Alternate Tokamak Operation Scenarios

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ITER International School 2022, July 25-29, UCSD, USA

PLARE
Plasma Laboratory for Advanced REsearch

SEOUL NATIONAL UNIVERSITY

Hometown Cha-Cha-Cha
갯마을 차차차

이상한 변호사 우영우

VERI TAS LUX MEA

Contents

- What to satisfy?

- How to satisfy them?

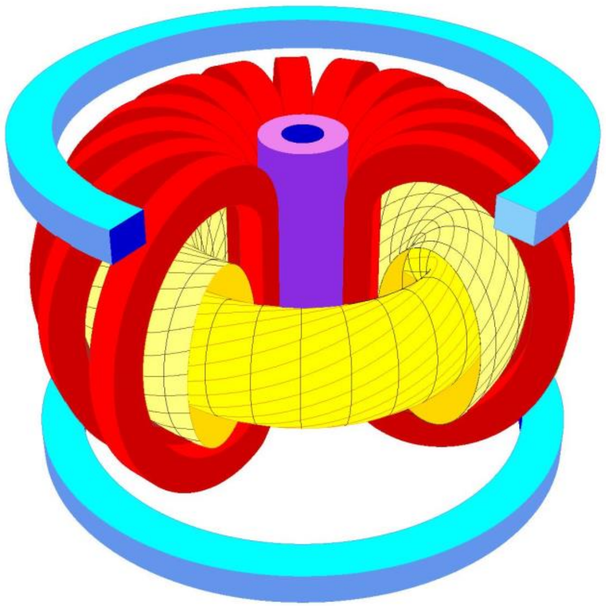
- H-mode
  - Why?
  - How to?
  - Characteristics?
  - How to overcome?

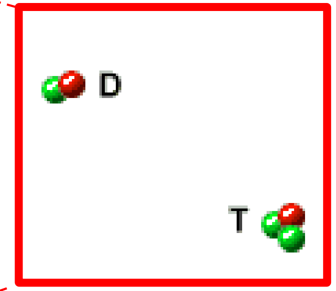
- Monotonic Shear / Flat Shear / Reversed Shear

- Your Challenge!

What to satisfy?

What is required for fusion reactor?

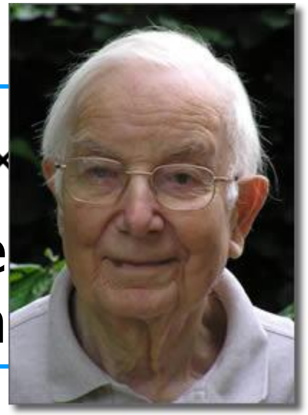




- Fuel: D, T
- Amount/density: n
- Heat insulation: τ
- Temperature: T

$n \times$

Crite ... red
(fusion ... duct)



J. D. Lawson

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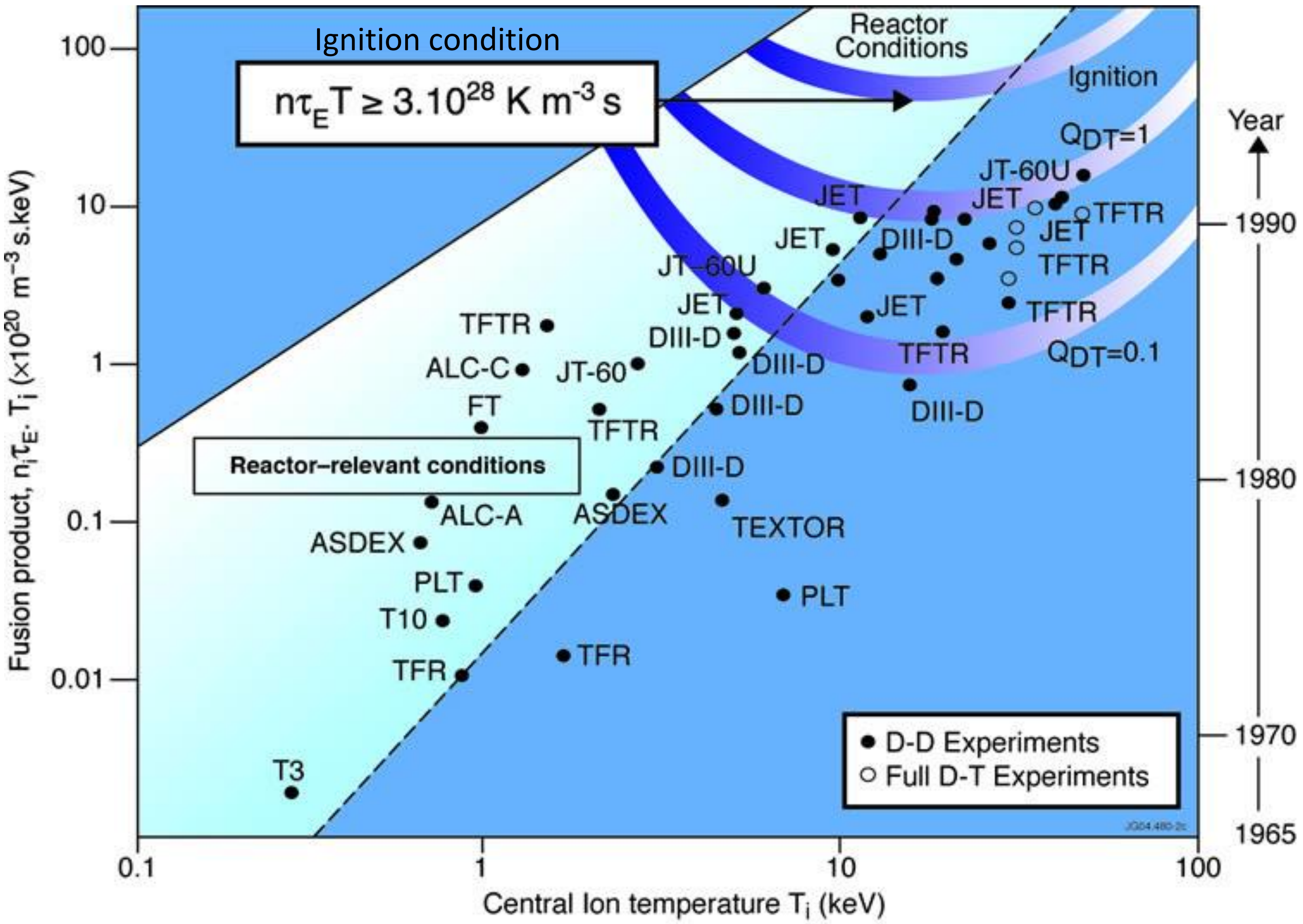
What to satisfy?



https://www.euro-fusion.org/2005/12/50-years-of-lawson-criteria/

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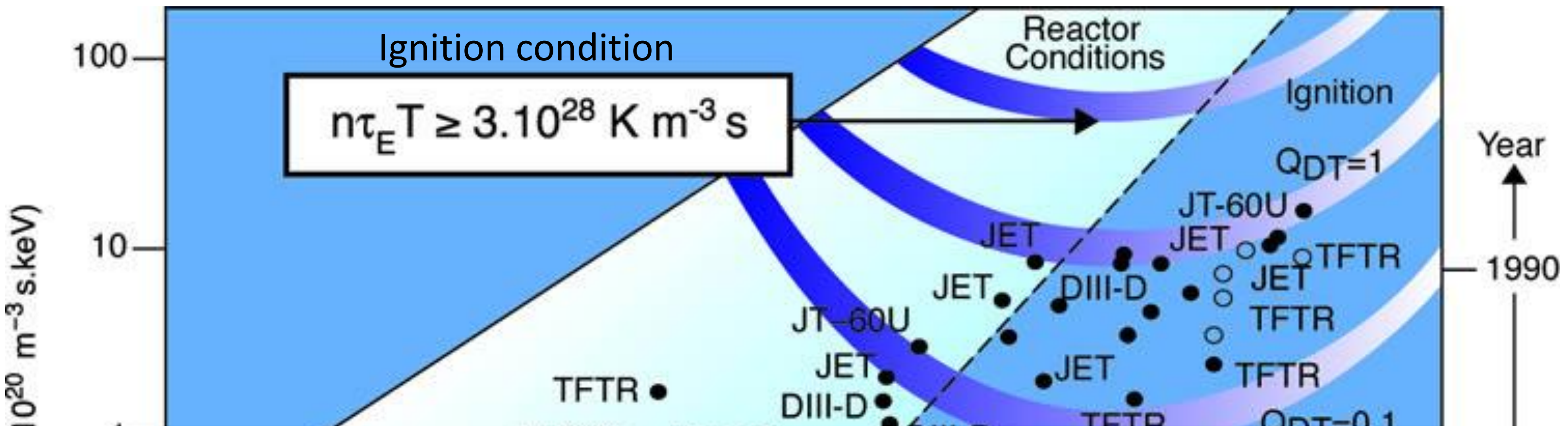
What to satisfy?



Present devices cannot reach the condition mainly due to small size.

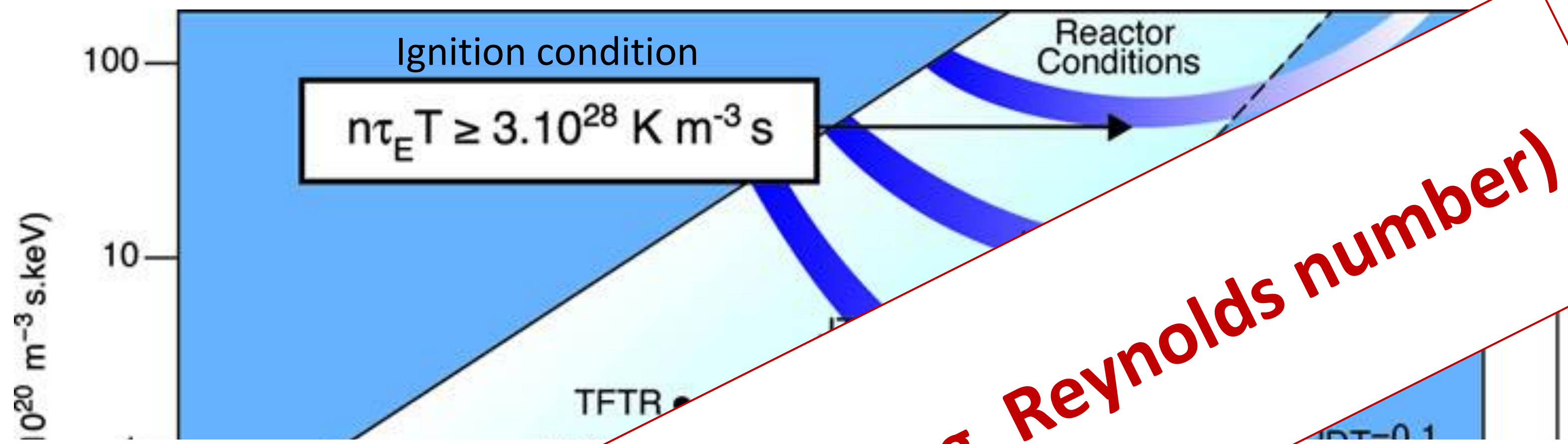
$$\tau_{th,E}^{IPB98(y,2)} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}$$

How can we explore and develop reactor-relevant scenarios with present devices?

How can we guarantee that developed scenarios can be reproduced in ITER and beyond?

https://www.euro-fusion.org/2005/12/50-years-of-lawson-criteria/

What to satisfy?



⇒ **Dimensionless parameters (e.g. Reynolds number)**

Present devices can… mainly due to small size.

$$\ldots^{0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}$$

…e and develop reactor-relevant … present devices?

…can we guarantee that developed scenarios can be reproduced in ITER and beyond?

https://www.euro-fusion.org/2005/12/50-years-of-lawson-criteria/

What to satisfy?

⇒ H. Zohm, this school

- High fusion performance (high $n\tau T$)

$$Q = P_{fus}/P_{ext} \approx P_{fus}/P_{heat} \sim (nT)^2/(nT/\tau_E) \sim nT\tau_E >>1$$

Figure of merit 1: β_N, H_{98}

This needs to be sustained for long in steady-state!

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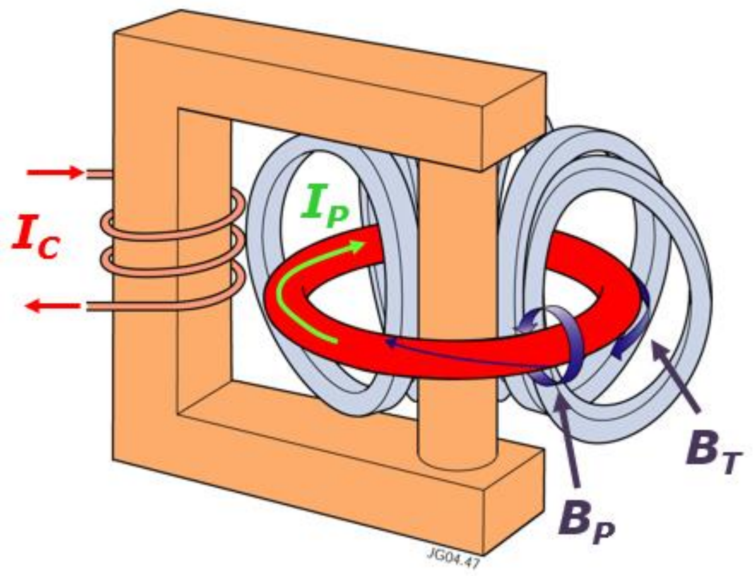
What to satisfy?



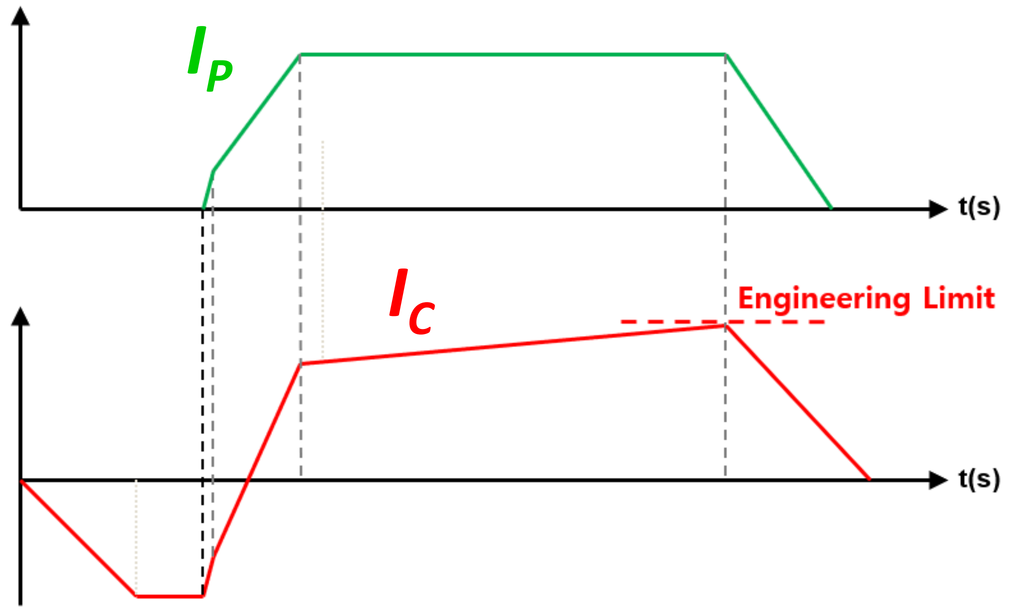
$I_P = I_{OH} + I_{NI}$

$$\frac{dI_C}{dt} \xrightarrow[\text{induction}]{\text{By}} I_{OH}$$

Faraday's law

$$v = -\frac{d}{dt}\int B \cdot ds$$

Standard inductive operation



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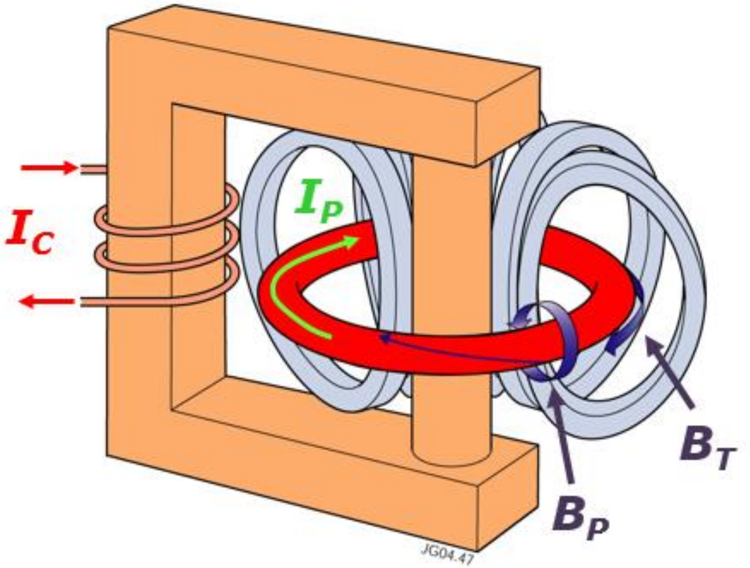
What to satisfy?



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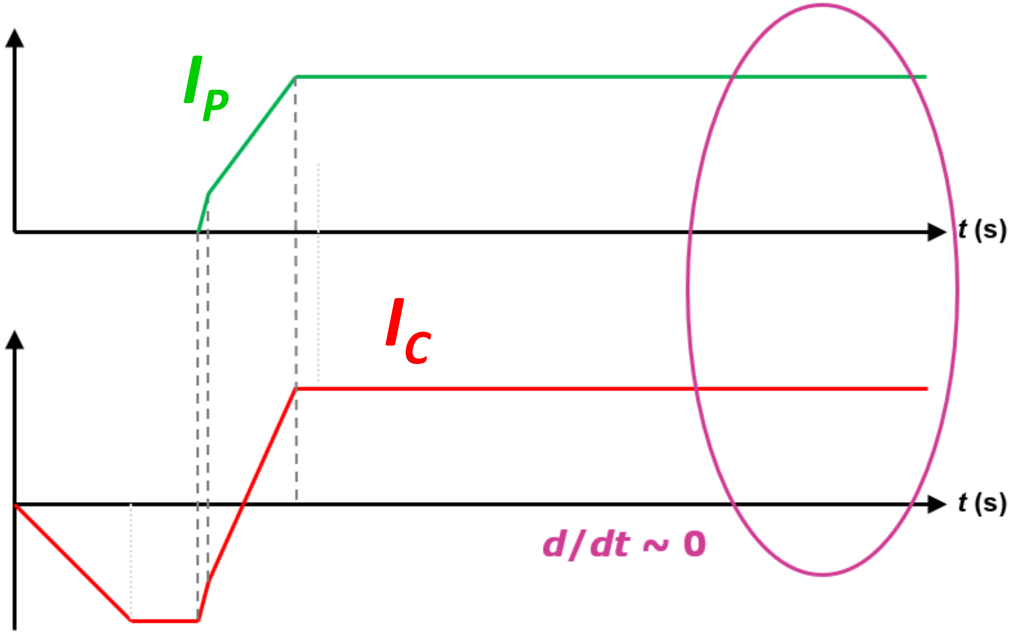
Faraday's law

$$v = -\frac{d}{dt}\int B \cdot ds$$

$I_P = \cancel{I_{OH}} + I_{NI}$

Non-inductive (steady-state) operation



What to satisfy?

- High fusion performance (high $n\tau T$)

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Figure of merit 1: β_N, H_{98}

- Steady-state operation ($f_{NI} = 1$)

$$j_{bs} \sim (r/R)^{1/2} \nabla p/B_{pol}$$

$$\rightarrow f_{bs} = I_{bs}/I_p = c_{bs} A^{-1/2}\beta_{pol} \qquad \beta_{pol} \propto \beta_N B/I \propto \beta_N q_{95}$$

Figure of merit 2: f_{bs}

⇒ *"Advanced Tokamak"*
(W.M. Nevins et al, IAEA FEC (1992))

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What to satisfy?

- High fusion performance (high $n\tau T$)

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Figure of merit 2: f_{bs}

- Long pulse operation ($\tau_{pulse} \gg \tau_W$) ⇒ *S.H. Han, this school*

Profile & MHD control, Particle & power handling, Engineering issues

⇒ *"Integrated Operation Scenarios"*

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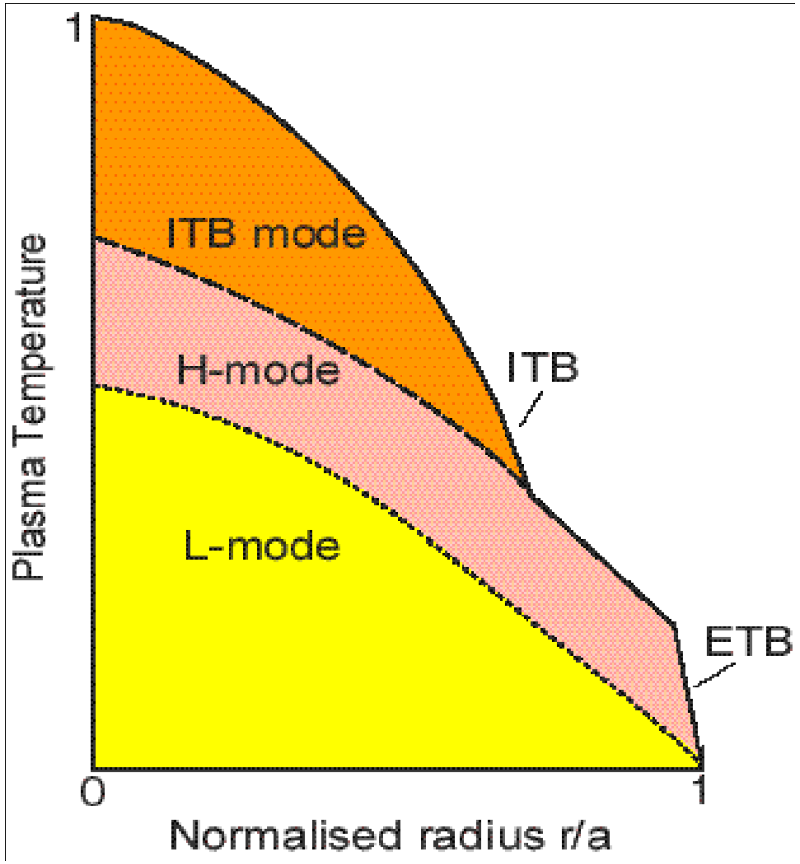
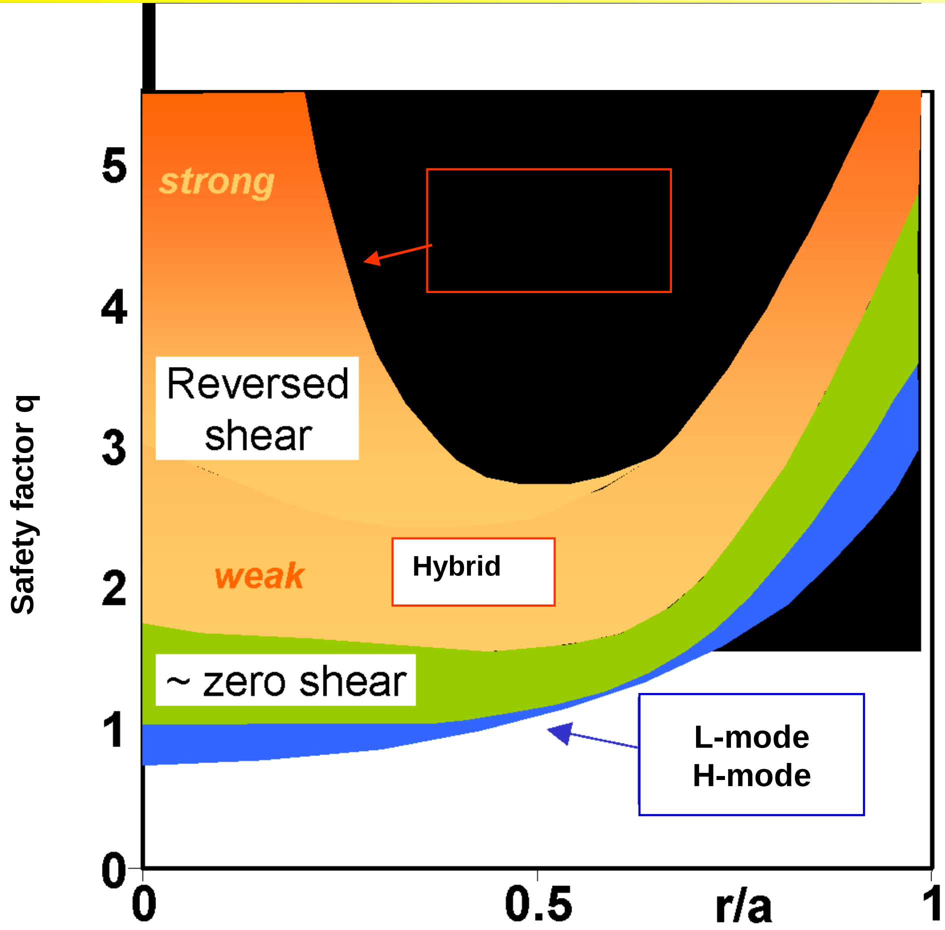
How to satisfy them?

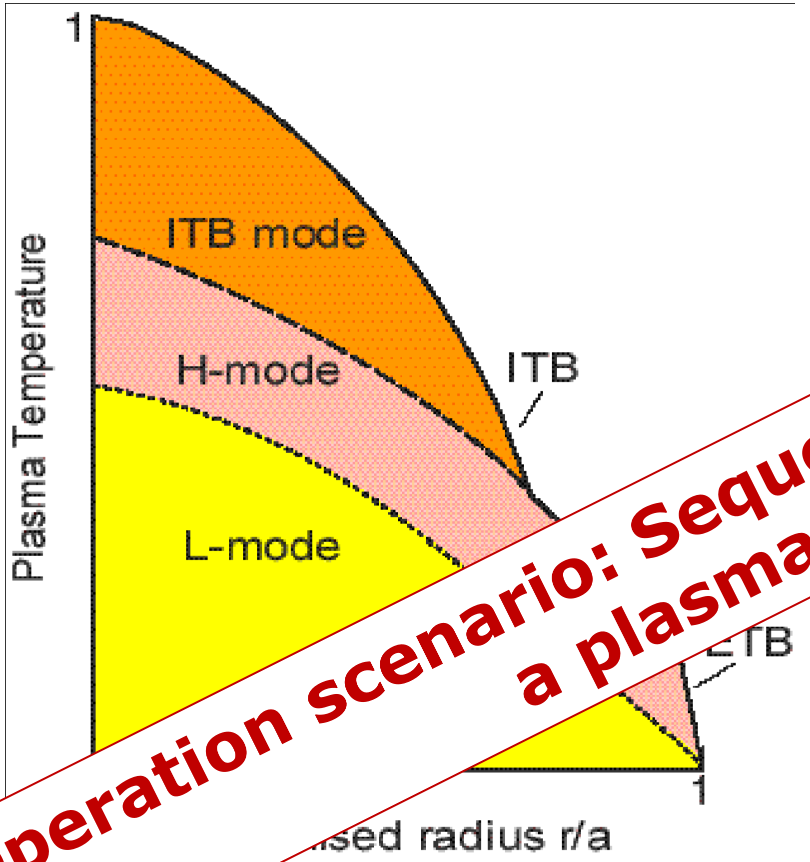


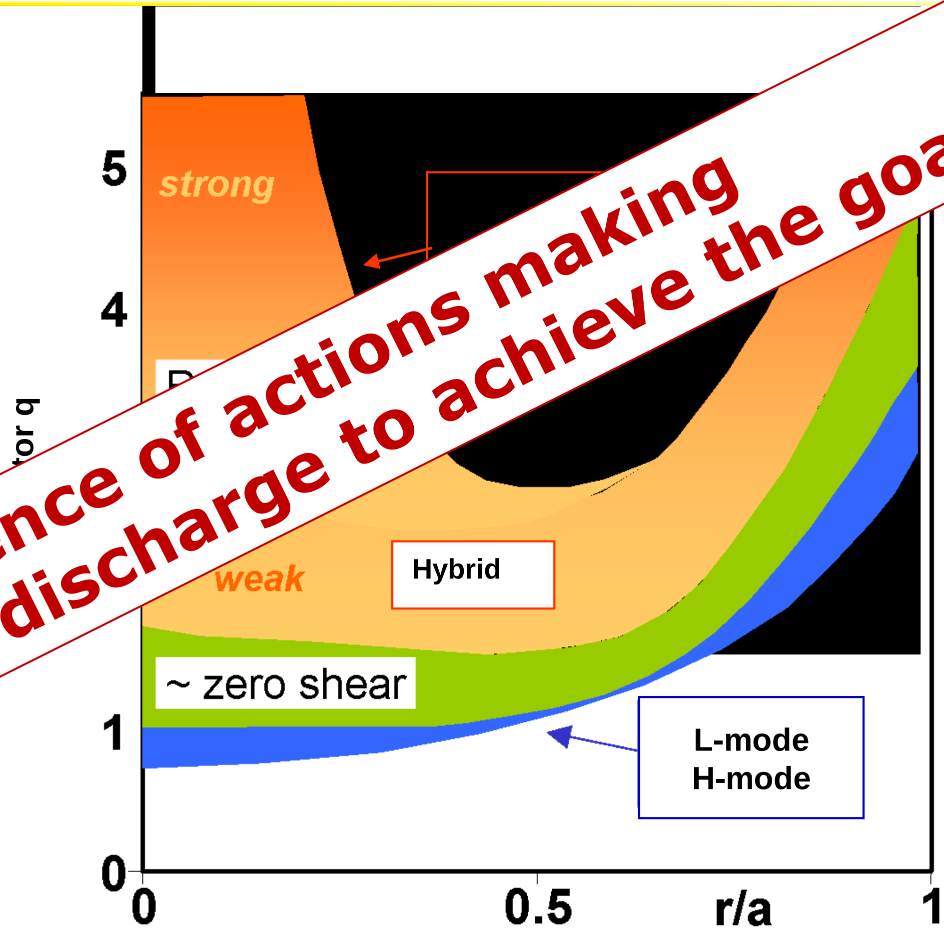


$q \approx \frac{r}{R}\frac{B_{tor}}{B_p}$

The target pressure profile and q-profile should be carefully set to avoid severe MHD instabilities (β_N) and minimize turbulence (H_{98}).

How to satisfy them?





