EUROfusion

Ion cyclotron resonance heating modelling of JET, ITER and DEMO scenarios within the European Integrated Modelling (EU-IM) framework

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EUROfusion-IM Team

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European Fusion Theory Conference - Ghent - 7-10/10/2019

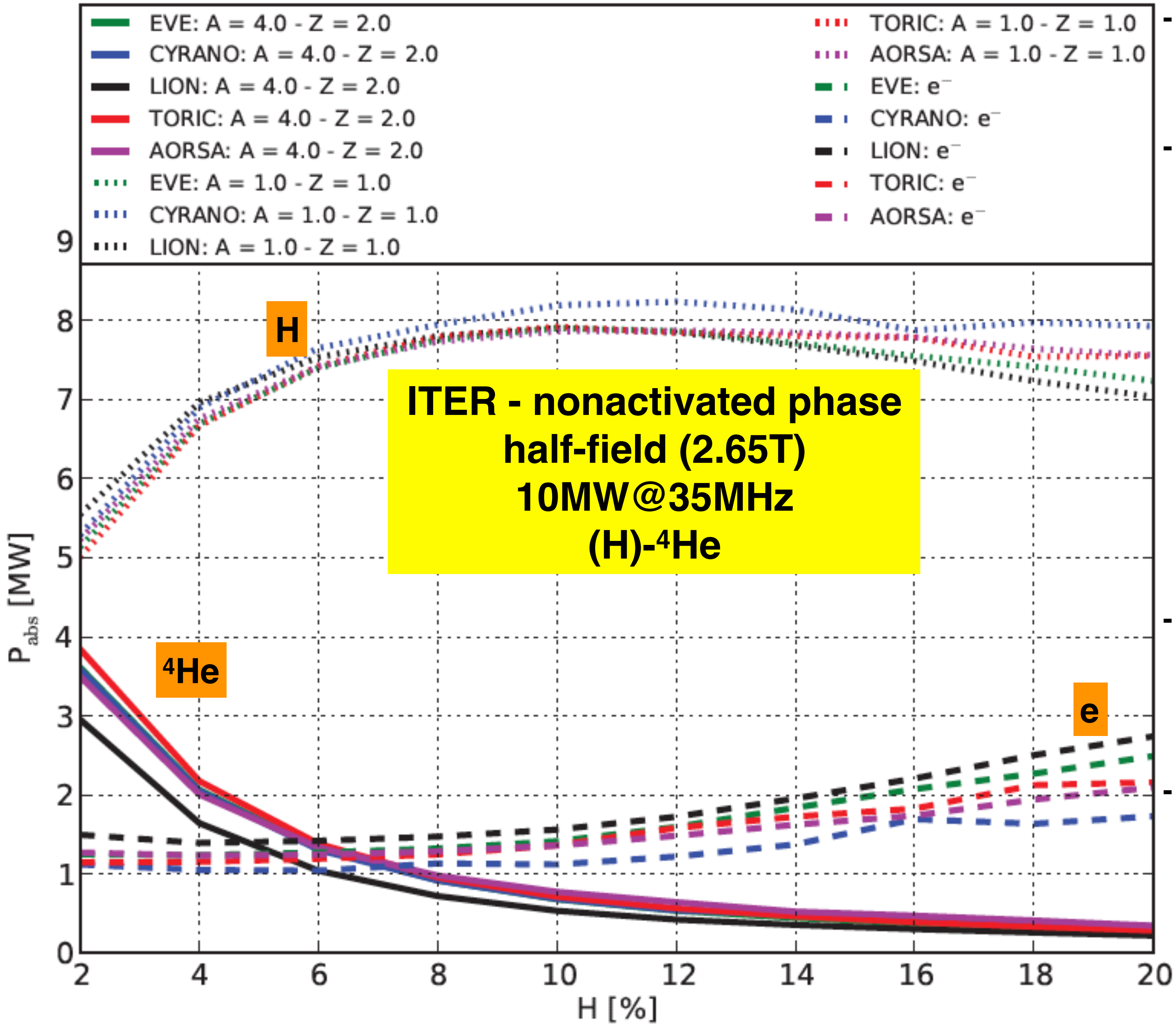
Contents

- Introduction & scope of this talk
- A few preliminary notes on ICRH in IMAS
- Practical examples & tool demonstration (accent on ‘quick-n-dirty’ modelling; other ICRH related efforts in IMAS sprinkled here and there):
  - ICRH-NBI synergy in JET ‘baseline’ shot 92436
  - Optimising RF performance in preparation of JET D-T
  - Determining suitable ITER low B_o field ICRH scenarios
  - Frequency choice of the DEMO ICRH system for the activated phase
- A quick note on the way forward
- Summary

Introduction & scope of this talk

- Theoretical/modelling **guidance** needed for preparation and analysis of experiments.
- "***Everything is coupled to everything else***" —> framework needed for modelling behaviour tokamak plasma allowing to zoom in on sub-aspects without user needing to know all details: **IMAS (Integrated Modelling & Analysis Suite)**, based on EUROfusion's Integrated Modelling efforts & aligned with ITER IMAS!
- Individual contributors focus on their field of expertise, delivering physics '**actors**' that can be interconnected (via a graphical interface) to pass on required information. Both 'quick & dirty' & detailed codes available.
- Specific subtasks involving actors can be auto-defined and run. Biggest application so far: **ETS (European Transport Simulator)**
- Info stored in **shared, standardised data structure** with 'shots' and possibility to have independent time evolving runs stored and usable by other users.
- This talk illustrates what IMAS offers for modelling scenarios in which combined minority/majority/beam ICRH heating is instrumental.

IMAS = benchmarking + vali- & veri-fication platform



ITER - nonactivated phase
half-field (2.65T)
10MW@35MHz
(H)-^{4}He

[R. Bilato et al., AIP Conference proceedings 1689, 060001 (2015)]

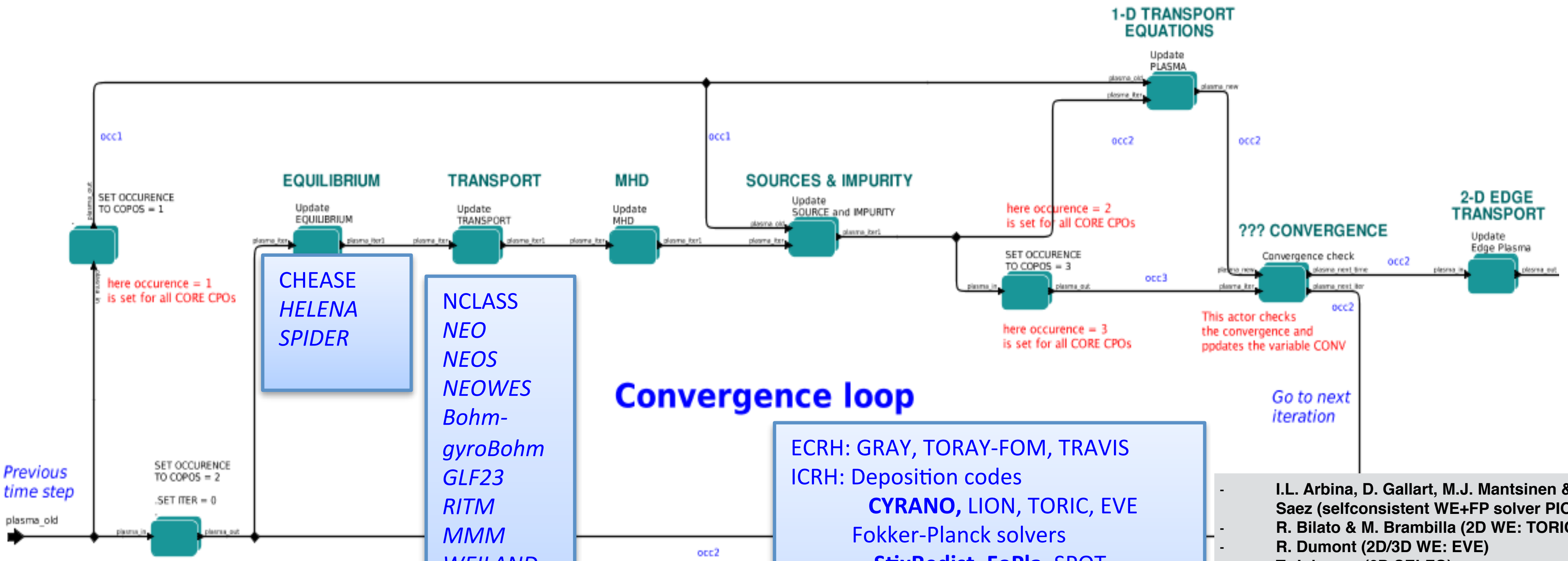
- **Easy comparison on basis of shared data files**
- **All WE codes share same input-output structure -> easily interchangeable (e.g. for testing scenarios requiring aspects only modeled in specific codes)**

