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Compatibility of Advanced Tokamak Plasma with High Density and High Radiation Loss Operation in JT-60U

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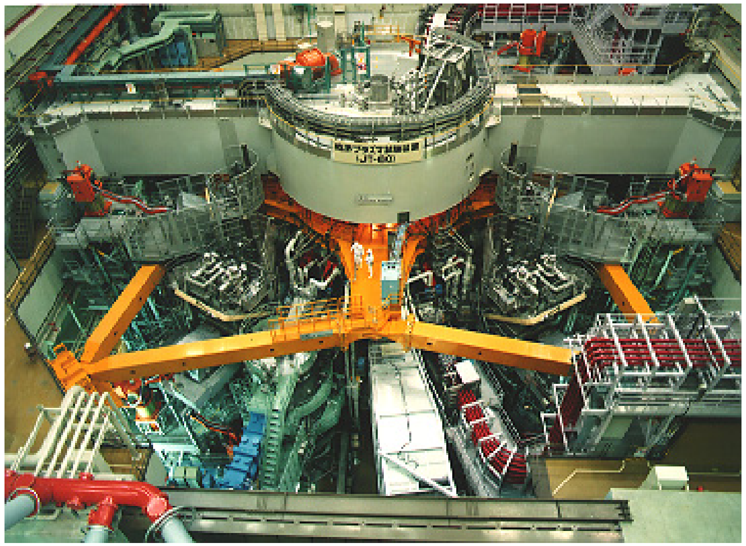

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Introduction

JT-60U

Advanced tokamak plasma with internal transport barrier (ITB)

- Reversed shear (RS) plasma
- High β_p H-mode plasma (weak positive shear)

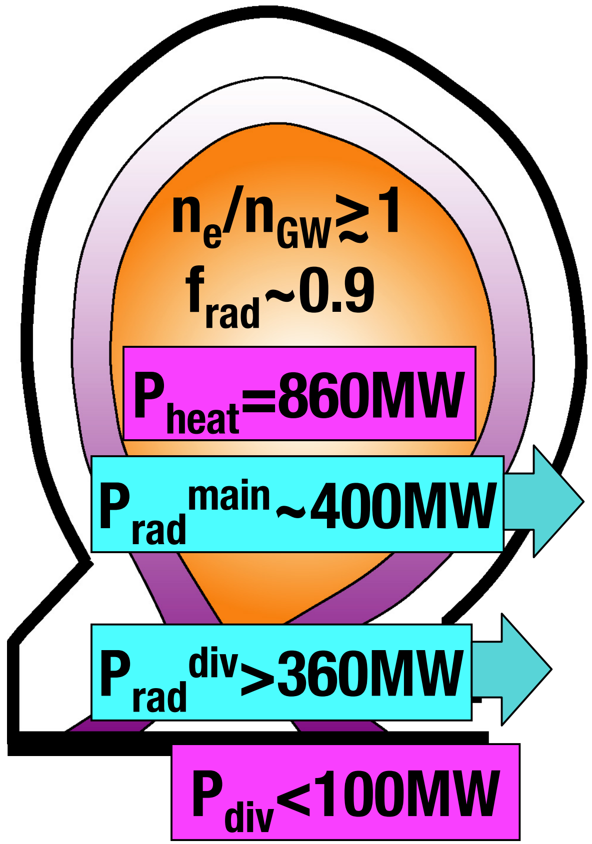
Density ITB

- Advantage for high density operation above the Greenwald density (n_{GW})
- Concern for high-Z impurity accumulation
  - Radiative cooling in the core plasma
  - Fuel dilution

Compatible ?

High density & high radiation loss operation

- Demonstration of high density operation above n_{GW}
- What happens with strong impurity accumulation ?



Example for A-SSTR2

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1. Extension of operation regime
    - High density with high confinement and high radiation loss fraction
2. Reversed shear plasma
    - High density operation
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    - Mechanism of confinement improvement
    - Impurity transport
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1. Extended regime to high density

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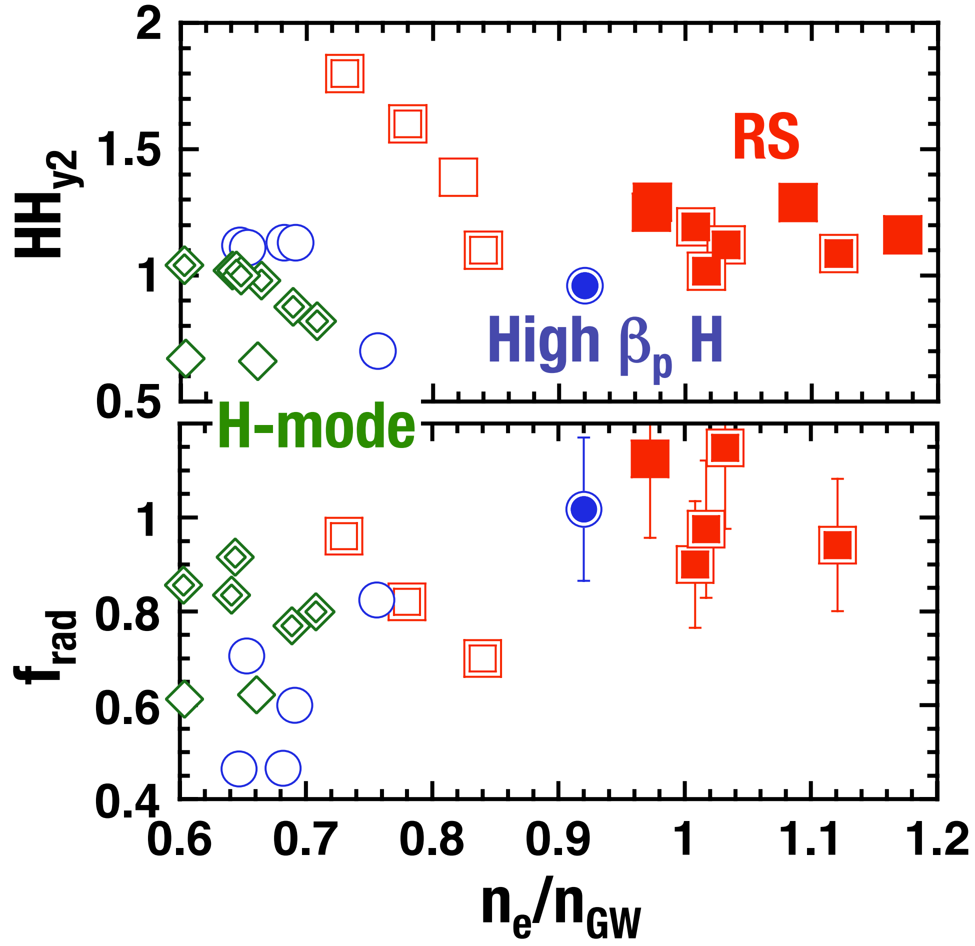
- Operation regime has been extended to high density ($n_e/n_{GW} \gtrsim 1$) with high confinement ($HH_{y2} \gtrsim 1$) and high radiation loss fraction ($f_{rad} > 0.9$).



