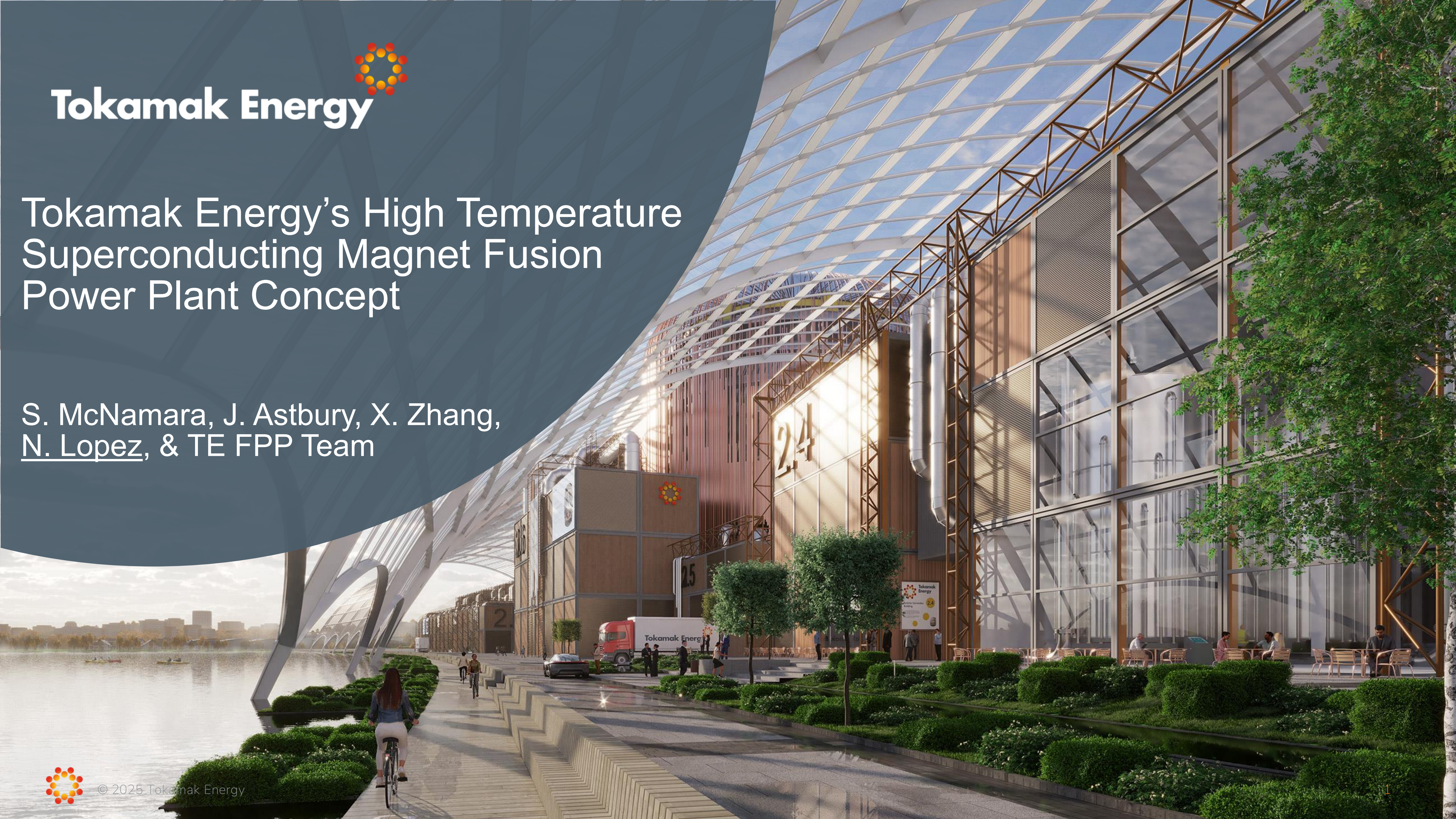
Tokamak Energy

Tokamak Energy’s High Temperature Superconducting Magnet Fusion Power Plant Concept

