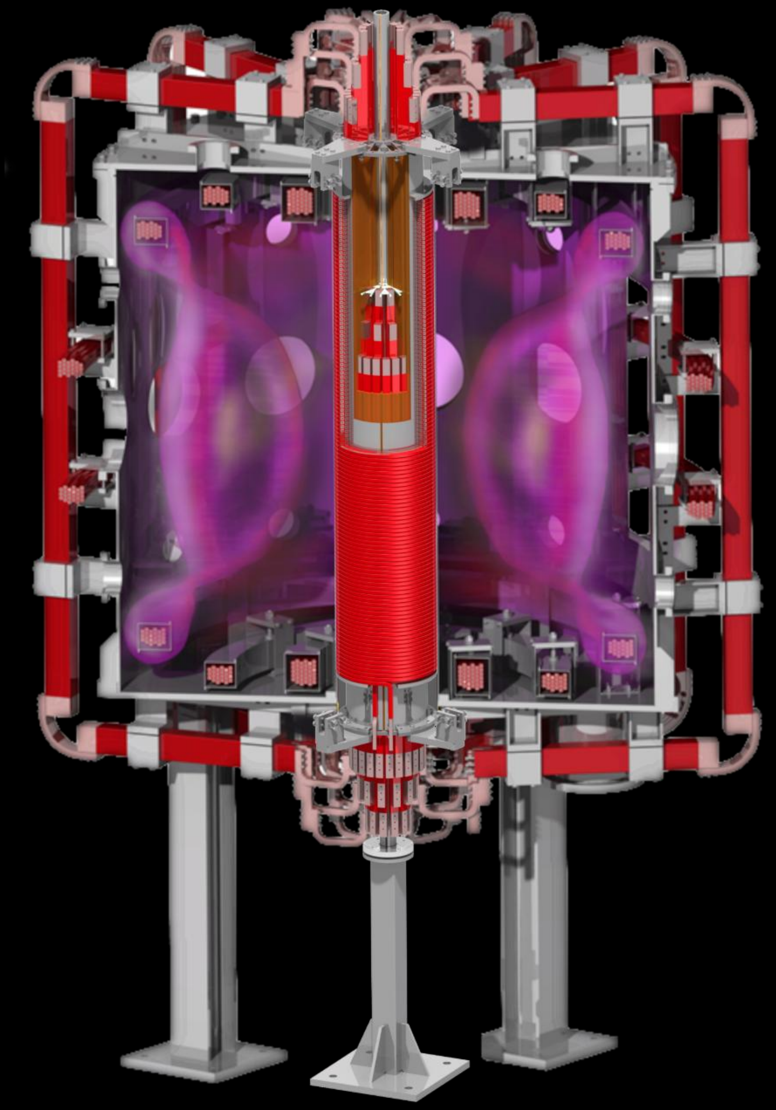


Enabling Research Project

High confinement scenarios at positive and negative triangularity in the SMART spherical tokamak

Monitoring of 2024 Activities

E. Viezzer, J. Galdon Quiroga
and PSFT, IPP-CAS, NCSRD, CSIC contributors

February 5th 2025

Outline

1. Overview of the project
2. Progress in 2024 and plans for 2025
3. Conclusions

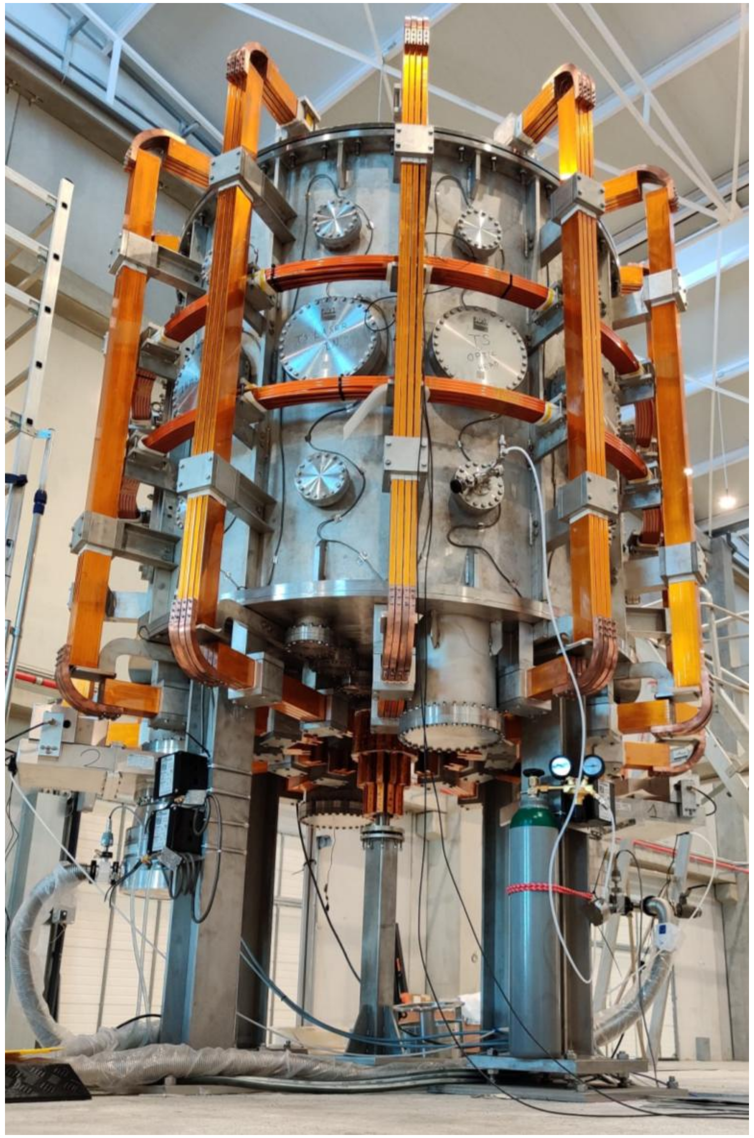
Outline

1. **Overview of the project**
2. Progress in 2024 and plans for 2025
3. Conclusions

SMall Aspect Ratio Tokamak (SMART)

- **SMART: new ST** [1,2,3] currently being commissioned at the University of Seville as **attractive**, **fast** and **economic** path to **compact fusion reactors**

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



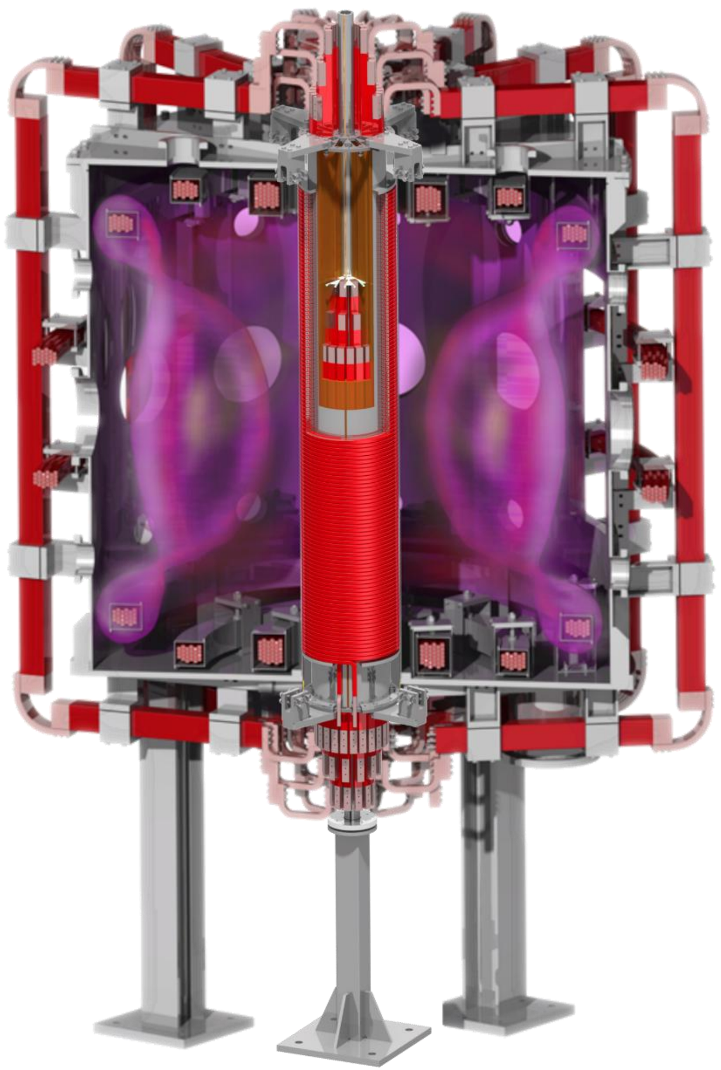
[1] A. Mancini et al., FED 2021
[2] S. Doyle et al., FED 2021
[3] M. Agredano et al. FED 2021

