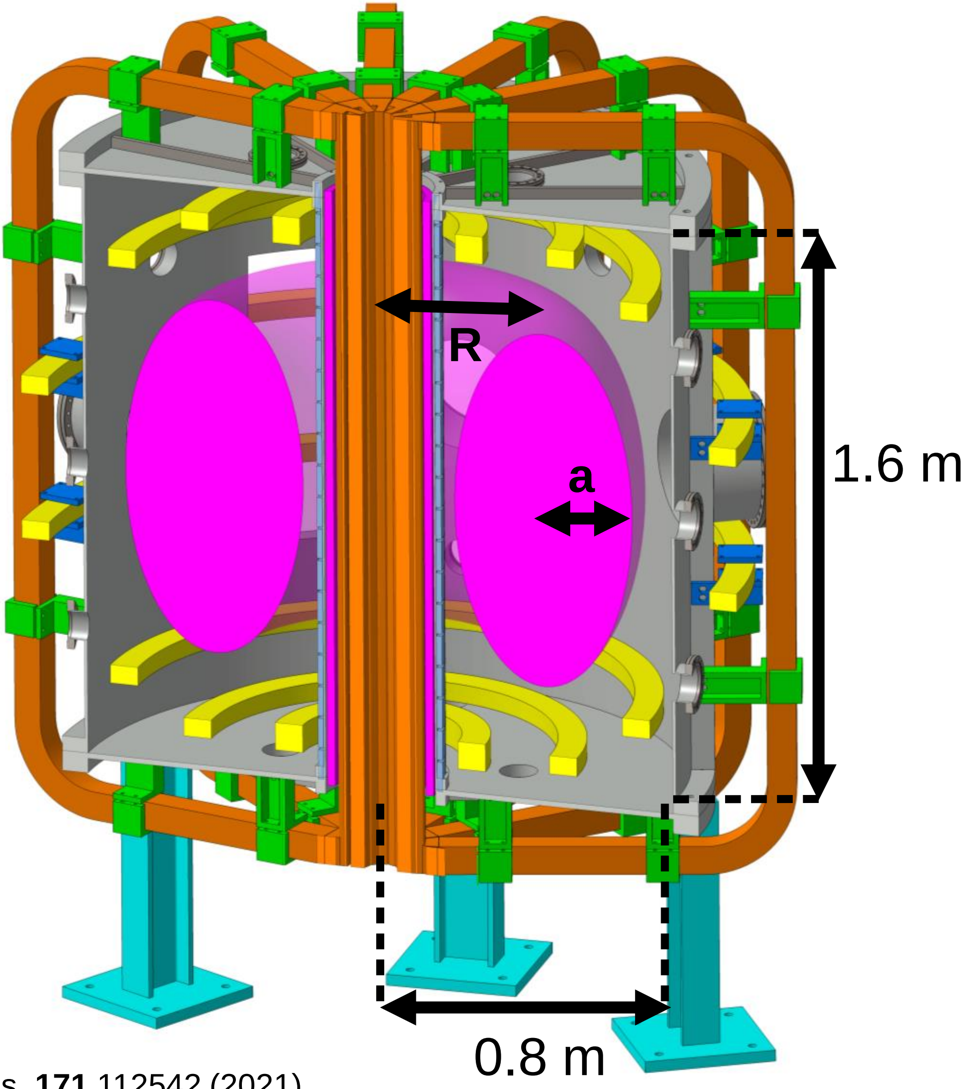
A. Mancini *et al*, Fus. Eng. Des. **171** 112542 (2021)

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

- 3 operational phases foreseen

Parameters	Phase 1	Phase 2	Phase 3
Plasma Current [kA]	100	>100	<500
Toroidal field [T]	0.1	0.3	1.0
Flat-top duration [ms]	150	>150	500
Microwave heating [kW]	6	6	200
Neutral beam injection [MW]	-	1	1



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

Outline

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- **Magnetic equilibrium and prospective discharge scenario**

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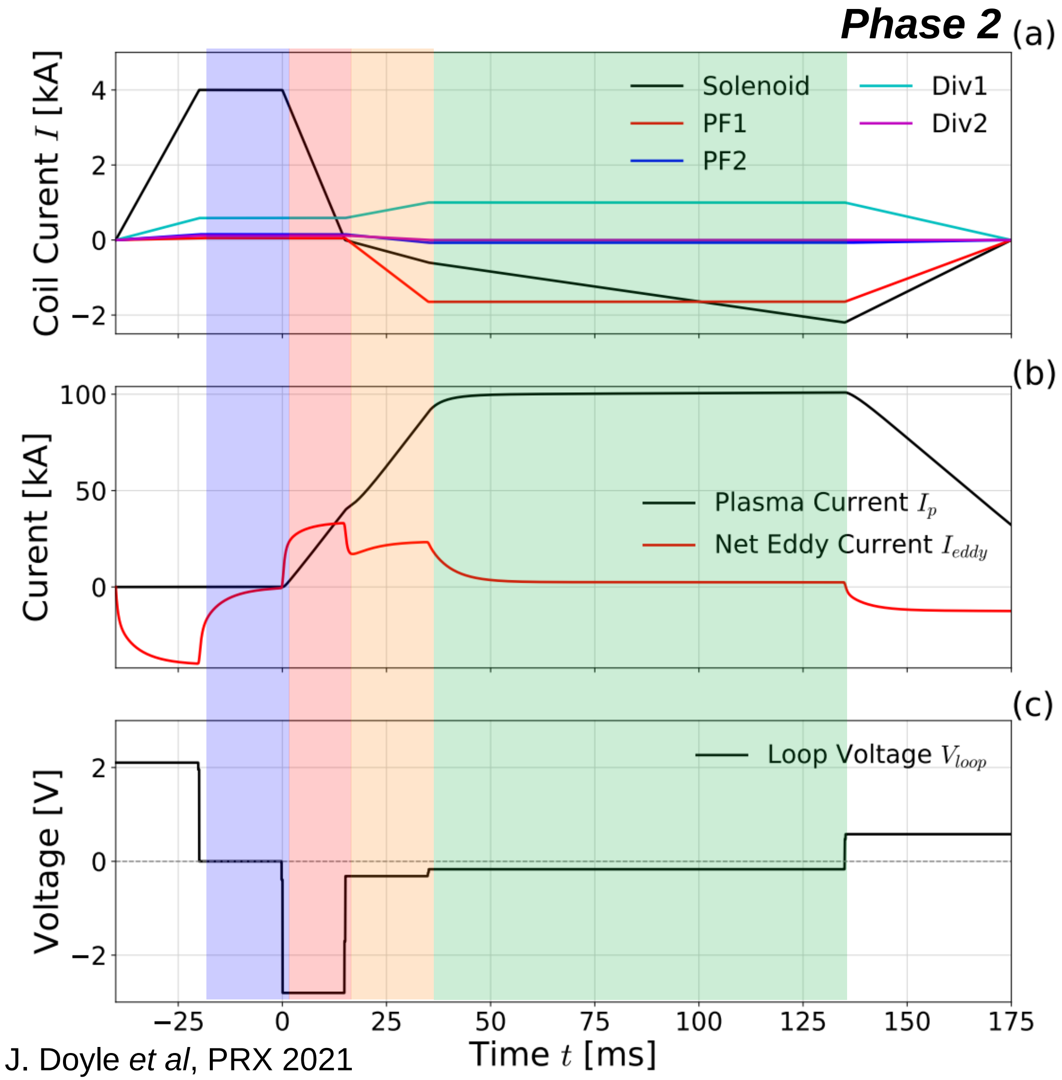
Prospective Discharge Scenario

- FIESTA solves Grad-Shafranov equation
  → Determine j from β_{pol}
  → Output: Plasma and vessel eddy currents

- Asymmetric solenoid ramp:
  - **Formation** of null-field: 16ms
  - **Breakdown** timescale: 8 ms
  - **Transition** timescale: 20 ms
  - **Flat-top** duration: 100 ms



S. J. Doyle *et al*, PRX 2021

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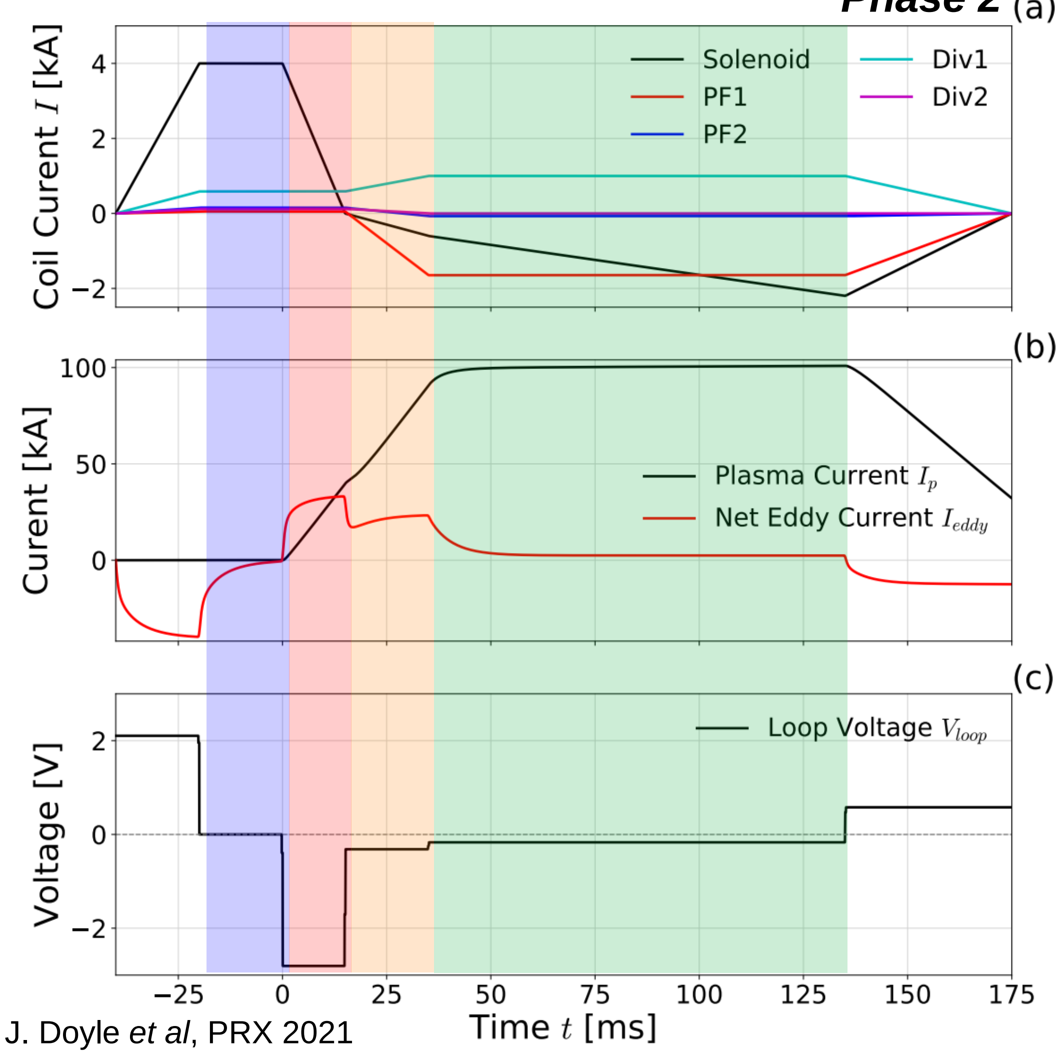
- Solenoid induced breakdown:
  - Sustained 8 ms ramp: -0.3 kA/s
  - Induces toroidal voltage: V_{loop} = -2.3 V

