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40 Years of ICRF Physics on the JET Tokamak: Highlights and Lessons Learned for Future Facilities

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Outline

Introduction to JET

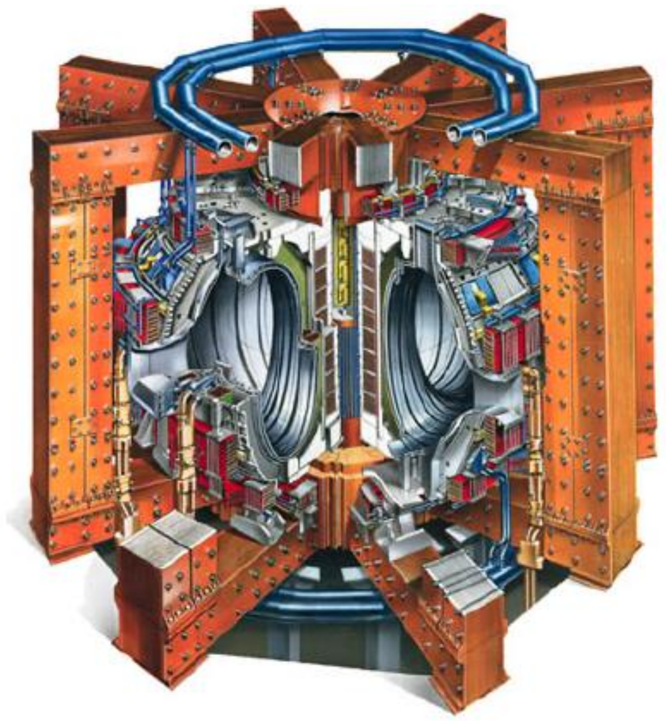
ICRF system capabilities at JET

Highlight contributions in ICRF physics

Conclusions with lessons learned for future devices

Technological aspects of ICRF operation at JET are covered by a **talk by P. Dumortier**.

JET technical specifications



D shaped cross-section

	Design	Achieved
Minor/major radius	1.25/2.96 m	
Toroidal field	3.45 T	4 T
Plasma current (limiter)	3.8 (4.8) MA	7 MA
Plasma current (X-point)		6 MA
Flat top duration	10 s (20 s)	60 s
Main fuel	H/D/T	H/D/T/He
NBI heating	15 MW	34 MW
ICRF heating (25–56 MHz)	9–12 MW	22 MW
LHCD (3.7GHz)		~6 MW
Combined heating		~37 MW

Jacquinot, Keilhacker & Rebut, Fusion Science Tech. 2008; Rimini et al., EPS2024 & PPCF 2025

JET Timeline

Red: machine configuration
Blue: campaigns with T

1983
1^{st} plasma

1986
X-point & 1^{st} H-mode

1991
Be limiter & X-point target

Preliminary Tritium Experiment

1992 - 1994
In-vessel coils & divertor

1994 - 2009
CFC wall & divertor studies

1997
DTE1

2003
Trace tritium experiment

2009/11
Be/W metal wall

2020/21
100% Tritium & DTE2

2023
DTE3

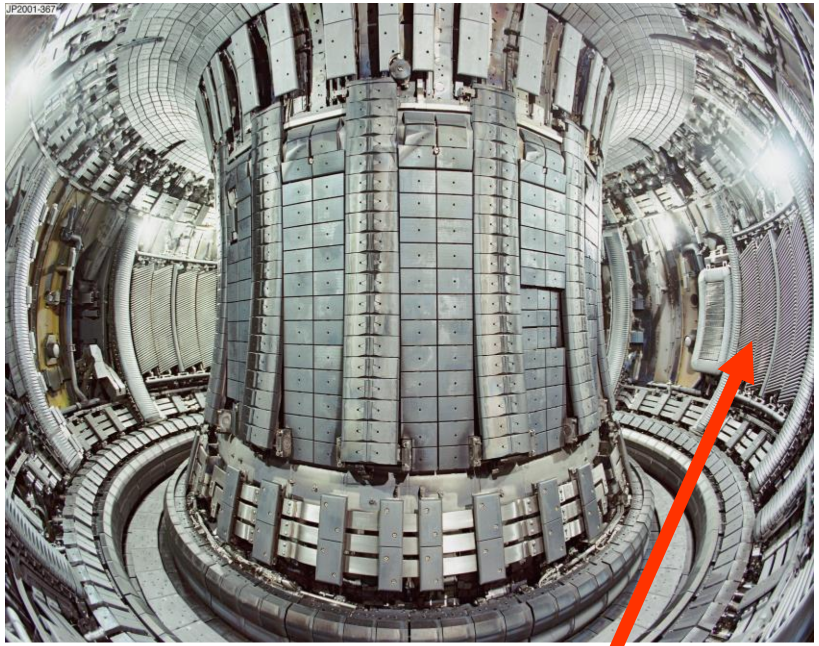
2024-
Decommissioning & Repurposing

Jacquinot, Keilhacker & Rebut, Fusion Science Tech. 2008; Rimini et al., EPS2024 & PPCF 2025

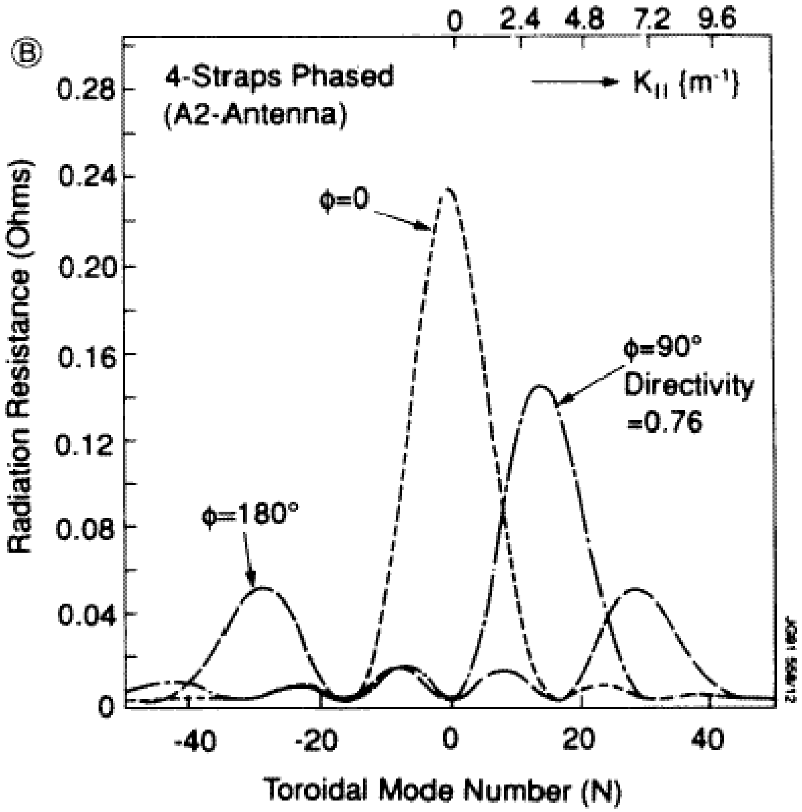
ICRF system at JET

Study of heating in conditions approaching those in a reactor was among main JET objectives.

Versatile ICRF system thanks to **wide frequency range** (25-56 MHz) and **flexible wave spectrum**.



ICRF antennas



Kaye et al. Fusion Eng. Design 1994; Dumortier, this conference

Experiments with several ICRF heating and current drive schemes

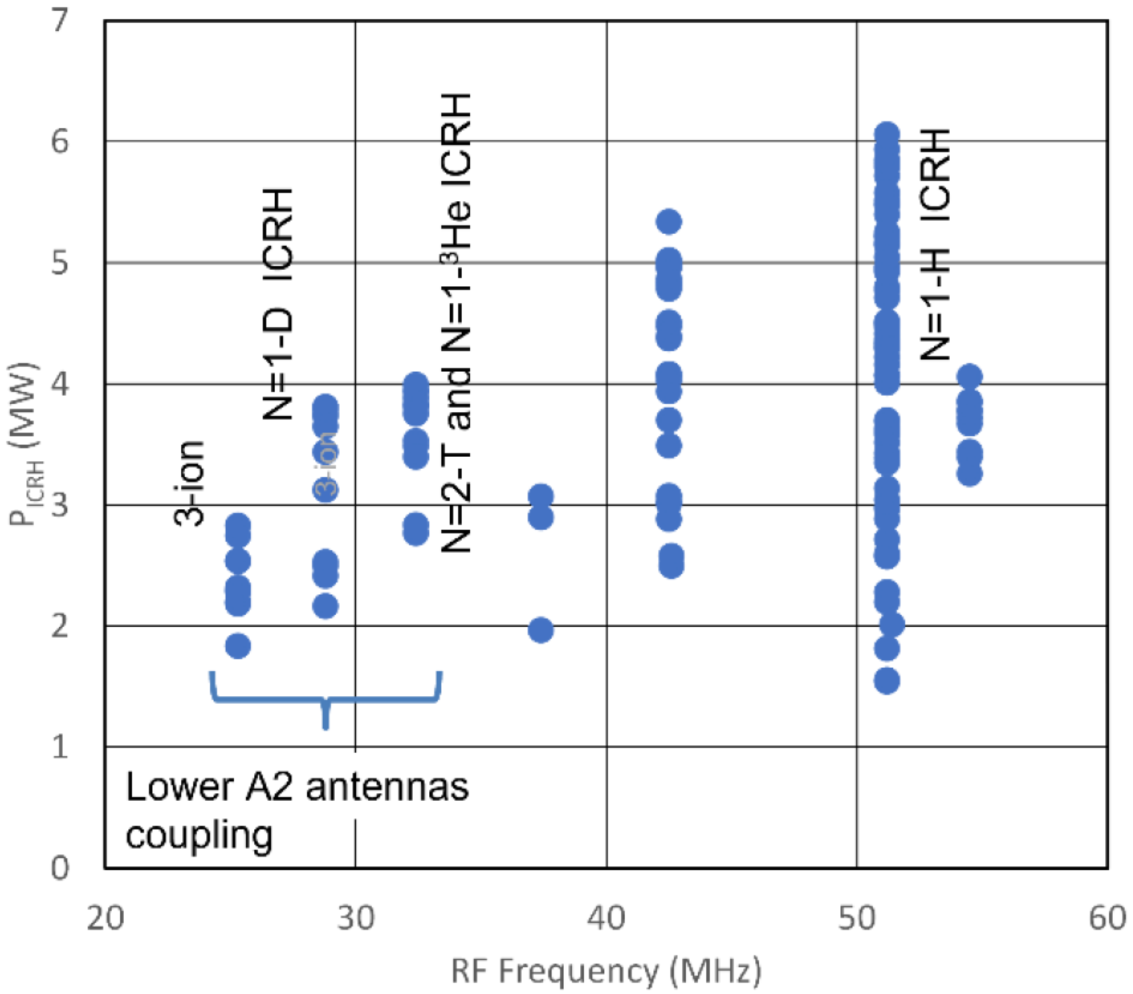
Absorption by ions when $\omega = n\omega_{ci} + k_{||}v_{||,i}$, $n>0$.