Main parameters of SMART

- Vacuum vessel dimensions: 1.6 m (diameter) x 1.6 m (height)
- Solenoid wrapped around 12 toroidal field coils
- 8 poloidal field coils
- Major radius R ~ 0.45 m, minor radius a ~ 0.25 m
- A = [1.4 – 3.0], $\kappa < 3$, $\delta = [-0.6, 0.6]$
- **3 operational phases foreseen**

Parameters	Phase 1	Phase 2	Phase 3
I_p [kA]	100	200-500	>500
B_t [T]	0.1	0.4	1.0
τ_{pulse} [ms]	150	500	>1000
P_{ECRH} [kW]	6	6	200
P_{NBI} [MW]	-	≤1	1

[D.Cruz-Zabala et al., NF 2024]

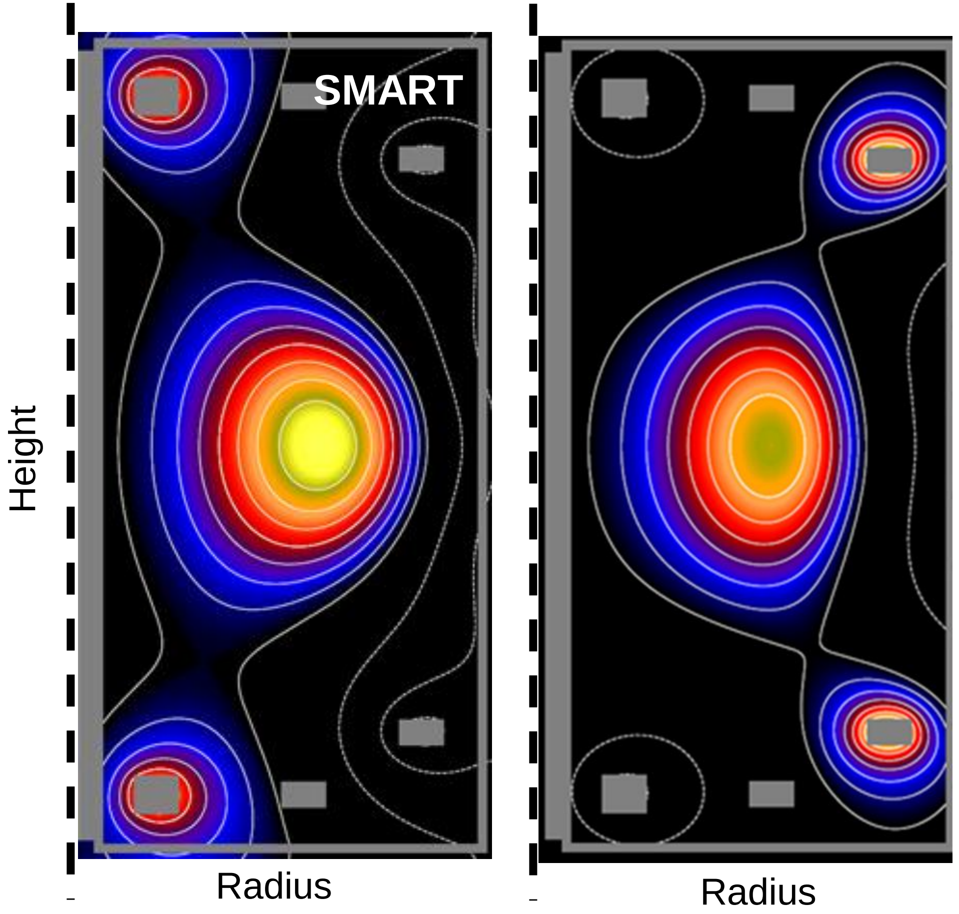


Initial diagnostic coverage

Diagnostic Method		Measurement
Magnetic Diagnostics	**Rogowski Coil**	I_{plasma}, I_{coils}
	Mirnov Coil	B, δB
	Flux Loop	ψ
	Diamagnetic loop	δΦ
Optical Diagnostics	**Interferometer** (COMPASS)	Line integrated n_e
	Thomson Scattering (PPPL)	$n_e(r)$, $T_e(r)$
	Passive radiation (PPPL)	Radiated power, low-f instabilities, impurity monitor
	Gas puff based CXRS	T_i (r), $v_i(r)$, $n_i(r)$
	Fast camera (Phantom v2512)	Discharge monitor

High level objectives of ENR project

- Equip SMART with NBI system to reach fusion relevant temperatures and achieve high confinement modes
- Implement interferometry and poloidal array of gas-puff CXRS to characterize the new scenario in negative triangularity
- Exploit new capabilities with dedicated experiments and simulations



Project organization

No	Title	Description	Expected date
WP PGP-CXRS			
Key Personnel: E. Viezzer (US), D. J. Cruz-Zabala (US), J. Ayllon-Guerola (US), Postdoc 1 (US), R. Lopez Cansino (US), L. Sanchis (US), G. Pellegrini (CSIC)			
1	CX_M1	Design of GP-CXRS system (geometry, optics, detector)	2024. Jun.
2	CX_M2	Construction of GP-CXRS system	2024. Oct.
3	CX_M3	Installation in SMART	2024. Dec.
4	CX_M4	Commissioning of GP-CXRS at SMART	2025. Jun.
5	CX_M5	First measurements of PGP-CXRS in NT and PT plasmas	2026. Dec.
WP Interferometry			
Key Personnel: M.Varavin (IPP-CAS), V.Ivanov (IPP-CAS), D.Kekrt(IPP-CAS); J.Galdon-Quiroga (US), J.Salas-Suarez (US), J.Ayllon-Guerola (US), Technician #1 (US),), G. Pellegrini (CSIC)			
1	IF_M1	Development of simulation tools and design	2024. Apr.
2	IF_M2	Laboratory tests at SMART	2024. July
3	IF_M3	Installation in SMART	2024. Dec.
4	IF_M4	Commissioning of IF at SMART	2025. Jun.
5	IF_M5	RT measurements and integration in DCS	2025. Dec.
6	IF_M6	Feasibility study of SDR technology	2025. Dec.
WP NBI			
Key Personnel: M.Garcia-Munoz (US), Postdoc #2 (US), Technician #1 (US), J. Ayllon (US), J. Gonzalez Martin (US); K.Bogar(IPP), S.Fukova (IPP), I.Mysiura (IPP), J.Varju (IPP).			
1	NBI_M1	Transport of components to SMART site.	2024. April
2	NBI_M2	Unpacking and assembling of NBI system	2024. Jun.
3	NBI_M3	Testing of subsystems and troubleshooting of NBI	2025. Nov.
4	NBI_M4	Conditioning of NBI to reach operation parameters	2025. May
5	NBI_M5	Training of US operators	2025. December
WP EXP			
Key Personnel: E.Viezzer (US), J.Galdon-Quiroga (US), M.Garcia-Munoz (US), D.Cruz-Zabala (US), Postdoc #1 (US), Postdoc #2 (US), J.Salas-Suarez (US), R. Lopez Cansino (US), J. Gonzalez (US), G. Pellegrini (CSIC)			
1	EXP_M1	Development of NT and PT ohmic plasmas in SMART	2025. Jun.
2	EXP_M2	Verification of plasma stability	2025. Jul.
3	EXP_M3	Development of NBI heated plasmas	2025. Dec.
4	EXP_M3	Comparison of NBI vs ohmically heated plasmas	2025. Dec.

WP MOD			
Key Personnel: L.Sanchis-Sanchez (US), M.Toscano (US), Postdoc #2 (US), Y.Kominis (UA), G.Anastassiou (US), P.Zestanakis (UA), D. Cruz-Zabala (US), M. Garcia Muñoz (US), J. Galdon (US), E. Viezzer (US)			
1	MOD_M1	Extension of resonance reduced model for low aspect ratio	2024. Dec.
2	MOD_M2	Implementation of resonance model in ASCOT	2024. Dec.
3	MOD_M3	Implementation of SMART NBI in TRANSP	2024. Jun.
4	MOD_M4	Predictive TRANSP modelling of PT and NT plasmas in SMART	2024. Dec.
5	MOD_M5	Benchmark resonance model with ASCOT	2025. Jul.
6	MOD_M6	Predictive simulations of resonances in support of NBI ops.	2025. Sept.
7	MOD_M7	Predictive TRANSP modelling of NBI heated plasmas in SMART	2025. Oct.
8	MOD_M8	Intrepretive transport analysis and comparison of NT vs PT	2025. Dec.

