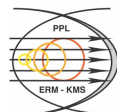


Alpha Particles without DT: Alternative Routes in Future JT-60SA Plasmas

R. Coelho
IPF/IST

Co-authors: Y. Kazakov, R. Novara, J. Garcia, V. Kiptily,
M. Nocente, K. Särkimäki, A. Snicker

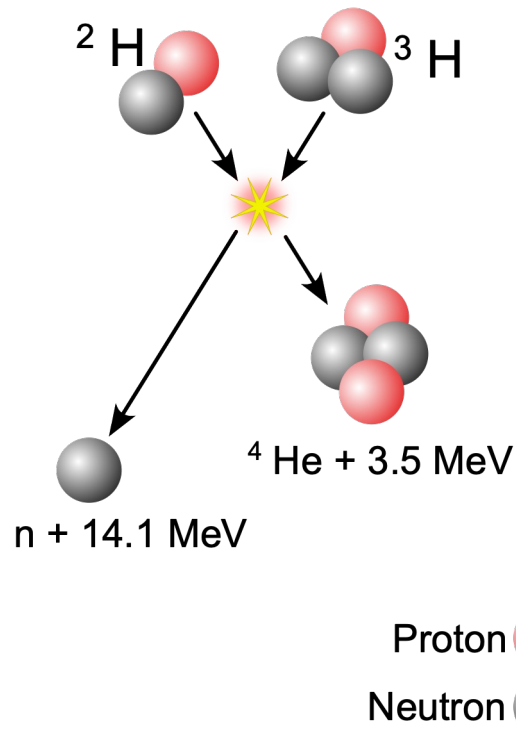


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Energetics of Conventional DT Fusion



Alphas (20%): essential source for sustained, self-collisional heating of the bulk thermal plasma in future FPP (*pilot PP will play a key exploratory role when $Q \sim 1-5$ is achieved*).

Neutrons (80%): Dominant kinetic energy carrier acting as the ultimate downstream energy reservoir for electricity generation and assisting in tritium self-sufficiency downstream (*Tritium blanket*).

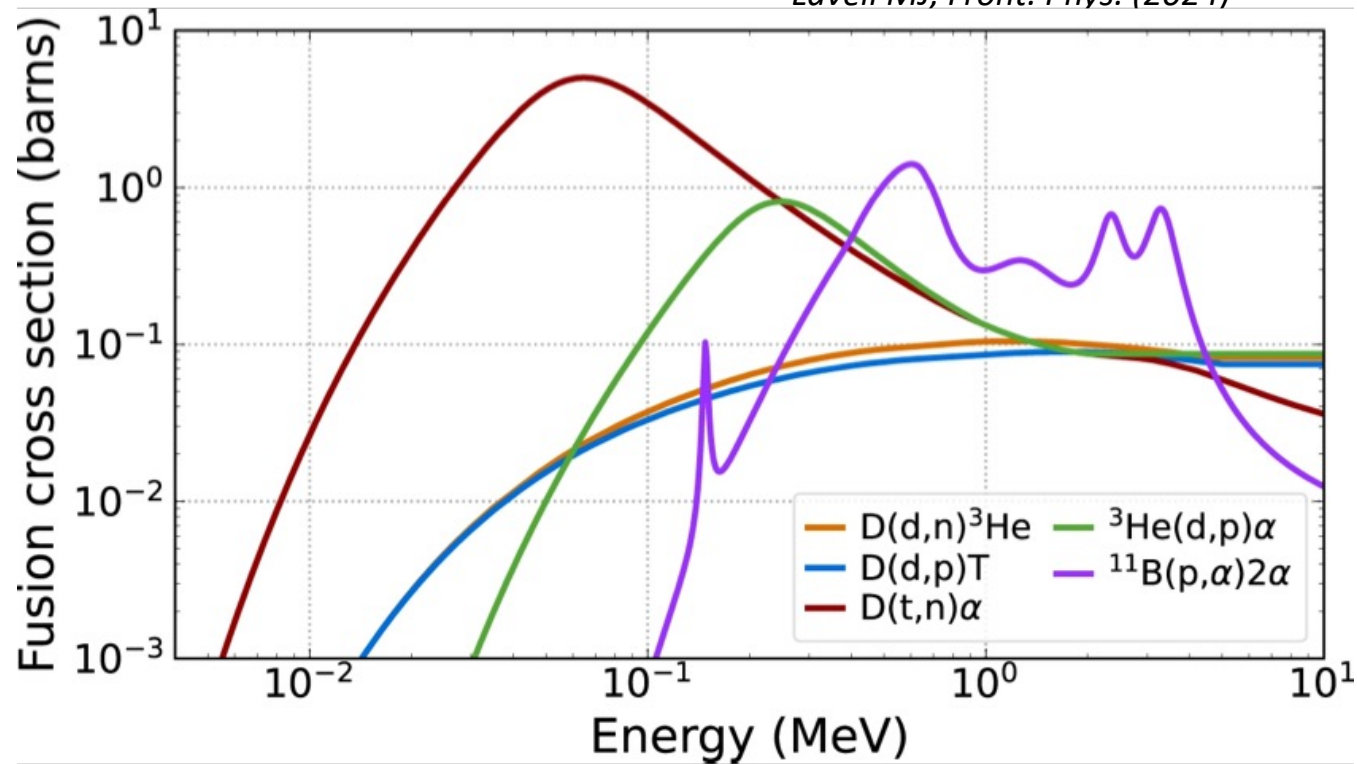
D $\Rightarrow$ 1 out of ~ 6500 hydrogen atoms $\rightarrow$ *Abundant in sea water*.

T $\Rightarrow$ very scarce : 7.5kg steady-state world wide inventory $\rightarrow$ *More later...*



Thermonuclear Cross Sections & Reactivity Constraints

Lavell MJ, Front. Phys. (2024)

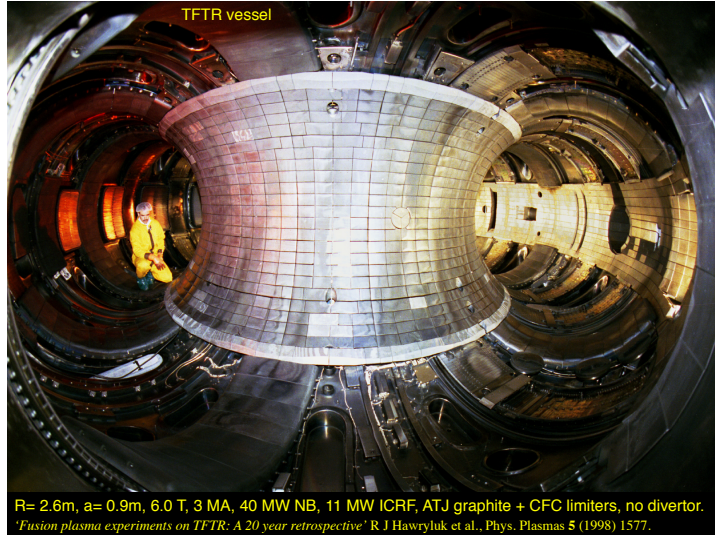


- DT exhibits a resonant peak at lower center-of-mass energies compared to alternative reactions
- When plasma is pressure limited and considering $\langle \sigma v \rangle \rightarrow$ soft spot for thermal-thermal fusion at $\sim 15\text{keV}$.

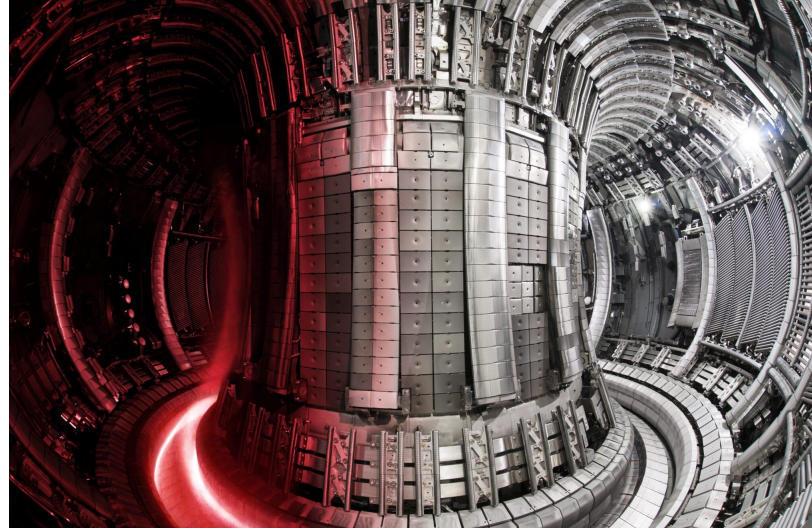
$\Rightarrow$ Beam-thermal fusion reactions using high energy beams are an alternative path though fundamentally limited since $N_{\text{beam}} \ll N_{\text{thermal}}$ (at least an order of magnitude)
 $\rightarrow$ *More on this later...*



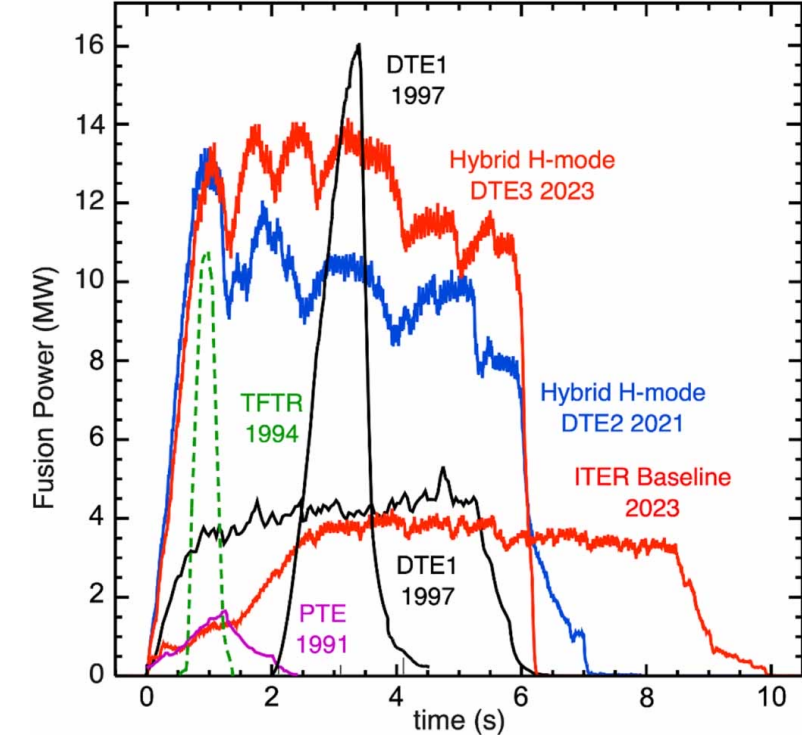
Probing burning plasmas with DT : TFTR & JET Milestone Experiments



TFTR Tokamak (1982-1997)



JET Tokamak (1983-2023)



