ELM Control by Edge Current Modification in JT-60U

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Motivation

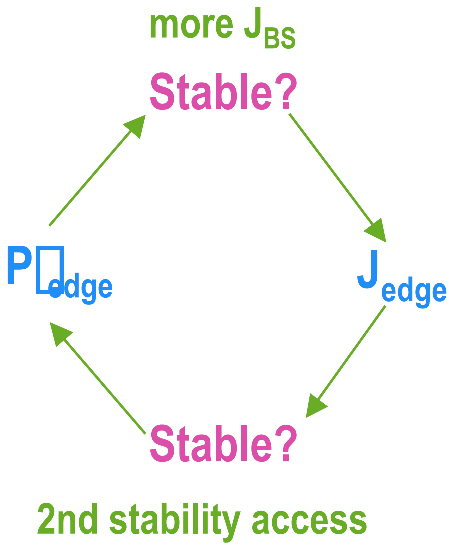
- Predictability of the edge pedestal height and control of divertor heat load are two of the major issues in the design of next generation tokamak burning devices
    - Predicted performance is sensitive to the edge pedestal height
- Both are strongly impacted by ELMs and their size
- A working ELM model is they are low-intermediate $n \sim 5$ - 30 peeling-ballooning modes [1,2].
    - ELM sizes are related to radial widths of unstable modes
- Recently, small ELM regime has been extended to low q regime by edge current modification and the role of J_{edge} investigated.
    - Current ramp experiment to vary J_{edge} directly
    - High collisionality experiment using impurity seeding

[1] Lao, *et al*, Nucl. Fusion 39, 1785 (1999)

[2] Ferron, *et al*, Phys. Plasmas, 7, 1976 (2000)

THEORY AND EXPERIMENT SUGGEST A MODEL OF ELMS AS LOW-INTERMEDIATE *n* PEELING-BALLOONING MODES

- **Driven by P'_{edge} and J_{edge} interacting through J_{BS} and 2nd ballooning access**
- **J_{edge} stabilizes high *n* ballooning modes but drives intermediate *n* peeling modes**
- **ELM sizes are related to the radial widths of the unstable modes**
- **Critical P'_{edge} is set by modes with the highest *n* without 2nd ballooning stability access**



more J_{BS}

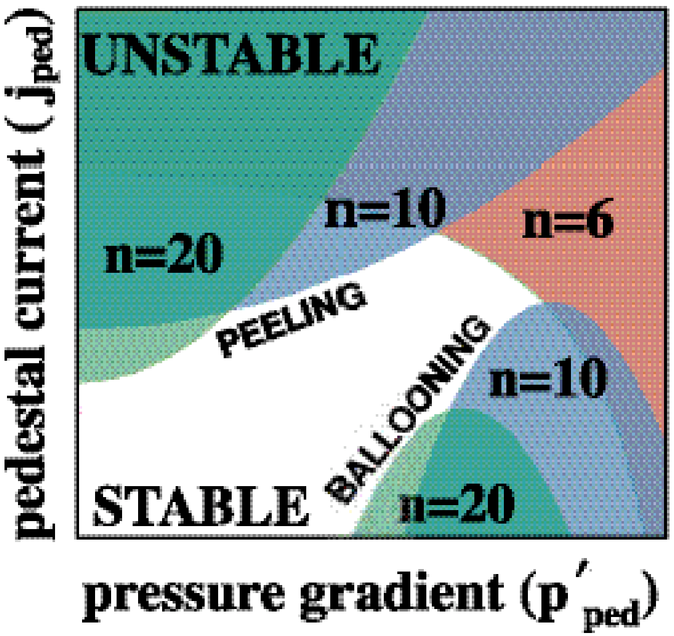
Stable?

P'_{edge}

J_{edge}

Stable?

2nd stability access



P.B.Snyder, *et al*, 19th IAEA, TH3/1

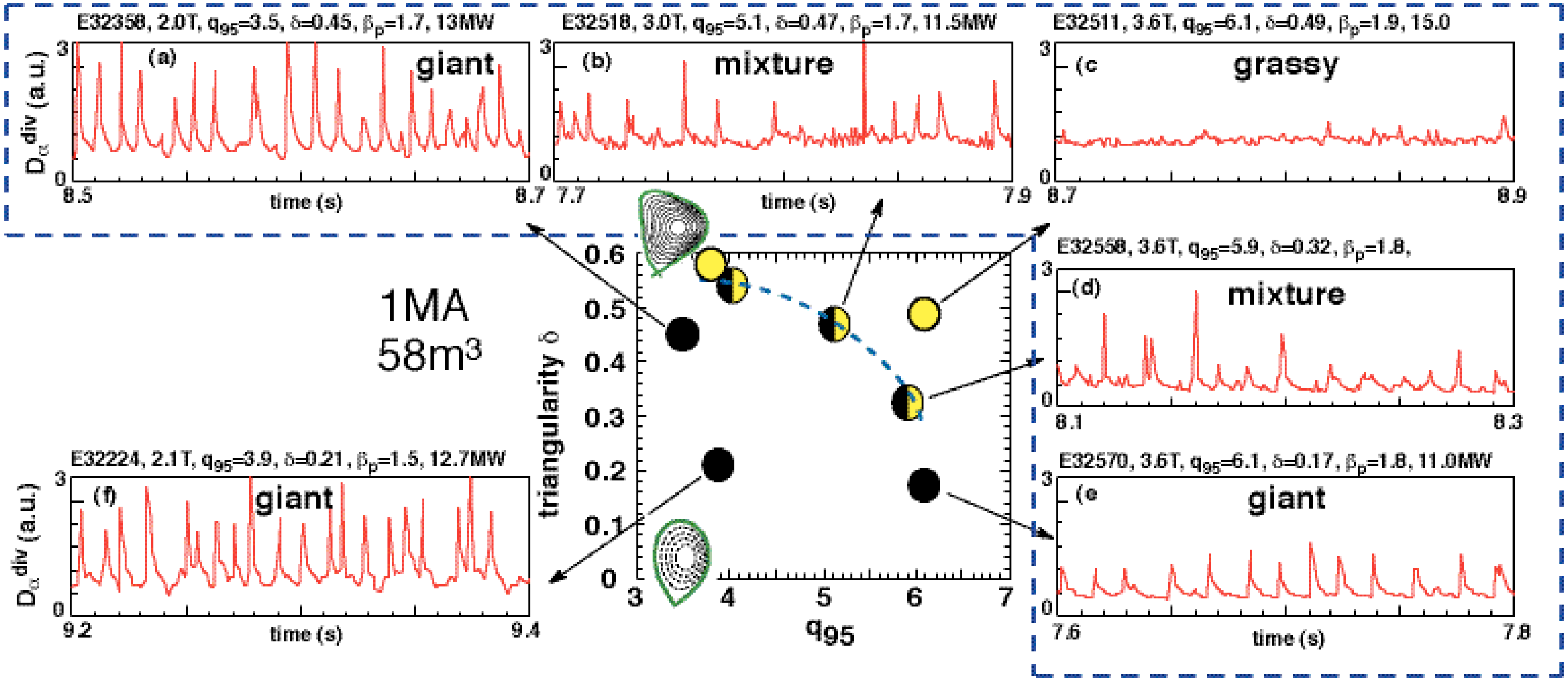
P.B.Snyder, H.R.Wilson, et al Phys. Plas. 9 2037(2002).

H.R.Wilson, P.B.Snyder, et al Phys. Plas. 9 1277(2002).

“Giant” and “Grassy” ELM regimes in JT-60U

JT-60U

- No edge profile modification
- **Giant (Large) ELM** : low δ or low q_{95}, f_{ELM} < 100Hz
- **Grassy (Small) ELM** : q_{95} >~6, δ>~0.45 and β_p >~1.6 , f_{ELM} ~ 1kHz
  very high δ (~0.6) lowers q_{95} boundary (<4)