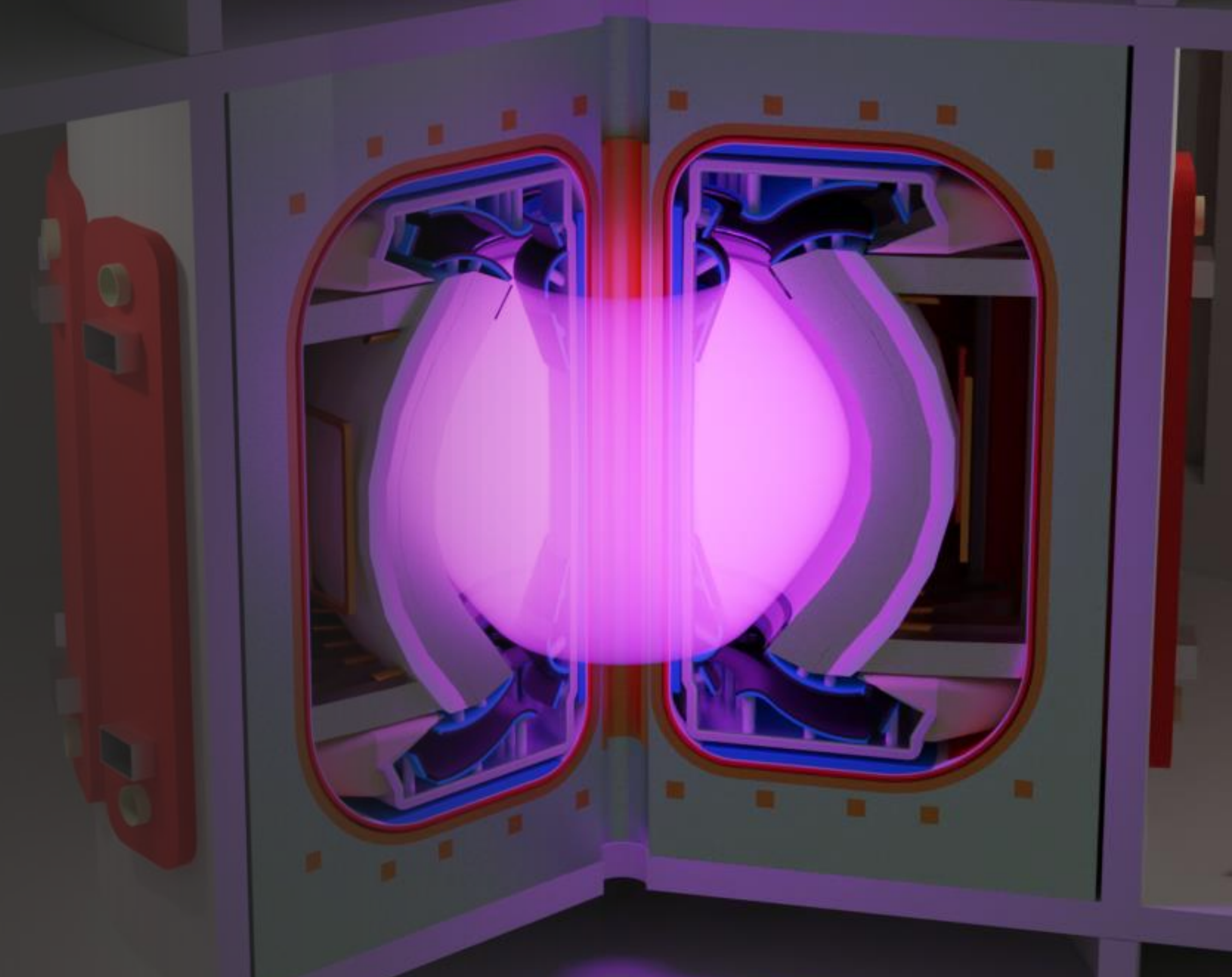
S. McNamara, J. Astbury, X. Zhang,
N. Lopez, & TE FPP Team



Tokamak Energy FPP Team

Shereen Abouelazayem
Aleksandra Alieva
Michail Anastopoulos
Thomas Anderson
Jack Astbury
Luis Black
Marcus Borscz
Sam Brown
Patrick Bunting
Alasdair Burchill
Kamya Chandrasekhar
Pavinder Cheema
Dion Dawson
Aleksei Dnestrovskii
James England
James Fowler
Michael Ginsberg
Vandeep Godhani
Edward Guise
Nathan Hinton
Sandeep Irukuvarghula
Filip Janky
Gurdeep Kamal
Marcel Kruip
Vivian Lee
Samara Levine
Jorge Lima
Nicolas Lopez*
Ian Loughran
Erik Maartensson
Chris Marsden
Liviu Mateescu
Steven McNamara
Sergei Medvedev
Maria Michalopoulou
Mohamed Mohamed
Konstantin Moshkunov
Jonathan Naish
Graham Naylor
Bas van Nugteren
Daniel O'Dea
Jim Pickles
Robert Pocock
Matthew Robinson
Michele Romanelli
Andrea Scarabosio
Mattia Scarpari
Aaron Scott
Andrew Shone
Alsu Sladkomedova
Anna Soldatova
Sophia Sparkes
James Stirling
George Stoneham
Ryan Suhardjo
Yuichi Takase
James Taylor
Sarah Terry
Richard Thwaites
José Trueba
Jari Varje
Elena Vekshina
Benjamin Vincent
Anatoliy Vorobev
Aaron Washington
Nathan Welch
Adrian Whitehead
Johannes Willis
Chris Wilson
Emma Wooldridge
Emre Yildirim
Laura Zhang

*presenting author



PPPL | SRNL SAVANNAH RIVER NATIONAL LABORATORY | OAK RIDGE National Laboratory | UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN | INL Idaho National Laboratory

THE MILESTONE PROGRAM

"Milestone Program" is a Federally-funded competitive technology development program that tasks awardees with maturing the technology and design readiness of a Fusion Pilot Plant (FPP).

In 2022 the U.S. Department of Energy (DOE) launched the Milestone Based Fusion Development Program.

U.S. DEPARTMENT OF ENERGY

Tokamak Energy INC.

18 months to a pre-conceptual design of an FPP

Milestone program lasts **5 years**, split over 3 budget periods.

First budget period is 18 months from July 2024 – Dec 2025.

The program provides private companies with access to **National Lab** expertise. Tokamak Energy will be working with range of Labs, **Universities** and **companies** to deliver a series of **milestones**.