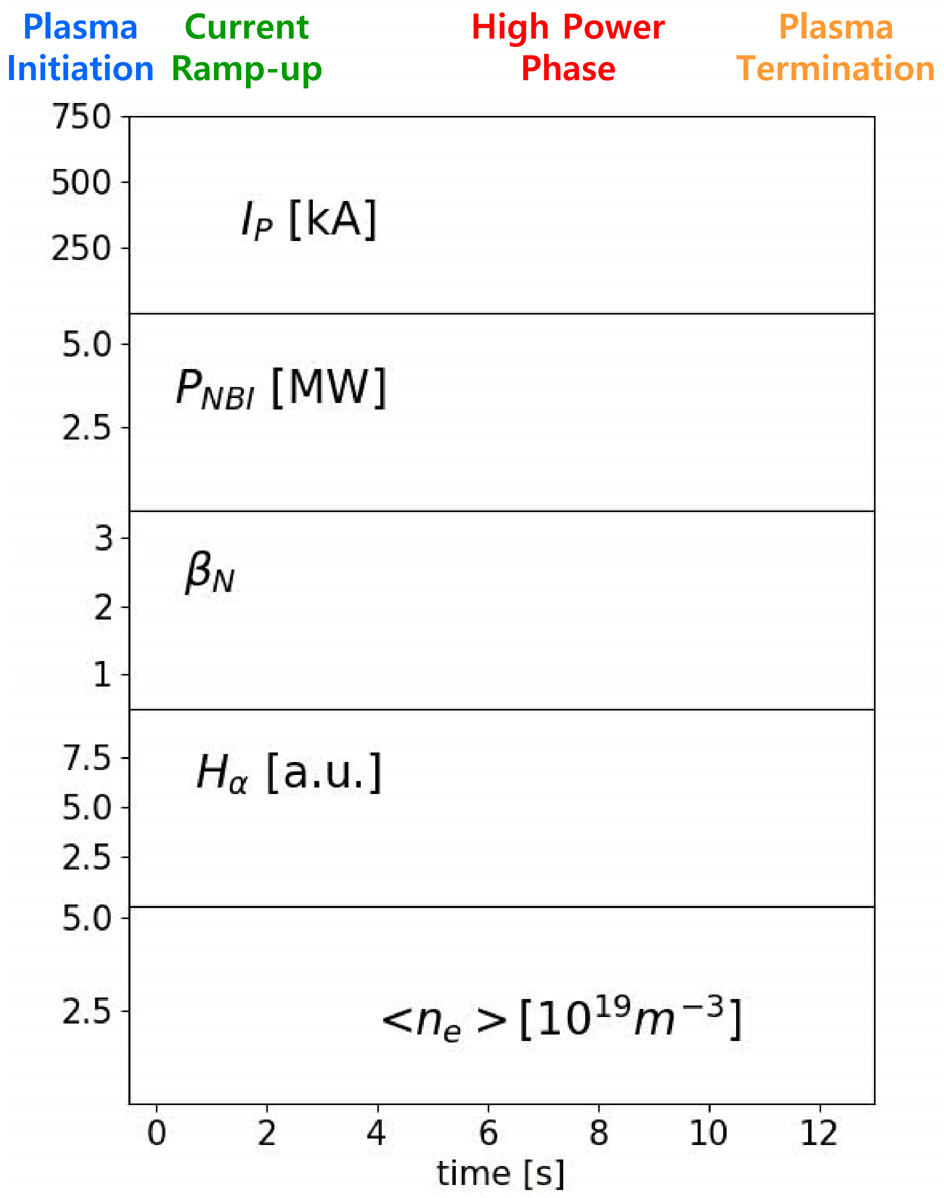
$q \approx \frac{r}{R}\frac{B_{tor}}{B_{p}}$

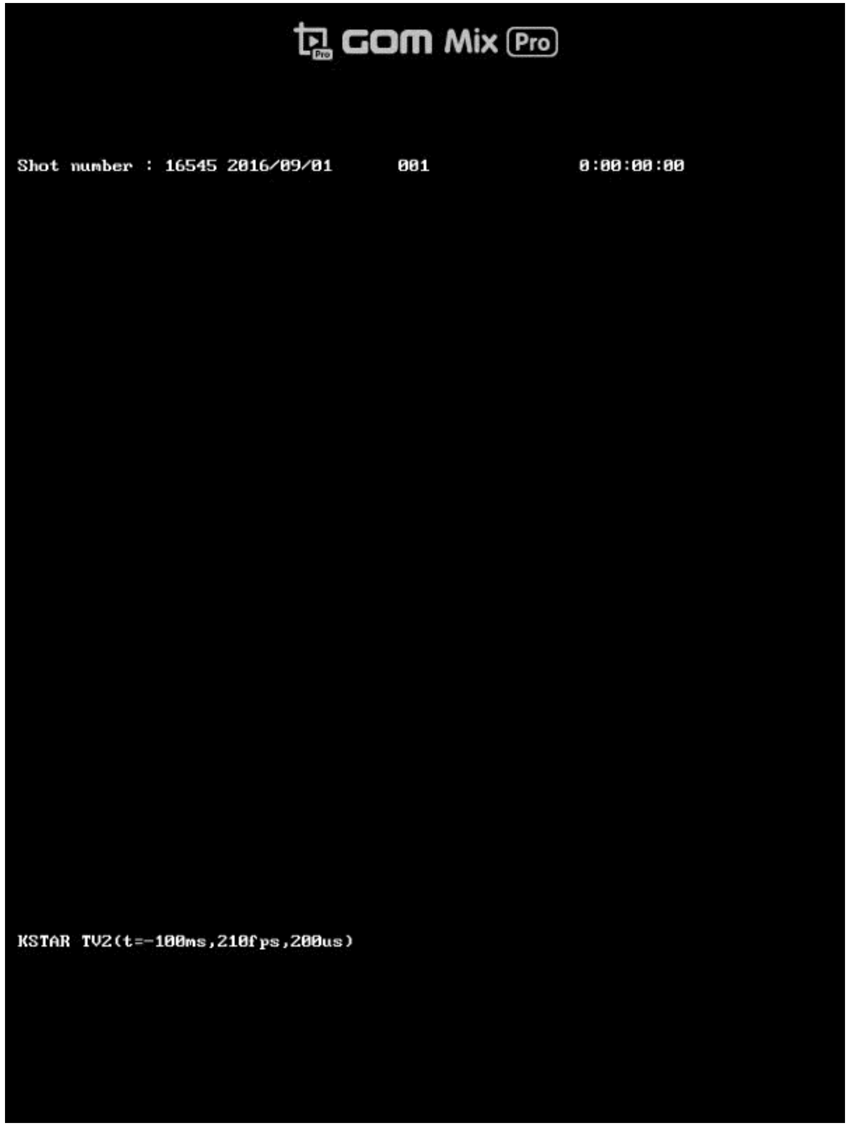
Operation scenario: Sequence of actions making a plasma discharge to achieve the goal.

Once we set the target profiles, we have to establish them in the experiment → Design an operation scenario!

Your item: coils, fueling, H&CD, etc

How to realise?





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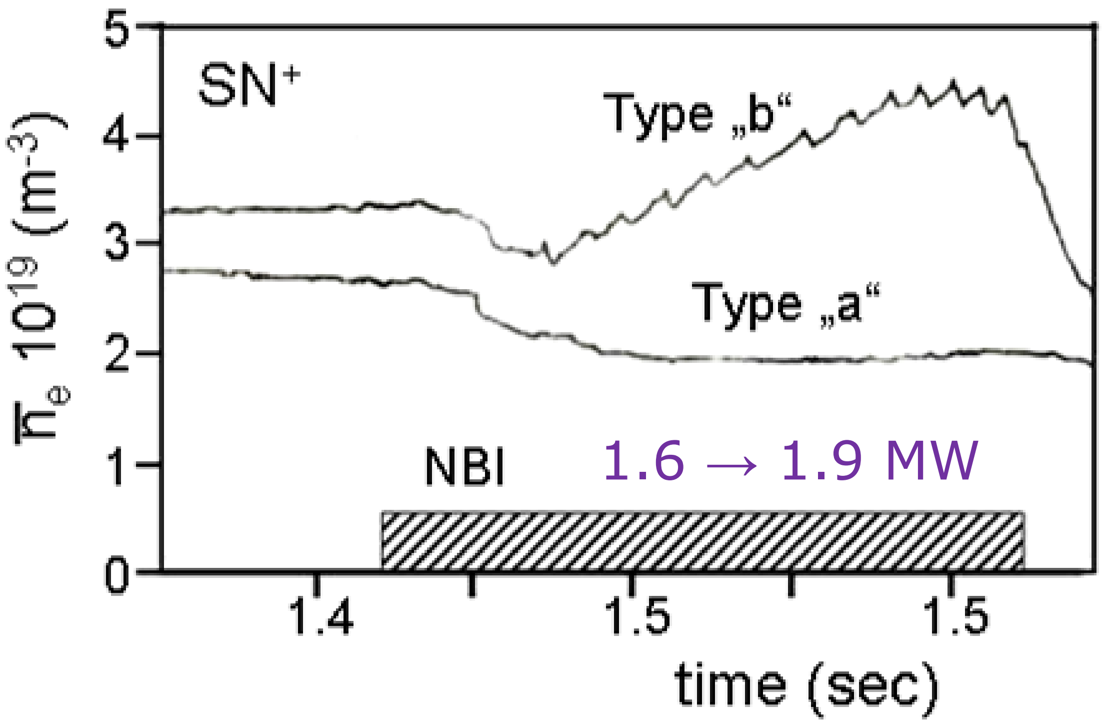
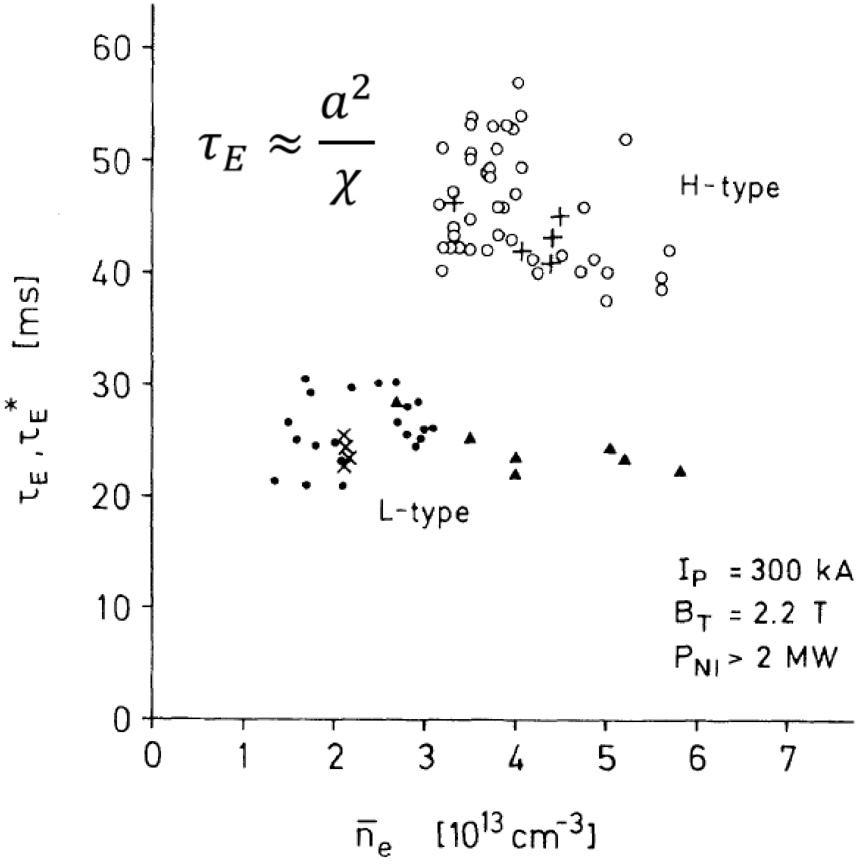
H-mode

- 1982 IAEA F. Wagner et al. (ASDEX, Germany)

A serendipity!

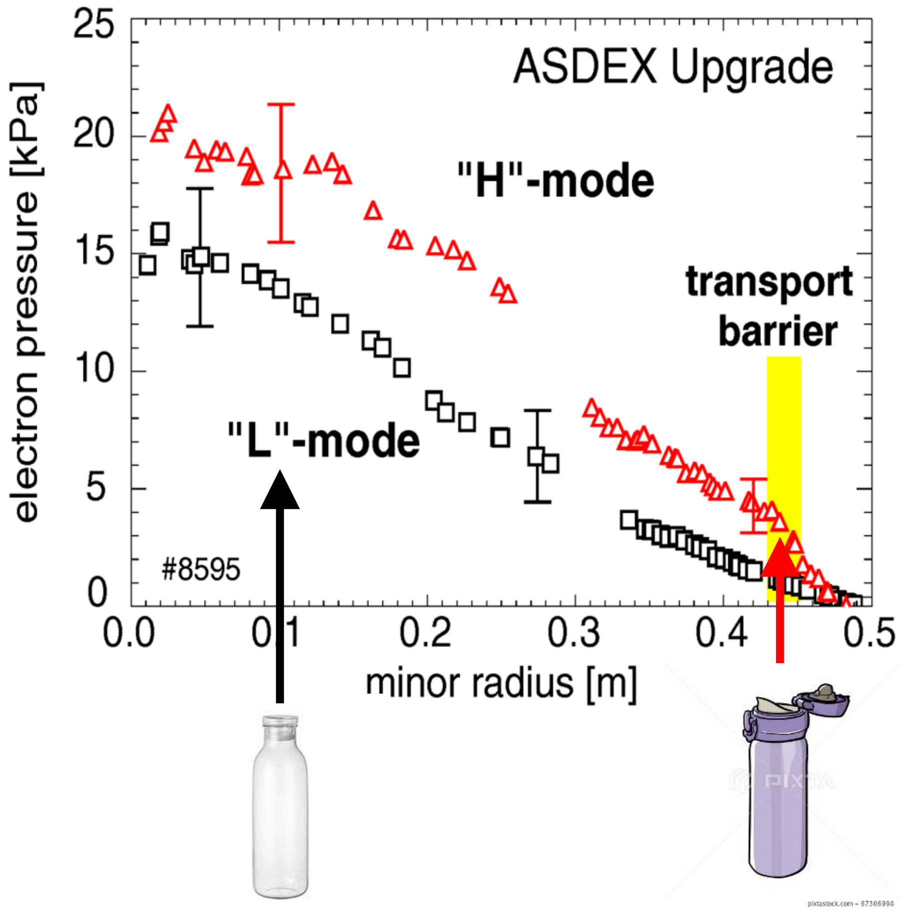




H-mode: Why?

- 1982 IAEA F. Wagner et al. (ASDEX, Germany)

- Transition to H-mode: State with reduced turbulence at the plasma edge
- Formation of an edge transport barrier: Steep pressure gradient at the edge



Hoover dam

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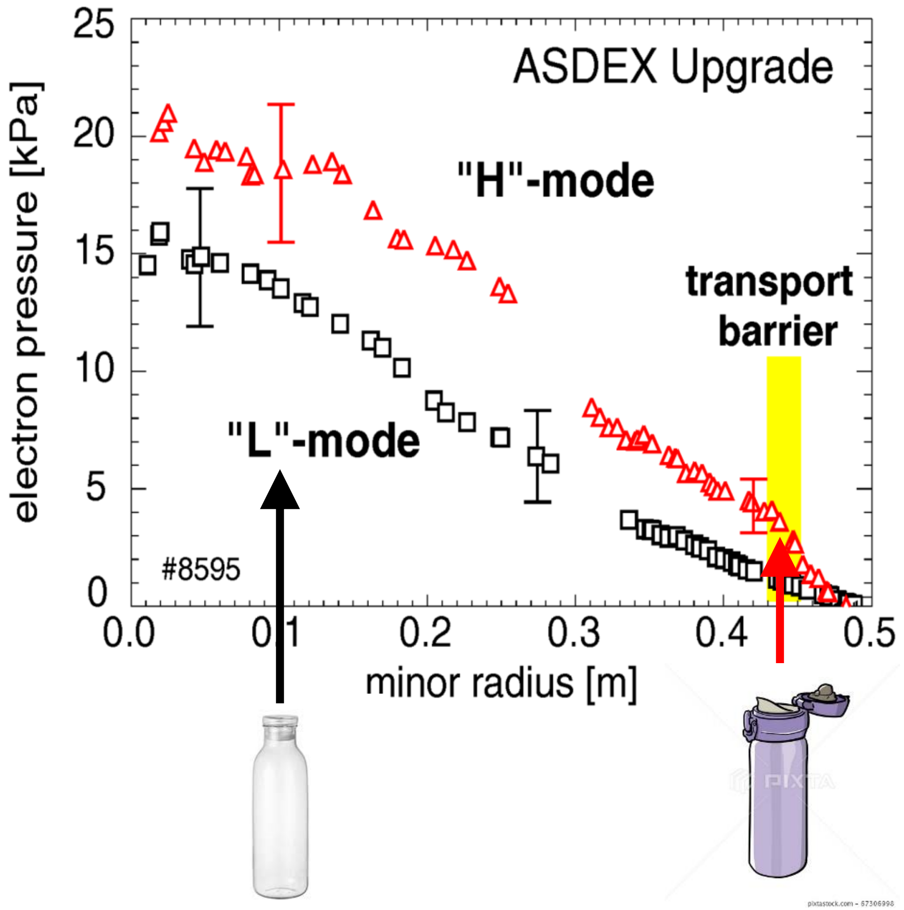

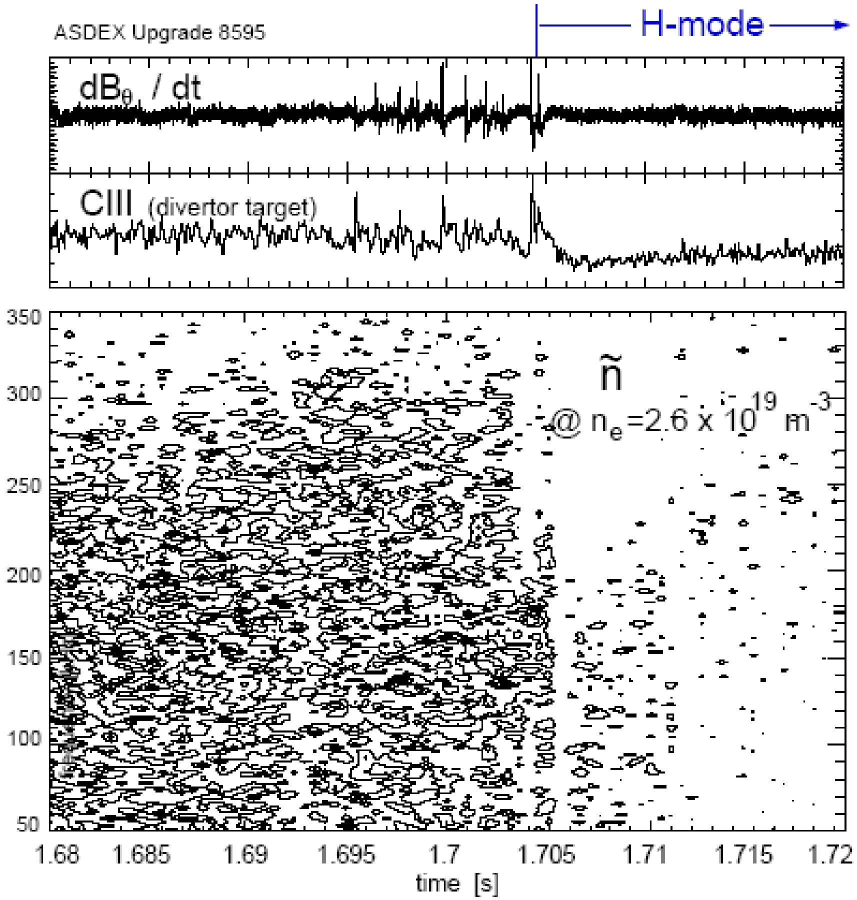

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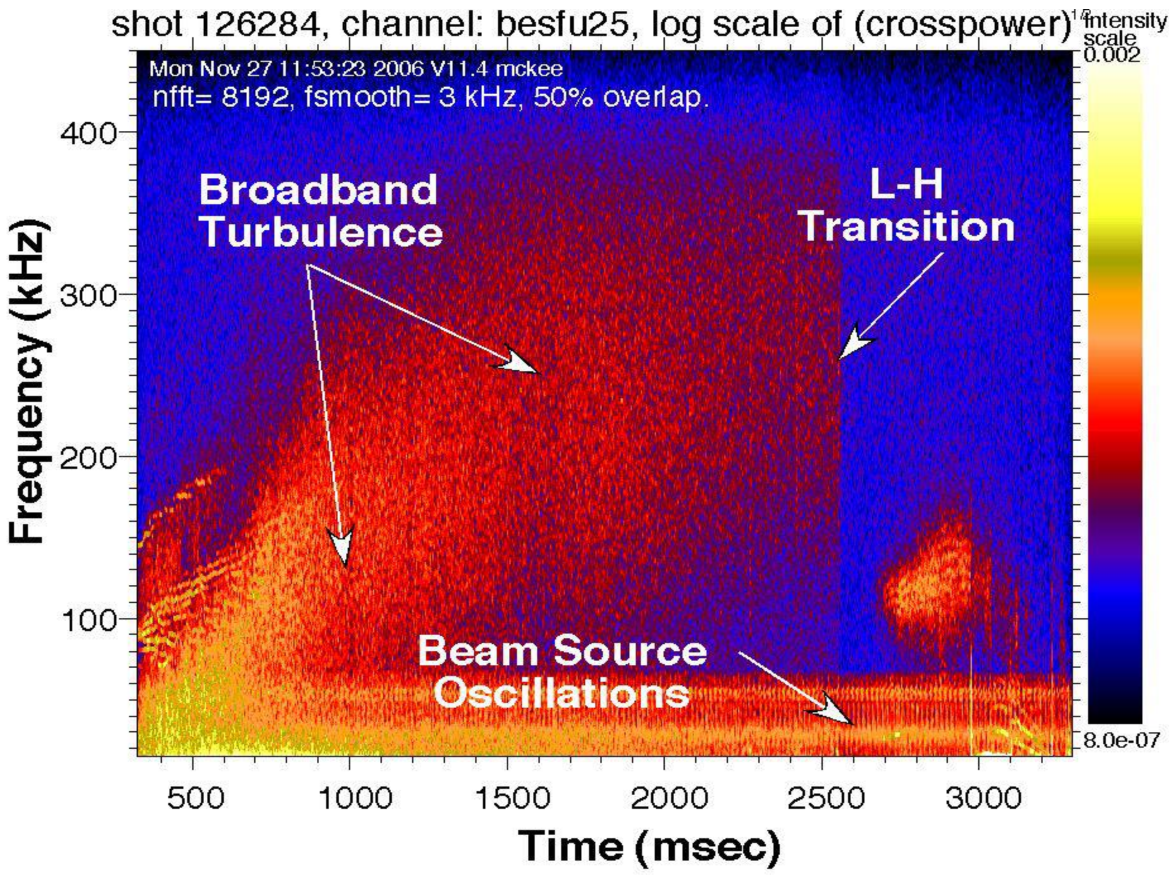

Density fluctuations at r/a = 0.65 measured by beam emission spectroscopy

G.R. McKee, et al. Plasma Fusion Res. ***2*** *S1025 (2007)*

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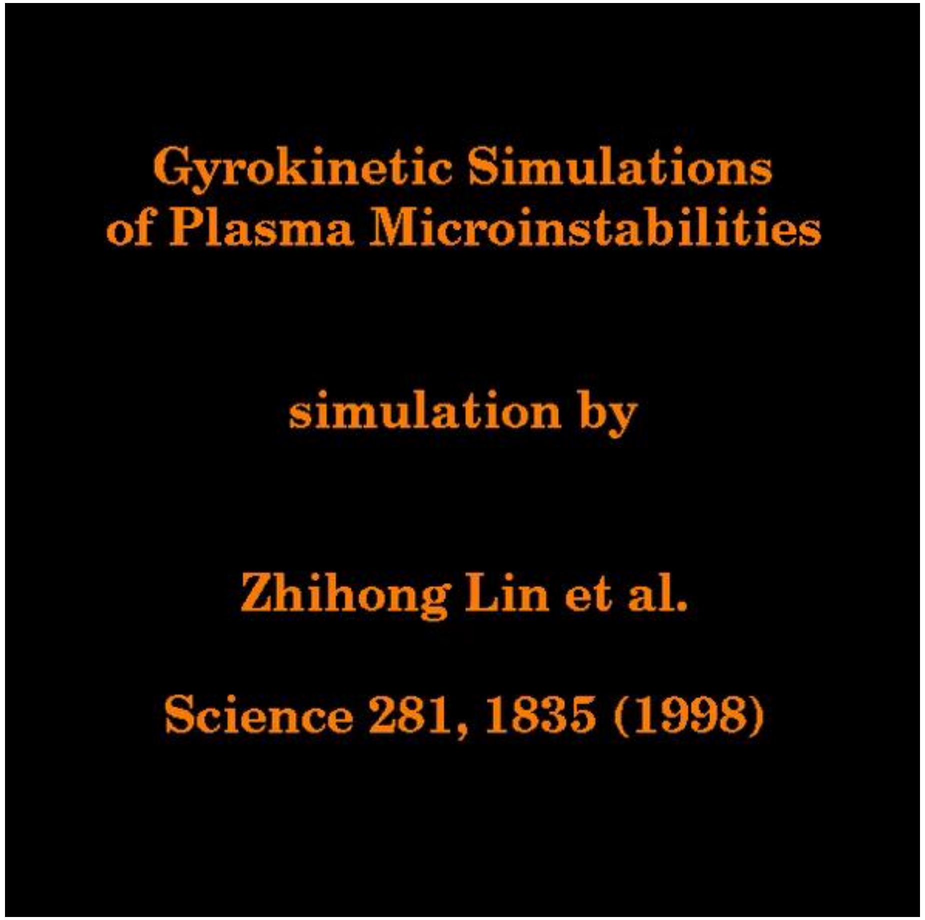
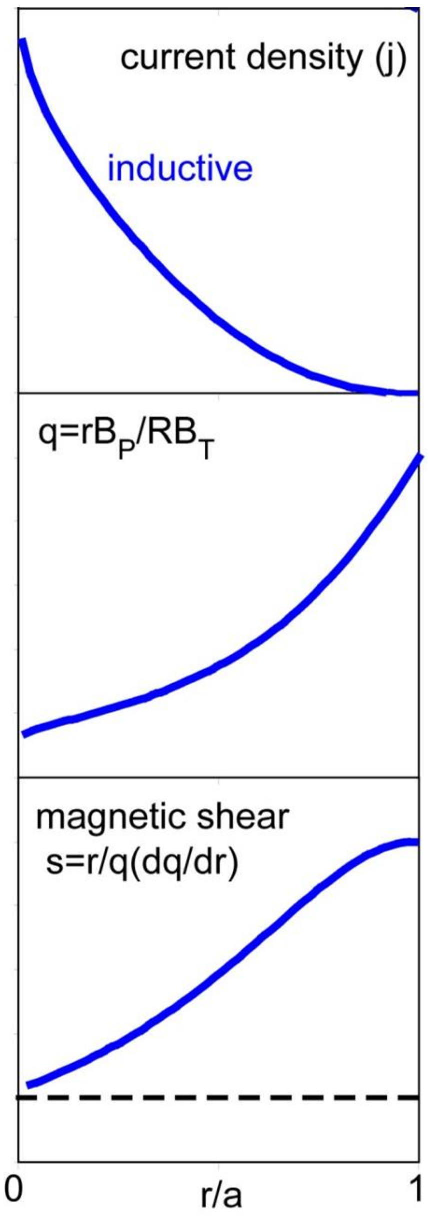


H-mode: How to?

- Impact of wall condition

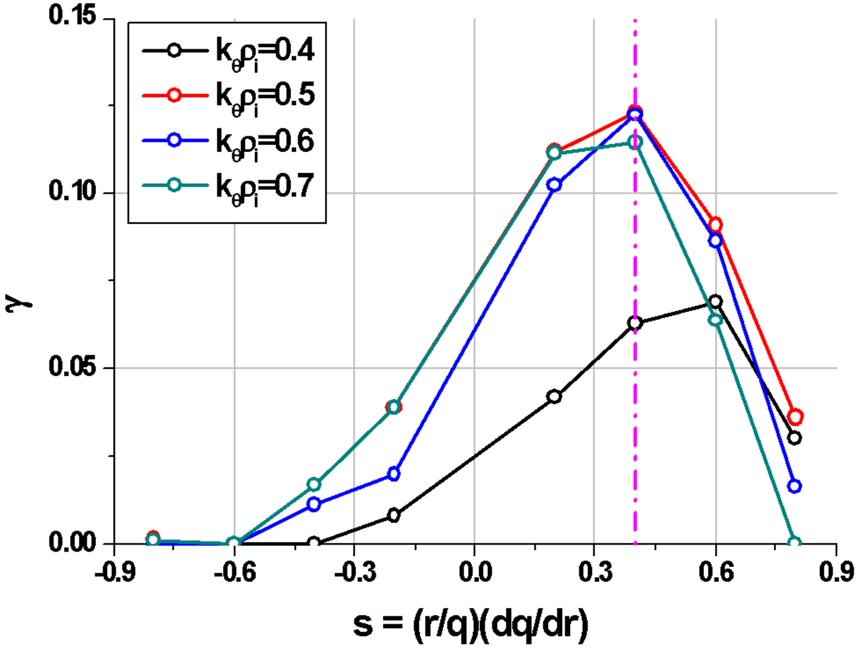
H-mode: Characteristics?



Target profiles not set!

- Naturally peaked current profile
- Monotonic *q*-profile

ITG (Ion Temperature Gradient) microinstability



*Y.-S. Na et al, NF **60** 086006 (2020)*

⇒ **Figure of merit 1:** *H_{98} ~ 1.0 (reference)*

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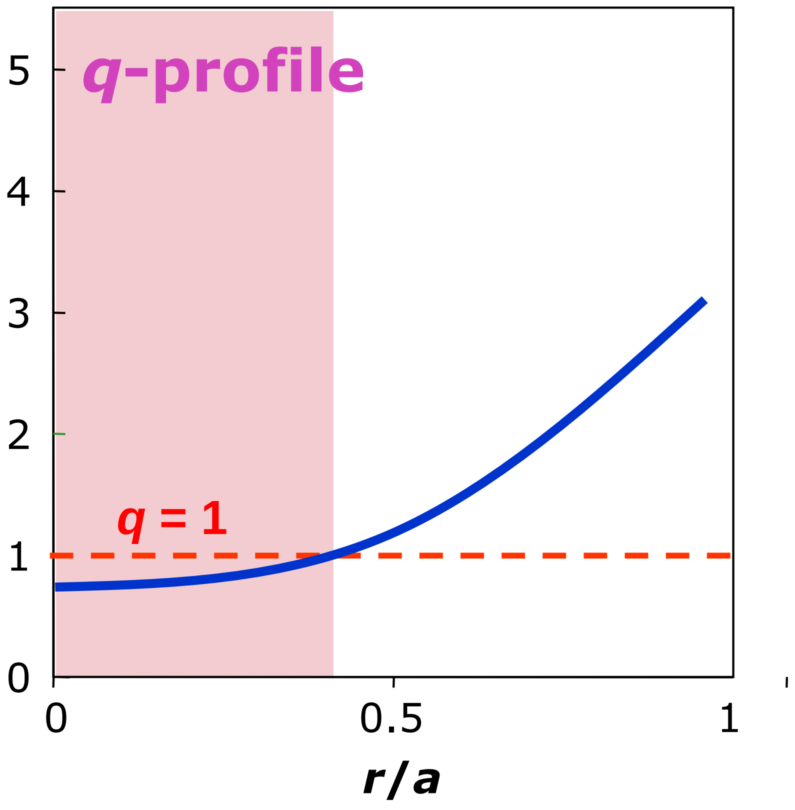
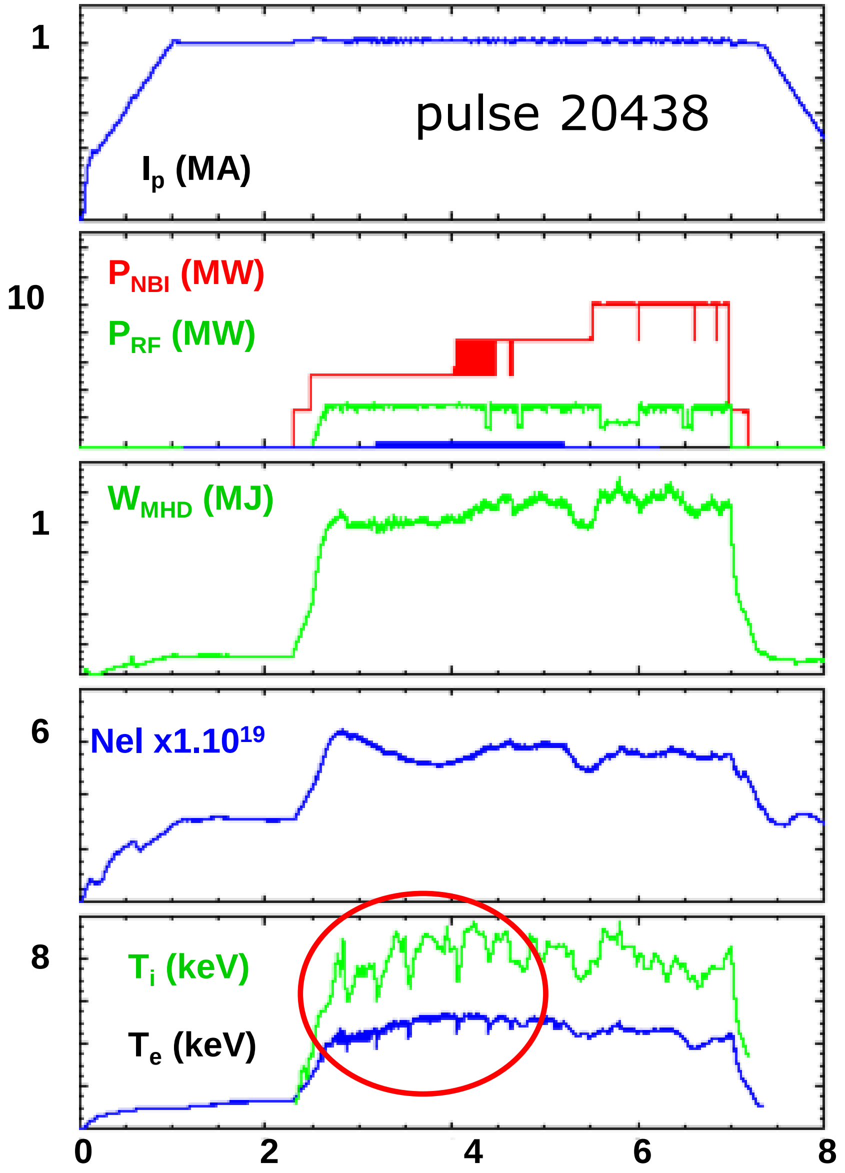
H-mode: Characteristics?

