EGENE simulations of scenario 4.2

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Outline

- Introduction
- Preliminary test: EGENE on Scenario 4.1
- Scenario 4.2 static equilibrium design
  - ✓ Start of flat top (SOF) case
- EGENE-METIS weak coupling on Scenario 4.2
  - ✓ Ramp up phase

Introduction

- CREATE-EGENE
  - ✓ CREATE-NL
  - ✓ CREATE-L

- Inputs
  1. Total plasma current $\mathbf{I_p}$
  2. Coil currents $\mathbf{I_{coils}}$
  3. Plasma current density $\mathbf{J_\varphi}$
     - i. **p', ff'**
     - ii. $\boldsymbol{\beta_p}$, $\mathbf{l_i}$

$$= \begin{cases} r\frac{dp(\bar{\psi})}{d\bar{\psi}} + \frac{f(\bar{\psi})}{\mu_0 r}\frac{df(\bar{\psi})}{d\bar{\psi}} \\ \left[\frac{r\beta_0}{R_0} + \frac{(1-\beta_0)R_0}{r}\right](1-\bar{\psi}^{\alpha_M})^{\alpha_N} \end{cases}$$

- Outputs
  1. Free-boundary equilibrium
  2. Linearized model

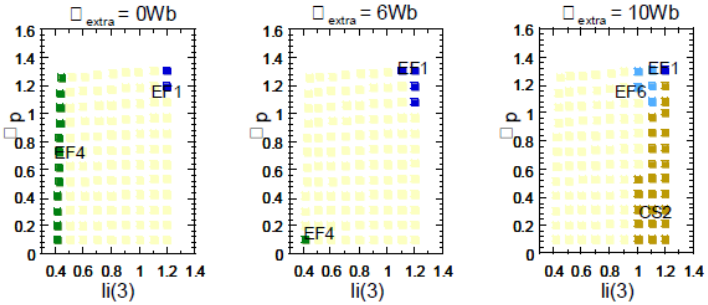
Preliminary test: EGENE on #4.1

- Preliminary test on Scenario 4.1
  - Static equilibria defined in Plant Integration Document (PID)
    - XPF: X-point formation
    - SOH: Start of heating
    - SOF: Start of flat top

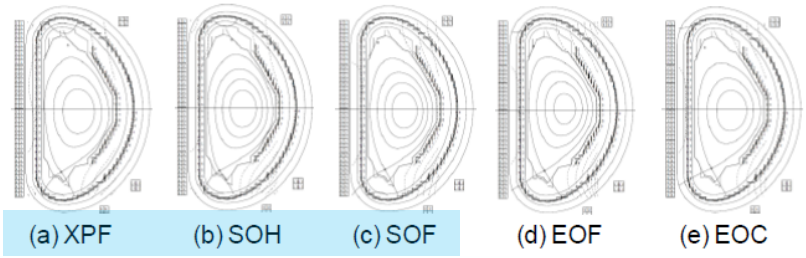
Table 1.2-5 Design Scenario 4: SN – ITER Like Inductive

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI
time (s)		-40.00	-10.00	0.00	0.06	0.16	4.66	5.76	13.16	116.46	121.86	177.96
I_p (MA)		0.00	0.00	0.00	0.00	0.10	1.42	1.84	4.6	4.6	3.33	0.00
q_{95}						50.86	9.19	7.39	2.73	3.10	3.36	
nom. li						0.85	0.85	0.85	0.85	0.75	0.90	
nom. β_P						0.10	0.21	0.35	0.53	0.79	0.47	
PF Coil Currents (kA) nominal li nominal betap	CS1	0.00	15.38	20.00	19.11	18.87	13.11	10.70	2.63	-6.19	-5.44	0.00
	CS2	0.00	15.38	20.00	19.19	19.18	12.39	9.89	-7.18	-14.07	-11.66	0.00
	CS3	0.00	15.38	20.00	19.19	19.08	10.62	8.11	-6.99	-14.44	-12.25	0.00
	CS4	0.00	15.38	20.00	19.09	18.85	15.15	14.13	-1.38	-9.53	-6.31	0.00
	EF1	0.00	0.00	1.52	0.96	1.67	-3.66	-5.43	-14.10	-10.23	-8.25	0.00
	EF2	0.00	0.00	-0.63	-1.24	-1.02	-0.10	0.26	-3.22	-9.15	-4.66	0.00
	EF3	0.00	13.96	18.14	17.32	17.26	13.25	11.58	5.60	1.91	0.58	0.00
	EF4	0.00	11.46	14.90	14.47	14.62	11.50	10.95	14.42	5.86	5.24	0.00
	EF5	0.00	0.00	-4.00	-3.80	-5.26	-3.41	-4.38	-5.65	5.72	1.39	0.00
	EF6	0.00	0.00	1.99	1.50	1.77	-1.05	-2.03	-10.76	-17.83	-11.68	0.00
Link to IDM Reference Data												

I. Start of Premagetization Phase in CS1-4 and EF3-4
II. Start of Premagetization Phase in EF1-2 and EF5-6
III. End of premagnetization Phase in PFC
IV. Plasma Break-down
V. Initial Plasma
VI. XPF (X point Formation)
VII. SOH (Start of Heating)
VIII. SOF (Start of Flattop)
IX. EOF (End of Flattop)
X. EOC (End of Cooling)
XI. End of Current in PFC



Available operational space in β_p and l_i at with the flattop current.
With extra flux of 0Wb (SOF), 6Wb and 10Wb.



