DEMO scenarios and use of ECRH/ECCD

G. Giruzzi

Association Euratom-CEA
CEA, IRFM (France)

irfm cea cadarache

Association Euratom-CEA

What is DEMO ?

- **No common definition in the fusion community**
- tentatively: a **1 GW** electrical power fusion reactor
- different design options among ITER partners

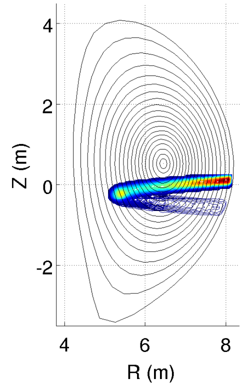
(Table: courtesy of K. Lackner)

- **e.g.:**
  - tokamak or stellarator ?
  - pulsed or steady-state ?
  - low or high aspect ratio ?

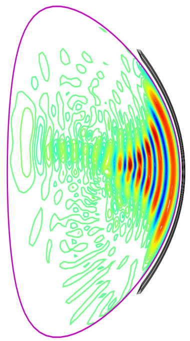
- **DEMO/reactor studies**
  - **EU**: based on PPCS studies *(Maisonnier et al., Nucl. Fus. 2007)*
  - **Japan**: SlimCS studies *(Tobita et al., Nucl. Fus. 2009)*
  - **USA**: based on ARIES studies *(Najmabadi et al., FST 2006)*
  - **Russia**: DEMO-S studies *(Shatalov et al., FED 2000)*
  - **…**

study	DEMO-S (RF)	DEMO-JAERI slim CS	DEMO-CREST OP4	ITER s-s:scenario 4-2	ARIES-AT
R_o	7,8	5,5	7,25	6,2	5,2
A	5,2	2,6	3,4	3,1	4
b/a	1,85	2,0	1,85		2,2
B_t	7,7	6	7,8	5,3	5,9
I_p	11,2	16,6	14,7	9	12,8
W_{magn} [GJ]	14	12	27	9,3	4
n/nGW	0,98	0,98	1,0		1,1
H	1 (RS)	1,3	1,2	1,5 (with ITP)	
$\beta_{N,therm}$	4,7	4,3	3,4	3	5,4
f_{bt}	0,59	0,77	0,5	0,6	0,91
γ_{CD}	0,47	0,41	0,3	0,45/0,2	0,4 (based on <n>)
$q_{div,ref}$ (80% radiation)	14,9	27,5	20,3	4,8	16
P_{heat}/Ro	78	121	103	22,5	68
P_{red}/P_{heat}		0.9			

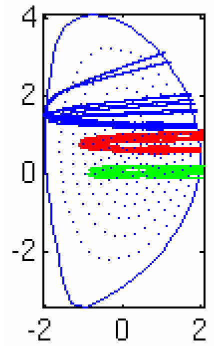
Which (and how many) H&CD systems in DEMO ?



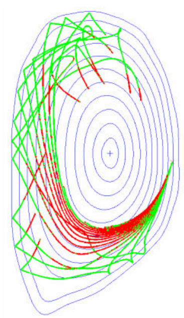
- **NBI**
  - heating, **co-CD**, highest efficiency (γ_{CD} ~ 0.5 A W^{-1} 10^{20} m^{-2})
  - on-axis + mildly off-axis (ρ ~ 0.2-0.4), broad deposition



- **ICRH**
  - **pure heating** (2nd T harm.), **ion heating**
  - **co-CD** or **cnt-CD** (FWCD)
  - mainly on-axis (peaked)



- **ECCD**
  - **co-CD**, limited off-axis efficiency (γ_{CD} < 0.2 A W^{-1} 10^{20} m^{-2})
  - **MHD** control: efficient and precise



- **LHCD**
  - **strongly** off-axis CD (ρ ~ 0.8)

1.5D modelling of DEMO scenarios with the CRONOS code

- **CRONOS simulations for a 7.5 m DEMO, 1 or 2 H&CD systems**

- **a q > 1 (pulsed) scenario for DEMO:**
  - based on first-principle transport model GLF23
  - using **only one CD system**: NBI
  - P_{fus} ~ 2.6 GW, 88 % non-inductive current, $f_{Greenwald}$ ~ 1.2, **Q = 26**,

- **a q > 1 (steady-state) scenario for DEMO:**
  - using **2 CD systems**: NBI and ECCD
  - P_{fus} ~ 2.8 GW, 99 % non-inductive current, $f_{Greenwald}$ ~ 1.2, **Q = 17**
  - **control issues** not yet explored

