Integrated modeling in support of ITER: the path from the commissioning phase to demonstration scenarios, issues and progress.

Francesca Poli

Princeton Plasma Physics Laboratory

Acknowledgements: R. Budny, J. Garcia, S-H Kim, T. Rafiq

Work supported by the US Department of Energy under DE-AC02-CH0911466
and by ITER under contract to PPPL IO/RFQ/13/9550/JTR EC Analysis

Purpose of this seminar and take-away message

- Give a sense of how the integrated modeling in support of ITER has changed its priorities over the past few years
- Highlight issues in our modeling tools
- Highlight connection with experiments and where contribution is most needed
- Stimulate contribution from the US community

NOTE: limit discussion to work published in the past 3 years

(Some of the) ITER physics goals and challenges

- Produce a plasma dominated by α-particle heating
- Produce a significant fusion power (Q=10) in long-pulse operation
- Demonstrate steady-state operation (Q=5)

Baseline (inductive)	Hybrid	steady-state (non-inductive)
Q>10 I_P=15MA (q_{95}=3) ~7m flattop	Q~5-10 I_P=12MA (q_{95}=4) ~15m flattop	Q~5 I_P=9MA (q_{95}=6) ~1hr flattop
I_{NI}/I_P~ 20% I_{BS}/I_P~ 10%	I_{NI}/I_P~ 50% I_{BS}/I_P~ 20%	I_{NI}/I_P~ 100% I_{BS}/I_P~ 50-60%
EC: 20 MW IC : 20MW NB: 33MW		EC upgrade? LH ?

Modeling over the past years driven by these goals

- Along two lines:
  - Operation scenario development and PCS (free-boundary)
  - Address specific physics issues (self-consistent transport)
- Baseline demonstration
  - Challenge: maintain performance and α dominated heating
  - Focus on coil limits, transport
- Hybrid access
  - Challenge: sustain q>1 and wide zone of low magnetic shear in the core.
  - focus on current ramp phase
- Steady state exploration
  - Challenge: sustain stationary, high non-inductive fraction
  - Focus on HCD mix, optimal current profile
  - Issue here is transport

Modeling over the past years driven by these goals

- Along two lines:
  - Operation scenario development and PCS (free-boundary)
  - Address specific physics issues (fix-boundary, self-consistent transport)
- Baseline demonstration
  - Challenge: maintain performance and α dominated heating
  - Focus on coil limits, transport
- Hybrid access
  - Challenge: sustain q>1 and wide zone of low magnetic shear in the core.
  - focus on current ramp phase
- Steady state exploration
  - Challenge: sustain stationary, high non-inductive fraction
  - Focus on HCD mix, optimal current profile
  - Issue here is transport

Simulation of the baseline has long history

Most of the modeling has focused on

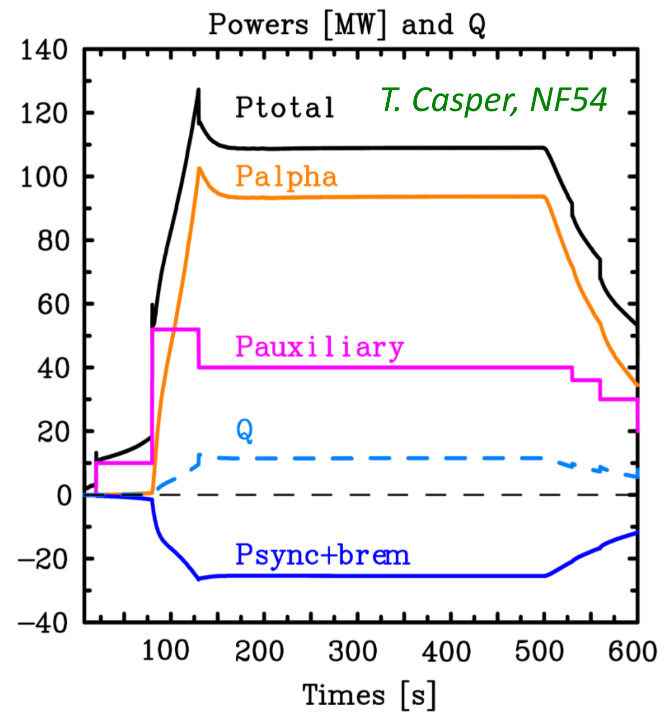
plasma shape control [*T. Casper NF54, Kessel NF49*]

These simulations usually use semi-analytic transport (robust), analytic profiles for the HCD (or profiles calculated offline)

⇒ The goal is to demonstrate that the target is achievable

Other work focused on specific issues:

- Plasma performance sensitivity to transport assumptions [*Budny NF48,NF49, Rafiq PoP16*, *Kritz NF51*]
- Alpha heating [*Budny NF52*]



⇒ They show that achieving the target depends on the transport assumptions: pedestal, rotation, thermal transport model

Self-consistent impurity transport is critical

- Entry to burn complicated by impurity behavior (Ar, W)
  - TSC, JETTO/SANCO, CORSICA [*Kessel, Kohl, Kim, NF 55 063038 (2015)*]

- Sensitivity of fusion power on n_e, n_{Ar}, RF heating, T_{ped}, ExB shear
  - TRANSP [*Rafiq, PoP 22, 042511 (2015)*]

- Assessment of critical W concentration: <7×10^{-5} in flattop for Q>5
  - ZIMPUR with ASTRA, CRONOS [*Hogeweij, NF 55 063031 (2015)*]

The above simulations change concentration and impurity profile peaking, but do not use self-consistent impurity transport.

=> Ongoing work in the EU and in the US to include self-consistent impurity transport in integrated modeling (standalone codes available).