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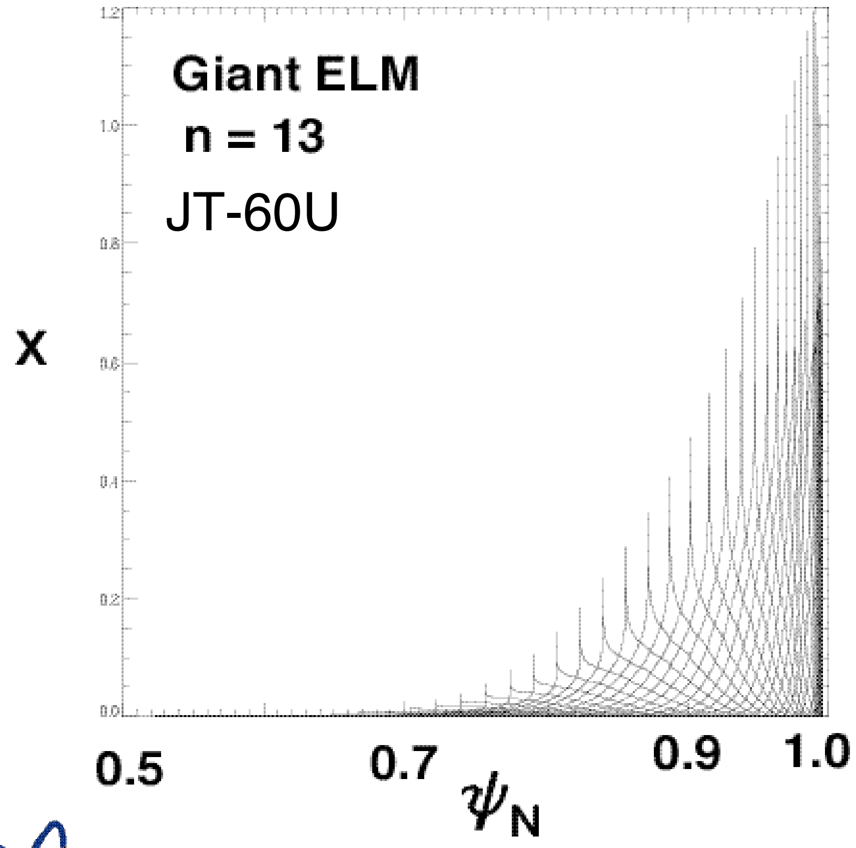
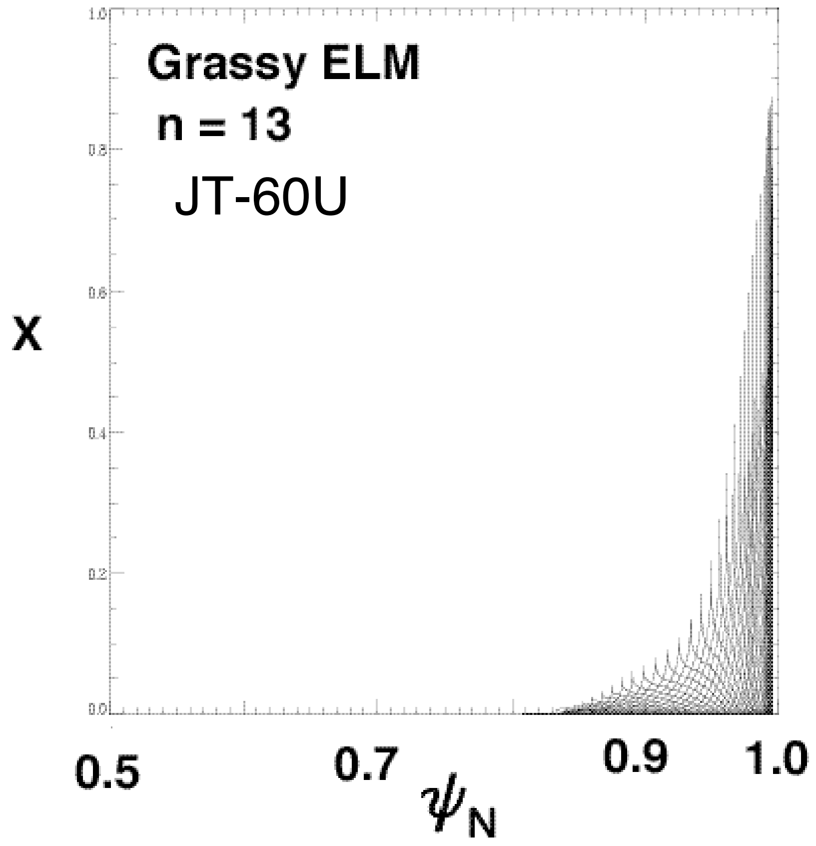
Predicted unstable modes in “Grassy” ELM discharges have a narrower radial width

JT-60U

- Eigen functions of marginally unstable modes computed using the ELITE code
- Changes in radial width related to difference in q profiles



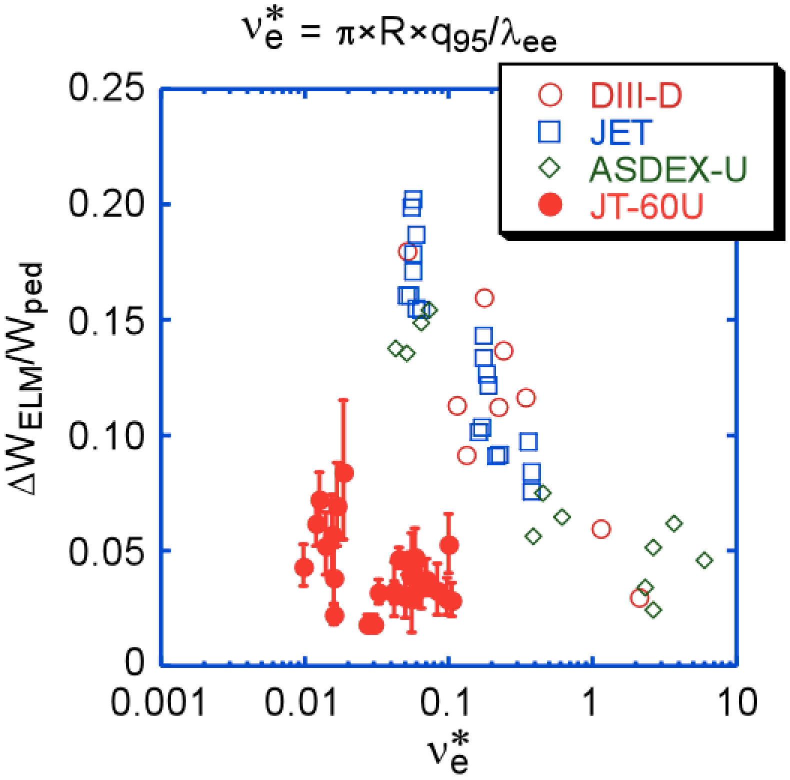


Lao, Kamada, *et al*, Nuc. Fusion 41, 295 (2001)

”Giant” ELMs can have various amount of energy loss related to □□

JT-60U

- **“Giant” ELM energy loss □W_{ELM} / W_{ped} tends to increase in lower collisionality □* (still small in JT-60U)**
- **ELM size may relate to mode structure.**

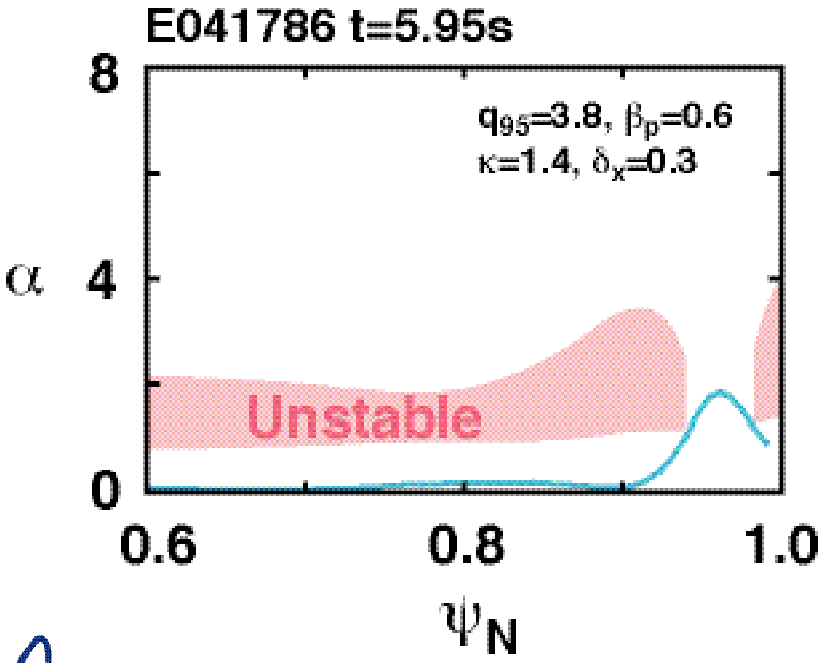


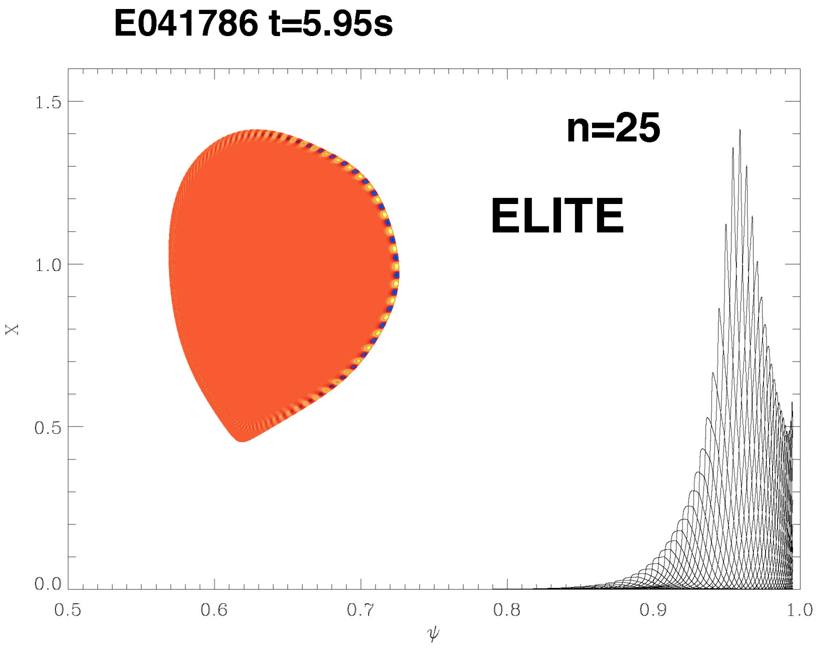
A. Loarte, et al., Fusion Energy 2000 ITERP/11