Phase 2



S. J. Doyle *et al*, PRX 2021

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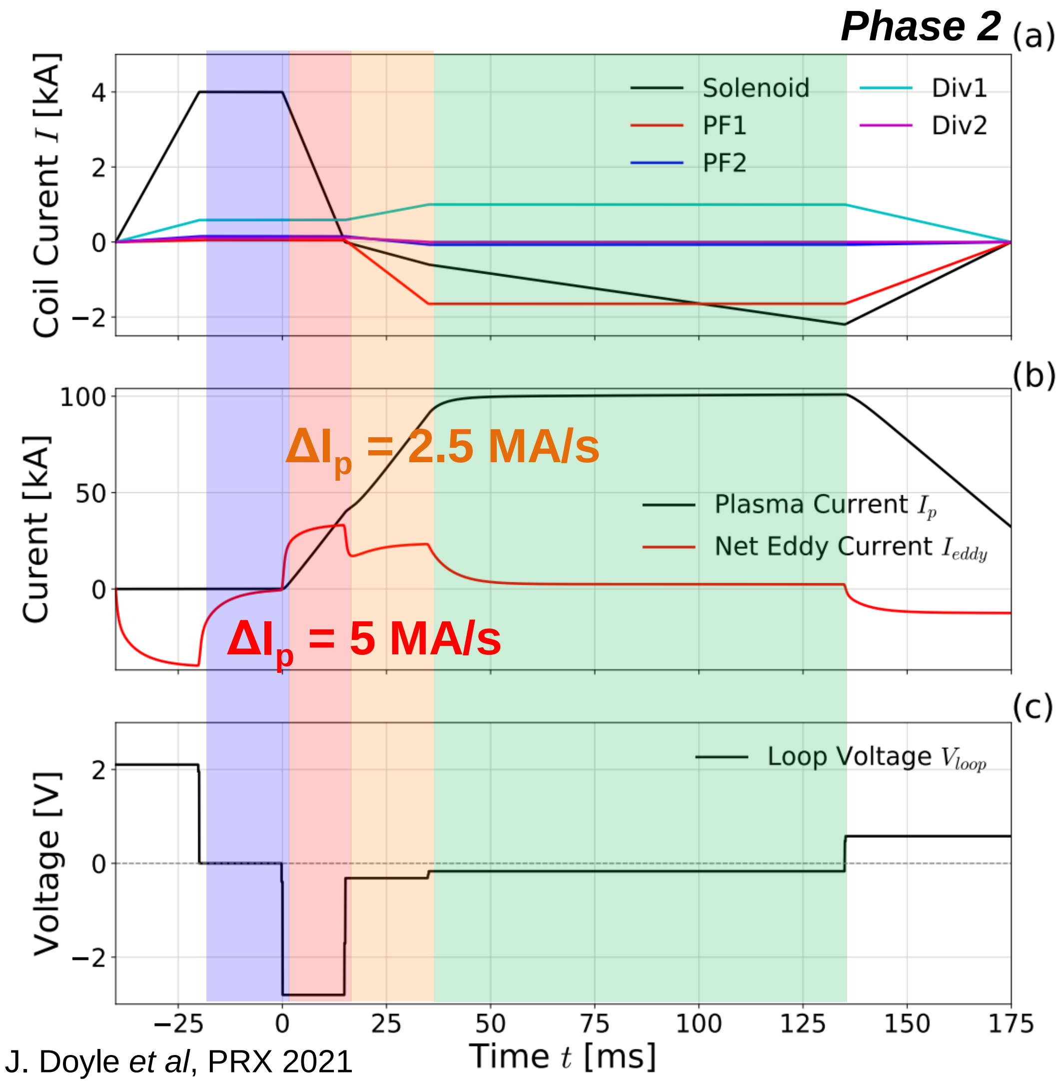
- I_p growth in 2 stages, I_p = 100 kA for 100 ms →
  PF and DIV coils in equilibrium configuration



Phase 2

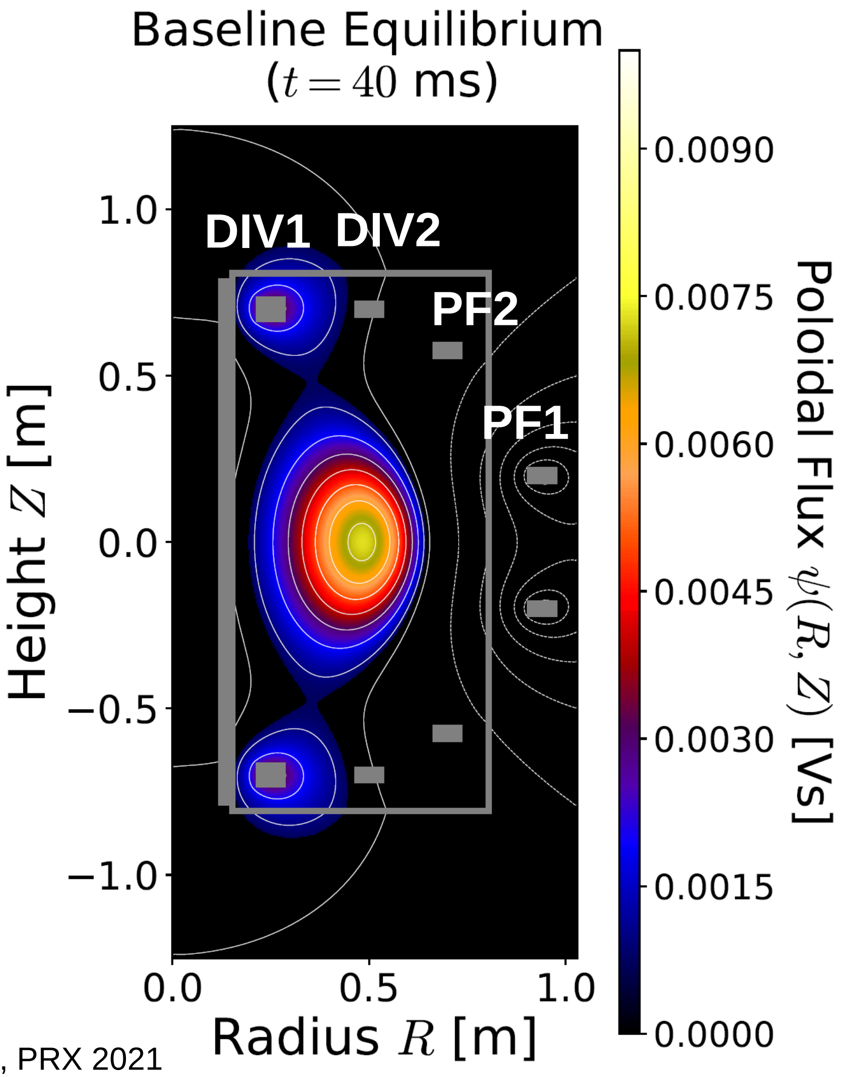
ΔI_p = 2.5 MA/s

ΔI_p = 5 MA/s

S. J. Doyle *et al*, PRX 2021

Plasma Shaping Controlled by PF and DIV Coils

- Aim for flexible shaping, including positive and negative triangularities
- Plasma equilibria for I_p = 100 kA, B_t = 0.3 T
- **Baseline equilibrium** – max. elongation
  → A = 1.85, κ = 2, δ = +0.2



S. J. Doyle *et al*, PRX 2021

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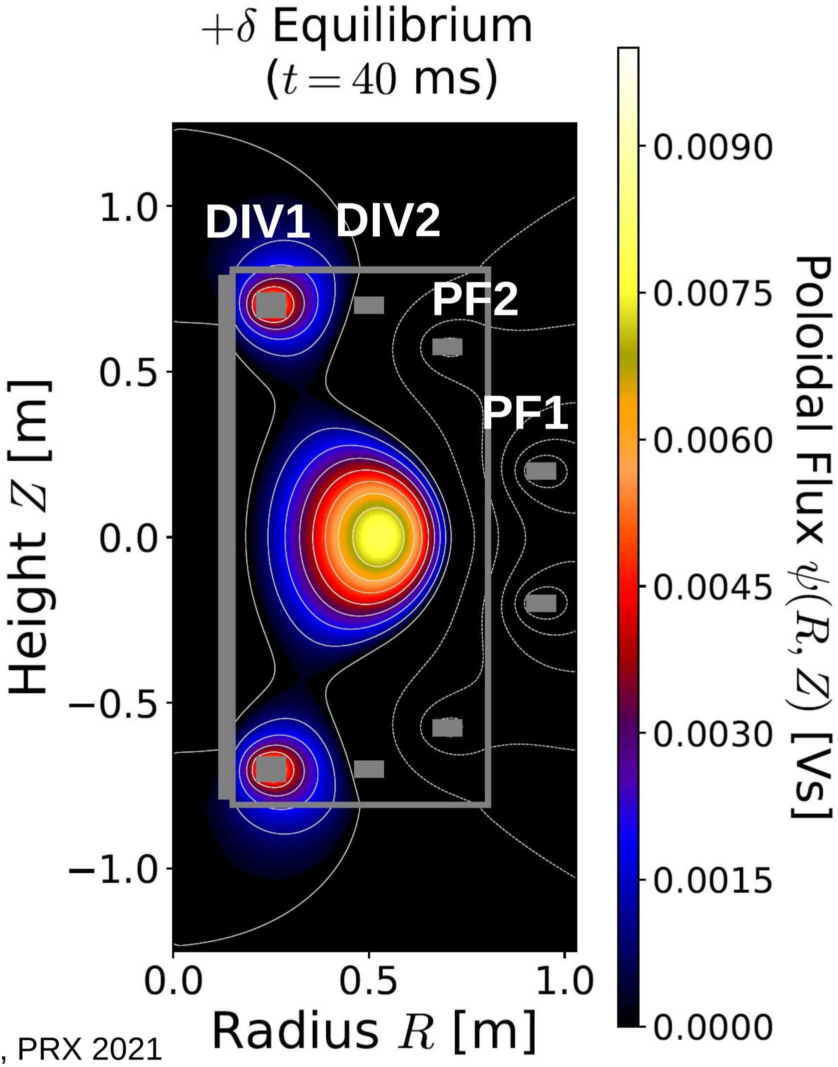
- **Positive triangularity** – min. elongation
  → A = 1.85, κ = 1.63, δ = +0.42