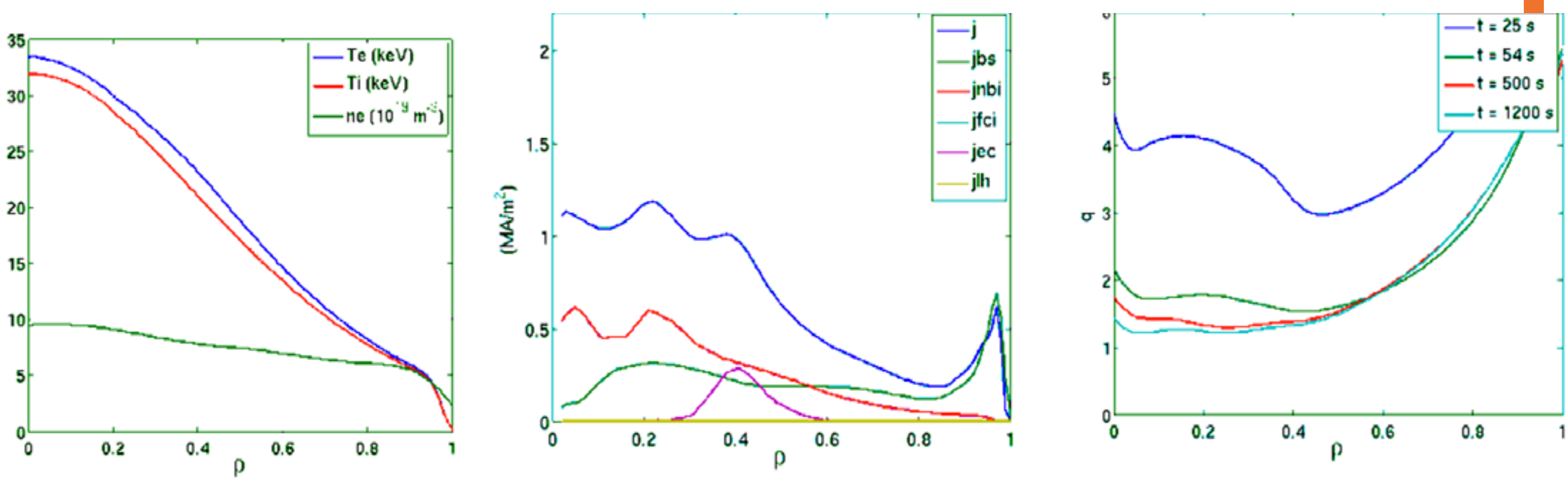
Modeling over the past years driven by these goals

- Along two lines:
  - Operation scenario development and PCS (free-boundary)
  - Address specific physics issues (self-consistent transport)
- Baseline demonstration
  - Challenge: maintain performance and α dominated heating
  - Focus on coil limits, transport
- Hybrid access
  - Challenge: sustain q>1 and wide zone of low magnetic shear in the core.
  - focus on current ramp phase
- Steady state exploration
  - Challenge: sustain stationary, high non=inductive fraction
  - Focus on HCD mix, optimal current profile
  - Issue here is transport

Hybrid scenario very sensitive to plasma parameters

[Besseghir, PPCF 55 (2013) 125012]

- Optimal operating point: H_{98}=1.3, q_{95}=4.3, $n_{e0}/n_e(0.8)$=1.45,T_{ped}=4.5keV β_N=2.65, β_p=1.45, $\ell_i(3)$=0.7, Q=7.8 (Bohm-Gyro-Bohm, GLF23)
- Use of off-axis EC important in ramp-up and ramp-down
- Reduce plasma shape and elongation in ramp-down
- Small deviations from optimal configuration degrade scenario



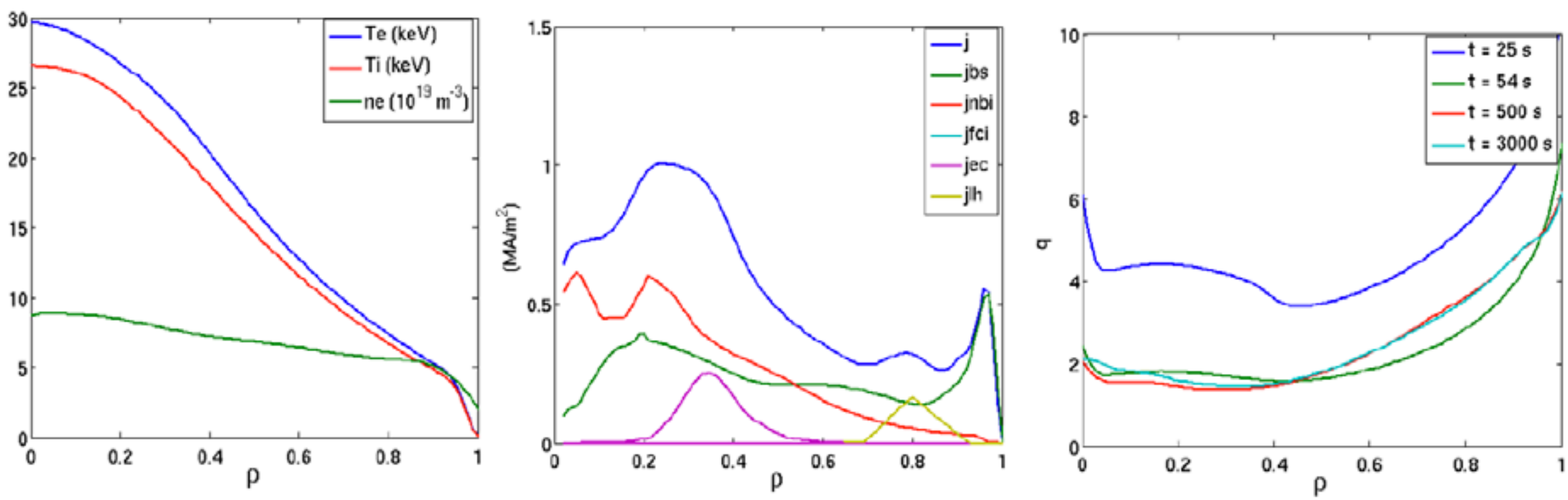
Modeling over the past years driven by these goals