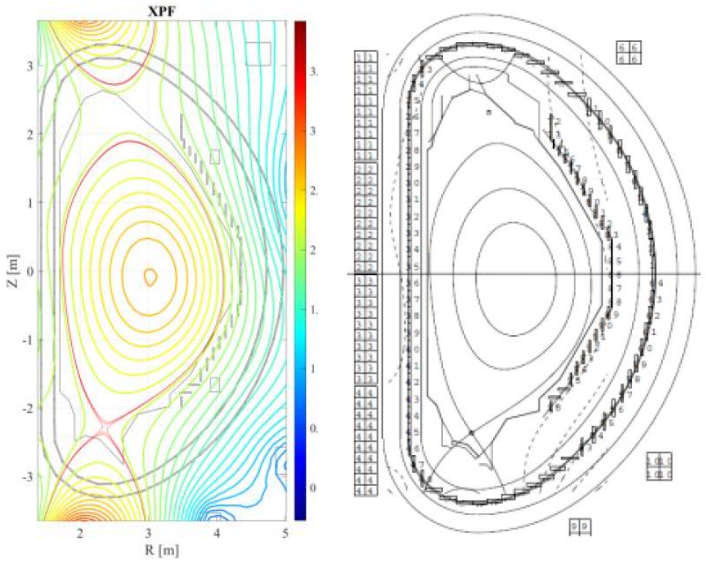
Equilibria corresponding to the snapshots listed in the table.

Preliminary test: EGENE on #4.1 - 2

- Inputs PID: $\mathbf{I_{coils}}$, $\mathbf{I_p}$, $\mathbf{\beta_p}$, $\mathbf{l_i}$
- Outputs EGENE: $\mathbf{q_{95}}$, $\mathbf{\beta_p}$, $\mathbf{l_i}$, **ψ surfaces**
- Agreement in terms of outputs and flux surfaces

XPF@1.42MA					
	PID	CNL	ε_{CNL} [%]	CL	ε_{CL} [%]
β_p	0.210	0.210	0	0.211	0
l_i	0.85	0.85	0	0.857	0.78
q_{95}	9.19	9.12	-0.74	-	-

CNL = EGENE CREATENL
CL = EGENE CREATEL



Scenario 4.2 static equilibrium design

- Research Plan → SOF target parameters (except for l_i)

