The sustainment of hybrid scenarios on JET and its possible extrapolation to ITER

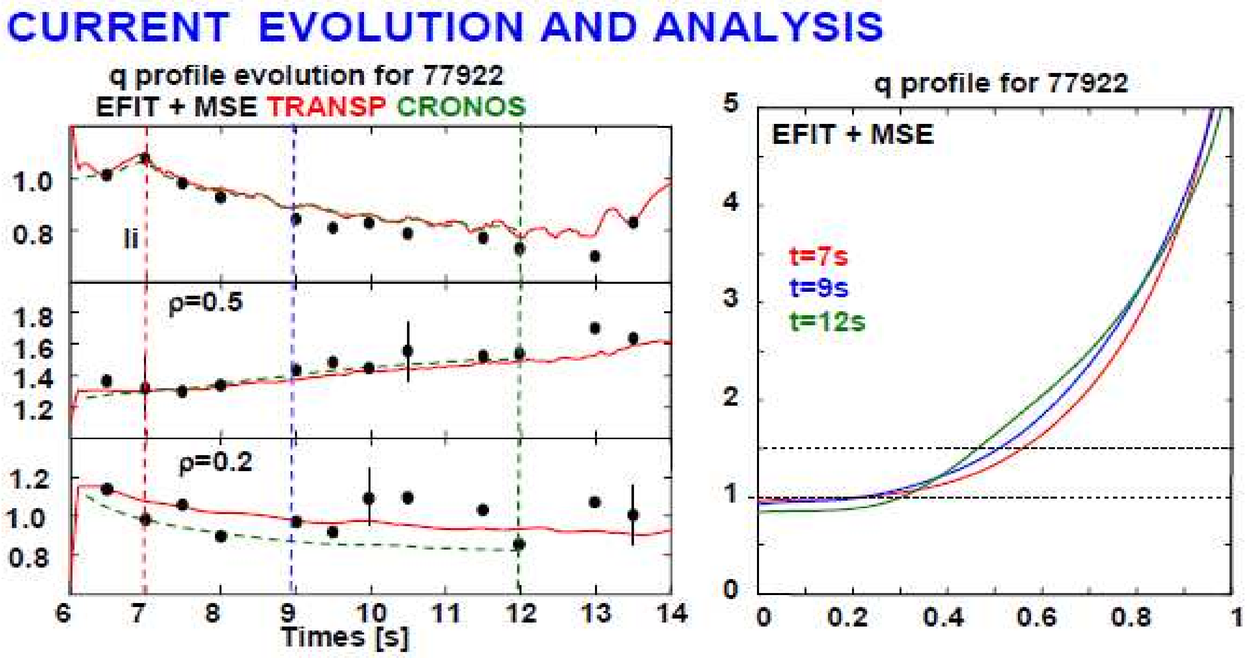
J. Garcia, G. Giruzzi

Outline

- Current diffusion on JET hybrid shots
- Analysis and comparison between shots 77922 (high triangularity and pedestal) and 75225 (low triang. and pedestal)
- The requirements for the sustainment of JET hybrid scenarios
- Comparison with JT60u shots and the role of bootstrap current
- Extension to ITER
- Conclusions

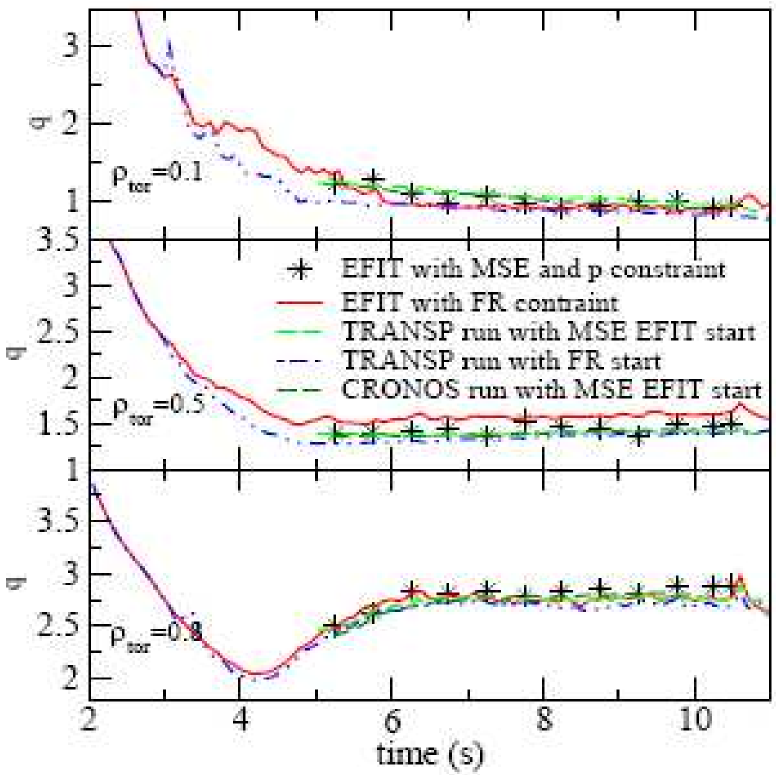
High triangularity hybrid shot

Joffrin E.. et al., 23rd IAEA Fusion Energy Conference, 11-16 October 2010, Korea, EXC/1-1.



- Current evolution seems to be neoclassical for shot 77922 (high triangularity)
- Only deviation when some MHD event appears
- The evolution is well reproduced by both TRANSP and CRONOS when appropriate initial conditions are chosen
- A clear evolution of the q profile is found which finally increases the magnetic shear

Low triangularity hybrid shot



J. Hobirk, et al. to be published

- Current evolution seems to be neoclassical for shot 75225 (low triangularity)
- The evolution is well reproduced by both TRANSP and CRONOS
- A clear evolution of the q profile is found which finally increases the magnetic shear although seems to be less strong than in shot 77922

JET hybrids and poloidal current

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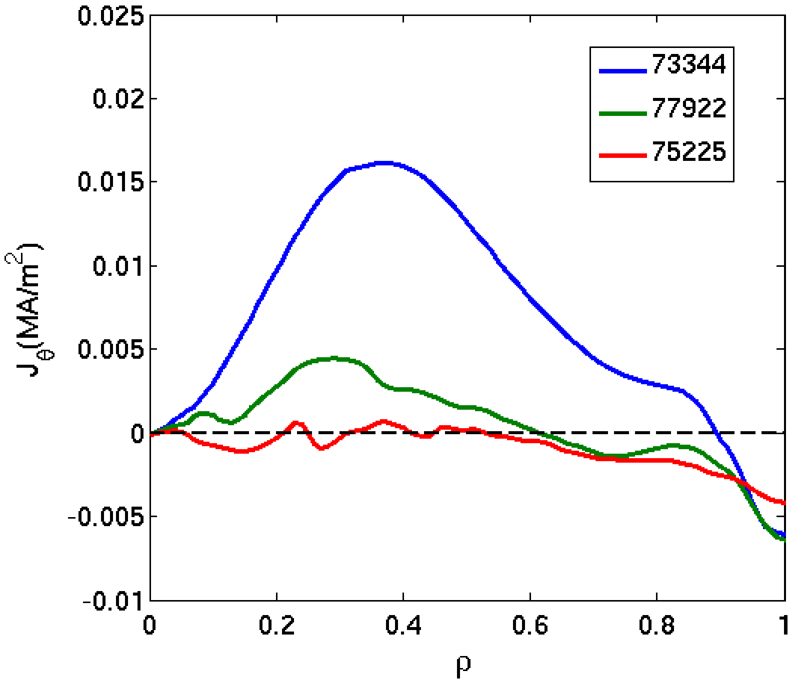


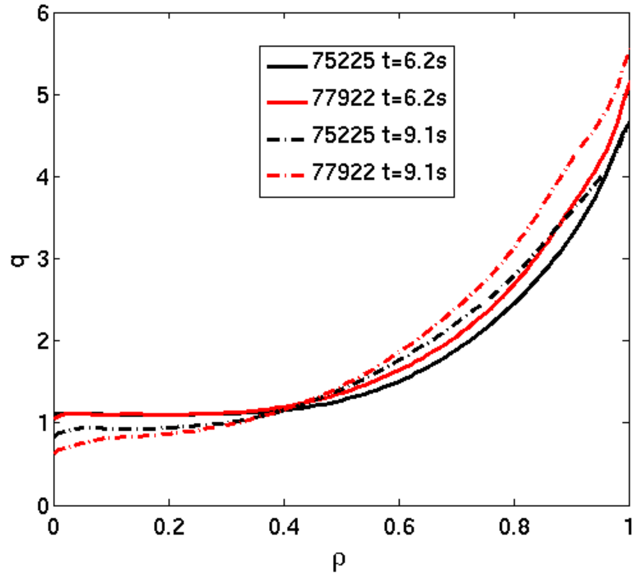
At j_θ=0 aproximately we have that:

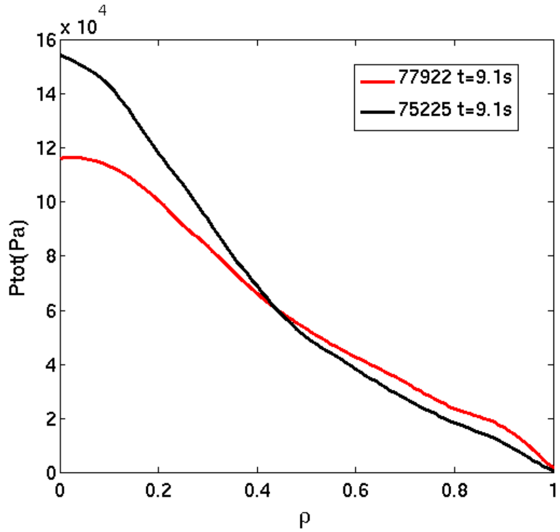
$$j_{bs}^{crit} = j_{bs}(j_\theta = 0) = \frac{\varepsilon^{1/2}(j_{ohm} + j_{cd})}{1-\varepsilon^{1/2}}$$

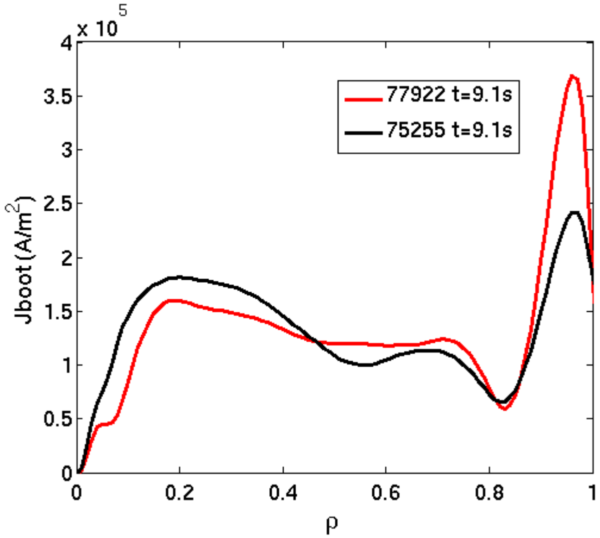
$$j_\varphi^{crit} = j_\varphi(j_\theta = 0) = j_{bs}^{crit} / \varepsilon^{1/2} = \frac{(j_{ohm} + j_{cd})}{1-\varepsilon^{1/2}}$$

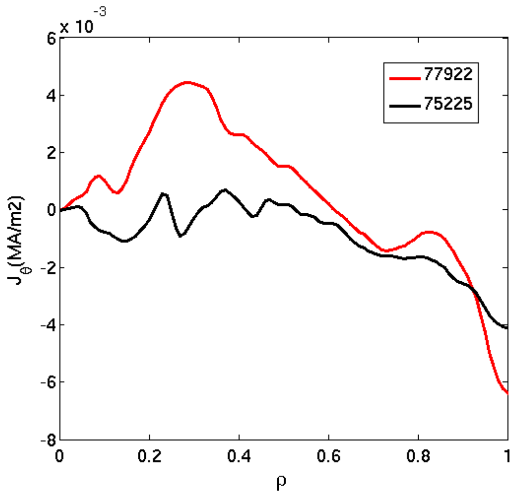
- According to **J. Garcia, G. Giruzzi, Phys. Rev. Lett. 104, 205003 (2010)** poloidal current can be used as a tool for the analysis of transition to advanced scenarios.
- For hybrid scenarios j_θ can be close to zero and flat
- JET hybrid shots 77922 and 75225 are very close (in particular for 75225)
- JET H mode 73344 is far from the j_θ~0 regime

Comparison between 77922 and 75225 shots









- At t=6.2s q profiles for both shots are very similar
- At t=9.1s 77922 (q95=4.5) has evolved more
- For 75225 (q95=4.0) bootstrap current at the edge is lower, but higher in the core
- Pressure profile is more peaked for shot 75225.
- These effects can be seen on the poloidal current.

Pressure profile

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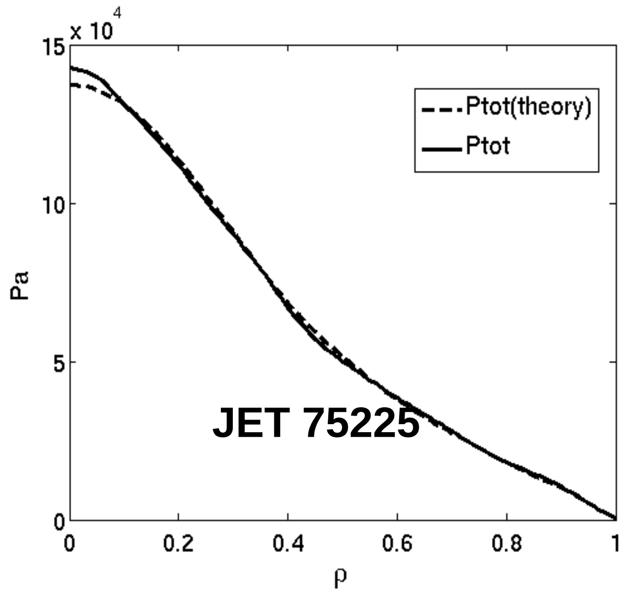
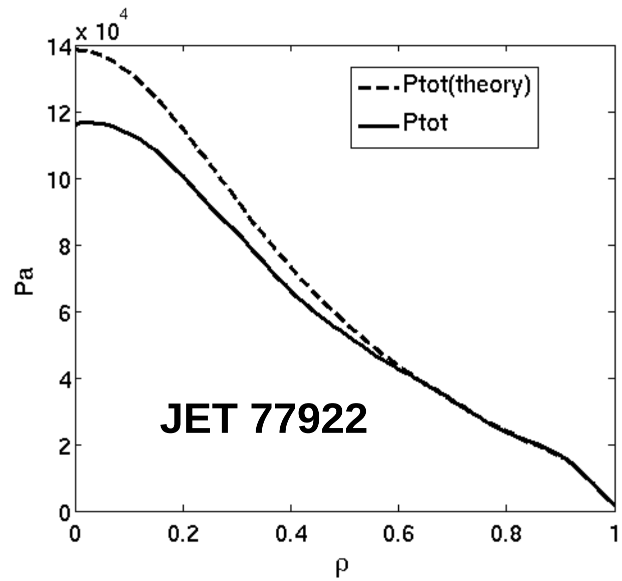


