Fast-Ion Edge Resonant Transport Induced by Externally Applied 3D Fields in AUG and ITER

Motivation

• Experiments in AUG show fast-ion losses induced by 3D fields in narrow poloidal spectrum range

• Poloidal spectrum of $n=2$ 3D fields was continuously modified by varying $\Delta \Phi_{UL}$

• Clear dependency of ELM activity, density pump-out and fast-ion losses on 3D fields poloidal spectrum

M. Garcia-Munoz et al., IAEA FEC 2016
Outline

• AUG
  • Impact of 3D Fields Poloidal Spectrum on Fast-Ion Losses
  • Edge Resonant Transport Layer (ERTL)
  • Impact of 3D Fields Spectrum and Plasma Response on ERTL
  • Conclusions

• ITER
  • Fast-Ion Losses Induced by 3D Fields in ITER
  • Impact of ERTL on Alpha Particles
  • Impact of ERTL on NBI ions
  • Conclusions
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Fast-Ion Response to Applied 3D Fields Studied
Varying 3D Field Poloidal Spectrum

- 3D fields poloidal spectrum modified by applying a toroidal phase difference between the upper and lower coil sets, $\Delta \Phi = \Phi_{\text{upper}} - \Phi_{\text{lower}}$

AUG

B-coils

Upper Coil Currents

$\Delta \phi$ Lower Coil Currents

$\Delta \phi = 40$

MARS-F

AUG

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Ascot Simulations Predict Strong Dependency of Fast-Ion Losses on 3D Fields Spatial Structure

- Orbit simulations using $n=2$ MARS-F fields reproduce $\Delta \Phi_{UL}$ (poloidal spectrum) dependency
- Additional 3D fields toroidal harmonics have some impact on total losses
- Plasma response (PR) and associated fast-ion losses change with poloidal spectrum
- Realistic NBI distribution was considered
Simulations Reproduce FILD Measurements in Narrow $\Delta\Phi_{UL}$ Range

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Edge Peeling Amplification has Stronger Impact on Total Losses than Internal Kink Amplification

• Strong peeling response at $\Delta \Phi_{UL}=0^\circ$ leads to slight amplification of total losses

• Internal kink amplification at $\Delta \Phi_{UL}=180^\circ$ does not modify significantly total losses
Each pixel represents a particle starting at corresponding \((E,R)\).

All particles fixed starting coordinates:
- \(z=0\) m
- \(\Phi=218^\circ\) (NBI#8)
- \(\Lambda=-0.5\) (NBI#8)

For each particle, \(\delta P_\Phi\) is calculated by averaging the \(\delta P_\Phi\) over time.
Calculations of $\delta P_\Phi$ due to 3D Fields Reveal Transport is Resonant and Localized within 5-10 cm Around Separatrix

- ASCOT is used to calculate fast-ion average $\delta P_\Phi$ induced by the externally applied 3D fields for all $\Delta \Phi_{UL}$
- Vacuum and MARS-F n=2+6 3D fields
- No TFC-ripple
- No collisions

$$P_\Phi = mRv_\Phi - Ze\psi$$

$\Delta \Phi_{UL}=40^\circ$

$<\delta P_\Phi> < 0$ (blue-black) $\rightarrow$ outwards transport

$<\delta P_\Phi> > 0$ (yellow-white) $\rightarrow$ inwards transport

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Calculations of $\delta P_\phi$ due to 3D Fields Reveal Transport is Resonant and Localized within 5-10 cm Around Separatrix

- Complex $\langle \delta P_\phi \rangle$ structures in E-R plane reveal transport is localized and mostly resonant rather than stochastic.