- localised **around $\omega = n\omega_{ci}$ (R_{res})**
- Several schemes to heat **minority and/or majority** ions
- **ICRF-driven fast ions** often have energies up to the **MeV range**.
- Due to large plasma size (80-100 m^3) and multi-MA current, ICRF-driven **fast ions are well-confined.**

Absorption by electrons when $v_{ph} = \omega / k_{||} = v_{||,e}$

- **direct electron damping** of fast waves
- **mode conversion** of fast waves to short-wavelength waves

ICRF schemes in DTE2



Jacquet et al. AIP Conf. Proc. 2023

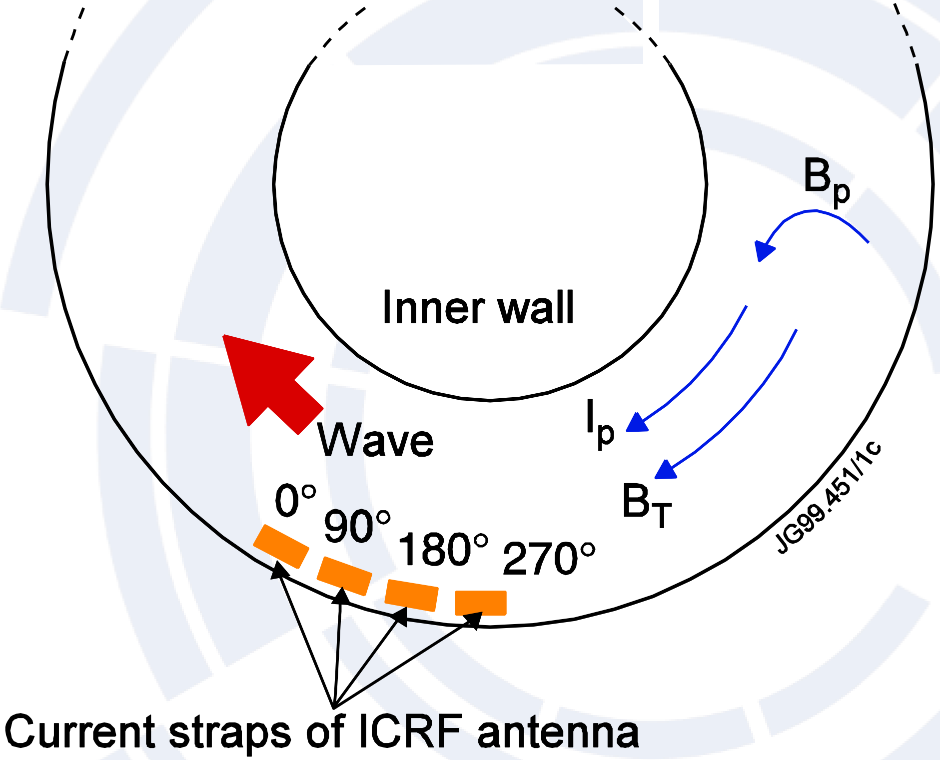
Flexible wave spectrum allows to modify the absorption of wave toroidal angular momentum and its effects on plasma

Absorption of waves $\Rightarrow$ **wave momentum** is also **transferred to the plasma**.

Relevant for **toroidally directed waves**.

Used to:

- drive current
- induce radial transport of resonating fast ions
- influence plasma rotation



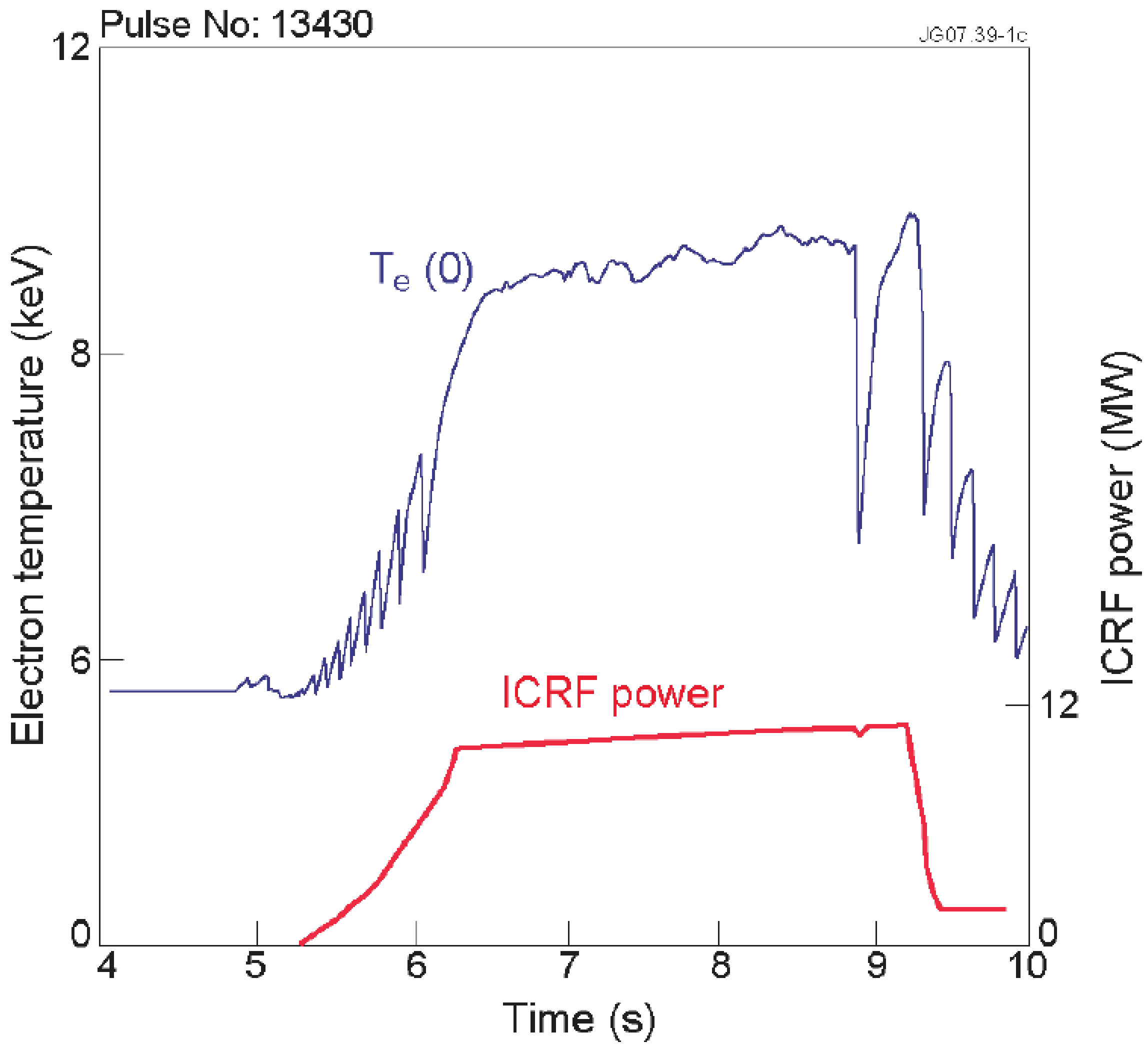
Highlight contributions in ICRF physics

- ICRF physics mechanisms
- Effects of ICRF-driven fast ions
- ICRF heating in D-T plasmas

Presented by “themes” in loose chronological order

Effects of ICRF-driven fast ions:

Stabilization of sawtooth instability by ICRF-driven fast ions



Central high-power ICRF heating
$\Rightarrow$ **Monster sawteeth** with periods up to 5 s, even though $q_0 < 1$.

Stabilisation is **due to ICRF-heated fast ions** with $\omega_{Drift} > \omega_{mode}$

Mechanism: Magnetic flux through the area defined by the fast ion precessional drift motion is adiabatically conserved $\Rightarrow$ Work done by electromagnetic perturbation against fast ion pressure.