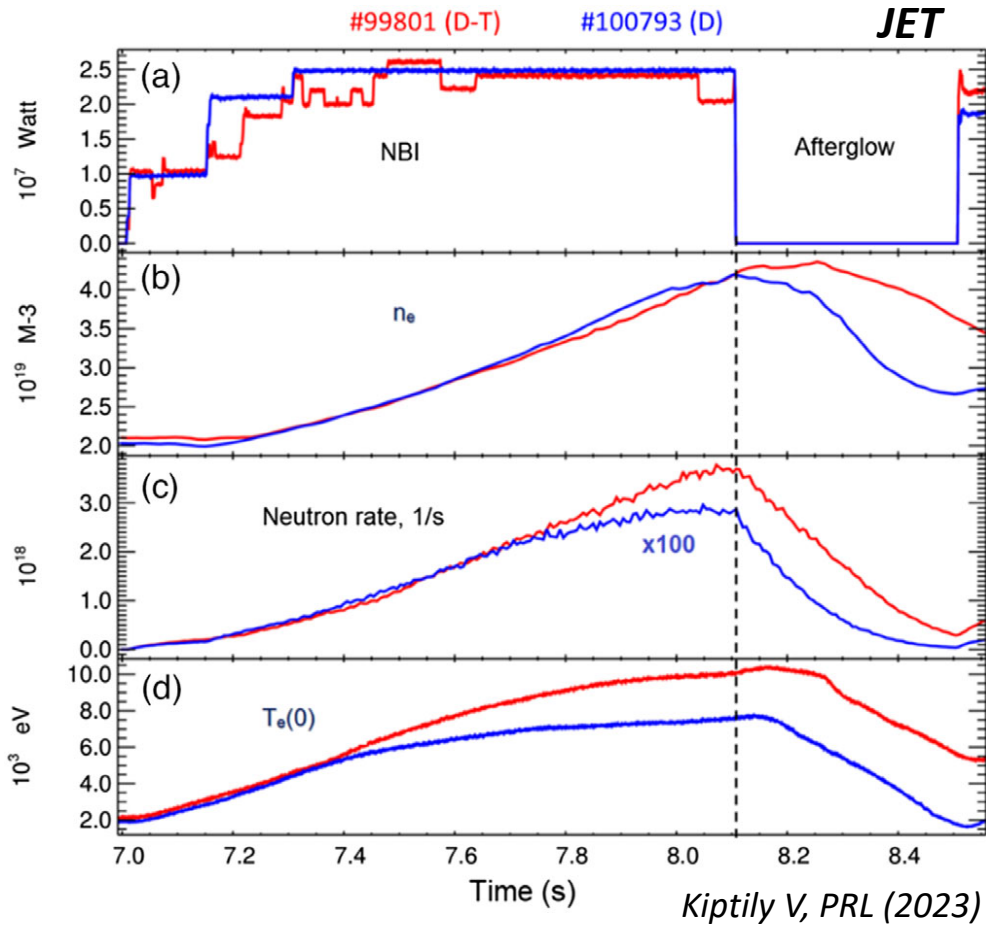
Rimini F, PPCF (2025)

- TFTR : first ever evidence of alpha-driven Alfvén Eigenmode and stochastic ripple diffusion of alphas close to the plasma edge → *fast-ion / alpha specific diagnostics were (are) crucial !*
- Performance Metrics at JET : #99971 the $P_{\text{fus}} \sim 10\text{MW}$ ($P_{\alpha} \sim 2\text{MW}$), corresponding to $Q \sim 0.3$ ($P_{\text{aux}} = 32\text{MW}$).



Experimental evidence of DT/Alpha effects

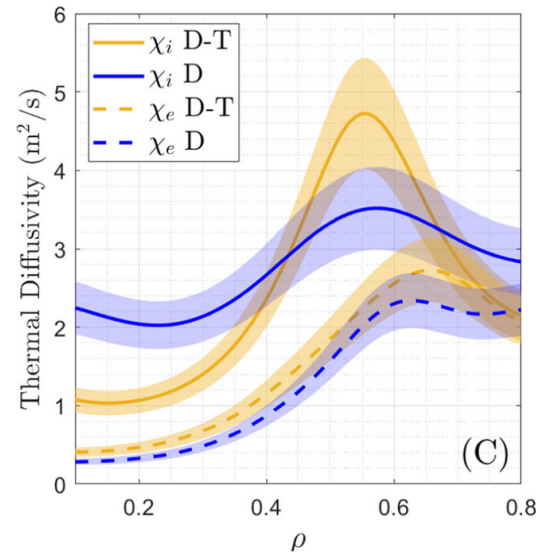
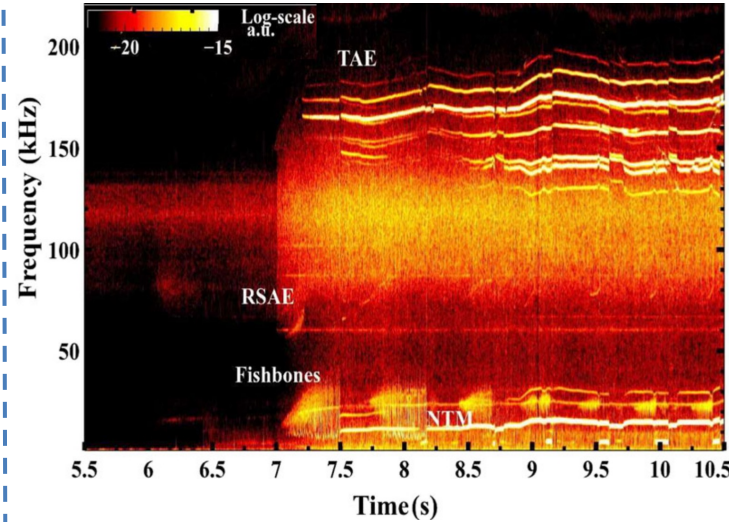
Electron heating in afterglow



See also: Siena A, NF (2025), Varela J, NF (2025)

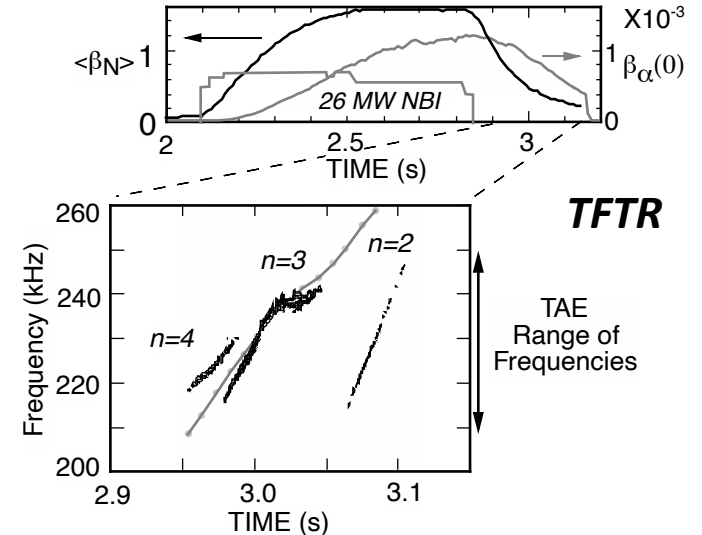
Improved confinement in DT (JET)

Garcia J, Nature Comm (2024)



TAEs driven in afterglow

Zweben SJ, NF (2000)



[see also Fitzgerald M, NF (2023)]

$\Rightarrow$ Alphas + other fast ions (FIs) co-exist so it's challenging to isolate alpha's role at high β_{fast} in potentially **non-linearly coupled** phenomena !



The Operational and Logistics Cost of Tritium

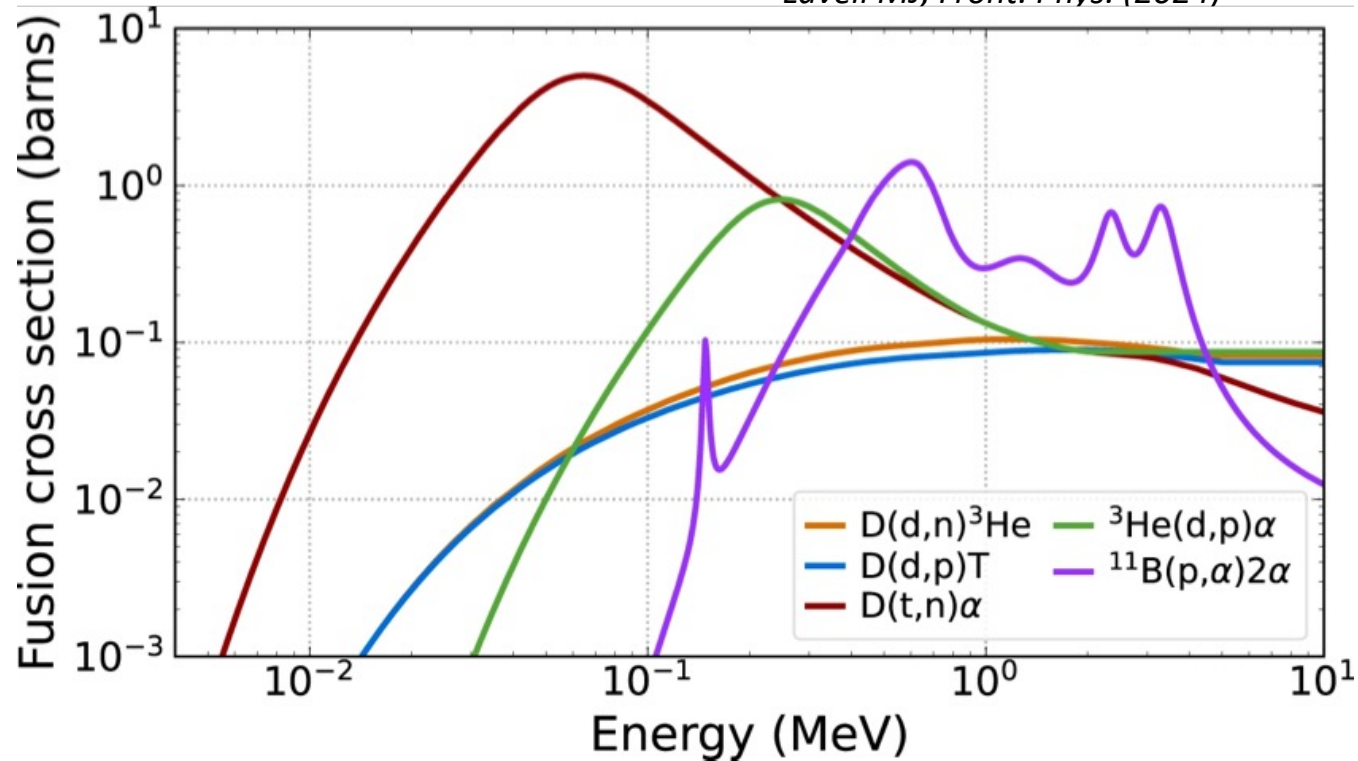
- ⇒ Tritium is extraordinarily **rare** (7.5kg steady-state world wide inventory), **expensive** ($\sim 32\text{k€}/\text{g}$), and subject to **rapid radioactive decay** (half-life ~ 12.3 years).
- ⇒ Running a DT plasma requires comprehensive nuclear-grade facility certification, strict radioactive inventory accounting, and extensive remote handling arrays.

The Scientific Question: Can we study identical alpha particle confinement and transport properties in standard, non-active experimental facilities?



Exploring Aneutronic and Alternative Fusion Channels

Lavell MJ, Front. Phys. (2024)



⇒ ^3He , while expensive, is not as rare as Tritium and has already been used frequently in Tokamak plasma discharges e.g. ICRH 3-ion schemes [Kazakov YO, PoP (2021)], alpha driven modes [Kiptily VG, PPCF (2022)].

⇒ ^{11}B is easily accessible and has even been tried already in the LHD stellarator [Magee RM, Nature Comm (2023)].

