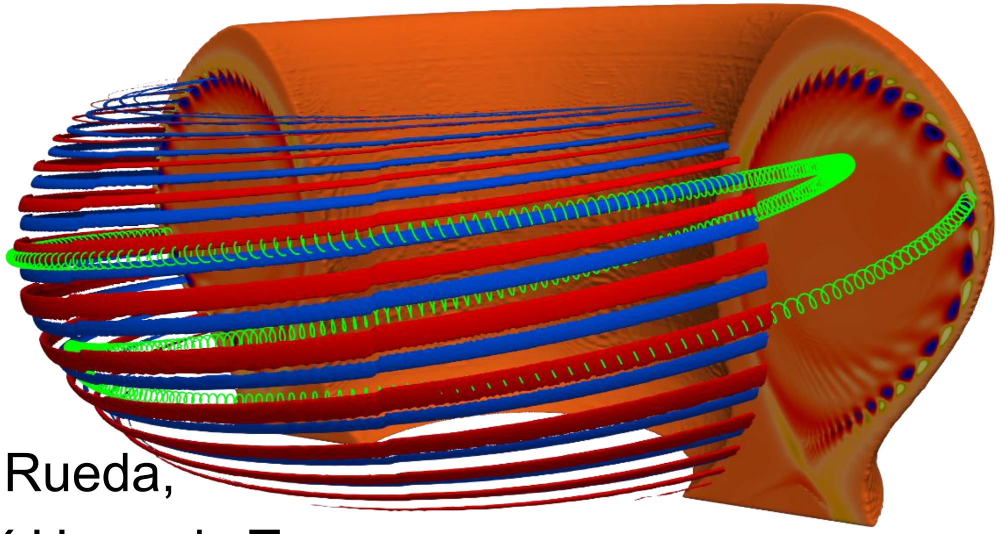
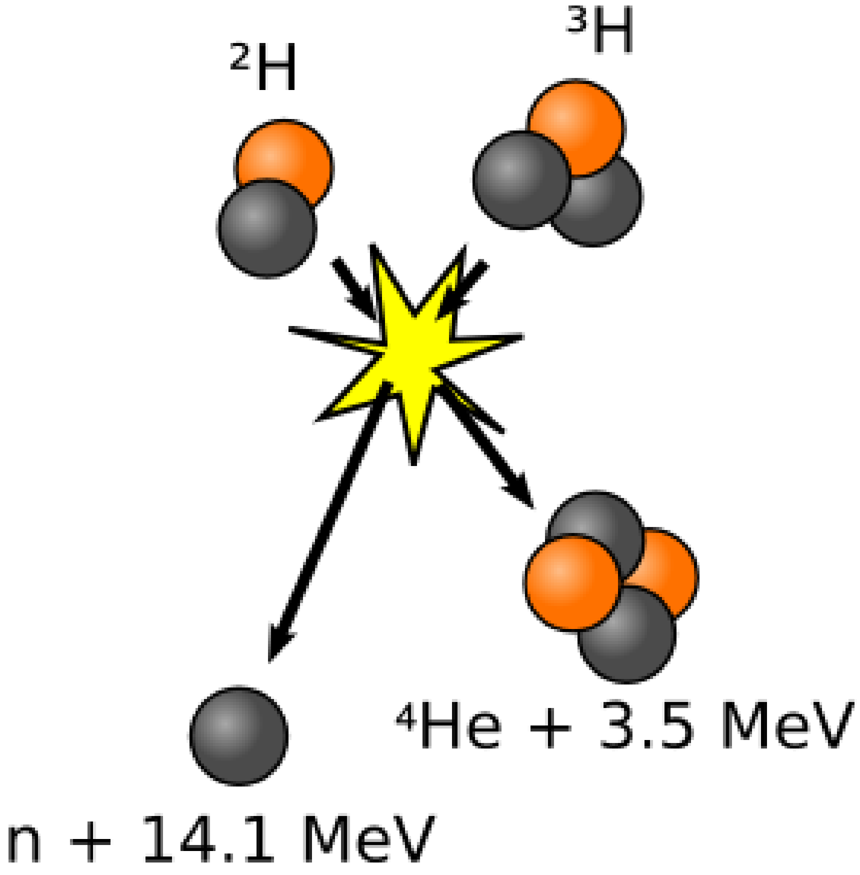
3D hybrid kinetic-MHD modelling of the interaction between Edge Localised Modes and Energetic Particles in the ASDEX Upgrade tokamak



J.J. Domínguez-Palacios Durán, M. García Muñoz, E. Viezzer,
S. Futatani, M. Toscano Jiménez, J. Galdón Quiroga,
J. González Martín, A. Jansen van Vuuren, P. Oyola, J. Rueda Rueda,
L. Sanchís, Y. Suzuki, Y. Todo, EUROfusion WPTE and ASDEX Upgrade Teams

Nuclear fusion is a promising energy source

- Mass deficit leads to large energy release due to $E = mc^2$



Nuclear fusion is a promising energy source

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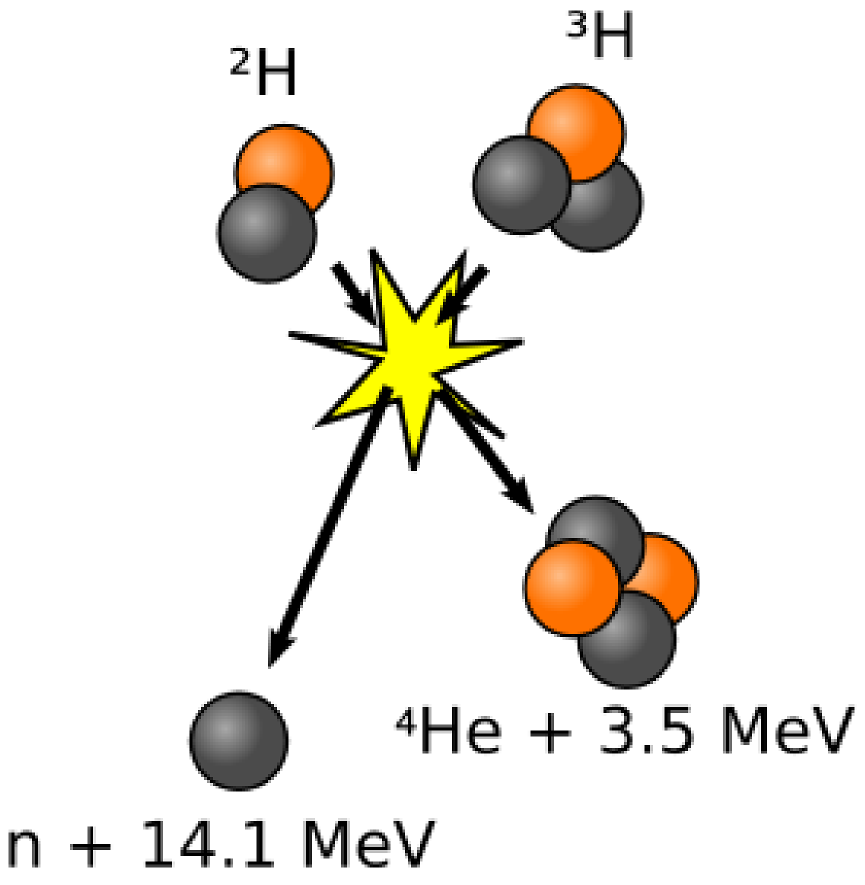
- 17.6 MeV is a huge number…



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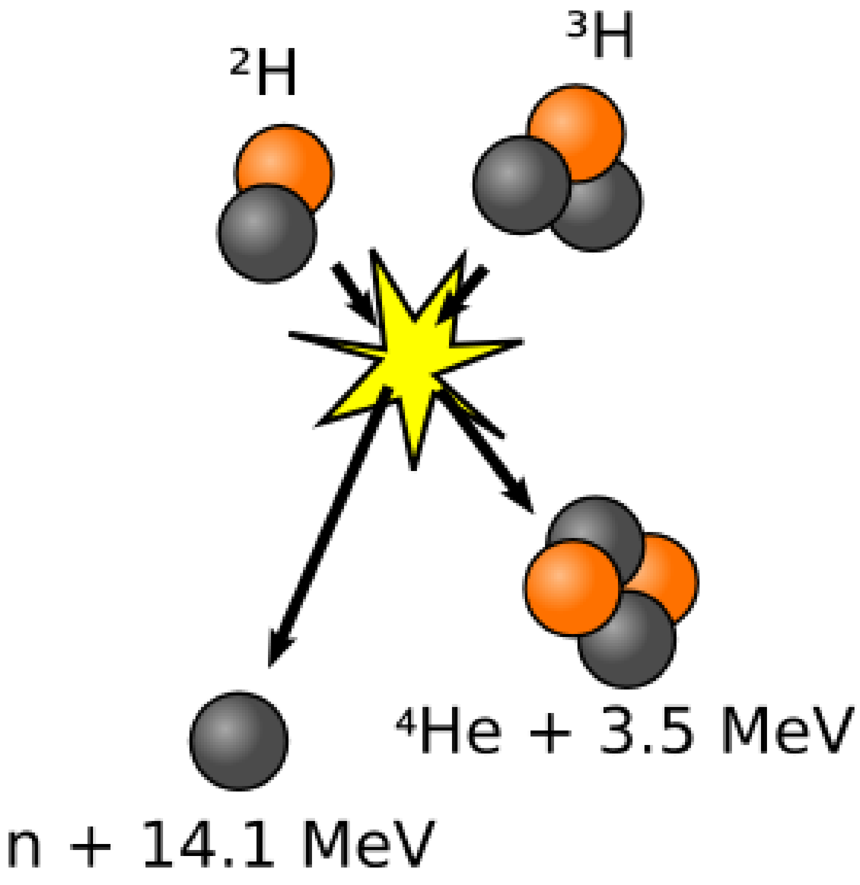
  - Combustion of gasoline relases ~ 50 kJ/g



Nuclear fusion is a promising energy source

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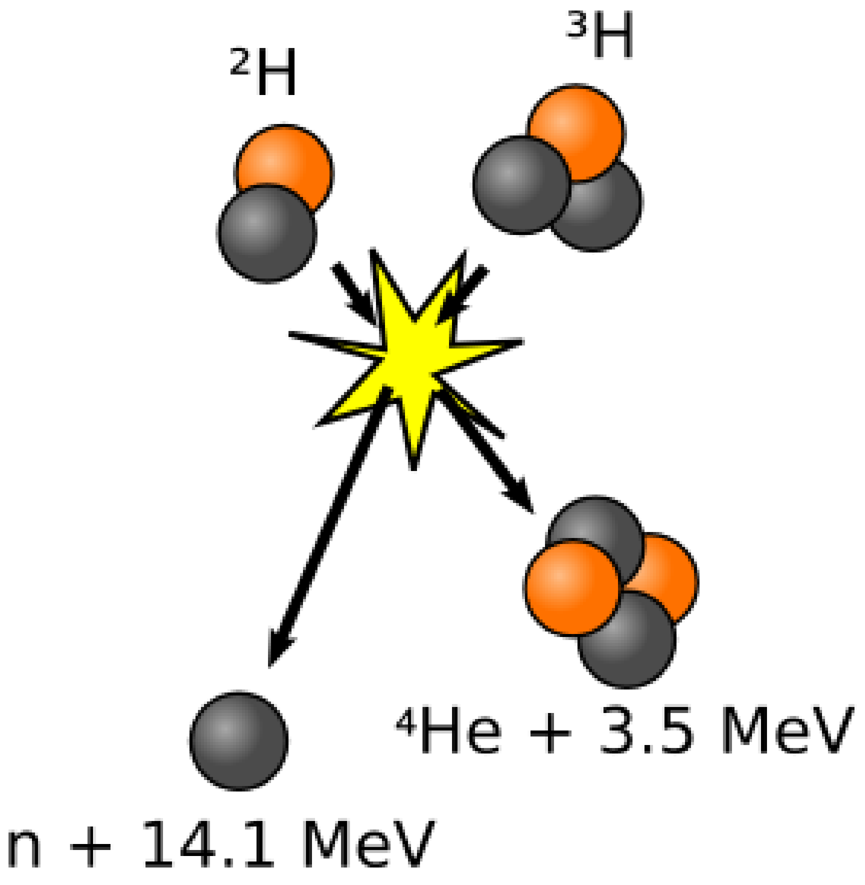
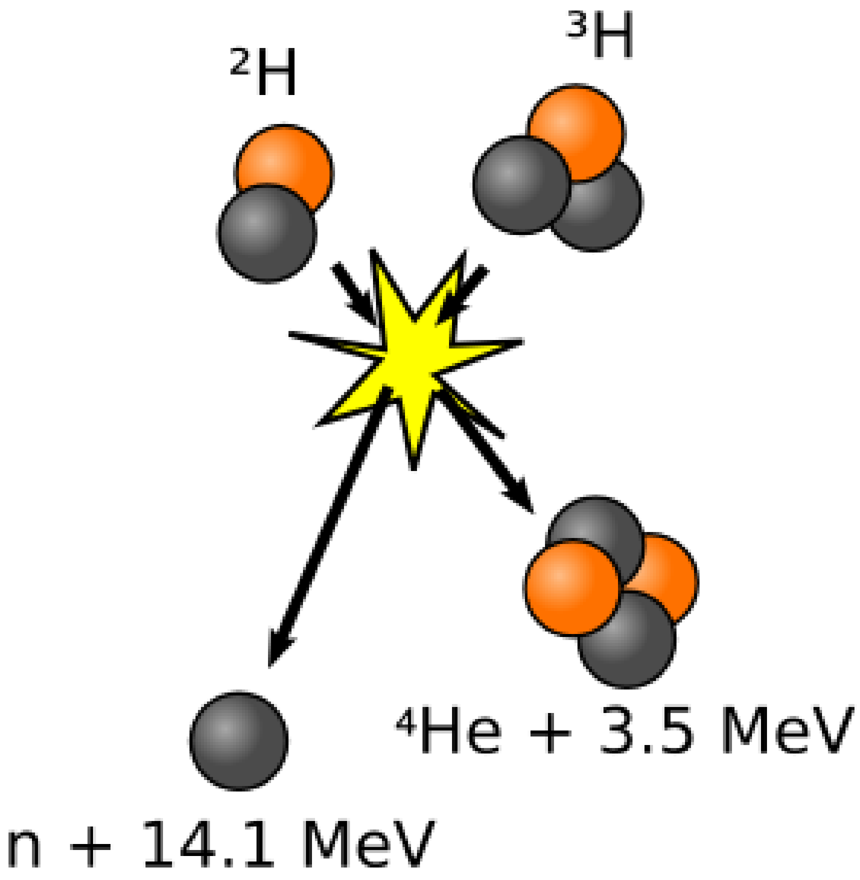
  - Combustion of gasoline relases ~ 50 kJ/g

  - Fission of ^{235}U releases ~ 10^8 kJ/g

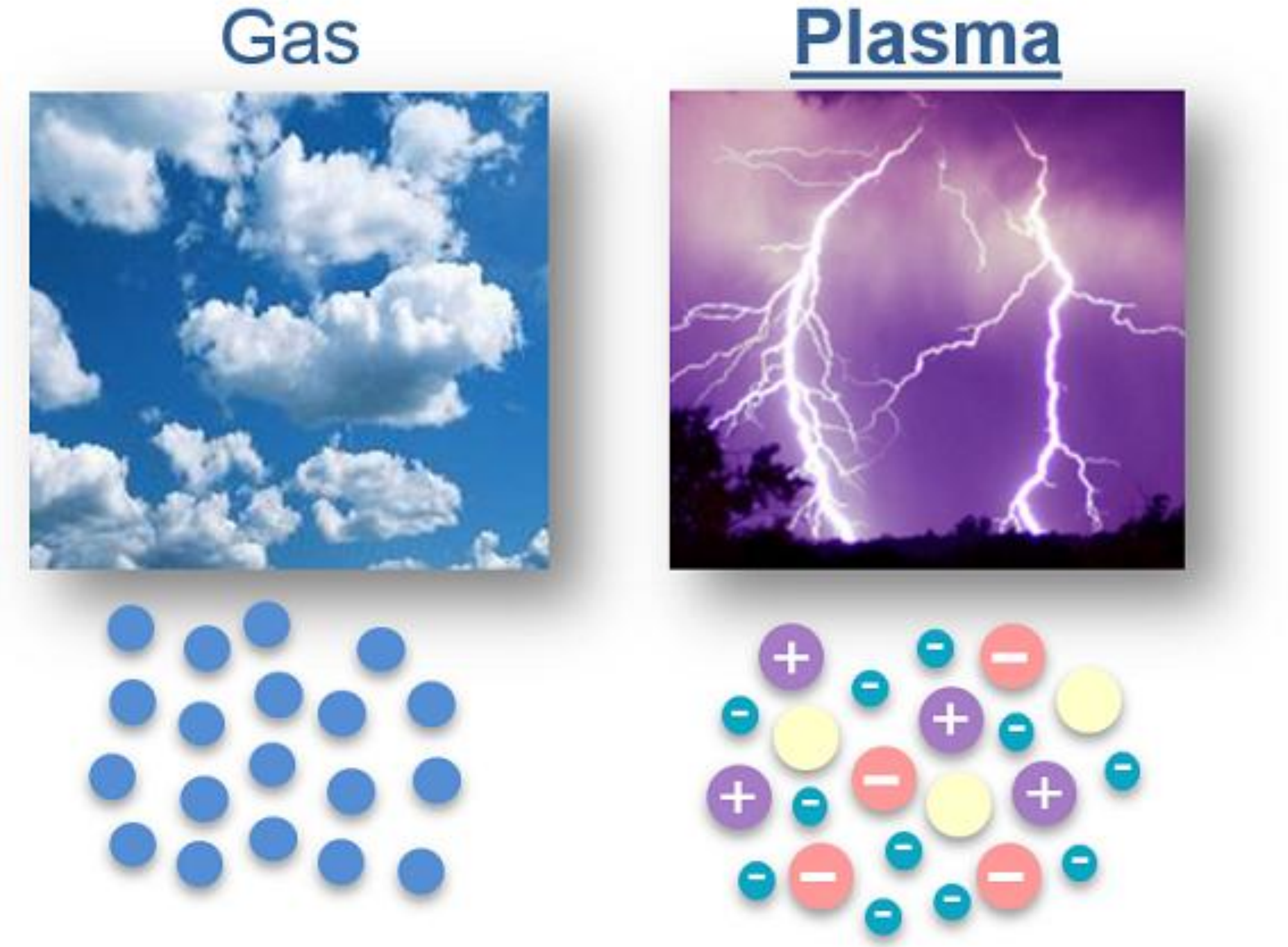


Nuclear fusion is a promising energy source

- Mass deficit leads to large energy release due to $E = mc^2$
- 17.6 MeV is a huge number…
  - Combustion of gasoline relases ~ 50 kJ/g
  - Fission of ^{235}U releases ~ 10^8 kJ/g
  - D-T fusion releases ~ 10^{11} kJ/g

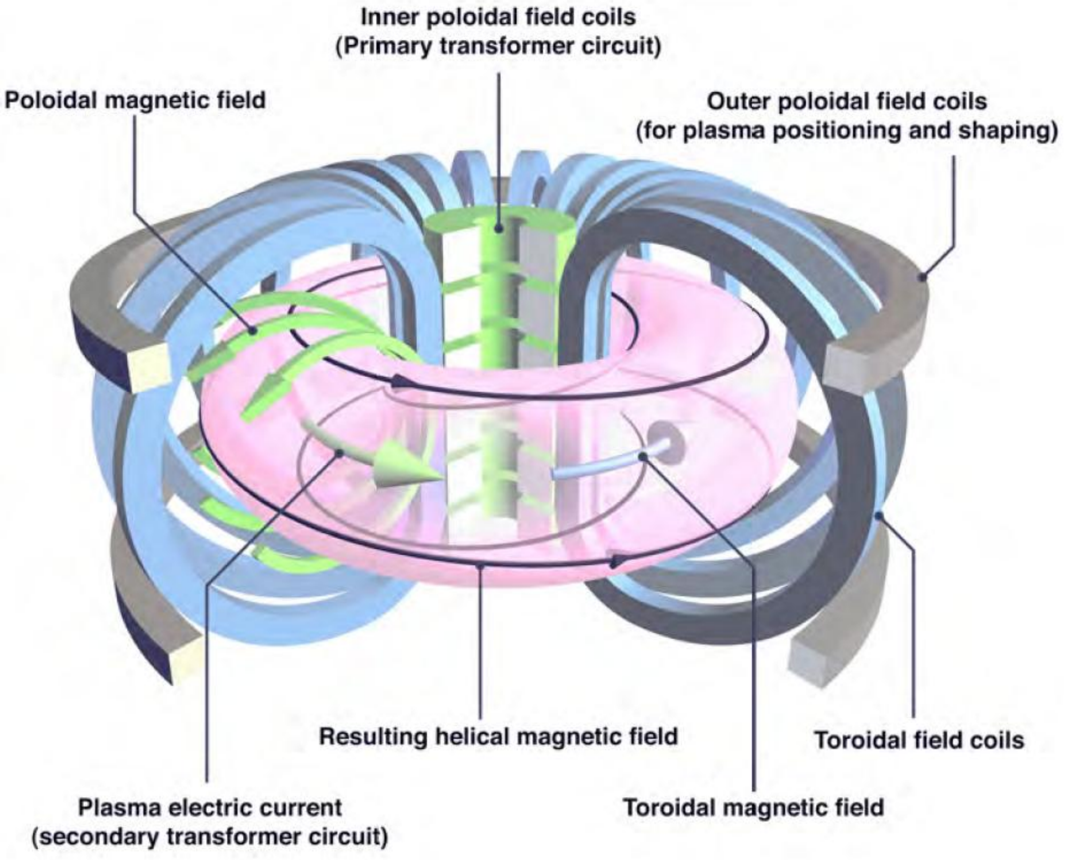


The fusion fuel is, and will be, in the plasma state in present and future fusion devices



The tokamak concept

- Magnetic confinement fusion device with torus shape
- Toroidal + poloidal magnetic field
- Poloidal field coils control plasma column position and shape of poloidal cross section



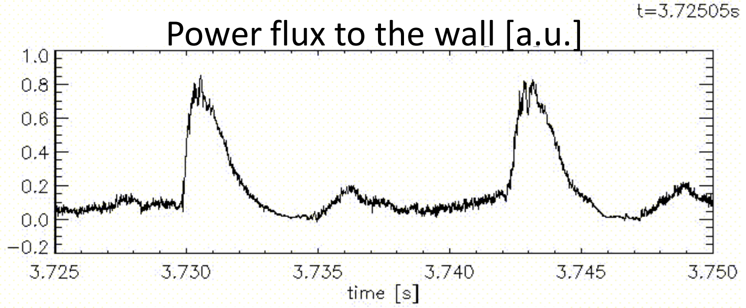
Future tokamaks are expected to operate in High confinement mode (H-mode)

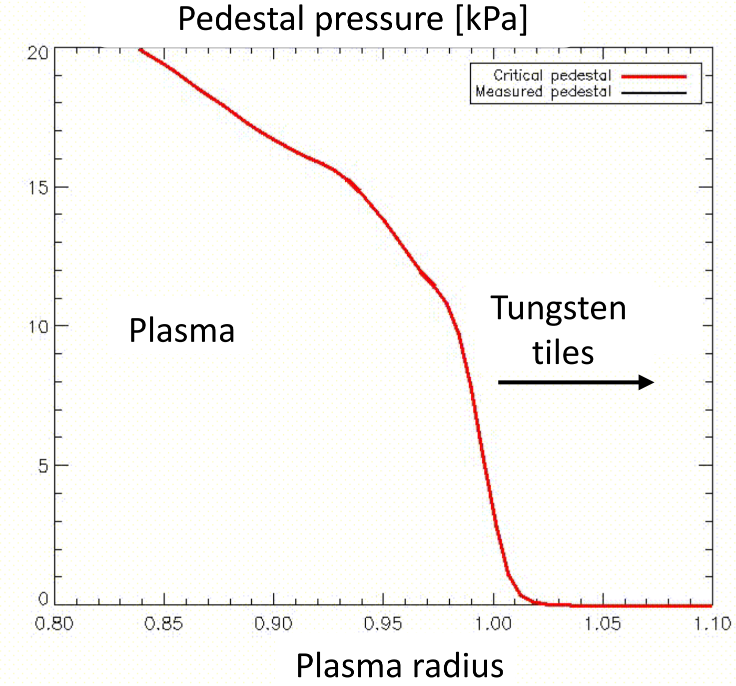
- H-mode has shown highest confinement rates in tokamaks

New Fusion Energy Record Pulse from JET DTE3 campaign - Pulse #104522
69 MJ in 6 second-long pulse fusing 0.2 mg of fusion fuel
https://www.youtube.com/watch?v=hQVzroA9qsE

Future tokamaks are expected to operate in High confinement mode (H-mode)

- H-mode has shown highest confinement rates in tokamaks
- Limited by ELMs[1]
  - Degradation of pedestal
  - Intolerable for future fusion devices





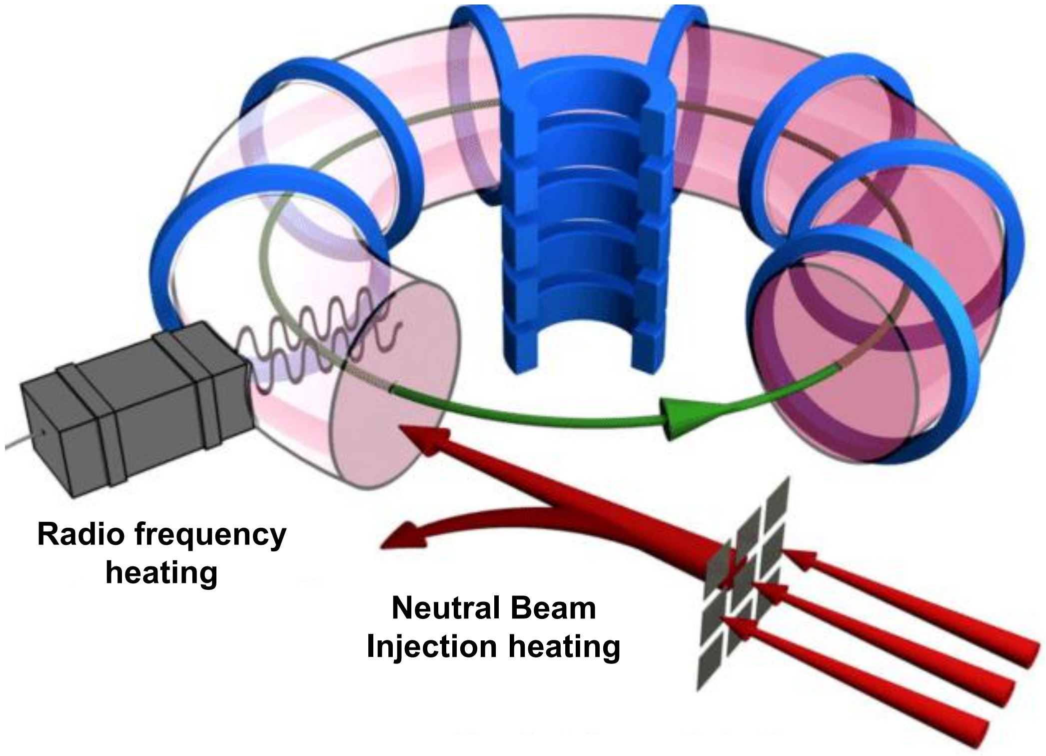
*A. Burckhart

[1] H. Hartmut, Plasma Phys. Control. Fusion **38**, 105 (1996)