- **Various available 2D wave equation solvers show similar performance**
- **Differences between predictions can be identified, helping to improve models.**

ASCOT/TRANSP/Exp.:

[P. Sirén, J. Varje, H. Weisen, L. Giacomelli, submitted to J. Instrum. (2019)]

ETS: the European Transport Simulator



CHEASE
HELENA
SPIDER

NCLASS
NEO
NEOS
NEOWES
Bohm-gyroBohm
GLF23
RITM
MMM
WEILAND
EDWM
TGLF
Qualikiz

Convergence loop

ECRH: GRAY, TORAY-FOM, TRAVIS
ICRH: Deposition codes
CYRANO, LION, TORIC, EVE
Fokker-Planck solvers
StixRedist, FoPla, SPOT
NBI: all possible combinations of
deposition codes BBNBI, NEMO
Fokker-Planck solvers
ASCOT, NBISIM2, RISK, SPOT,
Nuclear: AFSI, NUCLEARSIM

- **I.L. Arbina, D. Gallart, M.J. Mantsinen & X. Saez (selfconsistent WE+FP solver PION)**
- **R. Bilato & M. Brambilla (2D WE: TORIC)**
- **R. Dumont (2D/3D WE: EVE)**
- **T. Johnson (6D SELFO)**
- **J. Joly (WE: EVE + FP: SPOT)**
- **E. Lerche, D. Van Eester & P. Huynh (WE: CYRANO [2D] & TOMCAT [1D]; FP: StixReDist [1D] & FoPla [1D])**
- **M. Schneider (6D FP: SPOT)**
- **S. Sipila & J. Varje (6D FP: ASCOT & ASCOT-RFOF)**
- **L. Villard & O. Sauter (2D WE: LION)**

bold = used for examples in this talk

[P Strand, IAEA FEC 2018]

Self-consistent ICRH modelling … or not

RF induced power density
Fokker-Planck equation

energy of particle population

RF diffusion operator

$$P_{\mathrm{abs}} = \frac{\partial}{\partial t}\Big[\overbrace{\boxed{\int \mathrm{d}\vec v\, \mathrm{d}\vec x\, \varepsilon F_0}}\Big]\Big|_{\mathrm{RF}} = \int \mathrm{d}\vec x\, \mathrm{d}\vec v\, \varepsilon \frac{\partial F_0}{\partial t}\Big|_{\mathrm{RF}}$$

$$= \frac{1}{2}\mathrm{Re}\left\{\int \mathrm{d}\vec x\, \mathrm{d}\vec v\, \varepsilon \boxed{\nabla_{\vec v}.\frac{q}{m}[\vec E + \vec v \times \vec B]^* \int_{-\infty}^{t} \mathrm{d}t' \frac{q}{m}[\vec E + \vec v \times \vec B].\nabla_{\vec v}} F_0\right\}$$

$$= -\frac{1}{2}\mathrm{Re}\left\{\int \mathrm{d}\vec x\, \mathrm{d}\vec v \frac{q}{m}[\vec E + \vec v \times \vec B]^*.[\nabla_{\vec v}\varepsilon] \boxed{\int_{-\infty}^{t} \mathrm{d}t' \frac{q}{m}[\vec E + \vec v \times \vec B].\nabla_{\vec v} F_0}\right\}$$

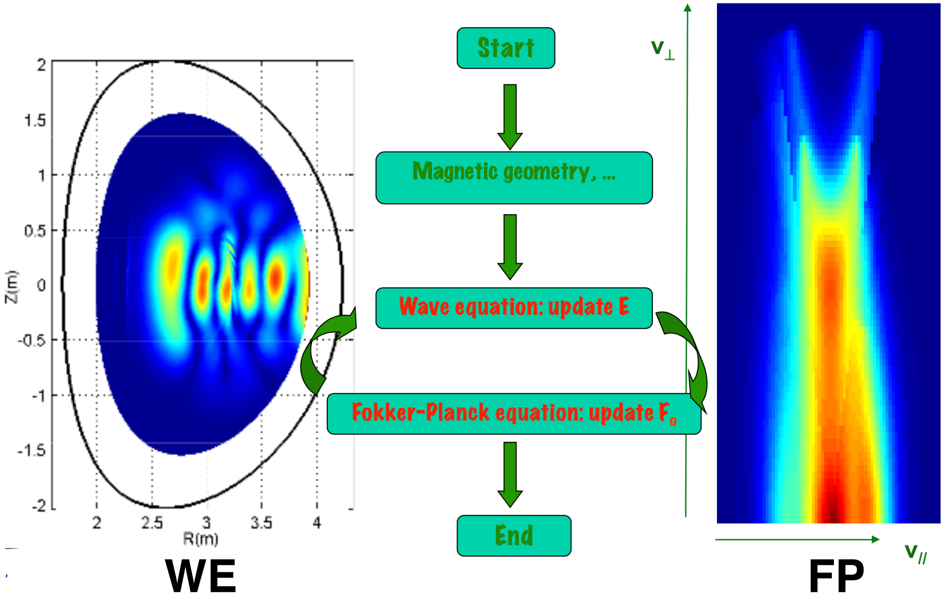
$$= \frac{q}{2}\mathrm{Re}\left\{\int \mathrm{d}\vec x\, \mathrm{d}\vec v\, \vec E^*.\vec v f_{\mathrm{RF}}\right\} = \frac{1}{2}\mathrm{Re}\left\{\underbrace{\int \mathrm{d}\vec x \boxed{\vec E^*.\vec J_{\mathrm{RF}}}}\right\}$$

RF perturbed distribution

work done by field on particle population

RF induced power density
wave equation

ε: energy
F_o: distribution



- Fully self-consistent approach [A. Kaufman, Phys. Fluids, 1972] tedious; STILL not realised …
- In practice: WE & FP exchange power density rather than E (exception FLR2 QL operator R.Bilato/ M.Brambilla: self-consistent truncated FLR2 approach).
- Often ≠ species RF heated: min/maj/beam -> ≠ FP eqs. Coupling ≠ FP eqs. forces review power balance:
    - Non-linear collision operator conserves particles, momentum, energy -> net input RF/NBI power requires net output; as $F_{o,e}$ converges most slowly: use ‘electron reservoir’ and only integrate ion FP equations.
    - Equipartition accounted for in FP but reserved for transport equation; to be taken out of FP equation (done solving for P_{RF}=0 & subtracting collisions)

Modelling baseline (H)-D-D_{NBI} JET shot 92436

Role of ICRH in D-T campaign:
- fusion ion heating
- high Z impurity chasing (ILW: W)
- ‘land’ the plasma

