EUROfusion

The role of MHD in controlling impurity accumulation in tokamaks

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JET IPP

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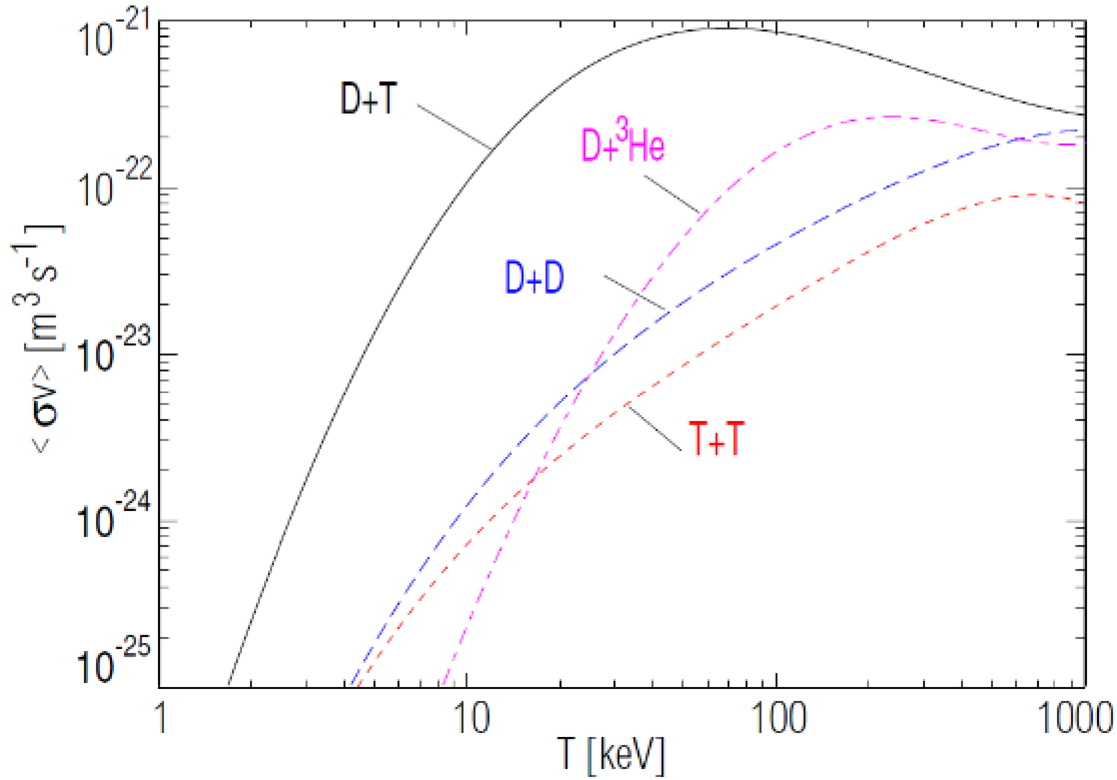
Fusion energy

Most promising way to harness fusion as an **energy source**:

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + n$$

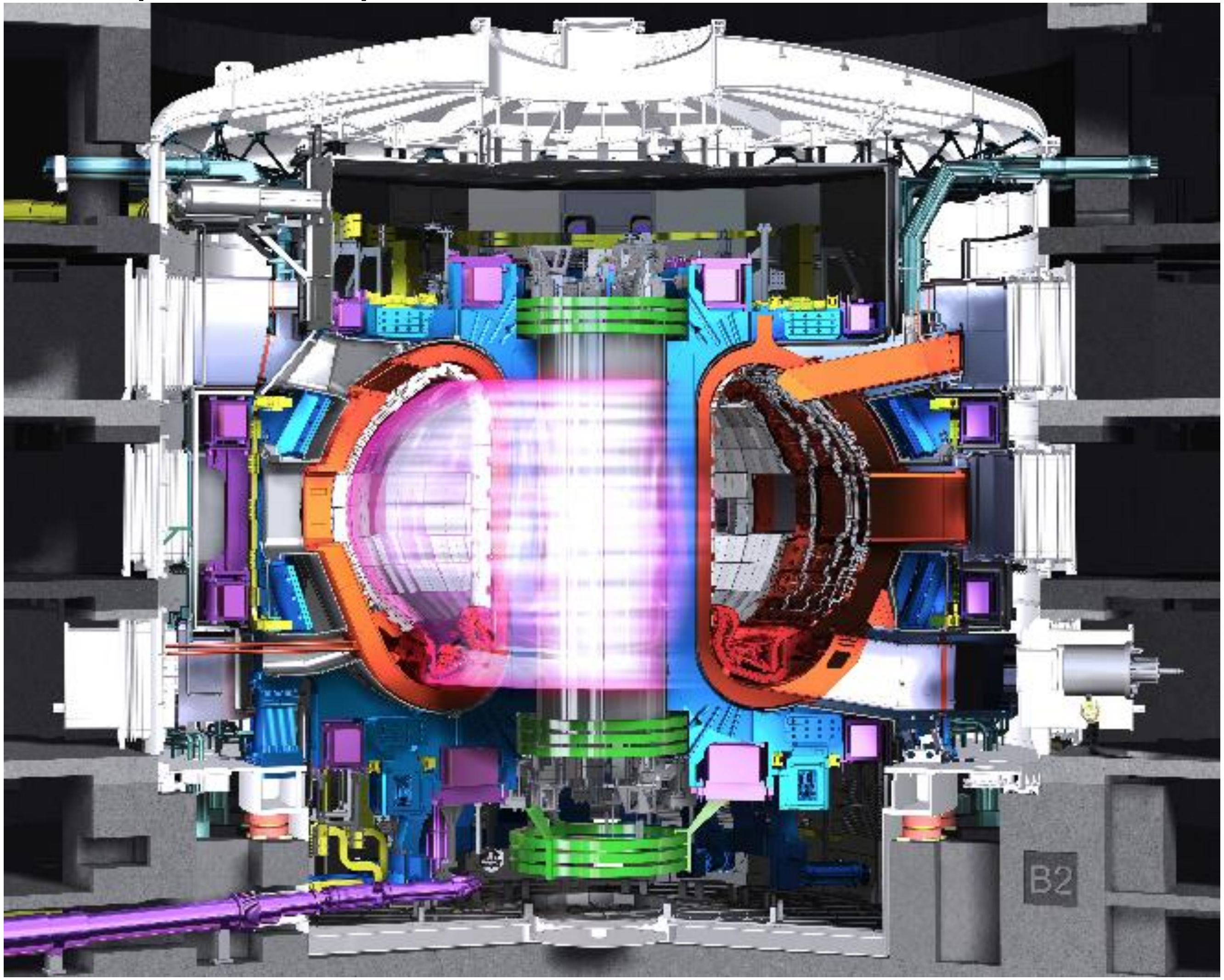
3.5 MeV *14.1 MeV*

- **Temperatures > 10 keV**
- **High densities**
- **Minimize energy losses**



Fusion energy, the Tokamak

One of the concepts developed to achieve this is the **tokamak**

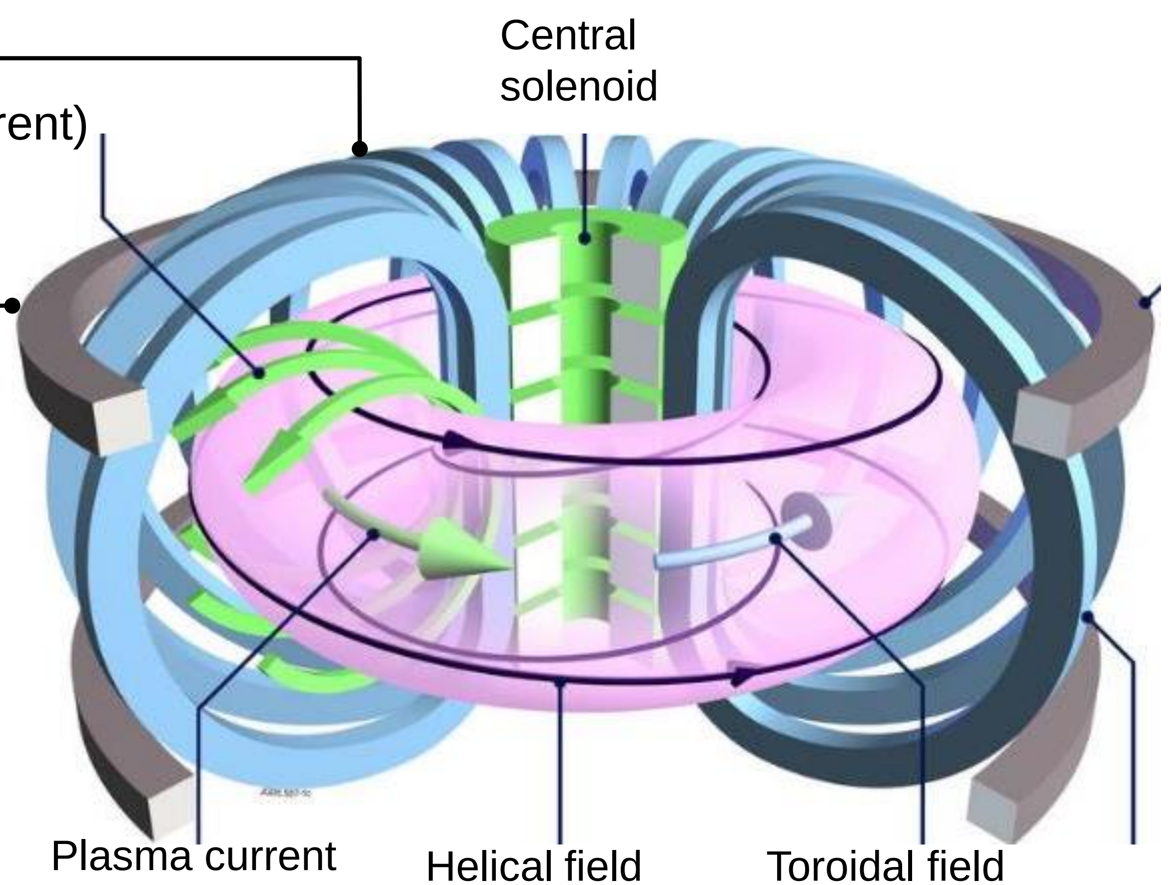


[https://www.iter.org/]

Fusion energy, the Tokamak

Confine , **heat** & **control** the plasma in a **toroidal geometry**

- **Helical magnetic field**
  - Toroidal field (coils)
  - Poloidal field (toroidal current)
  - Vertical field (coils)
- **External heating**
- **Control system**
- **…**



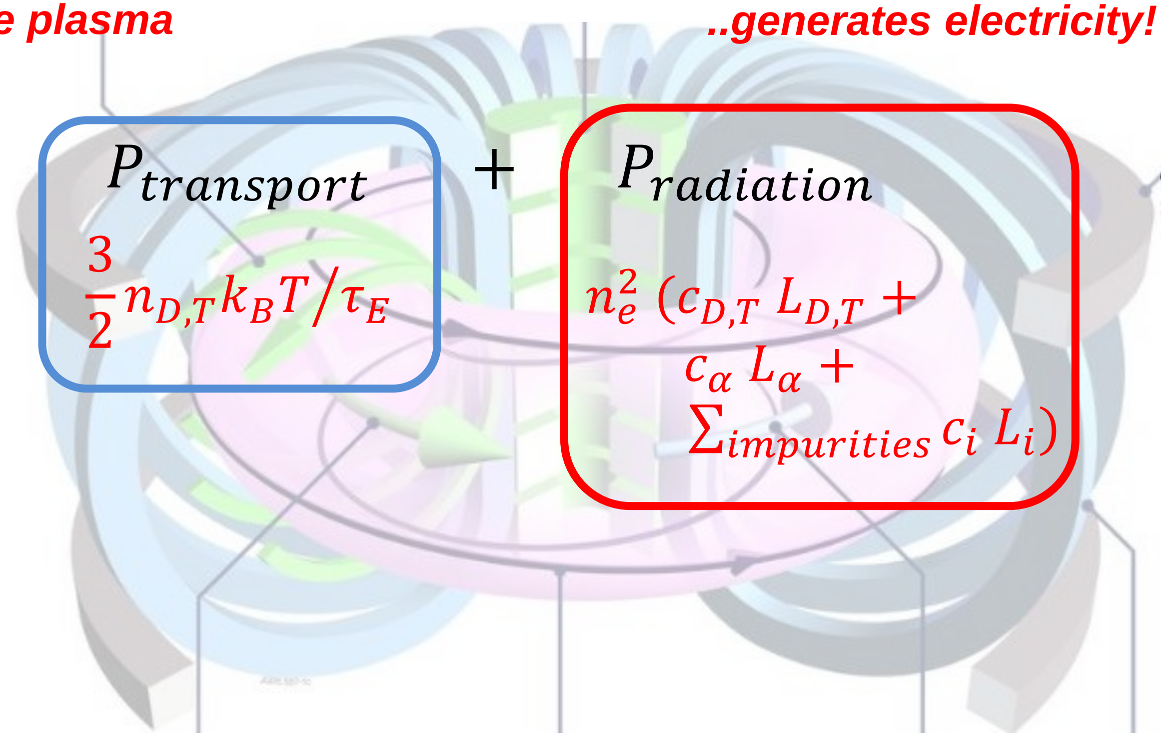
Fusion energy, the Tokamak

<u>Ideally</u> , the plasma should **self-sustain** itself with the **fusion-born alpha particles heating** balancing the **losses**

$$D + T \rightarrow {}^4He + n$$

14.1 MeV → hits wall..
..looses energy..
..heats up coolant..
..produces steam..
..generates electricity!

3.5 MeV → heats the plasma



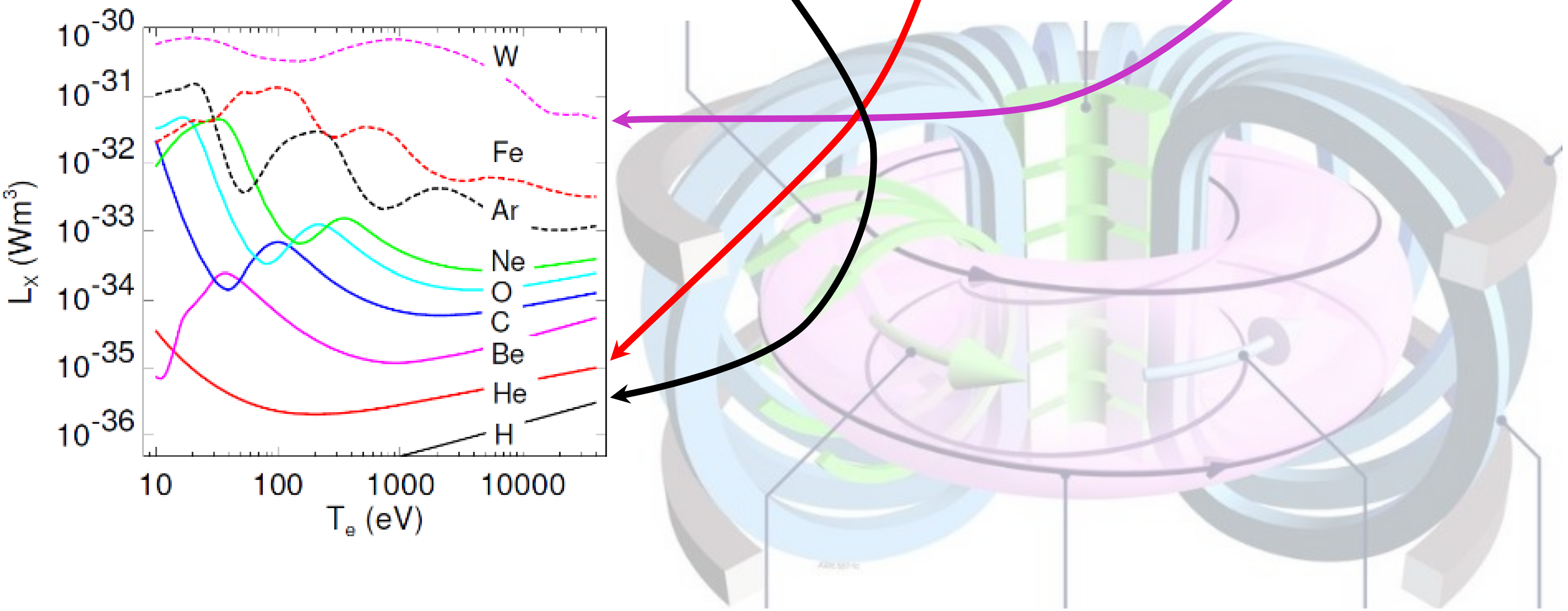
$$P_{\alpha-heating} = P_{transport} + P_{radiation}$$

$$n_D n_T \langle \sigma v \rangle E_\alpha = \frac{3}{2} n_{D,T} k_B T / \tau_E + n_e^2 \left(c_{D,T} L_{D,T} + c_\alpha L_\alpha + \sum_{impurities} c_i L_i\right)$$