Energetic particles are used to heat up the plasma

- Main heating mechanisms

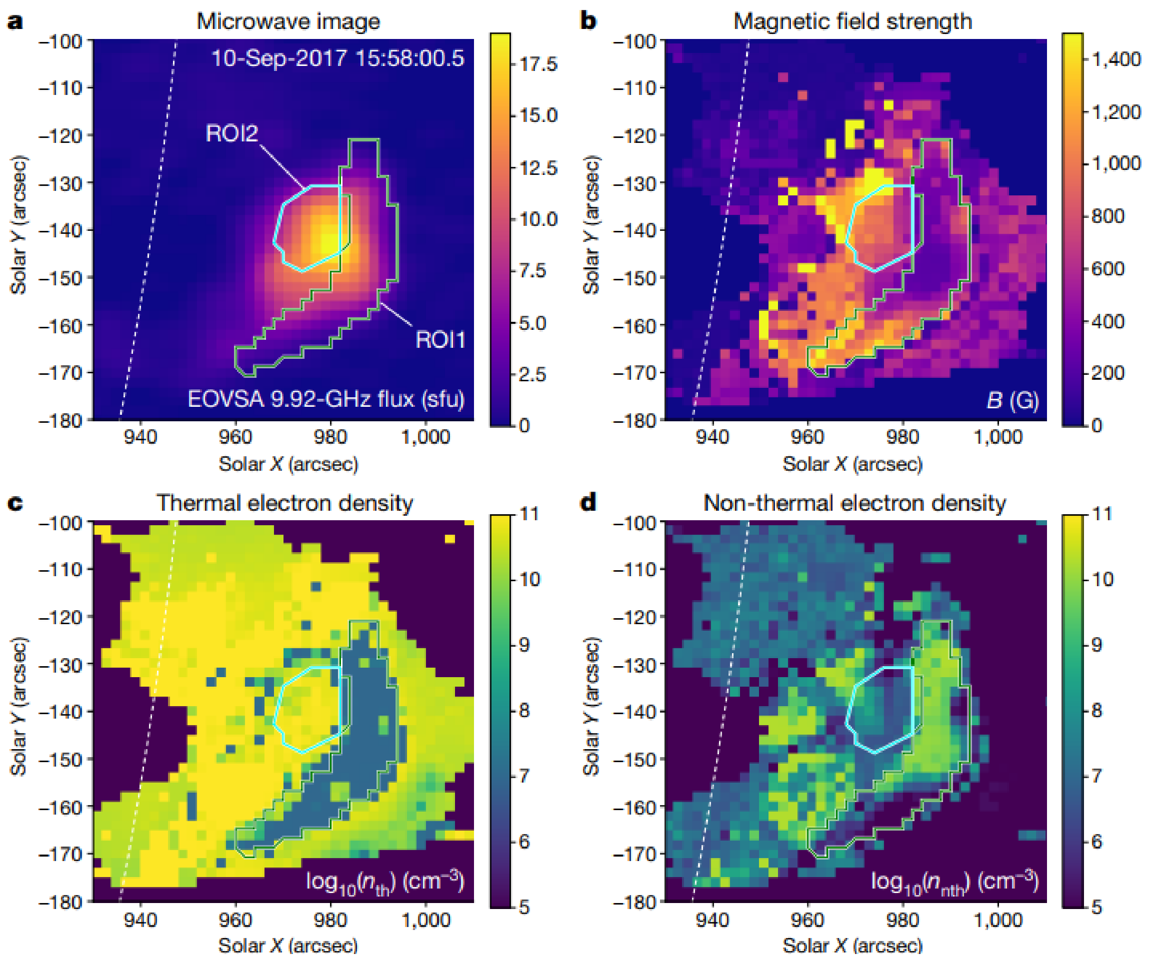
  - ➢ ICRF, ECRF (external)
  - ➢ NBI (external)
  - ➢ Fusion-born product (internal)



Energetic particles are used to heat up the plasma

- Main heating mechanisms
  - ➢ ICRF, ECRF (external)
  - ➢ NBI (external)
  - ➢ Fusion-born product (internal)

- Energetic particles are prone to a rich variety of wave-particle interactions due to their large velocities and long mean free path

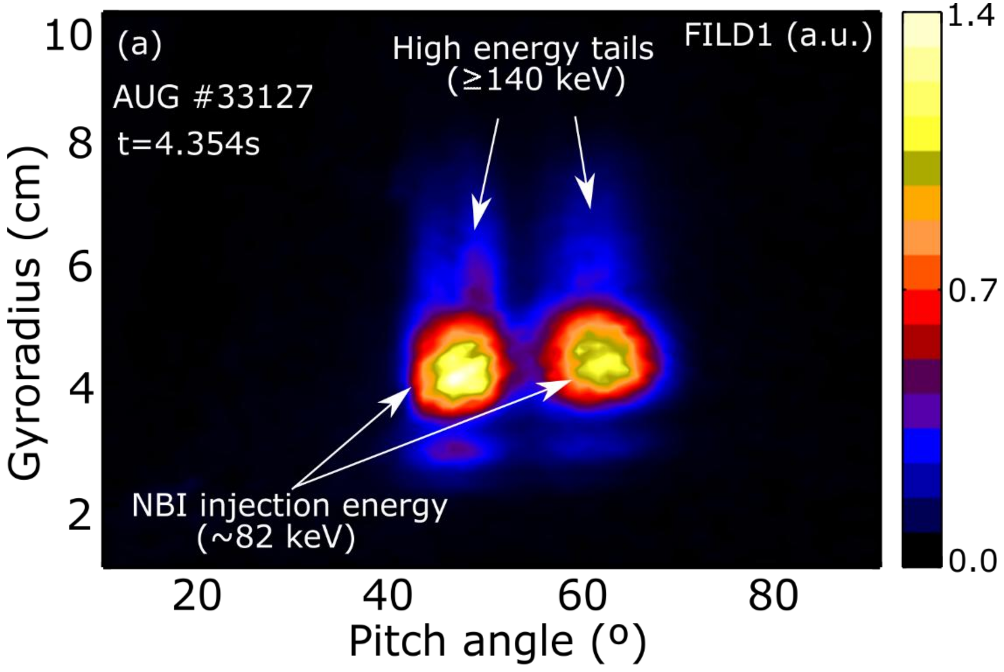


G.D. Fleishman *et al.*, Nature **606**, 674 (2022)

Experimental observations suggest interaction between ELMs and fast-ions

- Beam-ion acceleration during ELM crashes

- **Fast-ion kinetic effects on ELMs are needed!**



*J. Galdon-Quiroga *et al.*, 2018, Phys. Rev. Lett. **121**, 025002

Outline

- Hybrid kinetic-MHD MEGA simulation code
- Simulation results
- Conclusions & Outlook

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Navier-Stokes equations (1823, 1845) describe fluid dynamics

Navier
(Wikipedia)

Stokes
(Wikipedia)

$$\rho \frac{d\vec{u}}{dt} = -\nabla p + \rho\vec{g} - \nabla \cdot \overleftrightarrow{\Pi}$$

C.L. Navier, Sur les Lois du Mouvement des Fluides, Mémoires de L'Académie Royale des Sciences de L'Institut de France, Paris, VI, 389-440 (1827)
G. G. Stokes, On the Theories of the Internal Friction of Fluids in Motion, and of the Equilibrium and Motion of Elastic Solids. Cambridge University Press, 1880, pp. 75-129

MHD equations: the plasma is regarded as an electromagnetic fluid (Alfvén, 1942)

Navier
(Wikipedia)

Stokes
(Wikipedia)

Alfvén
(ITER website)

$$\rho \frac{d\vec{u}}{dt} = -\nabla p + \vec{j} \times \vec{B} - \nabla \cdot \overleftrightarrow{\Pi}$$

H. Alfvén, Existence of Electromagnetic-Hydrodynamic Waves, Nature **150**, 405-406 (1942)

MEGA: hybrid kinetic-MHD code to study the interaction between thermal plasma and energetic particles

Navier
(Wikipedia)

Stokes
(Wikipedia)

Alfvén
(ITER website)

Prof. Yasushi Todo
(NIFS website)

$$\rho \frac{d\vec{u}}{dt} = -\nabla p + (\vec{j} - \vec{j}'_{\mathrm{h}}) \times \vec{B} - \nabla \cdot \overleftrightarrow{\Pi}$$

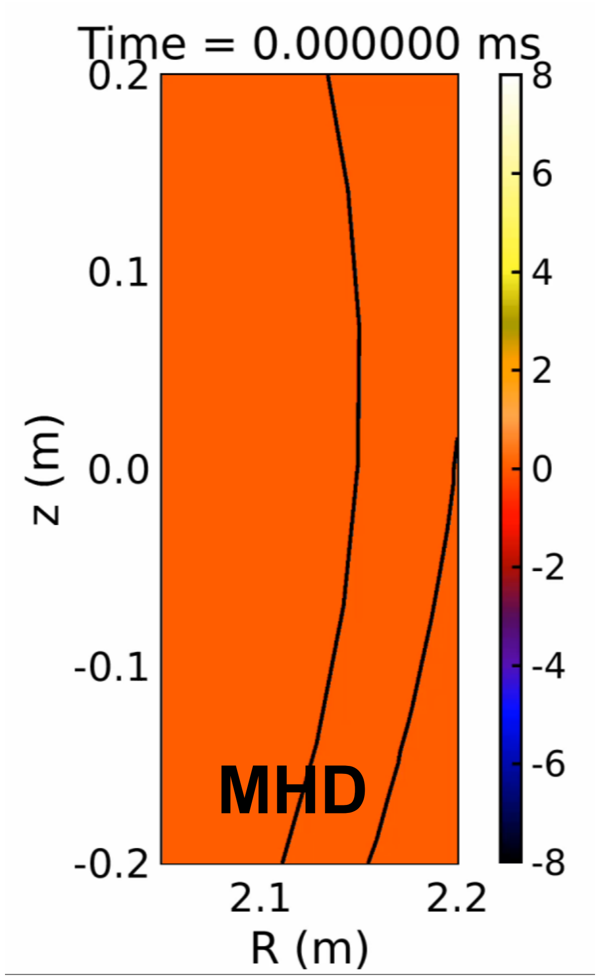
MEGA calculates the self-consistent interaction between MHD and EPs

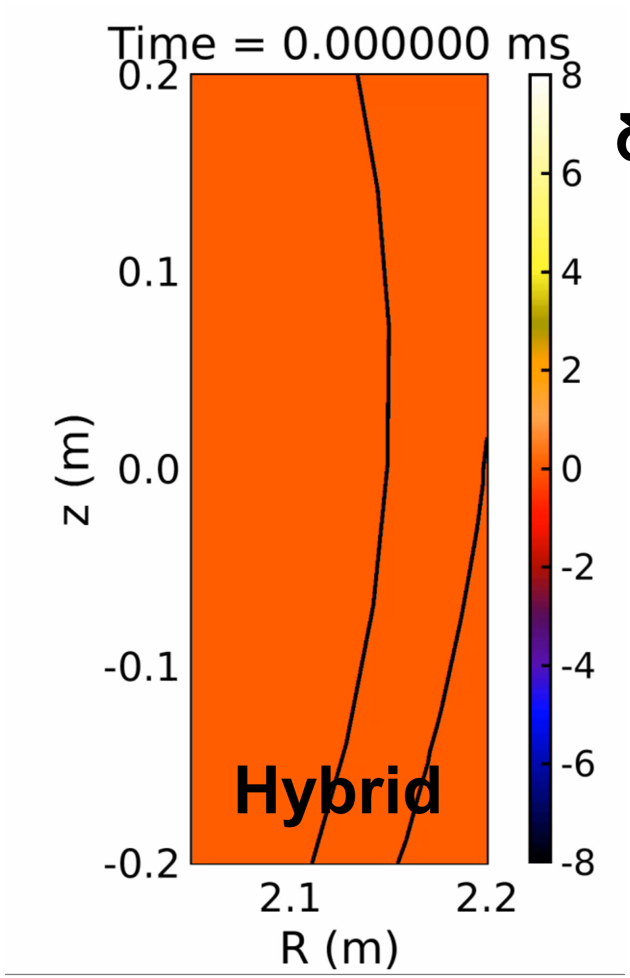
Y. Todo and T. Sato, Linear and nonlinear particle-magnetohydrodynamic simulations of the toroidal Alfvén eigenmode, Phys. Plasmas **5**, 1321 (1998)

Outline

- Hybrid kinetic-MHD MEGA simulation code
- Simulation results
- Conclusions & Outlook

Energetic-ions significantly modify perturbation structure



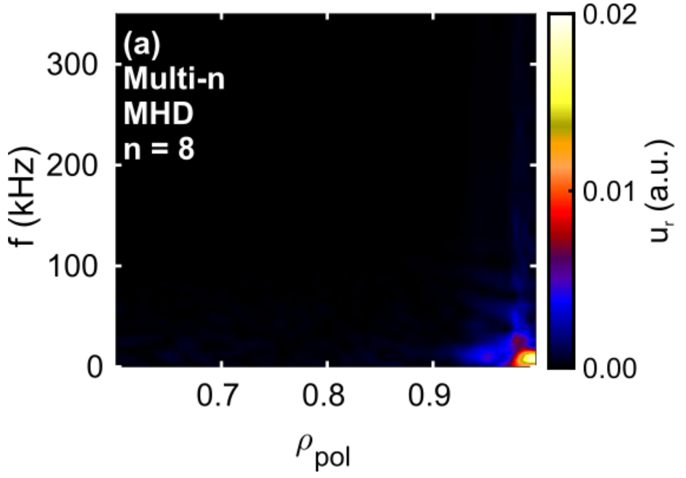


δp (kPa)

- The interaction with fast-ions modify the plasma flow pattern and, consequently, the shear of the structure

Spatial-frequency pattern of modes during ELM crash changes abruptly in the presence of fast-ions

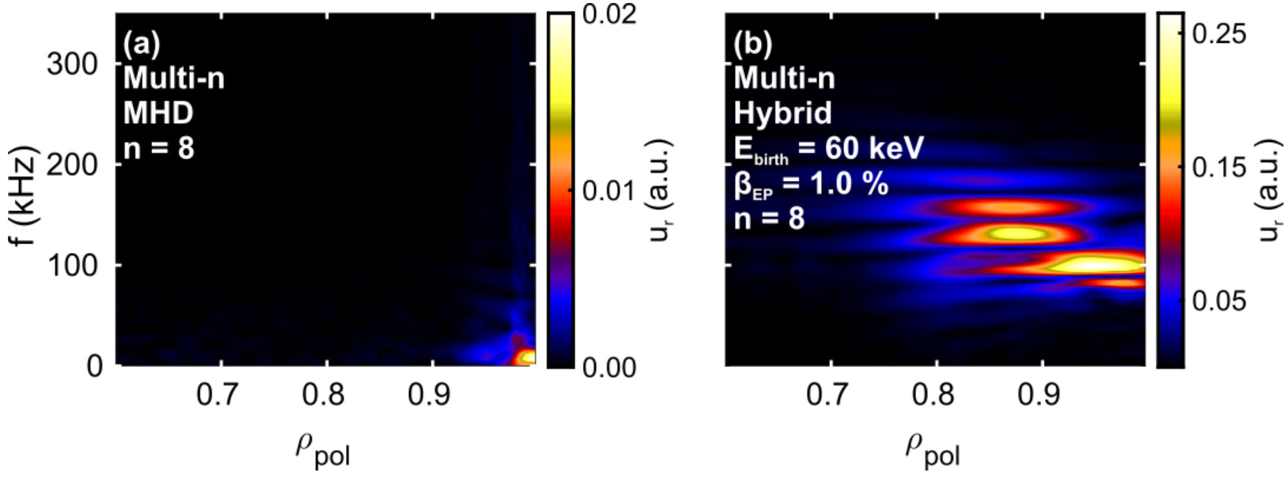
- In pure MHD simulations, f ~20 kHz



J. Domínguez-Palacios *et al.*, Nat. Phys. **21**, 43 (2025)

Spatial-frequency pattern of modes during ELM crash changes abruptly in the presence of fast-ions

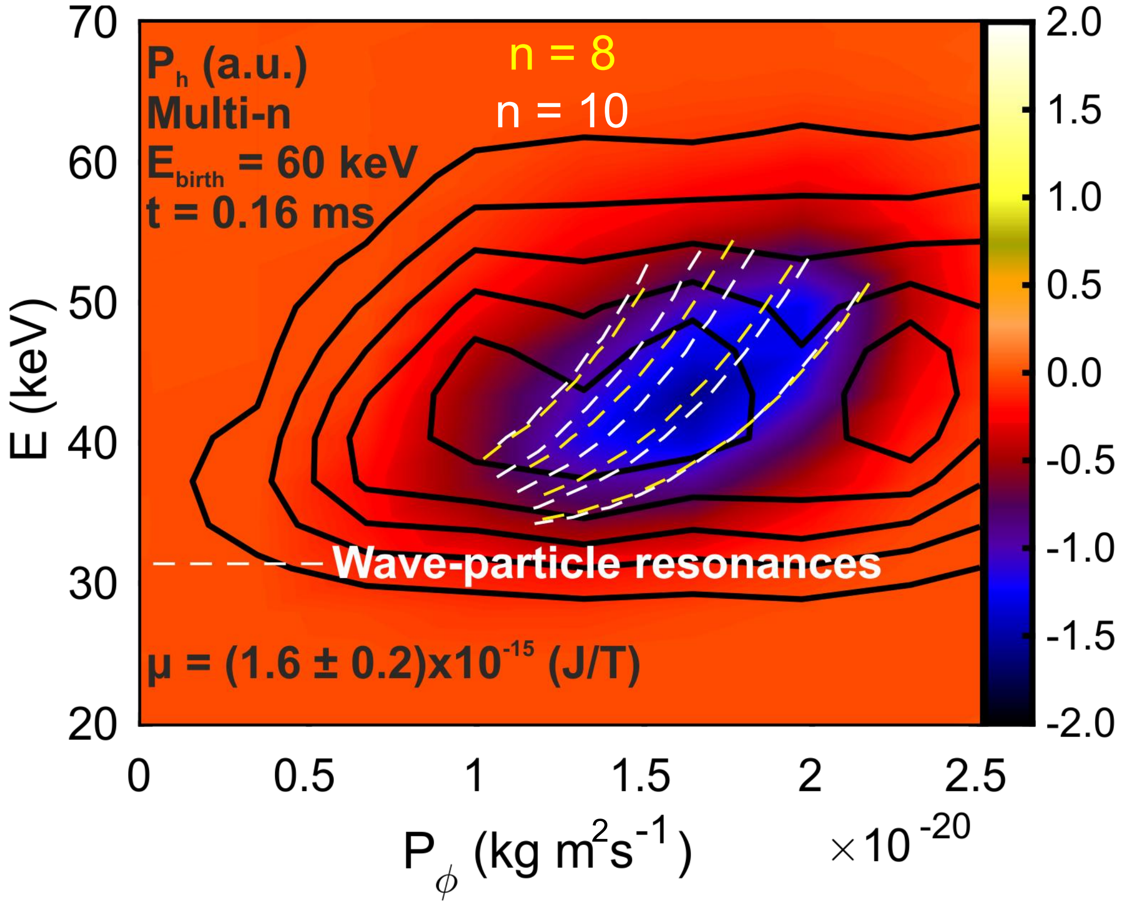
- In pure MHD simulations, f ~20 kHz
- In hybrid multi-n simulations, f ~ 200 kHz (n = 8)
- Modes also become radially broad in the presence of fast-ions



J. Domínguez-Palacios *et al.*, Nat. Phys. **21**, 43 (2025)

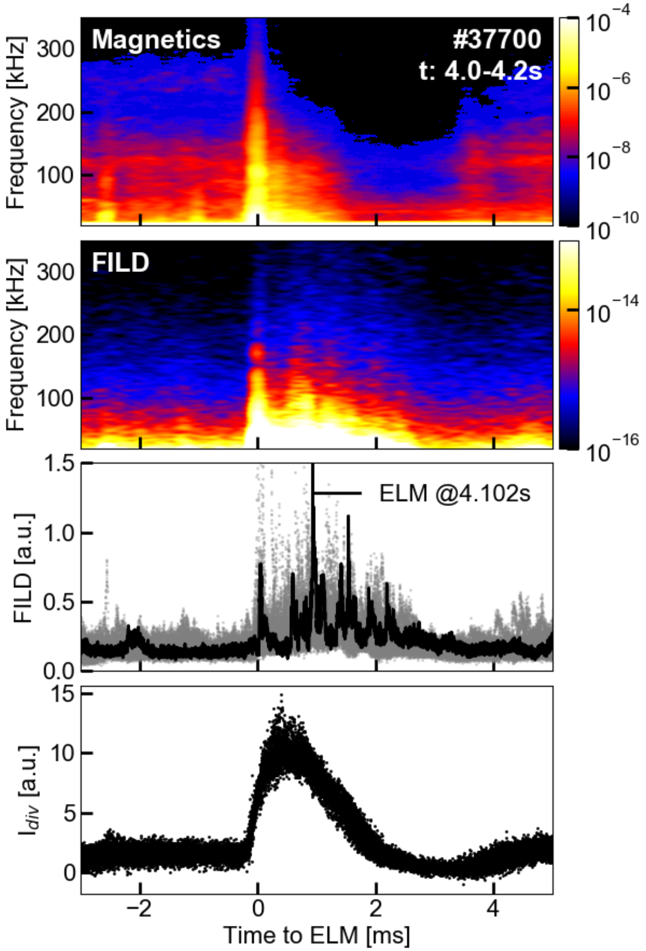
Role of energetic particle force is due to a resonant interaction with the electromagnetic perturbation

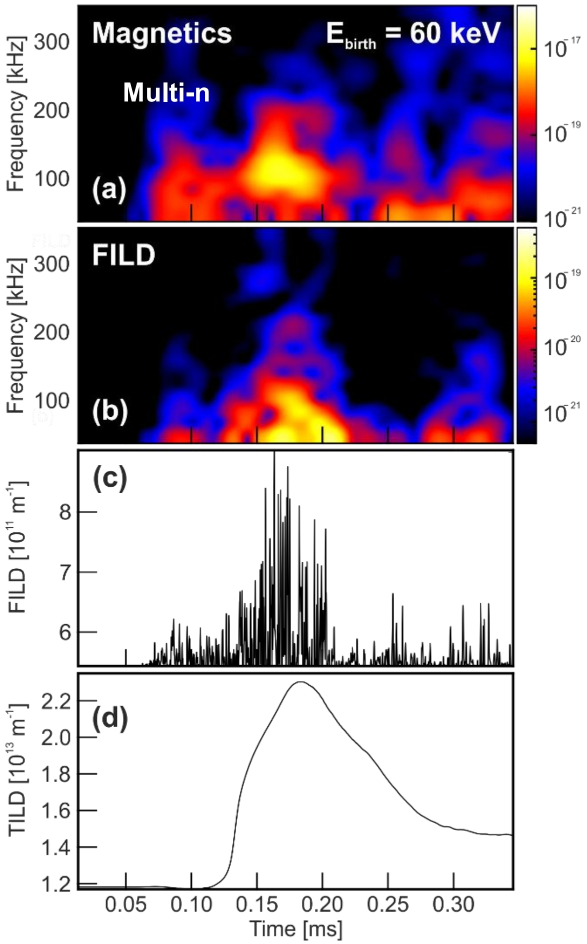
- **Power transfer**: $P_\mathrm{h} = \sum_l w_l \frac{dE_l}{dt}$
- **Resonance**: $\omega_n - n\omega_\varphi - p\omega_\theta \approx 0$
- Resonant interaction leads to net energy exchange that modifies ELM



J. Domínguez-Palacios *et al.*, Nat. Phys. **21**, 43 (2025)

MEGA synthetic diagnostics reproduce some key experimental observations





- Simulations qualitatively reproduce abrupt crash with magnetic and FILD frequency patterns extended to high frequencies. Divertor thermal currents show similar behaviour

J. Domínguez-Palacios *et al.*, Nat. Phys. **21**, 43 (2025)

Outline

- Motivation
- Hybrid kinetic-MHD MEGA simulation code
- Simulation results
- Conclusions & Outlook

Summary

- Fast-ion kinetic effects impact radial width, frequency and shear of perturbation

- Interaction mechanism: **resonant energy exchange between electromagnetic field of ELM and fast-ions**

- Fast-ion kinetic effects qualitatively help to understand experimental observations

Some open questions derived from this thesis

- What is the role of fast-ions in regimes absent of ELMs?
- What will happen in future burning plasmas?
  - Will fast-ions help to reduce ELM-induced heat flux on the divertor materials? Or do they have the opposite effect?

THANK YOU!

