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Progress of Hybrid modeling for JET and extrapolation to D-T

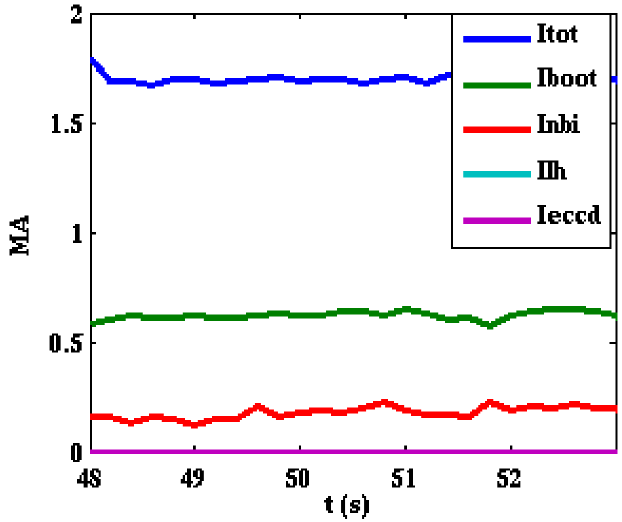
J. Garcia

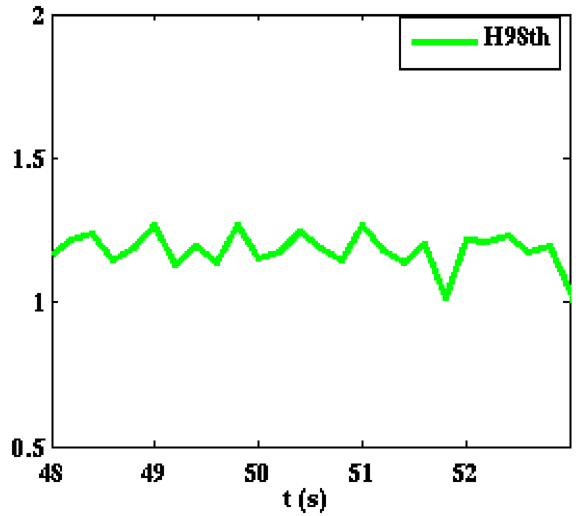
With the help of C. Challis, G. Giruzzi and G.Sips

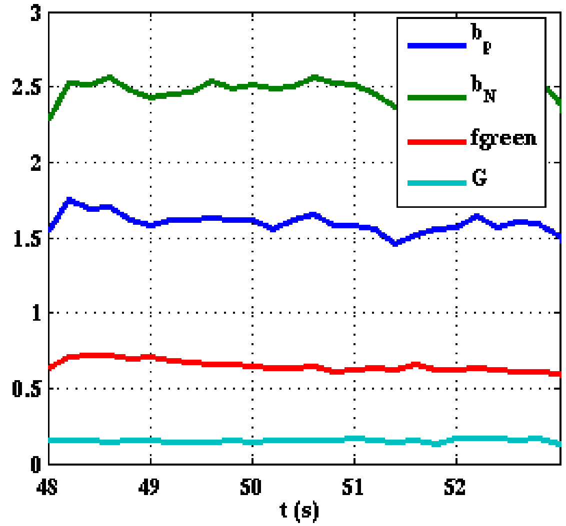
Outline

- Interpretative and predictive analysis of shot 77922
- Scenario1: Extrapolation of shot 77922 conserving f_G and H_{98} at Pnbi=34.8MW (and q_{95}=3)
- Scenario2: Extrapolation of shot 77922 at lower f_G and H_{98} at Pnbi=34.8MW (and q_{95}=3)
- Scenario3: Hybrid like scenario at Ip=2.3MA and Pnbi=34.8MW (and q_{95}=4)
- Comparison with ITER
- Conclusions

Shot 77922



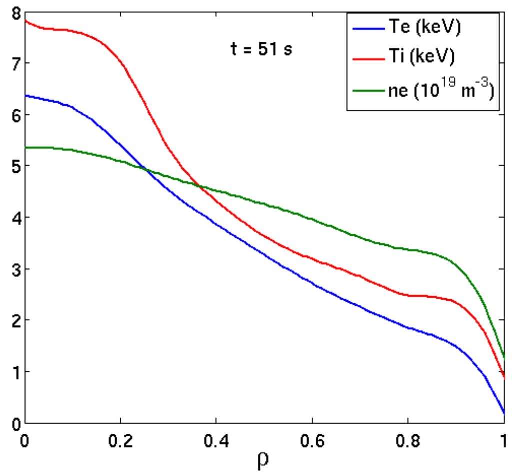


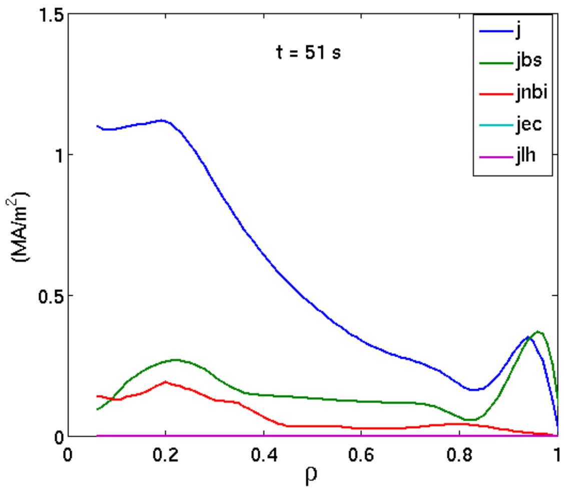


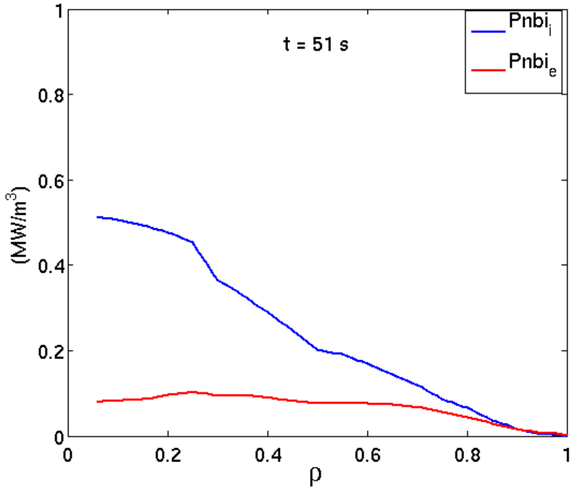
- Ip=1.7MA B_t=2.23T
- Iboot=0.63MA fboot=37%
- Ini=0.8 MA fni=47%
- Pnbi=16MW

- H_{98}=1.2
- β_N=2.5
- β_p=1.6
- q_{95}=4.1
- f_G=0.63

Shot 77922

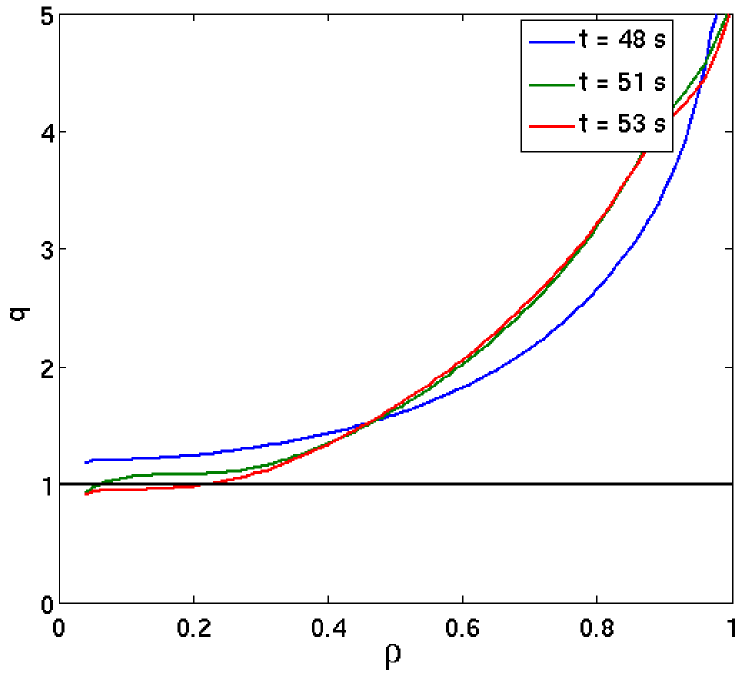






- Weak ITB for the ions
- Very high pedestal
- Off-axis bootstrap current contribution
- NBI power mainly coupled to the ions

Shot 77922



- Slow evolution of the q profile
- It remains rather flat in the core
- q_0 is close to 1