- Project divided in 3 Research lines and 5 Work Packages (WPs)
- Research Line 1: Instrumentation
  - WP1: PGP-CXRS
  - WP2: Interferometry
  - WP3: NBI
- Research Line 2: Experiments
  - WP4: EXP
- Research line 3: Modelling
  - WP5: MOD

Outline

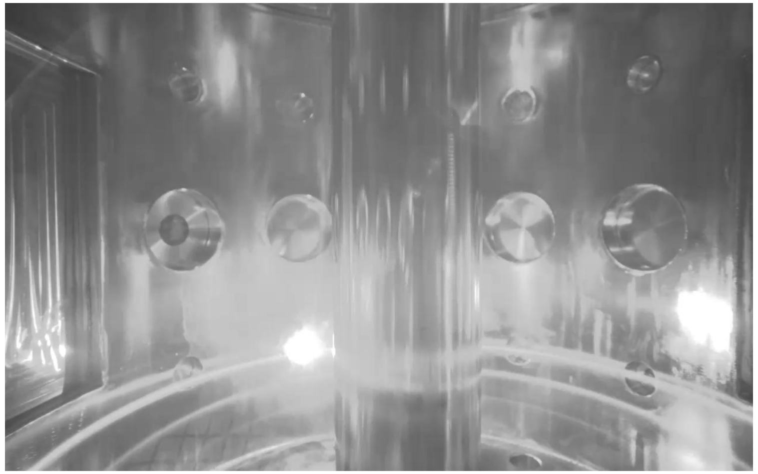
1. Overview of the project

2. **Progress in 2024 and plans for 2025**

3. Conclusions

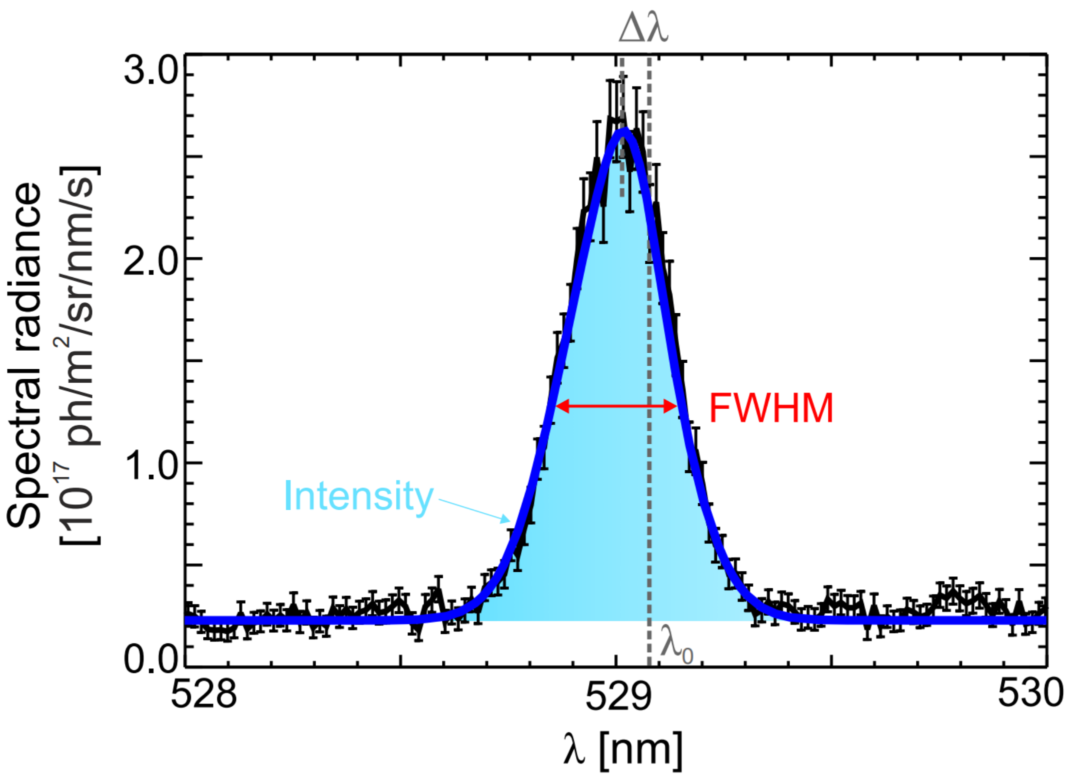
Current status of SMART

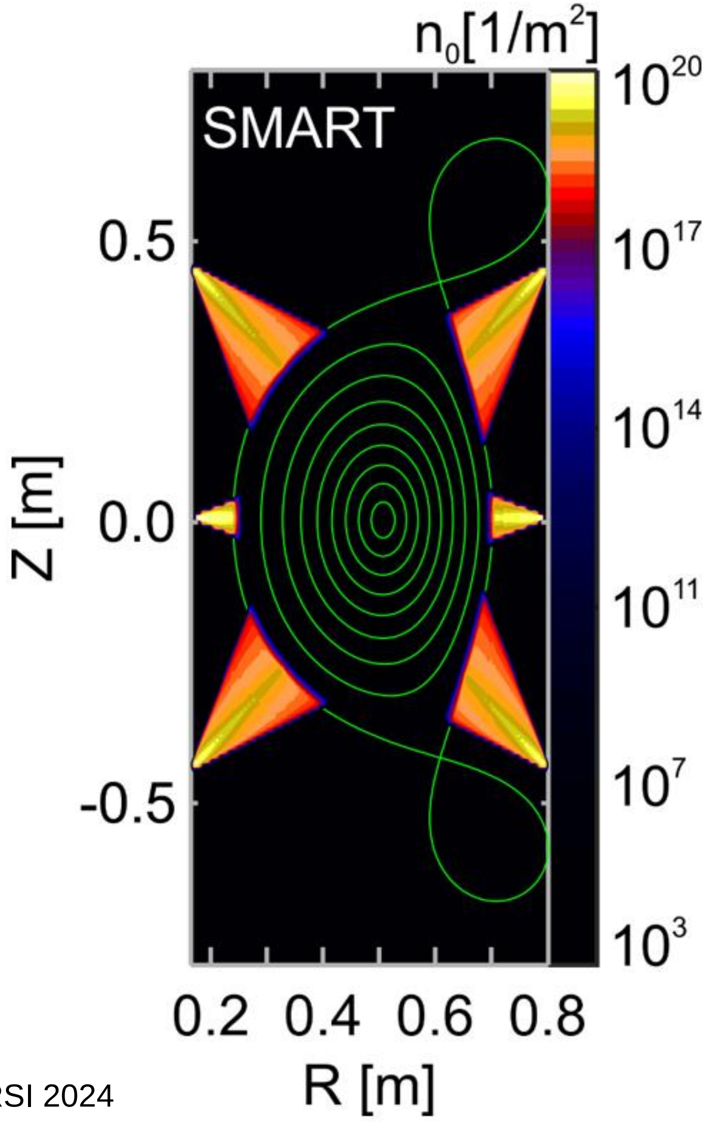
- **Phase I: Commissioning**
  - Vacuum system
  - TF, PF and DIV coils
  - Solenoid
  - Baking system (ongoing)
  - Diagnostics (ongoing): magnetics, fast-camera, CXRS, …
- **First solenoid induced plasma achieved!** (Dec. 2024)



WP1: PGP - CXRS

- SMART PGP-CXRS diagnostic: array of fast piezo valves that inject neutral gas to study impurity asymmetries and measure their temperature, density and rotation velocity