N. Oyama, et al., Fusion Energy 2002 EX/S1-1

Intermediate n mode should be considered for ELMs

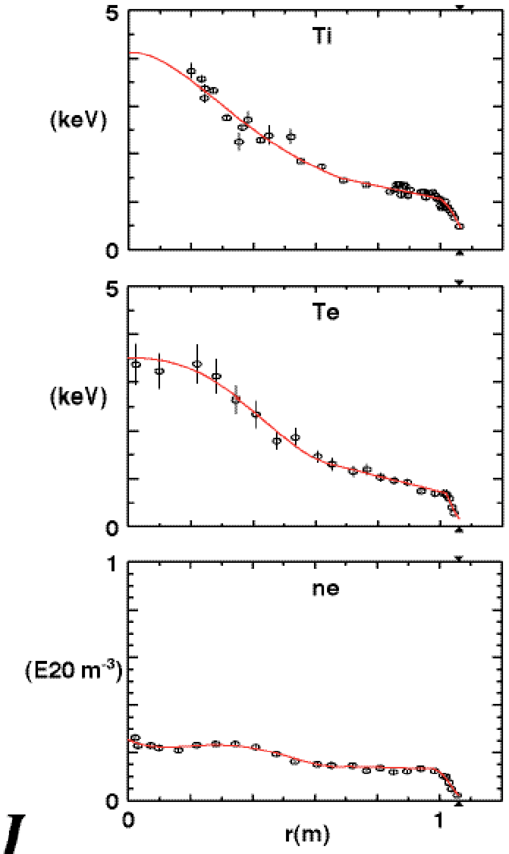
- Small □W_{ELM} / W_{ped} case (small “Giant” ELM) analyzed
- Stable to infinite n ballooning mode -> no ELM?
- Unstable to finite n peeling-ballooning mode -> ELM

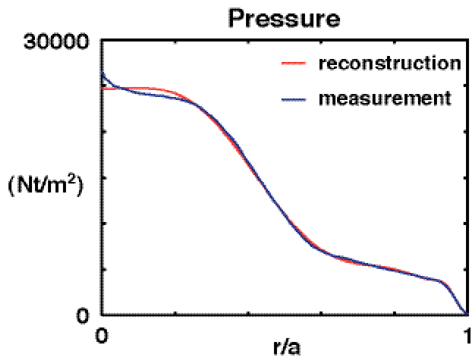


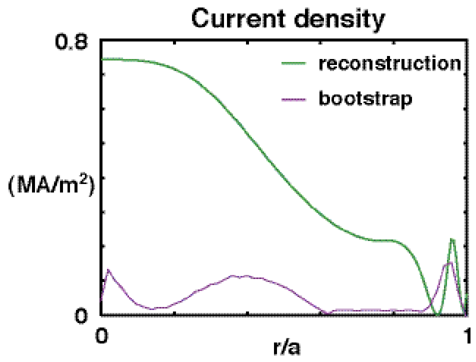


Accurate equilibrium reconstruction is crucial for proper interpretation of stability results

- Fine edge measurements, MSE, magnetics
- Fast ion losses(orbit, ripple,CX) considered
- Accurate reconstruction -> J_{edge} consistent with J_{BS} obtained



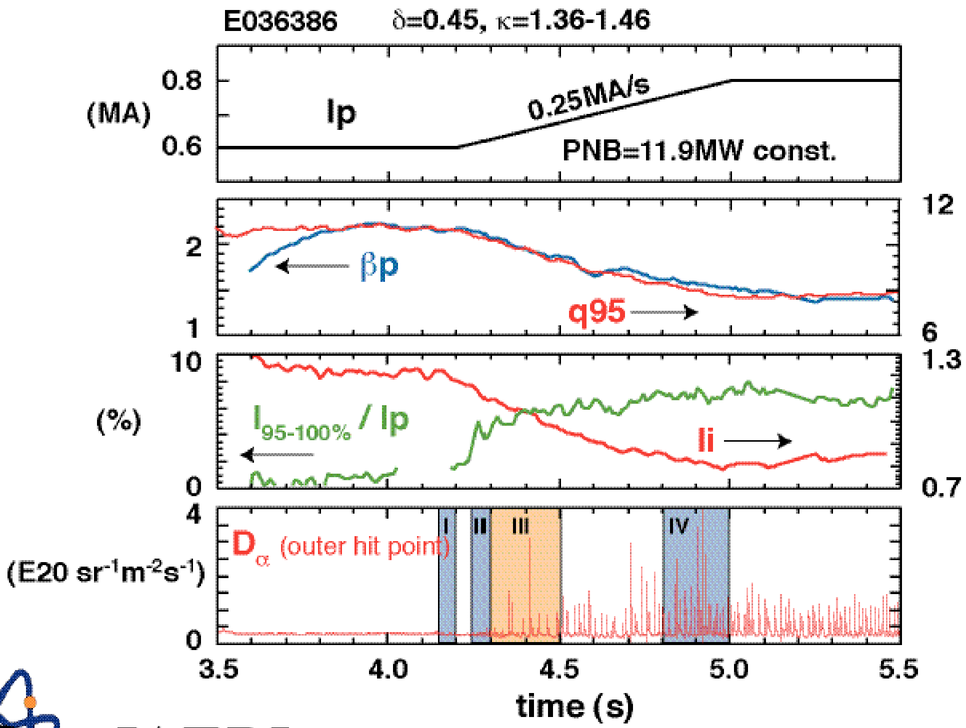


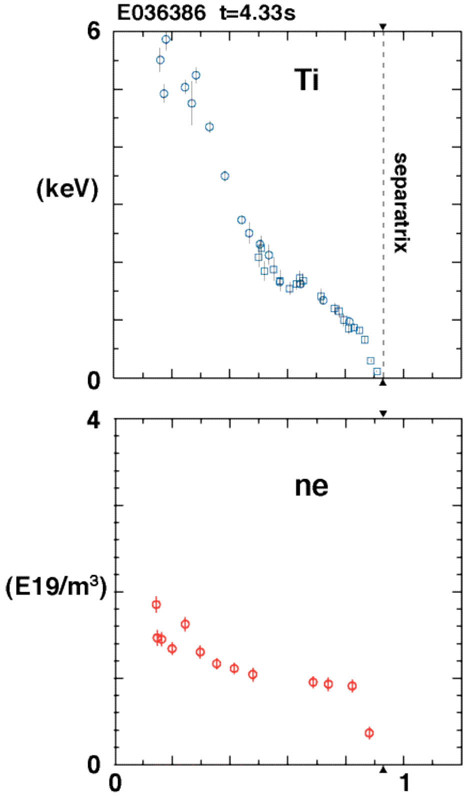


Ip ramp-up can cause a “Giant” ELM burst in “Grassy” ELM regime.

JT-60U

- Increase J_{edge} by Ip ramp-up (0.25MA/s)
- In small(grassy) ELM regime
  δ=0.45, q_{95}=8-10, β_p=1.5-2





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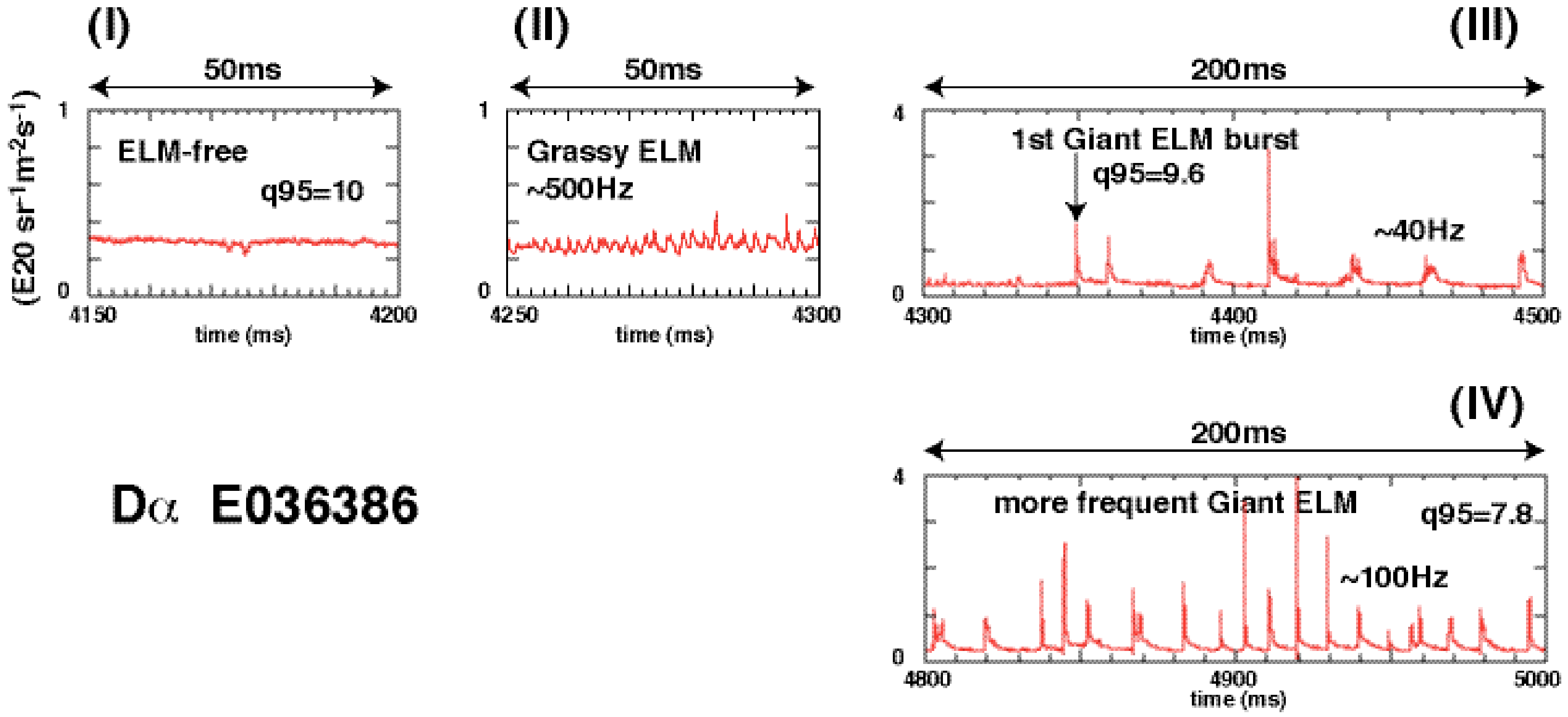
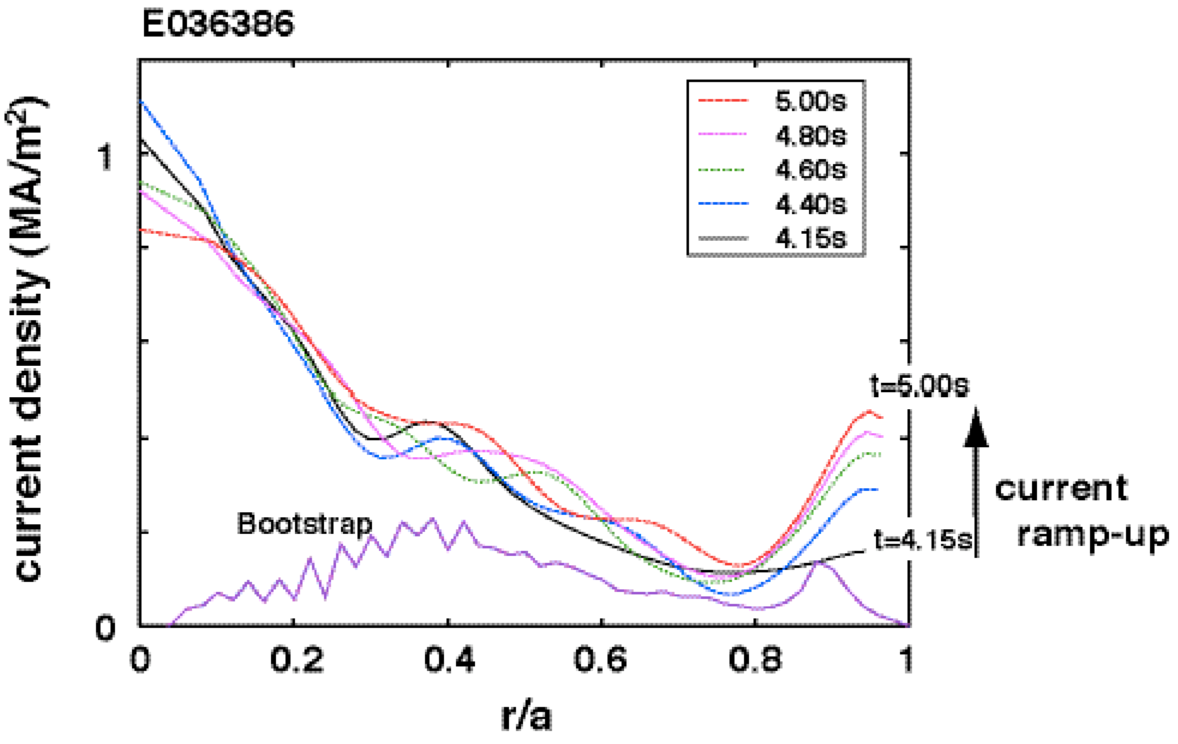
- **Current ramp-up affected ELM behavior has 4 pnases**
  - **(I) ELM free**
  - **(II) Grassy ELMs (f_{ELM}~500Hz)**
  - **(III) 1st giant ELM burst occurred at t=4.35s (f_{ELM}~40Hz)**
  - **(IV) More frequent giant ELMs (f_{ELM}~100Hz)**