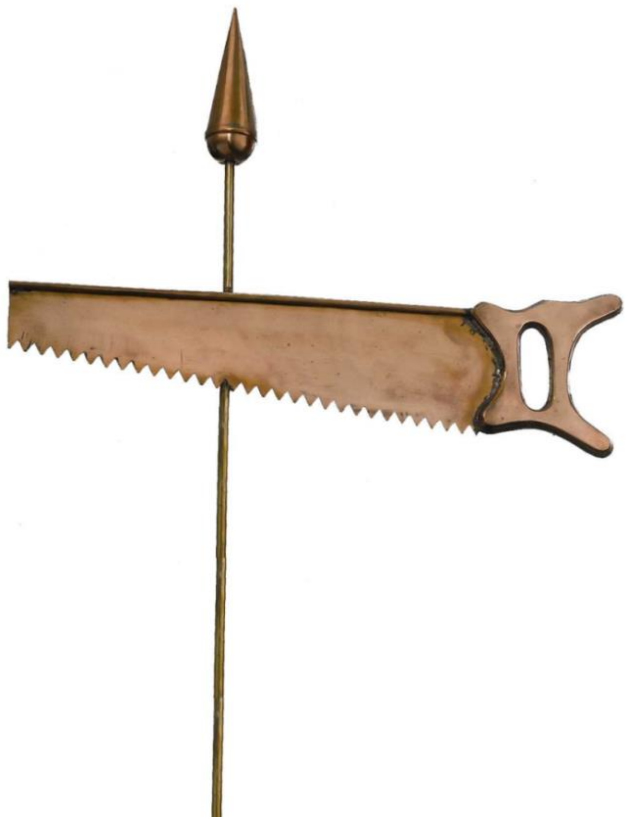
- Stability related with safety factor profile, $q(r)$



$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

Sawtooth

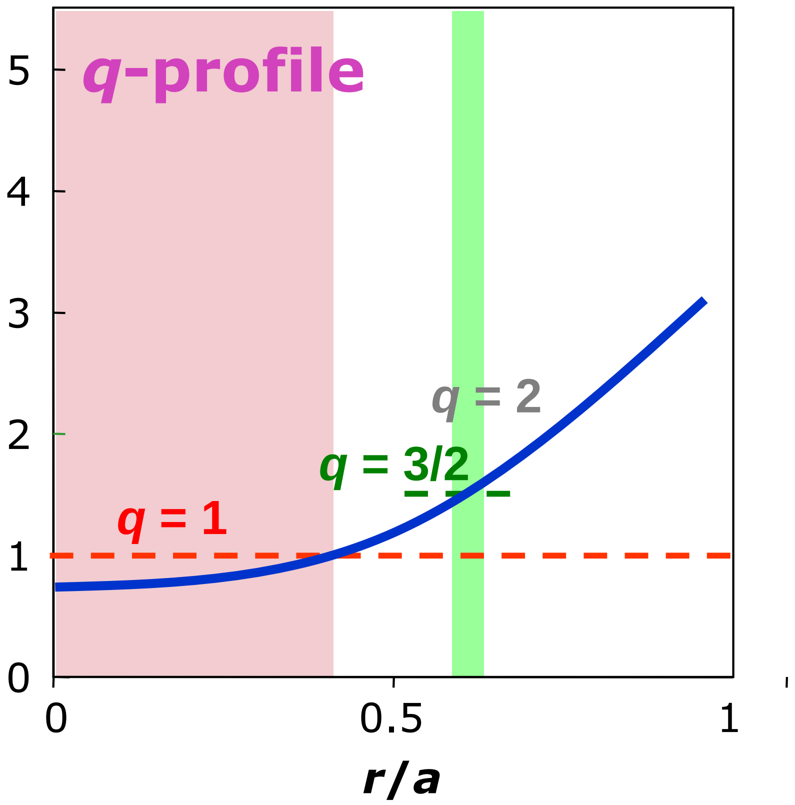




- nonlinear low-*n* internal mode
- internal (minor) disruption
- increasing energy transport in the plasma centre

H-mode: Characteristics?

- Stability related with safety factor profile, $q(r)$



$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

$q = 3/2$ and $q = 2$: ⇒ *F. Turco, this school*

(Neoclassical) Tearing Modes (TM/NTMs):

- limit the achievable β_N

- degrade confinement (+ disruptions)

- often triggered by sawteeth

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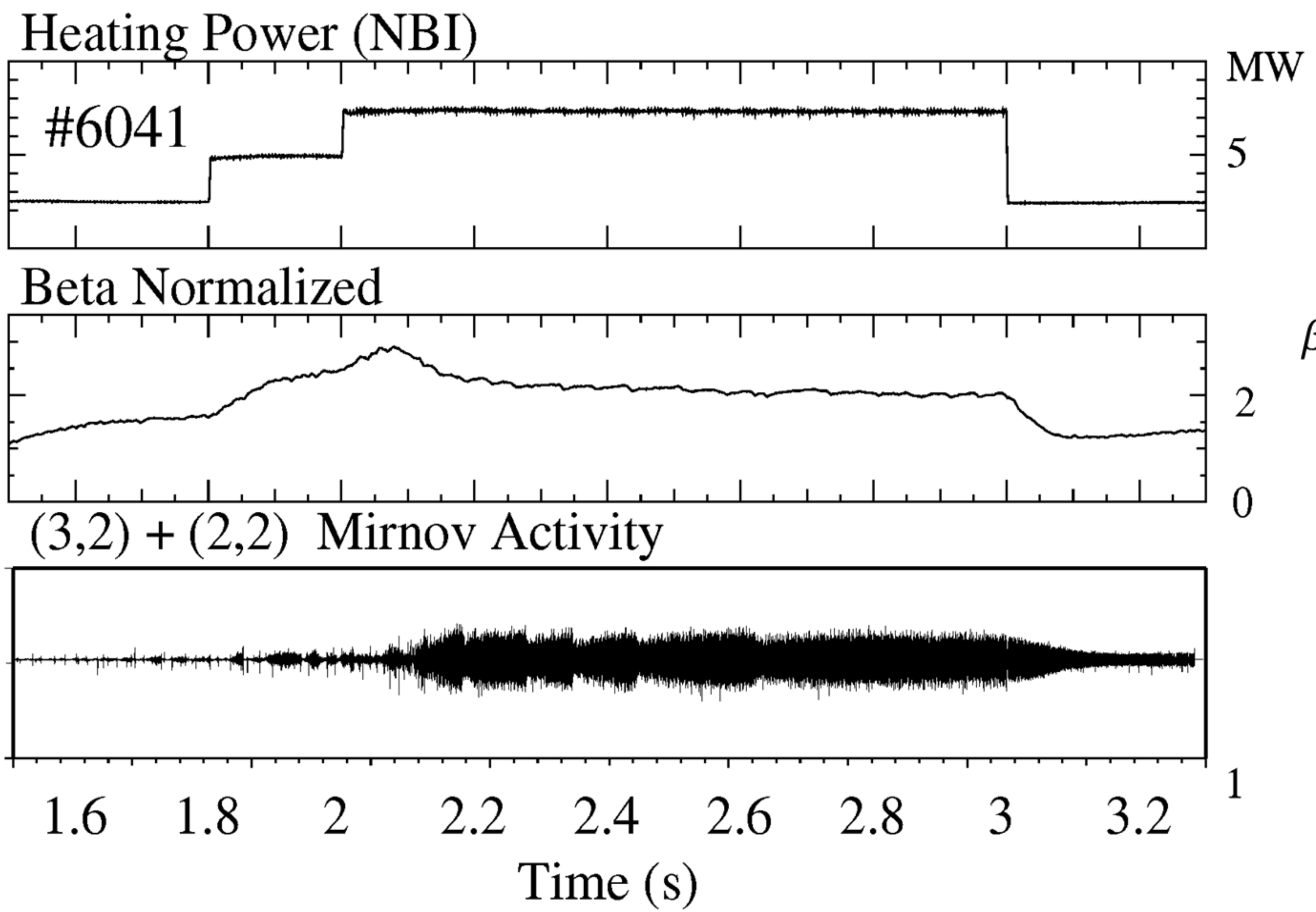
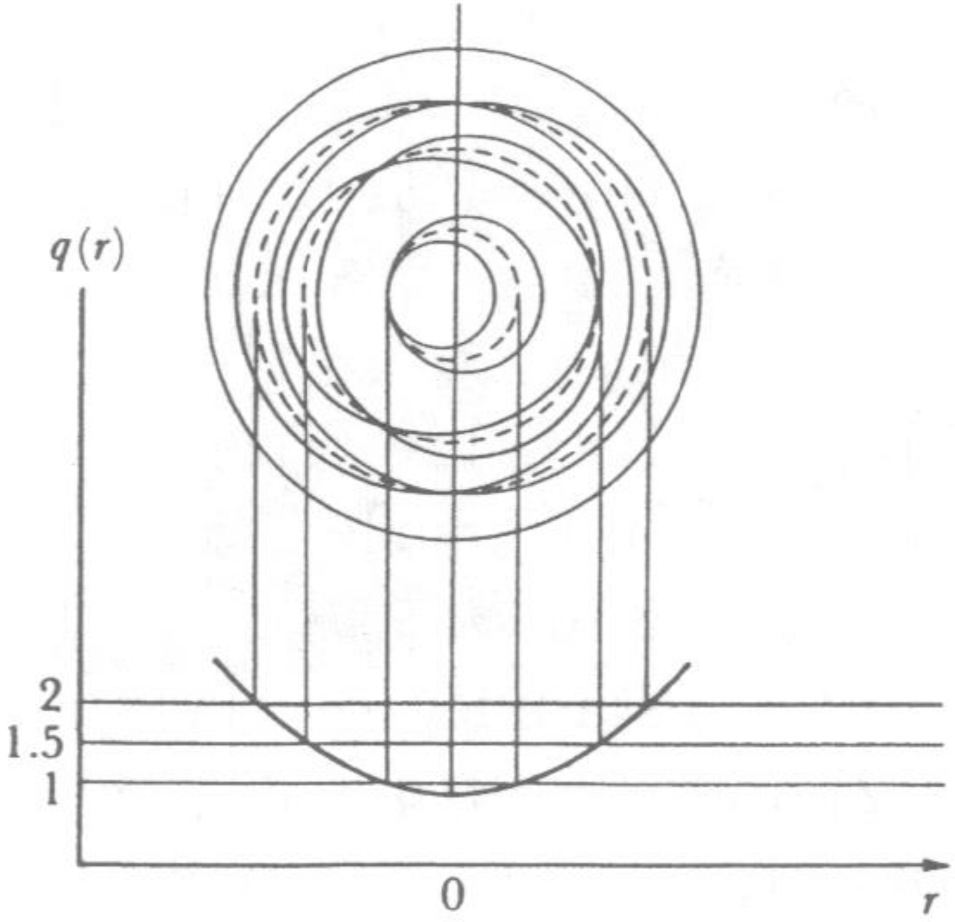
Neoclassical Tearing Mode (NTM)



$$\beta_t(\%) = \beta_N \frac{I_\varphi}{aB_\varphi}$$

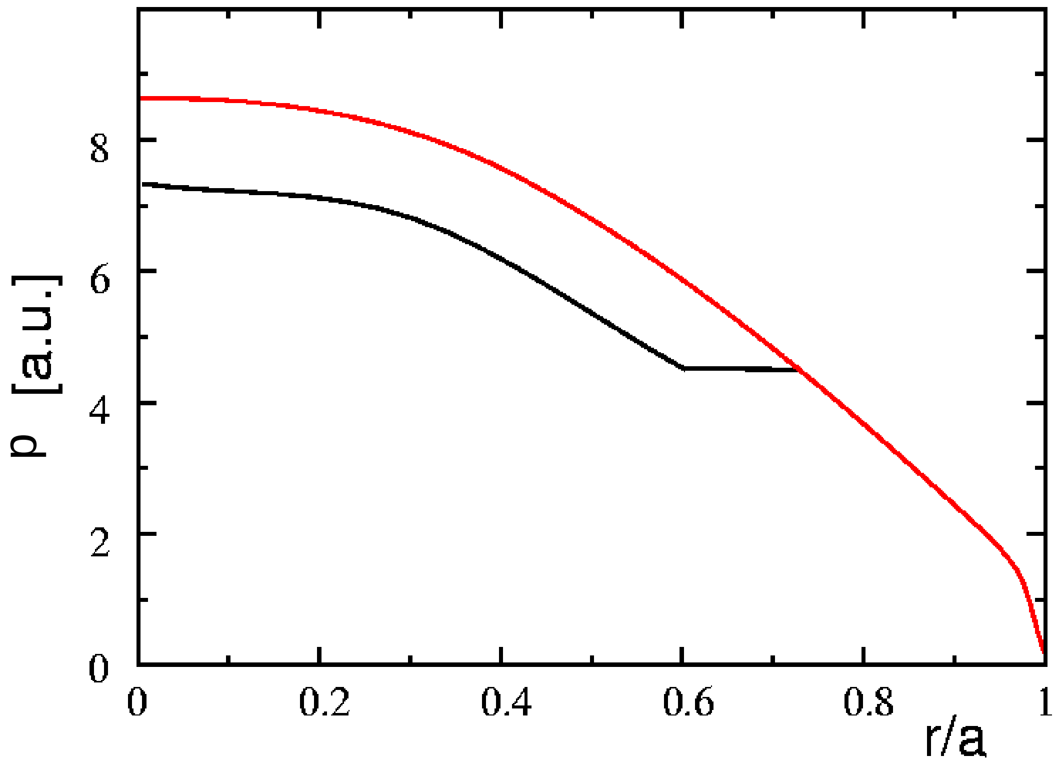
Neoclassical Tearing Mode (NTM)

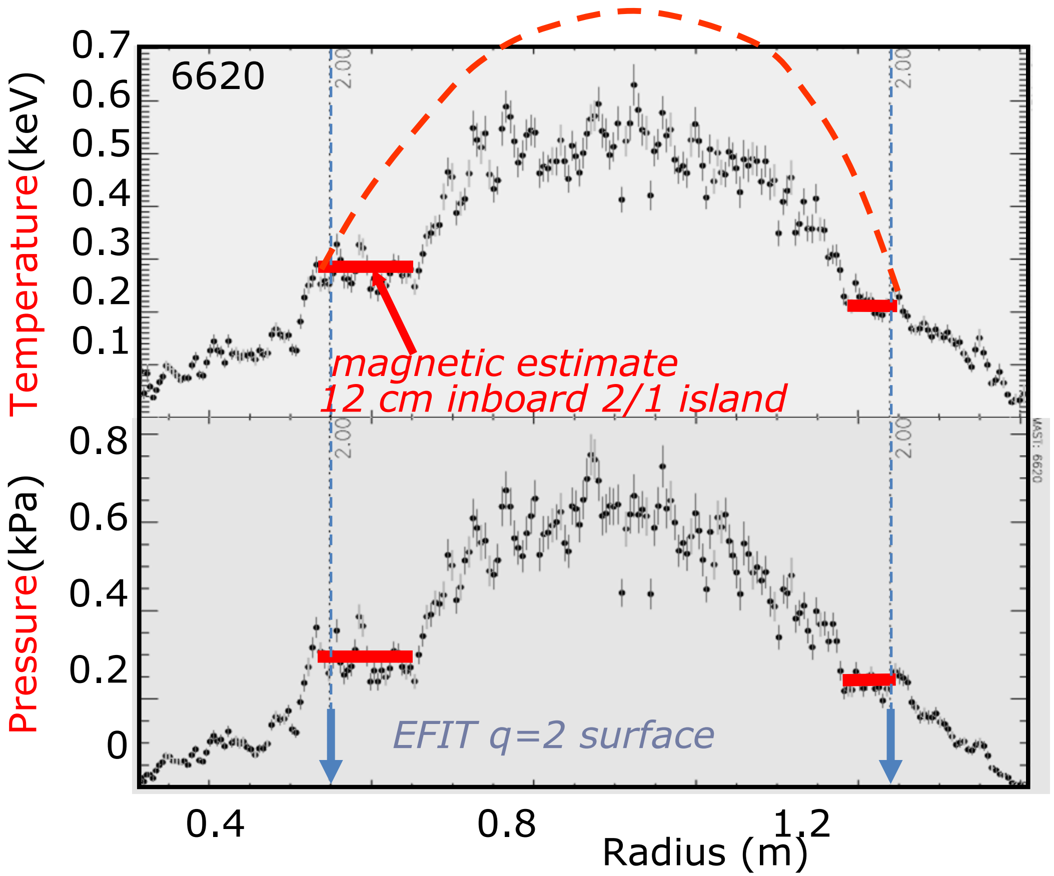


K. Miyamoto, "Controlled Fusion and Plasma Physics" Taylor & Francis (2007)

- Pressure flattening across magnetic islands due to large transport coefficients along magnetic field lines

Neoclassical Tearing Mode (NTM)

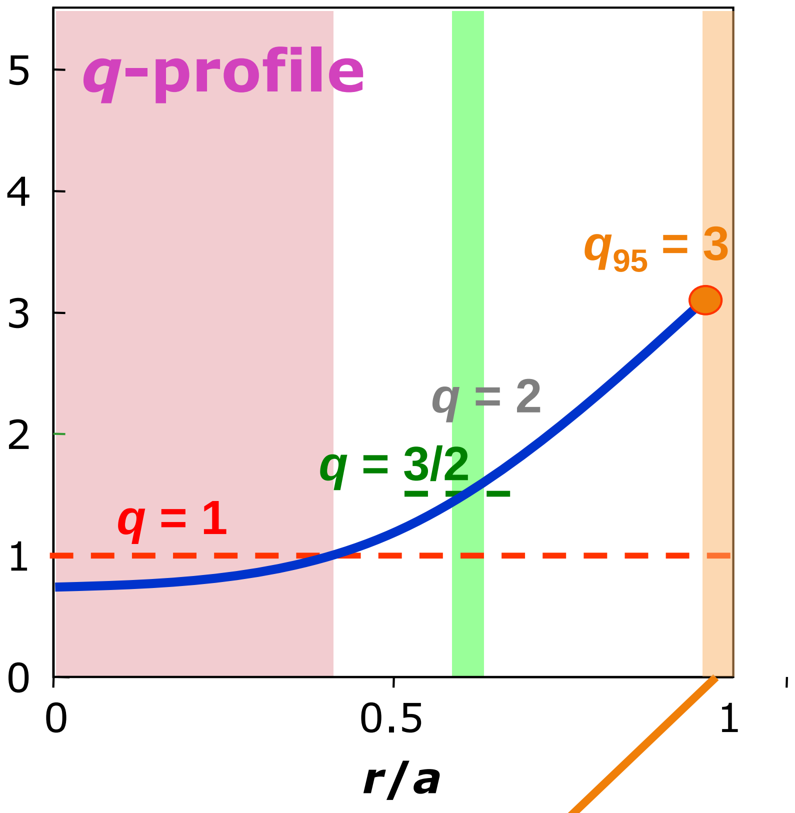




- Pressure flattening across magnetic islands due to large transport coefficients along magnetic field lines

H-mode: Characteristics?

- Stability related with safety factor profile, $q(r)$



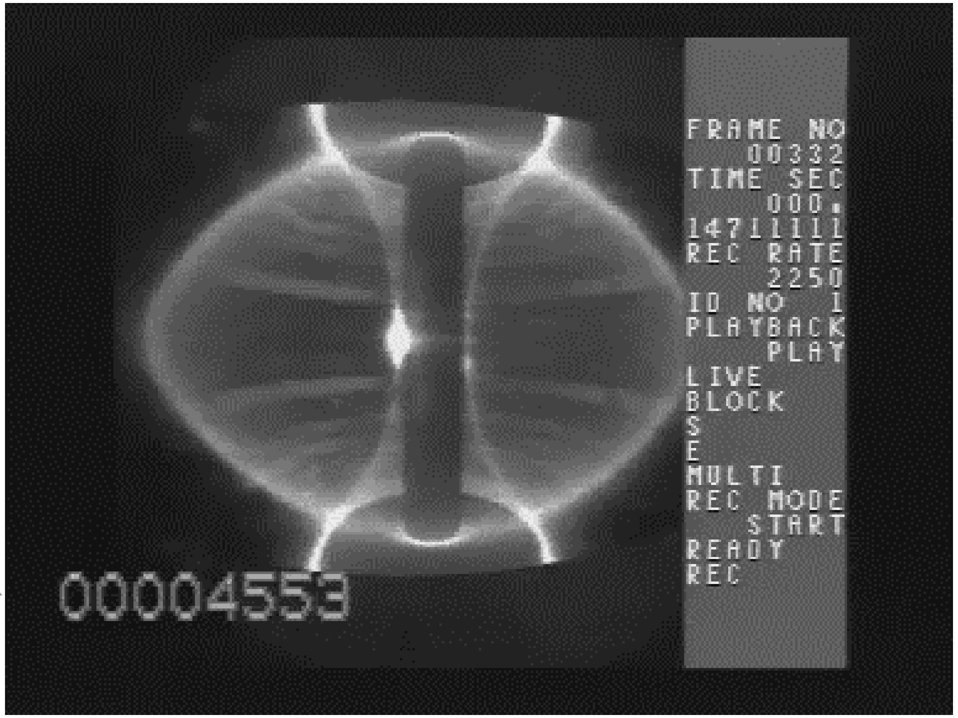
Periodic collapses of the ETB (ELMs)

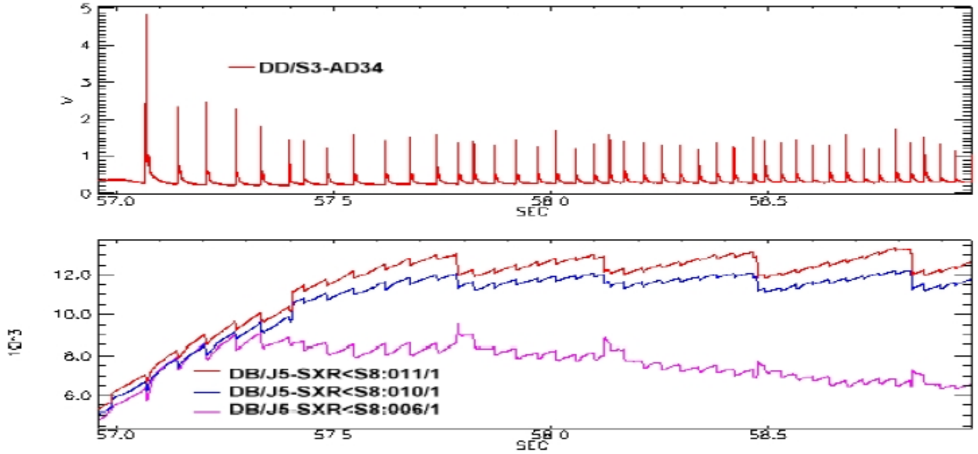
$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

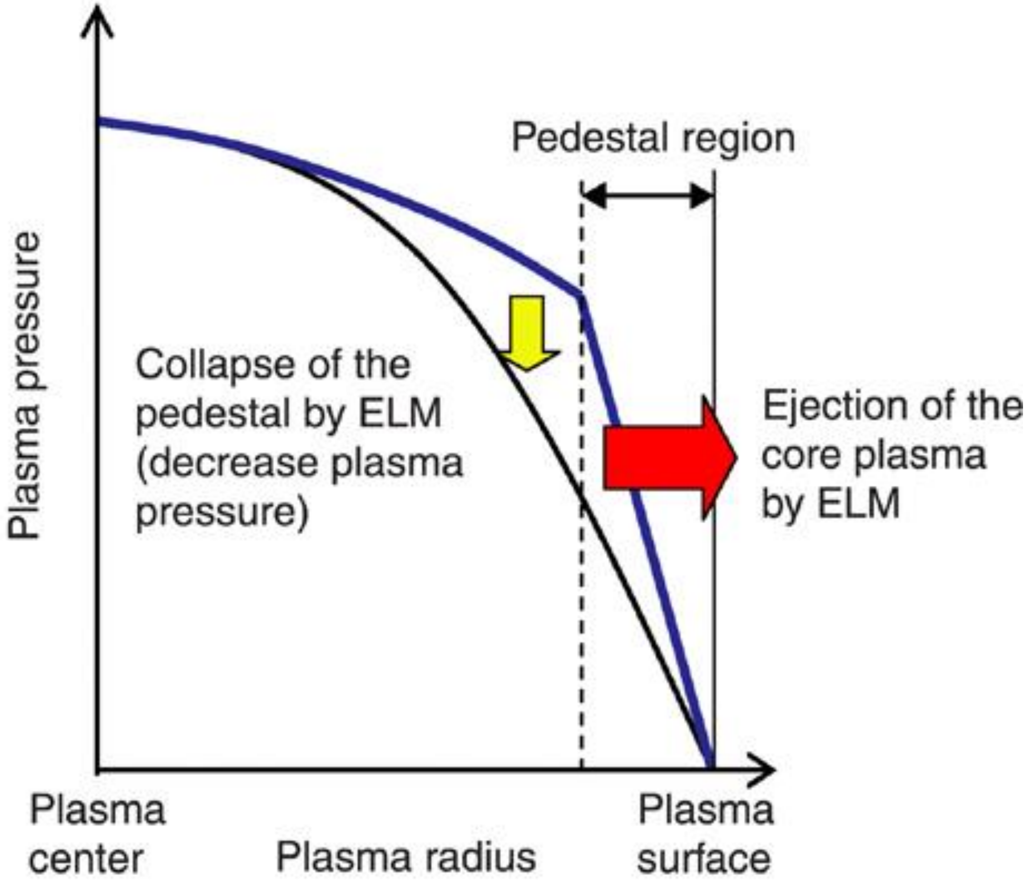
$q = 3/2$ and **$q = 2$**:
Neoclassical Tearing Modes (NTMs):
- limit the achievable β_N
- degrade confinement (+ disruptions)
- often triggered by sawteeth

q_{95} ($\propto 1/I_p$) = 3:
Safe operation at max. I_P

Edge Localised Mode (ELM)

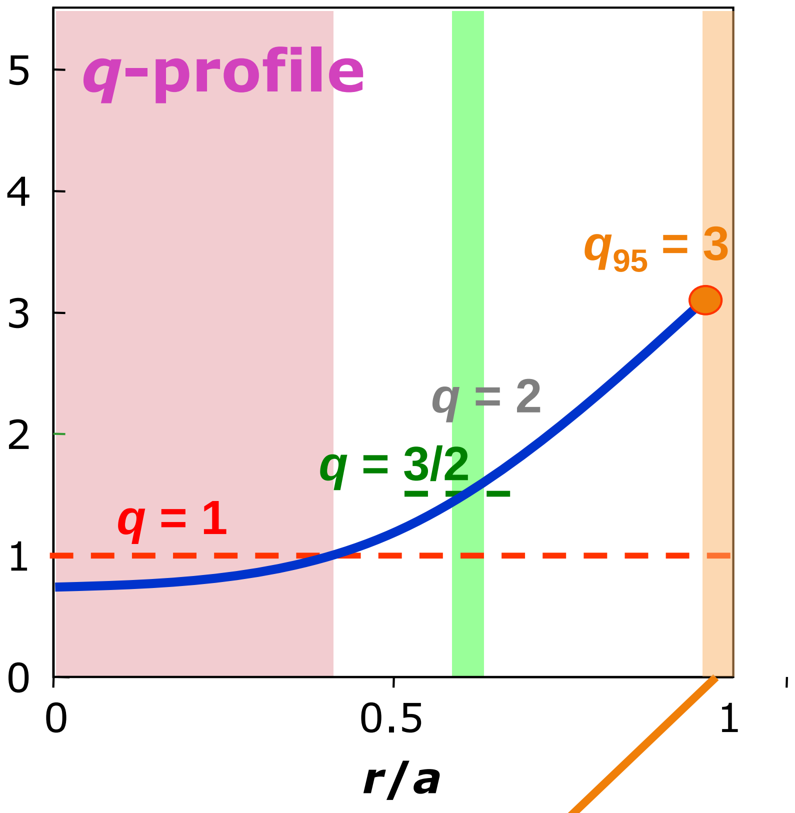






H-mode: Characteristics?

- Stability related with safety factor profile, $q(r)$



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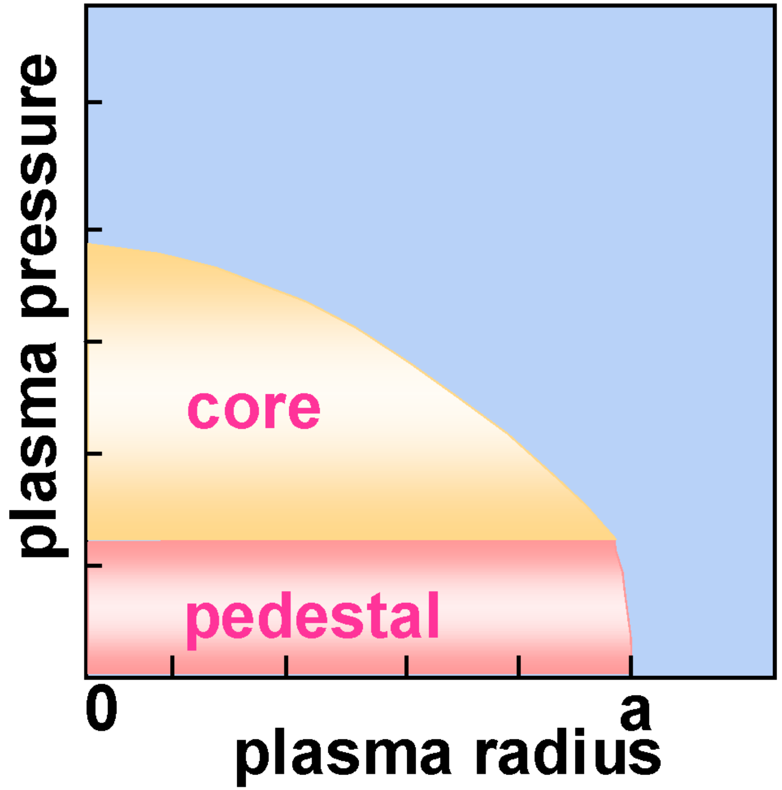
Safe operation at max. I_P

⇒ **Figure of merit 1:** $\beta_N < 2.0$

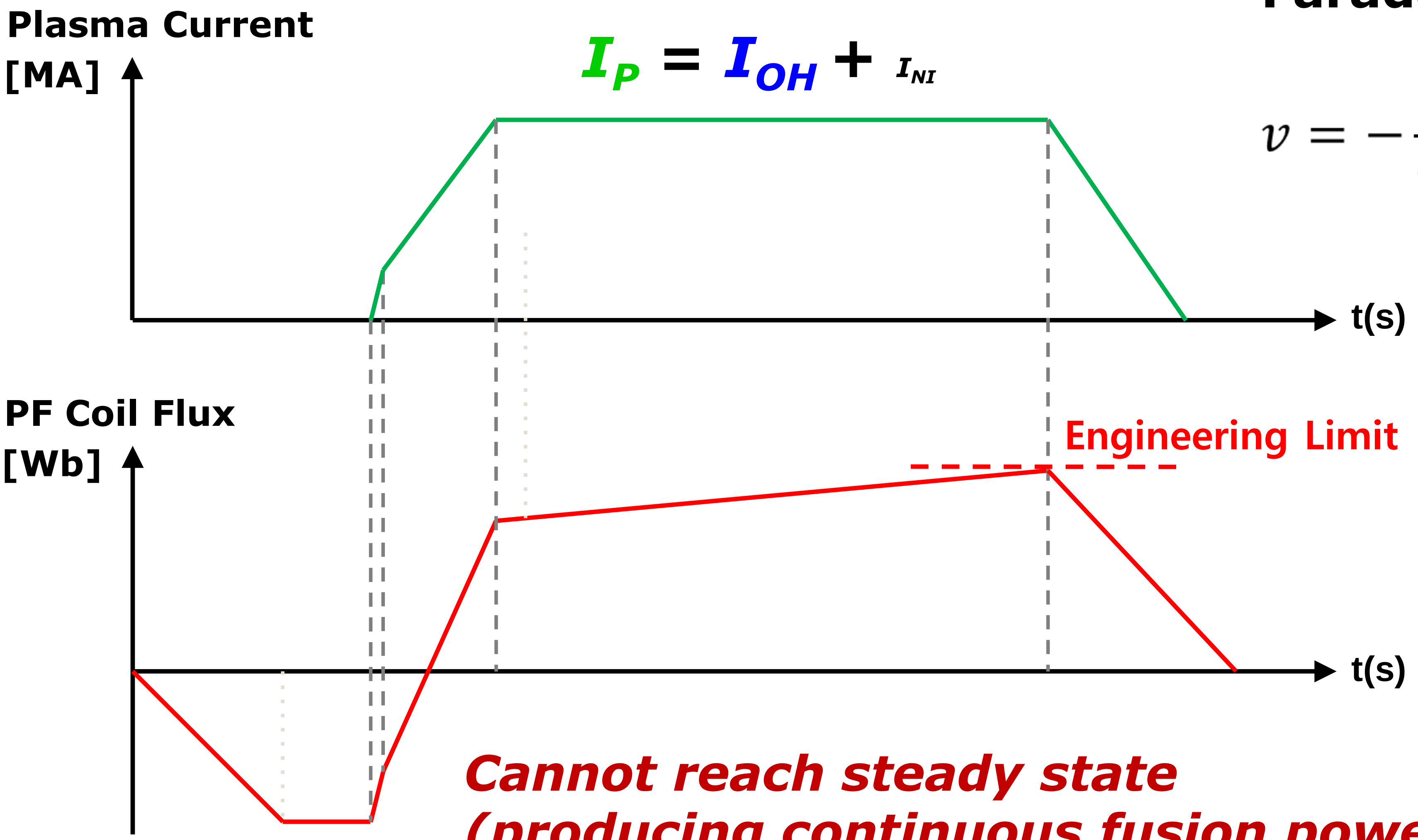
H-mode: Characteristics?



- Mild pressure gradient with steep edge pedestal (ETB)
  → low bootstrap current $J_{bs} \propto \nabla p$

⇒ Figure of merit 2: ***f_{bs} << 0.5***

H-mode: Characteristics?

