Modelling of transport and loss of EPs due to (low-frequency modes and) <u>3D fields</u>

finnfusi

VTT

A. Snicker et al.

ACADEMY OF FINLAND

29/06/2023 ITER Internation Summer School, Aix-en-Provence, France



- 1. Monte Carlo method/Intro
- 2. Non-axisymmetric fields
- 3. Low frequency modes
- 4. Useful tools/links
- 5. Concluding remarks

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This school should cover all topics related to fast-ions, right?Let's look at our program...



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				<u>Mon. 26</u>	<u>Tue. 27</u>	Wed. 28	<u>Thu. 29</u>	<u>Fri. 30</u>				•	Q
			09	00 Welcome from AMU Introduction to energ particles physics	J Energetic particle diagnostics etic	Diagnostics associated with redistribution of confined EPs and the causes	Diagnosing the loss of EPs and causes	Physics of observations of runaway electrons					\$
			10	00									+
				Coffee break	Coffee break	Coffee break	Coffee break	Coffee break					
			11	Sources of EPs (NBI, 1 fusion): theory & exper	CH, Control of EP-related iment instabilities, e.g., sawteeth AE	Kinetic-MHD hybrid , simulations of energetic- particle driven instabilities	EP instabilities: nonlinear effects and consequences	Modelling runaway electrons					
			12	00									
			13	00	Bus								
			14	Energetic particle instabilities: Linear phy near theshold	vsics Visit to TTER	Experimental observations of EP transport and loss (e.g., AE, 3D-fields, ripple, NTMs)	Reduced models of EP transport for scenario	Best Poster Prize					
								Closing session					
			15	00 Coffee break	Coffee break	Coffee break	Coffee break						
				Poster - 1	Visit to ITER	Poster Session - 2	Modelling of transport and loss of EPs due to low- frequency modes and 3D fields						
			16	00									
			47	Discussions		Discussions	Discussions						
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Simulations to understand and interpret the signals

VTT



Simulations to understand and interpret the signals

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Simulations to understand and interpret the signals

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Simulations to understand and interpret the signals





- My (biased) answer: we need it for everything we do!
- But remember:
 - We need theory understanding to develop Monte Carlo methods
 - We need experiments to validate our simulation models



Why Monte Carlo?

Monte Carlo is ideal for "engineering studies"



Examples of Monte Carlo

29/06/2023



ITER Internation Summer School, Aix-en-rrovence, trainee A Calmin (a)

A. Salmi et al. Contr. to Plasma Phys. 2008

Short history of orbit-following Monte Carlo

- 80s: simulations for a few 100s of ions, analytic geometry
- 90s: tabulated geometry, few thousands of ions
- 2000s: first attempts to 3D, geometry 100k ions
- 2010s: introduction of 3D wall
- Current state-of-the-art:
 - Tabulated extremely complicated 3D geometry with several components
 - Complicated 3D wall shapes (e.g. up to 1M triangle mesh)
 - Easily 5-10Ms of ions
 - Guiding center and gyro motion solvers



How we do Monte Carlo?

(My version of it...)

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The kinetic equation

How to solve the Fokker-Planck equation for fast-ions and neoclassical transport:

$$\frac{\partial f}{\partial t} + \dot{z} \cdot \frac{\partial f}{\partial z} = \left(\frac{\partial f}{\partial t}\right)_{coll} \quad (1)$$

• Notation: $z = (\vec{x}, \vec{v})$ or $z = (\overrightarrow{X_{GC}}, v_{par}, \mu)$, i.e. 5-6D phase-space

- Collision operator given by the Landau form (note: lecture 2)
 - Fast-ions interact only with the background Maxwellian plasma
- How does this relate to Monte Carlo, it is an ODE?!?

