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FÜR PLASMAPHYSIK

ICRH simulations for the Wendelstein 7-X stellarator

Wendelstein 7-X

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EUROfusion

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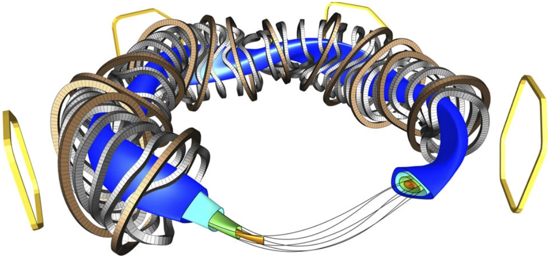
The ICRH system at Wendelstein 7-X



- W7-X is a large, superconducting, optimized stellarator being operated at Greifswald, Germany[1]
- the plasma can be heated via ECRH, NBI, and ICRH

[1]T. Sunn Pedersen et al., *Nature Communications* **7**, 13493 (2016)
[2]J. Ongena et al., *Phys. Plasmas* **21**, 061514 (2014)

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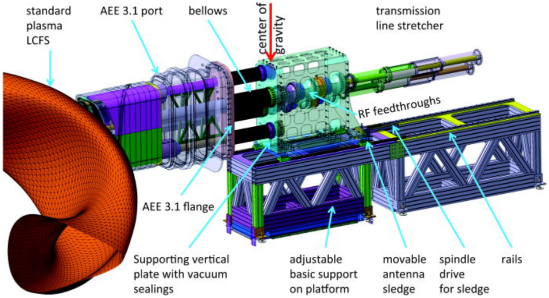

- W7-X is a large, superconducting, optimized stellarator being operated at Greifswald, Germany[1]
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The ICRH system:

- two-strap antenna whose shape is adjusted to the LCFS of the standard configuration[2]
- so far: 0- and π-phasing of the antenna straps
- operational frequencies: $f = 25$ or $37.5\ \mathrm{MHz}$
- typical heating scenarios at $2.5\ \mathrm{T}$:
  - H-minority heating at $37.5\ \mathrm{MHz}$
  - heating of ^{3}He (minority- or 3-ion scheme) at $25\ \mathrm{MHz}$
- other uses: low-field start-up and wall conditioning

[1] T. Sunn Pedersen et al., *Nature Communications* **7**, 13493 (2016)
[2] J. Ongena et al., *Phys. Plasmas* **21**, 061514 (2014)

Models of different complexity for describing ICRH physics in W7-X

- goal: give an overview of the tools currently used for ICRH modelling at W7-X

- SCENIC[3] is the workhorse for modelling ICRH in W7-X numerically
  - hot-plasma model
  - coupled to Fokker-Planck solver VENUS-LEVIS[4] to include contributions of fast ions to dielectric tensor
  - numerically expensive $\longrightarrow$ cheaper and simplified tools are desirable

- new overview tool has been developed[5] for quickly plotting locations of resonances, cut-offs, and evanescence layers $\longrightarrow$ complements the SCENIC modelling
  - cold-plasma model
  - interfaced with the VMEC webservice[6] for the magnetic equilibrium (magnetic field and coordinate transformations)
  - fast and flexible
  - can be used for initial analysis of an experiment and can inform planning of future experiments

[3] M. Jucker et al., *Comput. Phys. Commun.* **183**, 912-925 (2011)

[4] D. Pfefferlé et al., *Comput. Phys. Commun.* **185**, 3127-3140 (2014)

[5] C. Slaby, An overview tool for ICRH physics in Wendelstein 7-X, *IPP Report* (2024)

[6] M. Grahl et al., *IEEE Transactions on Plasma Science* **46**, 1114 (2018)