Fusion energy, the Tokamak and impurities

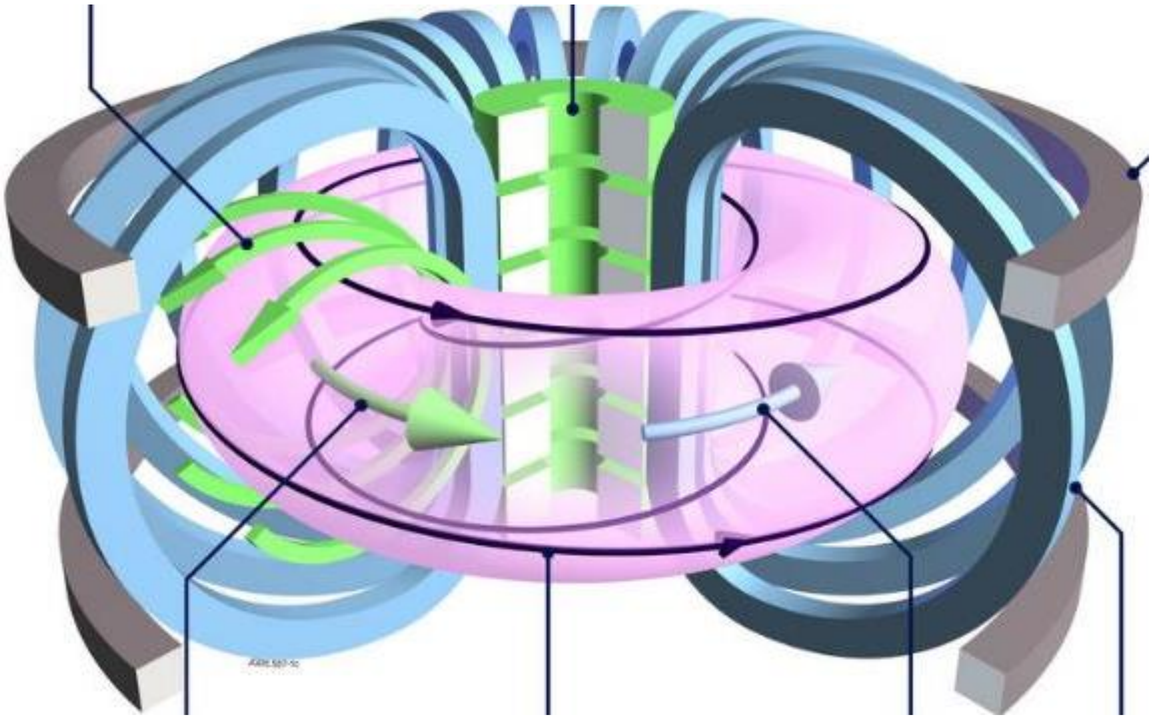
In this talk, we're interested in the **control of heavy impurities**

$$P_{radiation} = n_e^2 \left(c_{D,T} \boxed{L_{D,T}} + c_\alpha \boxed{L_\alpha} + \sum_{impurities} c_i \boxed{L_i}\right)$$



Fusion energy, the Tokamak and impurities

Impurities will always be present in fusion plasmas



Fusion energy, the Tokamak and impurities

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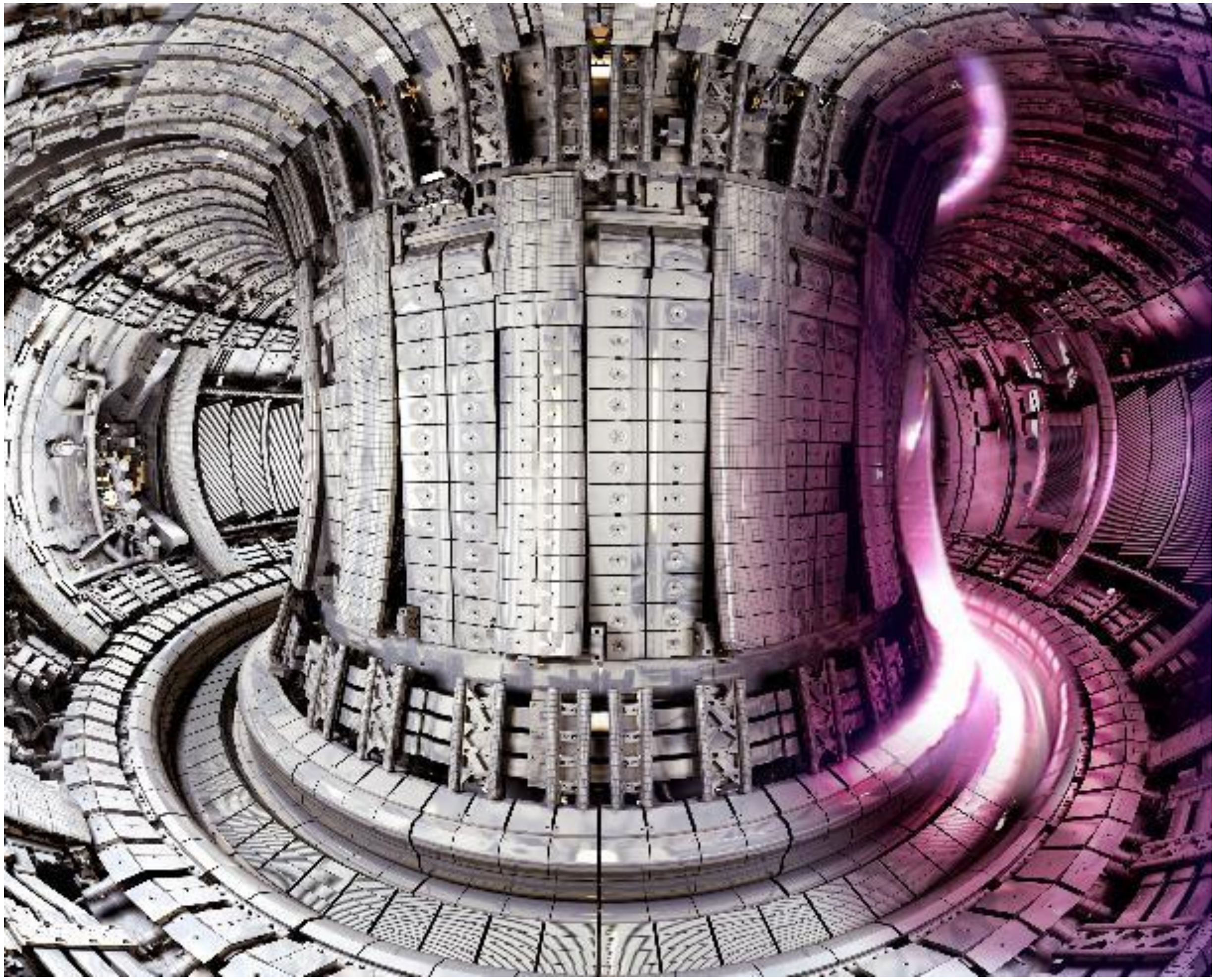


Fusion energy, the Tokamak and impurities

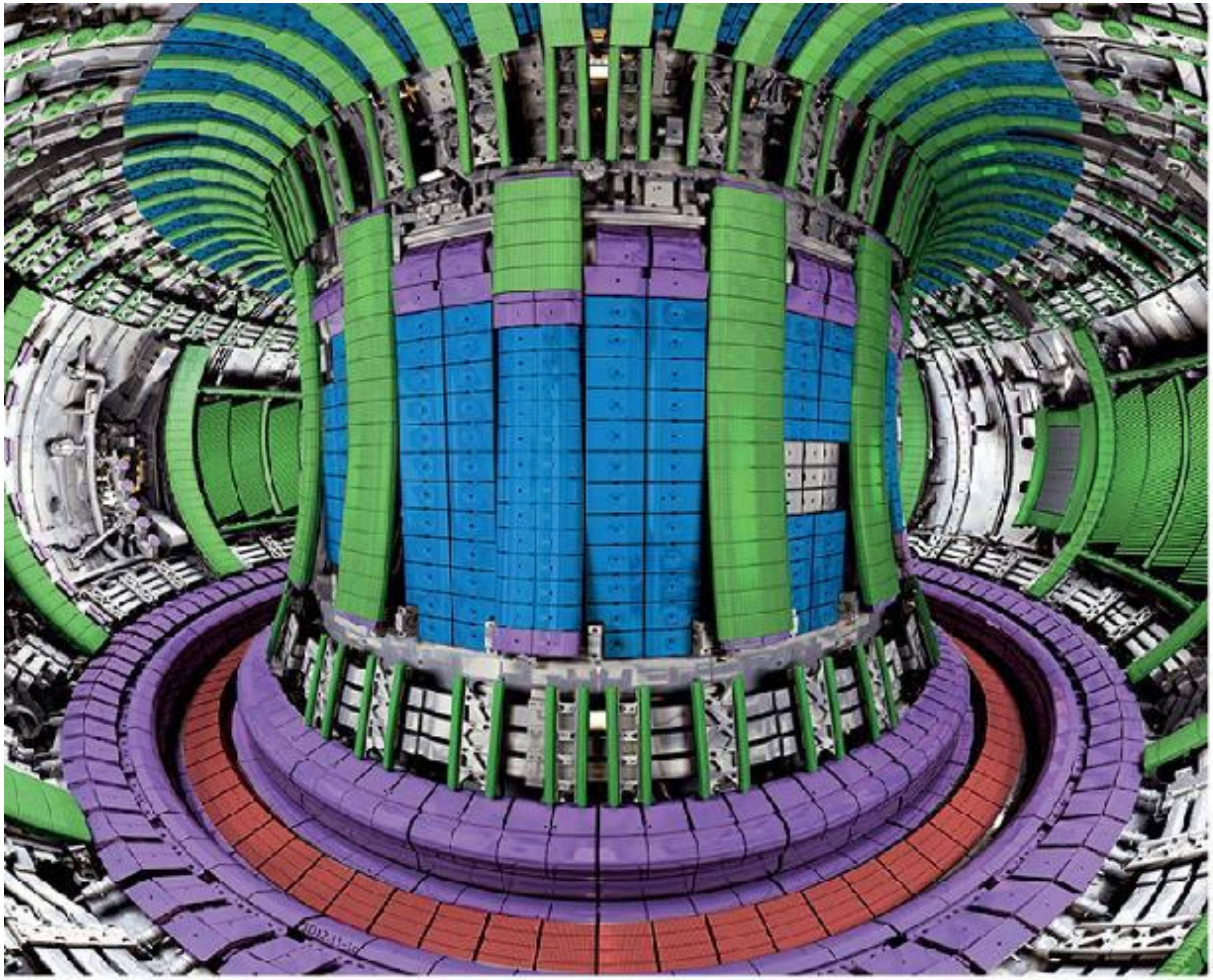
Impurities will always be present in fusion plasmas

<u>Eroded from PFCs</u>

*e.g. for JET: **bulk Be**,*

***Be-coated Inconel**,*

Bulk W**, **W-coated CFC



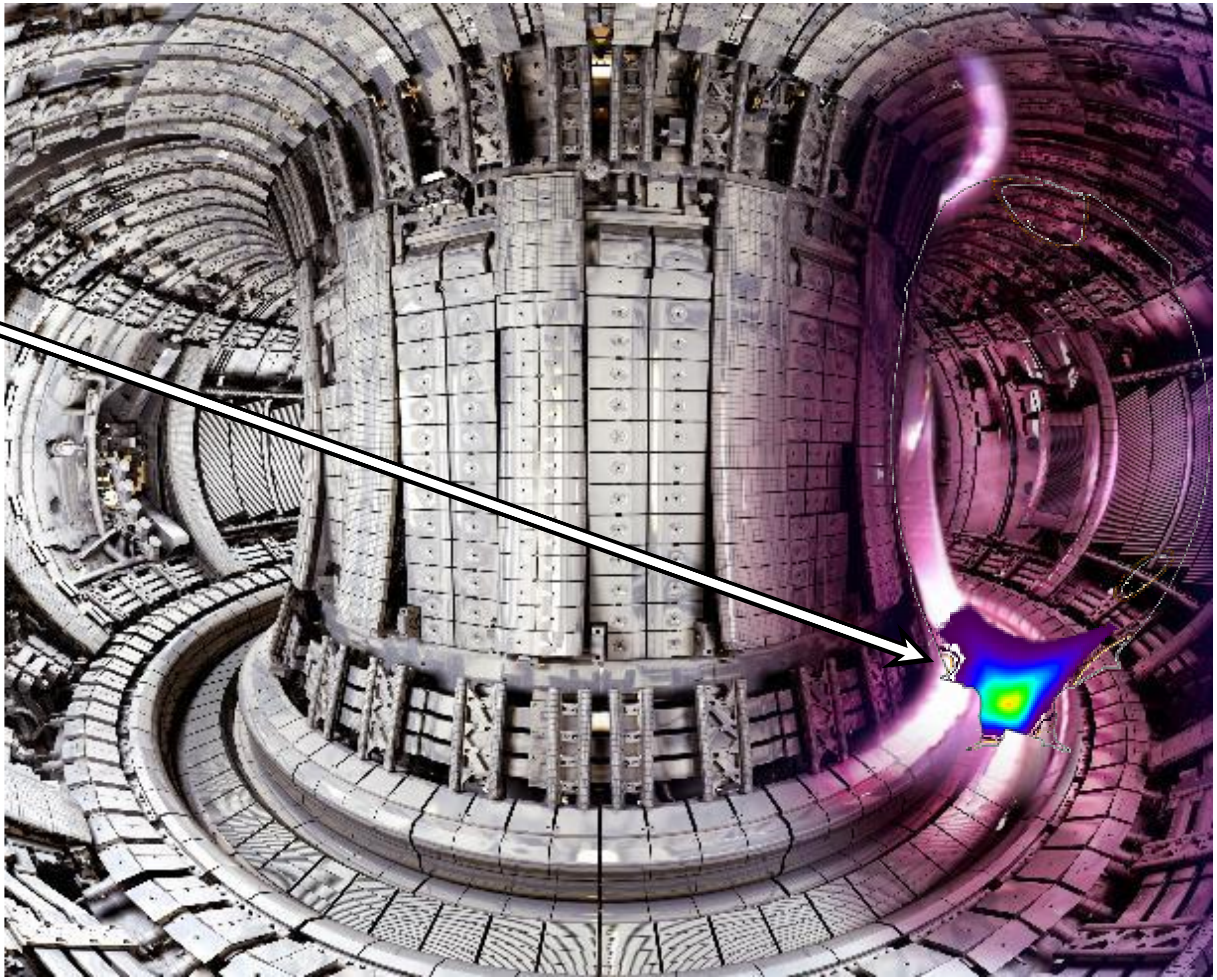
Fusion energy, the Tokamak and impurities

Impurities will always be present in fusion plasmas

<u>Eroded from PFCs</u>

<u>Deliberately injected</u>

e.g. N_2-seeding to decrease power loads to the divertor



[M Bernert PhD Thesis 2013, L Simons EPS-Conference 2018]