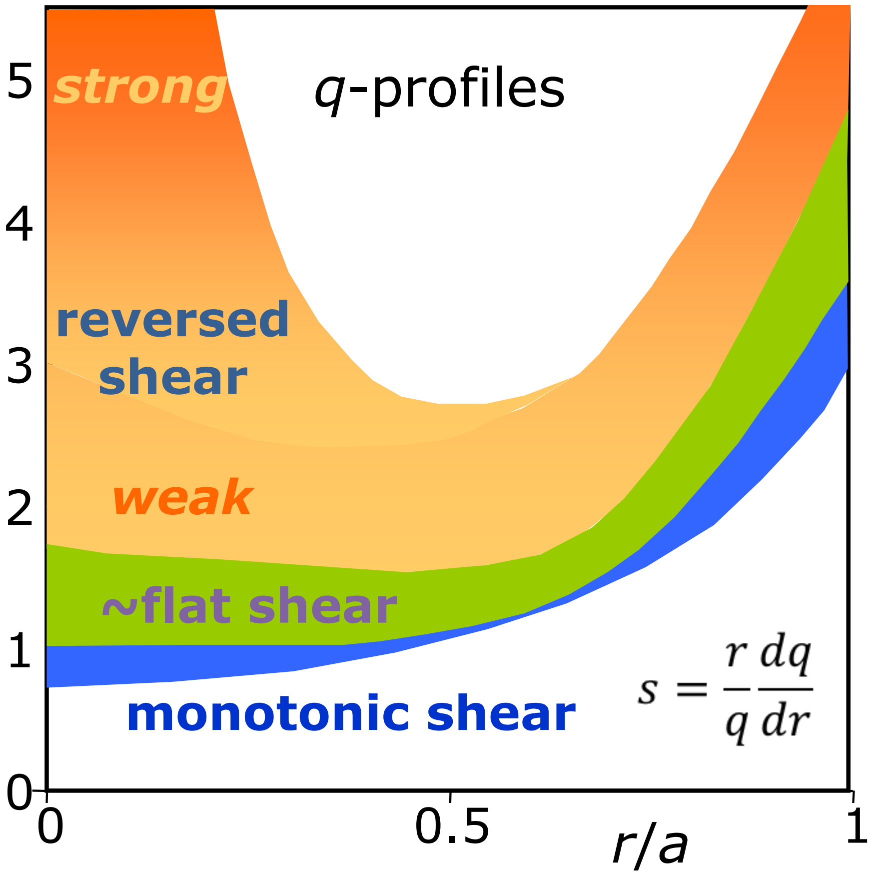


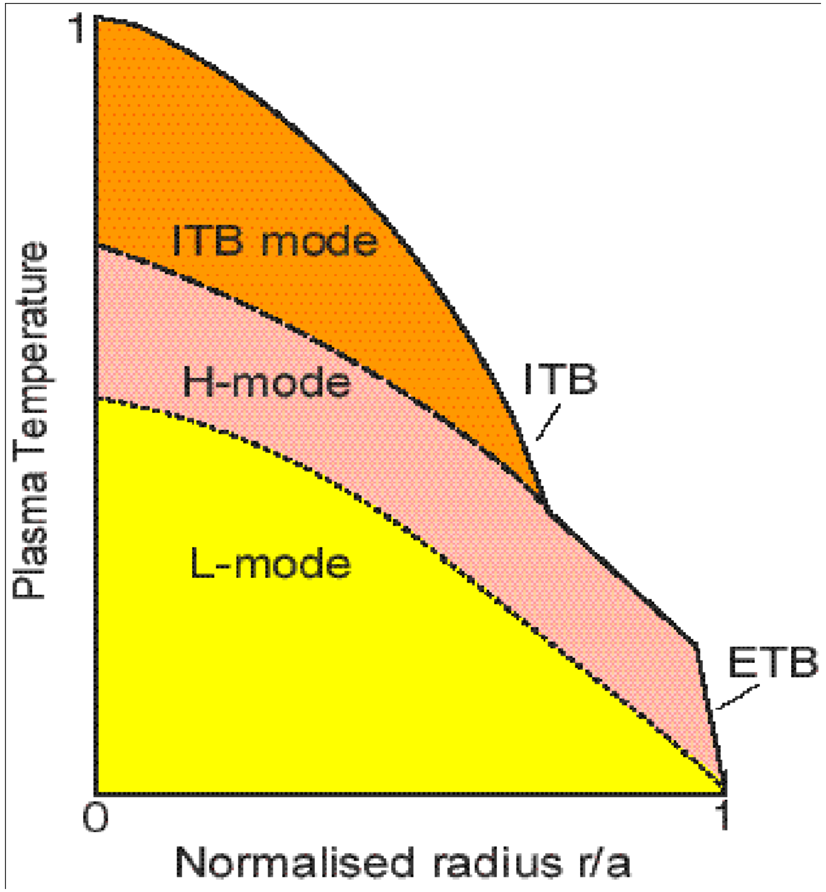
Faraday's law

$$v = -\frac{d}{dt}\int B \cdot ds$$

Cannot reach steady state (producing continuous fusion power by fully non-inductive operation)!

How to overcome?





Play with current and pressure profiles using your items (coils, fueling, H&CD, etc)!

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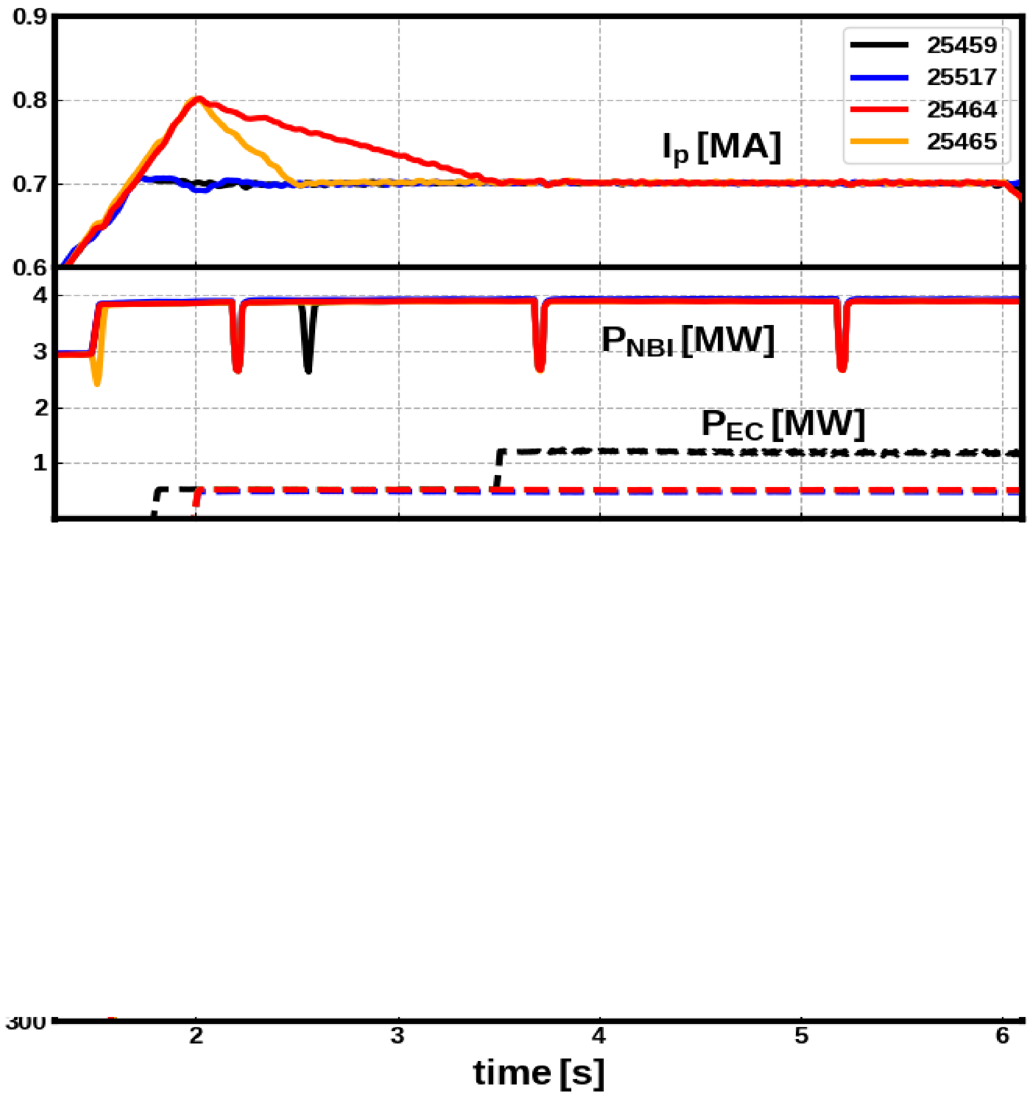
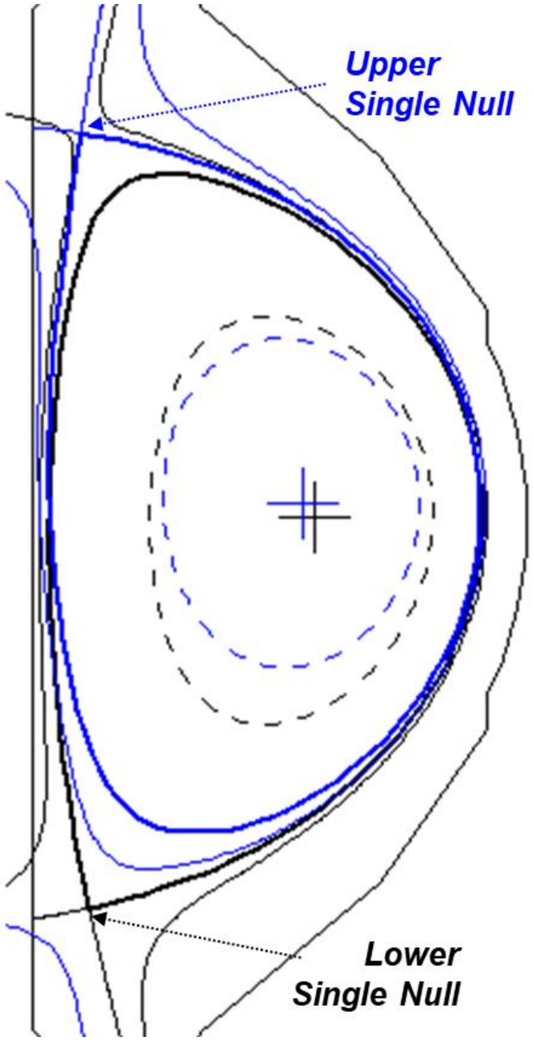
How to overcome?

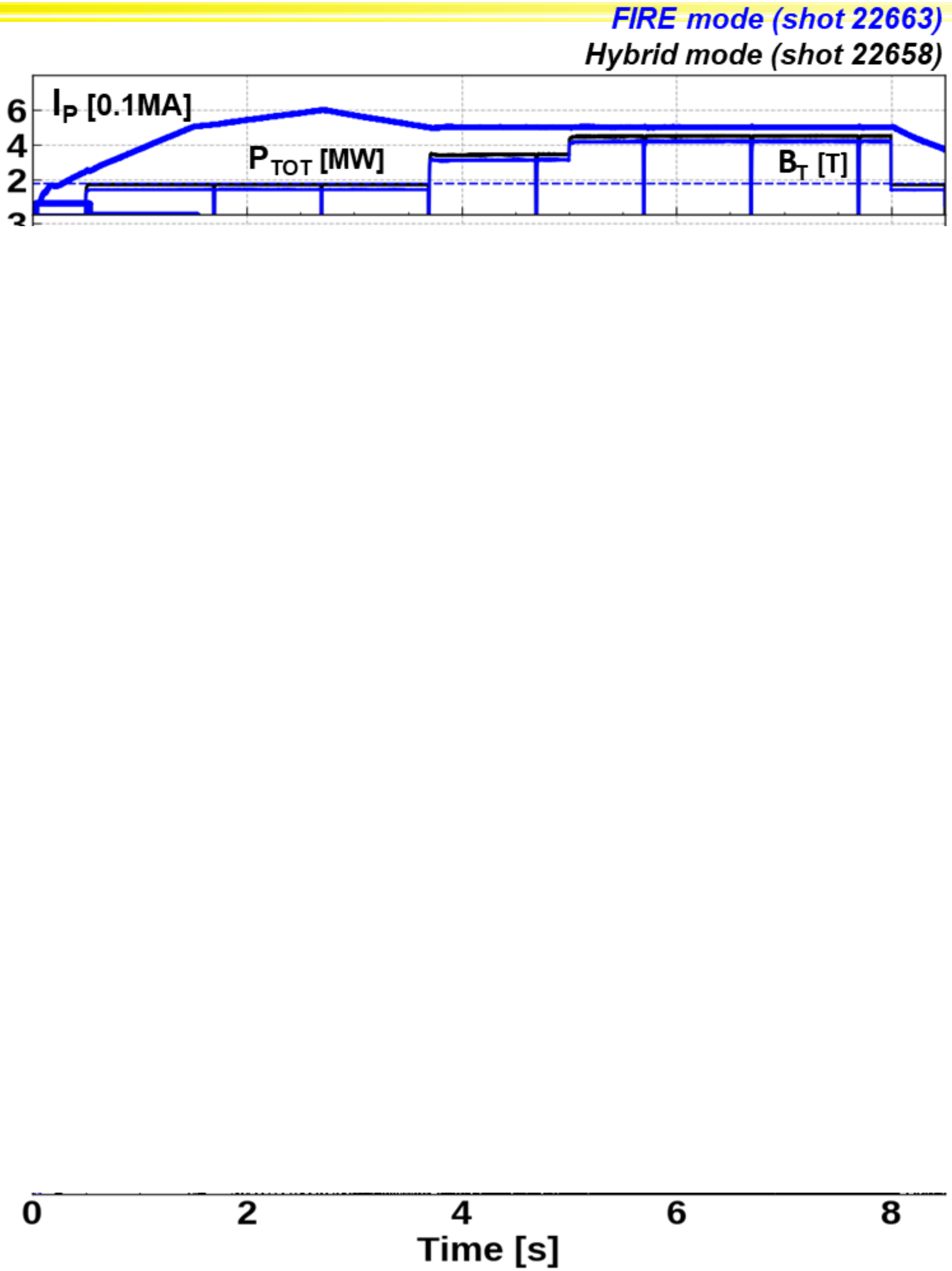


Plasma current overshoot

⇒ J. Mailloux, this school

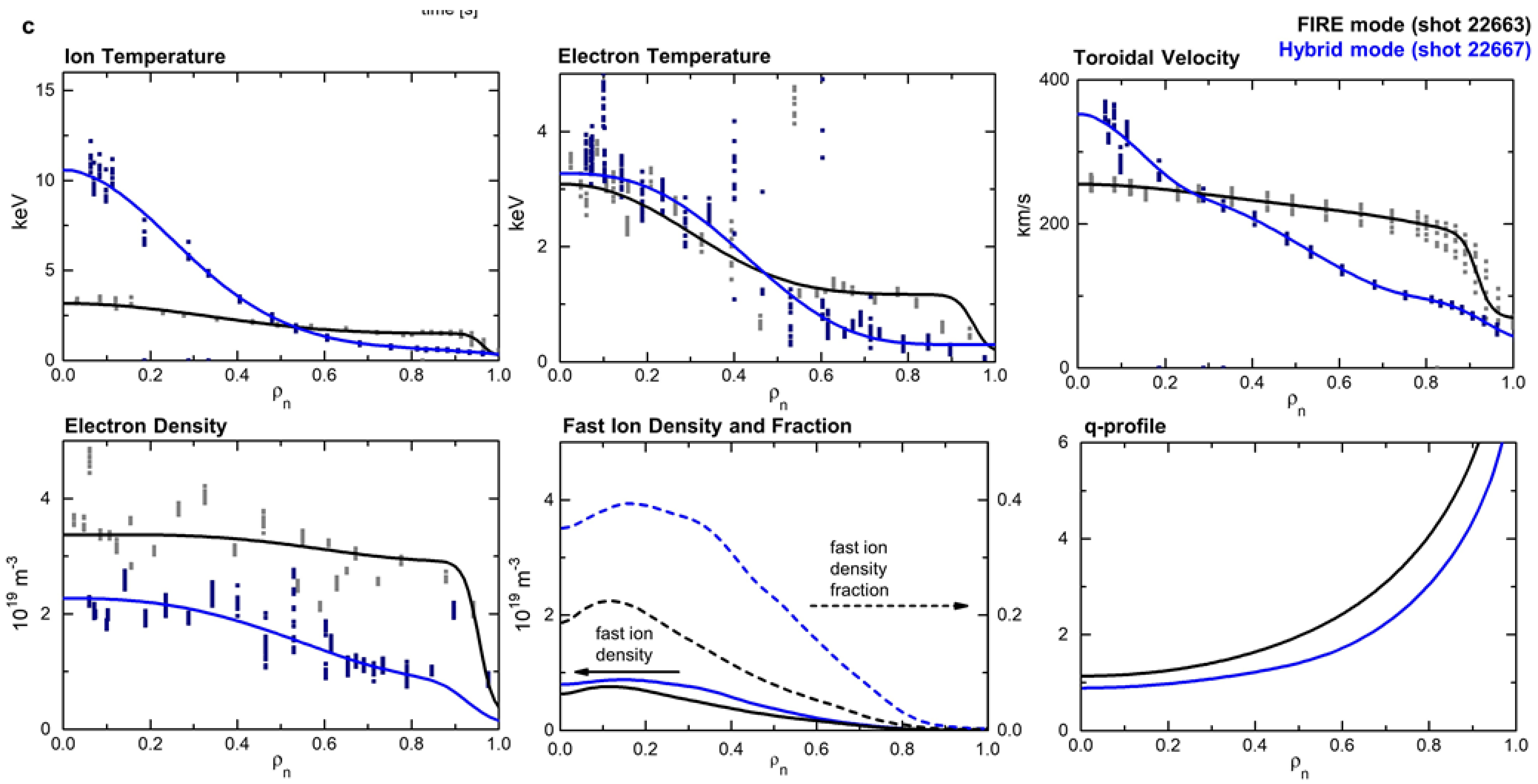
How to overcome?





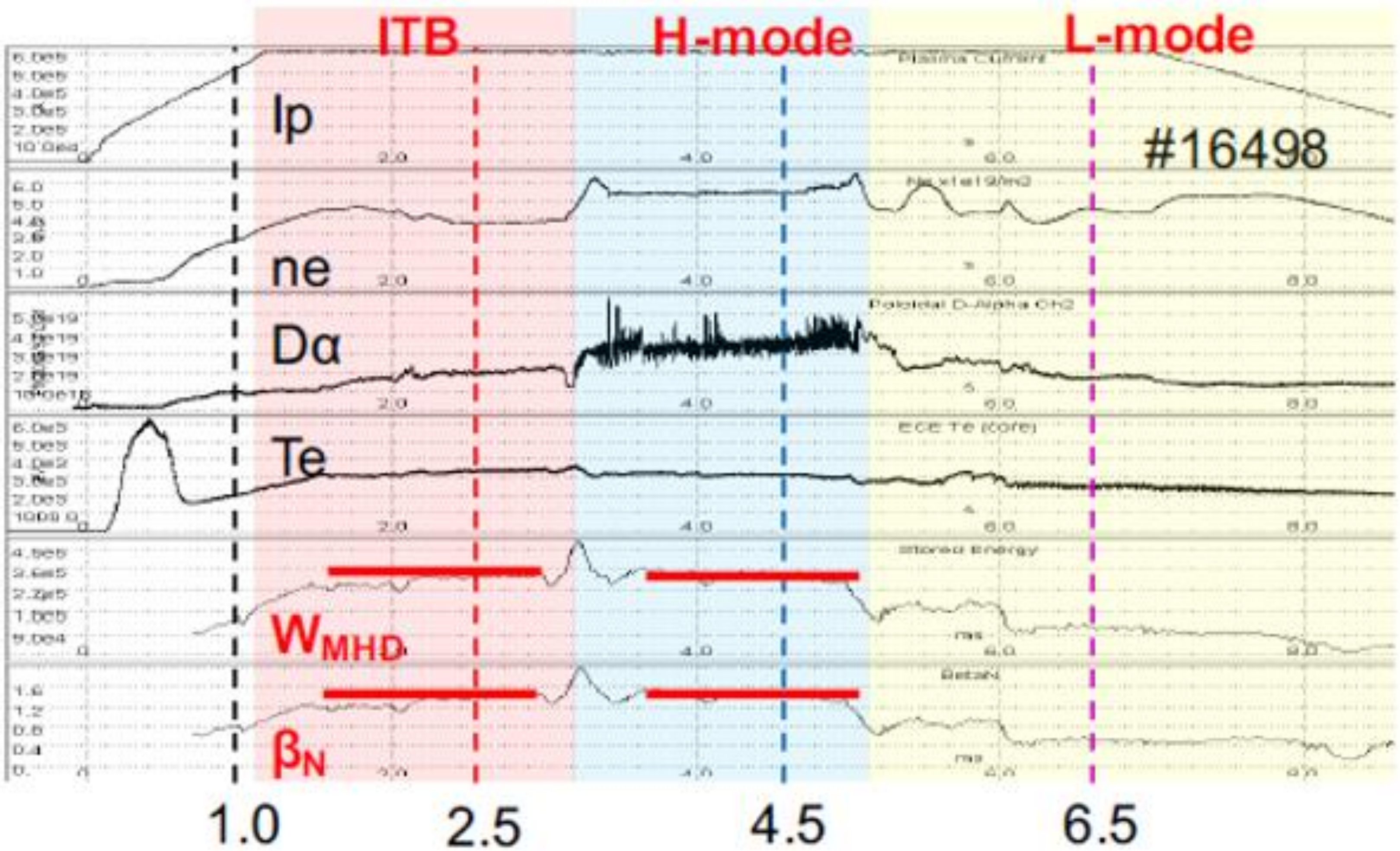
H. Han, S.J. Park, and Y.-S. Na et al., Nature in press (2022)

How to overcome?



H. Han, S.J. Park, and Y.-S. Na et al., Nature in press (2022)

How to overcome?



The plasma performance can be completely changed with the operation scenario even at the same I_p, B_t, P_{aux}, etc.

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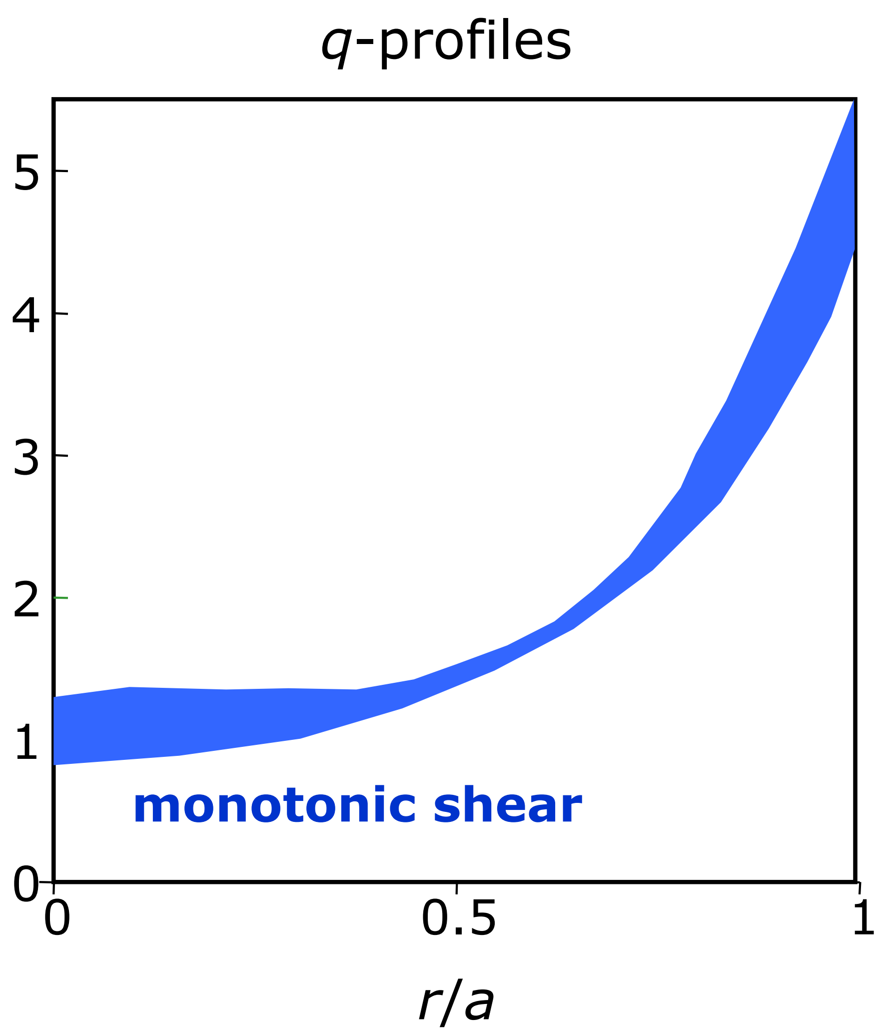
Monotonic shear – High l_i mode

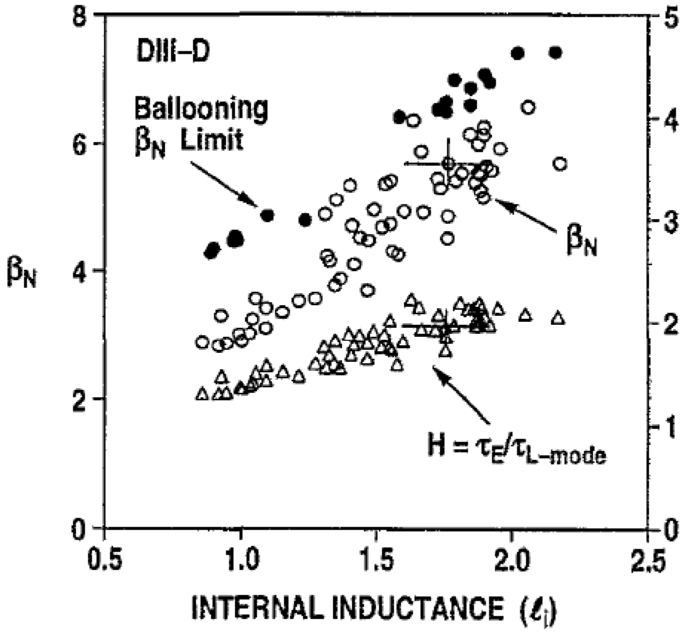


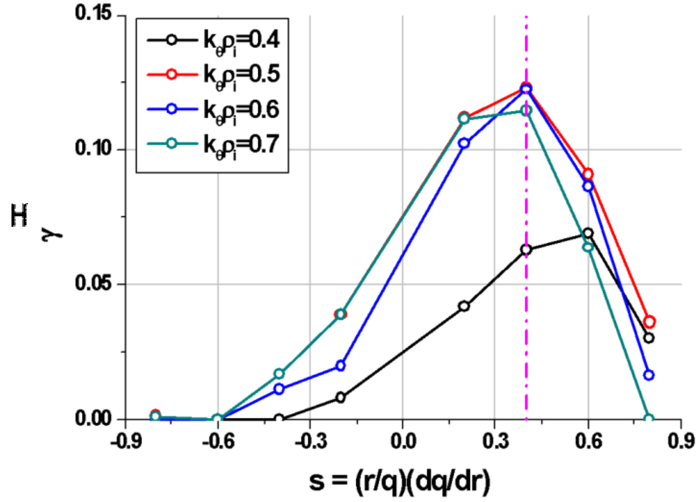
Rationale: $\beta_{N,max}$ ~ $4l_i$

Figure of merit 1: β_N, H_{98}

Figure of merit 2: f_{bs}

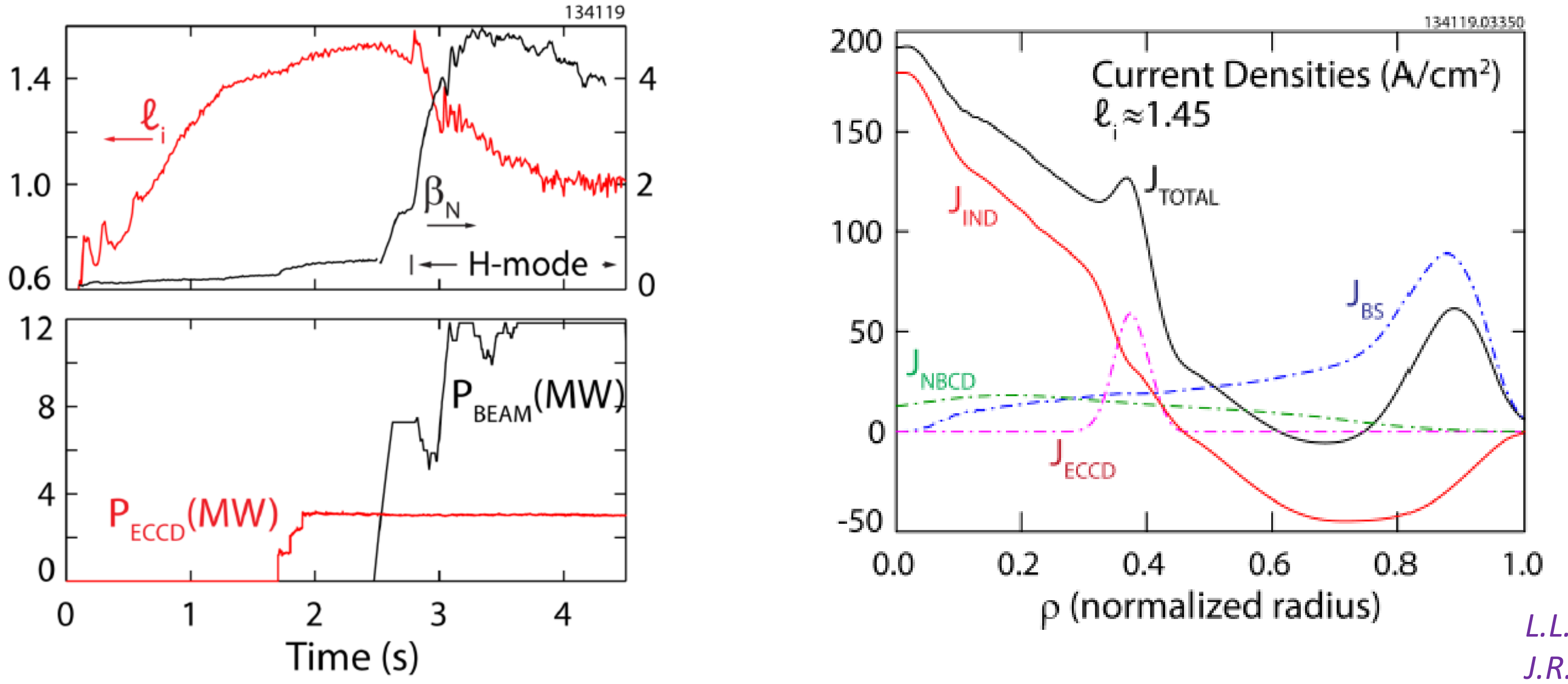
$$f_{bs} \propto \beta_{pol} \propto \beta_N B/I \propto \beta_N q_{95}$$





*E. J. Strait, Phys. Plasmas **1** 1415 (1994)*

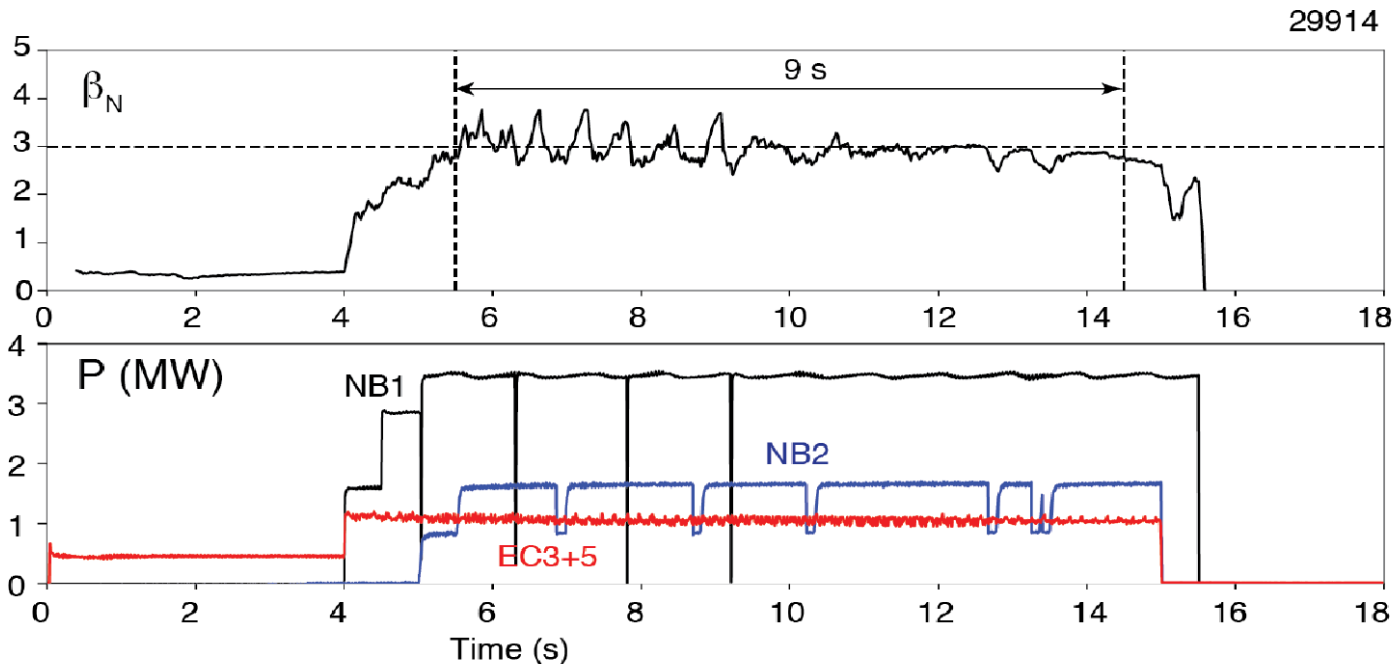
Monotonic shear – High l_i mode



*L.L. Lao et al, PRL **70** 3435 (1993)*
*J.R. Ferron et al, NF **55** 073030 (2015)*

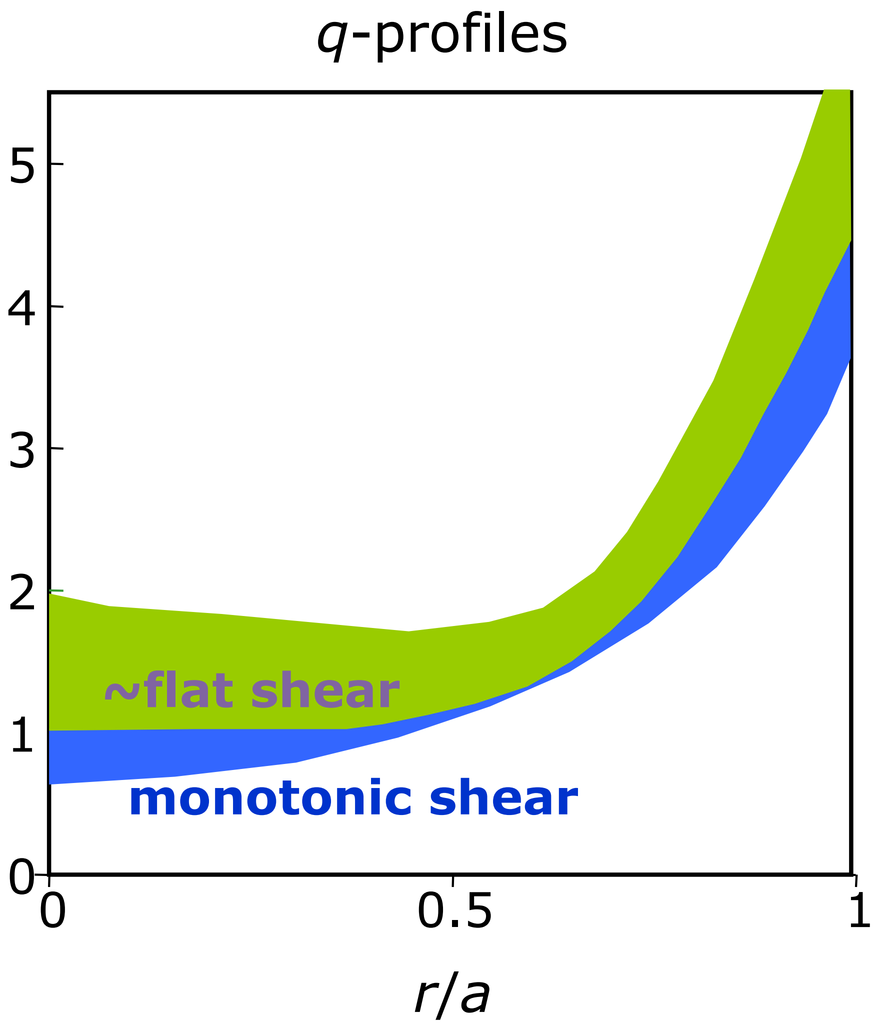
- A long Ohmic phase to allow current to penetrate to the axis
- No need for heating during the ramp-up
- ECCD to raise T_e to freeze in the inductive current ($q_{min} \sim 1$)
- β_N maintained above 4, confinement well above H-mode
- After H-mode transition, increased bootstrap current → reduced l_i
- Confinement and β_N vary as the current profile evolves.