Key : ITB control

- Fueling (NB, HFS pellet and gas-puffing)
- Heating
- Impurity seeding
- (Intrinsic impurity)
- Plasma configuration

Closed : New, Open : Old

Double lines : w impurity seeding

2. Reversed shear plasma

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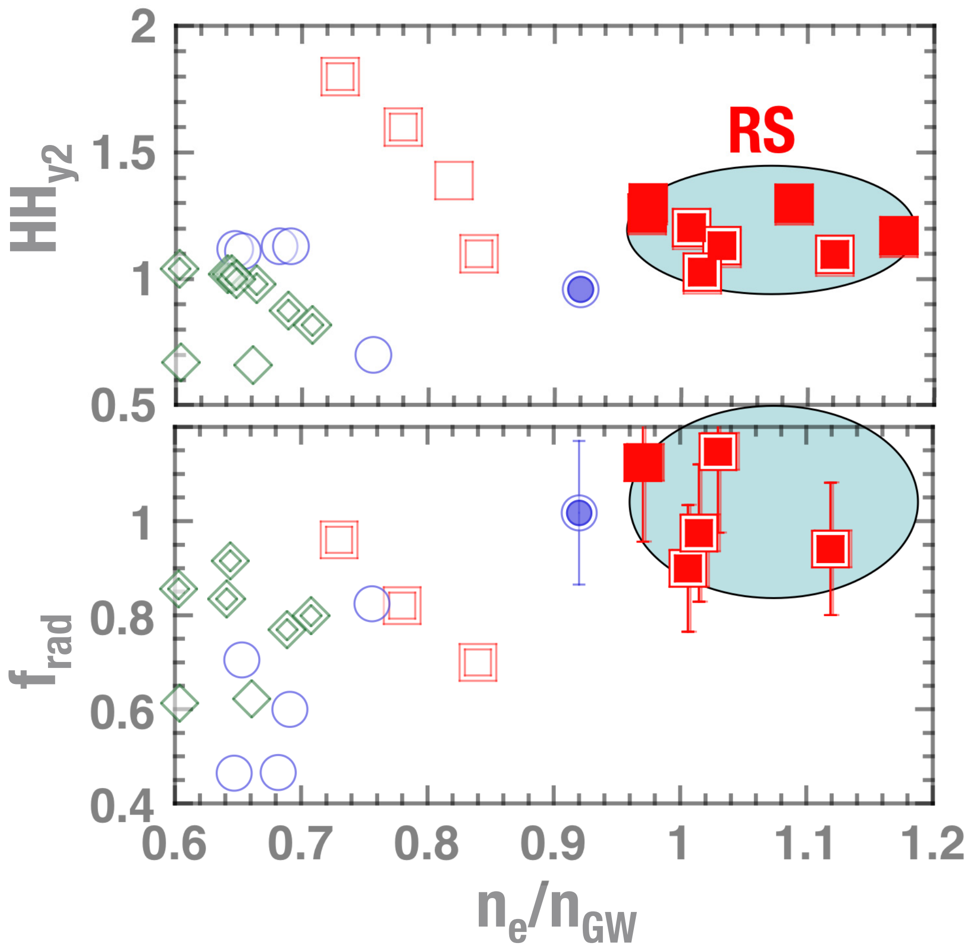
- High density operation
- Impurity accumulation
- Enhancement of divertor radiation by impurity seeding



