Multi-Time-Scale Energetic Particle Dynamics in JT-60U Simulated with MHD Activity, Sources and Collisions

A. Bierwage[1], K. Shinohara[1], Y. Todo[2], M. Yagi[1]

1: Japan Atomic Energy Agency, Japan

2: National Institute of Fusion Science, Japan

Discussions with K. Tani (NAT, Japan) are thankfully acknowledged.

This work is partially supported by JSPS Grants.

The simulations were carried out using the supercomputer system HELIOS at IFERC, Aomori, Japan, under the BA collaboration between Euratom and Japan, implemented by F4E and JAEA.

20th NEXT Workshop, Kyoto, Japan, January 13-14, 2015

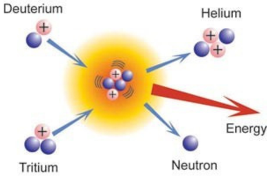
PREAMBLE:

Nuclear Fusion Research at JAEA

and

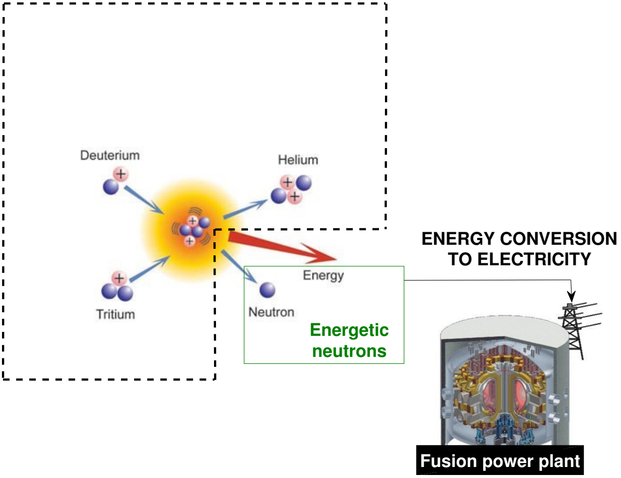
20 Years of Numerical EXperimental Tokamak (NEXT) Project

Fusion reaction most easily realized in lab: $T(d,n)^4He$



Figures: `iter.org` (reaction)

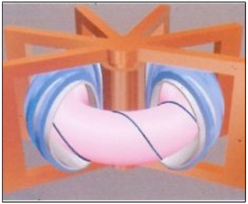
Final goal: Electric power plants driven by D-T fusion

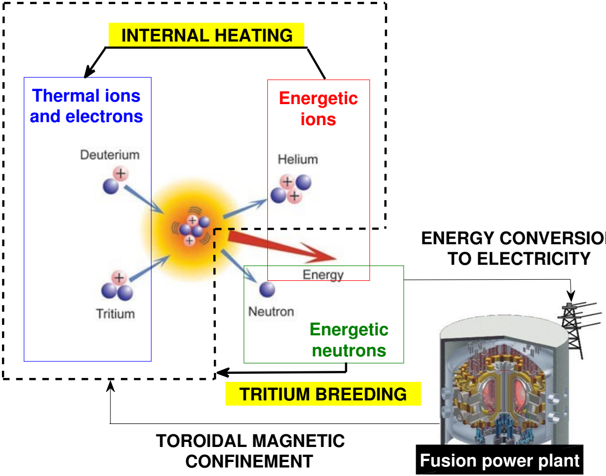


Figures: `iter.org` (reaction, power plant)

Mainstream: Self-sustained “burning” tokamak plasma

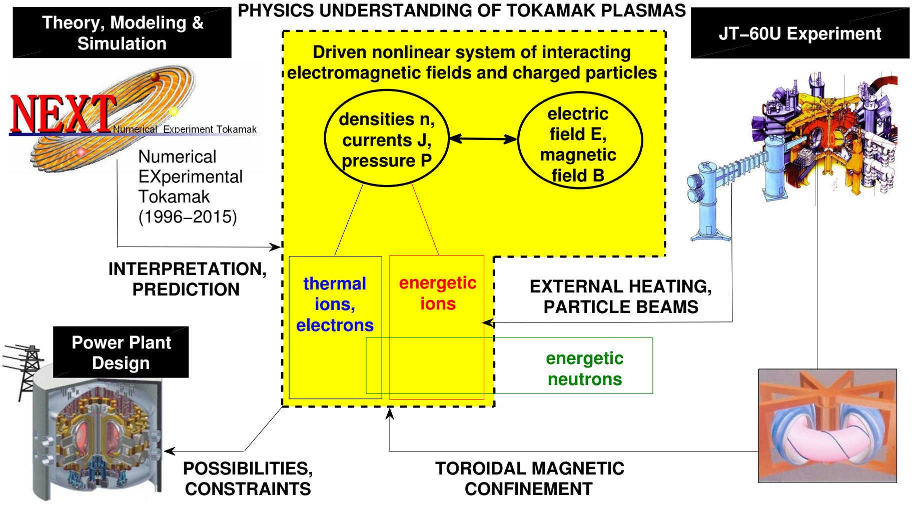
Tokamak:





Figures: `iter.org` (reaction, power plant)
“Harnessing the Power of Stars” J.Tachon, P.-J. Paris (tomamak)

Burning plasma physics research at JAEA



Figures: www-jt60.naka.jaea.go.jp (JT-60U)
"Harnessing the Power of Stars" J.Tachon, P.-J. Paris (tomamak)

Numerical EXperiment of Tokamak (NEXT) Project

Started in 1996 at JAEA, the main objectives of the NEXT project* are

1. to understand complex physical processes in present-days and next-generation tokamak plasmas,
2. to predict and evaluate the plasma performance of tokamak reactors, such as ITER (International Thermonuclear Experimental Reactor), and
3. to contribute to the progress in plasma physics and related research areas via numerical simulation.

Focus of this talk:

Advances in the study of interaction between MHD waves and fast ions.

