Modelling of Heating and Current Drive Systems

Antti Snicker, Senior Scientist

23/07/2026 ITER International School 2026

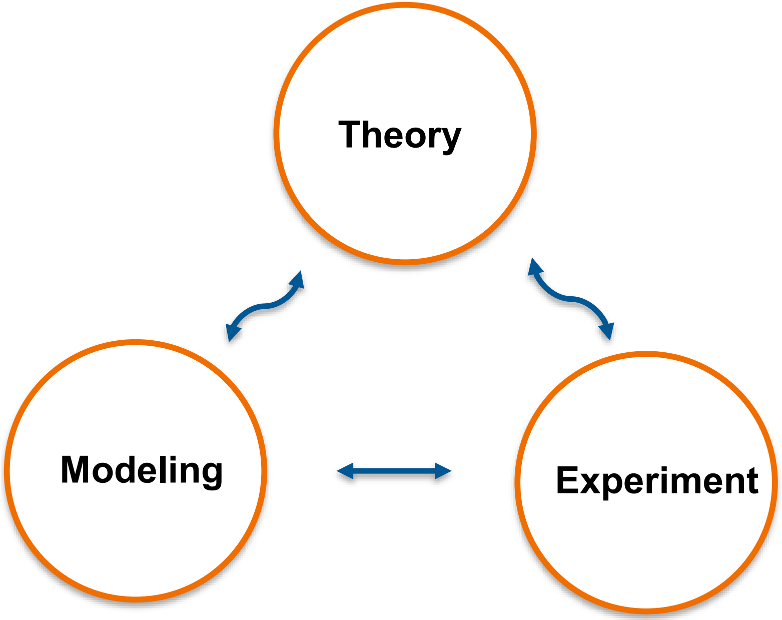
Focus: NBI, ICRH, ECRH

Not covering: theory, technology.

Disclaimer: Emphasis on my own/group’s work

Physics triangle

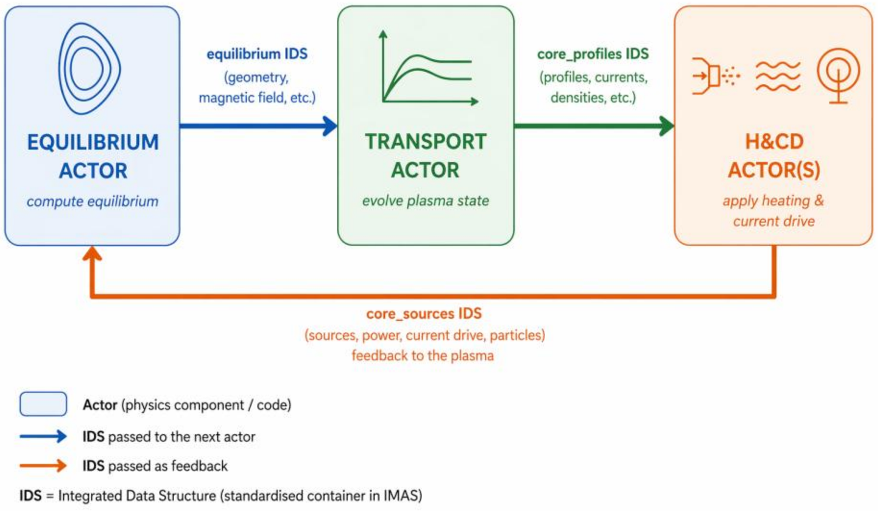
- Theory - Understanding fundamental processes
- Experiment - measuring and discovering physics
- Modeling - connecting theory and experiment



<u>Models with fundamental physics guide design of experiments!</u>

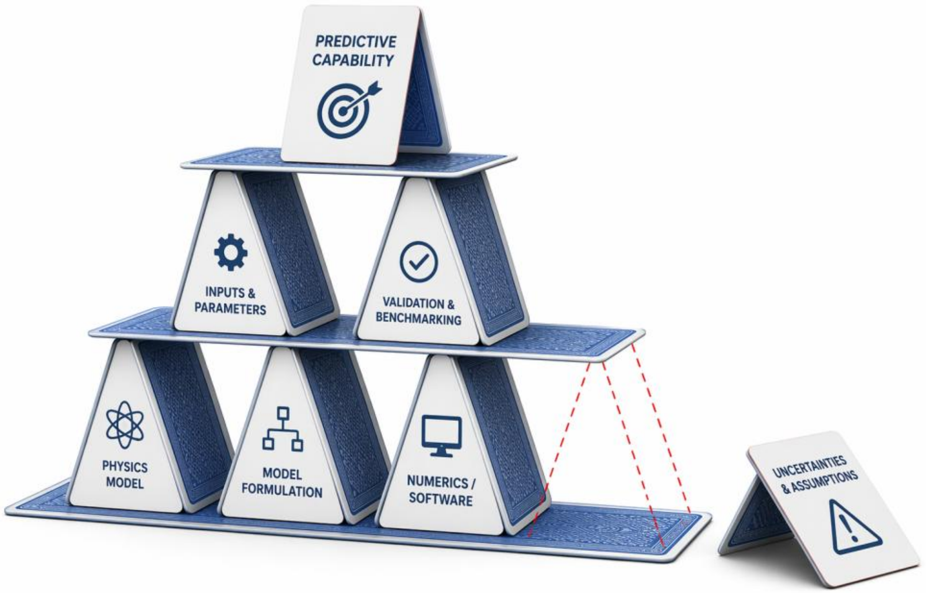
Integrated Modelling in ITER (IMAS)

- No single model describes the full fusion plasma
- Predictive capability comes from chaining models
  - Spanning multiple spatial and temporal scales
- Outputs of one model become inputs to another



What you should take away?

- Models rely on assumptions
- These define a range of validity
- Outside this range results become unreliable or misleading
- "Great model misused is worse than no model"



Content

Introduction
<u>Neutral beam injection (NBI)</u>
Electron cyclotron resonance heating (ECRH)
Ion cyclotron resonance heating (ICRH)
Lessons learned

Neutral Beam Injection (NBI): modeling

- Coupled multi-stage process
- Neutral source → beam attenuation → fast ion source → kinetic transport
- Requires integration of beam physics, kinetic transport, collisional processes
- Typical quantities of interest:
  - Current drive (profile or integrated)
  - NBI losses (fraction or MW/m^2)
  - Deposition (profiles or MW)
  - Shine-through (fraction or MW/m^2)

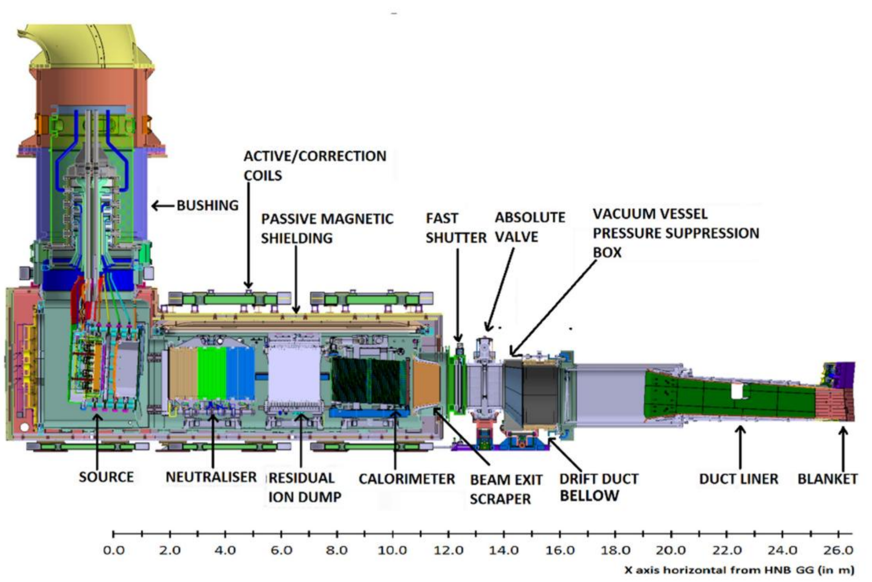


Figure: MJ Singh *et al.*, New Journal of Physics, 19(5):055004, 2017.