High n_e above n_{GW} in RS plasma

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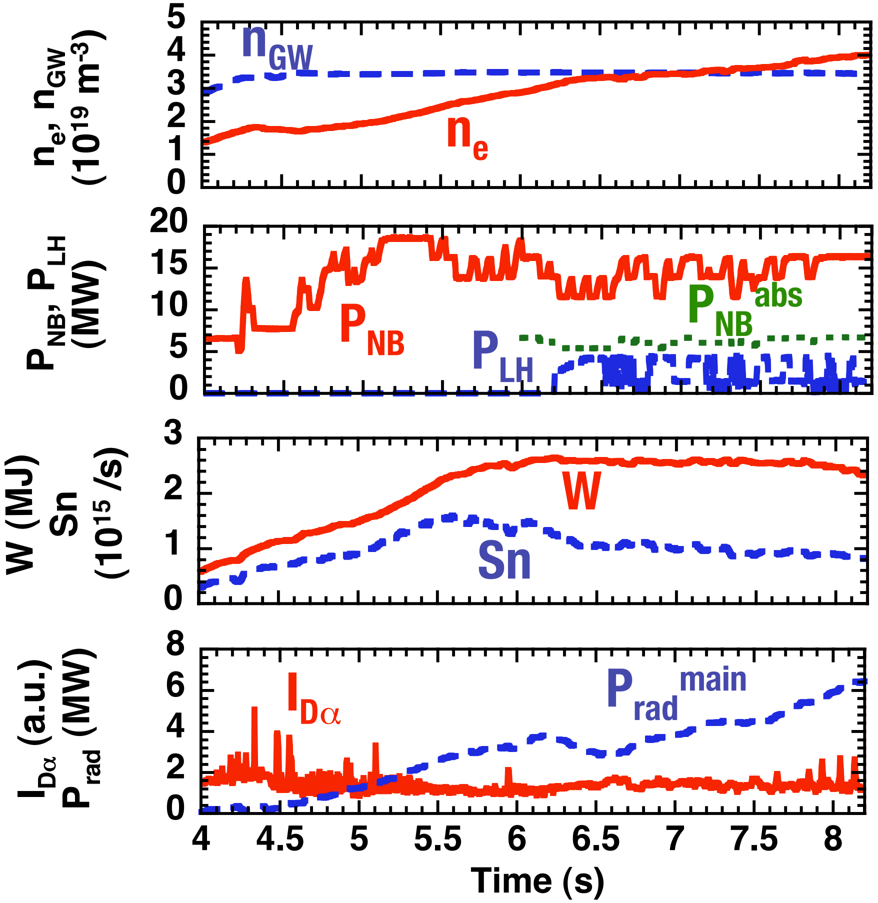
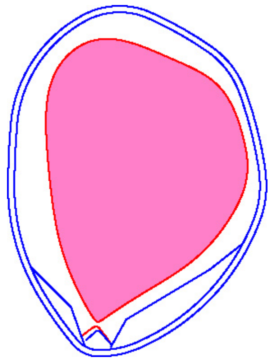
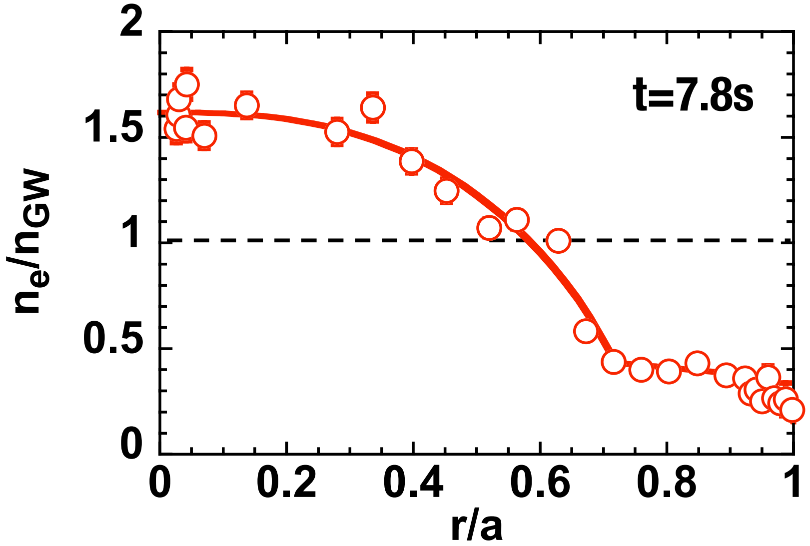
- Large Vp with NB and LH heating, and NB fueling only.
  - HH_{y2}=1.3, β_N=2 and f_{BS}~0.7 at n_e/n_{GW}=1.1.
  - $n_e(0)/n_{GW}$=1.6 with low n_e^{edge}/n_{GW} (~0.4) by tailoring n_e ITB.
  - Increase in P_{rad}^{main} (P_{rad}^{main}/P_{abs}~0.65) due to impurity accumulation.