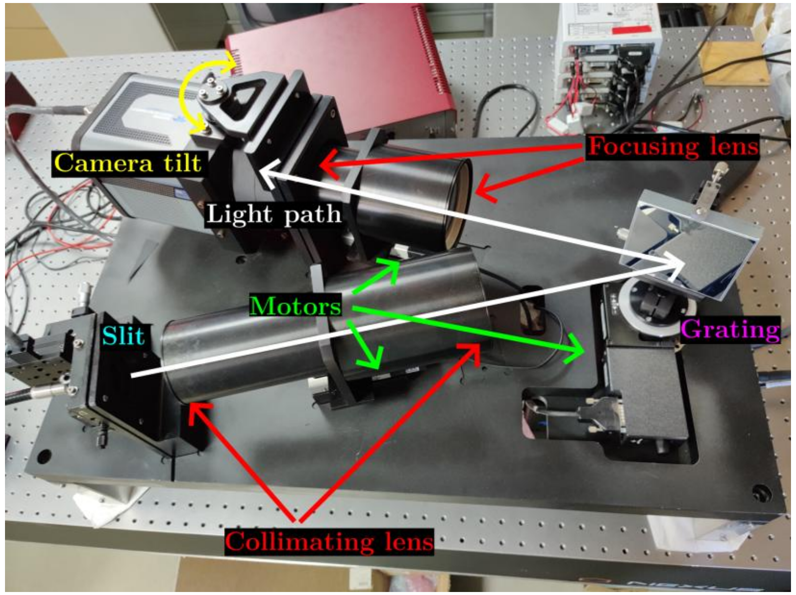


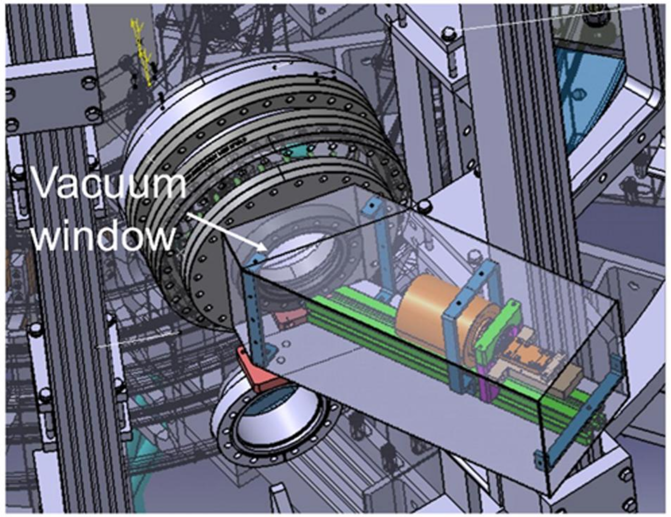
D. Cruz Zabala et al, RSI 2024

WP1: PGP - CXRS

- SMART PGP-CXRS diagnostic: array of fast piezo valves that inject neutral gas to study impurity asymmetries and measure their temperature, density and rotation velocity

- Progress in 2024:
  - Manufacturing completed
  - Lab tests & final calibration completed
  - Design and signal estimations published: D.J.Cruz-Zabala et al, RSI 2024



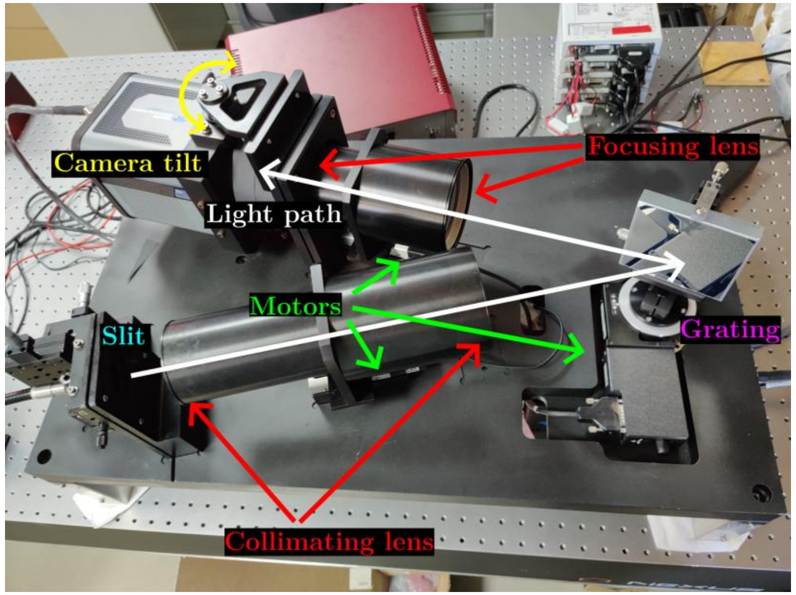


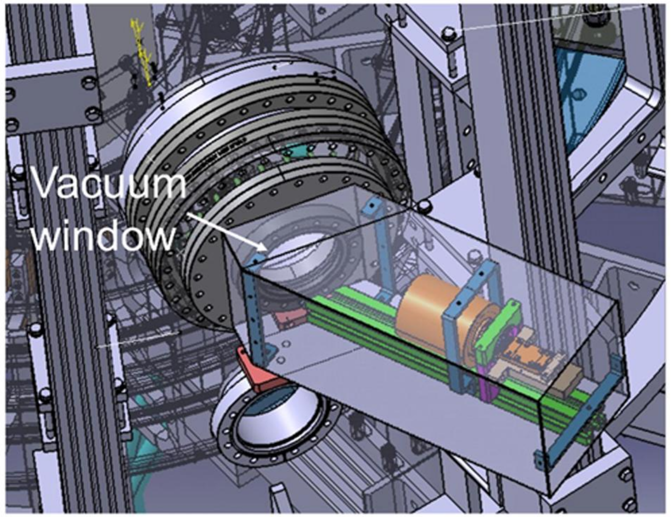
WP1: PGP - CXRS

- SMART PGP-CXRS diagnostic: array of fast piezo valves that inject neutral gas to study impurity asymmetries and measure their temperature, density and rotation velocity

- Progress in 2024:
  - Manufacturing completed
  - Lab tests & final calibration completed
  - Design and signal estimations published: D.J.Cruz-Zabala et al, RSI 2024

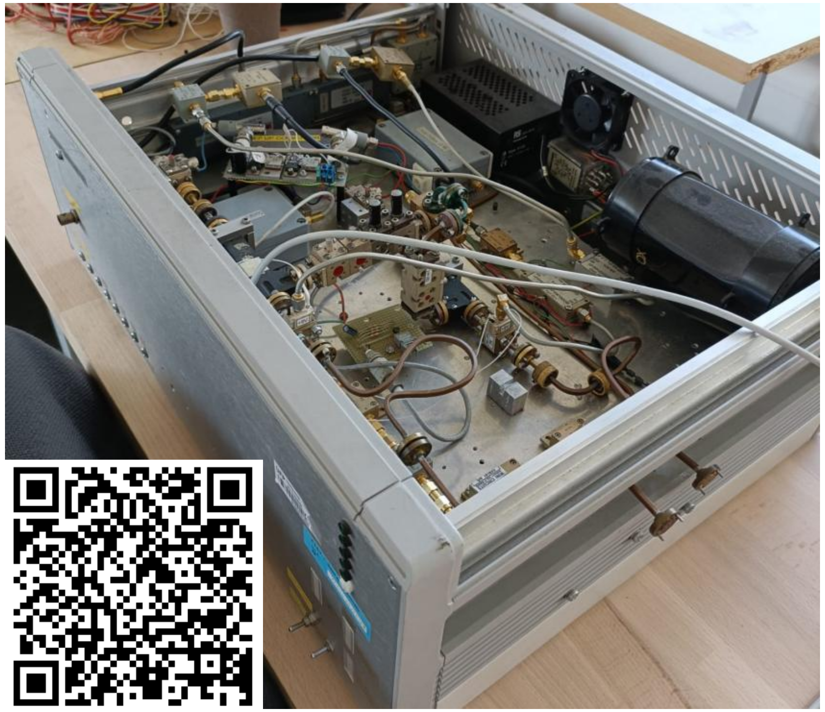
- Next steps:
  - Installation in SMART in next vessel opening





WP2: Interferometer

- SMART interferometer
  - 2mm microwave interferometer from COMPASS
  - Vertical → Radial chord
  - Beam focussing system