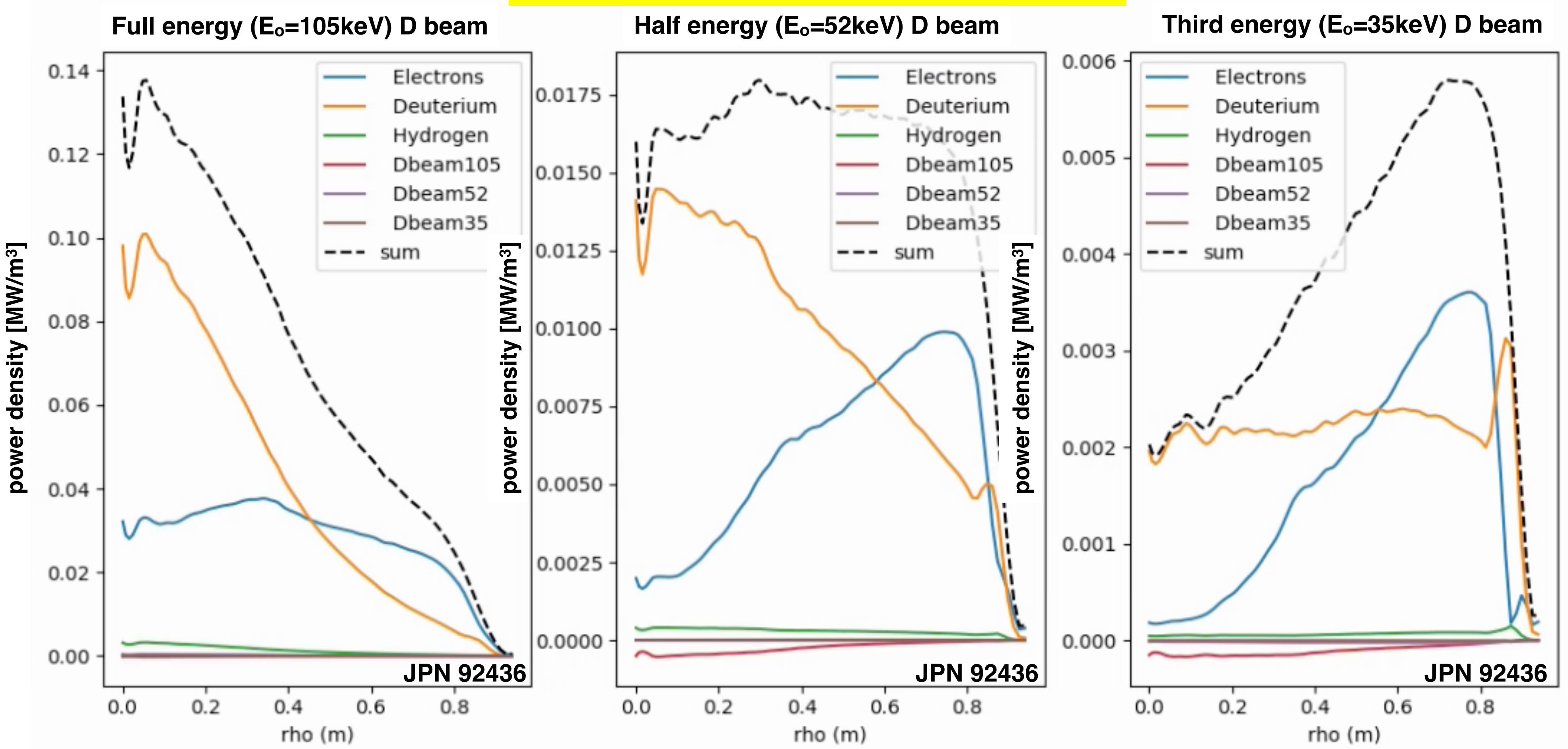
2 main roads to D-T operation:
- “Baseline”: (theoretical) performance scales with B_o and I_p
- “Hybrid”: current profile tailoring - Can we make it stationary?

JET “work horse” scheme: [N=1 H] + [N=2 D] + [N=2 D_{NBI}]

Modelling baseline (H)-D-D$_{NBI}$ JET shot 92436

sources computed by ASCOT code [E. Hirvijoki et al., Comput. Phys. Commun. 185 (2014) 1310]

[NBI-only collisional redistribution]



Full energy (E_o=105keV) D beam

Half energy (E_o=52keV) D beam

Third energy (E_o=35keV) D beam

- high energy source peaks in core, low energy source peaks in edge
- dominant indirect bulk ion heating in core (high E_{crit}), electron heating near edge
- note: beam helps to ‘preheat’ target for ICRH (even when (Doppler shifted) RF absorption by NBI particles is irrelevant NBI impacts on RF heating)

Distribution functions: local energy densities

H minority N=1 heating: thermal subpopulation affected; high energy tail formed

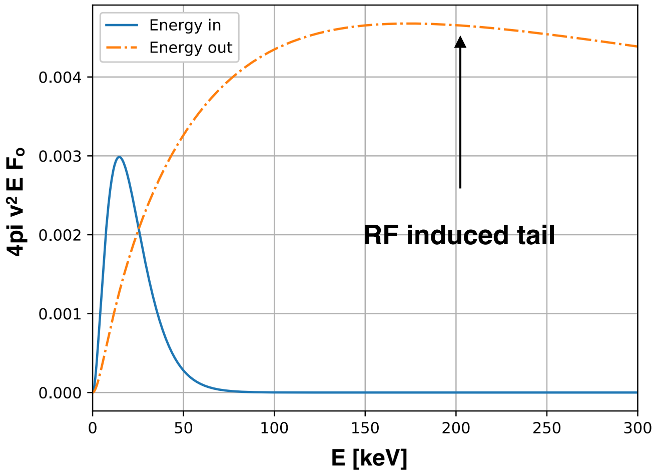
Coupled FP eqs. solved for 5 i populations

(rho~13cm)

D majority N=2 heating: thermal subpopulation ~ untouched; high energy particles dominantly affected