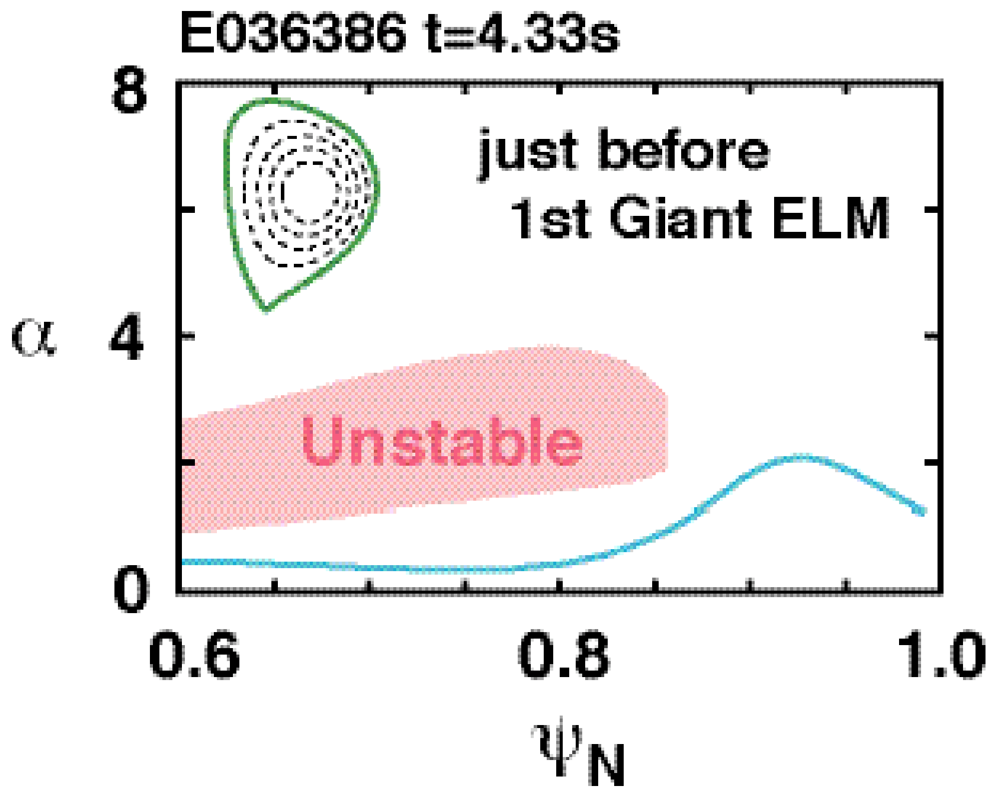
Edge current significantly increased during current ramp-up.

- Time-dependent experimental equilibria computed with SELENE code.
- Current ramp(0.25MA/s) increased the current contained in 0.8<r/a<1.
    - reached several times of edge bootstrap current



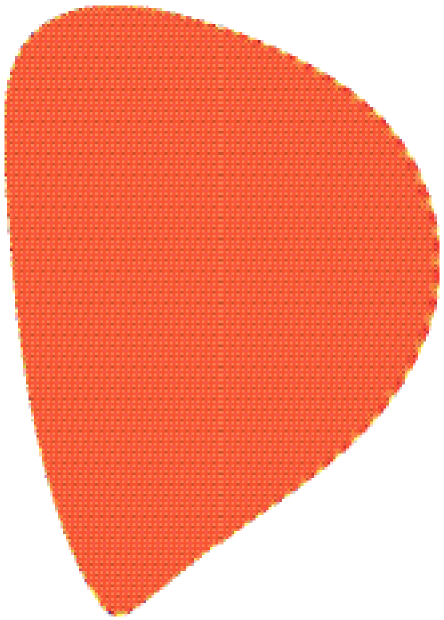
The edge region has 2nd stability regime access for high n ballooning during current ramp-up

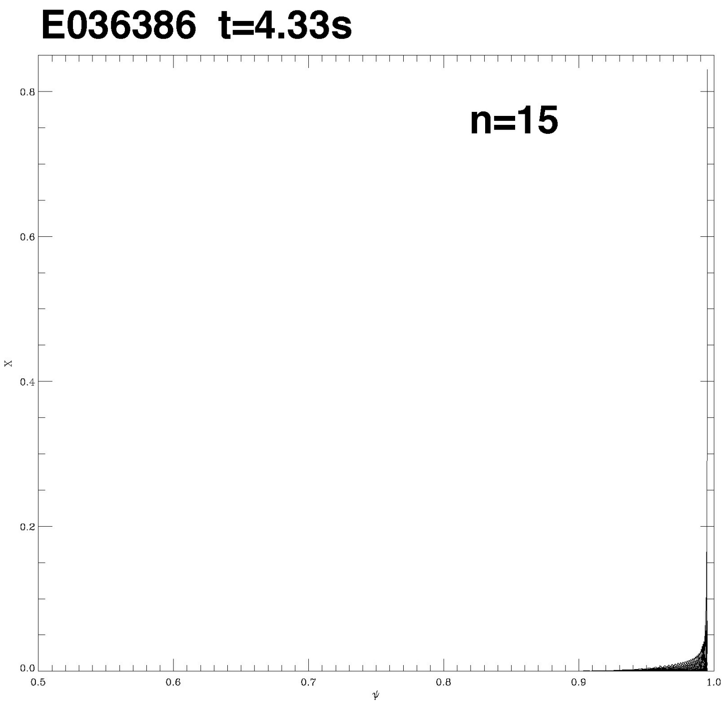
- BALOO code analysis
- Gap accessing to 2nd stability regime opened at the edge
- Large J_{edge} pushes away 1st boundary.