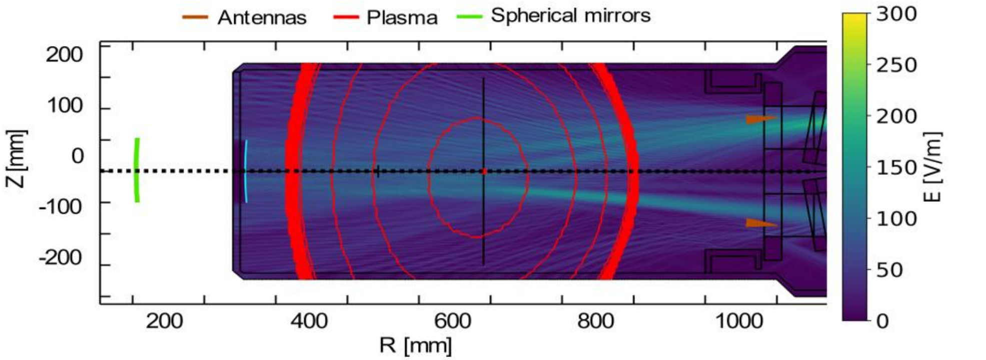


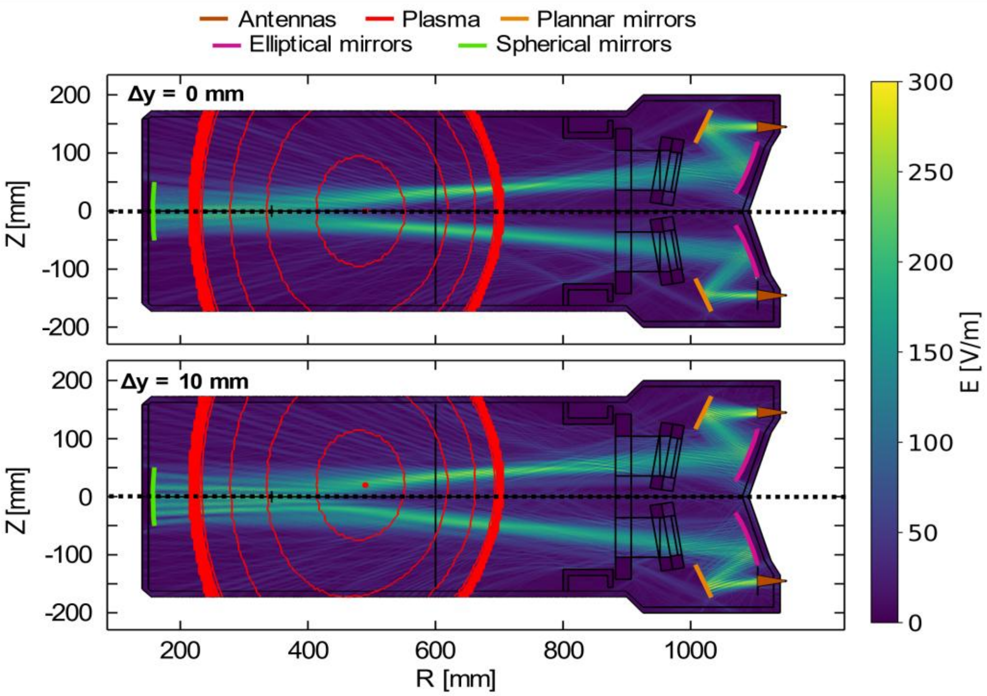
WP2: Interferometer

- SMART interferometer
  - 2mm microwave interferometer from COMPASS
  - Vertical → Radial chord
  - Beam focussing system

- Progress in 2024:
  - Lab tests at IPP-CAS competed
  - Beam focussing system design completed. Procurement on-going
  - Loan agreement with IPP-CAS on-going

- Next steps
  - Installation in SMART.
  - Commissioning of the focussing system



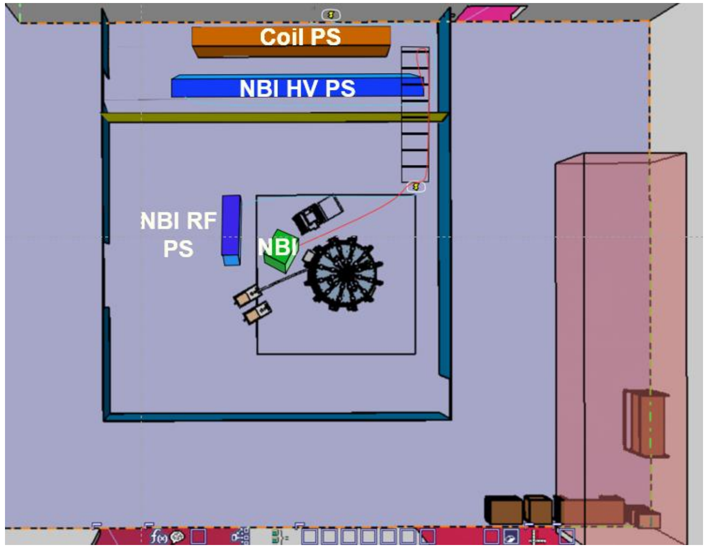


WP3: NBI

- SMART NBI:
  - On loan from IPP-CAS
  - H & He operation. Power ~ 300 kW.
    Injection energy ~ 25-30 keV

- Progress in 2024:
  - Continuous iterations between PSFT & IPP-CAS for implementation at SMART (infrastructure, CAD, transfer, radiation safety, …)
  - SMART team visit to IPP-CAS.
    - NBI lab tests. SMART team instructed

- Next steps:
  - Transfer to SMART expected in March 2025
  - IPP-CAS team visit for NBI commissioning



WP4: EXP

- Scope: experiments for
  - First NT vs PT plasmas
  - Verification of plasma stability
  - First NBI heated plasmas

- **No activities were foreseen for 2024**

- First physics operations expected in 2025
  - Development of PT and NT shaped scenarios
  - Characterize PT and NT Ohmic plasmas
  - Characterize PT and NT NBI heated plasmas

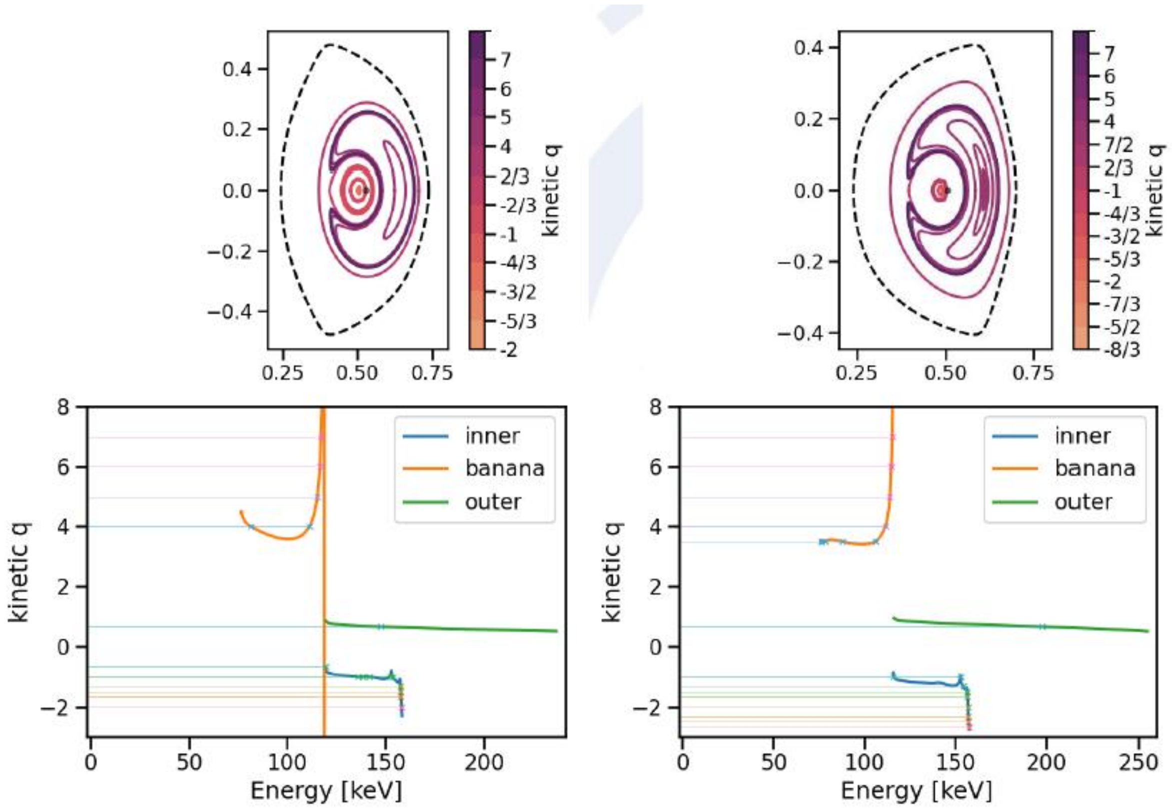
WP5: Modelling

- Scope:
  - Fast-ion resonance index model (RIM) in support of NBI operations and fast-ion physics
  - Predictive TRANSP modelling, including NBI, in support of operations

WP5: Modelling

- Scope:
  - Fast-ion resonance index model (RIM) in support of NBI operations and fast-ion physics
  - Predictive TRANSP modelling, including NBI, in support of operations

- Progress in 2024 – Resonance Index Model
  - Extended to low aspect ratio geometries. Benchmark with ASCOT (on-going)
  - Comparison between PT and NT configurations (on-going)
- Next steps:
  - Finalize benchmark with ASCOT
  - Predictive simulations for NBI ops.