Monotonic shear – High l_i mode



- β_N ~3 maintained aboout 10 s

~Flat shear

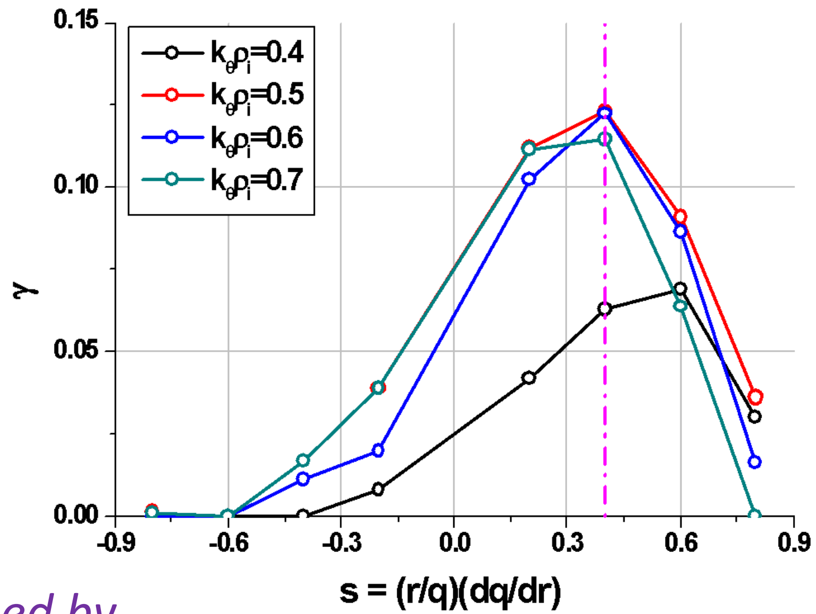


Rationale: mitigate sawtooth
reduce I_p

Figure of merit 1: β_N, H_{98}

Figure of merit 2: f_{bs}

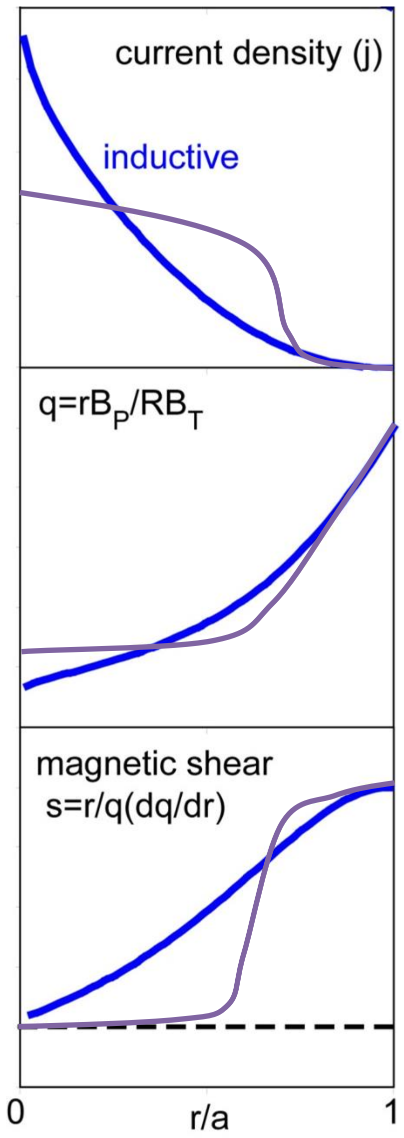
$f_{BS} \propto \beta_p \propto q_{95} \propto 1/I_p$

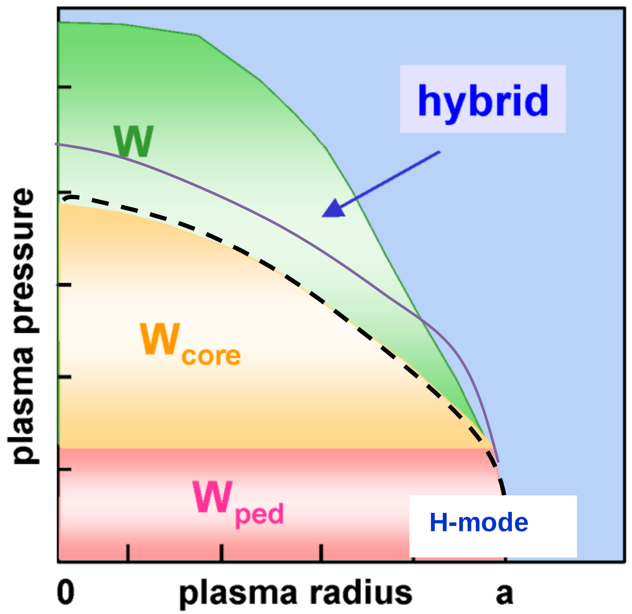


Proposed by
M. Kikuchi et al, NF 30 265 (1990)
A.C.C. Sips et al, PPCF 44 B69 (2002) and others

PLARE

~Flat shear

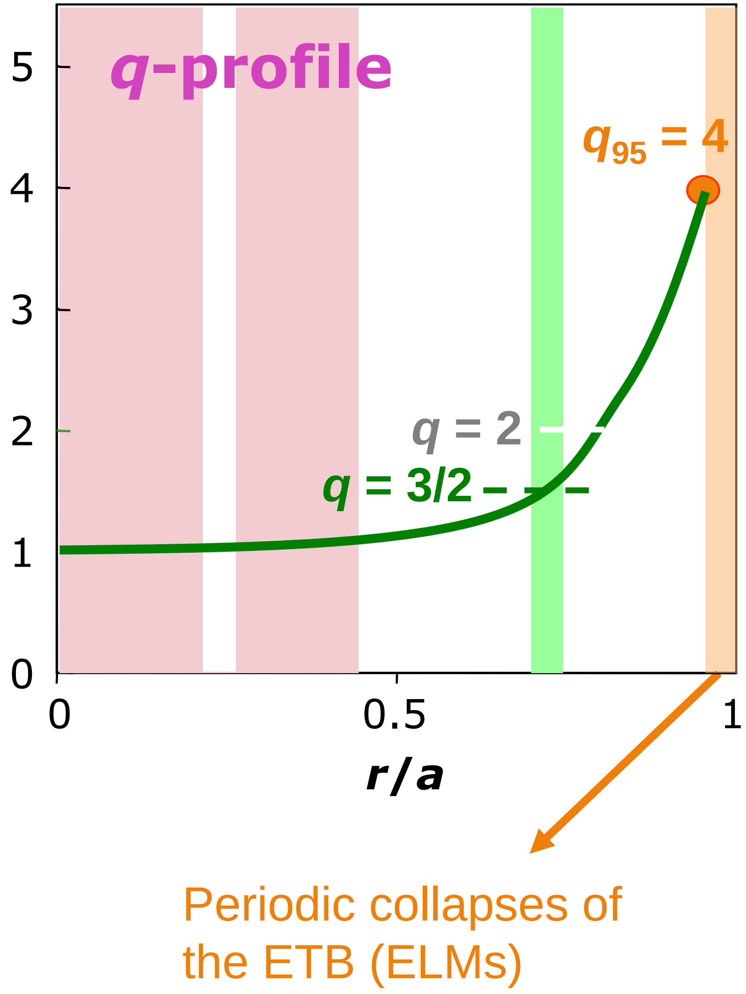




- Flat or slightly hollow central current profile
- Flat or slightly reversed central q-profile with $q_0 \sim 1$

- Higher pedestal pressure and/or steeper core pressure → higher bootstrap current $J_{BS} \propto \nabla p$

~Flat shear



q_0 ~ 1: generally no sawtooth,
sometimes with fishbones
(clamp q-profile)

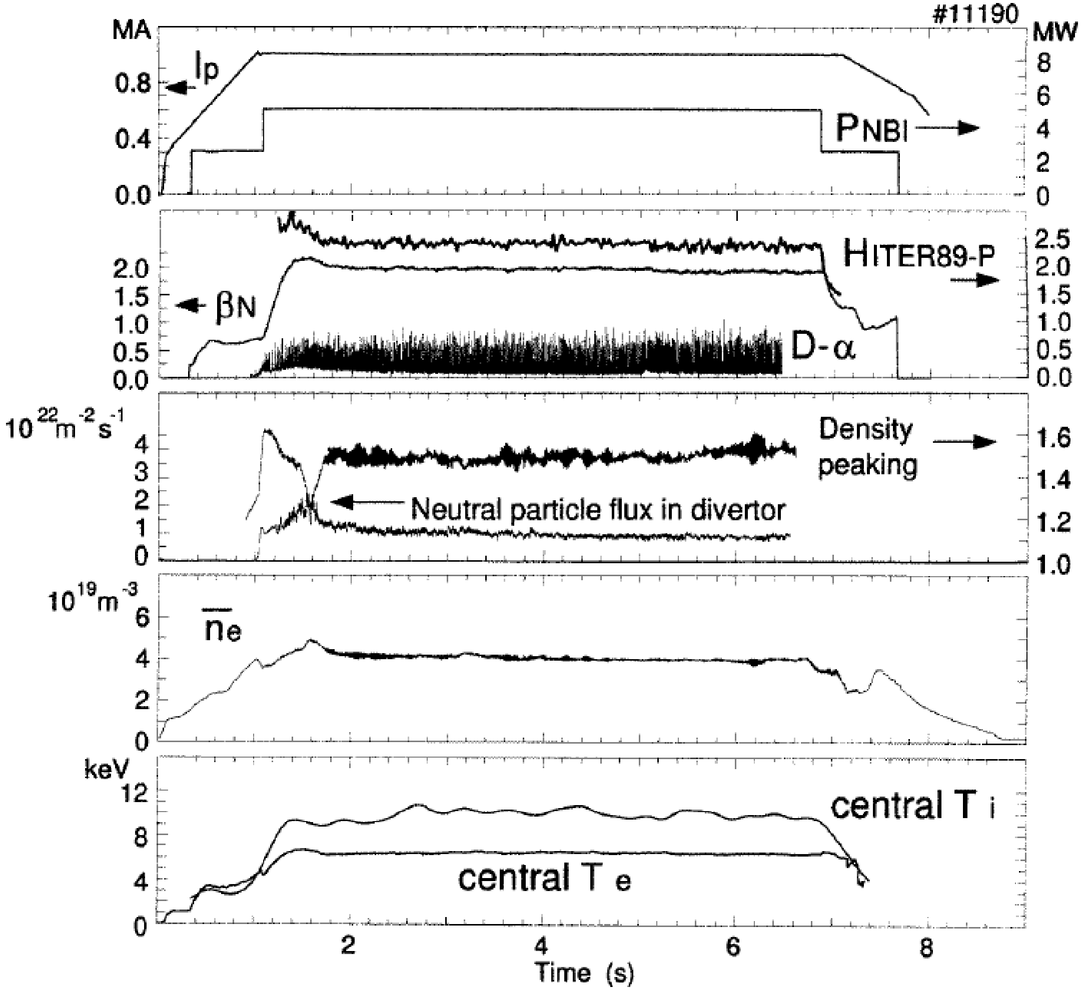
q = 3/2: 3/2 (N)TM
- clamp q-profile

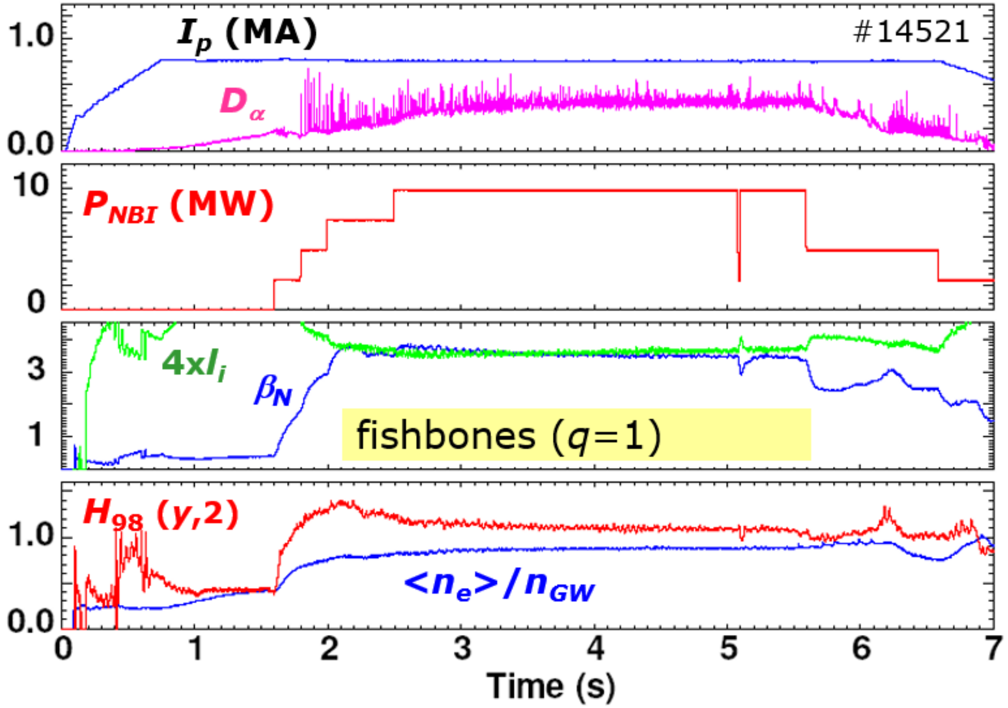
q = 2: 2/1 (N)TM
- limit the achievable β_N
- degrade confinement (+ disruptions)

Note) benign NTM activities due to FIR (Frequently Interrupted Mode)*

*S. Guenter et al, **87** 275001 PRL (2001)

Flat shear – Hybrid (Advanced Inductive) mode

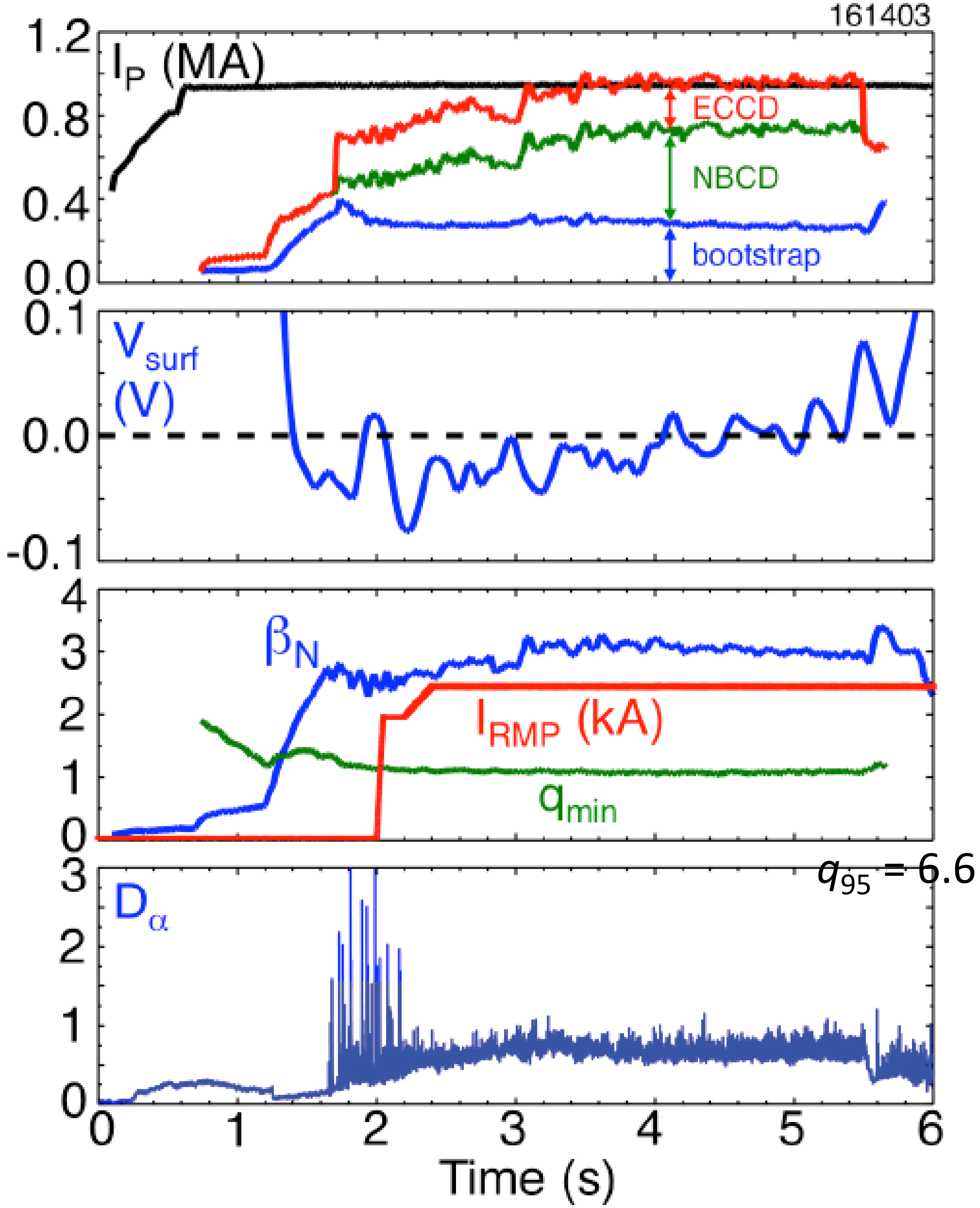




O. Gruber et al, PRL ***83*** *1787 (1999)*
A.C.C. Sips et al, PPCF ***44*** *B69 PPCF (2002)*

- High performance achieved with late as well as early heating
- **Well-reproduced in various devices, no delicate control needed.**
- Stationary *q*-profile sustained (by flux pumping (3/2 TM), fishbones, etc).

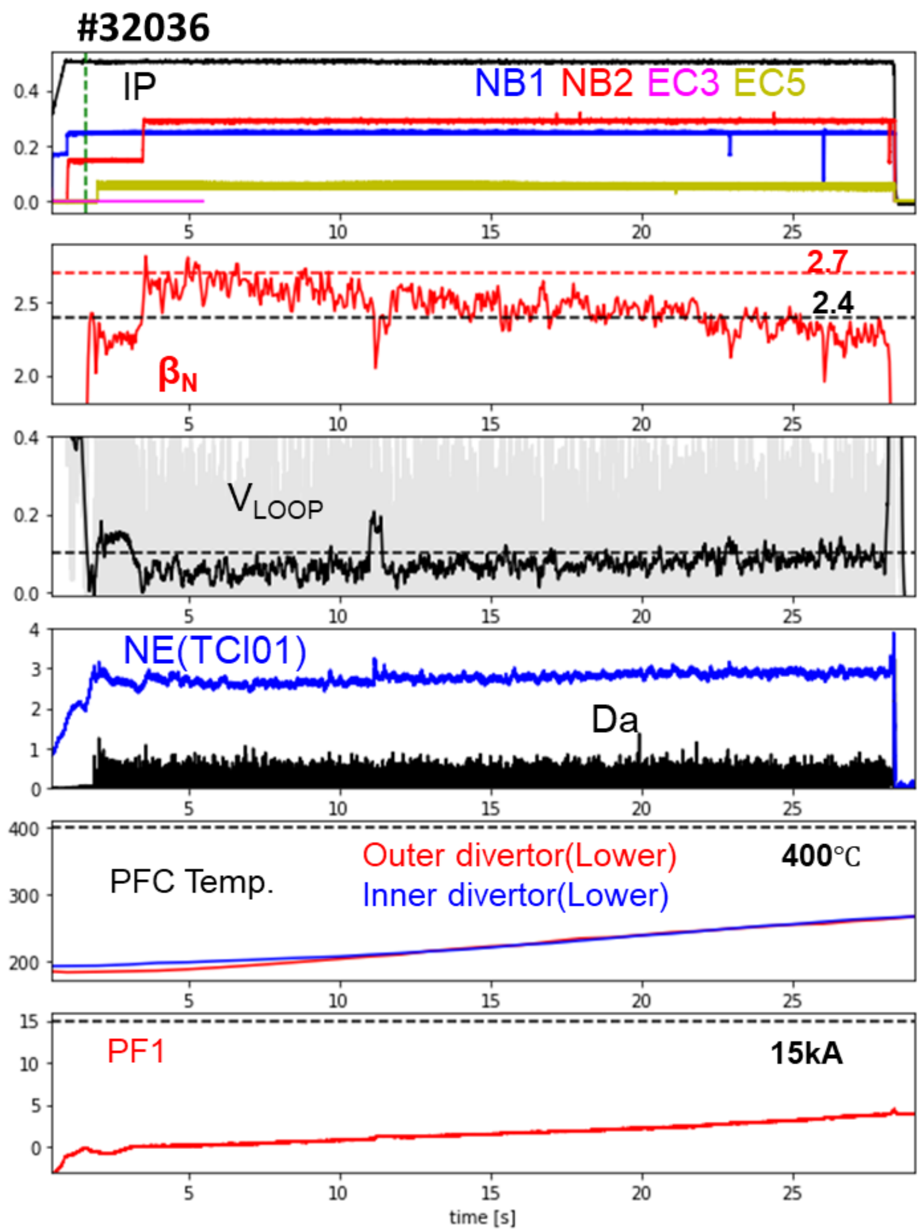
Flat shear – S-S Hybrid (Advanced Inductive) mode

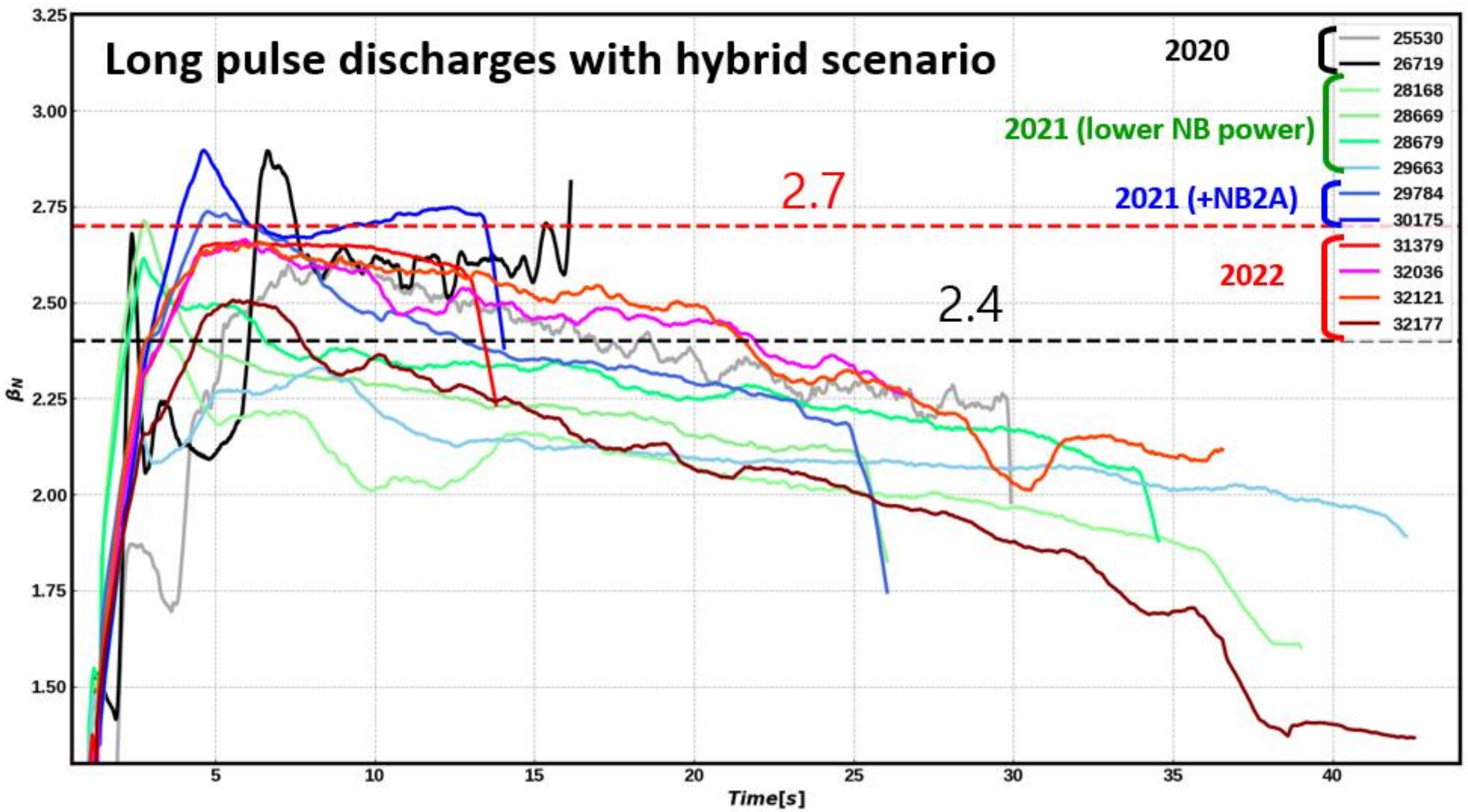


- **Fully non-inductive** obtained with $\beta_N \leq 3.7$ as FNSF-AT target
- Achieved by going to $\beta_p \geq 1.9$ and using all available ECCD power near the axis (efficient ECCCD)
- 3/2 TM redistributes current outward and avoids sawteeth, even with central ECCD
- **ELM suppression with RMP** (*n*=3 from I-coil with odd parity)
- Reproducible zero loop voltage

*C.C. Petty et al. NF **57** 116057 (2017)*

Flat shear – S-S Hybrid (Advanced Inductive) mode





- **Quasy-steady state** obtained with $\beta_N \leq 2.7$ for > 20 s
- Long-pulse operation being pursued but suffering from gradual performance degradation

⇒ *S.H. Han, this school*

Flat shear – JT-60U High β_p mode

VOLUME 72, NUMBER 23 PHYSICAL REVIEW LETTERS 6 JUNE 1994

Internal Transport Barrier on $q = 3$ Surface and Poloidal Plasma Spin Up in JT-60U High-β_p Discharges

Y. Koide, M. Kikuchi, M. Mori, S. Tsuji, S. Ishida, N. Asakura, Y. Kamada, T. Nishitani, Y. Kawano, T. Hatae, T. Fujita, T. Fukuda, A. Sakasai, T. Kondoh, R. Yoshino, and Y. Neyatani

Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Naka-machi, Naka-gun, Ibaraki-ken 311-01, Japan

(Received 27 May 1993)

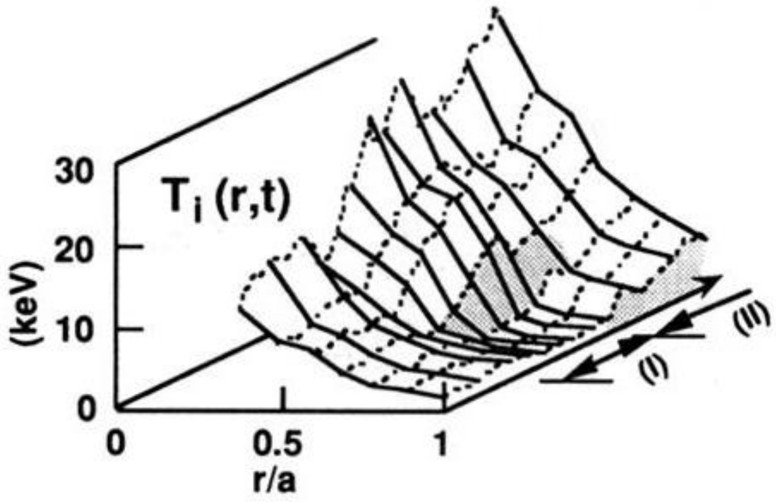
Spontaneous formation of an internal transport barrier was observed associated with improved confinement in the high-β_p discharges in the JT-60U tokamak. The radial location of the transport barrier was found to be on the $q = 3$ surface. A fast magnetohydrodynamic event localized at the transport barrier triggered the subsequent formation of an edge transport barrier that resulted in the further confinement improvement. In these discharges, a high poloidal plasma rotation velocity that significantly exceeded the prediction of the present neoclassical theory was also observed at $r/a = 0.8$.

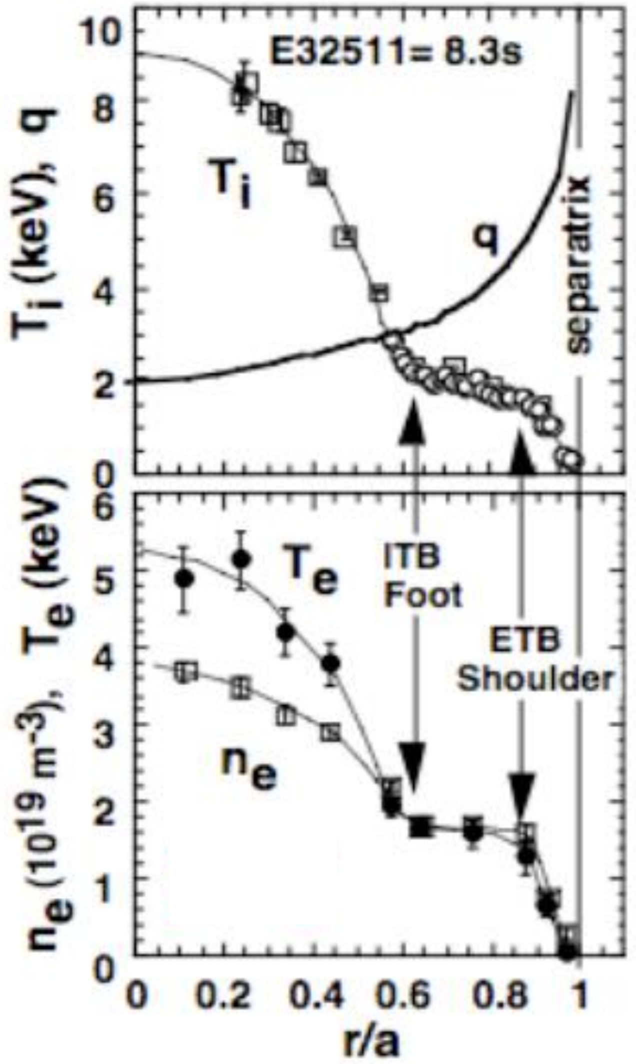
PACS numbers: 52.55.Fa, 52.25.Fi, 52.55.Pi

*Y. Koide et al, PRL **72** 3662 (1994)*

Flat shear – JT-60U High β_p mode

Tokamak operation in the high-β_p regime is a promising concept for a steady-state tokamak reactor [1,2]. Here the poloidal beta is defined as $\beta_p = 2\mu_0\langle p\rangle/B_p^2$, where $\langle p\rangle$ is the volume-averaged plasma pressure and B_p is the averaged poloidal magnetic field on the plasma surface. An energy confinement time, τ_E, more than 2 times that for L mode (for example, ITER89-P [3]) is required in the high-β_p regime to reduce the plasma current for ignition and hence to achieve efficient steady-state tokamak operation [4]. Improved confinement time was observed in the high-β_p regime ($\beta_p = 1-2$) in JT-60U where the confinement improvement factor, $\tau_E/\tau_E^{\text{ITER89-P}}$, increased with $\varepsilon\beta_p$ [5]. In this regime, the "high-β_p mode," a bootstrap-current fraction of up to 58% and a central ion temperature, $T_i(0)$, of 38 keV were achieved simultaneously. Recently the high-β_p mode regime was extented to a lower q regime ($q_{\text{eff}} \sim 4.3$; q_{eff} is the effective surface safety factor defined in Ref. [6]) by using current profile control to avoid sawteeth. And high fusion performance was attained in this regime [7,8]. This Letter describes two distinctive features of this high-β_p mode: (1) the formation of an "internal" transport barrier near the $q = 3$ rational surface and (2) the appearance of high poloidal plasma rotation velocity of $\sim$50 km/s in the plasma interior.