Table 1-3: Plasma Parameters for JT-60SA, DEMO and ITER

		JT-60SA							DEMO				ITER	
	Parameters	#1 Full Ip Inductive DN 41MW	#2 Full Ip Inductive SN 41MW	#3 Full Ip Inductive SN 30MW High density	#4-1 ITER like Inductive SN 34MW	#4-2 Advanced inductive (hybrid) SN 37MW	#5-1 High βN Full CD SN 37MW	#5-2 High βN Full CD SN 31MW	Slim CS	JA DEMO2014	EU DEMO1	EU DEMO2	scenario 2, Inductive II	scenario 6, Non-inductive Steady-stste
Size & Configulation	Plasma current, I_P (MA)	5.5	5.5	5.5	4.6	3.5	2.3	2.1	16.7	12.3	19.6	21.63	15.0	9.0
	Toroidal magnetic field, B_T (T)	2.25	2.25	2.25	2.28	2.28	1.72	1.62	6	5.94	5.67	5.63	5.3	5.18
	Major radius, R_P (m)	2.96	2.96	2.96	2.93	2.93	2.97	2.96	5.5	8.5	9.1	7.5	6.2	6.35
	Minor radius, a (m)	1.18	1.18	1.18	1.14	1.14	1.11	1.12	2.1	2.4	2.9	2.9	2.0	1.85
	Aspect ratio, A	2.5	2.5	2.5	2.6	2.6	2.7	2.6	2.6	3.5	3.1	2.6	3.1	3.4
	Elongation, κ_x, κ_{95}	1.95, 1.77	1.87, 1.72	1.86, 1.73	1.81, 1.70	1.80, 1.72	1.90, 1.83	1.91, 1.84	*, 2.0	*, 1.65	*, 1.65	*, 1.75	1.85, 1.70	2.0, 1.86
	Triangularity, δ_x, δ_{95}	0.53, 0.42	0.50, 0.40	0.50, 0.40	0.41, 0.33	0.41, 0.34	0.47,0.42	0.45, 0.41	*, ~0.4	*, 0.33	*, 0.33	*, 0.33	0.48, 0.33	0.5, 0.41
	Safety factor, q_{95}	3.2	3.0	3.0	3.2	4.4	5.8	6.0	5.4	4.1	3.25	4.4	3.0	5.4
	Shape Factor (=q_{95}Ip/(aBt))	6.7	6.3	6.2	5.7	5.9	7.0	7.0	7.2	3.5	3.9	5.8	4.3	5.1
	Plasma Volume (m3)	132	131	131	122	122	124	124	941	1647	2502	2217	831	730
Absolute Performance	Fusion output, P_{fus} (MW)	-	-	-	-	-	-	-	3000	1462	2037	3255	400	340
	Fusion gain, Q (SA: QDT equivalent)	~0.6	~0.5	~0.4	~0.3	~0.23	~0.2	~0.2	52	17.5	41	24	10	5.7
	Heating Power (α + external), Pheat (MW)	41	41	30	34	37	37	31	678	377	457	784	120	128
	Current drive power , PCD (MW)	10	10	10	10	17	17	13	59	84	50	133	40	60
	N-NB, P-NB, ECH power (MW)	10, 24, 7	10, 24, 7	10, 20, 0	10, 24, 0	10, 20, 7	10, 20, 7	7, 17, 7	59	84	50	133		
	Ion Temperature, Vol-ave., Central (keV)	6.3, 13.5	6.3, 13.5	3.7, 7.9	3.7, 8.0	3.7, 7.5	3.4, 7.1	3.1, 6.1	17, 28	16, *	13.1, 27.5	18.1, 34.8	8.0, 19	12.1, *
	Electron Temp., Vol-ave., Central (keV)	6.3, 13.5	6.3, 13.5	3.7, 7.9	3.7, 8.0	3.7, 7.5	3.3, 6.7	2.9, 5.8	17, 28	16, *	13.1, 27.5	18.1, 34.8	8.8, 23	13.3, *
	Electron Density, line-average, Vol-ave., Central (E20/m3)	0,63, 0.56, 0.77	0.63, 0.56, 0.77	1.0, 0.9, 1.23	0.91, 0.81, 1.11	0.69, 0.62, 0.84	0.5, 0.42, 0.66	0.53, 0.43, 0.79	*, 1.01, 1.7	*, 0.66, *	*, 0.80, 1.04	*, 0.85, 1.19	*, 1.01, 1.05	*, 0.65, *
	Stored Energy (Thermal, Fast ion) (MJ)	22.4, 4.0	22.2, 4.0	21.1, 1.3	18.0, 1.5	13.4, 2.1	8.4, 2.7	8.1, 1.7	942, 299	786, 182			320, 32	287, 100
	Energy Confinement Time τE(s) thermal, tota	0.54, 0.64	0.54, 0.64	0.68. 0.75	0.52, 0.57	0.36, 0.42	0.23, 0.31	0.25, 0.30	1.3, 1.8	2.7, *	4.2, *	4.0, *	3.7	3.1
	Current DiffusionTime (s)	34.1	32.7	16.6	15.2	14.6	12.6	10.8	514.2				198.6	314.8
	Flattop Duration (s)	100	100	60	100	100	100	100	S.S.	S.S.	pulse	S.S.	400	3000
Normalized Performance	Assumed Confinement improvement, H_H	1.3	1.3	1.1	1.1	1.2	1.3	1.38	1.3	1.31	1.1	1.4	1.0	1.61
	Normalized beta, β_N	3.1	3.1	2.6	2.8	3.0	4.3	4.3	4.3	3.4	2.6	3.8	1.8	2.9
	Bootstrap current fraction, fBS	0.29	0.28	0.25	0.3	0.4	0.68	0.79	0.77	0.61	0.35	0.61	0.15	0.46
	Non inductive CD fraction, fCD	0.51	0.5	0.36	0.43	0.58	1	1	1	1	0.44	1	0.21	1
	Normalized density, ne/ nGW	0.5	0.5	0.8	0.8	0.8	0.85	1.0	0.98	1.2	1.2	1.2	0.85	0.78
	Radiation Power Fraction (Prad / Pheat)						0.77		0.9	0.8				
	Fuel Purity, nDT/ ne	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.91	fHe=0.07	fHe=0.1	fHe=0.1	0.82	0.77
Non Dimentional Parameters	Toroidal beta, βt (%)	6.5	6.5	5.4	5	4.1	5.1	5.0	5.7	2.9			2.5	2.8
	Poloidal beta, βp	0.85	0.81	0.67	0.82	1.15	2.0	2.1	2.53	2.4	1.1	1.7	0.65	1.48
	fast ion beta, βfast (%)	0.98	0.98	0.31	0.4	0.5	1.24	0.87	1.25	0.67			0.23	
	Normalized Gyro radius, ρ*(poloidal)	0.020	0.020	0.015	0.018	0.024	0.036	0.037	0.013	0.016	0.0086	0.0094	0.009	0.019
	Normalized Collisionality, ν*	0.018	0.018	0.080	0.076	0.057	0.052	0.068	0.008	0.013	0.034	0.022	0.040	0.014

Scenario 4.2 static equilibrium design

- Scenario 4.2 static equilibria (XPF, SOH1,…)
  - Not defined in PID
  - Which inputs?

$$t_{eq}\ ,\ I_p,\ J_\varphi\ ,\ I_{coils} \rightarrow \textbf{Need to be defined}$$

- METIS time simulation* needed

  → $I_p(t)$, $\beta_p(t)$, $l_i(t)$, $p'(t)$, $ff'(t)$

  *see V. Ostuni talk

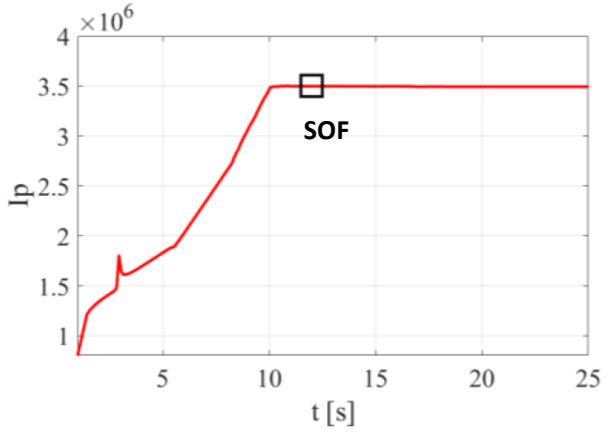
- Coil currents?
  - METIS/FEEQs *
  - Computed by EGENE using initial eq guess