Shot 77922 simulation with bgb

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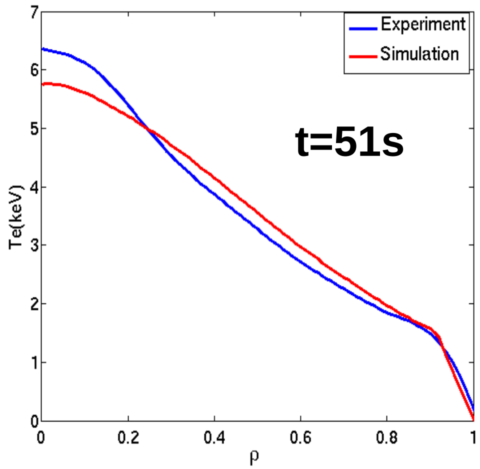
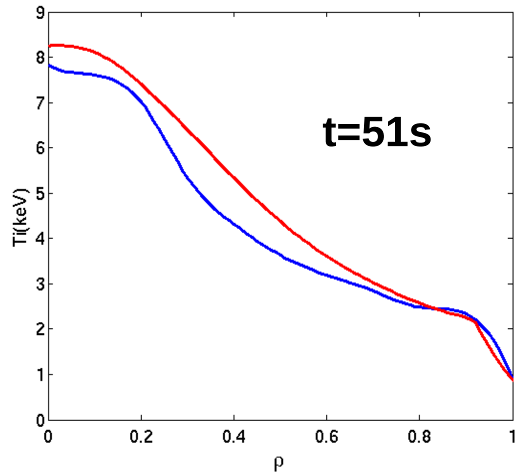
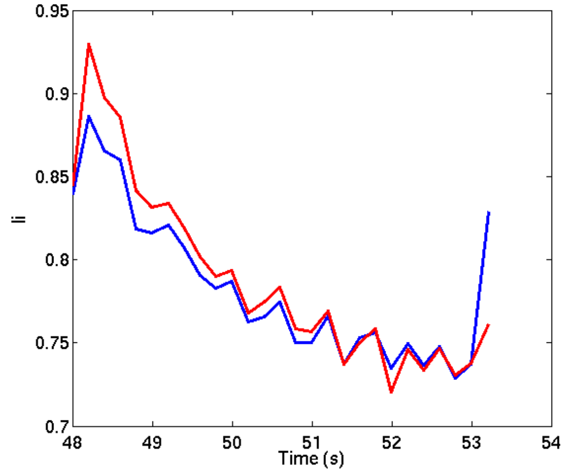
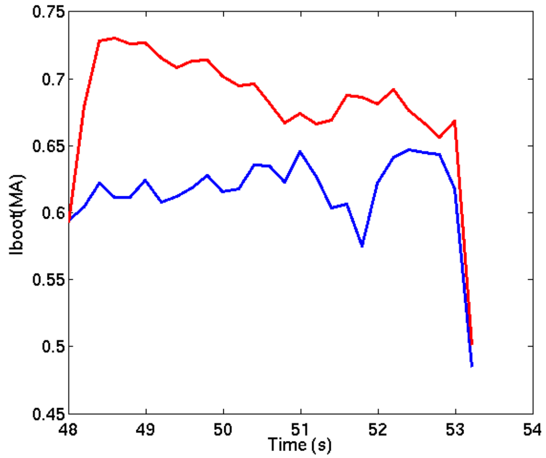


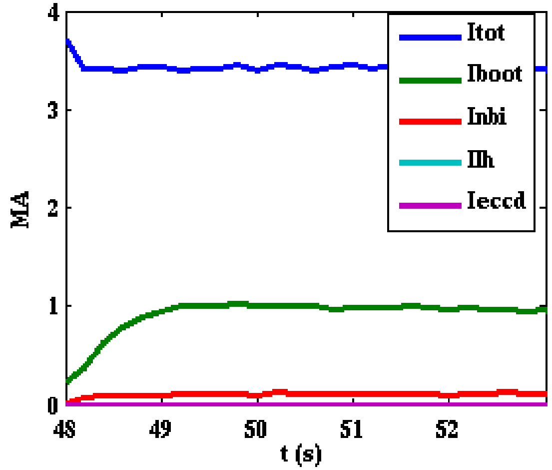


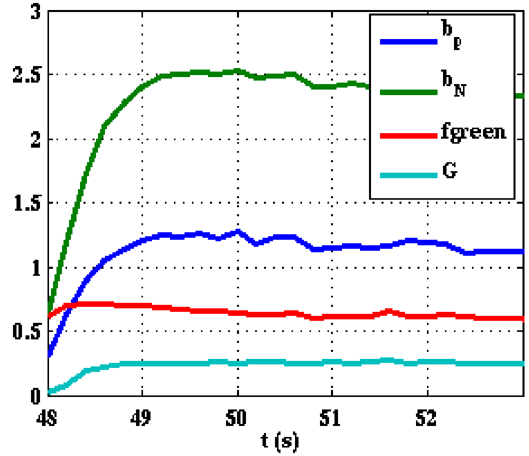


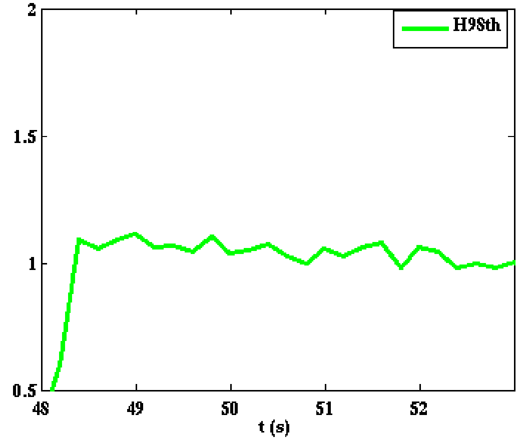


- Temperatures well simulated with Bohm-Gyrobohm (with experimental density profile)
- Li3 and bootstrap current are reasonably well simulated
- The pedestal temperatures are taken from the experiment

Scenario1: 77922 extrapolation conserving f_G and H_{98}







- Ip=3.45MA B_t=3.5T
- Iboot=0.98MA fboot=28%
- Ini=1.08 MA fni=31%

- H_{98}=1.05
- β_N=2.4
- β_p=1.2
- q_{95}=3 (for shot 77922 it was q_{95}=4)
- f_G=0.63

Scenario1: 77922 extrapolation conserving f_G and H_{98}

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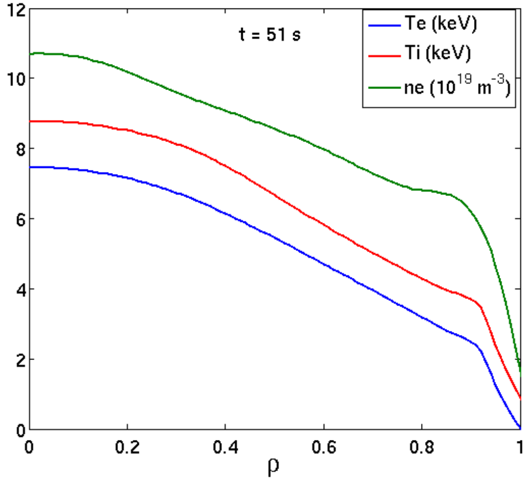

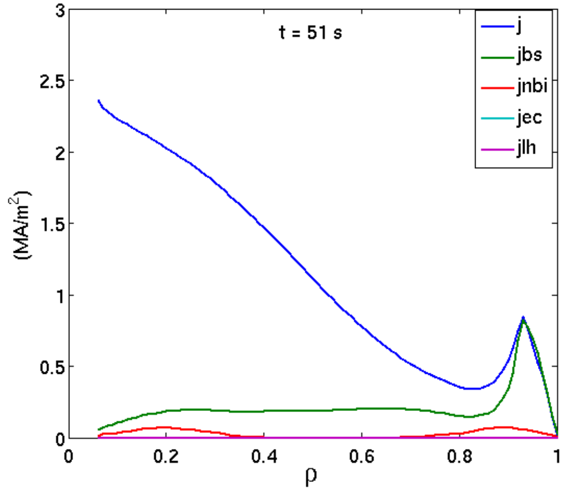

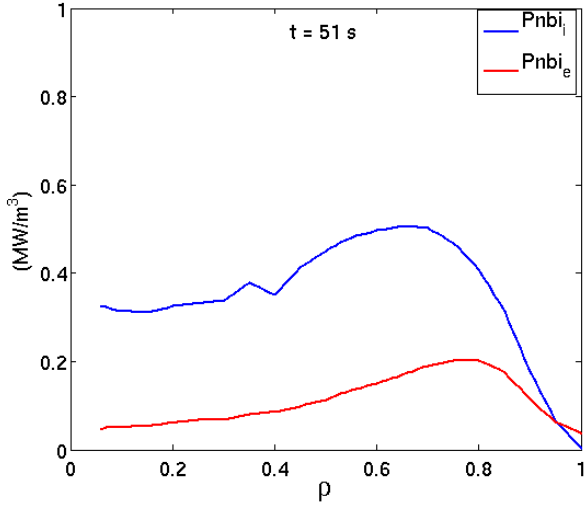

- The ratio Ti_0/Te_0 changes. The weak ITB for the ions is lost
- The NBI power is far off-axis which avoids the increasing of Ti_0
- The NBCD highly drops due to the density increasing

Scenario1: 77922 extrapolation conserving f_G and H_{98}

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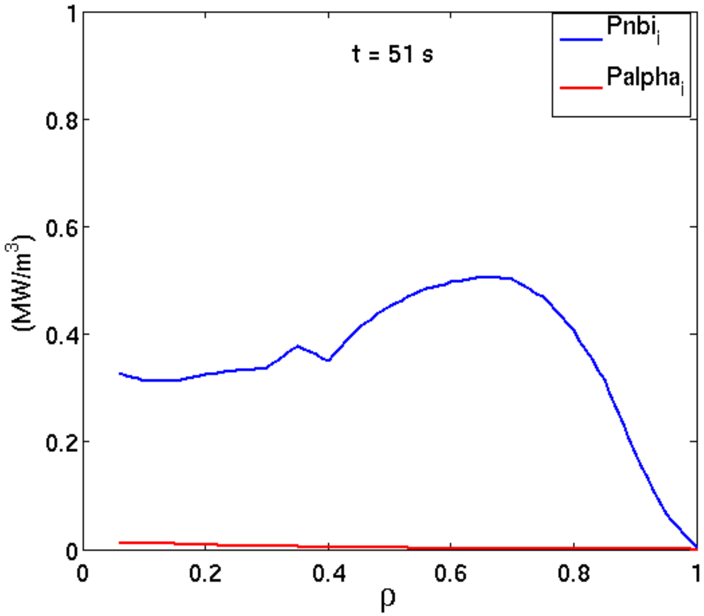