- Along two lines:
  - Operation scenario development and PCS (free-boundary)
  - Address specific physics issues (self-consistent transport)
- Baseline demonstration
  - Challenge: maintain performance and α dominated heating
  - Focus on coil limits, transport
- Hybrid access
  - Challenge: sustain q>1 and wide zone of low magnetic shear in the core.
  - focus on current ramp phase
- Steady state exploration
  - Challenge: sustain stationary high non-inductive fraction
  - Focus on HCD mix, optimal current profile
  - Issue here is transport

Developing steady-state from hybrid

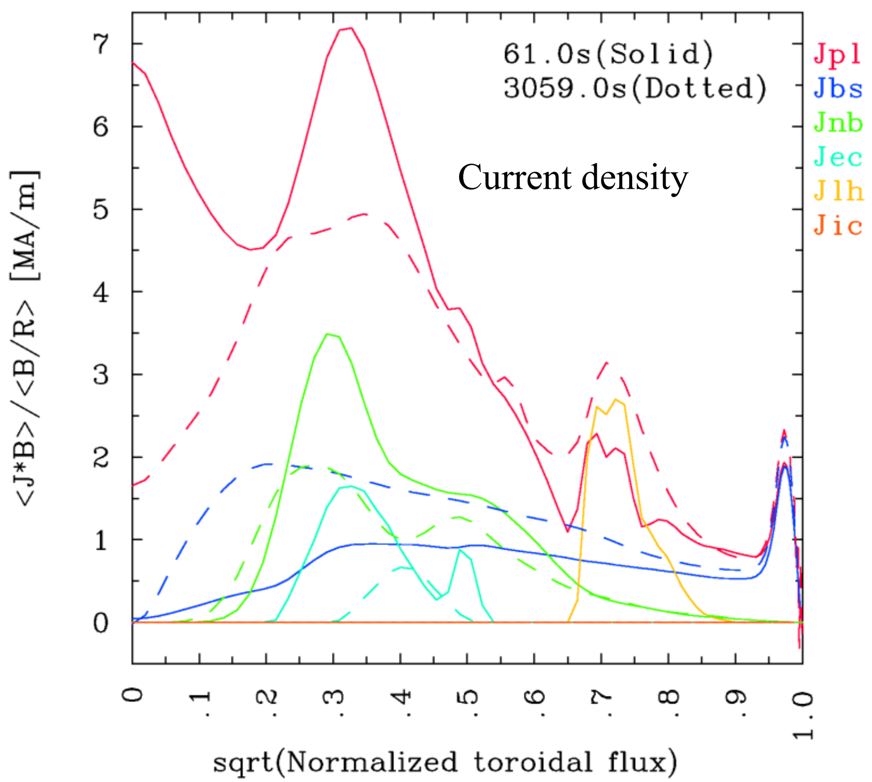
[Besseghir, PPCF 55 (2013) 125012]

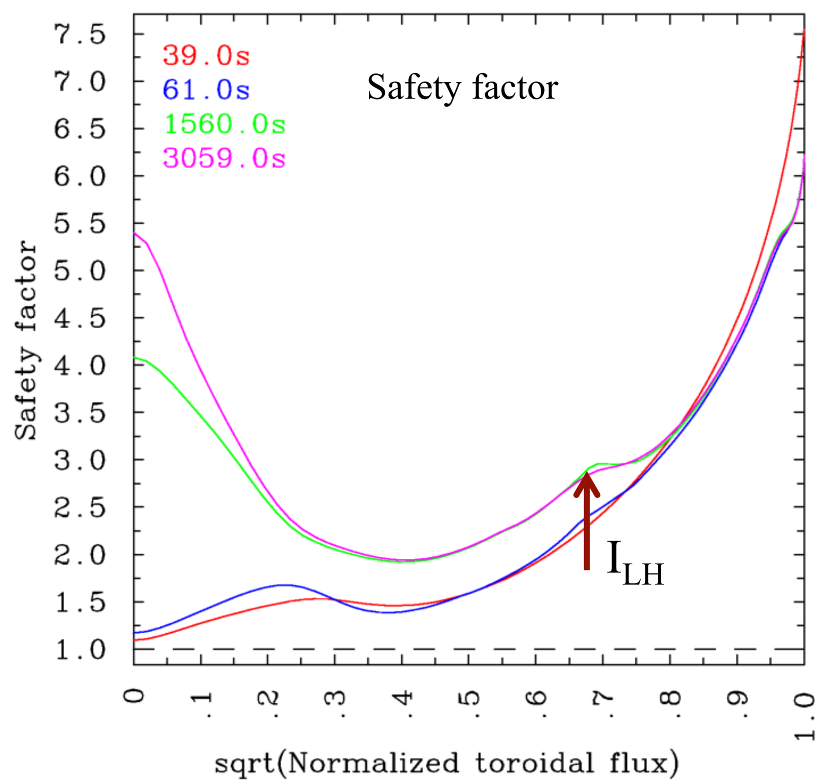
- H_{98}=1.35, reduce to I_P=10MA, add 15MW of LH, no ITBs
- β_N=2.70, β_p=1.66, $\ell_i(3)$=0.7, Q=5
- 100% non-inductive in fix-boundary, >90% non-inductive in free-boundary