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A simple cold-plasma model

- we use the cold-plasma dielectric tensor as derived by e.g. T.H. Stix[7] (for $\mathbf{B} = B\hat{\mathbf{z}}$)

$$\underline{\varepsilon} = \begin{pmatrix} S & \mathrm{i}D & 0 \\ -\mathrm{i}D & S & 0 \\ 0 & 0 & P \end{pmatrix} \tag{1}$$

with

$$S = 1 + \sum_\alpha \frac{\omega_{\mathrm{p}\alpha}^2}{\Omega_\alpha^2 - \omega^2} \qquad D = \sum_\alpha \frac{\omega_{\mathrm{p}\alpha}^2 \Omega_\alpha}{\omega\left(\Omega_\alpha^2 - \omega^2\right)} \qquad P = 1 - \sum_\alpha \frac{\omega_{\mathrm{p}\alpha}^2}{\omega^2} \tag{2}$$

and

$$\omega_{\mathrm{p}\alpha} = \sqrt{\frac{q_\alpha^2 n_\alpha}{m_\alpha \varepsilon_0}} \qquad \Omega_\alpha = \frac{q_\alpha B}{m_\alpha} \tag{3}$$

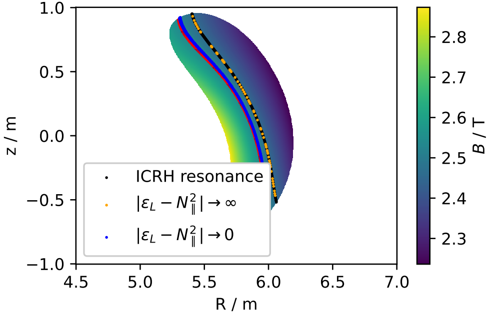
- can easily be derived from multi-fluid model, start with linearized momentum equation for species α, set $T_\alpha = 0$, which gives an expression

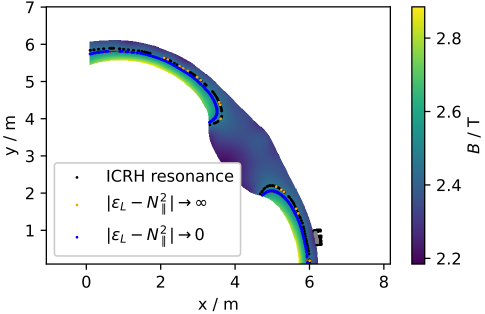
$$\mathbf{j} = \sum_\alpha q_\alpha n_\alpha \mathbf{u}_\alpha = \ldots = \underline{\sigma}\mathbf{E} \tag{4}$$

to be combined with Maxwell's equations

[7] T.H. Stix, *Waves in Plasmas*, American Institute of Physics, New York (1992)

Overview tool: ^{4}He-(H) minority-heating scheme: a basic scenario for W7-X





^{4}He-(H) minority-heating scheme

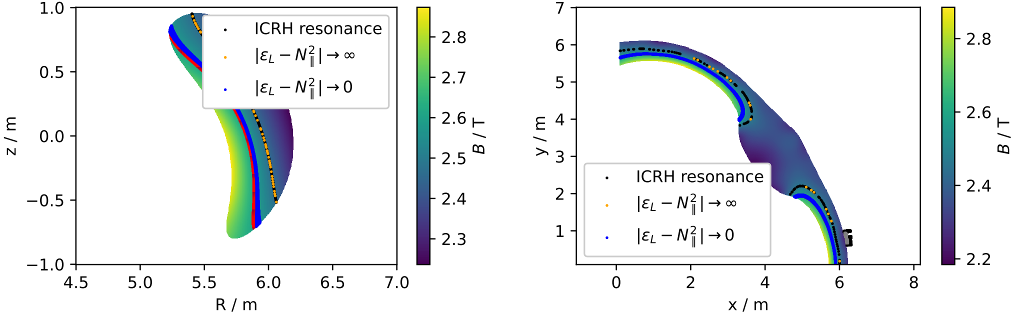
- density fractions ($n_{\mathrm{e},0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3}$)

species α	e^-	$^4\mathrm{He}$	H
n_α / n_e	1.0	0.475	0.05

- L-cutoff and evanescence layer form mode-conversion layer on the HFS of the ICRH resonance
- locations of L-cutoff and resonance not exactly the same
- with increasing minority-density fraction: MC-layer moves further to the HFS and away from the resonance location