Mandatory deliverables in budget period #1:

- Fusion Pilot Plant (FPP) pre-conceptual design
- Associated Technology roadmaps

Other deliverables:

- Enhanced performance on ST40
  - **See poster by M. Romanelli (ID: 3351) & talk by O. Asunta (ID: 3337)**
- Liquid lithium technology development
- HTS magnet manufacturing scale-up

Oak Ridge National Laboratory

PPPL

SRNL Savannah River National Laboratory

INL Idaho National Laboratory

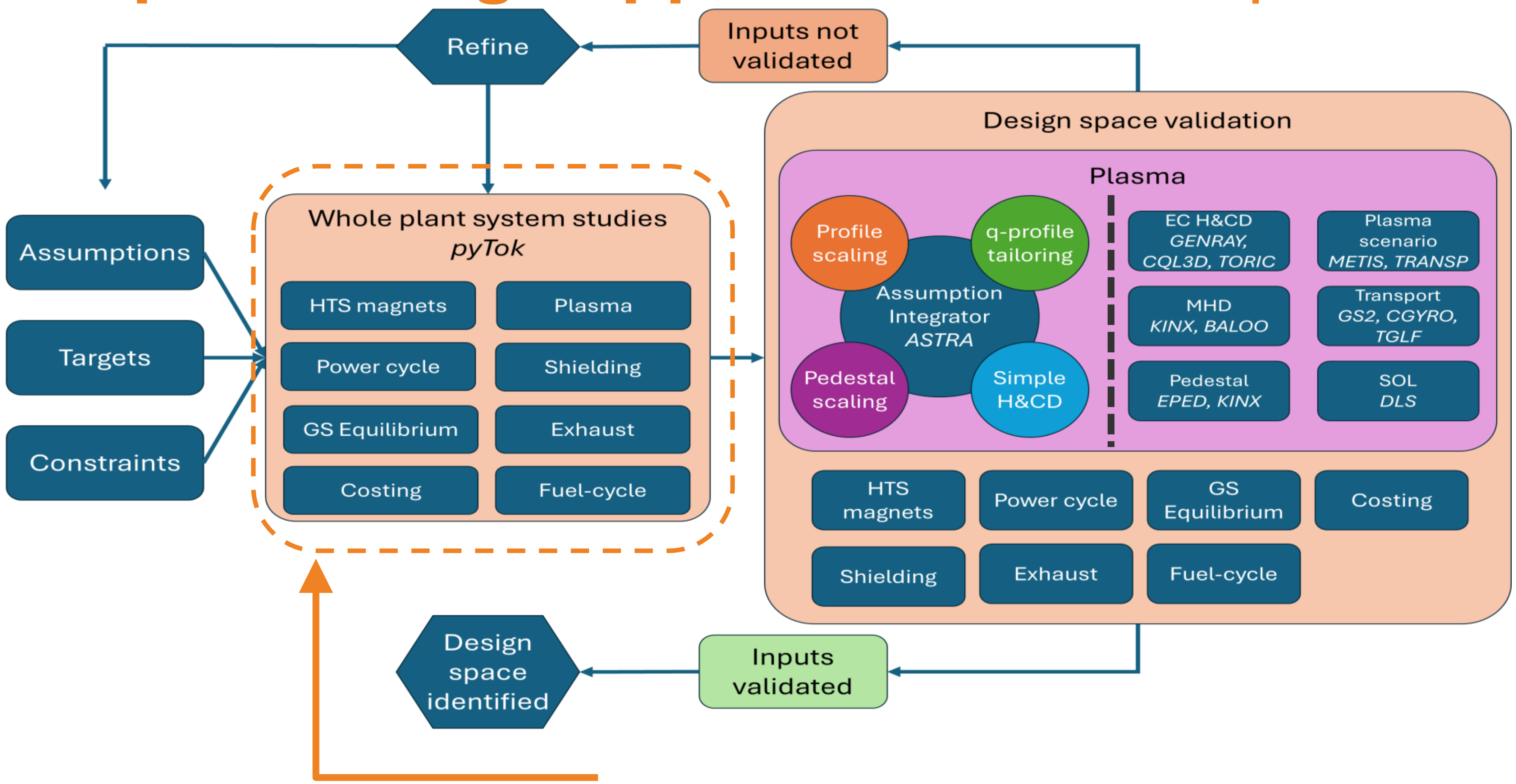
University of Illinois Urbana-Champaign

Design space identification

Systems-code analysis

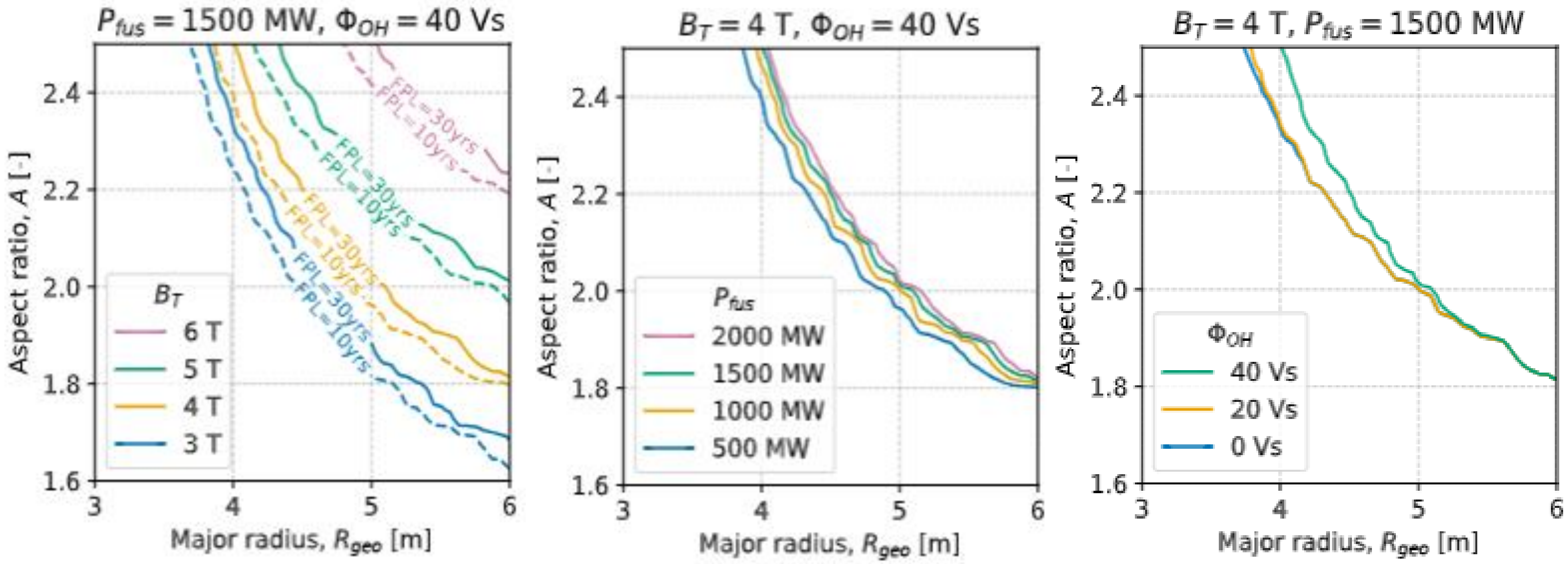