Relevance for a reactor: sawtooth stabilisation by fusion α's.

Campbell et al. PRL 1988; Porcelli et al. PPCF 1991

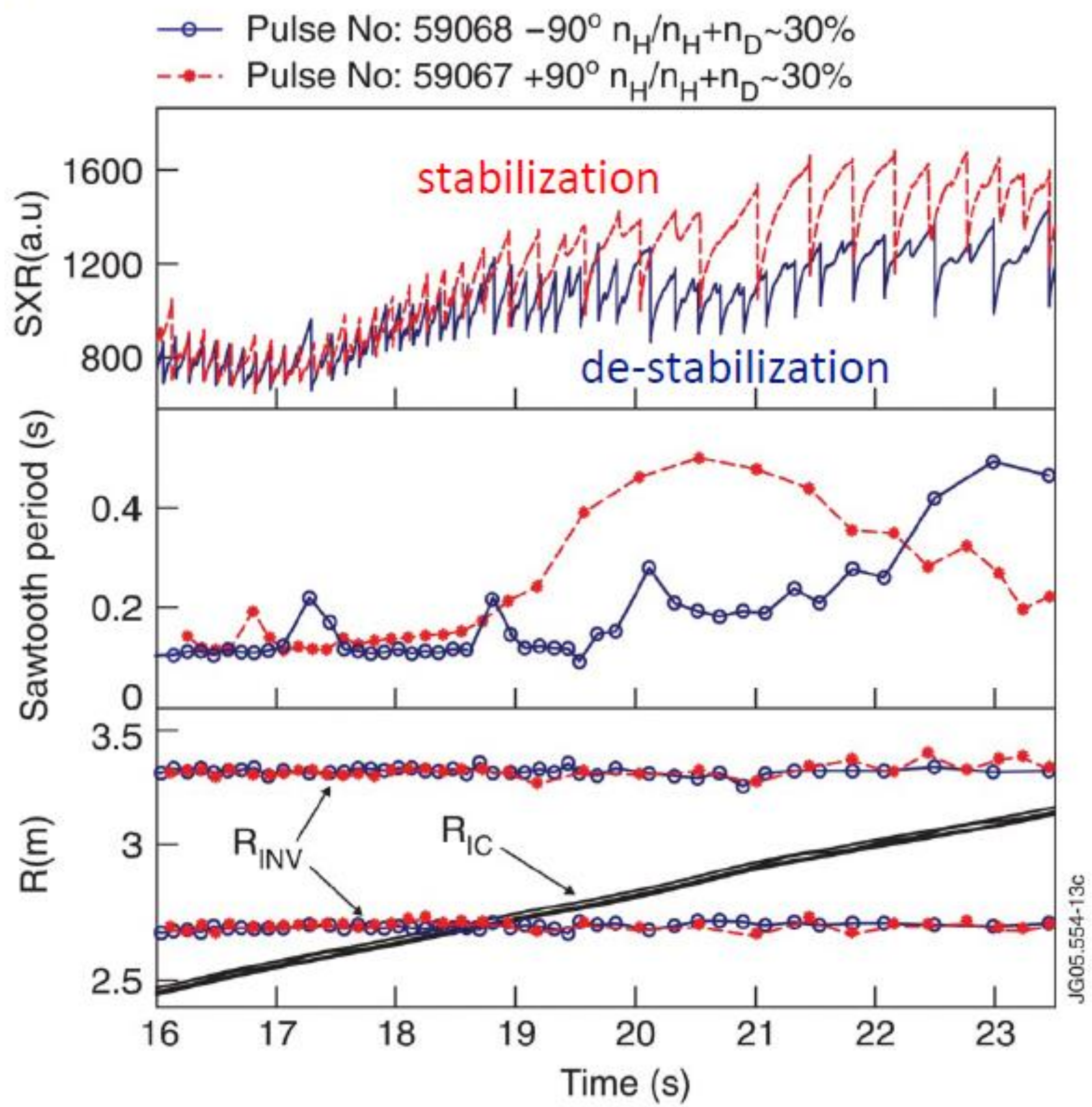
Effects of ICRF-driven fast ions:

Much research followed on modifications of sawtooth oscillations with ICRF waves

Reviewed by Mantsinen et al. AIP Conf. Proc. 2007, including

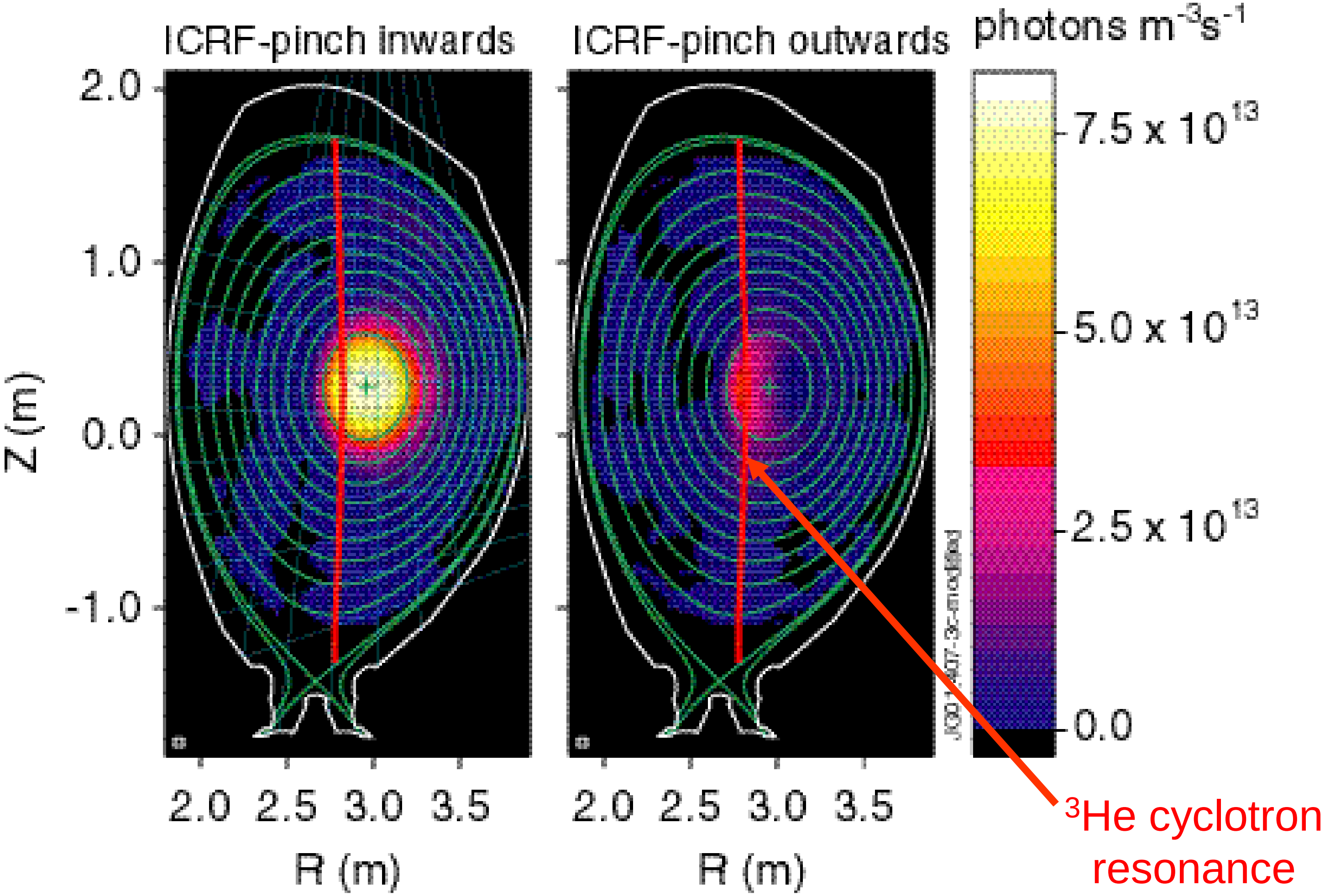
- Loss of fast-ion stabilisation at low plasma density
- **Stabilisation/destabilisation of sawteeth with ion cyclotron current drive (ICCD)** near q = 1
- Subsequent **effects on NTMs and impurity accumulation**
- Combination of fast-ion stabilisation and ICCD to investigate possibilities
  - to destabilise α-induced long-period sawteeth
  - to avoid NTMs triggered by α-induced long sawteeth.

Relevance for a reactor: control of sawteeth and their collateral effects by ICRF waves.