- Radial transport is inwards or outwards depending on perturbation poloidal spectrum and particles coordinates with respect to resonance.

\[ P_\phi = m R v_\phi - Z e \psi \]

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Overlapping of Multiple Linear / Non-Linear resonances Creates an Edge Transport Layer (ERTL)

• Orbital resonances intrinsic to magnetic background

\[ \frac{\omega_b}{\bar{\omega}_d} = \frac{n(l + 1)}{p_0(l + 1) \pm p'} \]

• Maximum transport caused by resonance overlap

• Non-linear resonances seem to play a key role*

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F. Zonca et al, NJP 17 (2015)0130052
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Edge Resonant Transport Changes Dramatically with 3D Field Poloidal Spectrum

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\[
\Delta \Phi_{UL} = 220^\circ
\]

\[
\Delta \Phi_{UL} = 40^\circ
\]

\[
\frac{\delta P}{\Phi} [\text{a.u.}]
\]

\[
E = 40 \text{keV}
\]

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Only Linear Resonances Remain Active when Perturbation Amplitude Decreases

- Number of overlapping non-linear resonances depends on perturbation amplitude
- If we make $l=0$ in the resonant equation, we retrieve the frequency ratio of linear resonances

$$\frac{\omega_b}{\bar{\omega}_d} = \frac{n(l + 1)}{p_0(l + 1) \pm p'} \quad \Rightarrow \quad \frac{\omega_b}{\bar{\omega}_d} = \frac{n}{p}$$
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\]
Plasma Response to Applied 3D Fields Modifies Fast-Ion Transport Locally

- Edge peeling response has an impact on fast-ion transport due to Edge Resonant Transport Layer

\[ \Delta \Phi_{UL} = 40^\circ \]

\[ \delta P_\Phi (10^{-16} \text{ kg m s}^{-1}) \]

- Internal kink response causes enhanced local transport due to internal resonance

\[ <\delta P_\Phi > < 0 \text{ (blue-black)} \rightarrow \text{outwards transport} \]

\[ <\delta P_\Phi > > 0 \text{ (yellow-white)} \rightarrow \text{inwards transport} \]
Fast-ion Transport Depends Strongly on the Injection Geometry with respect to the Perturbation

- NBI#8 injection is located at max negative $\delta P_\phi$ for $\Delta \Phi = 40$ deg contributing to the total losses

- $n=2$ perturbation symmetry is clearly shown in R-$\phi$ plots

- For a given pitch angle and coil configuration there is a net transport independent of the injection angle
Conclusions

- Fast-ions are extremely sensitive to the poloidal spectrum of externally applied 3D fields
- 3D fields induce resonant transport localized within 5-10 cm around separatrix
- Dominant fast-ion transport is not stochastic
- 3D fields can be used to taylor the fast-ion distribution
- $<\delta P_\phi>$ analysis represents a promising figure of merit to optimize ITER RMP coil configuration to avoid energy loss due to fast-ions
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• 2D 15 MA equilibrium
• TF ripple + FIs
• $n=4$ RMP vacuum fields

• $I_{\text{coil}}=90\text{kAt}$

• Realistic fusion born $\alpha$-particles and NBI distribution
ASCOT Predicts Up To 12.5% RMP Induced Alpha-Particle Loss with 8% Power Loss

- Simulation carried out using realistic alpha birth profile and n=4 RMP vacuum field

![Graph showing ITER and Divertor with poloidal and toroidal angles, and a color scale for power density.](image)

- Coils current: 90kAt
- Phase shift: 22.5°
- Particles species: alpha
- #Particle markers: 1M
Maximun alpha particle-transport is located within 20cm inside the separatrix

- Most intense signal spot is located at the trapped/passing boundary
- Maxima in $\langle \delta P_\phi \rangle$ match the spots in ITER synthetic signal
Maximum alpha particle-transport is located within 20cm inside the separatrix.

- Most intense signal spot is located at the trapped/passing boundary.
- Maxima in $\langle \delta P_\phi \rangle$ match the spots in ITER synthetic signal.

[J. Galdón-Quiroga, ITER 2016]
Both OFF and ON axis injectors were used to calculate $\delta P_\Phi$. 

![Graphs showing particle distribution and density profiles](image_url)
Most NBI Ions Are Born Near Trapped / Passing Boundary (!) :-o

- Trapped/passing boundary contains a very high density of resonances susceptible of being activated through the 3D perturbed fields

- $\langle \delta P_{\phi} \rangle$ is extreme radial and pitch-dependent

- Both NBI systems deposit most ions on the trapped/passing boundary
Most NBI Ions Are Born Near Trapped / Passing Boundary (!)