CORSICA simulations achieve Q=5 with H_{98}=1.6 and ITBs

- Sustain q>1.5-2.0 with 20MW of LH and semi-empirical Coppi-Tang transport
- High non-inductive fraction, but not 100% non-inductive
- EC deposition at mid-radius, NBCD off-axis





TSC/IPS-TRANSP: identify first MHD stable operational space, then look for optimal H/CD combination

⇒ Assume sustained ITBs in H-mode, H_{98}~ 1.6

⇒ Analyze ideal MHD stability of various heating mixes for up to 15% of pressure peaking factor and $n<1.1n_G$

⇒ Optimize HCD and ramp-up to access steady-state, with self-consistent transport

Conclude that

- ITER steady state plasmas should operate with

  broad current profile, q_{min}>2, ITBs at mid-radius

- LHCD is needed to get the target Q~5 at 9MA

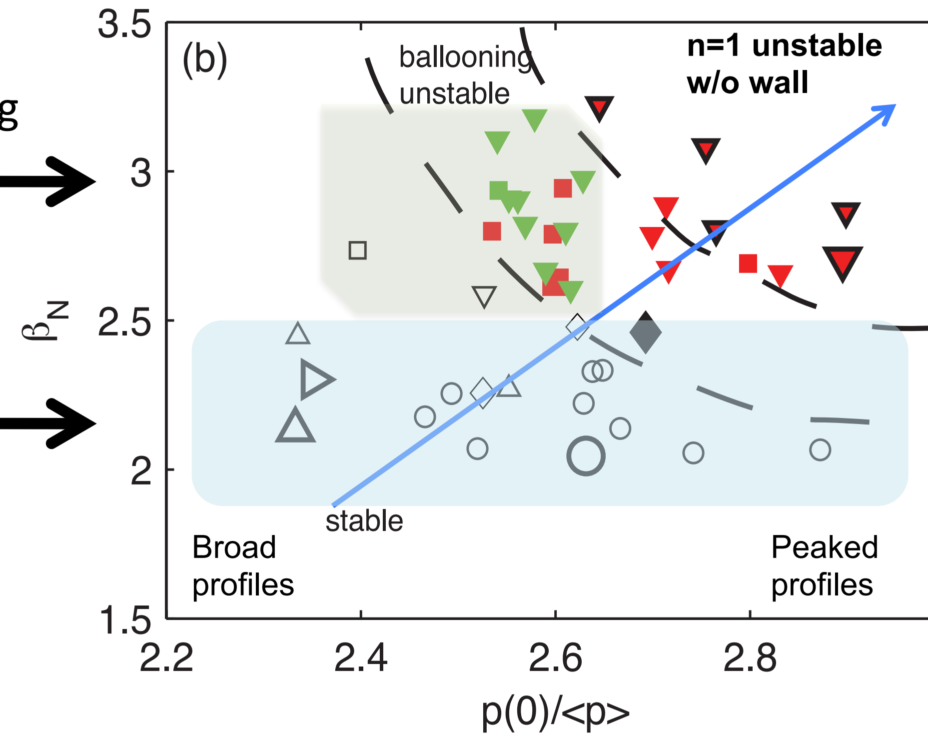
Ideal MHD stability sets limits to available operational space

Fix target H_{98}=1.6 and change H/CD mix

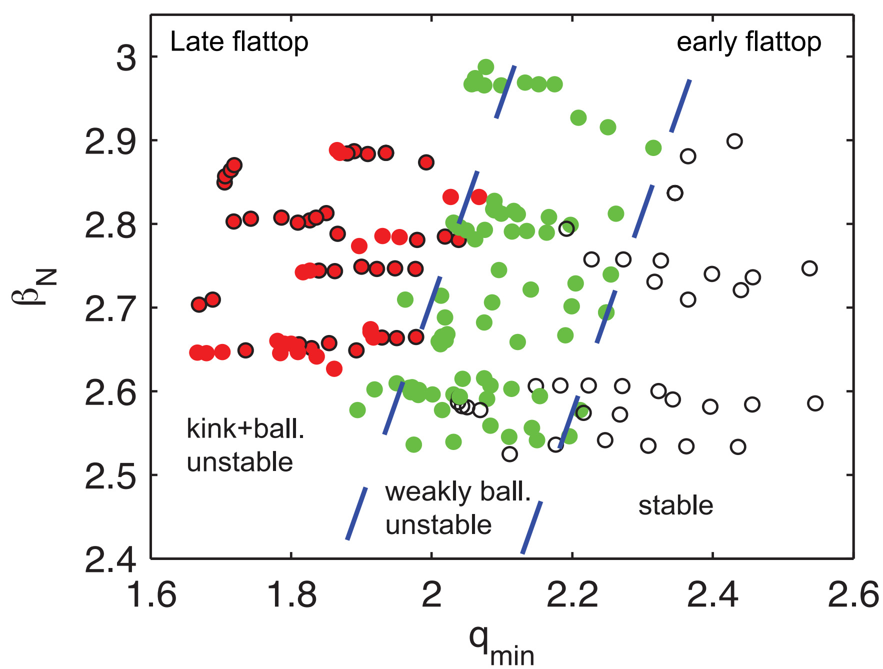
large β_N : stability depends on pressure peaking

low β_N : ideal MHD stable for a wide range of pressure peaking

[Poli, NF 52 (2012)]