(*) `http://www-jt60.naka.jaea.go.jp/english/theory/intro/index.html`

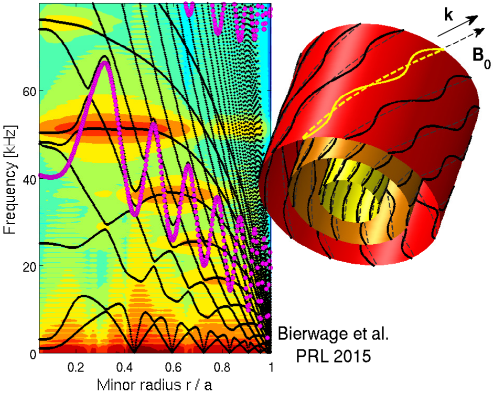
INTRODUCTION:

MHD Waves and Energetic Ions in Tokamak Plasmas

JT-60U plasma in reactor-relevant parameter regime

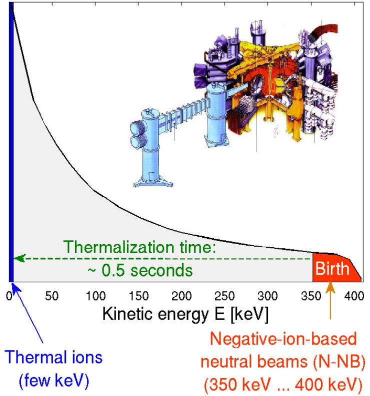
- **High plasma beta:**
  $\beta = \frac{2\mu P}{B^2} = \frac{\text{thermal pressure}}{\text{magnetic pressure}} \approx 3.5\%$ (power plant: $\beta \sim 5\%$)
- **Fast ions generated by powerful energetic particle beams:**
  up to 400 keV, 5 MW, $\beta_{\text{fast}} \sim \beta_{\text{total}}/2$ (power plant: 3.5 MeV ^{4}He)

Shear Alfven waves and slow magnetosonic waves in high-beta JT-60U plasma

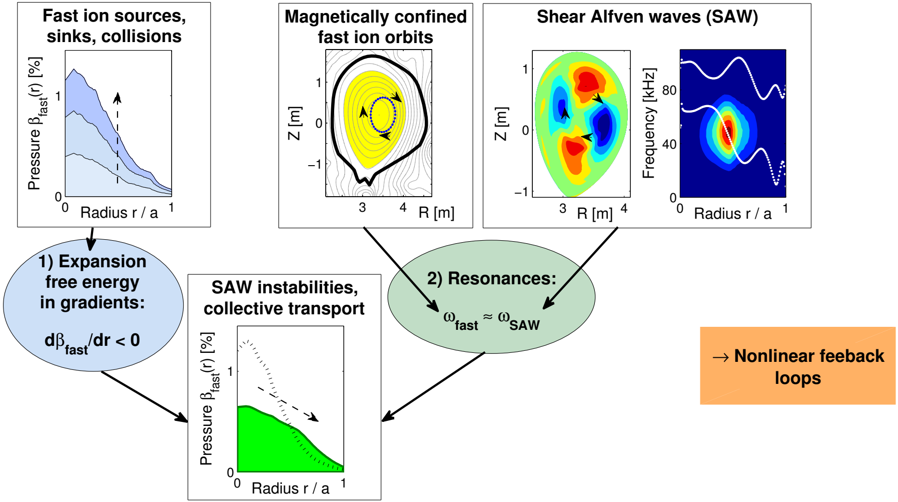


Bierwage et al. PRL 2015

Ion energy distribution in N-NB-driven JT-60U plasma



Physical effects governing fast ion dynamics in core plasma



⇒ Challenges: multiple time scales and complicated nonlin. interactions

Current research activities

- Study dynamics of fast-ion-driven modes.
- Analysis of linear and nonlinear resonant wave-particle interactions.
- Fast ion transport and bulk heating.
- Comparison between simulations and experiments (V&V).

Current research activities discussed in this talk

- Study dynamics of fast-ion-driven modes.
- Analysis of linear and nonlinear resonant wave-particle interactions.
- Fast ion transport and bulk heating.
- Comparison between simulations and experiments (V&V).

"Multi-Time-Scale ~~Energetic Particle Dynamics~~
Dynamics of Energetic Particle Modes
in JT-60U Simulated with MHD Activity,
Sources and Collisions"

Outline

"Multi-Time-Scale Dynamics of Energetic Particle Modes in JT-60U"

1. Simulation model and methods:
   Advances towards predictive simulations
   for energetic particle dynamics

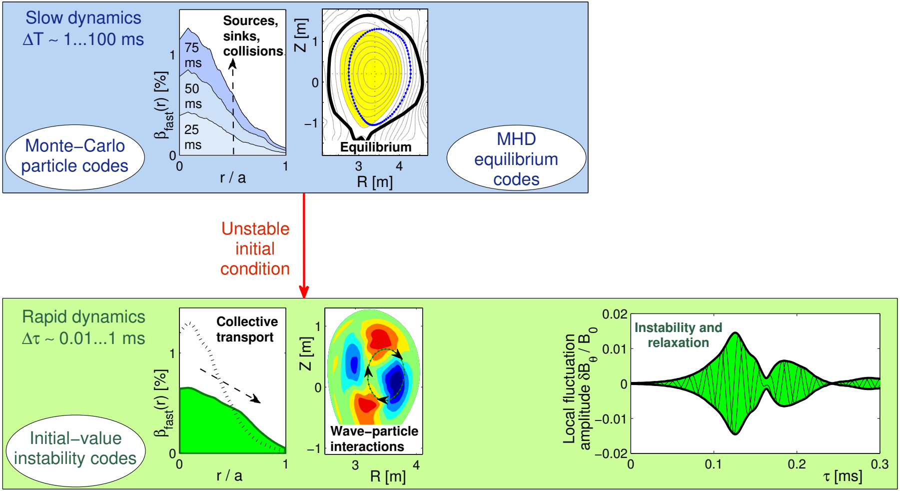
2. Meso- and long time scale (0.5 ms - 40 ms):
   Reproduced chirping bursts of JT-60U exp.