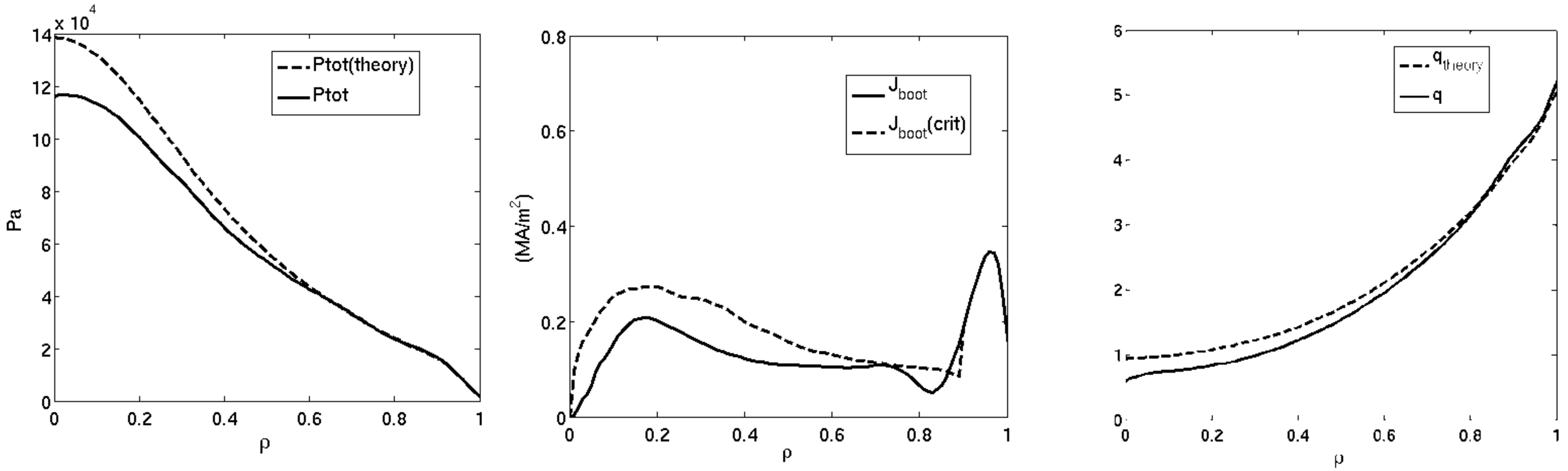


$$\nabla P_{crit} = j_{\varphi}^{crit} B_{\theta}^{crit}$$

$$P(r) - P(a) = \int_a^r \nabla P_{crit} dr$$

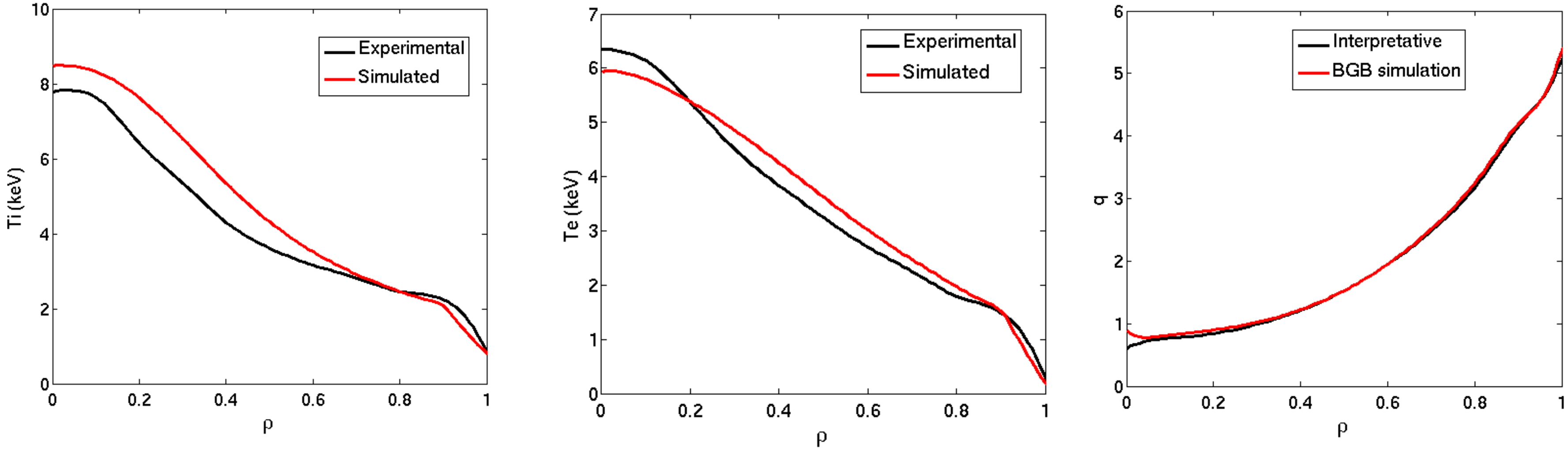
- The pressure profile for j_θ=0 condition can be theoretically evaluated.
- 75225 pressure profile is very well reproduced. A peaked profile is obtained.
- For shot 77922, the pressure profile is slightly below the one required

Bootstrap current profile for shot 77922



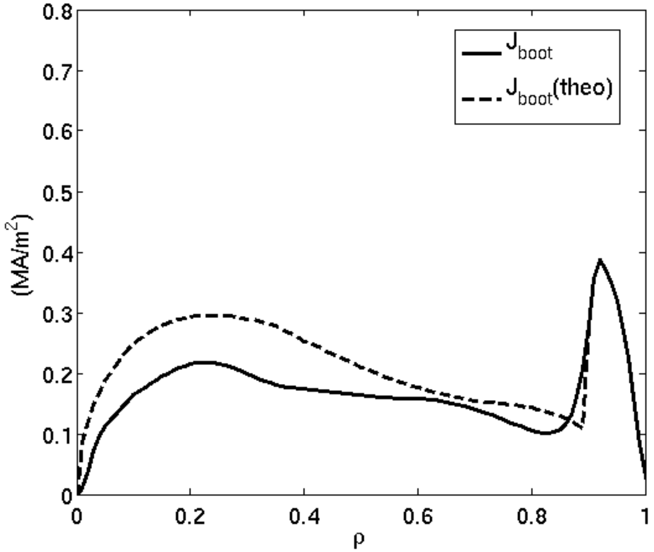
- The pressure profile and the bootstrap current are calculated for the condition j_θ=0
- Lack of enough pressure leads to a bootstrap current below the requirements
- With the additional current the scenario could be close to q_0=1

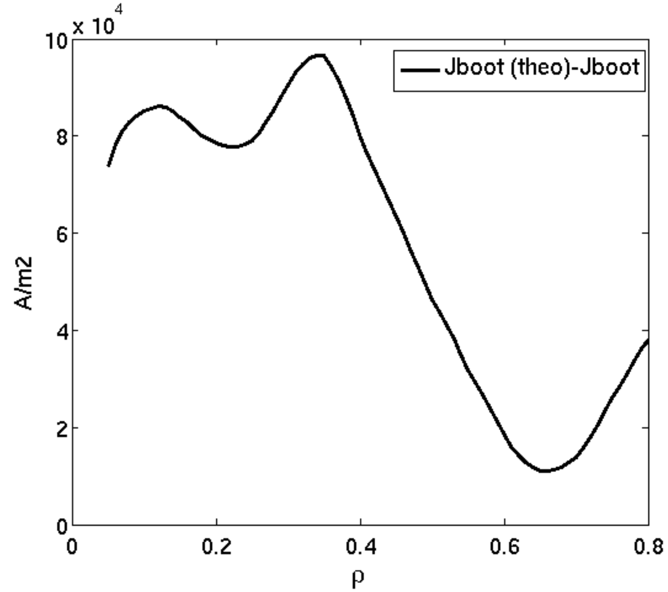
Simulation of shot 77922 with Bohm-GyroBohm transport model



- Bohm-GyroBohm transport model is used to simulate shot 77922
- Temperatures are in reasonable agreement with experiment
- q profiles of predictive and interpretative simulations are almost identical

Missing current





- Bootstrap current is below the requirements at j_θ=0
- The missing current is located mainly in the region 0<ρ<0.5 with a maximum at ρ=0.38
- A total of 150kA are required

Addition of off-axis current

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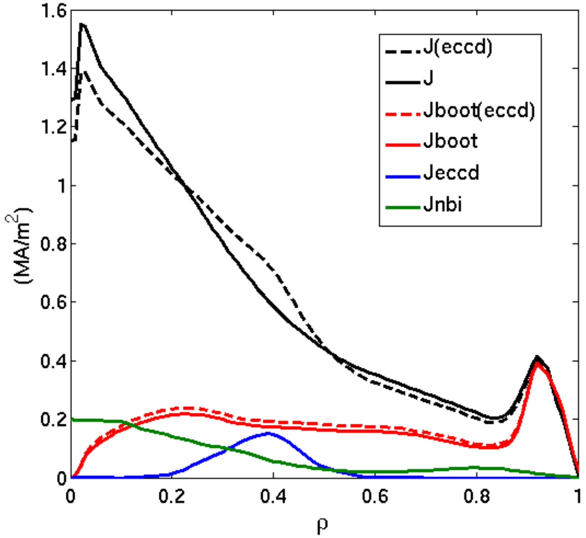

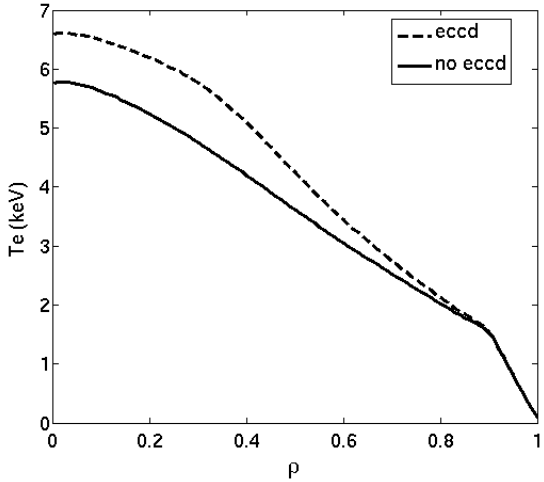

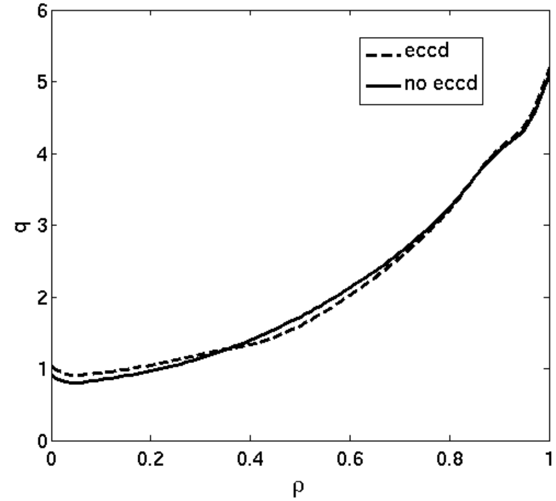

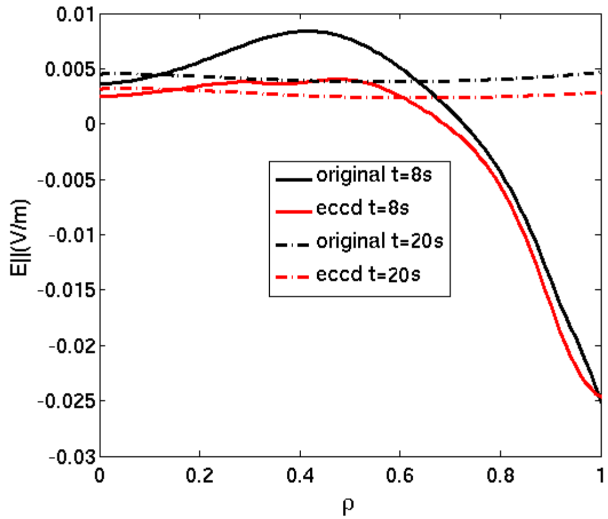

- As an example, ECRH/ECCD is used to provide the missing current
- With 4.5MW of ECRH, 90kA of ECCD are obtained at ρ =0.38
- 60kA of additional bootstrap current are obtained due to the increased electron temperature
- The q profile evolves as expected, increasing in the central part and decreasing outside
- The scenario is stationary

