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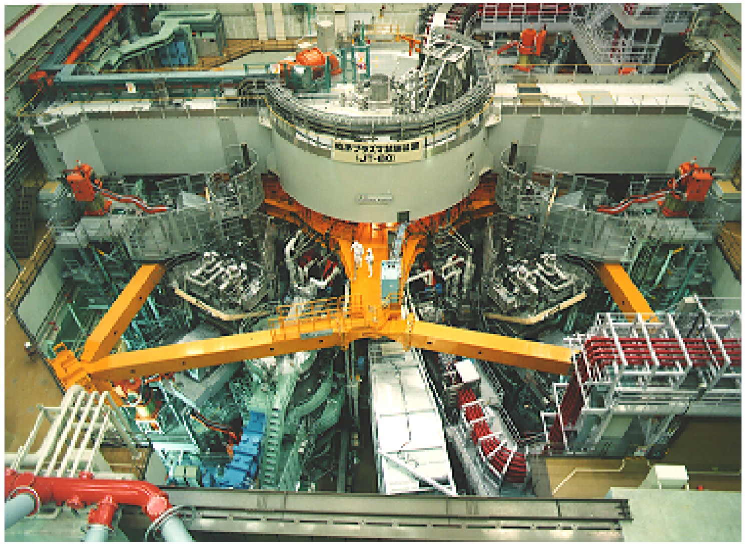
Compatibility of Advanced Tokamak Plasma with High Density and High Radiation Loss Operation in JT-60U

H. Takenaga 1), N. Asakura 1), H. Kubo 1), S. Higashijima 1), S. Konoshima 1), T. Nakano 1), N. Oyama 1), T. D. Rognlien 2), G. D. Porter 2), M. E. Rensink 2), S. Ide 1), T. Fujita 1), T. Takizuka 1), Y. Kamada 1), Y. Miura 1) and the JT-60 Team 1)



1) Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken, 311-0193, Japan

2) Lawrence Livermore National Laboratory, Livermore, CA 94551-9900, USA

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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)