Peeling-ballooning mode :
unstable to intermediate n modes

- ELITE code analysis
- unstable to intermediate n (=15) driven by edge current
- Consistent with observed small “Giant” ELM





E036386 t=4.33s

“Giant” and “Grassy” ELM regimes in JT-60U

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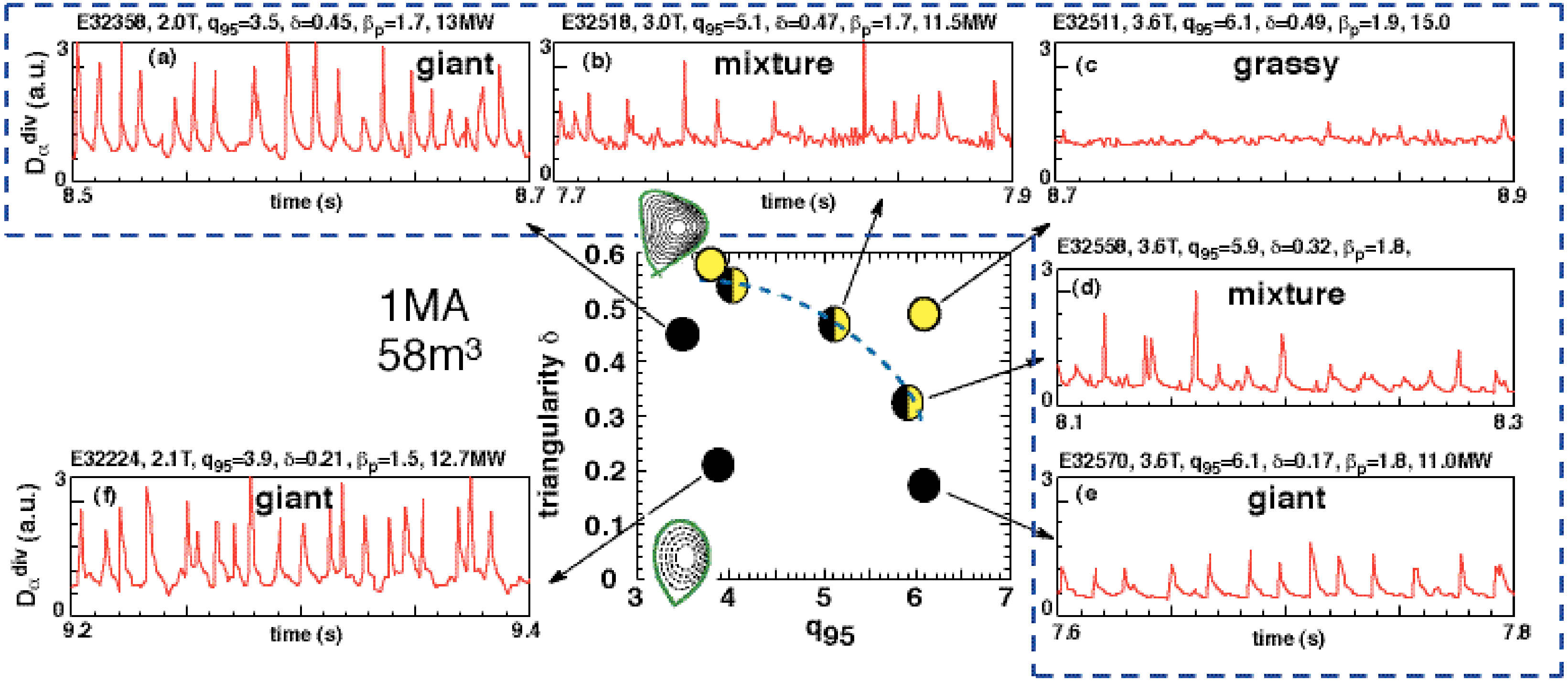
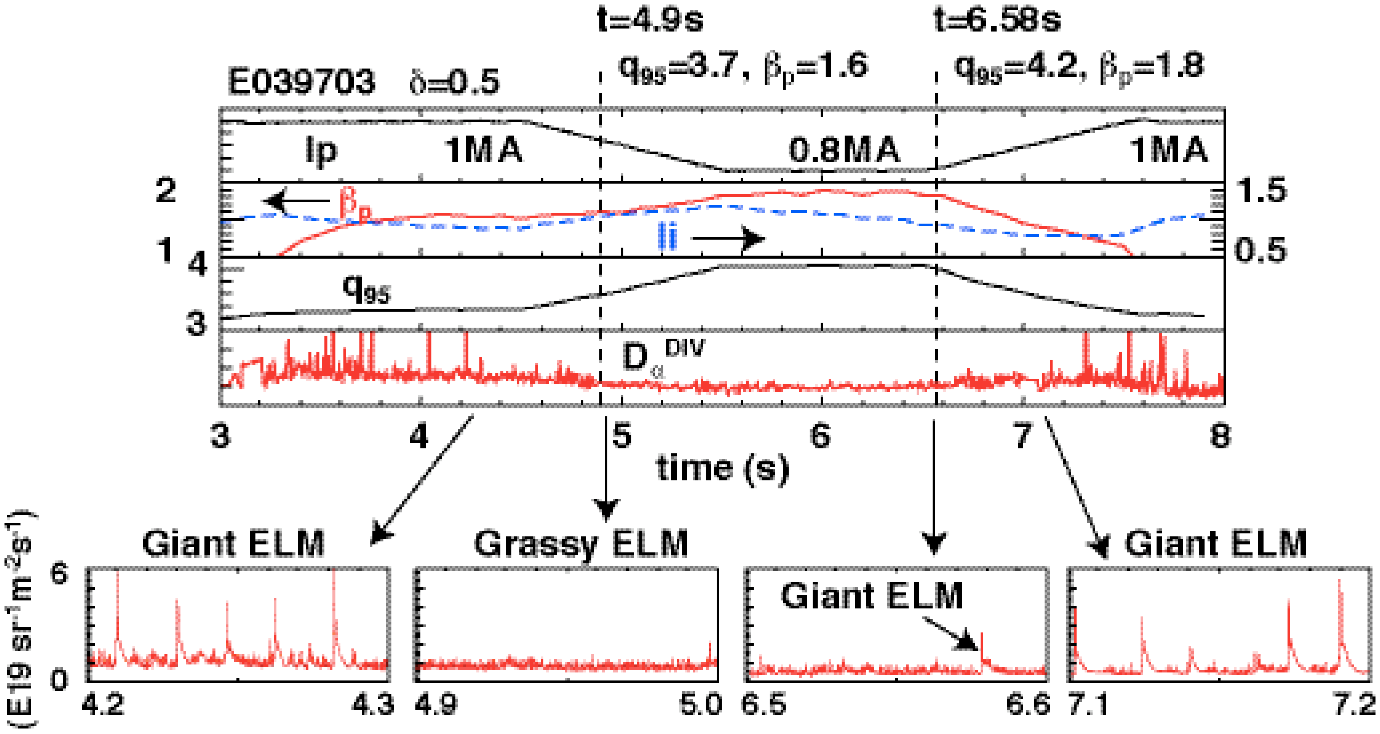


Ip ramp-down eliminates “Giant” ELMs at q_{95}<4.

JT-60U

- Ip ramp-down : -0.2MA/s
- Pure grassy ELM state was attained at t=4.9s.
  - δ=0.5, q_{95}=3.7, β_p=1.6 (normally giant ELM expected)
- Ip ramp-up triggered “Giant” ELM at higher q_{95}&β_p (t=6.58s).
  - δ=0.5, q_{95}=4.2, β_p=1.8



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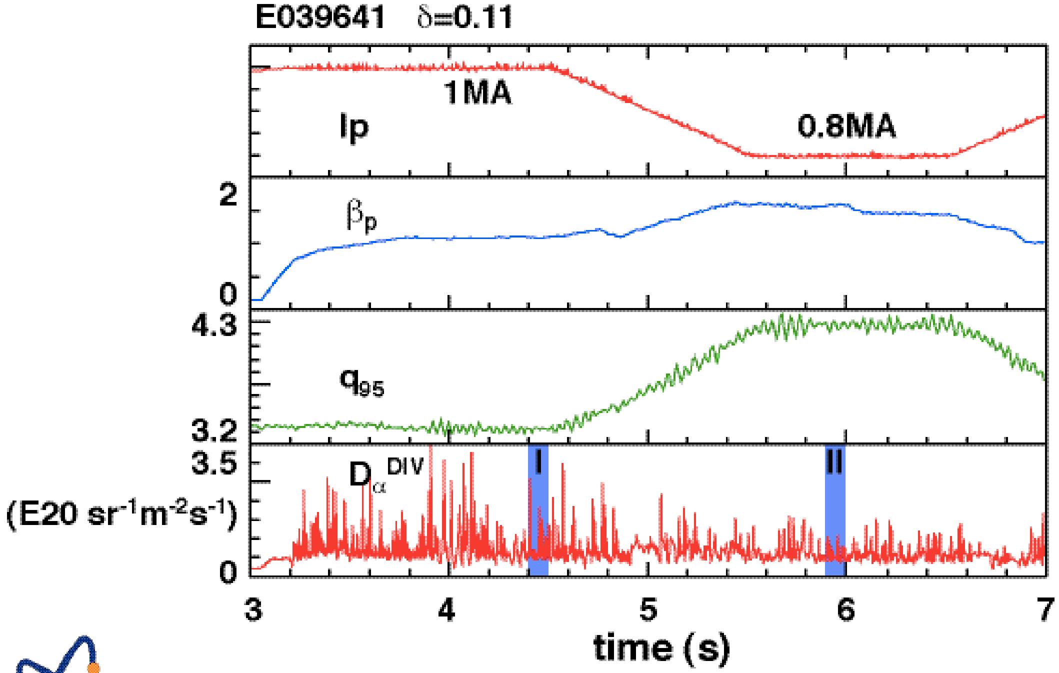
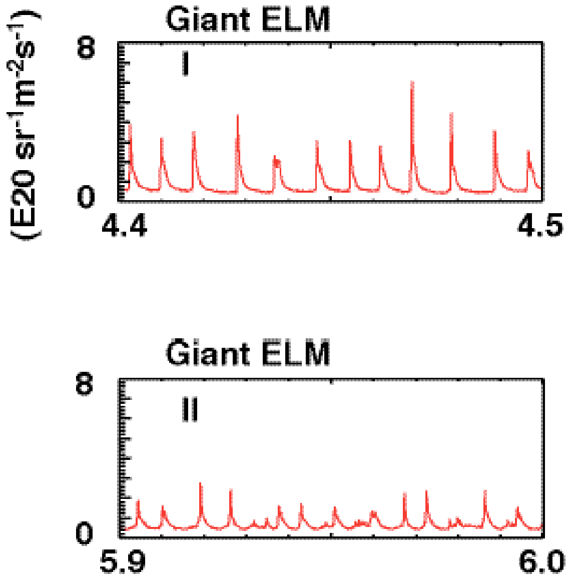
“Giant” ELMs persist at low δ despite Ip ramp-down

JT-60U

- Ip ramp-down (-0.2MA/s) at low δ (0.11)
- ELM amplitude decreased and f_{ELM} increased, but still “Giant” even at higher q_{95}=4.1 and β_p=1.6 at t=5.5s than E039703
- Less change at lower ramp rate (-0.1MA/s)
- Consistent with the peeling-ballooning model
  - Weaker magnetic well at low δ make stable regime narrower.