$\Rightarrow$ heating and fast-ion generation will become less efficient

Overview tool: ^{4}He-(H) minority-heating scheme: a basic scenario for W7-X



^{4}He-(H) minority-heating scheme

- density fractions ($n_{e,0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3}$)

species α	e^-	$^4\mathrm{He}$	H
n_α / n_e	1.0	0.45	0.10

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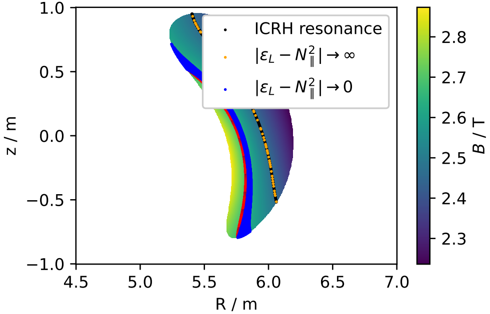

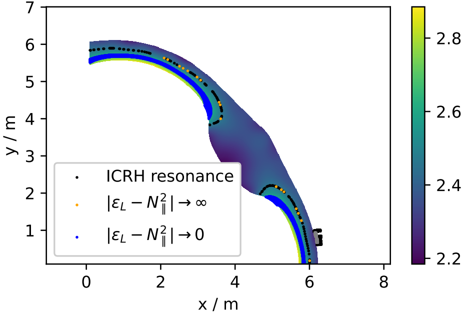

^{4}He-(H) minority-heating scheme

- density fractions ($n_{\mathrm{e},0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3}$)

species α	e^-	$^4\mathrm{He}$	H
n_α / n_e	1.0	0.425	0.15

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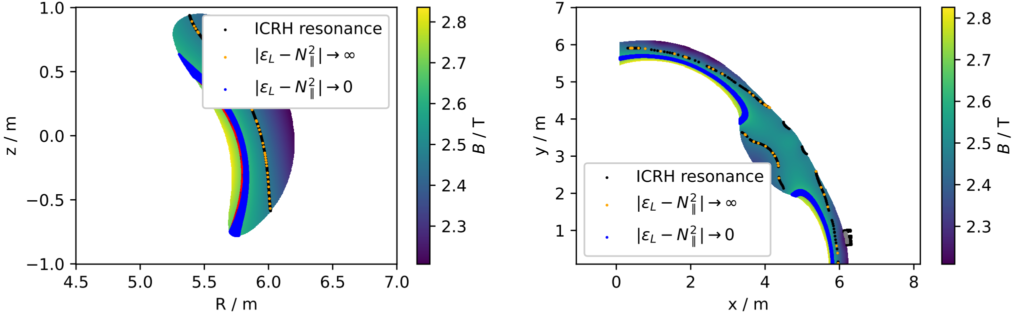

^{4}He-(H) minority-heating scheme

- density fractions ($n_{e,0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3}$)

species α	e^-	^{4}He	H
n_α/n_e	1.0	0.425	0.15

- magnetic configuration impacts the location of the ICRH resonance
- while in the standard configuration the resonance leaves the plasma, a resonance is present at all toroidal angles in the **low-mirror configuration**

$\Rightarrow$ implications regarding power absorption, heating, and fast-ion generation

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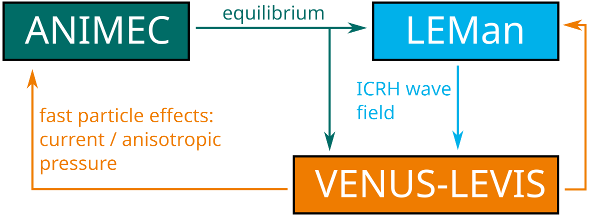
The SCENIC code