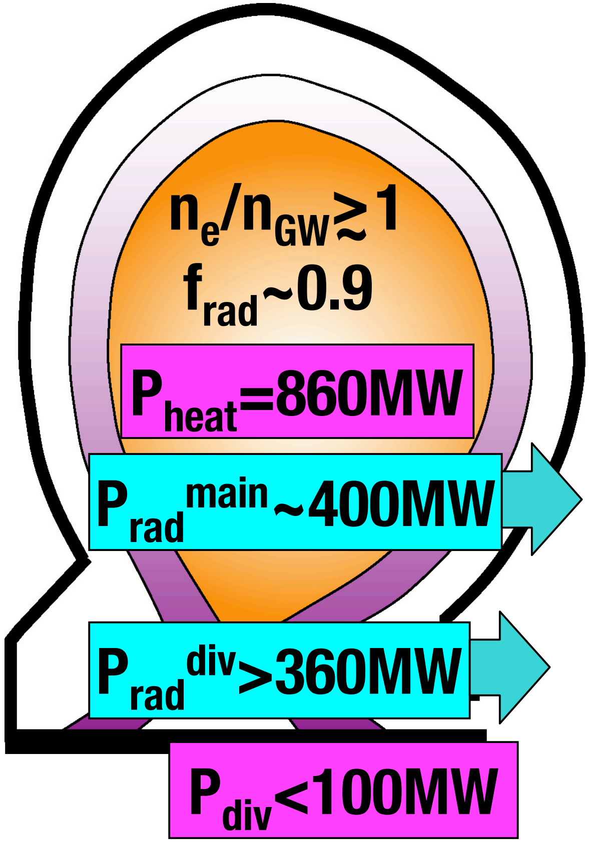
Density ITB

- 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

Contents

1. Extension of operation regime

- High density with high confinement and high radiation loss fraction

2. Reversed shear plasma

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

3. High β_p H-mode plasma

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

4. Discussion of applicability of impurity seeding to fusion reactor

- Dependence on density peaking and impurity accumulation

5. Summary

1. Extended regime to high density

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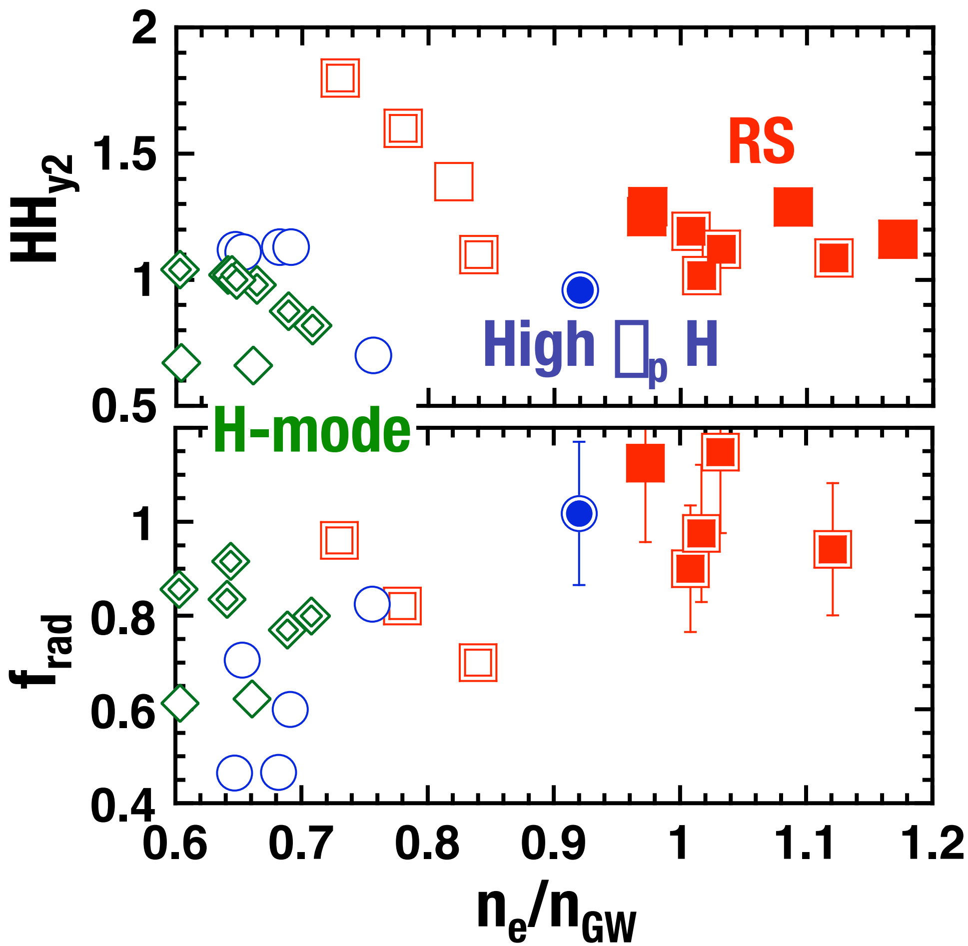
- Operation regime has been extended to high density ($n_e/n_{GW} \gtrsim 1$) with high confinement ($HH_{y2} \gtrsim 1$) and high radiation loss fraction ($f_{rad}>0.9$).



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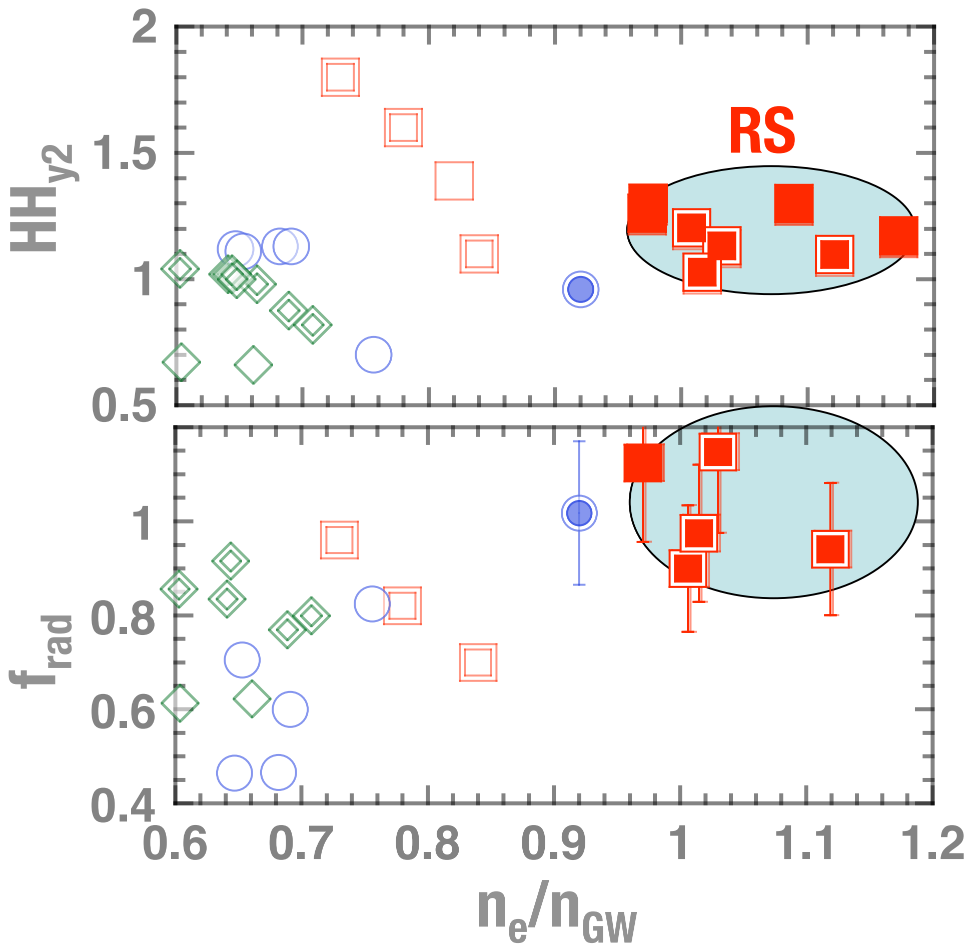
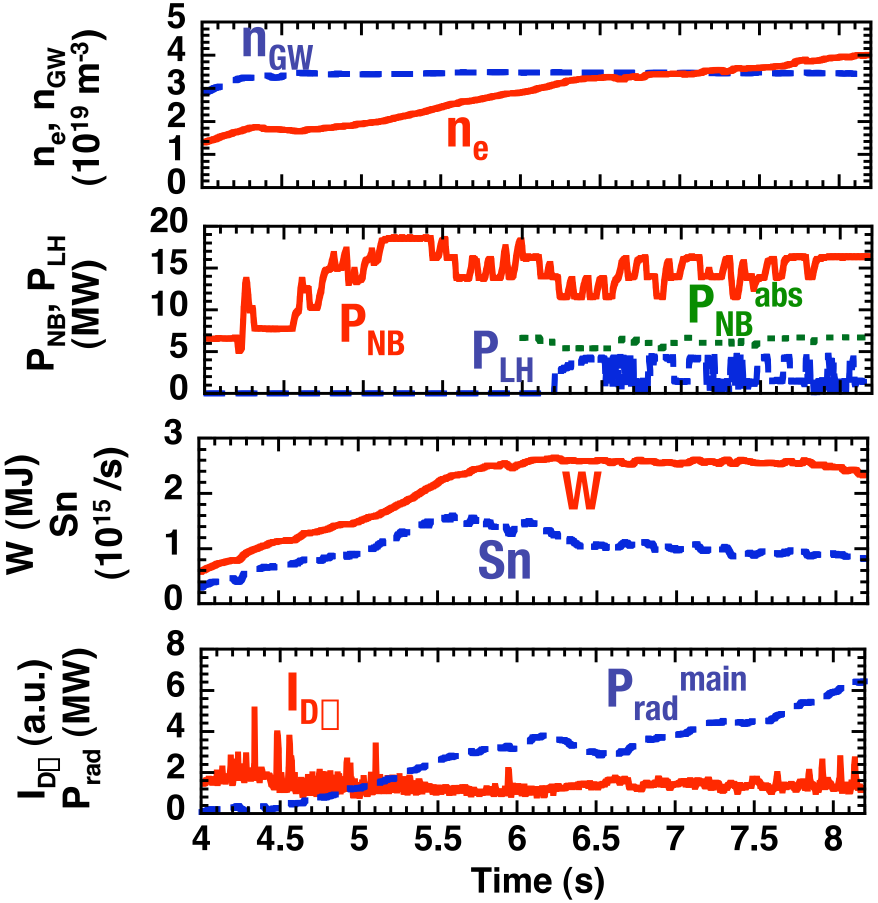
- High density operation
- Impurity accumulation
- Enhancement of divertor radiation by impurity seeding