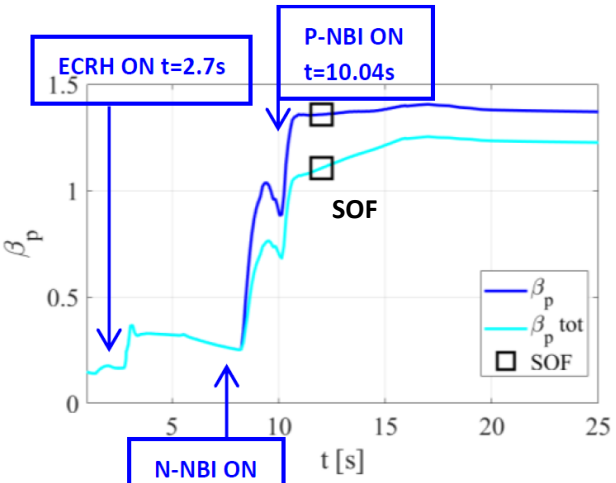
  *see V. Ostuni talk

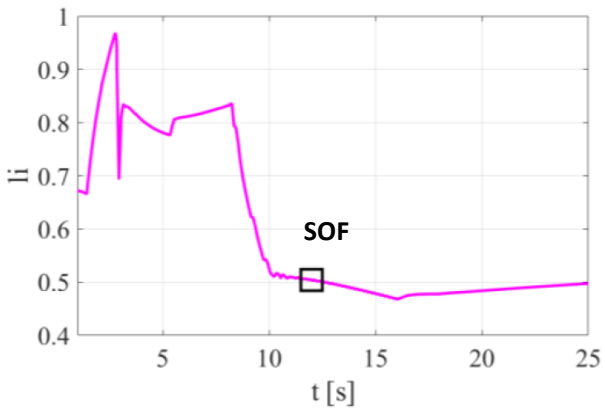
#4.2 SOF design -1

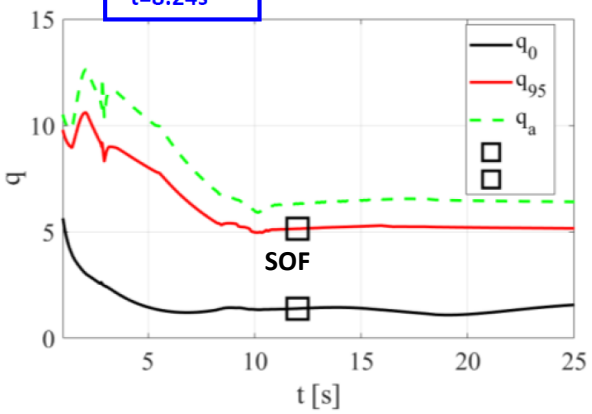
- METIS time evolution* of main quantities