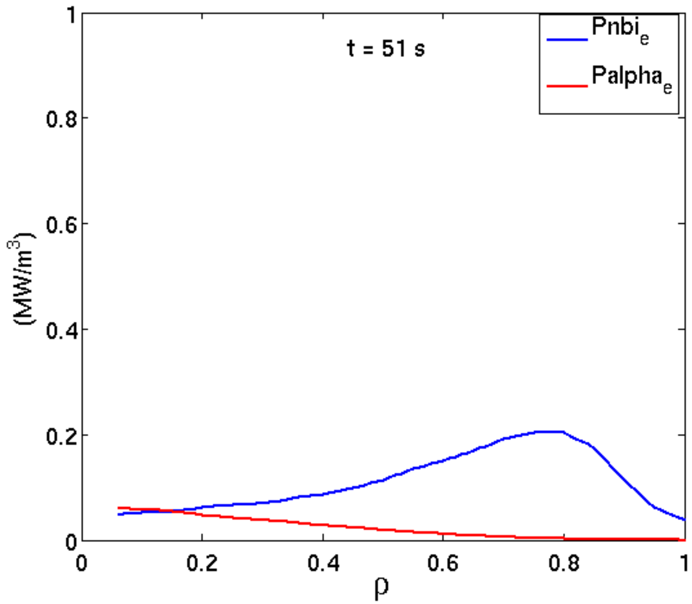

- The total alpha power is 1.1MW
- It is mainly coupled to the electrons

Scenario1: 77922 extrapolation conserving f_G and H_{98}

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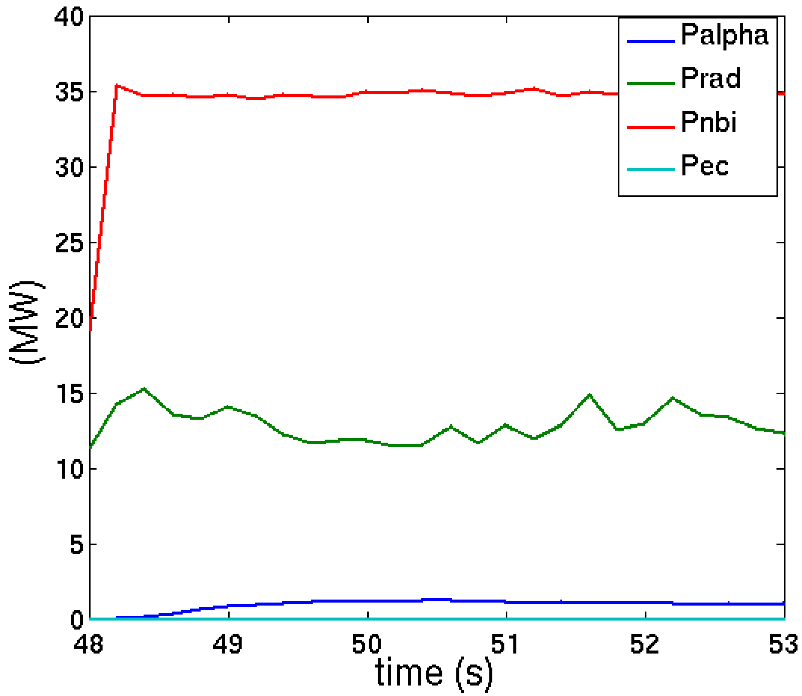

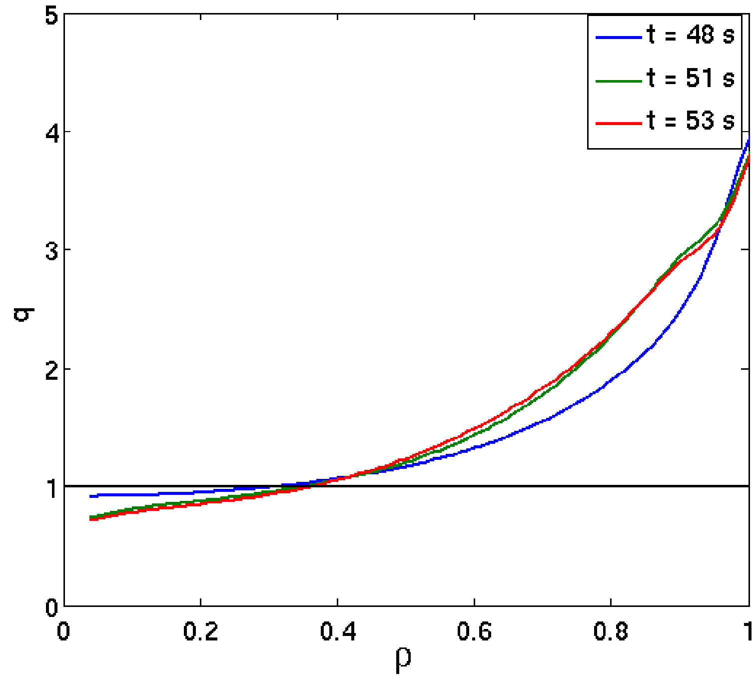

- Prad=12.5MW
- q_{95}=3, q_0=0.75
- The q profile drops well below 1
- The q profile is more similar to a typical H mode

Scenario2: 77922 extrapolation at lower f_G and H_{98}

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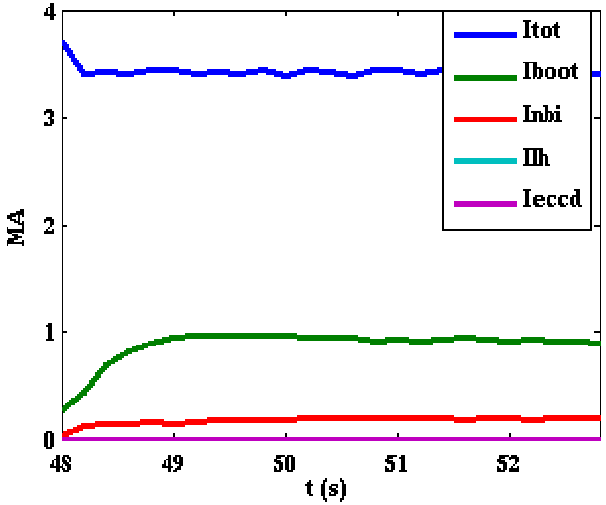
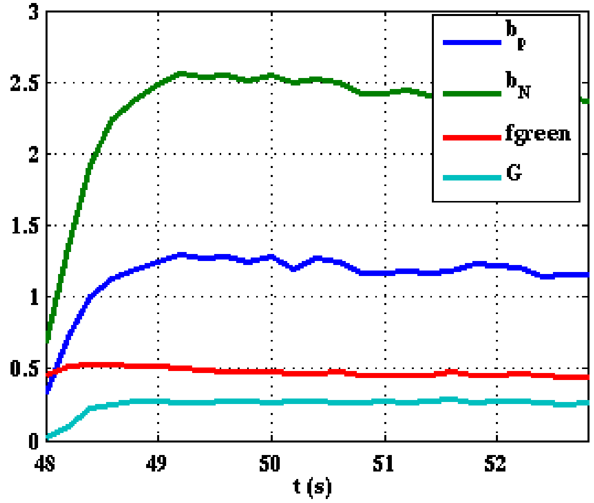
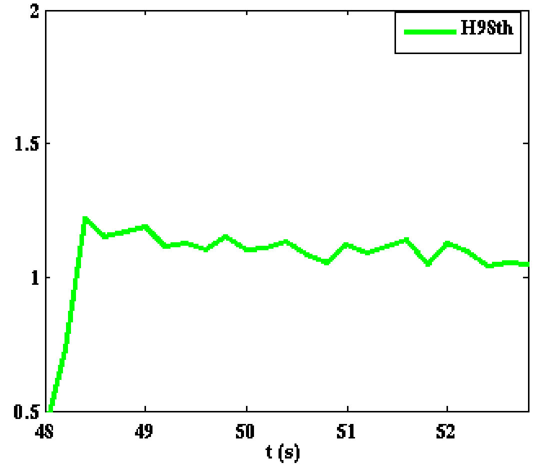