Fusion energy, the Tokamak and impurities

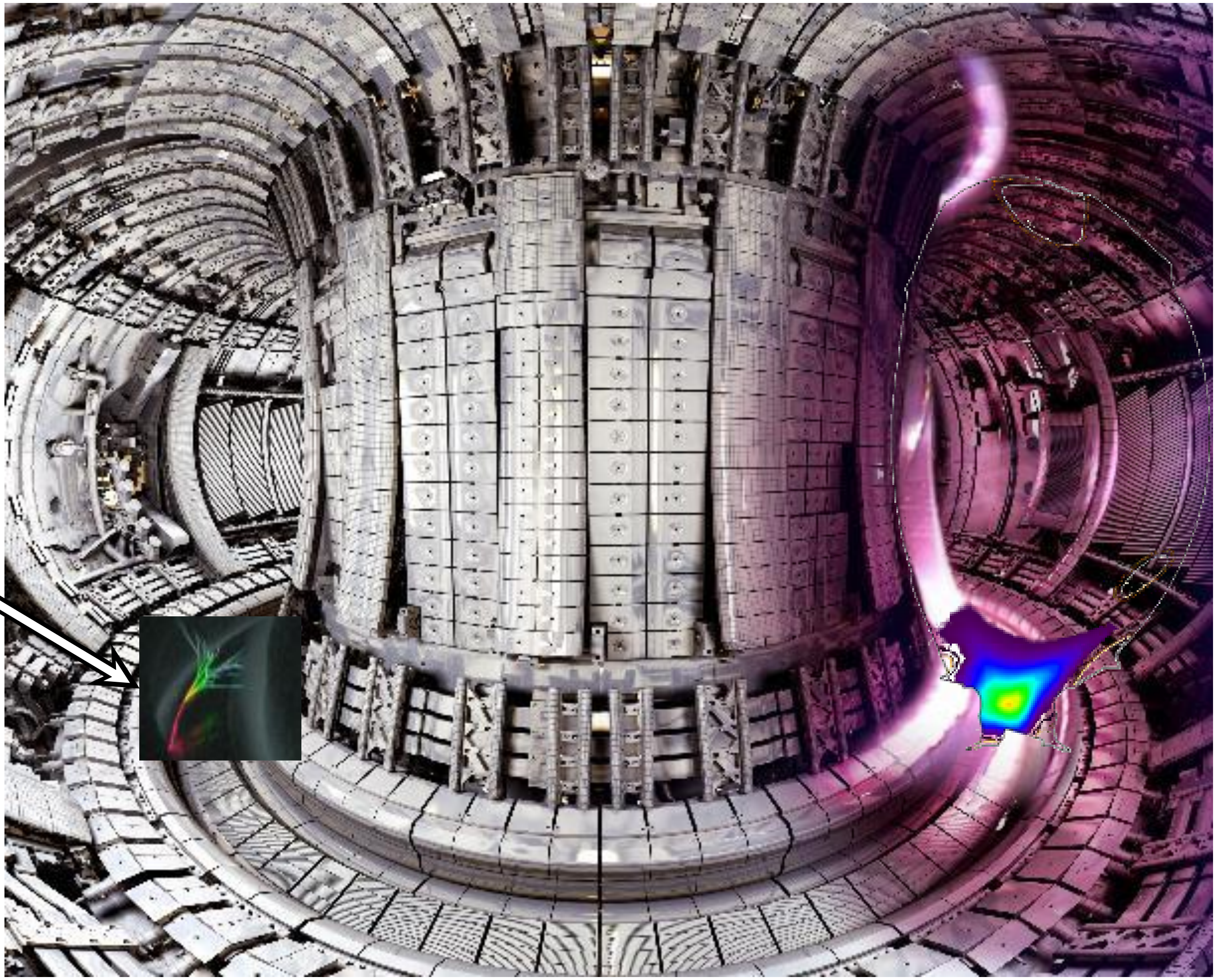
Impurities will always be present in fusion plasmas

Eroded from PFCs

Deliberately injected

Unintentionally injected

e.g. mobilized dust particles



[M Bernert PhD Thesis 2013, L Simons EPS-Conference 2018]

Fusion energy, the Tokamak and impurities

Impurities will always be present in fusion plasmas

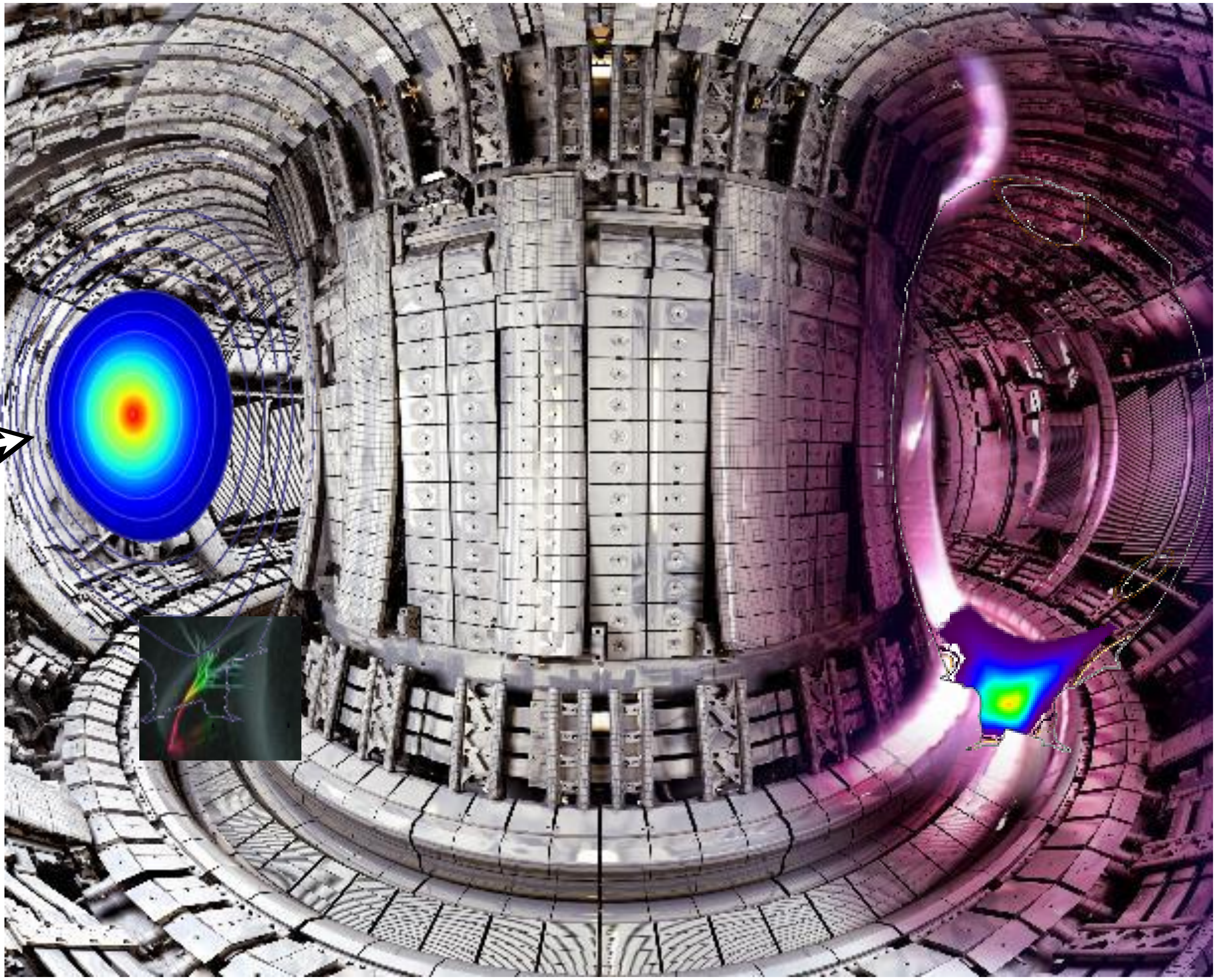
Eroded from PFCs

Deliberately injected

Unintentionally injected

He-ash

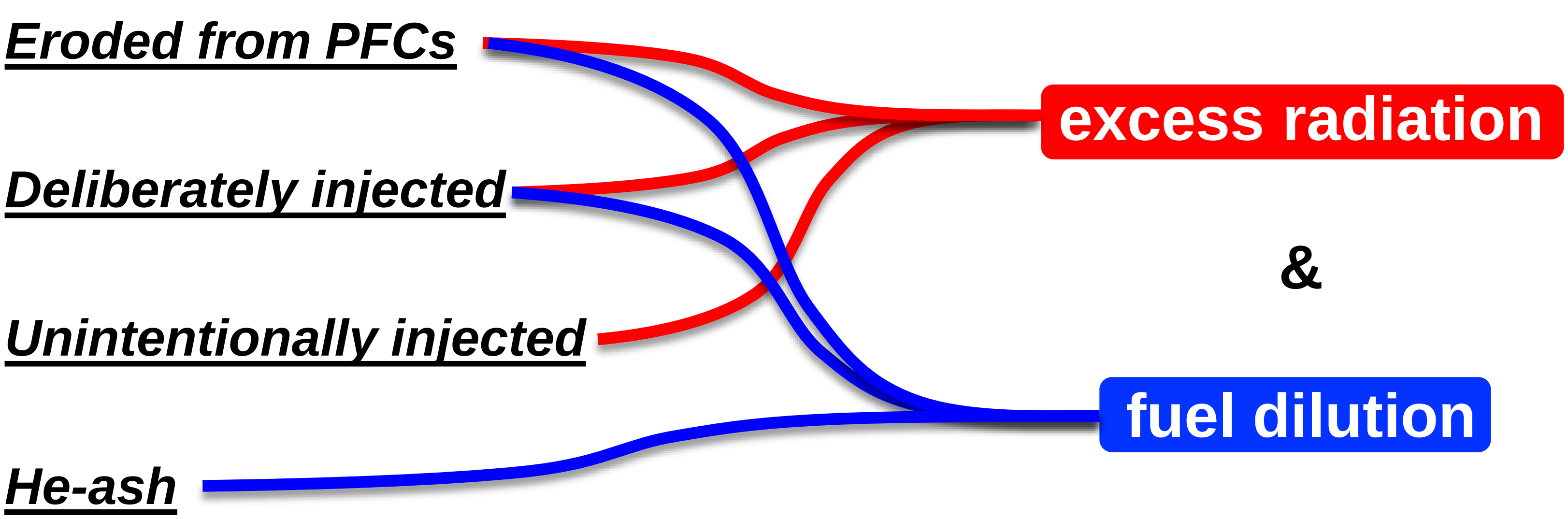
from fusion reactions



[M Bernert PhD Thesis 2013, L Simons EPS-Conference 2018]

Fusion energy, the Tokamak and impurities

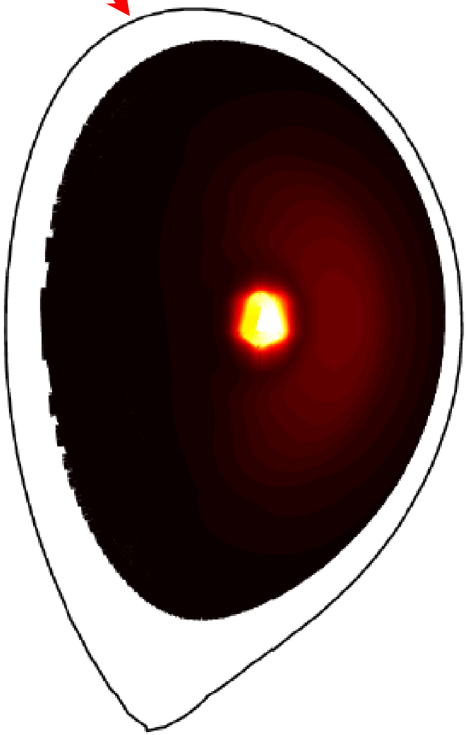
Impurities will always be present in fusion plasmas



¿ **How much control do we need / can we have** ?

Outline

- » Short review of **core impurity transport**
- » Known **control mechanisms** of **impurity accumulation**
- » **Role of MHD**
  - → **experimental evidence**
  - → **theory (…)**
- » Conclusions / Outlook



*What this talk will **not cover**:*

- ***Sources*** *at the wall*
- ***Penetration*** *across the* ***last-closed-flux-surface***
- ***In/out-flux*** *across the* ***pedestal***
- ***Low-Z (e.g. C, Be,) impurity transport***

Radial impurity transport

Modelled using a **diffusive** & **convective** ansatz:

$$\frac{R\,\Gamma_s}{n_s} = -\frac{RD_s}{n_s}\frac{\partial n_s}{\partial r} + RV_s$$

It is understood to be **driven** by **collisions** (*neoclassical*):

$$\frac{R\,\Gamma_s^{neo}}{n_s} \propto \frac{q_s^2 \sum_i \nu_{is}}{m_I}\left[\left(-\frac{R}{L_{n_I}} + \frac{1}{2}\frac{R}{L_{T_I}} + \frac{1}{q_s}\frac{R}{L_{n_s}}\right)P_A - 0.33 P_B f_c \frac{R}{L_{T_I}}\right]$$

and **turbulence** (*anomalous*)

$$\frac{R\,\Gamma_s^{turb}}{n_s} \propto \left(-\frac{R}{L_{n_I}} + C_T\frac{R}{L_{T_I}} + C_u u' + C_P\right)$$

governed by **gradients** , **plasma composition** (*main ion + impurity mix*) , **poloidal asymmetries** , etc.

Radial impurity transport & its control

Can be achieved by :

- Increasing the ion temperature gradient ↑
- Decreasing the main ion density gradient ↓
- Decreasing the magnetic shear ↓
- Increasing the toroidal rotation ↑

$$\frac{R\,\Gamma_s^{neo}}{n_s} \propto \frac{q_s^2 \sum_i \nu_{is}}{m_I}\left[\left(-\frac{R}{L_{n_I}} + \frac{1}{2}\frac{R}{L_{T_I}} + \frac{1}{q_s}\frac{R}{L_{n_s}}\right)P_A - 0.33 P_B f_c \frac{R}{L_{T_I}}\right]$$

$$\frac{R\,\Gamma_s^{turb}}{n_s} \propto \left(-\frac{R}{L_{n_I}} + C_T \frac{R}{L_{T_I}} + C_u u' + C_P\right)$$

Radial impurity transport & its control

Can be achieved by :

- **Increasing the ion temperature gradient** ↑
- **Decreasing the main ion density gradient** ↓
- **Decreasing the magnetic shear** ↓
- **Increasing the toroidal rotation** ↑
- **Increasing the sawtooth frequency** ↑

$$\frac{R\,\Gamma_s^{neo}}{n_s} \propto \frac{q_s^2 \sum_i \nu_{is}}{m_I}\left[\left(-\frac{R}{L_{n_I}} + \frac{1}{2}\frac{R}{L_{T_I}} + \frac{1}{q_s}\frac{R}{L_{n_s}}\right)P_A - 0.33 P_B f_c \frac{R}{L_{T_I}}\right]$$

$$\frac{R\,\Gamma_s^{turb}}{n_s} \propto \left(-\frac{R}{L_{n_I}} + C_T\frac{R}{L_{T_I}} + C_u u' + C_P\right)$$

…of course, all of these are <u>non-linearly coupled</u>…

Radial impurity transport & its control

Can be achieved by :

- **Increasing the ion temperature gradient** ↑
- **Decreasing the main ion density gradient** ↓
- **Decreasing the magnetic shear** ↓
- **Increasing the toroidal rotation** ↑
- **Increasing the sawtooth frequency** ↑

…using **external actuators** such as:

- **Heating** (NBI, ICRH, ECRH, …)
- **Current drive** (inductive, ECCD, NBCD, ICCD, …)
- **Fuelling** (gas or pellets)
- **Magnetic perturbations**

!!! All of which have **effects on MHD activity** as well **!!!**

What is the role of MHD?

We're still not sure how MHD influences impurity transport…

*Perhaps the most intriguing aspect of these observations is the **apparent correlation between impurity transport and MHD activity**. (..) A correlation such as this naturally suggests that the central MHD activity is somehow responsible for the change in impurity confinement. (..) **There is no theory that includes the effect of MHD modes on impurity transport**.*

[G L Jahns et al 1982 Nucl. Fusion 22 1049]

…and not much has been done since...

What is the role of MHD?

G L Jahns et al 1982 Nucl. Fusion 22 1049
K Ida et al 1986 Plasma Phys. Control. Fusion 28 879
A Weller et al 1987 Phys. Rev. Lett. 59 2303
R D Gill et al 1992 Nucl. Fusion 32 723
S V Putvinskij 1993 Nucl. Fusion 33 133
J A Wesson 1995 Plasma Phys. Control. Fusion 37 A337
S Günter et al 1999 Nucl. Fusion 39 1535
R Dux et al 1999 Nucl. Fusion 39 1509
M F F Nave et al 2003 Nucl. Fusion 43 1204
C Giroud et al 2007 Nucl. Fusion 47 313
A Gude et al EPS 2010 P4.124
L Delgado-Aparicio et al 2011 Nucl. Fusion 51 083047
M Sertoli et al 2011 Plasma Phys. Controlled Fusion 53, 035024
L Delgado-Aparicio et al 2013 Nucl. Fusion 53 043019
T Pütterich et al 2013 Plasma Phys. Controlled Fusion 55, 124036
L Xu et al 2013 Plasma Phys. Control. Fusion 55 032001
T Nicolas et al 2014 Phys. of Plasmas 21 012507
M Sertoli et al 2015 Plasma Phys. Controlled Fusion 57, 075004
M Sertoli et al 2015 Nucl. Fusion 55, 113029
J M Regaña et al EPS 2015 P2.170
C Angioni et al 2015 Physics of Plasmas 22, 055902
T Hender e al 2016 Nucl. Fusion 56, 066002
J-H Anh et al 2016 Plasma Phys. Control. Fusion 58 125009
M Goniche et al 2017 Plasma Phys. Controlled Fusion 59, 055001
P Piovesan et al 2017 Plasma Phys. Control. Fusion 59 014027
C Angioni et al 2017 Nucl. Fusion 57 056015
M Sertoli et al 2017 Physics of Plasmas 24, 112503
M Raghunathan et al 2017 Plasma Phys. Control. Fusion 59 124002

Theory
(N)TMs
1/1 modes

Mainly qualitative observations…

…a few attempts to perform quantitative estimates…

Year
1982
1986
1990
1994
1998
2002
2006
2010
2014
2018

What is the role of MHD?