The kinetic equation, with a stochastic twist

How to solve the Fokker-Planck equation:

$$\frac{\partial f}{\partial t} + \dot{z} \cdot \frac{\partial f}{\partial z} = \left(\frac{\partial f}{\partial t}\right)_{coll} \quad (1)$$

Let's consider a stochastic Ito process:

$$dz^i = K^i dt + \Sigma^i dW^i \quad (2)$$

- Here: K^i and Σ^i are related to the collisions (=convection and diffusion)
- dW^i is the so called Wiener process (=random numbers, of particular distribution)
- Kⁱ terms include deterministic terms, e.g. Hamiltonian motion, energy loss
- Σ^i terms include all stochastic terms, e.g. pitch-angle and energy diffusion
- Again, so WHAT, where is the Monte Carlo?!?

The kinetic equation, with a stochastic twist

• How to solve the Fokker-Planck equation:

$$\frac{\partial f}{\partial t} + \dot{z} \cdot \frac{\partial f}{\partial z} = \left(\frac{\partial f}{\partial t}\right)_{coll} \quad (1)$$

Translate this to a stochastic Ito process:

 $dz^i = K^i dt + \Sigma^i dW^i \quad (2)$

The catch is here: the solution of (1), the distribution function, can be obtained by sampling markers using (2) and collecting histograms of the individual and independent histories -> there is the Monte Carlo!!!

The kinetic equation, with a stochastic twist

Translate this to a stochastic Ito process:

 $dz^i = K^i dt + \Sigma^i dW^i \quad (2)$

- The catch part 1: the solution of (1) can be obtained by sampling markers using (2) and collecting histograms of the individual and independent histories -> Monte Carlo
- The catch part 2: It turns out that equation (2) is identical to single particle motion -> the characteristics are orbits of single particles-> the orbit-following Monte Carlo
- Individual and independent test particles -> (almost) ideal scaling
 -> HPC applications

If you are interested in further details...

- ...about the connection between the Ito process and Fokker-Planck in relation to fast-ions
 - E. Hirvijoki et al. Comp. Phys. Comm. 2014 and references therein
- ...about the collision operator (for particle and/or guiding center)
 - A.J. Brizard Phys. Plasmas 2004, E. Hirvijoki Phys. Plasmas 2014 and references therein

- 21

- 20

19

18

17

16

15

Final warning with Monte Carlo

Monte Carlo method is "easy", gives always an result, but...

- ...the devil is in the details
- ...carbage in (can be difficult to detect) -> carbage out (often easier)





2.75 3.00

Let's trust the science and take a short break... ... to reset our concentration onto the next topic

1. Monte Carlo method/Intro

2. Non-axisymmetric fields

- 3. Low frequency modes
- 4. Useful tools/links
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Modelling of transport and loss of EPs due to lowfrequency modes and 3D fields

Please help me: List all symmetry breaking (3D) fields!

List all symmetry breaking (3D) fields: - TF coils

- Ferritic Materials
- ELM/RMP coils
- Plasma response
- Error field coils
- Internal (MHD) modes

The toroidal field ripple, between friends TF ripple, Ferritic Inserts, and TBMs

Example: 3D fields for ITER

- TF ripple is always present
 - Can be mitigated with ferritic inserts
- TBMs will be (always) present
- ELM control coils are applied (always)
 - Different configurations can be considered
- Conclusion: The real life is complicated...
 - Need to consider multiple perturbations
- What is the effect of these on fast-ions?



A. Snicker et al 2015 Nucl. Fusion 55 063023

Banana diffusion and ripple-well trapping

- For trapped particles, banana tips are moving in (R,z)
 - As an side effect, bananas start diffusing
 - Cause radial transport, with tiny steps -> so called banana/TF diffusion
- Deeply trapped particles can get trapped between TF coils
 - So called ripple-well particles/super bananas
 - These are immediately lost with a christmas tree pattern



Banana diffusion and ripple-well trapping

- Deeply trapped particles can get trapped between TF coils
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 - These are immediately lost with a christmas tree pattern



Example for European DEMO

- -Black area: analytical super-banana region=ripple well
- -Red area: analytical banana diffusion

-Right: simulations (color=particles, dots=banana tips)

D. Pfefferlé et al 2016 Nucl. Fusion 56 112002

Numerical example – banana diffusion...