Back Up

Energetic particle dynamics in MEGA (1/2)

- Drift-kinetic description of particle motion

$$\vec{u}_{\mathrm{gc}} = \vec{v}_{\parallel}^{*} + \vec{v}_{E}^{*} + \vec{v}_{B}^{*}$$

$$\vec{v}_{\parallel}^{*} = \frac{v_{\parallel}}{B^{*}}\left(\vec{B} + \rho_{\parallel} B \nabla \times \hat{b}\right)$$

$$\vec{v}_{E}^{*} = \frac{1}{B^{*}}\vec{E} \times \hat{b}, \vec{v}_{B}^{*} = -\frac{\mu}{q_{\mathrm{h}} B^{*}} \nabla B \times \hat{b}$$

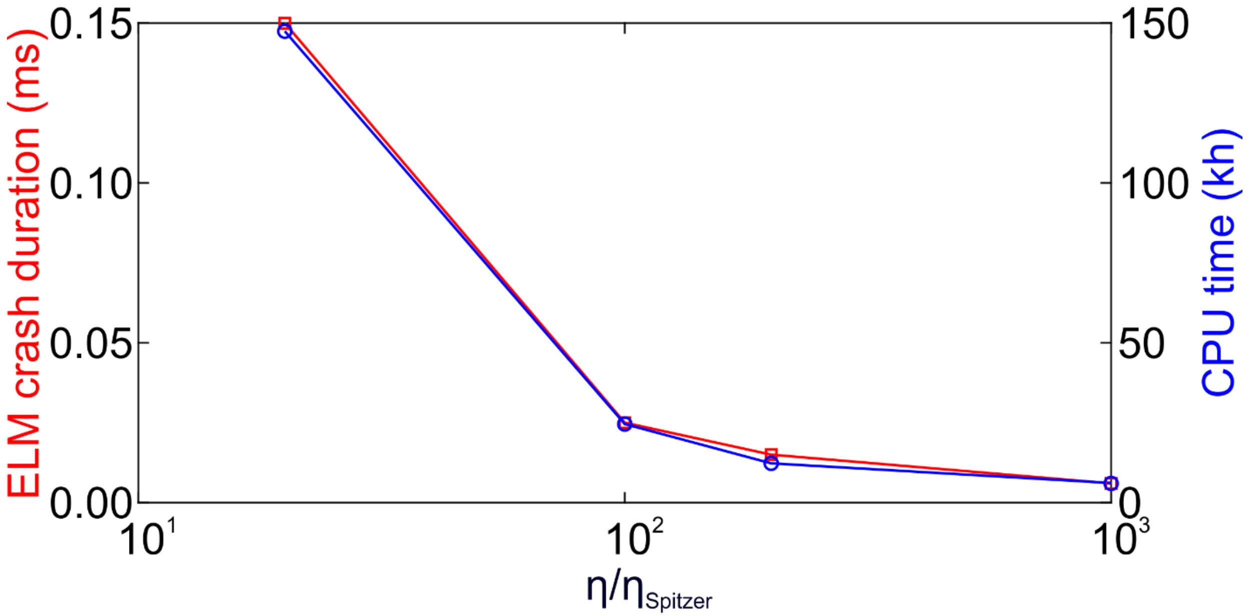
$$\rho_{\parallel} = \frac{m_{\mathrm{h}} v_{\parallel}}{q_{\mathrm{h}} B}, \mu = \frac{m_{\mathrm{h}} v_{\perp}^{2}}{2B}$$

$$\vec{B}^{*} = B\left(1 + \rho_{\parallel} \hat{b} \cdot \nabla \times \hat{b}\right)$$

$$m_{\mathrm{h}} v_{\parallel} \frac{d v_{\parallel}}{dt} = \vec{v}_{\parallel}^{*} \cdot \left(q_{\mathrm{h}} \vec{E} - \mu \nabla B\right)$$

- Electromagnetic field gyro-averaged (FLR effects)

ELM crash duration strongly depends on plasma resistivity



- ELM crash duration is shorter when η decreases

- To simulate with $\eta = \eta_{\text{Spitzer}}$ and ELM crash duration of 1-2 ms, 130 years of wall-time are needed

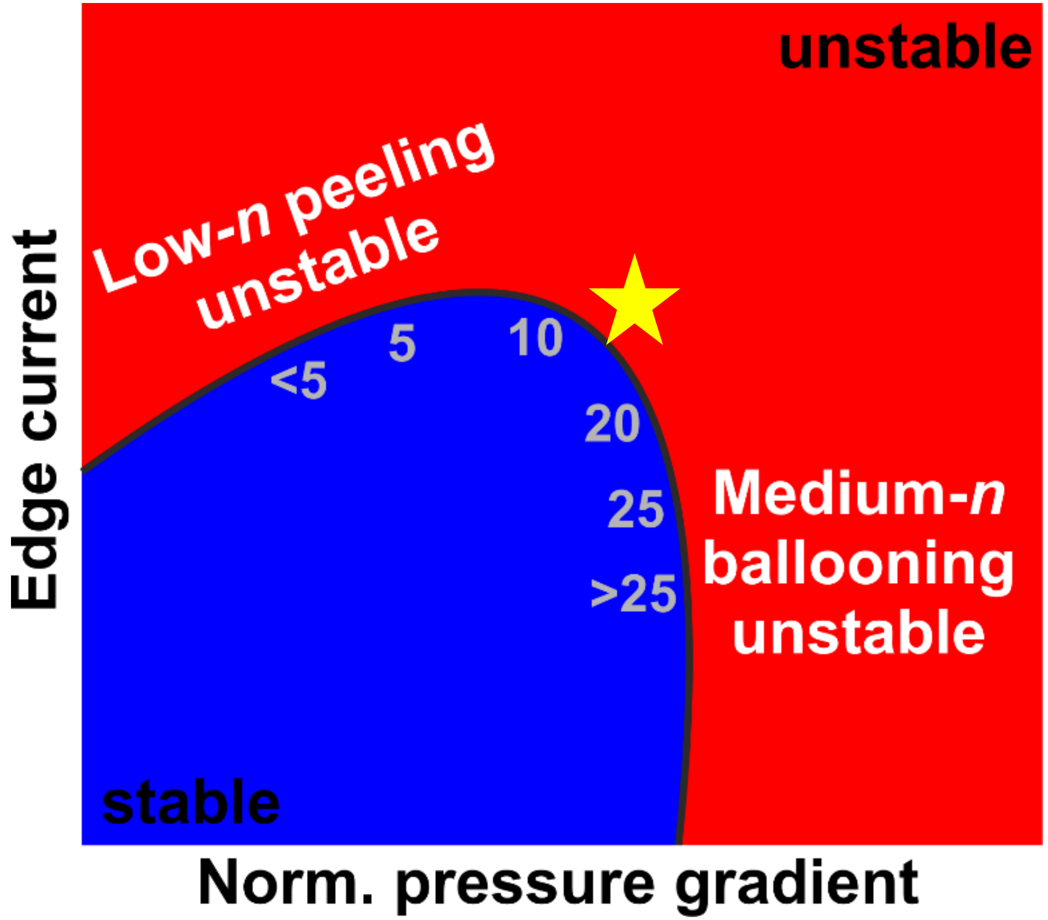
- We expect to see same striking similarities in synthetic diagnostics when simulation with $\eta = \eta_{\text{Spitzer}}$ is affordable

How to “best” describe ELMs theoretically?

- Linear MHD: coupled peeling-ballooning modes driven by ∇p and j [1]

- Linear MHD is not enough because…
    - ➢ Cannot capture growing and mitigation phases of instabilities
    - ➢ Impossible to simulate heat and particle transport due to ELMs with linear MHD

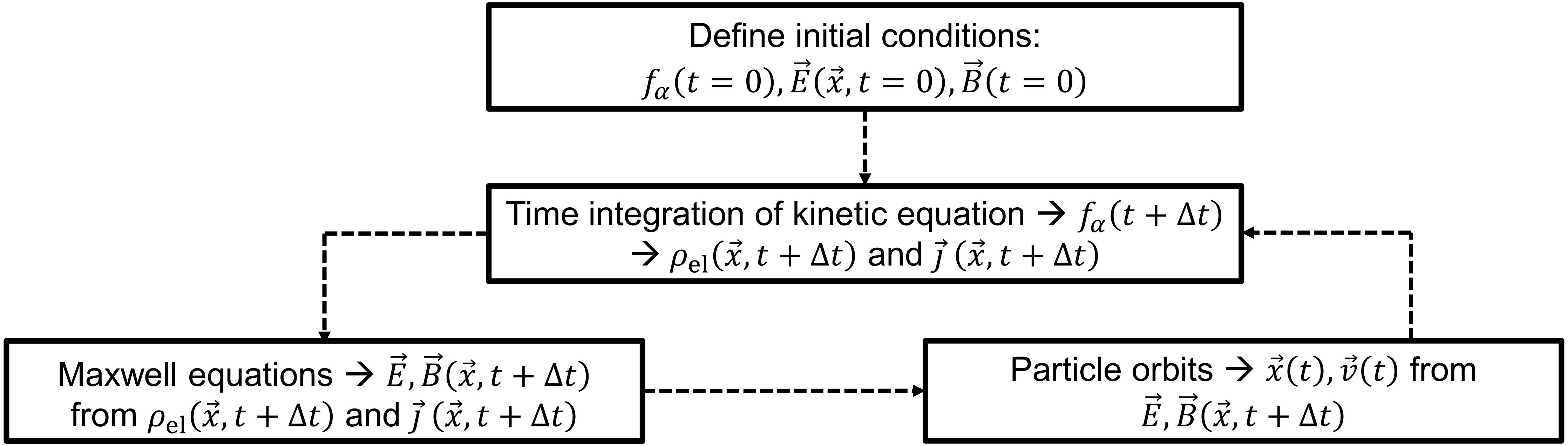
- **Nonlinear models are essential to simulate the key ELM physics**[2]



*E. Viezzer

[1] J.W. Connor *et al.*, Phys. Plasmas **5**, 2687 (1998)
[2] G.T.A. Huysmans *et al.*, Phys. Plasmas **22**, 021805 (2015)

Solving the kinetic equation



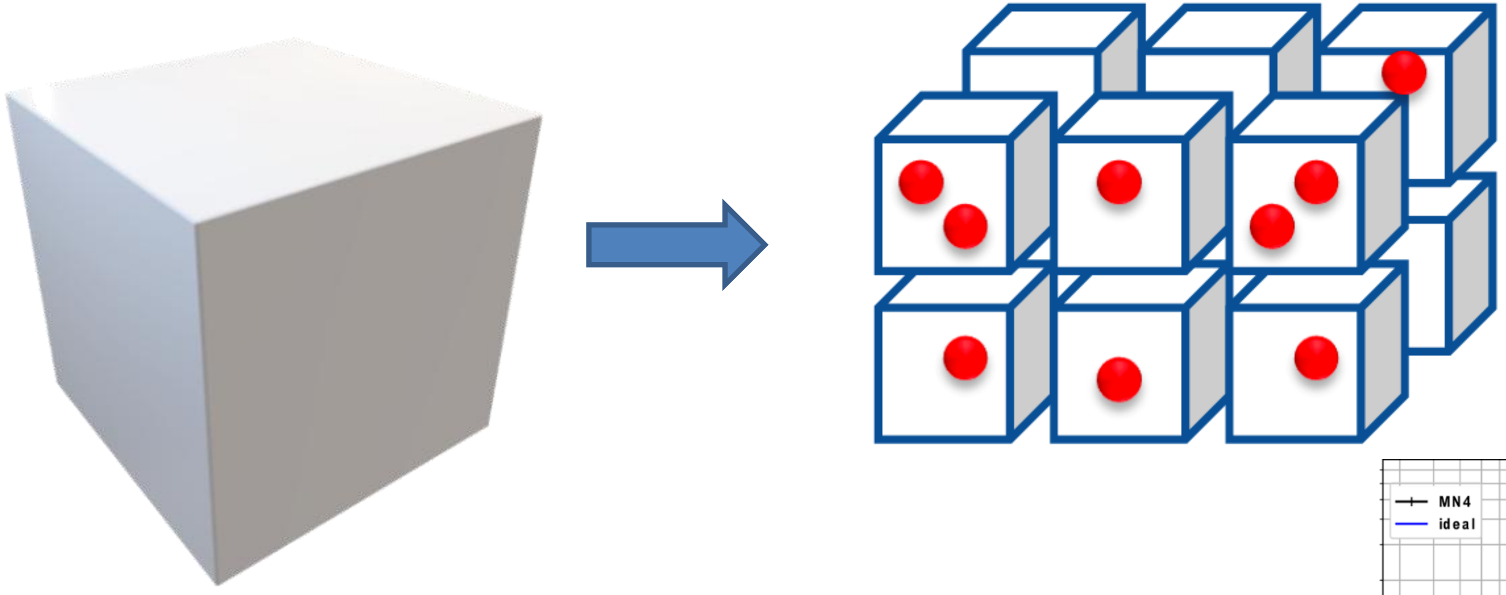
- Difficulties of kinetic equation
  - Not possible to solve analytically for most of cases of interest
  - No universal choice of collision term
  - Still has a relatively large size

Why do we need a kinetic equation?

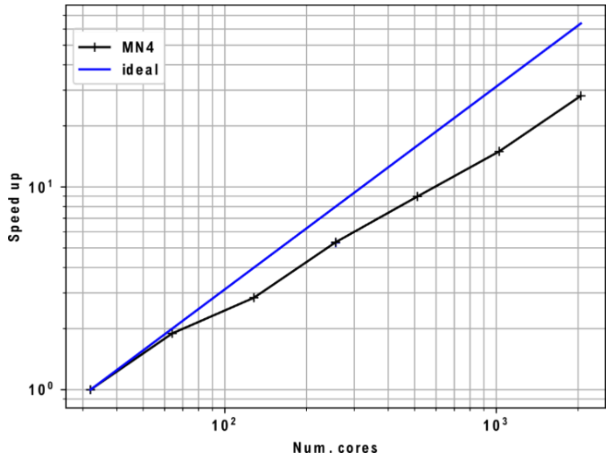
- Solving particle equation of motion is not feasible because
  - ➢ The exact form of the electromagnetic field is not known a priori → impossible to carry out an analytical study
  - ➢ There are 10^{23} particles → impossible to solve computationally such a many-body problem
- Statistical description of the plasma: **kinetic equation**

Parallelization used in the simulations

- Particles and fluid fields are 3 dimensionally sub-divided → MPI parallelization



- Good scaling until 2048 cores of MareNostrum IV



*Courtesy by J. Gonzalez-Martin

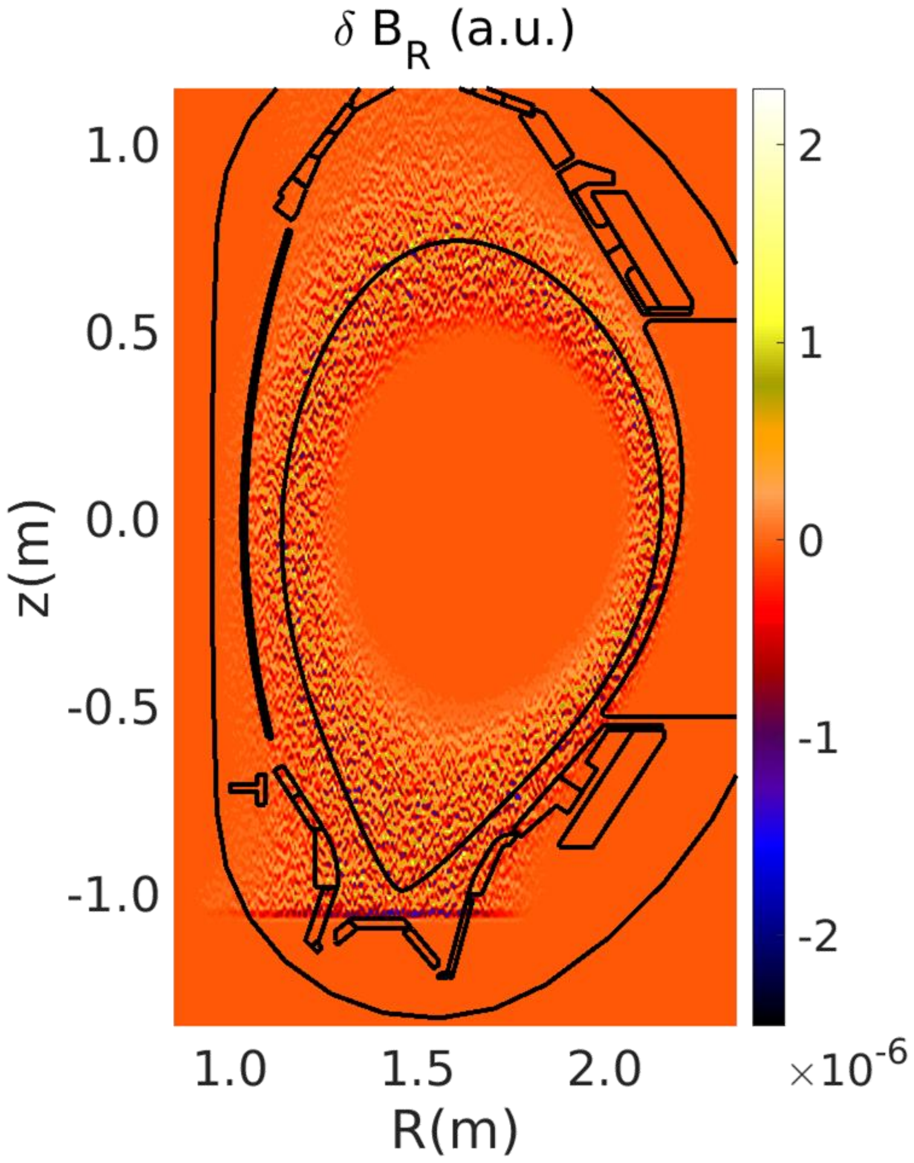
Initial seed perturbation in MEGA

- Initial magnetic field perturbation $\delta\vec{B}$ at noise level and given by

$$\delta\vec{B} = \nabla \times \vec{F}$$

- $\vec{F}$ denotes a random vector field

- Divergence-free nature of magnetic field ensured[1]



[1] Y. Hu *et al.*, Phys. Plasmas **23**, 022505 (2016)

General workflow of MEGA

(1)

User inputs

- Simulation domain
- 2D equilibrium
- Kinetic profiles
- Numerical and physical parameters

General workflow of MEGA

(1) **(2)**

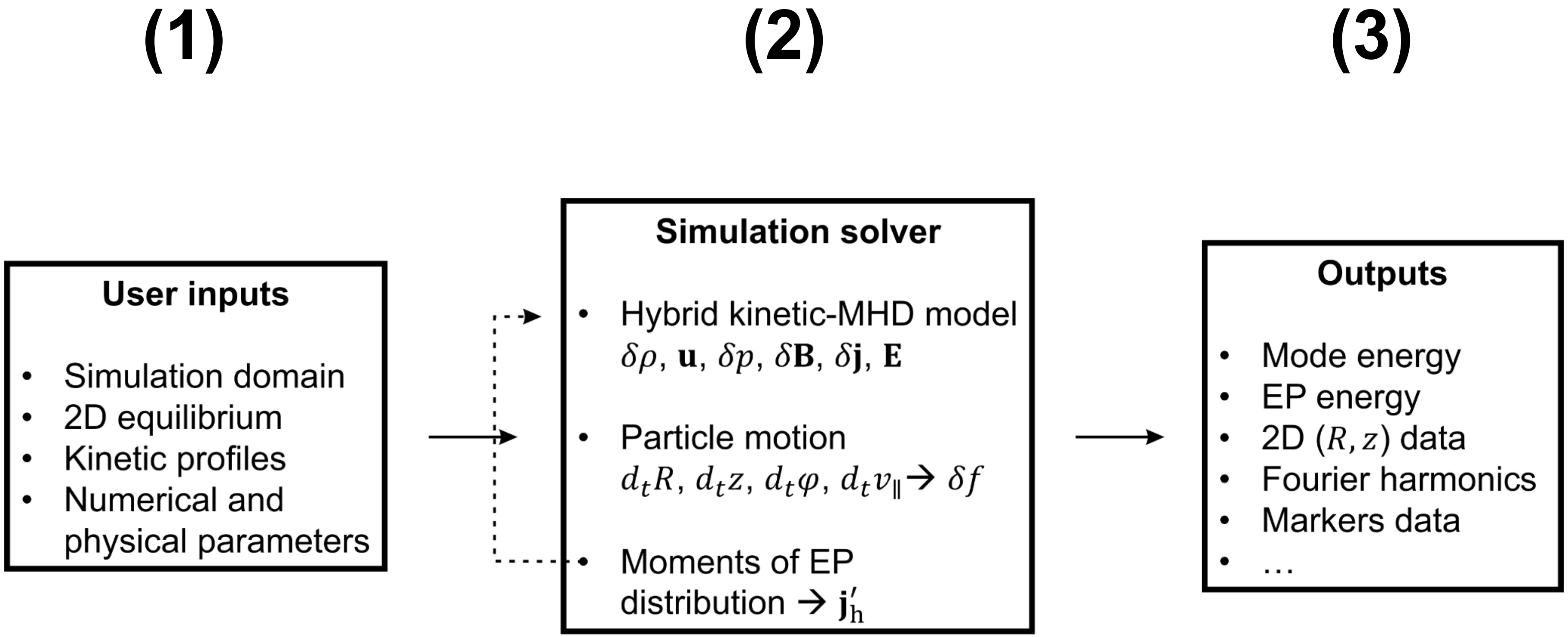
User inputs

- Simulation domain
- 2D equilibrium
- Kinetic profiles
- Numerical and physical parameters

Simulation solver

- Hybrid kinetic-MHD model
  $\delta\rho$, $\mathbf{u}$, δp, $\delta\mathbf{B}$, $\delta\mathbf{j}$, $\mathbf{E}$
- Particle motion
  $d_t R$, $d_t z$, $d_t \varphi$, $d_t v_\parallel \rightarrow \delta f$
- Moments of EP distribution $\rightarrow \mathbf{j}_\mathrm{h}'$

General workflow of MEGA



Energetic particle dynamics in MEGA

- Kinetic equation solved with δf method → $f = f_0 + \delta f$

- For collisionless particles, noting that $\vec{z} \equiv (\vec{x}, \vec{v})$

$$\left.\frac{dw}{dt}\right|_{\vec{z}=\vec{z}_i} = -V_i \left(\frac{dE}{dt}\frac{\partial f_0}{\partial E} + \frac{dP_\varphi}{dt}\frac{\partial f_0}{\partial P_\varphi}\right)_{\vec{z}=\vec{z}_i}, w(\vec{z} = \vec{z}_i, t = 0) = 0$$

- In δf method, $w_i = V_i \delta f_i$ with w_i weight of i-th particle. f_0 is given analytically and represents off-axis slowing down NBI distribution

$$p_{EP} = \beta_{EP} \frac{B_0^2}{2\mu_0} \exp\left[-\left(\frac{\Psi_\mathrm{N} - \Psi_{\mathrm{N}_0}}{\sigma_{\Psi_\mathrm{N}}}\right)^2\right]$$

$$I(v, \Lambda) = \frac{1}{v^3 + v_\mathrm{crit}^3} \frac{1}{2} \mathrm{erfc}\left(\frac{v - v_\mathrm{birth}}{\Delta_v}\right) \exp\left[-\left(\frac{\Lambda - \Lambda_0}{\Delta_\Lambda}\right)^2\right]$$

Confinement methods

- Gravitational confinement
- Inertial confinement
- Magnetic confinement

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- Gravitational confinement
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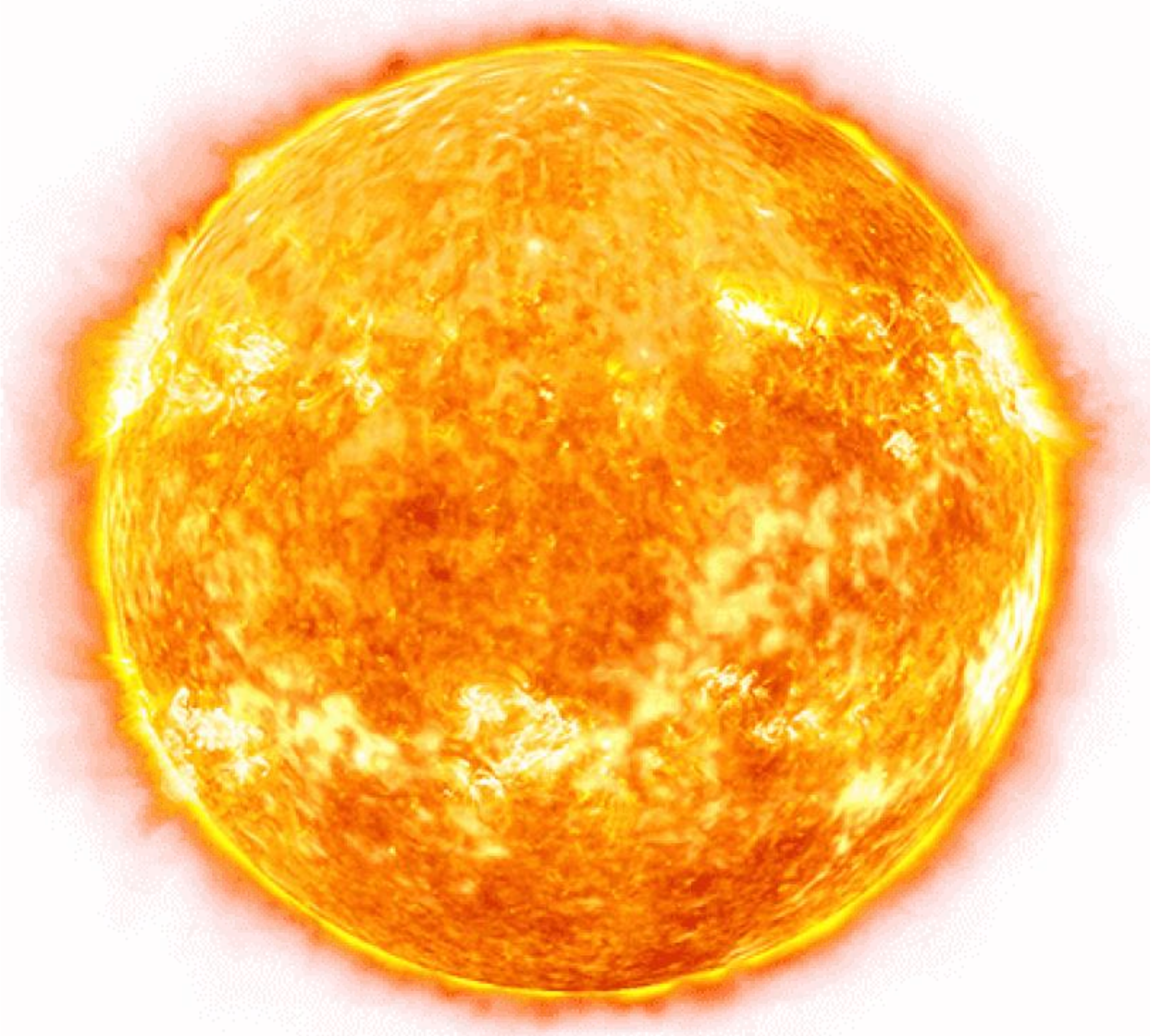

Confinement methods

- Gravitational confinement
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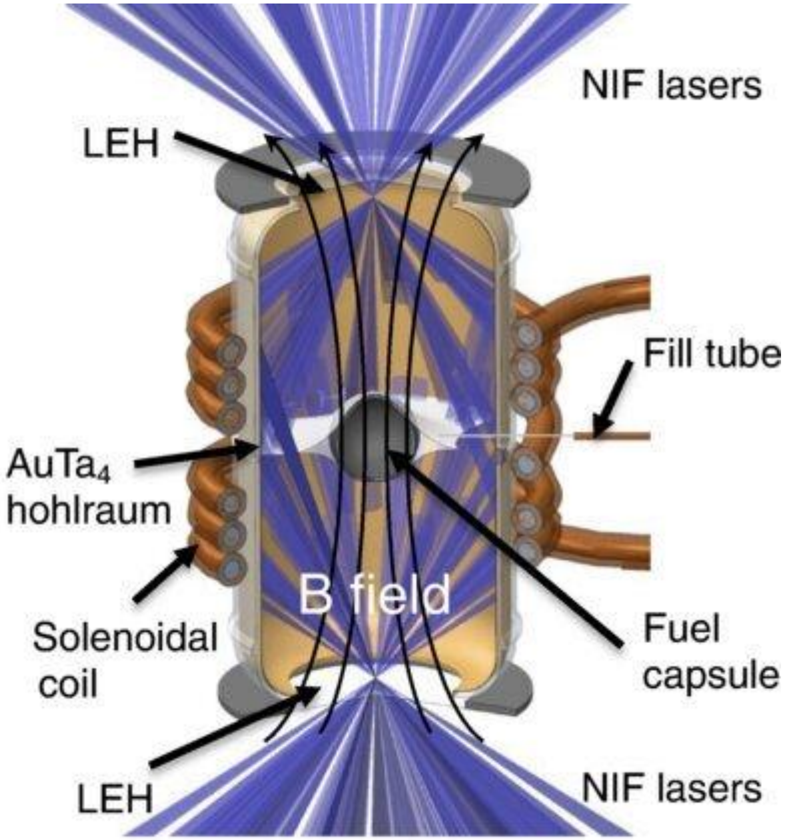

