Modelling of hybrid regime – present status

V. Parail for JET-EFDA Contributors and ISM Working Group

Outline

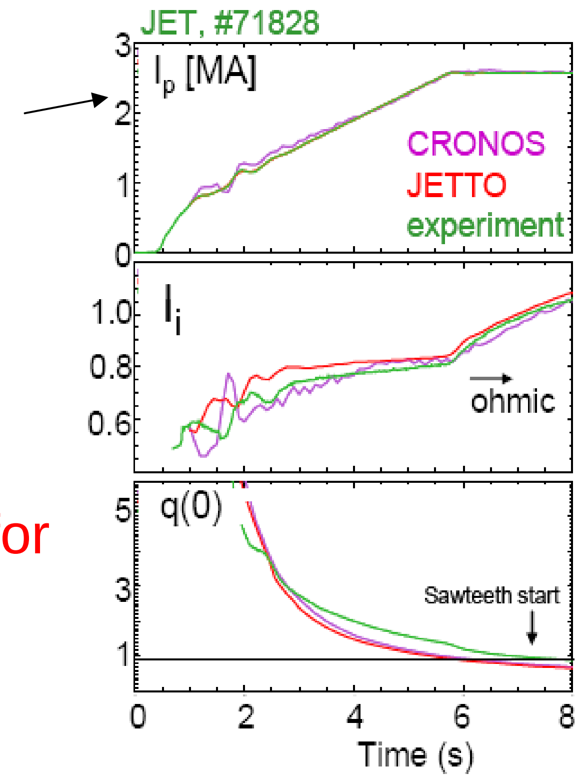
- Modelling of present day experiment;
- Modelling of ITER:
  - Sensitivity study of heating/current drive mix;
  - Edge transport barrier scan;
  - MHD stability of edge barrier;
  - Density peaking;
  - Sensitivity study of transport model wrt current profile;
- Summary, where do we go from here?

Modelling of present day experiment (1)

- Hybrid scenario is much less understood than “usual” type-I ELMy H-mode (even definition of hybrid regime is multiple rather than unique);
- In terms of modelling it means that:
  - Modelling concentrates on some specific features of hybrid scenario rather than doing fully integrated modelling;
  - Same “incomplete” approach is used in extrapolation to ITER, which I would describe as sensitivity study;
  - Present day experiments study is focused on the current ramp-up optimisation in order to get a desired target q-profile;
  - Much less attention is paid to a modelling of edge transport barrier formation and related issue of edge MHD stability;
  - Also plasma transport close to top of edge barrier and related issue of the role of peaked density profile in this region as a source of reduced transport reduction is not sufficiently explored area

JET Ip ramp-up pulses selected by the ISM for publication

- JET ITER-like Ip ramp exp. (q_{95}~3) *
  - 70497(constant q_{95}~3, ohmic), 71827 (ohmic), 71828 (ohmic)
  - 72516 (4MW NBI+Ti during the ramp), 72507 (ICRH)
  - + database analysed by I. Voitsekovitch** (72460,64,65,67,72504,72723,72467,72505,72507)
- advanced scenario q_{95}~5
  - JET 72823 with LHCD versus 72818 ohmic + low NBI for diagnostics (MSE/CXS)
- simulations include Interpretative/predictive using TRANSP(J. Fereira, I. Jenkins, I Voitskekovitch, Yu Baranov), CRONOS (Imbeaux, Hogeweij), ASTRA (J. Hobirk), JETTO (F. Kochl)
- predictive models
  - Based on 0-D scaling law, Bohm/Gyro-Bohm, GLF23, Coppi-Tang



*Sips et al Nucl. Fusion **49** (2009) 085015 + EPS 2008

** Voitsekovitch et al paper on pinboard PPCF

tasks of project #7 (Xavier’s project)

- Define target q profile on the basis of the MHD stability window identified by S2-2.3.1 (**Assessment of beta limit in AT scenario**) & ILW constrains S2-2.3.2 (**Develop JET start-up scenarios for the ITER-like Wall**)
- Modelling of standard current rise using initial conditions for hybrid and steady state scenario from experiment in ohmic/LHCD prelude.
- Domain of accessible q-profiles on JET (and ITER)
- Modelling of the effect of Ip overshot (dwell time, height) on the target q profile.
- Sensitivity studies and influence of initial conditions (target q-profile, Zeff) ? A bad breakdown may affect the q-profile.
- Modelling of the effect of pedestal formation in the first 2s of the pulse.

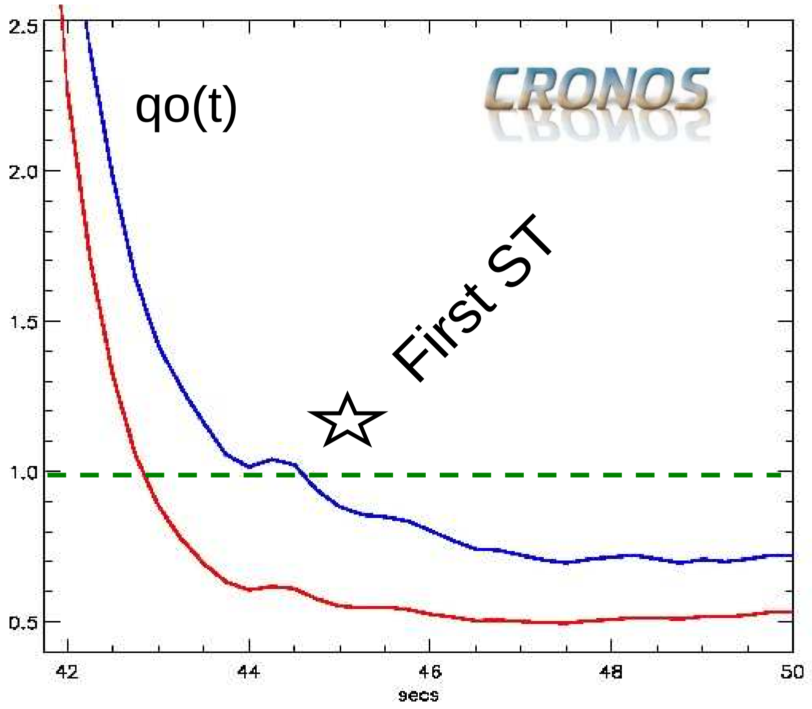
Sensitivity studies : influence of Zeff

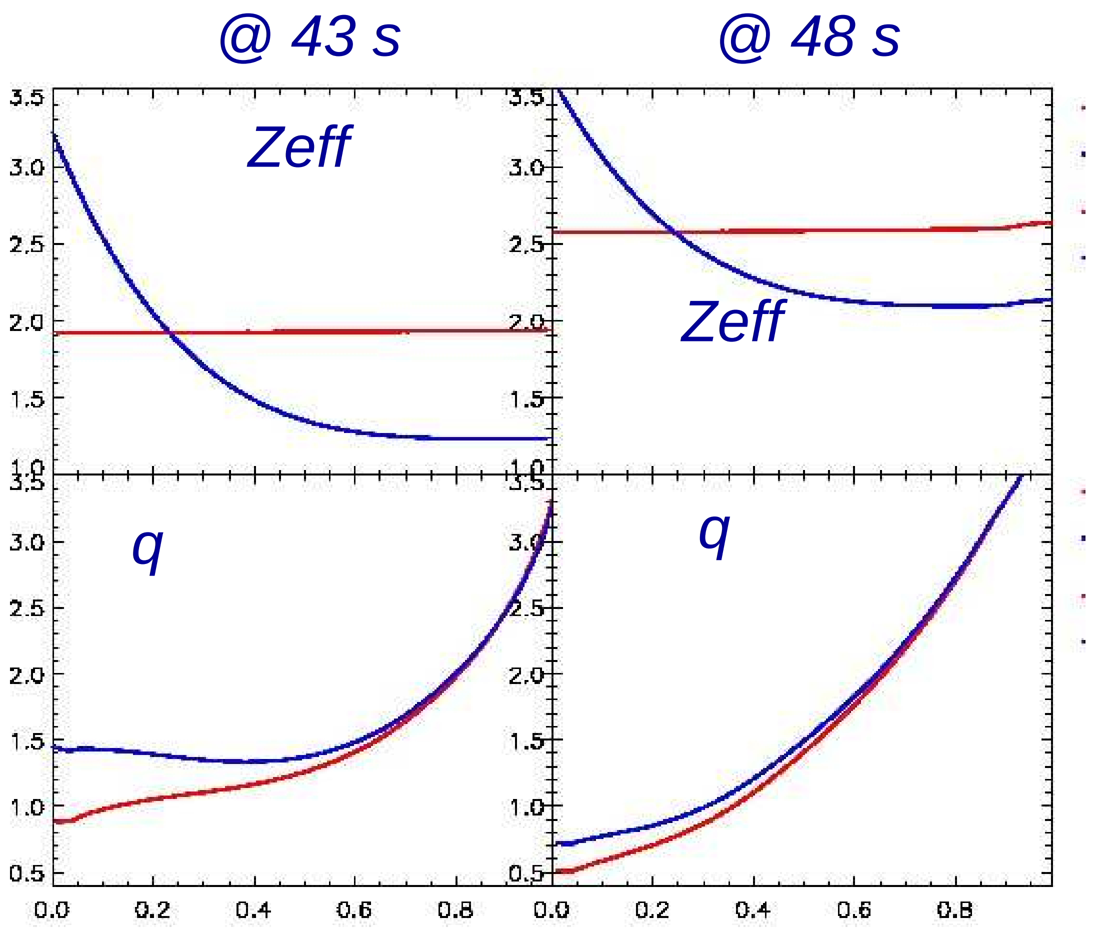
- A strong Zeff sensitivity in the predictive simulation of (ohmic) ramp-up was found when transport models depends on q(r,t) e.g. Bohm/Gyro-Bohm model
  - Increase of Zeff → faster decrease q(r,t) and lower q(r,t) ($\propto 1/Z_{eff}$) → decrease $\chi_e \propto q^2$ ($\propto 1/Z^2{}_{eff}$) → increase T_e
  - integrated modelling, coefficients in front χ_e has to re-scaled by a factor 3.3 to reproduce experimental data when Z_{eff} is increased by 40%

I Voitsekhovitch

too fast drop of q0 by assuming flat Zeff in database

#75447

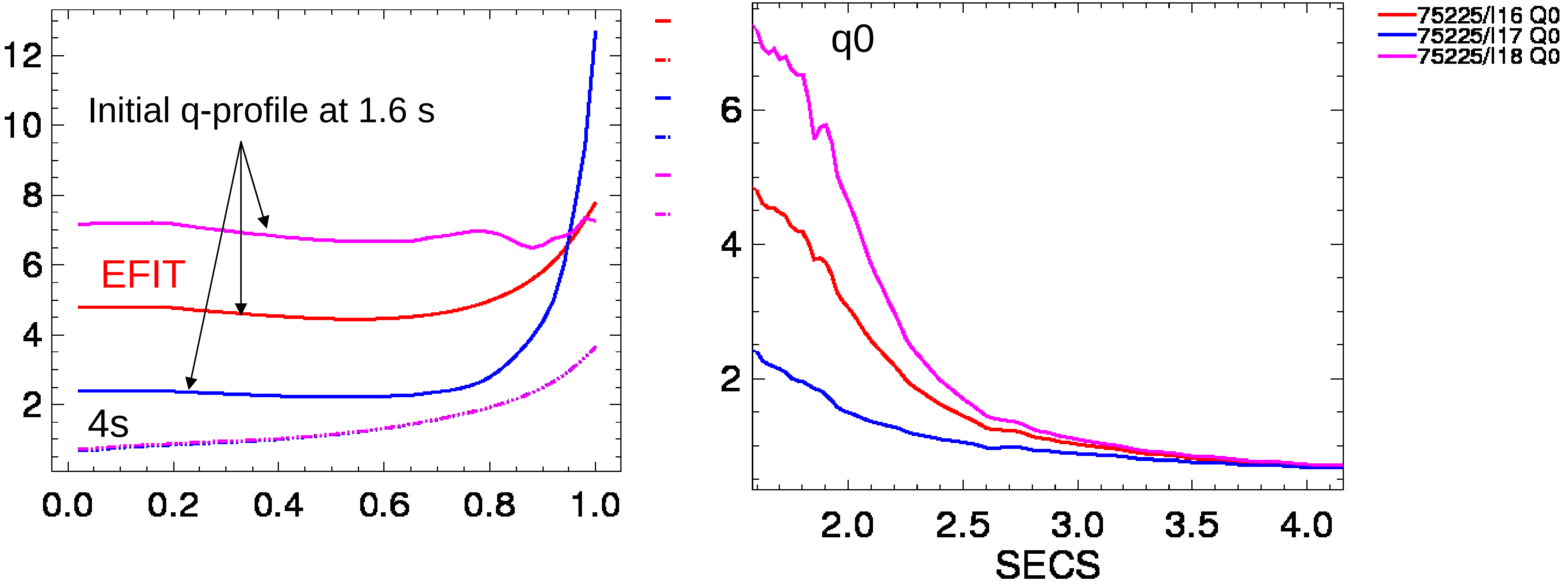




q0 time traces from
41.75 (start or run)
until 50 s:
Red: flat Zeff (value from exp);
Blue: peaked Zeff

D. Hogeweij

Sensitivity to initial q-profile (low triangularity HS 75225)



- *TRANSP simulations of current diffusion with measured ne, Te and KS3/ZEFV are started at 1.6 s with different initial profiles (EFIT/Q is red);*

- *In all cases q-profiles become similar before the NBI heating (NBI starts at 4.8 s)*