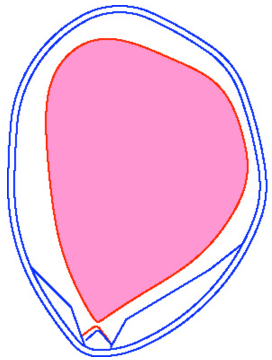


High n_e above n_{GW} in RS plasma

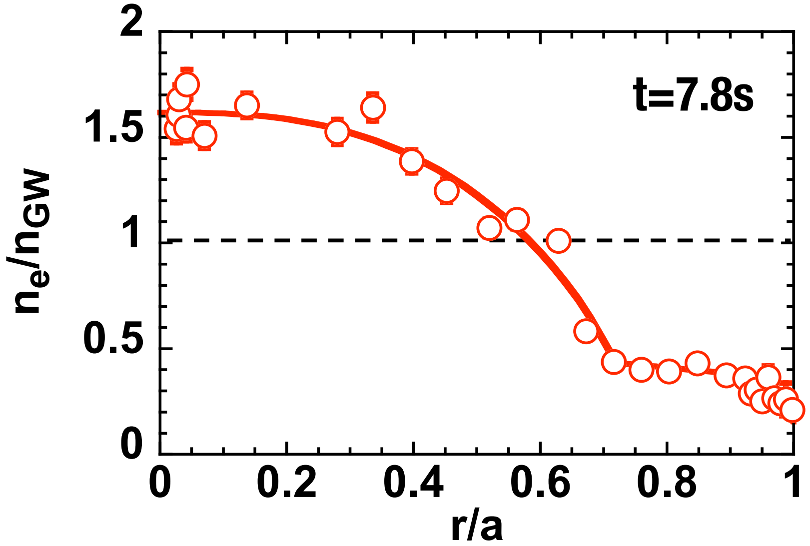
JT-60U

- 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.