Neutral Beam Attenuation → NBI Source

- Beam propagation via ray tracing / beamlets
- Attenuation: electron ionization + charge exchange
- $dI/ds = -n_e \sigma_{ion} I - n_i \sigma_{CX} I$
- Output: NBI birth distribution

- Tools:
  - BBNBI
  - NUBEAM
  - FAFNER
  - RABBIT
  - Etc…

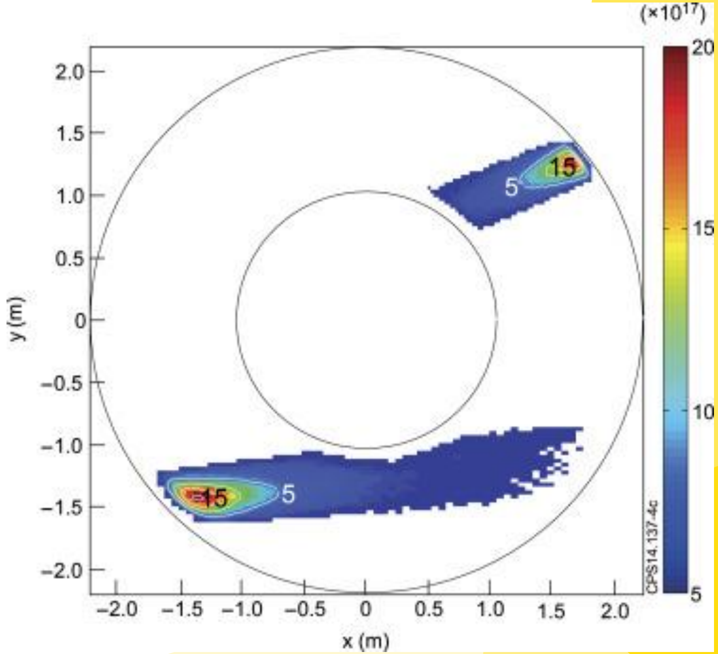


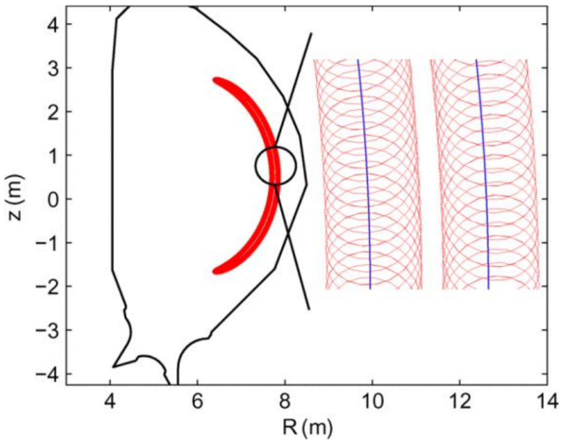
Figure: O Asunta *et al.*, Comp. Phys. Comm., **188,** 33, 2015.

NBI Transport: Kinetic Modelling

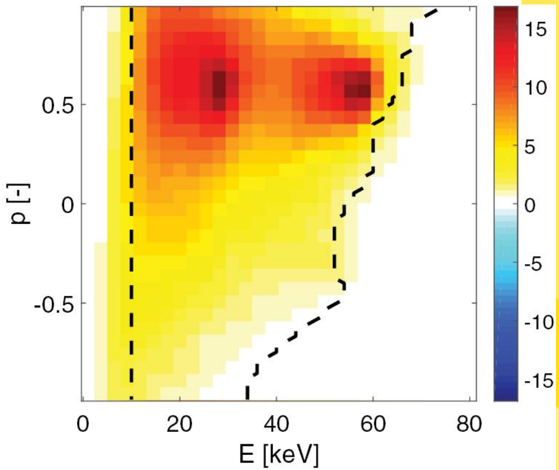
- Guiding centre approximation
- Collisions: slowing-down + pitch scattering

$$\frac{\partial f}{\partial t} + \dot{Z}\cdot\nabla_Z f = C[f] = -\nabla_Z\cdot(Af) + \nabla_Z\cdot(D\nabla_Z f)$$

- Tools:
  - ASCOT5
  - NUBEAM
  - LOCUST
  - RABBIT
  - Etc…



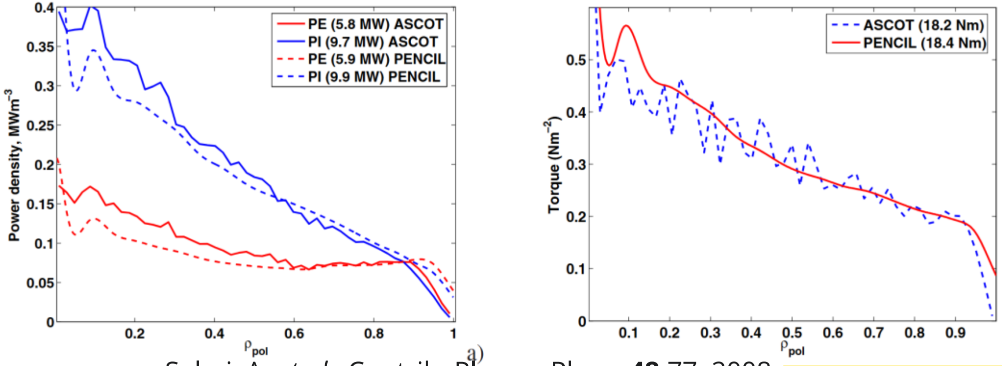
A. Snicker *et al.*, *IEEE Transactions on Plasma Science*, **38**, 2177, 2010



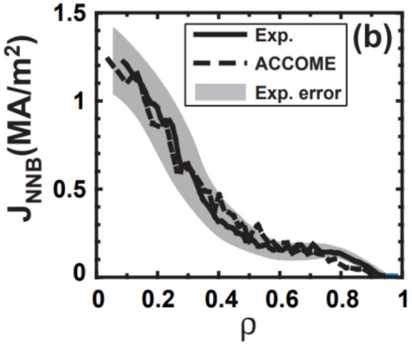
M. Salewski *et al* 2016 *Nucl. Fusion* **56** 106024

From NBI to plasma

- NBI particles deposit energy
- NBI particles drive current
- NBI particles input torque
- These outputs close the loop with transport and equilibrium solvers



Salmi, A. *et al.*, Contrib. Plasma Phys., **48** 77, 2008.



T. Oikawa **et al.,** Nucl. Fusion, **40** 435, 2000

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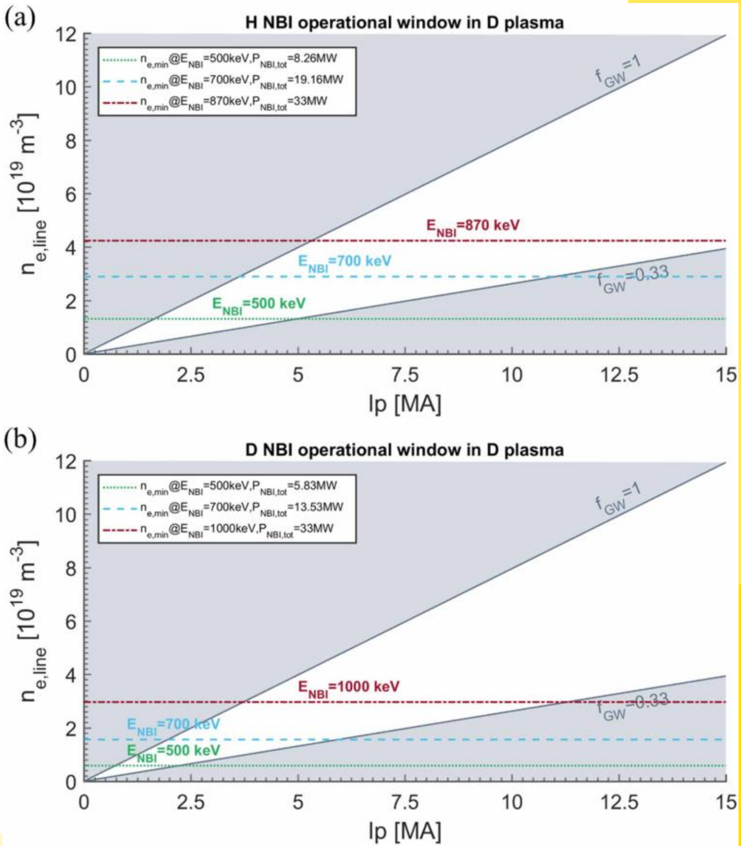
NBI shine-through in ITER