MHD ***claimed / observed*** to have **beneficial** or **detrimental** effects on impurity accumulation depending on mode type

1. **Sawtooth cycling (m=1 precursors)**

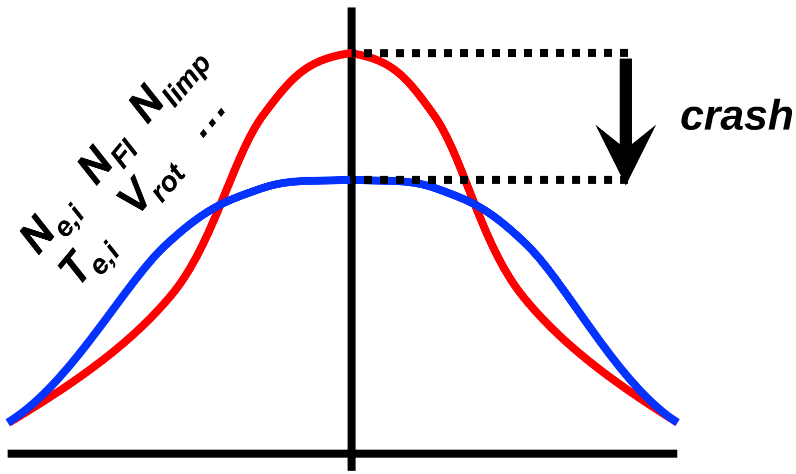
2. **Saturated m=1 modes**

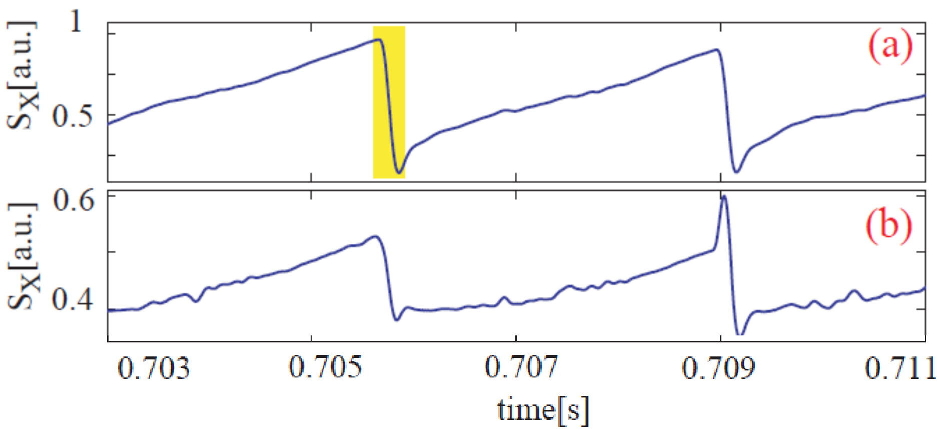
3. **(Neoclassical) Tearing Modes (m>1)**

Fishbones (m=1) not discussed *: similar to continuous m=1 modes, but too little evidence and published research…*

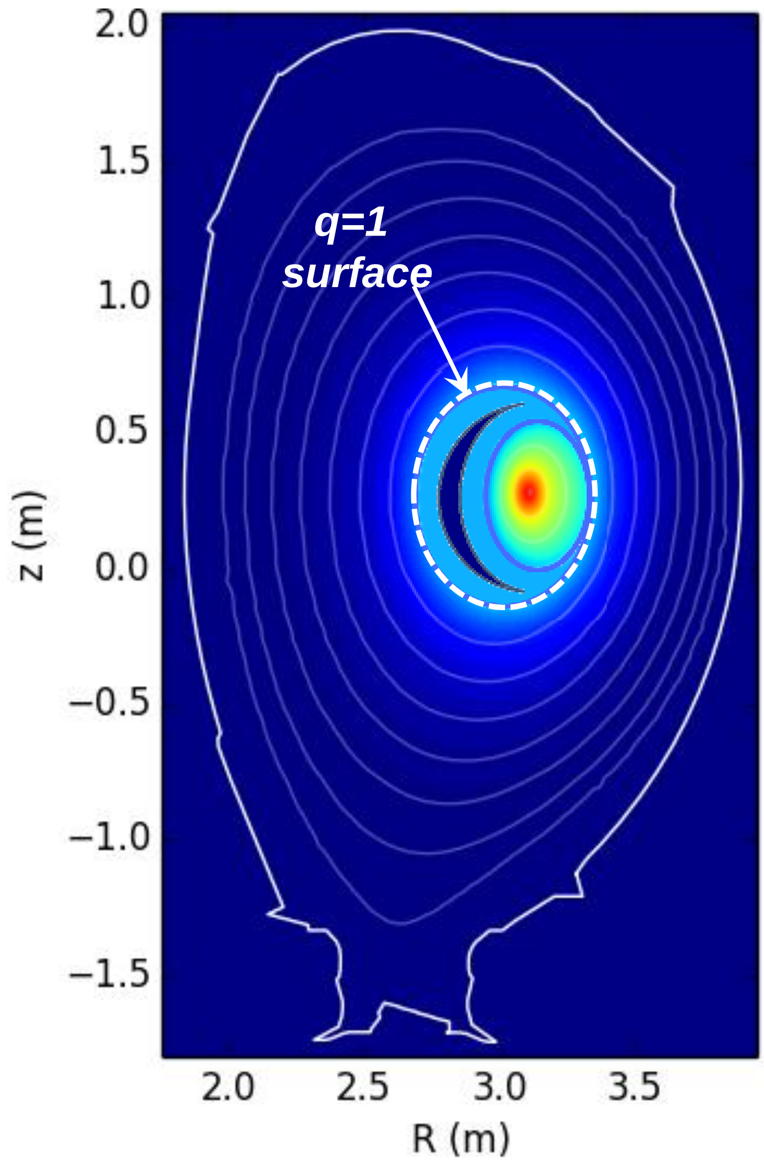
Sawtooth cycling (m=1 precursor)

Periodic collapse of core profiles inside ~ q=1 surface





[I. Furno 2001 Nucl. Fusion 41 403]



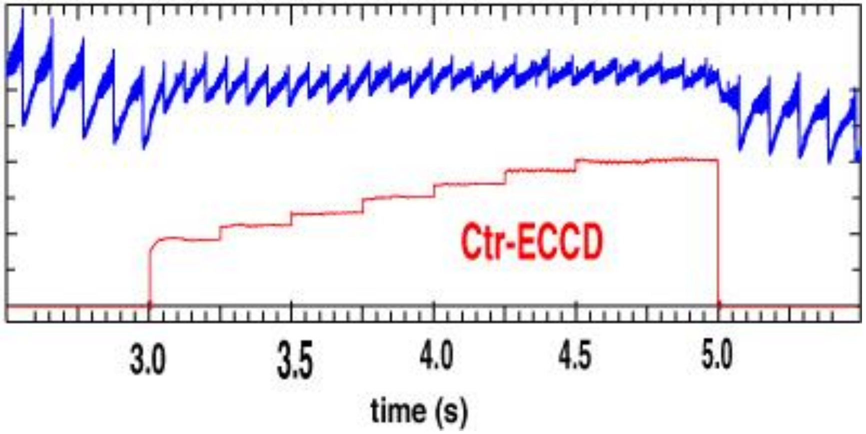
Sawtooth cycling (m=1 precursor)

Periodic collapse of core profiles inside ~ q=1 surface

Prevent impurity accumulation increasing the frequency using external heating/current drive acting on:

- **temperature**
- **current profile**
- **fast particle** population
- **toroidal rotation**
- **…**

AUG



[A Mück 2005 PPCF 47 1633]

Sawtooth cycling (m=1 precursor)

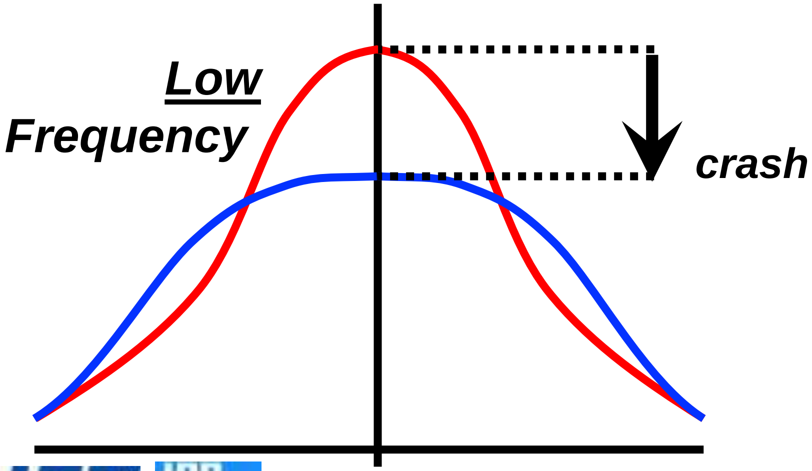
Periodic collapse of core profiles inside ~ q=1 surface

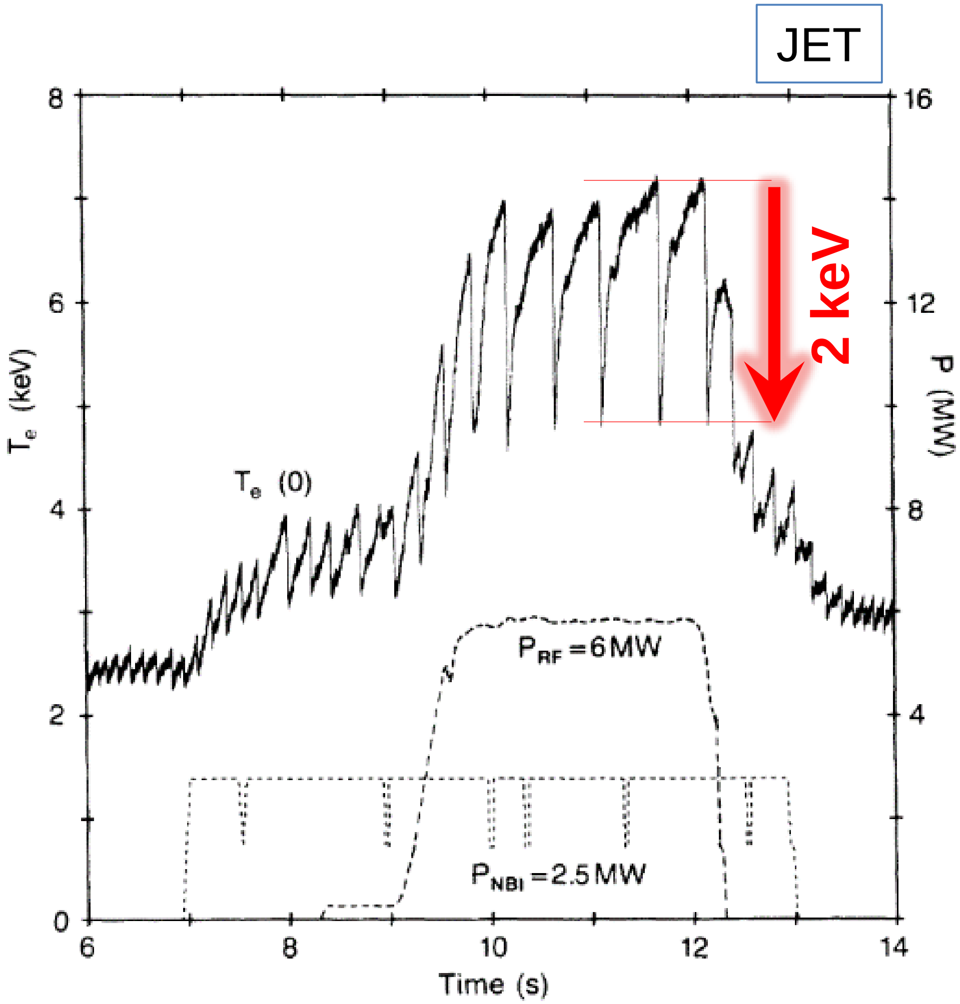
Prevent impurity accumulation increasing the frequency

using external heating/current drive

BUT

- ***reduction in P_{fus}*** *: flat $T_{e,i}$ inside r_{inv} (~ mid radius in ITER?)*





[D Campbell 1988 PRL 60, 2148]

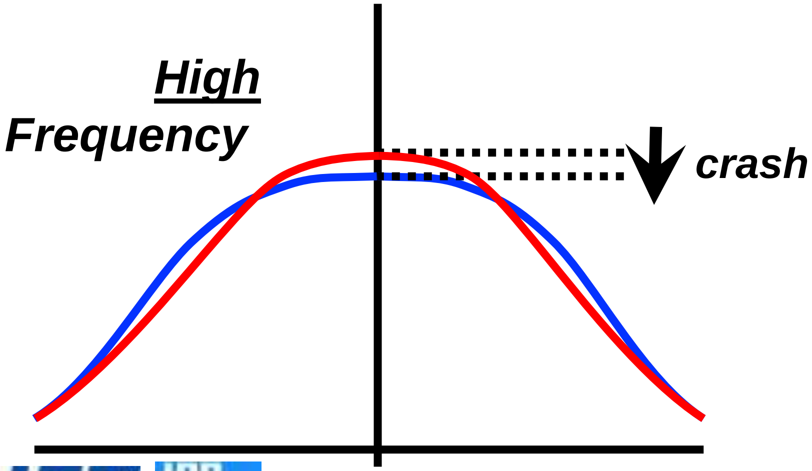
Sawtooth cycling (m=1 precursor)

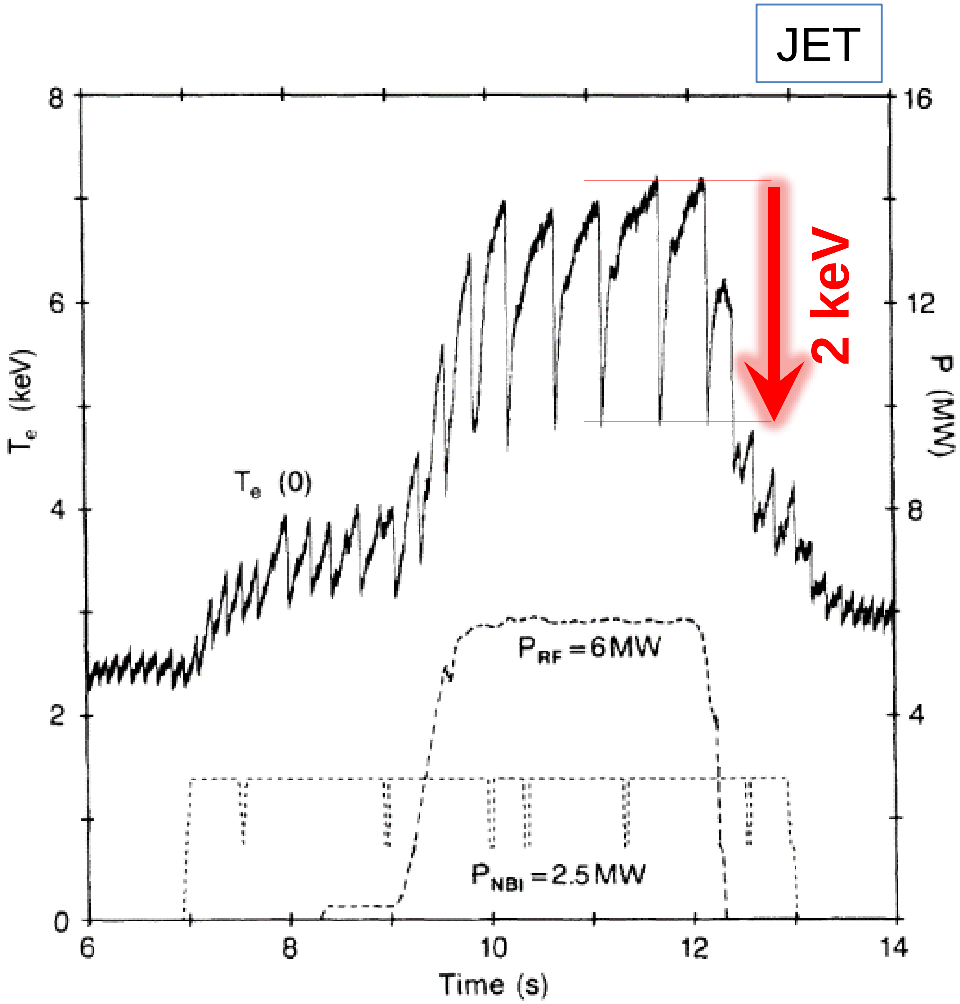
Periodic collapse of core profiles inside ~ q=1 surface

Prevent impurity accumulation increasing the frequency using external heating/current drive

BUT

- ***reduction in P_{fus}*** *: flat $T_{e,i}$ inside r_{inv} (~ mid radius in ITER?)*





[D Campbell 1988 PRL 60, 2148]

Sawtooth cycling (m=1 precursor)