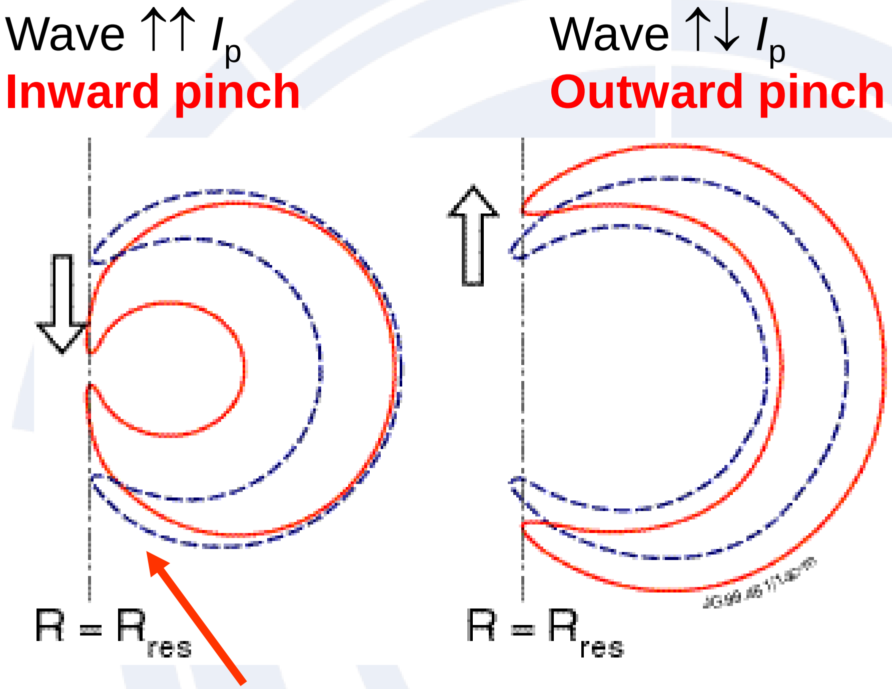


Sauter et al. PRL 2002; Eriksson et al. PRL 2002; Westerhof et al. NF 2002; Mayoral et al. PoP 2004; Graves et al. PRL 2009 & Nature 2012

ICRF physics mechanisms/Effects of ICRF-driven fast ions:
Experimental evidence for ICRF-induced particle pinch



Eriksson et al. PRL 1998; Mantsinen et al. PRL 2002; Kiptily et al. NF 2002



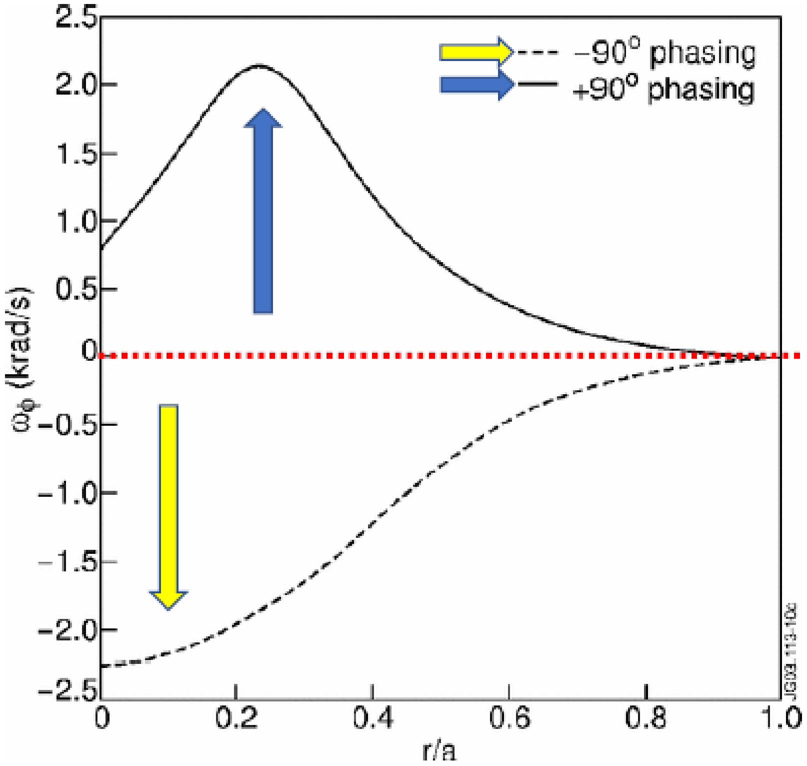
Eventually co-passing orbits residing on the low-field side of R_{res}

Hellsten et al. PRL 1995

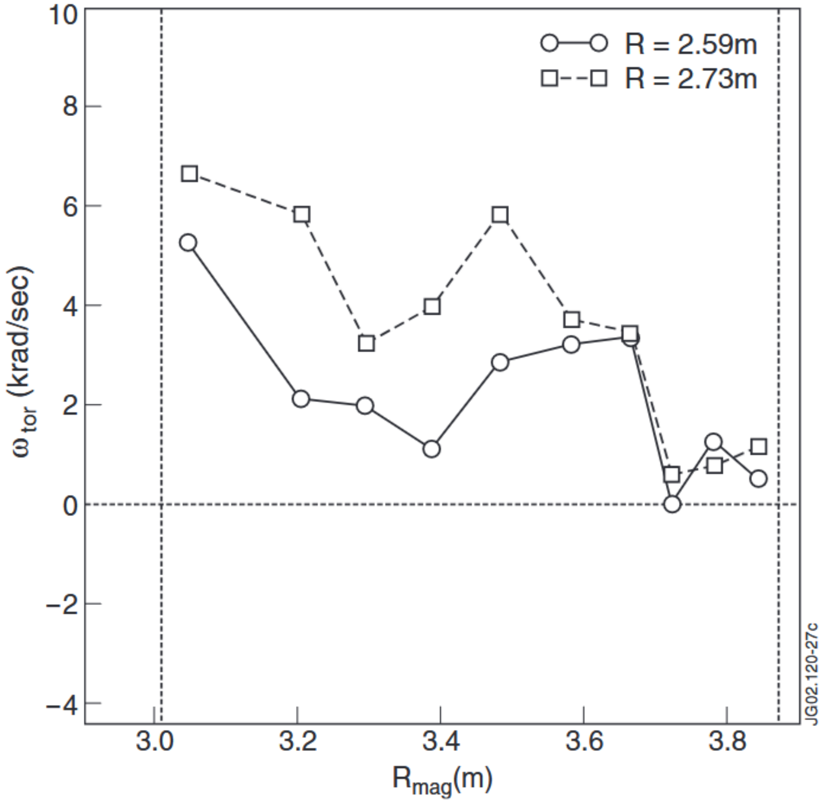
Relevance for a fusion reactor: control ICRF-driven fast ion population and the profile of resulting plasma heating

ICRF physics mechanisms:
Effects of ICRF waves on plasma rotation

Change of antenna phasing



Change of resonance position



ICRF heating affects plasma rotation - even in the absence of absorption of net toroidal momentum.

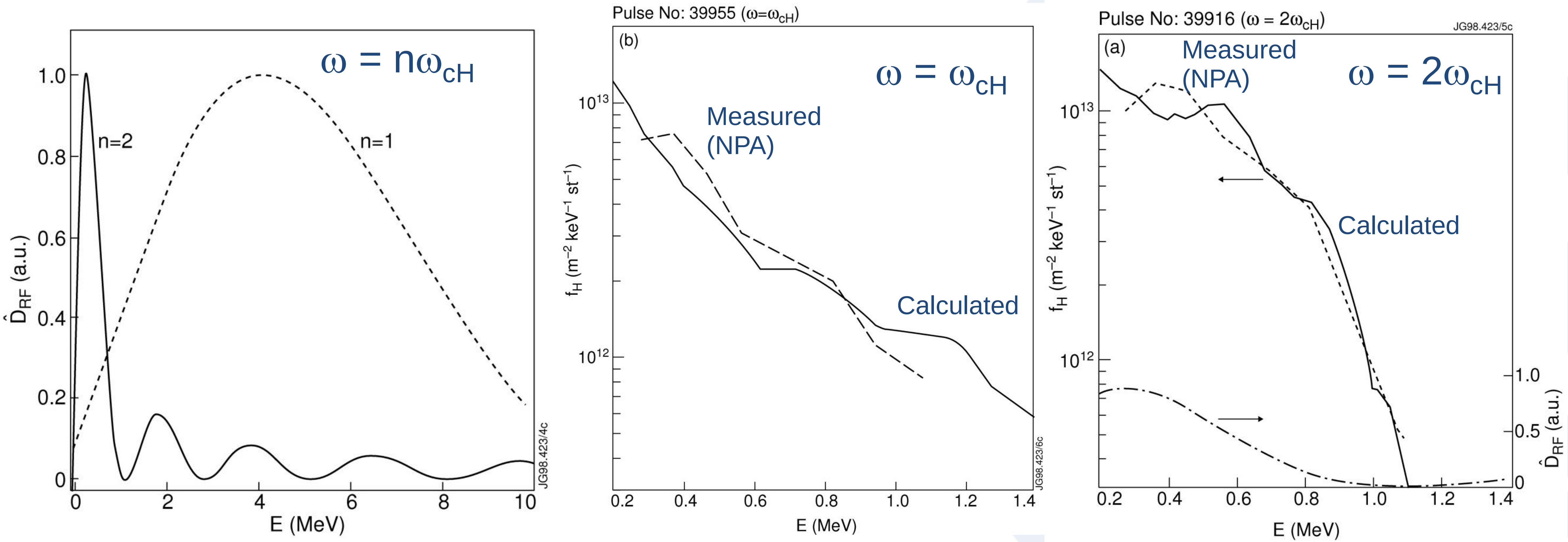
It can be modified by the change of ICRF parameters (phasing, resonance location, minority concentration etc).

Eriksson et al. PRL 2004; Noterdaeme et al. NF 2004; Lin et al. EPS 2010

Relevance for a reactor: modification of plasma rotation using ICRF waves e.g. for scenario optimization

ICRF physics mechanisms:
Experimental confirmation of finite Larmor radius (FLR) effects

FLR effects are important for wave-particle interaction, especially for n > 1.