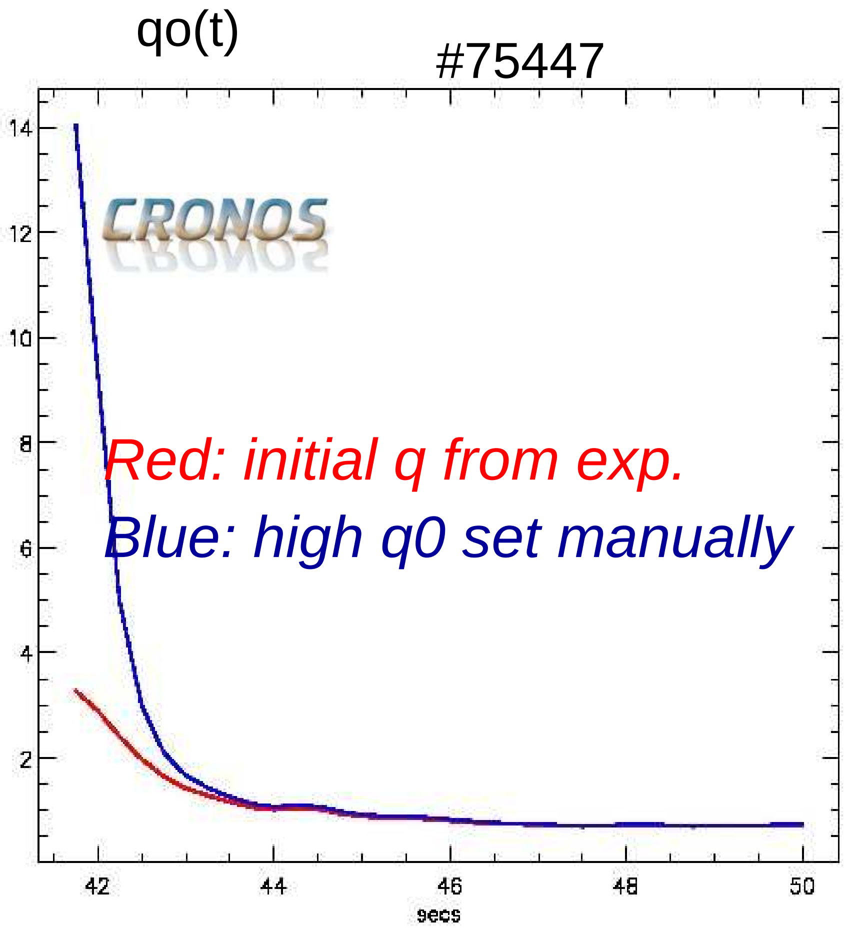
I Voitsekhovitch & I Jenkin

Sensity studies to initial q-profiles

early start (~42 s): effect of choice disappears in ~ 2 s

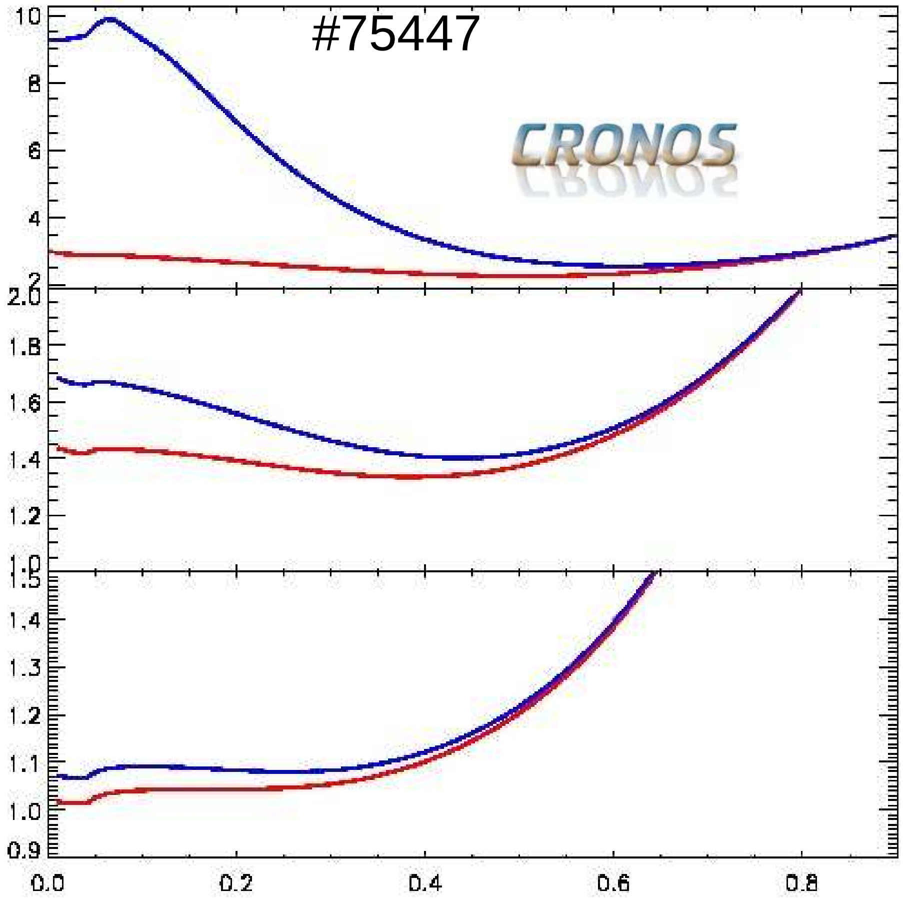
q profiles @ 42, 43, 44 s

→ Effect nearly died away after 2 s



Red: initial q from exp.

Blue: high q0 set manually

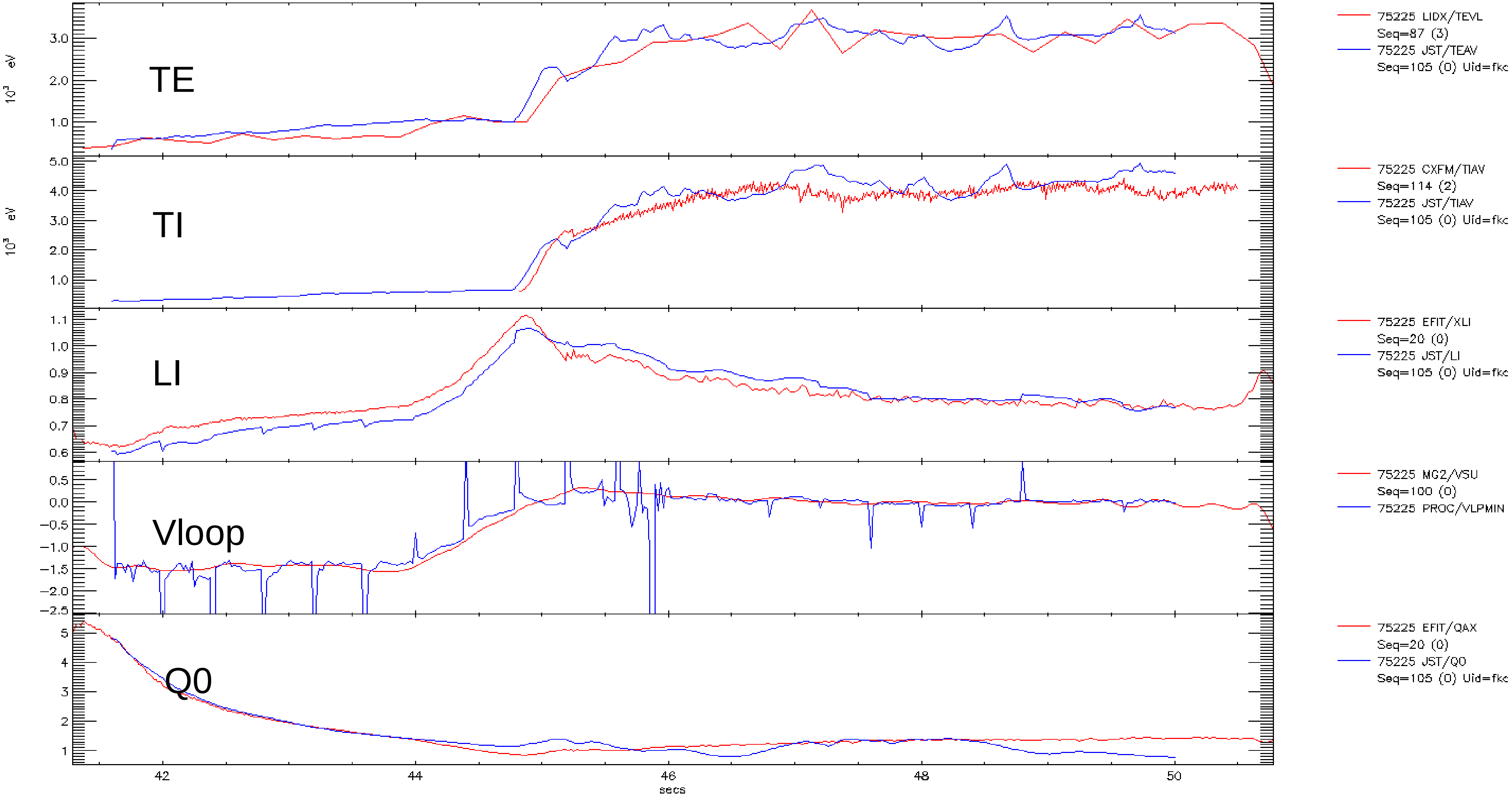


D. Hogeweij

Predictive modelling of Hybrid using JETTO Bohm/Gyro-Bohm

JETTO EXP

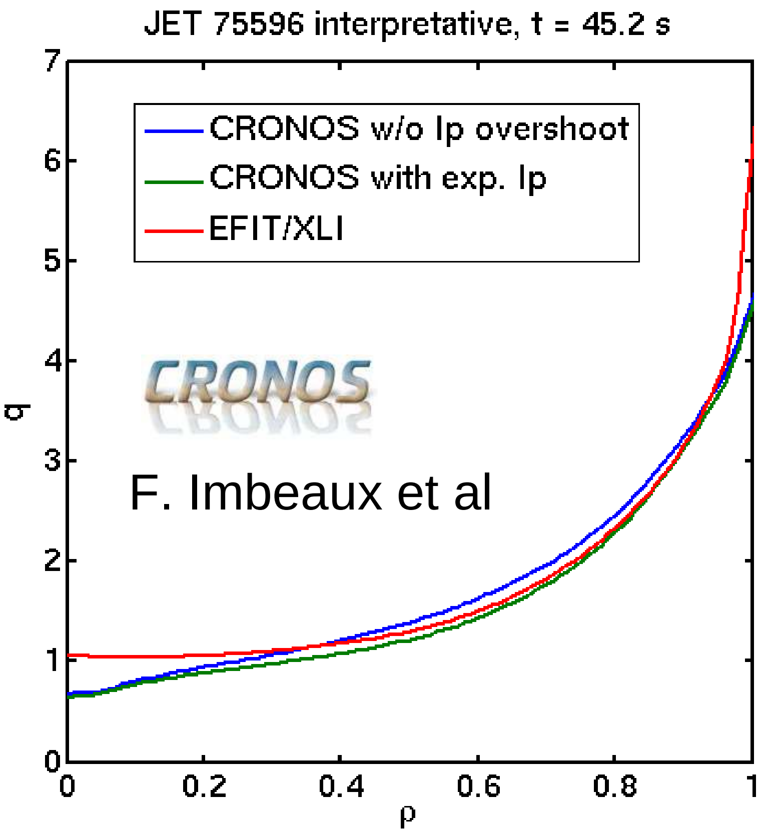
Low δ # 75225



F. Koechl

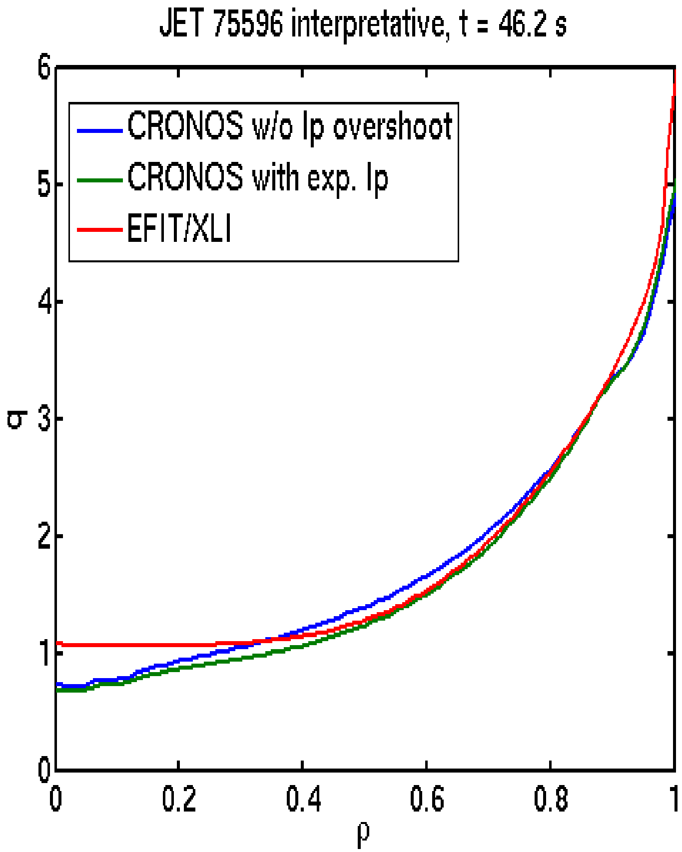
Modelling of target q-profile for hybrid regimes

- High delta: 75596, simulation with / without Ip overshoot
- Only the Ip reference is changed. Using Te profile and boundary from experiment
- Simulations do not feature the flat q-profile inside r = 0.3 → they are both shifted to higher li after t = 45 s.
- There are sawteeth in this shot !!!