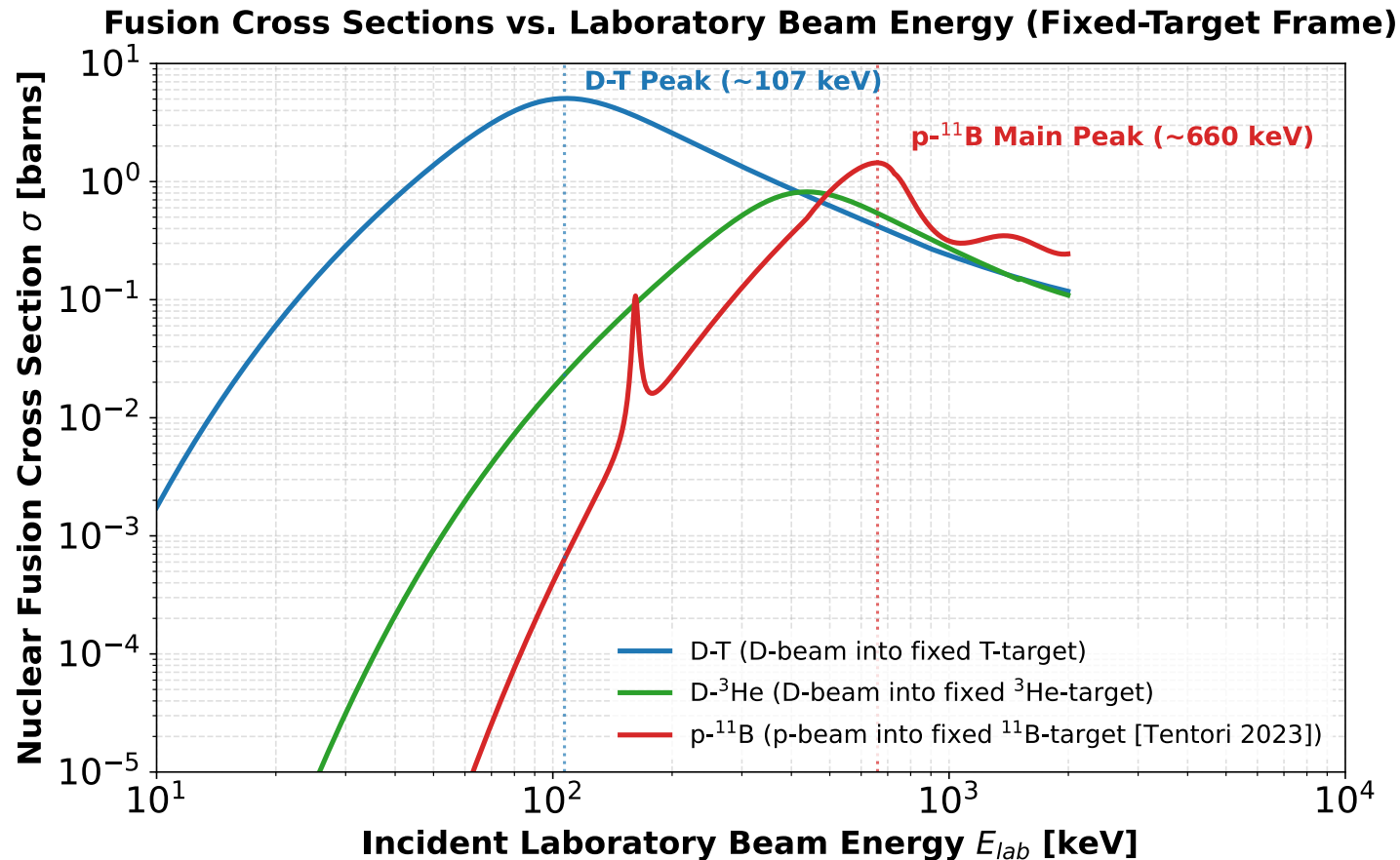
⇒ Either ^3He or ^{11}B need however to be at *significantly higher energy than Tritium*...

- $D_{beam} + ^3\text{He} \rightarrow ^4\text{He} + p + 18.35\text{MeV}$
- $H_{beam} + ^{11}\text{B} \rightarrow ^{12}\text{C}^* \rightarrow ^8\text{Be}^* + ^4\text{He} \rightarrow 3\ ^4\text{He} + 8.68\text{MeV}$



Beam Injection assisted fusion reactions

The Beam Solution $\Rightarrow$ To maximize reaction rates, we require an energetic beam to inject particles directly near the cross-section resonances.



For *fusion power* the **relevant quantity** is $\langle \sigma v \rangle \Rightarrow$ maxima slightly pushed to higher energy e.g.

◆ $E_{D\text{-beam}}(\text{D-T}) \sim 127\text{keV}$

◆ $E_{D\text{-beam}}(\text{D-}^3\text{He}) \sim 450\text{-}500\text{keV}$

JET beam system : $E_{beam} \lesssim 125\text{keV}$

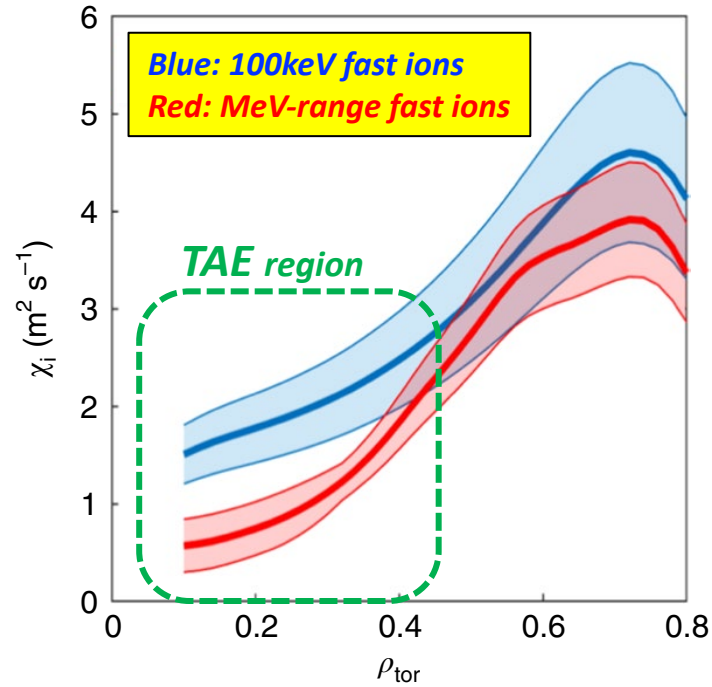
ITER beam system : $E_{beam} =$
870 (H) or 1 MeV (D)

Sweet spot for D³He and p¹¹B : 500-700keV



Insights from JET studies using D-³He (MeV ions D_{NBI}+ICRH and alphas) (1)

Reduced thermal ion heat diffusivity (χ_i)



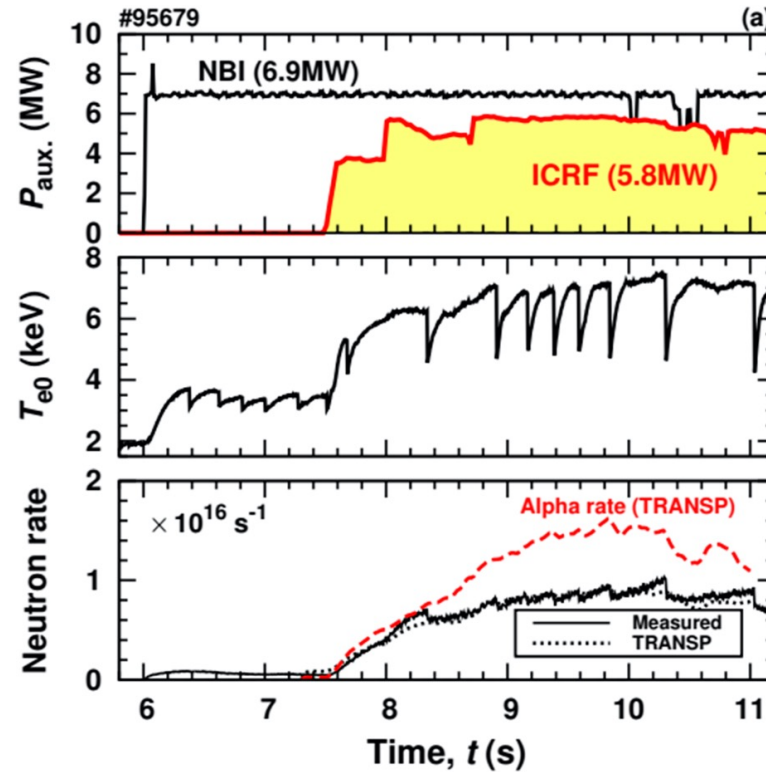
Mazzi S, Nature Physics (2022)

See also:

Na Y, Nature Reviews Physics (2025)

Ishizawa A, Communications Physics (2025)

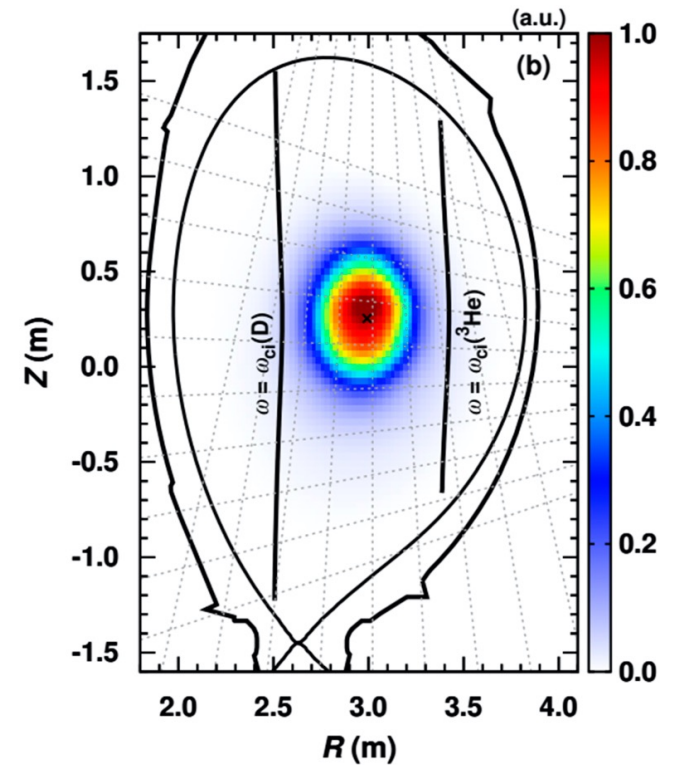
Mazzi S, Rev Mod P. Physics (2026)



Best case scenario

$$n(^3\text{He})/n_e \sim 20\text{-}25\% \Rightarrow n_\alpha \sim 1\text{-}2 \times 10^{16} \text{s}^{-1}$$

Inferred D-D neutron emission

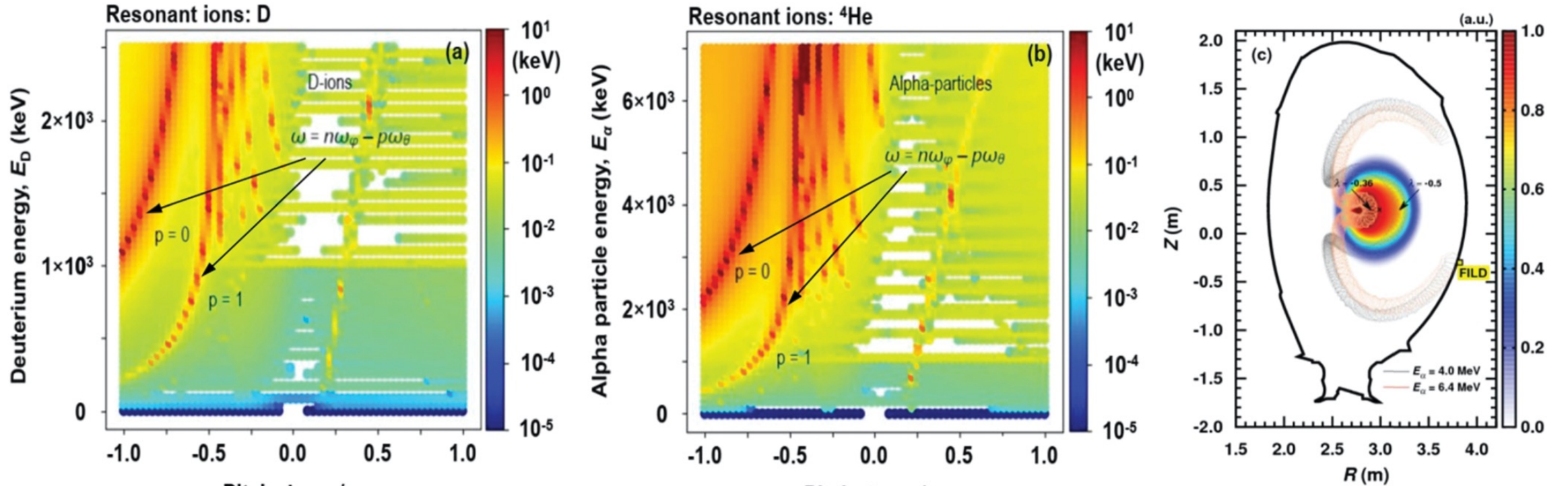


Mailloux J, NF (2022)
Kazakov YO, PoP (2021)
Nocente M, NF (2020)



Insights from JET studies using D-³He (MeV ions D_{NBI}+ICRH and alphas) (2)

Alpha particle driven EAEs (n=-1)



Kiptily V, NF (2021)

⇒ Despite a birth rate of $1-2 \times 10^{16} \text{s}^{-1}$, only alpha particle distribution featuring $\lambda \lesssim 0$ particles can tap the resonances of the n=-1 mode and drive it unstable (**NBI+ICRH yields co-passing only distribution**).