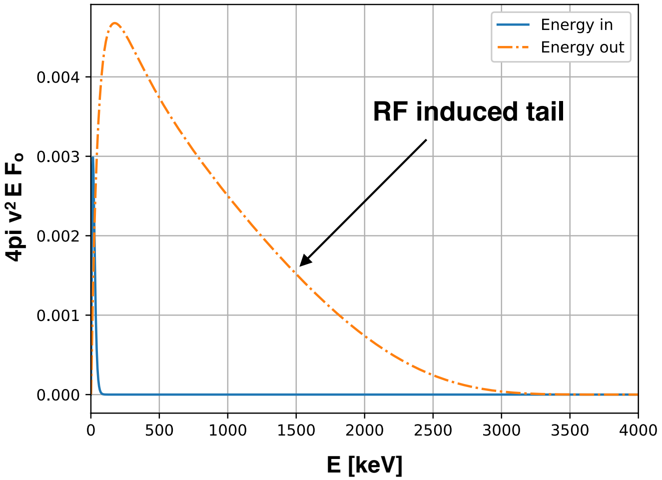
JPN 92436

H minority



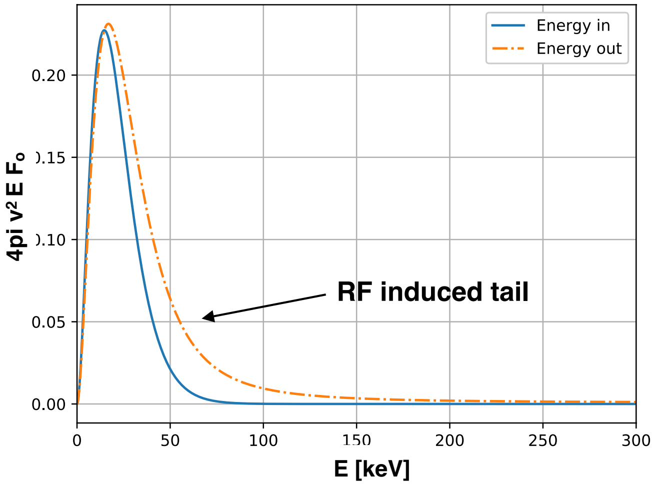
RF induced tail

H minority: detail



RF induced tail

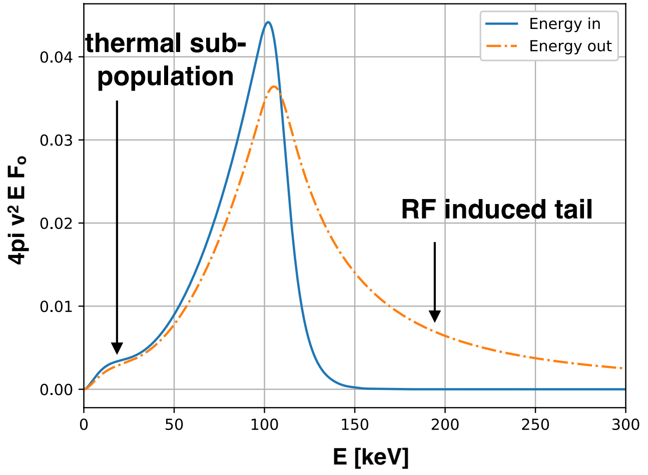
D majority



RF induced tail

D beam N=2 heating: thermal subpopulation ~ untouched; high energy particles dominantly affected

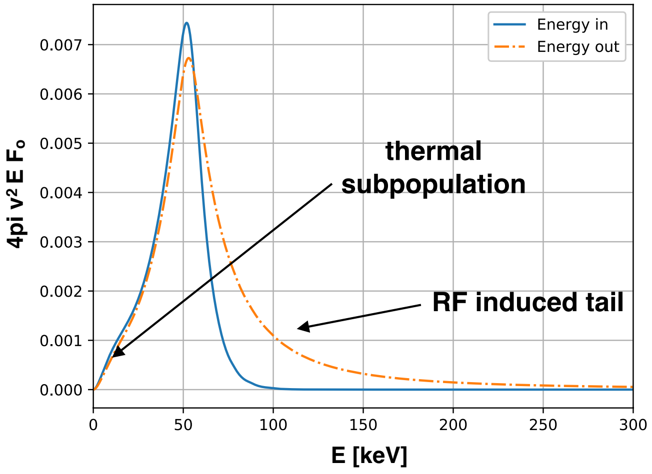
Full energy (E_o=105keV) D beam



thermal sub-population

RF induced tail

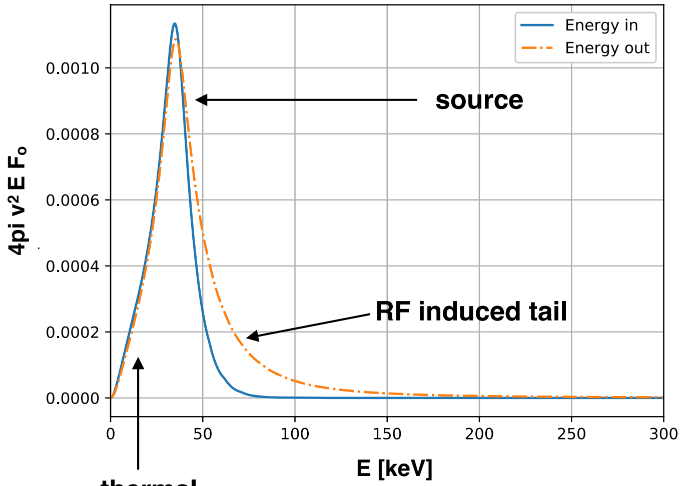
Half energy (E_o=52keV) D beam



thermal subpopulation

RF induced tail

Third energy (E_o=35keV) D beam



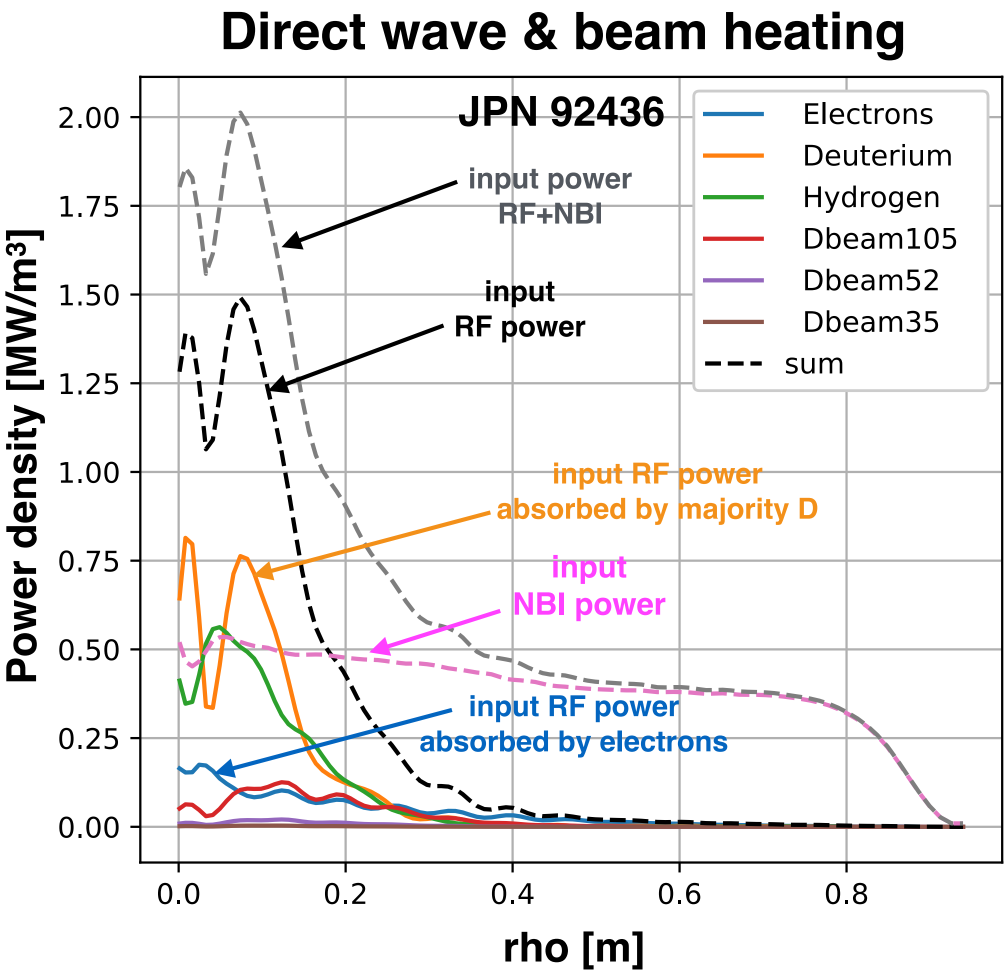
source

RF induced tail

thermal subpopulation

- **High energy H tail formed**
- **D bulk preheated by NBI & forming tail at high energy (not shown)**
- **ICRH depopulates D NBI thermal region former high energy tail**