I_p=1.0 MA, B_T=2.5 T, q_{95}=6.1, δ=0.45, V_p=78 m^3



Increase in n_e with constant T_e inside ITB at small outer-gap

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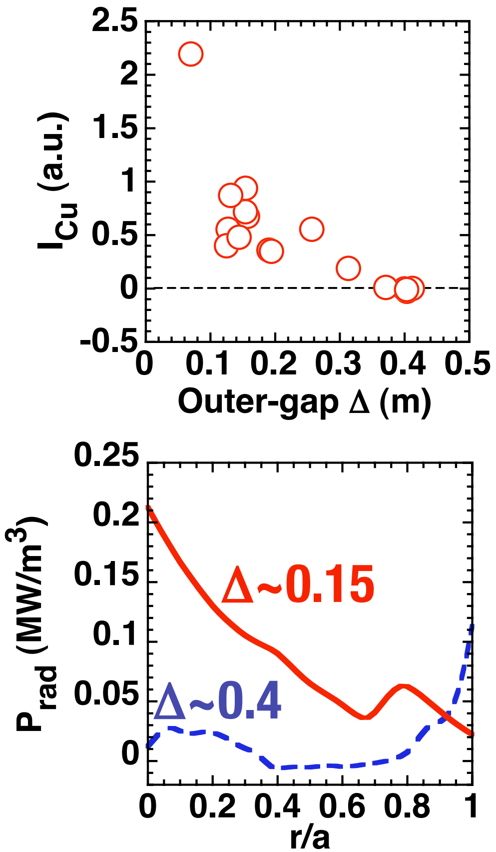
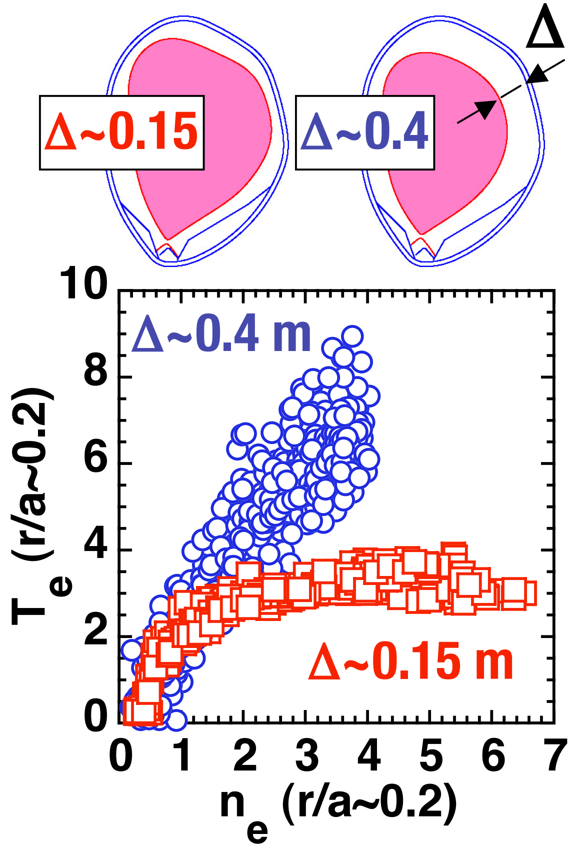
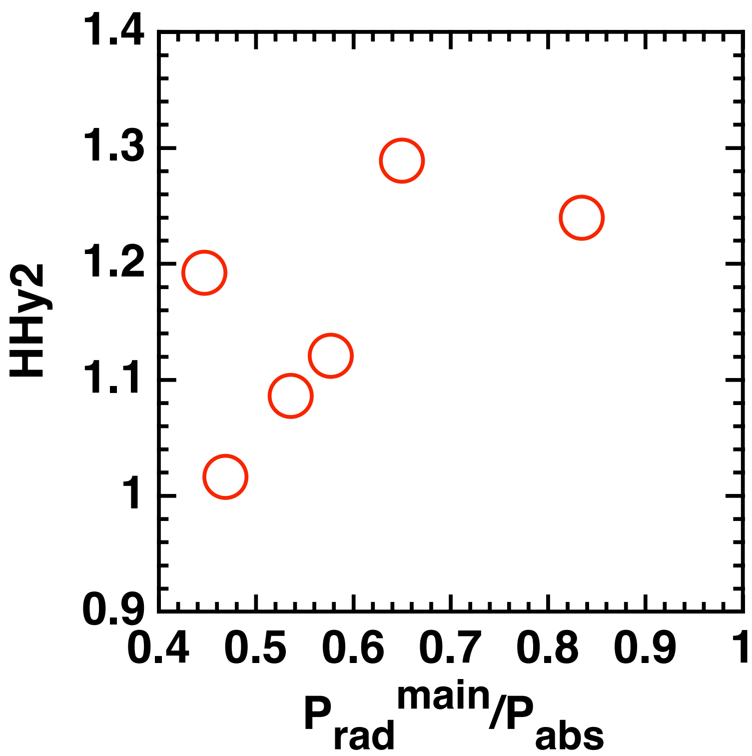
- Cu line intensity increases with decreasing the outer-gap (Δ).
- Off-axis heating, radiative cooling and NB fueling could be responsible for relationship between central n_e and T_e.
- $HH_{y2}=1.2$ with $P_{rad}^{main}/P_{abs}\sim 0.8$.