*see V. Ostuni talk





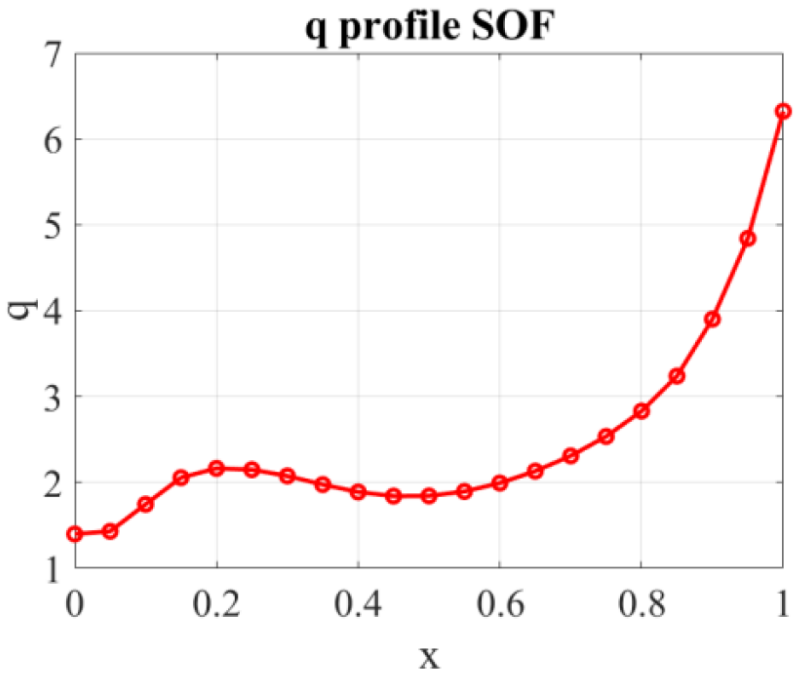


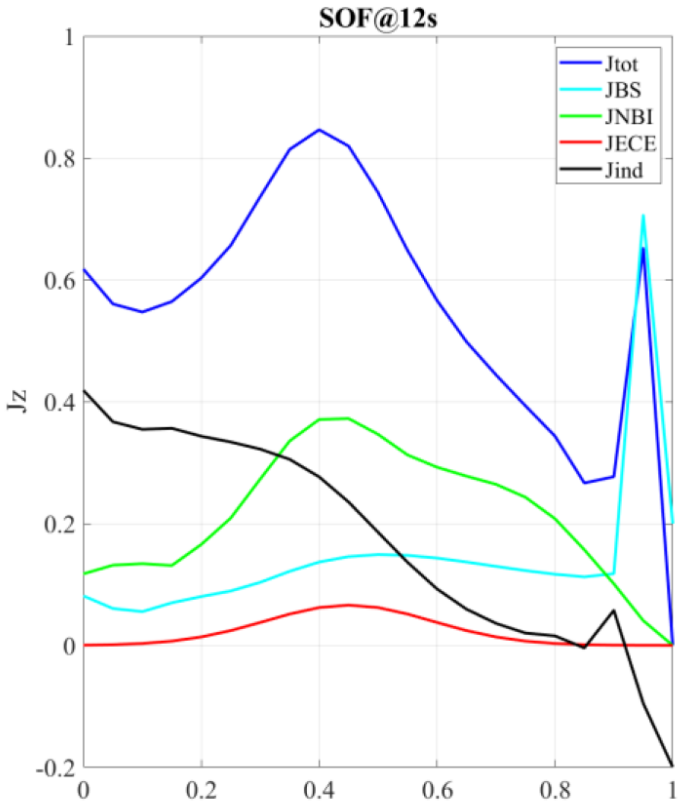


- **Which J_φ in EGENE input?**

#4.2 SOF design -1

- METIS SOF q & J_φ profiles* *see V. Ostuni talk





- **Which J_φ in EGENE input?**

#4.2 SOF design -2

- 3 different approaches to model $\mathbf{J_\varphi}$ in EGENE

1) "Scaled equilibrium" from SOF 4.1 using
   - l_i of SOF 4.1 (PID) → $l_i = 0.85$
   - β_p of SOF 4.2 (Research plan) → $\beta_p = 1.15$

2) β_p , l_i METIS output
   → $\beta_p = 1.36$
   → $l_i = 0.5$

3) p', ff' profiles METIS output

$$J_\varphi = r\frac{dp(\bar{\psi})}{d\bar{\psi}} + \frac{f(\bar{\psi})}{\mu_0 r}\frac{df(\bar{\psi})}{d\bar{\psi}}$$

#4.2 SOF design -2

- For cases 1) & 2):

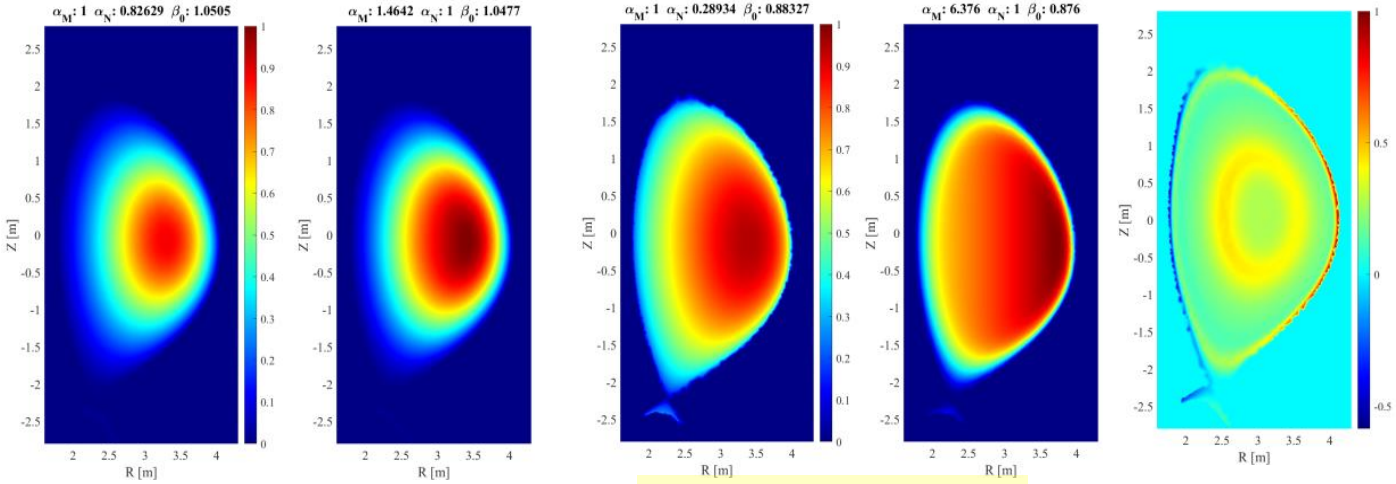
$$J_\phi = \lambda[\beta_0 \frac{r}{R_0} + (1-\beta_0)\frac{R_0}{r}](1-\bar{\psi}^{\alpha_M})^{\alpha_N}$$

a) Fixed α_M = 1 i.e. “linear profile” → estimated α_N and β_0
b) Fixed α_N = 1 i.e. $q_0 \sim 1$ → estimated α_M and β_0
c) Fixed $\beta_0 \sim \beta_p$ → estimated α_M and α_N