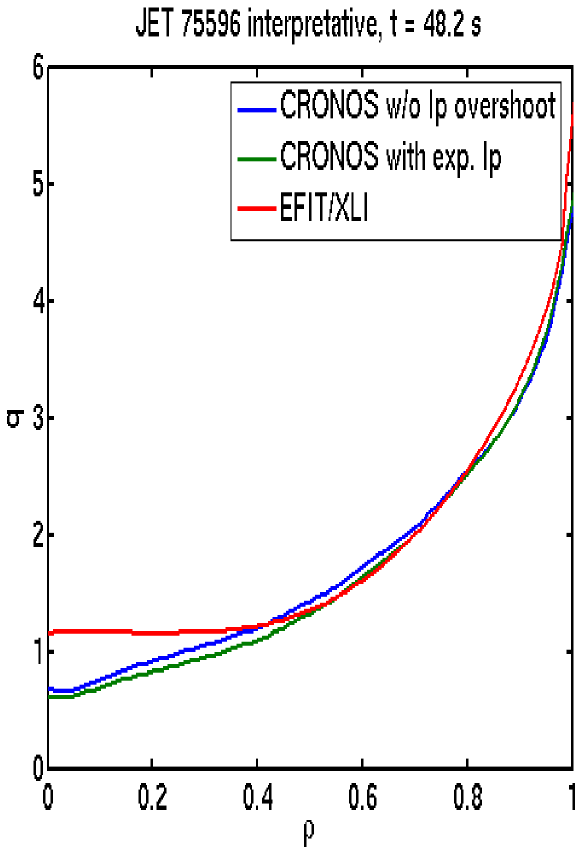


JET 75596 interpretative, t = 45.2 s

F. Imbeaux et al



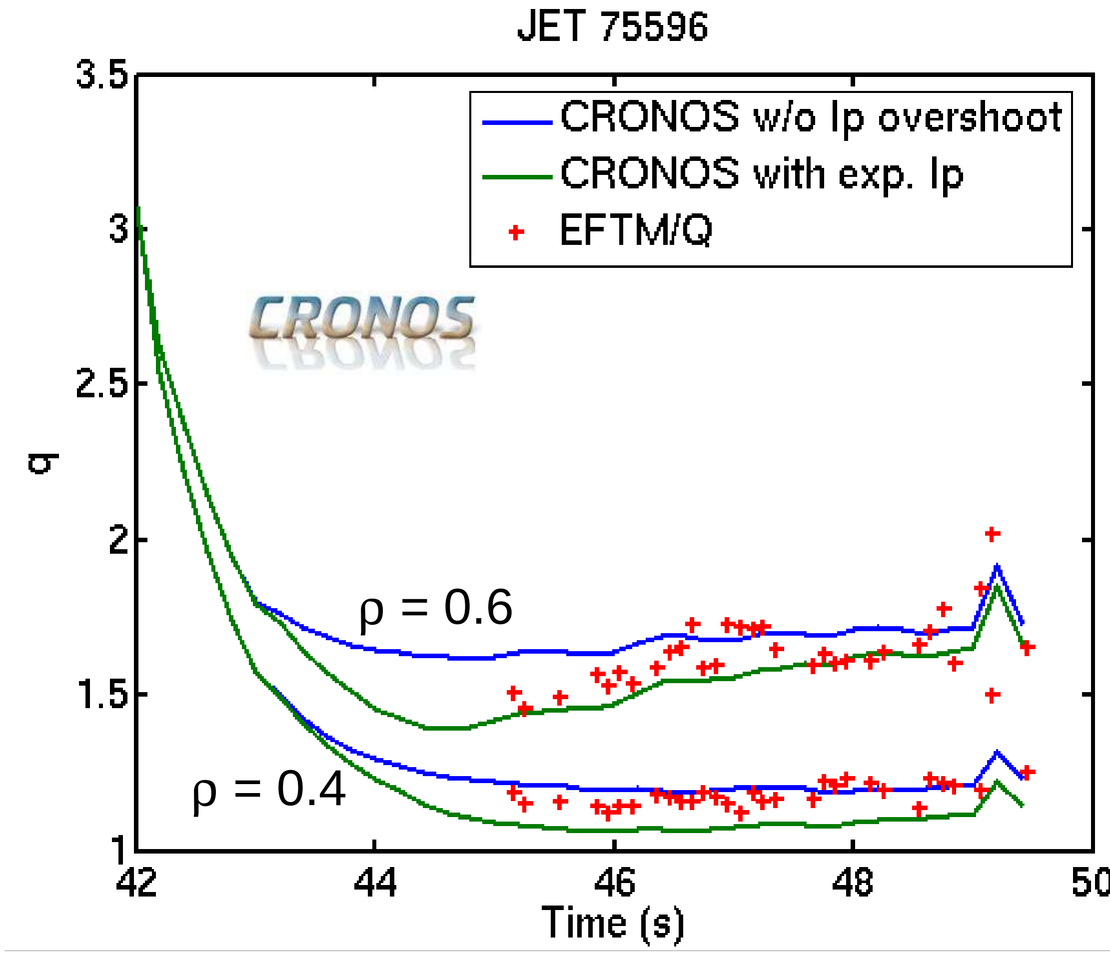
JET 75596 interpretative, t = 46.2 s

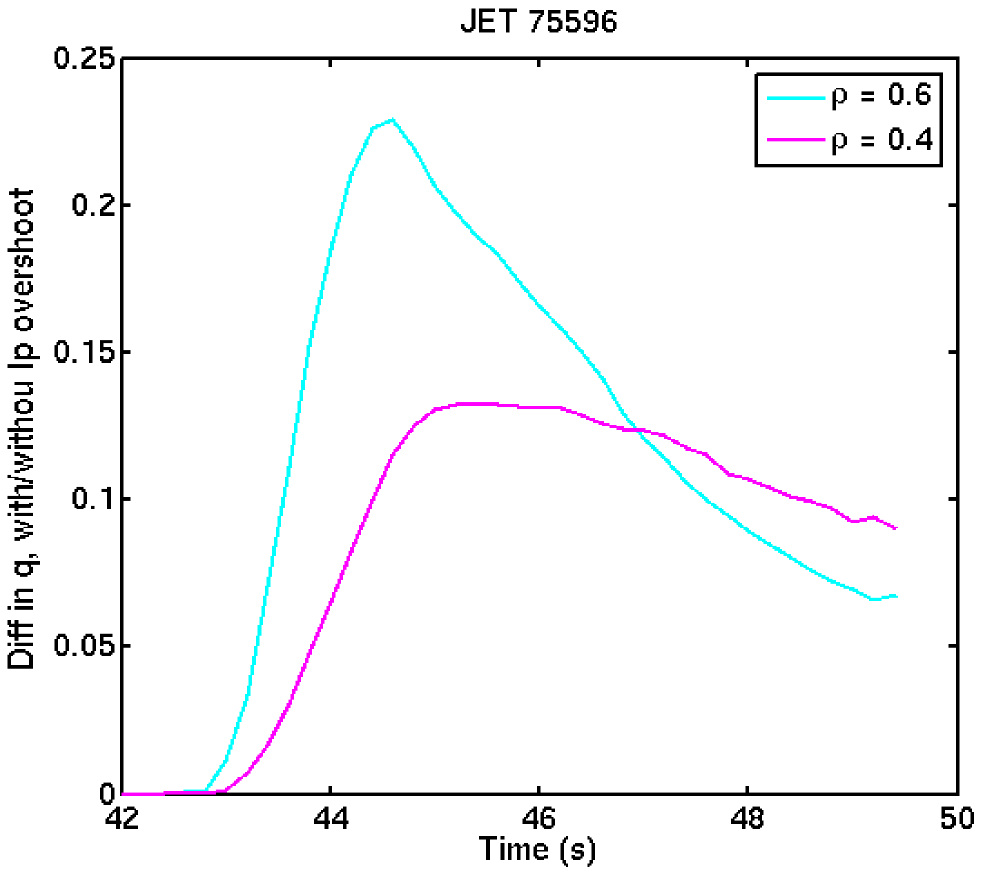


JET 75596 interpretative, t = 48.2 s

Modelling of target q-profile for hybrid regimes

- High delta : 75596, simulation with / without Ip overshoot
- Only the Ip reference is changed. Using Te profile and boundary from experiment
- Relative q-profile evolution is in better agreement with EFTM for the simulation with Ip overshoot
- Δq is max ~ 0.25, is below 0.1 after t = 48 s.





Modelling of ITER (1)

- Modelling of ITER:
  - **Sensitivity study of heating/current drive mix**;
  - **Edge transport barrier scan**;
  - MHD stability of edge barrier;
  - Density peaking;
  - Sensitivity study of transport model wrt current profile;

Hybrid scenarios dependence on heating and pedestal features

J. Garcia

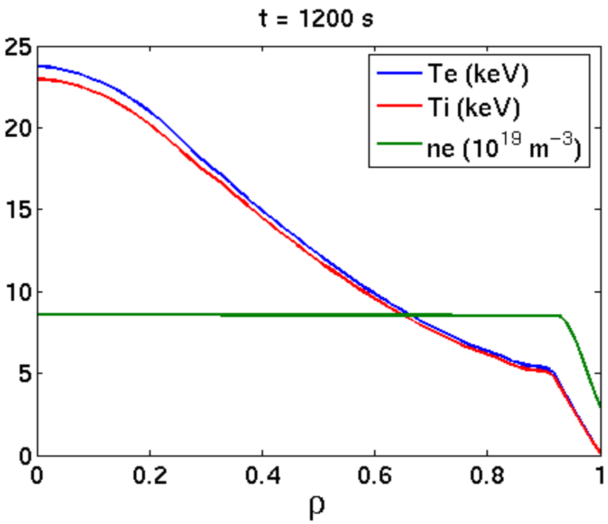
General Parameters

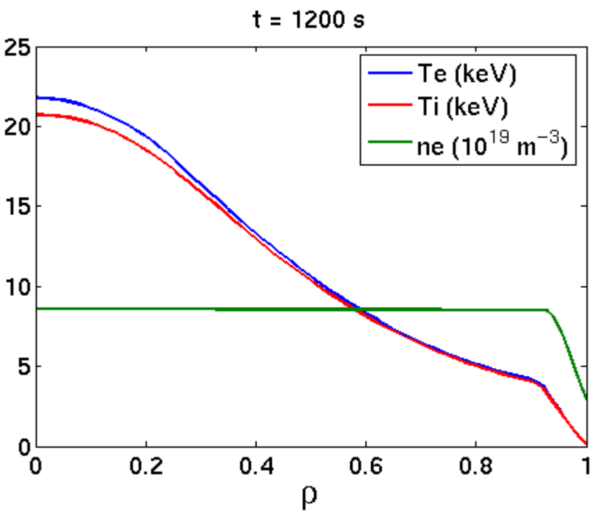
- Ip=12 MA, ne0=nped=8.6E19 m-3
- Greenwald limit fraction=0.88
- Pedestal located at 0.925
- Temperature height scan from 3 keV to 5 keV
- CRONOS is used
- Transport model: GLF23
- Two heating systems analyzed: NBI (Nemo used) and ECRH (REMA used)
- Original run: Picrh=20 MW, Pnbi=33 MW

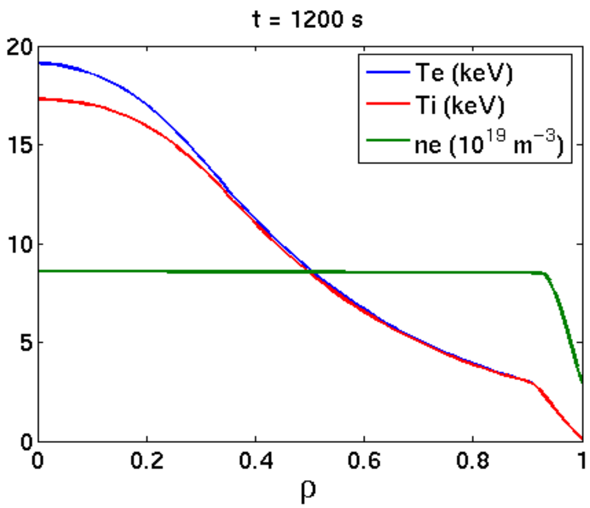
C. Kessel, G Giruzzi et al., Nucl. Fusion 47 (2007) 1274–1284

- Second run: More ECRH power to compensate lower cd efficiency: Picrh=20 MW, Pecrh=42 MW

NBI heating: Temperature profiles

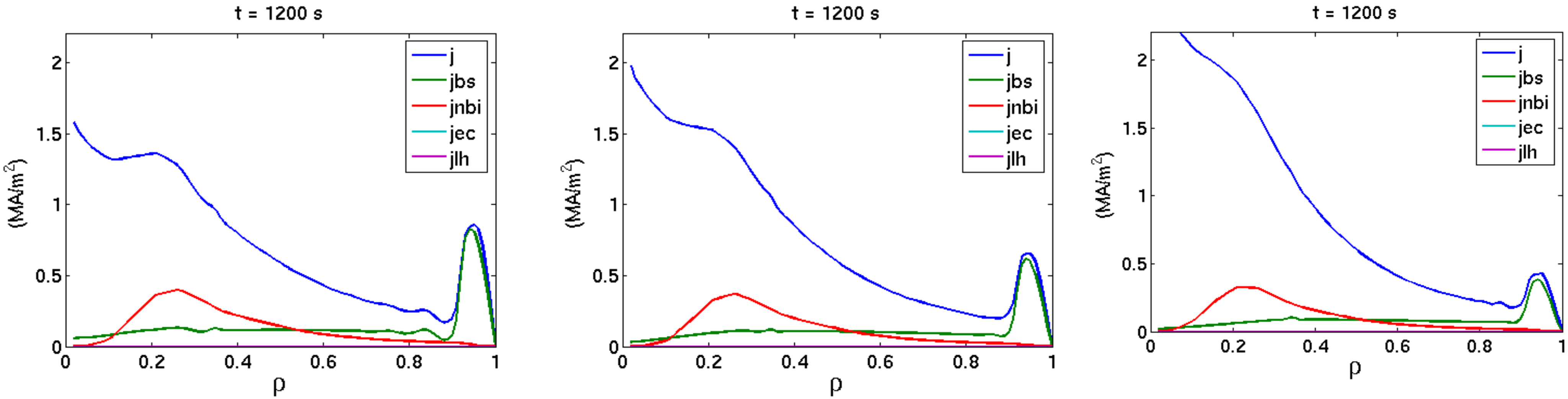






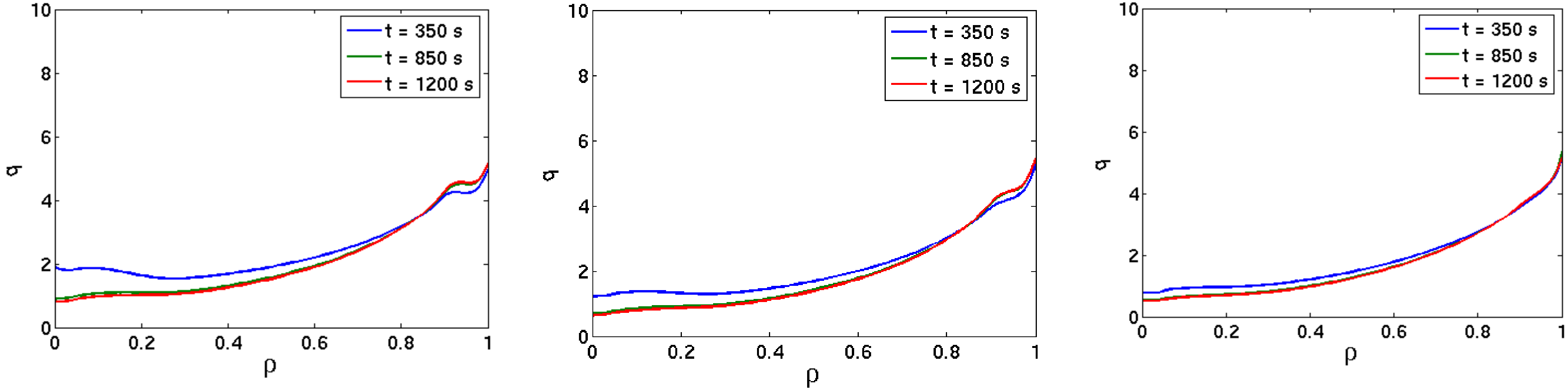
- Te0 drops from 24 keV to 19 keV
- Ti0 drops from 23 keV to 17.3 keV
- Power gain Q from 7 to 3.8