33MW NB+40MWLH+20MWIC



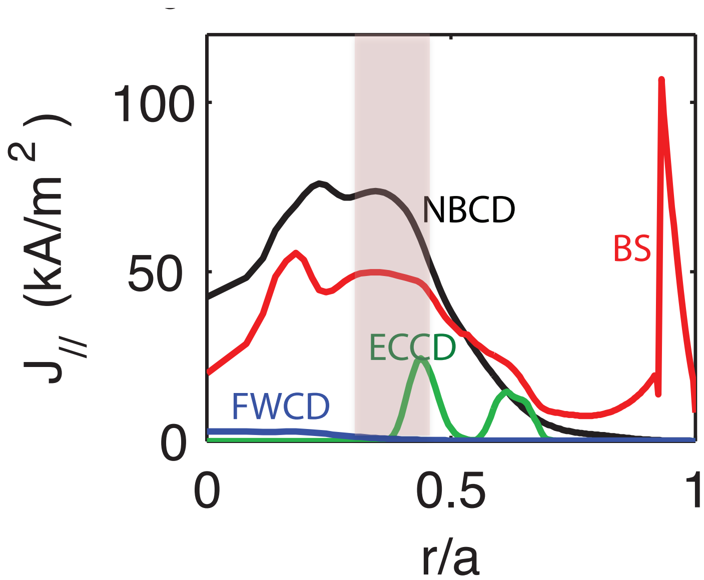
Plasmas should sustain q_{min}>2 during the burning phase

Baseline heating mix results in fully non-inductive discharges at low current and hence low Q

[Poli, PoP 20, 056105 (2013)]

- Distribution of EC power affects ITB formation and sustainment
  - ⇒ EL needed in ramp-up to form e-ITBs
  - ⇒ UL needed in flattop to stabilize ITB foot
- with EC deposition at mid-radius **I_{NI}~6.4 MA**