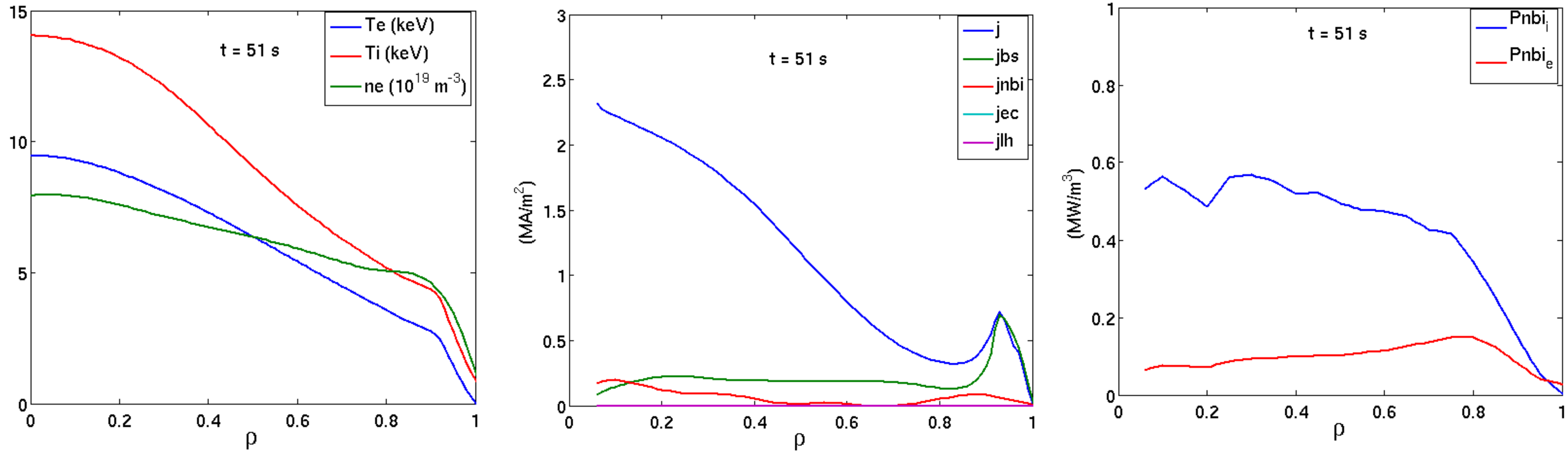




- Ip=3.45MA B_t=3.5T
- Iboot=0.92 MA fboot=27%
- Ini=1.12 MA fni=32%

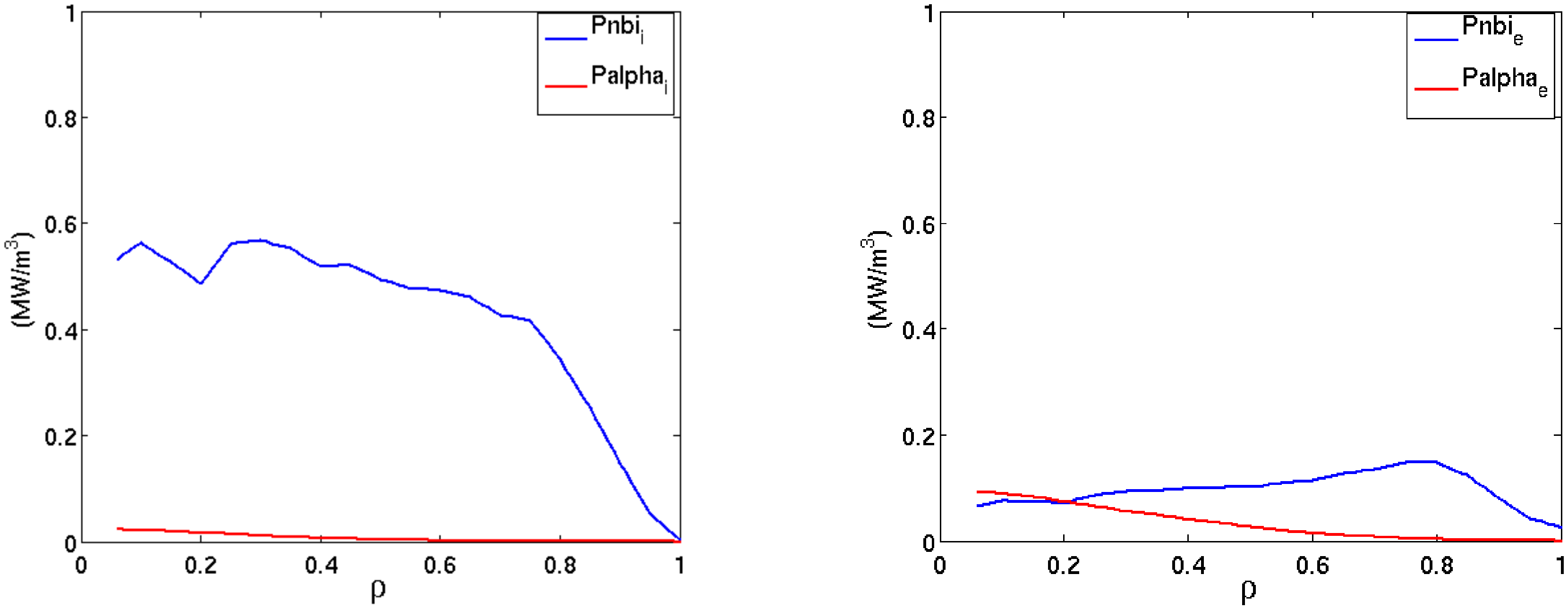
- H_{98}=1.1
- β_N=2.4
- β_p=1.2
- q_{95}=3 (for shot 77922 it was q95=4)
- f_G=0.46

Scenario2: 77922 extrapolation at lower f_G and H_{98}



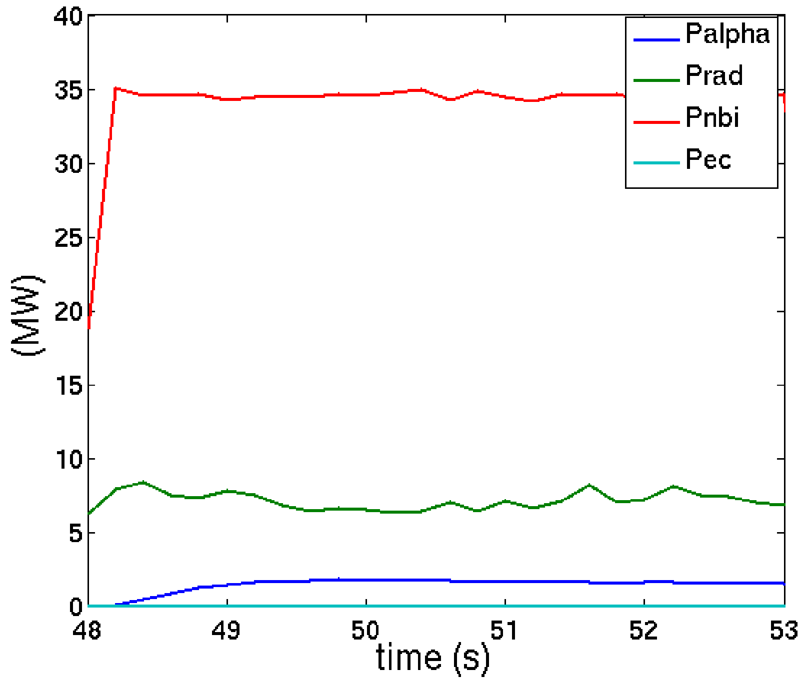
- The temperature pedestal is increased when density is lower at the edge
- The ratio Ti_0/Te_0 obtained increases at lower density
- The NBI power becomes more on-axis

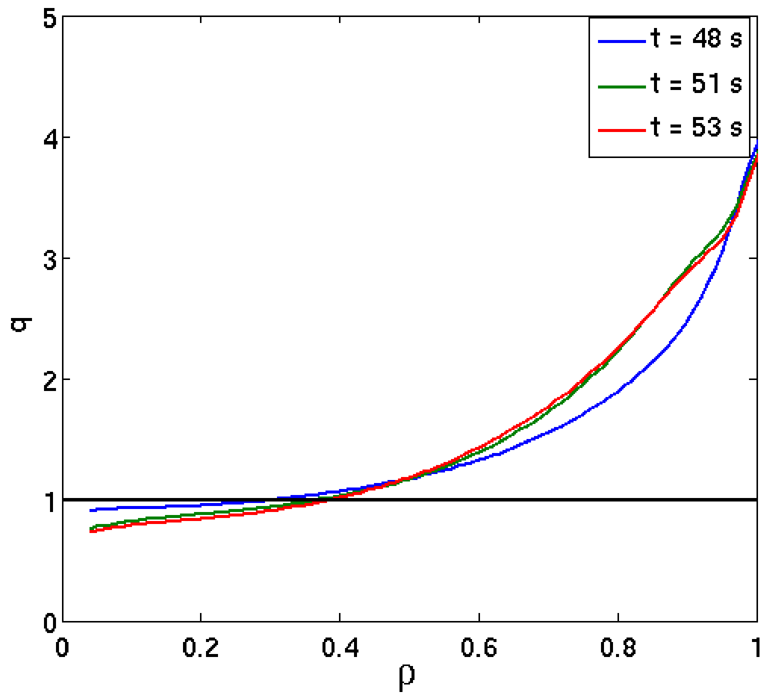
Scenario2: 77922 extrapolation at lower f_G and H_{98}



- The total alpha power is 1.6 MW
- It is 40% more than in the higher density case

Scenario2: 77922 extrapolation at lower f_G and H_{98}





- Prad=7.5MW
- q_{95}=3, q_0=0.75
- The q profile behavior is very similar to the previous case

Scenario3: Hybrid-like JET scenario@Ip=2.3MA

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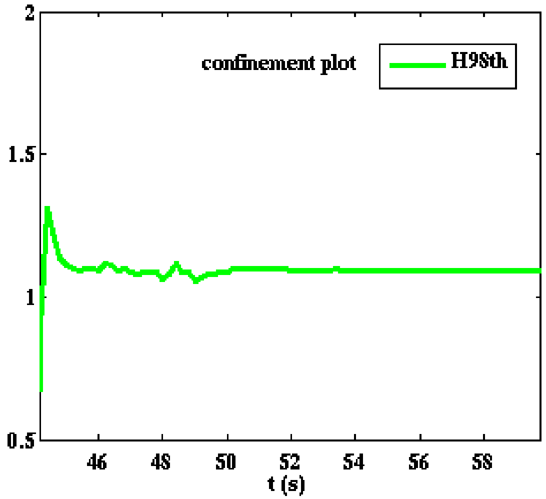