- the numerical tool used to model ICRH physics in 3D equilibria is the SCENIC code[8] developed at EPFL



$$\nabla^2 \mathbf{A} + k_0^2 \hat{\epsilon} \cdot \mathbf{A} + ik_0 \hat{\epsilon} \cdot \nabla \phi = -\frac{4\pi}{c} \mathbf{j}_{\mathrm{ant}}$$

$$\nabla \cdot (\hat{\epsilon} \cdot \nabla \phi) - ik_0 \nabla \cdot (\hat{\epsilon} \cdot \mathbf{A}) = -4\pi \rho_{\mathrm{ant}}$$

$$\left\langle \Delta v_\perp^2 \right\rangle = \tau^2 \gamma \frac{Z_\alpha^2}{m_\alpha^2} \left| E^+ e^{-i\psi} J_{n-1} \left(\frac{k_\perp v_\perp}{\Omega_c} \right) + E^- e^{+i\psi} J_{n+1} \left(\frac{k_\perp v_\perp}{\Omega_c} \right) \right|^2$$

$$\dot{\mathbf{X}} = v_\parallel \frac{\mathbf{B}^\star}{B_\parallel^\star} + \frac{\mathbf{E}^\star \times \mathbf{b}}{B_\parallel^\star}$$

$$\dot{v}_\parallel = \frac{q}{m} \frac{\mathbf{B}^\star \cdot \mathbf{E}^\star}{B_\parallel^\star}$$

- SCENIC implements iterative procedure of three (coupled) codes
  - ANIMEC: anisotropic equilibrium / otherwise similar to VMEC
  - LEMan: full-wave code / plasma enters with its dielectric tensor using a hot-plasma model accurate to all orders in Larmor radius
  - VENUS-LEVIS: particle following in W7-X equilibrium using pre-computed ICRH wave field to apply ICRH kicks to the particles in a Monte-Carlo sense

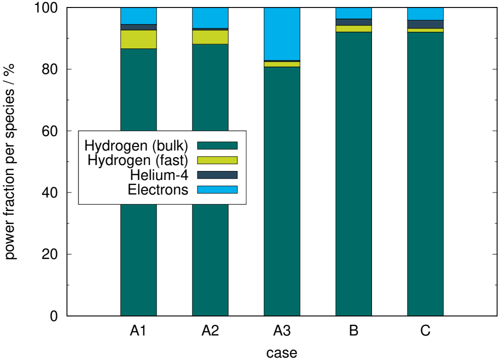
[8] M. Jucker et al., *Comput. Phys. Commun.* **183**, 912-925 (2011)

The SCENIC code

What do we use SCENIC for?

- provide theoretical support for ICRH operation at W7-X
- assess power absorption, build-up of a fast-ion distribution function and particle losses
- model “standard heating scenarios” such as the minority heating scenario of H in a ^{4}He-plasma (first scenario to be investigated in detail for W7-X)
  - verify that power is indeed absorbed by H-minority
  - check fast-ion generation capabilities of this scheme
- model advanced heating scenarios such as the 3-ion scheme or combined RF-NBI scenarios
- provide input (profiles, distribution functions, lost-particle data) for other fast-ion codes

Direct RF-power absorption for (H)-^{4}He minority scheme in W7-X



- scan of the minority concentration (5% - 15%) performed[9]
- the simulations confirm that most of the power ($> 90\%$) goes to Hydrogen minority
- electrons usually receive the second largest amount of power
- their fraction can increase significantly if too much Hydrogen is in the plasma (case A3)
- very little power goes to the bulk Helium

A*: $n_{\mathrm{e},0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3}$ with increasing minority fraction

B: $n_{\mathrm{e},0} = 1.0 \cdot 10^{20}\ \mathrm{m}^{-3}$

C: $n_{\mathrm{e},0} = 1.5 \cdot 10^{20}\ \mathrm{m}^{-3}$

[9] C. Slaby et al., *J. Phys.: Conf. Ser.* **2397**, 012006 (2022)

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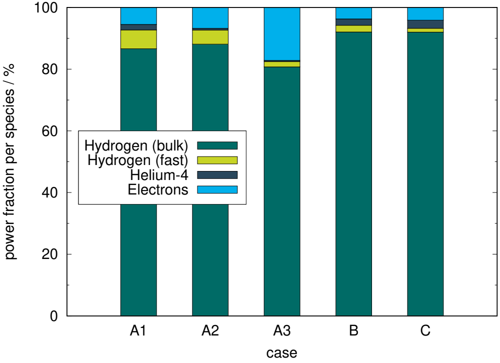