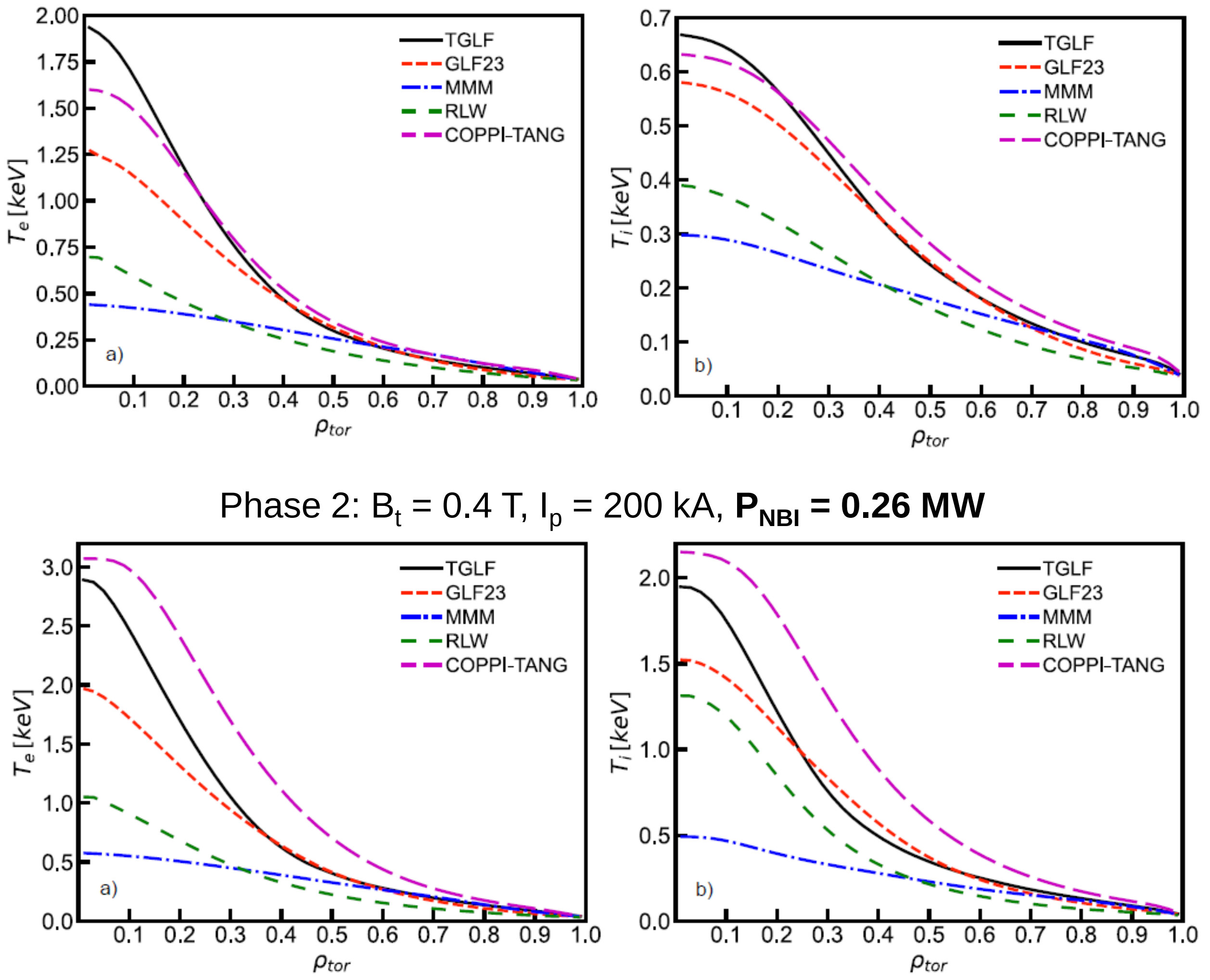
WP5: Modelling

- Scope:
  - Fast-ion resonance index model (RIM) in support of NBI operations and fast-ion physics
  - Predictive TRANSP modelling, including NBI, in support of operations

- Progress in 2024 – TRANSP
  - NBI implemented for SMART in TRANSP.
  - Predictive simulations for Phase 2&3 comparing different transport models [D.J.Cruz-Zabala et al., NF 2024]
- Next steps:
  - Interpretive TRANSP analysis and comparison of PT vs NT

B_t = 0.4 T, I_p = 200 kA, **Ohmic**

Phase 2: B_t = 0.4 T, I_p = 200 kA, **P_{NBI} = 0.26 MW**



Where are we?

Completed	On-going / on-time	Delayed

No	Title	Description	Expected date
		WP PGP-CXRS	
		Key Personnel: E. Viezzer (US), D. J. Cruz-Zabala (US), J. Ayllon-Guerola (US), Postdoc 1 (US), R. Lopez Cansino (US), L. Sanchis (US), G. Pellegrini (CSIC)	
1	CX_M1	Design of GP-CXRS system (geometry, optics, detector)	2024. Jun.
2	CX_M2	Construction of GP-CXRS system	2024. Oct.
3	CX_M3	Installation in SMART	2024. Dec.
4	CX_M4	Commissioning of GP-CXRS at SMART	2025. Jun.
5	CX_M5	First measurements of PGP-CXRS in NT and PT plasmas	2026. Dec.
		WP Interferometry	
		Key Personnel: M.Varavin (IPP-CAS), V.Ivanov (IPP-CAS), D.Kekrt(IPP-CAS); J.Galdon-Quiroga (US), J.Salas-Suarez (US), J.Ayllon-Guerola (US), Technician #1 (US),), G. Pellegrini (CSIC)	
1	IF_M1	Development of simulation tools and design	2024. Apr.
2	IF_M2	Laboratory tests at SMART	2024. July
3	IF_M3	Installation in SMART	2024. Dec.
4	IF_M4	Commissioning of IF at SMART	2025. Jun.
5	IF_M5	RT measurements and integration in DCS	2025. Dec.
6	IF_M6	Feasibility study of SDR technology	2025. Dec.
		WP NBI	
		Key Personnel: M.Garcia-Munoz (US), Postdoc #2 (US), Technician #1 (US), J. Ayllon (US), J. Gonzalez Martin (US); K.Bogar(IPP), S.Fukova (IPP), I.Mysiura (IPP), J.Varju (IPP).	
1	NBI_M1	Transport of components to SMART site.	2024. April
2	NBI_M2	Unpacking and assembling of NBI system	2024. Jun.
3	NBI_M3	Testing of subsystems and troubleshooting of NBI	2025. Nov.
4	NBI_M4	Conditioning of NBI to reach operation parameters	2025. May
5	NBI_M5	Training of US operators	2025. December
		WP EXP	
		Key Personnel: E.Viezzer (US), J.Galdon-Quiroga (US), M.Garcia-Munoz (US), D.Cruz-Zabala (US), Postdoc #1 (US), Postdoc #2 (US), J.Salas-Suarez (US), R. Lopez Cansino (US), J. Gonzalez (US), G. Pellegrini (CSIC)	
1	EXP_M1	Development of NT and PT ohmic plasmas in SMART	2025. Jun.
2	EXP_M2	Verification of plasma stability	2025. Jul.
3	EXP_M3	Development of NBI heated plasmas	2025. Dec.
4	EXP_M3	Comparison of NBI vs ohmically heated plasmas	2025. Dec.

		WP MOD	
		Key Personnel: L.Sanchis-Sanchez (US), M.Toscano (US), Postdoc #2 (US), Y.Kominis (UA), G.Anastassiou (US), P.Zestanakis (UA), D. Cruz-Zabala (US), M. Garcia Muñoz (US), J. Galdon (US), E. Viezzer (US)	
1	MOD_M1	Extension of resonance reduced model for low aspect ratio	2024. Dec.
2	MOD_M2	Implementation of resonance model in ASCOT	2024. Dec.
3	MOD_M3	Implementation of SMART NBI in TRANSP	2024. Jun.
4	MOD_M4	Predictive TRANSP modelling of PT and NT plasmas in SMART	2024. Dec.
5	MOD_M5	Benchmark resonance model with ASCOT	2025. Jul.
6	MOD_M6	Predictive simulations of resonances in support of NBI ops.	2025. Sept.
7	MOD_M7	Predictive TRANSP modelling of NBI heated plasmas in SMART	2025. Oct.
8	MOD_M8	Intrepretive transport analysis and comparison of NT vs PT	2025. Dec.