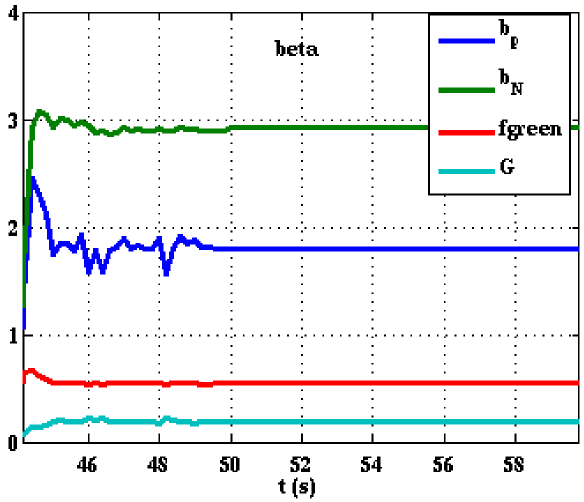

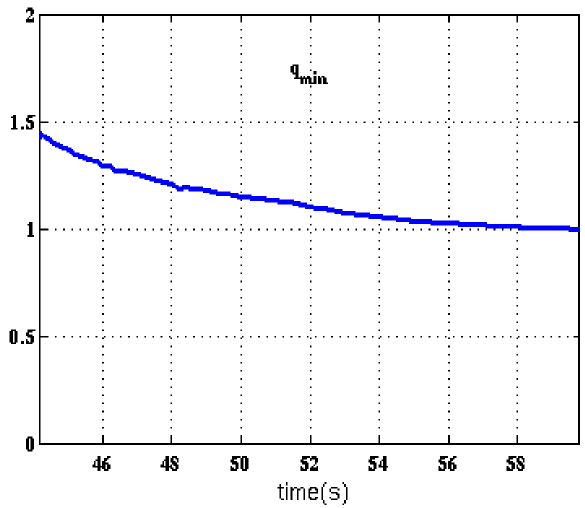

- H_{98}=1.1
- β_N=2.8
- β_p=1.8
- q_{95}=4
- Palpha=0.6 MW
- q_0=1
- f_G=0.55

Scenario3: Hybrid-like JET scenario@Ip=2.3MA

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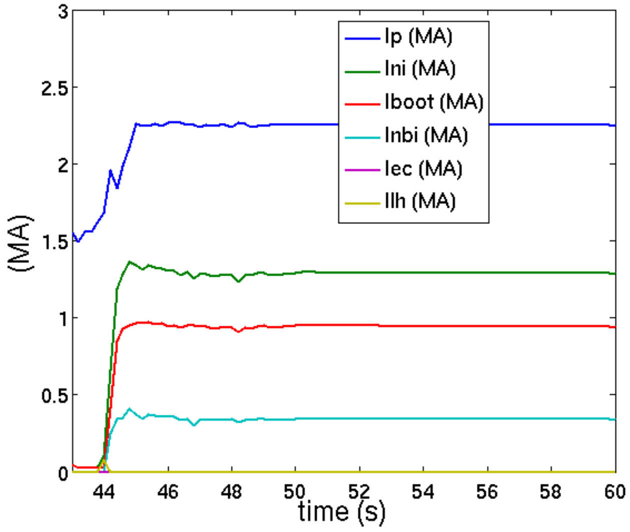
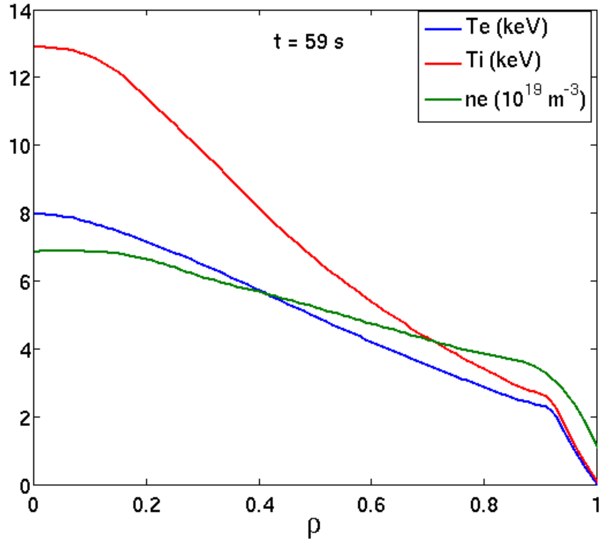
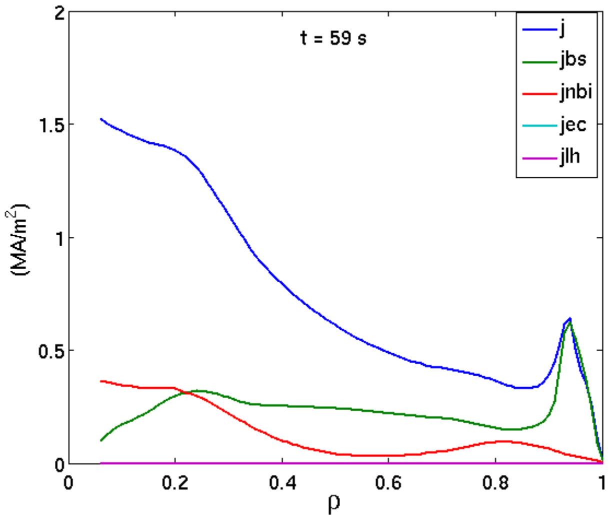
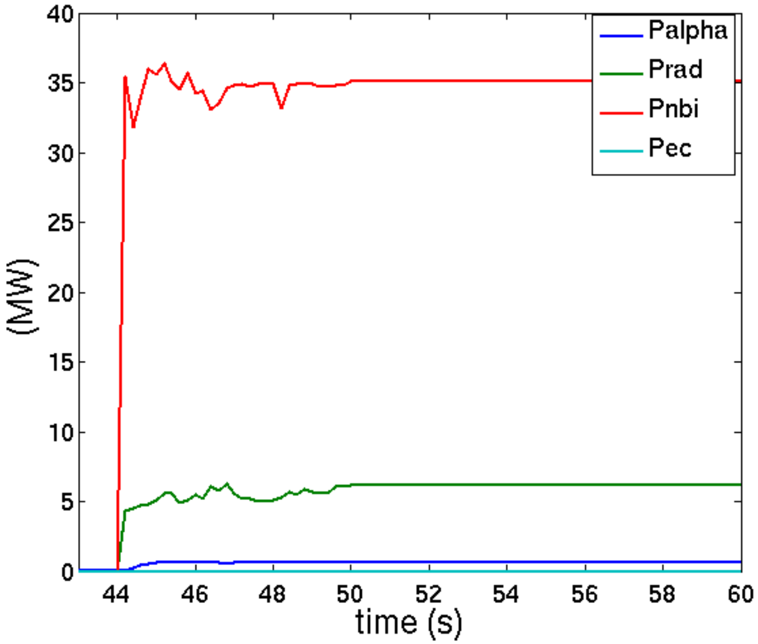


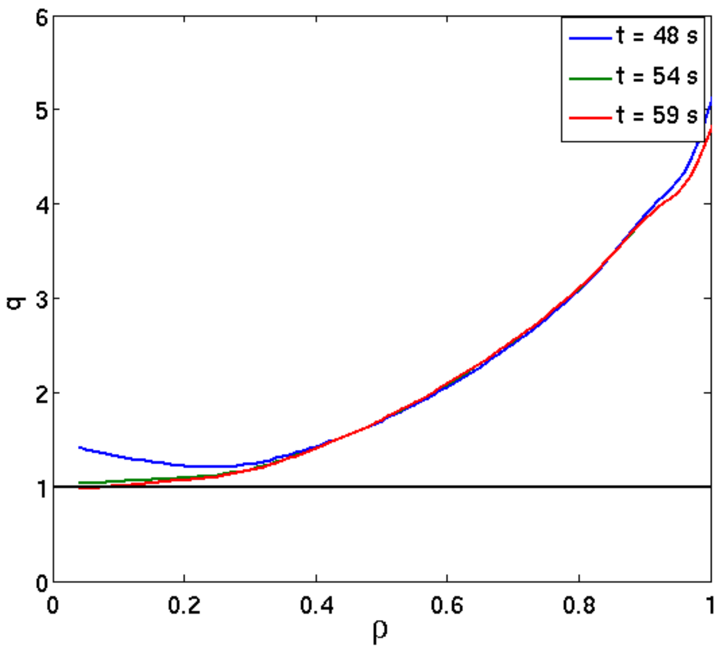




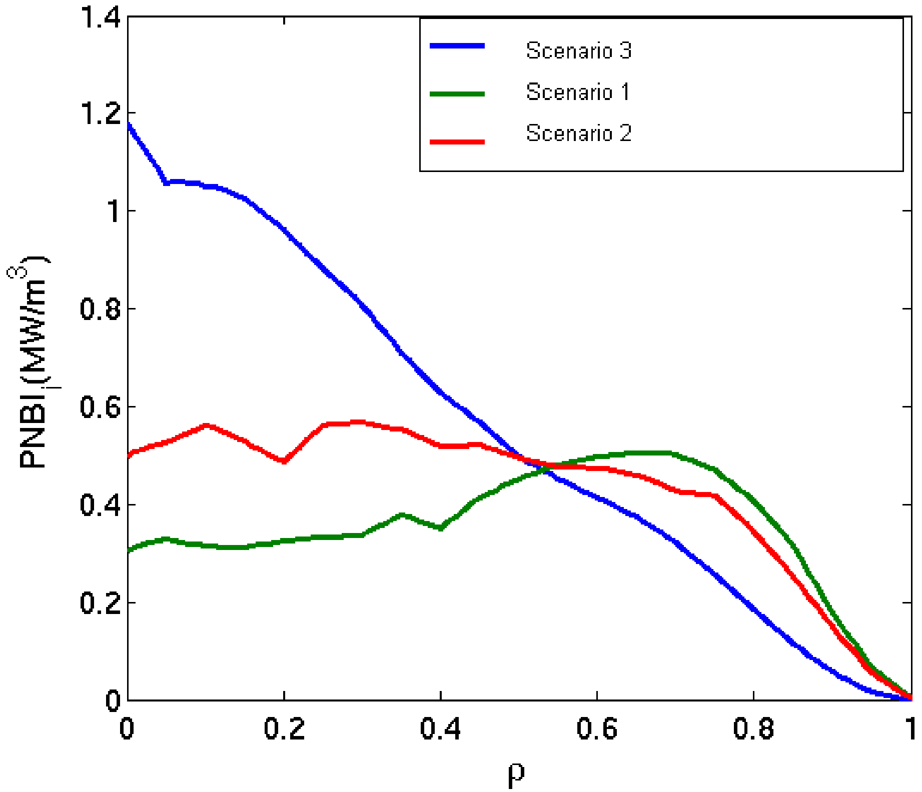
- Ip=2.3MA B_t=3T
- Iboot=0.97MA fboot=42%
- Ini=1.25 MA fni=54%
- The pedestal temperatures are calculated with a scaling