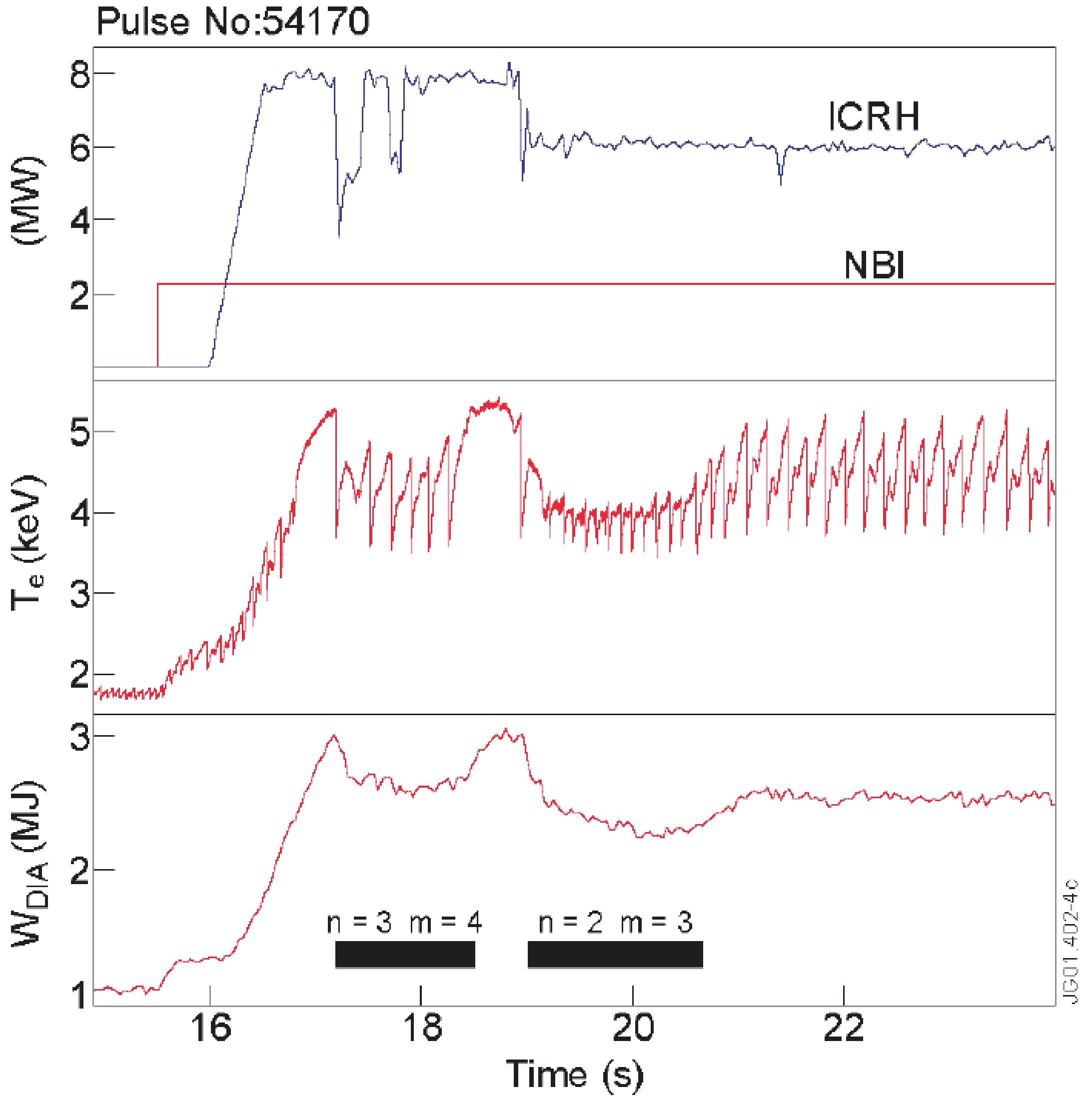


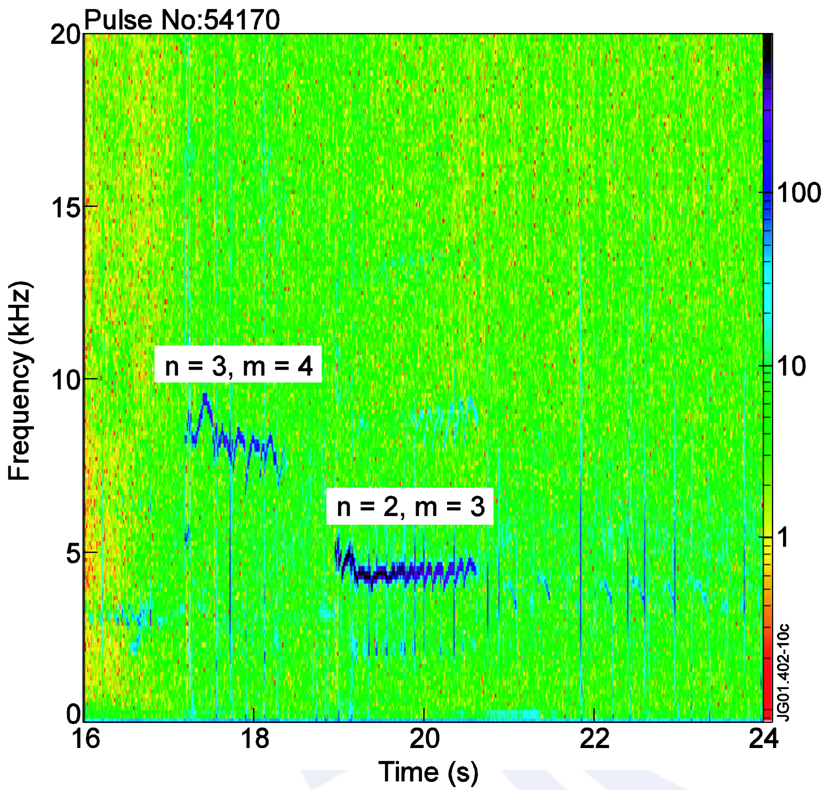
Mantsinen et al. NF 1999; Salmi et al. PPCF 2006

Relevance for a reactor: control of ICRF-driven fast ions in velocity space

ICRF physics mechanisms/Effects of ICRF-driven fast ions:

“Artificial” alpha’s with third-harmonic ICRF heating of ^{4}He beam ions

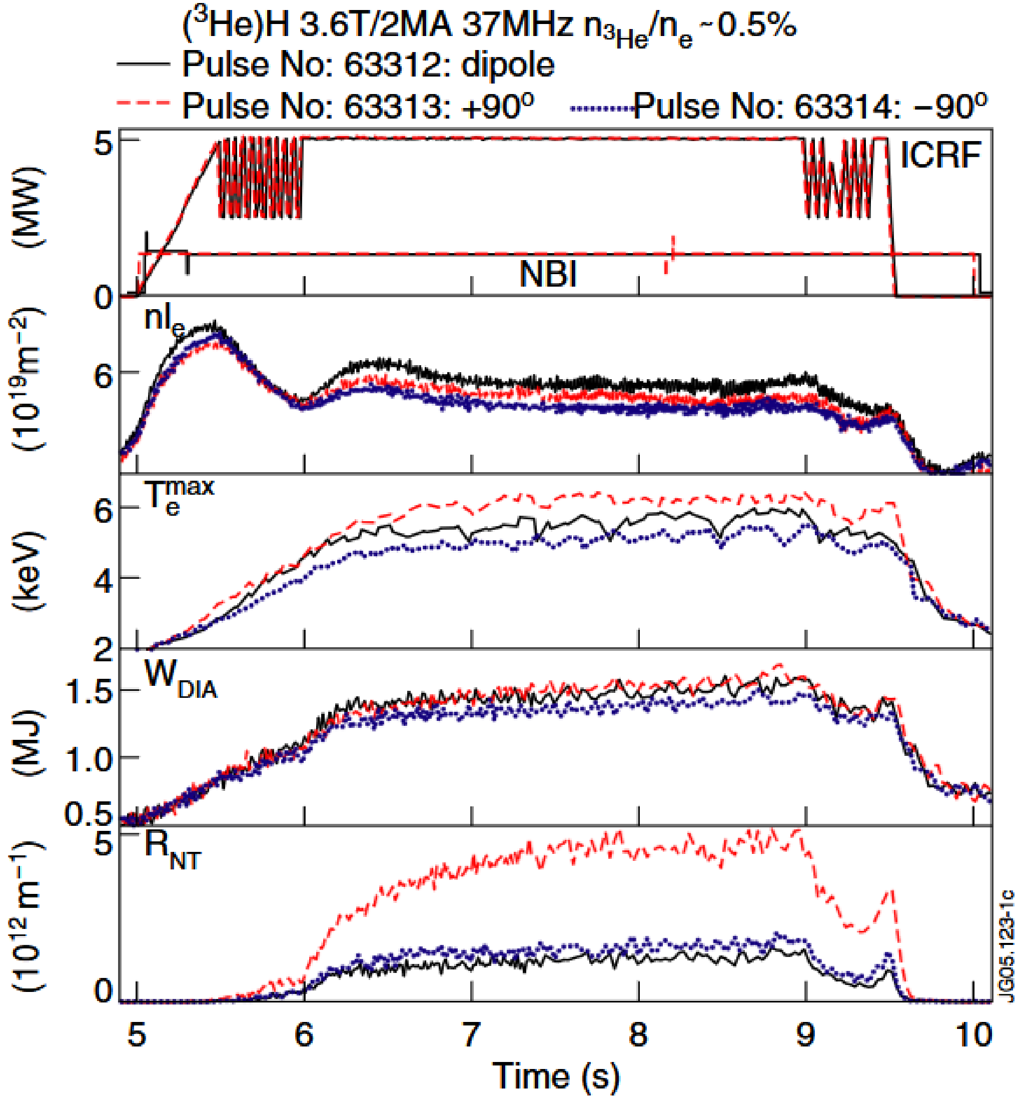




Relevance for a reactor: testing α-diagnostics and studies of α´s and their effects in plasmas for non-activated operation.