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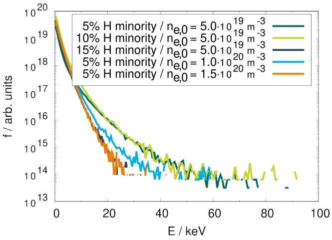
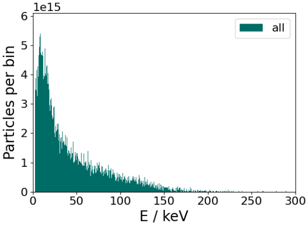
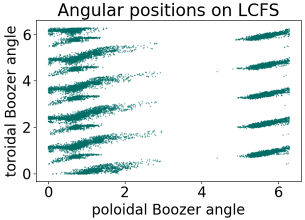
take-away message: regular minority scheme offers good power absorption over a wide range of plasma parameters

[9] C. Slaby et al., *J. Phys.: Conf. Ser.* **2397**, 012006 (2022)

Fast-ion distribution functions and lost particles





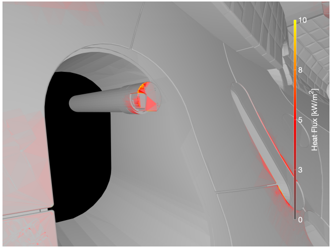


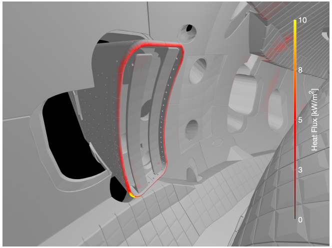
- H minority absorbs least amount of power at 15% concentration at $n_{\mathrm{e},0} = 5.0 \cdot 10^{19}\ \mathrm{m}^{-3} \Longrightarrow$ fewer fast ions (power is also shared among more particles)[10]
- SCENIC only simulates the interior of the plasma, $s \leq 1$, but records lost-particle data
- data used to restart particles in an ASCOT simulation which is able to treat the SOL and includes a full model of the 3D wall with all components

$\Rightarrow$ find hot spots / compare to NBI / assess machine safety aspects

[10] C. Slaby et al., *J. Phys.: Conf. Ser.* **2397**, 012006 (2022)

ICRH-induced wall loads





- shown are the wall-loads on the MPM and the ICRH antenna itself
- power going to the wall is less than for NBI-generated fast ions[11] (understandable since ICRH antenna only injects $\approx 1\ \mathrm{MW}$) $\rightarrow$ acceptable wall loads[12]
- simulations show that MPM is hit by fast ions $\rightarrow$ good news for FILDs

[11] J. Kontula et al., *Plasma Phys. Control. Fusion* **65**, 075008 (2023)
[12] C. Slaby et al., *J. Phys.: Conf. Ser.* **2397**, 012006 (2022)

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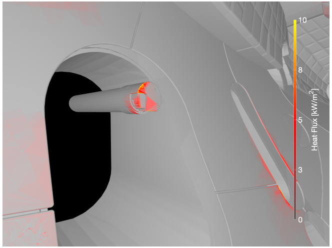

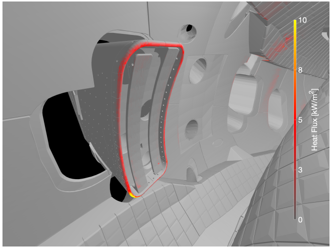

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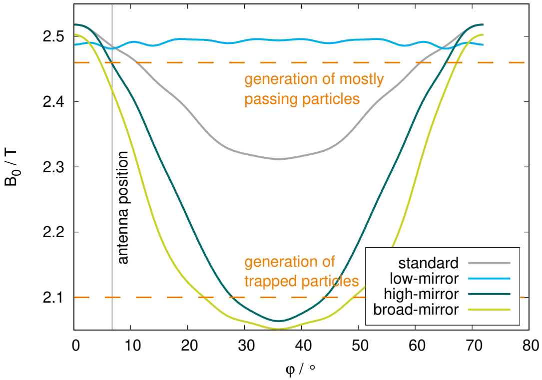
- simulations show that MPM is hit by fast ions $\rightarrow$ good news for FILDs
- SCENIC-ASCOT coupling established / heat loads to be reassessed for other heating schemes