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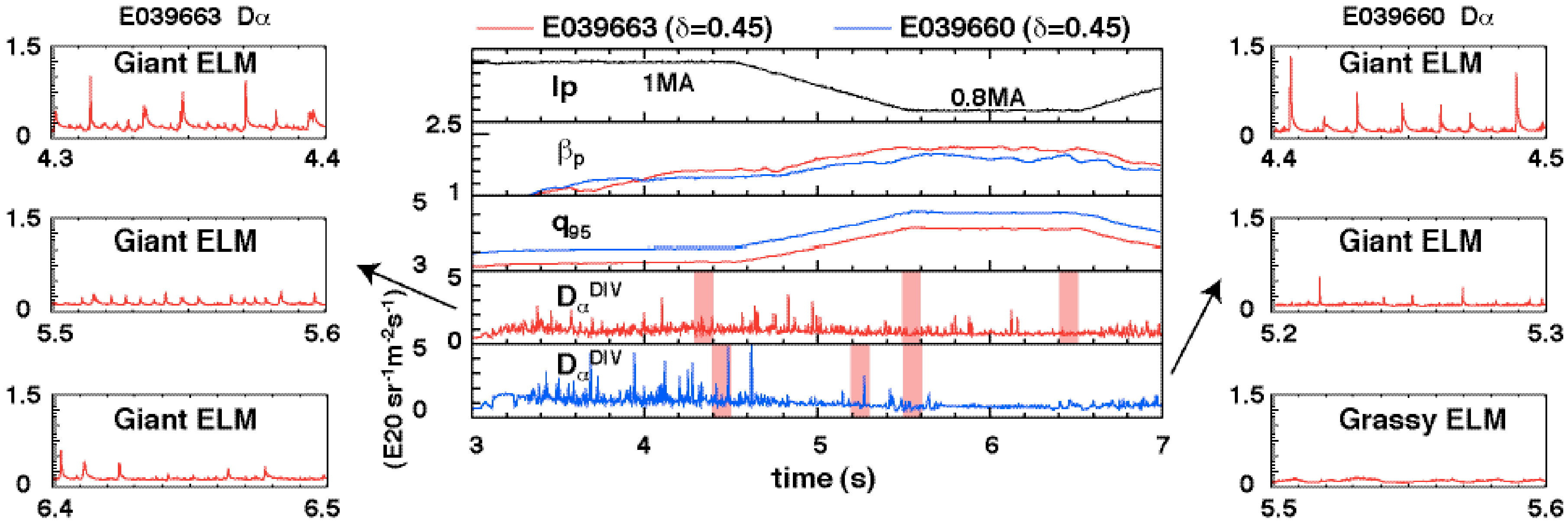
Effects of Ip ramp depend sensitively on q_{95} and □ at low q_{95} region.

JT-60U

- **In E039663, Ip ramp-down (-0.2MA/s) at slightly lower □(0.45) than E039703 (□=0.5)**
  - **"Giant" ELM became smaller and "Grassy" ELM dominant, but "Giant" ELM still existed at q95=4.1 (same as E039703).**
- **In E039660 with same □(0.45) and slightly higher q_{95}=4.5 than E039663, "Giant" ELM disappeared.**



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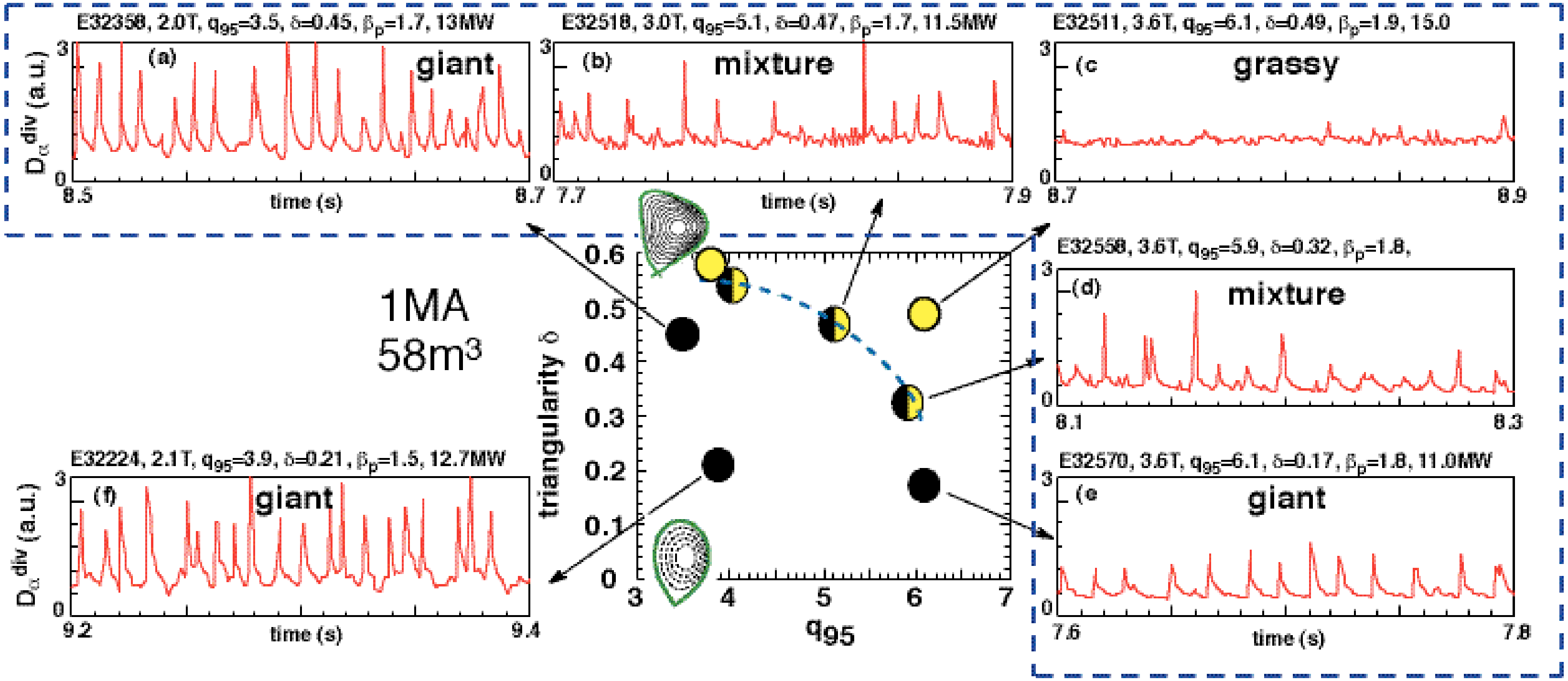

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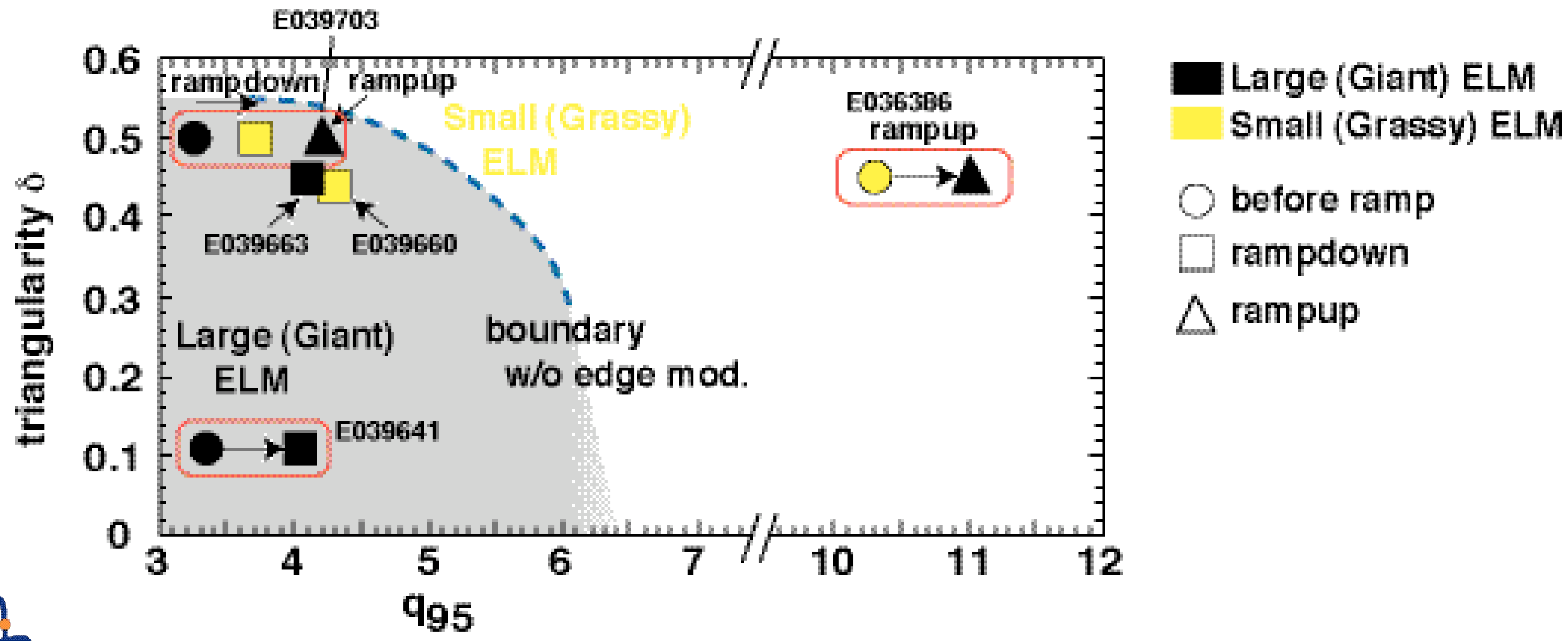
Edge current modification shifts the “Grassy” and “Giant” ELM boundary.