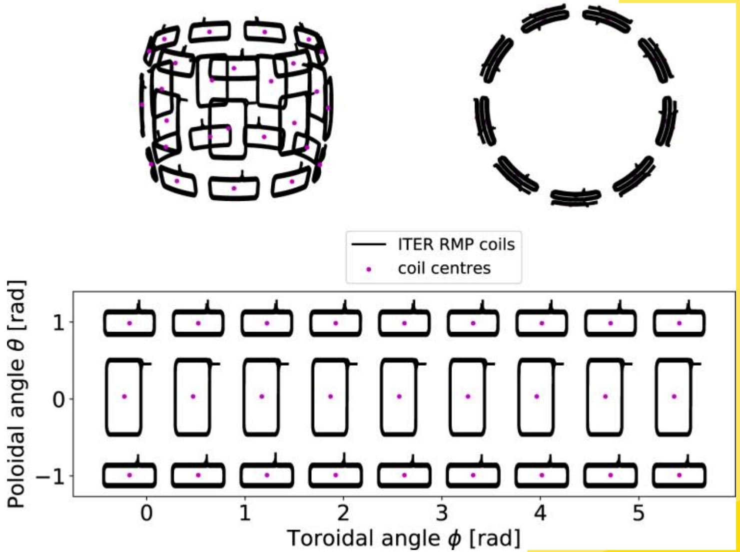
- ITER plans to operate with H and D NBI
- Shine-through can be a real risk
- Uncertainty on the collisional cross-sections
  - ➢ Need to validate on JT-60SA N-NBI
- Shine-though poses a limit for min n_e



P. Vincenzi *et al* 2025 *Nucl. Fusion* **65** 036009

NBI transport/confinement in ITER

- Transport dictated by magnetic field geometry
  - Finite number of TF coils
  - Error fields
  - ELM control coils
  - ➢ Perturbations dominate over Coulomb collisions
- In the absence of 3D fields
  - NBI particles well confined
  - Reduced models are generally fine
- Additional modeling requirements for 3D
  - Details do matter (e.g. plasma response)
  - Reduced models generally fail -> MC rules
  - Unexpected loss mechanisms may appear…



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

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

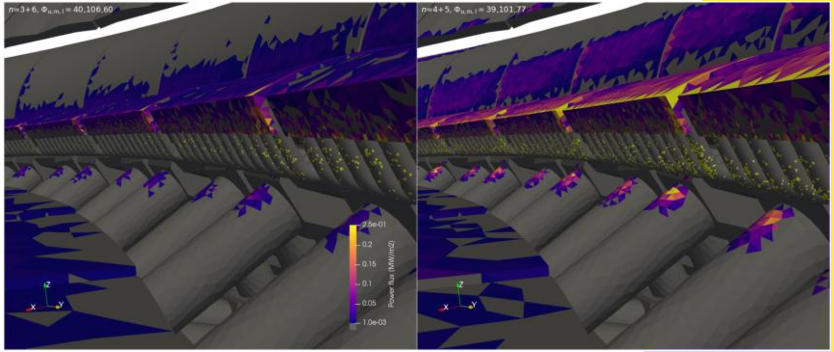
Scenario	α wall load (MW)	α divertor load (kW)	NBI wall load (kW)	NBI divertor load (MW)
7.5 MA	-/-	-/-	12/13	0/3
+TBM	-/-	-/-	19/19	0/3
9 MA	160/160	130/150	6/5	2/4
+TBM	250/270	130/180	15/14	2/9
12.5 MA	510/530	190/190	3/3	1/1
+TBM	580/640	190/210	7/8	1/3
15 MA	20/19	120/120	2/-	1/-
+TBM	39/42	110/130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

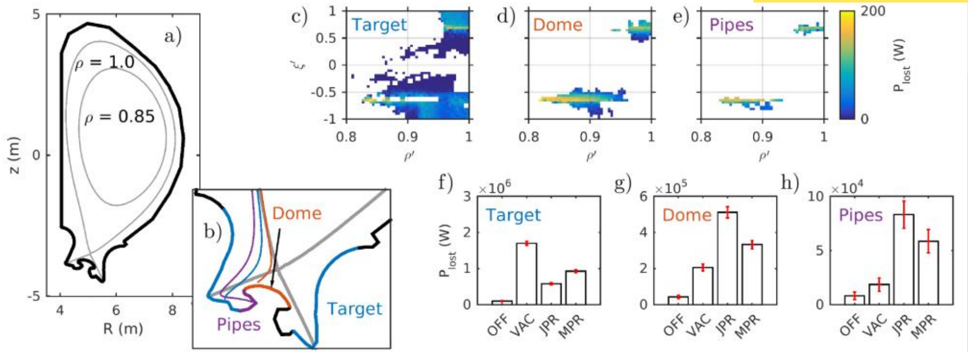
T. Kurki-Suonio *et al* 2016 *Nucl. Fusion* **56** 112024

NBI transport/confinement in ITER

- NBI heat load under the divertor dome
  - Unexpected location
  - Confirmed by multiple models (LOCUST, ASCOT, OFMC)
  - Heat loads of the order of 0.25MW/m^2
- Mechanism explained later on
  - Toroidal variation of the poloidal field
  - Modified orbits hit under the dome pipes



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



Konsta Särkimäki *et al* 2018 *Nucl. Fusion* **58** 076021

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Introduction

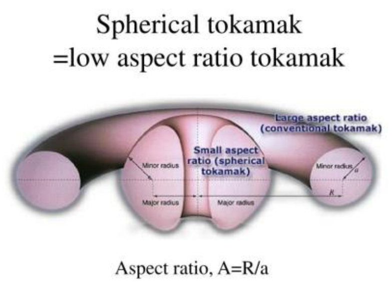
<u>Neutral beam injection (NBI)</u>

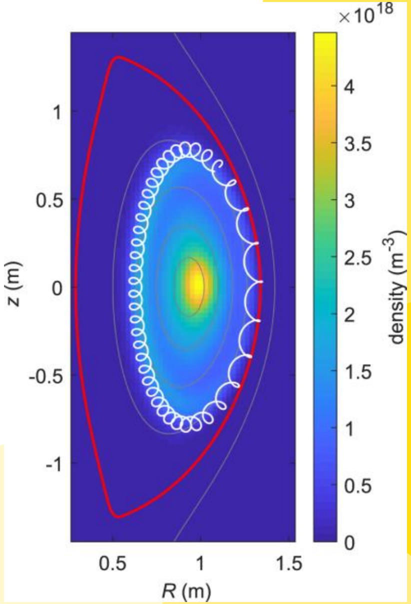
- <u>Introduction</u>
- <u>ITER NBI modeling</u>
- <u>MAST-U NBI modeling</u>

MAST-U is a spherical tokamak

- Features of spherical tokamaks
  - Compact size vs. performance
  - High beta, high bootstrap current
  - Limited space
  - Lower achievable B_{phi}

- Implications for fast ions
  - **Large orbit widths and gyro radius (see right)**
  - Increased prompt losses
  - Sensitivity to MHD
  - **NBI particles probe edge plasma**
  - ➢ Guiding center approximation fails
  - ➢ Interaction with edge neutrals

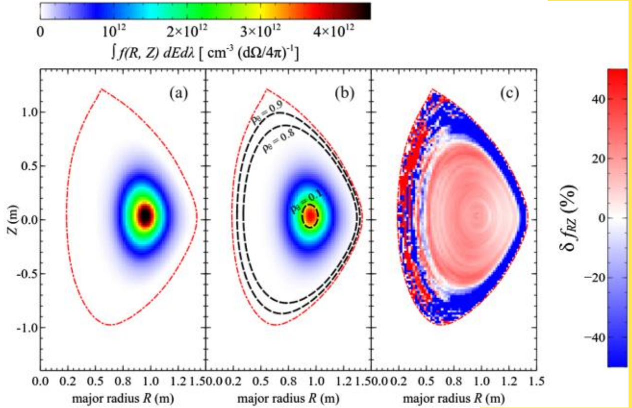




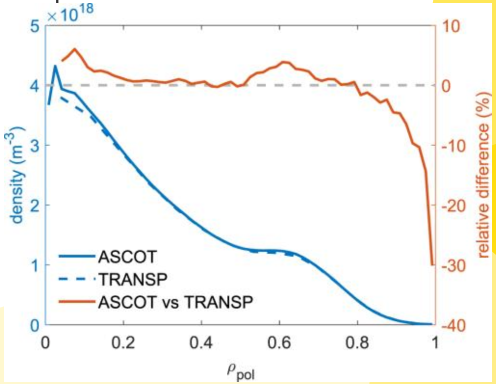
P Ollus *et al* 2022 *Plasma Phys. Control. Fusion* **64** 035014