Mantsinen et al. PRL 2002; Kiptily et al. NF 2002; Pamela et al. NF 2002

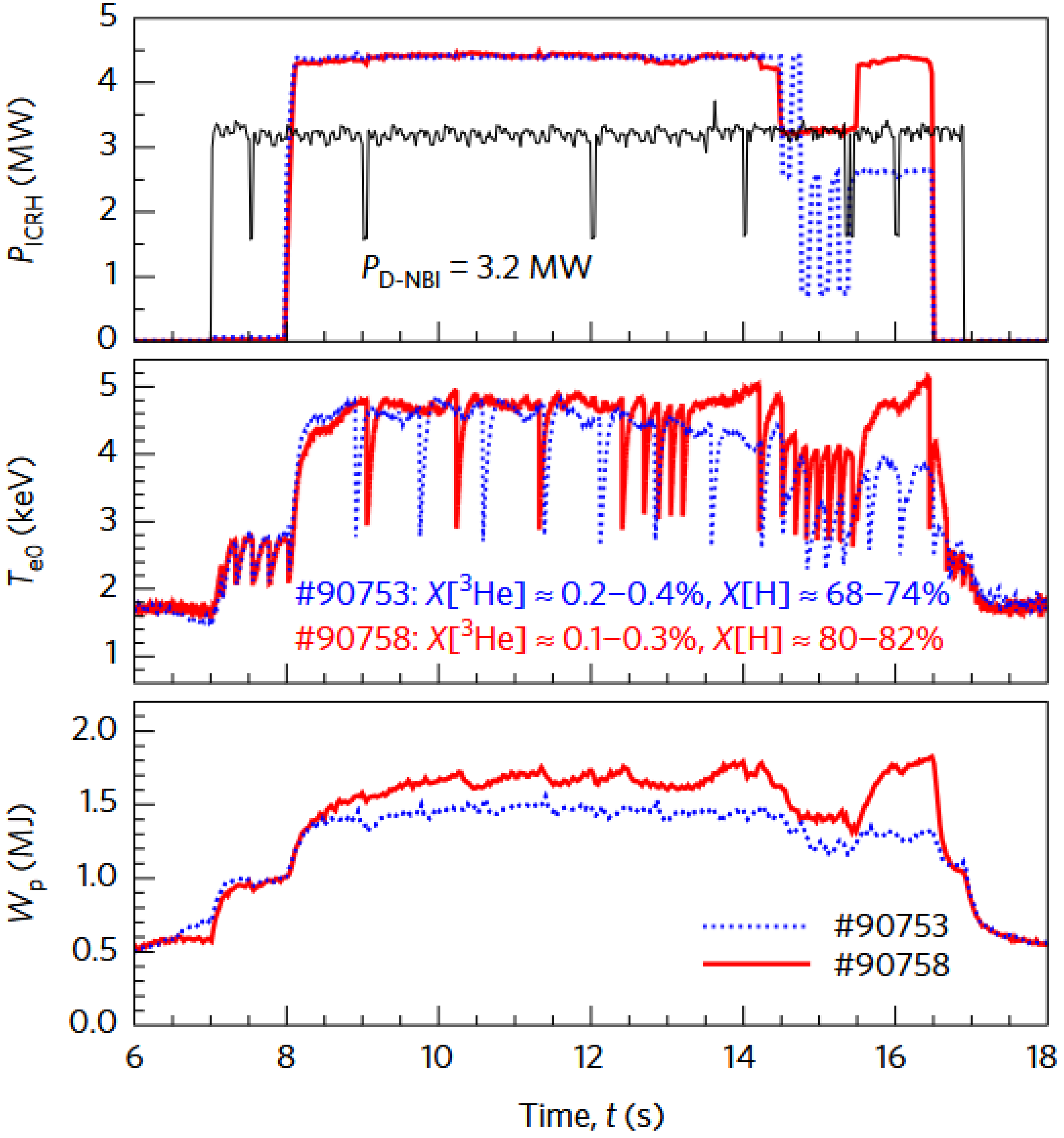
ICRF physics mechanisms:
ICRF heating schemes for non-activated operation



Relevance for a reactor: availability of tested ICRF heating schemes for non-activated plasma operation, useful as part of commissioning of a new device

Mantsinen et al. AIP Proc 2001; Mayoral et al. NF 2006; Lerche et al. PPCF 2011; Van Eester et al. EPJ Web Conf. 2017

Three-ion ICRF schemes: demonstration and rich physics results



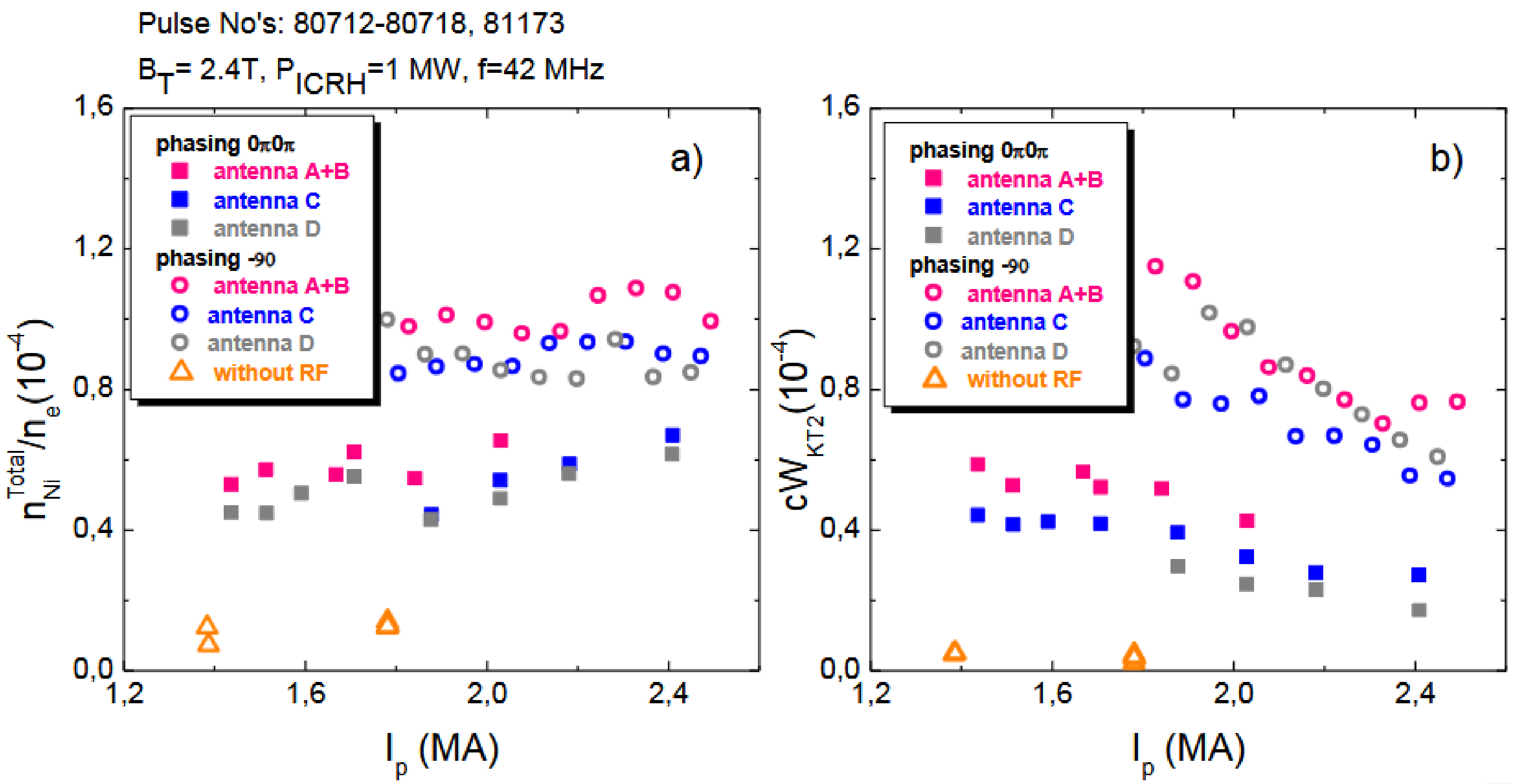
Demonstrated:

- Generation of ICRF-driven fast ion populations in MeV range
- Coupling ICRF power on plasma impurities, including ^{9}Be in 50%:50% D-T plasmas, for bulk ion heating

Relevance for a reactor: expanded choice of tested ICRF schemes for a reactor

Kazakov et al. Nature Phys 2017; PoP 2021; AIP Conf Proc. 2023 and references therein

Heavy impurities (Ni and W) during ICRF heating in JET with Be/W wall



ICRF heating increases plasma impurity content due to sputtering from plasma-facing components.