NBI heating: Current density profiles



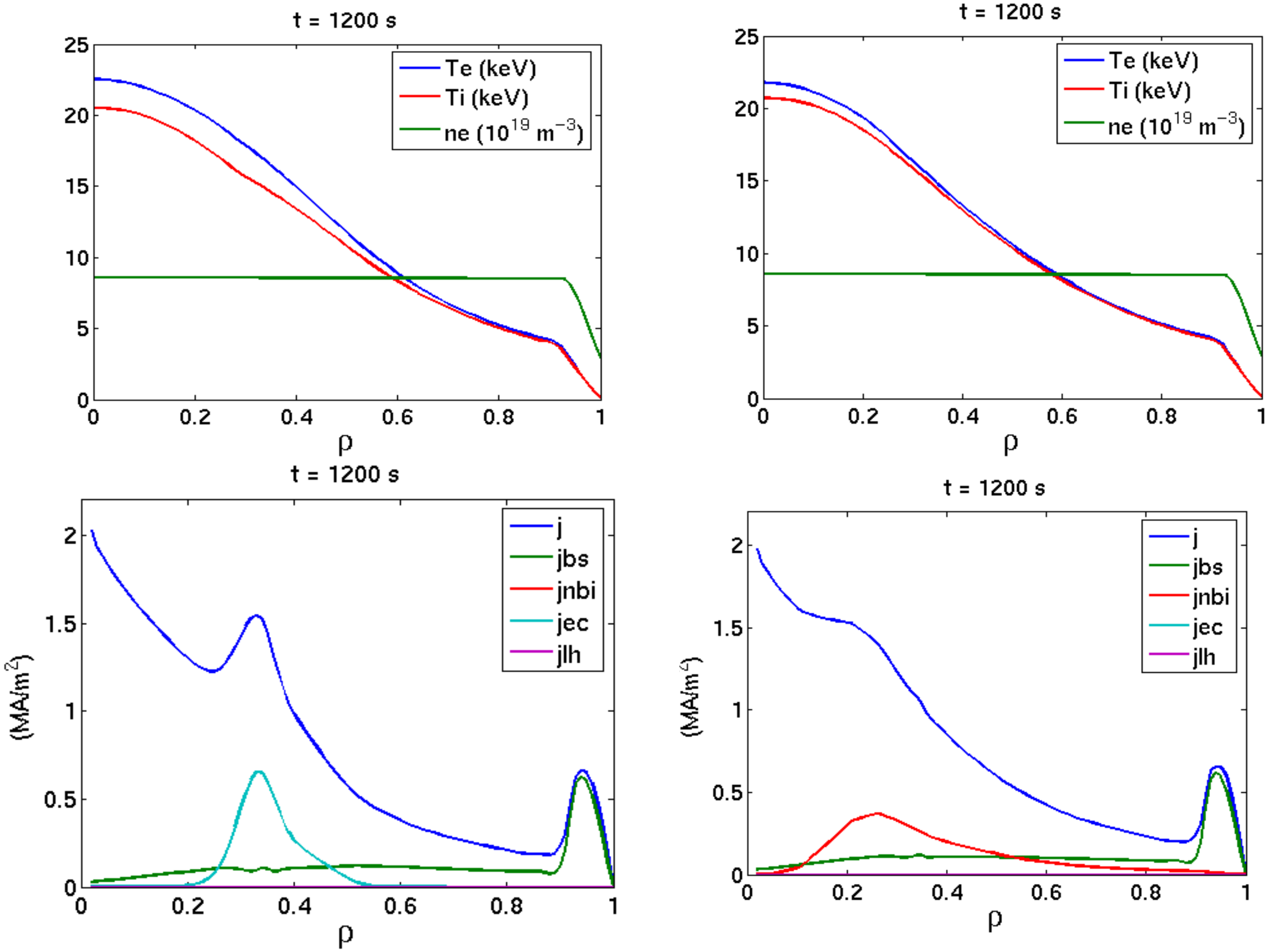
- Current density profile globally dominated by NBI current drive and bootstrap current at the edge
- Non inductive current fraction from 52% to 32%
- Bootstrap current fraction from 38% to 20%

NBI heating: q profiles



- Surface q=1 is r=0.1 for tped=5 keV
- Surface q=1 is r=0.37 for tped=4 keV
- Surface q=1 is r=0.4 for tped=3 keV

Comparison ECRH vs NBI for tped=4 keV



- Temperatures almost identical
- Q=5.5 for NBI and 5 for ECRH
- Ieccd=1.3 MA
- Inbi=2.0 MA

Summary

	Te0/Ti0	Q/H$_{98}$	fni/fboot	r(q=1)/t(q=1)
5 keV NBI	23.7/23.0	7/1.15	52%/38%	**0.1/680s**
5 keV ECRH	22.8/21.0	5.7/1.15	45%/33%	**0.05/600s**
4 keV NBI	22.0/20.7	5.5/1.03	44%/27%	**0.37/430s**
4 keV ECRH	**22.5/20.5**	**5/1.05**	**40%/28%**	**0.2/440s**
3 keV NBI	19.2/17.3	3.8/0.85	32%/20%	**0.4/268s**
3 keV ECRH	18.8/16.3	3.8/0.9	27%/19%	**0.47/185s**

Conclusions

- The pedestal features are essential for the hybrid scenario.
- Correct determination is important
- Reduced r(q=1) surfaces with ECRH.
- Base scenario to be considered will be with 4 keV.
- A scenario with reduced ECRH and more LH heating will be studied during this week. (J. Citrin)
- A scenario with lower total current is on the way. (J.Citrin)
- Results benchmark with JETTO (J. Ferreira)
- MHD analysis (J. Lonnroth)

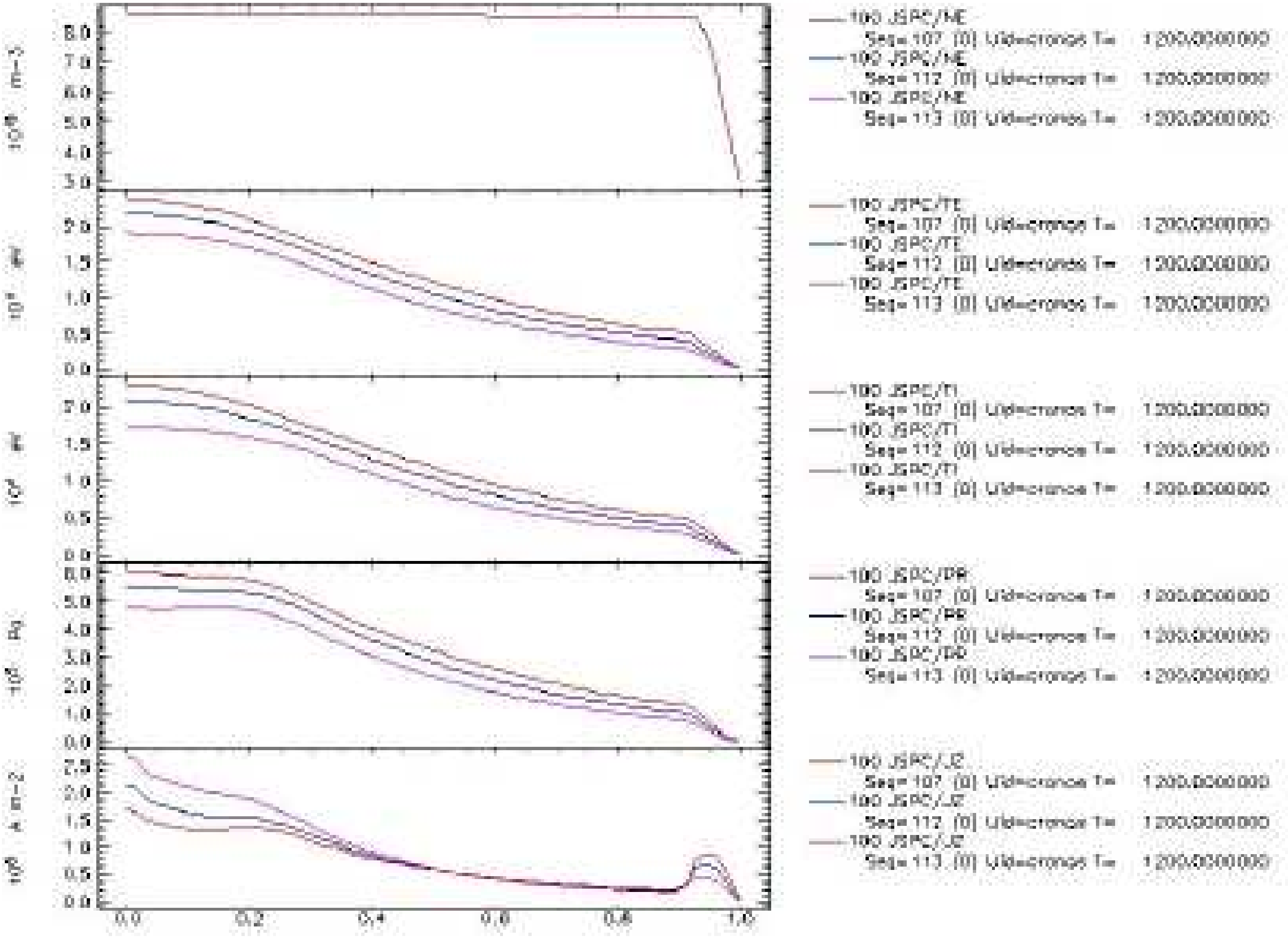
Modelling of ITER (1)

- Modelling of ITER:
  - Sensitivity study of heating/current drive mix;
  - Edge transport barrier scan;
  - **MHD stability of edge barrier**;
  - Density peaking;
  - Sensitivity study of transport model wrt current profile;

MHD stability of edge barrier (1)

J. Lonnroth, S. Saarelma

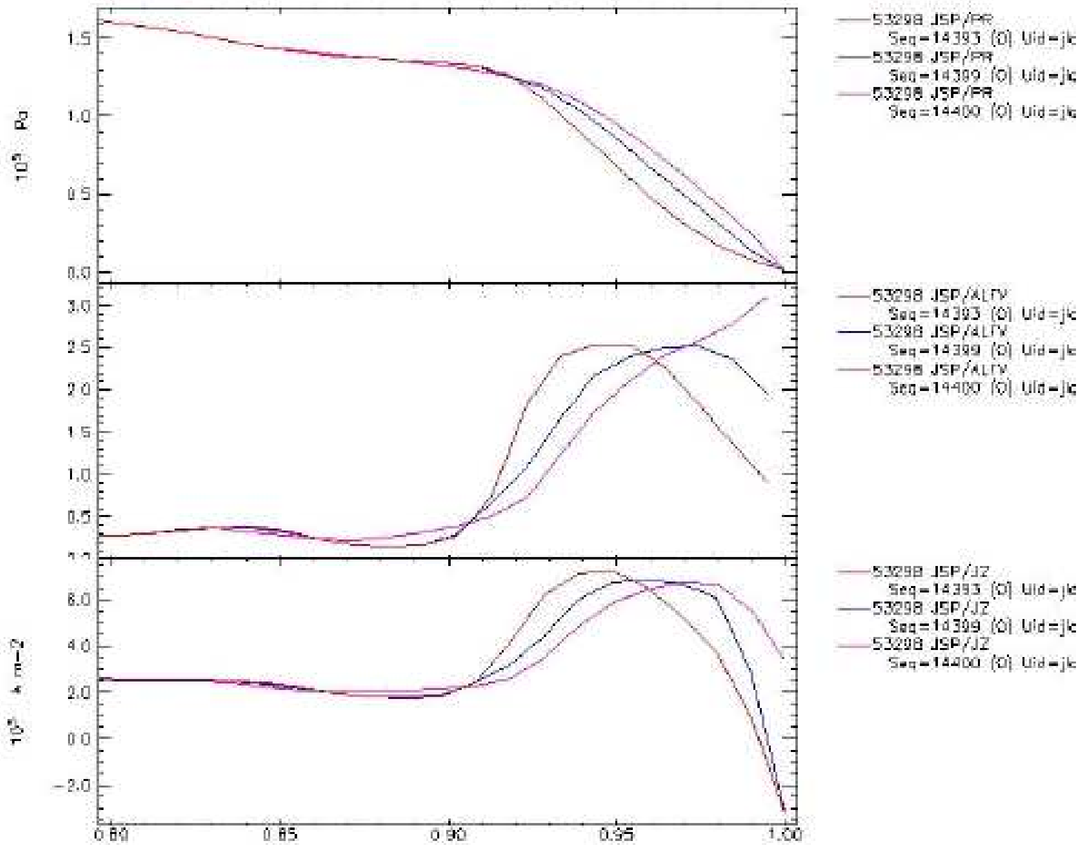
- The hybrid scenario has been analysed in a similar way to Scenario 2. The starting point has been three CRONOS simulations with different pedestal heights: 5 keV, 4 keV and 2.7 keV.



MHD stability of edge barrier (2)

J. Lonnroth, S. Saarelma

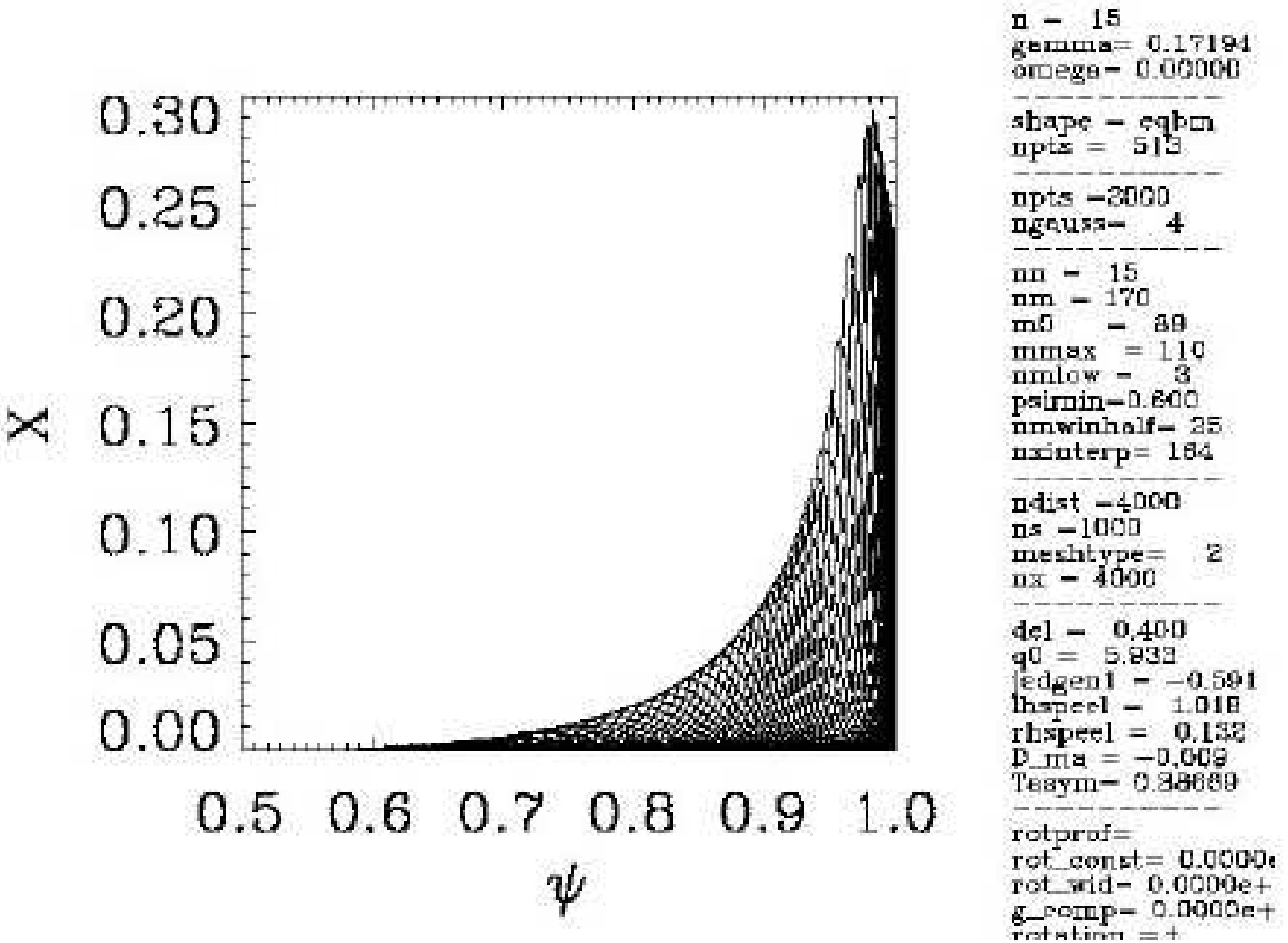
- Three different pressure and current profiles were prepared for each pedestal height and they were all analysed with MISHKA and ELITE;
The analysis with MISHKA-1 indicates that all three plasmas are deeply unstable against a wide range of toroidal mode numbers in the range n = 2…25 for Teba=5keV. ELITE gives a similar result with the caveat that the convergence on a solution is quite poor for the plasmas with negative toroidal edge current density.