Scenario3: Hybrid-like JET scenario@high current





- Pnbi=35MW
- Palpha=0.6MW
- Prad=6MW
- q_{95}=4
- The q profile is rather flat in the core and remains very close to 1



- More on-axis NBI power coupled to ions for the hybrid-like case (close to the original 77922 shot)
- Significant increase for scenario 2 compared to scenario 1

Comparison between scenario 1 and scenario3

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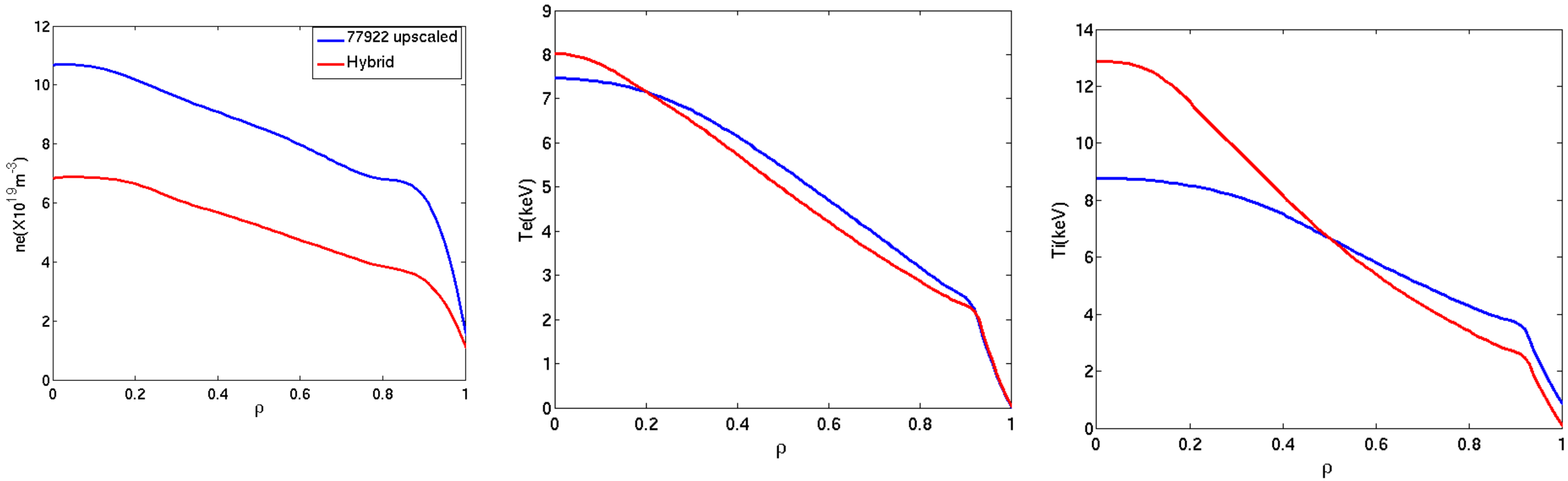
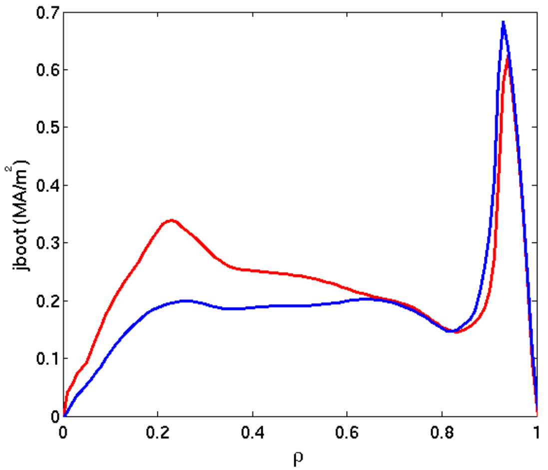
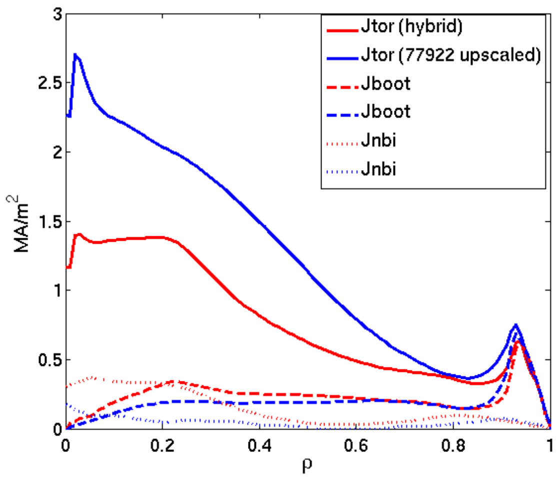
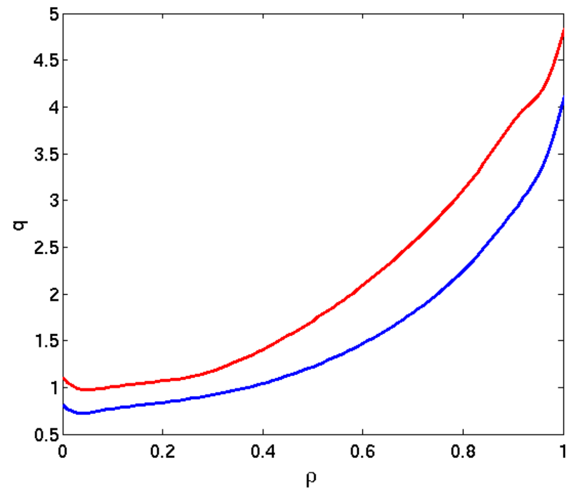


- The density is downscaled by a factor of 1.5
- The electron temperature is similar in both cases
- The central ion temperature is much higher for the hybrid-like case due to the NBI power
- The pressure at the pedestal is much higher for scenario 1

Comparison between scenario 1 and scenario3

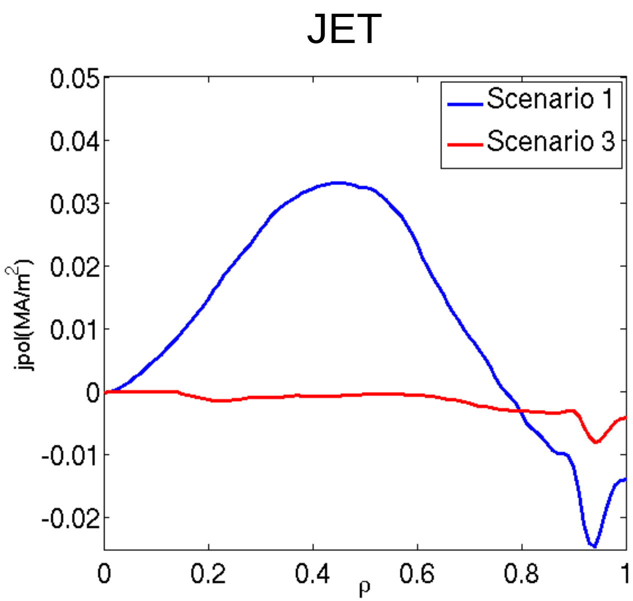


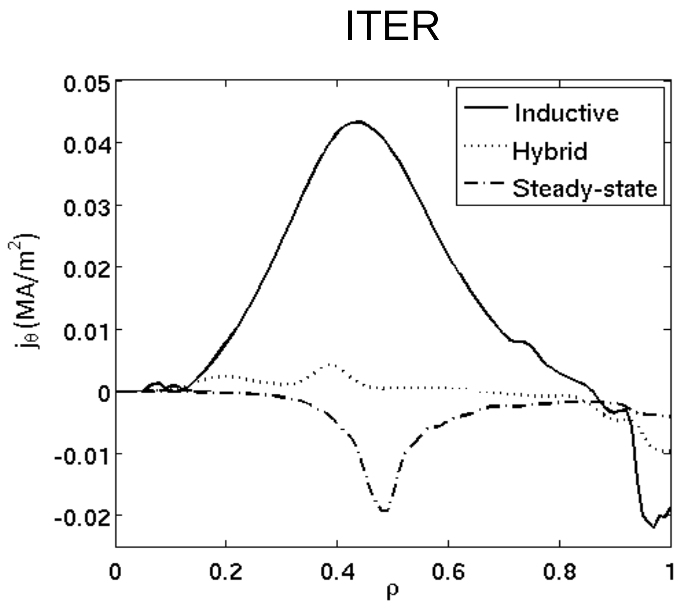




- The total boostrap current is almost the same in both cases
- For the hybrid-like case the bootstrap current lost at the edge is recovered in the core, mainly at ρ=0.2
- The NBCD is much higher for the hybrid-like case due to the lower density
- All these facts make the difference for the q profile