S. J. Doyle *et al*, PRX 2021

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- Plasma equilibria for I_p = 100 kA, B_t = 0.3 T
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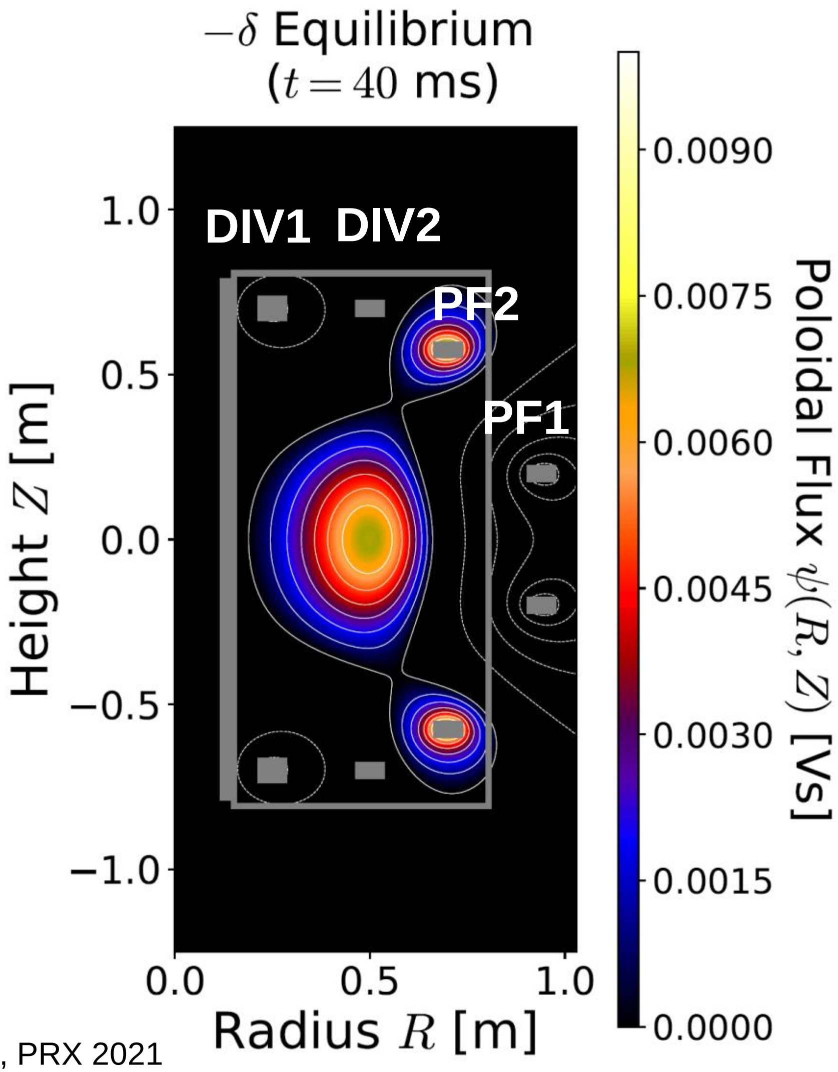
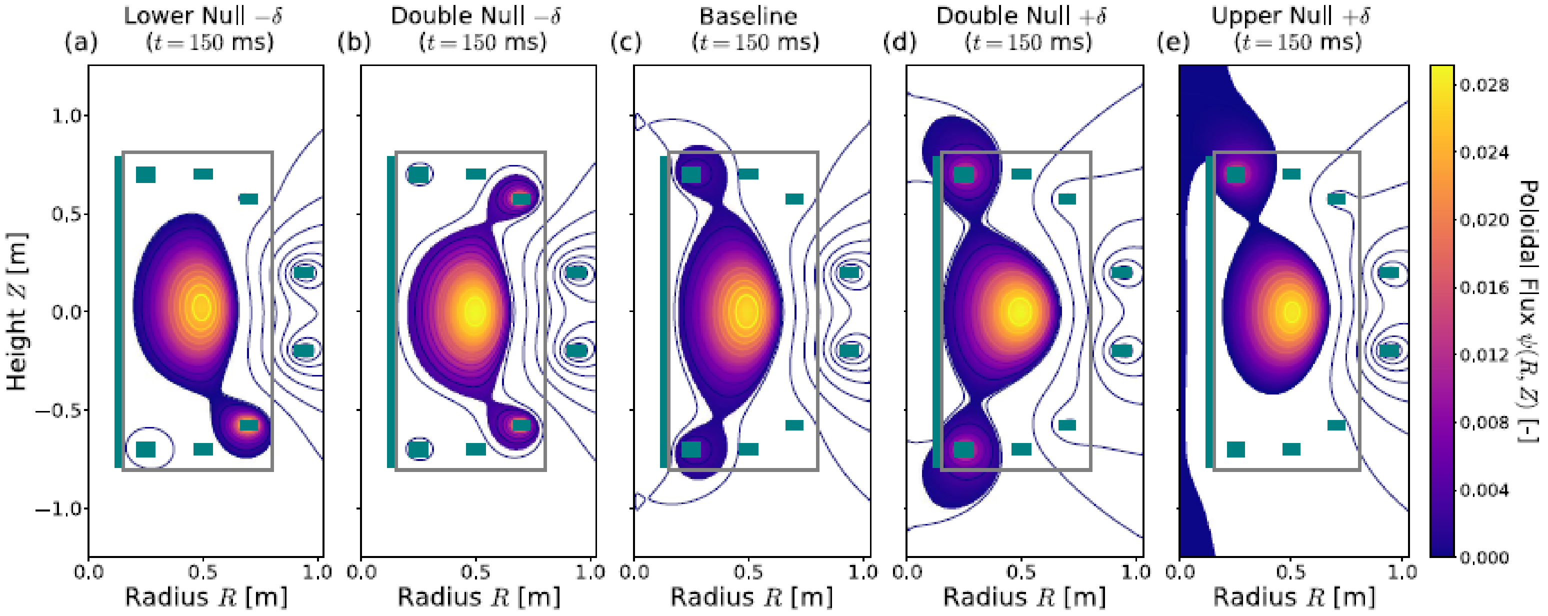
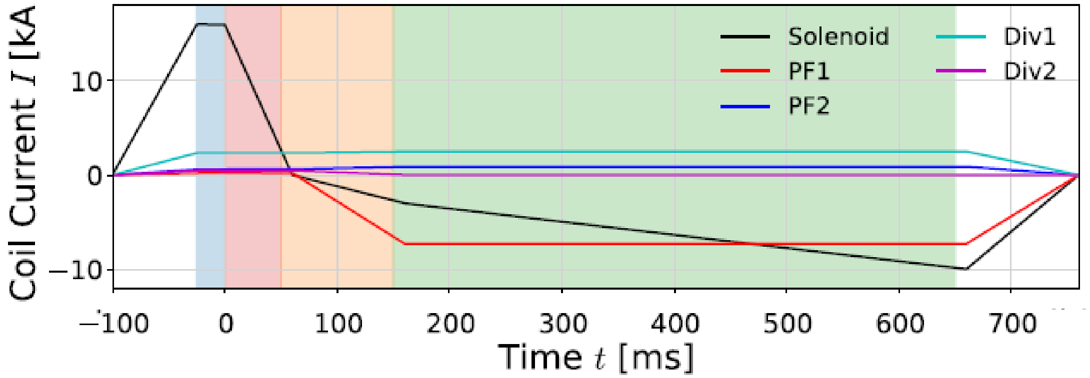
- Positive triangularity – min. elongation
  → A = 1.85, κ = 1.63, δ = +0.42
- **Negative triangularity** – max. triangularity
  → A = 1.88, κ = 1.63, δ = -0.5