Power balance: direct & indirect heating



Direct wave & beam heating

JPN 92436

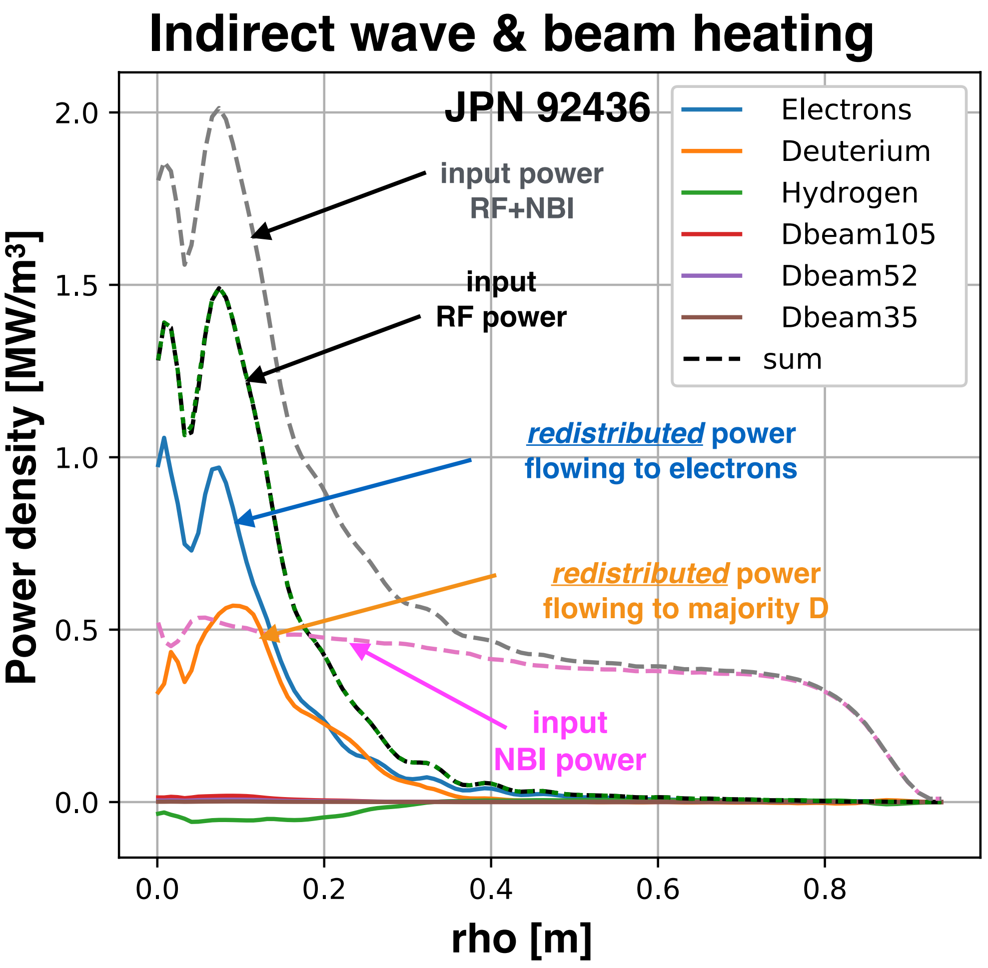
input power RF+NBI

input RF power

input RF power absorbed by majority D

input NBI power

input RF power absorbed by electrons



Indirect wave & beam heating

JPN 92436

input power RF+NBI

input RF power

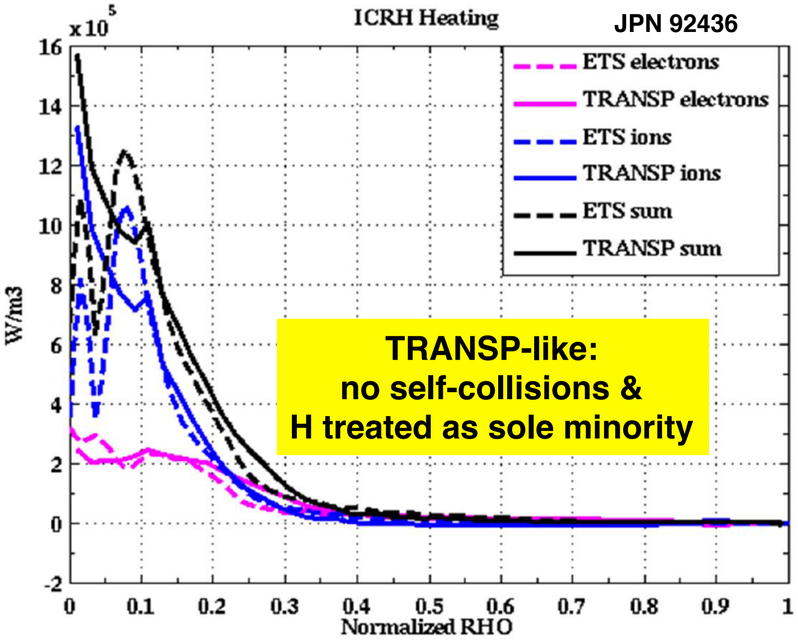
__redistributed__ power flowing to electrons

__redistributed__ power flowing to majority D

input NBI power

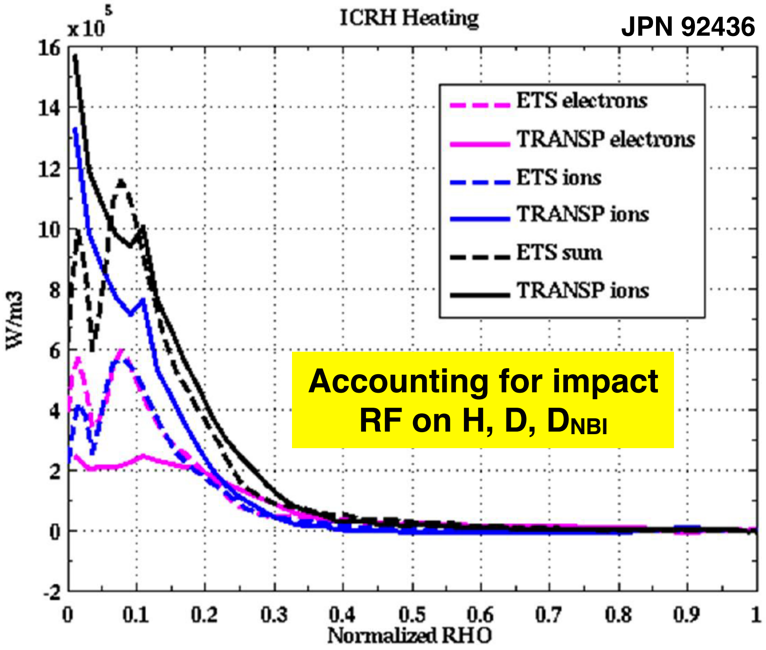
- **electrons significantly indirectly heated in core region**
- **beams (heated at N=2) equally yield power electrons (but contribute to ion ‘preheating’)**
- **H minority dominantly heating electrons**