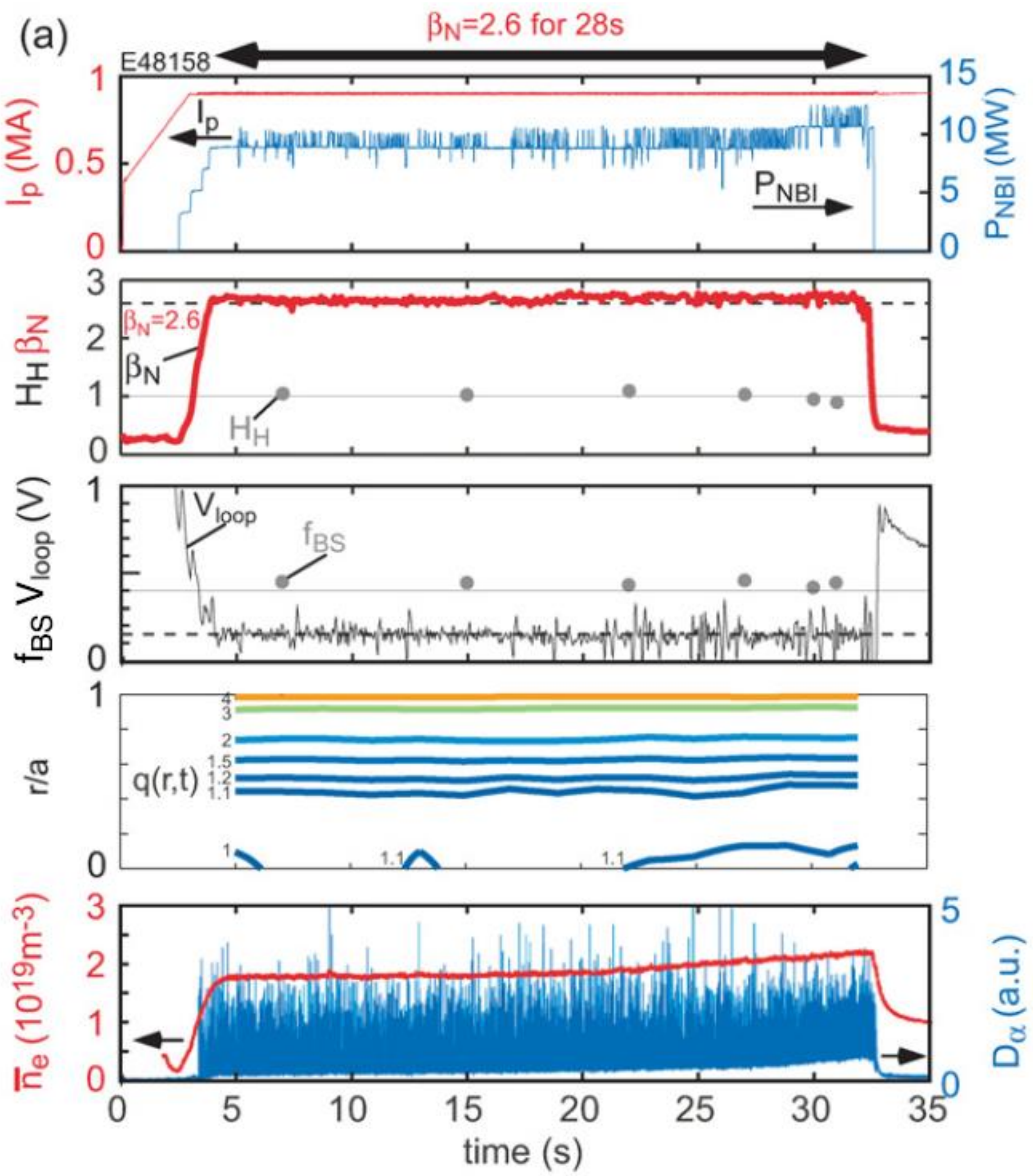




*Y. Koide et al, PRL **72** 3662 (1994)*

*Y. Kamada, PPCF **42** A65 (2000)*

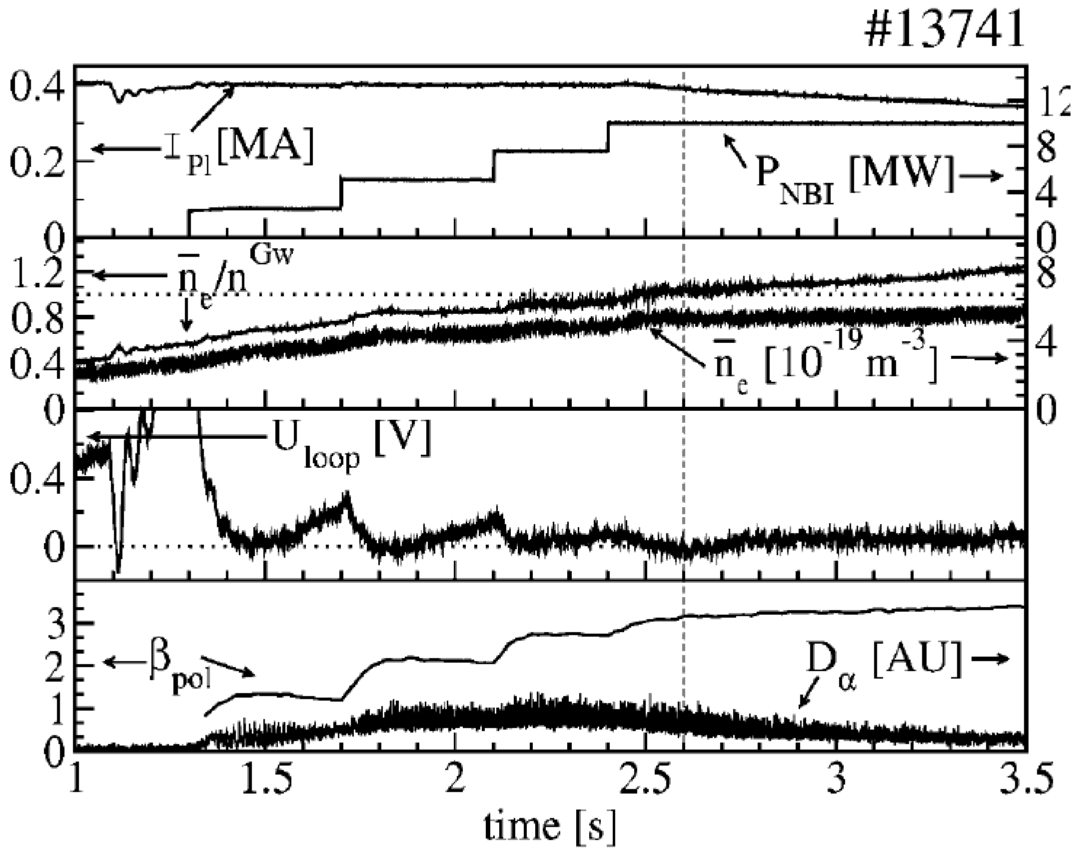
Flat shear – JT-60U High β_p mode (Hybrid mode)

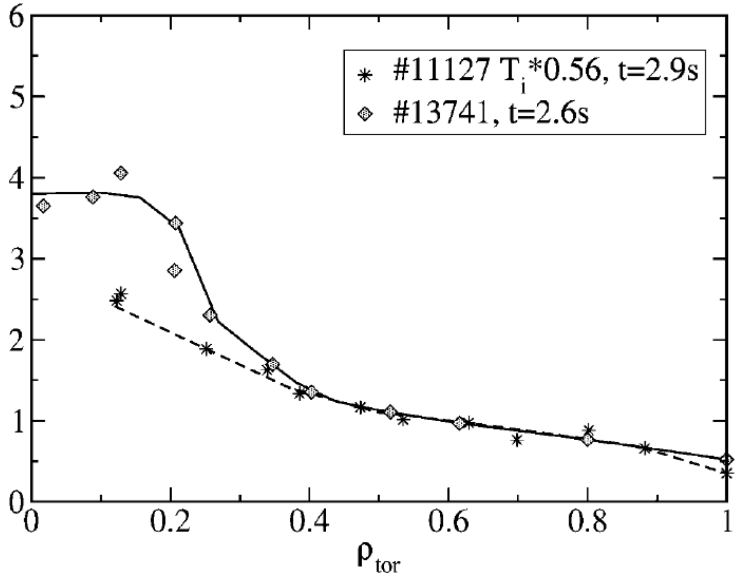


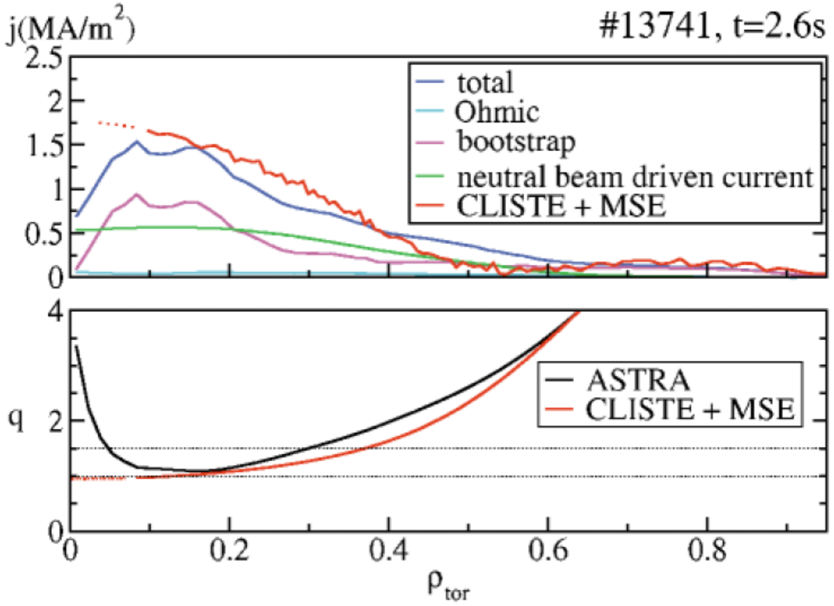
- Long pulse hybrid scenario based on high β_p ELMy H-mode plasmas **with weak ITB** (I_P = 900 kA, B_T = 1.54 T, q_{95} ~ 3.2)
- β_N > 2.6, H_{98} ≥ 1, G ≥ 0.54, f_{BS} = 0.43 **sustained for 28 s**
- No NTMs but with infrequent sawtooth and n = 1 mode
- **Gradual confinement degradation due to wall recycling**

*N. Oyama et al, NF **49** 104007 (2009)*

Flat shear / RS – AUG High β_p mode



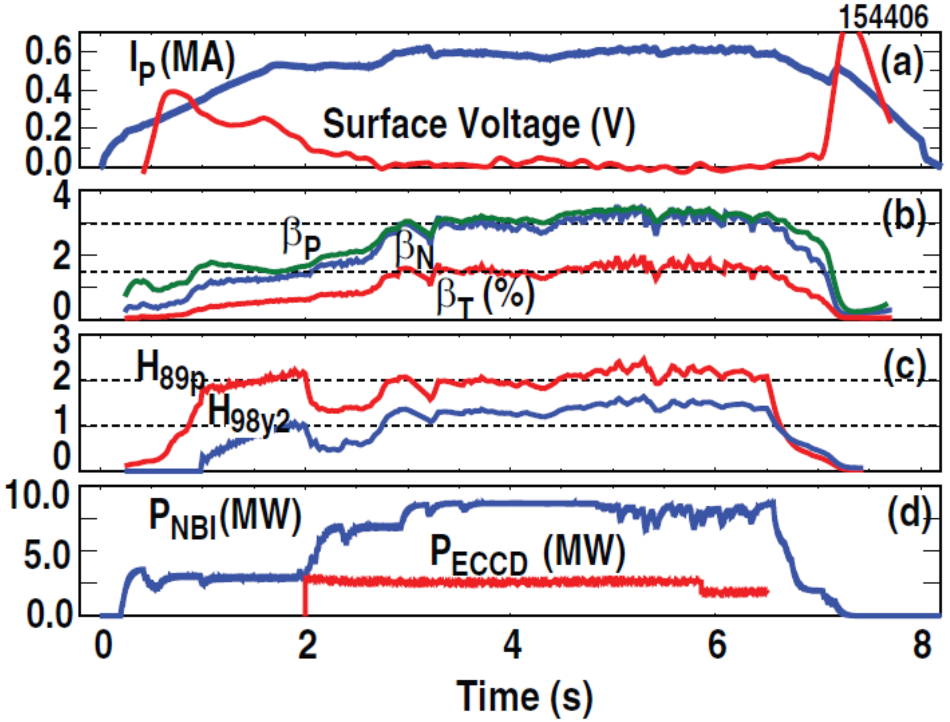


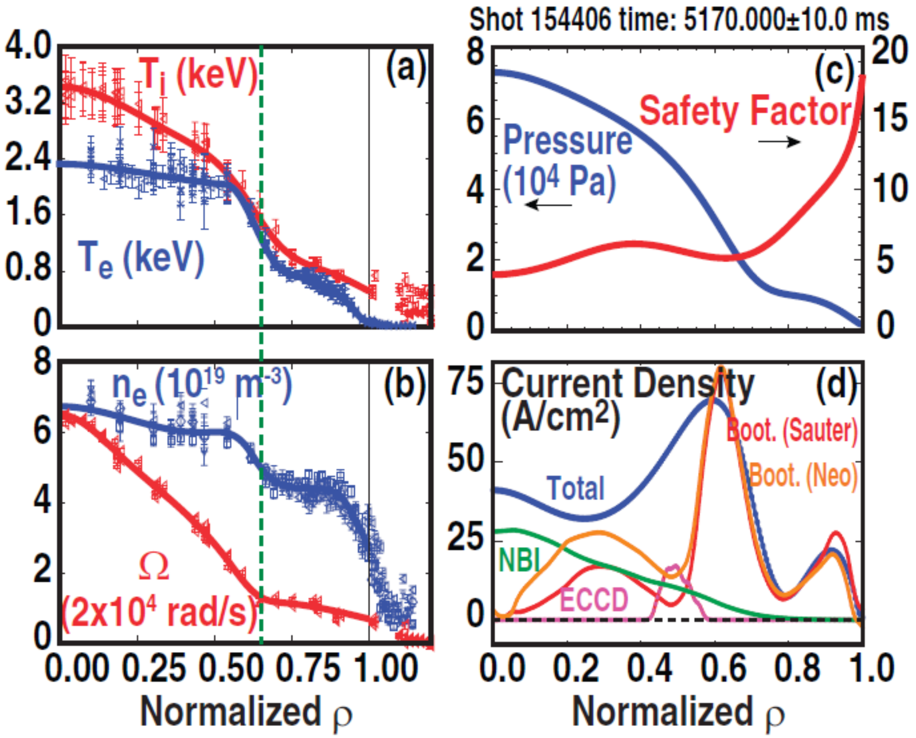


- I_P = 400 kA, B_T = 2 T, $\boldsymbol{q_{95}}$ **= 9**
- ITBs with f_{BS} = 0.51, f_{NB} = 0.43
- β_p = 3, β_N = 2.7, H_{89} ~ 1.8
- High density $\boldsymbol{f_{GW}}$ **~ 1.0**
- No confinement limiting MHD activities

J. Hobirk et al, PRL ***87*** *085002 (2001)*

Flat shear / RS – DIII-D High β_p mode

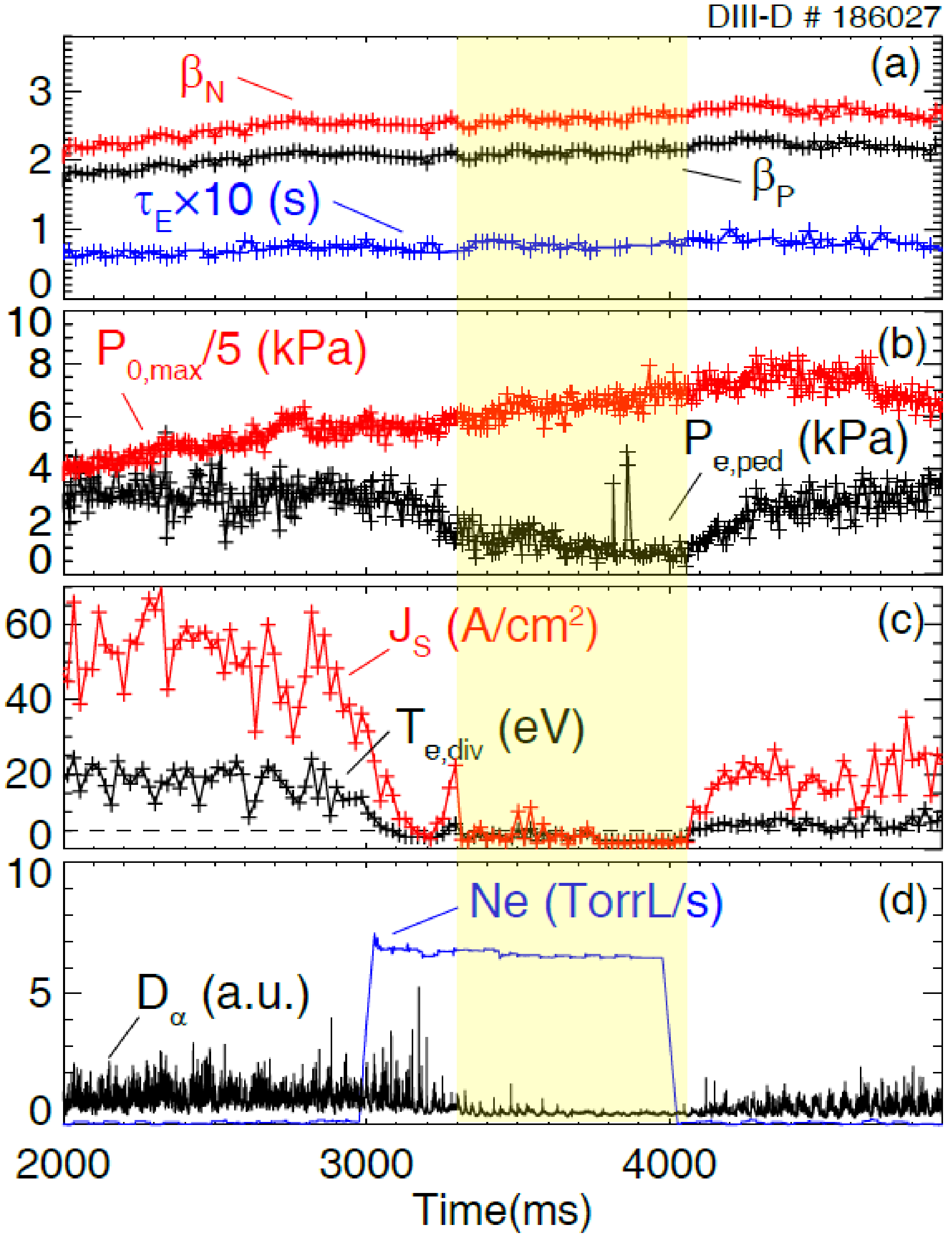




*A.M. Garofalo et al, NF **55** 123025 (2015)*

- q_{min} > 2.0 with q_{95} ~7.0-12.0
- **Broad ITBs (ρ~0.7) at f_{GW}~1.0-1.1, low NB torque < 2 Nm:**
  - low ω_{ExB} effect
  - high Shafranov shift effect
  - **No strong impurity accumulation**
- $H_{98} \geq 1.5$, $\beta_p \sim 3$, $\beta_N \sim 3$, $f_{BS} > 0.8$
- Higher performance **if AE activity and fast ion transport reduced** (below $\nabla\beta_{fast,crit.}$)

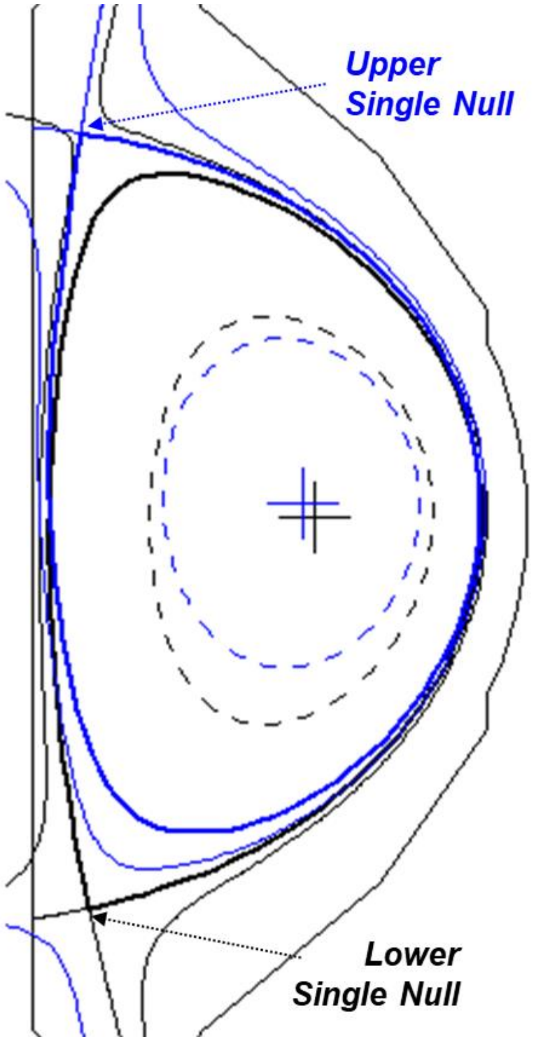
Flat shear / RS – DIII-D High β_p mode

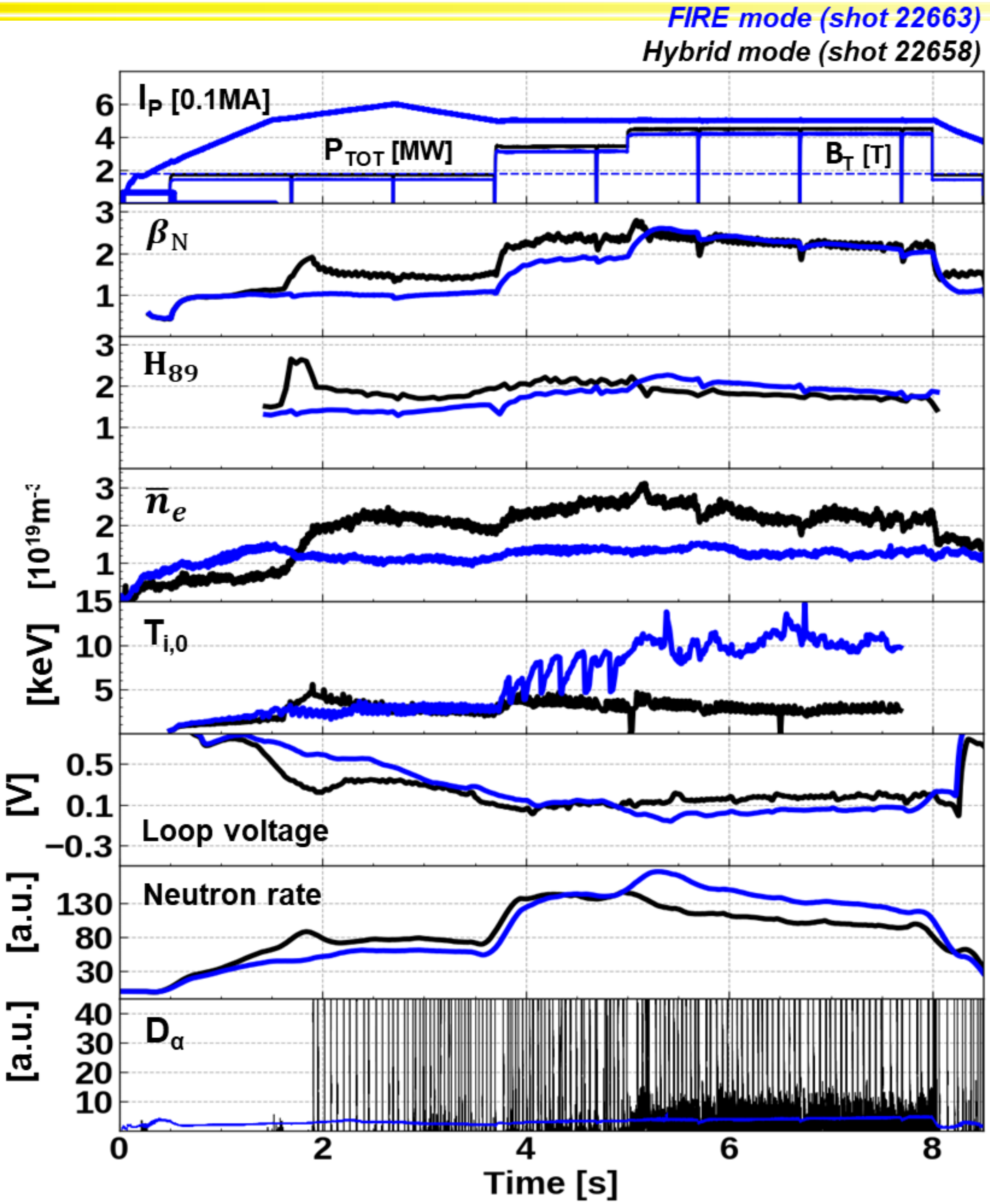


- **Full divertor detachment** with good energy confinement, H_{98} ~1.5 **(for the first time in a tokamak)**
- Pedestal pressure degraded due to detachment
- **The growing ITB** compensated the loss

L. Wang et al., Nat. Commun. ***12*** *1365 (2021)*

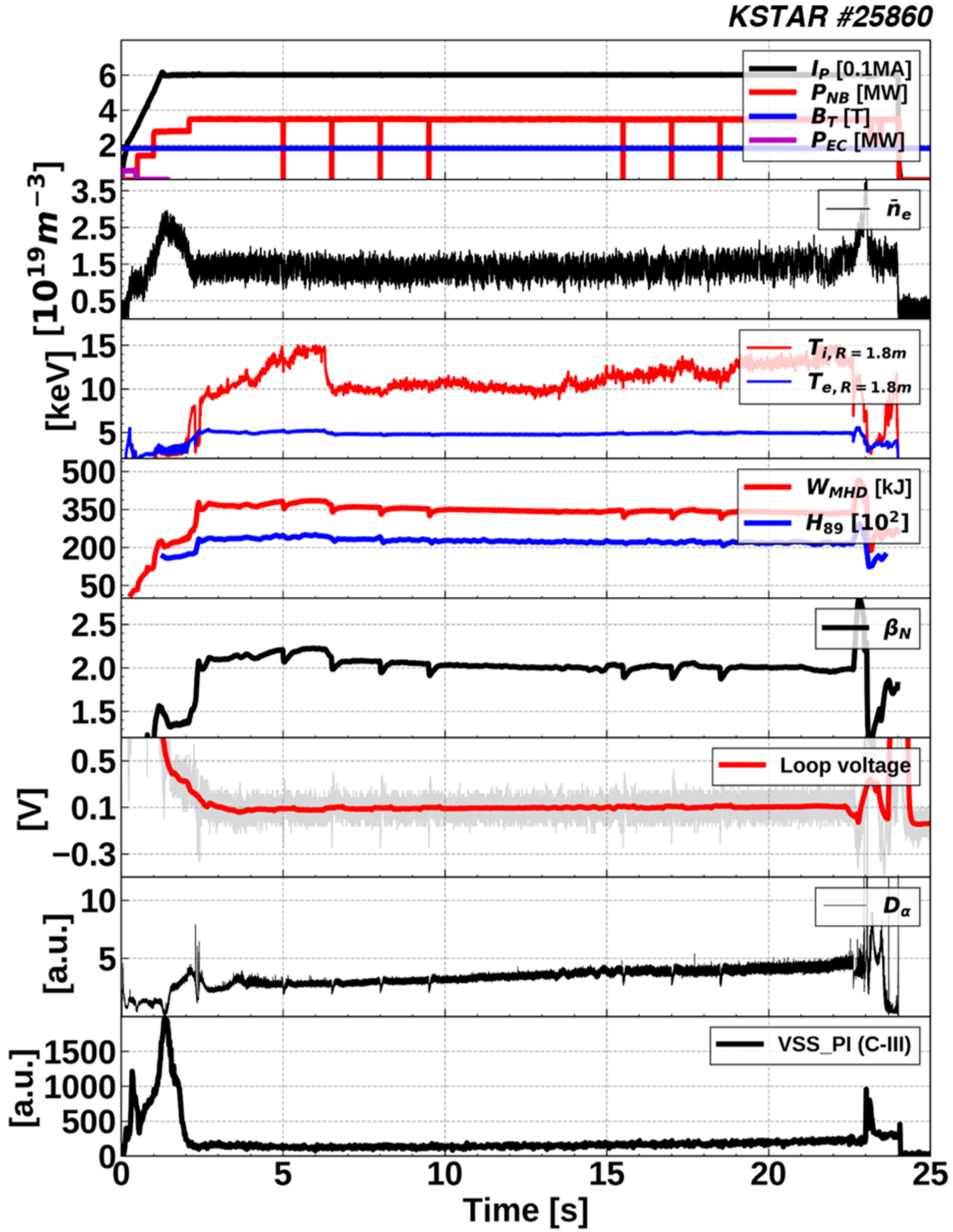
Flat shear – FIRE (Fast Ion Regulated Enhancement) mode



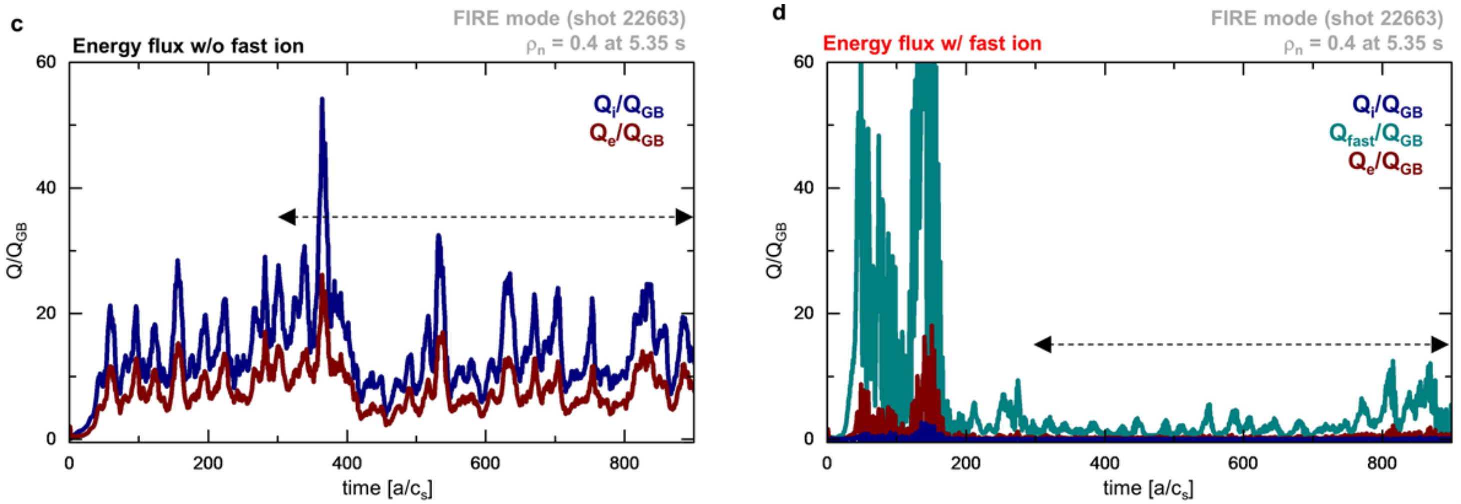


H. Han, S.J. Park, and Y.-S. Na et al., Nature in press (2022)

Flat shear – FIRE (Fast Ion Regulated Enhancement) mode



- High performance (β_N, H_{98}) **comparable to hybrid mode**
- Reduced heat load on divertor **w/O ELMs (I-mode)**
- Almost **fully non inductive** (V_{loop} < 0.1 V)
- Stationary long pulse without delicate feedback control (~30 s)
- No clear impurity accumulations
- **Stabilising turbulence by fast ions**