3. Short and meso-time scale (10 μs - few ms):
   Predicted+confirmed pulsations and phase jumps

4. Summary, conclusion, outlook

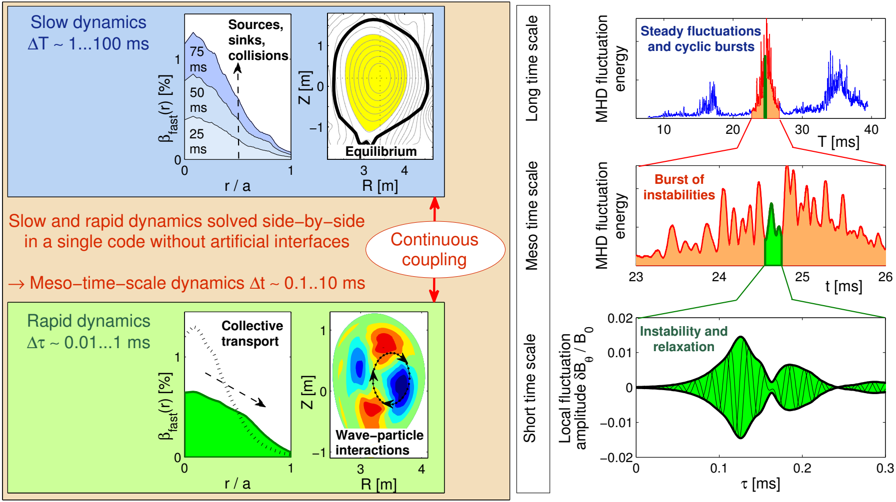
A. Computational parameters, resources, efficiency.
   Fast ion redistribution due to MHD activity.

Conventional approach: Separation of temporal scales



- **Pros:** Clear separation of physical effects. Trends revealed by varying free parameters. [e.g., Bierwage *et al.*, *Nucl. Fusion* **54** (2014) 104001]
- **Cons:** Overestimation of fast ion confinement in MC codes. Overestimation of fluctuation level and transport in instability codes.

Advanced method: Self-consistent long-time simulation



- **Pros:** Meso-*t*-scale dynamics covered. Bridge between models and experiments.
- **Cons:** Complicated. Computationally expensive.

[2014 IAEA FEC: Todo TH/7-1, Bierwage TH/P7-39]

Hybrid model for MHD and fast ion dynamics in MEGA

- Bulk plasma modeled as 3-D MHD fluid: full MHD model, (R, φ, Z) finite difference grid, 4th-order Runge-Kutta solver

$$\begin{aligned}
\rho_{\rm m}\partial_t \mathbf{V} =& -\rho_{\rm m}\left[\boldsymbol{\Omega}\times\mathbf{V} + \tfrac{1}{2}\boldsymbol{\nabla}V^2\right] + (\mathbf{J} - \mathbf{J}_{\rm fast}^{\rm eff})\times\mathbf{B} - \boldsymbol{\nabla}P \qquad (1)\\
&- \rho_{\rm m}\left[\nu\boldsymbol{\nabla}\times\boldsymbol{\Omega} - \tfrac{4}{3}\nu\boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\mathbf{V})\right],\\
\partial_t\mathbf{B} =& -\boldsymbol{\nabla}\times\mathbf{E}, \qquad (2)\\
\partial_t\rho_{\rm m} =& -\boldsymbol{\nabla}\cdot(\rho_{\rm m}\mathbf{V}), \qquad (3)\\
\partial_t P =& -\boldsymbol{\nabla}\cdot(P\mathbf{V}) - (\Gamma-1)P\nabla\cdot\mathbf{V} \qquad (4)\\
&+ (\Gamma-1)\left\{\eta J^2 + \nu\rho_{\rm m}[\Omega^2 + \tfrac{4}{3}(\boldsymbol{\nabla}\cdot\mathbf{V})^2]\right\};
\end{aligned}$$

with $\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{J}$, $\mu_0\mathbf{J} = \boldsymbol{\nabla}\times\mathbf{B}$, $\boldsymbol{\Omega} = \boldsymbol{\nabla}\times\mathbf{v}$ and no-slip boundary.

- Fast ions modeled as guiding centers: PIC method, $\mathrm{d}\mu/\mathrm{d}t = 0$

$$\mathrm{d}_t\mathbf{R}_{\rm gc} = \mathbf{v}_\parallel^* + \mathbf{v}_{\rm E} + \mathbf{v}_B, \qquad m v_\parallel \mathrm{d}_t v_\parallel = \mathbf{v}_\parallel^*\cdot[e_{\rm H}\mathbf{E} - \mu\boldsymbol{\nabla}B] \qquad (5)$$

with $\mathbf{v}_\parallel^* = v_\parallel[\mathbf{B} + \rho_\parallel B\boldsymbol{\nabla}\times\mathbf{b}]/B^*$, $\rho_\parallel = v_\parallel/\Omega_{\rm L}$, $B^* = B(1 + \rho_\parallel\mathbf{b}\cdot\boldsymbol{\nabla}\times\mathbf{b})$.

Loss boundary condition at wall. FLR simulated via satellite particles.

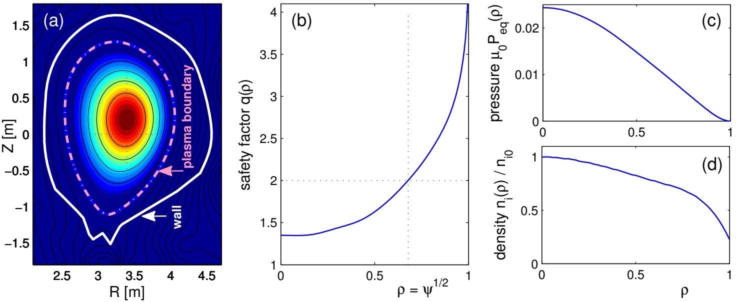
Trubnikov collision operators (slowing down, scattering, diffusion).