- Take full 3D geometry of the ITER first wall
 - Move "one wall tile" radially
 - Calculate losses on that tile
 - Plot lossess vs. radial displacement
- Losses concentrate on the displace tile!







Radial movement of the "limiter tile"

Lost power vs. radial displacement decay length of $11 \text{mm} \ll R_L$

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Mitigation by Ferritic Inserts is effective!

Ferritic materials located between the TF coils

- When toroidal field present, material saturates -> magnetization
- Additional perturbations due to NBI ports and TBMs

Table 1. NBI ion losses for the axisymmetric 2D equilibrium, unmitigated ripple and ferritic insert configurations.

Configuration	NBI losses
Unmitigated Ripple 16 coils	609kW
Unmitigated ripple 18 coils	49kW
Ripple + 25% FI mass	19kW
Ripple + 50% FI mass	8 kW
Ripple + 75% FI mass	3kW
Ripple + ferritic inserts	1kW
2D equilibrium	<1kW



Varje, J., et al. Fusion Eng. and Des. 2019

S. Äkäslompolo et al. Fusion Eng. and Des. 2015

TBM mock-up coil experiments/simulations

- DIII-D run experiments with a coil mocking up a TBM
 - Simulations were compared against experiments using various configurations
 - Several codes joint the effort (ASCOT, OFMC, SPIRAL)



What about passing particles?

- Passing ions can also resonate with the TF ripple
- If TF ripple is large, a stochastic region can form
 - Diffusion strong in stochastic fields
- The origin of the stochasticity
 - Overlapping resonances (the first lecture...)
 - Will become important in a moment...





Jari Varje et al 2016 Nucl. Fusion 56 046014

What about confined particles?

- So far, concentrating on the losses
- Alphas are boringly well confined
- Does 3D field modify these alphas?
- ITER 15 MA scenario
 - Alpha particle driven current
 - Alpha particle driven torque
- Current drive equilibrium effect
- Torque depends on 3D fields
 - Losses/transport plays a role $(j_R x B_{\varphi})$



Figure 6. Comparison of ASCOT (red) and SPOT (blue) shielding factor Γ for the current density (a) and simulated alpha particle current density (b), both with and without the electron shielding effect, as a function of ρ_{ρ} .



Figure 7. Toroidal current density (a) and torque density (b) given by alpha particles in a 9 MA Q = 5 steady-state ITER scenario with a variety of 3D perturbations. For reference, the 2D case is also shown.

A. Snicker et al 2015 Nucl. Fusion 55 063023

The resonant magnetic perturbation coils (RMPs) and/or ELM control coils (ECCs), and plasma response models



Signifigance of RMP/ELM control coils

- Typically n=~2-4 toroidal perturbations
 - Fast-ions can be resonant: $\omega = 0 = n * \omega_t p * \omega_p$
 - Near plasma edge, geometric resonances are dense
- Importance of the poloidal spectrum
 - One conf. can expel fast-ions, other confines them
 - · Possibility to tailor fast-ion distribution at the edge



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Jari Varje et al 2016 Nucl. Fusion 56 046014



General observation: total losses decrease, locally anything can happen

- Plasma response:
 - Mitigates island/stochasticity deeper
 - Increases stochasticity at the edge





Jari Varje et al 2016 Nucl. Fusion 56 046014



Local increase of fast-ion losses due to plasma response part 1: the ITER FILD

- What is the fast-ion flux at the ITER FILD pinhole?
 - About 10 years ago, pessimistic guess with vacuum approach...



M. Garcia-Munoz, Rev Sci Instrum 87, 11D829 (2016)

Power loads using: RMP (n=3), TF, FI (vacuum)



Power loads using: RMP (n=3), TF, FI (PR)





Local increase of fast-ion losses due to plasma response part 2: the divertor

- Local increase under the divertor dome, at the cooling pipes
 - All codes reproduce these findings (LOCUST, OFMC, ASCOT...)
 - Are these of numerical nature? What is the reason for these losses?