- **a q > 2 (advanced) scenario for DEMO:**
  - simple transport model allowing **ITB** formation
  - using 2 CD systems: NBI and ECCD
  - goals of the scenario not attained

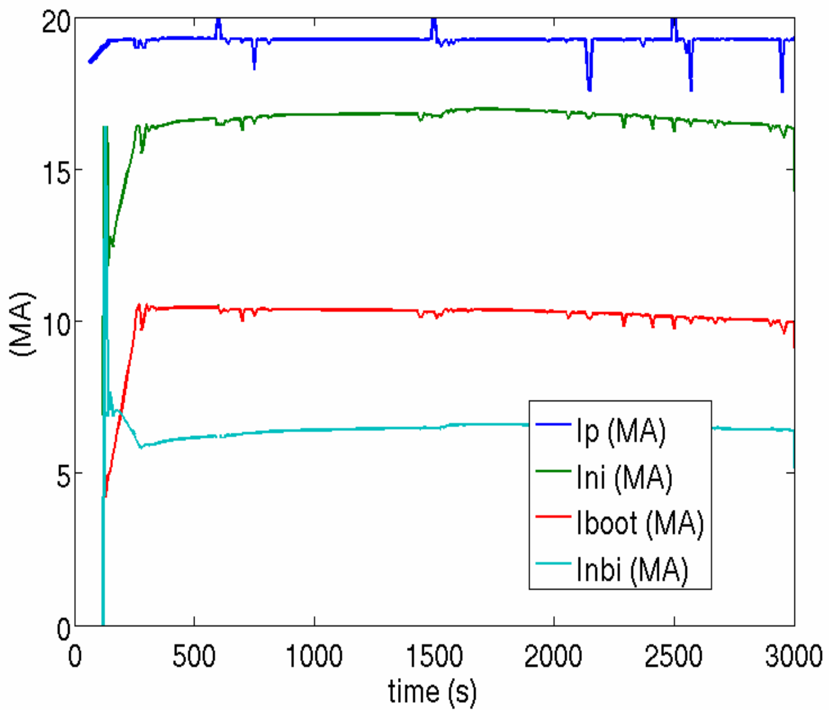
*J. Garcia et al., Nucl. Fusion **48** (2008) 075007*
J. Garcia et al., IAEA 2008, paper FT/P3-15

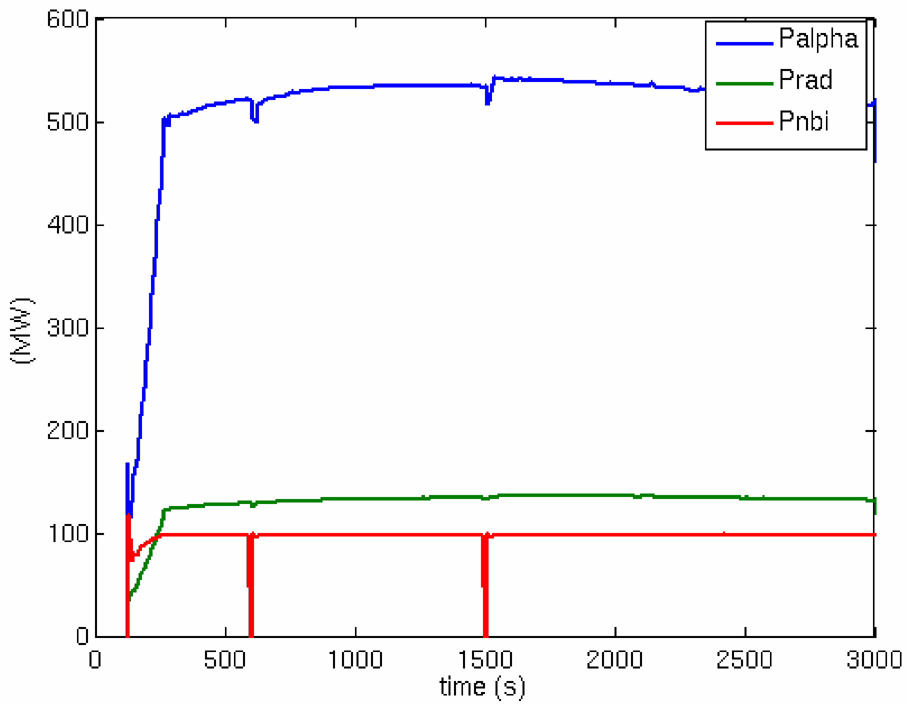
Simulations performed: Pulsed and Steady-State DEMO