Steady-state operation = Spherical & Advanced Tokamaks

Pre-conceptual design approach: Iterative, parallel assessment

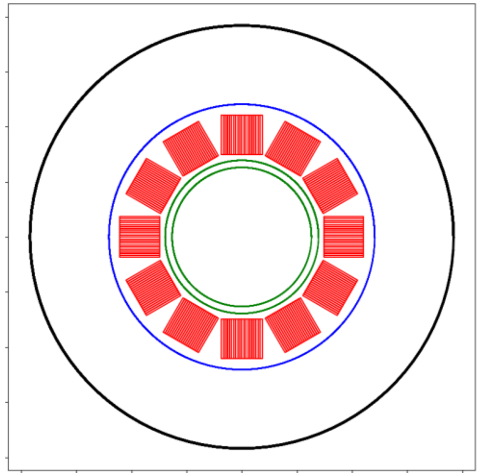


- **Design-space identification with PyTok** (TE-developed whole-plant system code):
  1. Simplified models for all major plant systems
  2. Parametric CAD generation for cost & neutronics modelling
  3. Free-boundary equilibrium via FreeGS
  4. Large parameter space optimization & sensitivity studies

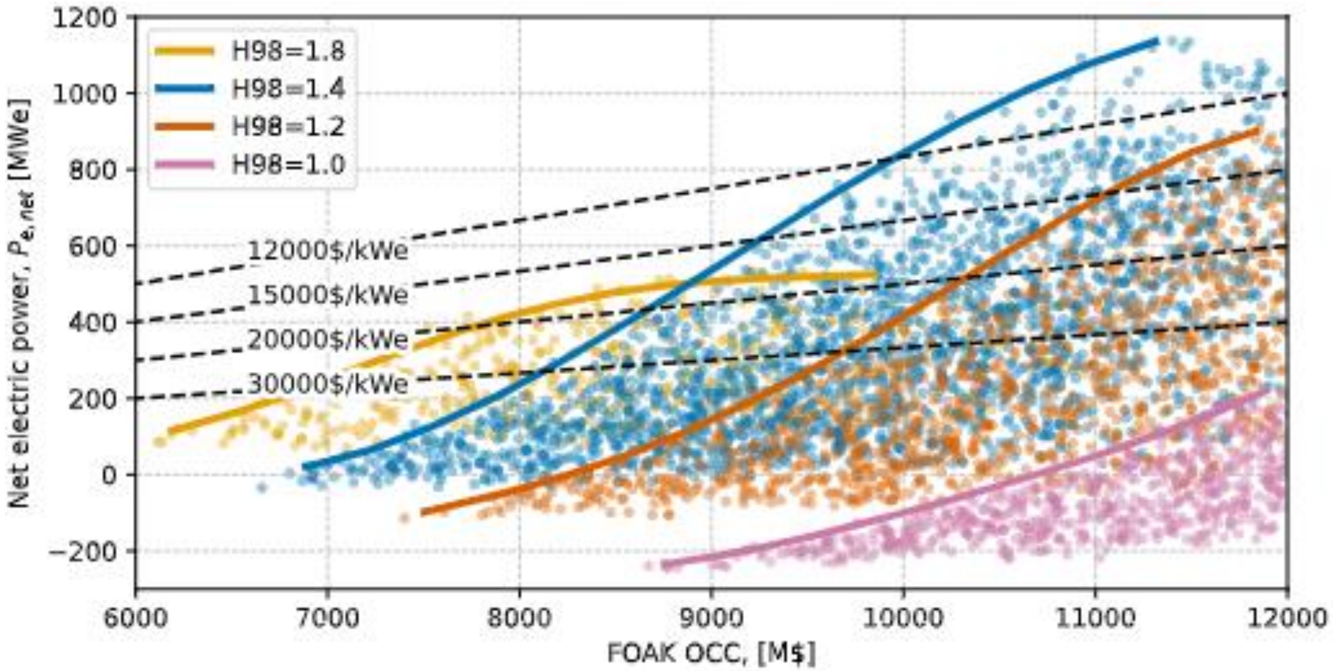
Key tradeoffs in design space:
Machine size vs solenoid capacity vs toroidal field strength