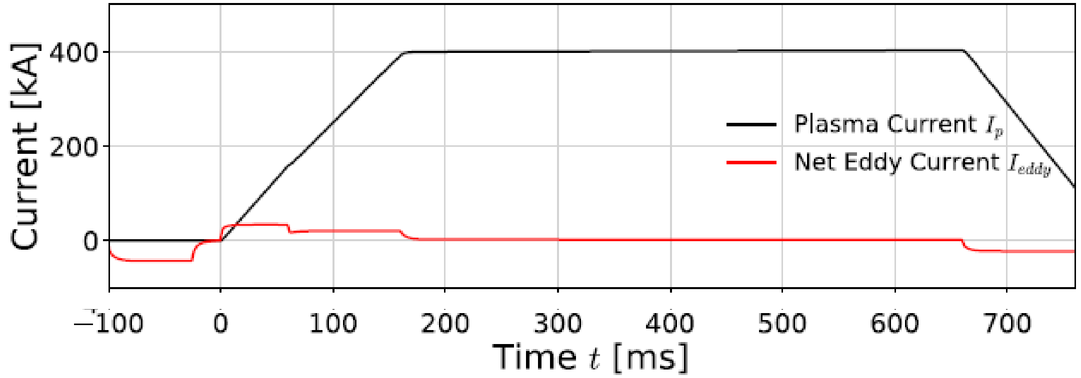


S. J. Doyle *et al*, PRX 2021

Phase 3 Explores Wide Shaping Range at Relatively High I_p / B_t







S. J. Doyle *et al*, PRX 2021

ASTRA Predicts Boost in Confinement From Phase 1/2 to Phase 3

- **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 2**

$$P_{LH\_ITPA08} = 0.0488\, n_{20}^{0.717}\, B_T^{0.803}\, S^{0.941}$$

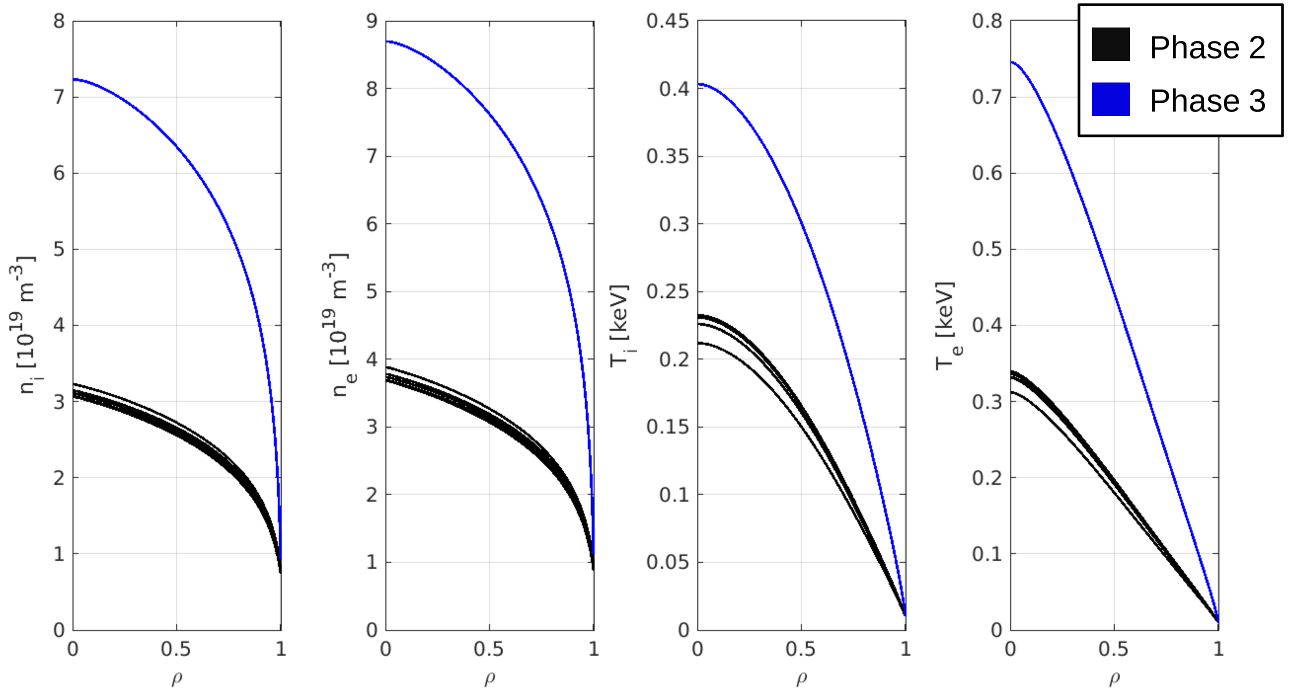
- B_t=0.3T
- n_e= 5x10^{19} m^{-3}

P_{LH}= 60 kW

P_{OH}=166 kW > P_{LH}

f_{bs}=15%

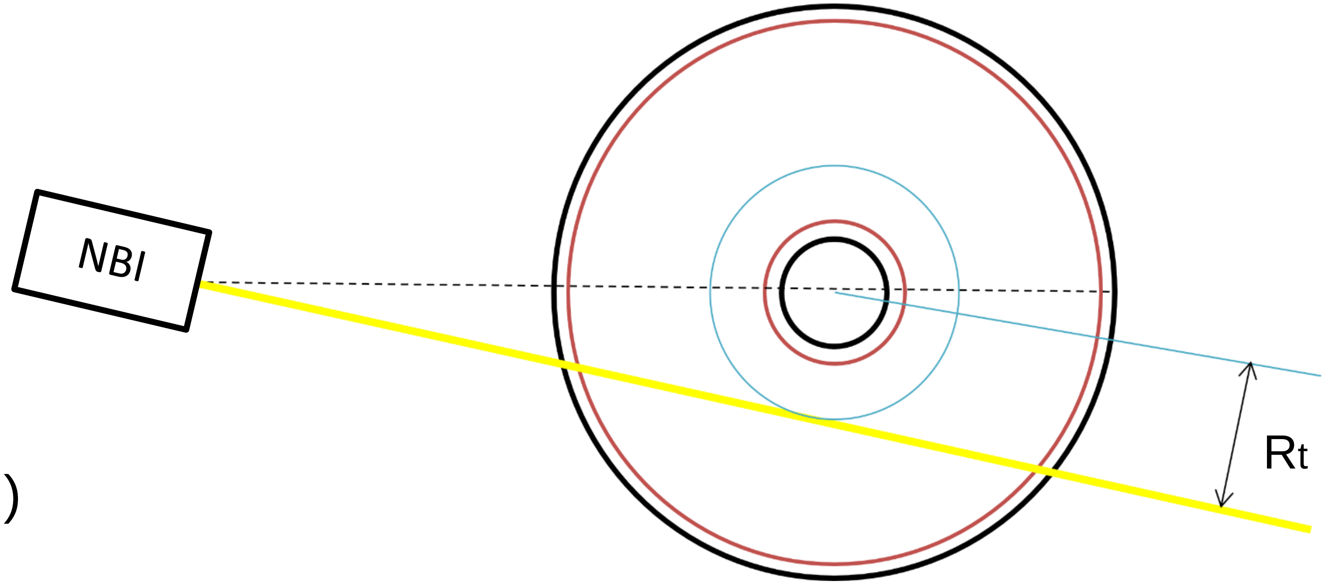
τ_e<10 ms

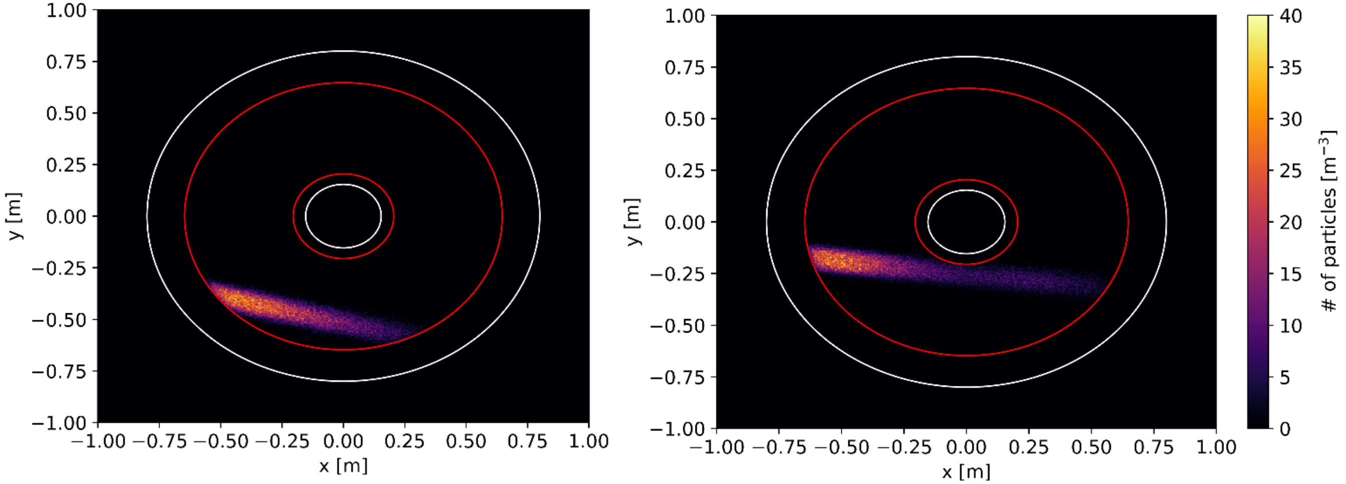


Full Orbit ASCOT Code Used To Optimize NBI Heating

- Monte-Carlo full orbit **ASCOT**[3] code with
  - Realistic profiles from **ASTRA**
  - 2D wall
  - NBI parameters / geometry
    - 1M particles (25 keV, H beam)
    - Beam divergence (aperture of beam)
    - Focal distance of beam

- Scan in beam tangency radius to
  - ➢ Minimize shine-through
  - ➢ Minimize prompt losses
  - ➢ Maximize beam current drive





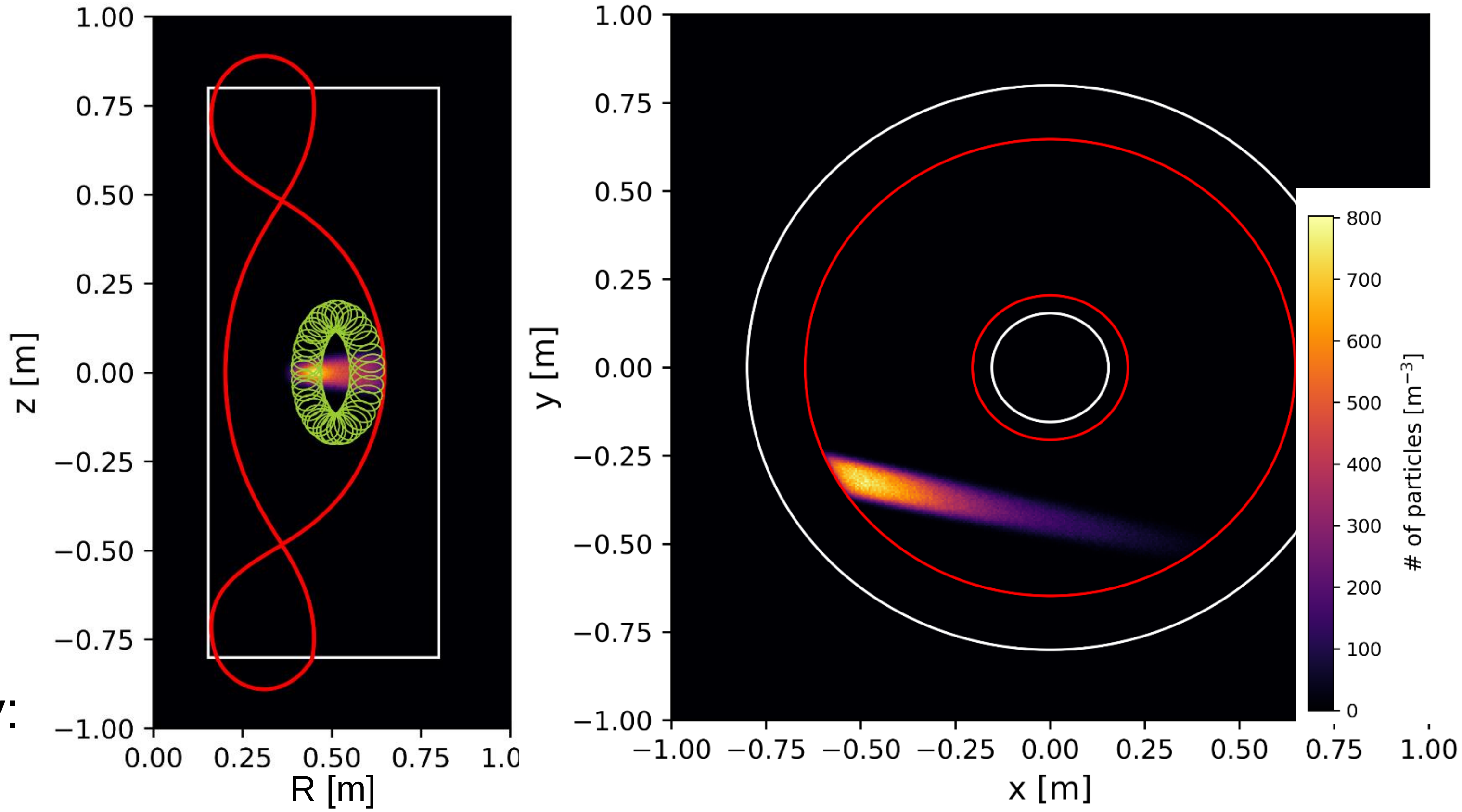
E. Hirvijoki et al, Comp. Phys. Comm. **185** 1310 (2014)

L. Velarde, MSc thesis (2021)

Optimum Configuration for OFF-axis Heating

ID	Rtan [m]	Shine-through	Prompt losses	Current drive
1	0.36	-	4.5%	0.69
2	0.4	4.3%	0.5%	0.66
3	0.44	4.8%	0.0039%	0.64

- Tangency radius of 0.4m → minimizes total losses (<5%)
- Next steps include losses induced by:
    - TF ripple
    - CX reactions
    - MHD fluctuations