Talk Outline

- The JT-60SA Device.
- Methodology.
- Modelling Scenarios & alpha birth rates
- Interplay with MHD & Ripple
- Outlook and Conclusions.

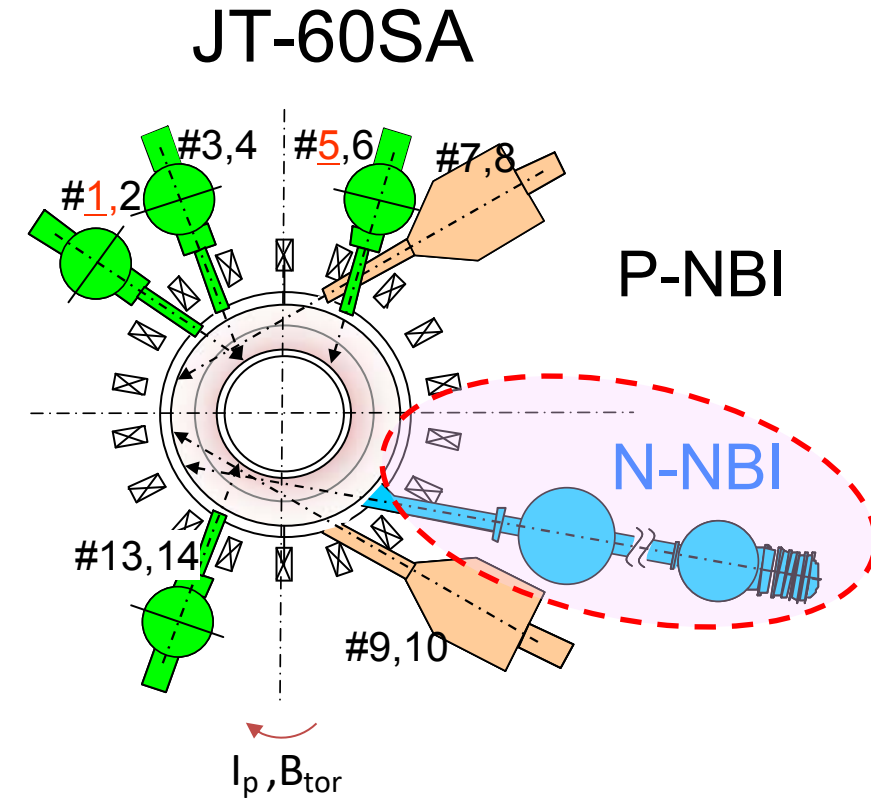
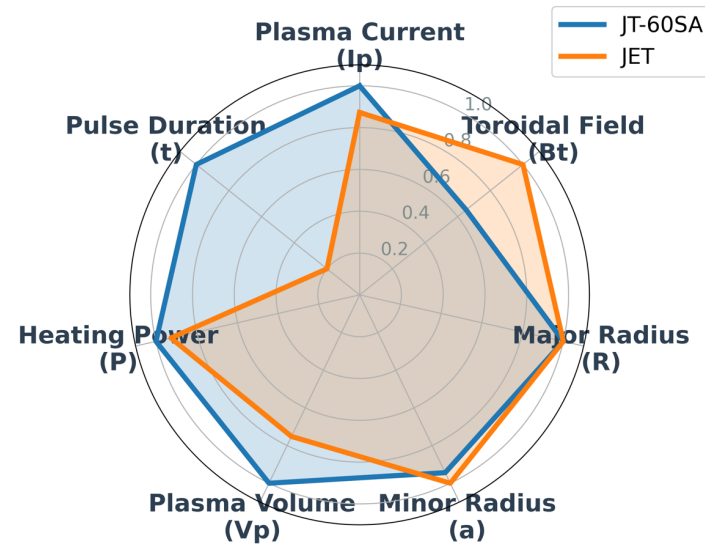


JT-60SA Architectural Overview and Fast Ion Drive

- The world's largest operating superconducting tokamak, engineered to sustain high normalized pressure ($\beta_N \sim 3.5 - 4.3$).
- **NBI system:** 12 positive ion sources (**P-NBI**) delivering up to 24 MW total at 85 keV. Two negative ion sources (**N-NBI**) delivering 10 MW at up to 500 keV.

Main plasma parameters

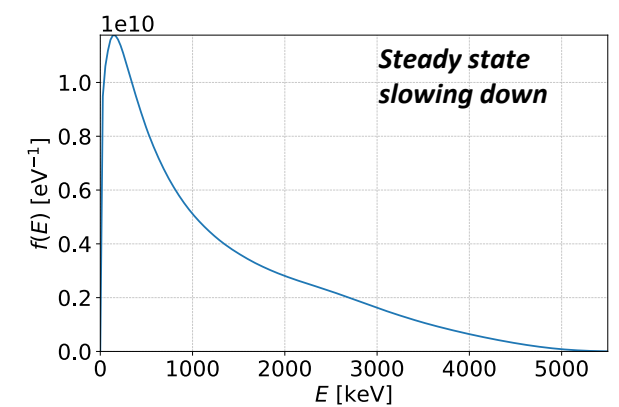
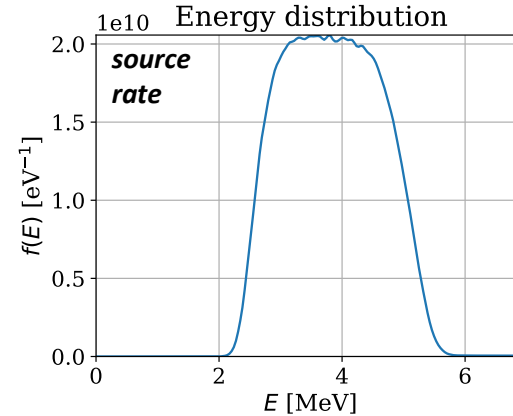
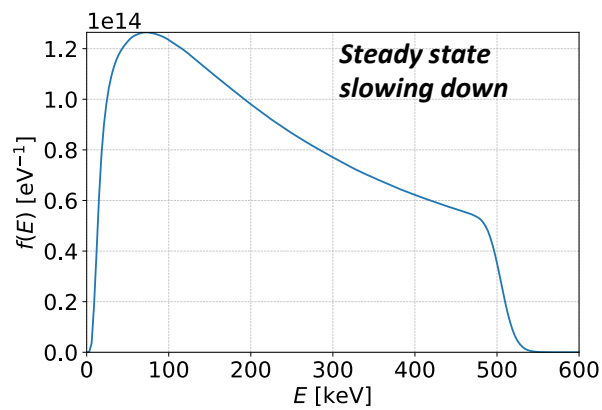
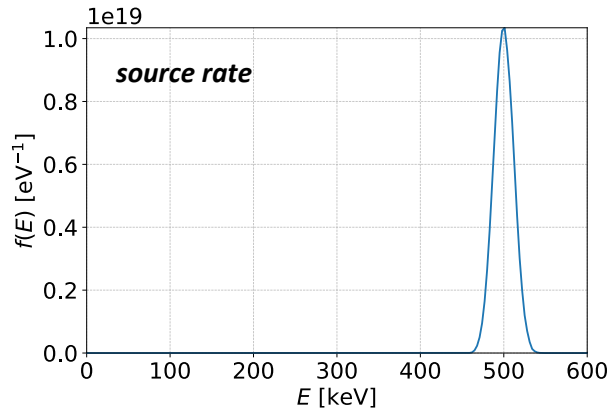
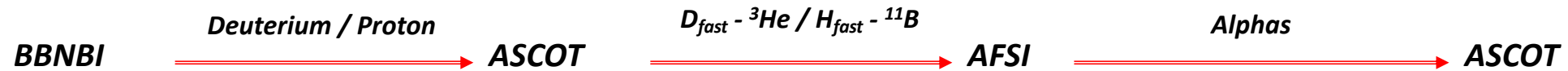
R_0, a	2.96m, 1.2m
B_t, I_p	2.25T, 5.5MA
Plasma vol.	130m ³
T (flat-top)	100s





Modelling suites

- Scenario modelling: CRONOS/METIS/JINTRAC (EU) and TOPICS/GOTRESS (Japan) used by the *Experimental Team* → In this talk **CRONOS** and **METIS** predictive scenarios will be explored.
- NBI beam deposition, beam-target fusion reaction and fast ion distribution slowing down is modelled using the **ASCOT5** suite.

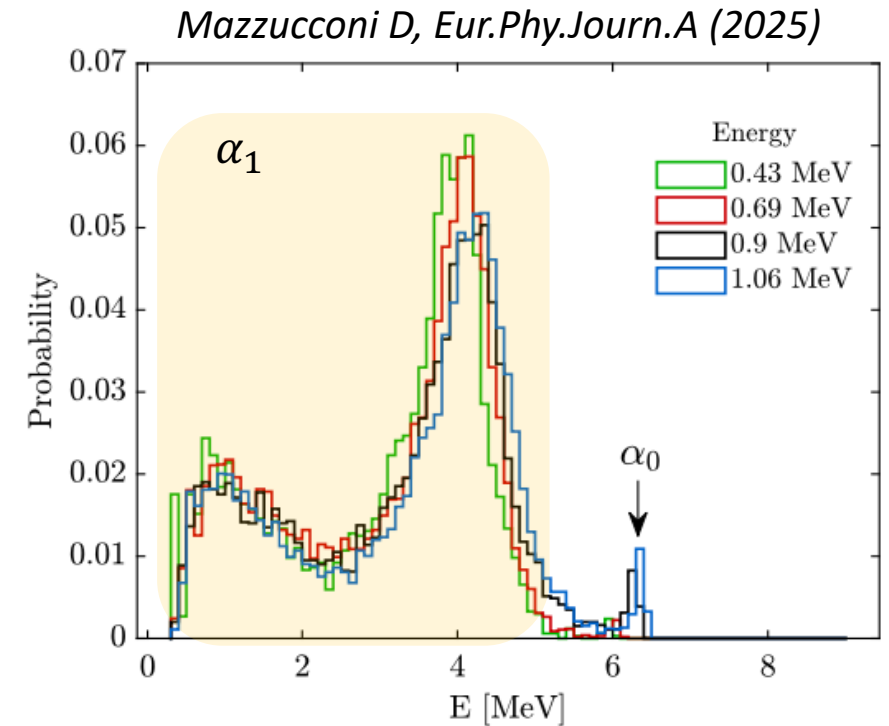




Fusion cross sections in ASCOT5

- Analytic Bosch&Hale formulae for D-³He (DT_He4n, DHe3_He4p, DD_Tp/He3n).
- Analytic formulae for p-¹¹B [Tentori A, NF (2023)] → cast high energy alpha pair inside ASCOT5 calculation.