ICRH - NBI synergy: minority <-> all species FP



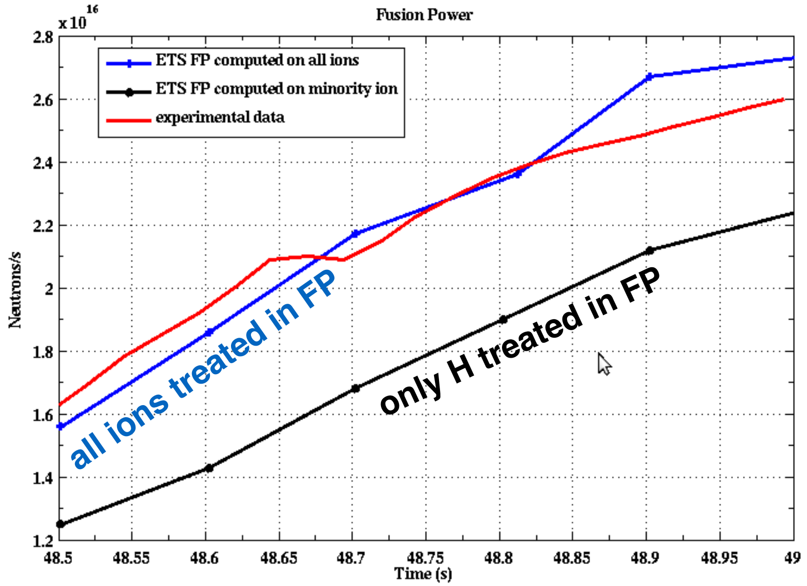
JPN 92436

TRANSP-like:
no self-collisions &
H treated as sole minority



JPN 92436

Accounting for impact RF on H, D, D_{NBI}



all ions treated in FP

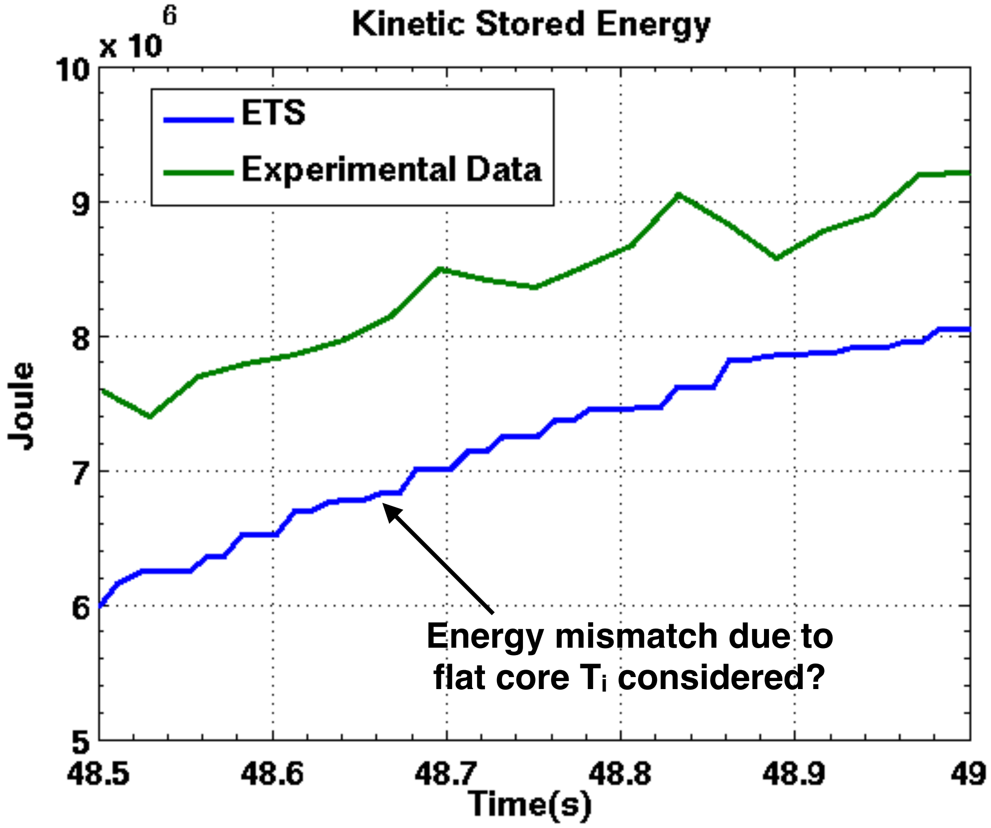
only H treated in FP

Neutron rate	ETS - H only in FF	ETS - all i in FP	Exp
D-D [10^{16}n/s]	1.20	1.60	
D-D_{nbi} [10^{16}n/s]	1.07	1.06	
D_{nbi}-D_{nbi} [10^{16}n/s]	0.04	0.04	
Total [10^{16}n/s]	2.32	2.70	2.60

[Ph. Huynh, RF Power in Plasmas, Hefei, 2019]

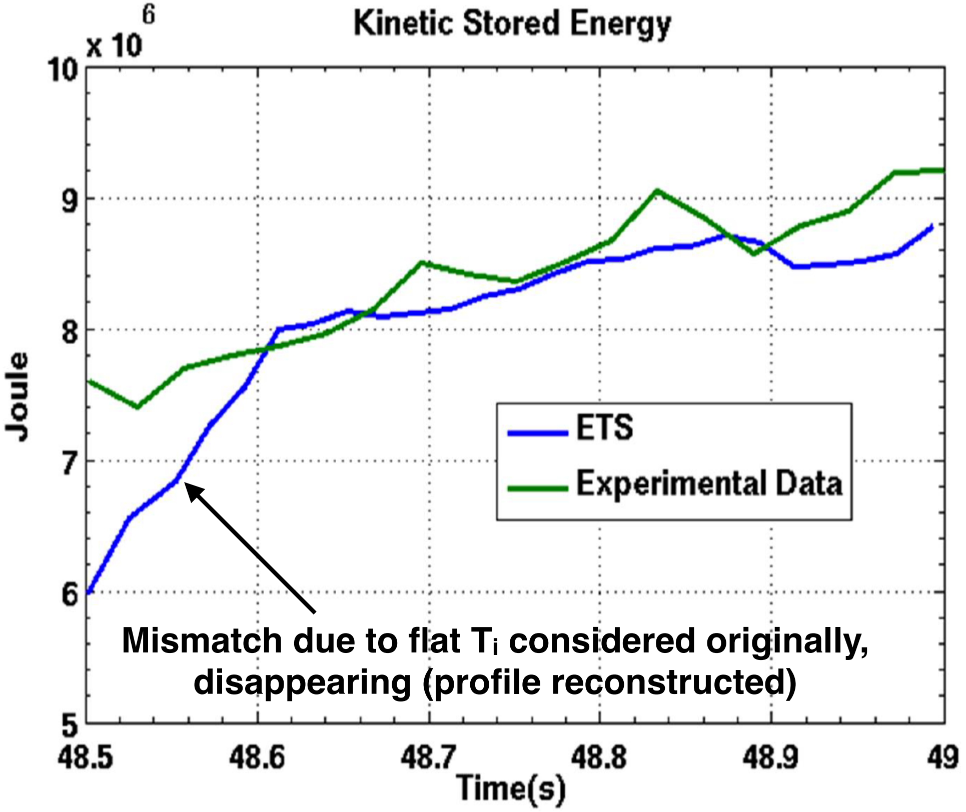
ICRH - NBI synergy: minority <-> all species FP

interpretative



Energy mismatch due to flat core T_i considered?

predictive



Mismatch due to flat T_i considered originally, disappearing (profile reconstructed)

[Ph. Huynh, RF Power in Plasmas, Hefei, 2019]

Beyond 1D FP: Fast D with & without iterations EVE [R. Dumont] & SPOT [M. Schneider]

JET D_{NBI}: up to 20% of R_{DD} is due to synergy
& $T_{eff,NBI}$ increases from 40 to 60keV with 5MW of RF heating & 22MW D_{NBI}

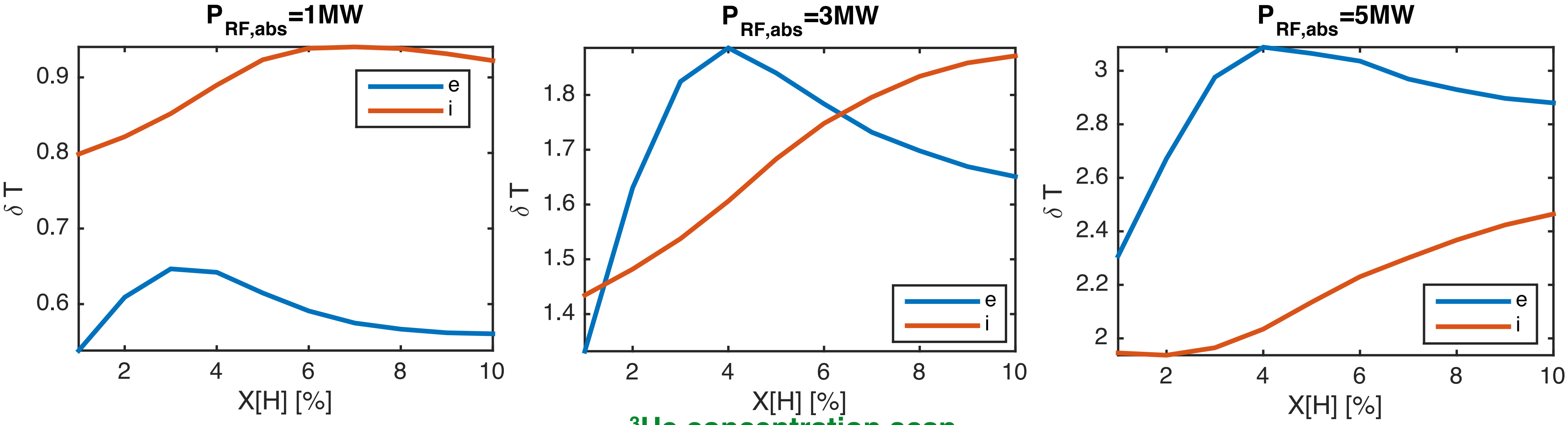
[J. Joly et al, Plasma Phys. Control. Fusion 61 (2019) 075017]