MEGA: Todo *et al*, *Phys. Plasmas* **12** (2005) 012503, *Phys. Plasmas* **13** (2006) 082503

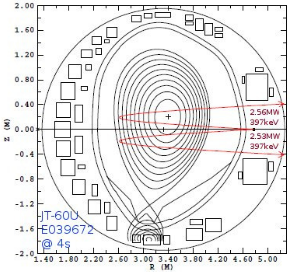
Simulation setup: JT-60U shot E039672 @ $t = 4$s

JT–60U, shot E039672, 4.0s

R_0 = 3.395 m
B_0 = 1.1661 T
a_{lfs} = 0.670 m
ρ_A/a_{lfs} = 0.117
f_{A0} = 202.7 kHz
n_{i0} = 1.731×10^{19} m^{-3}
I_p = 0.584 MA
Ψ_0 = –0.250 Tm^2
β_J = 0.965
β_0 = 0.0358



- **MHD equilibrium and profiles:**
  - $\mathbf{B}(R,Z)$, $P(R,Z)$ reconstructed numerically
  - enforce $\nabla P_{\rm eq} = \mathbf{J}_{\rm eq} \times \mathbf{B}_{\rm eq}$, fit $n_{\rm i}^{\rm exp}$
- **Coupling between MHD and fast ions:**
  - include only $n = 1$ harmonic
    (wavelength = torus circumference)
    to focus on $n = 1$ modes observed in exp.
- **Fast ion source:**
  - deposition profile computed for pair of tangential N-NBs



Outline

"Multi-Time-Scale Dynamics of Energetic Particle Modes in JT-60U"

1. Simulation model and methods:
   Advances towards predictive simulations
   for energetic particle dynamics

2. Meso- and long time scale (0.5 ms - 40 ms):
   Reproduced chirping bursts of JT-60U exp.

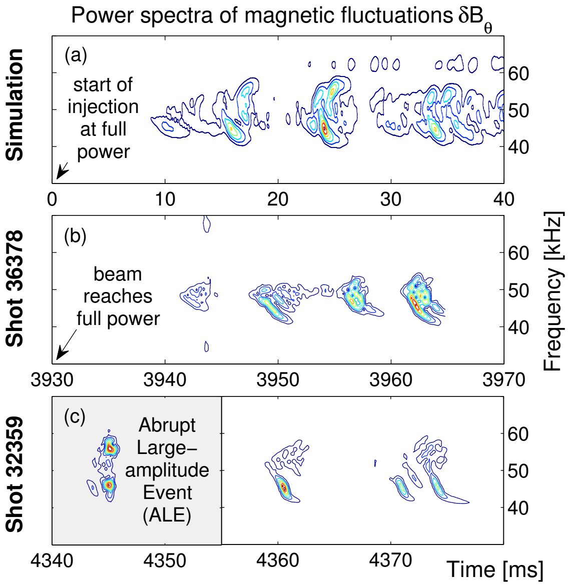
3. Short and meso-time scale (10 μs - few ms):
   Predicted+confirmed pulsations and phase jumps

4. Summary, conclusion, outlook

A. Computational parameters, resources, efficiency.
   Fast ion redistribution due to MHD activity.

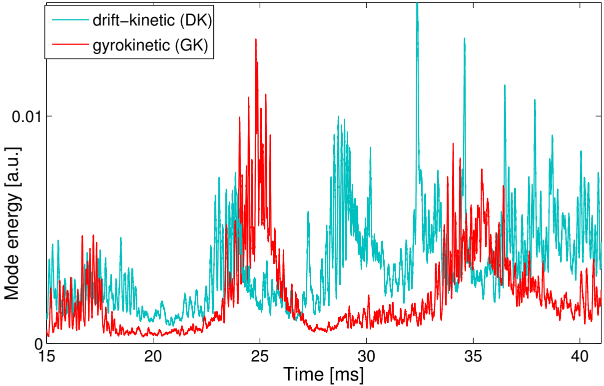
MHD dynamics on 0.5 ms - 40 ms scale

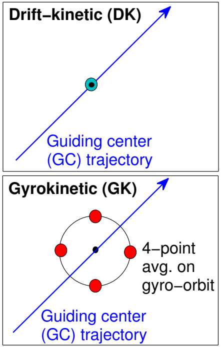
V&V: Reproduced chirping bursts of JT-60U



- Robust features:
  - down-/up-chirping in 40-60 kHz band,
  - few ms life time,
  - periods of 5-15 ms.
- Agreement shows that:
  - essential mechanisms of fast ion dynamics and plasma response are modelled correctly,
  - sim. results are relevant for rapidly chirping bursts.
- Note:
  - sim. measures signals at the mode location
  - exp. measurements are done outside of the plasma

FLR effect (gyroaveraging) proved to be essential for reproducing intermittency of bursts



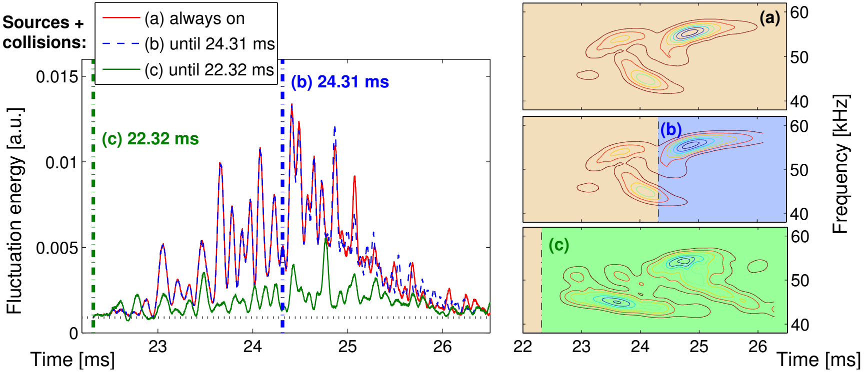


- FLR effect in the form of gyroaveraging (often ignored previously) reduces wave-particle coupling strength and leads to
  - Longer quiet periods between bursts.
  - Lower fluctuation levels during quiet periods.

⇒ New mechanism (besides damping) that controls intermittency!

[For damping effect, see Todo *et al.*, *Nucl. Fusion* **52** (2012) 033003]

Effect of sources and collisions (S&C) on bursts



- Results of turning S&C off at (b) peak or (c) start of a burst:
  - (b): Decay phase and chirping indep. of S&C.
  - (c): S&C is essential for rise of base level of fluctuation energy, but even without S&C burst and chirps still occur at lower amplitude.
- Implications:
  - No retardation. ⇔ Dominant resonances are near birth energy.*
  - We may learn sth. about deviation from marginal stability. ⇒ Study more!