- Dominant driver of machine major radius = **Magnetic Field Strength**
- Component lifetime & fusion output have small influence on device size
  - 1m shielding with 5cm attenuation length (HVL)
    - **Small** change in thickness = **Big** change in neutron tolerance
- Solenoid size unimportant provided it can fit in the space left by TF coil build
  - TF coil build = rectangular, cannot be packed infinitely close within circle



Key tradeoffs in design space:
Cost vs performance vs confinement



- **Price** is **decreasing** function of Overnight Capital Cost (OCC) & net output power at fixed H_{98}
  - **Small incremental cost** to change from negative to positive net power
- Cost is very sensitive to confinement enhancement
  - **Lower confinement** generally requires much **higher cost** to reach same output power
    - Sets requirement on minimum viable confinement
  - Steady-state design points are highly coupled (heating mostly alpha, current mostly bootstrap)
    - Confinement has outsized influence on overall performance

Candidate design points from overall design space

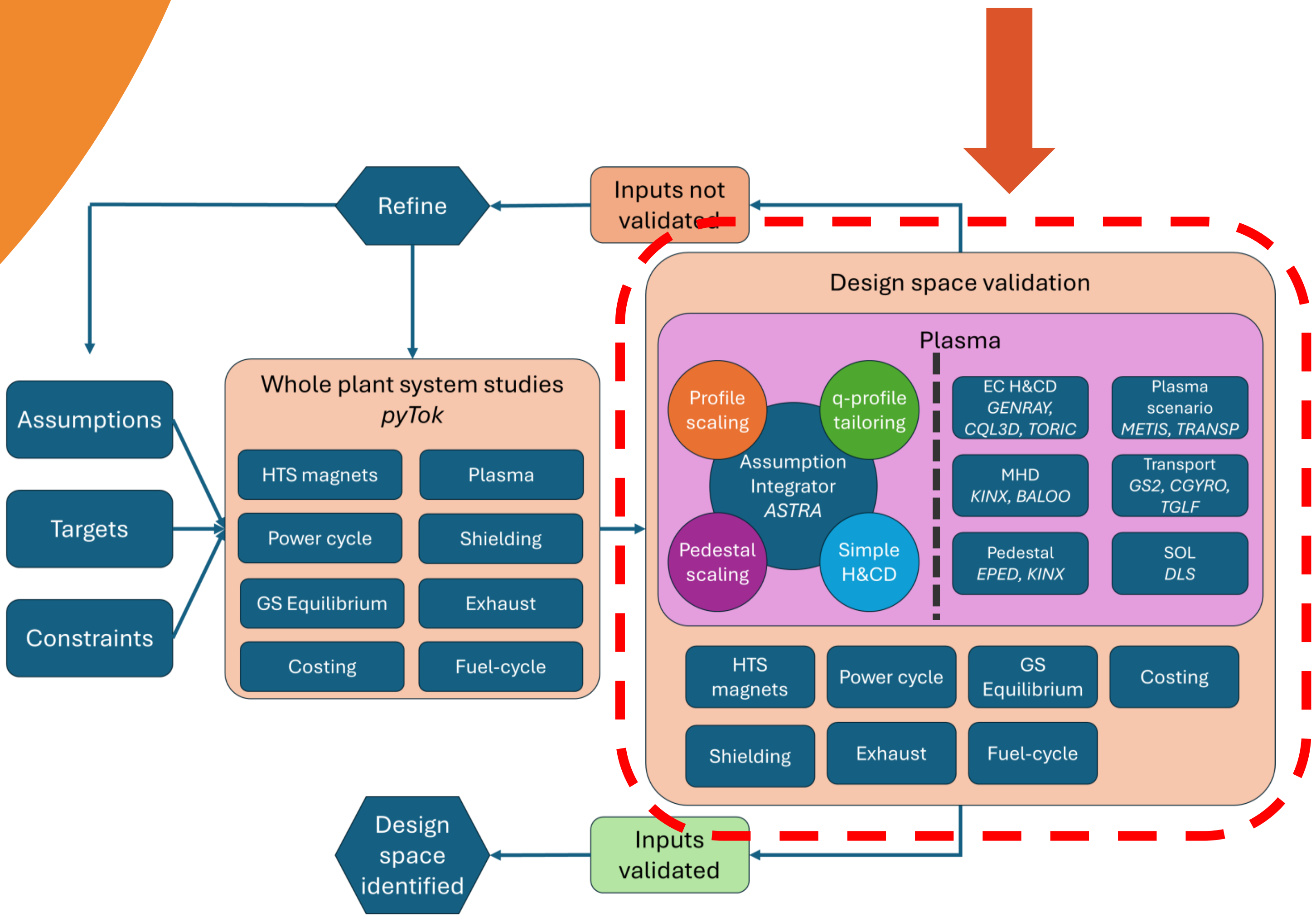
	$H98^* = 1.4$			$H98^* = 1.2$		
Toroidal field [T]	3.0	4.0	5.0	3.0	4.0	5.0
Major radius [m]	5.0	5.0	5.0	5.0	5.0	5.0
Aspect ratio [-]	1.9	2.05	2.25	1.9	2.05	2.25
Plasma current [MA]	19.6	18.0	16.2	20.1	18.4	16.4
Fusion power [MW]	1450	1485	1485	1490	1500	1500
Heating & Current Drive Power [MW]	125	120	115	195	185	175
Fusion gain [-]	11.5	12.6	13.2	7.6	8.2	8.5
Net electric [MWe]	320	350	360	220	250	260
No-wall β_N limit ratio, C_{β_N} [-]	1.0	0.88	0.85	0.93	0.81	0.78
FOAK ONC [M$]	9,100	9,700	10,300	10,200	10,700	11,300