S.H. Ward et al 2022 Nucl. Fusion 62 126014

K. Särkimäki et al 2018 Nucl. Fusion 58 076021

Toroidal variation of the poloidal field identified as the transport channel

- Losses show similar characteristics as ripple diffusive losses (left)
- Losses are located at passing-trapped boundary (right)
 - Similar for JOREK and MARS-F (bottom)





To summarize what we learned so far...

Coordinates are the "orbit coordinates", ξ'=pitch ρ'=radius @OMP



Let us play a guess game

What ITER scenario do you think will cause the largest fastparticle losses? (Assuming TF ripple + FIs + TBMs)

- 1. H-mode baseline, 15MA, 5.3T, alpha particles
- 2. Hybrid scenario, 12.5MA, 5.3T, alpha particles
- 3. Advanced scenario, 9MA, 5.3T, alpha particles



Never underestimate the geometry!!!

- 1. H-mode baseline, 15MA, 5.3T, alpha particles
- 2. Hybrid scenario, 12.5MA, 5.3T, alpha particles
- 3. Advanced scenario, 9MA, 5.3T, alpha particles

 Table 1. Total power load to first wall and divertor in the different scenarios for different magnetic configurations described in the text.



Scenario α wall load (MW) α divertor load (kW) NBI wall load (kW) NBI divertor load (MW) 7.5 MA -/--/-12/13 0/3 19/19 +TBM -/--/-0/3160/160 130/150 6/5 2/4 9 MA +TBM 250/270 130/180 2/9 15/14 12.5 MA 510/530 190/190 3/3 1/1 +TBM 580/640 190/210 7/8 1/3 15 MA 20/19 120/120 21-1/-+TBM 39/42 110/130 7/-1/-+ECC 70/160 1900/1300 9/10 1150/1300



Note: Each entry has two numbers separated by a slash: 'vacuum approximation'/'with plasma response'.

T Kurki-Suonio et al 2017 Plasma Phys. Control. Fusion 59 014013

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Neoclassical tearing modes

- Can be approximated to be static perturbations
 - Resonances do occur
 - Can interplay with the TF ripple
- For reactors, NTMs are controlled
 - Low amplitude
 - Typically small transport



A. Snicker et al 2013 Nucl. Fusion 53 093028

 Table 1. Percentage of total alpha power lost for each of the NTM and TF ripple cases, and an additional row showing the difference between the large combined modes and no modes cases for each ripple case.

		Ripple Cases			
NTM Cases		None	Planned	Upper-bound	
No Modes		1.73%	1.95%	2.13%	
Small Combined		1.74%	1.95%	2.14%	
Large 3/2	SPARC	1.78%	2.01%	2.21%	
Large 2/1		1.90%	2.12%	2.28%	
Large Combined		1.91%	2.15%	2.34%	
Difference between Large Combined and No Modes Cases			0.20%	0.21%	

A E Braun et al 2022 Plasma Phys. Control. Fusion 64 125014

Neoclassical tearing modes interacting with TF ripple and RMPs

- Radial location of NTMs is important (q=1.5 vs. q=2)
 - Deep -> redistribution, edge -> possible losses
 - Other transport can take over at the edge, synergy effects likely!



E Strumberger et al 2008 New J. Phys. 10 023017

A. Snicker, et al. 27th IAEA Fusion Energy Conference (FEC 2018), 2019.

Sawtooth and fast-ions

- Fast-ions can stabilize the sawtooth instability
 - Long crash times can be problematic...
- Simulations indicate significant effect



D. Kim et al 2018 Nucl. Fusion 58 082029

Fishbones and fast-ions

- Fishbones observed to cause small drop in neutron rate
- Simulations model accurately this drop



C. Perez von Thun et al 2012 Nucl. Fusion 52 094010

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Sharing is caring...

- It takes time and effort to develop orbit-following Monte Carlo tools
- (Not) everyone should build their own!
- Several open source options available, please help yourself

Interactive tool to...