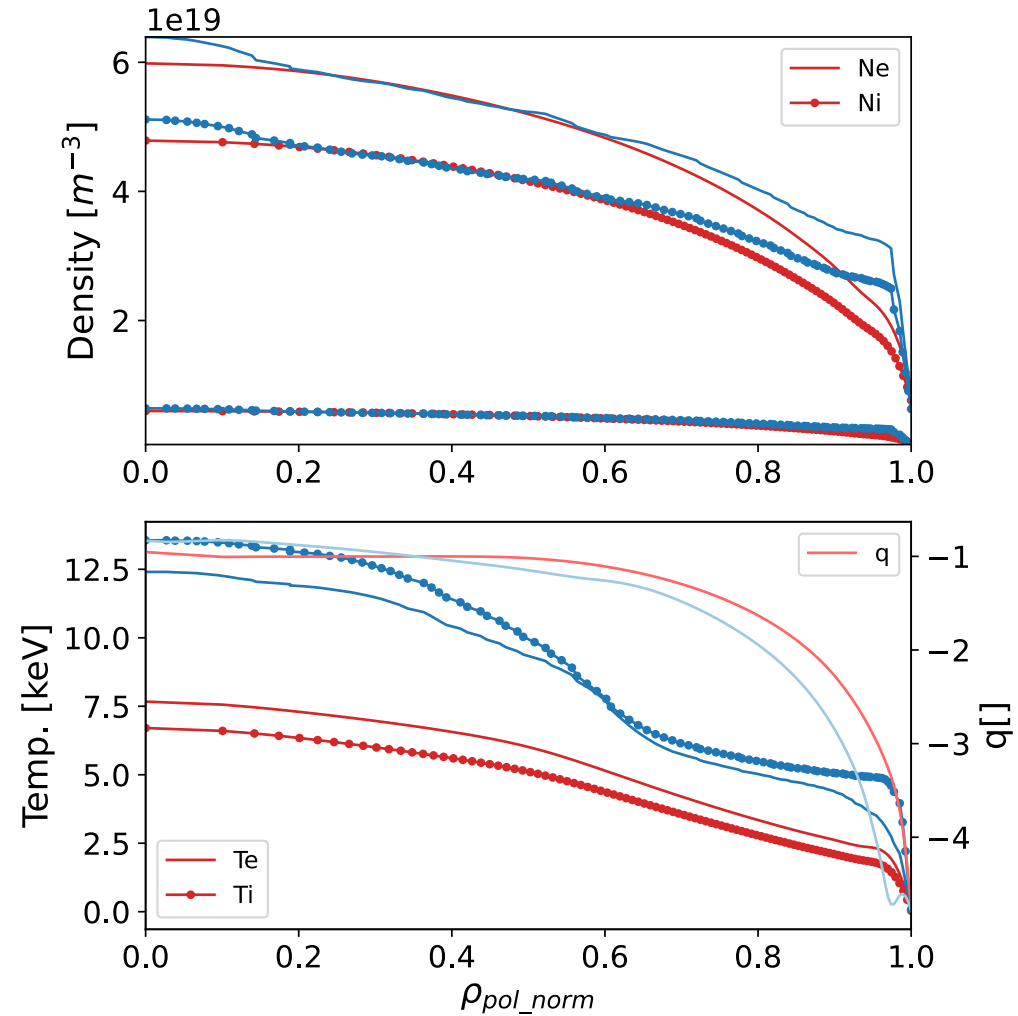
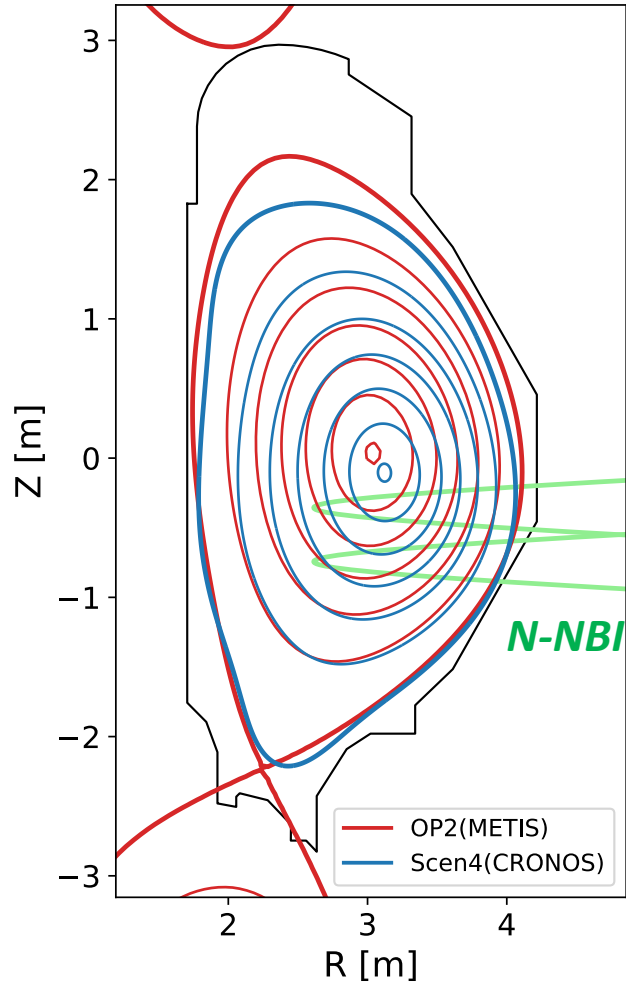
- The α_0 decay channel is insignificant at $E_{\text{proton}} < 2\text{MeV}$.
- In the α_1 decay channel, **first alpha $\sim 3.8\text{MeV}$** (significant ΔE), **next 2 alphas with $\sim 0.08\text{-}4.94\text{MeV}$** ($E_{\text{kin}}^{8\text{Be}} \sim 1.9\text{MeV} + \sim 3\text{MeV}$ of excitation energy)
- *Assume for simplicity we have 2 alphas which will share the 8.68MeV (low energy 3rd alpha discarded)*





Modelled scenarios

Flux surface map



Scenario 4 (CRONOS)

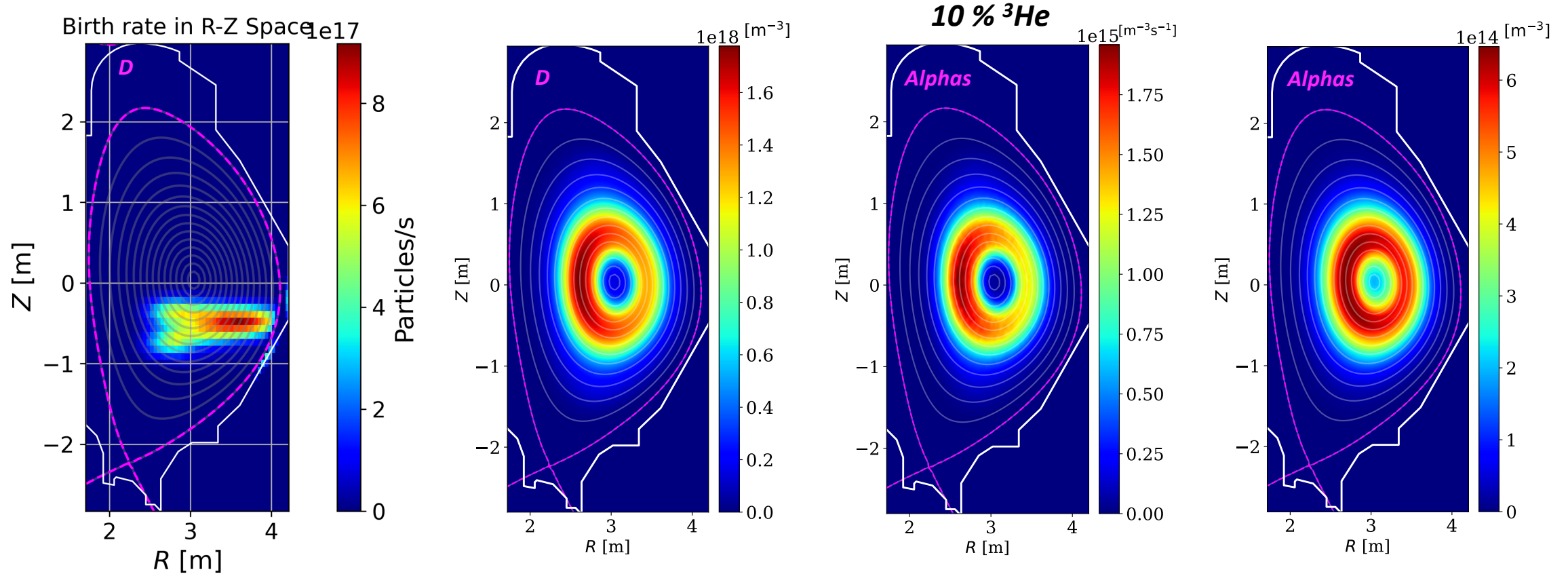
- $I_p = \mathbf{3.5MA}$ and $B_T = 2.28T$.
- D plasma + 1.75% C impurity.
- **10MW N-NBI** and **20MW P-NBI**.
7MW of ECRH.

OP2 Scenario (METIS)

- $I_p = \mathbf{4.6MA}$ and $B_T = 2.28T$.
- D plasma + 1.75% C impurity.
- **10MW N-NBI** and **6MW P-NBI**.
1.5MW of ECRH.
- Flat $|q| \sim 1$ at the core (ST model)



Spatial distributions and power density expectations



- N-NBI beams are off-axis $\rightarrow$ fast-ion density is hollow (off-axis) $\rightarrow$ *alpha distribution also off-axis.*
- Beam particle density is $\sim 1/30$ thermal ion density $\rightarrow P_{fusion}^{D-T} \sim 20 \times P_{fusion}^{D-3He} \rightarrow P_{\alpha}^{D-3He} \sim 30 - 50 \text{ kW}$