(*) Bierwage & Shinohara, *Phys. Plasmas* **21** (2014) 112116

Outline

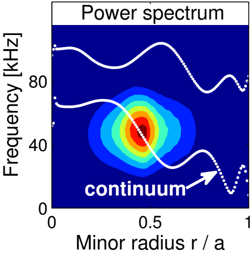
"Multi-Time-Scale Dynamics of Energetic Particle Modes in JT-60U"

1. Simulation model and methods:
   Advances towards predictive simulations
   for energetic particle dynamics

2. Meso- and long time scale (0.5 ms - 40 ms):
   Reproduced chirping bursts of JT-60U exp.

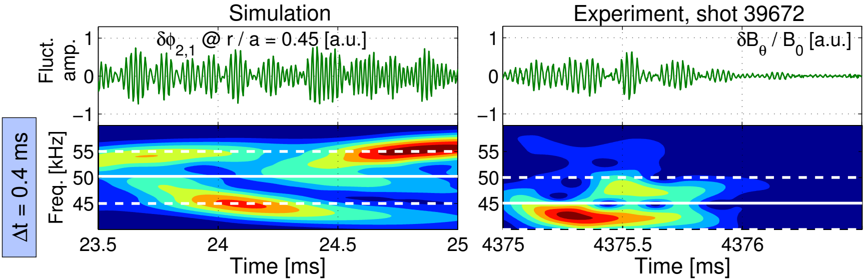
3. Short and meso-time scale (10 μs - few ms):
   Predicted+confirmed pulsations and phase jumps

4. Summary, conclusion, outlook



A. Computational parameters, resources, efficiency.
   Fast ion redistribution due to MHD activity.

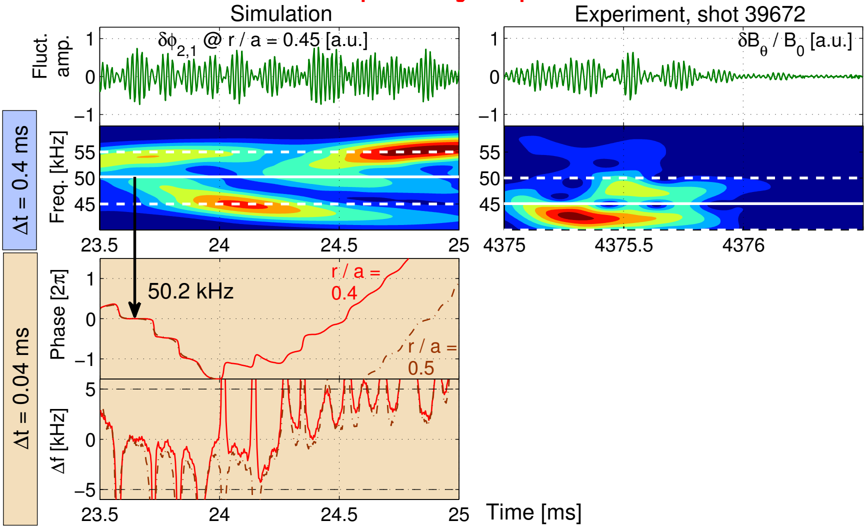
MHD dynamics on 10 μs - few ms scale



- Previously reported chirping dynamics based on 0.4-1 ms FT windows.
- However: Time traces of raw signal exhibit pulsations on shorter scale.

MHD dynamics on 10 μs - few ms scale

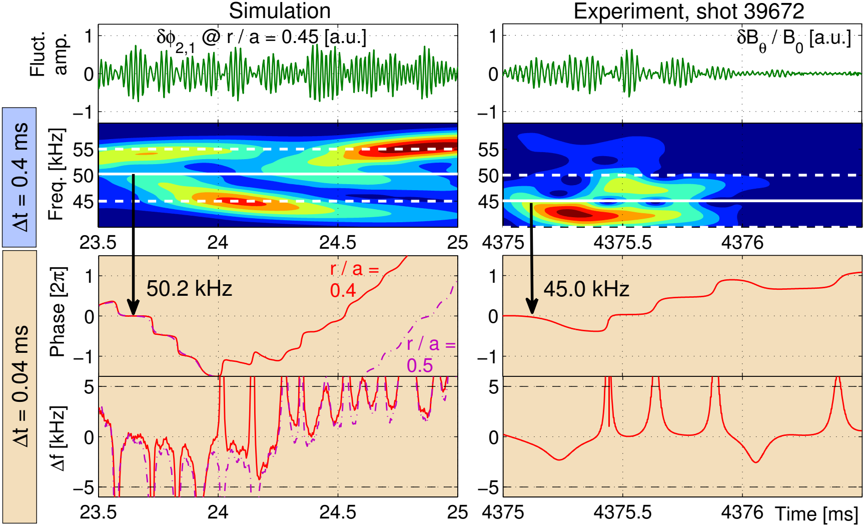
Found: Pulsations and phase jumps



- Analysis on 0.04 ms scale reveals: Phase jumps ($\pm\pi$) between pulses. Wave freq. varies less ($\pm$2.5 kHz) than averaged chirps ($\pm$5 kHz).

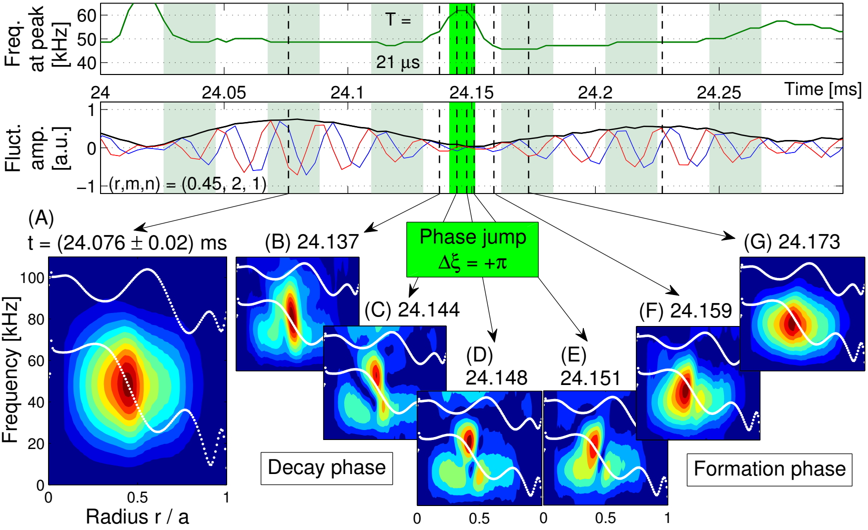
MHD dynamics on 10 μs - few ms scale

Found: Pulsations and phase jumps



- Pulses and phase jumps discovered in sim. are also found in exp. data.
- Not considered in theories for chirping. ⇒ Improve physical picture!