Confinement methods

- Gravitational confinement
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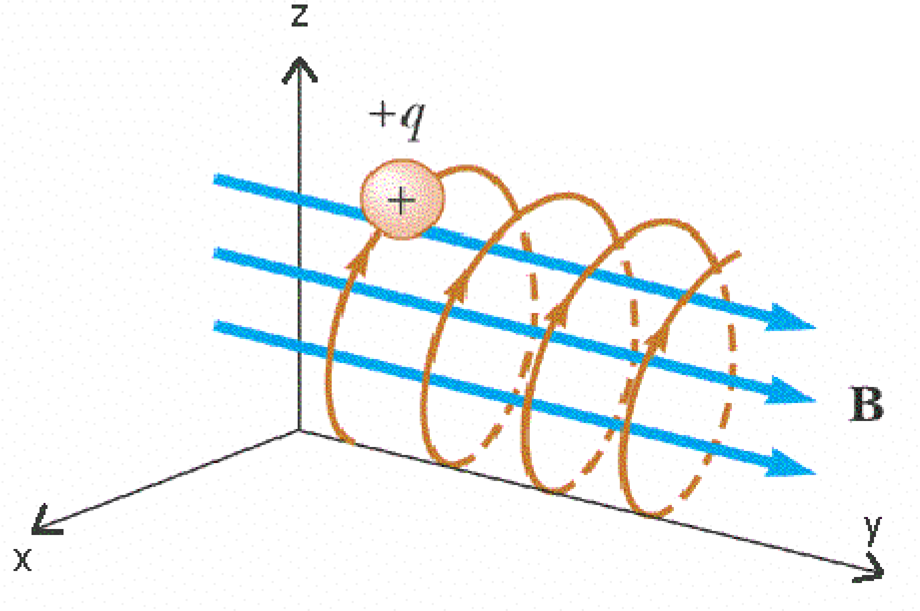
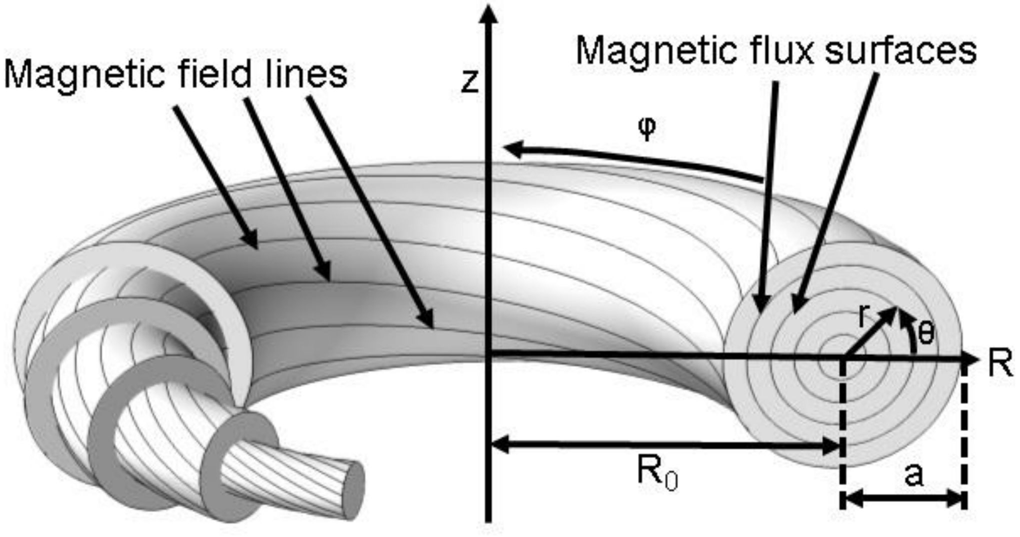


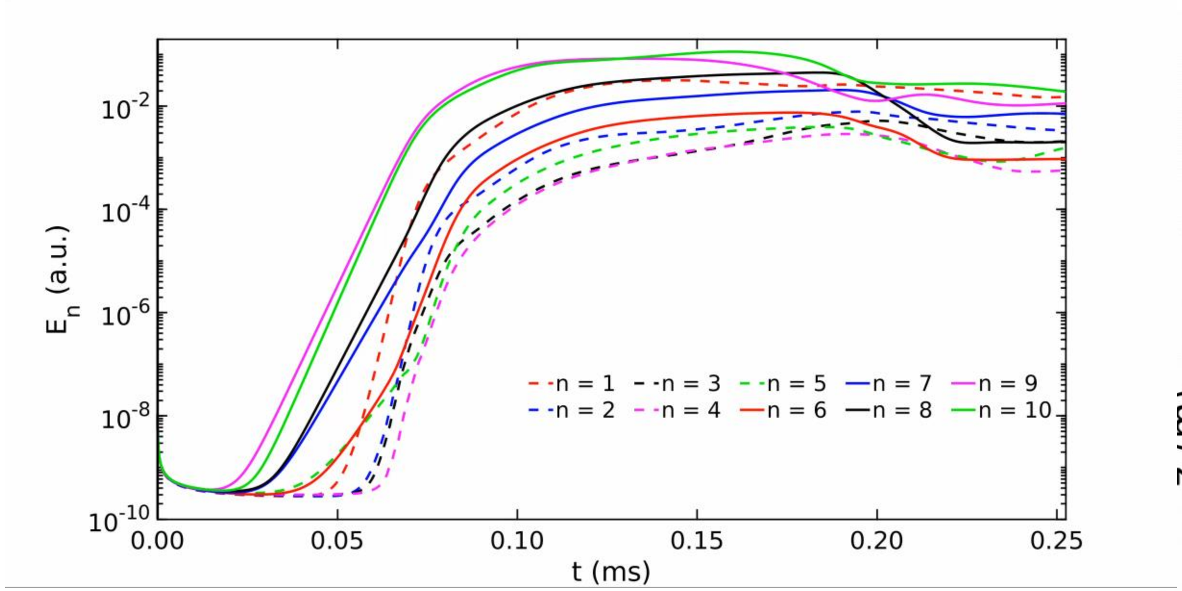
Coordinates in a tokamak

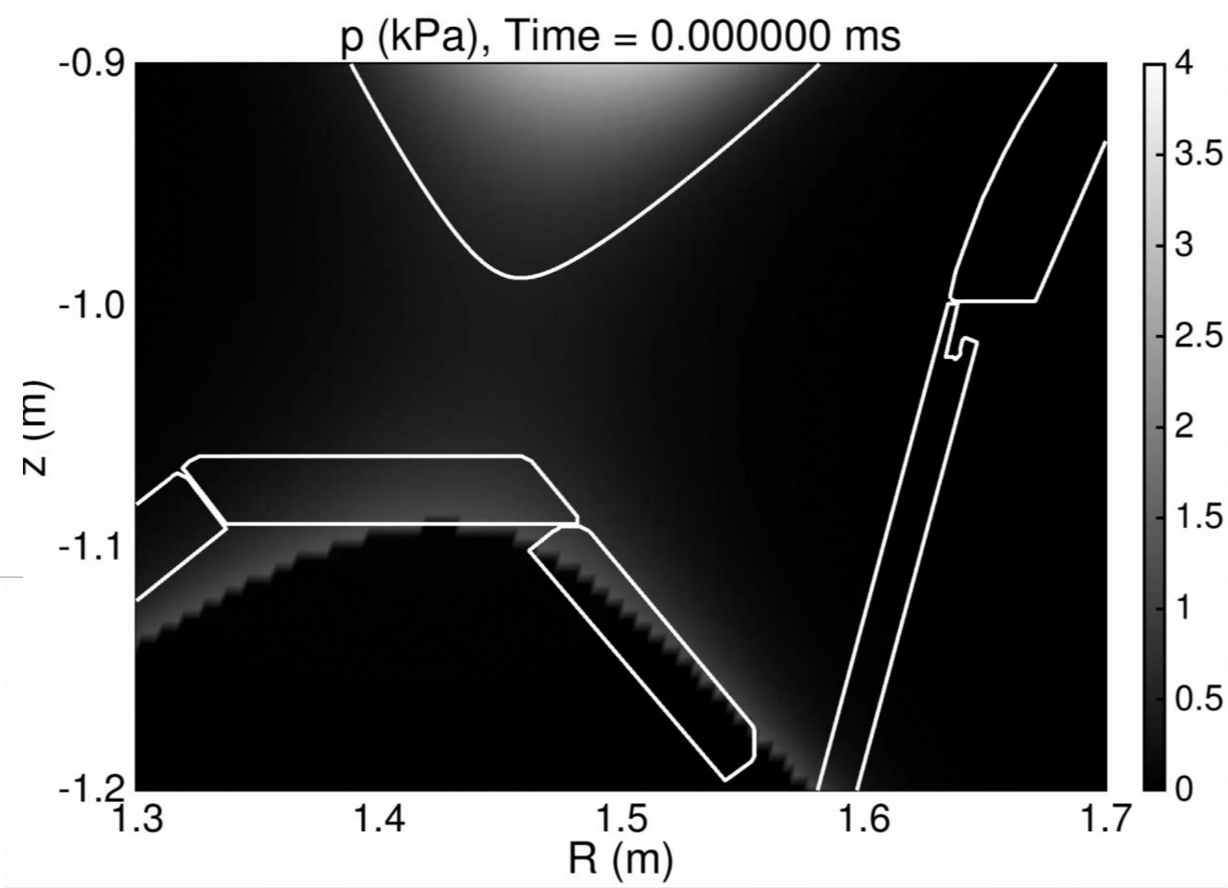
- (R, φ, z) or (r, φ, θ) coordinates
- Poloidal magnetic flux Ψ labels magnetic surfaces
- Normalized poloidal flux $\Psi_{\mathrm{N}} = \frac{\Psi - \Psi_0}{\Psi_{\mathrm{a}} - \Psi_0}$, and $\rho_{\mathrm{pol}} = \sqrt{\Psi_{\mathrm{N}}}$
- Safety factor profile $q = \frac{\text{number of toroidal turns}}{\text{number of poloidal turns}}$



A. Lebschy, PhD Thesis, 2018.

Loss of drive in nonlinear stage (2/2)





- Modes saturate and filaments extend into SOL

- Filaments arrive to outer divertor

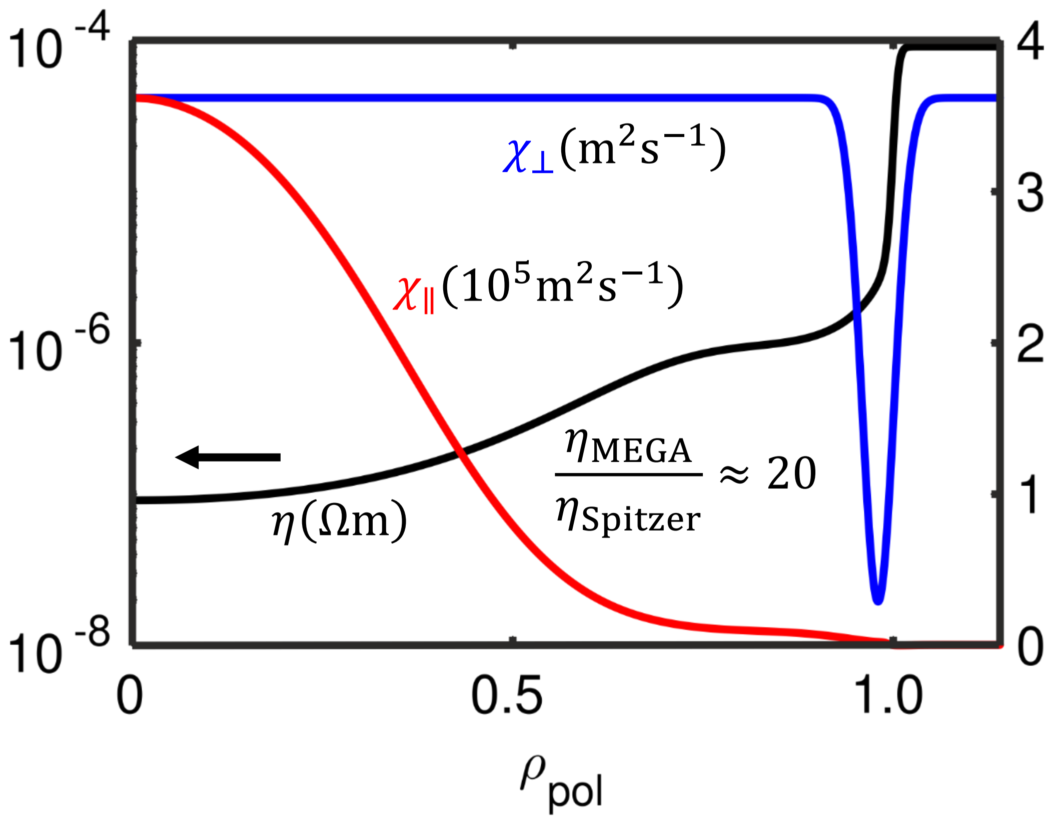
Energy principle: MHD stability analysis of the plasma

- Stability test for arbitrary plasma displacement $\vec{\xi}$
- Potential energy: $\Delta W\left[\vec{\xi}^*, \vec{\xi}\right] = -\frac{1}{2}\int d\vec{x}\,\vec{\xi}^* \cdot \overleftrightarrow{F} \cdot \vec{\xi}$ → when $\Delta W > (<) 0$ plasma is stable (unstable)
- Destabilization comes from plasma region

$$\Delta W_{\mathrm{F}} = \frac{1}{2}\int_F d\vec{x}\left[\underbrace{\frac{\left|B_{1_\perp}\right|^2}{2\mu_0}}_{\text{Magnetic field energy}} + \underbrace{\frac{B_{0_\perp}^2}{2\mu_0}\left|\nabla\cdot\vec{\xi}_\perp + 2\vec{\xi}_\perp\cdot\vec{\kappa}\right|^2}_{\text{Compression of equilibrium field and plasma}} + \underbrace{\gamma p_0\left|\nabla\cdot\vec{\xi}\right|^2}_{\text{Adiabatic compression}} \underbrace{- 2\left(\vec{\xi}_\perp\cdot\nabla p_0\right)\left(\vec{\kappa}\cdot\vec{\xi}^*\right)}_{\text{Pressure driven}} \underbrace{- \frac{j_{0_\parallel}}{B_0}\left(\vec{\xi}_\perp^*\times\vec{B}_0\right)\cdot\vec{B}_1}_{\text{Current driven}}\right]$$

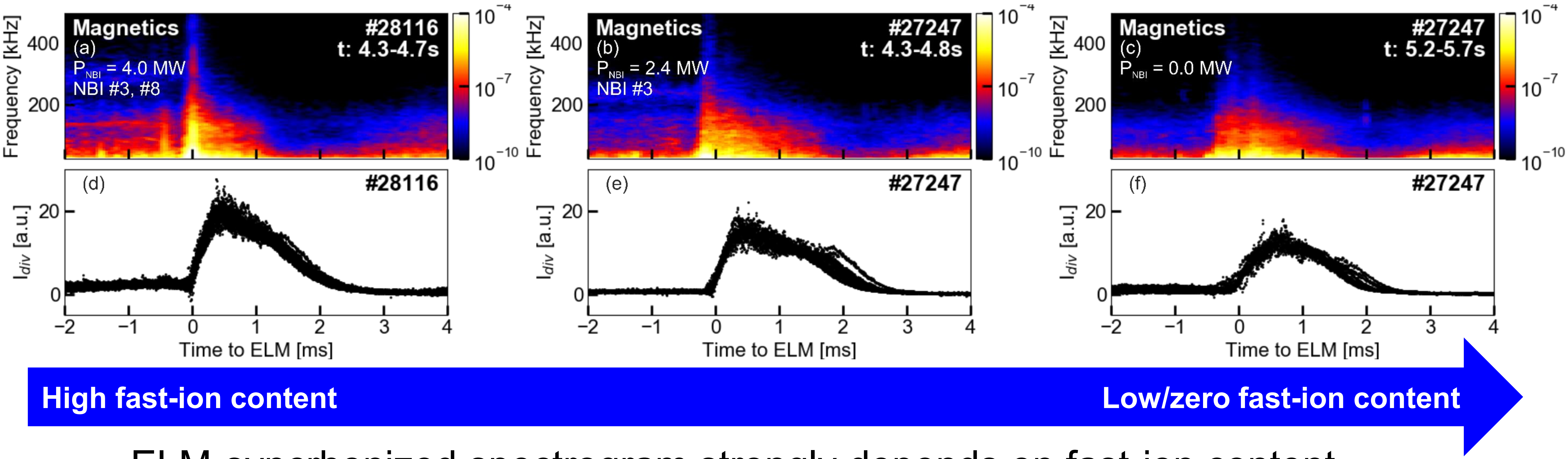
Transport coefficient in the simulations

- Temperature-dependent viscosity and resistivity using **Spitzer's law**
- Ad-hoc profiles for perpendicular thermal diffusivity and particle diffusivity are used to mimic **ETB**[1]
- Temperature-dependent parallel thermal diffusivity using **Braginskii's law**



[1] E. Viezzer *et al.*, Plasma Phys. Control. Fusion **62**, 024009 (2020)

In experiments, ELM looks remarkably different with and w/o fast-ions



- ELM-synchronized spectrogram strongly depends on fast-ion content
  - ➢ With larger fast-ion content (low collisionality), ELM crash lasts shorter
  - ➢ Magnetic burst at $f > 300$ kHz enhanced with larger fast-ion content

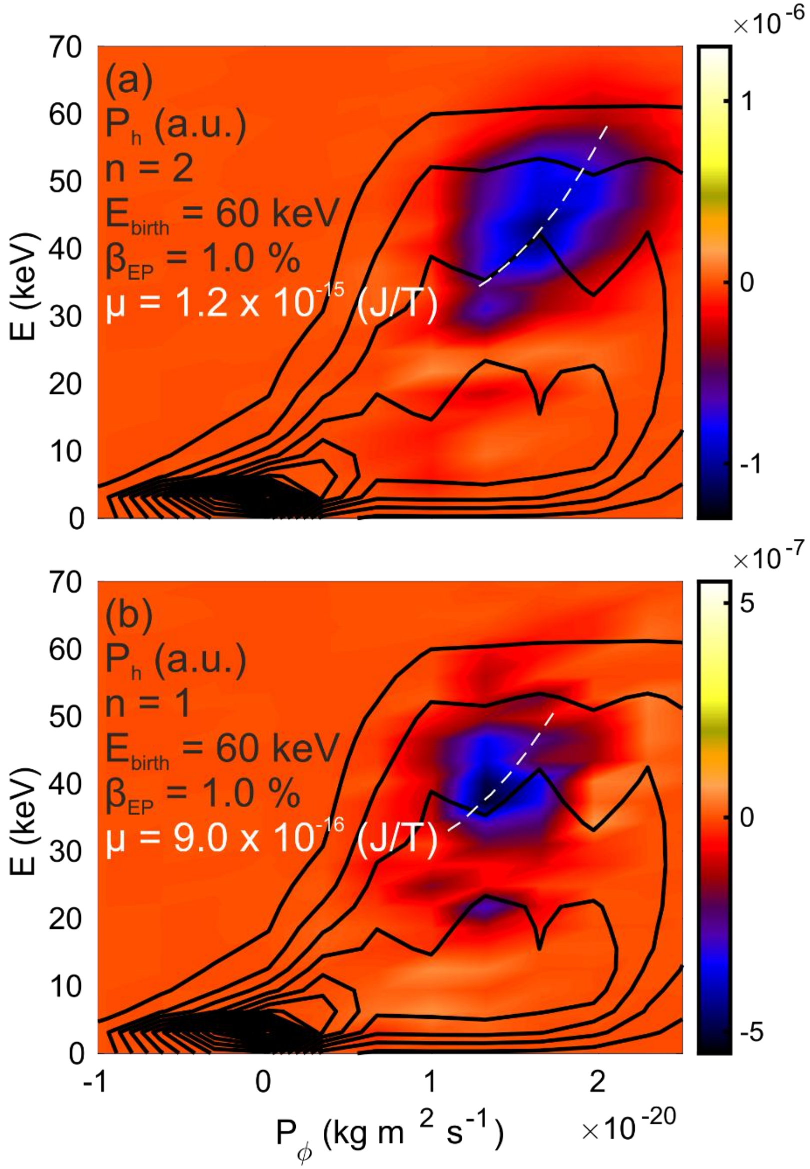
Power transfer with low-n mode numbers

- $P_\mathrm{h} \propto \vec{E}$ → We can calculate P_h for $\vec{E}_n$

- Phase-space structures aligned with resonant condition[1]

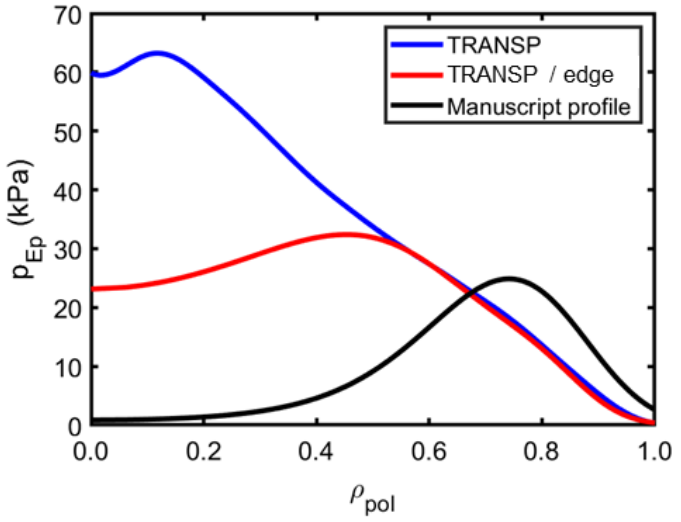
$$\omega_n - n\omega_\varphi - p\omega_\theta \approx 0$$

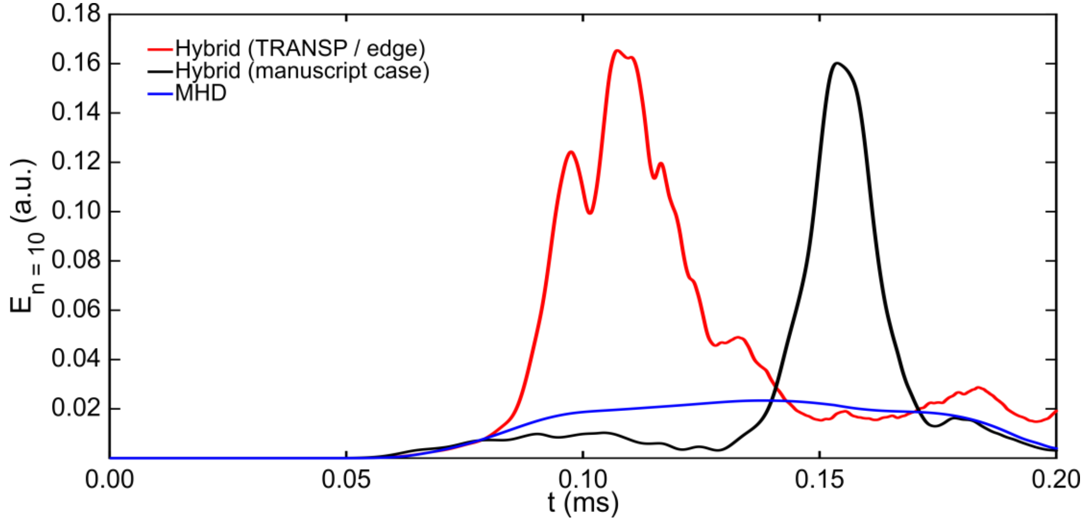
- Resonant energy exchange between low-n modes and fast-ions observed



[1] W.W. Heidbrink *et al.*, Phys. Plasmas **27**, 030901 (2020)

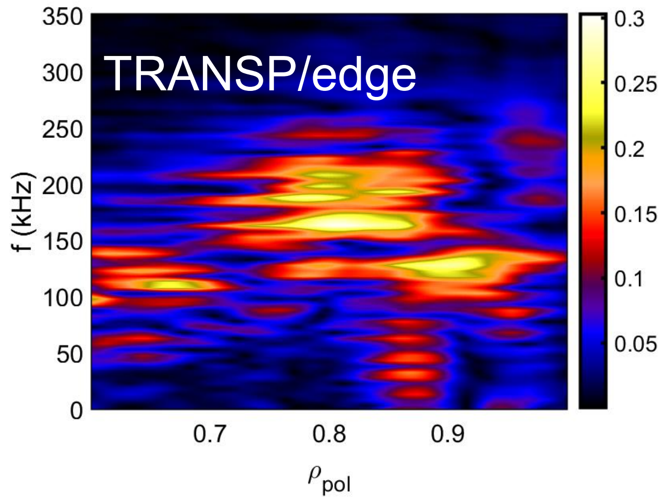
Hybrid kinetic-MHD simulations with TRANSP predicted profiles show similar observations





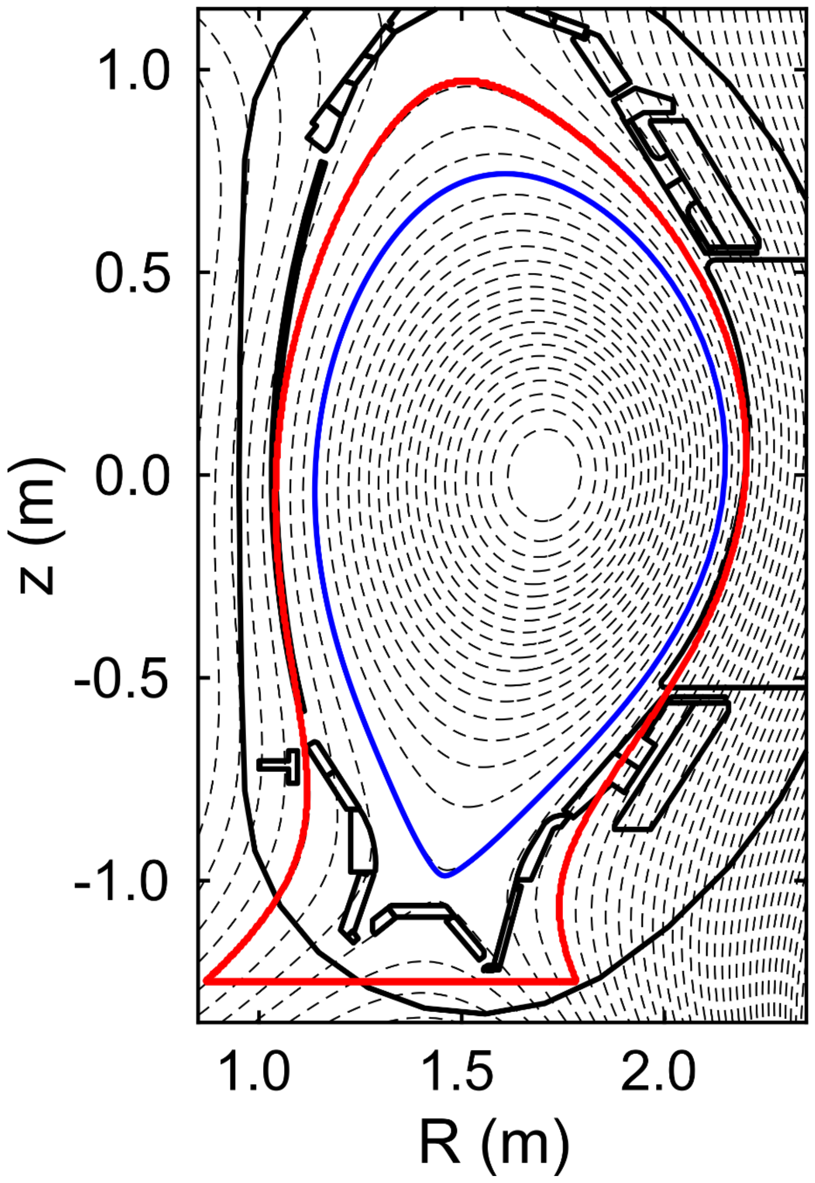
- Fast-ion pressure profile used in MEGA slightly overestimates fast-ion pressure at plasma edge

- Simulations with a TRANSP/edge-like profile still show similar mode energy evolution and impact on the spatial-frequency pattern