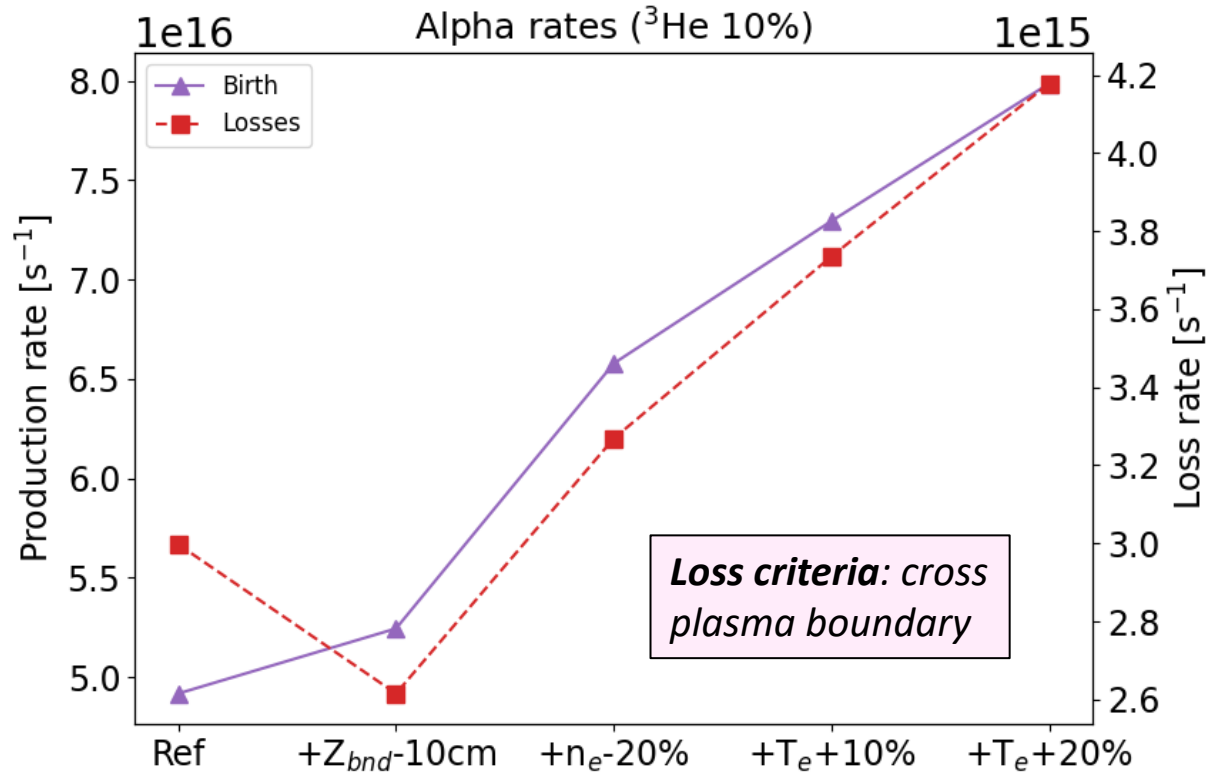


Staged optimization in Scenario 4 (D-³He only)

- Alpha production rate *increases* ~ *linearly* with *He³ %*.
- DD neutron rates: $4.36 \rightarrow 6.98 \times 10^{16} \text{s}^{-1}$

Strategy

- 1) Establish first the ³He(%).
- 2) Slightly shift plasma centroid closer to N-NBI path (if feasible).
- 3) Juggle with plasma density & temperature to raise fast ion slowing down time.



Coelho R, NF (2026)

Extrapolating to 25% He³, *scenario 4* of JT-60SA would reach $\sim 20 \times 10^{16} \text{s}^{-1}$ ($\text{rate}_{\text{JET}} \times 10$) !

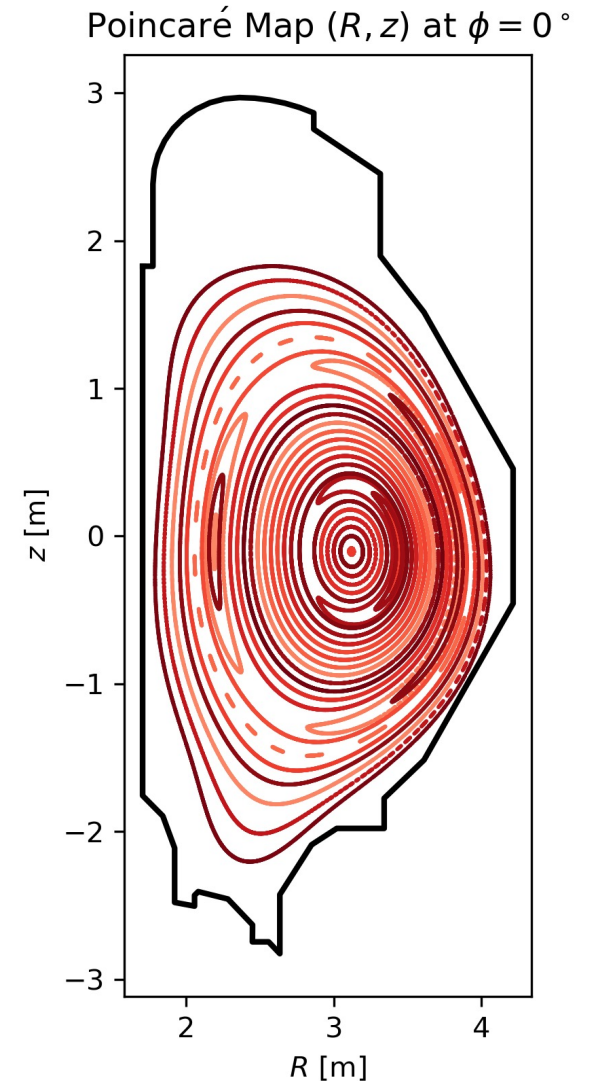
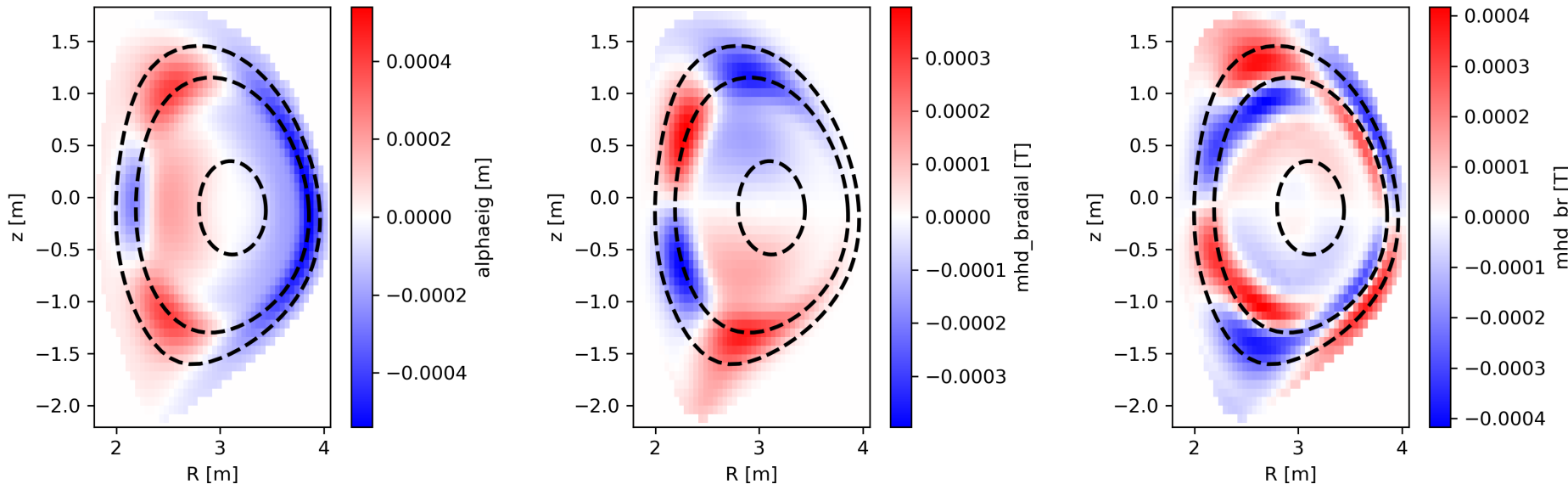
→ If JET had operated at 10MW (7MW used) NBI it would at most reach $\sim 3 \times 10^{16} \text{s}^{-1}$...



Alpha loss mechanisms considered (Scenario 4)

- Prompt losses (typically on time scales $< 10\mu s$).
- Collisional losses (time scales $\lesssim 0.1s$).
- MHD perturbations (static $n=1$ with $m=1$, $m=2,3$ or $m=1,2,3$; phase chosen as “*worst case scenario*”).
- No Ripple **but** fast ion orbit is “*lost*” when crossing plasma boundary (“*rhomax*” end condition).

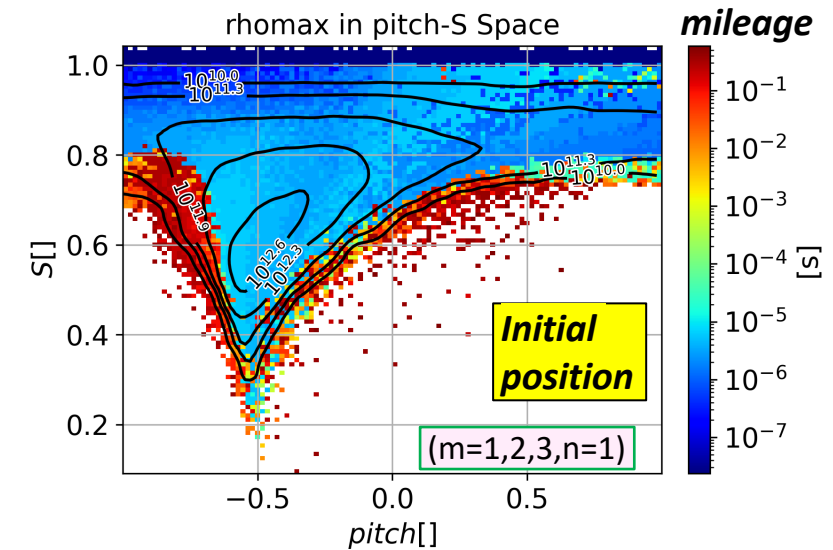
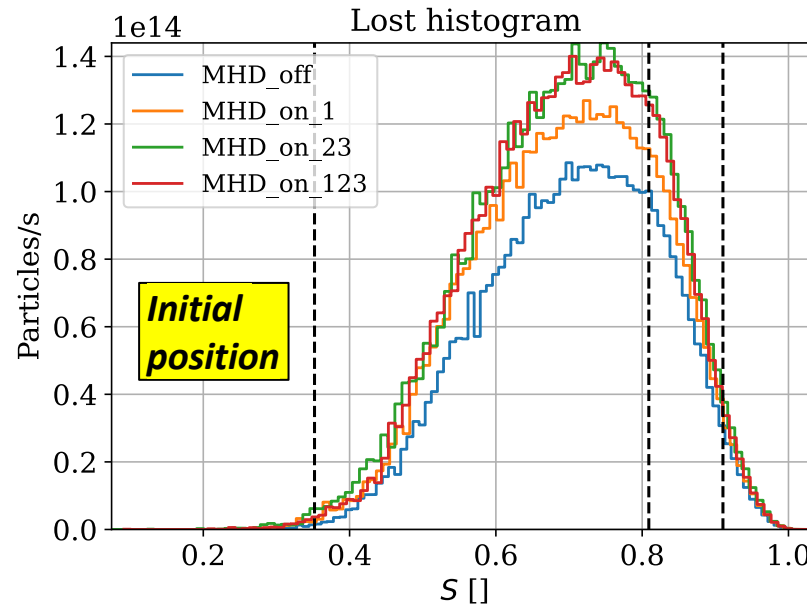
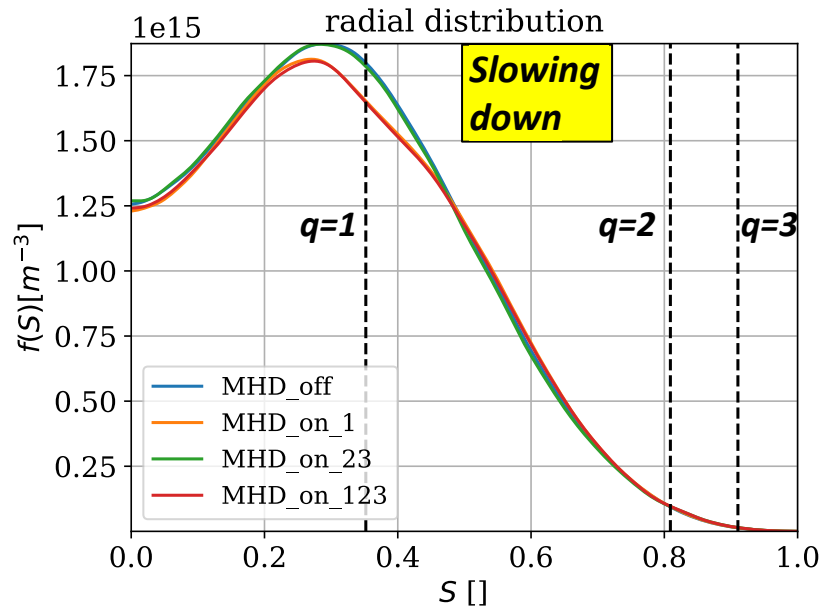
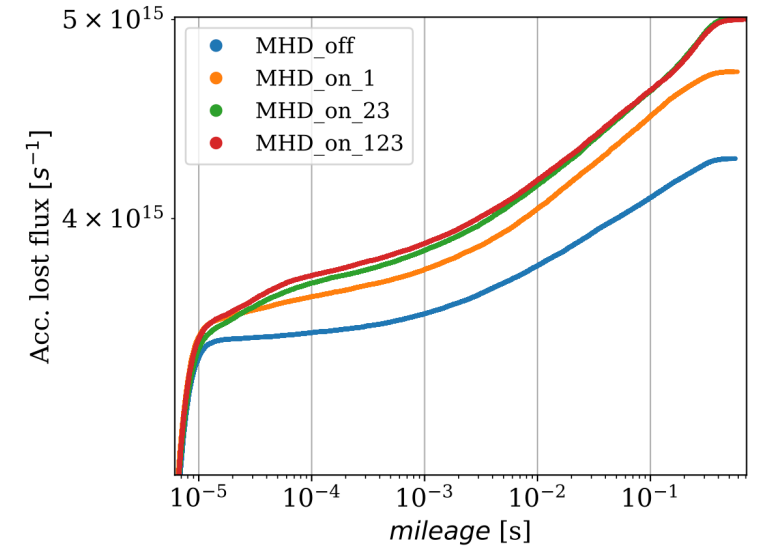
($m=1,2,3, n=1$) static MHD perturbation and $q=1,2,3$ rational surfaces