Guiding centre vs gyro motion

- Strong gradient in the field
  - Guiding centre approximation breaks
  - ➢ Trace full gyro motion
- Modification to distribution function
  - Both in MAST (above) and MAST-U (below)
  - Guiding centre overestimates at the edge
  - Difference is large enough to measure
- Experimentally shown to matter
  - Neutron emission and energy spectrum A Sperduti *et al* 2021 *Plasma Phys. Control. Fusion* **63** 015015
  - FIDA P Ollus *et al* 2024 *Plasma Phys. Control. Fusion* **66** 025009



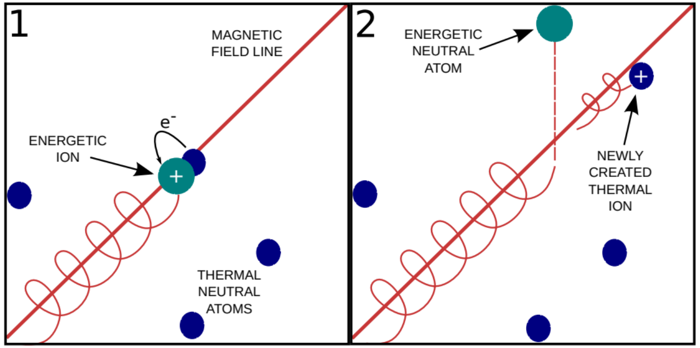
A. Sperduti *et al* 2021 *Nucl. Fusion* **61** 016028



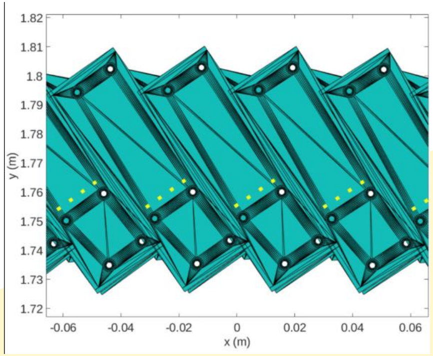
P Ollus *et al* 2022 *Plasma Phys. Control. Fusion* **64** 035014

Charge exchance (CX) reactions

- NBI ions probe edge region
  - Overlap with neutral density
- MAST-U with limited pumping
  - Particularly high neutral density
- NBI transport can be modified by CX
- Experimentally validated
  - Bolometer loads P Ollus *et al* 2025 *Plasma Phys. Control. Fusion* **67** 055039
  - FIDA P Ollus *et al* 2024 *Plasma Phys. Control. Fusion* **66** 025009



P. Ollus. Modelling charge exchange losses of beam ions in the MAST-U spherical tokamak. Master’s thesis, Aalto University, 2019. Available at: https://urn.fi/URN:NBN:fi:aalto-201912226660.



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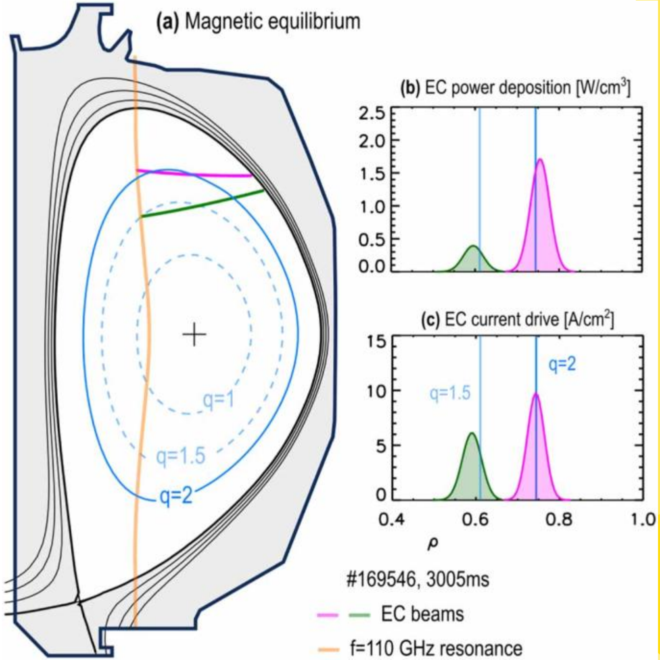
Electron cyclotron heating and current drive

- NBI modeling tracks particles
- EC modelling follows waves
- Wave-particle interaction occurs at cyclotron resonance
- Beam steered with mirrors
  - Narrow absorption
  - Control of local deposition

➢ Goal: simulate heating and current drive profiles



L. Bardóczi *et al* 2023 *Nucl. Fusion* **63** 096021

Modeling EC absorption and current drive

Equilibrium → Kinetic profiles → Ray tracing → Absorption + current drive → Integrated modeling

- Plasma determines wave propagation
- Ray tracing computes beam trajectories
- Absorption determines deposited power
- Numerical models provide ECCD efficiency
- Outputs coupled to transport solvers

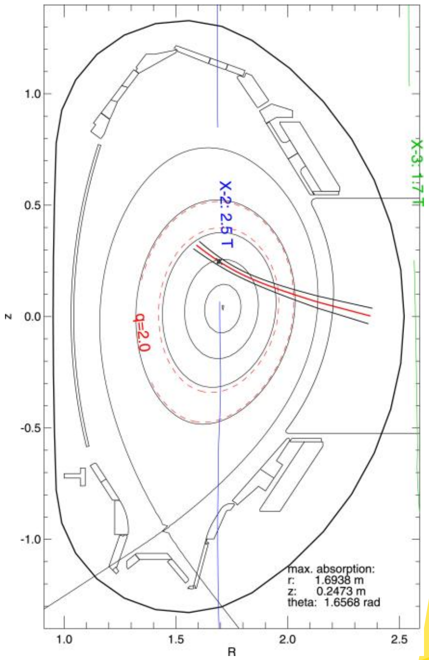
Ray tracing method

- EC wavelengths (~2mm) are typically much smaller than plasma scale lengths (~1m)
- Geometrical optics approximation is valid
- Waves are represented as rays
- Computationally efficient and widely used
- Various implementations:
  - TORBEAM
  - TRAVIS
  - GRAY
  - GENRAY
  - TORAY
  - Etc…

$$D(\mathbf{r}, \mathbf{k}, \omega) = 0$$

$$\frac{d\mathbf{r}}{dt} = -\frac{\partial D/\partial \mathbf{k}}{\partial D/\partial \omega}$$

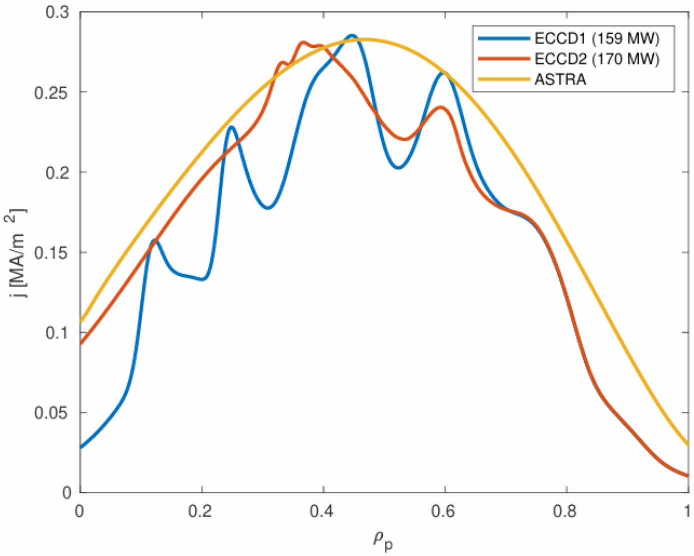
$$\frac{d\mathbf{k}}{dt} = \frac{\partial D/\partial \mathbf{r}}{\partial D/\partial \omega}$$



E. Poli *et al.* Comp. Phys. Comm.,**225**, 36 2018

From absorption to current drive

- Ray tracing determines absorbed power
- Absorbed power modifies electron distribution
- Parallel electrons dominantly heated
- ➢ Asymmetry produces a net plasma current
- Modern EC tools combine ray tracing with current-drive models
  - ECCD profile
  - Total driven current
  - Current drive efficiency