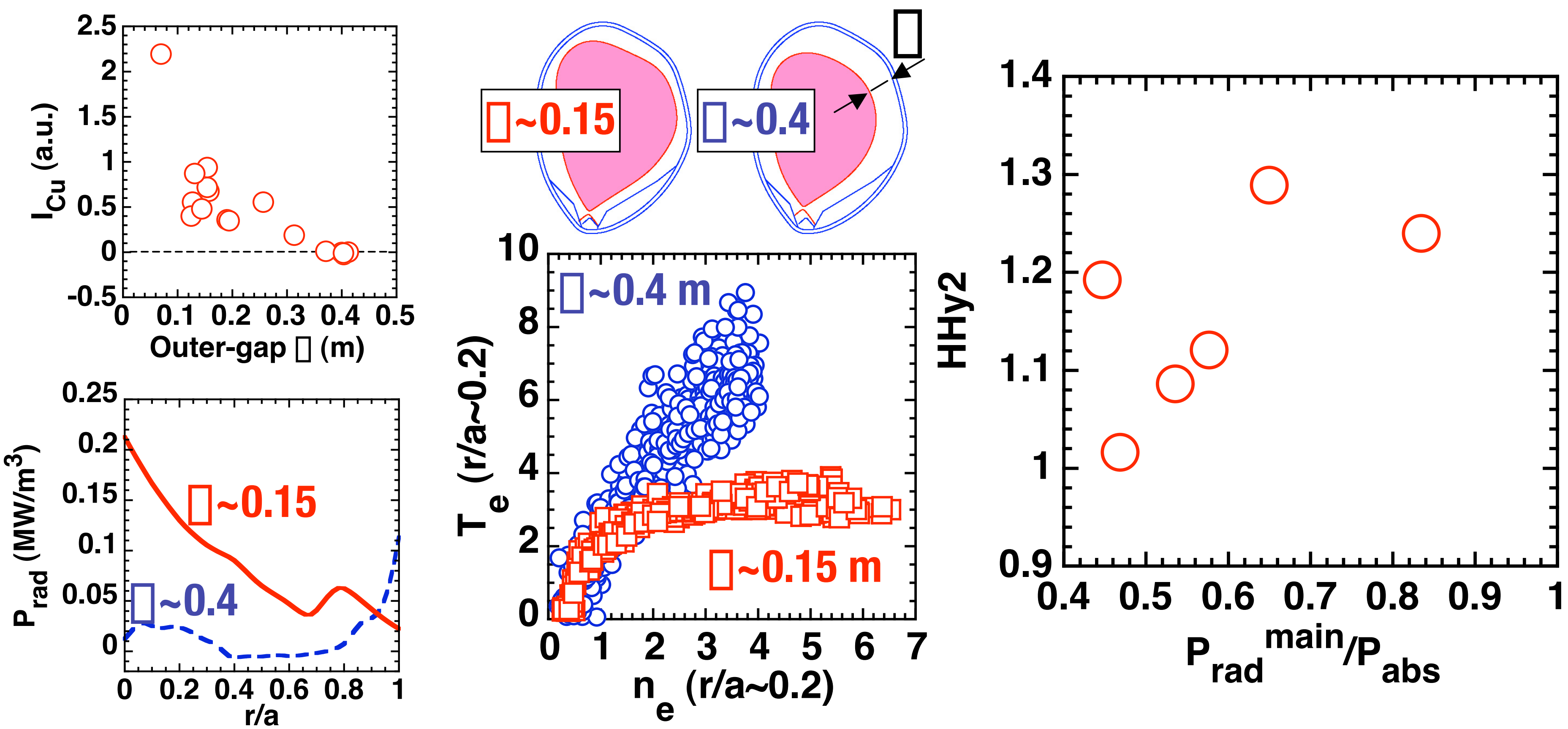
I_p=1.0 MA, B_T=2.5 T,
q_{95}=6.1, δ=0.45,
V_p=78 m^3



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

JT-60U

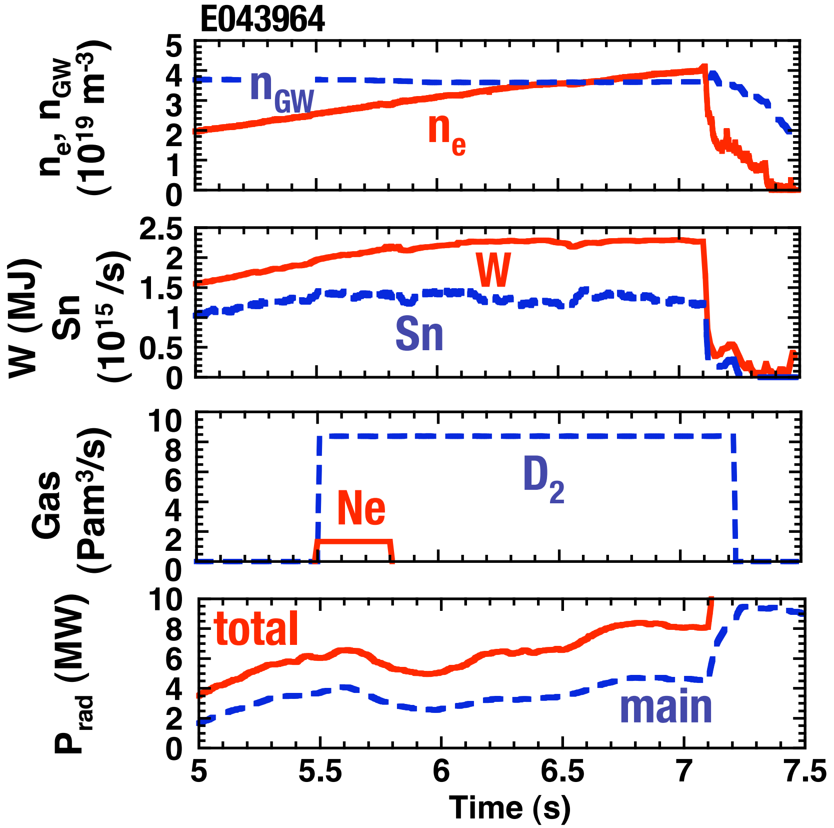
- Cu line intensity increases with decreasing the outer-gap (☐).
- Off-axis heating, radiative cooling and NB fueling could be responsible for relationship between central n_e and T_e.
- HH_{y2}=1.2 with P_{rad}^{main}/P_{abs}~0.8.