Periodic collapse of core profiles inside ~ q=1 surface

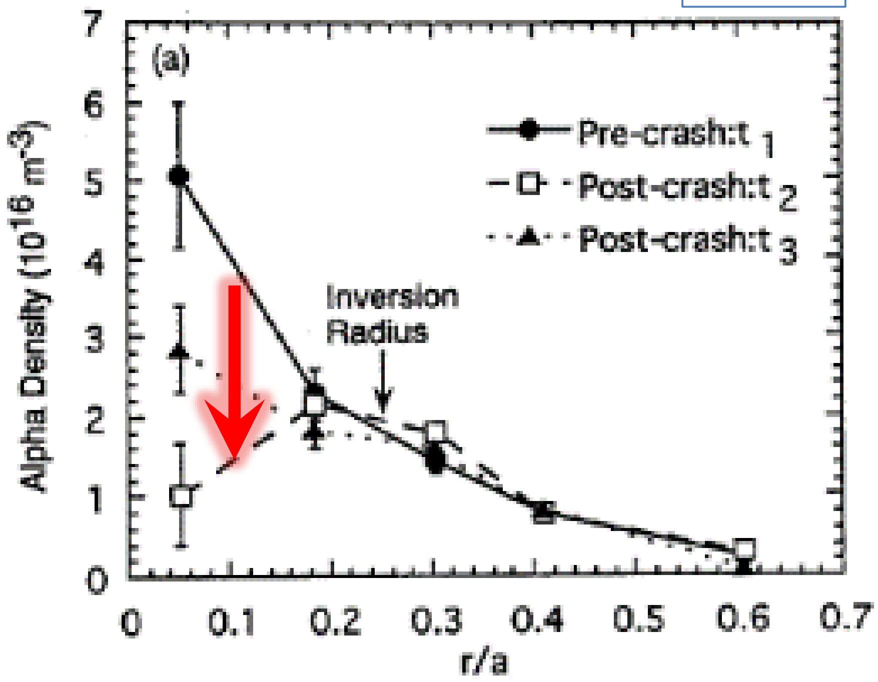
TFTR

[Prevent impurity accumulation increasing the frequency]() using external heating/current drive

BUT

- ***reduction in P_{fus}*** *: flat $T_{e,i}$ inside r_{inv} (~ mid radius in ITER?)*

- ***reduction of P_{α}*** *: expulsion of non-thermalized α-particles*



[B C Stratton 1996 NF 36 1586]

Sawtooth cycling (m=1 precursor)

Periodic collapse of core profiles inside ~ q=1 surface

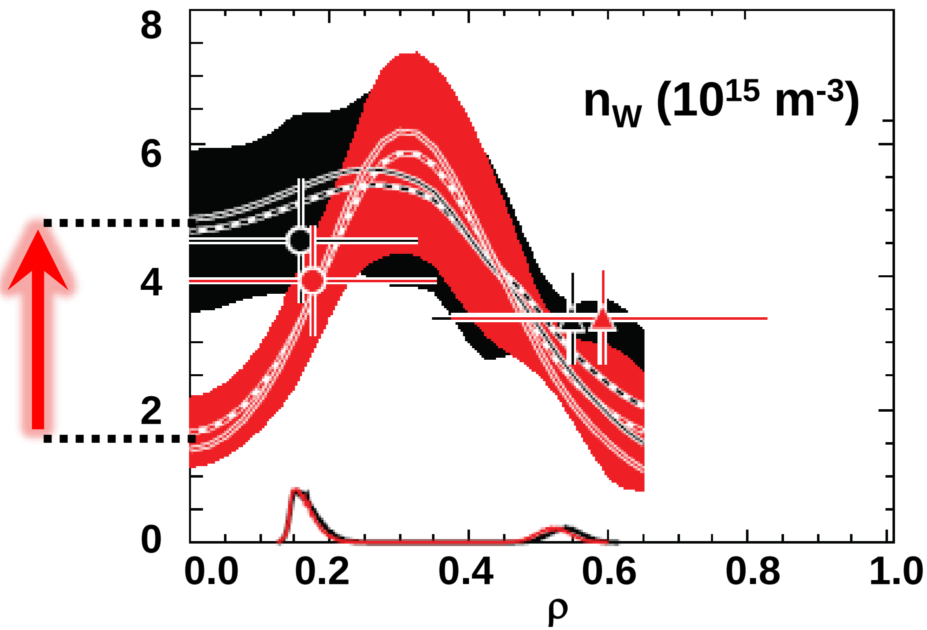
Prevent impurity accumulation increasing the frequency

using external heating/current drive

BUT

- ***reduction in P_{fus}*** *: flat $T_{e,i}$ inside r_{inv} (~ mid radius in ITER?)*
- ***reduction of P_{α}*** *: expulsion of non-thermalized α-particles*
- ***penetration of impurities*** *: for hollow impurity profiles*

AUG



[M Sertoli 2015 NF 55 113029]

What is the role of MHD?

MHD ***claimed / observed*** to have **beneficial** or **detrimental** effects on impurity accumulation depending on mode type

1. **Sawtooth cycling (m=1 precursors)**
   - **Beneficial** to control impurity accumulation & avoid early NTM trigger
   - Can be **detrimental** for confinement & expel non-thermal α-particles

2. **Saturated m=1 modes**

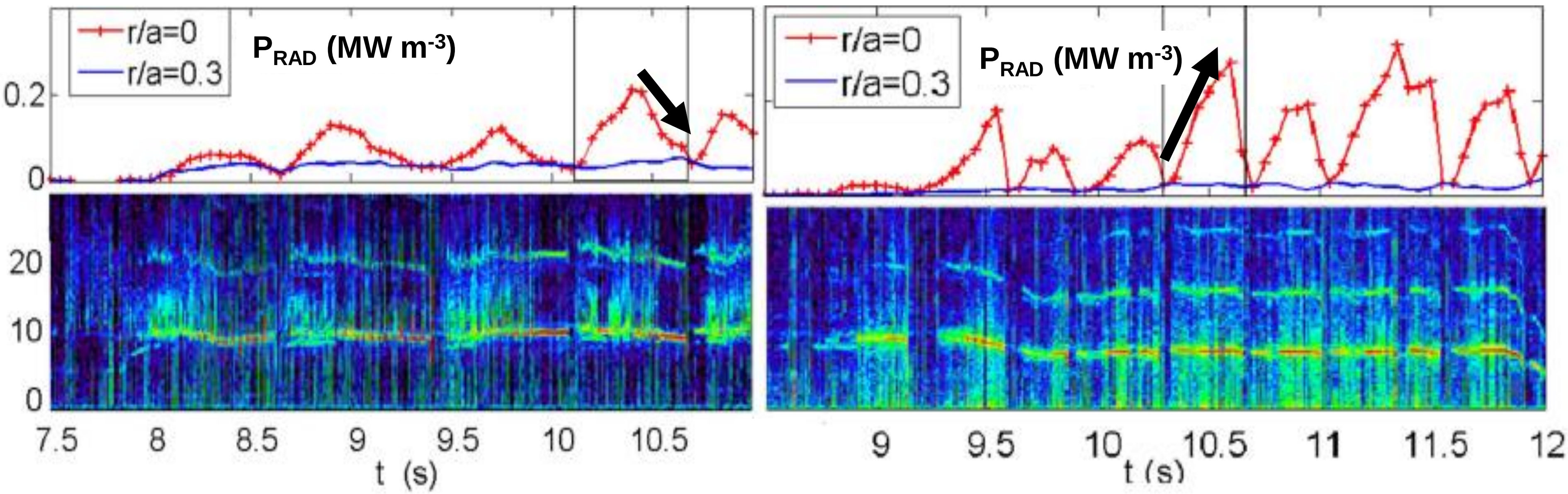
3. **(Neoclassical) Tearing Modes (m>1)**

Saturated m=1 modes (*sawtoothing plasmas*)

Very **diverse transport behaviour** with **“similar” MHD activity** …

ICRH inside q=1 surface | *ICRH close to q=1 surface*

JET

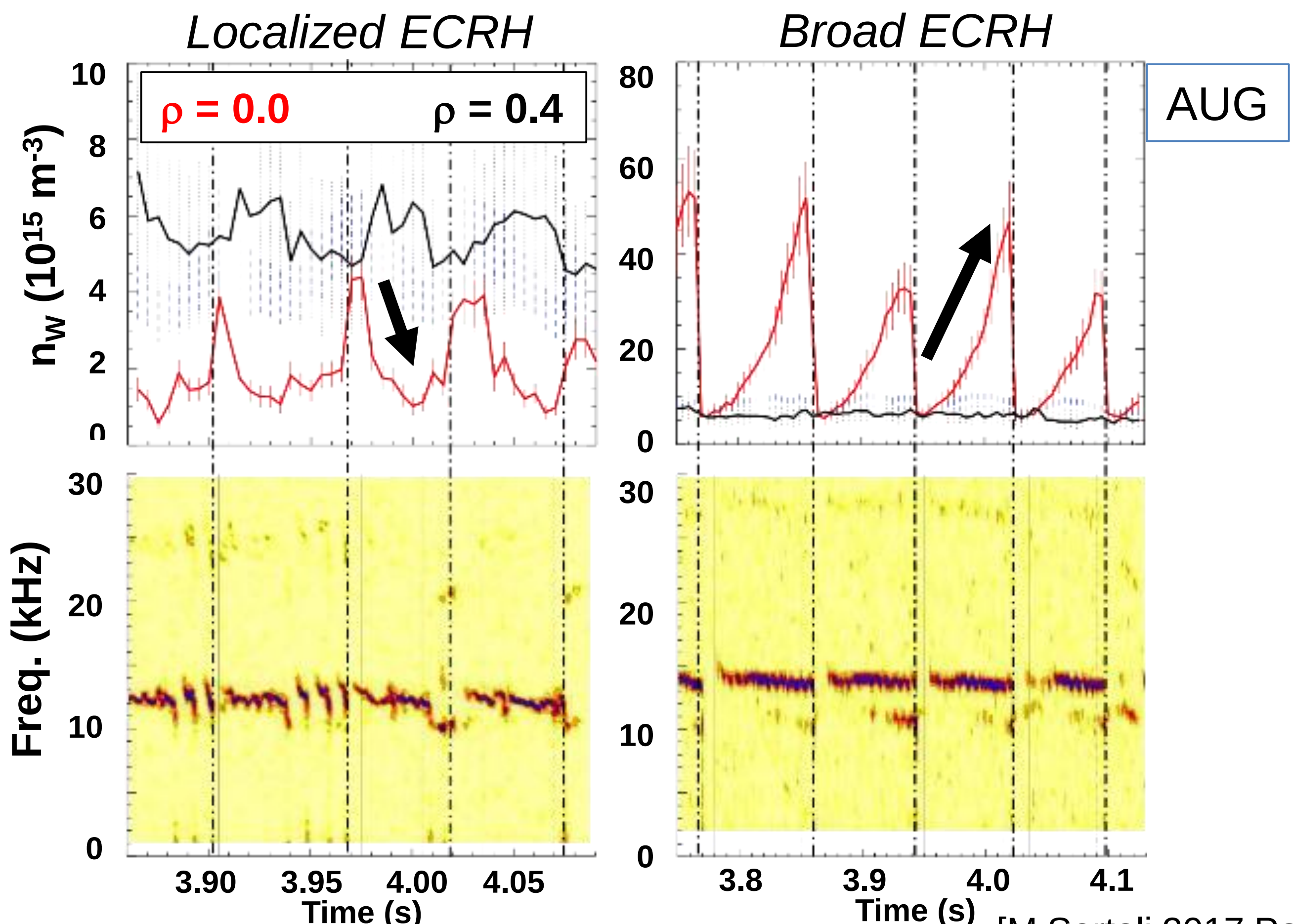


[M Goniche 2017 PPCF 59 055001]

Saturated m=1 modes (*sawtoothing plasmas*)

Very **diverse transport behaviour** with **"similar" MHD activity** …

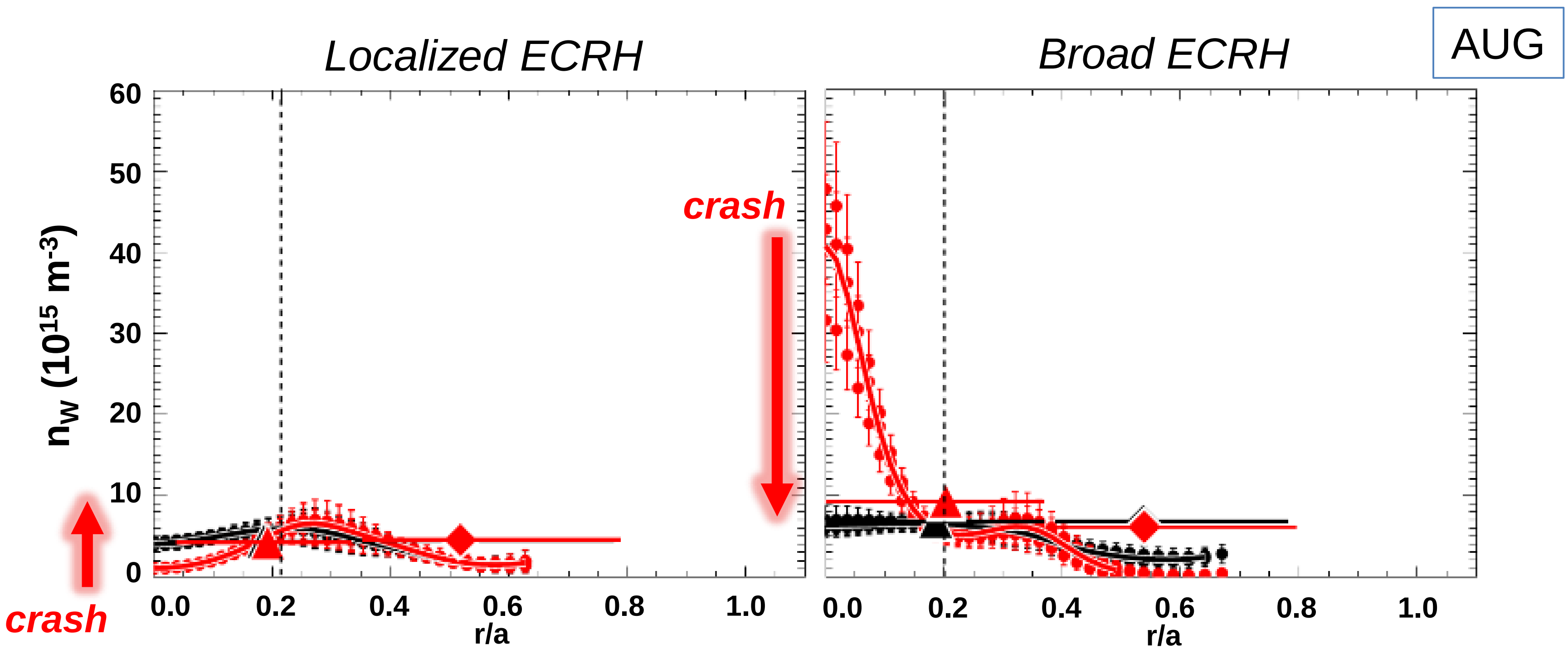
...also with **different external heating** methods



[M Sertoli 2017 PoP 24 112503]

Saturated m=1 modes (*sawtoothing plasmas*)

Very **diverse transport behaviour** with **"similar" MHD activity** …
...also with **different external heating** methods



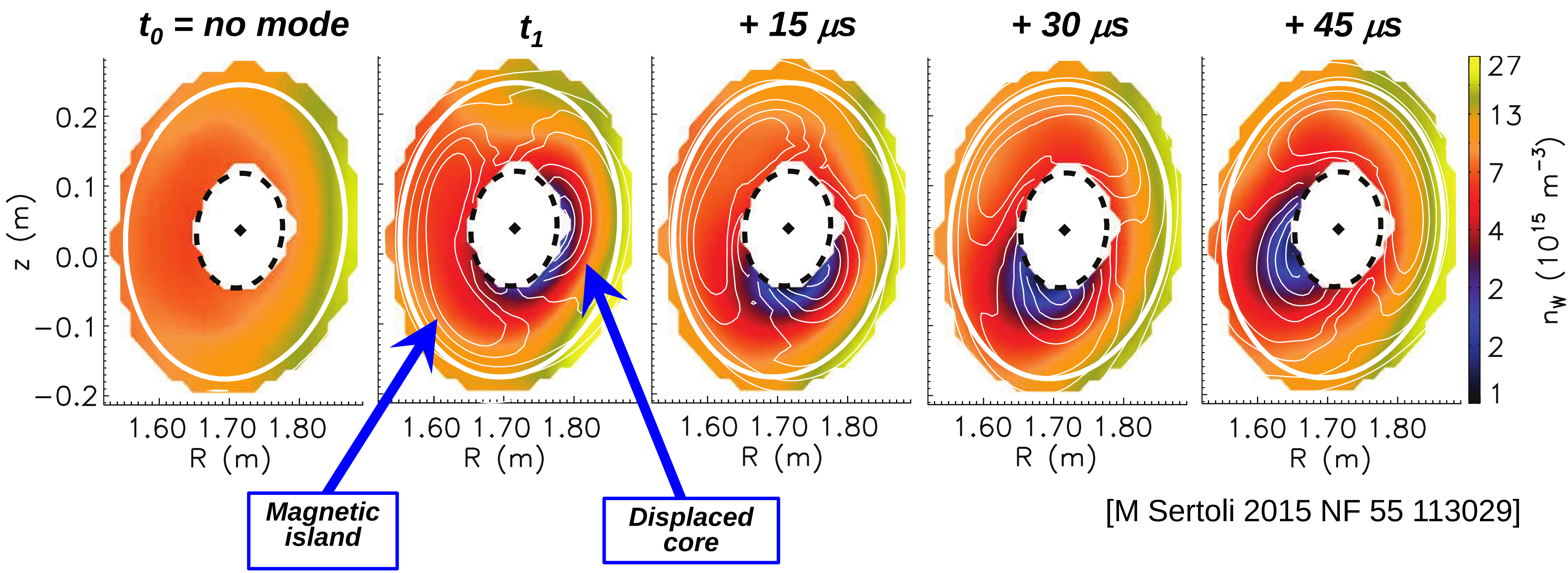
[M Sertoli 2017 PoP 24 112503]

Saturated m=1 modes (*sawtoothing plasmas*)

Very **diverse transport behaviour** with **“similar” MHD activity** …
...also with **different external heating** methods

The hollowness is due to an **impurity hole** in the **displaced core** !