MHD stability of edge barrier (3)

J. Lonnroth, S. Saarelma

- The figure shows the eigenfunction of an n = 15 mode, as calculated by ELITE for the magenta case, which has the largest pressure gradient.

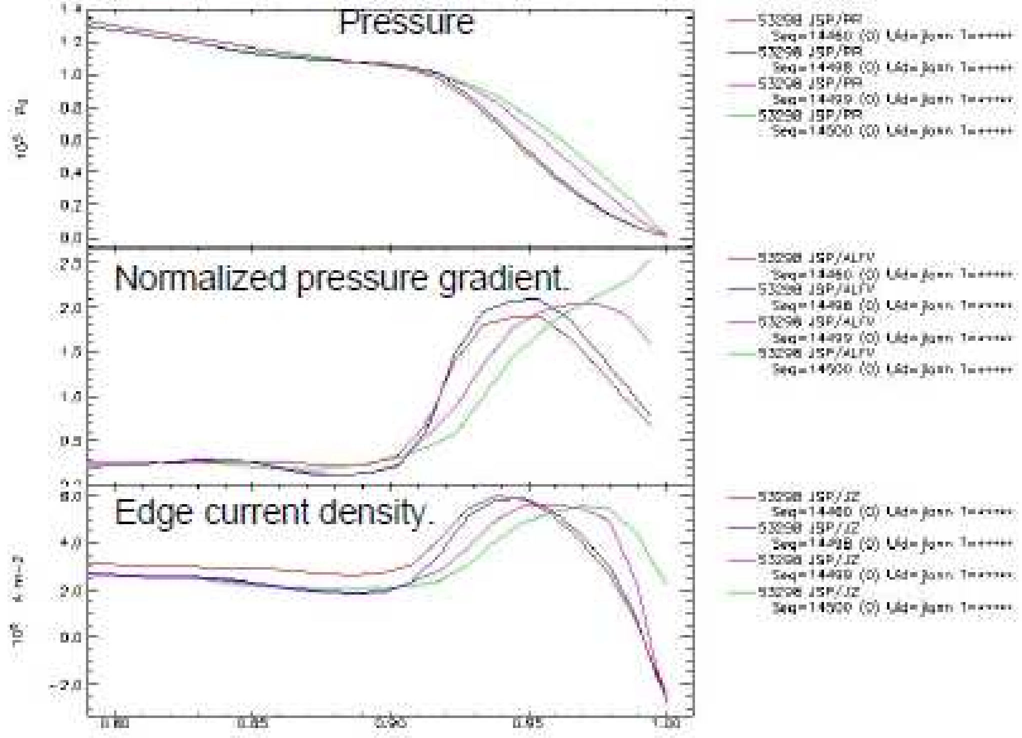


```
n = 15
gamma= 0.17194
omega= 0.00000
---------------
shape = eqbm
npts = 513
---------------
npts =2000
ngauss=   4
---------------
nn = 15
nm = 170
m0    = 89
mmax  = 110
nmlow =   3
psimin=0.600
nmwinhalf= 25
nxinterp= 184
---------------
ndist =4000
ns =1000
meshtype=   2
nx = 4000
---------------
del =  0.400
q0 =  5.933
jedgen1 = -0.591
lhspeel =  1.018
rhspeel =  0.132
D_ma = -0.009
Tesym= 0.88669
---------------
rotprof=
rot_const= 0.0000e
rot_wid= 0.0000e+
g_comp= 0.0000e+
rotation =t
```

MHD stability of edge barrier (4)

J. Lonnroth, S. Saarelma

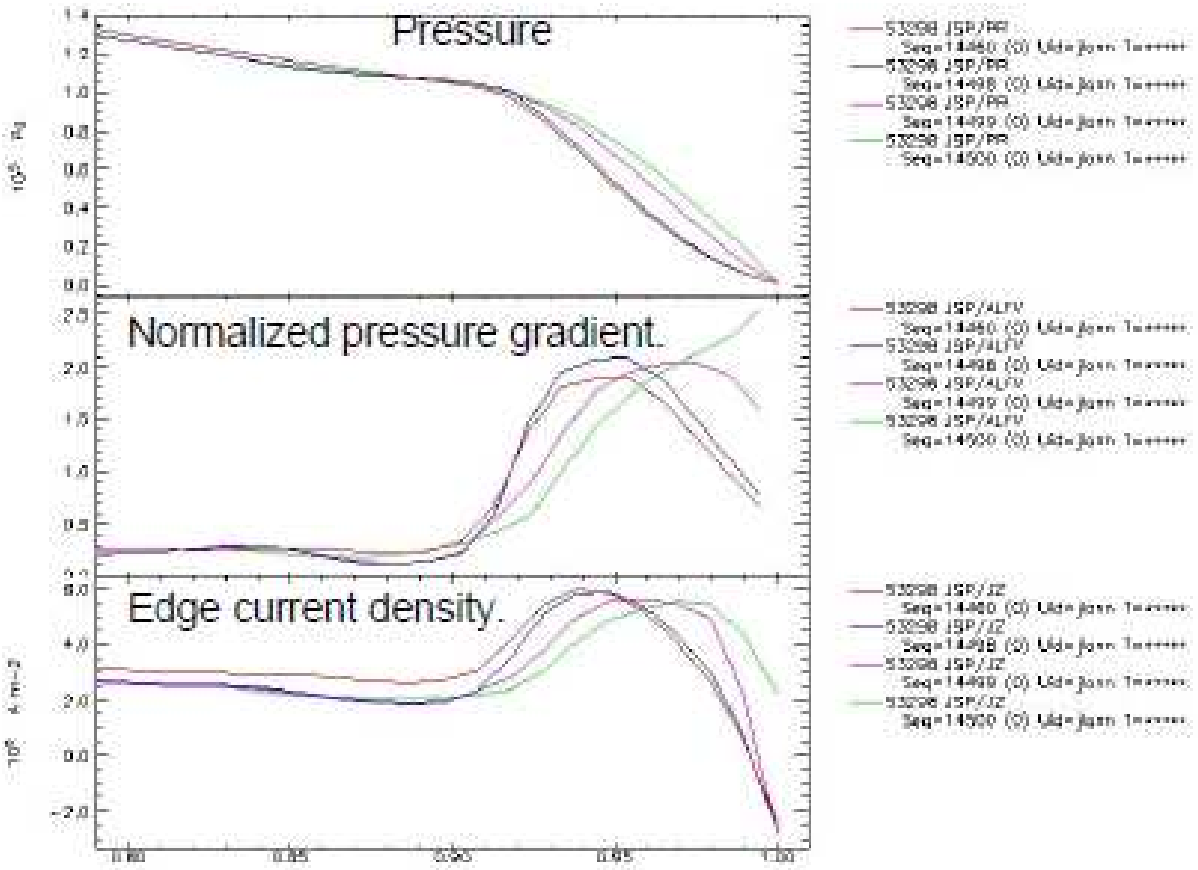
- The MHD stability of three cases with Teba=4keV has been analysed.
- MISHKA-1 indicates that the green case, which has the steepest pressure gradient, is deeply unstable The magenta case is unstable according to MIHSKA-1. The red case, which is the original JETTO run, is probably also unstable, but the solutions are not well converged due to the negative edge current density.
- ELITE shows green case to be unstable and has convergence problems with the other two cases.
- The conclusion is still that all three cases are probably at least marginally unstable.



MHD stability of edge barrier (5)

J. Lonnroth, S. Saarelma

- Finally, the MHD stability of three cases with Teba=2.7keV has been analysed. MISHKA-1 indicates that the green case, which has the steepest pressure gradient, is quite close to marginal stability, possibly slightly unstable against some low n modes in the range n = 2…8. The magenta case is stable according to MIHSKA-1 and so is the red case, which is the original JETTO run. ELITE indicates that the green case is stable and has again convergence problems with the other two cases.



Modelling of ITER (1)

- Modelling of ITER:
  - Sensitivity study of heating/current drive mix;
  - Edge transport barrier scan;
  - MHD stability of edge barrier;
  - **Density peaking**;
  - Sensitivity study of transport model wrt current profile;

Particle simulation and density peaking for ITER hybrid scenario

J. Garcia, J.F. Artaud

Association Euratom-CEA
CEA/Cadarache, France

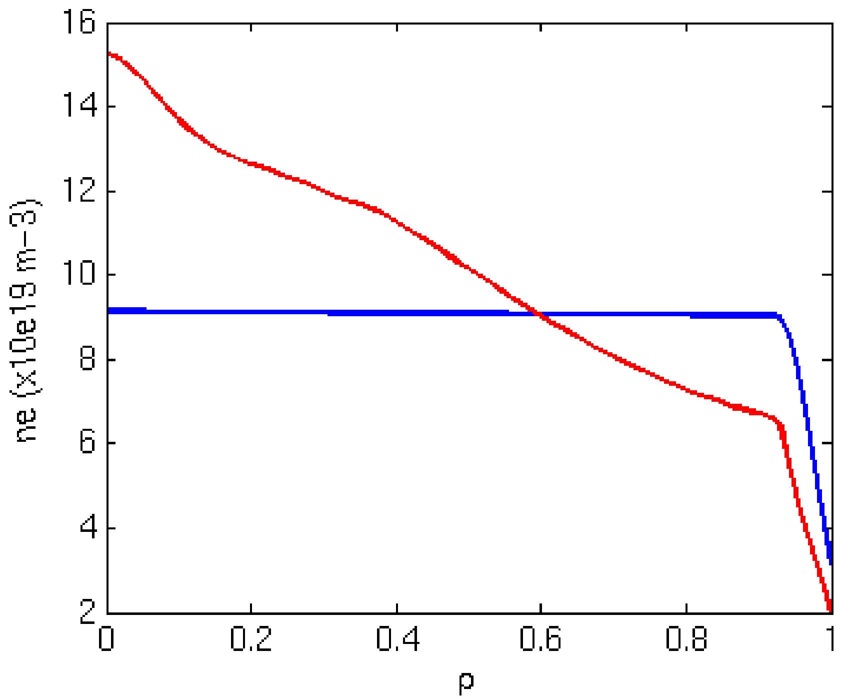
- Best case of J.Citrin hybrid scenario with tped=4 keV used

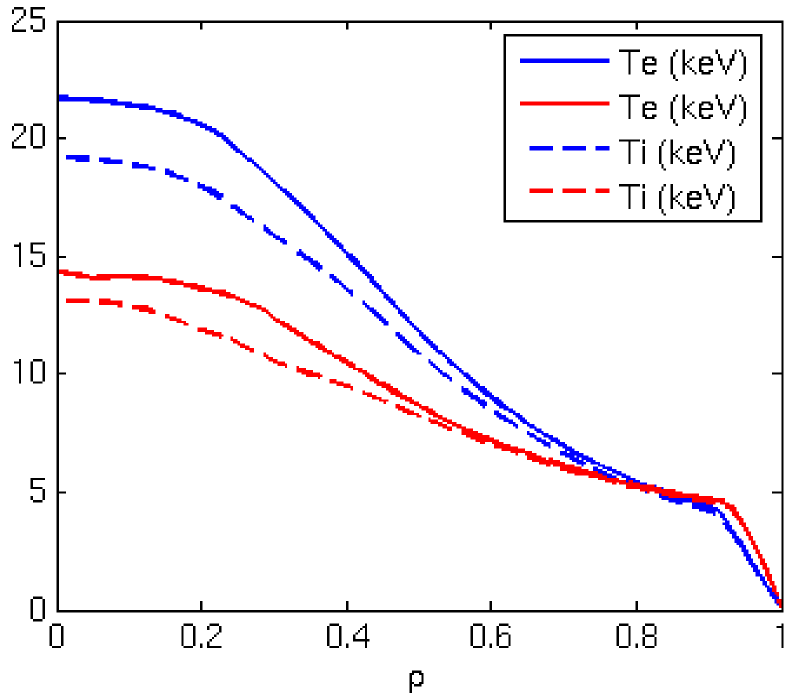
- NBI and ECRH/ECCD heating systems used