Parameter	Pulsed	Steady-State	Advanced
Major radius R (m)	7.5	7.5	7.5
Minor radius a (m)	2.5	2.5	2.5
Elongation/Triangularity	1.9 / 0.47	1.9 / 0.47	2.0 / 0.58
B_t (T)	6.0	6.0	6.0
I_p (MA)	19	19	14
$n_{e,0}$ (10^{20} m^{-3})	1.25	1.25	1
n_e/n_G	1.20	1.20	1.4
T_{ped} (keV)	7.8	7.8	4.5
P_{NBI} (MW)	98	98	50
P_{IC} (MW)	0	0	0
P_{EC} (MW)	0	66 (0)	30
P_{LH} (MW)	0	0 (66)	0
P_{fus} / P_{add} (MW) / Q	2600 / 98 / 26	2820 / 164 / 17	1750 / 80 / 17
P_{syn} / P_{brems} (MW)	28 / 104	34 / 107	36 / 60
f_{BS} (%) / f_{NI} (%)	53 / 88	56/ 99	70 / 95
q_0 / q_{95}	2.6 / 6	10 / 6	6 / 9

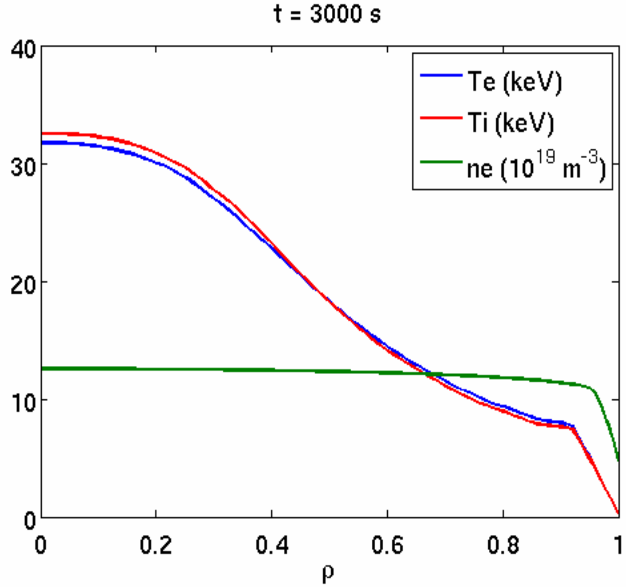
Pulsed scenario
Global parameters

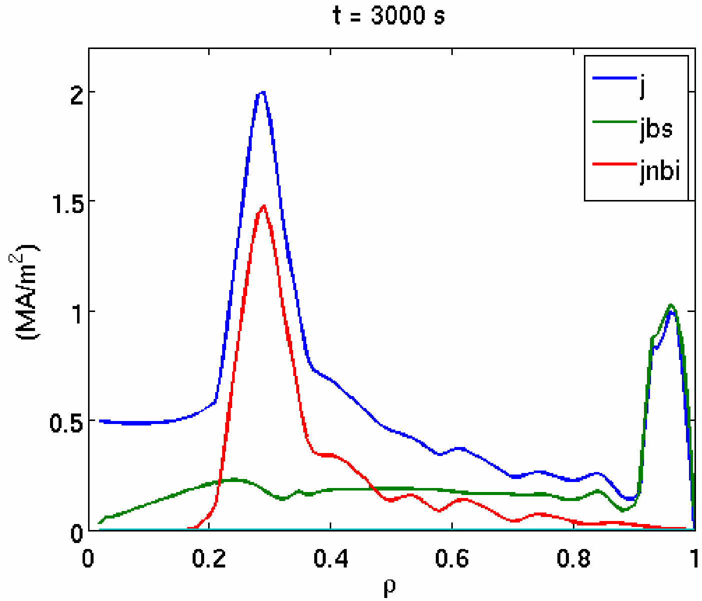
- I_p = 19 MA, B_T = 6 T, n_{e0} = 1.25 10^{20} m^{-3}
- $f_D/(f_D+f_T)$ = 50%, f_{Be} = 3%, f_{Ar} = 0.12%, τ_{He}^*/τ_E = 5 (Z_{eff} ~ 1.9)
- P_{NBI} = 98 MW (2 MeV, **off-axis**)
- **transport model: GLF23** T_{ped} ≈ 7.8 keV *(~ Cordey scaling)*