AUG



[M Sertoli 2015 NF 55 113029]

Saturated m=1 modes (*sawtoothing plasmas*)

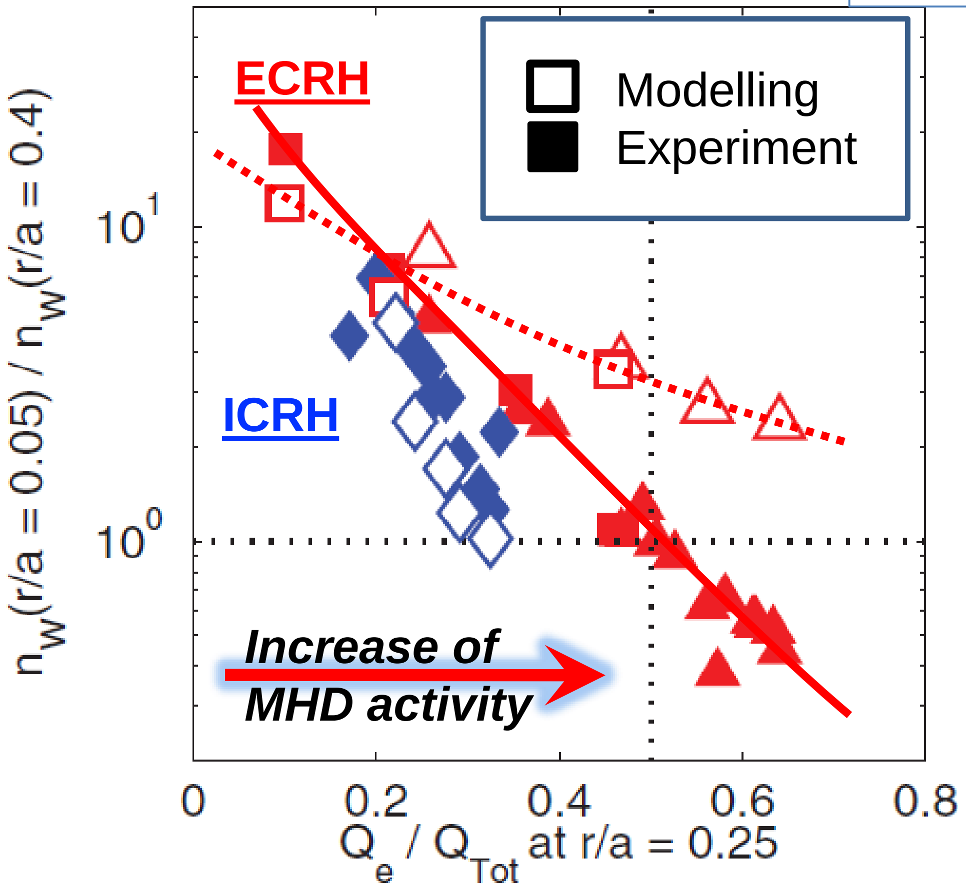
Comparison with modelling difficult because tokamak **neoclassical** and **turbulence** codes

AUG

- **Axisymmetry** (*ideal*)
- **No magnetic islands** (*resistive*)

ICRH: general trend reproduced

ECRH: central hollowness missed



[C Angioni 2017 NF 57 056015]

Saturated m=1 modes (*no sawteeth*)

MAST

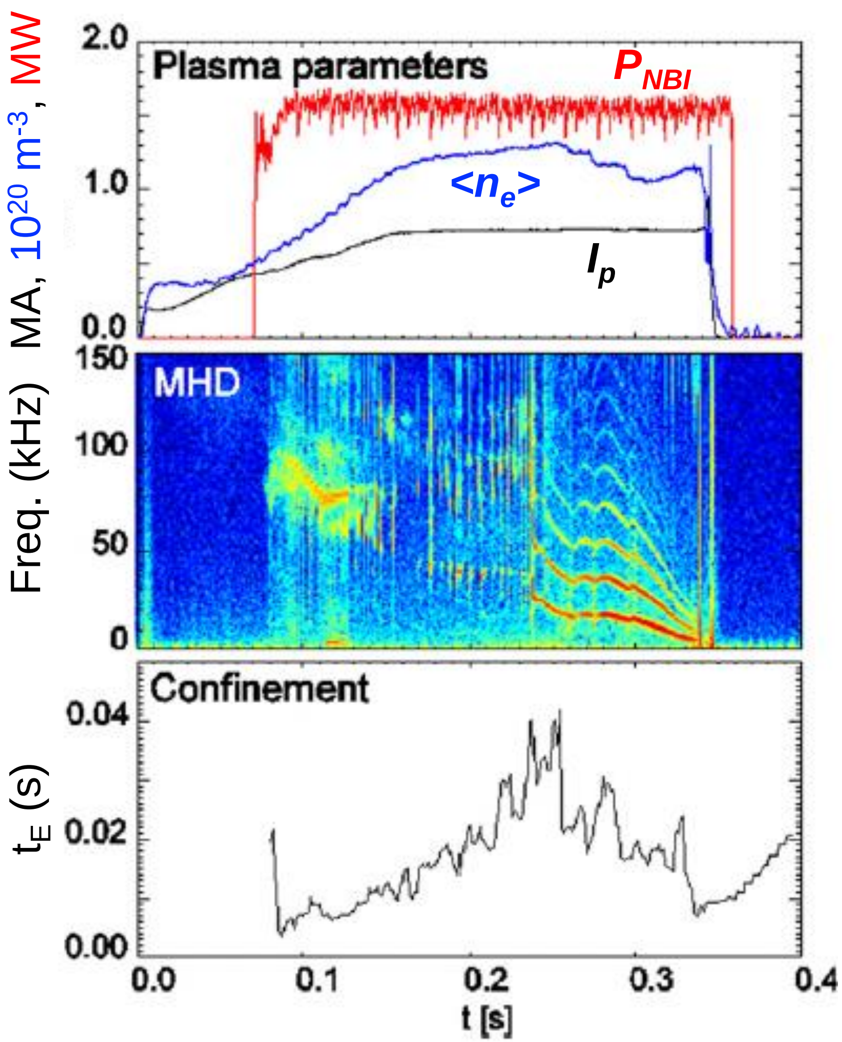
Sometimes associated with **increased impurity accumulation**

Spherical tokamak (NBI only)

1. **Density and temperature reduction**

2. **Toroidal rotation decrease**

3. Central **impurity accumulation**



[I Chapman 2010 NF 50 045007]

Saturated m=1 modes (*no sawteeth*)

Sometimes associated with **increased impurity accumulation**

<u>JET-like simulation</u>

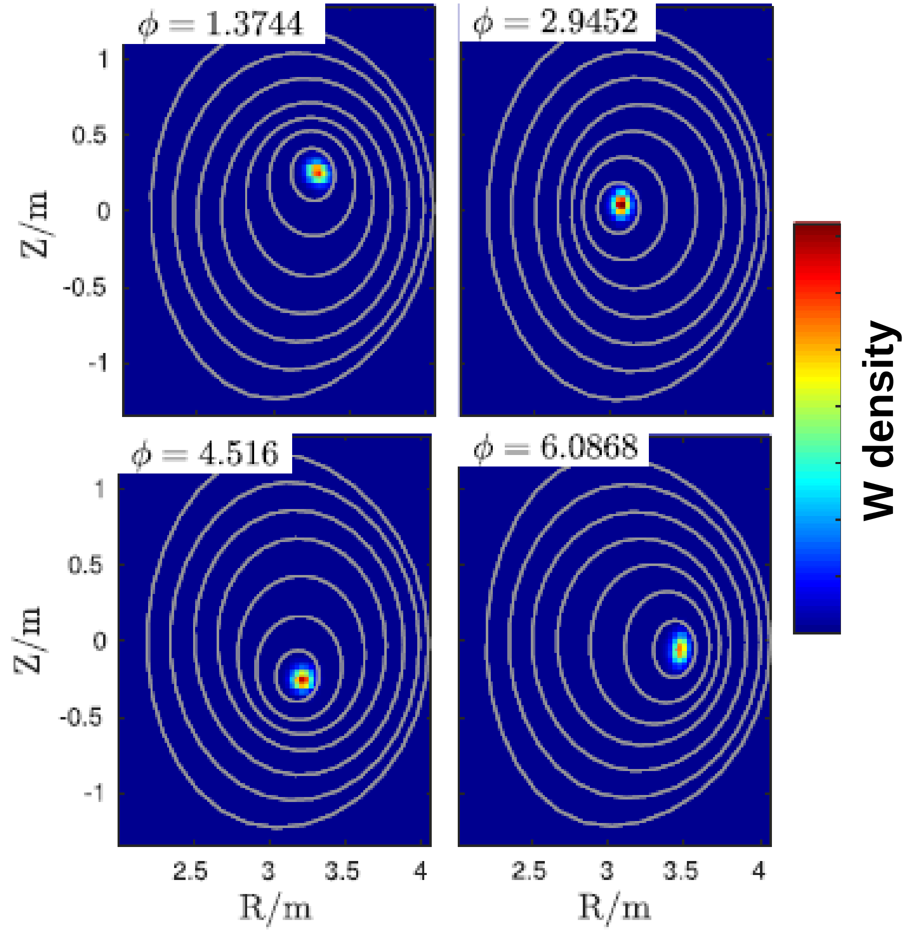
Ideal m=1 mode equilibrium

+ **guiding-center orbit following** code

+ **rotation**

→ enhanced **impurity accumulation**

JET-like simulation



[M Raghunathan 2017 PPCF 59 124002]

Saturated m=1 modes (*no sawteeth*)

JET-like simulation

Sometimes associated with **increased impurity accumulation**

JET-like simulation

Ideal m=1 mode equilibrium

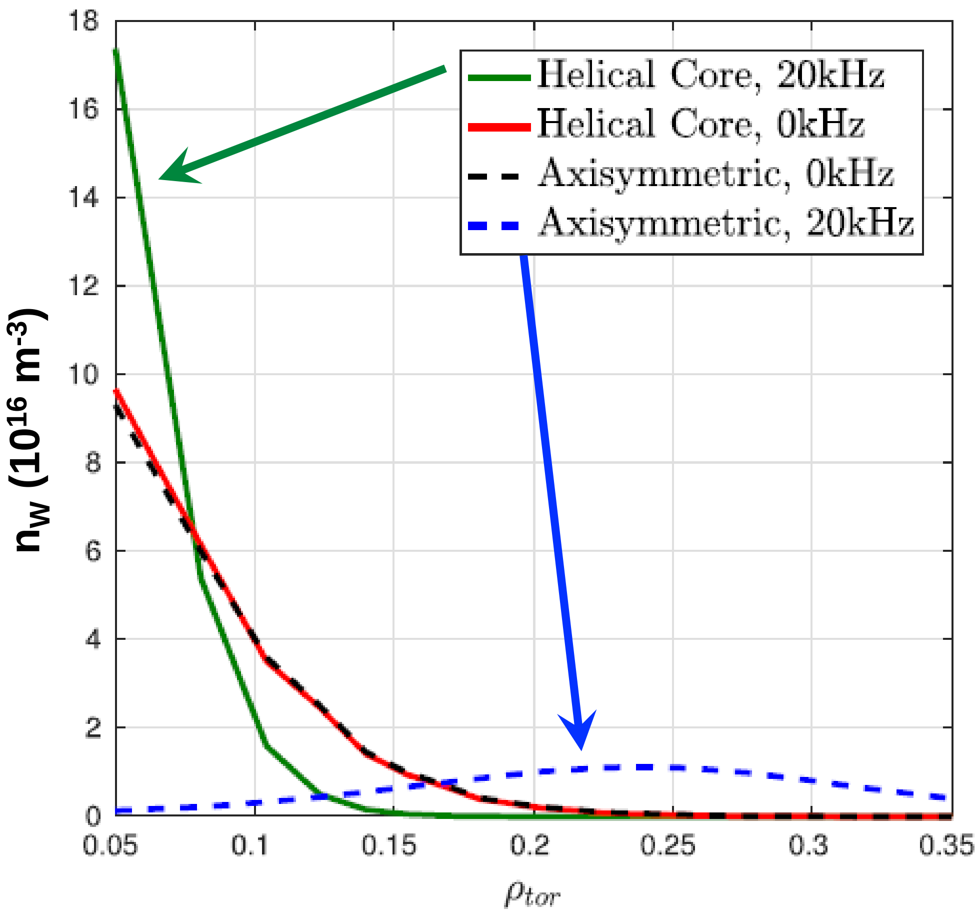
+ **guiding-center orbit following** code

+ **rotation**

→ enhanced **impurity accumulation**

BUT :

- **No** temperature screening $\nabla T_i = 0$
- **No** magnetic island
- **No** benchmark vs. neoclassical
- **No** turbulence



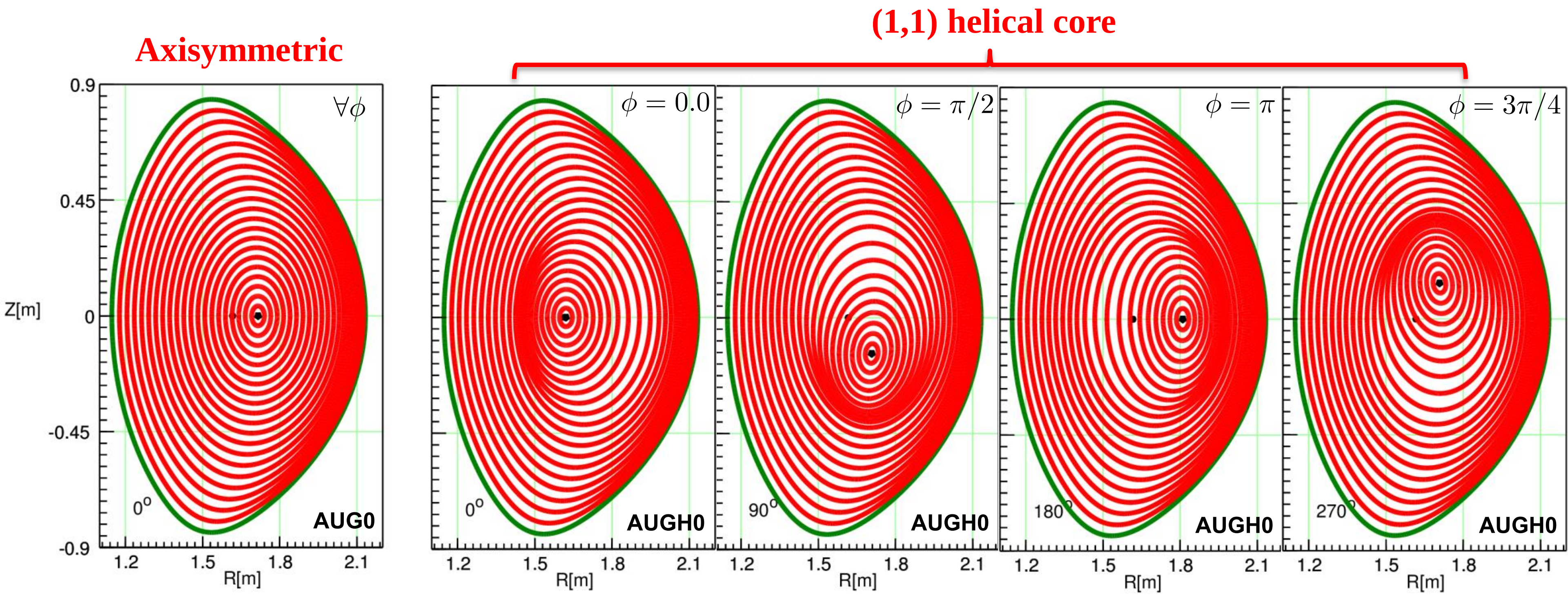
[M Raghunathan 2017 PPCF 59 124002]