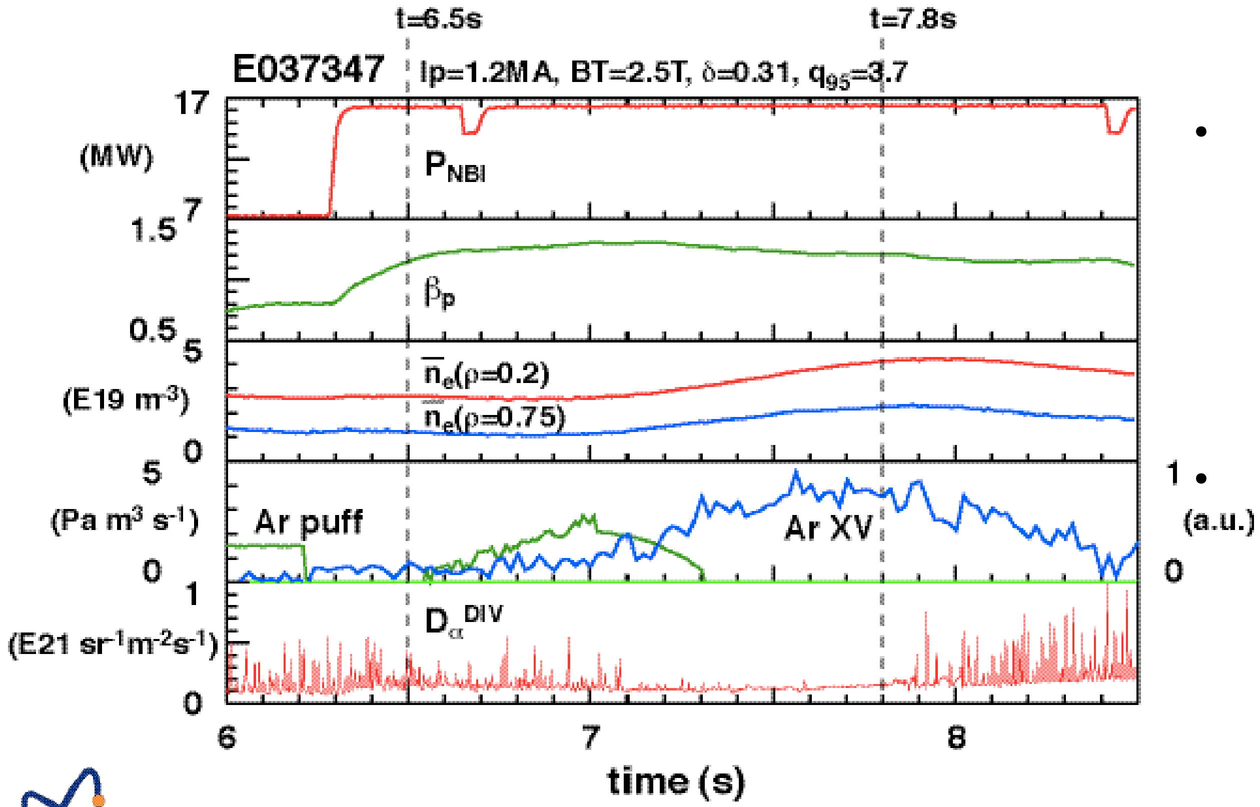
JT-60U

- Current ramp-down shifts the boundary to lower δ and q_{95}.
- Current ramp-up shifts the boundary to higher δ and q_{95}.
- Role of J_{edge} is consistent with the peeling-ballooning ELM model.



Large ELMs disappeared in the impurity seeded discharge

- Ar seeding with outer leg on the dome of W-shaped divertor
- With increasing n_e and n_{Ar}, f_{ELM}(giant) decreased and giant ELM completely disappeared.



- t=6.5s : large ELMs

  n_{ped}/n_{GW}=40%

  n_{Ar}/n_e=0.3%

  T_e^{ped}=1.2keV

  Zeff=2.8 (const.)

- t=7.8s : small ELMs

  n_{ped}/n_{GW}=60%

  n_{Ar}/n_e=0.9%

  T_e^{ped}=0.9keV

  Zeff=4.5 (const.)

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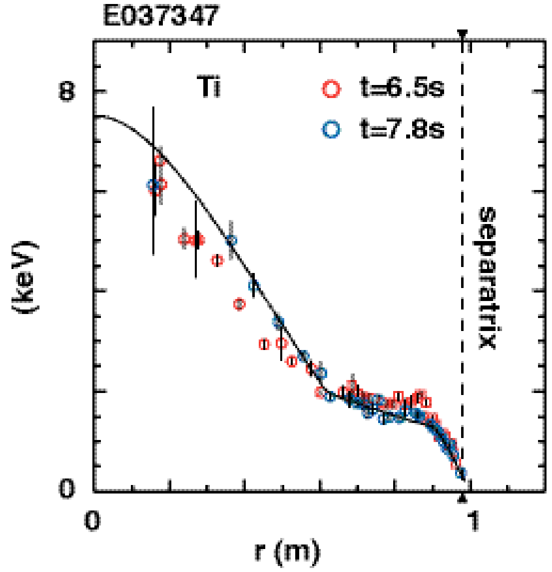
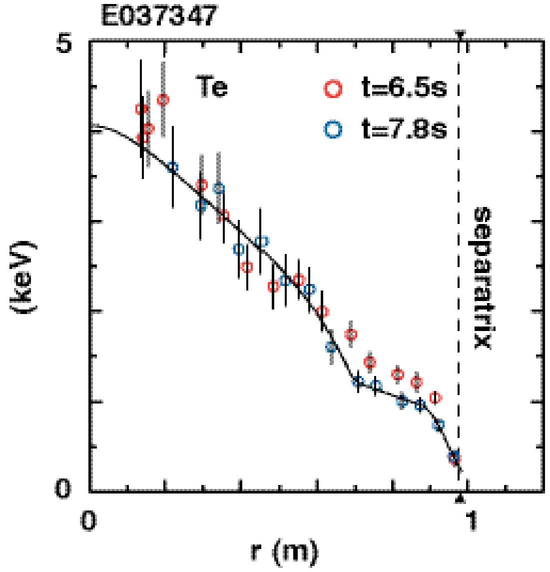
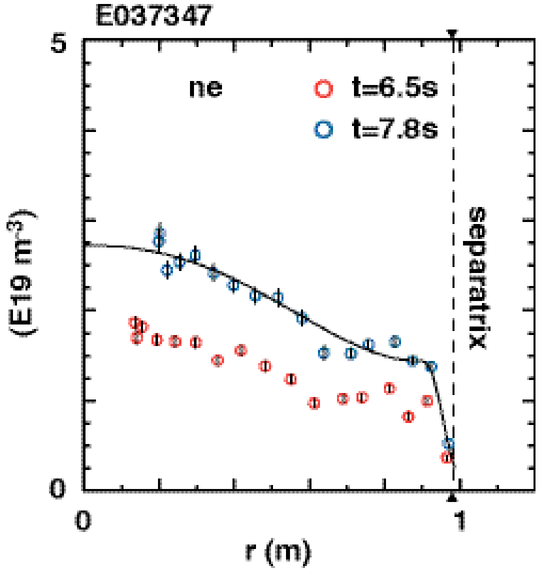
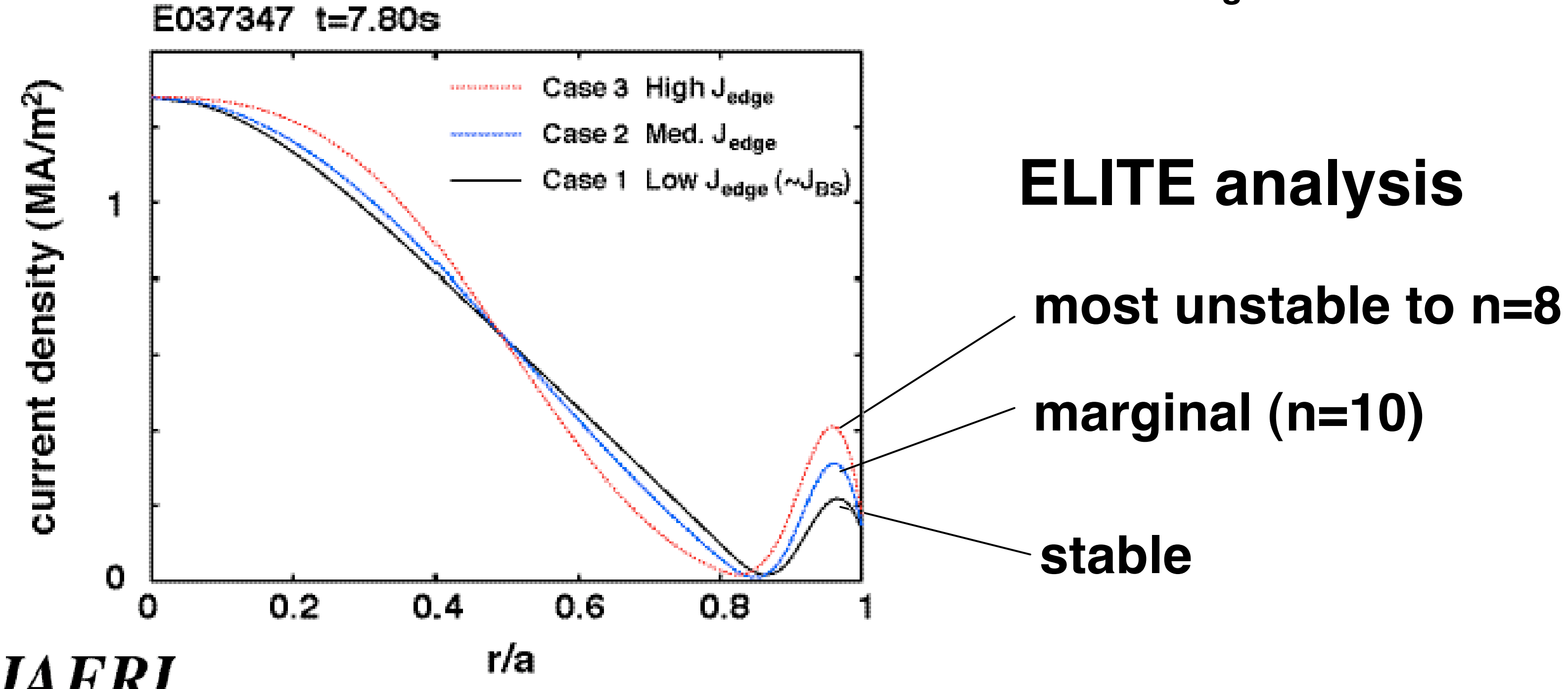