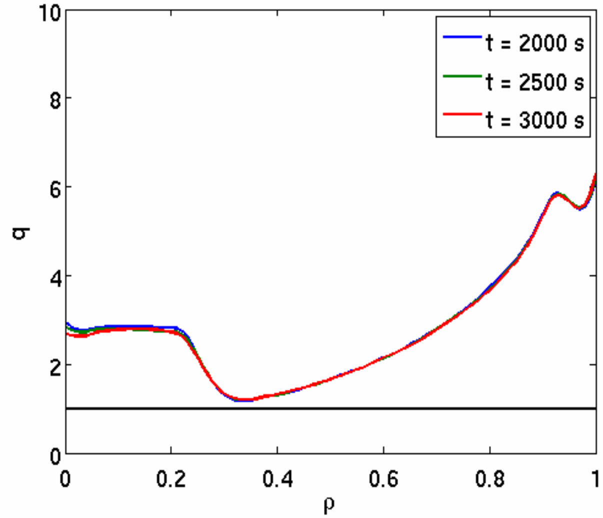




Pulsed scenario
Profiles at t = 3000 s



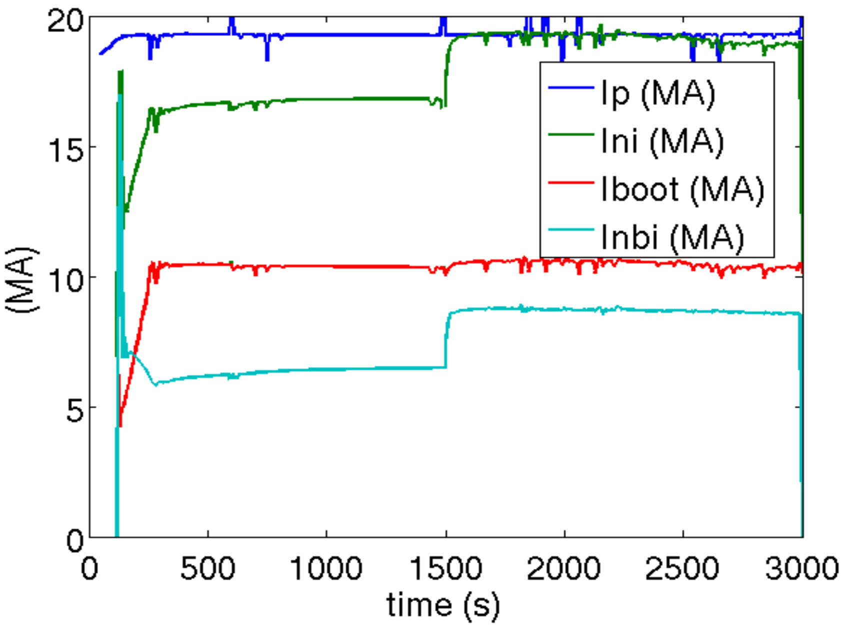


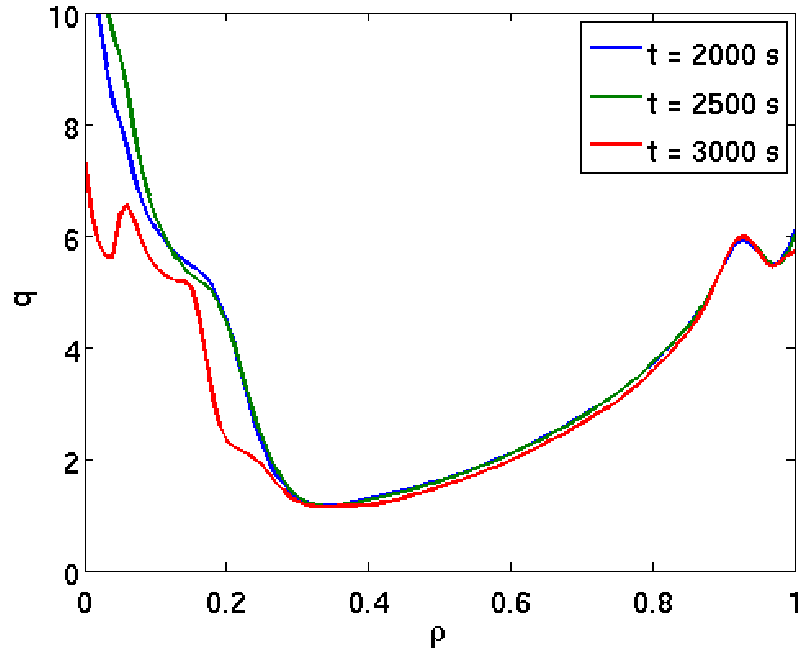


f_{bs} = 53%, f_{ni} = 88%
Q = 26

Increase of NBI power → f_{ni} ~ 1 → loss of q-profile control