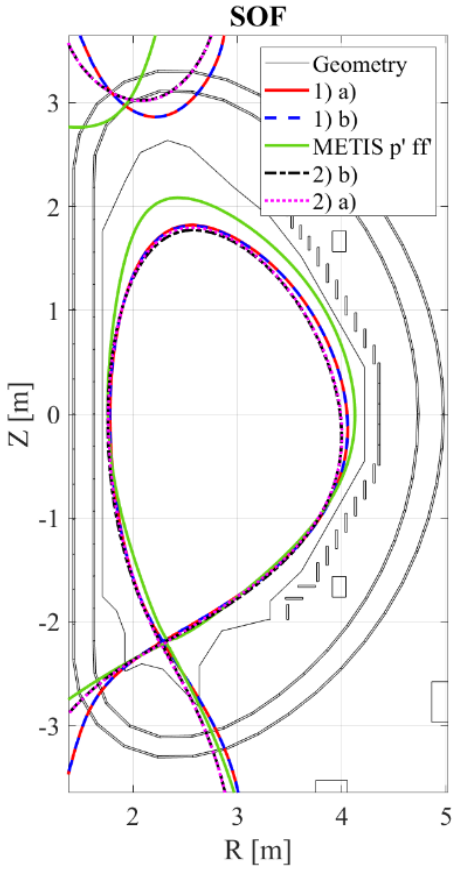
#4.2 SOF design -3

Within the chosen approach

- Agreement in β_p, l_i & plasma shape



1)a) 1)b) 2)a) 2)b) 3)

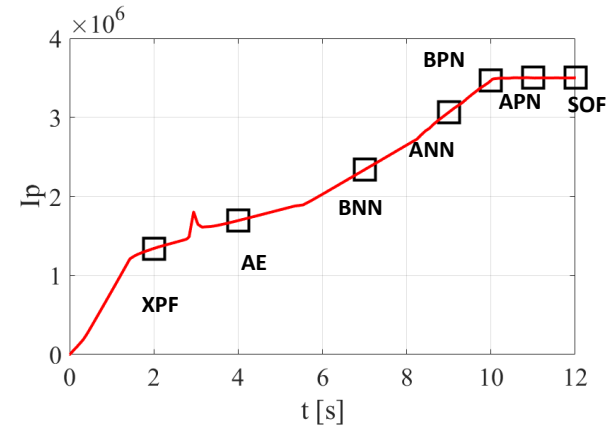


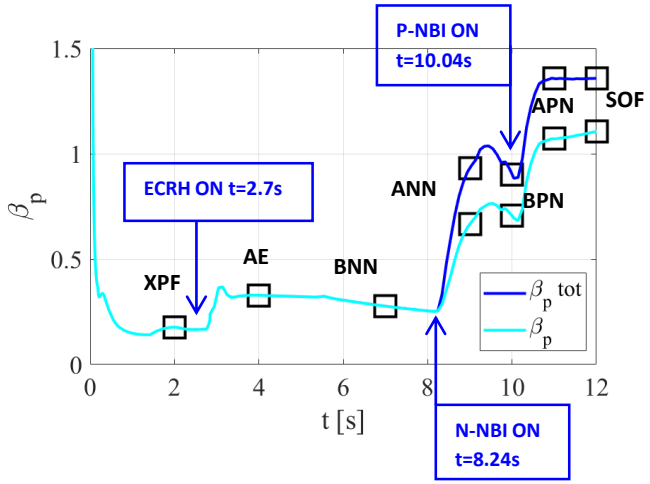
	PID	1) a)	1) b)	METIS	2) a)	2) b)	3)
I_p	**3.5**	3.5	3.5	**3.5**	3.5	3.5	3.5
β_p	**1.15**	1.15	1.15	**1.36**	1.36	1.36	1.48
l_i	**0.85 (#4.1)**	0.85	0.85	**0.50**	0.55	0.55	0.56
q_0	-	0.68	0.81	**1.40**	1.44	1.61	2.12
q_{95}	**4.4**	3.75	3.74	**5.15**	3.85	3.75	4.29

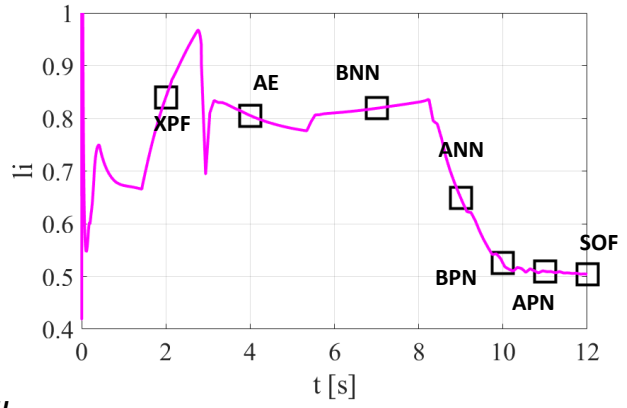
EGENE-METIS WEAK COUPLING -1

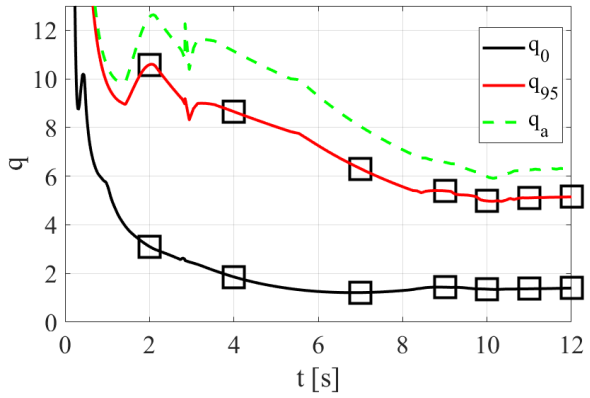
- Eq time instants defined using METIS simulation *