Pending confirmation with TRANSP sims for different scenarios

L. Velarde, MSc thesis (2021)

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  - **Coils configuration**
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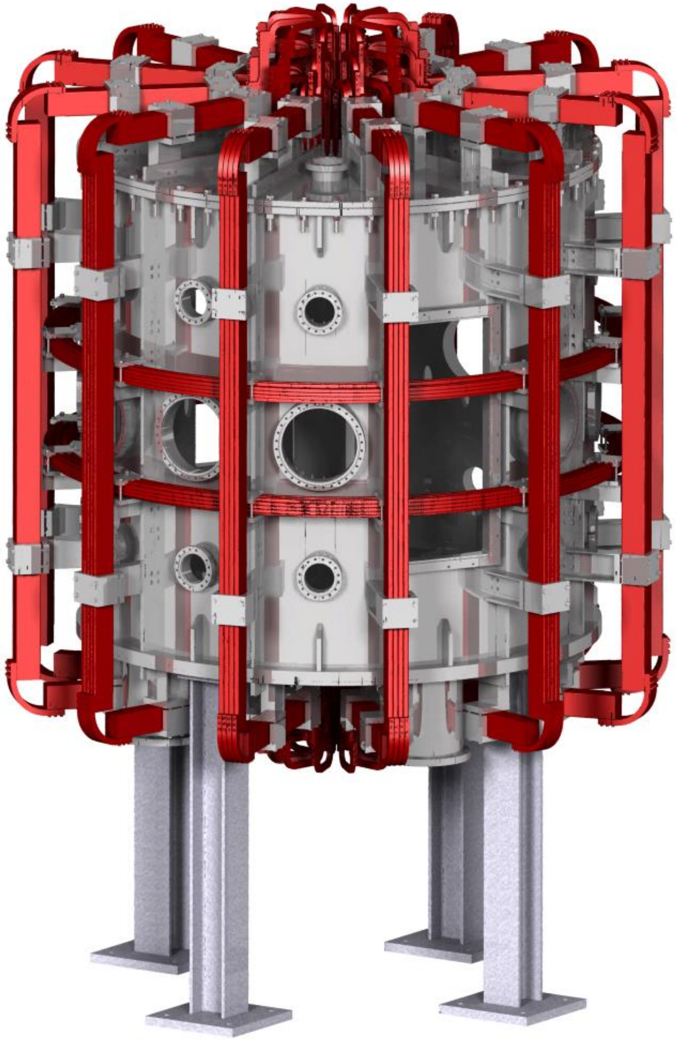
SMART Vacuum Vessel

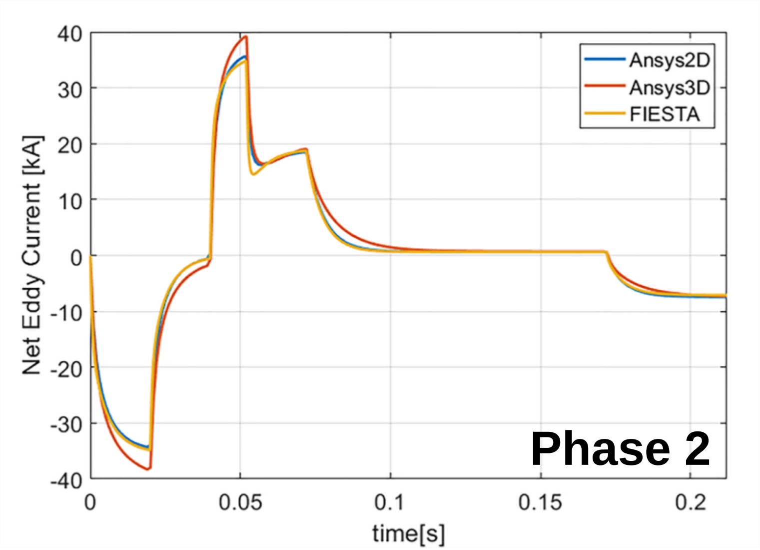


- Overall height of 2,6 m
- Diameter of 2,1 m
- Upper Lid **bolted** and Lower Lid **welded**
- 2 rectangular ports 30×80 cm for NBI and maintenance purposes (customized one)
- 6 lateral ports with CF 300 DN and 24 CF 100 DN
- 6 upper ports & 4 lower ports CF 100 DN
- 4 lower ports CF 250 DN for vacuum
- 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 Design Optimised with Realistic Finite Element Analysis

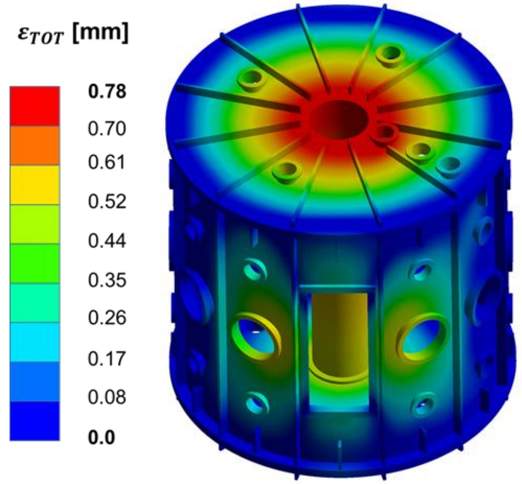
Optimization criteria

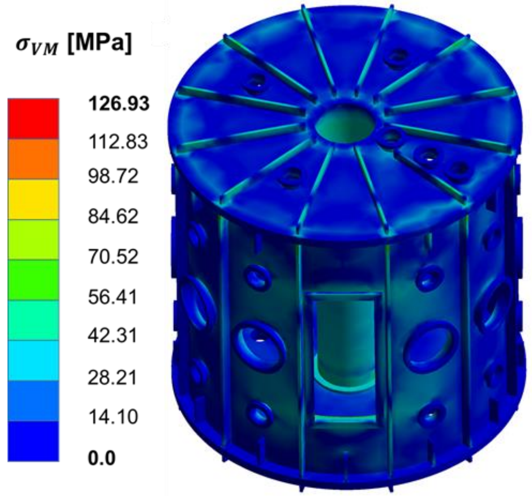
- Minimization of induced eddy current
- Ensure mechanical integrity against transient (JxB forces) and static loads (pressure)
- Ensure Ultra High Vacuum (UHV) during operation and baking
- Covers all three phases without important changes and including off-normal events, e.g. VDE, disruptions…



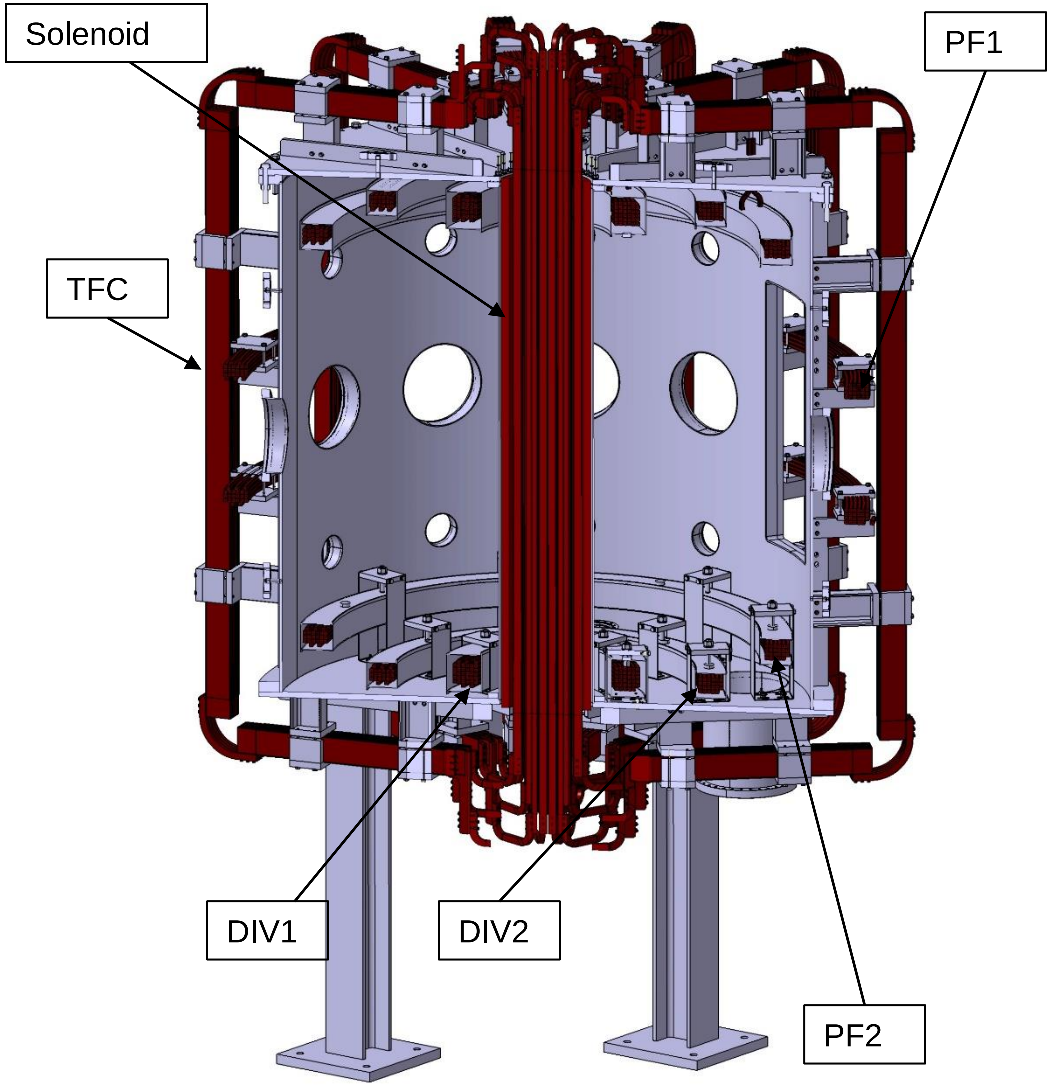
Phase 2

Max loads during VDE in phase 3





SMART Coils



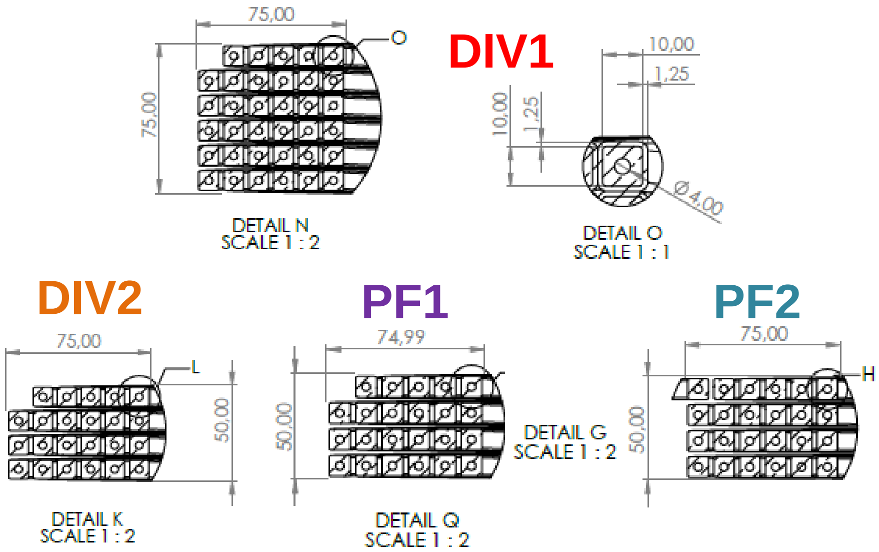
Coil dimensions obtained by iterative process including target plasma parameters and technical restrictions