[11] J. Kontula et al., *Plasma Phys. Control. Fusion* **65**, 075008 (2023)
[12] C. Slaby et al., *J. Phys.: Conf. Ser.* **2397**, 012006 (2022)

Finding scenarios that favour the generation of deeply trapped fast ions

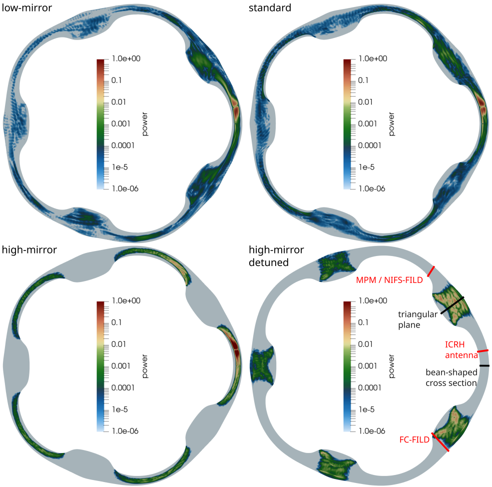
- generating deeply trapped collisionless fast ions (needed to prove the optimisation) is an experimental challenge ⇒ NBI does not populate deeply trapped orbits well[13]

- ICRH antenna is located in a region of high field strength → mostly passing particles will be generated if resonance is placed in front of the antenna
- ICRH antenna more flexible than NBI → change antenna frequency to place the resonance in the triangular plane thus generating deeply trapped fast ions



[13] S.A. Lazerson et al., *Phys. Plasmas* **31**, 072506 (2024)

Shifting the resonance

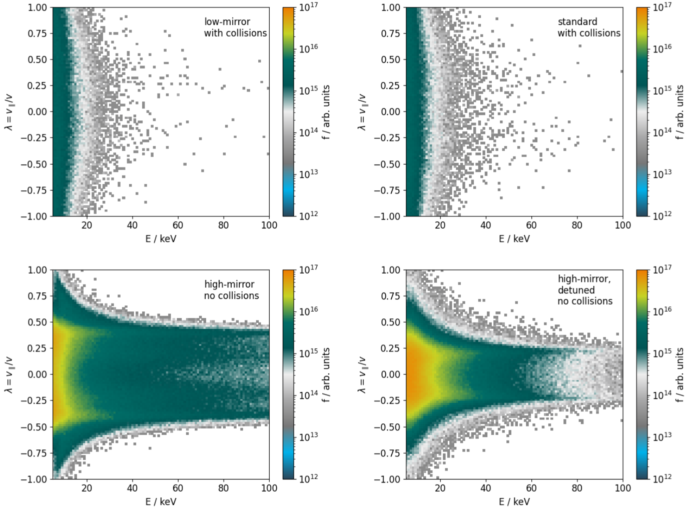


- LEMan simulations confirm that regions of power deposition can indeed be shifted to regions of low B (if the mirror ratio of the configuration allows for it)[14]
- detuning not possible in low-mirror or standard configuration
- antenna position and locations of some important fast-ion diagnostics indicated in the bottom-right plot
- experimentally: only $f_{\mathrm{ant}} = 25\ \mathrm{MHz}$ or $37.5\ \mathrm{MHz}$ were originally foreseen $\rightarrow$ performing such detuned scenarios would require changes to the generators and a re-tuning of the transmission lines

$\Rightarrow$ a plan for future operation phases

[14] C. Slaby et al., *accepted by Plasma Phys. Control. Fusion* (2025)