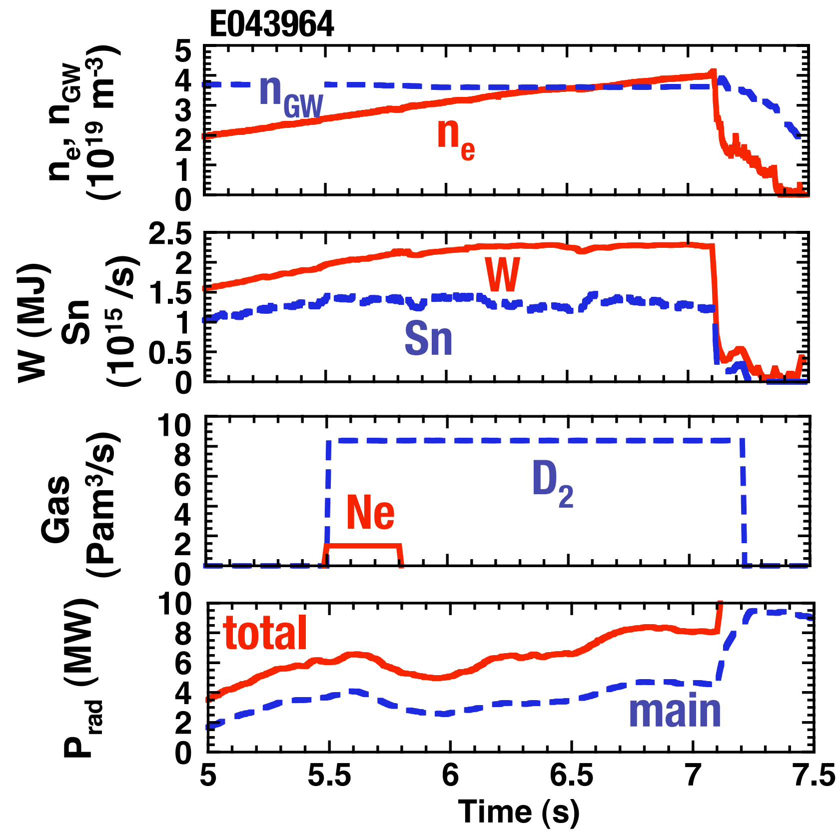


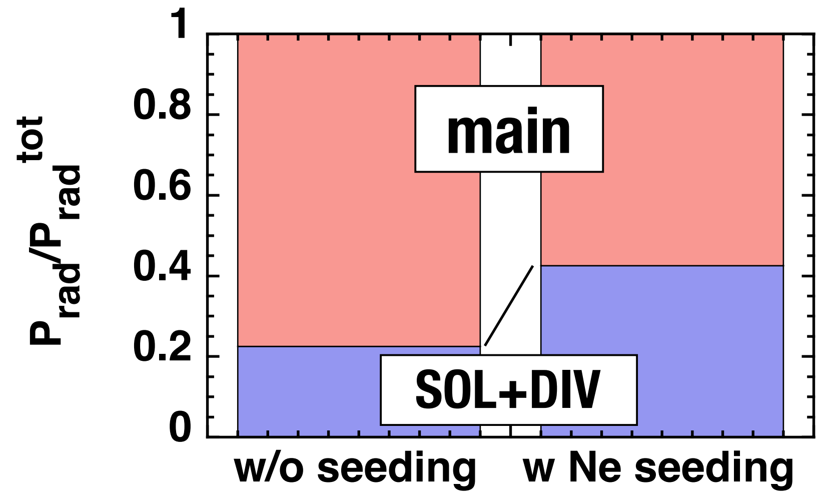


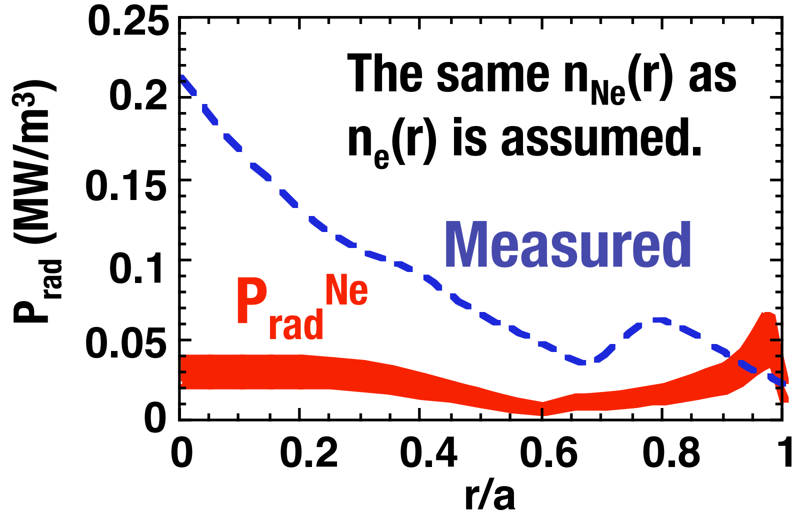
Enhanced divertor radiation by Ne seeding

JT-60U

- Ne puff with D_2 gas at Δ=0.13 m.
  - HH_{y2}=1.1, f_{rad}=0.93 at n_e/n_{GW}=1.1.
  - Divertor radiation ratio increases from ~20% w/o seeding to 40% with Ne seeding.
  - Small contribution of Ne to P_{rad}^{main}.







3. High β_p H-mode plasma

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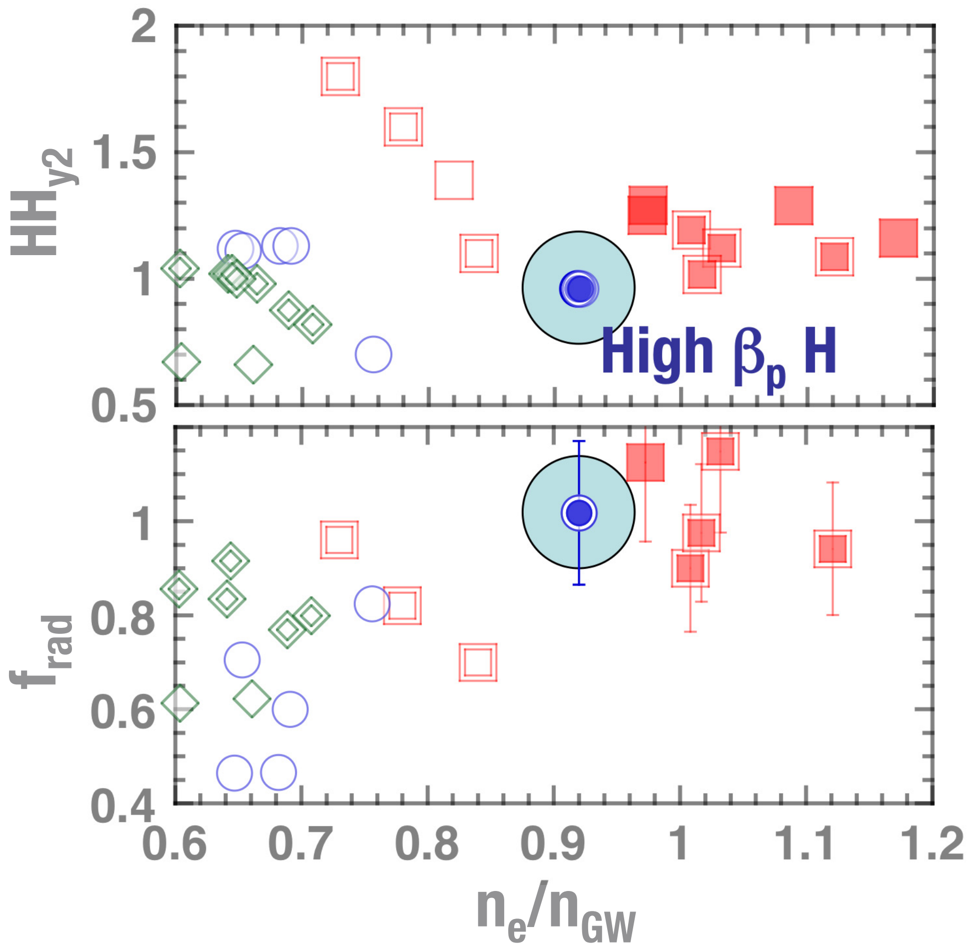
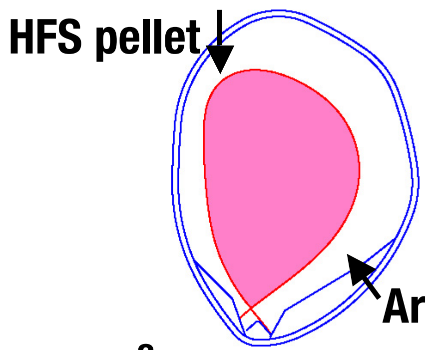
- High density operation with HFS pellets and impurity seeding
- Mechanism of confinement improvement
- Impurity transport