E. Poli et al. EPJ Web of Conferences **313**, 01005 (2024)

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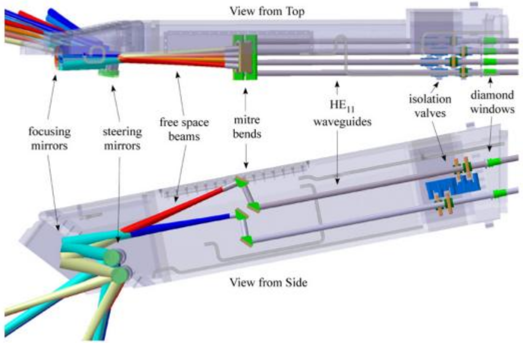
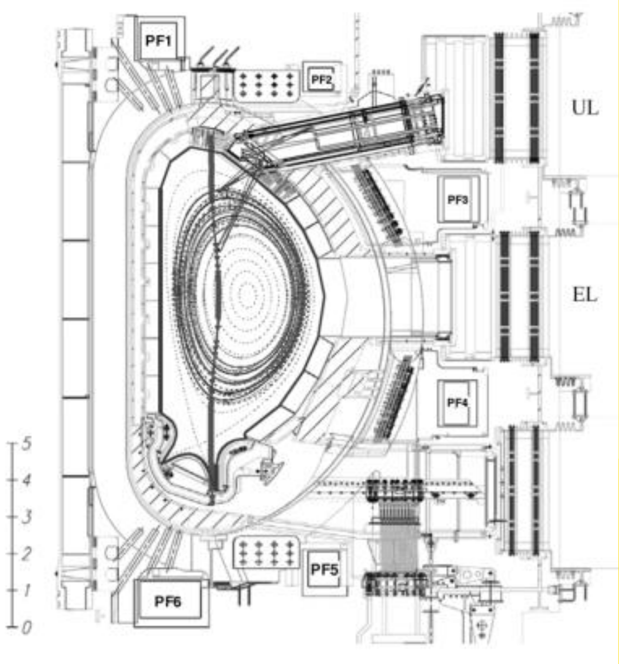
Introduction
Neutral beam injection (NBI)
<u>Electron cyclotron resonance heating (ECRH)</u>

- **Introduction**
- **<u>NTM mitigation in ITER</u>**
- EC with electron density fluctuations

ITER ECCD for neoclassical tearing mode (NTM) control

- NTMs are significant risk for plasma performance
- Can be mitigated with local current drive
- ➢ ECCD is optimal tool for this
- Launcher steering is a key requirement
- Modelling supports design and operation planning

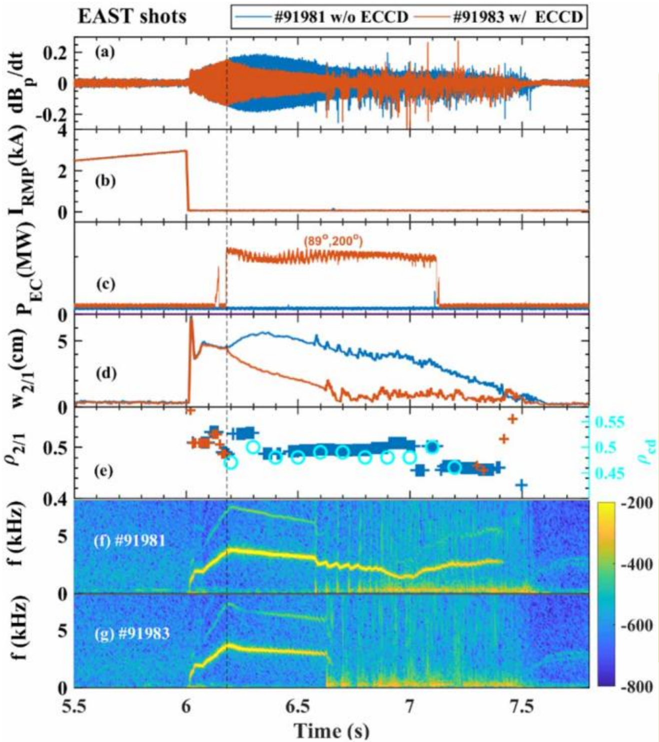




M.A. Henderson *et al* 2008 *Nucl. Fusion* **48** 054013

NTM stabilization requirements in ITER

- ECCD replaces missing bootstrap current
- Need to deposit **inside** the island
- Criterion on current density
  - ➢ Narrower beam beneficial
- ITER design based on
  - Wide modeling effort
  - Validation with current experiments



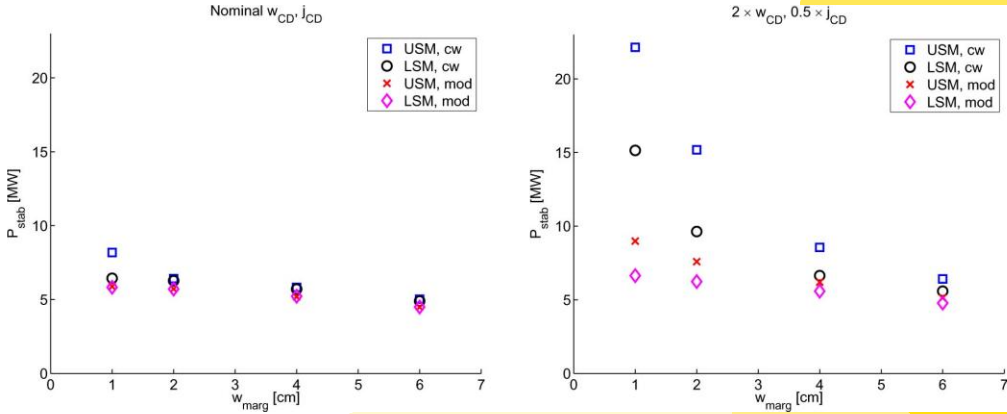
Y. Zhang *et al* 2024 *Nucl. Fusion* **64** 076016

NTM stabilization requirements in ITER

- ECCD replaces missing bootstrap current
- Need to deposit **inside** the island
- Criterion on current density
  - ➢ Narrower beam beneficial
- ITER design based on
  - Wide modeling effort
  - Validation with current experiments
- ITER NTM mitigation challenge
  - ECCD needs to reach q=2 and q=3/2
  - Enough power
  - Sufficiently narrow beam

$$\eta_{\mathrm{NTM}} \equiv \frac{j_{\mathrm{ECCD}}}{j_{\mathrm{BS}}} \gtrsim 1.2$$

H Zohm et al 2007 Plasma Phys. Control. Fusion 49 B341



E. Poli *et al* 2015 *Nucl. Fusion* **55** 013023

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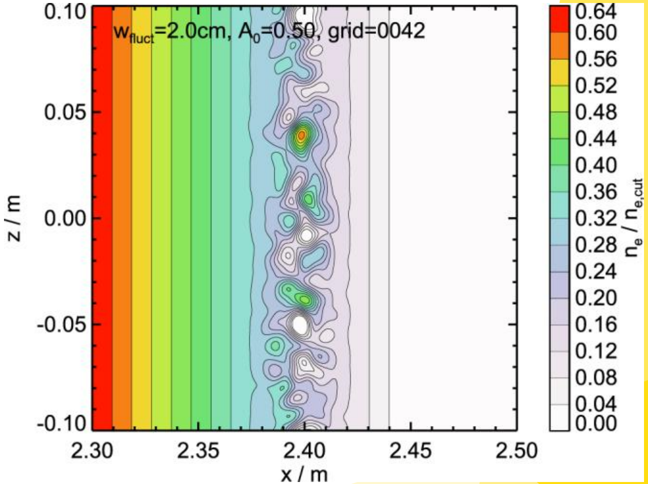
- NTM mitigation in ITER
- <u>EC with electron density fluctuations</u>