Spatio-temporal pulsation of Energetic Particle Modes*



- Resonant drive at certain freq. keeps phases of dispersive waves aligned.
- Complicated interaction between mode structure and fast ion distrib.

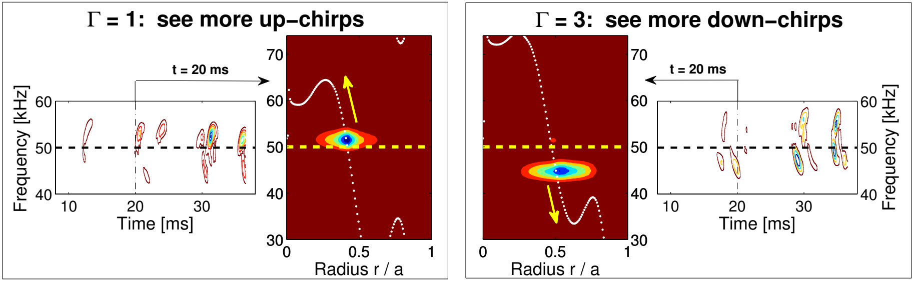
(*) Theoretical prediction of EPM: Chen, *Phys. Plasmas* **1** (1994) 1519

Struct. of Shear Alfvén Wave continuum affects chirping

For ideal monoatomic gas (3 degrees of freedom, isotropic collisions) $\Gamma = C_p/C_V = 1 + 2/F = 5/3$. For strongly magnetized tokamak plasma (electrons, deuterons, high-Z impurities) appropriate Γ value not known.

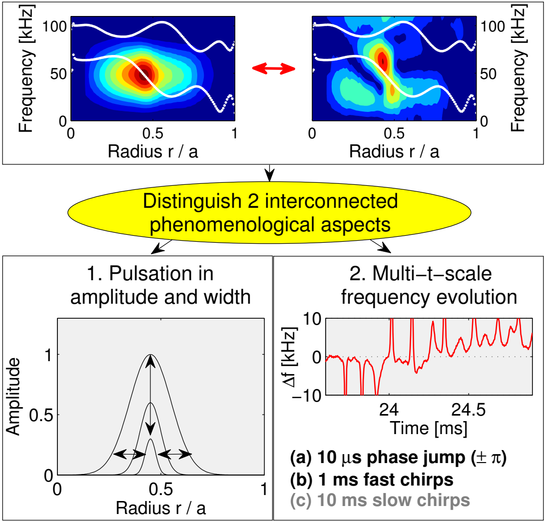
$$\partial_t P = -\boldsymbol{\nabla}\cdot(P\mathbf{V}) \underbrace{-(\Gamma - 1)P\nabla\cdot\mathbf{V}}_{\text{compressional response}} \ldots \quad \Rightarrow \quad \text{controls continuous SAW spectrum}$$

$\Rightarrow$ Γ affects dominant direction of chirping:

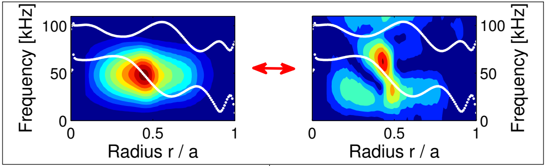


- Dominant component of signal tends to chirp towards nearest accumulation point, where $\mathrm{d}\omega_\mathrm{A}(r)/\mathrm{d}r$ is small.
- One out of several new ingredients for a complete theory of chirping.

Spatial-temporal pulsation of EPM: Summary

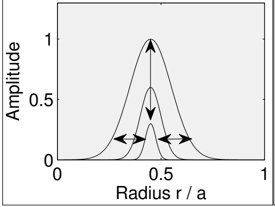


Spatial-temporal pulsation of EPM: Summary

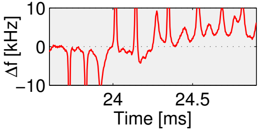


Distinguish 2 interconnected phenomenological aspects

1. Pulsation in amplitude and width



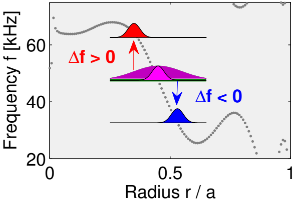
2. Multi–t–scale frequency evolution



(a) 10 μs phase jump (± π)
(b) 1 ms fast chirps
(c) 10 ms slow chirps

Underlying physics:

(I) Dispersion of wave packets



(II) Particle dynamics

... to be (re)examined ...

→ **complicated evolution of phase space islands**

→ **repeated trapping and detrapping in wave fields**

- To complete the picture: Clarify self-consistent evolution of drive.

Revisit theory of phase space dynamics [Berk *et al.*, *Phys. Lett. A* **234** (1997) 213], which assumed small deviation from marginal stability and dominance of discrete eigenmodes with constant mode structure, ignoring continuous spectra.

Outline

"Multi-Time-Scale Dynamics of Energetic Particle Modes in JT-60U"

1. Simulation model and methods:
   Advances towards predictive simulations
   for energetic particle dynamics

2. Meso- and long time scale (0.5 ms - 40 ms):
   Reproduced chirping bursts of JT-60U exp.

3. Short and meso-time scale (10 μs - few ms):
   Predicted+confirmed pulsations and phase jumps

4. Summary, conclusion, outlook

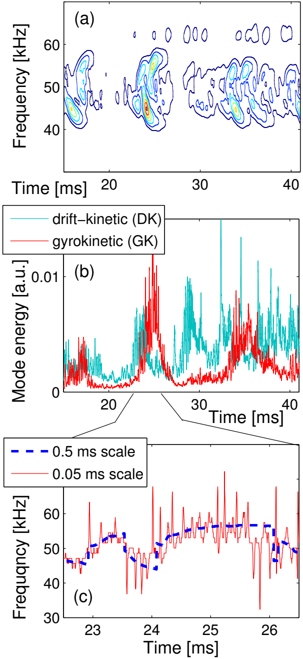
A. Computational parameters, resources, efficiency.
   Fast ion redistribution due to MHD activity.