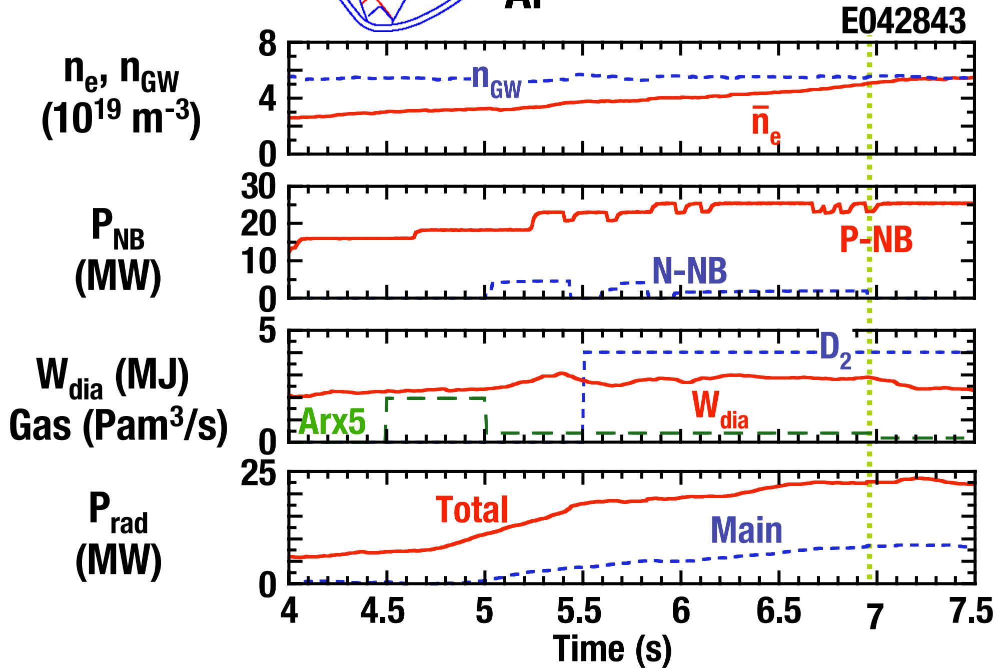
High HH_{y2} and high f_{rad} by Ar seeding and HFS pellets

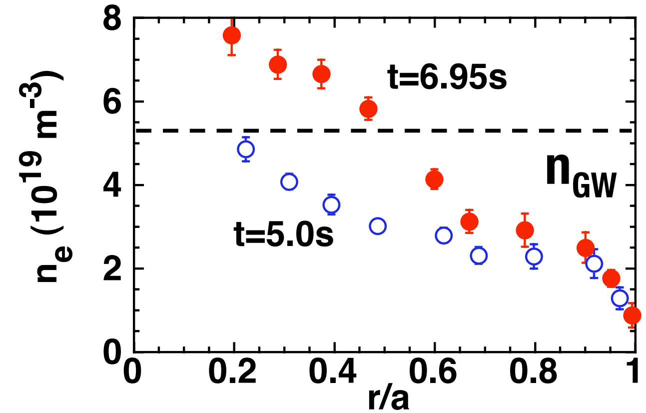
JT-60U

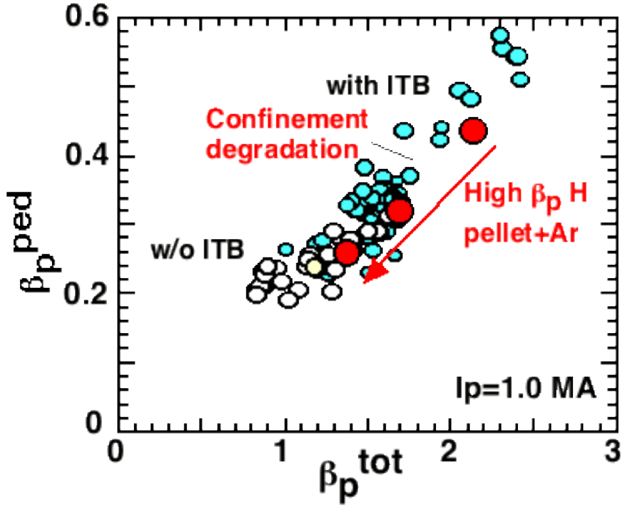
- Ar seeding and HFS pellet with small D_2 gas-puffing in small Vp.
  - HH_{y2}=0.96 and f_{rad}~1 at n_e/n_{GW}~0.92 at t=6.95s.
  - Peaking of $n_e(r)$ and enhanced pedestal pressure.