Alternative methods for the calculation of missing current

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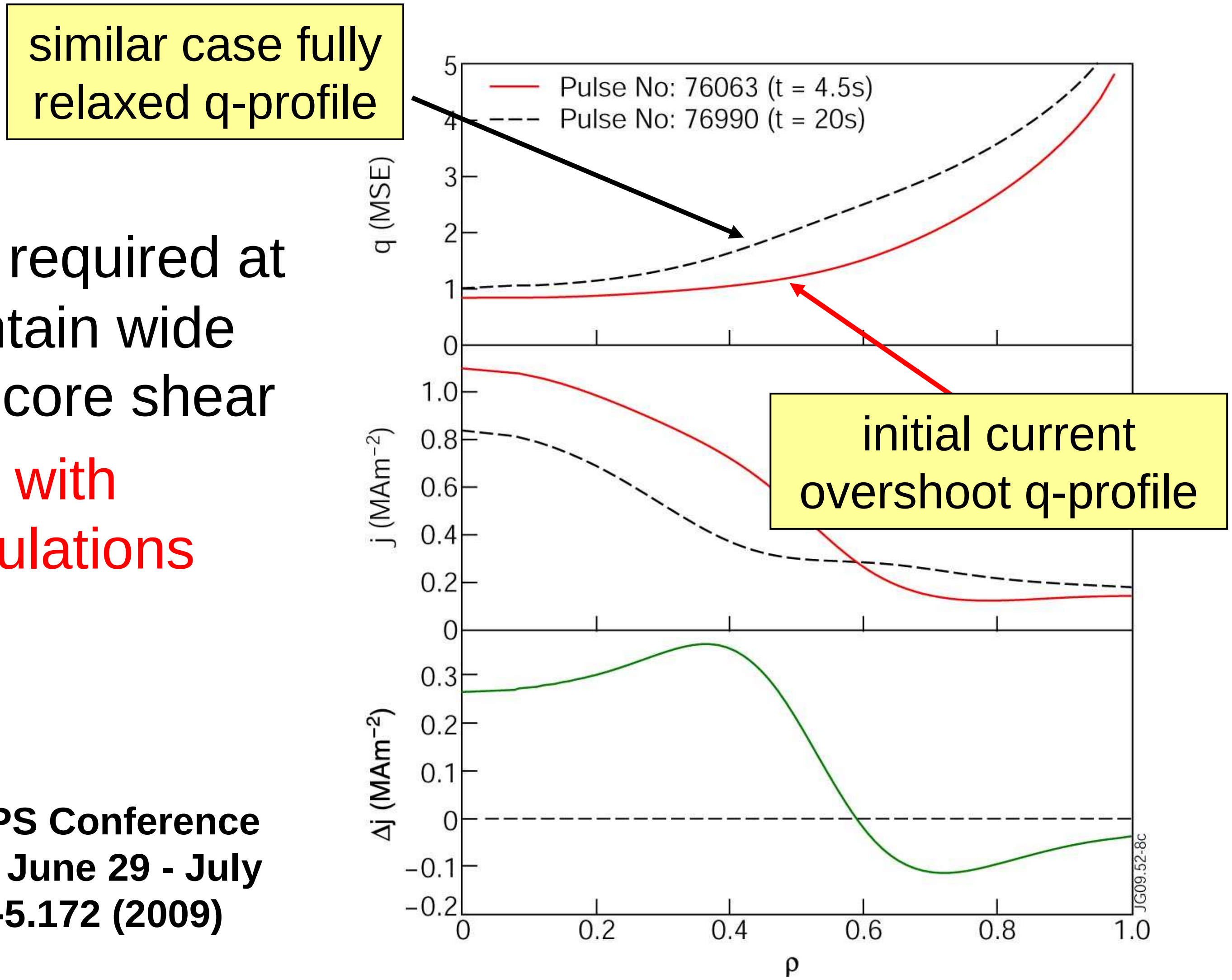
- Current drive required at ρ~0.4 to maintain wide region of low core shear
- In agreement with previous calculations



C. Challis et al., 36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.33E, P-5.172 (2009)

Comparison to JT60u hybrids: Why sometimes more off-axis current is not needed

JT60U shots analysis and comparison to JET

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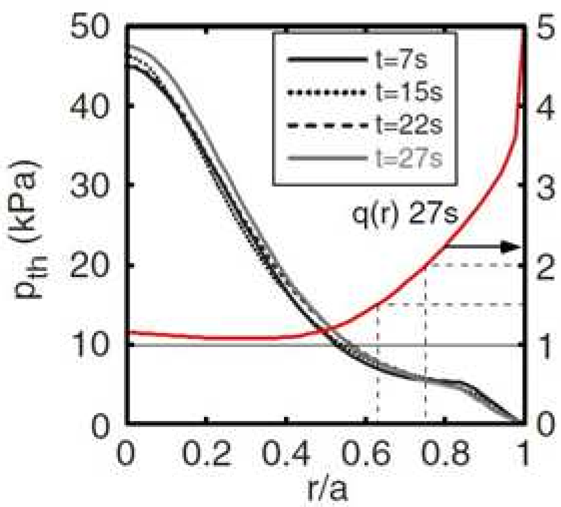
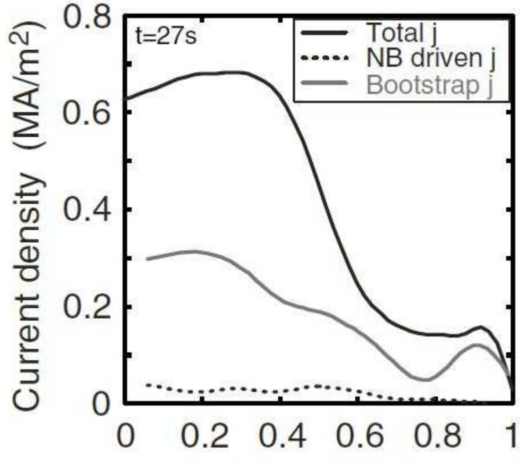
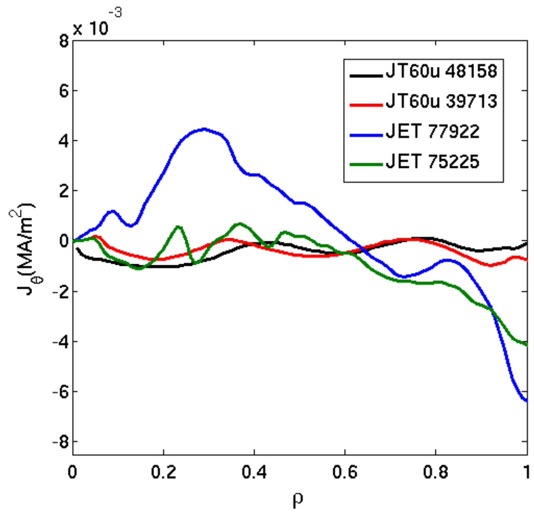
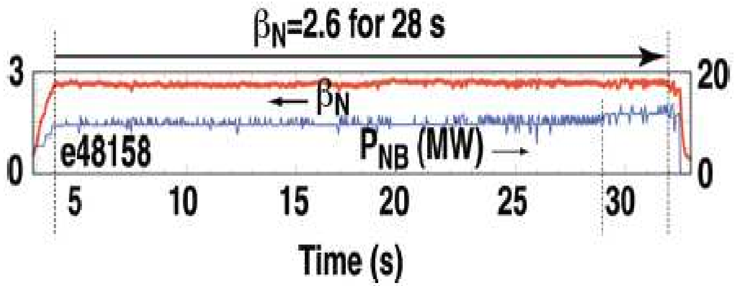






N. Oyama et al., Nucl. Fusion **49** (2009) 065026



Luce T. et al., 23rd IAEA Fusion Energy Conference, 11-16 October 2010, Korea, ITR/1-5.