Electron density fluctuations break the geometrical optics approximation

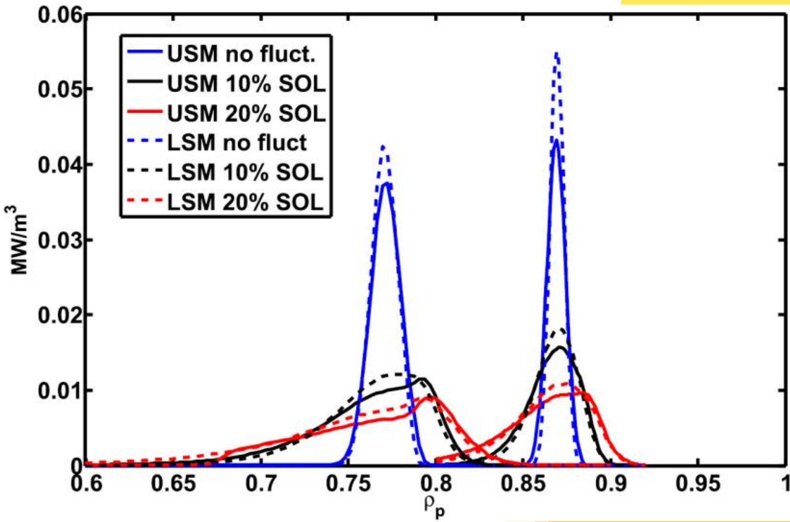
- Electron density fluctuations present in tokamaks
  - Fluctuation amplitudes vary, increase towards the edge
- Density fluctuations act as random lenses
  - ➢ **Geometrical optics not valid**
  - ➢ Disperse the beam
  - ➢ Broadening of the beam
- In the absence of geometrical optics
  - Full wave solvers
  - Wave-kinetic models such as WKBeam
- How does the fluctuations modify NTM mitigation?



A Köhn *et al* 2018 *Plasma Phys. Control. Fusion* **60** 075006

Effect of density fluctuations on EC beam

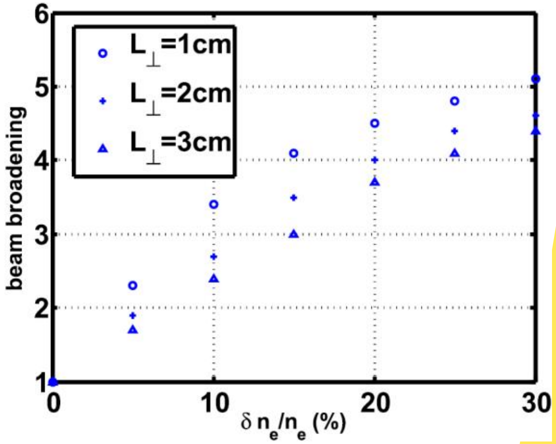
- ITER edge plasma with density fluctuations
- Fluctuations scatter the EC beam
- WKBeam predicts statistically broadened beam
- Broadening can be significant
- ➢ Density fluctuations can transform a well-localized ECCD beam into a substantially broader profile



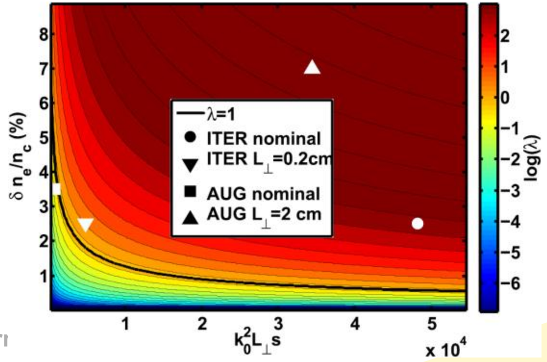
A. Snicker *et al* 2018 *Nucl. Fusion* **58** 016002

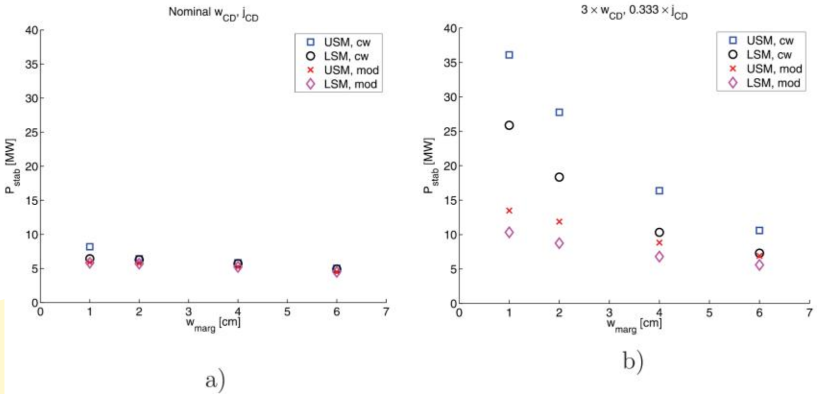
Impact on NTM mitigation

- In ITER, factor of 3-5 broader beam
  - NTM mitigation strategy is challenged
- Need to implement EC modulation
  - Inject power only when island large enough
- Alternatively, inject beam with a clever geometry
- When does this matter:



A. Snicker *et al* 2018 *Nucl. Fusion* **58** 016002





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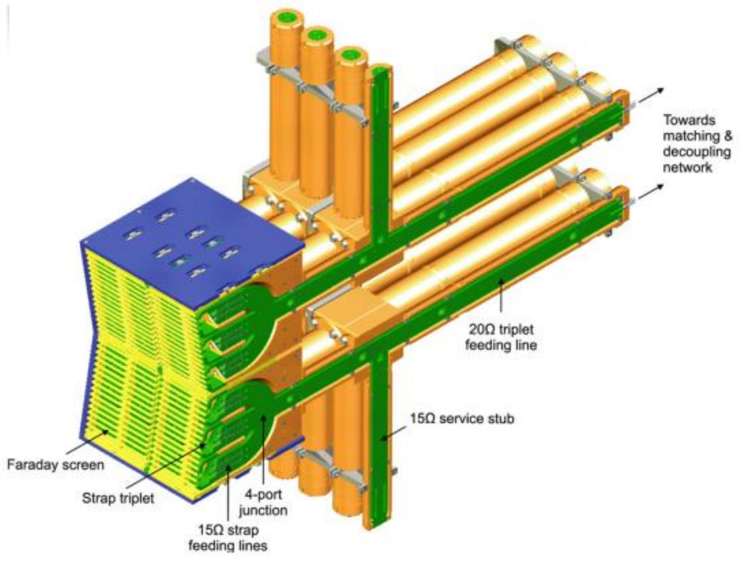
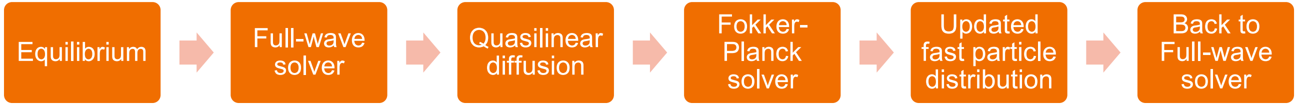
Modeling of ion cyclotron (IC) heating

- RF waves propagate through a multi-species plasma
- Power is absorbed at ion cyclotron resonances
- Absorption accelerates ions in velocity space
- Energetic ions interact with the equilibrium
- ➢ IC modeling significantly more difficult vs EC modeling
- ➢ The wave absorption depends on the ion distribution function, but the ion distribution function depends on the wave absorption
- ➢ Coupled wave and kinetic modeling



A. Messiaen *et al* 2010 *Nucl. Fusion* **50** 025026

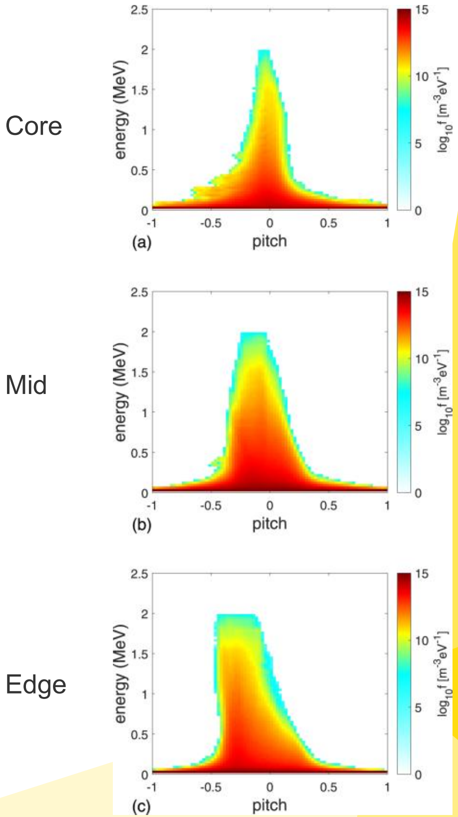
Integrated modeling of ion cyclotron (IC) heating