Q~1.6

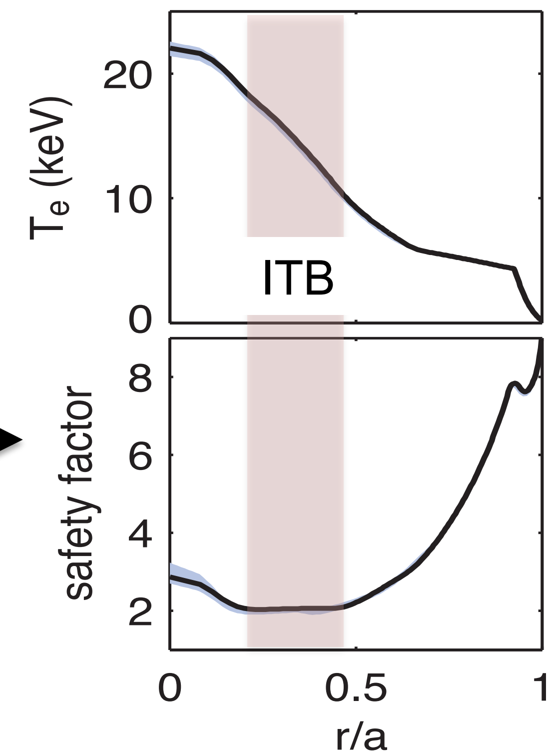


Bootstrap current peak and ρ_{ITB} inside mid-radius

CDBM transport model

H_{98} ~ 1.3
β_N ~ 1.77

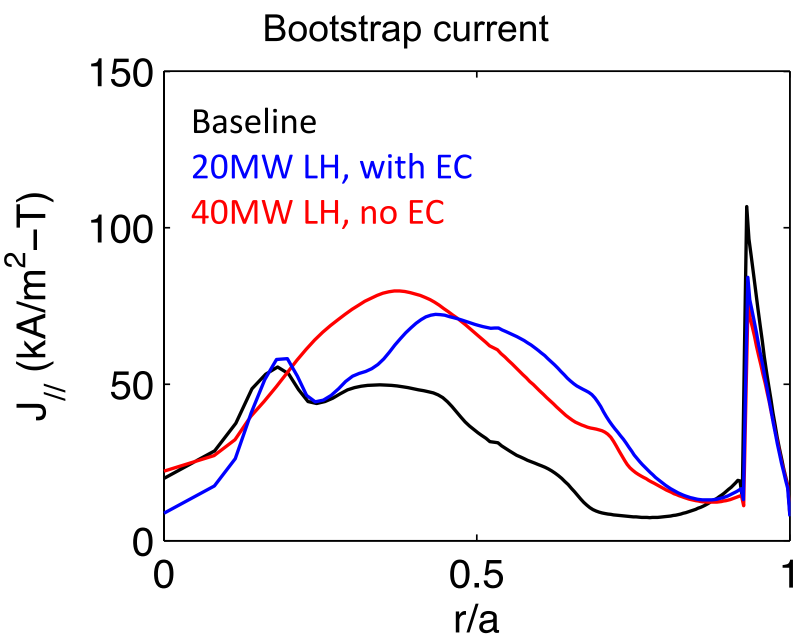
Ideal MHD stable

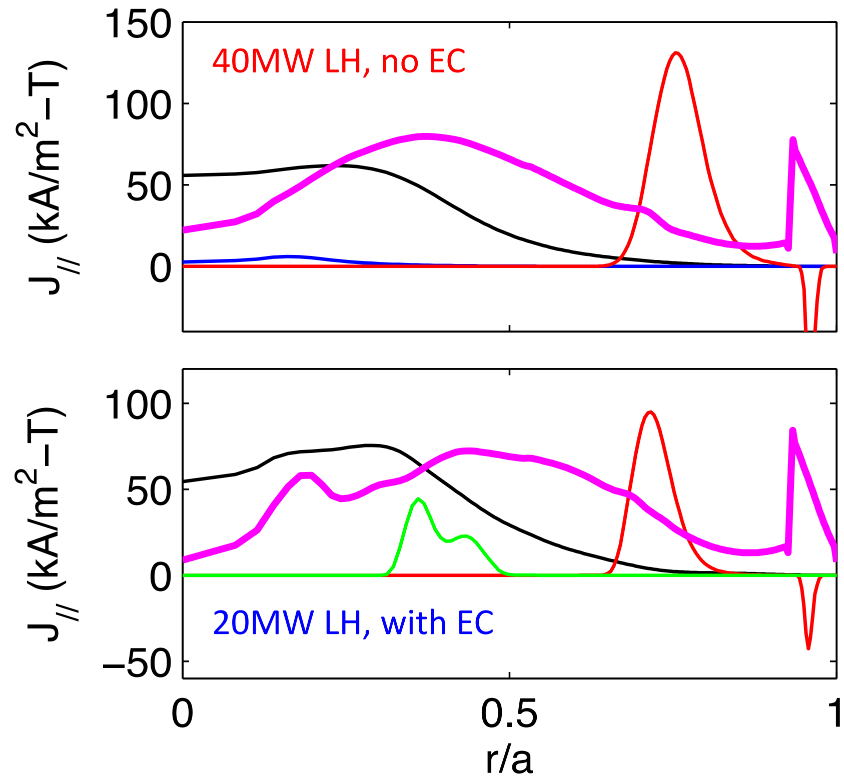


Baseline heating mix good candidate for demonstration of fully non-inductive operation with ITBs at low current

20 MW of coupled LH with 20MW of EC can enhance the plasma performance toward the ITER goals

[Poli, NF 54 (2014)]





	LH/no EC	LH+EC
I_{NI} (MA)	8.7-9.5	8.8±0.2
Q	3.7-3.9	5
β_N	1.68-1.80	2.3±0.2
H_{98}	1.45	1.65±0.03

40MW of LH does not achieve the same performance as 20MW each of EC and LH

Summary and open issues from integrated modeling of ITER demonstration discharges

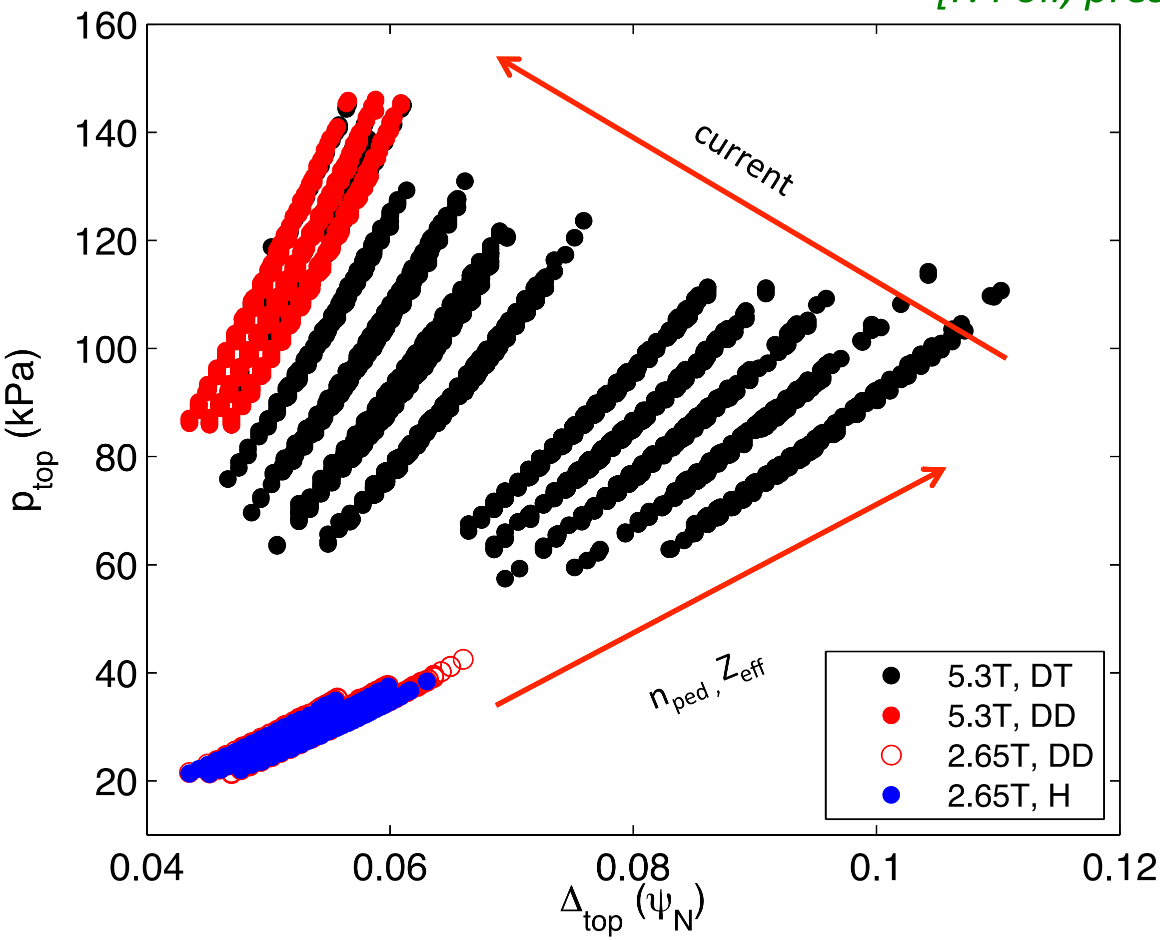
- Advanced scenarios sensitive to deviations from operating point
- Ramp-up evolution is critical for access to hybrid and steady-state
- ITER needs LH to achieve its SS goals, BUT combined with ECCD (no LHCD => need to assume twice as high pedestal [*Murakami, NF52*]
- Plasma performance depends on pedestal assumptions