- JT60u shot 48158: q is maintained flat and above 1 with a very peaked pressure profile
- High off-axis bootstrap current
- Hybrids are very close to j_θ=0 although tends to be better for JT60u than JET

comparison

Comparison between JT60u 48158 and JET 77922

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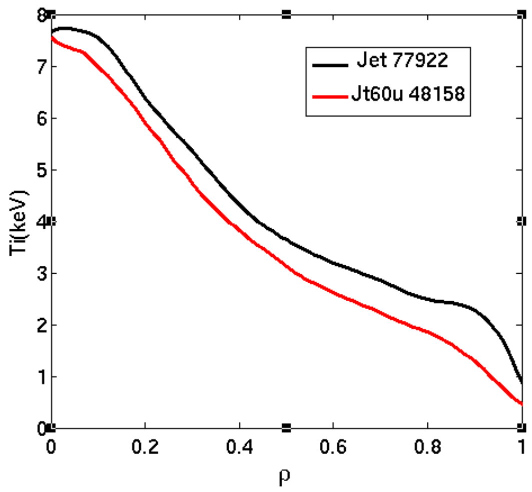
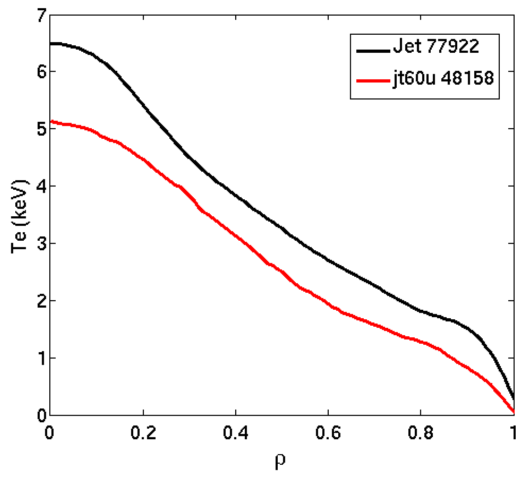
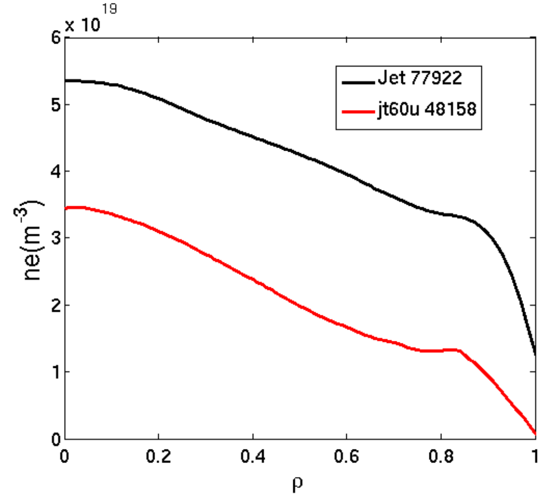
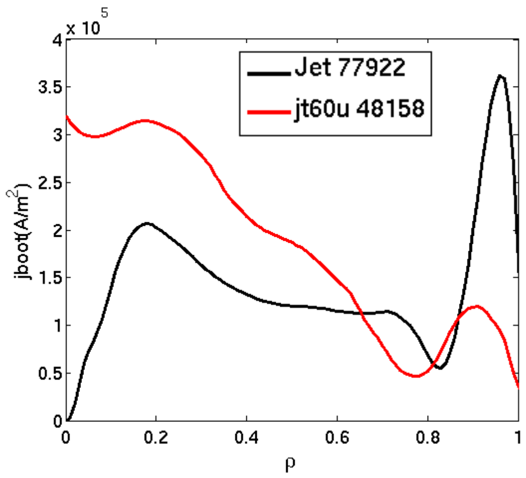




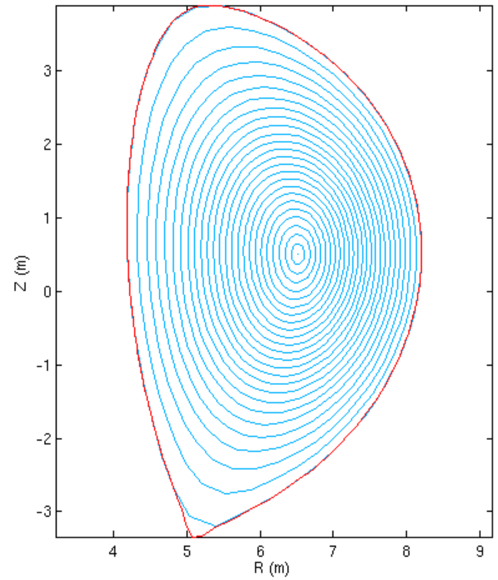




- Slightly higher density peaking and ion temperature gradient for JT60u
- Bootstrap current is lower at the edge for JT60u shot but higher in the core
- Bootstrap current is high enough to sustain the q profile in JT60u.
- No additional current needed

Simulations of ITER hybrid scenario with the same scheme as in JET

- **I_p = 11 MA**, B_T = 5.3 T
- **dI_p /dt= 0.18 MA/s**, B_T = 5.3 T, f_G=0.4 during ramp-up. f_G=0.85 flat-top phase
- **EC wave launch**: top launchers, 8MW during ramp-up, 20MW flat-top
- **ICRH:** 20 MW, **NBI:** 33MW (off-axis and on-axis)
- n_e profile fixed, picked profile, $n_e(0) \approx 0.95\ 10^{20}\ m^{-3}$
- $\rho_{ped} \approx 0.95$, $n_{ped} \approx 0.55\ 10^{20}\ m^{-3}$, $\mathbf{T_{ped}} \approx$ **4.5 keV**
- **Bohm-GyroBohm transport model during ramp-up**
- **H_{98}=1.3 with Bohm-GyroBohm shape for flat-top phase**



ITER simulations with the same current scheme

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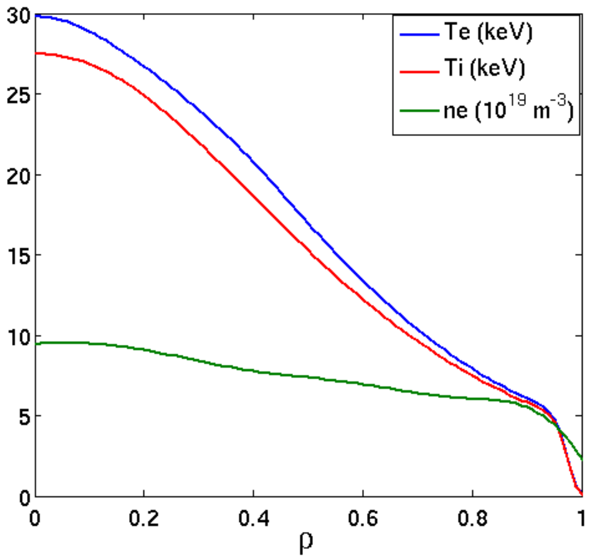
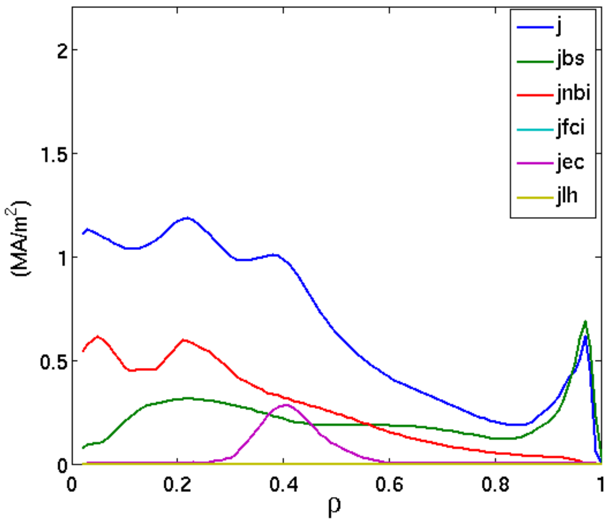
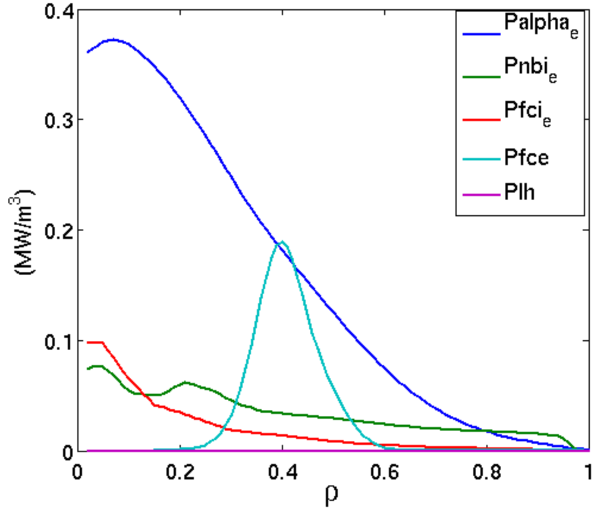
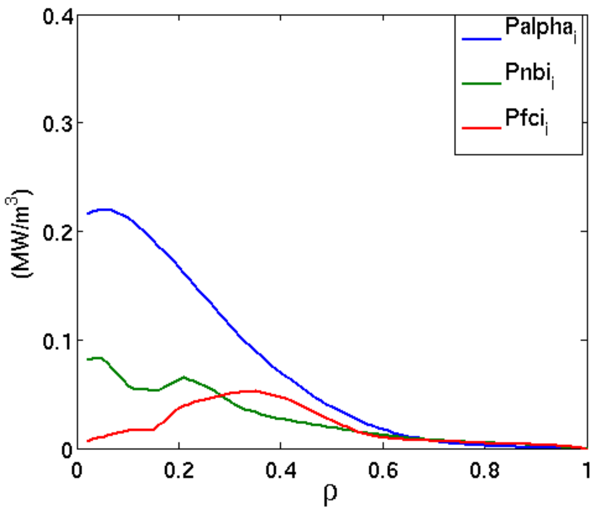