[J. Joly, PhD Thesis (in preparation)]

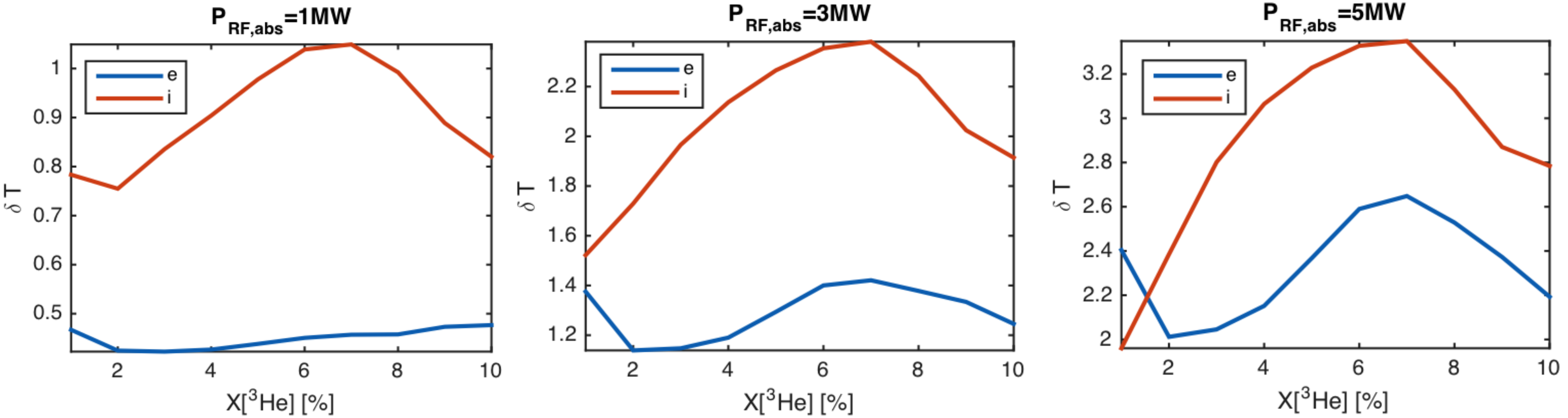
Role coupled power: JET baseline H & ^{3}He scan

Core temperature change due to RF

H concentration scan



^{3}He concentration scan



- Power increase -> temperature increase
- Low P_{RF}: $P_i > P_e$ both for H as ^{3}He (no high energy tails formed; energy < critical energy)
- ^{3}He minority favours core ion heating; $P_e > P_i$ requires high power & low concentration
- Optimum ion heating @ X[^{3}He]~7% for (^{3}He)-D; increasing with power in (H)-D
- Optimal e heating at X[H]~4% for (H)-D and low X[^{3}He] or X[^{3}He]~7% for (^{3}He)-D
- At high power, using H minority favours e heating and ^{3}He favours i heating unless X[^{3}He] small

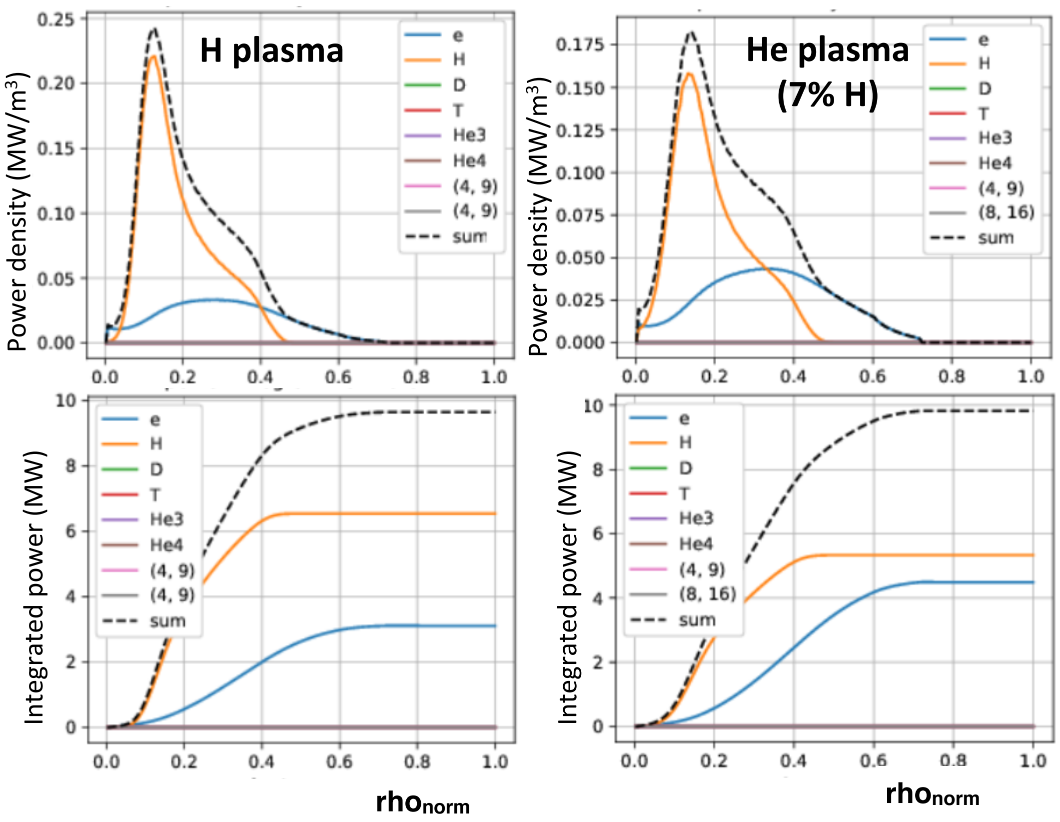
[simplified transport model used: coupled transport equations ≠ species]

ITER: low B_o field testing

METIS transport code used to provide kinetic profiles and equilibrium at 5MA/1.8T with 20MW EC and 10MW IC; $N_e=0.5N_{GW}$

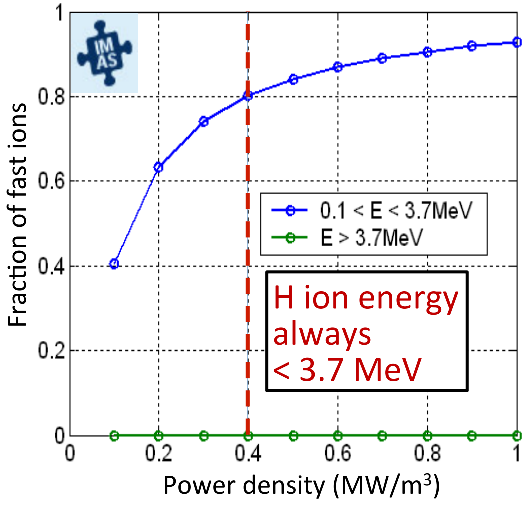
TOMCAT code used to establish heating efficiency