Saturated m=1 modes (*no sawteeth*)

…all this with current **tokamak tools** and adapting them to deal with MHD…

Alternative route: adapt **stellarator codes** (*EUTERPE, XTOR-2F, SFINCS*)

- **(1,1) helical core** in AUG geometry (displacement ξ ~10 cm)



[J Regaña 2015 EPS-Conference P2.170]

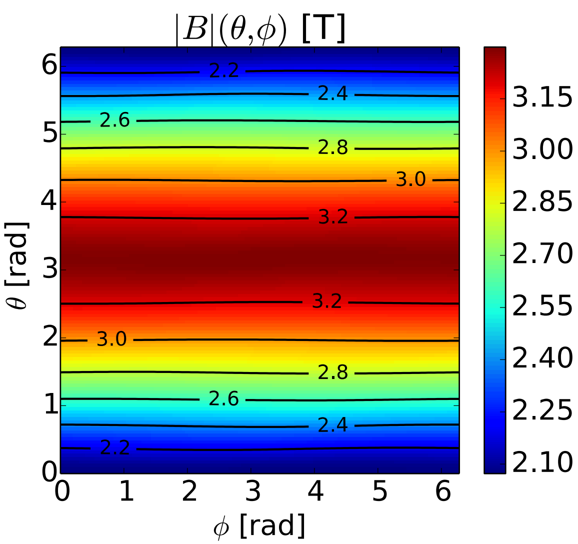
Saturated m=1 modes (*no sawteeth*)

…all this with current **tokamak tools** and adapting them to deal with MHD…

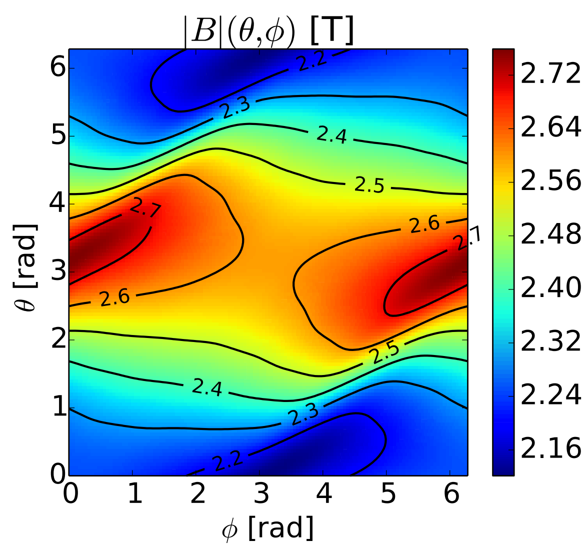
Alternative route: adapt **stellarator codes** (*EUTERPE, XTOR-2F, SFINCS*)

- **(1,1) helical core** in AUG geometry (displacement ξ ~10 cm)
- strong **deviation from toroidal symmetry**

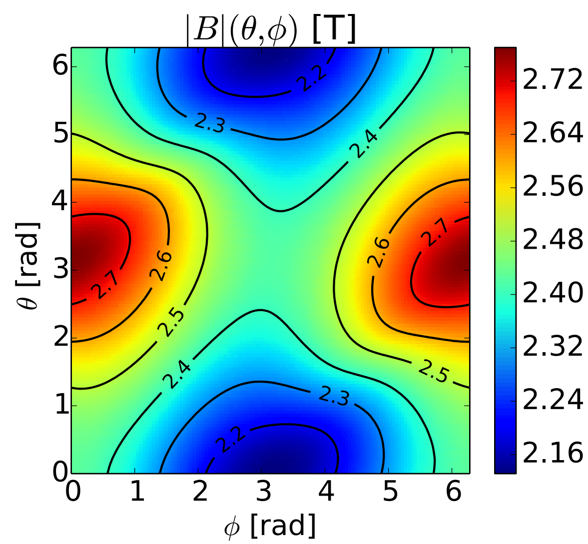
r/a ~ 0.8



r/a ~ 0.35



r/a ~ 0.2



[J Regaña 2015 EPS-Conference P2.170]

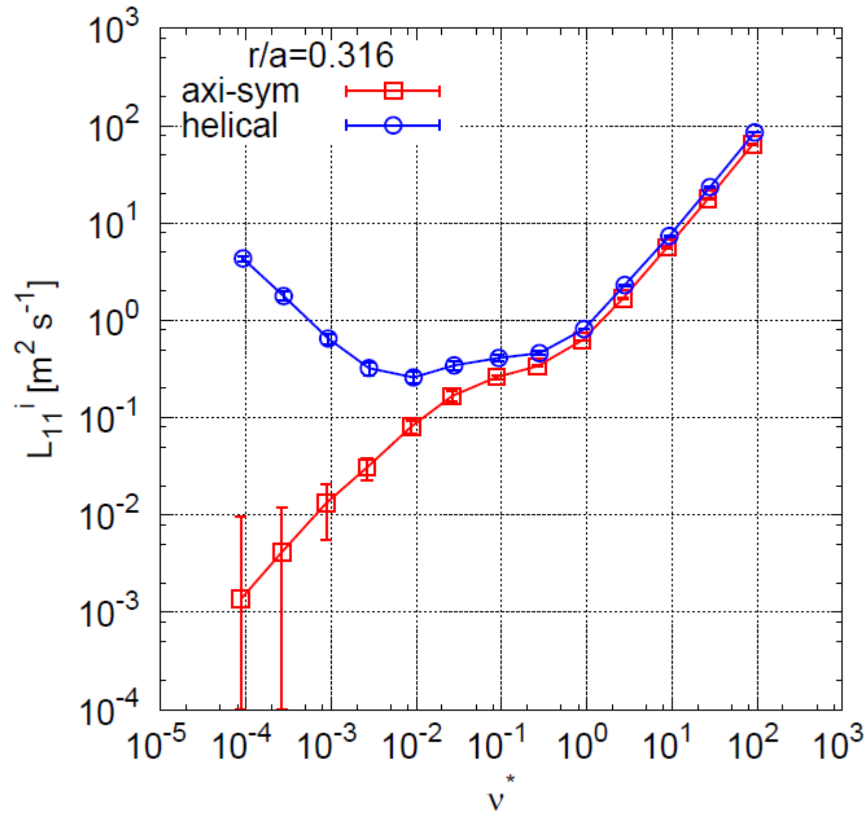
Saturated m=1 modes (*no sawteeth*)

…all this with current **tokamak tools** and adapting them to deal with MHD…

Alternative route: adapt **stellarator codes** (*EUTERPE, XTOR-2F, SFINCS*)

- **(1,1) helical core** in AUG geometry (displacement ξ ~10 cm)
- strong **deviation from toroidal symmetry**
- **1/ν scaling** of particle flux in helical core

Stellarator-like
transport in a
non-axisymmetric
Tokamak
could be possible



[J Regaña 2015 EPS-Conference P2.170]

What is the role of MHD?

MHD ***claimed*** / ***observed*** to have **beneficial** or **detrimental** effects on impurity accumulation depending on mode type

1. **Sawtooth cycling (m=1 precursors)**
   - **Beneficial** (+ *avoidance of early NTM trigger*)
   - Can be **detrimental** for confinement & expel non-thermal α-particles

2. **Saturated m=1 modes**
   - **Beneficial** / **Detrimental** depending on plasma parameters…

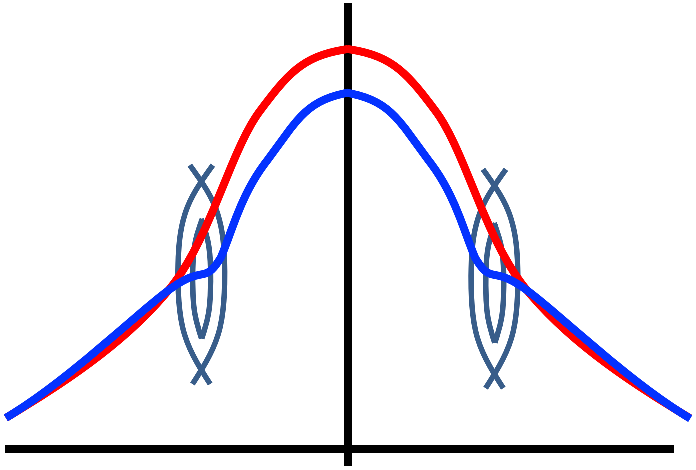
3. **(Neoclassical) Tearing Modes (m>1)**

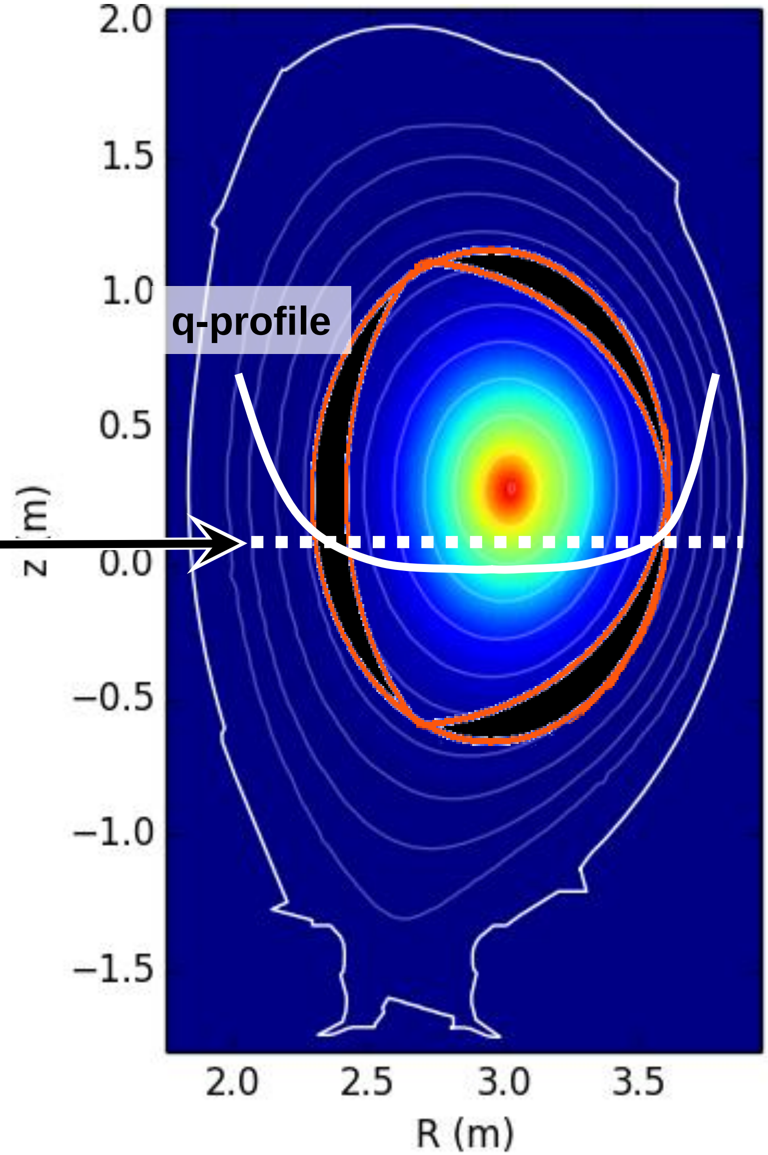
(Neoclassical) Tearing Modes (m>1)

m>1 (neoclassical) **tearing modes** are **performance-limiting** and can lead to **disruptions**

Typical mode numbers and location:

m/n	q
4/3	1.3
3/2	1.5
2/1	2.0

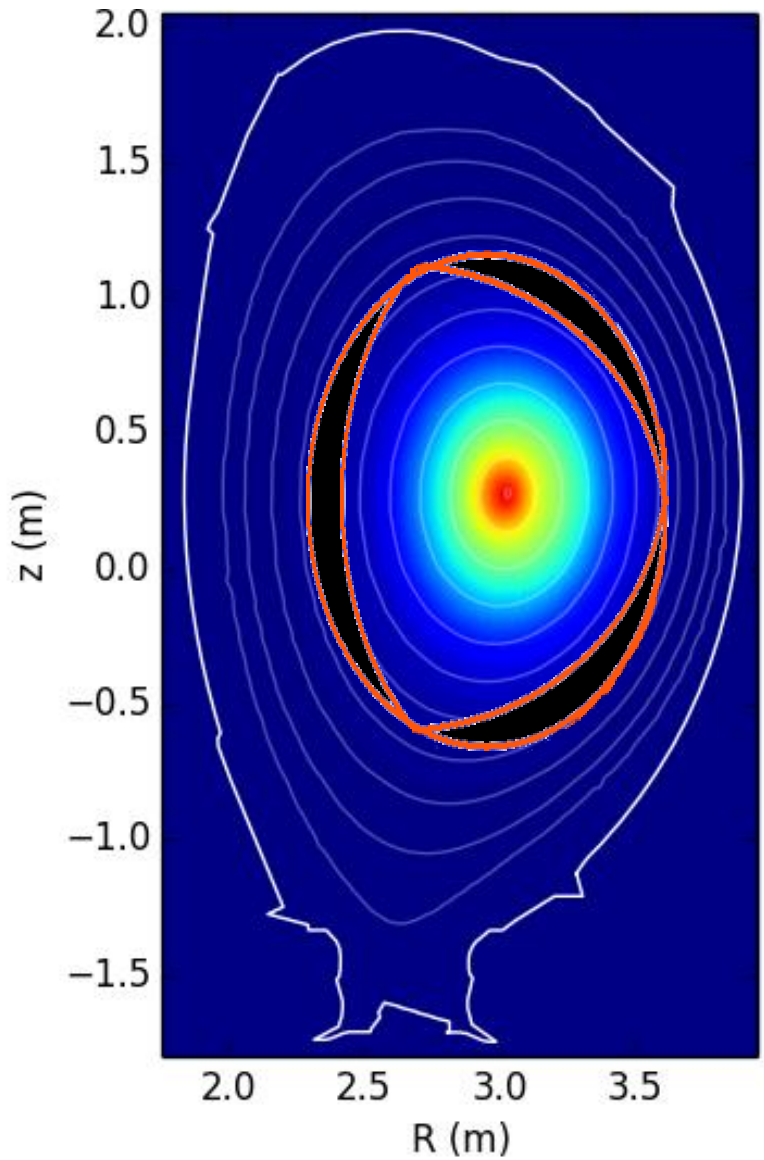




(Neoclassical) Tearing Modes (m>1)

m>1 (neoclassical) **tearing modes** are **performance-limiting** and can lead to **disruptions**

Very **little work** published on **(N)TM ↔ impurity** interactions…



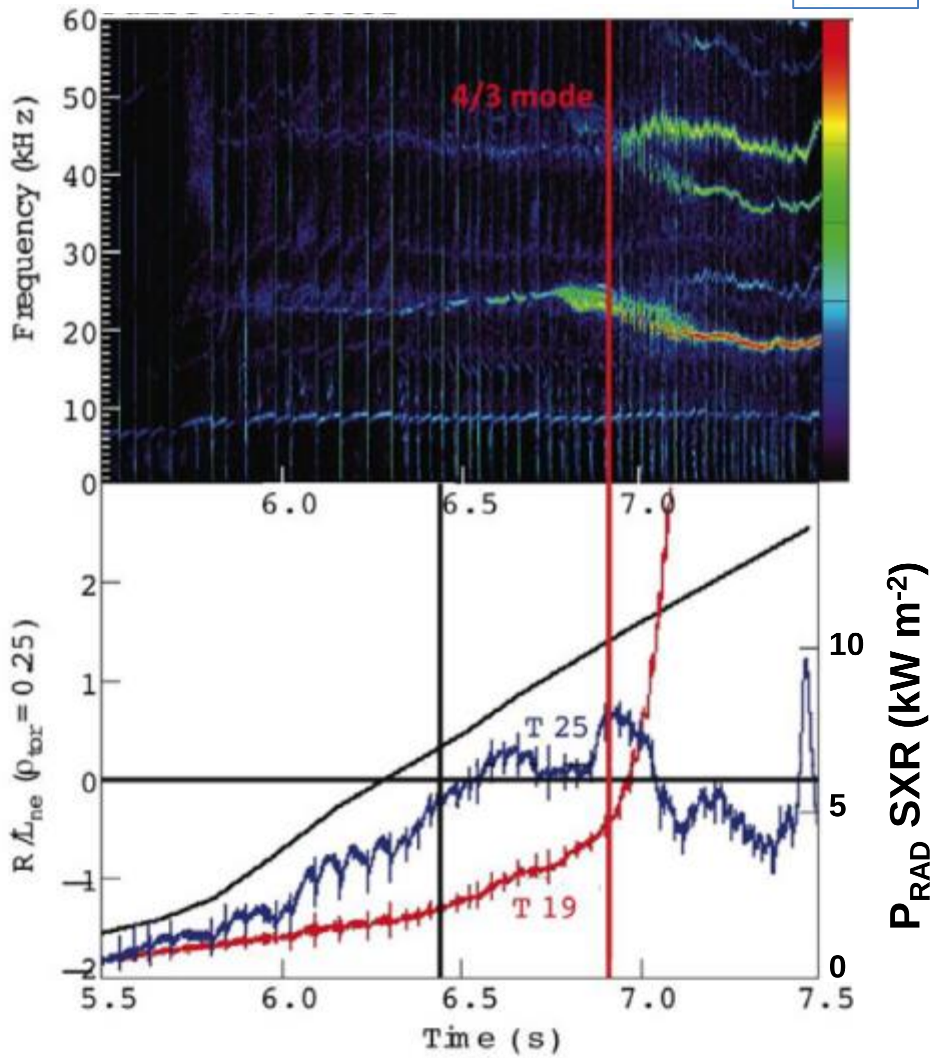
(N)TM → impurities
C Giroud et al 2007 Nucl. Fusion 47 313
C Angioni et al 2015 Physics of Plasmas 22, 055902
T Hender e al 2016 Nucl. Fusion 56, 066002
M Sertoli et al 2017 Physics of Plasmas 24, 112503
Impurities → (N)TMs
L Delgado-Aparicio et al 2011 Nucl. Fusion 51 083047
D A Gates et al 2012 PRL 108 165004
A Botrugno et al 2014 JPS Conf. Proc. 1 015024
P Buratti 2015 EPS P2.115