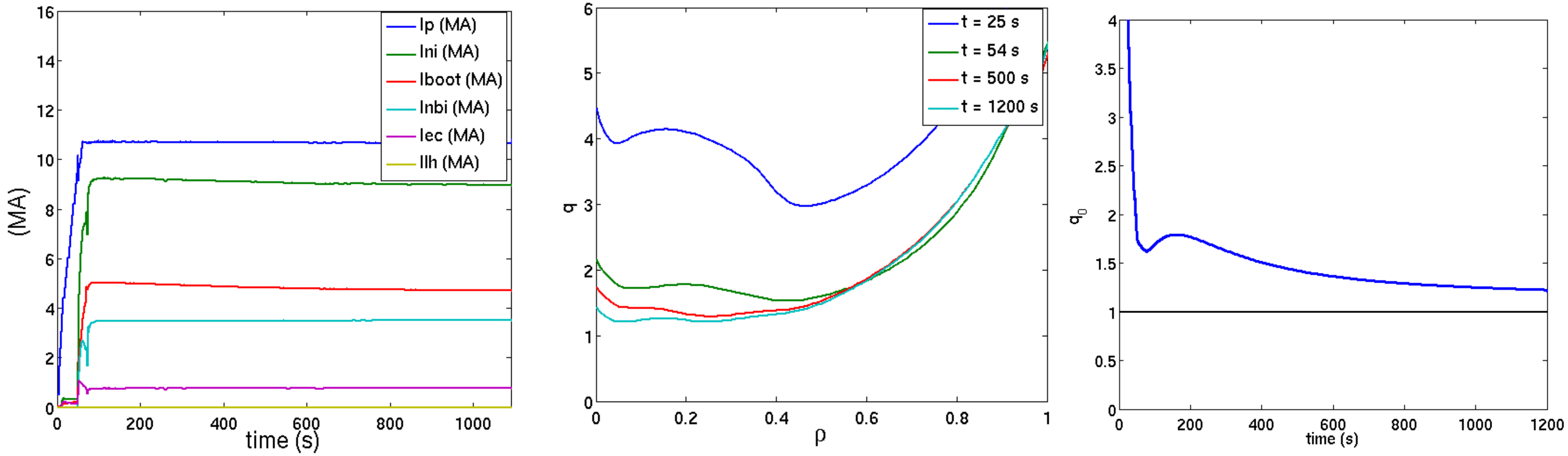






- The current configuration is nearly the same one used for JET.
- Peaked density profile, checked with GLF23
- The on-axis NBI power helps to peak the pressure profile
- The ICRH power is on-axis for the electrons and off-axis for the ions
- **β_N=2.7, β_p=1.6, Q=7**

ITER simulations with the same current scheme



- Ini=8.65MA (fni=79.6%), Iboot=4.4MA (fboot=41.0%), Inbcd=3.5MA (fnbcd=31.8%), Ieccd=0.75MA (feccd=6.8%),
- There is almost no evolution of q from 500s until t=1200s
- q profile remains above 1 and stationary

The physics in the background

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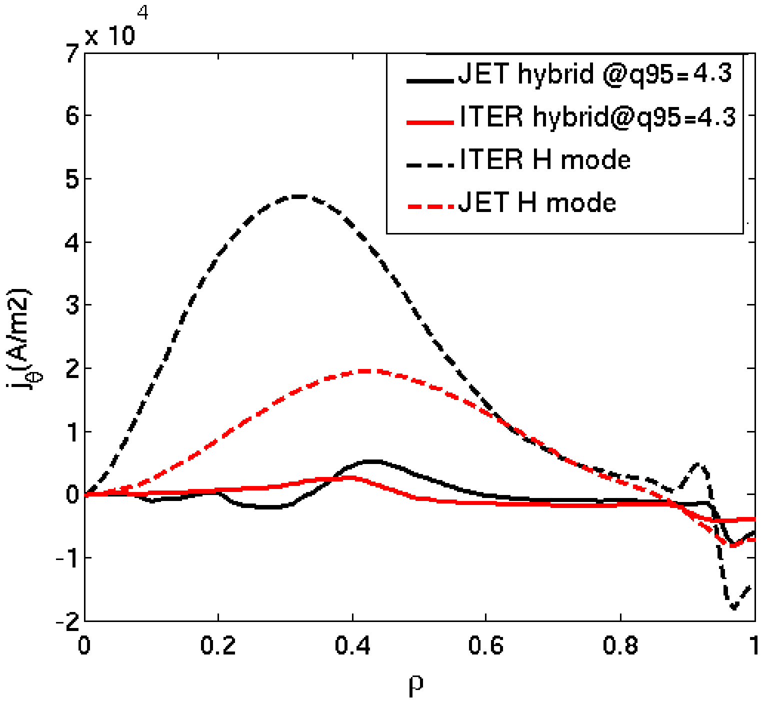

comparison

- By matching the current and heating configuration for JET and ITER very similar poloidal current profiles are obtained
- The way is to reduce the current to have almost a flat profile at j_θ=0
- The final state of the plasma is then very similar for both cases

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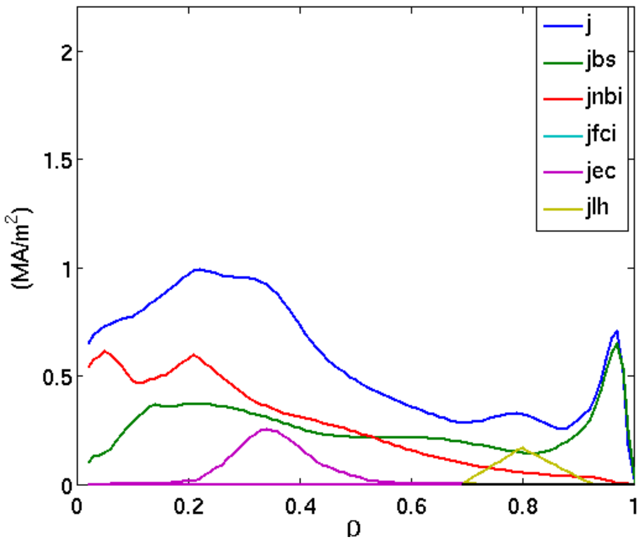
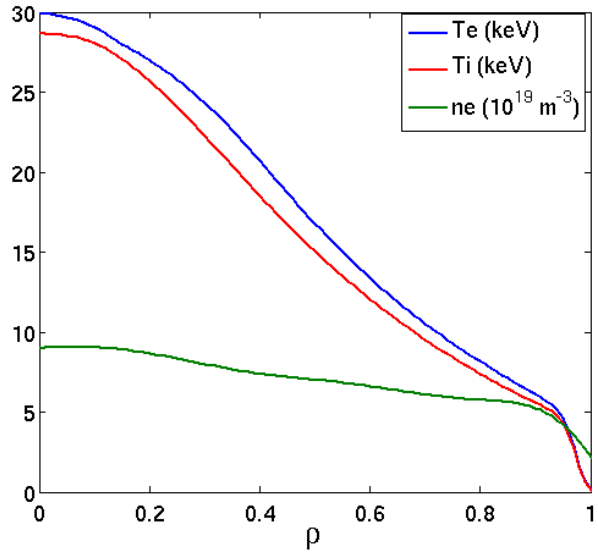
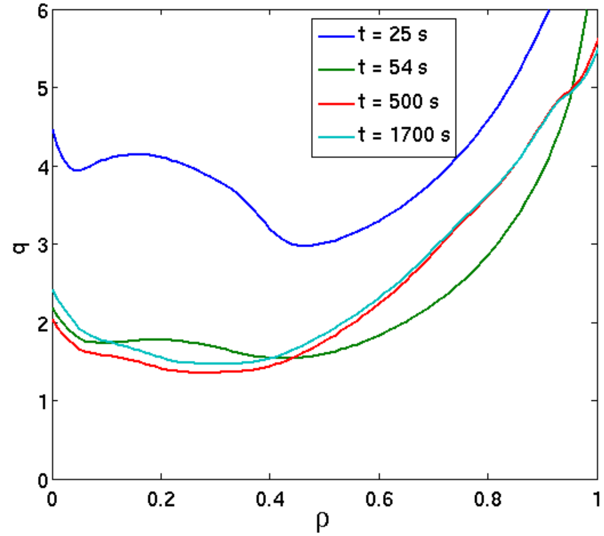
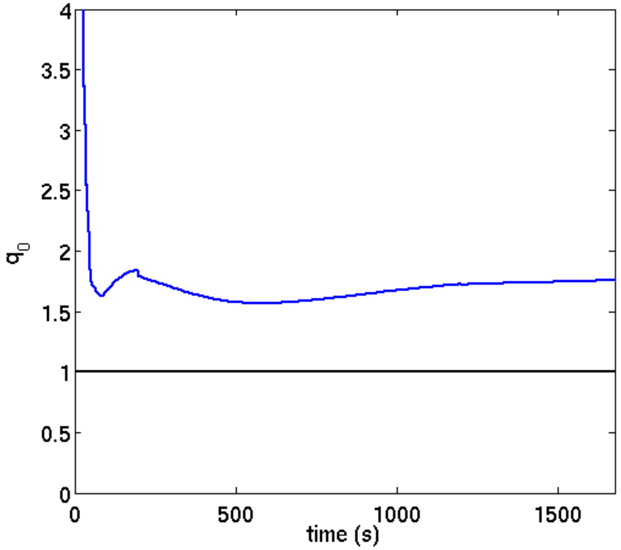
Extension to higher q_{95} (Steady-State scenario)