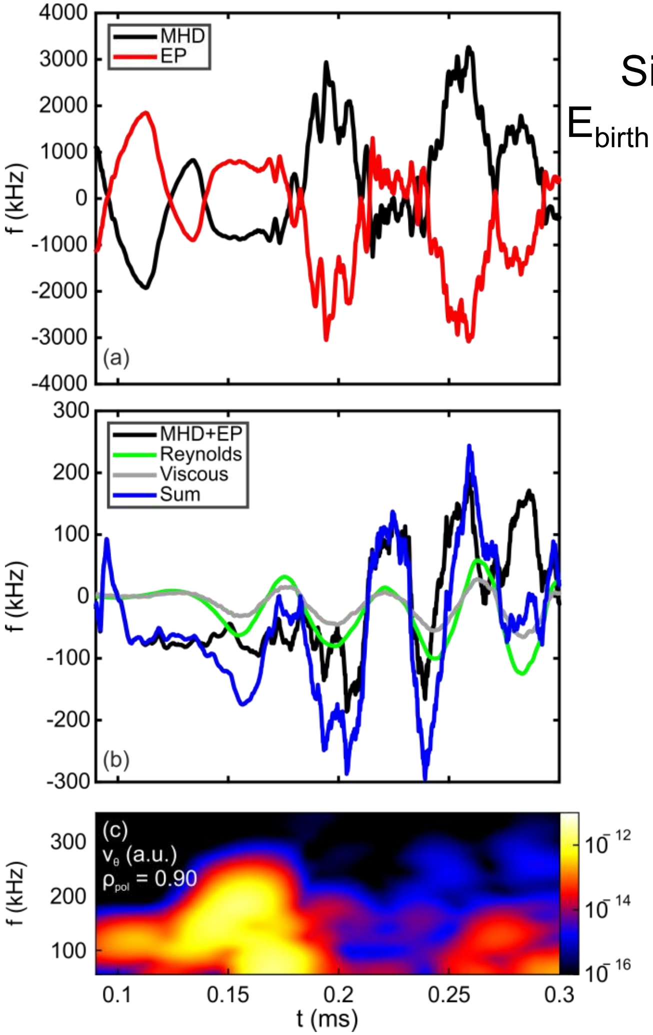
Boundary conditions in the simulations

- $\vec{u} = \vec{0}, \delta\rho = \delta p = 0$ outside area enclosed by red line (binary mask) seen in right figure
- At boundary of simulation domain, $\delta\vec{B} \cdot \hat{n} = 0$ and $\vec{E} \times \hat{n} = \vec{0}$ → perfect conducting wall boundary condition
- Distribution function of particles $f = 0$ at boundary of simulation domain



Imbalance of forces in hybrid kinetic-MHD simulations of ELMs

- In hybrid kinetic-MHD simulations, the frequency is significantly boosted
- Main forces driving mode frequency are MHD and energetic particle forces
- Reynolds force plays a key role in the total contribution of forces to mode frequency



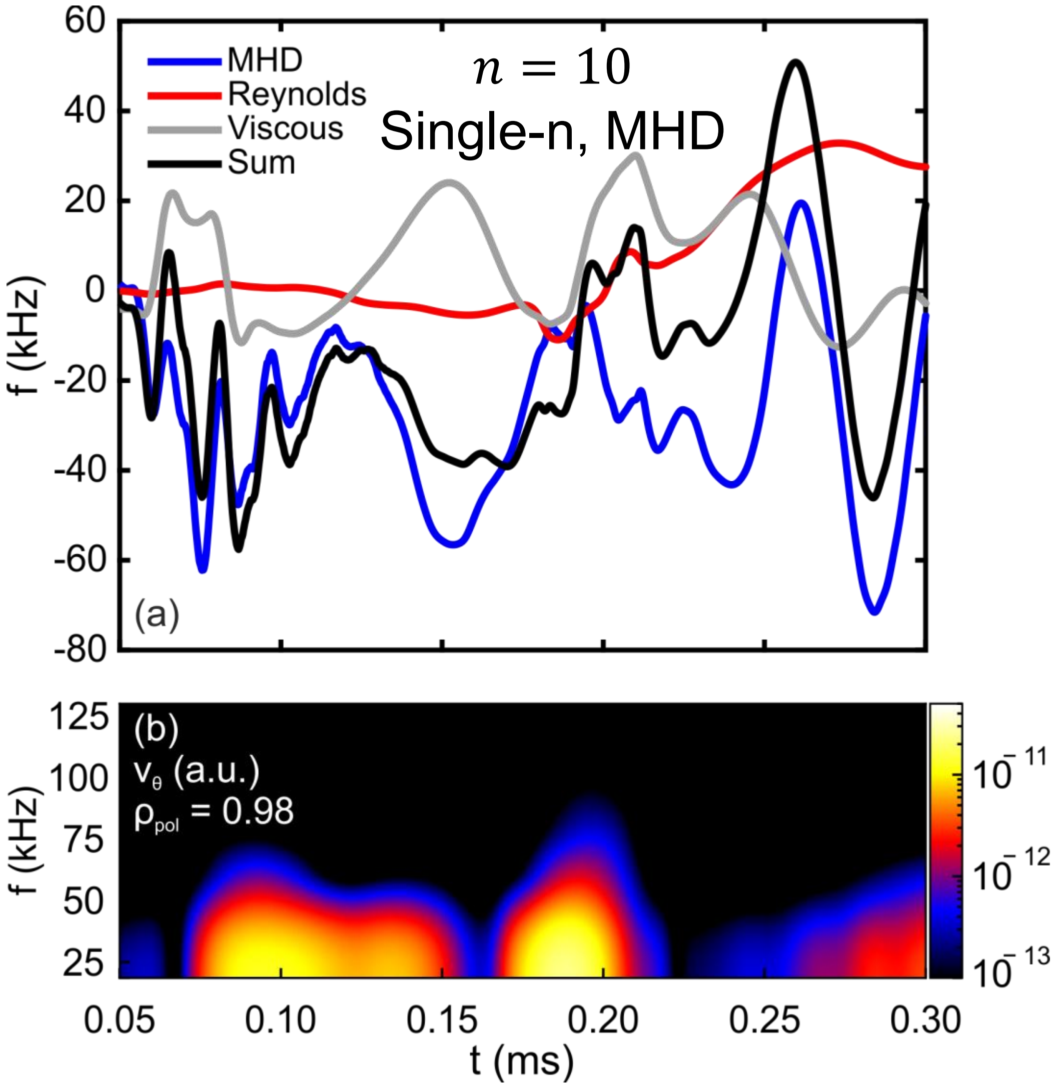
Single-n
E_{birth} = 60 keV

Mode rotation brought by imbalance of forces in the MHD momentum equation

- **MHD force** $(= -\nabla p + \vec{j} \times \vec{B})$ determines mode frequency

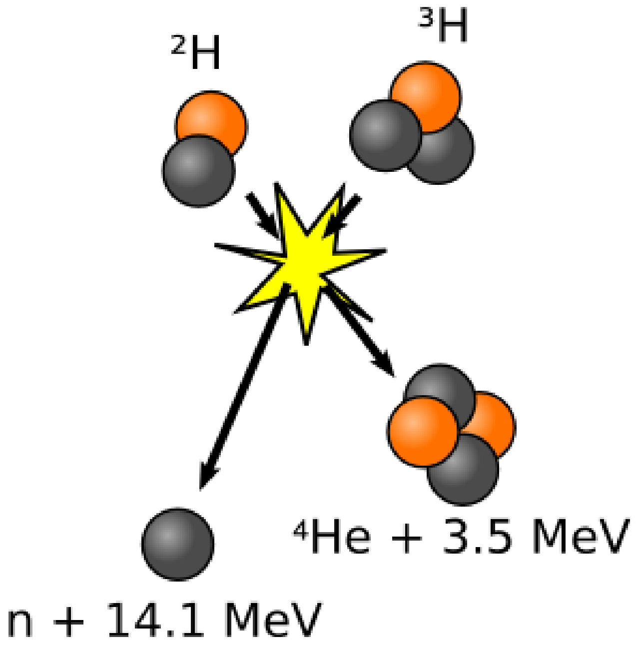
- **Viscous force** $[= -\nabla \times (\nu\rho\nabla \times \vec{u}) + \frac{4}{3}\nabla(\nu\rho\nabla \cdot \vec{u})]$ generally damps mode frequency in nonlinear phase

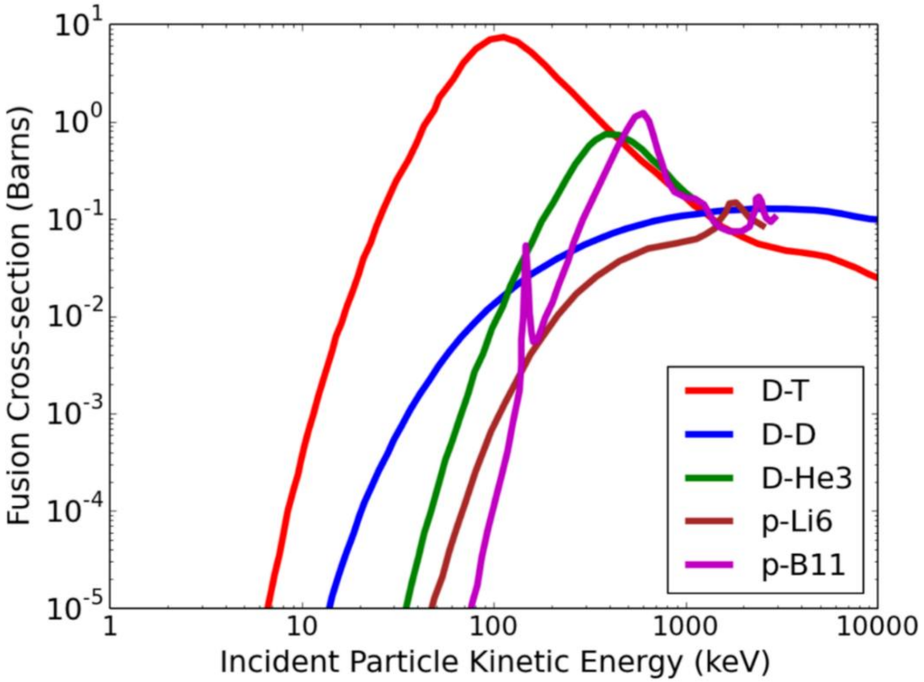
- **Reynolds force** $[= -\nabla \cdot (\rho\vec{u}\vec{u})]$ play major role long after ELM in mode frequency



Nuclear fusion reaction on Earth

- Mass deficit leads to large energy release due to $E = mc^2$
- D-T reaction has the largest cross section for achievable temperatures





The ignition condition

- We need plasma conditions such that $Q_{\text{out}} \gg Q_{\text{in}}$

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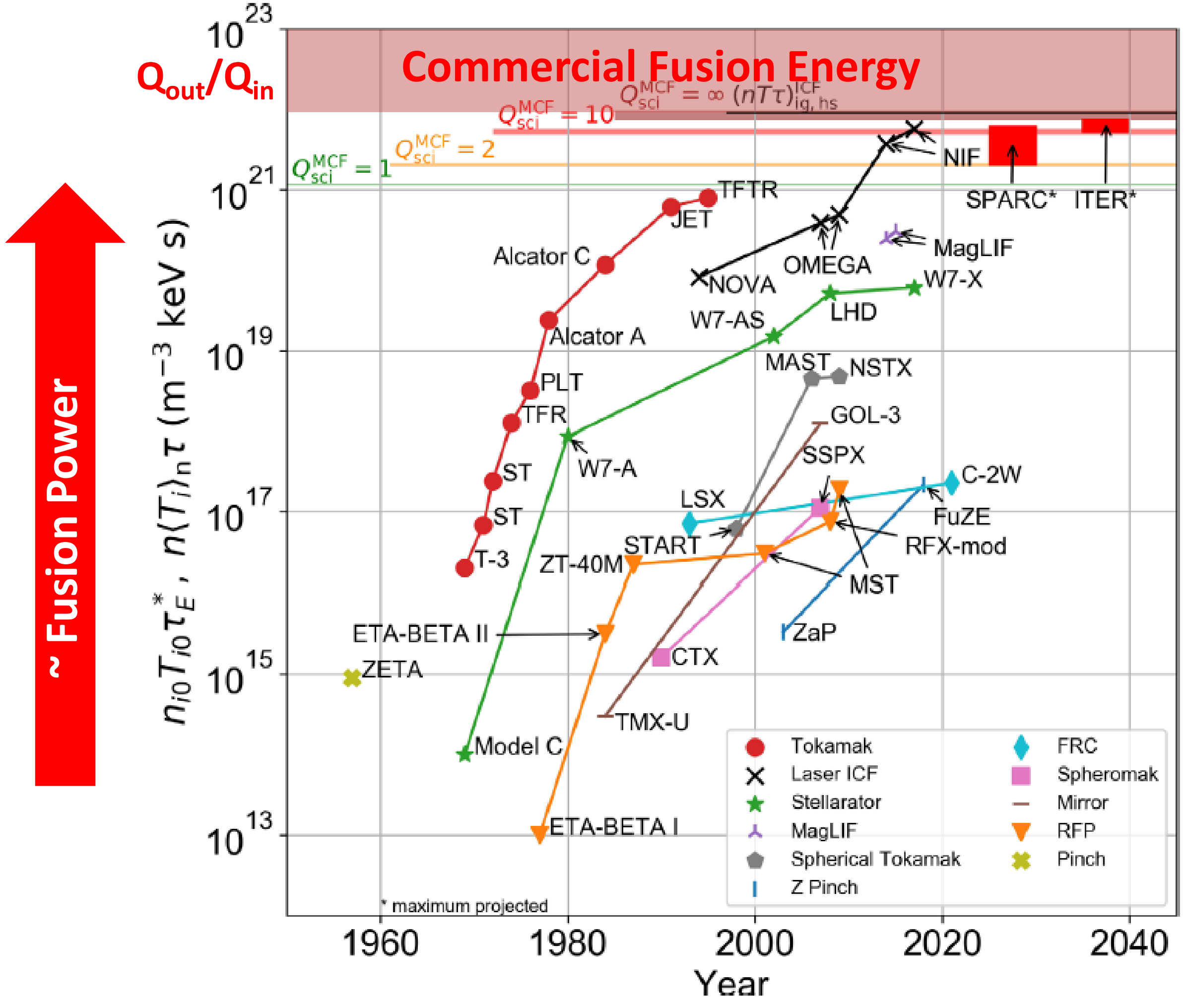
- Lawson criteria[1]

$$nT\tau_E > 5 \times 10^{21}\ \mathrm{m^3\ s\ keV}$$

n: plasma density
T: plasma temperature
τ_E: energy confinement time



Wurzel and Hsu, Phys. Plasmas **29** 062103 (2022)

[1] J.D. Lawson *et al.*, Proc. Phys. Soc. B **70**, 6 (1957)

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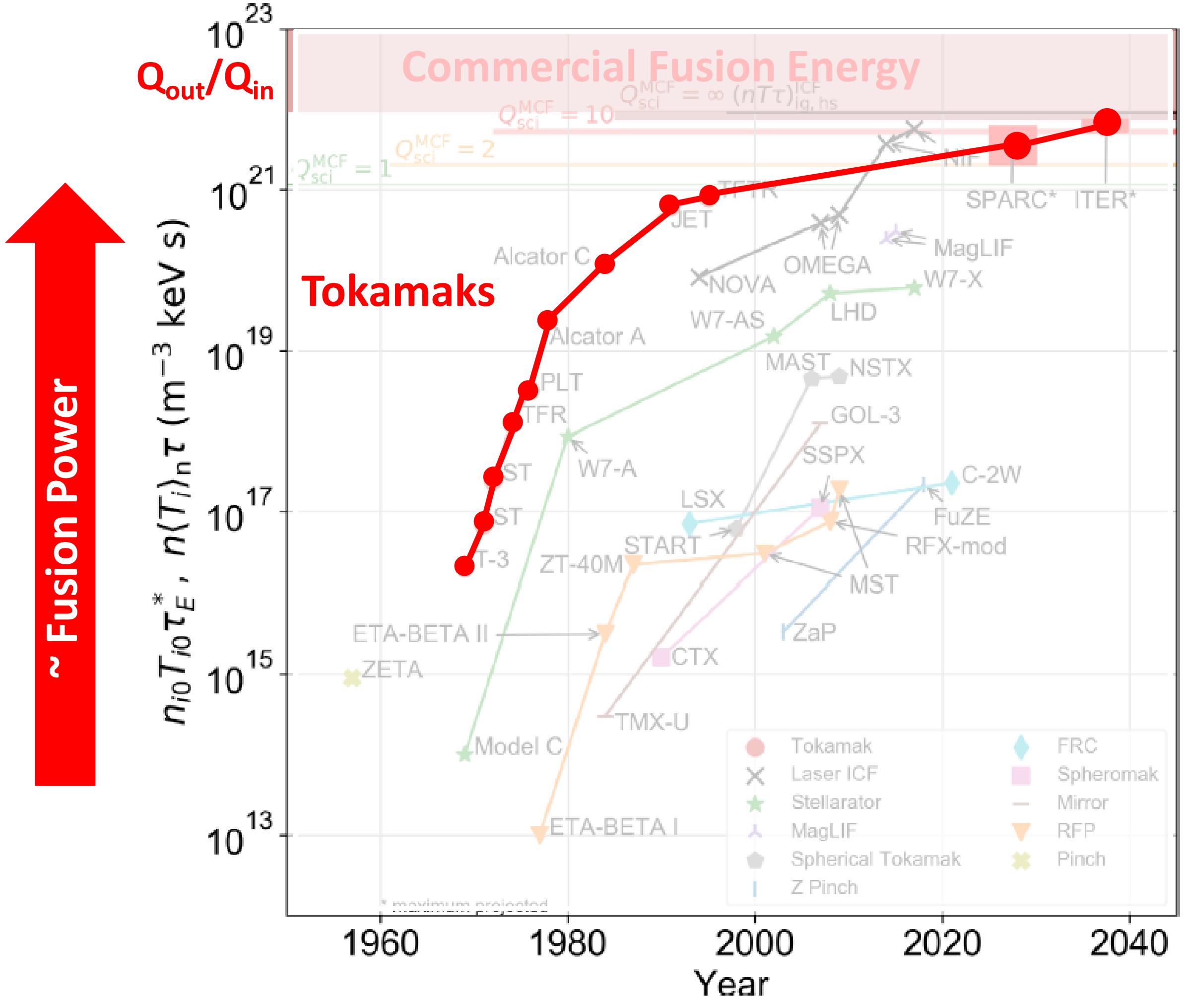
- Magnetic confinement (tokamaks) are the most advanced concept



Wurzel and Hsu, Phys. Plasmas **29** 062103 (2022)

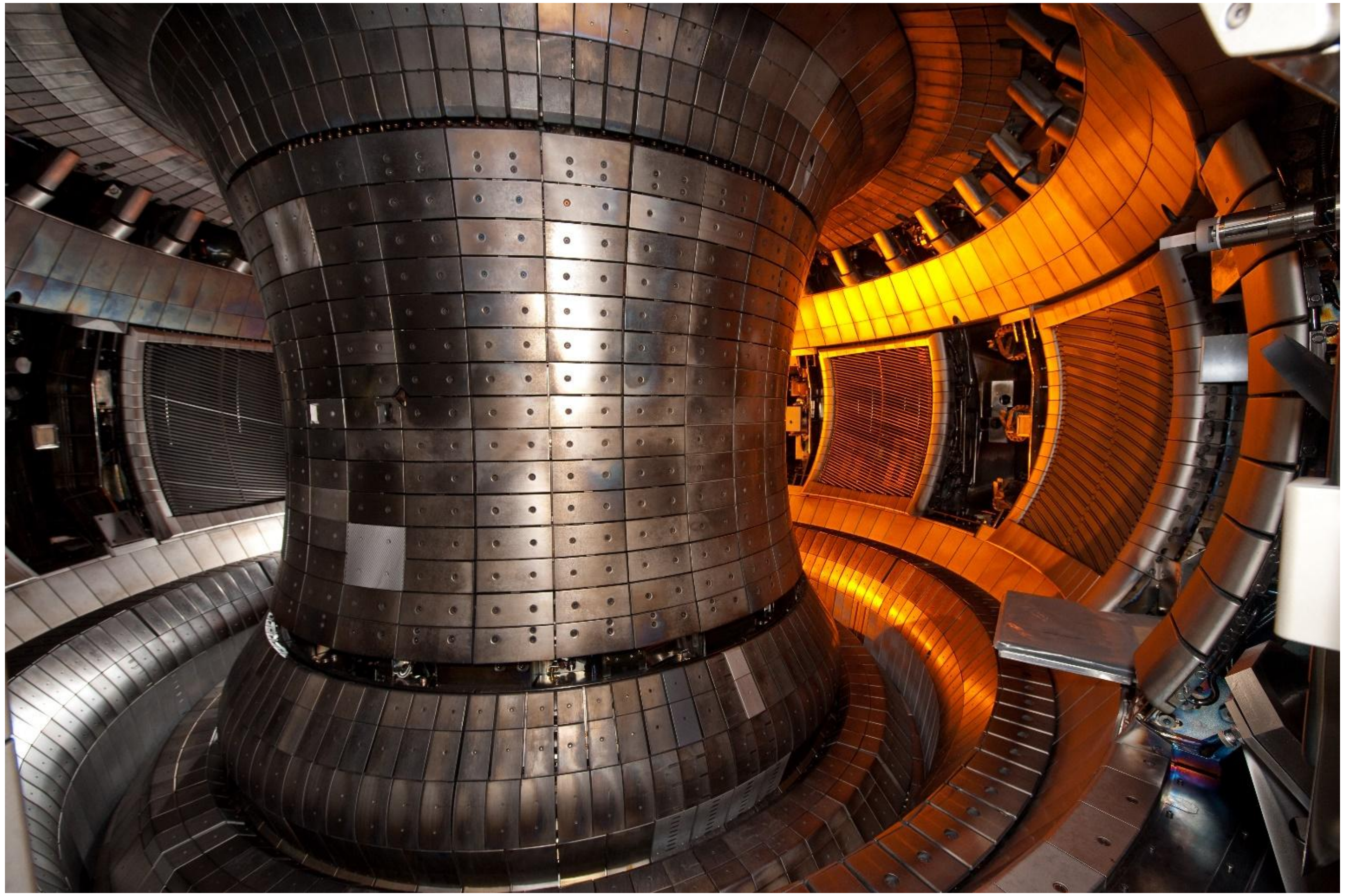
[1] J.D. Lawson *et al.*, Proc. Phys. Soc. B **70**, 6 (1957)

ASDEX Upgrade tokamak (AUG)

- Medium-sized tokamak located at Max-Planck Institute for Plasma Physics (Garching, Germany)

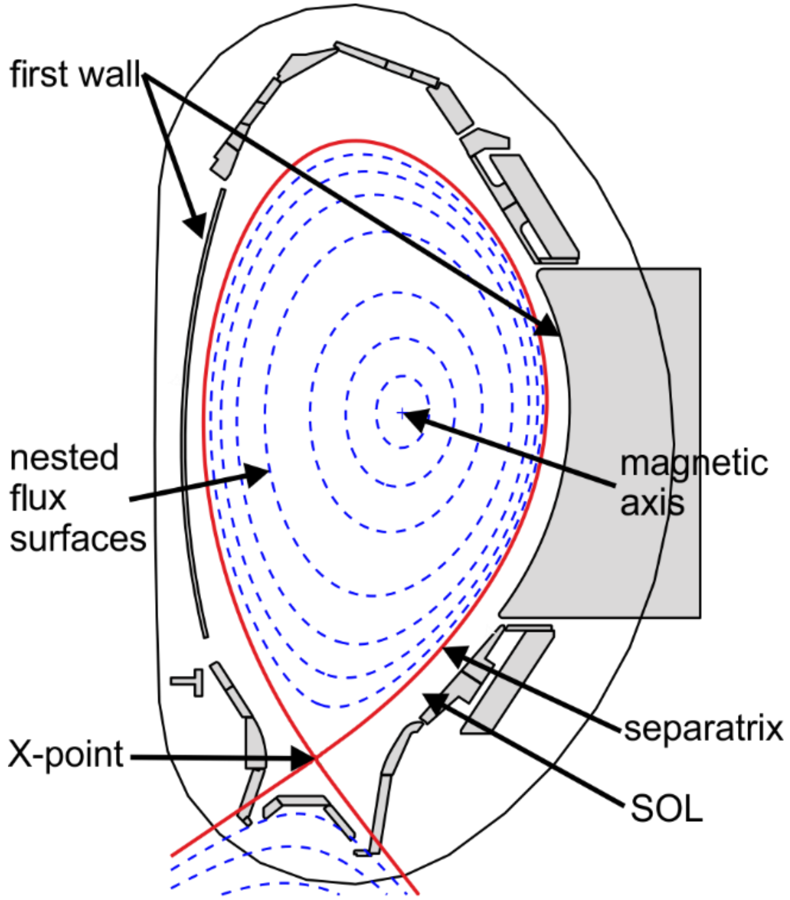
- Main parameters of AUG

Major radius R_0	1.65 m
Minor radius a	0.5 m
Plasma current I_p	0.4 – 1.2 MA
Toroidal magnetic field B_t	1.8 – 2.8 T
External heating power	up to 30 MW
Main ion	D, H, He



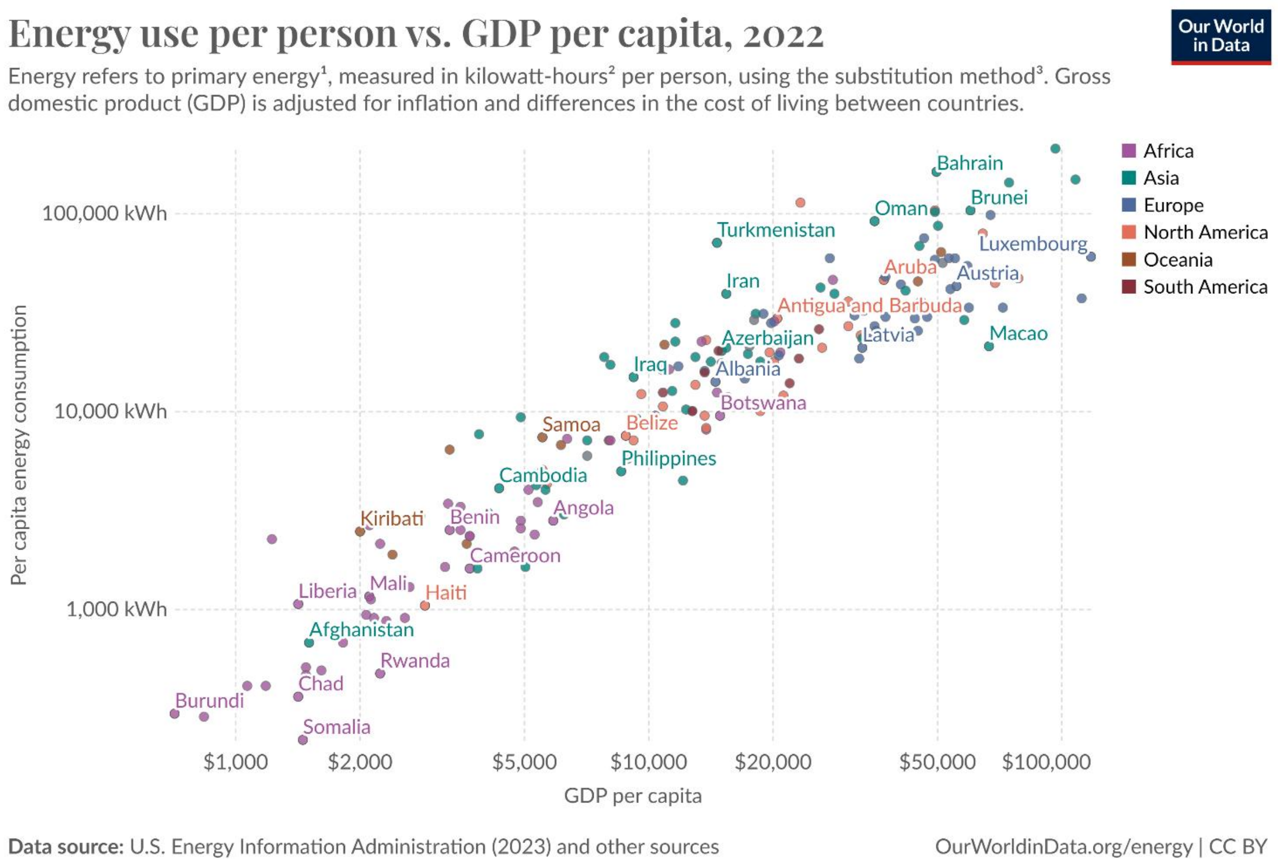
The plasma shape in a tokamak

- Separatrix: boundary of confined plasma
- Nested flux surfaces are labeled by poloidal magnetic flux Ψ
- Normalized poloidal flux $\Psi_N = \frac{\Psi - \Psi_0}{\Psi_s - \Psi_0}$, and $\rho_{\mathrm{pol}} = \sqrt{\Psi_{\mathrm{N}}}$
- SOL: unconfined region