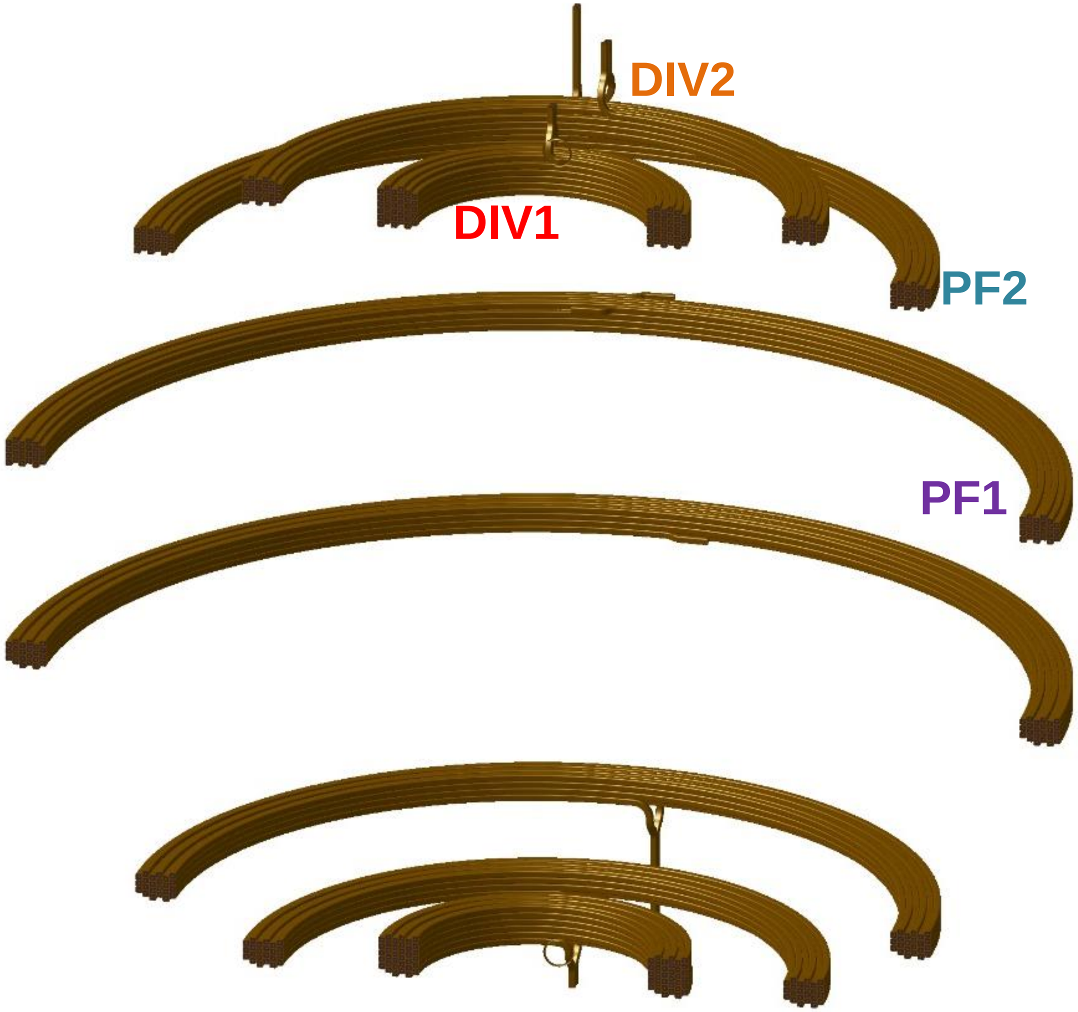
- DIV1, DIV2 and PF2 coils are placed inside for improving physics performance (control) and reducing coils current
- PF1 and TFC are left outside
- Supports of TFC and PF1 are attached to VV ribs
- Inner coils support attached to lids through welded bolts
- Inner coils supports accommodate deformation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

Poloidal Field Coils

8 Poloidal Coils for shaping and plasma control

- All coils with 24 turns except DIV1 with 35 turns
- Coils made of H enamel-coated LUVATA (OFHC) copper with inner hole for cooling during pulse and baking operation @ 150-200 ºC
- Kapton insulation between turns

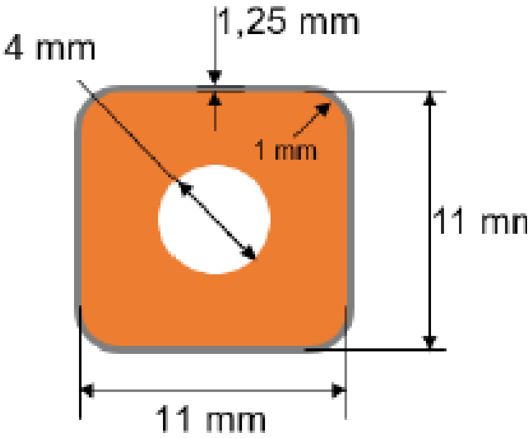


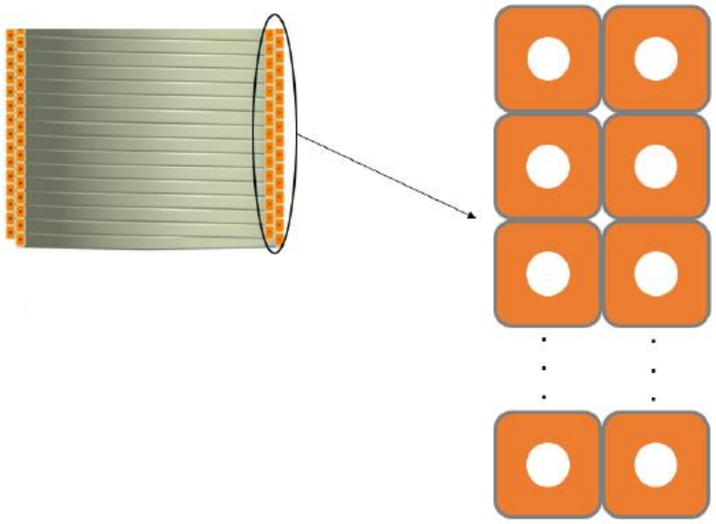


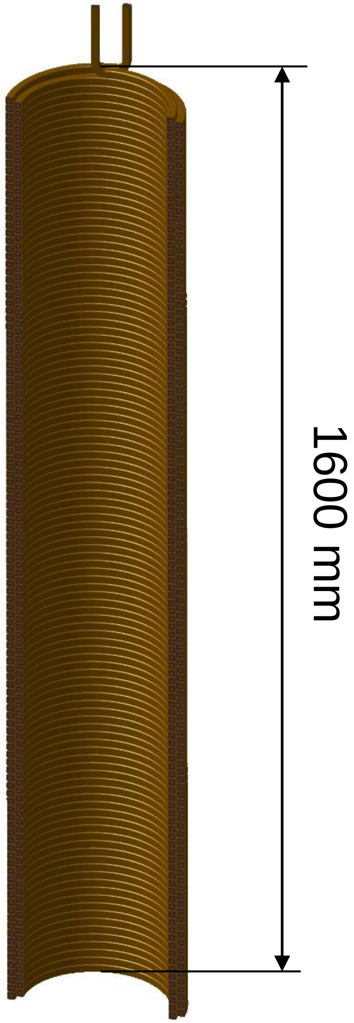
Solenoid

230 turns of H enamel-coated LUVATA (OFHC) copper with Kapton insulation between turns

- Height = 1600 mm
- Diameter = 300 mm
- 11x11 mm conductor section with inner hole for cooling during/after pulse and baking