- Full wave solution provides the wave parameters
- Quasilinear operator describes scattering of ions
- Fokker-Planck solves for distribution function
- Updated distributions are fed to full wave solver
- Iterated until convergence
- ➢ Self-consistent wave and particle solutions

Generation of energetic IC ions

- Resonant ions are accelerated predominantly in perpendicular velocity
- Strongly anisotropic distributions emerge
- Distributions become highly non-Maxwellian
- Orbit effects become increasingly important
- ➢ IC generation can be coupled with orbit-following
- Example loop:
  - TORIC for full wave
  - SFPQL for quasilinear operator + FP
  - RFOF for MC operator
  - ASCOT for orbit-following

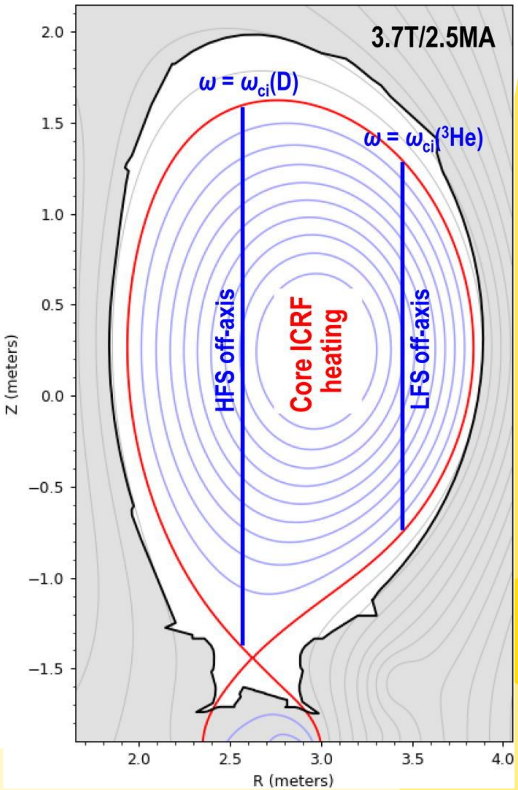


Seppo Sipilä *et al* 2021 *Nucl. Fusion* **61** 086026

ICRH Heating Regimes Depend on Plasma Composition

- **Minority heating**
  - Resonant minority species absorbs RF power
  - Strong fast-ion tail develops
  - Classical ICRH scenario
- **Three-ion heating**
  - Additional ion species modifies wave polarization
  - Enhanced electric field at resonance
  - Very efficient ion heating possible
  - Sensitive to species concentrations
- **Mode conversion**
  - Wave energy converts to short wavelength modes
  - Power transferred predominantly to electrons
  - Reduced energetic-ion population

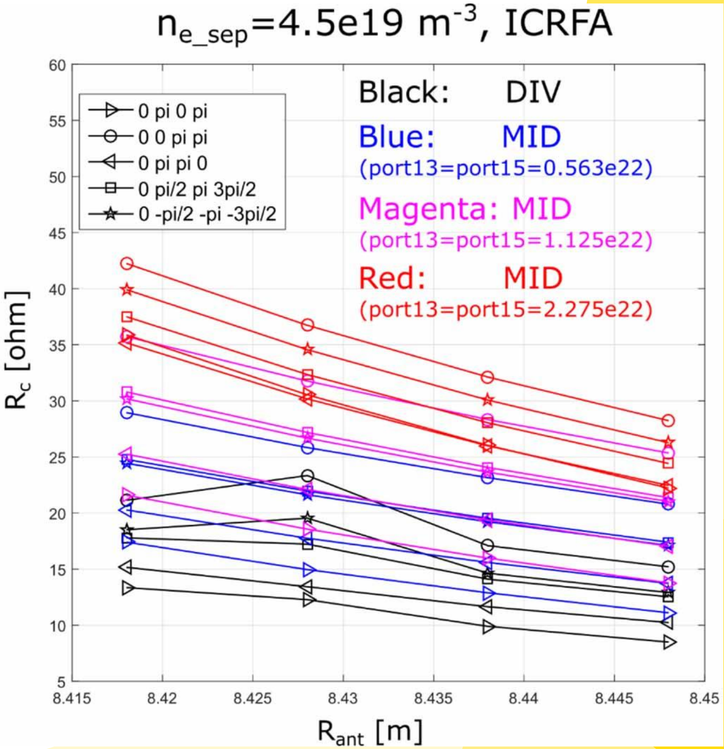
➢ The dominant absorbing species is not always obvious and must be predicted self-consistently



Y. Kazakov *et al.* Phys. Plasmas 28, 020501 (2021)

Coupling of ICRH power

- IC wave is evanescent in vacuum
- Need to:
  - Buff gas in front of the antenna
  - Bring the antenna close to plasma
- Detailed modeling complicated:
  - 3D plasma parameters (density)
  - 3D geometry of the antenna
- Essential for the ITER upgrade 10MW -> 20 MW



W. Zhang *et al* 2023 *Nucl. Fusion* **63** 036008

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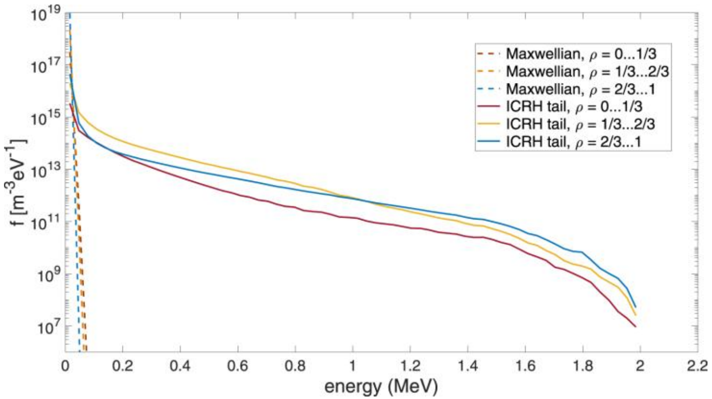
- **Introduction**
- <u>**Application for AUG modeling**</u>
- How to model stellarators?

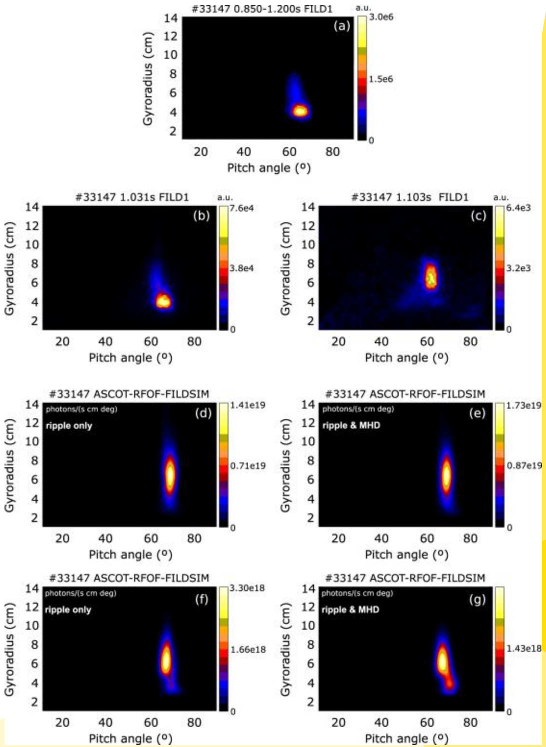
ASCOT/RFOF predicted fast ion losses in AUG

- Fundamental H and 2nd harmonic NBI D heating
- Fast ion loss detector (FILD) signals predicted
- Synthetic and measured FILD signals agree