Remaining issues:

- a model for flux pumping is still missing
- Neoclassical current diffusion applicable to ITER ?
- first principle model for ITB formation is still missing

ITPA-IOS/PEP activity on implementation of a pedestal reduced model in time-dependent simulations

[F. Poli, presented at the IOS fall meeting, 2015]



About 8500 point:

- 711 DD @ 2.65T
- 1872 DD @ 5.30T
- 1235 H @ 2.65T
- 4677 DT @ 5.30T
- 987 baseline
- 2326 Hybrid
- 1364 Steady State

Scan over n_{ped}, Z_{eff} β_N

For parametrization also:
$\delta_{nominal}$±0.01
$\kappa_{nominal}$±0.05

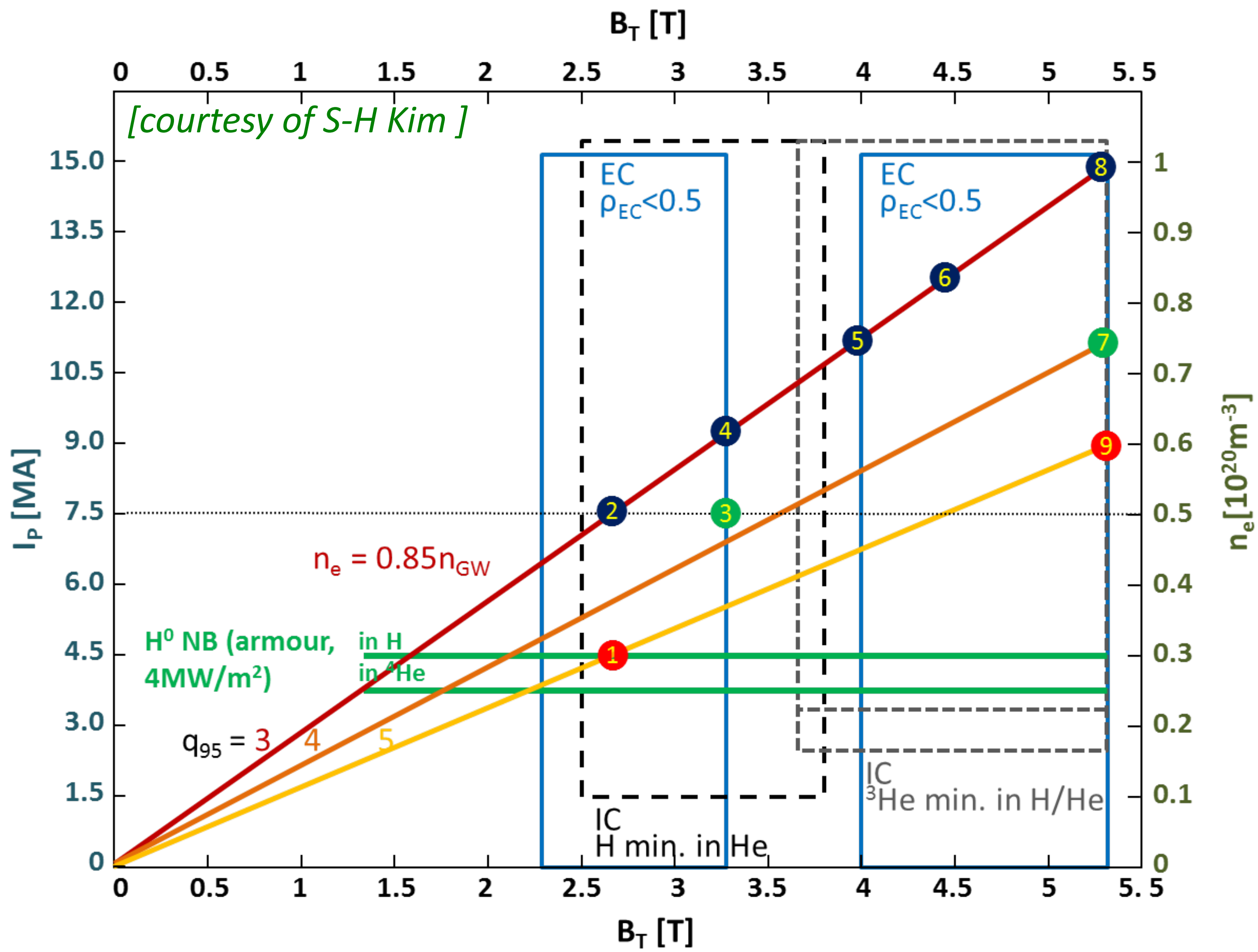
He plasma simulations not available, because of present limitations of EPED1 (Z=1)

(working with O. Meneghini on implementation of NEUPED in TRANSP)

Priorities and focus have changed in the past two years

- The path to the baseline includes verification of:
  - Operation at Lower current and lower field
  - Non-active and low-activation phase before DT campaign
  - Disruption mitigation
  - Access to good quality H-mode
  - Power handling to the divertor
  - Shape and position control
  - Power handling in all phases of the discharge

Development of a path to the demonstration discharges, with emphasis on the pre-DT phase



- Path at constant q_{95}
- Path at constant B_T
- step-up from low B_T, I_P to high B_T,I_P

➢ Low current
  - H-mode (He and/or H) (disruption mitigation)

➢ Intermediate steps
  - Demonstrate access to H-mode
  - reduce risk in approaching to full-field /full-current operation