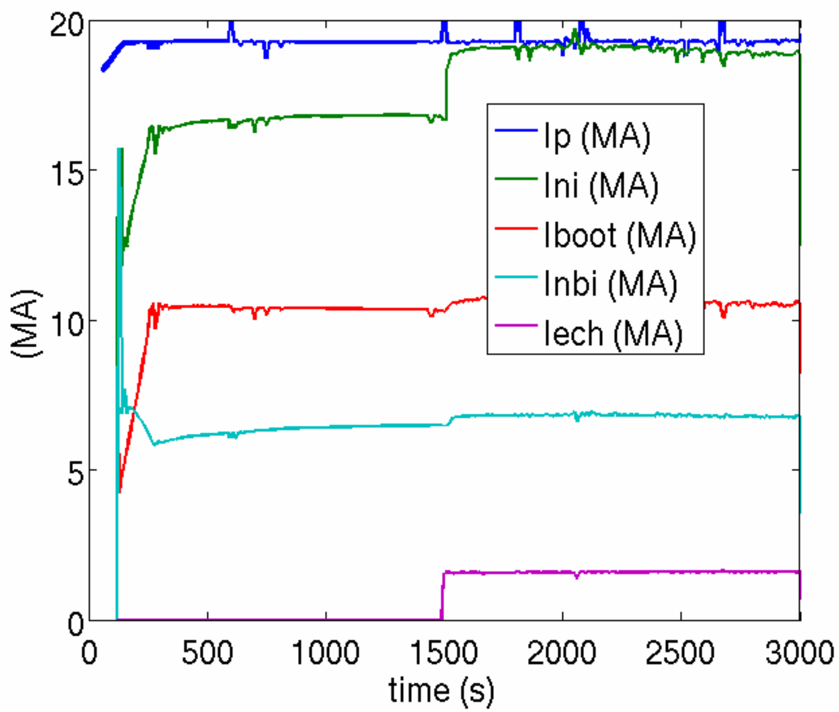
- I_p = 19 MA, B_T = 6 T, n_{e0} = 1.25 10^{20} m^{-3}
- $f_D/(f_D+f_T)$ = 50%, f_{Be} = 3%, f_{Ar} = 0.12%, τ_{He}^*/τ_E = 5 (Z_{eff} ~ 1.9)
- P_{NBI} = **128 MW** (2 MeV, **off-axis**),
- **transport model: GLF23** T_{ped} ≈ 7.8 keV