- Pressure at the pedestal maintained constant

- Gas Puff used for fueling

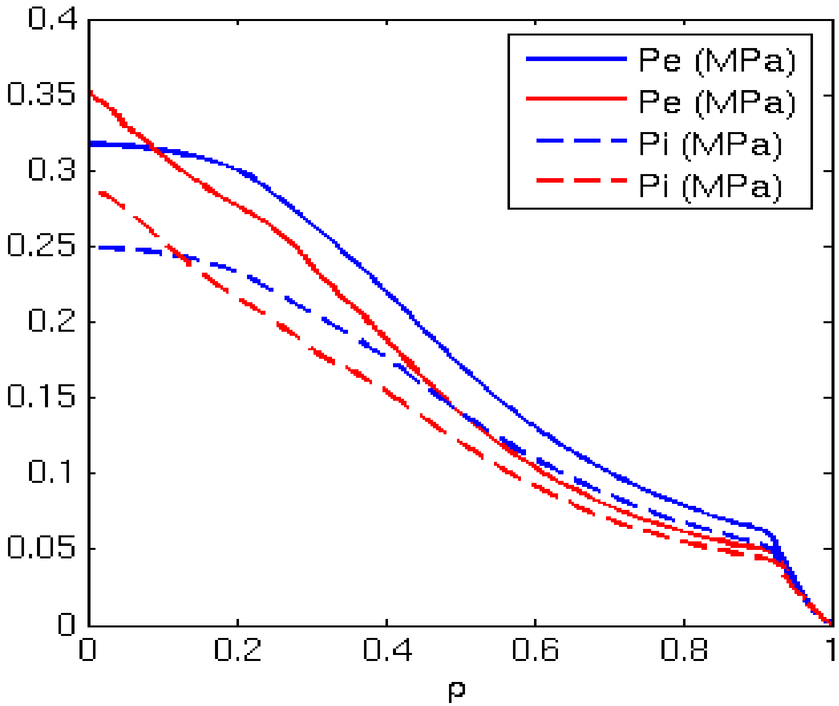
Density peaking influence

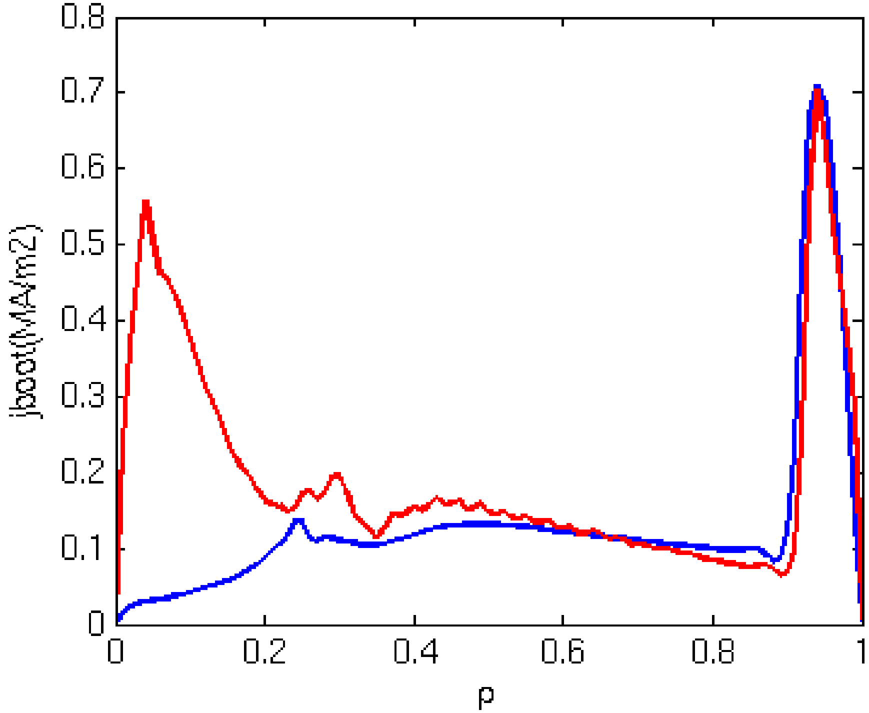




- Same average density for both scenarios: 8.7x10^{19} m-3
- Tped=4keV in original case. Tped=4.6 keV picked density case (in order to have the same pedestal pressure)
- Temperatures clearly drop
- The GLF23 pinch is strong. Peaking factor≈2

Density peaking influence





- Pressure profile drops for peaked density
- Alpha power drops from 70MW to 52MW. *Note that this conclusion contradicts to what we conclude for Scenario-2.*
- Bootstrap current increases from 3.7MA to 3.9MA
- Bootstrap current from the edge almost constant

ITER advanced scenarios

- Benchmark of GLF23 with density peaking profiles should be carried out with other codes

- Analysis with GYRO necessary

- Has anyone tried the same exercise with ITER reference scenario?
- Yes, see above
- What about with other machines?

- Particle transport in CRONOS must be clearly improved (problems to control average density)

- Pellet fueling must be analyzed

Modelling of ITER (1)

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  - MHD stability of edge barrier;
  - Density peaking;
  - **Sensitivity study of transport model wrt current profile**;

Optimization of ITER Hybrid Scenario performance with the CRONOS suite of codes

Jonathan Citrin[1], Jean-François Artaud[2], Jeronimo Garcia[2],
Dick Hogeweij[1], Frédéric Imbeaux[2]

[1] FOM Rijnhuizen, The Netherlands

[2] CEA Cadarache, France

Importance of q-profile shaping

q-profile shape can be **optimized for improved confinement**, when transport model contains q and s dependencies (such as GLF23)

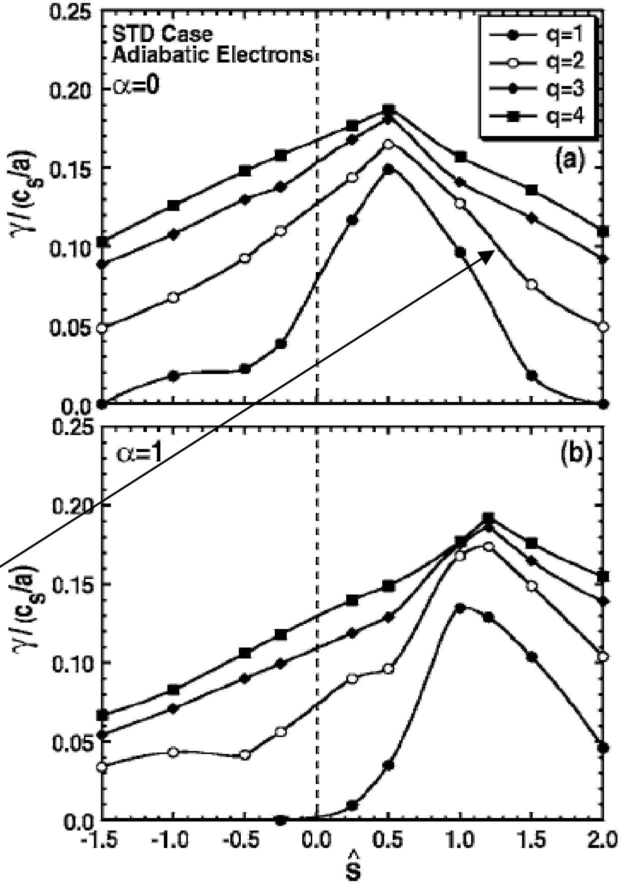
Optimizing the q-profile shape with non-inductive current drive reduces the density necessary for P_{fus}=350MW.

↓

At the same Greenwald fraction, the current can thus also be reduced, decreasing I_{ohm}, and increasing t(q=1).

We are mostly in this region, therefore we want to maximize s/q throughout the q-profile

GYRO ITG linear growth rates



Kinsey, Waltz, Candy (Phys. Plasmas 2006)

Philosophy of this work

CRONOS simulations between 40-1200 sec (sometimes 3000) with the targets:

| P_{fus}>350MW | P_{loss}<~110MW | Q>5 | $t_{discharge}$ & t(q=1) >1000sec |

- All combinations of heating/current drive considered: LH(0-20MW), EC(0-50MW), NBI(0-50MW), IC(0-20MW). Path to optimum q-profile studied.
- GLF23 transport model for energy channel (no rotation or α-stabilization included)
- Prescribed flat density (cases with prescribed peaked density also considered)
- Scenario optimization attempts at assumed T_{ped}=3,4,5 keV (set at x=0.92)

For each given scenario, n_e was set such that P_{fus}~350MW

Source modules used:

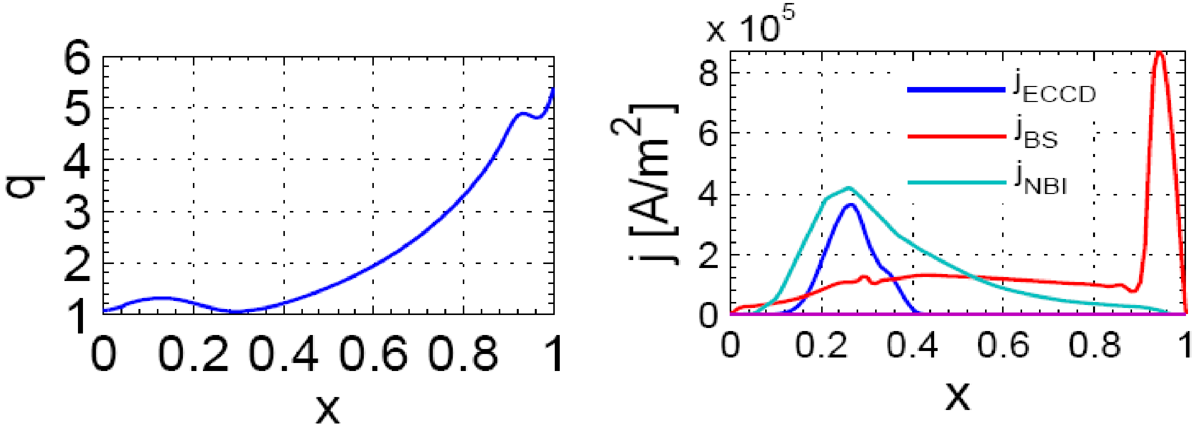
REMA (EC), DELPHINE/LUKE (LH), PION (IC), NEMO (NBI)

Optimum results: T_{ped} = 5keV

Why is the NBI and EC combination optimum?

It combines the following, all contributing to minimizing I_{ohm} needed (through dependency on n_e) in order to obtain 350MW:

- High CD efficiency (NBI)
- ECCD deposition radius control to lock q(x~0.3) to 1, maximizing s/q
- Low amount of outboard NI current (between 0.4-0.9), maximizing s/q



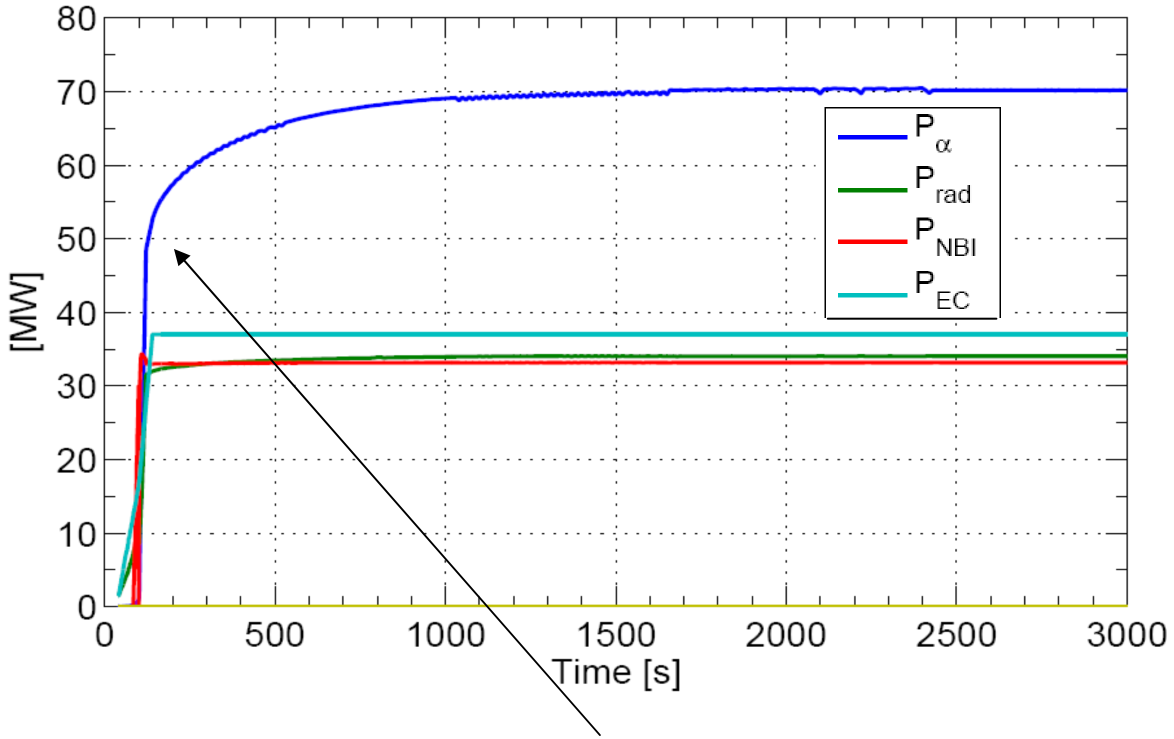
Due to GLF23 stiffness , it was found that scenarios not sensitive to *heating* mix, but rather primarily sensitive to *current drive mix for* q-profile shaping

Optimum results: T_{ped} = 4keV

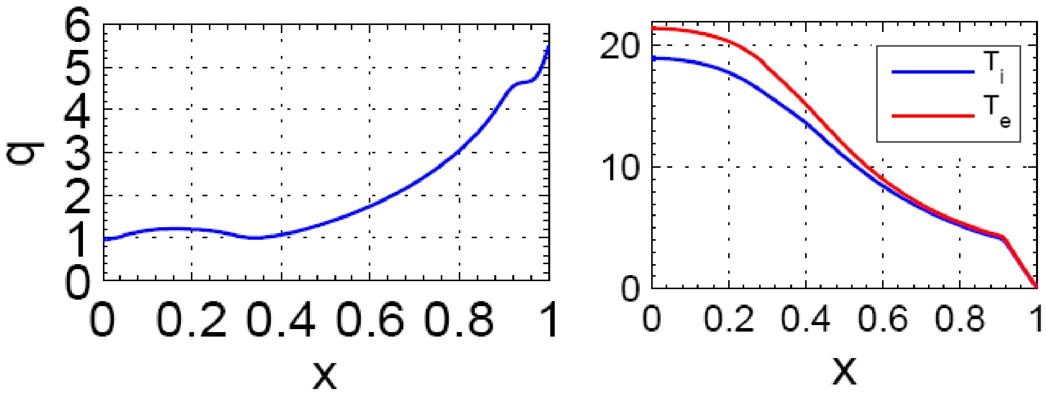
H/CD mix: 37EC, 33NBI (off-axis)

I_p = 11.8 MA
f_{GWald} = 0.95
P_{fus}(3000) = 351 MW
Q(3000) = 5
P_{loss}(3000) = 114 MW
t(q=1) = 1050 sec
r(q=1) = 0.02, at 3000 sec
β_N(3000) = 2.02

flattop flux-consumption: 114.1 Wb (40mV)



t=2800 s

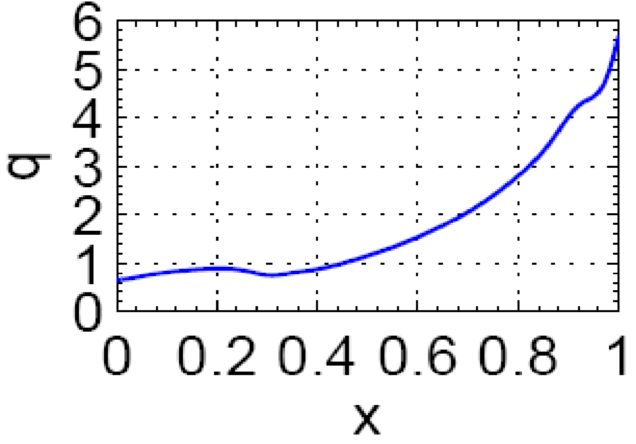


Initial flattop P_α dependent on L-mode ramp-up and current drive strategy. If the relaxed q-profile is satisfactory, then careful L-mode strategy (q-profile matching) maximizes time of Q>5 and the number of neutrons per discharge.