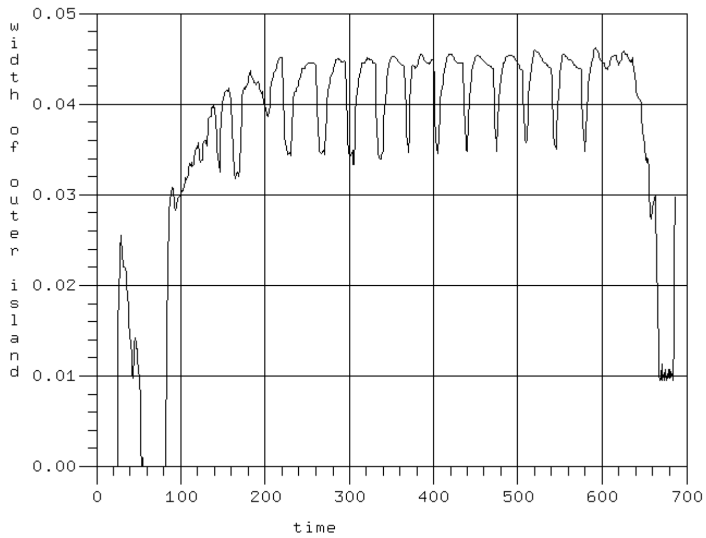
➢ Full current
  - System performance

The modeling of the path to the baseline needs self-consistent simulations

- US-EU collaboration (free-boundary, self-consistent HCD):
  - CORSICA (S-H Kim): focus on scenario development
  - JINTRAC (F. Kohl) : focus on density evolution with edge plasma model
  - TRANSP (F. Poli) : focus on power management (for combined NTM control and plasma profile control) [*ITER contract to PPPL*]

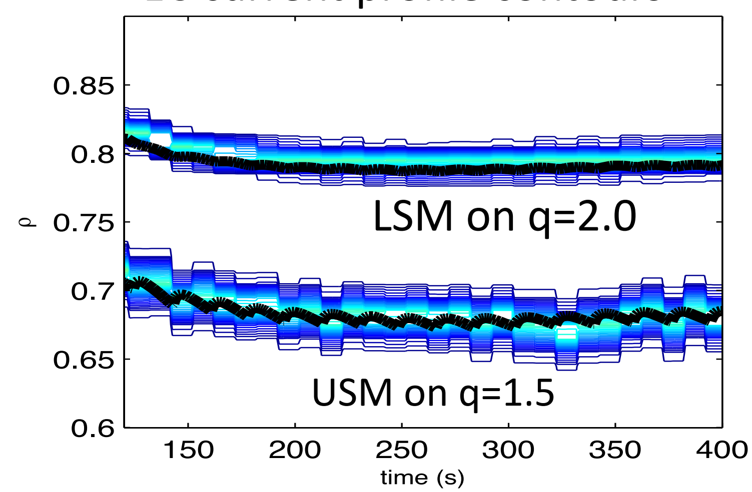
- Ongoing work in TRANSP:
  - Self-consistent modeling of equilibrium and HCD sources with free-boundary
  - Self-consistent multi-channel transport (impurities work in progress)
  - Implementation of NEUPED neural network for the reduced pedestal model
  - Implementation of a Generalized Rutherford Equation for NTM evolution
  - In the pipeline: implementation of a reduced model for the plasma edge

Priority in EC power management is NTM control



Generalized Rutherford equation calculates NTM island evolution

EC current profile contours



Real-time EC controller uses TORBEAM to track the magnetic surfaces and handle power switch between mirrors

This approach can only provide guidance on min/max EC power needs given some assumptions.
The remaining power is dedicated to other applications

HCD specific issues in the non-neutronic phase

NBI Minimum density due to beam shine-through (H-NBI with 870keV): ~3.0-3.5x10^{19} m^{-3}

JINTRAC simulations indicate n_e<2.5x$10^{19}m^{-3}$ => use H pellets
Good H-mode accessibility in He, H plasmas requires ~0.5 n_{Gw} (≤4x$10^{19}m^{-3}$)
=> above shine-thru limits, but integrated shine-thru in flattop ~10% of P_{NB}
Implications: use lower beam energy, but P~$E^{2.5}$ => not enough margin for H-mode access
access H-mode at lower density, probably shorter flattop
H-L back transition at the end of flattop

Where input is most needed:

Experiments: expand helium database: pedestal, L-H mode threshold and hysteresis, impurities, confinement with N_2, Ar/Ne seeding
experiments with helium plasma and H pellets, heated by RF

Modeling: confinement, transport, pedestal assumptions in helium, L-H transition

RF specific issues in the non-neutronic phase

ICRF 1H majority in H plasma (~42MHz), 2He3 minority in H plasma (~53MHz) [expensive]

1H minority in He plasma(~42MHz), 2He3 minority in He plasma (~53MHz) [expensive]

TRANSP/NUBEAM simulations indicate that NBI contributes to n_H=0.35n_e => H majority heating

Where input is most needed:

Modeling: self-consistent interaction between RF and fast ions

Experiments: experiments with helium plasma, RF heated (heating in ramp-down)

Both: power coupling with the density gradient at the separatrix (H-mode)

power coupling during the L-H/H-L transitions (plasma-antenna distance)

(Some) US-BPO specific contribution to ITPA

ITPA-IOS has recently started a coordinated activity on the non-active phase, including:

- Modeling and experiments
- Coordination with ITPA-PEP for pedestal assumptions
- Coordination with ITPA-TC for specific transport issues

Experiments targeted to:

- Helium plasmas => comparison with deuterium (ELMs, pedestal, L-H transition, with H pellets, heating in ramp-down with RF)

Modeling:

- Confinement in helium plasma
- RF-NBI interactions
- Modeling of ITER ICRH antenna-SOL coupling (VORPAL, AORSA)

Coordination is important: there is already work done out there … waiting to be collected.