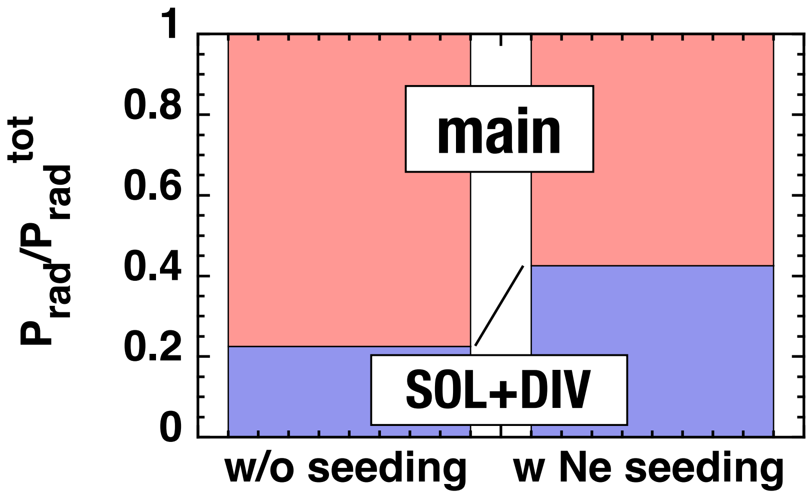


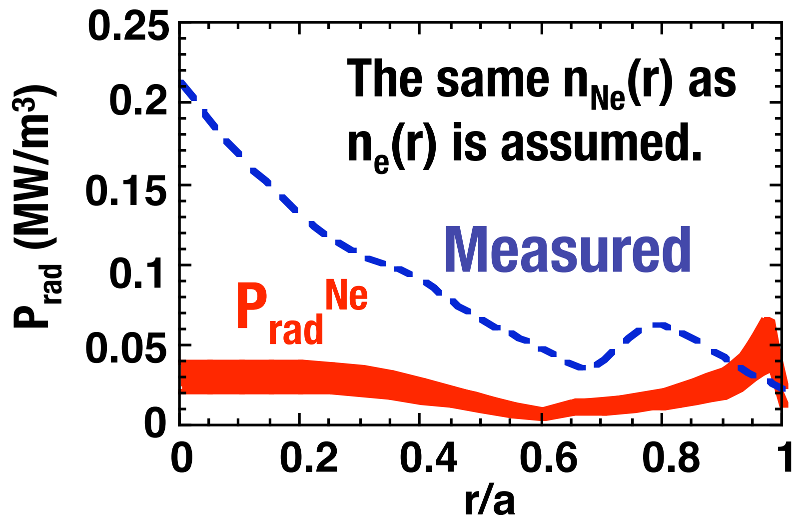
Enhanced divertor radiation by Ne seeding

JT-60U

- Ne puff with D_2 gas at □=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 □$_p$ H-mode plasma

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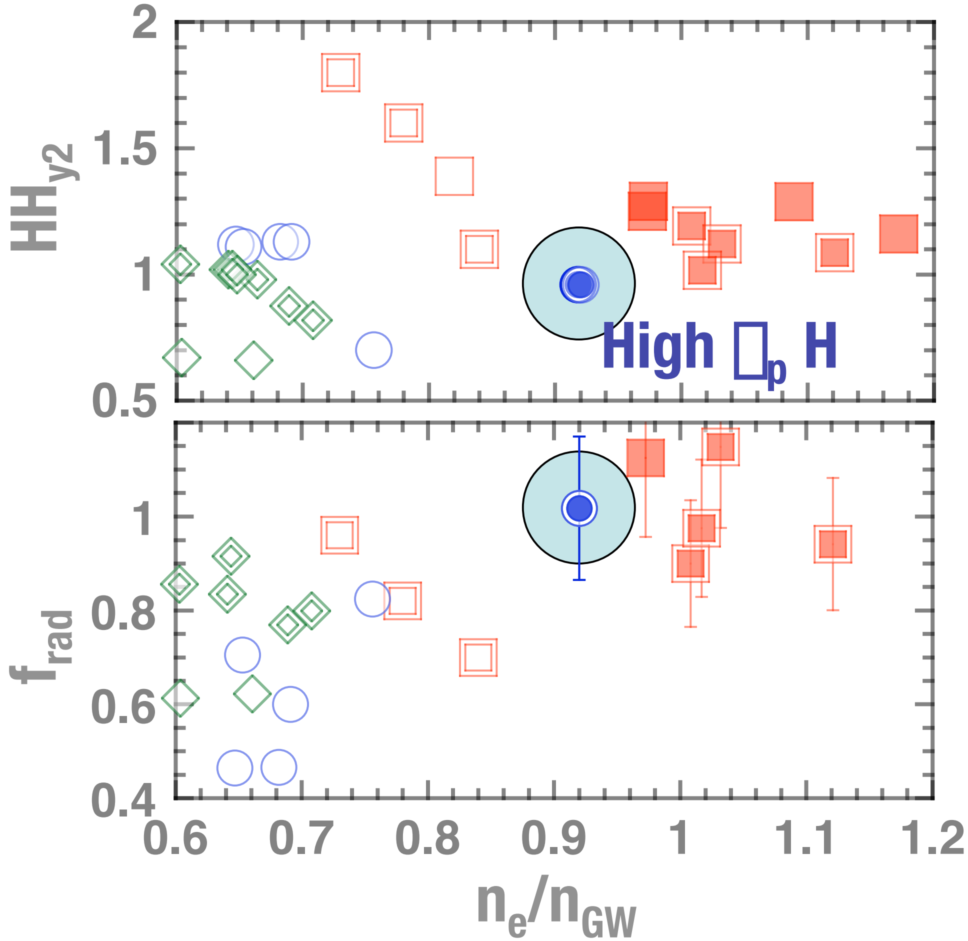
- High density operation with HFS pellets and impurity seeding
- Mechanism of confinement improvement
- Impurity transport