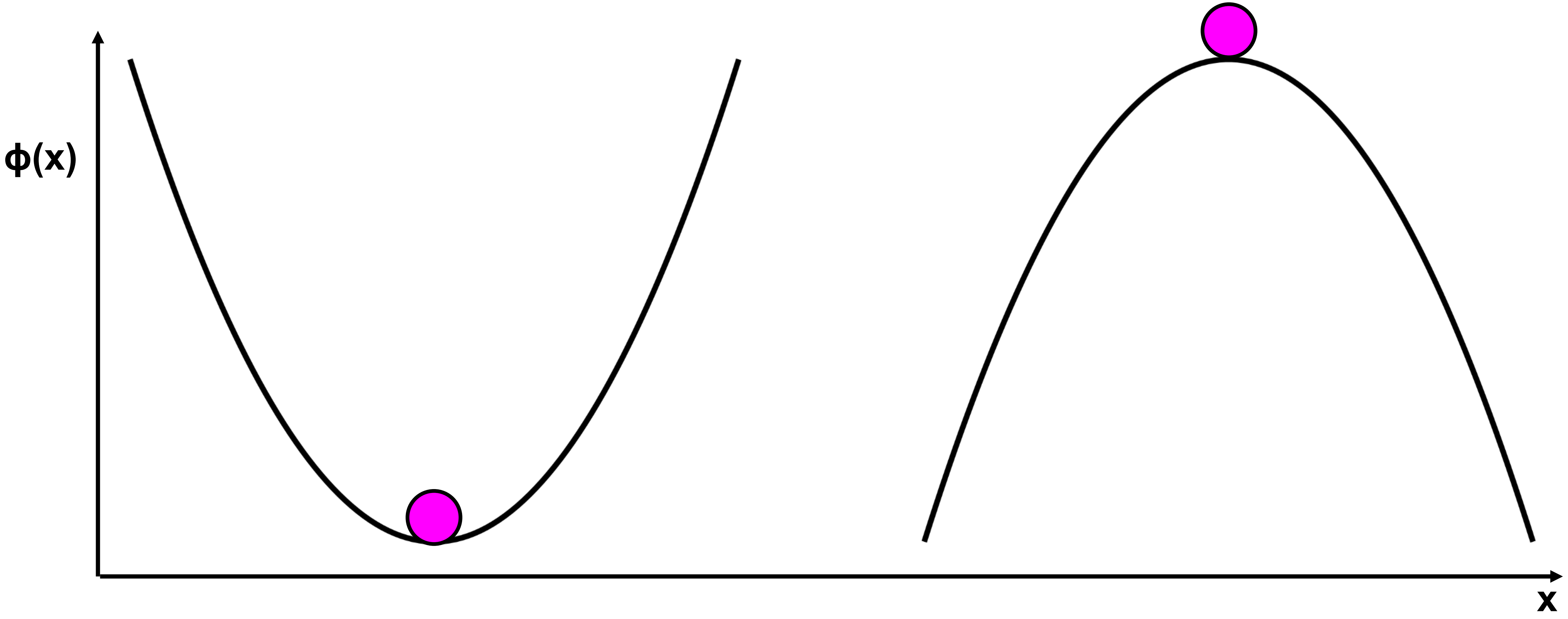


*D.J. Cruz-Zabala PhD thesis

Energy consumption is correlated with wealthiness

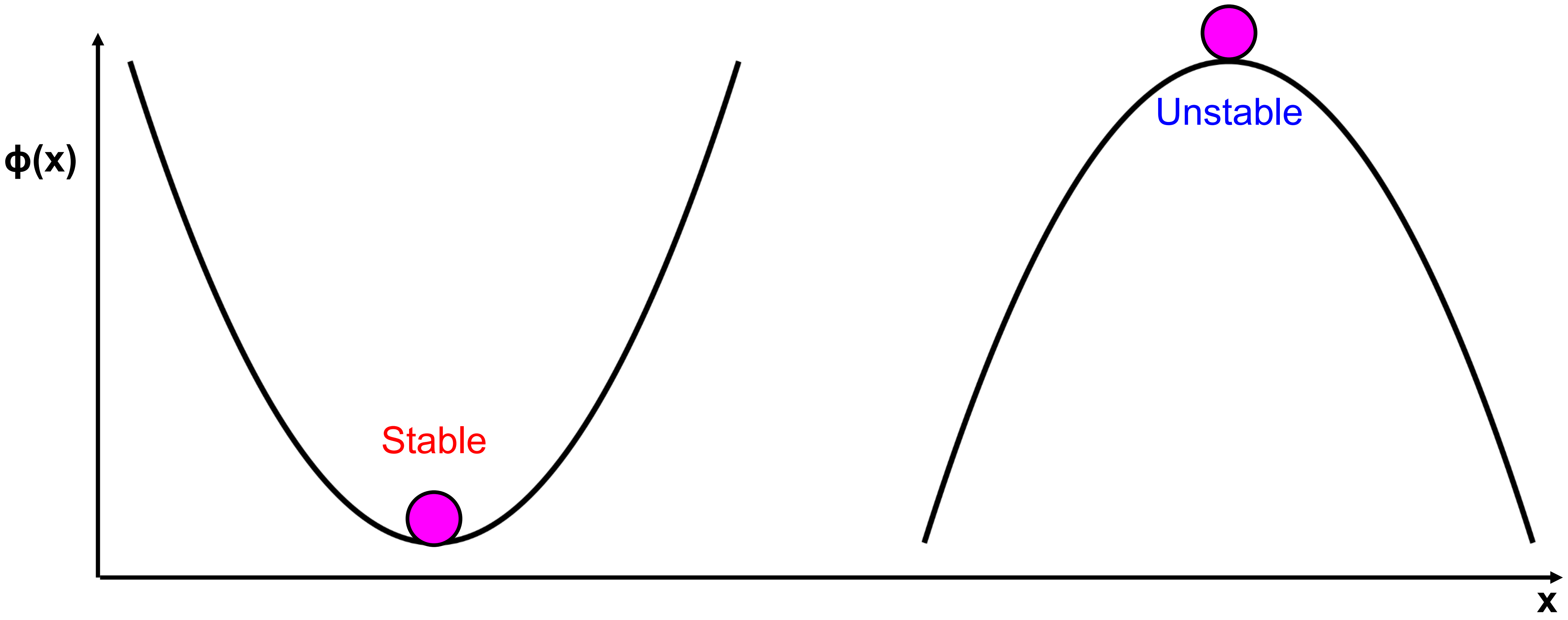


The stability analysis of a particle in classical mechanics



- In classical mechanics, particle stability depends on how the potential $\phi(x)$ is modified by a perturbation around equilibrium

The stability analysis of a particle in classical mechanics



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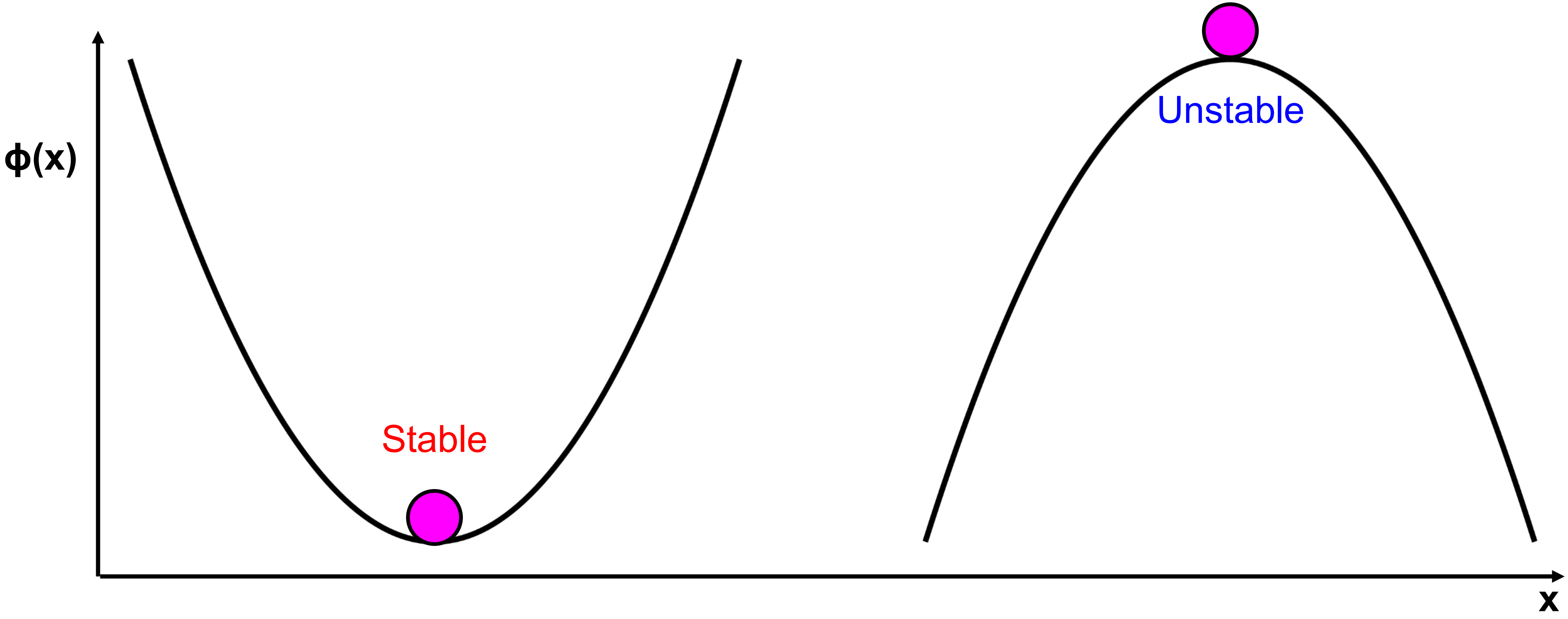
The stability analysis of a particle in classical mechanics

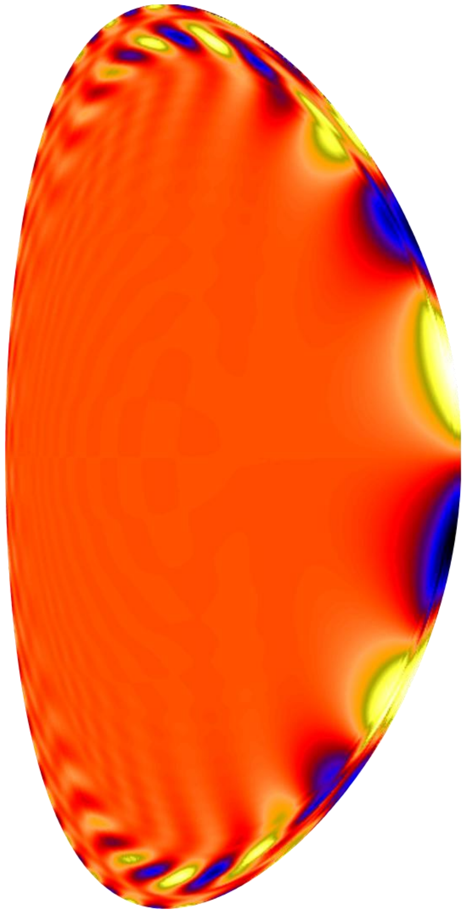


- In classical mechanics, particle stability depends on how the potential $\phi(x)$ is modified by a perturbation around equilibrium

- A similar analysis can be developed in MHD theory

Destabilizing mechanism of MHD instabilities

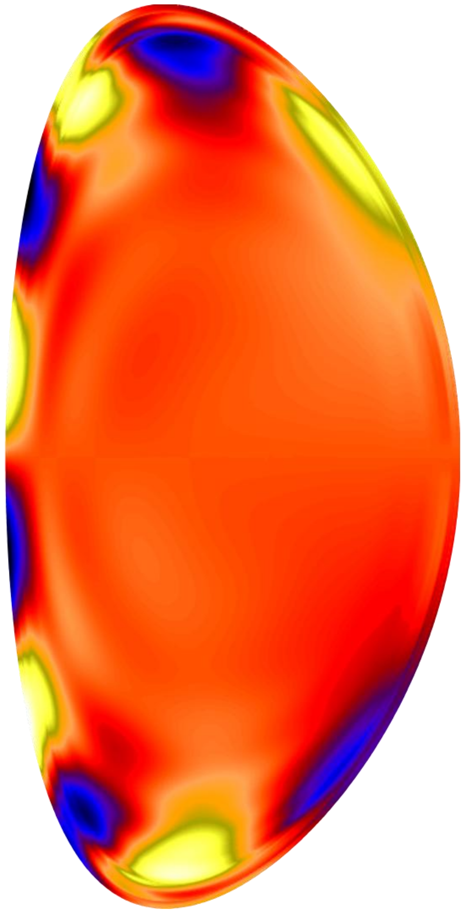
- Pressure-driven instabilities
  - ➢ Located in bad curvature region
  - ➢ E.g.: ballooning modes



Ballooning

Destabilizing mechanism of MHD instabilities

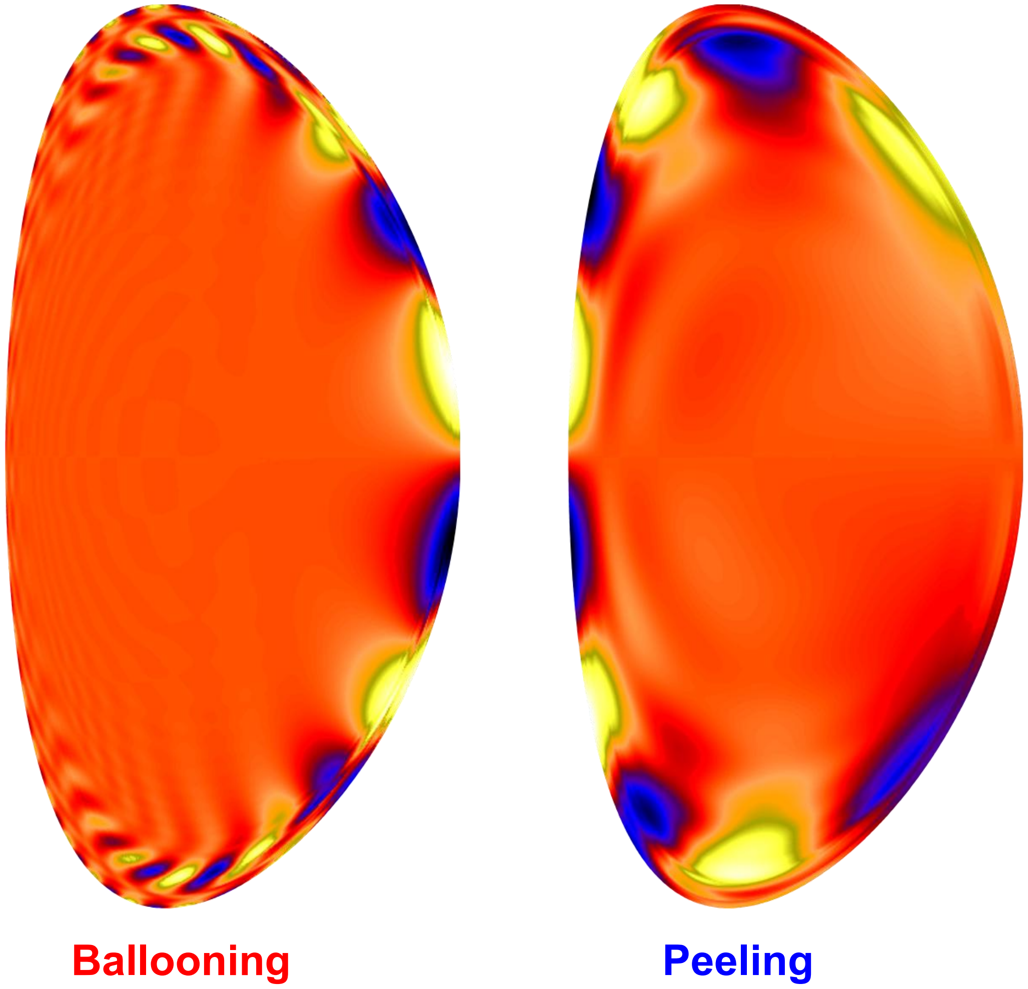
- Current-driven instabilities
  - E.g.: peeling-modes



Peeling

Destabilizing mechanism of MHD instabilities

- Pressure-driven instabilities
  - Located in bad curvature region
  - E.g.: ballooning modes
- Current-driven instabilities
  - E.g.: peeling-modes
- ELM onset is described as coupled peeling-ballooning modes[1]



[1] J.W. Connor *et al.*, Phys. Plasmas **5**, 2687 (1998)

The MEGA code

- Nonlinear hybrid kinetic-MHD code that calculates the self-consistent interaction between energetic particles and thermal plasma[1]

[1] Y. Todo *et al.*, Phys. Plasmas **5**, 1321 (1998)

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- Current coupling scheme in **MHD momentum equation**

$$\frac{\partial(\rho\vec{u})}{\partial t} = -\nabla\cdot(\rho\vec{u}\vec{u}) - \nabla p + (\vec{j} - \quad) \times \vec{B} - \nabla\times(\nu\rho\nabla\times\vec{u}) + \frac{4}{3}\nabla\times(\nu\rho\nabla\times\vec{u})$$

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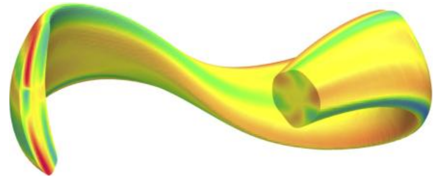
- Widely used in fusion community

CFQS

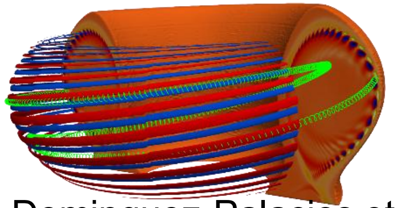


H. Wang et al., NF (2022)

Heliotron-J

P. Adulsiriswad et al., NF (2020)

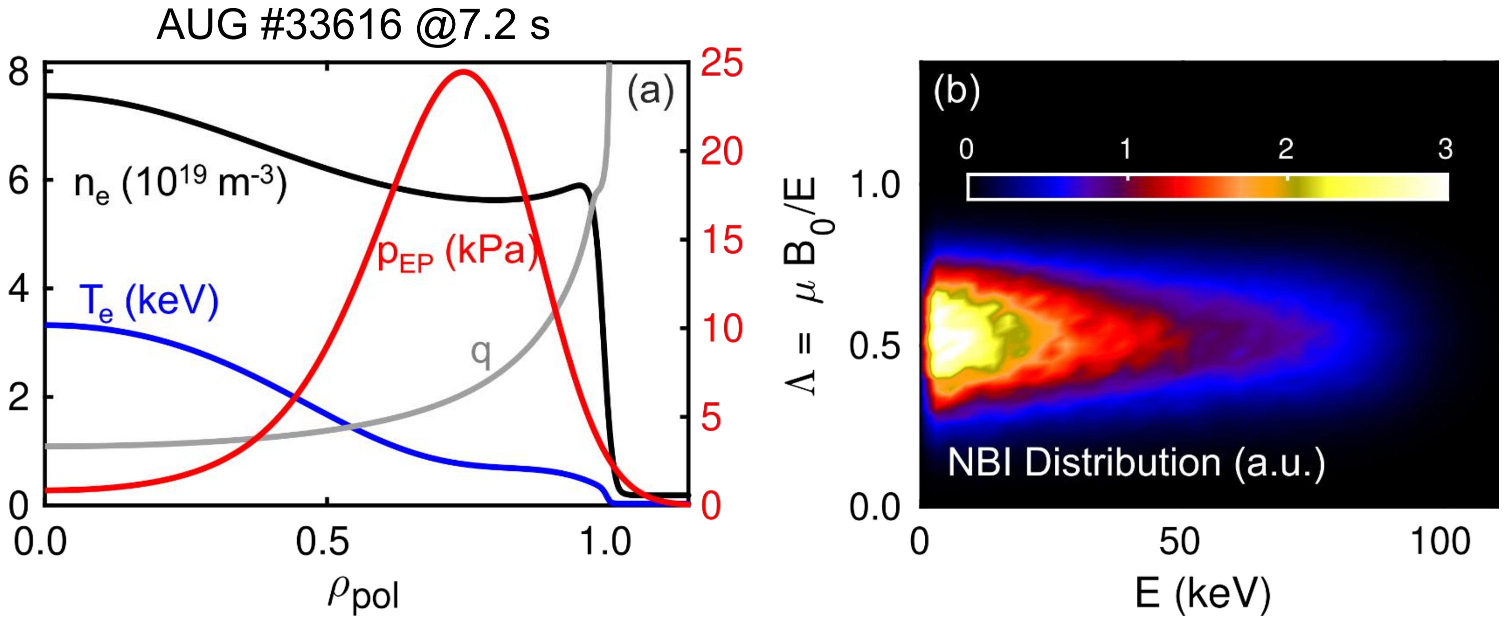
AUG



J. Dominguez-Palacios et al., Nat. Phys. (Submitted)

[1] Y. Todo *et al.*, Phys. Plasmas **5**, 1321 (1998)

Realistic initial conditions for bulk plasma and energetic particles



- Thermal plasma: measured kinetic profiles used as initial conditions[1] and standard MHD model[2]

- Fast-ions: on/off-axis slowing down NBI distribution

[1] A.F. Mink *et al.*, Nucl. Fusion **58**, 026011 (2018)
[2] Y. Todo *et al.*, Phys. Plasmas **24**, 081203 (2017)

Numerical methods of MEGA

- Time integration: 4th order explicit Runge-Kutta method
- Fluid fields

→ Spatial derivatives: 4th order finite difference method

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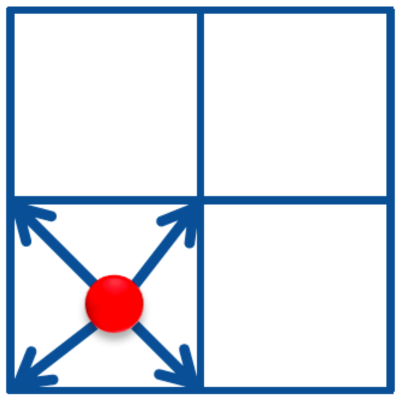

Information of particle distributions is assigned to grids

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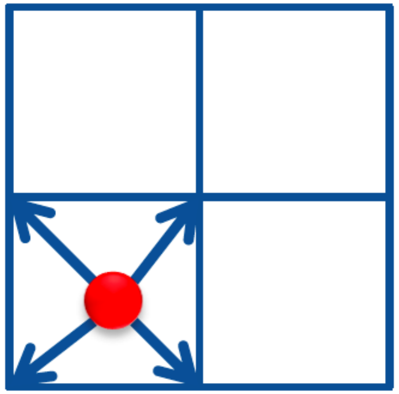

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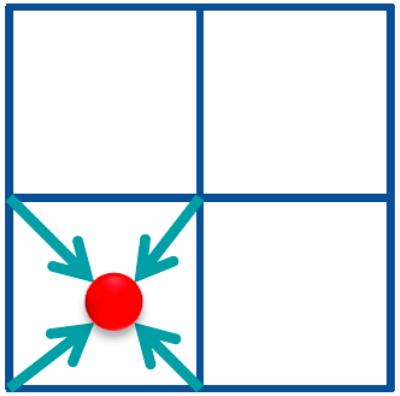

Forces on a particle are derived from the fields

Numerical methods of MEGA

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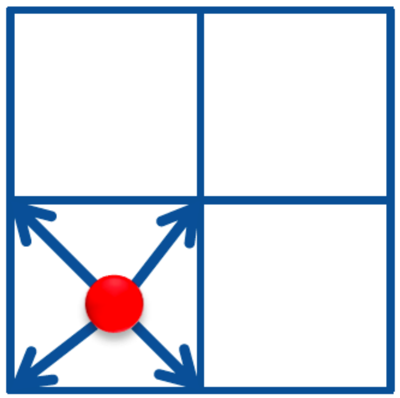
- Fluid fields

  → Spatial derivatives: 4th order finite difference method

- Particles

  → 1st order particle-in-cell (PIC) with δf or full-f method

  → FLR effects on particle orbits



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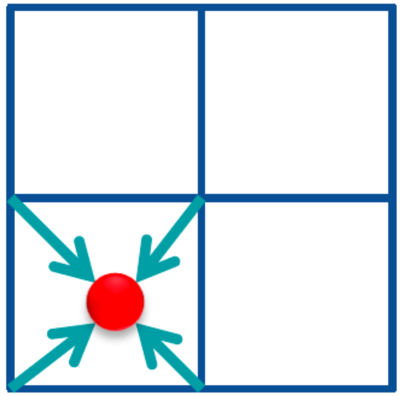