E037347
Ti
t=6.5s
t=7.8s
separatrix
(keV)
8
0
0
1
r (m)


E037347
Te
t=6.5s
t=7.8s
separatrix
(keV)
5
0
0
1
r (m)


E037347
ne
t=6.5s
t=7.8s
separatrix
(E19 m-3)
5
0
0
1
r (m)

Reduced J_{edge} may play a role in the disappearance of “Giant” ELM.

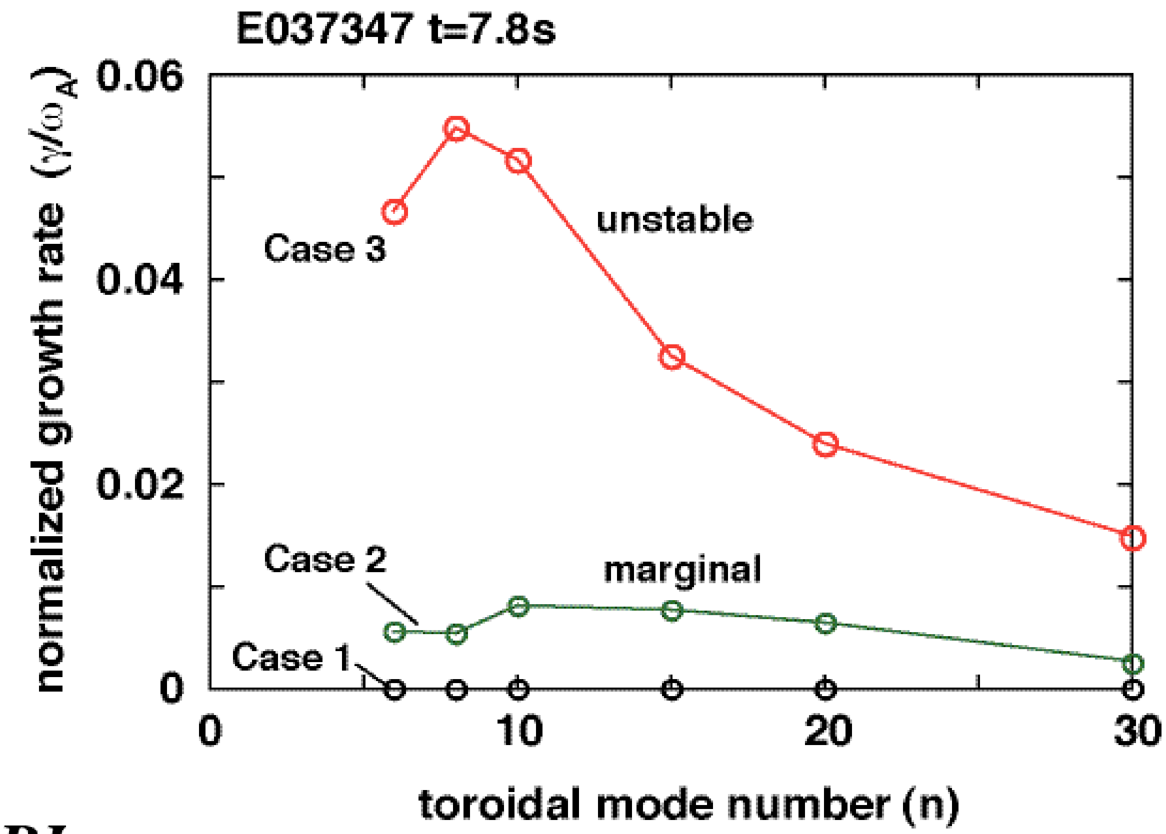
- test stability for model equilibria with different J_{edge}
- scan J_{edge} from J_{BS} (Z_{eff}=4.5) to 2xJ_{BS}
  - Ar rich edge region has higher Z_{eff} than spatial constant value.
  - Impurity and neutral particles from divertor may also affect the edge.
  - “Real” J_{BS} would be lower than the computed.
- ELITE shows peeling-ballooning stable around J_{edge}~J_{BS}



ELITE analysis

High J_{edge} case is most unstable to n=8 and has a large growth rate.

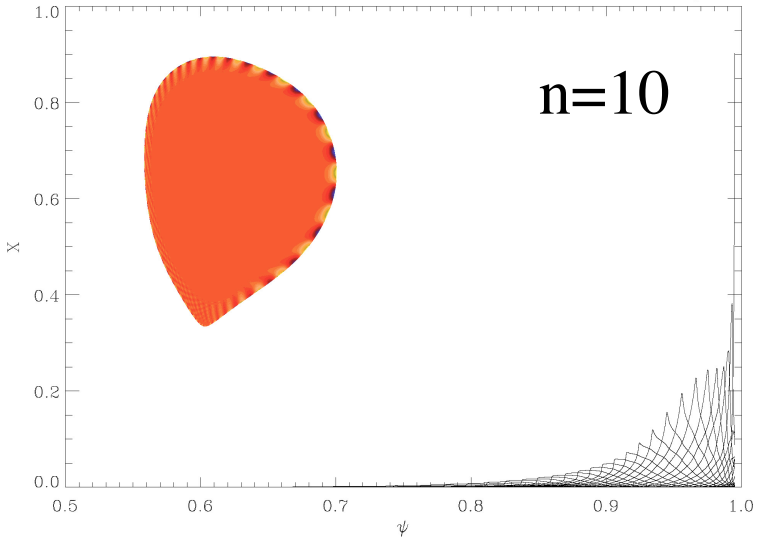
- Mode growth rate computed with ELITE
- Case 1 with $J_{edge} \sim J_{BS}$ (Z_{eff}=4.5) stable
- Case 3 with highest J_{edge} most unstable to n=8



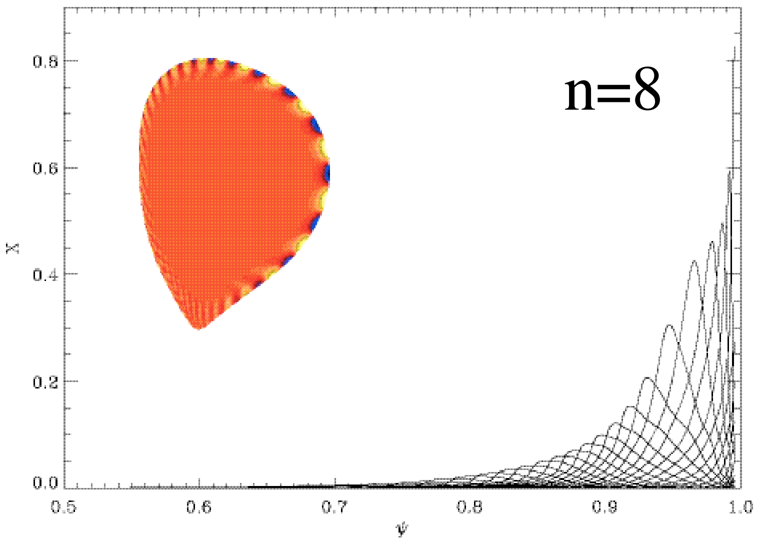
High J_{edge} case has a larger mode width

- As J_{edge} increases, most unstable mode moves to longer wavelengths and radial mode width increases
  - Stronger coupling between peeling and ballooning terms
  - Expect smaller ELMs at reduced J_{edge}, consistent with exp.

E037347 t=7.8s Case 2 medium J_{edge}



E037347 t=7.8s Case 3 High J_{edge}



Summary

In JT-60U, small ELM regime has been explored and the peeling-ballooning ELM model has been tested using different experimental approaches.

- Current ramp can shift the “Grassy” and “Giant” ELM parameter boundary. “Giant” ELM at $\square$=0.45, q_{95}=10 & $\square_p$=2 and “Grassy” ELM at $\square$=0.5, q_{95}=3.7 & $\square_p$=1.6 demonstrated.
- Effects of current ramp depend on $\square$ and q_{95}.
- Current ramp results can be explained by peeling-ballooning ELM mode.
- “Giant” ELM disappeared in impurity seeding experiments. Consistent with peeling-ballooning ELM model.