Comparison between scenario 1,3 and ITER

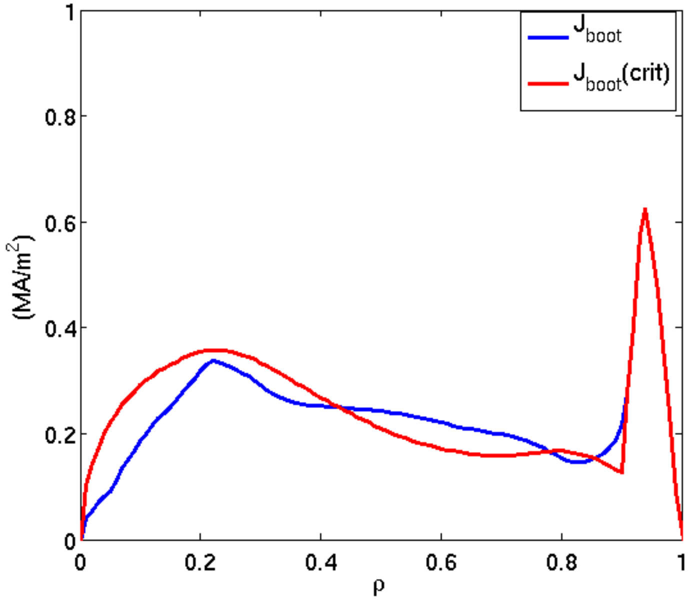




J.Garcia and G.Giruzzi PRL 104, 205003 (2010)

- The hybrid-like scenario for JET was specifically designed to have jpol=0 in steady-state
- The jpol profiles for the JET hybrid scenario and those ideally obtained for ITER are very similar

Bootstrap current in scenario 3

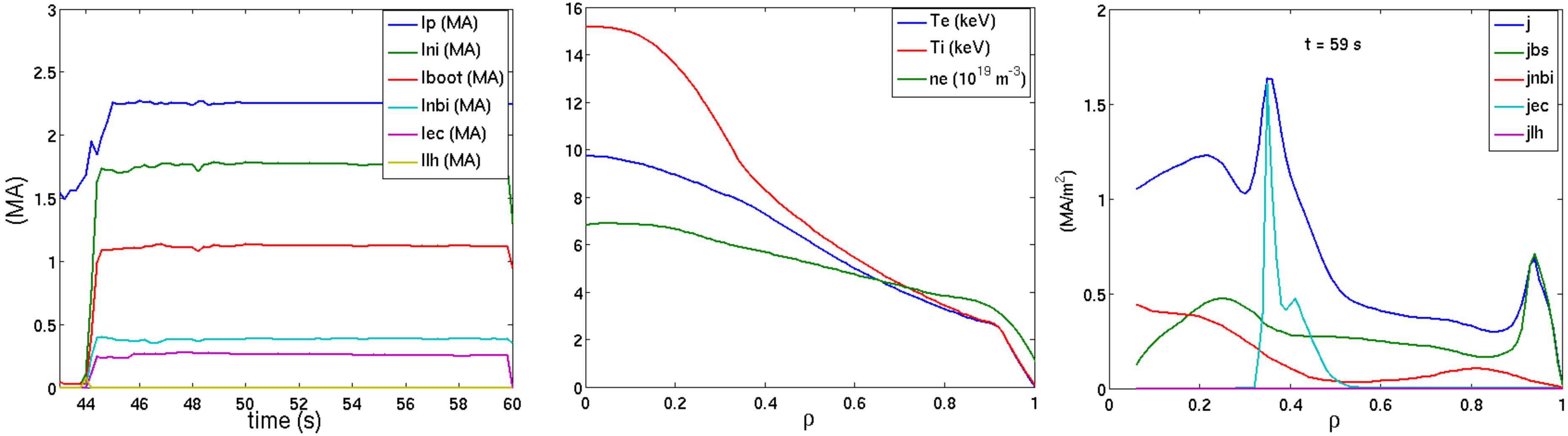


$$j_{bs}^{crit} = j_{bs}(j_\theta = 0) = \frac{\varepsilon^{1/2}(j_{ohm} + j_{cd})}{1 - \varepsilon^{1/2}}$$

J.Garcia and G.Giruzzi PRL 104, 205003 (2010)

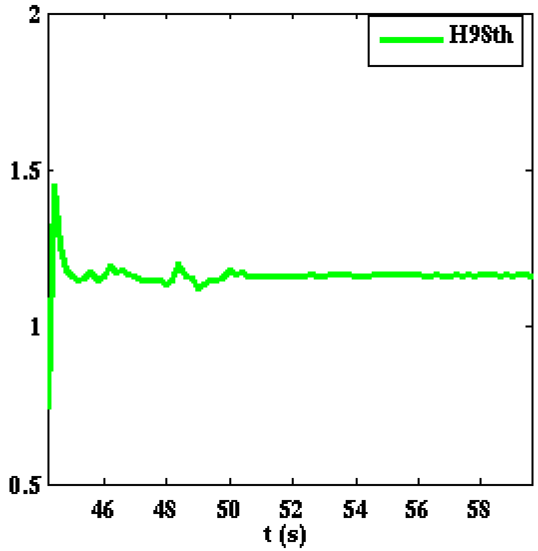
- The condition jpol=0 leads to a specific bootstrap current profile for the transition to advanced scenarios
- The bootstrap current obtained matches the one required
- The bootstrap current has a maximum at ρ=0.25
- In order to have this, a weak transport improvement must be obtained at that region (rotation, density peaking..)
- On-axis heating is needed to take profit of this transport improvement and increase the bootstrap current

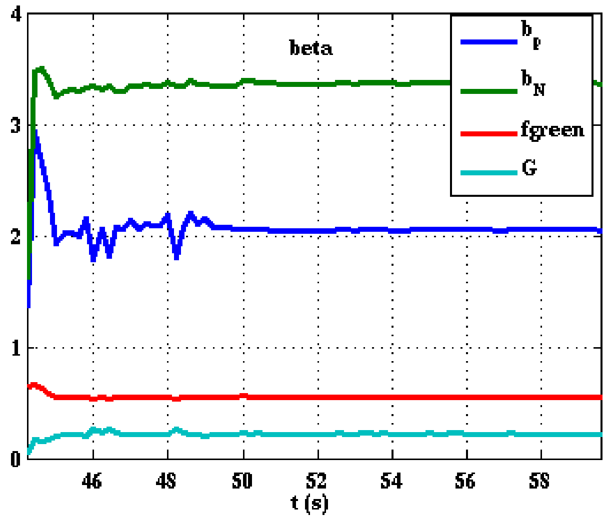
Scenario 3 with ECRH/ECCD

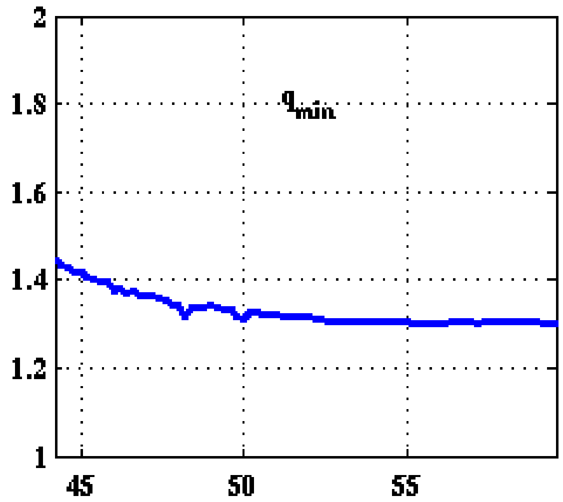


- Ip=2.3MA B_t=3T
- Iboot=1.13MA fboot=50%
- Ini=1.77MA fni=77%

Scenario 3 with ECRH/ECCD

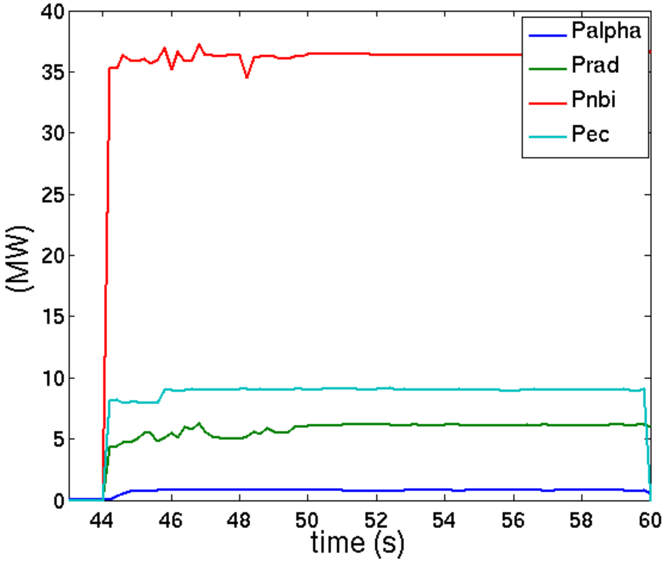


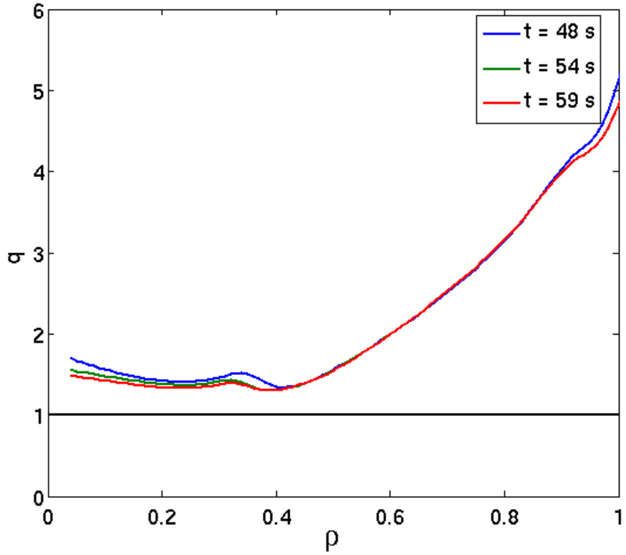




- H_{98}=1.18
- β_N=3.4
- β_p=2.1
- q_{95}=4
- Palpha=0.8 MW q_0=1.3
- f_G=0.55

Scenario 3 with ECRH/ECCD





- Pnbi=35MW
- Palpha=0.8MW
- Pecrh=8MW
- Prad=6.2MW
- The ECCD current allows to sustain the q profile above 1 in a safer way
- The q profile obtained is quite flat
- This feature can be used to extend the hybrid scenarios to higher current