Forces on a particle are derived from the fields

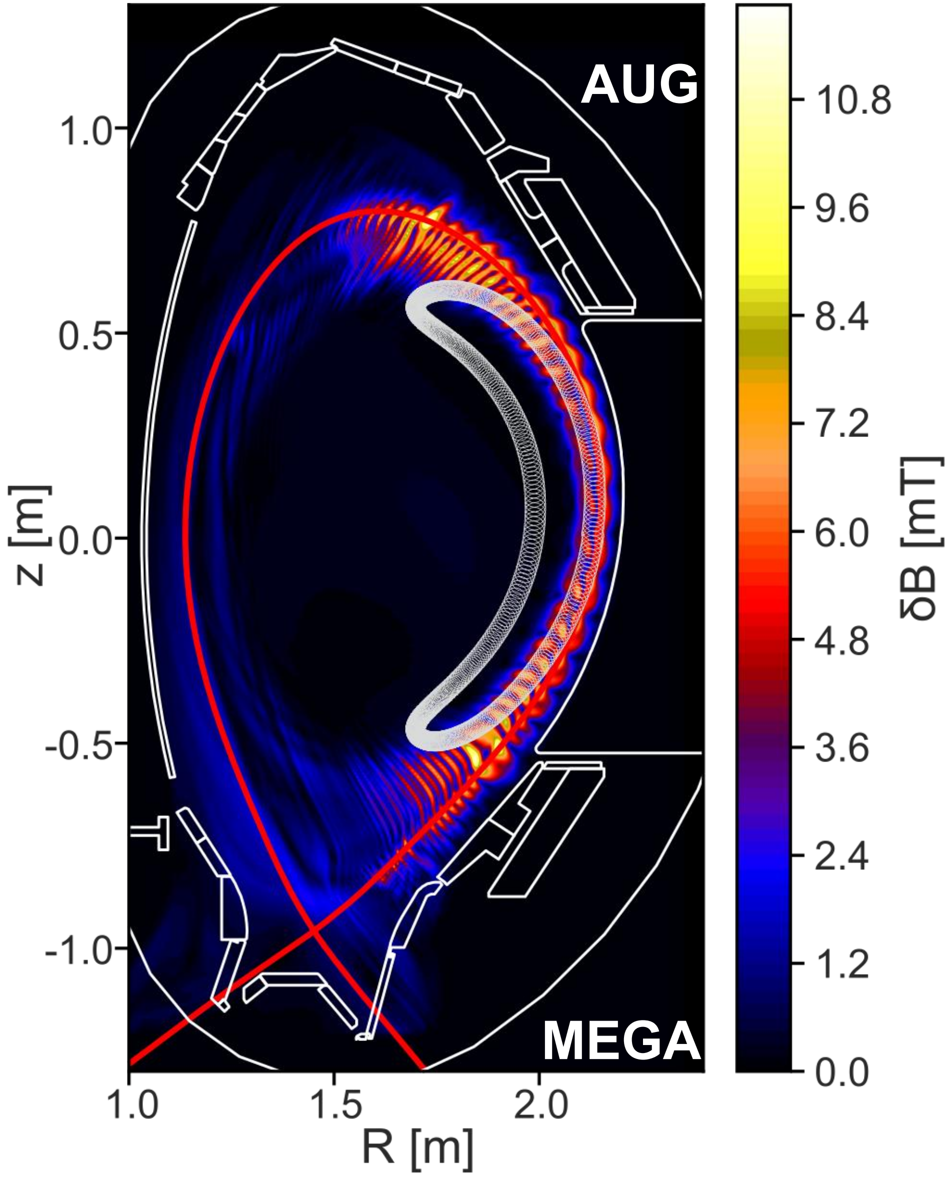
Simulation domain in MEGA

- SOL and Private Flux Region below X-Point included in simulation domain

  → ELM relevant area

  → Important to study the interaction with fast-ions

- 3D cartesian grids of cylindrical coordinates → inclusion of SOL and PFR depends only on magnetic field topology[1, 2]

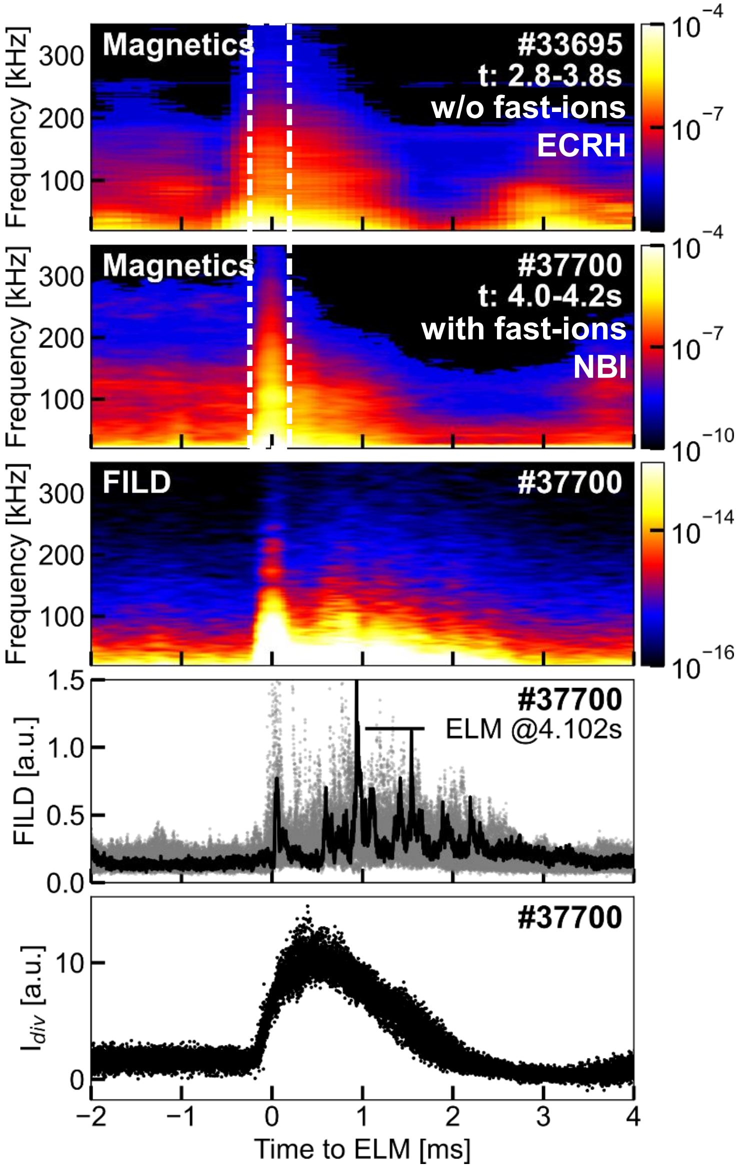


[1] R. Khan *et al.*, Phys. Plasmas **14**, 062302 (2007)
[2] N. Mizuguchi *et al.*, Nucl. Fusion **47**, 579 (2007)

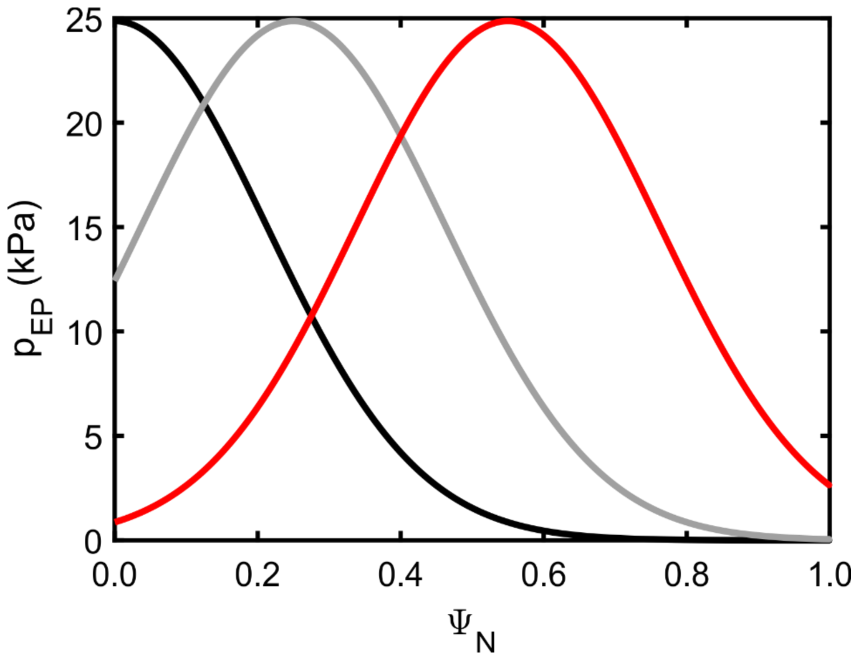
In experiments, ELM looks remarkably different with and w/o fast-ions

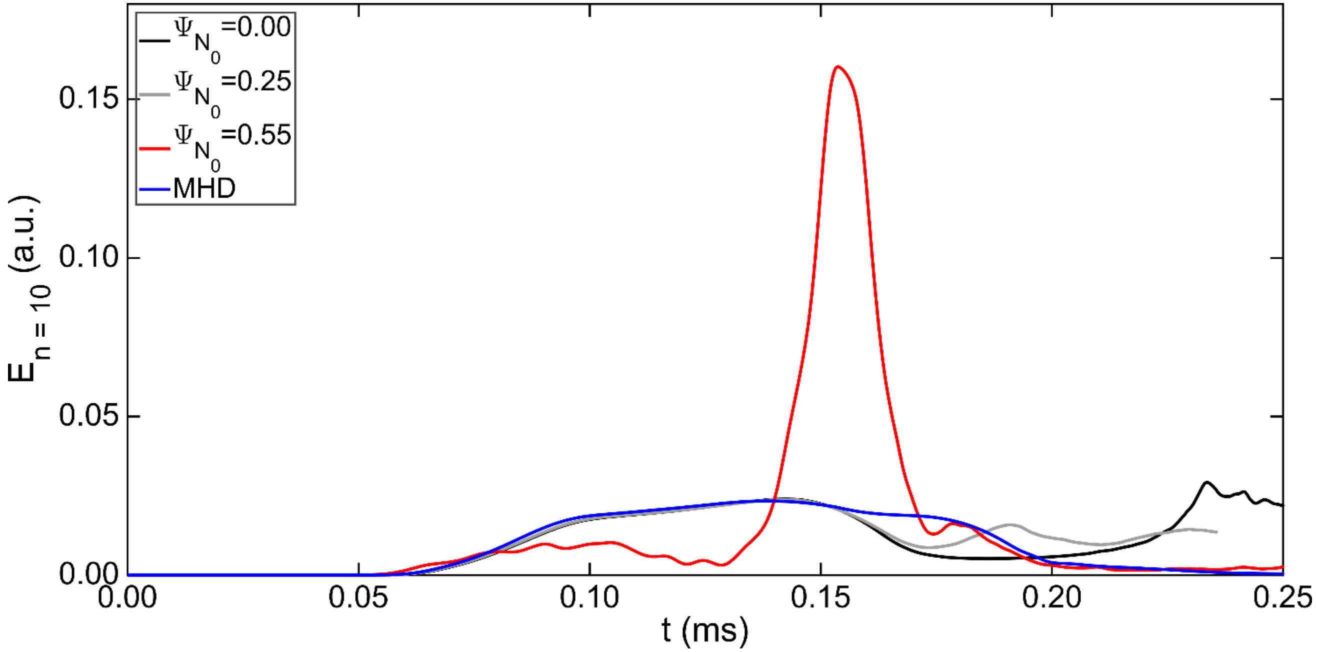
- **ELM synchronised magnetic spectrograms seem to depend strongly on fast-ion population**
  - ➢ **Large fast-ion content** in NBI heated discharges with low collisionality lead to abrupt crashes (<**100 μs**) that are extended to high frequencies (~**300 kHz**)
    - ➢ Amplitude of low-frequency oscillations (<200 kHz) decay in ~ 2 ms
  - ➢ In discharges with **no fast-ion** sources and high collisionality, ELM crashes seem to last longer and have lower amplitudes especially at high frequencies

- **In NBI heated discharges, FILD and magnetic spectrograms show striking similarities**



Impact of off-axis peak location on ELM



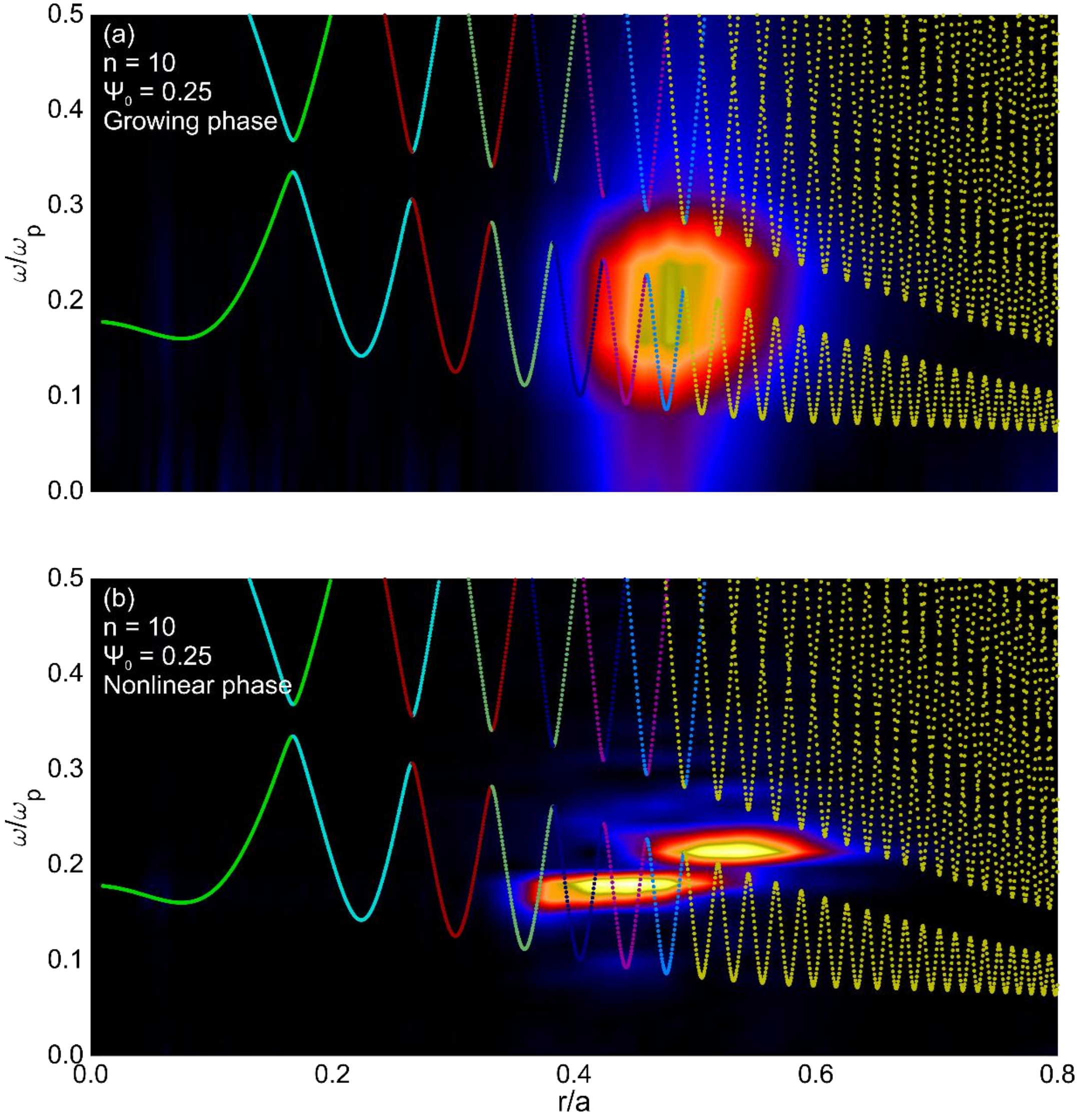


- Only when we have enough fast-ion population at the plasma edge, a significant impact on ELMs can be observed

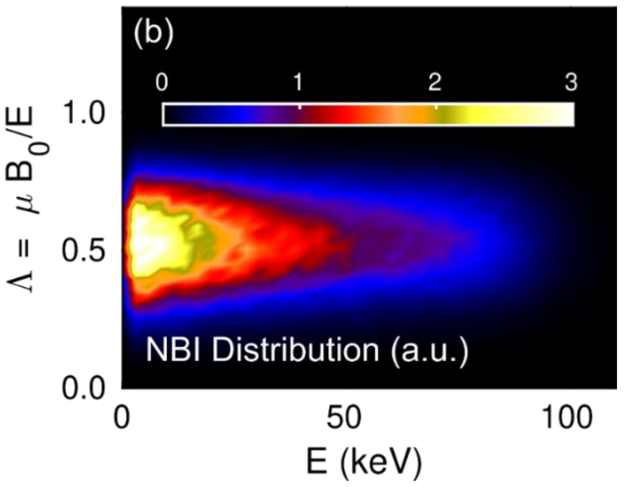
- For core-localized distribution, energetic particle driven mode appears after ELM

Identifiying core instability in simulations with core-localized distribution

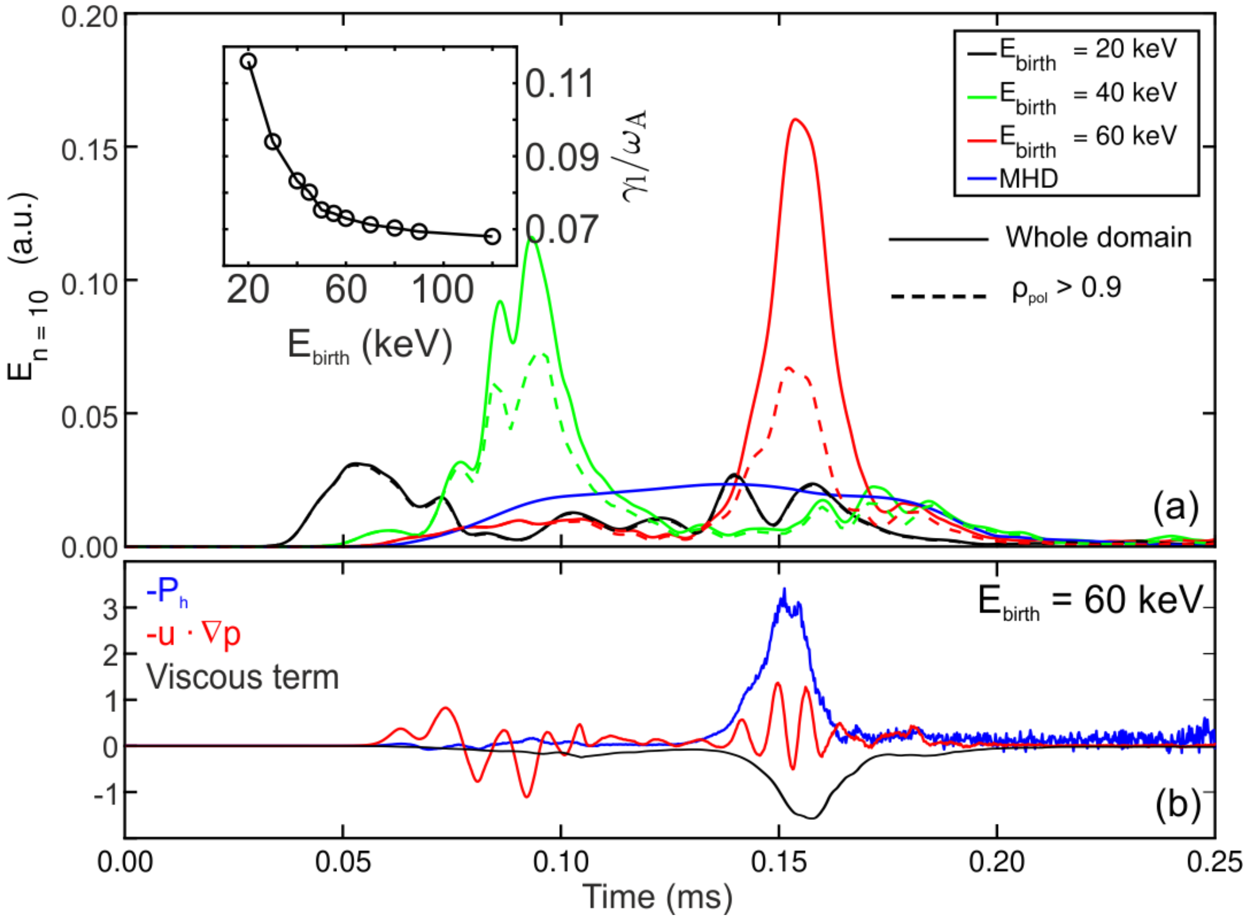
- The mode appearing after ELM is EPM
  - Does not fall in TAE gap
  - Discrete perturbation that crosses Alfvén continuum
- EPM saturates and perturbation extends radially inwards and outwards
- Motivates new study: **interplay between EP driven modes and ELMs**



Fast-ion birth energy impact on ELMs

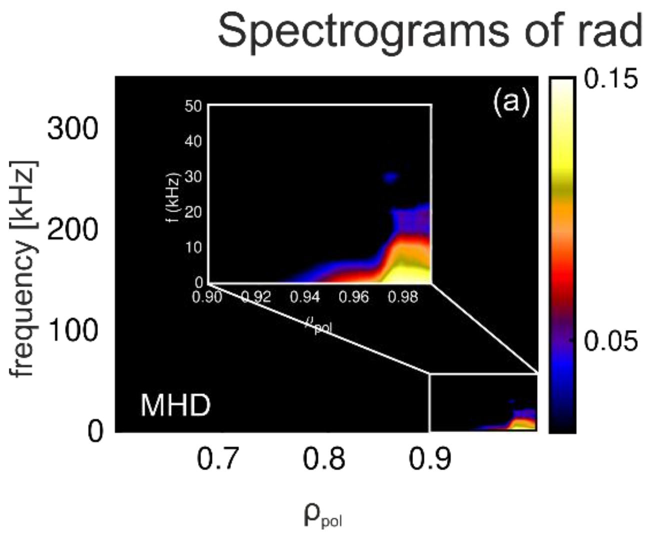


- γ decreases with E_{birth}
- ELM radial width is affected by fast-ion kinetic effects
- Hybrid simulations qualitatively reproduce abrupt crash (dominated by fast-ions) and pure MHD mild crash



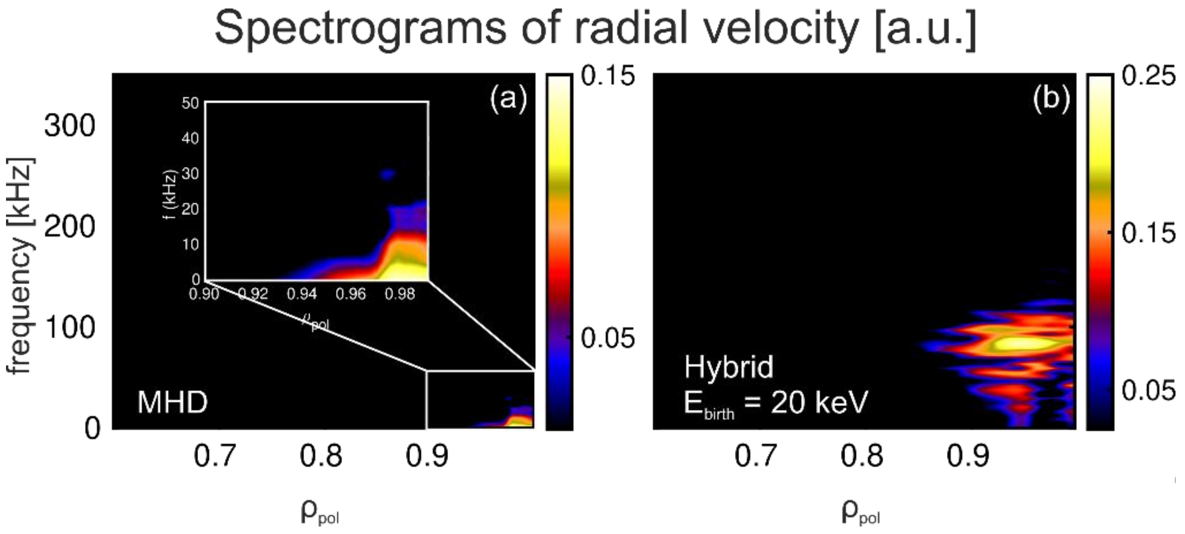
Spatial-frequency pattern of ELM in the presence of energetic particles

- In pure MHD simulation, $f < 20$ kHz



Spatial-frequency pattern of ELM in the presence of energetic particles

- In pure MHD simulation, $f < 20$ kHz
- In hybrid simulations, ELM crash frequency pattern depends on fast-ion energy with dominant $f > 100$ kHz