+ literature on density limit, disruptions, MGI, …

(N)TM effects on impurities

JET

"*The .. rise of core W, in correspondence to the electron density peaking, is followed by (an) NTM, which further accelerates the accumulation ...*"



[C Angioni 2014 NF 54 083028]

(Neoclassical) Tearing Modes (m>1)

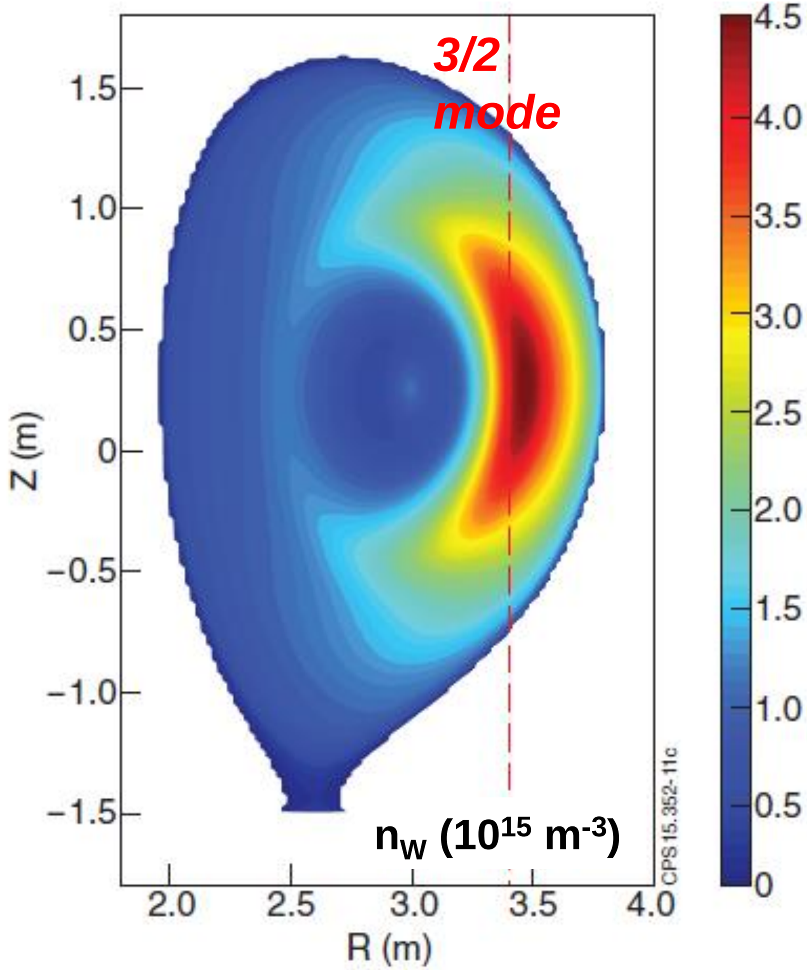
(N)TM effects on impurities

“*The .. rise of core W, in correspondence to the electron density peaking, is followed by (an) NTM, which further accelerates the accumulation …*”

“*..in the presence of a LFS localised W density .. the impact of the island is to move W rapidly inward, into a region where the neoclassical transport less favourable..*”

…causality still to be proven…

JET



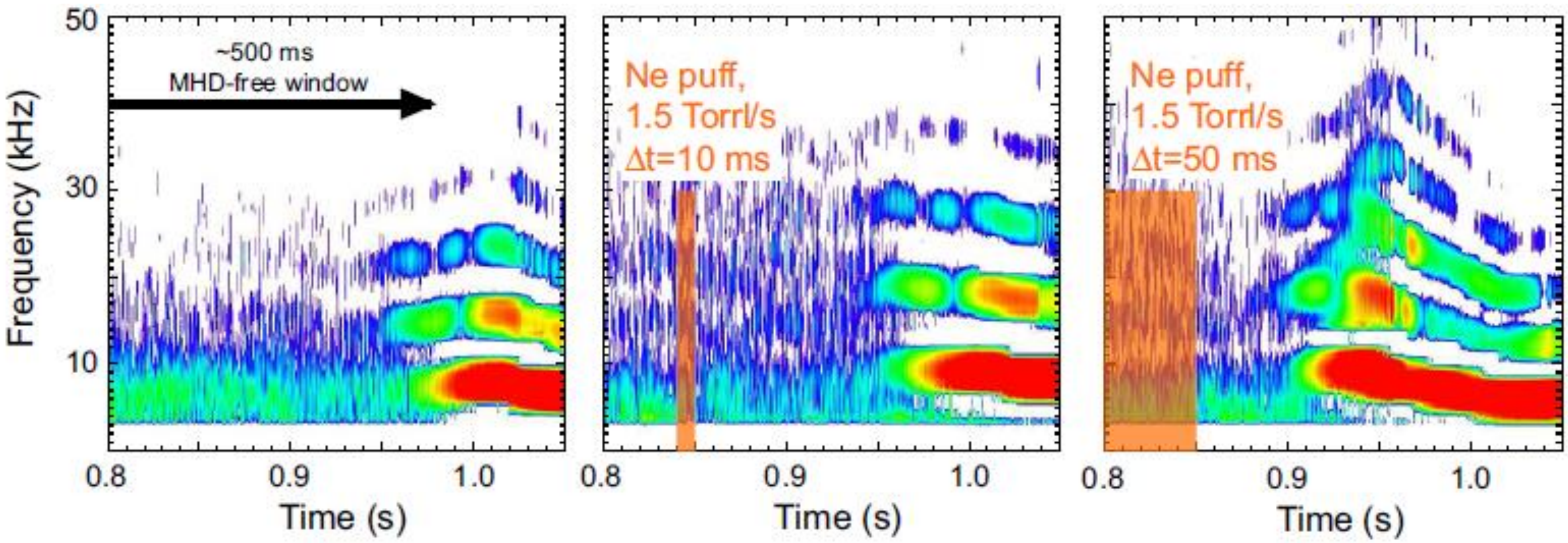
[T Hender 2016 NF 55 066002]

(Neoclassical) Tearing Modes (m>1)

Impurity effects on (N)TMs

Early (N)TM onset in neon-seeded discharges due to **changes in Zeff** & **current profile**

NSTX



[L Delgado-Aparicio 2011 NF 51 083047]

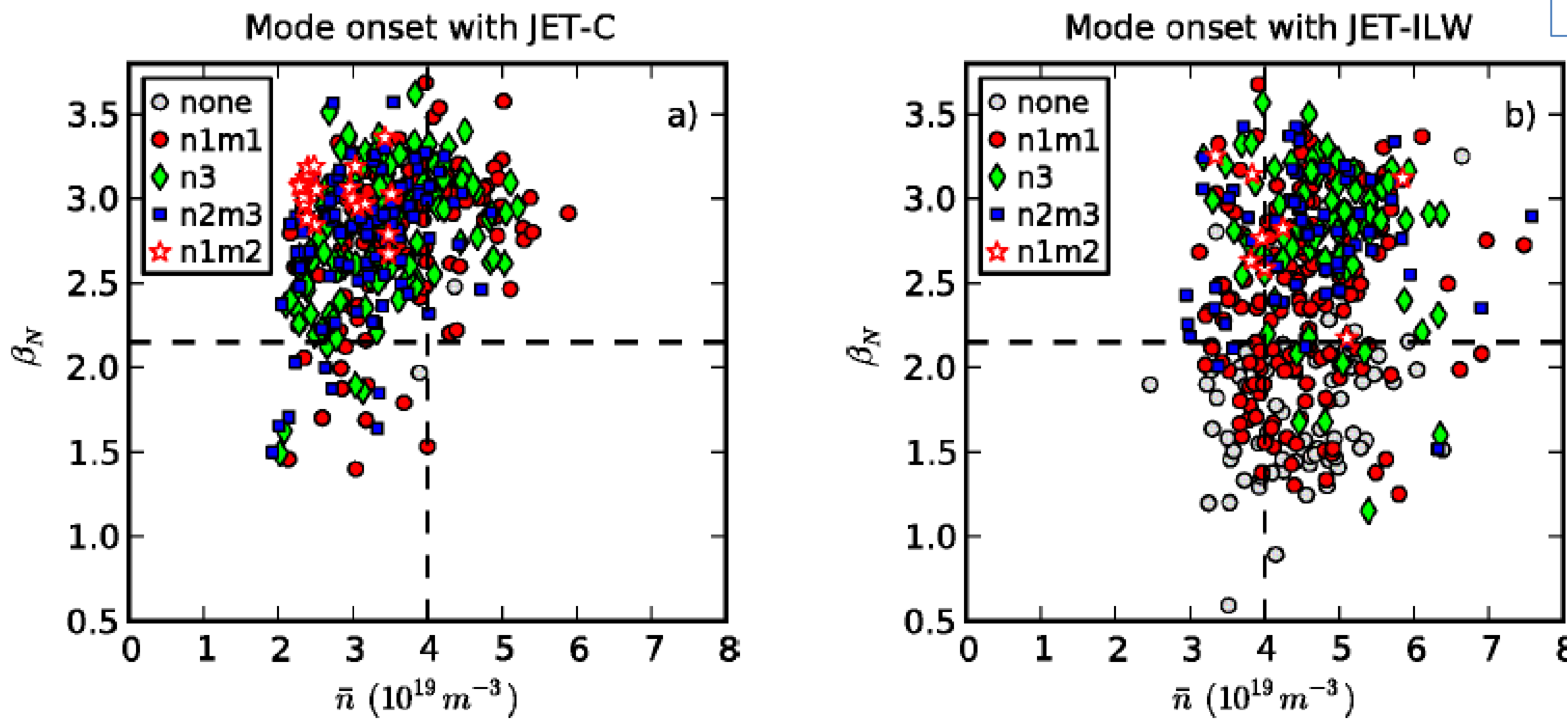
(Neoclassical) Tearing Modes (m>1)

Impurity effects on (N)TMs

Early (N)TM onset in neon-seeded discharges due to **changes in Zeff** & **current profile**

Tearing mode onset in JET-ILW at lower β_N than in JET-C : **are impurities to blame?**

JET



[P Buratti 2015 EPS Conference P2.115]

What is the role of MHD?

MHD ***claimed / observed*** to have **beneficial** or **detrimental** effects on impurity accumulation depending on mode type

1. **Sawtooth cycling (m=1 precursors)**
   - **Beneficial** (+ *avoidance of early NTM trigger*)
   - Can be **detrimental** for confinement & expel non-thermal α-particles

2. **Saturated m=1 modes**
   - **Beneficial** / **Detrimental** depending on plasma parameters

3. **(Neoclassical) Tearing Modes (m>1)**
   - **Detrimental** to control impurity accumulation ; impurity radiation / Zeff-contribution can lead to early (N)TM excitation

Input from theory

Inclusion of **MHD effects** in **impurity transport modelling** (neoclassical & turbulent) in tokamaks requires:

- **non-axisymmetric geometry** (ideal modes)
- treatment of **magnetic islands** (resistive modes)

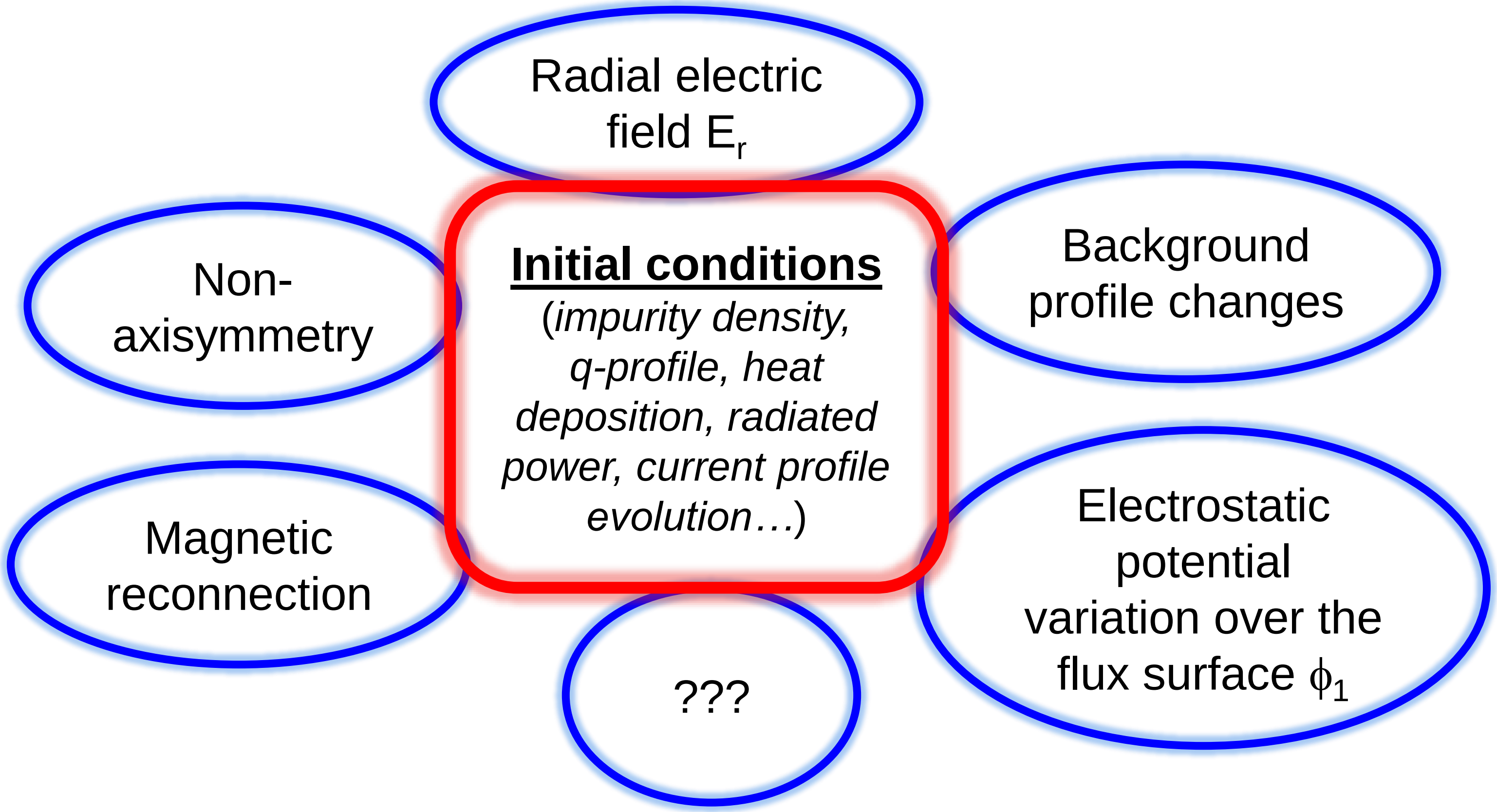
There are a few codes that can *partly* deal with this:

EUTERPE , XTOR-2F , SFINCS , VENUS-LEVIS , …

…but still much work to do before we can compare to experiment…

Summary

Changes in impurity transport associated with MHD are a complex matter, and **initial conditions play a crucial role**:



Outlook

Observations don’t show a clear picture…

and

theory isn’t of much help…

…but the question is:

¿ Is this relevant ?

Outlook

¡ It is relevant !

(N)TMs

NO – if (N)TM control is not available

YES – if (N)TM is actively controlled

YES – if impurities lead to an early mode onset at lower β_N

1/1 modes (continuous / saturated / fishbones)

YES – since they are very common and don't usually degrade performance

YES – if the q=1 surface in ITER will be close to mid-radius

YES – **if they can be tailored to help keep control impurities**