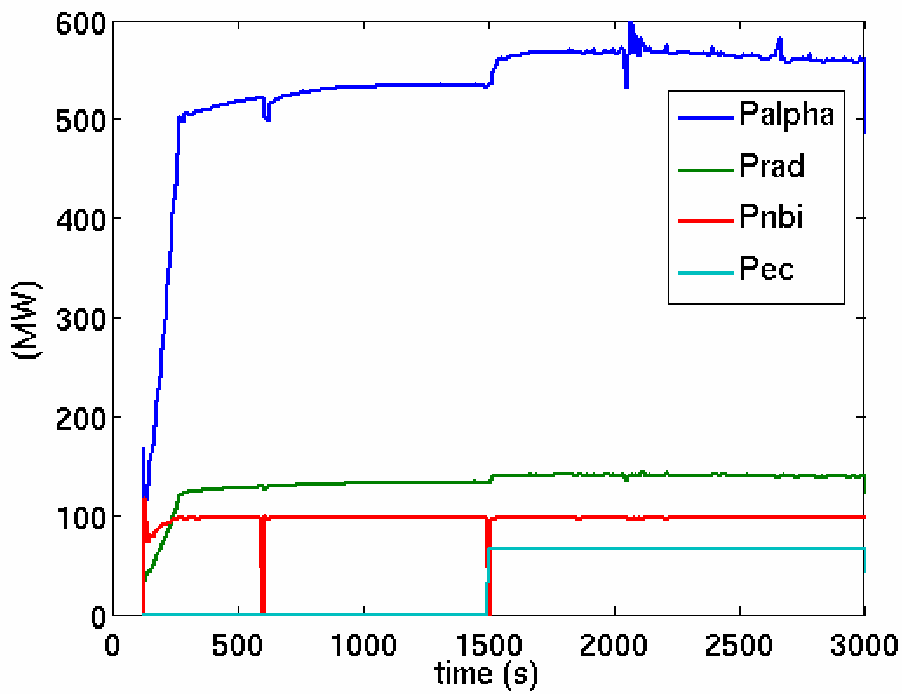




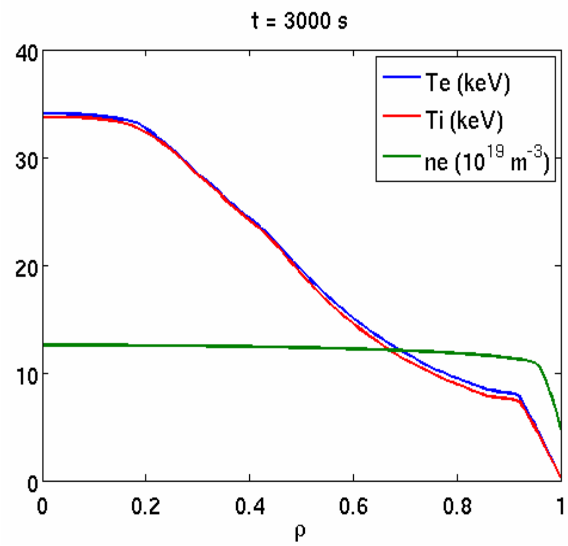
Steady-state scenario with ECCD
Global parameters

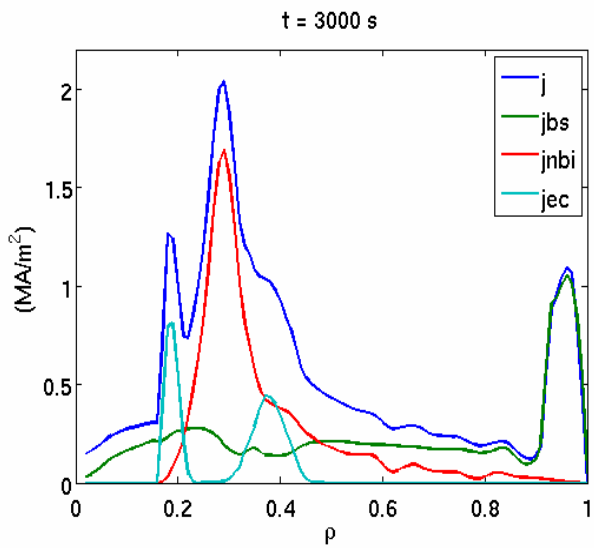
- I_p = 19 MA, **B_T = 6 T**, n_{e0} = 1.25 10^{20} m^{-3}
- $f_D/(f_D+f_T)$ = 50%, f_{Be} = 3%, f_{Ar} = 0.12%, τ_{He}^*/τ_E = 5 (Z_{eff} ~ 1.9)
- P_{NBI} = 98 MW (2 MeV, **off-axis**), P_{EC} = 66 MW (**200 GHz**, t > 1500 s)
- **transport model: GLF23** $T_{ped} \approx$ 7.8 keV