	XPF	AFTER ECRH (AE)	BEFORE N-NBI (BNN)	AFTER N-NBI (ANN)	BEFORE P-NBI (BPN)	AFTER P-NBI (APN)	SOF
t_{eq} [s]	2	4	7	9	10	11	12



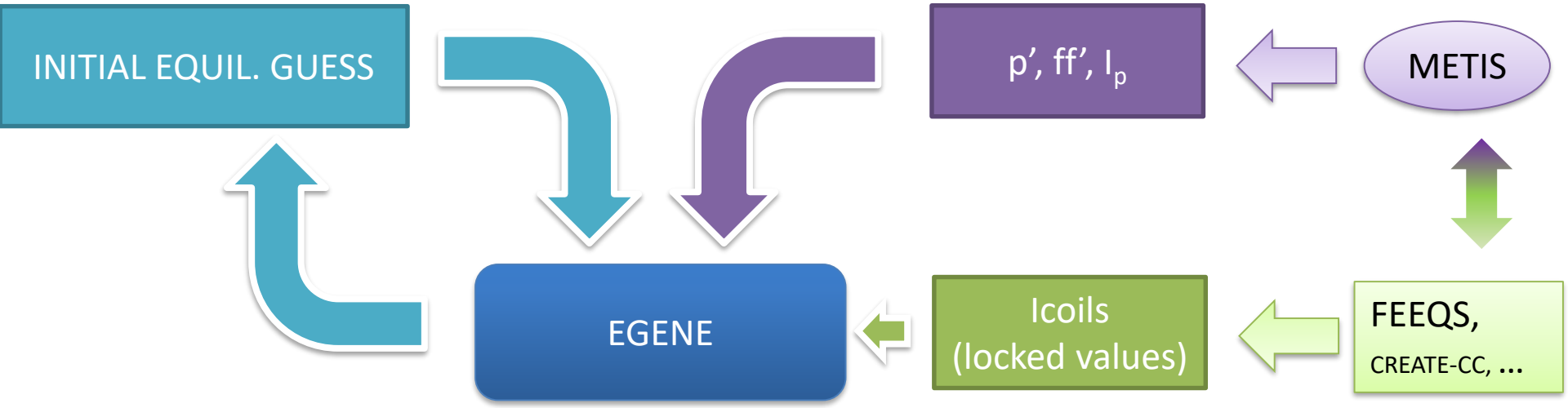






*see V. Ostuni talk

EGENE-METIS WEAK COUPLING -2



- Minor changes plasma shape managed with linearized models
- The procedure is repeated for each time step

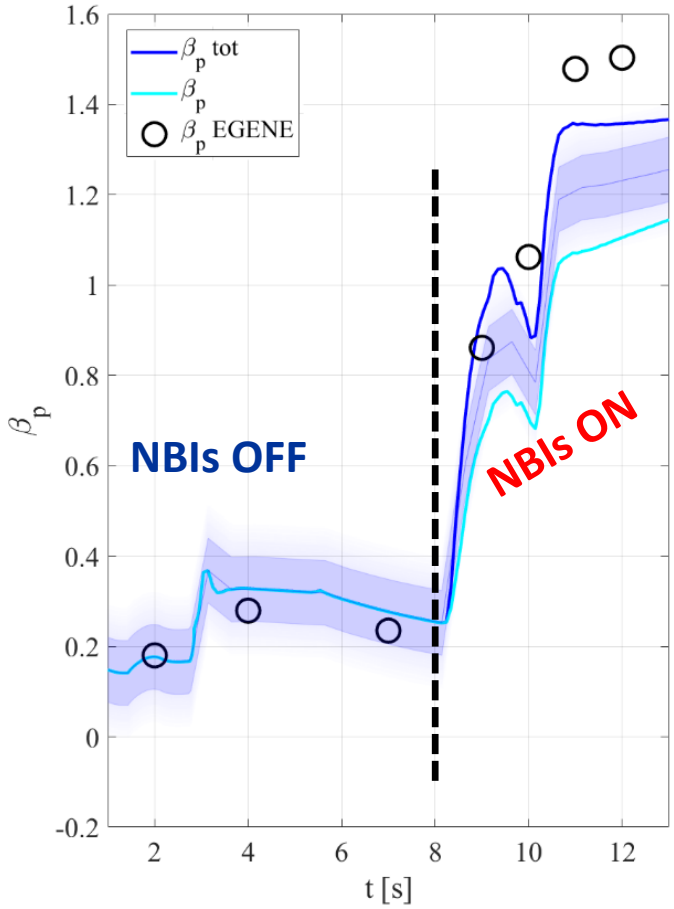
- Initial guess scheme:

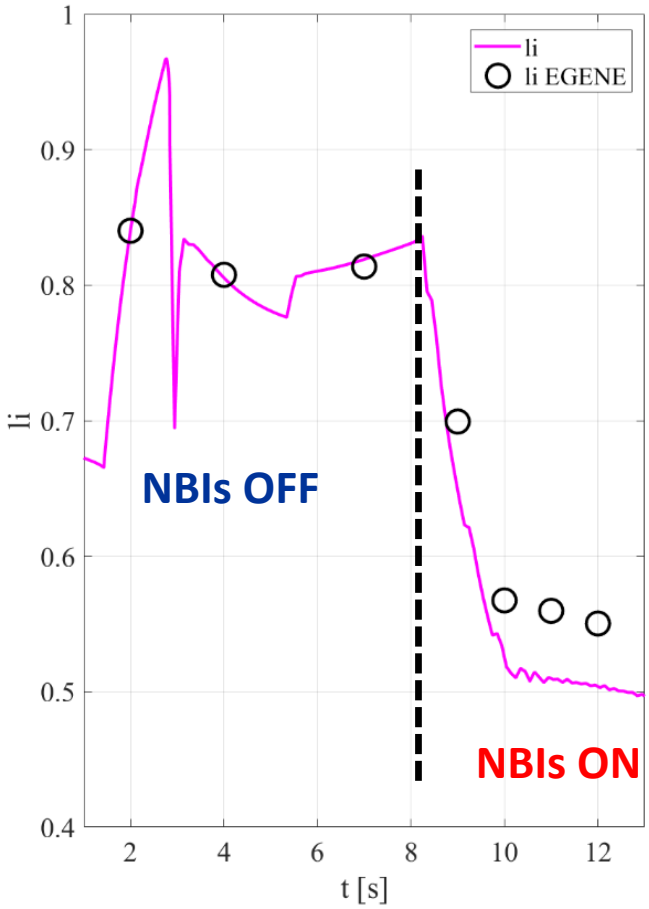
XPF #4.1
(page 5)

	XPF	AFTER ECRH (AE)	BEFORE N-NBI (BNN)	AFTER N-NBI (ANN)	BEFORE P-NBI (BPN)	AFTER P-NBI (APN)	SOF
teq [s]	2	4	7	9	10	11	12

WEAK COUPLING RESULTS

- EGENE vs METIS outputs
  - NBIs OFF → β_p, l_i agreement
  - NBIs ON → β_p mismatch (same definitions?)
    → l_i mismatch (slightly different plasma shapes)





Conclusions

- METIS-EGENE weak coupling can be successfully used to produce new scenario snapshots

- Particular focus on transition to "full power" phase
  - → match of β_p and li
  - → Match of plasma shape

- Need of a reliable tool to compute active coil currents
  - If left to EGENE → number steps to change shape may become very large.

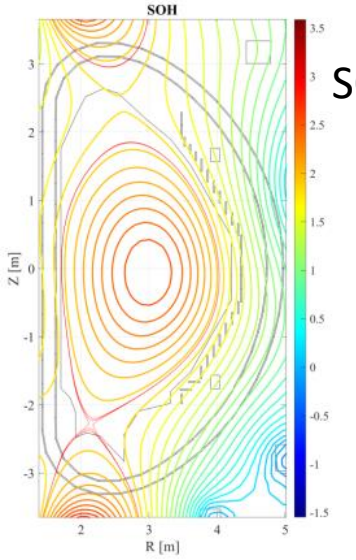
- Database of equilibria providing "nearest" linearized model to a given target snapshot

Preliminary test: EGENE on #4.1 - 3

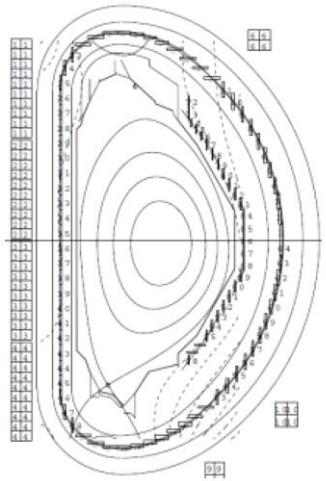
CNL = EGENE CREATENL
CL = EGENE CREATEL

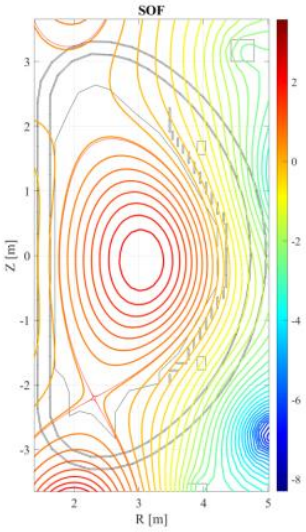
SOH@1.84MA					
	PID	CNL	ε_{CNL} [%]	CL	ε_{CL} [%]
β_p	0.35	0.35	0	0.35	0
l_i	0.85	0.85	0	0.857	0.78
q_{95}	7.39	7.35	-0.49	-	-

SOF@4.6MA					
	PID	CNL	ε_{CNL} [%]	CL	ε_{CL} [%]
β_p	0.53	0.53	0	0.53	0
l_i	0.85	0.85	0	0.855	0.6
q_{95}	2.73	2.71	-0.55	-	-



SOH





SOF