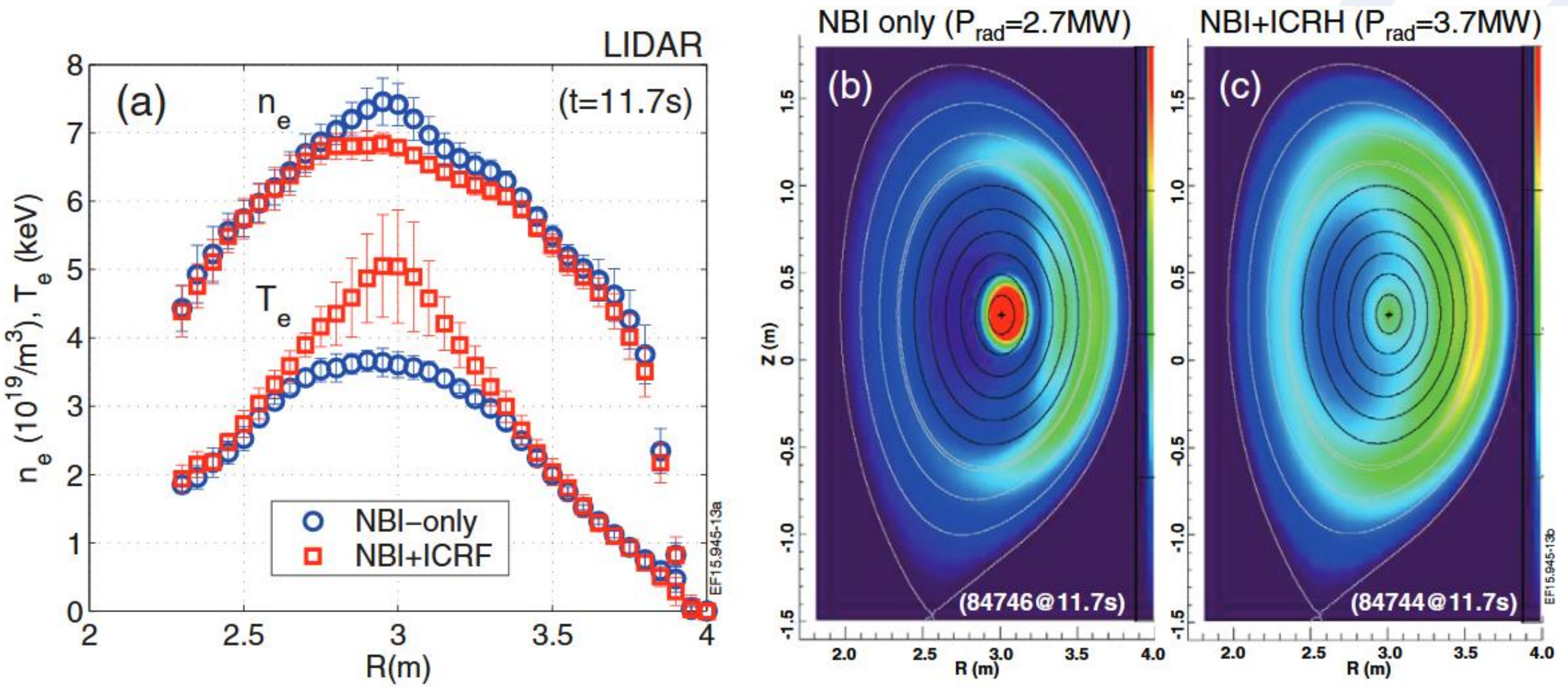
The effect depends on ICRF power, ICRF phasing and ICRF scheme, and can be **reduced by optimization of strap voltage**. **Localized gas puffing** at ICRF antennas (used for coupling maximization) also **helps**.

Czarnecka et al. PPCF 2012 & AIP Conf. Proc. 2014; Bobkov et al., Nucl. Mater. Energy 2019

Relevance for a reactor: recipes to minimize ICRF-wall interaction and related impurity release

ICRF physics mechanisms:
ICRF heating for core impurity control in JET with Be/W wall

High power ICRF heating near the axis can **mitigate against W accumulation** in high-performance plasmas. Thereby, better fusion performance is obtained.



Primary control mechanism via impact on turbulence in reducing main ion density peaking (which drives inward neoclassical convection), increased T screening and turbulent W diffusion.

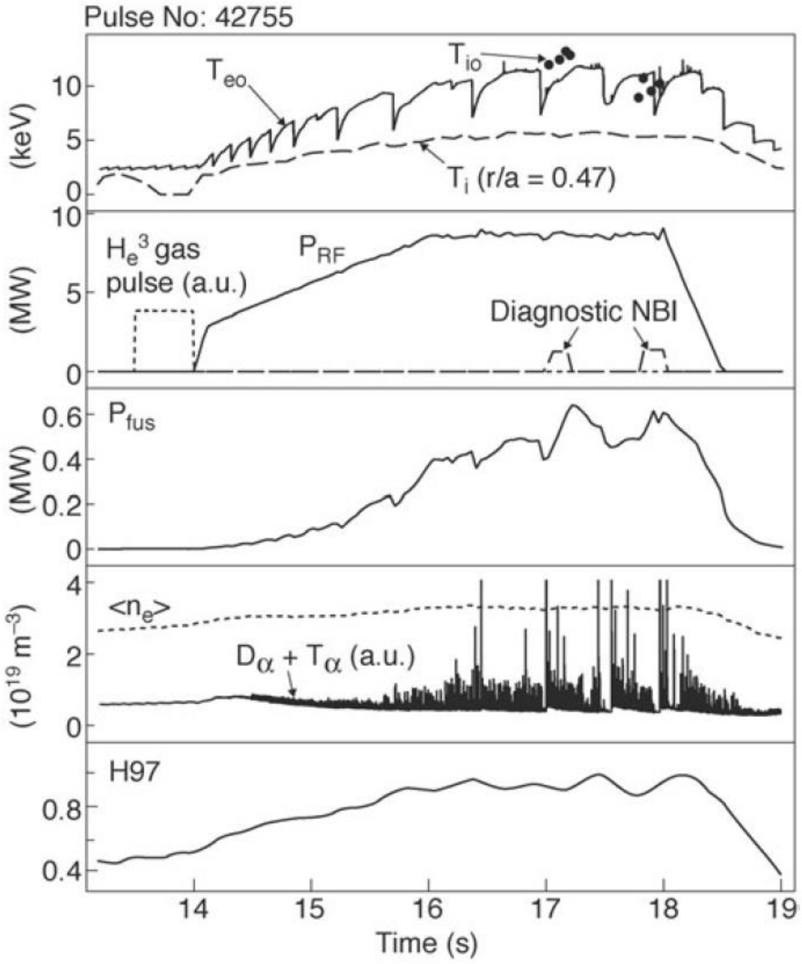
Lerche et al. NF 2016; Goniche et al. PPCF 2017; Casson et al. NF 2020

Relevance for a reactor: techniques for avoidance of impurity accumulation with metallic walls

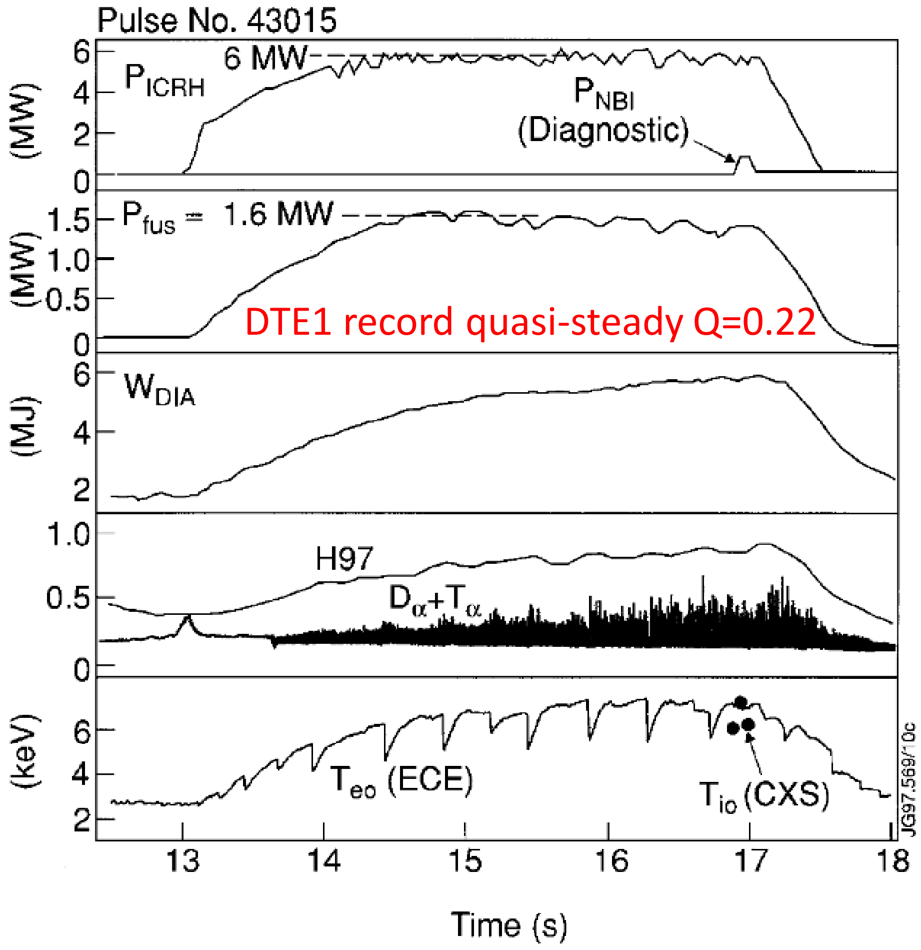
ICRF heating in D-T plasmas:
Dedicated experiments to study different ICRF heating schemes in DTE1

H, D, T and ^{3}He minority, and second harmonic H, T and D

^{3}He minority in 50%:50% D:T plasma



D minority in T-rich plasma



Relevance for a reactor: good performance of a variety of ICRF schemes confirmed in D-T plasmas