- WP GP-CXRS: on track
- WP IF: transport to SMART delayed. Good progress with focussing system design.
- WP NBI: transport to SMART delayed. But good progress being achieved.
- WP EXP: -
- WP MOD: on track

Outline

1. Overview of the project

2. Progress in 2024 and plans for 2025

3. **Conclusions**

Progress towards scientific deliverables

Year	Description	Risk
2024	Installation of interferometry diagnostic in SMART	Low
2024	Installation of poloidal array of gas-puff CXRS diagnostic in SMART	Low
2024	Extension of reduced model for resonant transport to small aspect ratio geometry	Low
2024	Implementation of complete SMART geometry (including NBI) in TRANSP	Low
2025	Commissioning of upgraded interferometer diagnostic in SMART	Medium
2025	First 2D maps of ion temperature, impurity density and rotation in spherical tokamak plasmas: comparison of NT vs PT	Medium
2025	Installation of the NBI system in SMART	Medium
2025	Analysis of thermal and fast-ion resonances in NT vs PT in small aspect ratio plasmas.	Low
2025	Comparison of performance of NT vs PT plasmas in SMART	Medium
2025	First NBI heated plasmas in SMART	Medium-High

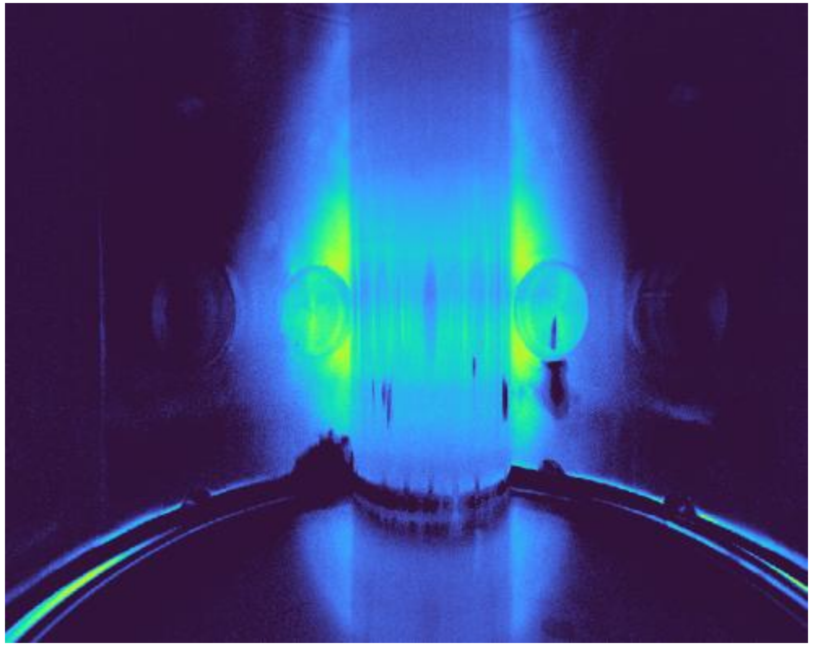
- 2024:
  - SD3 & 4 achieved (SD 4 published in NF, SD3 to be published when completed)
  - SD1 & 2 delayed, but will be achieved in 2025 (systems ready, just pending installation). Low risk.

Overview of publications / conferences

- D.Cruz-Zabala et al., *"Performance prediction applying different reduced turbulence models to the SMART tokamak"*, Nucl. Fusion 64 126071 (2024)
- E.Viezzer et al., *"Diagnostics overview for the first experimental campaign at the SMART spherical tokamak"*, European Physics Society Conference (2024)
- E.Viezzer et al., *"Diagnostics overview for the first experimental campaign of SMART"*, International Spherical Torus Workshop (2024)
- J.Salas et al., *"Preparation of unambiguous mm-wave interferometer for the SMART tokamak"*, International Spherical Torus Workshop (2024)
- J.Salas et al., *"Microwave diagnostics in SMART"*, submitted to European Conference on Plasma Diagnostics (2025)
- A.Rodriguez Gonzalez et al, *"Commissioning and first measurements of the visible light diagnostics of the SMART tokamak"*, submitted to ECPD 2025
- D.J.Cruz-Zabala et al., "*Achievements and challenges of the first experimental campaign at the SMall Aspect Ratio Tokamak (SMART)*", submitted to Symposium of Fusion Energy (2025)
- More to come …

Conclusions

- First solenoid induced plasma achieved in SMART
- Regular reporting and dedicated team meetings
- Good overall progress of project deliverables
- Main inconvenience: delay in transport of NBI and Interferometer from IPP-CAS to SMART site. Loan agreements signed → Systems expected soon at SMART



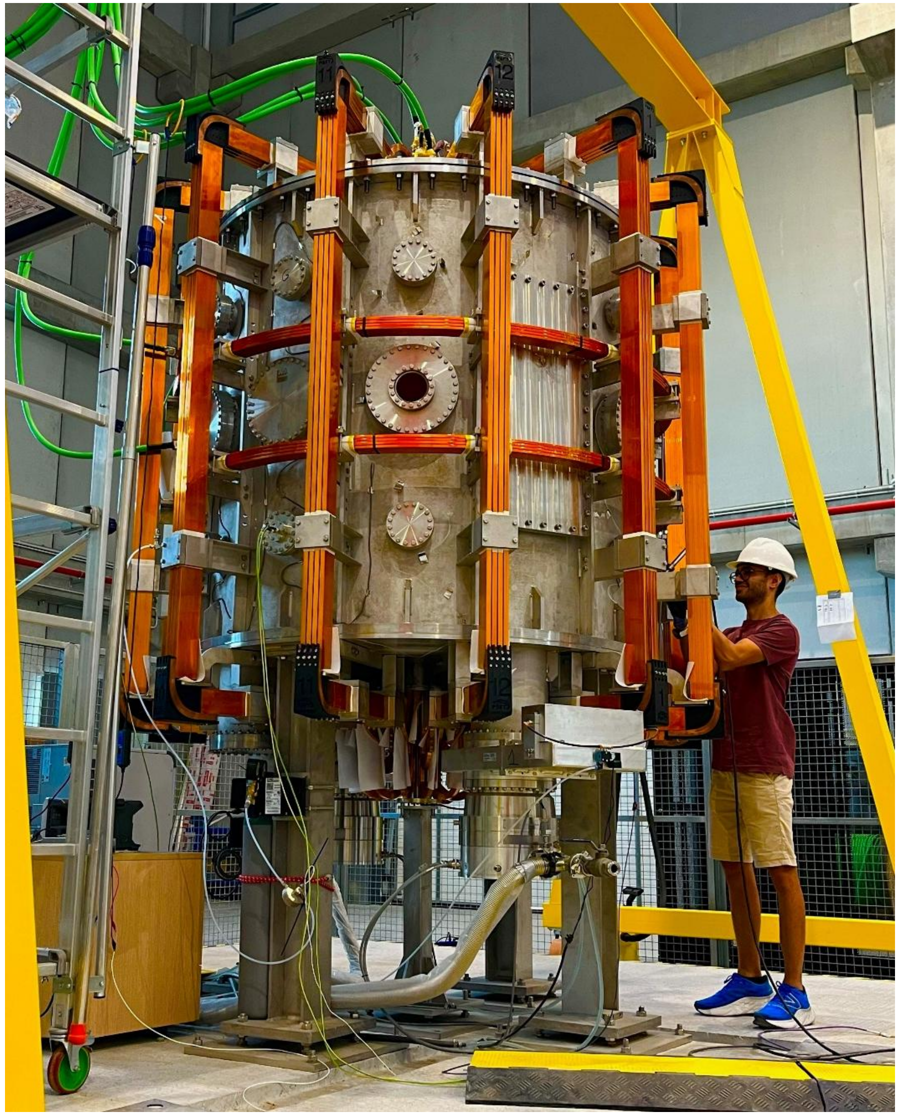
Backup slides

Status of SMART

- Power supplies currently being commissioned
  - Solenoid, PF coils, DIV coils done
  - TF coils: currently under commissioning, fine-tuning of filters to avoid ripple

- Diagnostics:
  - see talks by A. Rodriguez, J. Salas
  - Magnetics (not covered by ENR) ready to be installed