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

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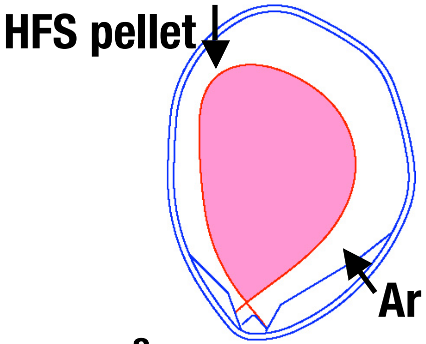
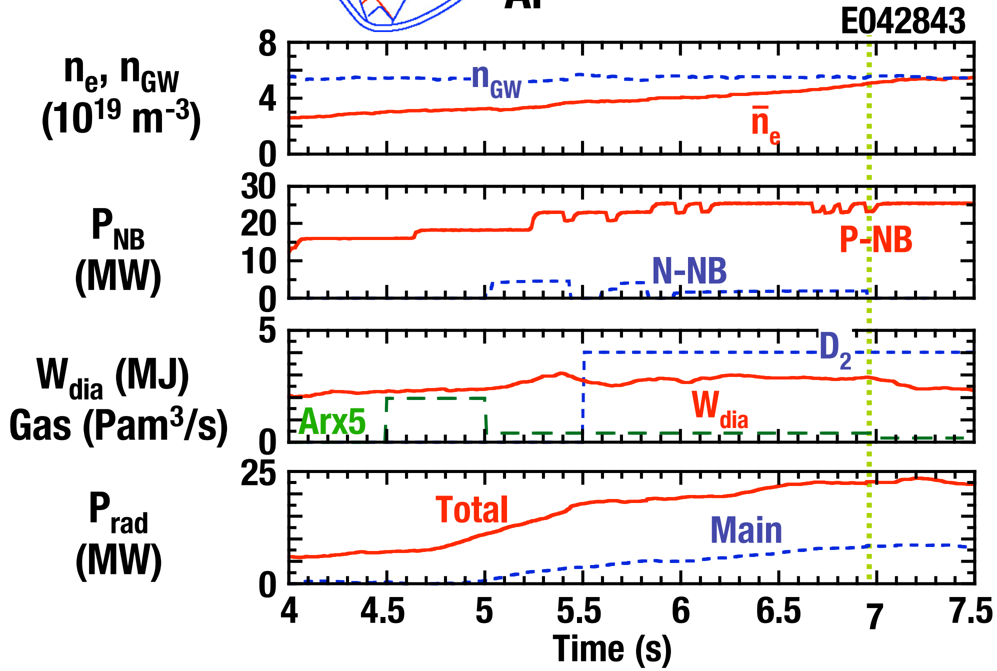
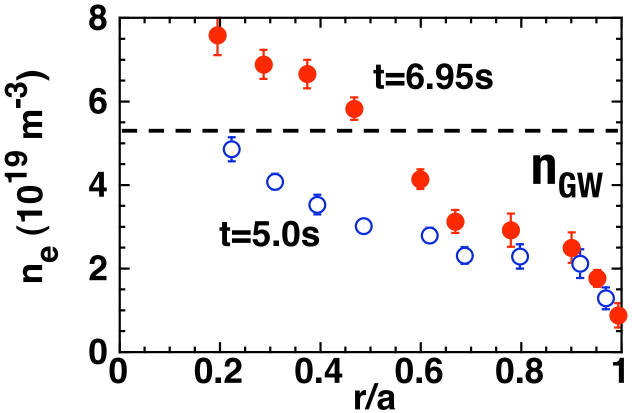
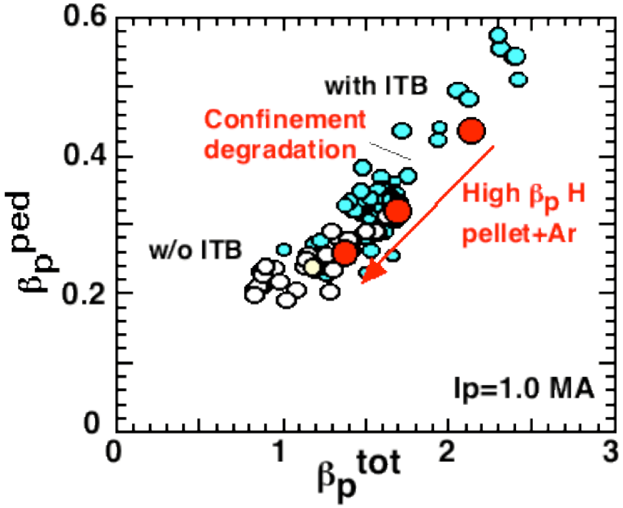
- Ar seeding and HFS pellet with small D_2 gas-puffing in small Vp.
  - HH_{y2}=0.96 and f_{rad}~1 at n_e/n_{GW}~0.92 at t=6.95s.
  - Peaking of $n_e(r)$ and enhanced pedestal pressure.