I_p=1.0MA, B_T=3.6 T,
q_{95}=6.2, δ=0.37



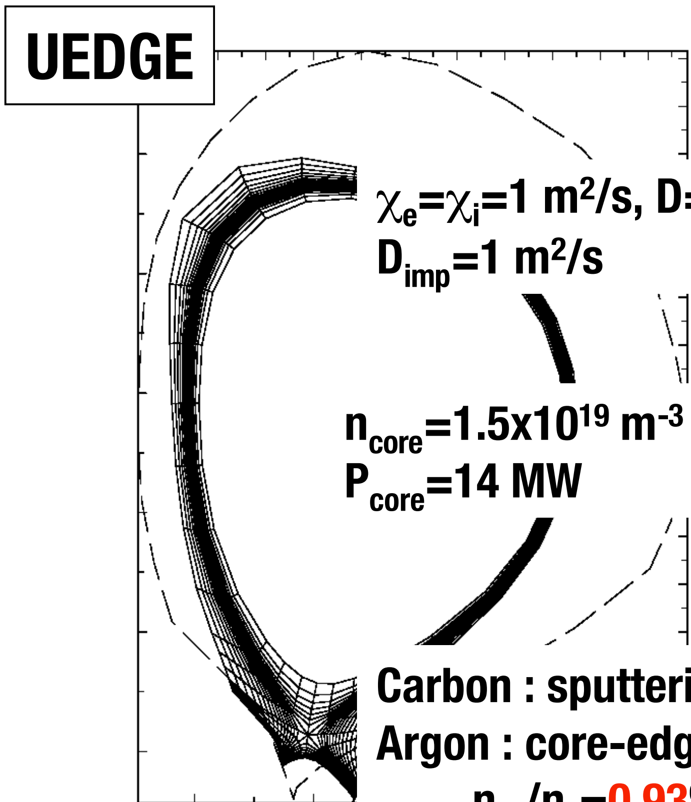




Central radiation is ascribed to Ar

JT-60U

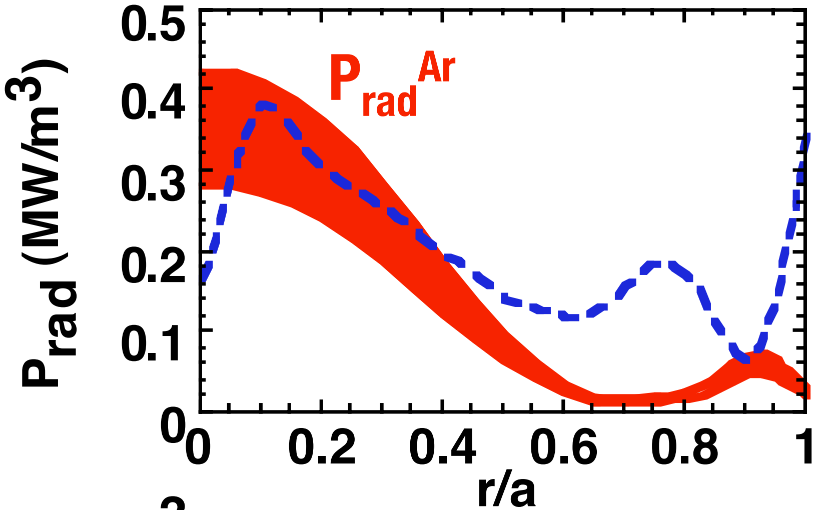
- $n_{Ar}(r)$ evaluated from soft x-ray profile is more peaked by a factor of 2 inside the ITB than $n_e(r)$.
- n_{Ar}/n_e~1% in the center and 0.5% outside the ITB from Bremsstrahlung.
- P_{rad}^{Ar}~0.4 $P_{rad}^{SOL+DIV}$.

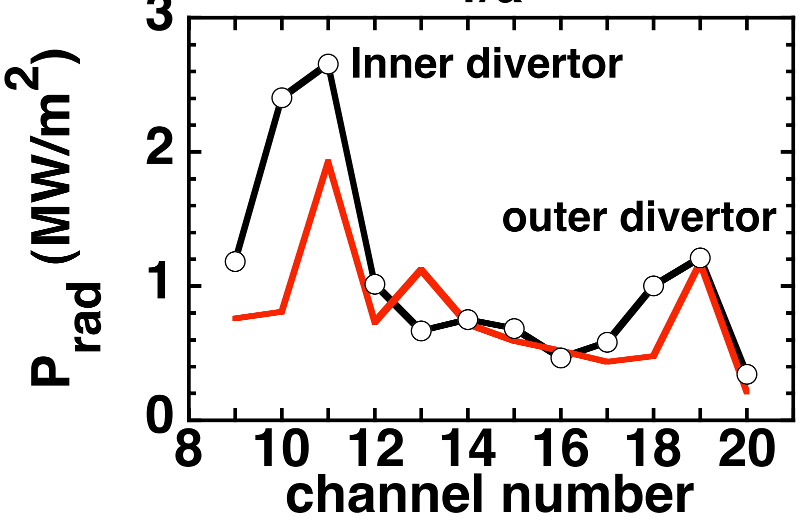


$\chi_e=\chi_i=1$ m²/s, D=0.25 m²/s, $D_{imp}=1$ m²/s

$n_{core}=1.5\times10^{19}$ m^{-3}
$P_{core}=14$ MW

Carbon : sputtering (Haasz rate)
Argon : core-edge density
$n_{Ar}/n_e=0.93\%$





Core radiation loss from Ar can be compensated with slightly enhanced confinement in a fusion reactor.