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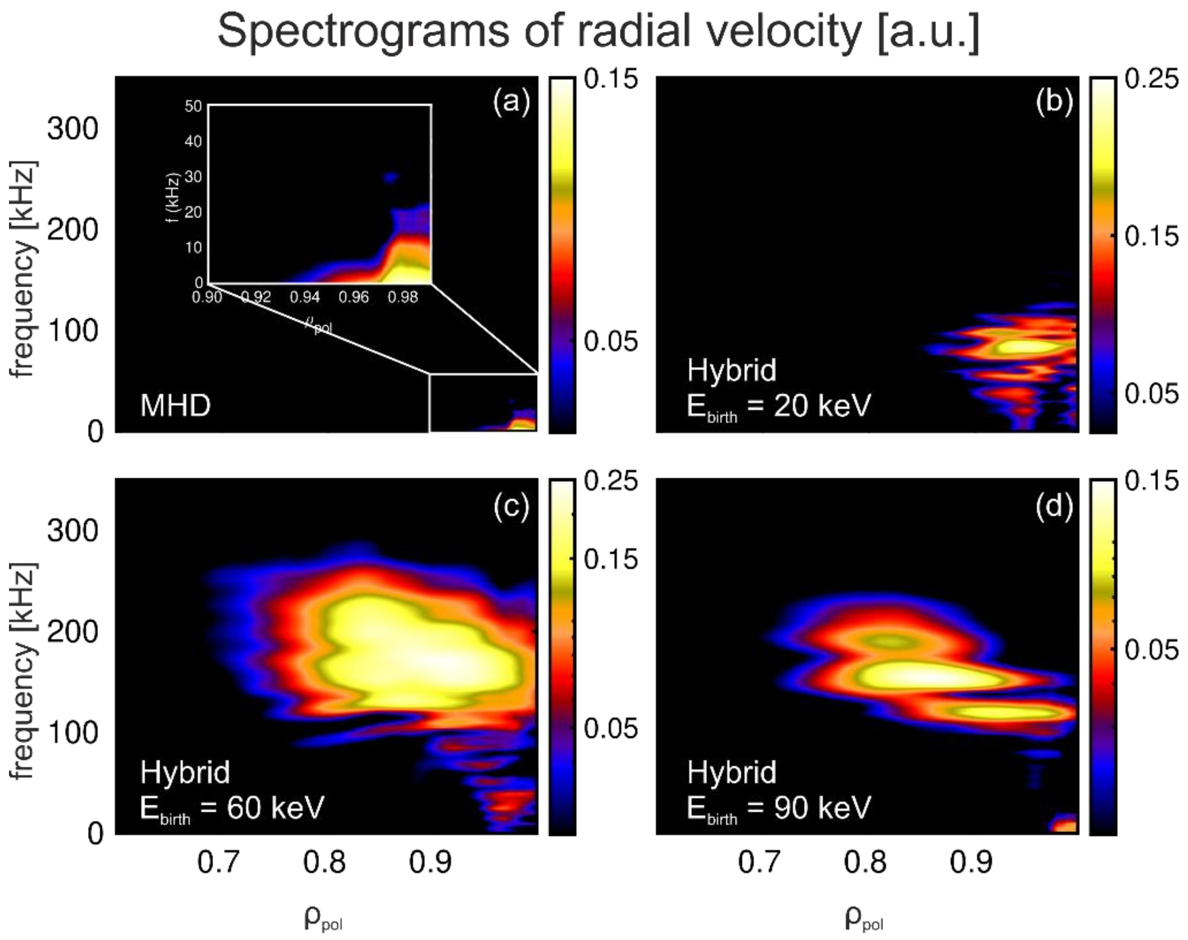
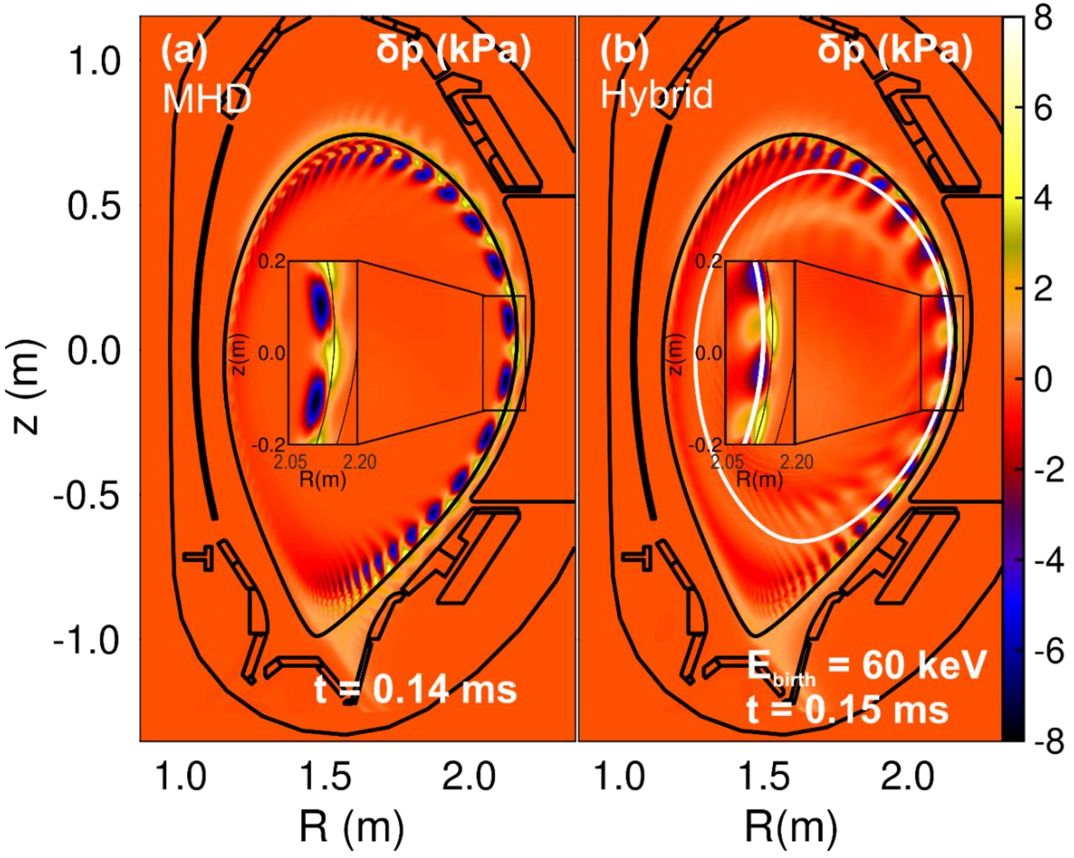
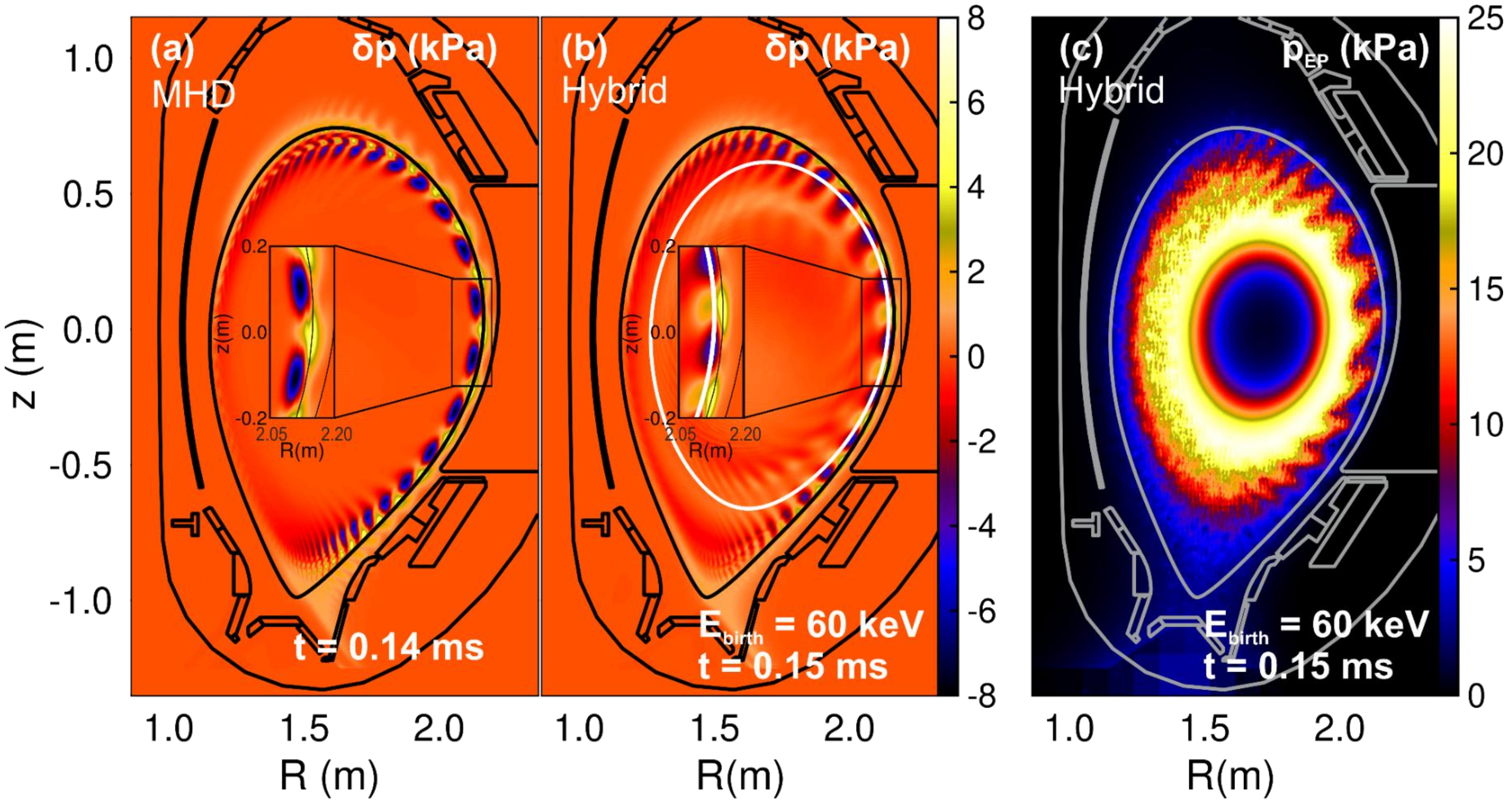


Fast-ion kinetic effects alter ballooning mode structure



- Fast-ion kinetic effects modify the shearing of the ballooning mode

ELMs cause significant fast-ion redistribution



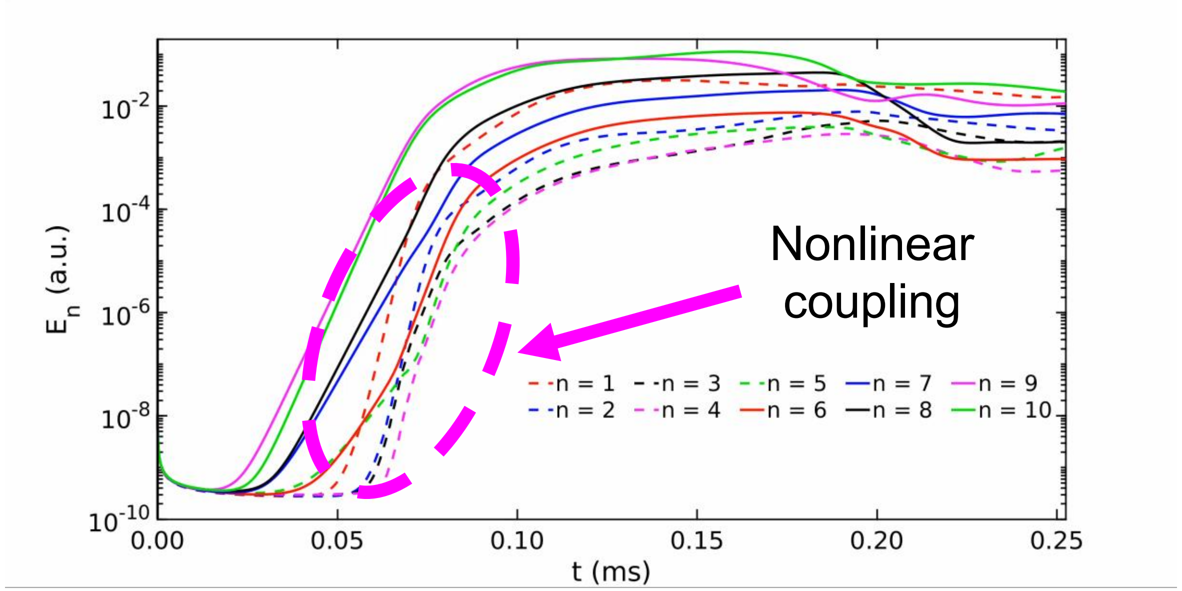
- Fast-ion kinetic effects modify the shearing of the ballooning mode
- ELMs cause fast-ion redistribution with ballooning, finger like structure with significant radial extension

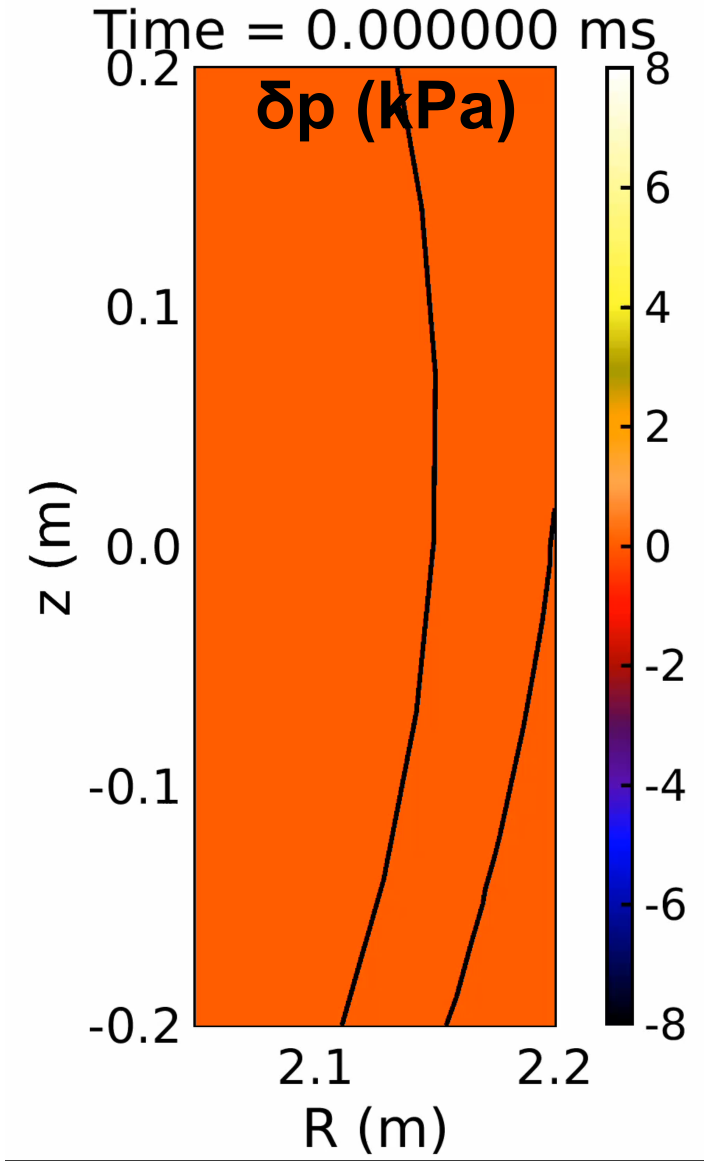
The energy release in fusion is huge!

	combustion energy (kcal/mol)	combustion energy (kcal/g)	combustion energy (kJ/g)
hydrogen (H_2)	68	34.0	142
methane (CH_4)	213	13.3	56
gasoline (C_8H_{18})	1303	11.5	48

- 2 tons of carbon produces ~ 10^3 kJ to power household's electrical appliances
- The energy release in D-T reaction is ~ 10^{11} kJ / g
- It is huge compared to typical combustion reactions!

How does an ELM look like in a MHD simulation?

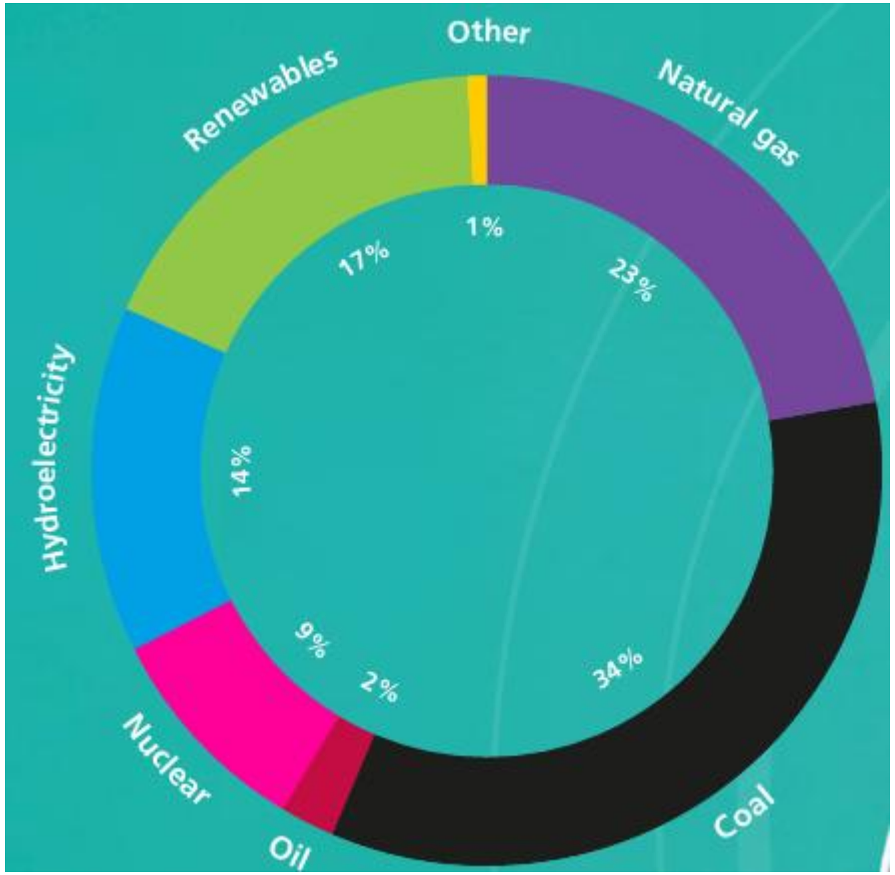




- Initial growth of high-n ballooning modes
- Nonlinear coupling between modes
- Saturation → particle release → pressure flattening

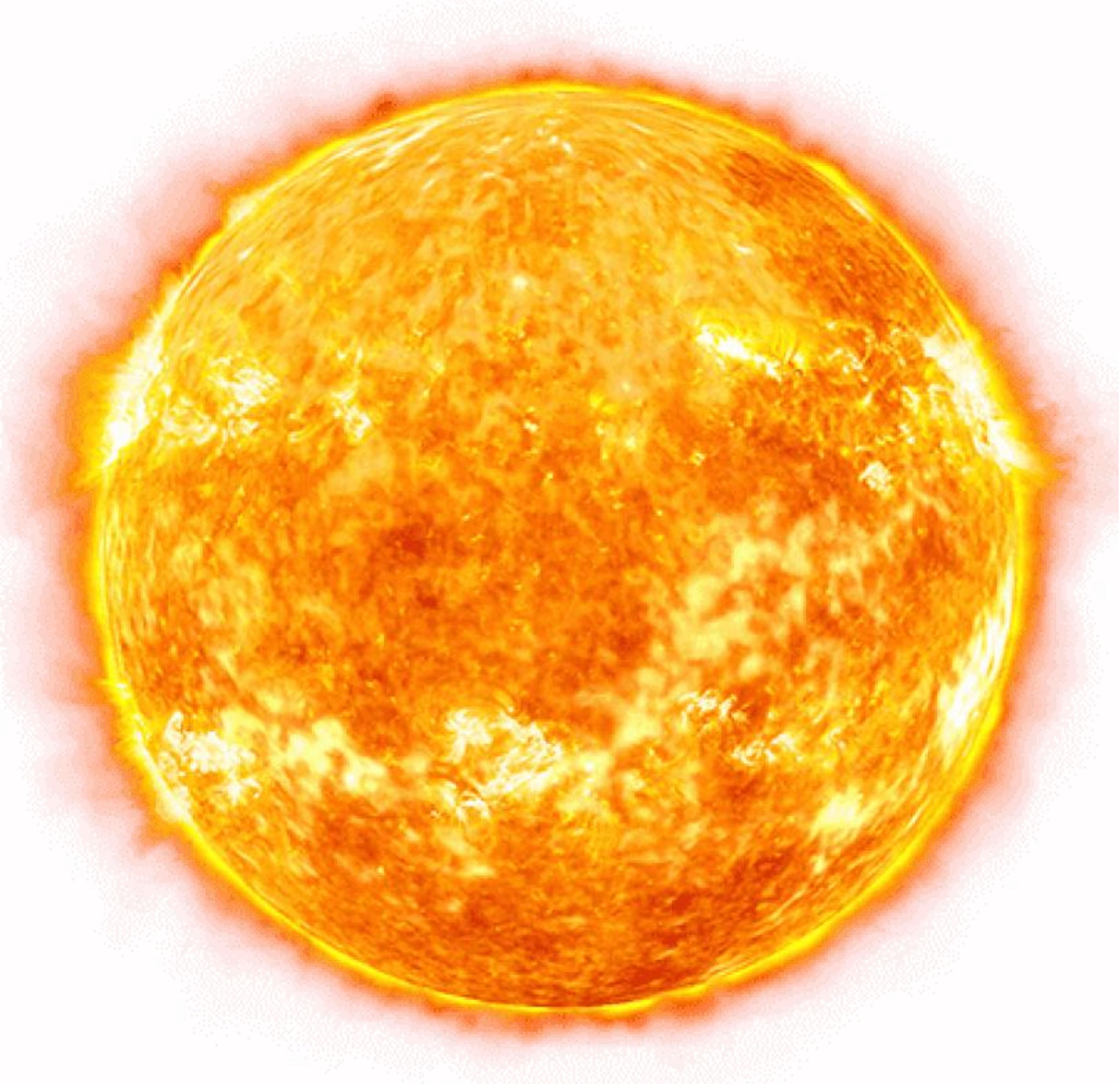
J.J. Domínguez-Palacios Durán *et al.*, Phys. Plasmas **33**, 052510 (2026)

The world energy demand relies mostly on fossil fuels



Statistical Review of World Energy 2025 by Energy Institute

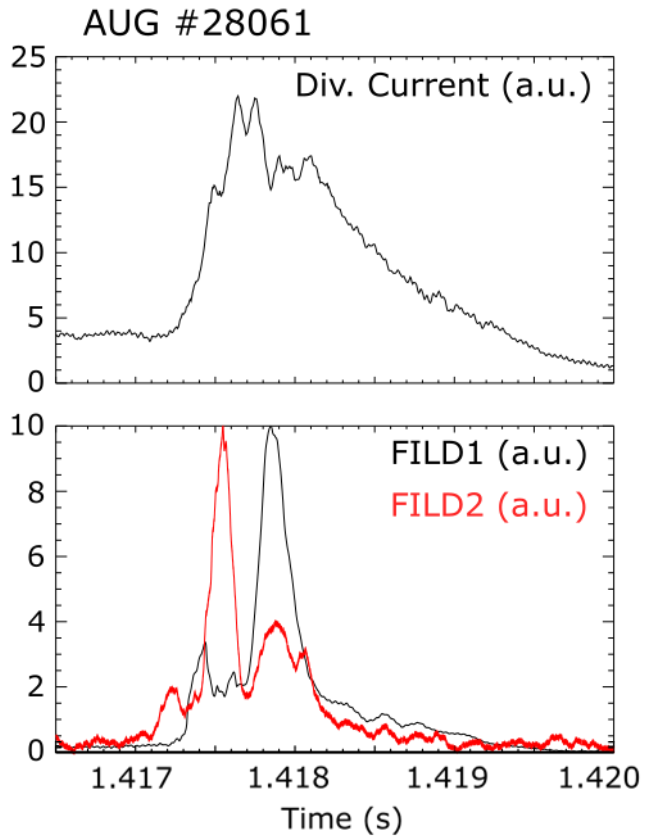
Nuclear fusion: the energy source of stars



Experimental observations suggest interaction between ELMs and fast-ions

- Fast-ion losses measured during ELM crashes

  - FILD1 and FILD 2 located at same θ and different φ, both measuring FI losses



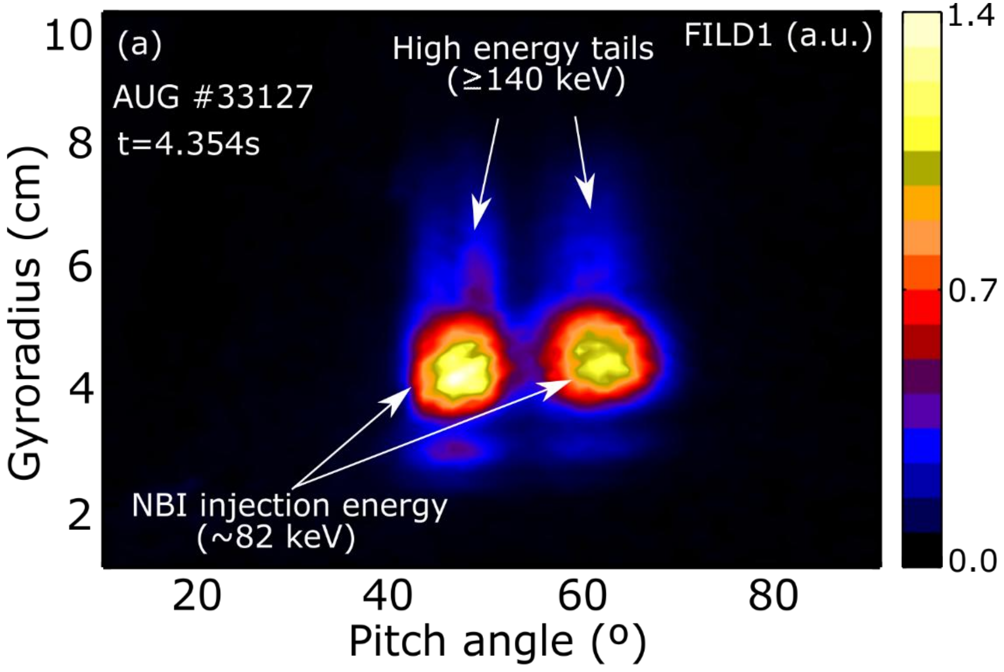
*J. Galdon-Quiroga *et al.*, 2018, Phys. Rev. Lett. **121**, 025002

Experimental observations suggest interaction between ELMs and fast-ions

- Fast-ion losses measured during ELM crashes

  - FILD1 and FILD 2 located at same θ and different φ, both measuring FI losses

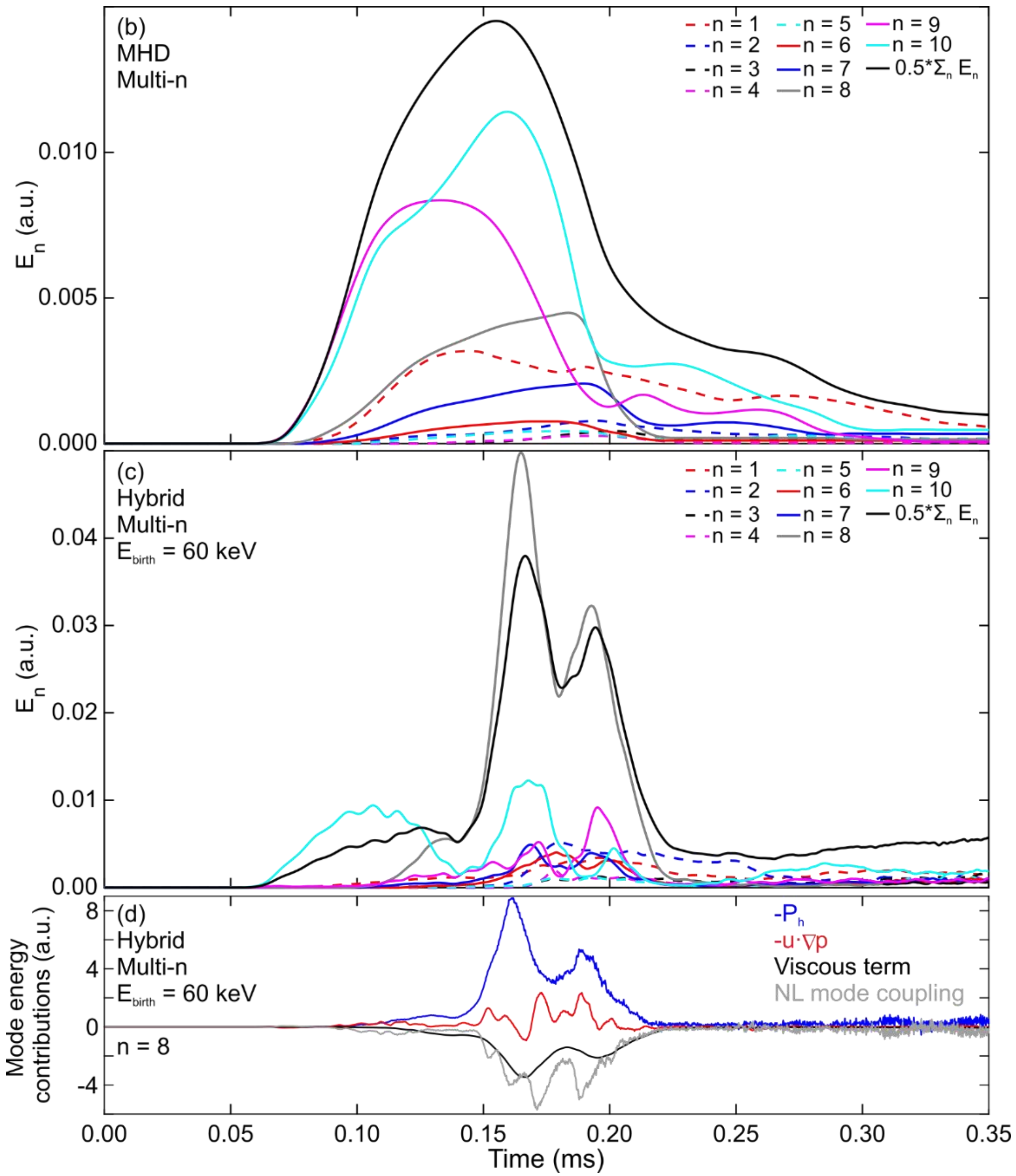
- Beam-ion acceleration during ELM crashes



*J. Galdon-Quiroga *et al.*, 2018, Phys. Rev. Lett. **121**, 025002

Fast-ions strongly affect modes energy evolution in multi-n simulations

- MHD multi-n: n = 9, 10 are most dominant modes
- Fast-ions modify the most dominant mode
  - ➢ n = 8 most unstable with EP kinetic effects
- Peak mode energy larger in hybrid single-n simulation compared to $\sum_n E_n$



J. Domínguez-Palacios *et al.*, Nat. Phys. **21**, 43 (2025)


EJEMPLOS DE ESTADO DE PLASMA
Rayo
Sol
Luces de Neón
Neon Lights
Aurora Boreal
Nebulosa
Arco de Soldadura