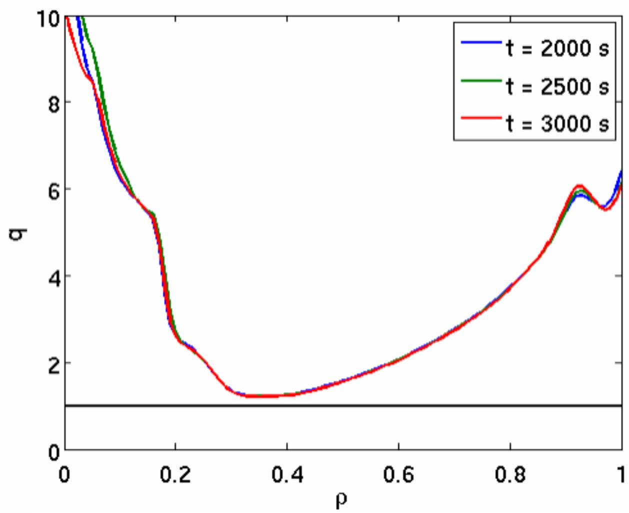


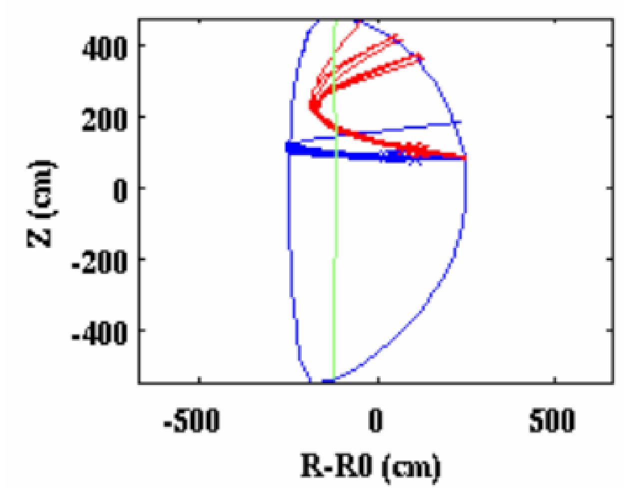


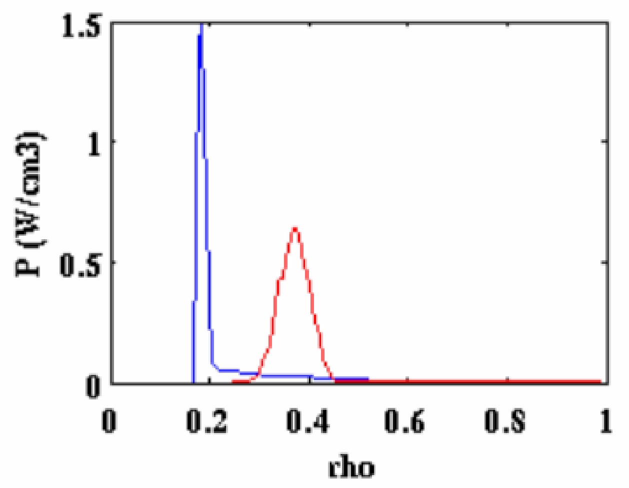
Steady-state scenario with ECCD
Profiles at t = 3000 s











f_{bs} = 56%, f_{ni} = 99%
Q = 17

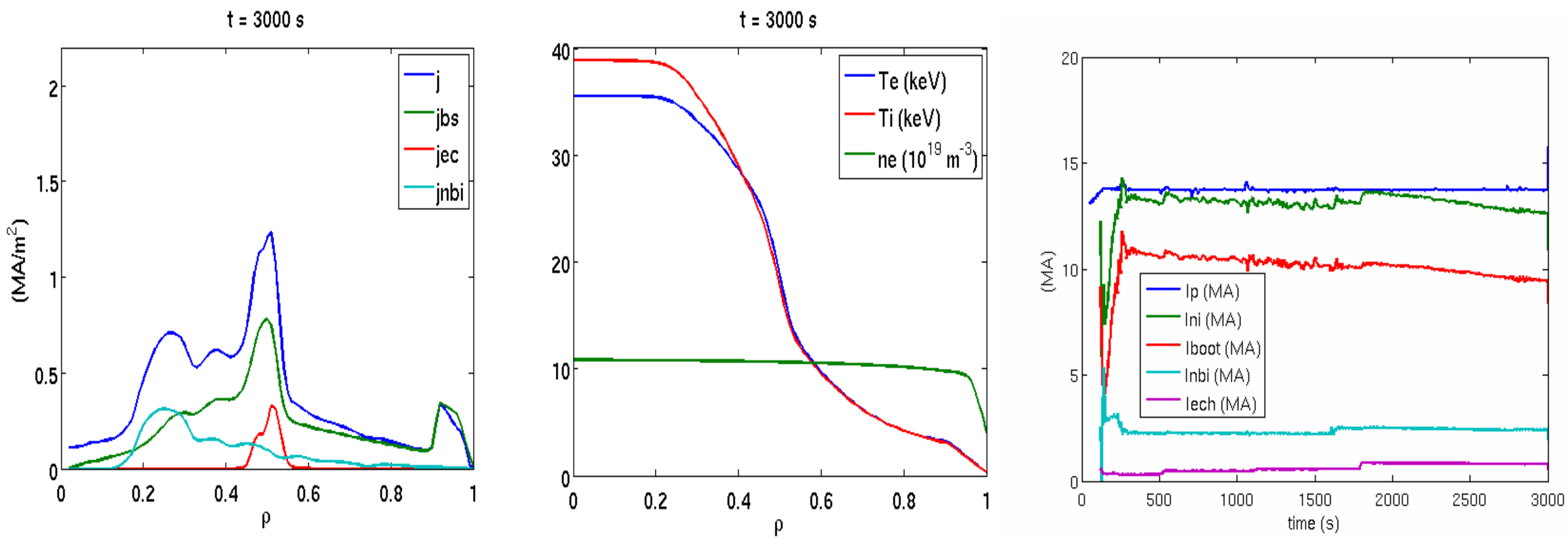
DEMO advanced scenario with ITB: Goals not attained so far