H. Han, S.J. Park, and Y.-S. Na et al., Nature in press (2022)

Reversed Shear

Rationale: No sawtooth, mild/no NTM
reduce I_p, ITB

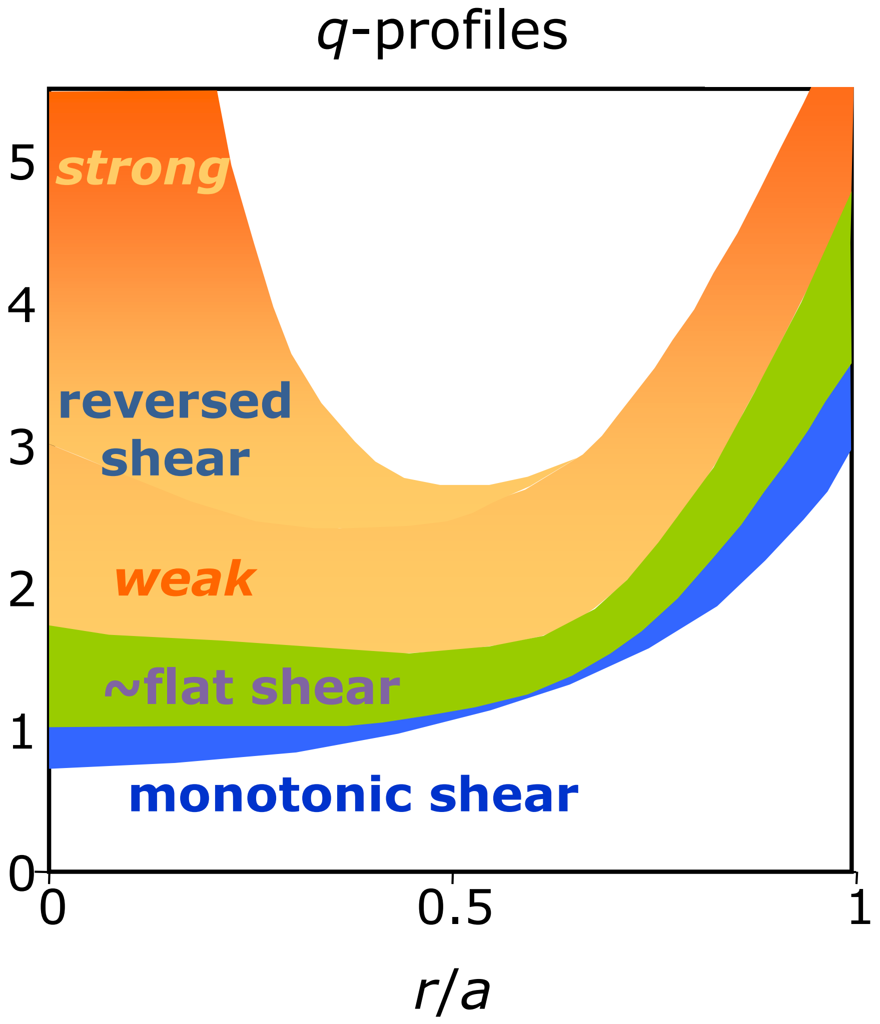
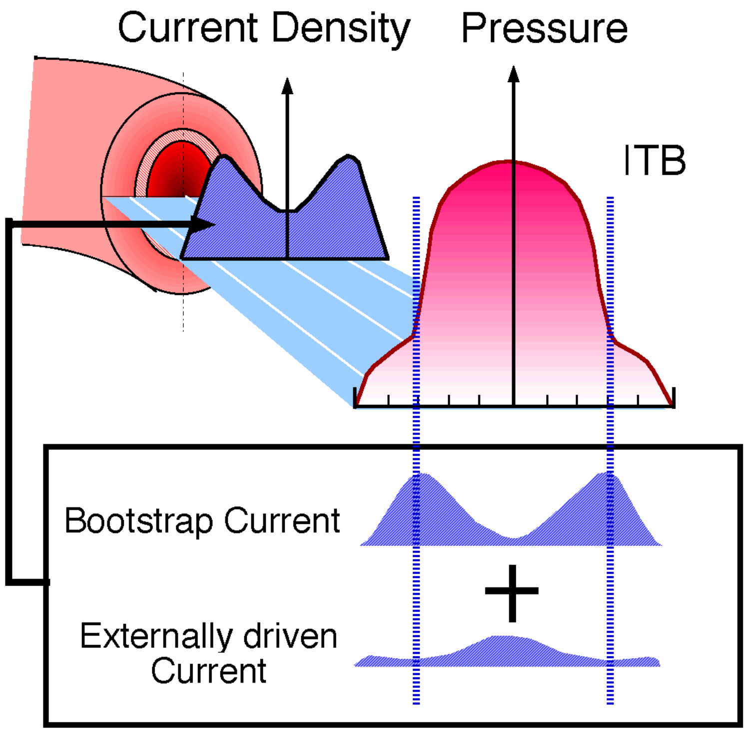


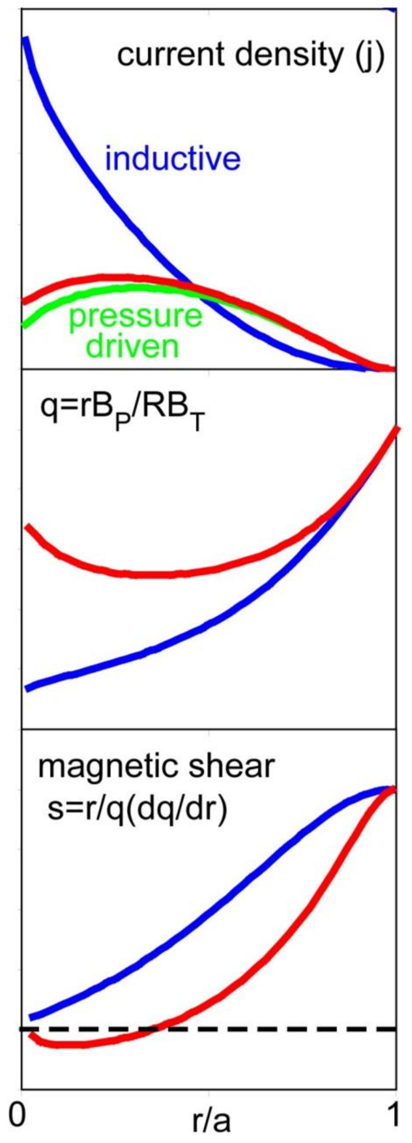
Figure of merit 1: β_N, H_{98}

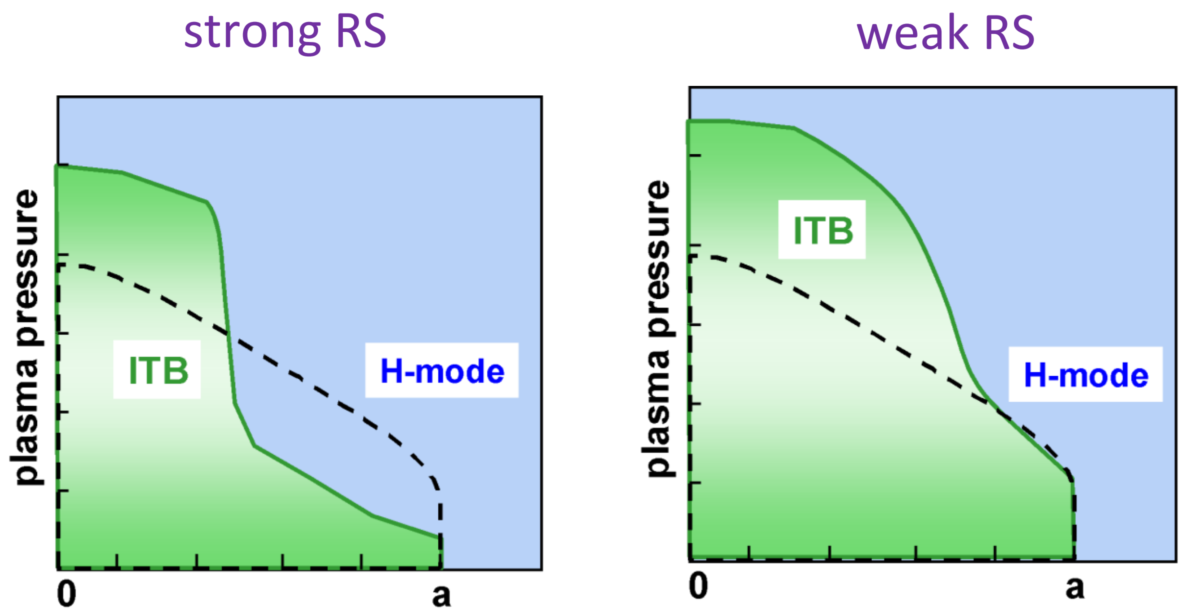
Figure of merit 2: f_{bs} $\quad f_{BS} \propto \beta_p \propto q_{95} \propto 1/I_p$



Proposed by
T. Ozeki et al IAEA-CN-56/D-4-1 (1992)
*C.E. Kessel et al, PRL **72** 1212 (1994) and others*

Reversed Shear

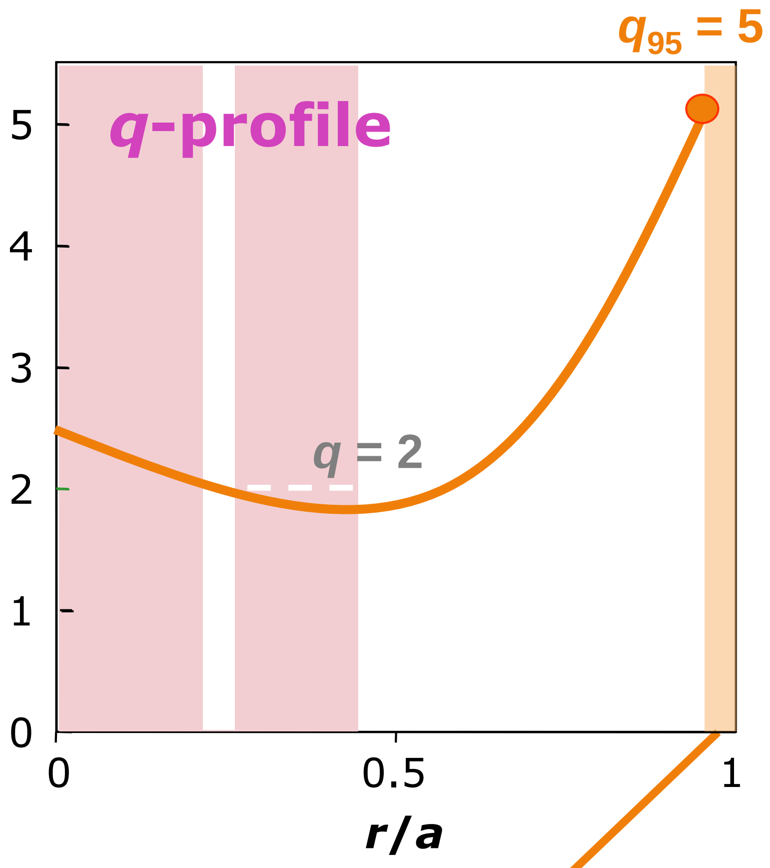




- Hollow current profile
- Reversed q-profile
- With negative magnetic shear
- Higher pressure gradient region in the core (ITB) w or w/o the edge pedestal
  - High bootstrap current
  - strong RS: good confinement, poor stability

$$J_{BS} \propto \nabla p$$

Reversed Shear



Periodic collapses of the ETB (ELMs)

No q_0 = 1: No sawtooth/fishbone

No q = 3/2: No 3/2 NTM

Negative/flat shear region:

infernal mode (low n kink-ballooning mode)

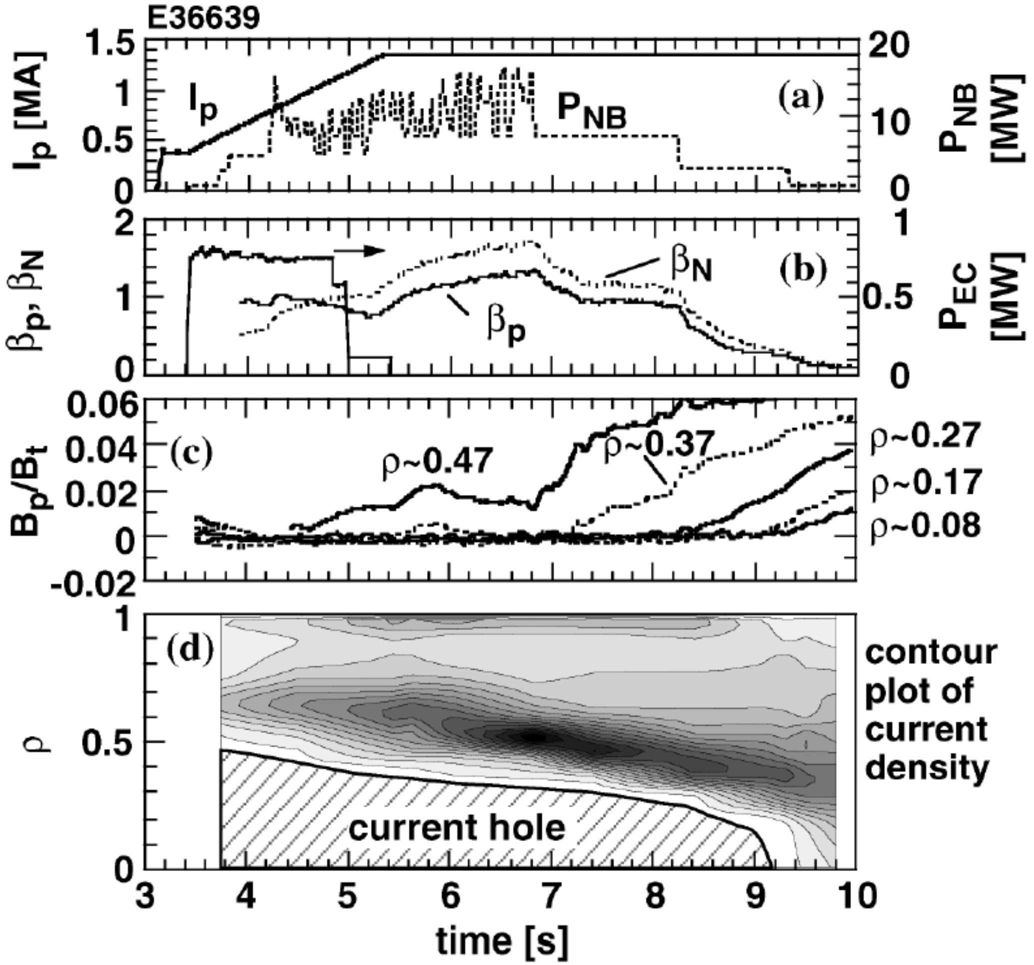
Note) no NTMs in the negative shear region

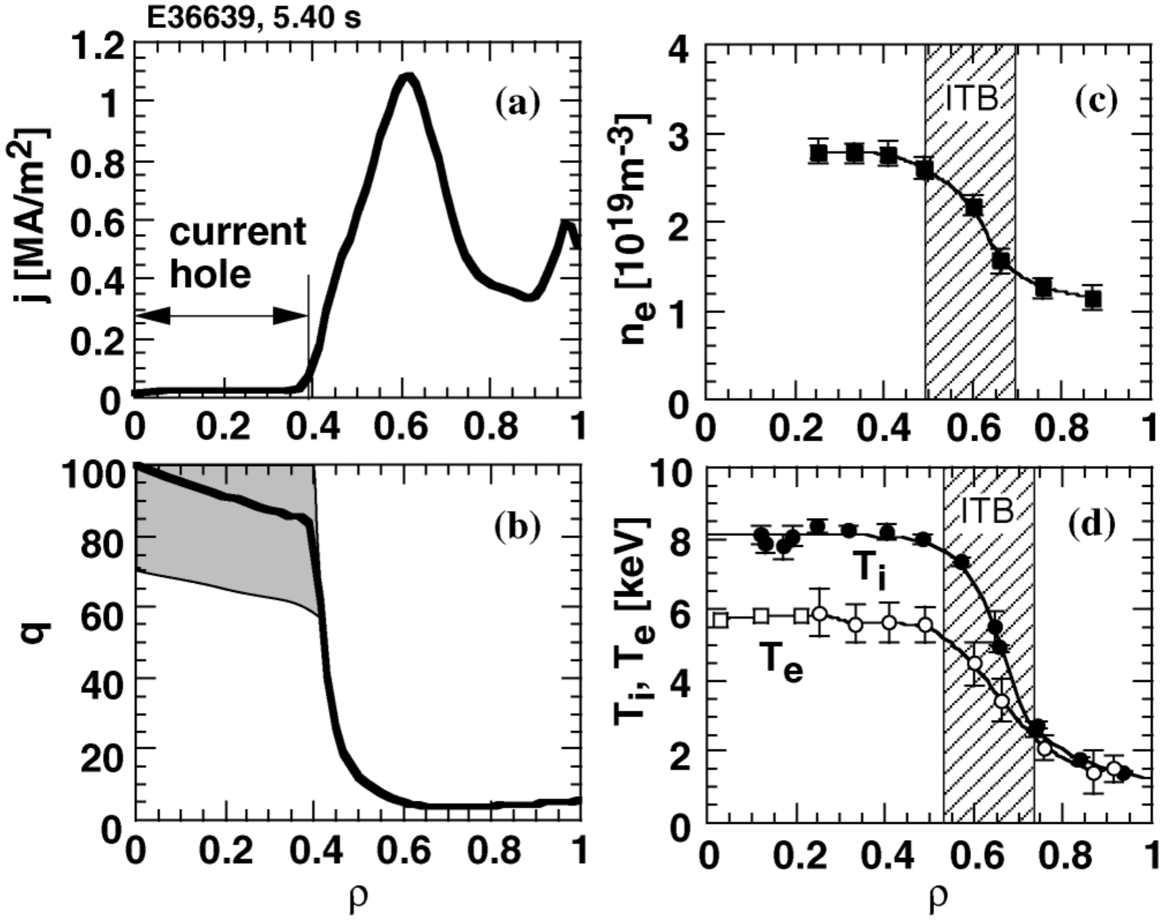
q = 2: Double tearing modes

- enhance MHD activities
- even trigger sawtooth crashes

Higher q: fast particle instabilities such as Alfven Eigenmodes

Strong RS – Current Hole Regime

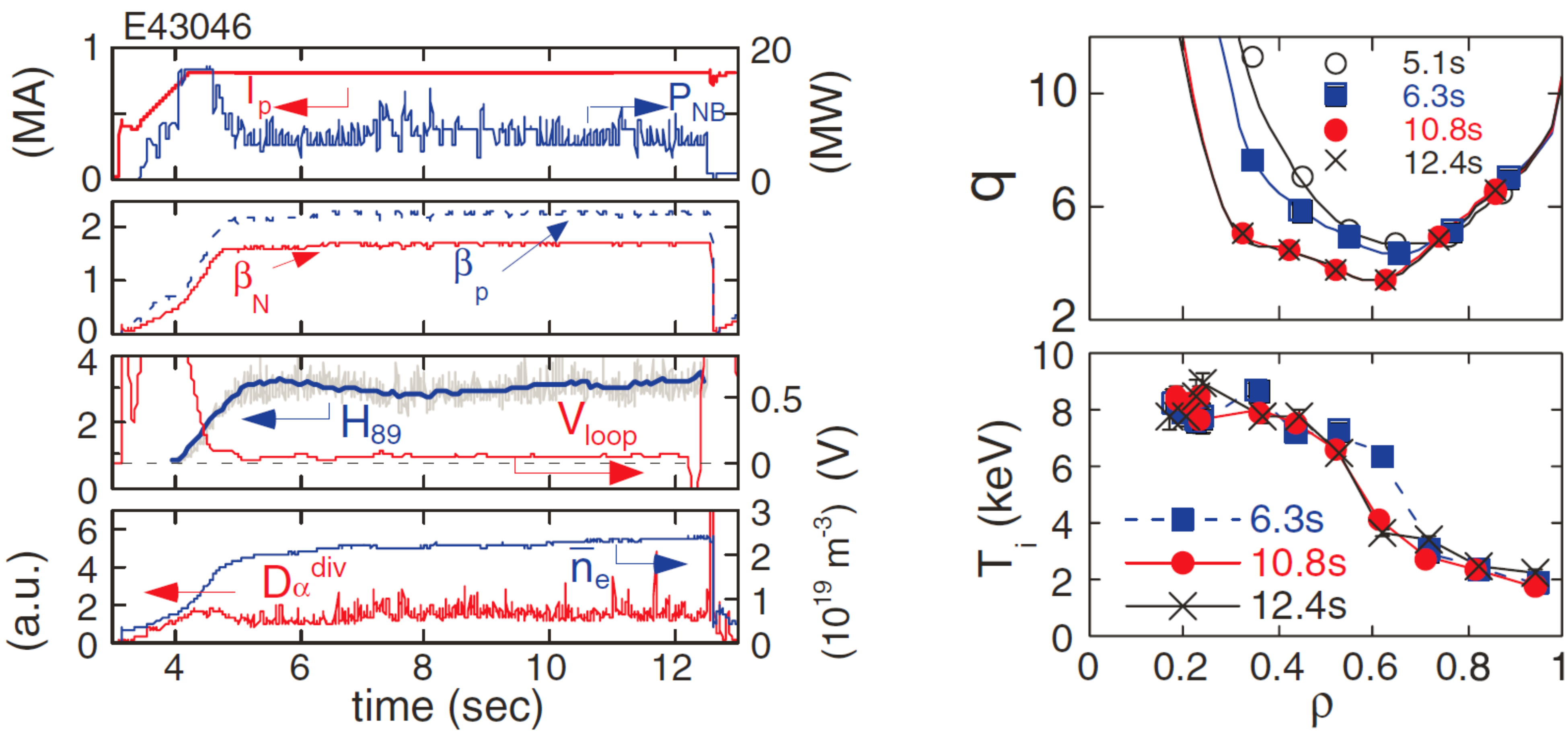




- Zero current density at the centre
- H_{98} = 1.16-1.45 with ITB **but low β_N**
- Observed in JET first and JT-60U

*T. Fujita et al, PRL **87** 245001 (2001)*

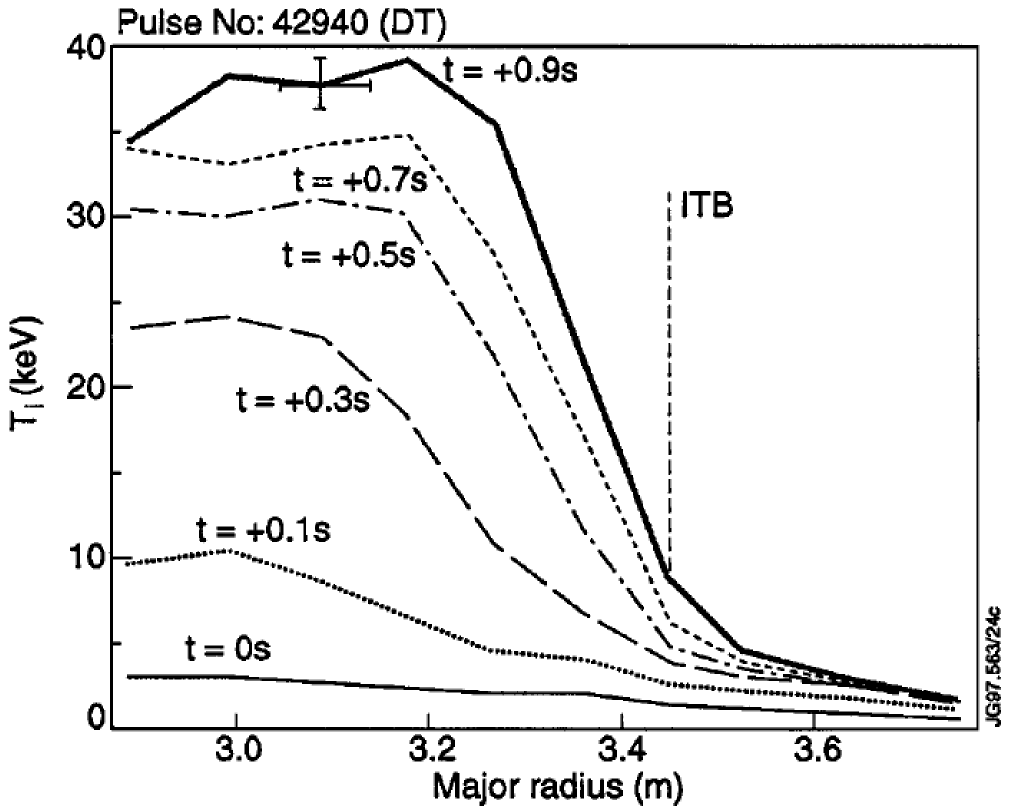
Strong RS



S. Ide et al, NF ***45*** *S48 (2005)*

- I_P = 800 kA, B_T = 3.4 T
- ITB+ETB with f_{BS} = 0.8 and f_{NI} ~ 1.0 **but low β_N**
- Suffered from disruption when q_{min} ~ 4

Strong RS – Optimised Shear

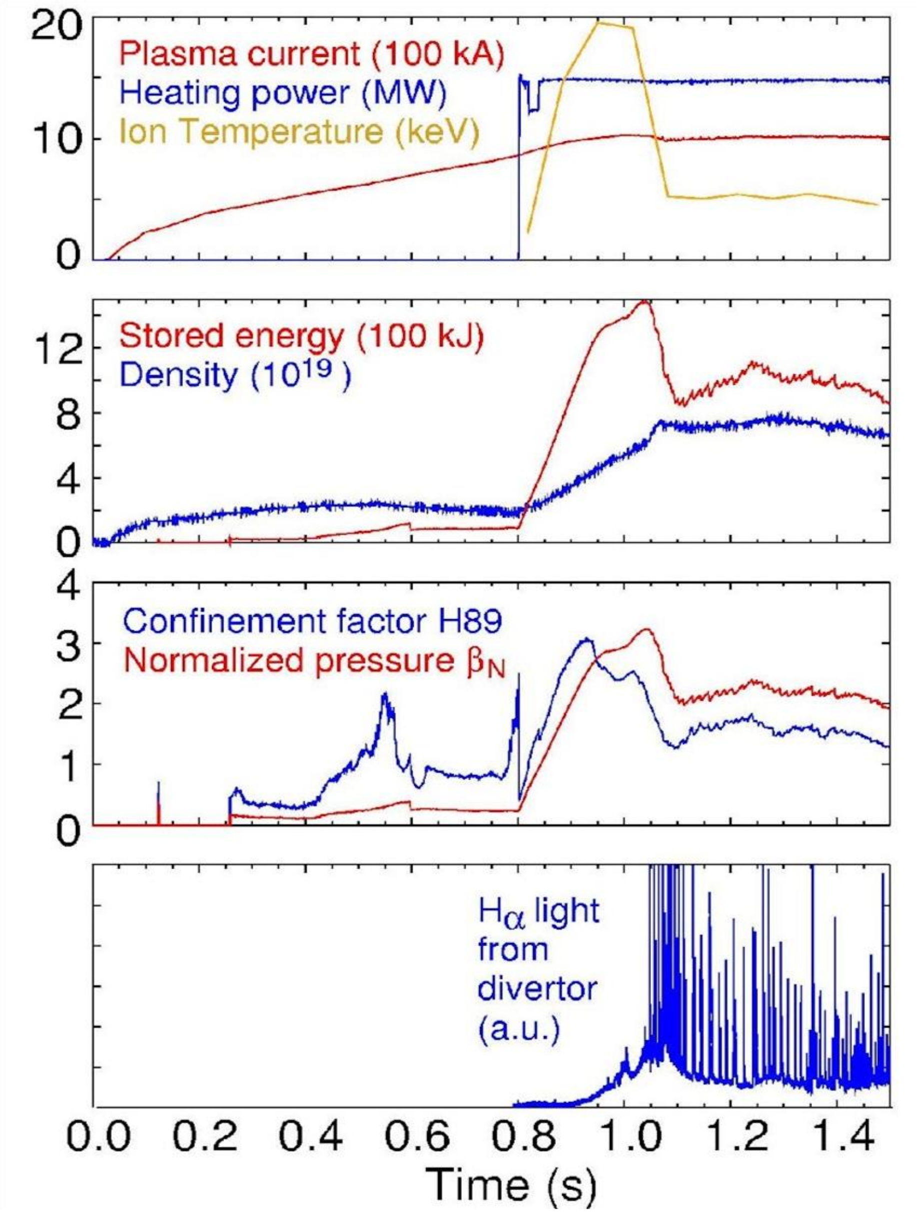


- **DT plasmas.** ITB w/o ETB. I_P = 3.4 MA, B_T = 3.85 T, q_{95} = 3.9
- Rise of T_i from ~3 to **~40 keV** in < 1 s
- $\boldsymbol{f_{BS}}$ **= 0.15**, H = 1.5, β_N = 1.9
- **Disruption** due to global n = 1 ideal kink mode due to strong pressure peaking

*C. Gormezano et al, PRL **80** 5544 (1998)*

RS – AUG ITB

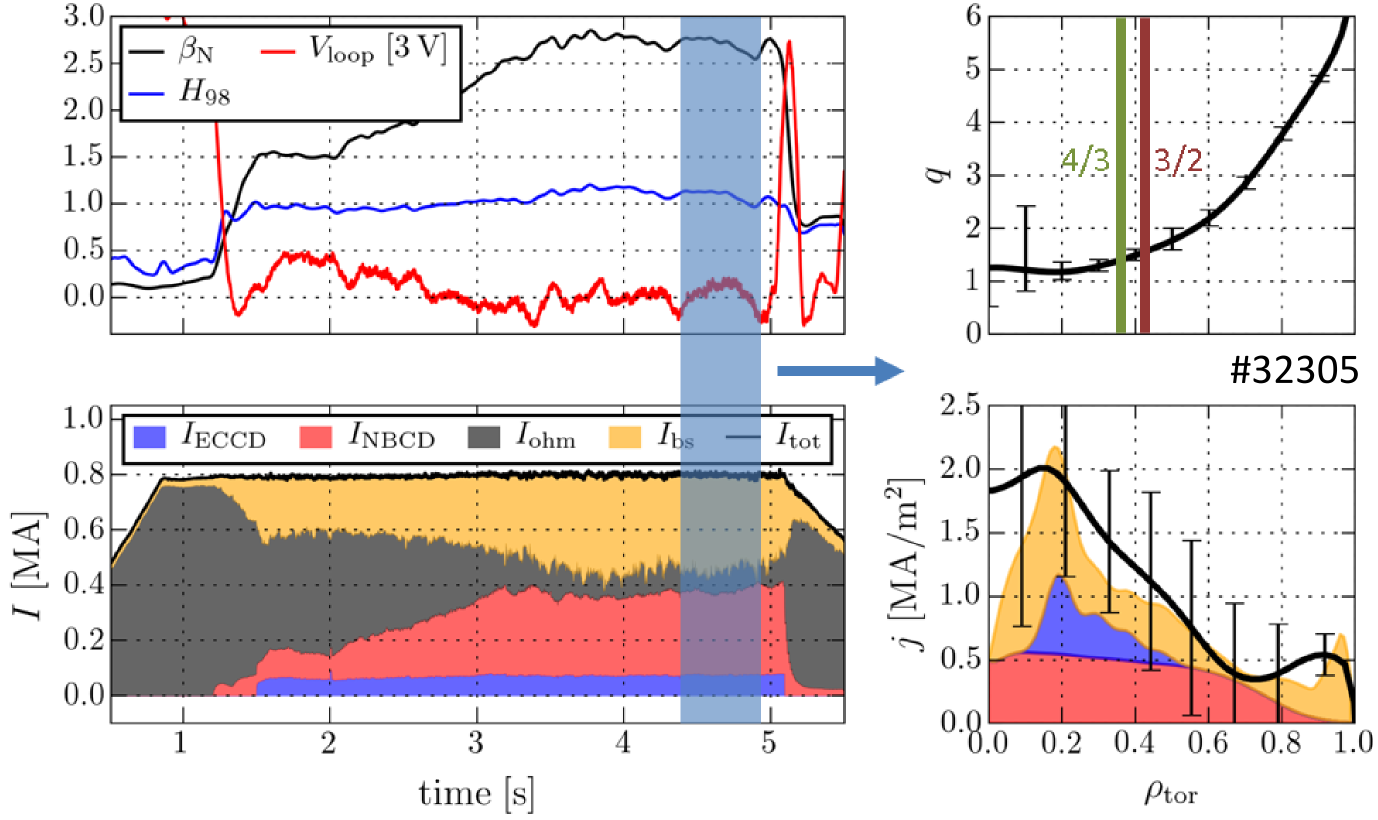
ASDEX Upgrade



- Formation of an ITB at low n_e, with 15 MW NBI power
- $T_i > T_e$, high rotation shear
- ITBs are relatively short lived, only few τ_E .
- Good, transient performance: $H_{89} \sim 3$, $\beta_N \sim 3$
- **ITB not compatible with H-mode edge barrier and large ELMs.**