- The scenario can be extended to higher q95=5 (Ip=10MA)
- **H_{98}=1.4, β_N=2.85, β_p=1.75, Q=5.0**
- The q profile remains at q>1.5, most of it below 2 with a very weak negative shear
- It is a steady-state scenario, fni=100% (Addition of 20MW of LH)

IRFM

Conclusions

- Current diffusion on JET hybrid shots seems to be neoclassical and well reproduced by TRANSP and CRONOS
- The poloidal current is a good measurement of hybrid scenarios and its proximity to stationarity
- The pressure profile and the bootstrap current are key ingredients
- From the condition $j_\theta=0$ the current and pressure requirements can be calculated
- Some off-axis current is necessary to stop the current evolution in hybrid scenarios (like 77922 on JET). Situation tends to be different in JT60u because of the larger bootstrap current and better alignment
- The analysis done for JET can be extended to ITER with similar results

Comparison

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	JET Hybrid@q95=4.3	ITER Hybrid@q95=4.3
H_{98}	1.25	1.3
β_N	2.8	2.7
β_p	1.7	1.6
fboot	43%	41%
qmin	≈1	≈1

comparison

irfm

Comparison

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	JET 77922	Jt60u 48158
Bt(T)	2.3	1.54
Ip(MA)	1.7	0.9
$\mathbf{H_{98}}$	1.30	1.0-1.1
$\boldsymbol{\beta_N}$	2.8	2.6
$\boldsymbol{\beta_p}$	1.6	1.4
q_{95}	4.3	3.2
fboot	36%	43%

comparison

	ITER hybrid	ITER steady-state
Ip	11MA	10MA
H_{98}	1.3	1.4
β_N	2.7	2.85
β_p	1.6	1.75
fboot	41%	50%
fni	80%	100%
Q	7	5
qmin	≈1	≈1.5

Jt60u versus JET sustainment of advanced scenarios at q≈2

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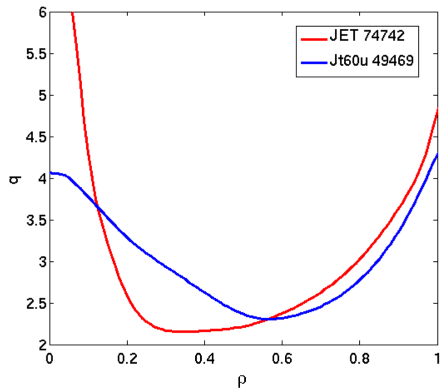
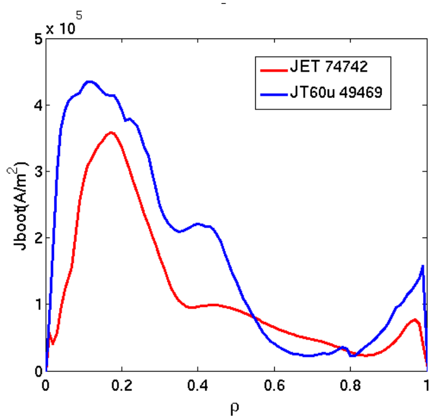
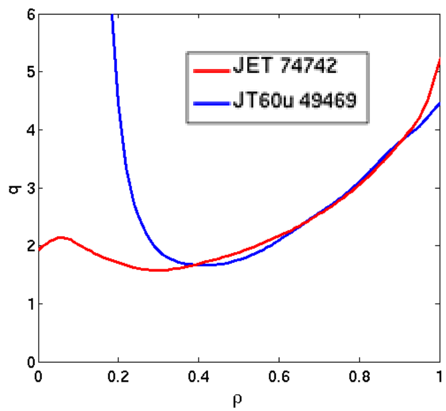
CRONOS

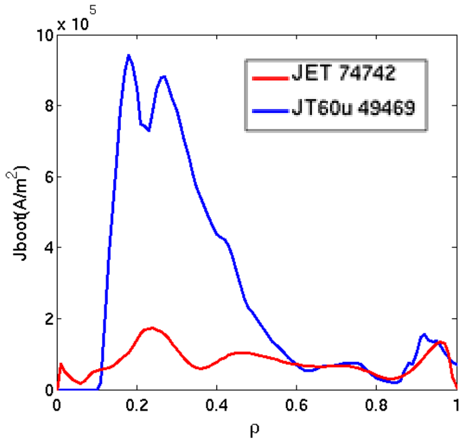




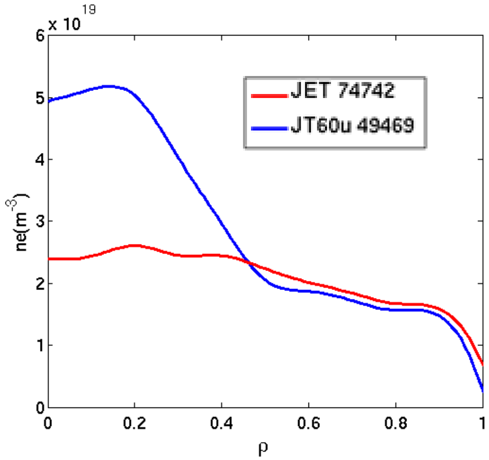
Litaudon X. et al., 23rd IAEA Fusion Energy Conference, 11-16 October 2010, Korea, EXC/P4-12.

Initial phase





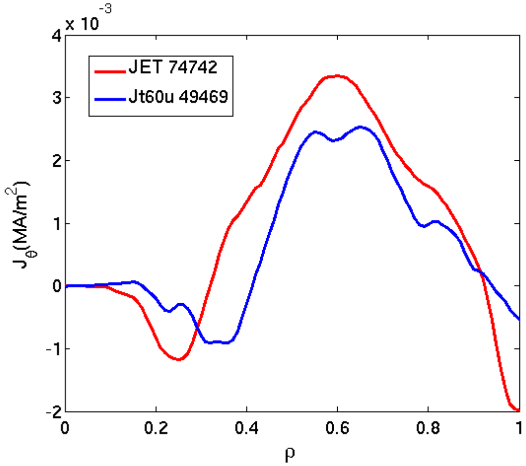
Later phase

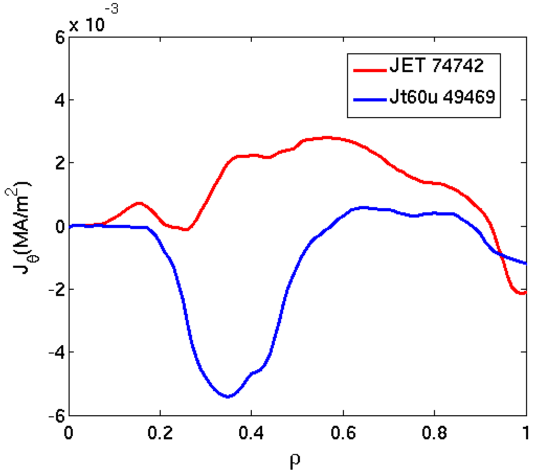


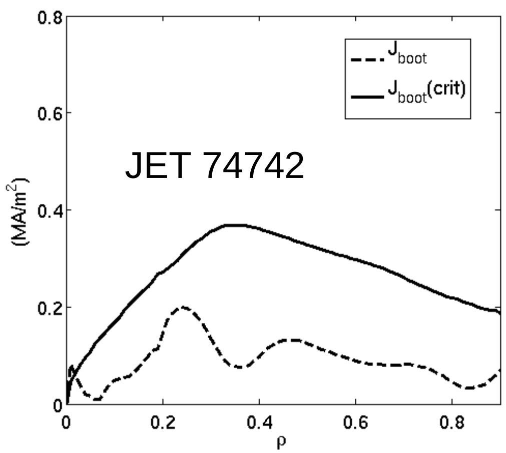
- JET-JT60u identity plasmas experiments (same initial conditions)
- In jt60u the sustainment of advanced scenarios at q≈2 can be done through the bootstrap current
- In JET, the lack of enough bootstrap current leads to the loss of the scenario
- **Physics behind this process is the same one than for hybrids scenarios at q≈1**