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







Central radiation is ascribed to Ar

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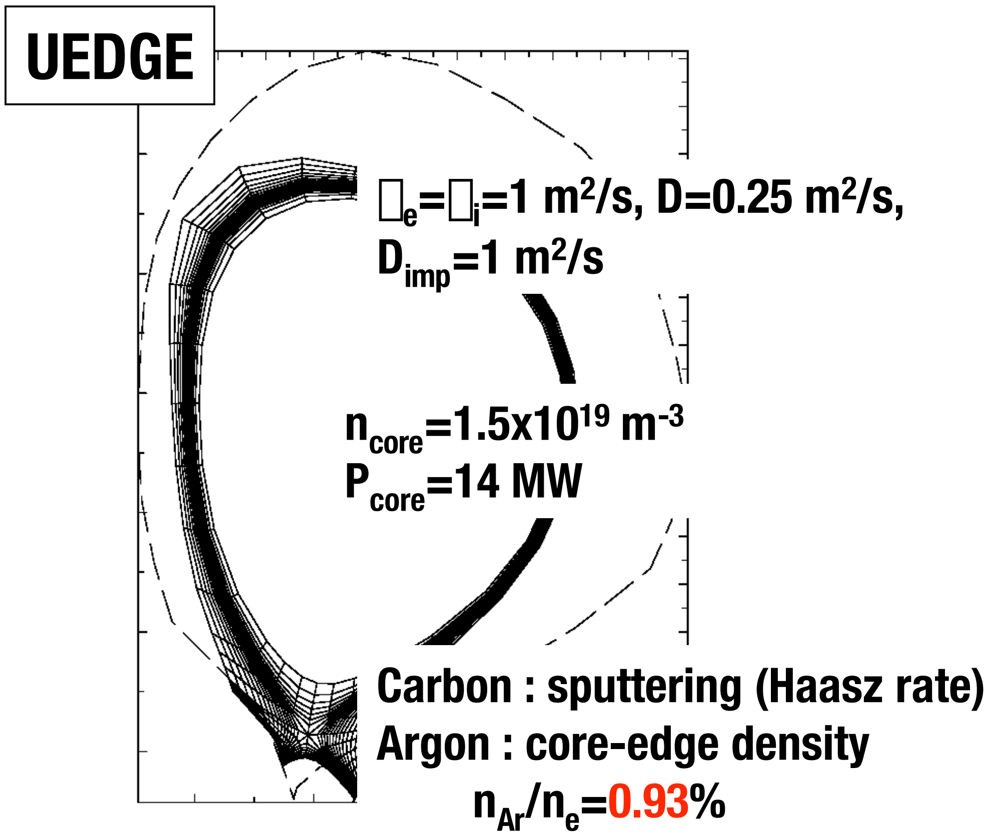
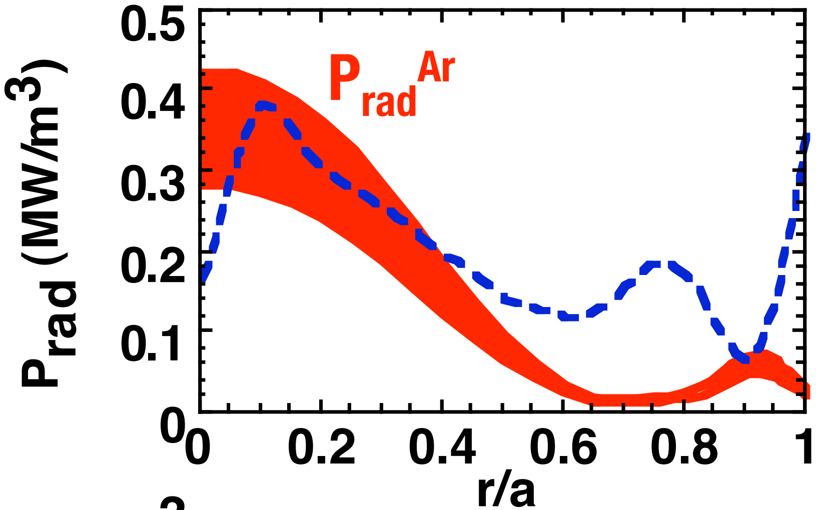
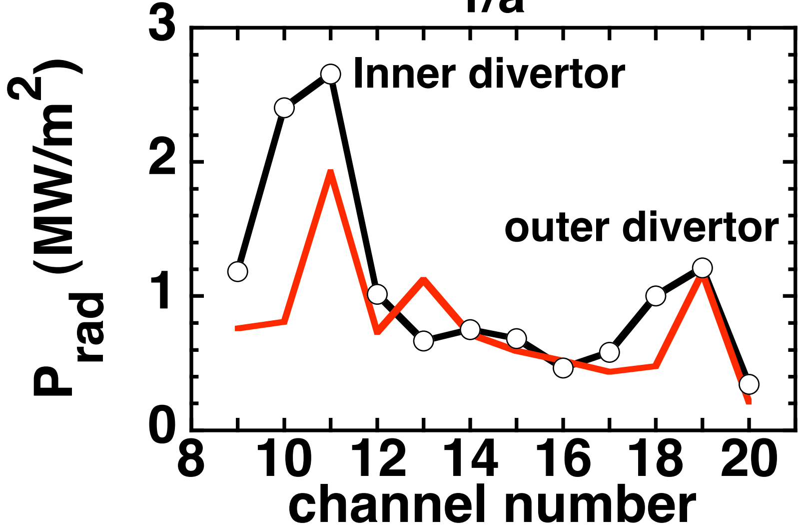
- $n_{Ar}(r)$ evaluated from soft x-ray profile is **more peaked by a factor of 2** inside the ITB than $n_e(r)$.
- n_{Ar}/n_e~1% in the center and 0.5% outside the ITB from Bremsstrahlung.
- P_{rad}^{Ar}~0.4 $P_{rad}^{SOL+DIV}$.