H IC

D NBI



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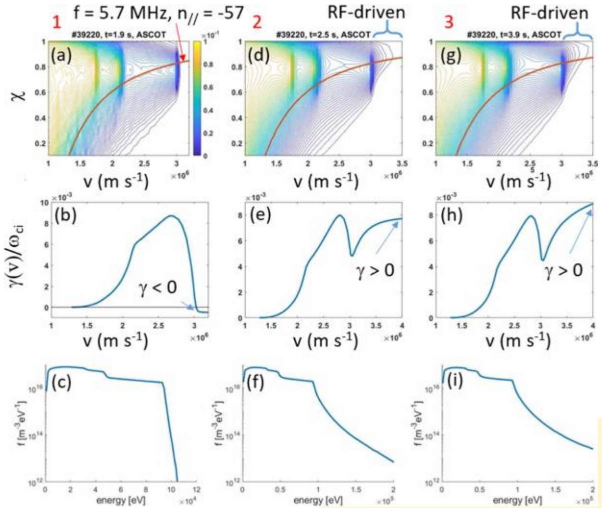
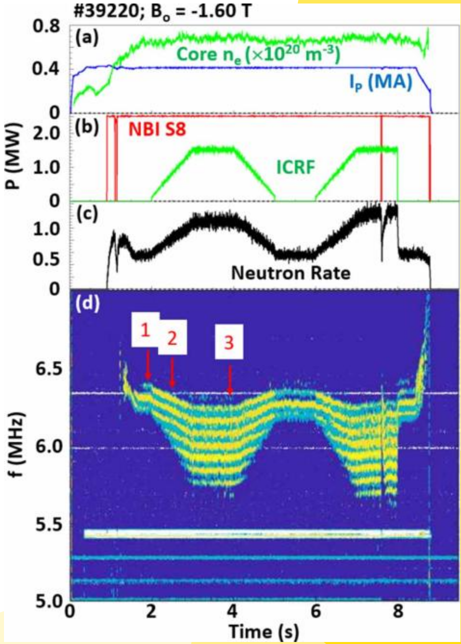
Prediction of modes driven by IC heated ions

- ASCOT+RFOF simulated accelerated IC ions
- Distribution functions used for mode stability
- Predicted modes match observed modes





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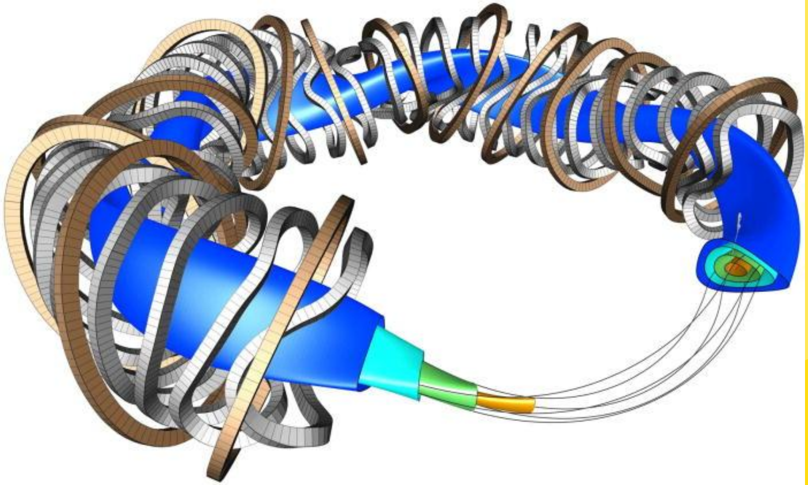
Electron cyclotron resonance heating (ECRH)
Ion cyclotron resonance heating (ICRH)

- Introduction
- Application for AUG modeling
- How to model stellarators?

ICRH in Stellarators: Beyond the Tokamak Paradigm

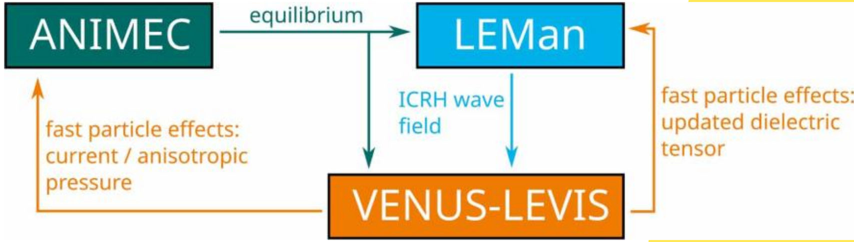
- Tokamak ICRH models assume axisymmetry
- Stellarators exhibit fully 3D geometry
- Cyclotron resonances vary along trajectories
- Fast-ion orbits strongly non-axisymmetric
- Wave-particle interaction can no longer be described using the simplest QL diffusion assumptions
- Alternative solutions:
  - ”Brute-force approach” gyro-orbits with (**E**,**B**) fields
  - Coupled integrated 3D workflow

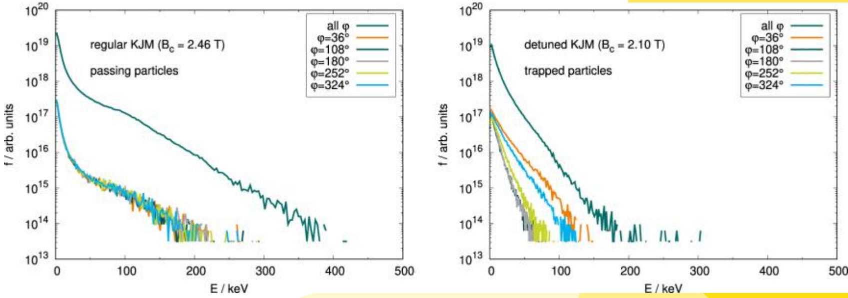


T. Sunn Pedersen *et al.* Phys. Plasmas 24, 055503 (2017)

SCENIC modeling for W7-X

- ICRH ions mimic fusion alphas
- IC efficiency depends on magnetic configuration
- Resonance shifted toroidally with frequency
- Modelling supports optimization of future fast-ion confinement experiments





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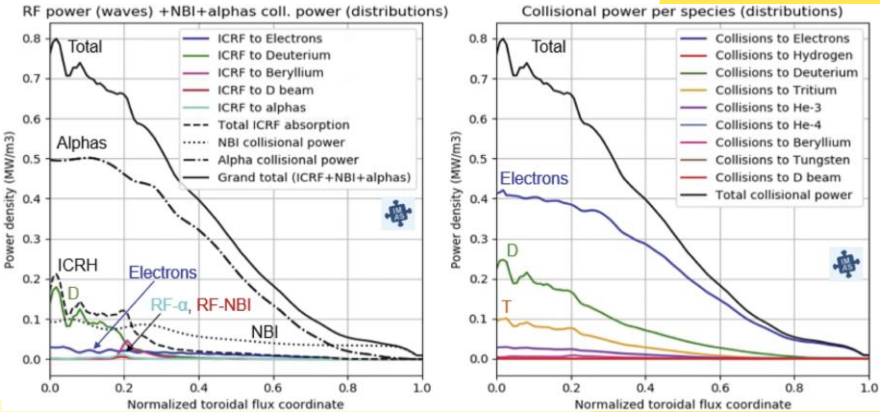
<u>Lessons learned</u>

Interactions Between Heating and Current Drive Systems

- Heating systems modify the plasma observed by other actuators
  - ICRH can accelerate NBI-produced fast ions
  - ECRH modifies temperature and current profiles
  - Changes in profiles affect NBI deposition and RF absorption
- Integrated scenarios require simultaneous consideration of all actuators
- ➢ IMAS is ideal for this kind of analysis

Table 1. List of H&CD codes currently available in the IMAS H&CD workflow.

H&CD sources	ECH	ICRH	NBI	Nuclear reactions
Wave or particle source	GENRAY [9]	CYRANO [13]	BBNBI [21]	AFSI [24]
	GRAY [10]	LION [14]	NEMO [22]	SPOT (α)
	GRAYSCALE [11]	PION [15]		
	TORBEAM [12]	TOMCAT [16]		
Fokker–Planck calculation		ASCOT [17]	ASCOT	ASCOT
		FOPLA [18]	FOPLA	FOPLA
		PION	RISK [23]	SPOT
		SPOT [19]	SPOT	
		STIXREDIST [20]		



Mireille Schneider *et al* 2021 *Nucl. Fusion* **61** 126058

H&CD systems modeling varies in difficulty

- EC modeling
  - Generally ”easy” and uncoupled
  - Ray tracing methods work most of the time
  - Density fluctuations or blobs challenge this approach
- NBI modeling
  - Two-stage approach necessary
  - Deposition of neutrals studied separately
  - Ion transport using orbit-following/FP codes
  - Guiding center approximation can fail
- IC modeling
  - Generally most difficult
  - Waves coupled to particle kinetics
  - Stellarators challenge all main assumptions

"All models are wrong, but some are useful."
— George E. P. Box

”The art of (H&CD) modelling is not knowing how to use the models but knowing which model is applicable for the given problem.”
— Antti Snicker

VTT

beyond the obvious

Thank you!

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