Evaluating the losses / redistribution (Scenario 4 optimized - 10% ^3He)

	Part. Flux (10^{16} s^{-1})	Power (kW)
<i>Birth</i>	8.1	50
Reference	5.3%	4.9%
(m=1,n=1)	5.8%	5.4%
(m=2,3,n=1)	6.2%	5.6%
(m=1,2,3,n=1)	6.2%	5.6%

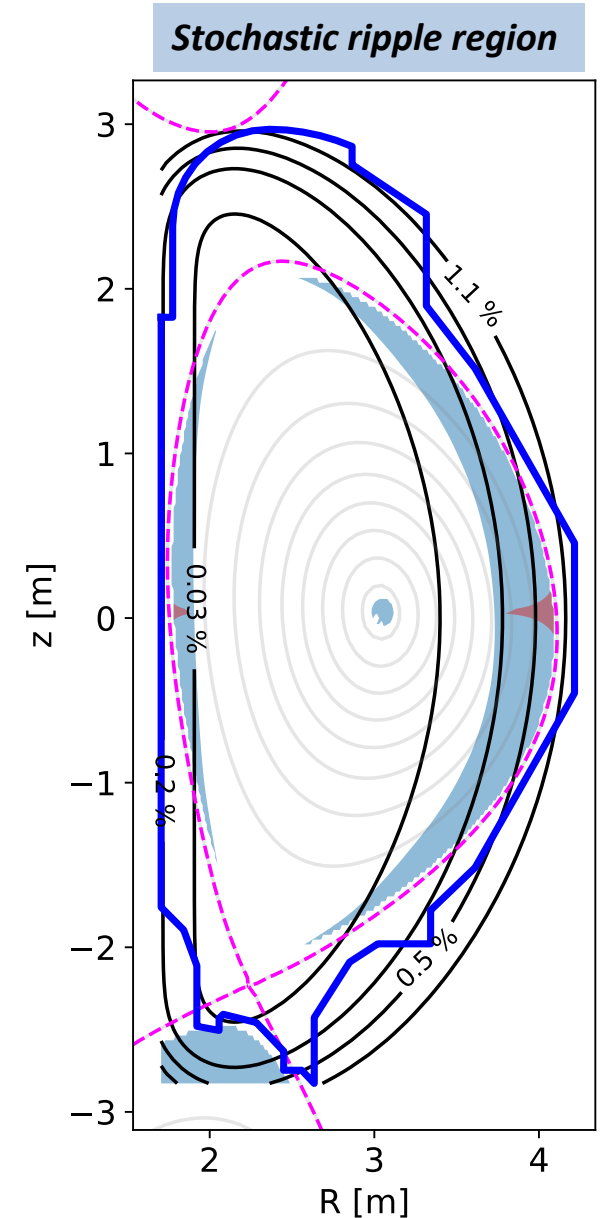
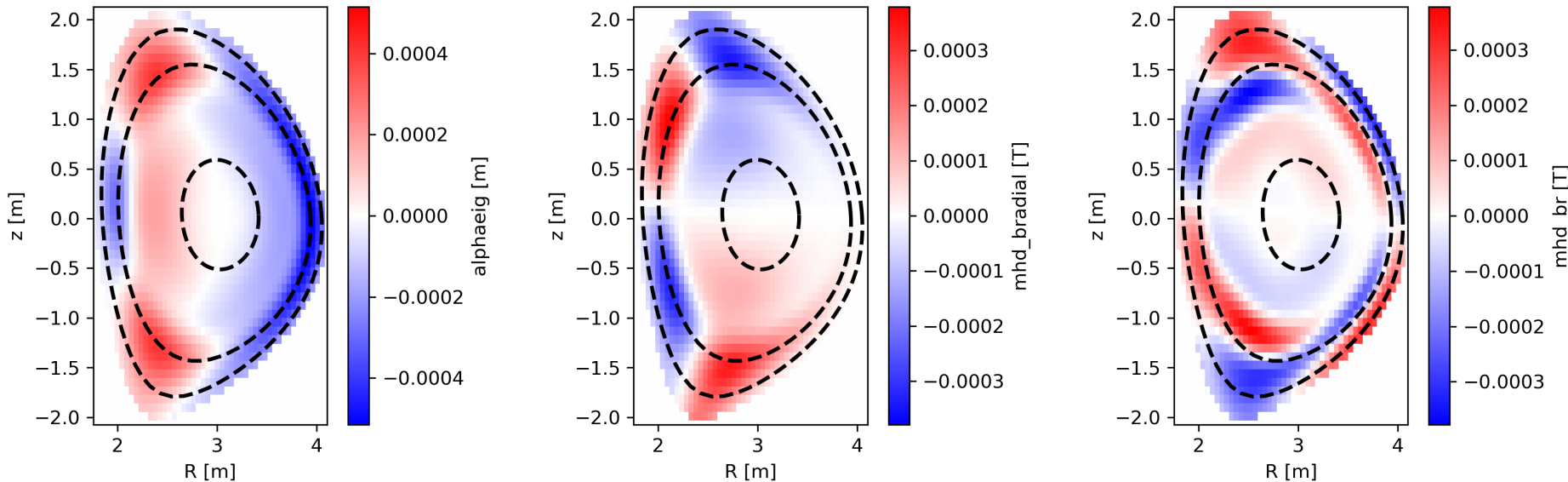




METIS scenario using FEEQS equilibrium

- Free-boundary equilibrium FEEQS *includes SOL region*.
- No variants considered (*Reference scenario only*). ***$I_p=4.6\text{MA}$ should provide better confinement than the 3.5MA Scenario 4...***
- Same MHD perturbations as Scenario 4 (*smaller (2,1) island though...*).
- Ripple ($\sim 1\%$ at bound.) ***is retained*** and marker lost if hitting the wall.

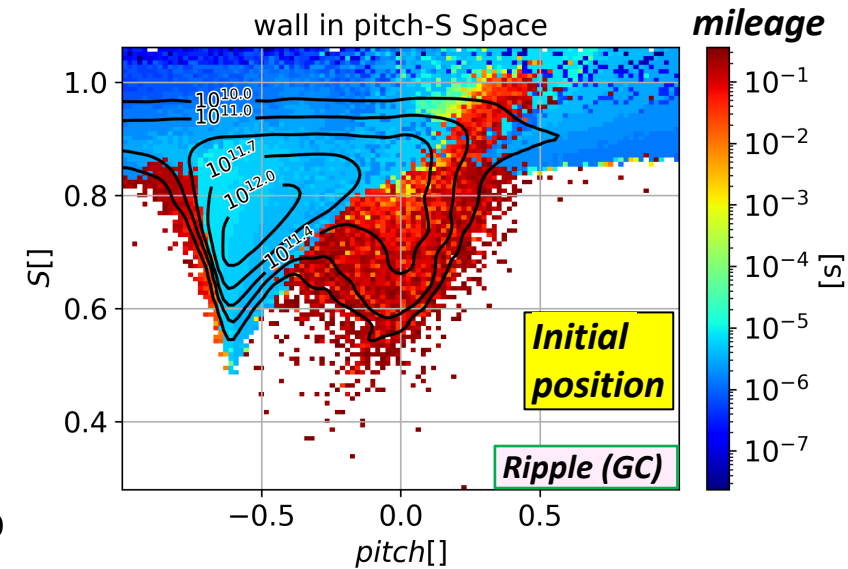
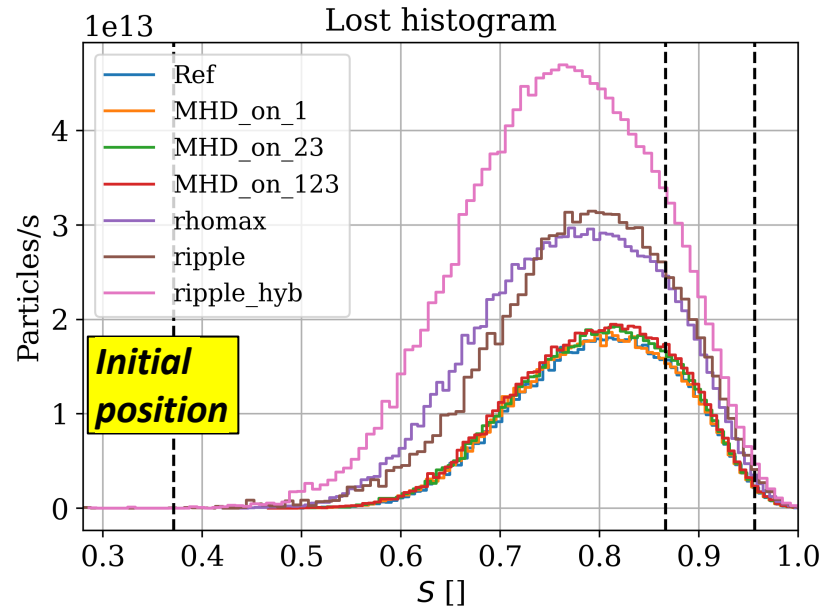
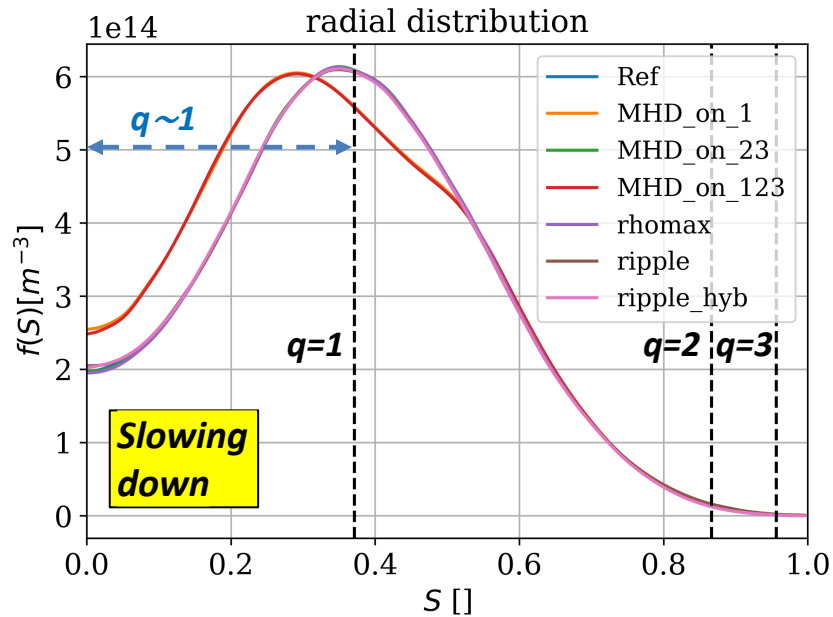
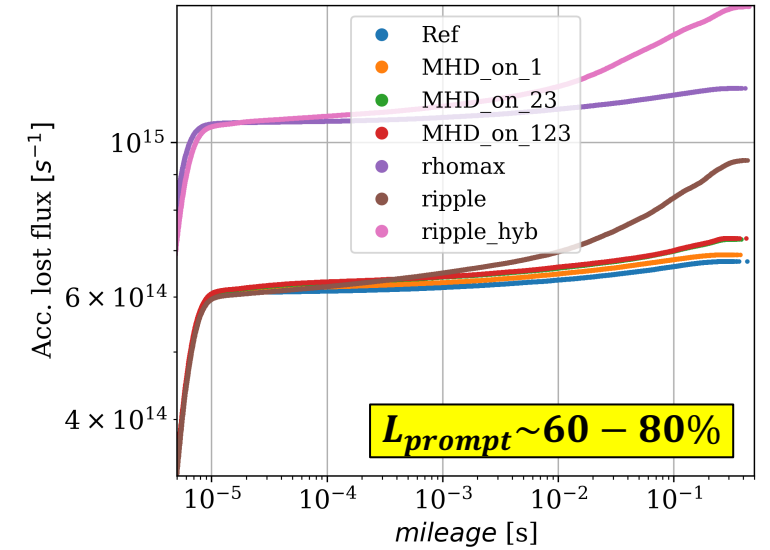
($m=1,2,3, n=1$) static MHD perturbation and $q=1,2,3$ rational surfaces