- There are multiple (potentially) attractive design points that satisfy overall plant requirements
  - Targets: 300 – 400 MWe Net Power, 30 year TF coil FPL, $\beta_N \leq \beta_{N,no\ wall}$, divertor exhaust $^P/_R \leq$ 25 MW/m
- At fixed R=5m, $\boldsymbol{H_{98}^*}$**=1.4 has multiple options**, but H_{98}^*=1.2 cannot reach target net power

Key question: does more comprehensive plasma modelling support these trends?

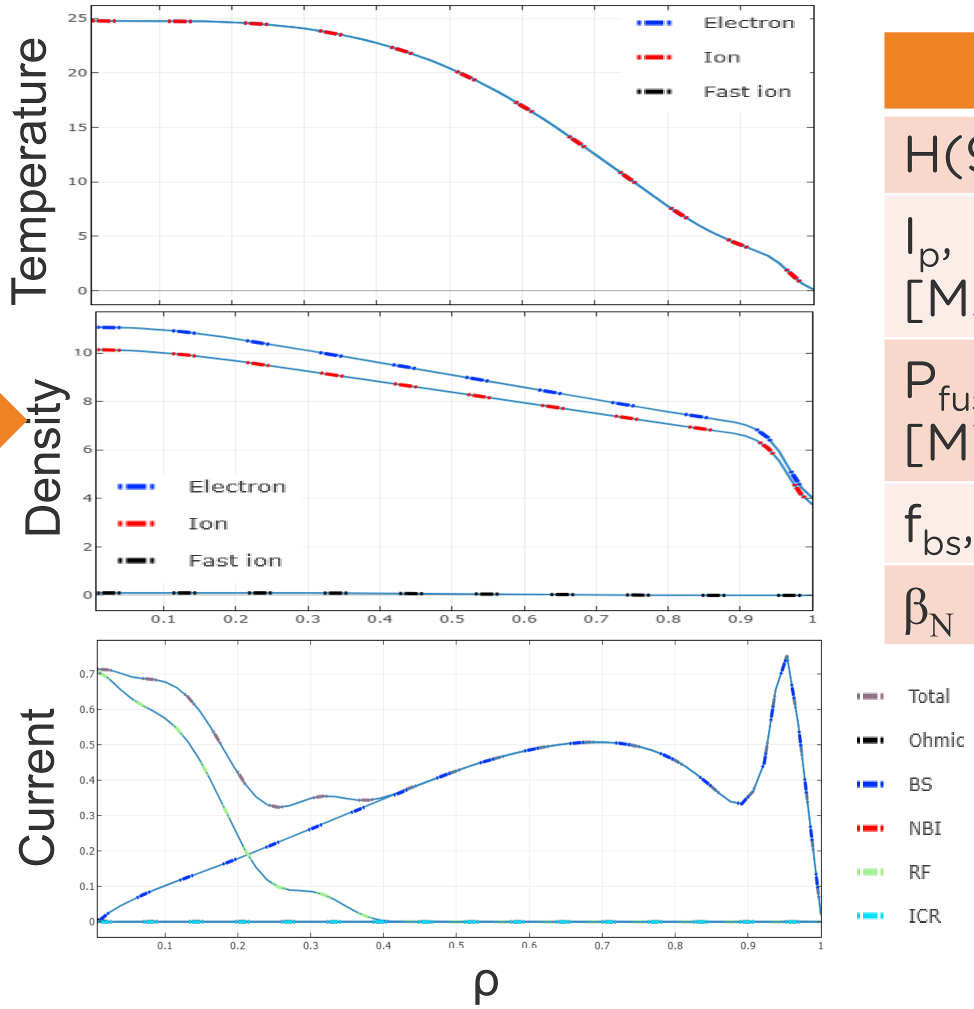
- Select single design point to proceed with in more detail