B_0 (T)	5.3		2.65		1.8		3	3.3
I_p (MA)	15		7.5		5		8.5	9.5
P_{AUX} (MW)	30						73	
Main ion	H	He	H	He	H	He	H	H
Te^0 (keV)	10	13	7.2	11	14	16	14	11
Ti^0 (keV)	12	16	6.0	12	7.0	8.0	10	9.3
ne^0 (10^{19} m^{-3})	5.6	5.5	2.8	3.0	1.9	1.9	3.2	3.4
ni^0 (10^{19} m^{-3})	5.4	2.9	2.7	1.7	1.8	1.0	2.2	2.3



- Best scheme: N=2 H heating in H and He plasmas (f=52.5MHz, n_{tor}=40)
- Very efficient single pass absorption (FLR scaling)
- More refined modelling done by PION code [L.-G. Ericsson et al, NF 33 (1993) 1037] installed under IMAS [I.L. Arbina, 46th EPS Conference on Plasma Physics, Milan (2019), P4-1079]

CYRANO & StixReDist codes used to provide input for assessment first orbit losses at 1.8T/5MA: for realistic power densities fast particles confined



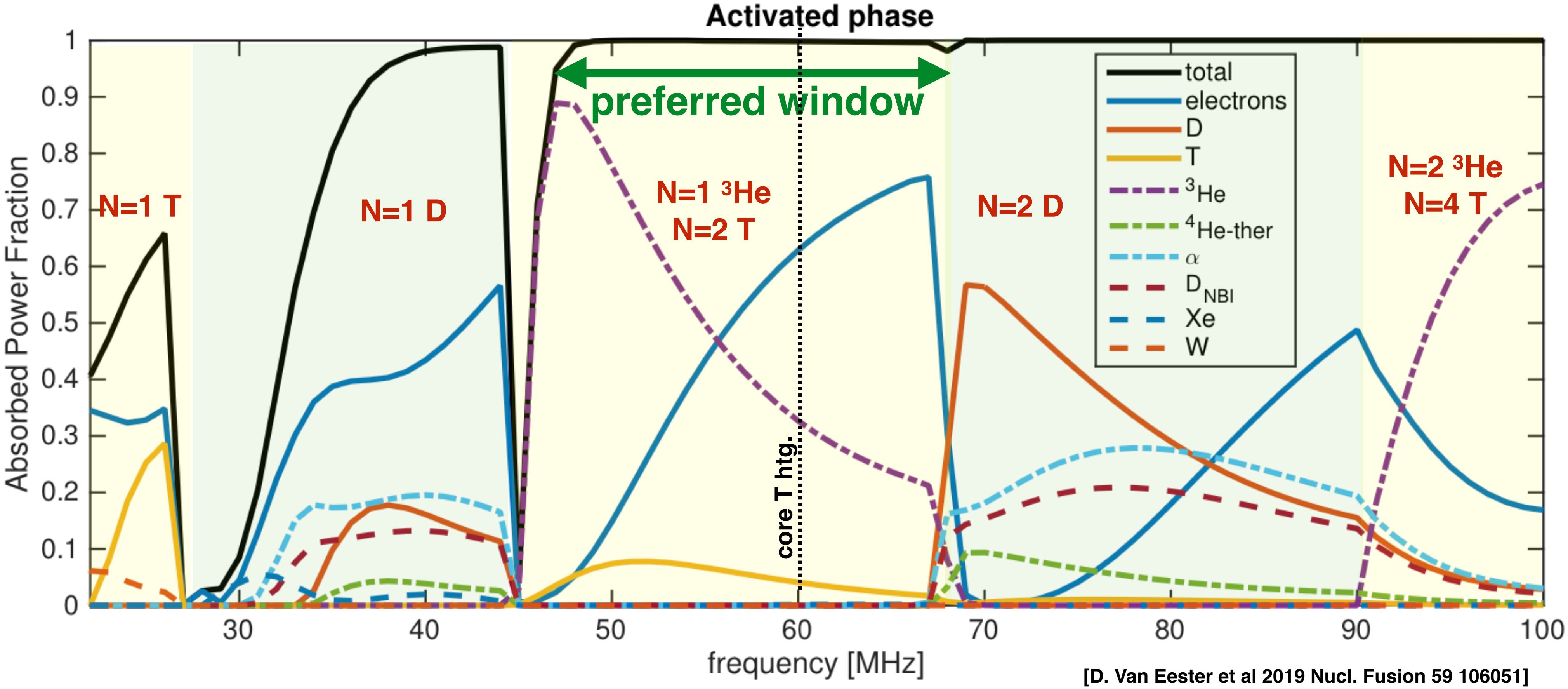
H ion energy always < 3.7 MeV

[M. Schneider et al, Nucl. Fusion 59 (2019) 126014]

[M. Schneider - 27th IAEA FEC - Ahmedabad (India) - 22-27/10/'18 - TH/6-1]

DEMO activated phase ICRH scenario assessment

DEMO-1 parameters : R_o=9m, a_p=2.9m, B_o=5.855T; I_p=17.75MA; T_o=28keV; N_o=10^{20}/m^3

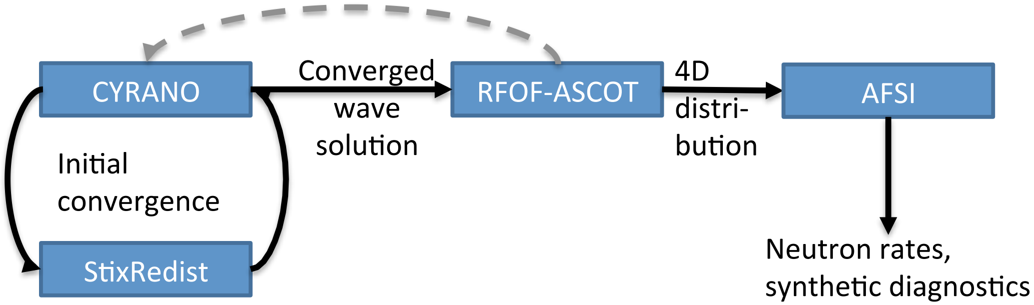


[D. Van Eester et al 2019 Nucl. Fusion 59 106051]

- **Several possible windows depending on frequency chosen**
- **D fuel heating schemes spoiled by parasitic fusion born alpha particle absorption**
- **Significant e damping unavoidable**
- **~100% SPA from f~50MHz (very high f window not examined)**
- **Proposed scheme identical as for ITER's activated phase (^{3}He)-D-T with small % of ^{3}He in early phase, D-T when steady burn reached**
- **f=60MHz allows core fuel ion heating but e absorption exceeds ion absorption; nearby frequency optimal for CD (but low CD - comparable to other foreseen schemes - only: dedicated efforts needed e.g. Fisch proposal)**

The way forward

- Further improvement of models (e.g. RF kick operator in Monte-Carlo ASCOT to enable treating ICRH-NBI synergy)



- better integration
- more validation & benchmarking
- exploitation
- exploitation
- exploitation

Summary

- **IMAS** framework has **matured**
- EU-IM offers platform for code **validation** and **benchmarking**
- Gradually more intensive use yields further improved models; number of papers based on IMAS modelling steadily increasing
- Various ICRH-related examples based on IMAS tools discussed:
  - JET modelling **synergy** ICRH-NBI: baseline shot 9243 [good agreement with exp. parameters; need to include tail formation all RF heated species (min, maj, beam)]
  - JET modelling **H vs ^{3}He** heating [good qualitative agreement with exp.; available RF power crucial factor]
  - ITER modelling: ICRH scenarios in early non-activated phase low B_o-field identified (**N=2 H**); first orbit losses assessment satisfactory
  - DEMO modelling of ICRH scenarios: opt for identical scenario as ITER (**N=1 ^{3}He** & **N=2 T** in early phase discharge; **N=2 T** later)
- Further upgrading ongoing & needed but
- **IMAS tools are ready for exploitation!!**