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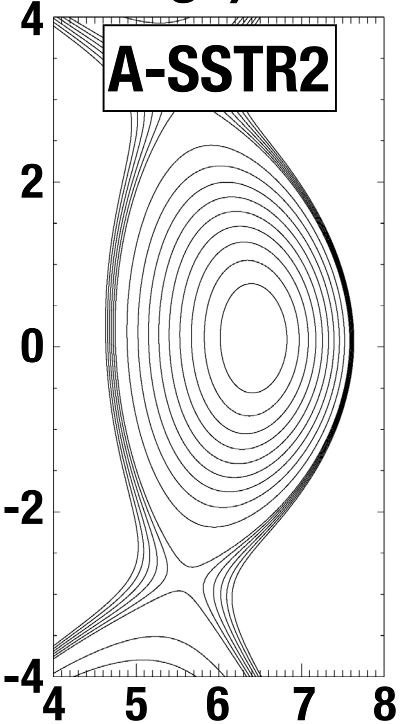
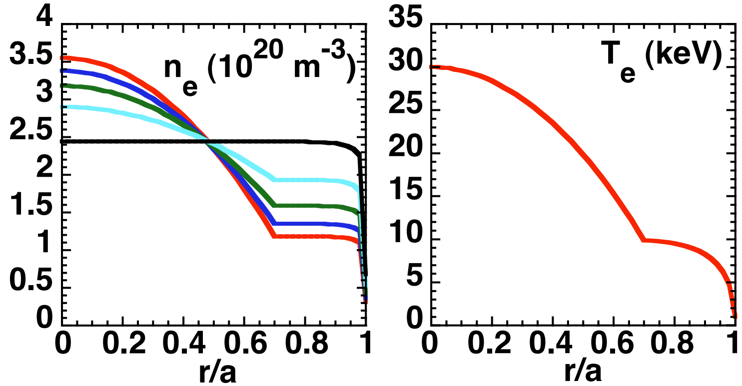
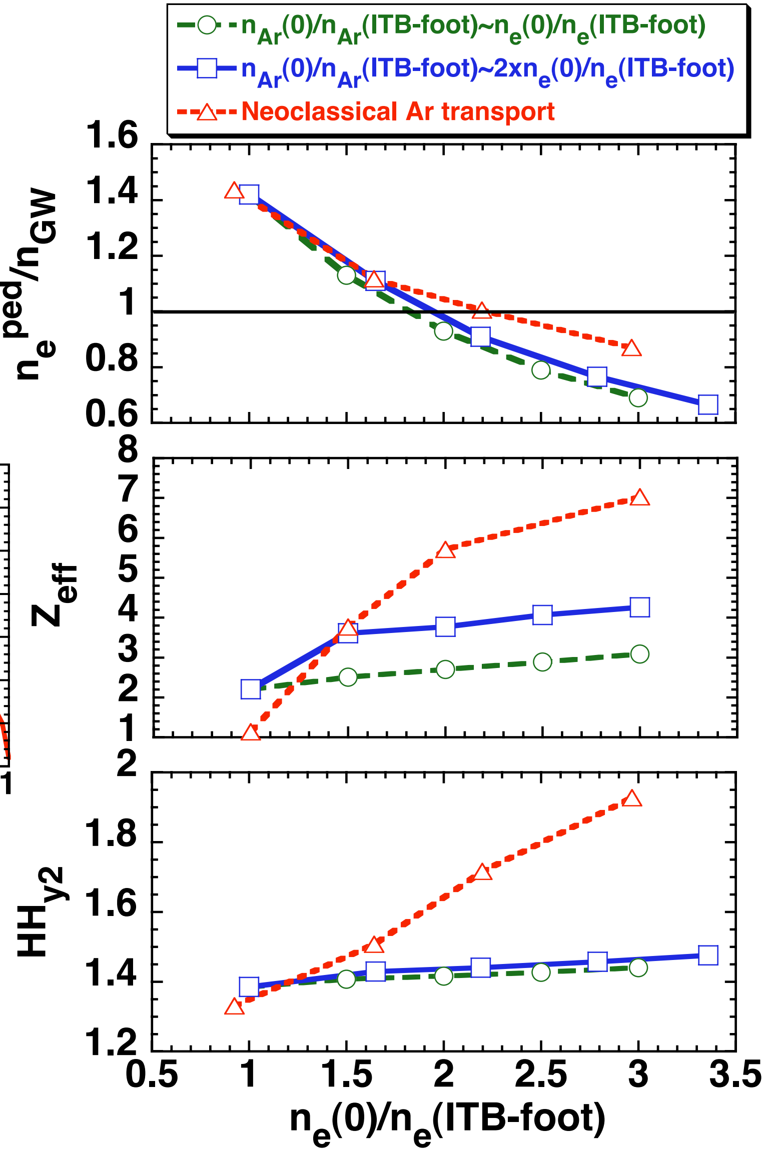
- Edge density can be reduced by density peaking.
- HH_{y2}=1.4-1.5 with more peaked $n_{Ar}(r)$ by a factor of 2 than $n_e(r)$.
- Z_{eff}=4 for 400MW radiation (0.5% Ar at edge).





I_p=12MA, B_T=11T, R_p=6.2m, a=1.5m, Fusion output ~4GW, P_{rad}^{main}~400MW, Aux. heating=60MW



Summary

JT-60U

- Operation regime of advanced tokamak plasmas has been extended.
  - RS : n_e/n_{GW}=1, HH_{y2}=1.2, P_{rad}^{main}/P_{abs}~0.8.
    n_e/n_{GW}=1.1, HH_{y2}=1.1, f_{rad}=0.93 with enhanced P_{rad}^{div} by Ne seeding
  - High β_p H : n_e/n_{GW}=0.92, HH_{y2}=0.96, f_{rad}~1 with HFS pellet and Ar seeding
- In both RS and high β_p H-mode plasmas, the high n_e/n_{GW} is achieved due to a peaked density profile inside the ITB.
- Ar accumulation by a factor of 2, as observed in the high β_p H-mode plasma, is acceptable in a fusion reactor for impurity seeding.
- Future work
  - Density ITB formation under the low central fueling.
  - Optimization of radiation ratio for main and Div.&SOL plasmas.