Summary and conclusion

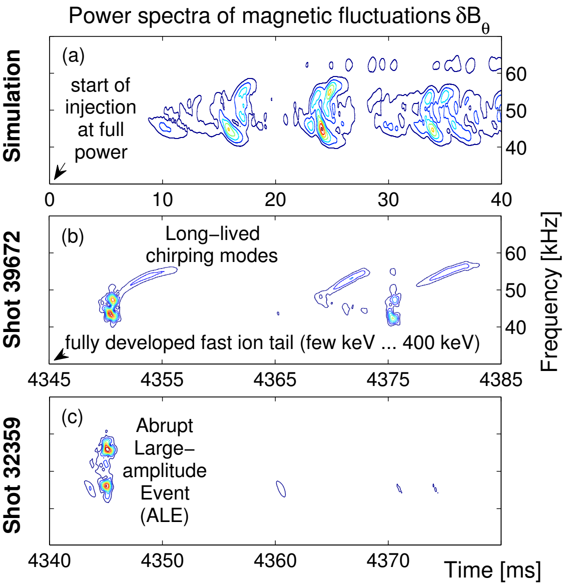
- **Major numerical advances:**
  1. Developed self-consistent simulation framework with MHD, sources and collisions:
     Promises new insights and better predictions!

- **Multi-time-scale simulation results:**
  2. Reproduced rapid chirps ($\sim$ 1 ms) from experiments and demonstrated importance of fast ion FLR effects:
     Successful V&V!
  3. Analysis of chirps revealed spatio-temporal pulsations of EPMs ($\sim$ 100 μs) and phase jumps ($\sim$ 10 μs) in both sim. & exp.:
     Sucessful V&V. New building blocks for more complete theory of chirping modes.

- **Open questions:**
  - Reason for $\pm\pi$ phase jumps?
  - Particle dynamics during EPM pulsation?



Outlook



- Physics:
  - Wave-particle interactions.
  - Burstiness and marginal stability.
  - Kinetic effects of bulk ions, bulk ion heating.
- V&V, Prediction:
  - Apply to other machines and other modes.
- Long-lived chirping modes:
  - lasting about 5 ms
  - sensitive to plasma equil.
  - may require fully developed fast ion tail (below 300 keV)
- Abrupt Large Events
  - 4-10 times larger δB_θ
  - may involve $n > 1$ modes*

(*) Bierwage *et al*, *Nucl. Fusion* **54** (2014) 104001

Outline

"Multi-Time-Scale Dynamics of Energetic Particle Modes in JT-60U"

1. Simulation model and methods:
   Advances towards predictive simulations
   for energetic particle dynamics

2. Meso- and long time scale (0.5 ms - 40 ms):
   Reproduced chirping bursts of JT-60U exp.

3. Short and meso-time scale (10 μs - few ms):
   Predicted+confirmed pulsations and phase jumps

4. Summary, conclusion, outlook

A. Computational parameters, resources, efficiency.
   Fast ion redistribution due to MHD activity.

A1. Numerical parameters and computational resources

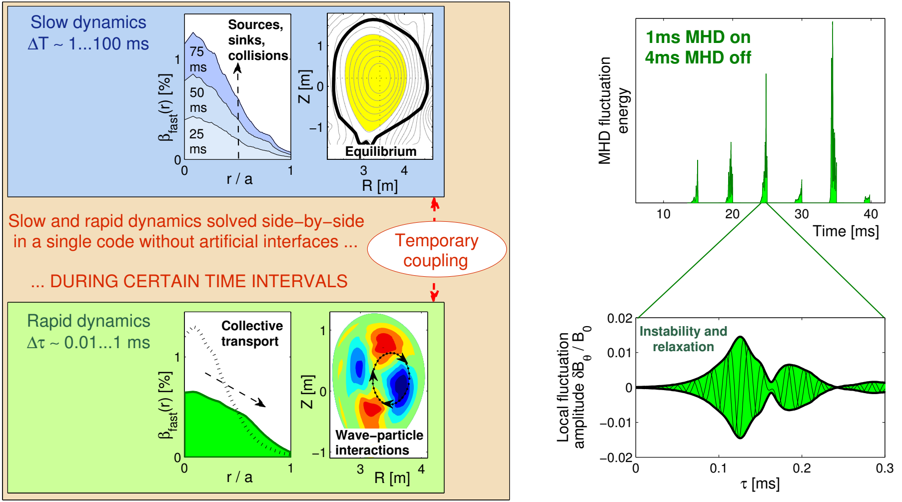
- Setup discussed here:
  - MHD fluctuations with single toroidal mode number $n = 1$ interacting with 2 fast ion beams
  - Step size: $\Delta t_{\mathrm{MHD}} = 0.05\,\tau_{\mathrm{A0}} = 0.04\,\mu\mathrm{s}$ ($\Delta t_{\mathrm{PIC}} = 4 \times \Delta t_{\mathrm{MHD}}$)
  - Spatial grid: $N_R \times N_\varphi \times N_Z = 384 \times 32 \times 352$
  - MPI domains: $M_R \times M_\varphi \times M_Z = 32 \times 4 \times 32$ (4096 MPI processes on 256 nodes with 16 cores each)
- Simulation of 50 ms physical time:
  - 13.9×10^6 time steps, accumulating 3.38×10^6 simulation particles
  - Wall time: 11.3 days for 25 ms, 26 days for 50 ms (160k node hours)

HELIOS at

IFERC-CSC

http://www.iferc.org/csc/csc_for_researchers/csc_introduction.html

A2. Compromise: Multi-phase simulation method

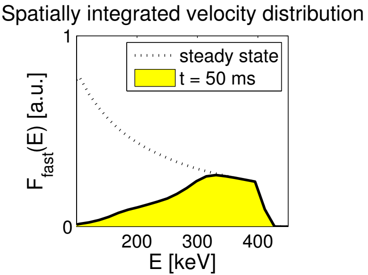


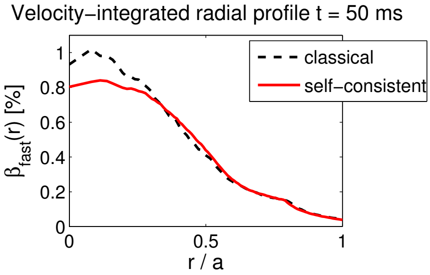
- **<u>Pros:</u>** Efficient and useful for prediction of realistic fast ion profiles.