- Trapped/passing boundary contains a very high density of resonances susceptible of being activated through the 3D perturbed fields
- $<\delta P_\phi>$ is extreme radial and pitch-dependent
- Both NBI systems deposit most ions on the trapped/passing boundary
Conclusions

- Transport layer due to high density of resonances at the boundary is maximized between 8.00 - 8.25 m

- Trapped/passing boundary leads to a significant fast-ion radial transport

- Most NBI ions are born near trapped / passing boundary

- Is there a coil configuration that avoids critical activation of the boundary resonances?
Thank you for your attention! 😊
Fast-Ion Radial Transport Studied in Terms of Variation of Canonical Angular Momentum

\[ P_\phi = mRv_\phi - Ze\psi \]

- The canonical angular momentum is held constant for axisymmetric magnetic fields

\( \delta P_\Phi < 0 \) Outwards
\( \delta P_\Phi > 0 \) Inwards
Fast-ion transport induced by static 3D fields can be explained by nonlinear wave-particle resonant theory

- Assuming a generic periodic perturbation

\[
f(r, \theta, \xi) = \sum_{m,n} e^{in\xi-im\theta} f_{m,n}(r)
\]

Perturbation written in laboratory system

\[
f(r, \theta, \xi) = \sum_{n,m,p} e^{i(n\omega_d+p\omega_b)\tau} P_{n,m,f}(\vec{r})
\]

Perturbation written as particles ‘see’ it

- Including orbit fluctuations introduces **nonlinear** particle orbit distortions

\[
f(r, \theta, \xi) = \sum_{m,n,p,l} e^{i(n\omega_d+p\omega_b-\omega_0)\tau} e^{il(n\omega_d+p\omega_b-\omega_0)} P_{m,n,p} \cdot f_{n,m,l}(\vec{r})
\]

\[n,m,p,l \in \mathbb{Z}\]

- Assuming nearly stationary fluctuations (\(\omega_0=0\)) and introducing bounde harmonic \(p=p_0+p'\)

\[
n(l+1)\omega_d - p_0(l+1)\omega_b - p'\omega_b = 0 \rightarrow \frac{\omega_b}{\omega_d} = \frac{n(l+1)}{p_0(l+1) \pm p'}
\]

[F. Zonca et al, NJP 17 (2017)0130052]
Realistic Magnetic Fields Have Been Calculated to Reproduce the Experimental Conditions for Shot #33143

- Broadest stochastic region for $\Delta \phi = 40$ deg
NBI Distribution Simulated Using Real Injection and Plasma Parameters

- Significant number of NBI ions are born in plasma periphery

![Graph showing NBI ion distribution in AUG NBI#8.](image)

**Graph Details**:
- **Y-axis**: NBI ions/m²
- **X-axis**: R [m]
- **Color Scale**: #Particles $[10^{16}$ cm$^{-2}$ s$^{-1}$]
- **Separatrix** indicated on the graph.
Thermonuclear Alpha-Particle Distribution Calculated Using Realistic Kinetic Profiles
Edge Weighted Initial Particle Distribution to Improve Statistics of Losses

Weight of markers assigned to represent real alpha birth rate given by kinetic profiles, i.e. larger number of markers at the edge with smaller weight.
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Realistic alpha birth distribution

Weighted alpha birth distribution
Losses at FILD Studied for Different n=4 RMP Toroidal Phases

δBr caused by n=4 RMP on poloidal cross-section

Poincaré plots for each perturbation toroidal phase

Red line indicates FILD toroidal location
Collisions break wave-particle phase locking blurring out resonances in ERTL

- Energy slowing down and pitch scattering takes fast-ions out of the resonant region of velocity space
- By increasing the collisionality we intensity this effect until blurring out the resonant structures
Full Range Simulation Shows
Resonances are Located at the Edge
Calculations of $\delta P_\phi$ due to 3D Fields Reveal Transport is Resonant and Localized within 5-10 cm Around Separatrix

\[ P_\phi = mRv_\phi - Ze\psi \]

- NBI#8 birth profile shows a significant population at the edge transport layer

$<\delta P_\phi> < 0$ (blue-black) $\rightarrow$ outwards transport

$<\delta P_\phi> > 0$ (yellow-white) $\rightarrow$ inwards transport