Start et al. PRL 1998 & NF 1999; Eriksson et al. NF 1999

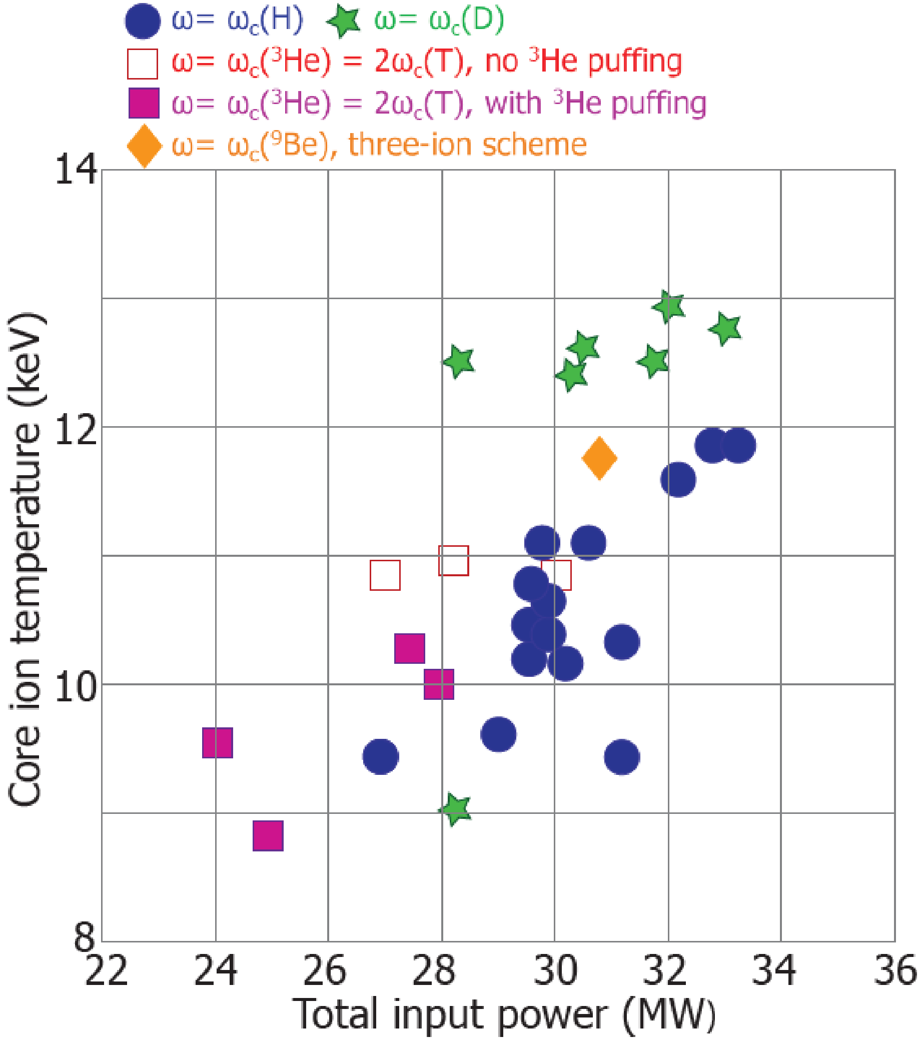
ICRF heating in D-T plasmas:
Integration and characterization of reactor-relevant ICRF schemes in high-performance plasmas in DTE2 & DTE3

For given total input power, **all D-T ICRF scenarios led to higher T_i as compared with H minority heating** which is the reference scenario at JET. This result is in line with ICRF theory.

Relevance for a reactor: confirmed bulk ion heating capabilities of ICRF heating schemes in reactor-relevant conditions.

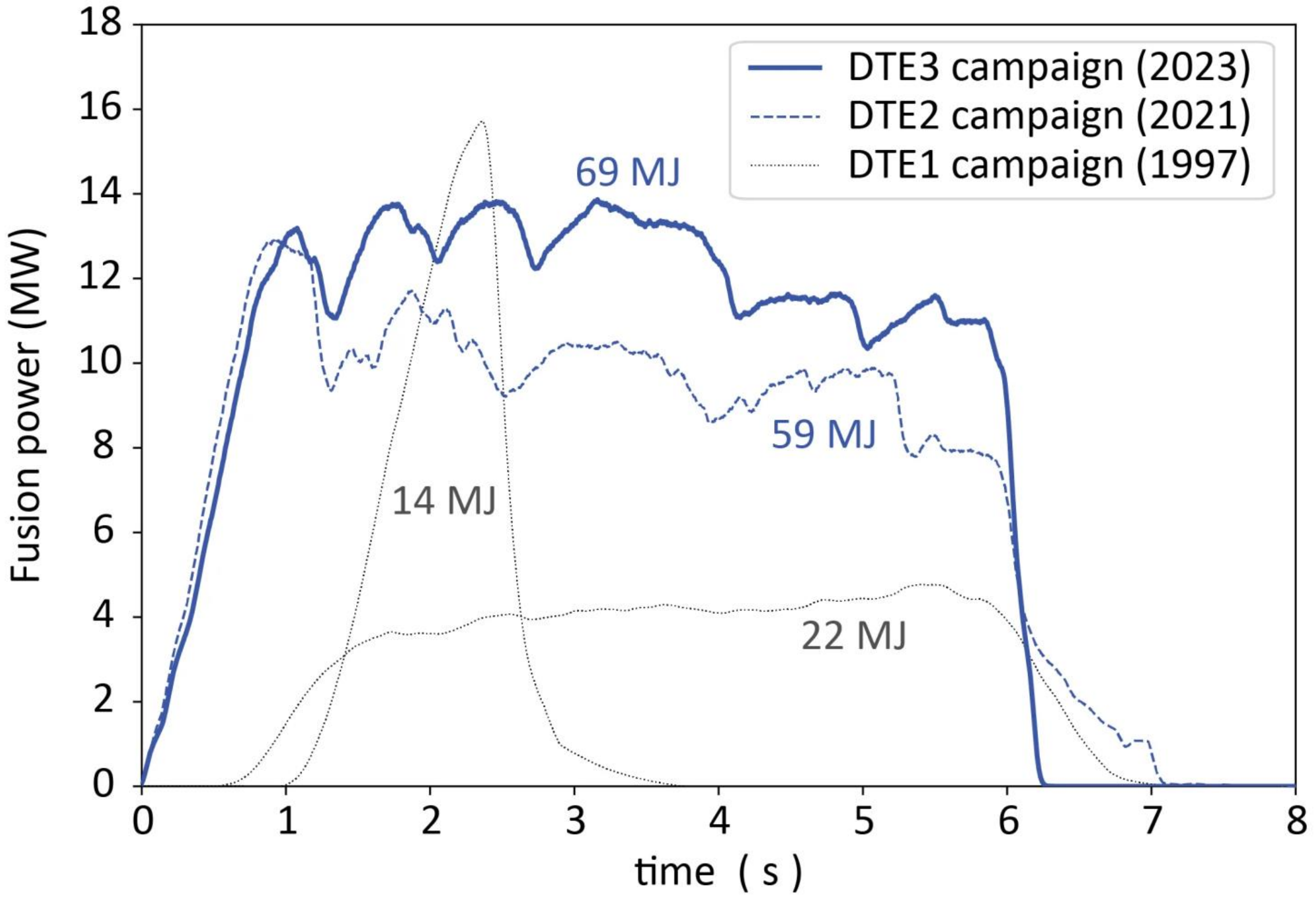
Jacquet AIP Conf Proc 2023; Mantsinen et al. NF 2023; Maslov et al. NF 2023; Lerche et al. AIP Conf Proc. 2023; Kazakov et al. AIP Conf Proc. 2023

Average over one second during high-power phase



Disclaimer: Variation in T_i is partly due to differences in ICRF and NBI power, injected gas rate, D-T isotope mixture, plasma current and magnetic field.

ICRF contribution to D-T fusion power records at JET



ICRF heating played an important role by **providing bulk ion heating and enhancing fusion yield by ICRF-accelerated NBI deuterons** ($\omega \approx \omega_{cH} = 2\omega_{cD}$ in DTE1; $\omega \approx \omega_{cD}$ in DTE2-DTE3).

Relevance for a reactor: integration of ICRF heating in high-performance scenarios to help reach the conditions needed for high fusion power.

Rimini et al. NF 1999; Mantsinen et al. PPCF 1999; Maslov et al. NF 2023; Lerche et al. AIP Conf Proc 2023

Conclusions

JET made many significant contributions to ICRF physics thanks to its flexibility in the choice of ICRF frequency and phasing.

Some **general lessons learned** for future devices:

- ICRF heating can provide localized bulk ion or bulk electron heating, rotation and current drive. **Aim for flexibility in the choice of frequency and phasing** for this versatility.
- In reactor-scale plasmas, ICRF heating is the only external heating scheme able to provide predominant bulk ion heating. Make sure to **include it in the heating strategy**; it may be difficult to reach high central ion temperatures with dominant electron heating alone.
- ICRF physics includes non-linear phenomena which can make it quite complex. **Modelling is indispensable** to guide experiments and to improve understanding of underlying physics.
- In large devices, fast ion confinement is good. **Ion cyclotron damping on resonant ions is likely to win** over direct electron damping.

Thank you for your attention

Suggested discussion topics:

- What is your favourite JET ICRF physics result?
- Which result do you consider most significant?
- Do you recall something important that I did not have time to mention?

  Please share to celebrate all the achievements!