Evaluating the losses / redistribution (METIS with 10% ^3He)

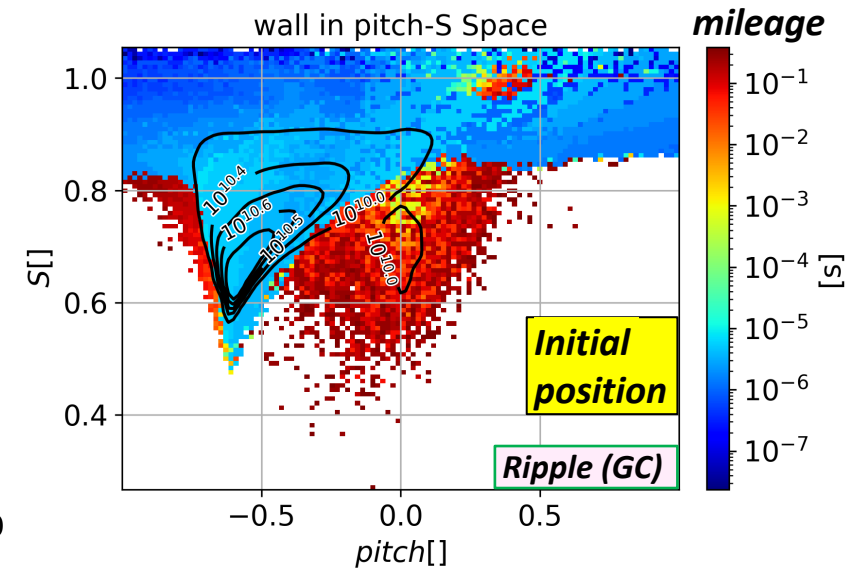
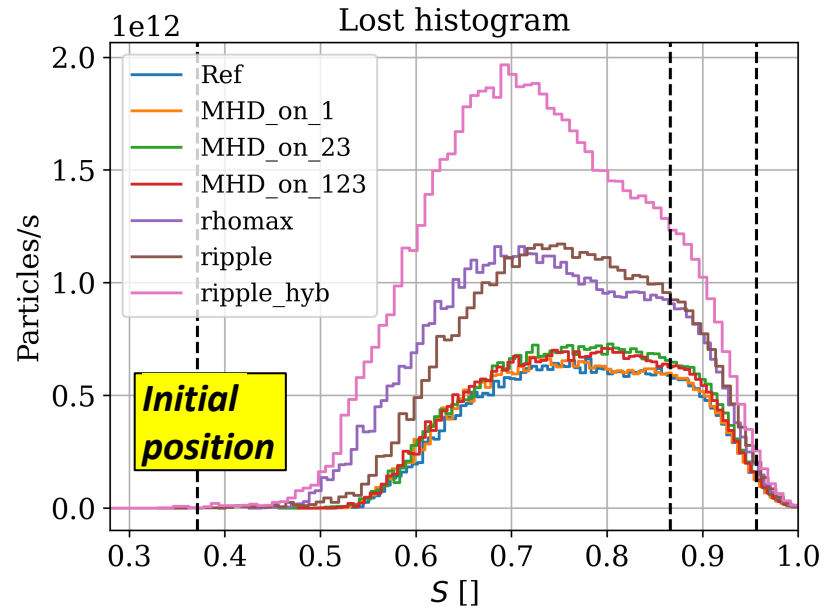
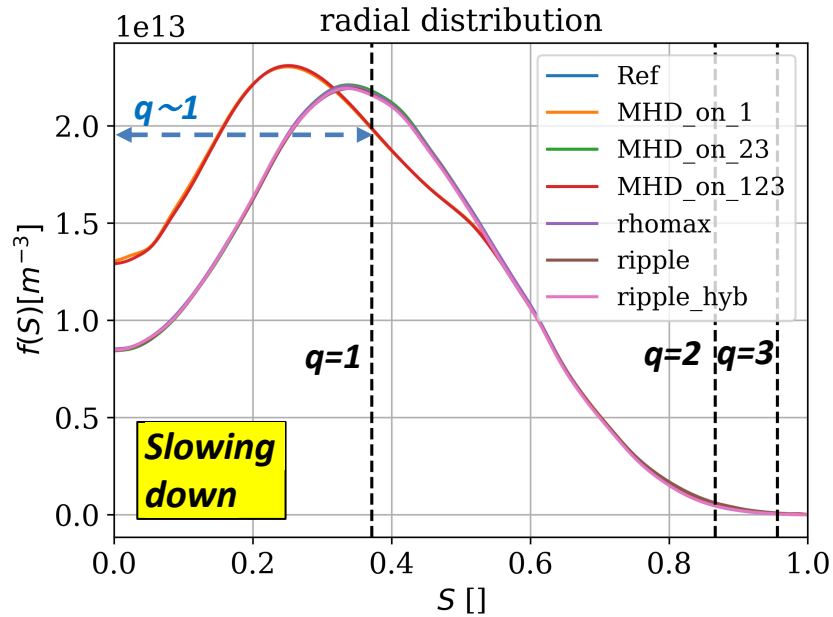
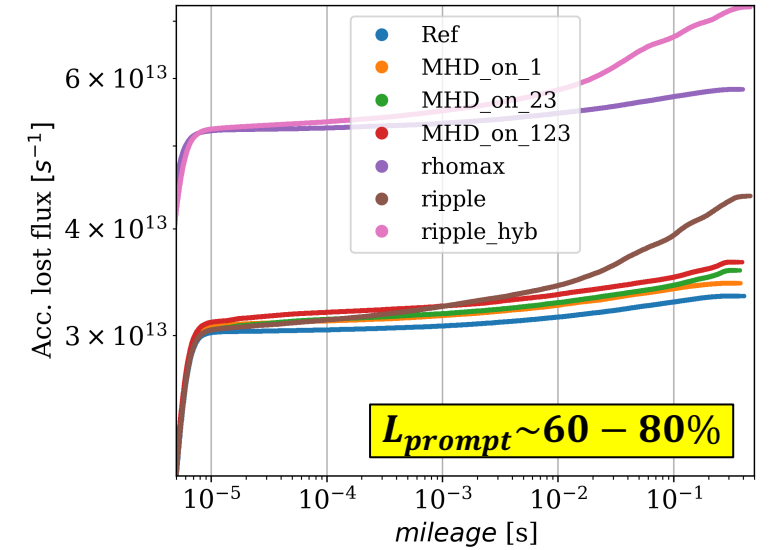
	Part. Flux (10^{16} s^{-1})	Power (kW)
Birth	4.9	30
Reference	1.4%	1.3%
(m=1,n=1)	1.4%	1.4%
(m=1,2,3,n=1)	1.5%	1.4%
rhomax	2.4%	2.4%
Ripple (GC)	1.9%	1.6%
Ripple (hybrid)	3.2%	2.8%





Evaluating the losses / redistribution (METIS with 1% ^{11}B)

	Part. Flux (10^{15} s^{-1})	Power (kW)
<i>Birth</i>	1.7	1.24
Reference	1.96%	1.89%
(m=1,n=1)	2.0%	1.94%
(m=1,2,3,n=1)	2.1%	2.0%
rhomax	3.4%	3.3%
Ripple (GC)	2.6%	2.2%
Ripple (hybrid)	4.3%	3.8%





Comparative Fast ion regimes in D-³He and p-¹¹B regimes

- Per % of seeded ³He :

$$\alpha_{rate}(Scen. 4) = 5 - 8 \times 10^{15} s^{-1} \quad \alpha_{rate}(OP2 - METIS) = 5 \times 10^{15} s^{-1}$$

- Per % of seeded ¹¹B :

$$\alpha_{rate}(OP2 - METIS) = (\times 2) \quad 1.7 \times 10^{15} s^{-1} \quad \mapsto \quad D-^3He \text{ yield is } \sim 50\% \text{ higher than } p-^{11}B$$

- Lower rates were successfully measured at JET (γ -ray diagnostics) $\rightarrow$ encouraging and offers opportunity to study alpha particles in JT-60SA (see V. Kiptily talk at this meeting)
- Alpha confinement deteriorates at lower plasma current (I_p) Scenario 4 (**x2.2 higher particle flux lost** for reference case when using **rhomax** end condition).
- **Magnetic ripple** has higher effect on alpha loss (*especially when full orbit effect are retained when orbit steps into the SOL – hybrid run mode – using rhomax end condition is a good proxy though ... unless we need to evaluate wall power loads... !*)
- Static MHD (*no E-field*) can either **redistribute** (m=1) or **enhance** losses (m=2) $\rightarrow$ *alpha birth distribution is off-axis $\rightarrow$ Resonant AEs / fishbones should be addressed though...*



Summary & Strategic Outlook

- ***A unique strategic device:*** JT-60SA provides a critical, non-radioactive platform to study alpha particle physics without tritium handling overhead.
- ***Exploiting the 500 keV N-NBI:*** Essential ingredient either using D or H in ^3He or ^{11}B seeded plasma respectively.
- ***Assisting path towards Burning Plasmas:*** At **higher alpha birth rates and plasma current** than JET, JT-60SA can provide useful insights in alpha physics i.e. alpha driven instabilities, plasma transport moderator, development/testing of alpha scoped diagnostics.
 - Lessons to be learned for **ITER** burning plasmas, before **BEST** and **SPARC** operation.