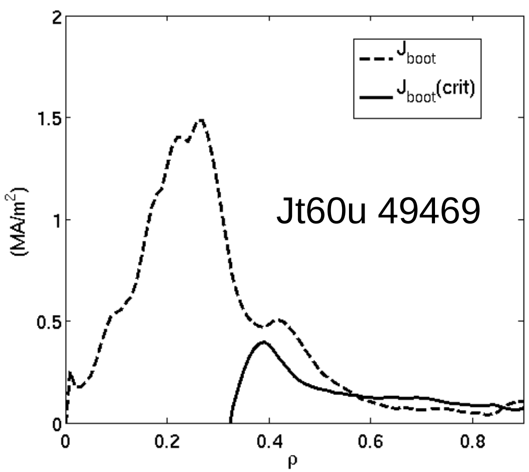
Jt60u versus JET sustainment of advanced scenarios

Initial phase | **Later phase**









- J_θ is very similar at the starting point
- Situation is the opposite after some seconds
- The bootstrap current for JET is well below the requirements
- The bootstrap current for JT60u is almost everywhere above the requirements
- A minimum bootstrap current is necessary to self-sustain an advanced scenario

Extension to higher q_{95}

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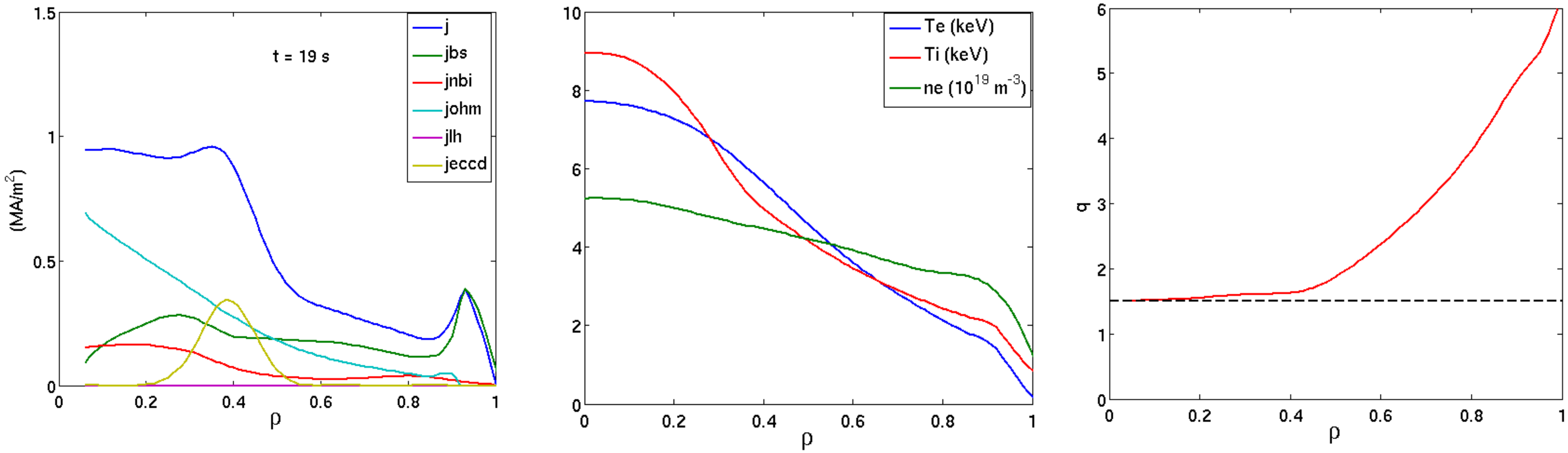
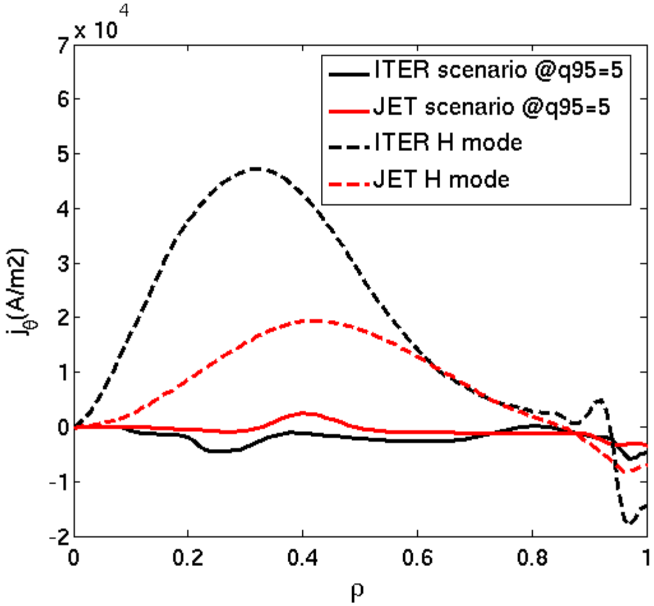


- Other q_{95} configurations can be used with the same curret scheme
- With 7MW of ECRH at q95=5 the q profile is above 1.5 and below 2
- 3/2 NTM can be avoided
- A mild ITB is formed for the ions which increases the bootstrap current at ρ=0.3



- By matching the current and heating configuration for JET and ITER very similar poloidal current profiles are obtained
- The way is to reduce the current to have almost a flat profile at $j_{\theta}=0$
- The final state of the plasma is then very similar for both cases

JT60u hybrid shot 39713 (International Profile Data Base)

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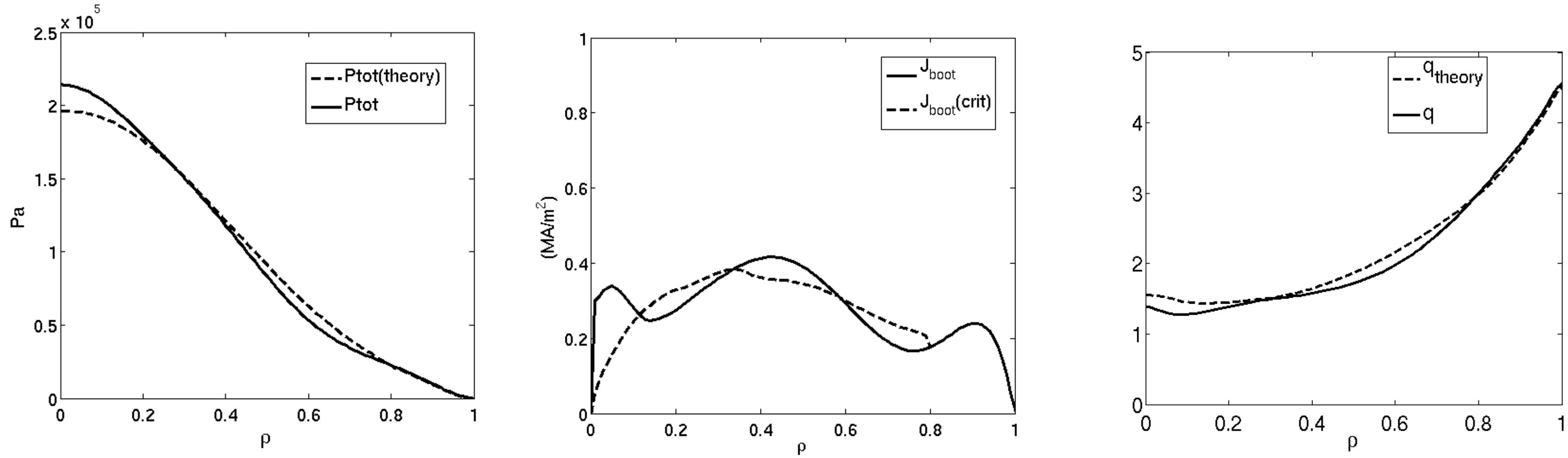
Euratom-CEA
CRONOS



- Pressure, bootstrap current and q profiles are well reproduced by the condition $j_\theta=0$
- The peaked pressure profile drives enough off-axis bootstrap current to sustain the q profile