  [Todo *et al.*, *Nucl. Fusion* **54** (2014) 104012]

- **<u>Cons:</u>** Only rudimentary meso-t-scale dynamics ($\lesssim$ 1 ms).

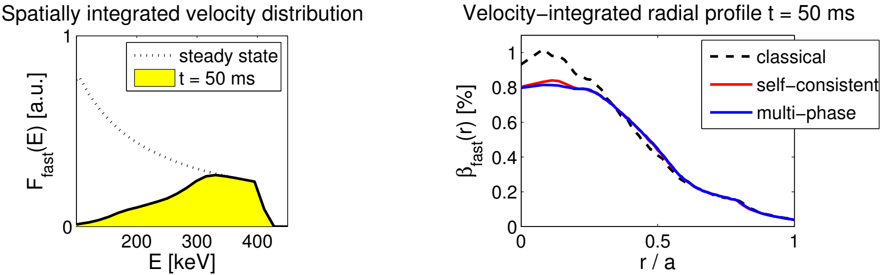
A3. Effect of MHD activity on fast ion distribution





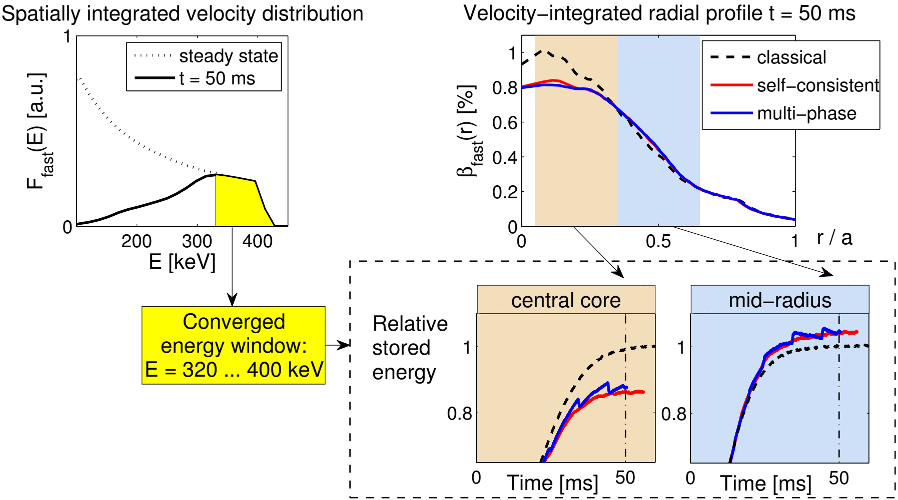
- Classical (no MHD): Overestimates fast ion gradients ⇒ unstable.
- Self-consistent: Fast ion energy in central core reduced by ≈ 15%.

A3. Effect of MHD activity on fast ion distribution



- Classical (no MHD): Overestimates fast ion gradients ⇒ unstable.
- Self-consistent: Fast ion energy in central core reduced by ≈ 15%.
- Multi-phase (MHD 1ms on/4ms off): Reproduces self-consist. sim. result.

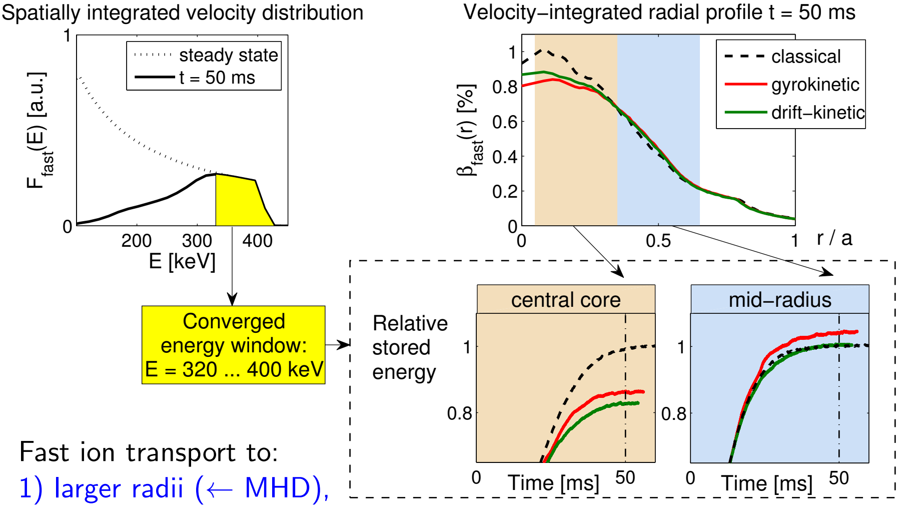
A3. Effect of MHD activity on fast ion distribution



- Classical (no MHD): Overestimates fast ion gradients ⇒ unstable.
- Self-consistent: Fast ion energy in central core reduced by ≈ 15%.
- Multi-phase (MHD 1ms on/4ms off): Reproduces self-consist. sim. result.

A4. Effect of MHD actitivty on fast ion distribution

Found: FLR affects transport in radius and energy



- Fast ion transport to:
  1) larger radii (← MHD),
  2) lower energies (← collisions with thermal particles and MHD).
- Drift-kinetic (no FLR): Underestimates radial transport by $\lesssim 5\%$. Overestimates energy transfer to bulk plasma by $\lesssim 5\%$. For $n = 1$!