Fast-ion distribution functions for detuned scenarios

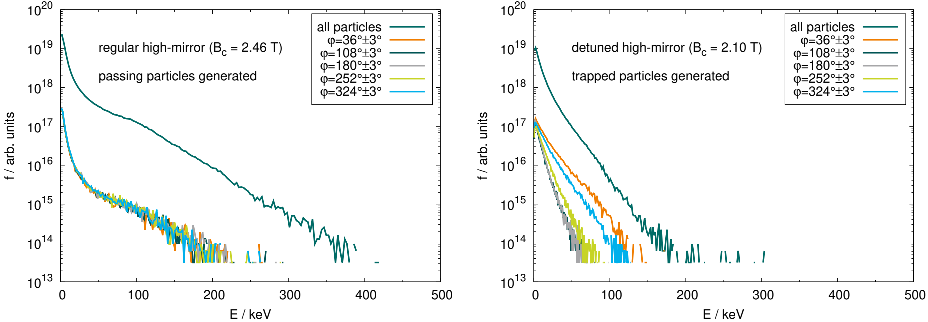


- collisions rapidly isotropize velocity space and prevent formation of a highly energetic fast-ion distribution function
- without collisions, the beneficial effect of detuning the antenna frequency can be seen more clearly

$\Rightarrow$ extent of distribution function in λ-direction becomes more narrow

- simulations with collisions but with higher T_e (increases slowing-down time) $\Rightarrow$ they fall between the extremes shown here

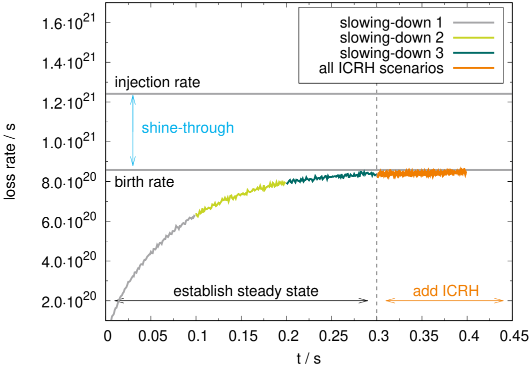
Toroidal asymmetry of the fast-ion distribution function (collisionless)



- if passing particles are generated, the distribution function is identical at every toroidal angle
- if predominantly trapped fast ions are generated, the particles cannot leave the field period in which they are generated in and more fast ions reside in modules close the ICRH antenna → detectors should be placed there (much better signal-to-noise ratio)[15]

[15] C. Slaby et al., *accepted by Plasma Phys. Control. Fusion* (2025)

Combined RF-NBI scenarios

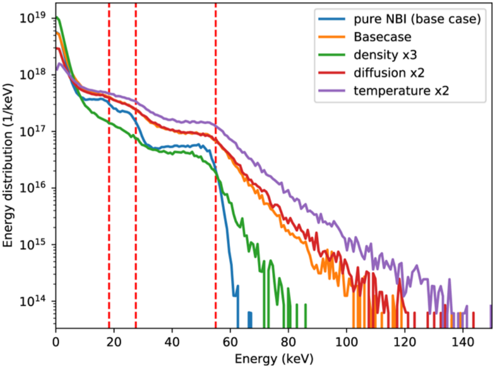


- SCENIC can model NBI deposition and the subsequent slowing-down of the NBI ions[16,17]
- typically several slowing-down simulations necessary until steady-state is reached
- adding ICRH accelerates the already fast particles further

$\Rightarrow$ higher energies ($> 100\ \mathrm{keV}$) can be reached compared to using only NBI

[16] M. Machielsen et al., *J. Plasma Phys.* **89**, 955890202 (2023)
[17] C. Slaby et al., *20th European Fusion Theory Conference (EFTC)*, Padua, Italy (2023)

Combined RF-NBI scenarios



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[17] C. Slaby et al., *20th European Fusion Theory Conference (EFTC)*, Padua, Italy (2023)

Contents

Summary and conclusions

- ICRH physics at W7-X is investigated with the SCENIC code
  - direct RF-power absorption, fast-ion generation, trapped and passing, RF-NBI
- also simpler tools than SCENIC are in use for designing and analyzing experiments with ICRH
  - ICRH overview tool
- see poster Wednesday-23 by D. Hartmann for first experimental results with the ICRH antenna at W7-X

Ongoing and future work

- development of a new ICRH full wave code based on integral kernels and finite elements instead of Fourier expansions (ENR project led by LPP ERM-KMS Brussels)
  - better coupling to antenna models (e.g. PETRA-M), local mesh refinement
  - see also I-16 by P.U. Lamalle and poster Tuesday-21 by B. Reman for the theory behind the approach and first numerical results