- I_p = 14 MA, B_T = 6 T, $\beta_N \approx 3.3$, plasma in flat-top phase
- P_{NBI} = 50 MW (2 MeV), P_{EC} = 30 MW, $T_{ped} \approx 4.5$ keV
- simple core transport model: $\chi_e = \chi_i = \chi_{i,neo} + 0.4\,(1+3\rho^2)\,F(s)$ (m^2/s)

F(s): shear function allowing an ITB formation for s < 0

Fusion power ~ 1.75 GW → Electrical power < 1 GW

f_{bs} = 70%, f_{ni} = 95%, Q = 17

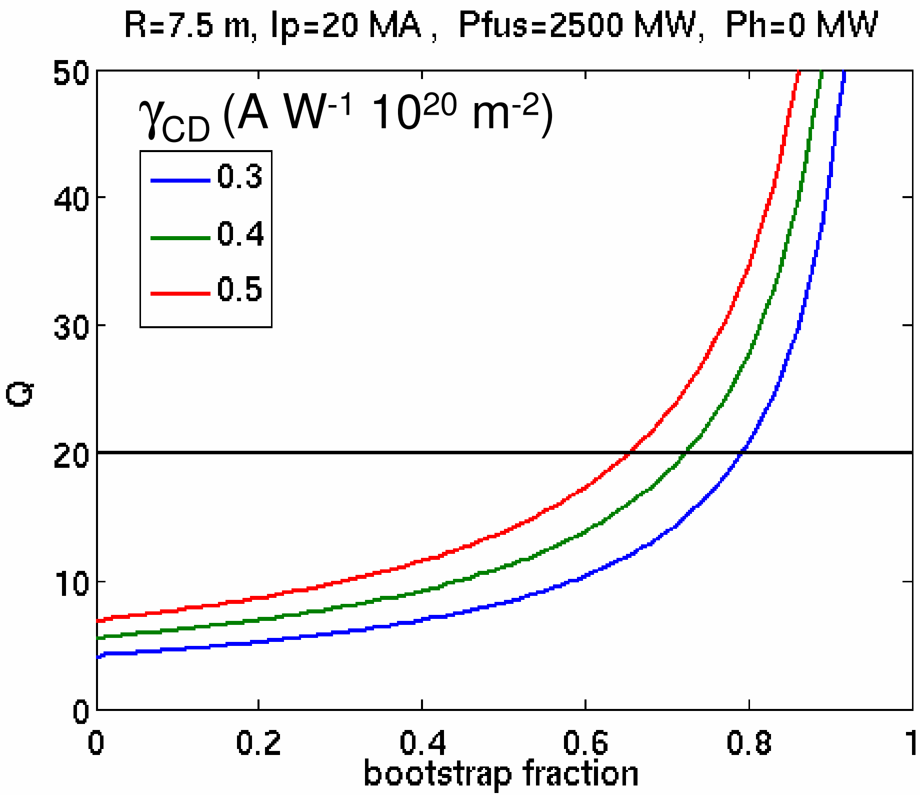


CD efficiency and bootstrap

For steady state ($V_{loop} = 0$)

$$Q = \frac{P_{fus}}{P_h + \frac{\overline{n}_e R I_p}{\langle \gamma_{CD} \rangle}(1 - f_{bs})}$$

P_h: pure heating power



- **for R=7.5 m, Q > 20, 1 or 2 CD systems:**
  - recipe for steady state scenario not found so far
  - even at T_{ped} ~ 8 keV, $f_G > 1$
  - combination of NBI and ECCD likely to be optimum

Use of ECRH/ECCD on DEMO

- **functions of EC waves in DEMO: same as in ITER ?**
  - plasma startup
  - heating for access to H-mode
  - q-profile control (mid-radius CD)
  - MHD control (NTM, other ?)
  - CD for steady-state ?
  - Bootstrap control ?
  - Impurity control ?
  - Disruption control ?

- **likely system requirements:**
  - frequency ~ 200 GHz, cw, power ~ 50 – 100 MW
  - full control of absorption location
  - efficiency / availability / reliability

    (to be quantified in function of the missions of DEMO …)