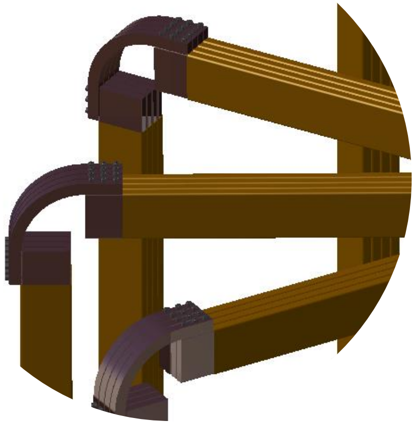




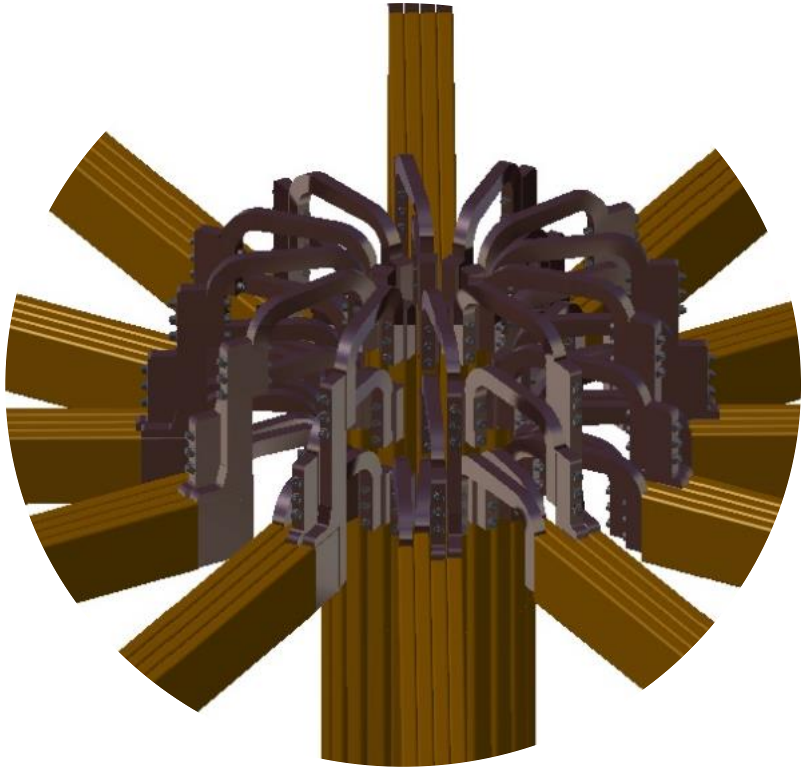


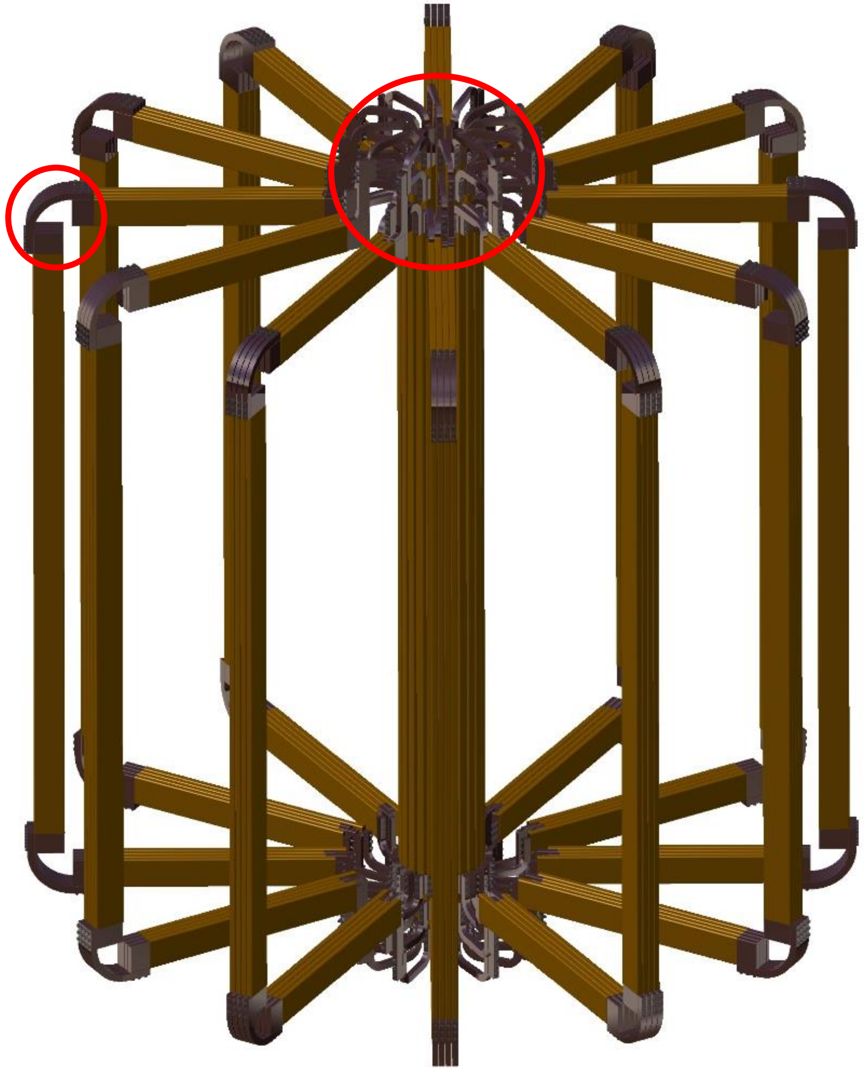
Toroidal Field Coils

- Toroidal Field Coils all made of H enamel-coated OFHC copper
- 12 toroidal field coils for a total of 48 number of turns (4 turns each)



Flexible joints of lamellae cooper

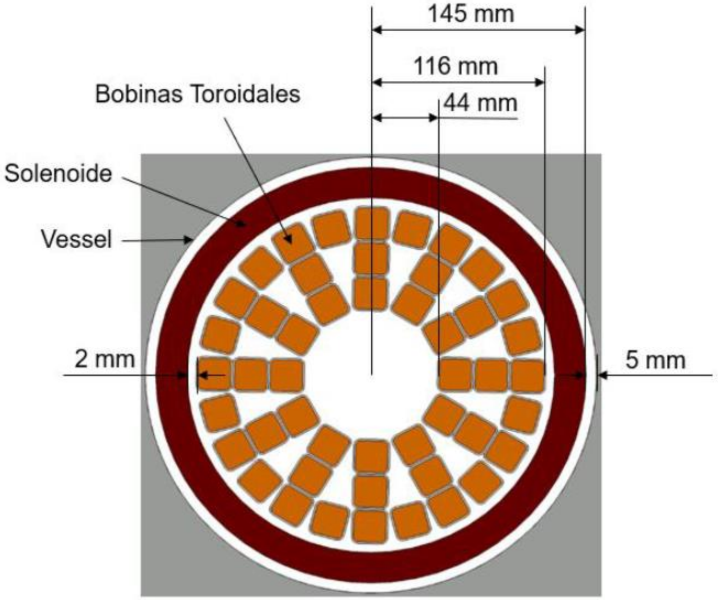


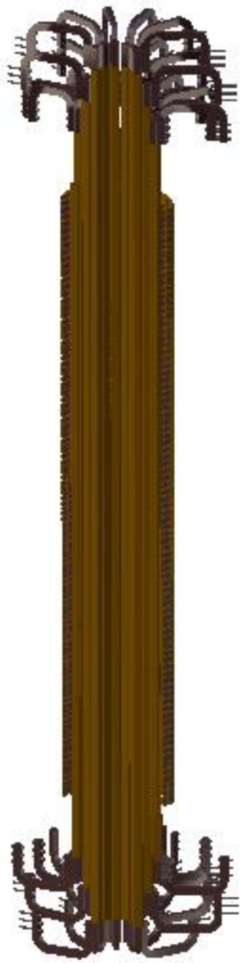


Central Stack (CS) – Design for Phase 2

Challenge: Accommodate TF coils inner limbs and solenoid within 300 mm diameter

- TF coils inner limb placed inside solenoid to reduce demand on power supply
- TF coils do not require cooling in phase 2
- Adjustments may have to be done to achieve phase 3 goals

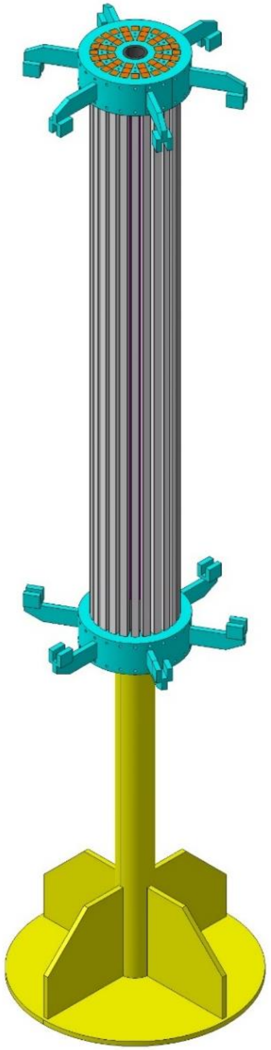




CS Assembly

CS supporting structure is composed by:

- Pedestal
- Two torsional rings (upper/lower) housing TFC inner limbs and withstand torsional loads
- A central rod helps reacting centering force
- Set of bars helps maintaining position of the rod during the assembly and transfer loads to central rod
- Six arms connects the two rings to the ribs of the vessel
- Lower ring withstands solenoid weight

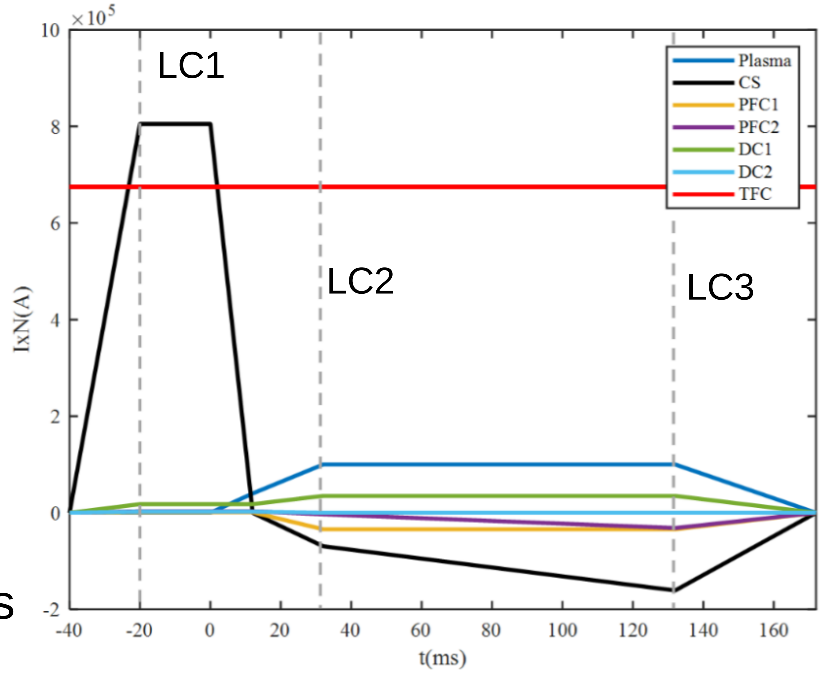


Finite Elements Analysis Predicts Negligible Forces in Coils During Phase 2

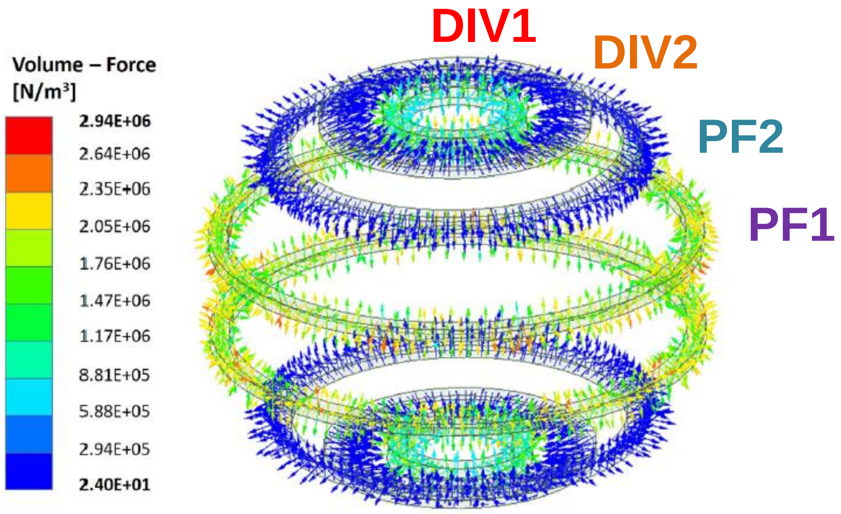
- **Loading Cases (LC)** used to estimate forces on each coils assuming all other fields

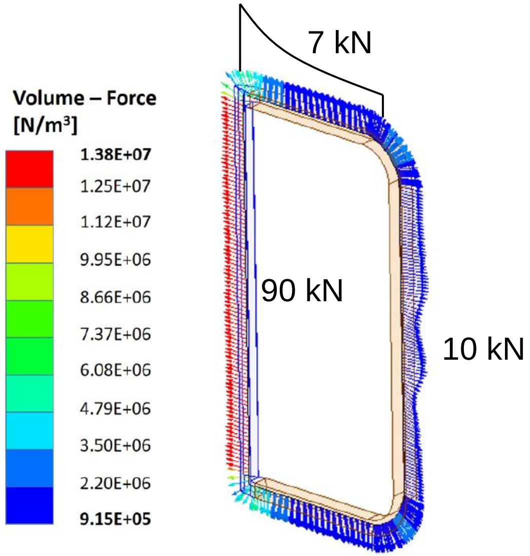
- **PFCs:**
  - **Vertical loads** due to attraction / repulsion
  - **Hoop load** generate negligible stresses in coils