PLARE

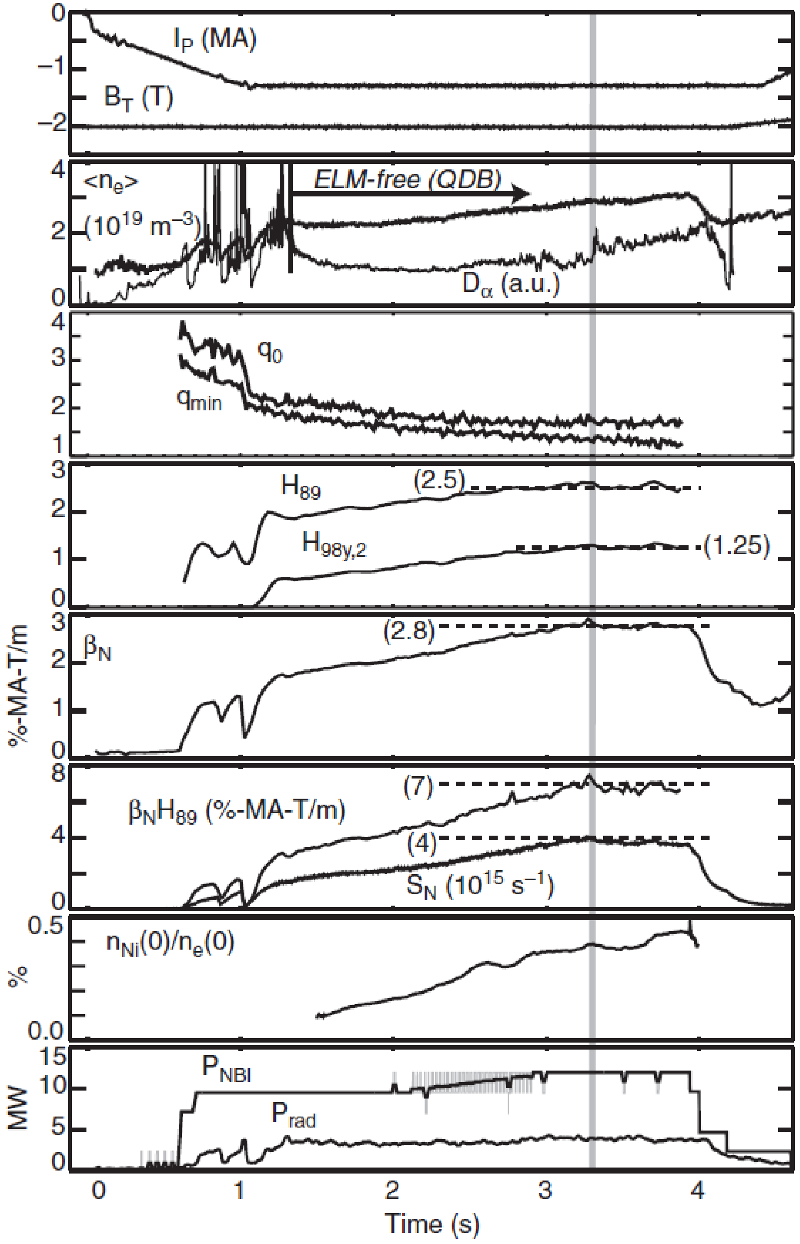
RS – AUG AT mode

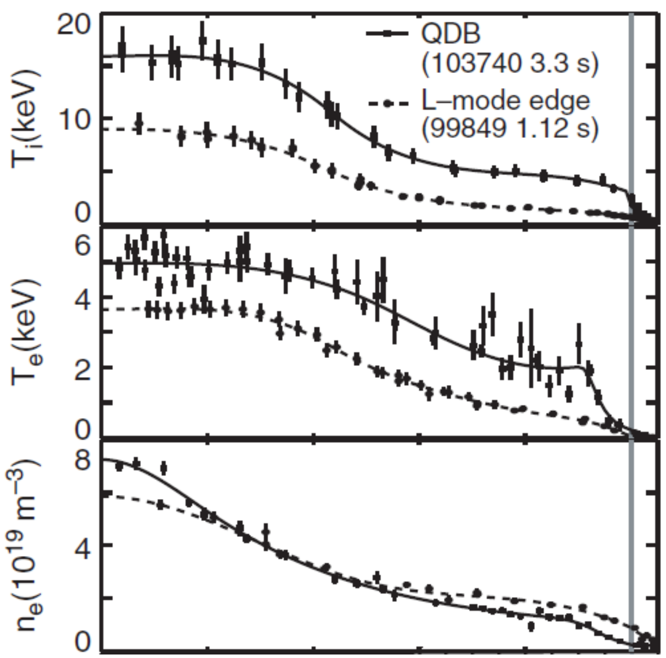


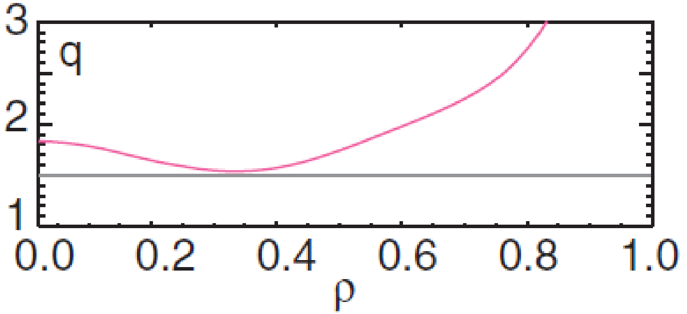
- **First AT developed in full W-coated ASDEX Upgrade**
- I_P = 800 kA, B_T = 2.5 T, q_{95} = 5.3 with ~12 MW NBI power
- f_{BS} = 0.50, f_{NB} = 0.4, f_{EC} = 0.1
- Increase β after current relaxation
- β_N = 2.7, H_{98} > 1.1

J. Stober et al, IAEA FEC PDP-4 (2016), ITPA IOS TG Spring (2017)

RS – Quiescent Double Barrier





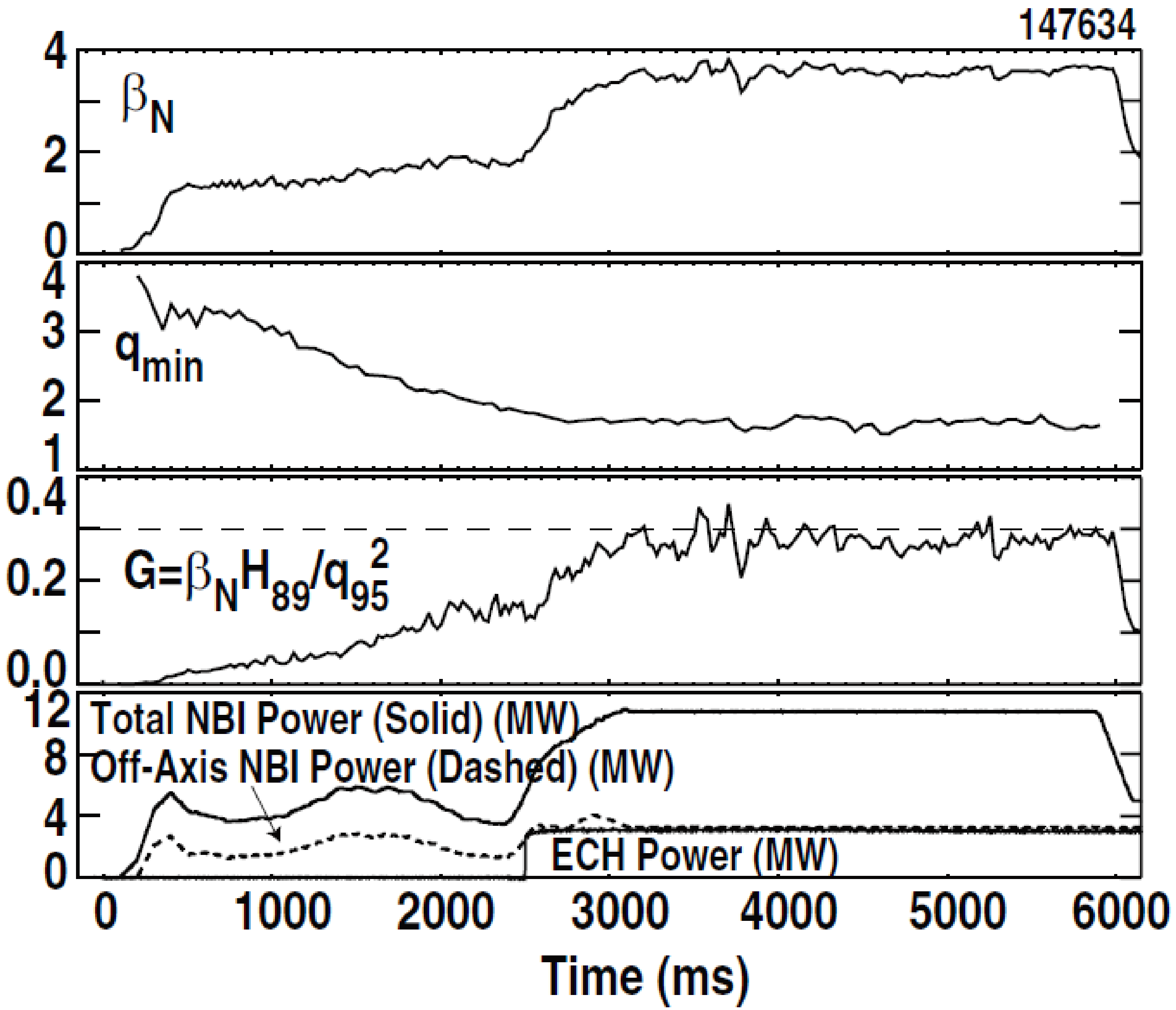


- I_p = -1.3 MA, B_t = 1.8-2.1, q_{95} = 3.5-4.5
- **ITB+ETB without ELMs** (but with EHO, AE mode)
- High performance but with **peaked *n_e***

- misalignment of BS current
- reduced beta limit
- **increased impurity content**

*C.M. Greenfield et al, PPCF **44** A123 (2002)*

RS – High q_{min}



- Sustained q_{min}~1.5, q_{95}~6.2, β_N ~3.8
- Marginally stable to 2/1 NTMs
- Addition of off-axis NBI can broaden profiles, raise β_N limits, & reduce anomalous fast-ion transport
  → Predicted *n* = 1 kink ideal limit ~5

*C.T. Holcomb et al Nucl. Fusion **54** 093009 (2014)*

Characteristics of developed AS's

	AS	Advantages	Questions
Monotonic shear	High l_i mode	- High β_N below no-wall limit - Efficient on-axis CD	- How to sustain high l_i in stationary conditions? (replace J_{IND} with on-axis CD) - How to avoid n = 1 TM?
Flat shear	Hybrid mode	- High β_N, H - No delicate control - S-S with f_{CD}~0.5, f_{BS}~0.5	- Mechanism of preventing current diffusion? - Can this phase be sustained in long-pulse (> 30 s)? - Relatively low f_{BS} - Can it be maintained with low torque?
	High β_p mode	- High β_N, H - S-S with high f_{BS} - Low disruptivity - No impurity accumulation / detachment	- How to keep high β_N while reducing q_{95} by avoiding RWM? - How to sustain in stationary conditions? - How to avoid energetic particle transport?
	FIRE mode	- high β_N, H - S-S - No impurity accumulation	- How to increase the density? - How to increase f_{BS}? - How to improve the performance by avoiding H-mode transition?

Characteristics of developed AS's

	AS	Advantages	Questions
Reversed shear	- Current hole - OS - NCS - QDB	- high *H* - S-S with high f_{BS}	- How to increase β_N and reduce q_{95} while avoiding RWM? - Current profile control to sustain ITBs? - How to avoid strong density peaking and impurity accumulation?
	- High q_{min}	- High ideal MHD β_N-limits - high f_{BS}	- How to avoid q>2 tearing modes? - How to obtain high H w/o ITB?

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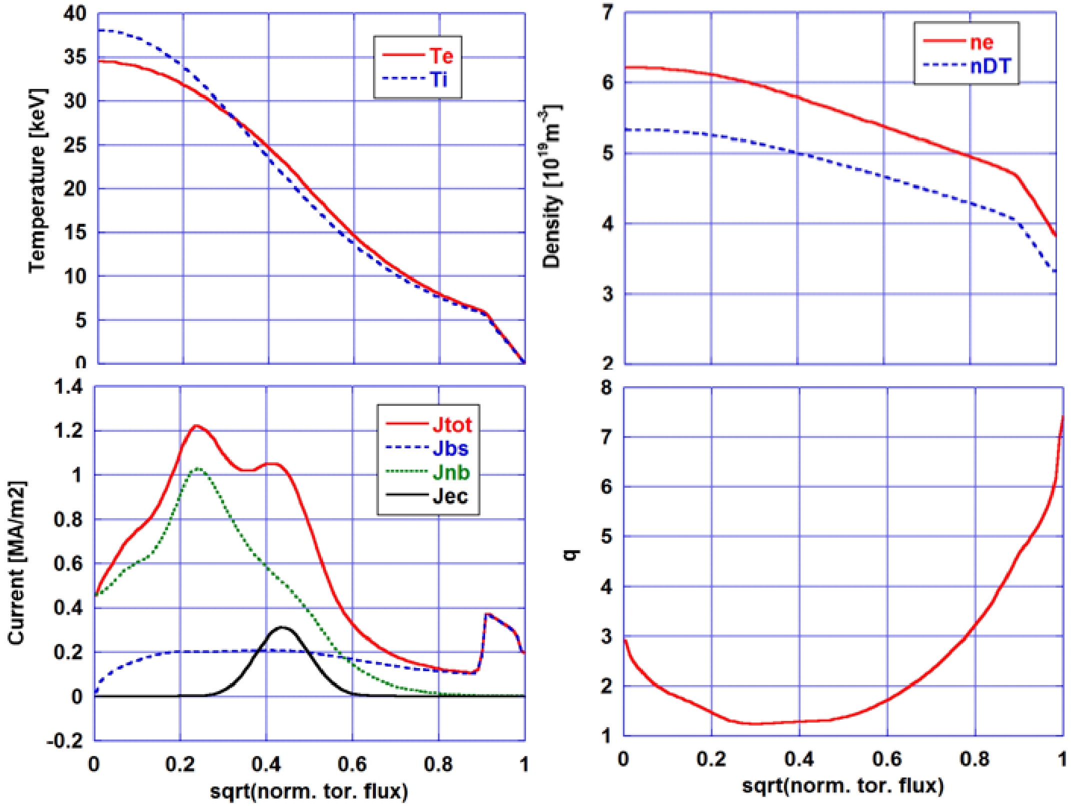
Contents

Your Challenge – ITER SS scenarios

Target steady-state plasma at 10 MA

- **1.5-D ASTRA modelling**
  - ✓ EPED1+SOLPS used for pedestal and boundary
  - Q=5.02, f_{GW}=0.69
  - H_{98}=1.52, β_N=3.02
  - q_{min}=1.23
  - Relatively high $l_i(3)$~0.87 mainly due to the absence of off-axis driven current by LHCD



[NF60, A.R. Polevoi]

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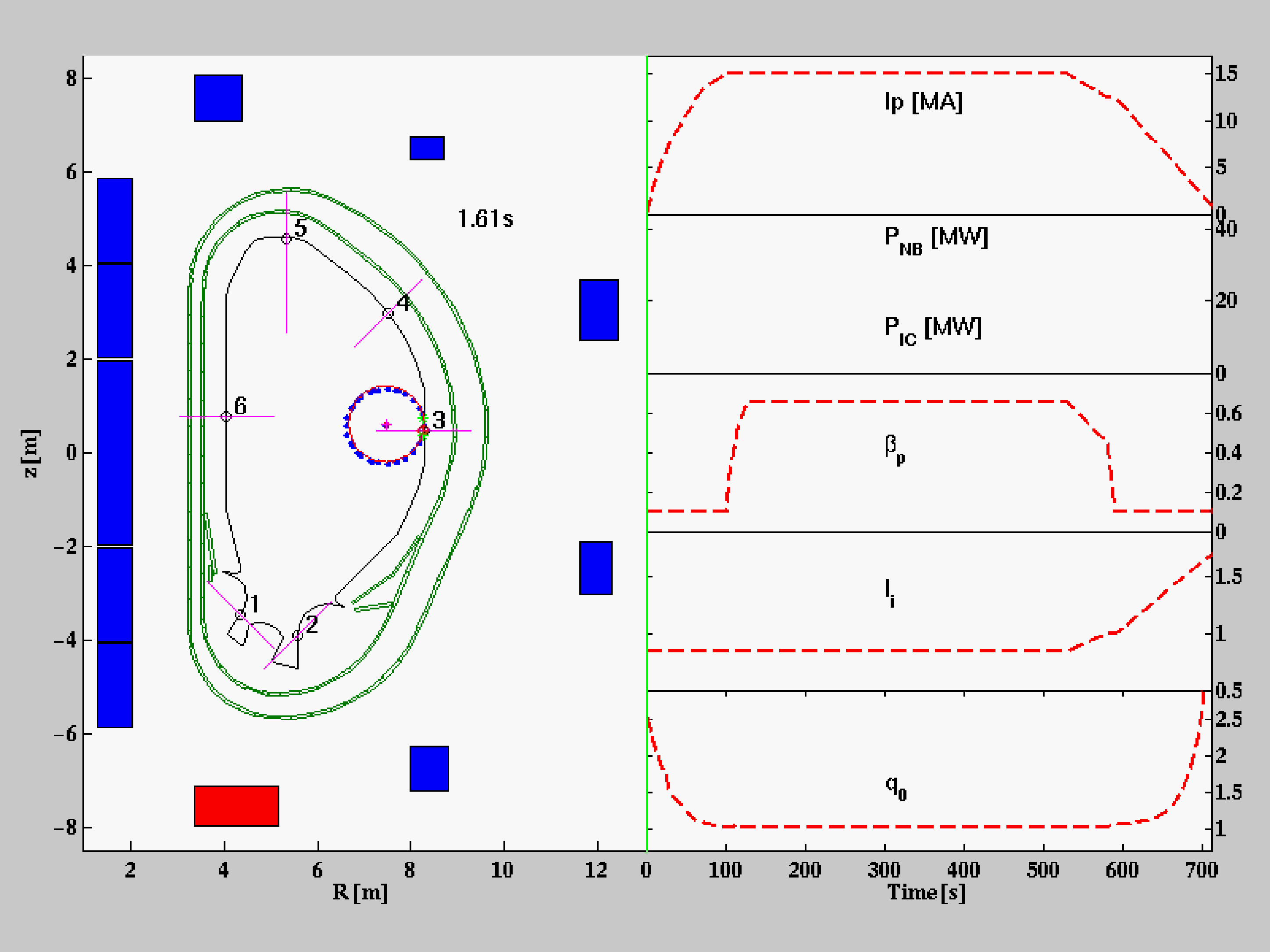
Your Challenge – ITER SS scenarios



Courtesy of S.H. Kim (ITER)

Your Challenge!

- ***Most of alternative / advanced scenarios were just***

termeasures. The first was to modify JT-60 to operate with a lower X-point divertor. Installation of new divertor coils below the vacuum chamber was challenging but necessary to produce the lower X-point configuration. Mutual trust between Kishimoto and Hiroshi Ishizuka, Director of the Hitachi local office, enabled this modification to be completed in seven months. However, Kishimoto [1] noted that the H-mode result with lower X-point was "really disappointing" since the confinement improvement over the L-mode was small. On the other hand, the lower X-point experiment produced a "serendipity" called high β_p enhanced confinement. This phenomena was discovered by Shinichi Ishida [14] having enhanced core confinement similar to the TFTR supershot [15].

*M. Kikuchi et al, EPJ H **43** 551 (2018)*

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Your Challenge!

- ***Most of alternative / advanced scenarios were just***

a Serendipity!

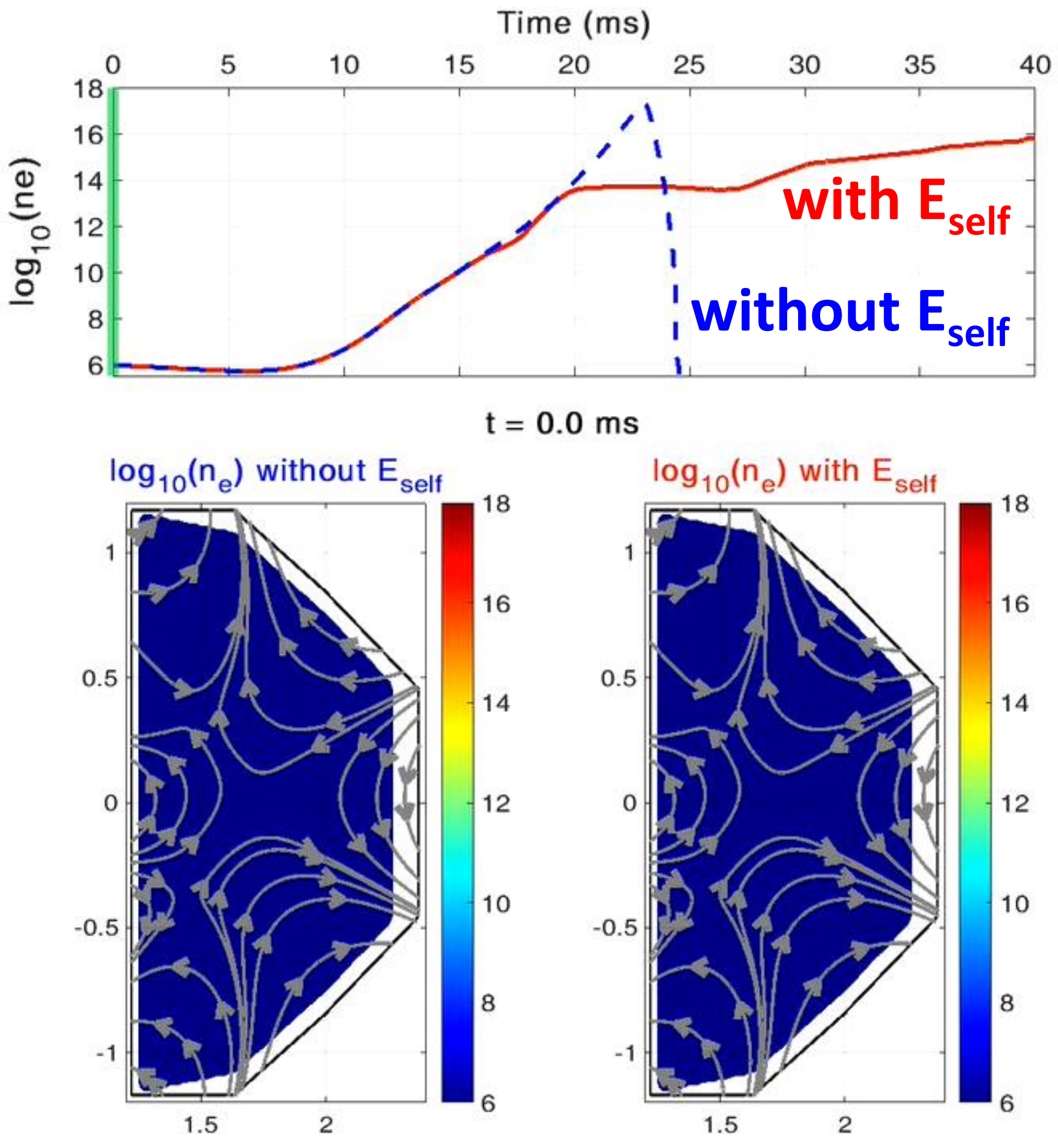
- ***Play with your machine (if allowed) or codes.***

Look at failed shots!

If you want to see, you will see!

Seek, and you will find ***[Matthew 7:7]***

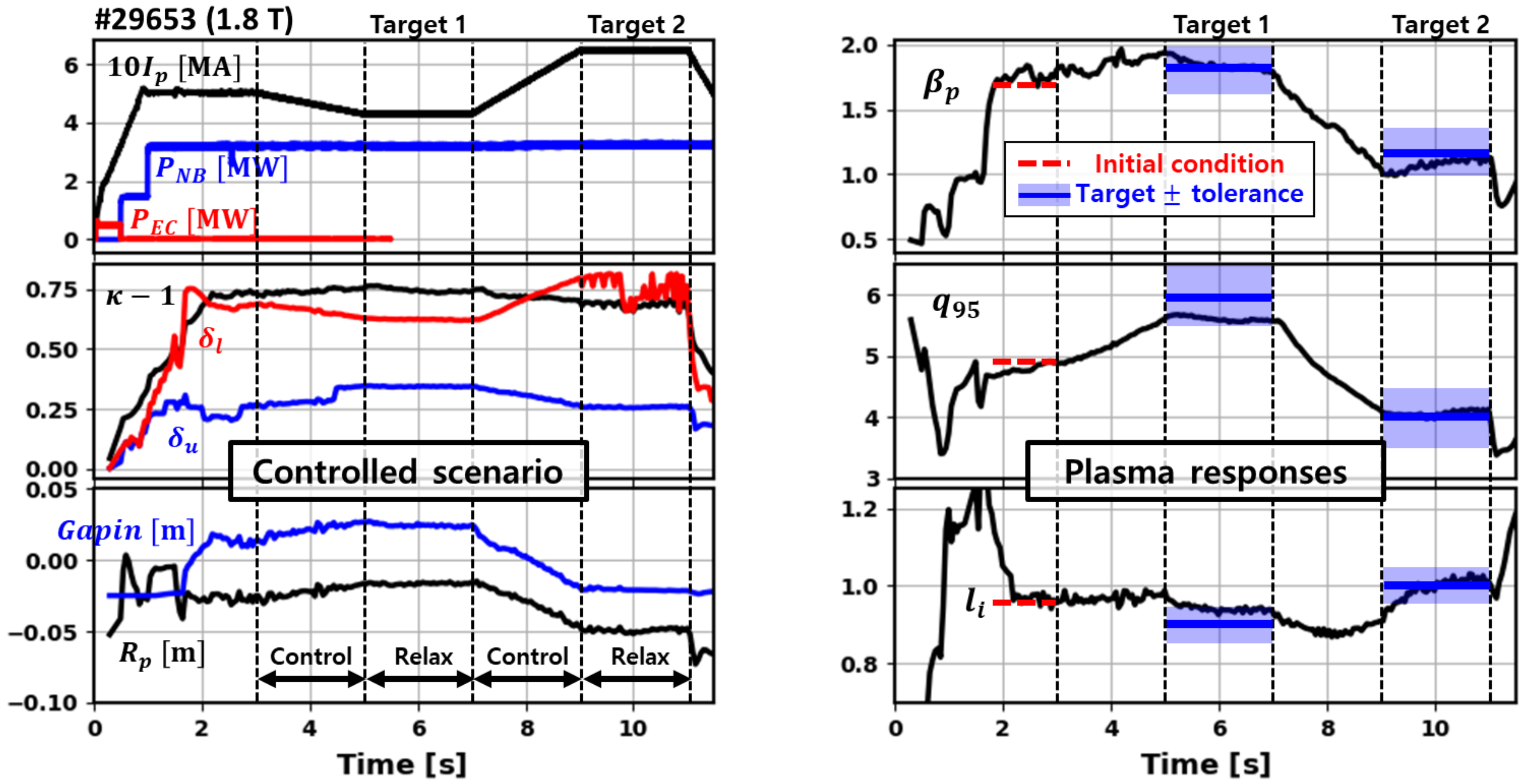
Your Challenge – Develop code to test your ideas!



M.G Yoo, Poster on Thursday

M.G Yoo and Y.-S. Na et al,
Nature Comm. ***9*** *3523 (2018)*

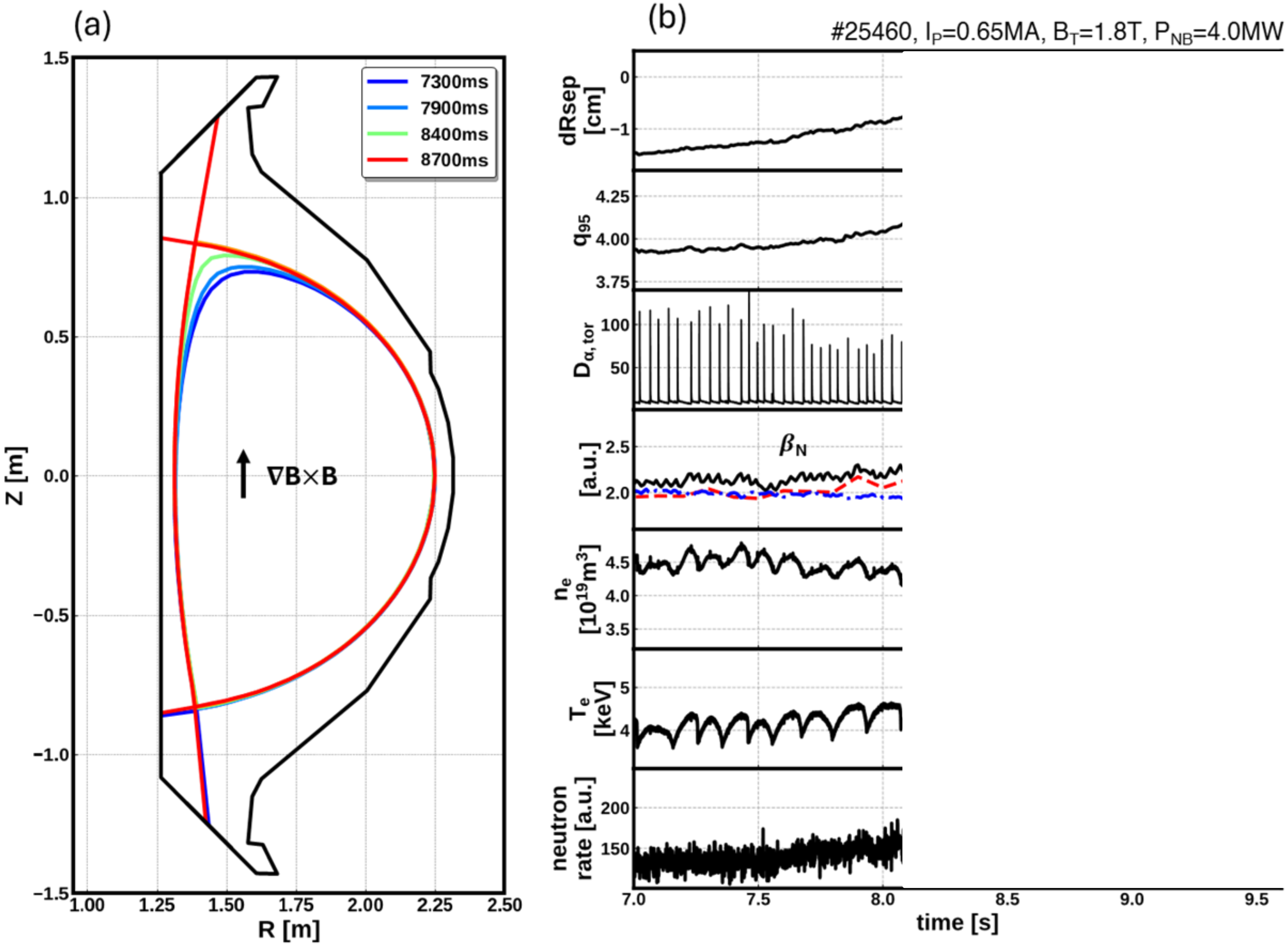
Your Challenge – Apply new tools!



⇒ *E. Kolemen, this school*

*J. Seo et al, NF **61** 106010 (2021)*
*J. Seo et al, NF **62** 086049 (2022)*

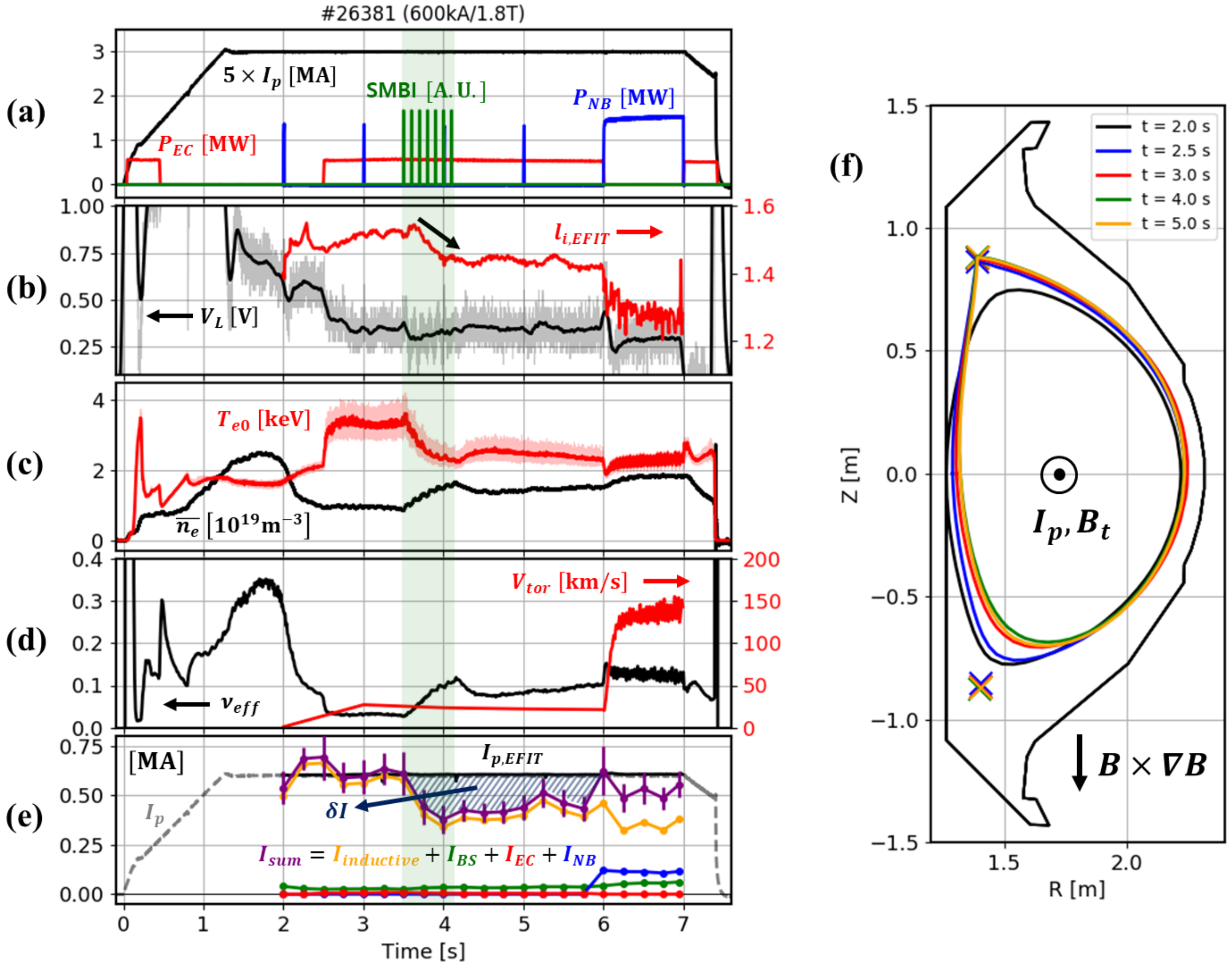
Your Challenge – Breaking the rules!



B. Kim et al, Poster on Tuesday

Your Challenge – Find new one!

KSTAR



Y.-S. Na, J.M. Seo et al., Nature Comm. submitted (2022)

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Summary

- What to satisfy?
- How to establish them?
- H-mode
  - Why?
  - How to?
  - Characteristics?
  - How to overcome?
- Monotonic Shear / Flat Shear / Reversed Shear
- Your Challenge!

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