- NBI (see talk by F. Puentes): loan agreement ready to be signed



Temperature profiles have been predicted using different turbulence models in PT

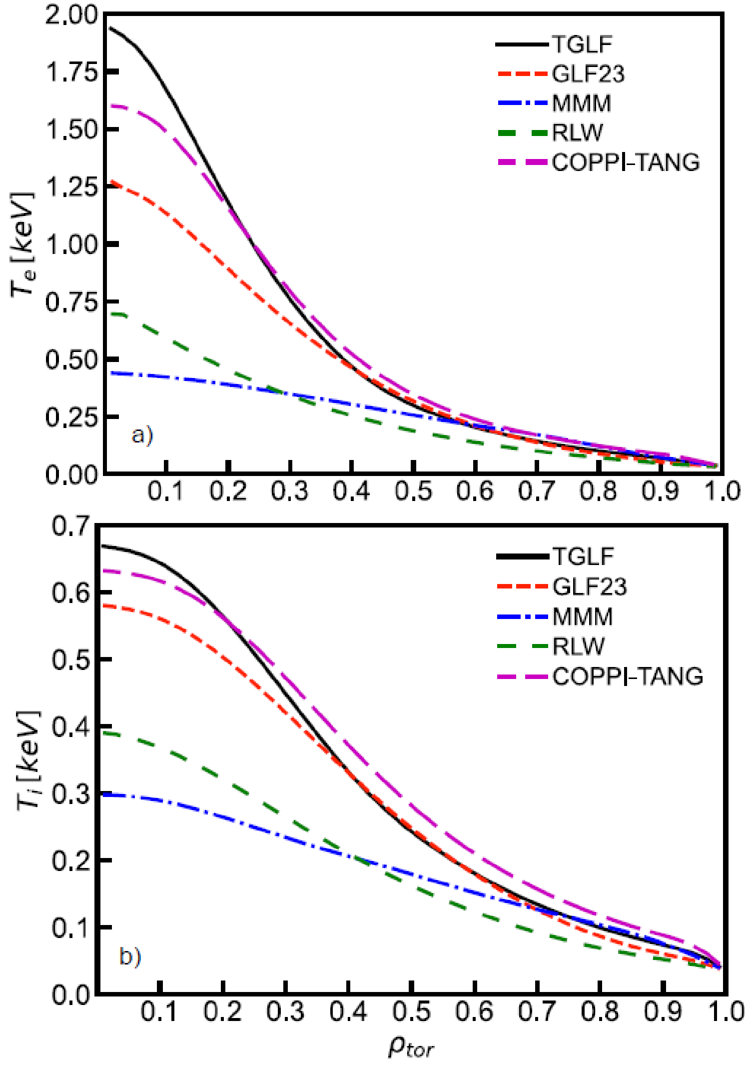
- Models that have been tested:
  - **TGLF:** Trapped Gyro-Landau Fluid [1]
  - **GLF23**: Gyro-Landau Fluid [2]
  - **RLW**: Rebut-Laila-Watkins [3]
  - **MMM**: Multi-Mode model [4]
  - **CDBM**: Current Diffusive Ballooning Mode [5]

- In **STs** with high ν^* and β_e, **micro tearing modes** (MTM) might be **important** [6]

- **RLW** and **MMM**, which are the models that include MTM, are the most pessimistic ones

- In these simulations n_{GW} ~ 30%, $T_{e,sep}$ and $T_{i,sep}$ are fixed to 30 eV and rotation is neglected

B_t = 0.4 T, I_p = 200 kA, Ohmic

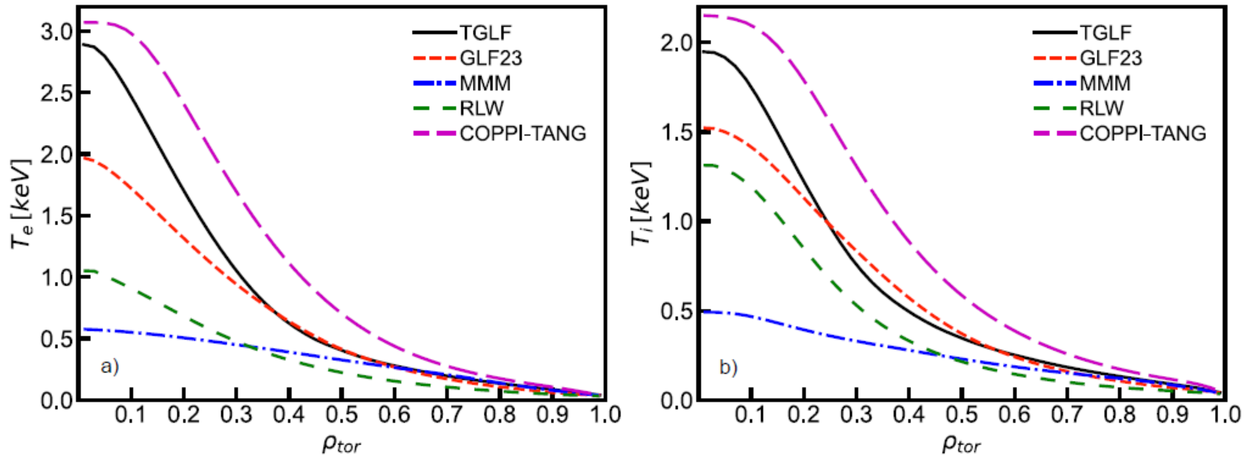


[1] G. M. Staebler *et al.*, PoP, 2007
[2] R. E. Waltz *et al.*, PoP, 1997
[3] P. H. Rebut, *et al*. 12th IAEA Fusion Conf., 1988
[4] T. Rafiq *et al.*, PoP, 2021
[5] A. Fukuyama *et al.*, PPCF, 1999
[6] S. M. Kaye et al., PoP, 2014

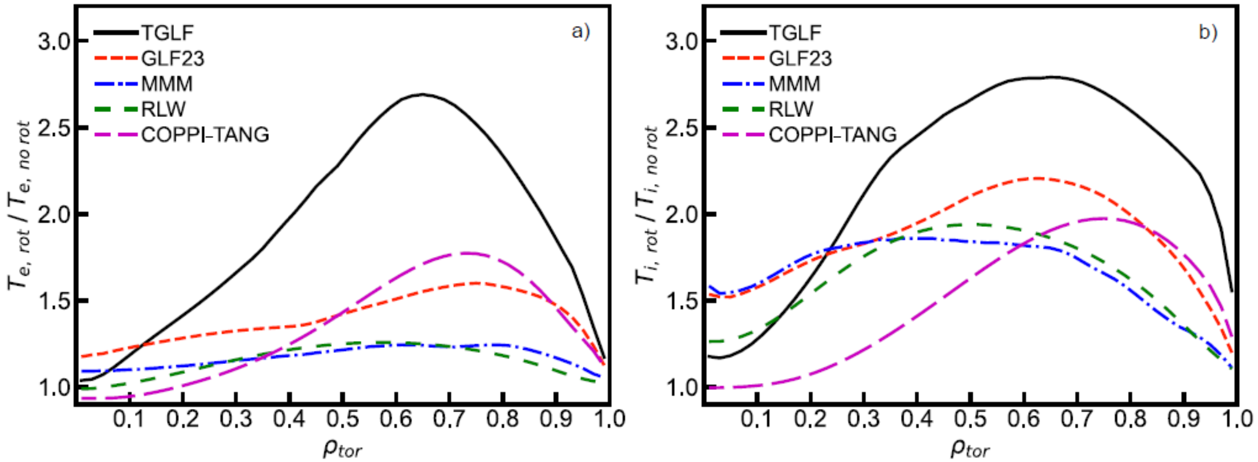
NBI has been implemented in TRANSP to predict phase 2 and phase 3 plasmas

- NBI from COMPASS has been optimized for SMART:
  - E_{inj} = 25 keV
  - P_{NBI} = 0.26 MW
  - R_{tan} = 0.44 m
- MMM provide similar temperatures compared to GLOBUS-M2
- TGLF clearly underestimates electron and ion turbulent transport
- Including rotation enhances predicted temperatures, as expected

Phase 2: B_t = 0.4 T, I_p = 200 kA, P_{NBI} = 0.26 MW



Ratio between predicted temperaturas w. rotation / w.o. rotation



Phase 3 scenario has been predicted using the MMM model

- B_t = 1T, I_p = 0.5 MA, P_{NBI} = 1MW
- n_{GW} of 25% and 75% have been considered
- n_{GW} = 25% shows similar properties of a GLOBUS-M2 plasma
- n_{GW} = 75% shows high confinement β = 3.8
- Large contribution of the BS current → longer plasma discharges