- **TFCs:**
  - Constant in-plane loads < 90 kN
  - Out-of-plane loads in external legs are negligible



Vertical load	Force$_1$ [N]	Force$_2$ [N]	Force$_3$ [N]
PF1	2	**2468**	1933
PF2	39	**201**	129
DIV1	**894**	313.6	296
DIV2	**192**	0	0

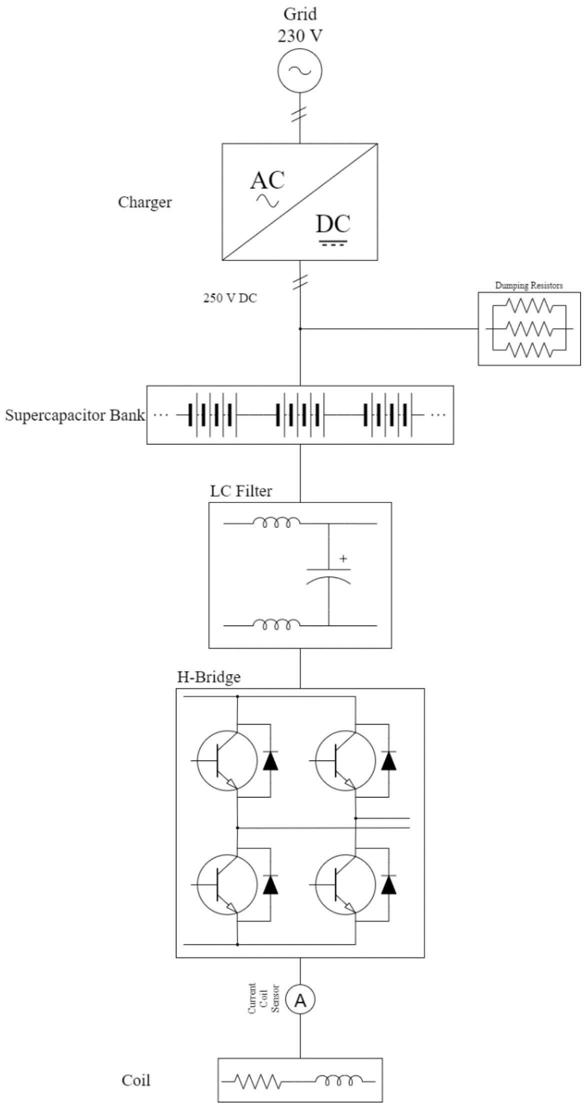




Power Supply

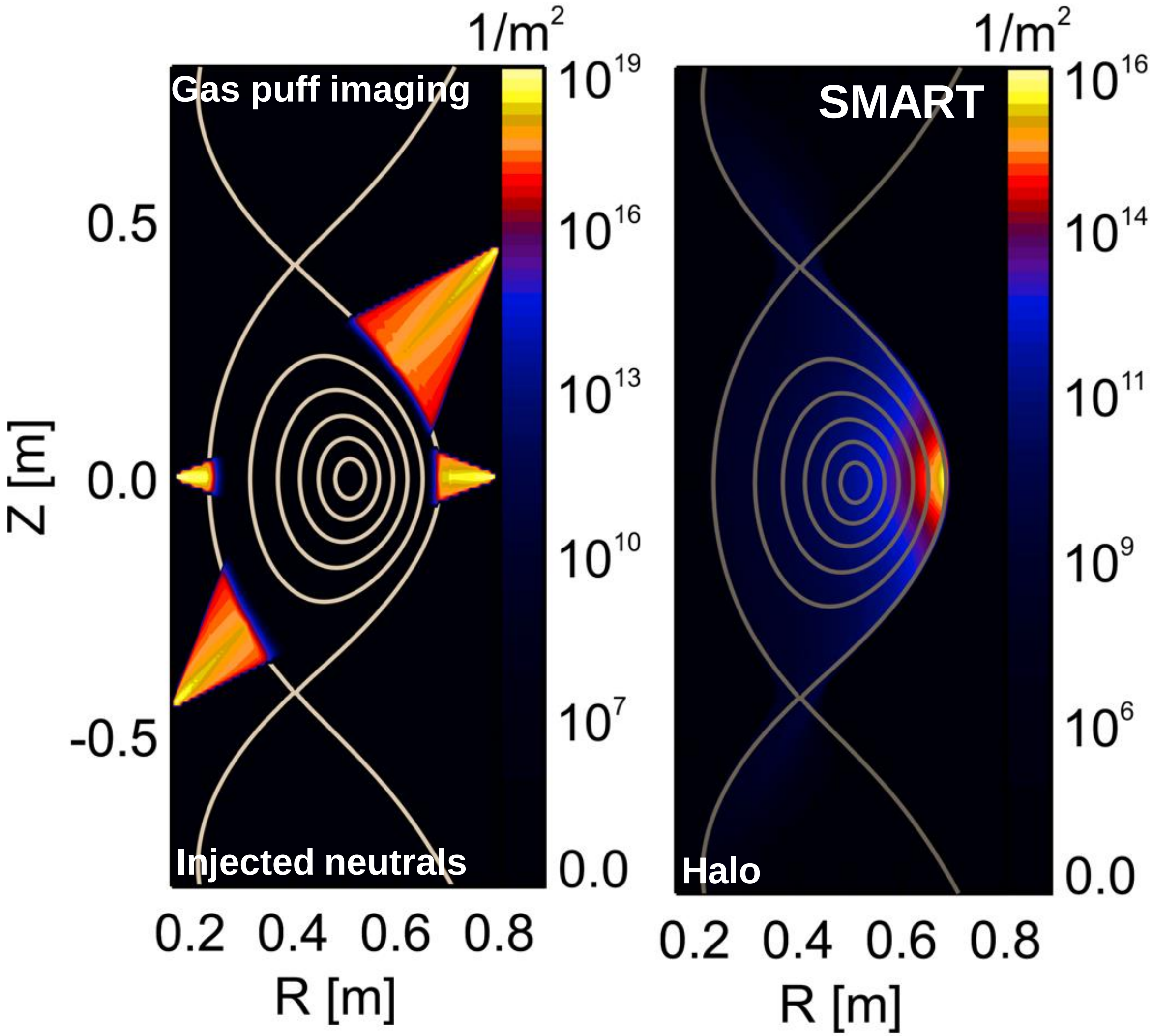
Modular power supply based on suparcaps and IGBTs for fast switching (H-bridge as converter)

- Power supply allows arbitrary current waveform between the specified limits
- Current waveforms are totally programmable before discharge (FPGA)
- Positive and negative currents are possible
- Coil current ripple < 2% of maximum current
- Closed loop control in real time



Diagnostics

Diagnostic Method		Remark
Magnetic Diagnostics	**Rogowski Coil**	3 out-vessel 2 in-vessel
	Pick-up Coil	48 pick-up coils
	Flux Loop	10 loops
Optical Diagnostics	**Gas puffing CXRS**	Profiles of n_i and T_i
	Interferometer	Line integrated n_e
	Fast camera (Phantom v2512)	< 1MHz
	Soft X-ray array	AXUV16ELG Photodiode
	Thomson Scattering	Nd:YAG Laser 1.2J/pulse 10ns
Particles	**Langmuir probes**	Midplane and strike points



Outline

- SMART’s missions
- Magnetic equilibrium and prospective discharge scenario
- Device
    - Vacuum Vessel
    - Coils configuration
    - Power supply
    - Diagnostics
- **Timeline**
- Summary

Project Timeline

2017
2018

Idea

- Preliminary simulations
- Possible companies contacted

Secured funding through grant applications

2019
January

- **Final design**
- Realistic prospective equilibria
- Risk analysis
- Contracts with companies placed
- Monitoring companies and final modifications

2021
2022

Tokamak assembly

- @ companies
- In torus hall

2022
April

Commissioning

2022
July

Operation Starts

- Get familiar with new machine

2023
July

Phase 1 goals achieved!

2024
-

Upgrade to phase 2

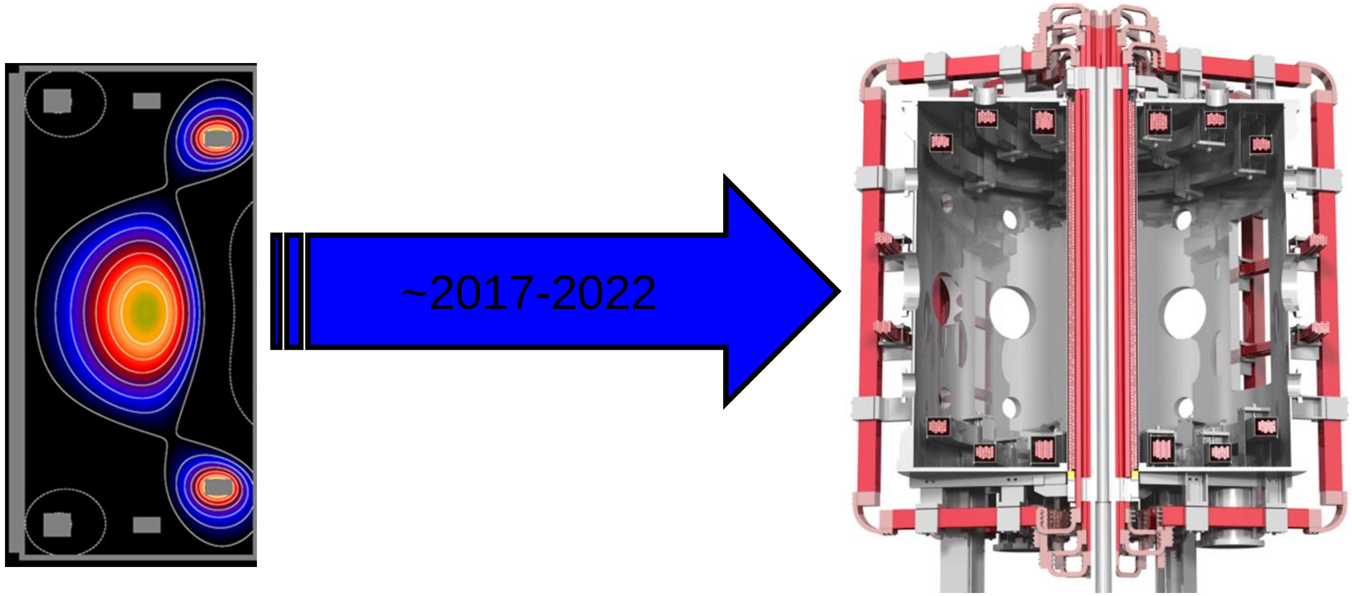
- NBI +
- Power supply

2025
-

Phase 2 goals achieved!

2026
-

Upgrade to phase 3



Status of Tokamak Buildings

Torus and power supply halls

Tokamaks Components Are Being Assembled

Outline

- SMART’s missions
- Magnetic equilibrium and prospective discharge scenario
- Device
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- **Summary**

Summary

- SMART – a **new and exciting, compact spherical tokamak** will be coming online soon

  - 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!

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