Summary of pedestal scan

					at final time step			
T_{ped} [keV]	I_p [MA]	f_G	NBI/EC [MW]	$f_{bootstrap}$/ $f_{non\text{-}inductive}$	P_{fus} [MW]	Q	t(q=1) [s]	q=1 radius [x]
5	11.5	0.9	33/17	0.36 / 0.62	365	7.2	∞	0
4	11.8	0.95	33/37	0.31 / 0.59	351	5	1050	0.02
3	12.2	0.95	16.5/50	0.26 / 0.47	348	5.2	360	0.44

T_{ped}=3 keV q-profile



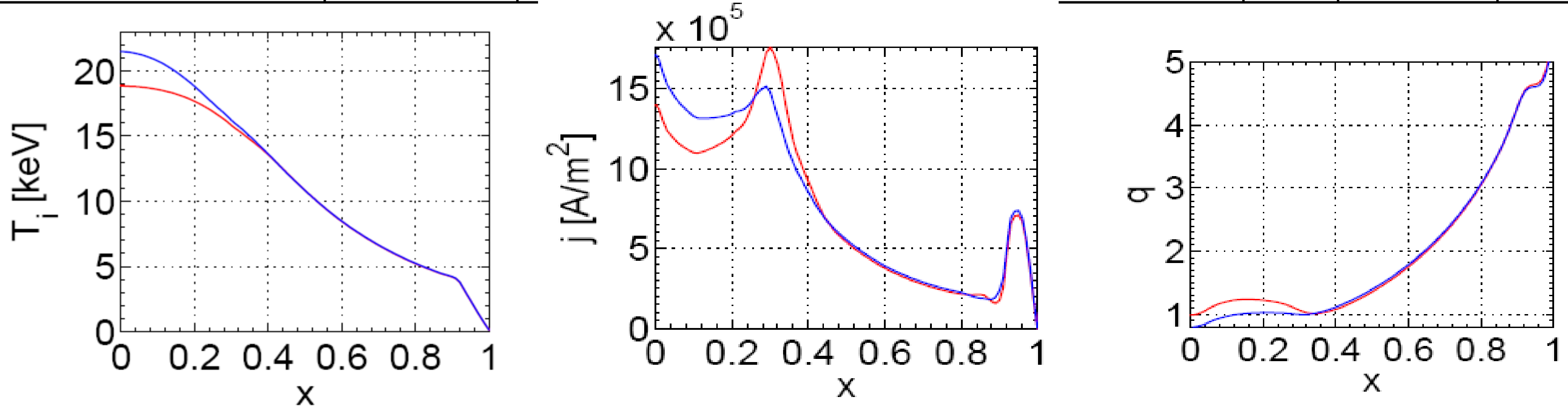
No hybrid scenario satisfying all defined constraints predicted with T_{ped} = 3 keV

Of critical importance to obtain prediction for pedestals in the hybrid regime!

Inclusion of ICRH

CRONOS

					at final time step			
Heating Mix	**T_{ped}[keV]**	**I_p[MA]**	**I_{ohm}[MA]**	**t(q=1) [s]**	**P_{fus}[MW]**	**Q**	**$f_{bootstrap}$**	**$f_{non-inductive}$**
37EC / 33NBI	4	11.8	4.86	1050	346	4.9	0.31	0.59
20EC / 33NBI / 17IC	4	11.8	5.45	420	362	5.2	0.32	0.54



Increase of 0.7MA I_{ohm} only would result in ~300s decrease in t(q=1)

600s decrease in t(q=1) due to the sharper temperature profile with addition of IC!

(note: T_i increase in x=0-0.25 may be exaggerated, since χ_e, χ_i are prescribed there)

ICRH not good for hybrid scenarios: provides no current, and forms non-optimal temperature profile

Conclusions

- **The q-profile shaping by the current drive mix sets the stiff profiles.** Hybrid Scenario performance thus not highly sensitive to heating mix, but rather the current drive mix.

- With a NBI and EC current drive mix, **T_{ped} = 4keV is now seen to be sufficient for q>1** for t(q=1)>1000sec (and tiny inversion radius later), an **improvement compared to previous simulations** with similar settings of GLF23 and pedestal width.

- **LHCD shown to be not beneficial for hybrid scenario** from a core confinement perspective

- **ICRH shown to be not beneficial for hybrid scenario**, due to lack of current drive and the increased peaking of the temperature profile

- Increased transport with peaked density case may not be a ‘show-stopper’, especially since the pedestal height would rise.

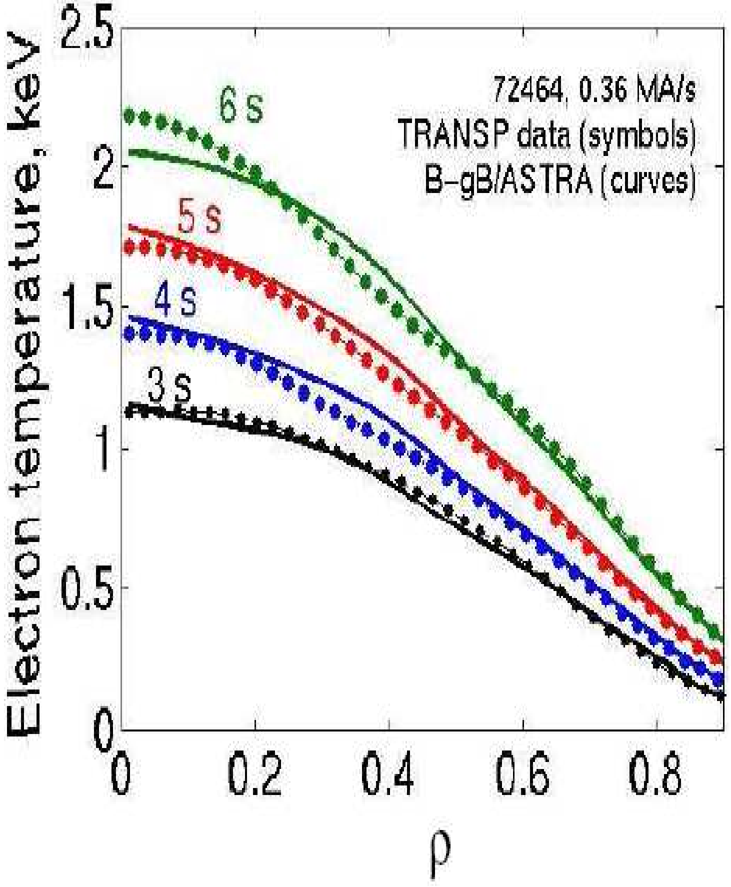
- The optimum current drive mix points to a need to **upgrade the ECCD system up to 40MW**

Summary, where do we go from here? (1)

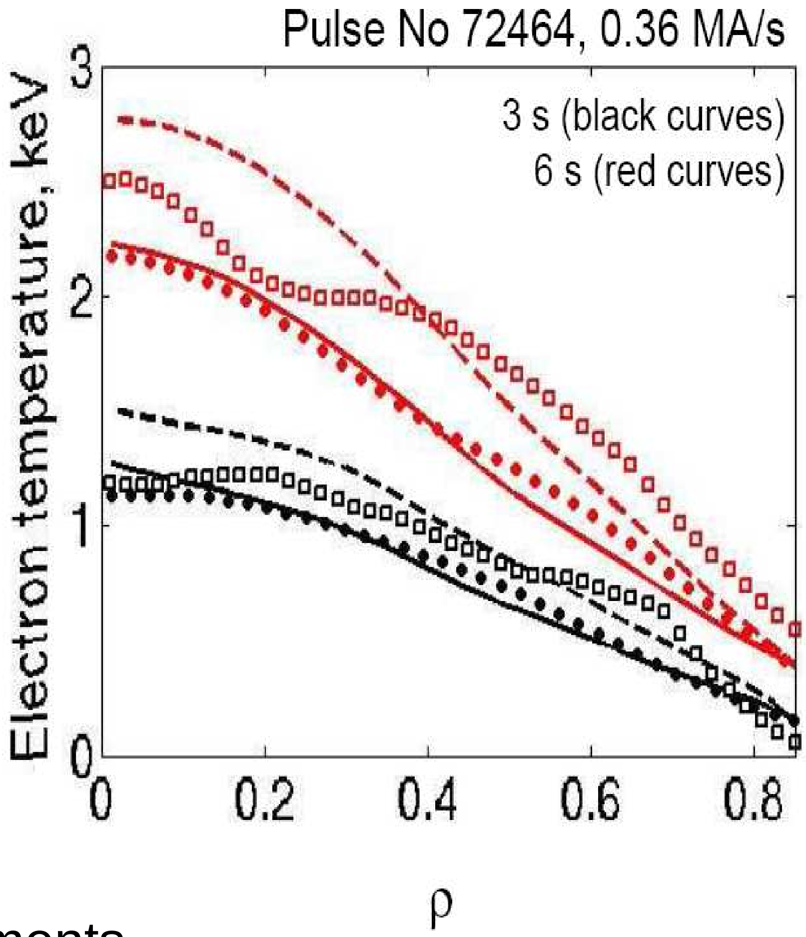
- In my view, we should work more with first principle turbulence simulation codes like GYRO or QuaLiKiz rather than GLF23;
- Predictive modelling of ion density is very important for self-consistent assessment of hybrid scenario and need to be used routinely;
- Transport on top of pedestal need to be studied using turbulence simulation codes as well - GLF23 is not good near plasma edge;
- MHD stability of edge barrier as well as plasma core need to be used routinely;
- Sooner or later we need to include impurity into the scope of predictive modelling.

Te simulation with q dependent Bohm/gyro-Bohm model & sensity to Zeff

Initial Zeff



Zeff increased by 40%

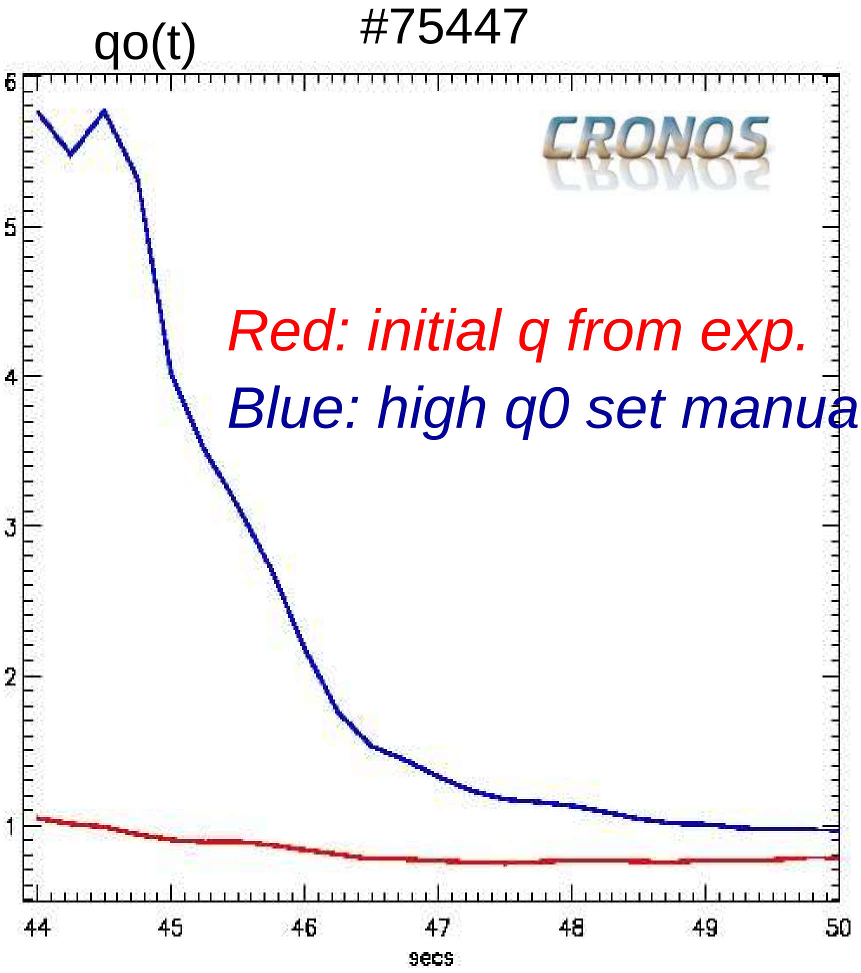


- Experiments
  - ECE: closed symbols & LIDAR: open symbols
- Modelling with Z_{eff} 40% higher
  - Dashed curves: original Bohm/gyro-Bohm scaling
  - Solid curves: rescaled by factor 3.3

I Voitsekhovitch

Sensity studies to initial q-profiles

late start (44 s): effect of choice lasts 6s

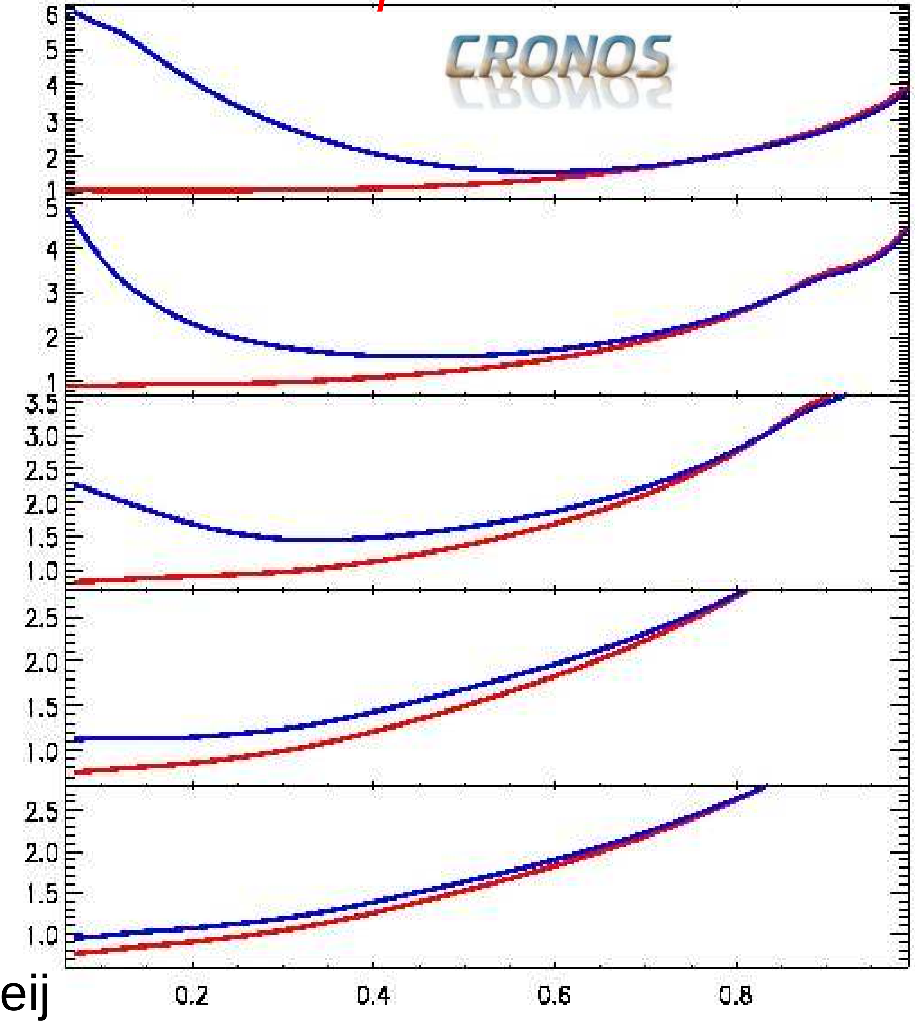


Red: initial q from exp.