ITER hybrid

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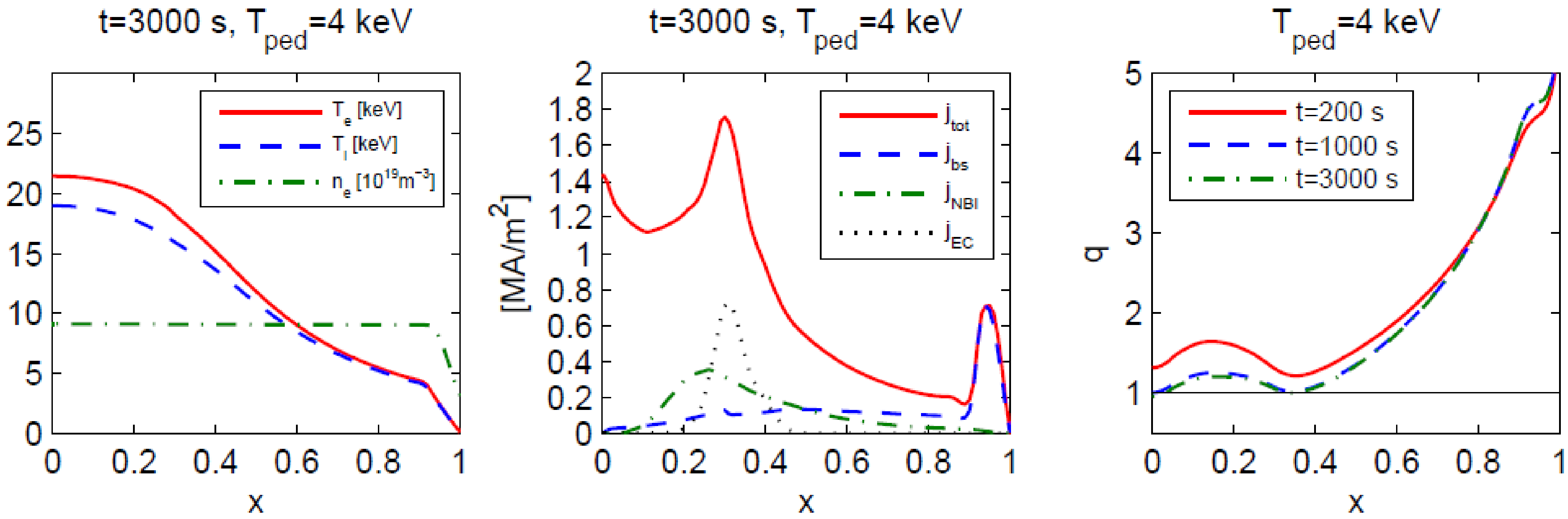
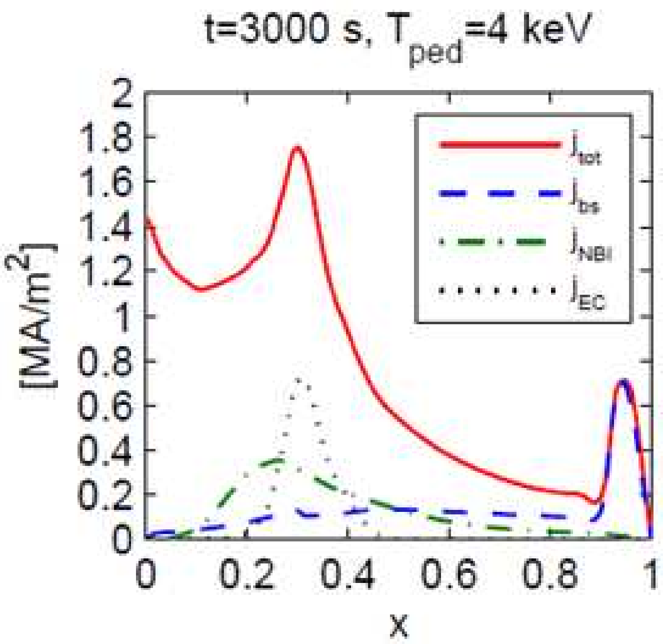


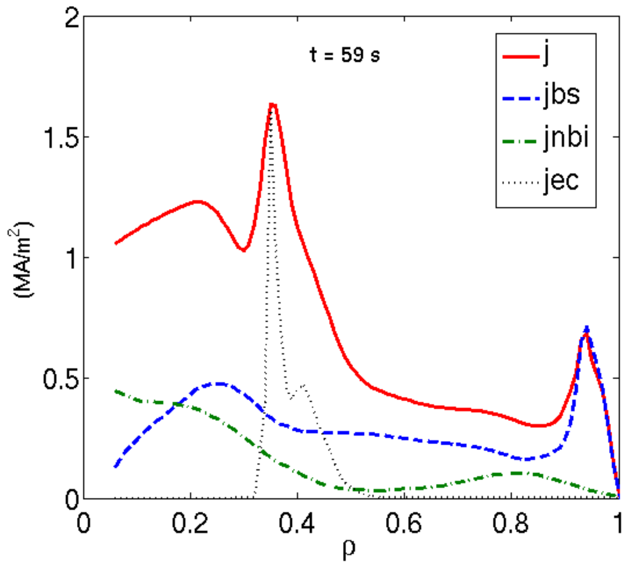
J. Citrin et al., accepted in Nucl. Fus.

- The best ITER hybrid scenario, with reasonable pedestal Tped=4keV, was obtained with off-axis NBCD+ECCD
- The evolution of the q profile is very slow and it takes 1000s to drop below 1

ITER and JET (with ECCD) hybrids

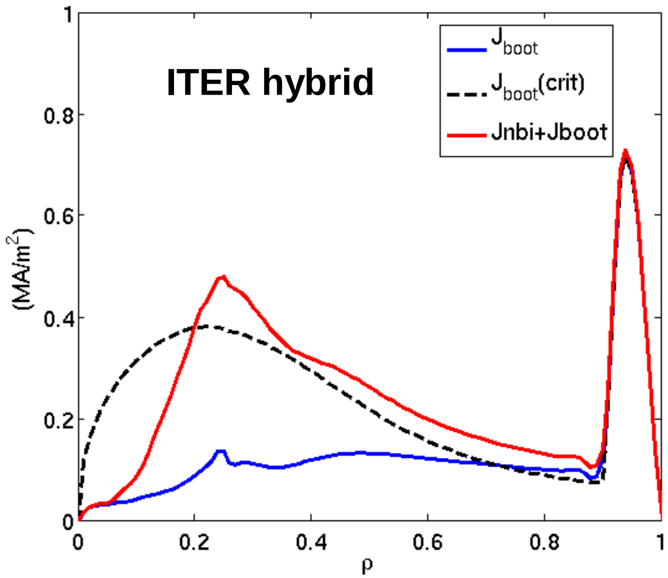
J. Citrin et al., accepted in Nucl. Fus.

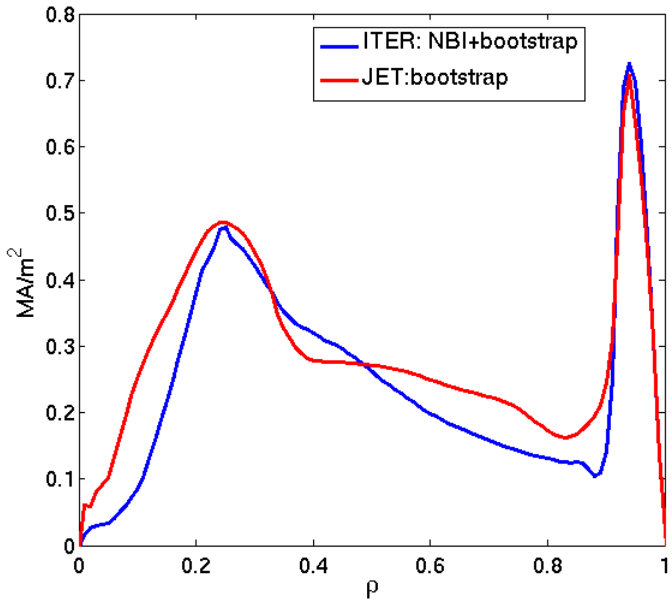




- The current configuration for ITER and JET with ECCD is very similar
- The main difference is between NBCD and bootstrap current

ITER and JET (with ECCD) hybrids





- According to the jpol=0 condition a large off-axis bootstrap current is needed for hybrid scenarios (as usually happens for DIIID-D)
- Since with GLF23 it is difficult to get this current, the remaining current is obtained by NBCD for the ITER scenario
- In the case of JET and ITER, the current configuration is very similar
- More off-axis bootstrap current is needed in the ITER hybrid case analyzed by J. Citrin in order to obtain better performance

Conclusions

- The NBI power deposition is a key element for confinement prediction
- The NBI coupling to the ions limits the density. High Greenwald fraction does not lead to the highest alpha power
- This feature limits the direct extrapolation of present day experiments to higher densities
- A hybrid-like scenario has been found at Ip=2.3MA and Bt=3T with q_{95}=4 and Pnbi=34.8MW
- This scenario was created to have jpol=0, showing strong similarities with ITER advanced scenarios
- The off-axis current (mainly bootstrap) is essential for hybrids scenarios for q profile tailoring
- The ECRH/ECCD off-axis heating system can help the establishment of flat q profiles in the core and to improve confinement