Physics Assessment of Design Point

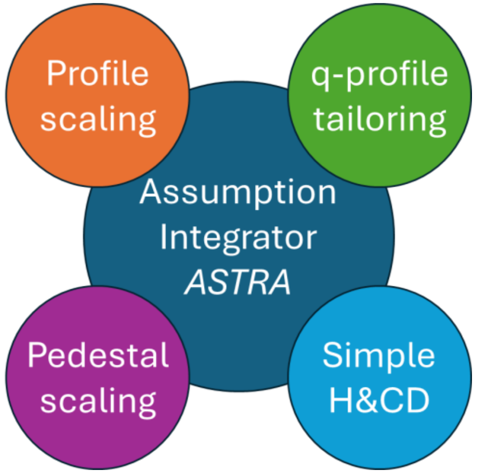


‘Template’ flattop plasma obtained from assumption integrator

PyTok	
H(98*)	1.4
I_p, I_{OH}, I_{EC} [MA]	14.8, 0, 1.7
P_{fus}, P_{EC} [MW]	1574, 72.5
f_{bs}, f_{GW}	0.88, 1.0
β_N	3.38

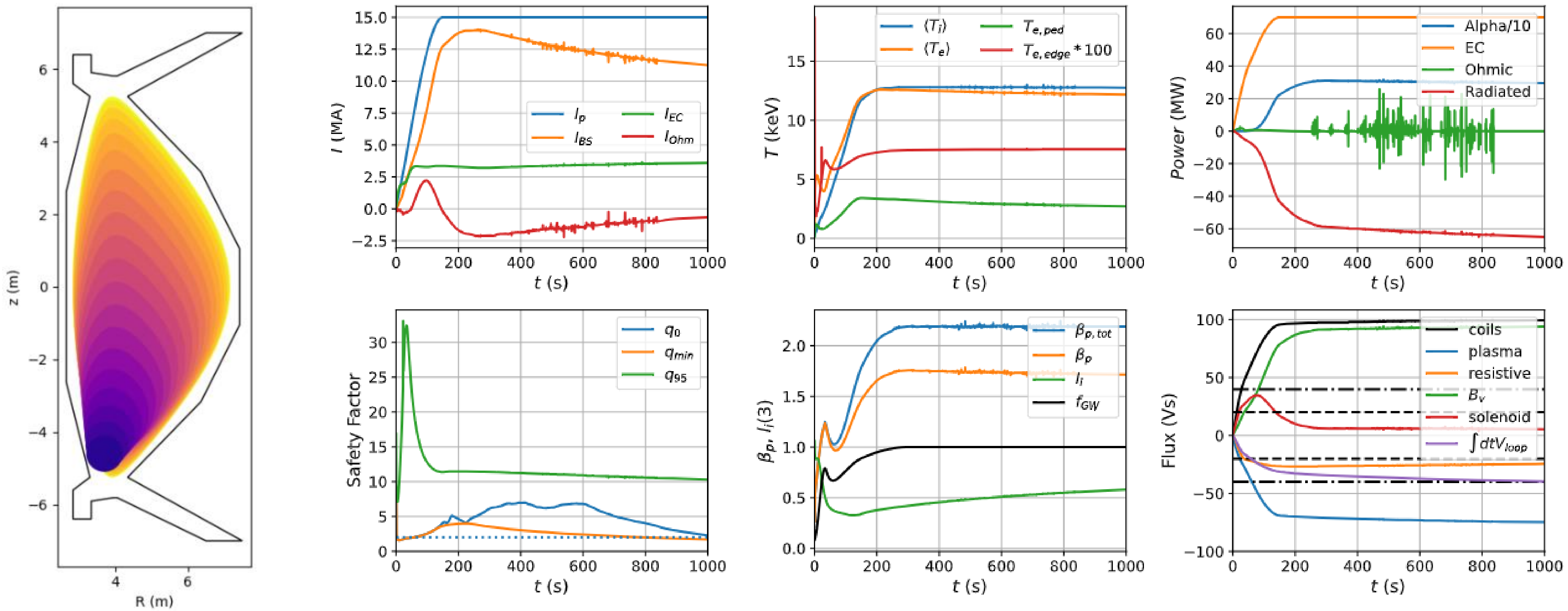


ASTRA	
H(98*)	1.5
I_p, I_{OH}, I_{EC} [MA]	13.1, 0, 1.3
P_{fus}, P_{EC} [MW]	1389, 46.6
f_{bs}, f_{GW}	0.90, 1.0
β_N	3.80



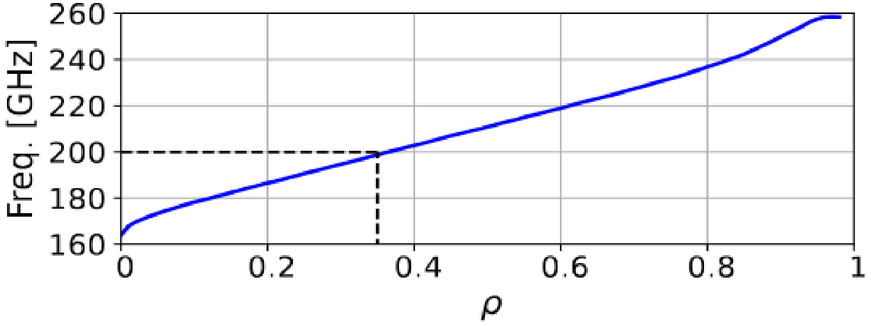
- ASTRA-SPIDER 1.5D transport code used as an ***assumption integrator*** to develop consistent flat-top plasma operating points by combining several low fidelity models.
  - Converts **0D PyTok output** into **1D profiles + 2D equilibrium** for further specialized analysis
    - **Results then update the reference flattop or even the global design point**