Blue: high q0 set manually

q profiles @ 44, 45, 46, 48, 50 s

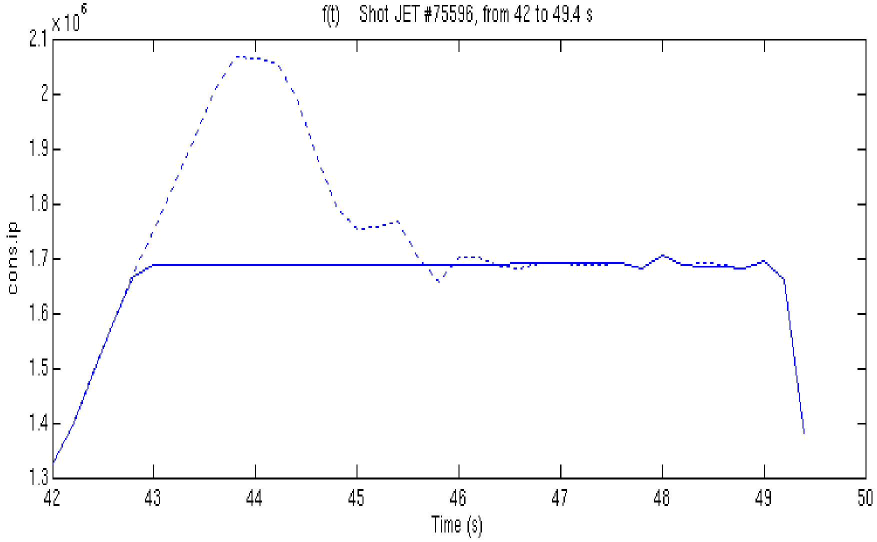
→ Effect still present after 6 s

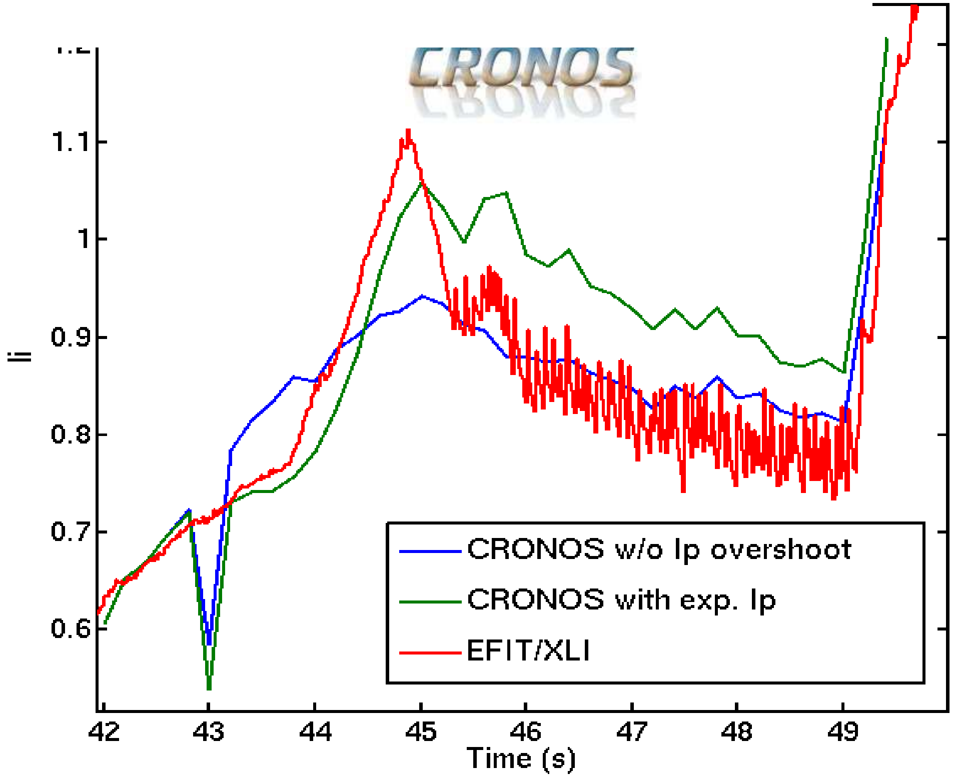


D. Hogeweij

Modelling of target q-profile for hybrid regimes

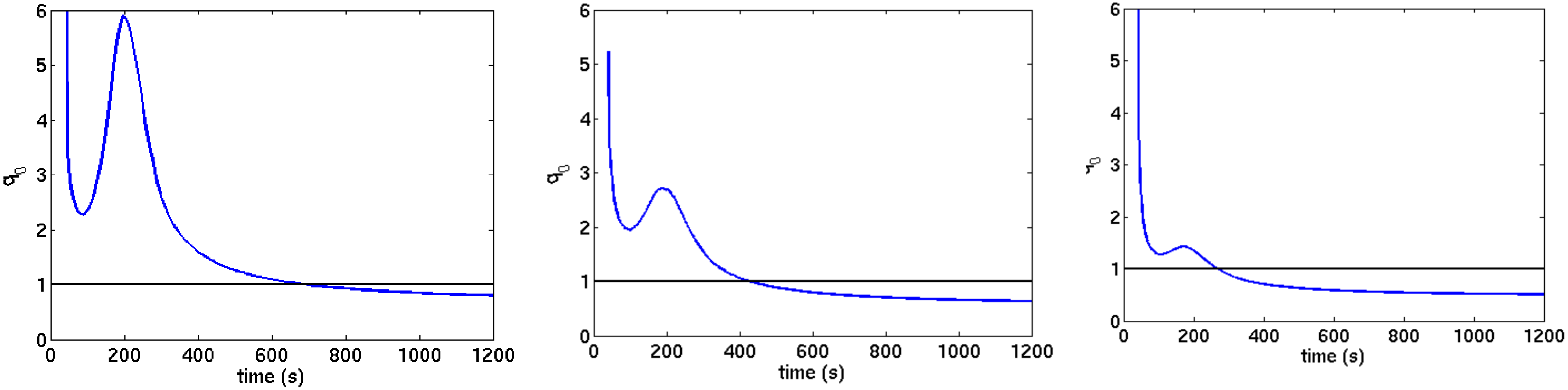
- High delta : 75596, simulation with / without Ip overshoot
- Only the Ip reference is changed. Using Te profile and boundary from experiment
- Simulation with Ip overshoot fits much better the t = 43 – 45 s phase, where Ip is changing. Then, after the L-H transition, shows a deviation of ~ 0.1 in li, decreasing with time
- Simulation without Ip overshoot does not fit properly the t = 43 – 45 s phase, where Ip is changing. Then, after the L-H transition, shows a good agreement with EFIT/li. By chance ? Small deviation increasing with time





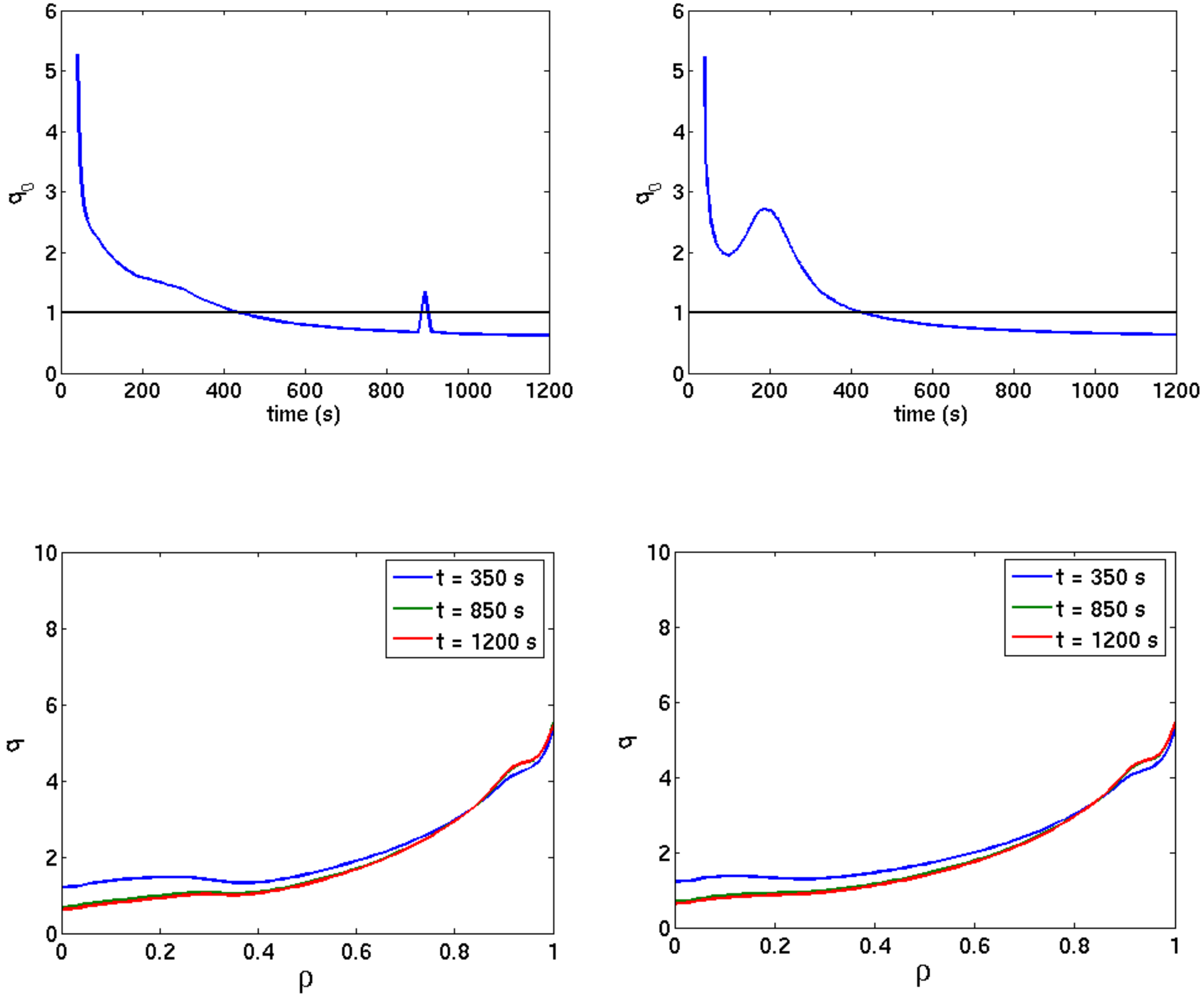
F. Imbeaux et al

NBI heating: q0 time evolution



- Time to q=1 is 680s for tped=5 keV
- Time to q=1 is 430s for tped=4 keV
- Time to q=1 is 268s for tped=3 keV

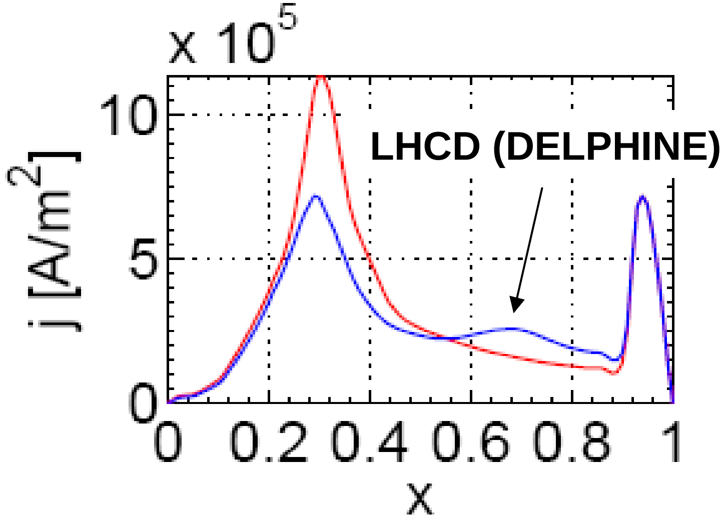
Comparison ECRH vs NBI for tped=4 keV



- Time for q0=1 is almost the same
- r(q=1) highly reduced for ECRH

Inclusion of LH in optimum T_{ped}=4keV case

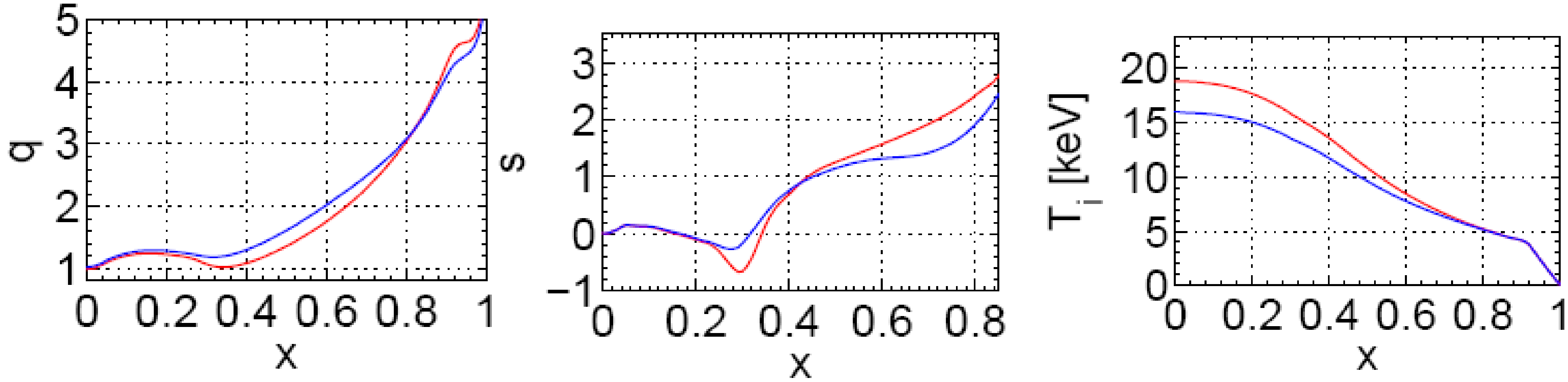
All profiles at t = 1200 sec



— 33NBI/20EC/17LH **P_{fus} = 273MW, t(q=1) = 1220s**

— 33NBI/37EC **P_{fus} = 348MW t(q=1) = 1050s**

Same P_{fus} reduction effect seen with LUKE, but slightly less dramatic due to less predicted current



Inclusion of LH leads to less optimal q-profile from a confinement point of view