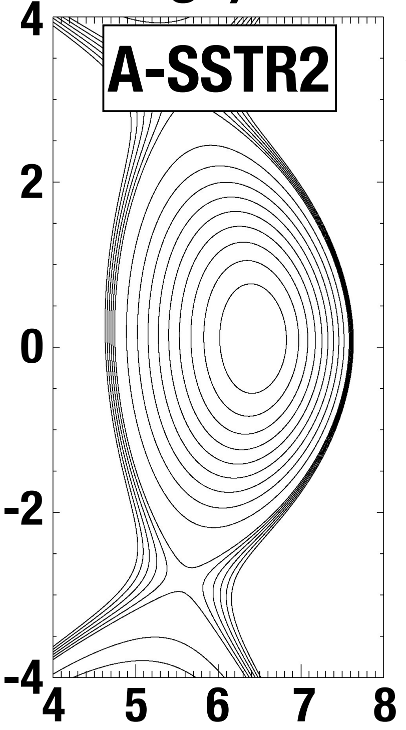


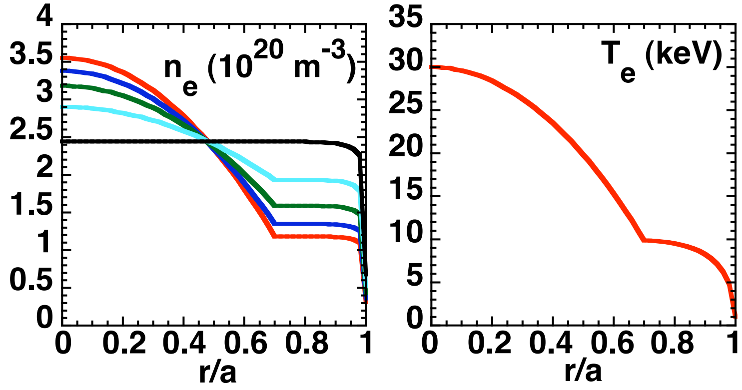


Core radiation loss from Ar can be compensated with slightly enhanced confinement in a fusion reactor.

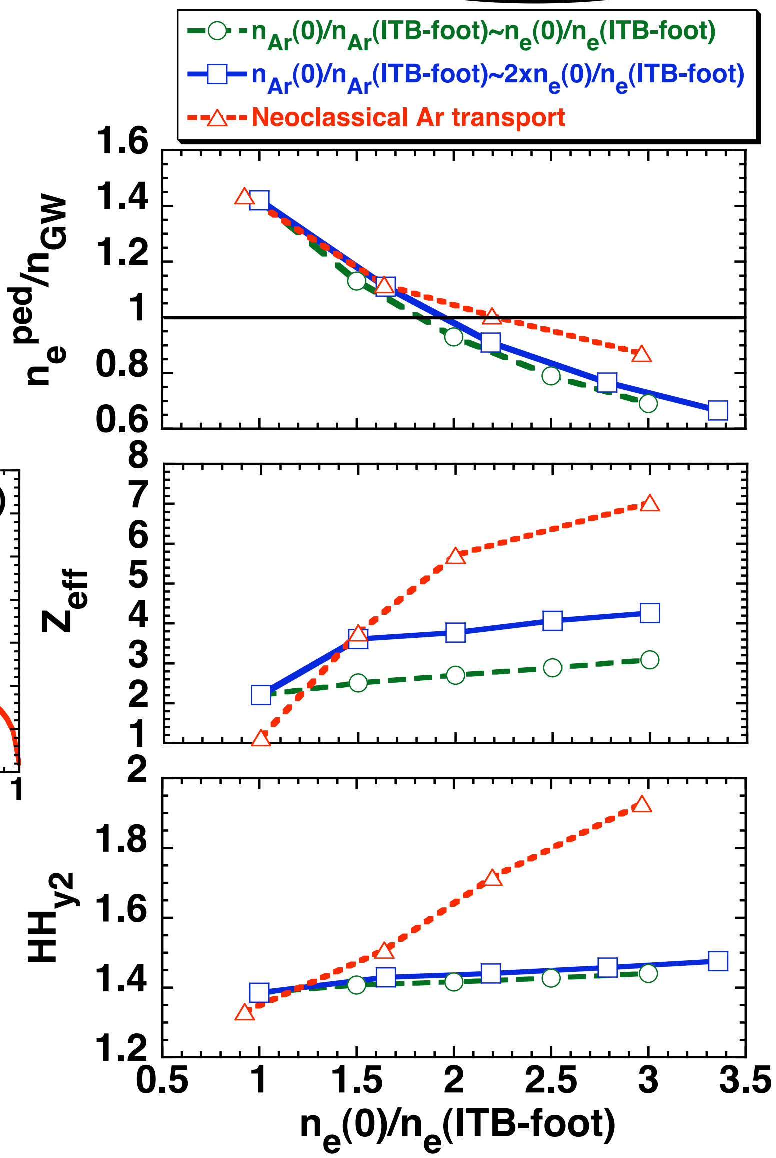
JT-60U

- 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.