Highlights: Rampup time-dependent scenario modeling



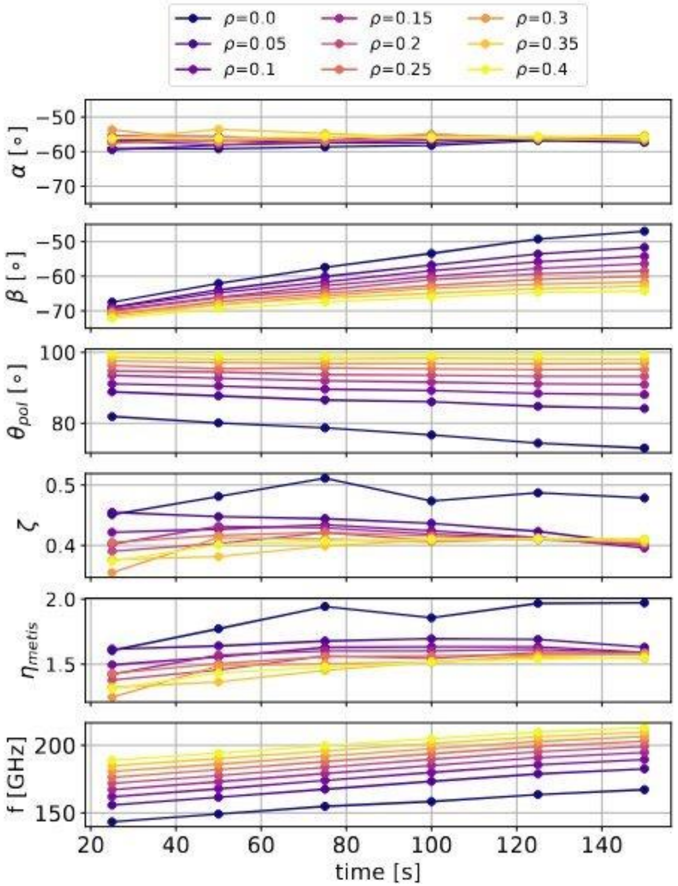
- Plasma scenario scoping done with fast transport code **METIS**
    - Magnet & solenoid scoping using METIS outputs, converted to free-boundary equilibria, then re-optimized
- Plasma evolves from lower-single-null to full-current double null in 150 sec
- **Fusion burn during rampup** – corresponding β_{pol} & B_v increase allows partial solenoid recharge
    - Total solenoid flux < 40 Vs, Vertical field flux ~ 90 Vs
- H_{98} = 1.5, $\chi_i = \chi_e$ gives 300 MW alpha heating, 5x300 = **1.5 GW total fusion power**

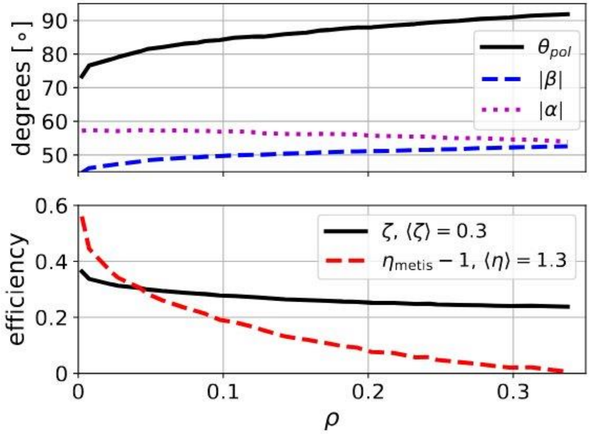
Highlights: Electron cyclotron H&CD modelling

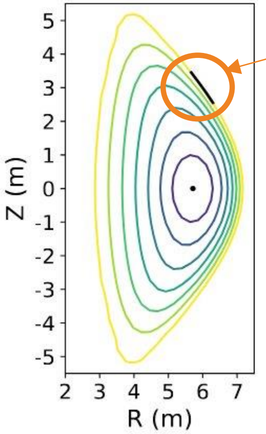


Flattop

Rampup







EC Launchers Here

- EC = main auxiliary HCD system: needed for **rampup** & **flattop**
- EC launchers designed using new physics-based optimization framework
  - **Each scenario takes ~few minutes to scope out!**
- Efficient ECCD (>50 kA/MW) can be achieved with:
  - **Fundamental O-mode** with frequencies **160 – 200 GHz**
  - **Low-field side top launch** with **~50 degree** toroidal & poloidal injection angles

Summary

- Tokamak Energy is preparing a pre-conceptual design for a Fusion Pilot Plant for the US DOE Milestone Program
- Attractive design points identified with TE-developed system-code PyTok
- Higher fidelity physics modelling ongoing to either confirm or reject design point proposed by PyTok
- Further details will be presented at in **series of talks at APS DPP** & **upcoming series of publications**

Tokamak Energy

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CONTACT US:

STEVEN MCNAMARA

Steven.McNamara@tokamakenergy.com

www.tokamakenergy.com

Tokamak Energy Ltd
173 Brook Drive
Milton Park
Oxfordshire OX14 4SD
United Kingdom