- ...calculate (and visualize!) orbits
- …calculate weight functions
- ...split diagnostic signals to orbits
- …and more

29/06/2023



H . Järleblad et al. CPC (in review) henrikj@dtu.dk



IMAS (and H&CD workflow)

- Integrated modeling
- InterfaceDataStructures
- Perfect for benchmarks
- Official ITER platform
- Includes FP codes
 - IC: STIXREDIST, FOPLA
 - NBI: RISK, ASCOT, NBISIM
 - Alphas: ASCOT
- The main platform to run ITER analysis
- Contact Simon Pinches and/or Mireille Schneider

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IMAS Infrastructure			IC wave solver	tomcat	TOMCAT	ssh://git@git.iter.org/heat/tomcat.git				
IMAS Databases			IC Fokker-Planck solver	stixredist	STIXREDIST	ssh://git@git.iter.org/heat/stixredist.git				
ITER Computing Cluster			IC Fokker-Planck solver	fopla	FOPLA	ssh://git@git.iter.org/heat/fopla.git				
Physics Components & Workflow:		Neutral Beam	NBI particle source	nemo	NEMO	ssh://git@git.iter.org/heat/nemo.git				
EP-WF - Energetic Particle Stabi		Injection, Nuclear	NBI Fokker-Planck solver	risk	RISK	ssh://git@git.iter.org/heat/risk.git				
 HCD-WF - Python HC&D worl 		(+ Optional IC-	NBI or nuclear reactions or IC-accelerated ions	spot	SPOT	ssh://git@git.iter.org/heat/spot.git				
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> JINTRAC			NBI Fokker-Planck solver	nbisim	NBISIM	ssh://git@git.iter.org/heat/nbisim.git				
 HFPS - High Fidelity Plasma Sirr 			NBI particle source	bbnbi parallel bbnbi serial						
LOCUST-GPU			Nucleo contine anticle course	-f-:	ASCOT					
Minerva/Bayes tutorial			Nuclear reactions particle source	ansi	ASCOT	ssn://git@git.iter.org/traj/ascot.git				
> PDS - Pulse Design Simulator			NBI and nuclear reactions Fokker-Planck solver	ascot_parallel, ascot_serial						
SMITER			IC-accelerated ions Fokker-Planck solver	ascot4rfof_parallel, ascot4rfof_serial						
N COLDC ITED										

ASCOT(5)

- Releasing open source github
- Tutorial, documentation...
- If interested in, contact me:
 - antti.snicker@vtt.fi



🕷 / Basic usage / Tutorial

View page source

Tutorial

This example gives a general overview on how to pre- and postprocess ASCOT5 simulations.

- 1. First simulation: step-by-step
- 2. Contents of the HDF5 file
- Python interface to libascot.so
- 4. Input generation
- 5. Post processing
- 6. Live simulations

First simulation: step-by-step

Go to your ascot5 folder where you compiled the code and type ipython3 to begin this tutorial. Then repeat these steps:

1. All pre- and post-processing is done via Ascot object. To create a new ASCOT5 data file, use create=True .

[]: import numpy as np from a5py import Ascot

- a5 = Ascot("ascot.h5", create=True)
- 2. The following lines initialize test data. We will go through the input generation in detail later.
- []: # Use pre-existing template to create some input data a5.data.create_input("options tutorial") a5.data.create_input("bfield analytical iter circular") a5.data.create input("wall rectangular") a5.data.create input("plasma flat")

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Conclusions

- Orbit-following Monte Carlo well-developed and widely needed
- Care needs to be taken in setting up the simulations
- We understand the transport and losses due to 3D field
 - · Can routinely estimate these using given equilibria/perturbation
 - Monte Carlo methods well-suited since geometry always plays a role
- Low-frequency modes not causing significant risk (reactor-scale)
- These tools can be both informative but also educational!



beyond the obvious

A. Snicker

Discussion items, outside the neoclassical transport with Monte Carlo

- Monte Carlo operators for ICRH heating, and CX reactions
- How to build your Monte Carlo simulation inputs?
- What about reversing the time? Can we do "backwards Monte Carlo"?