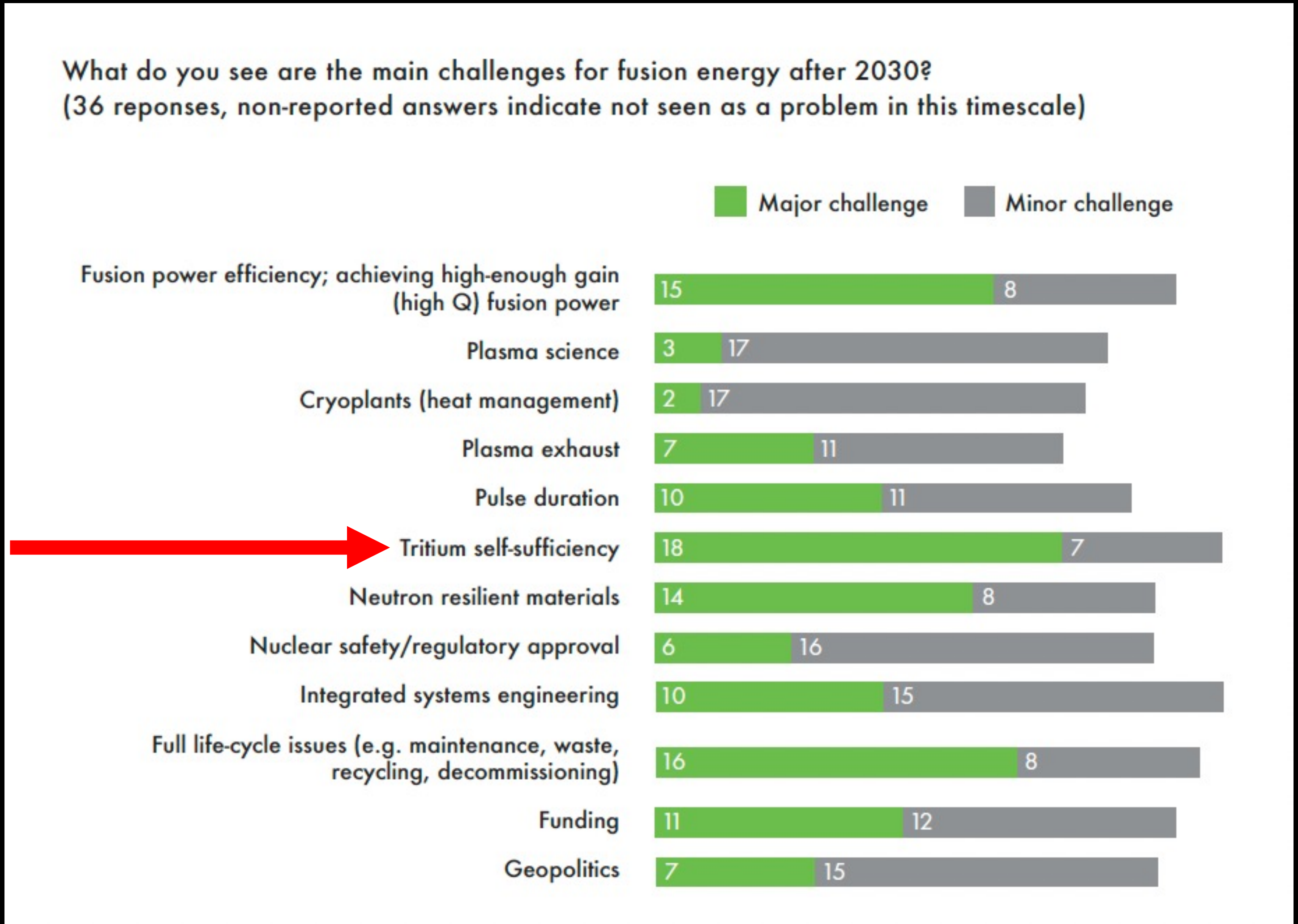
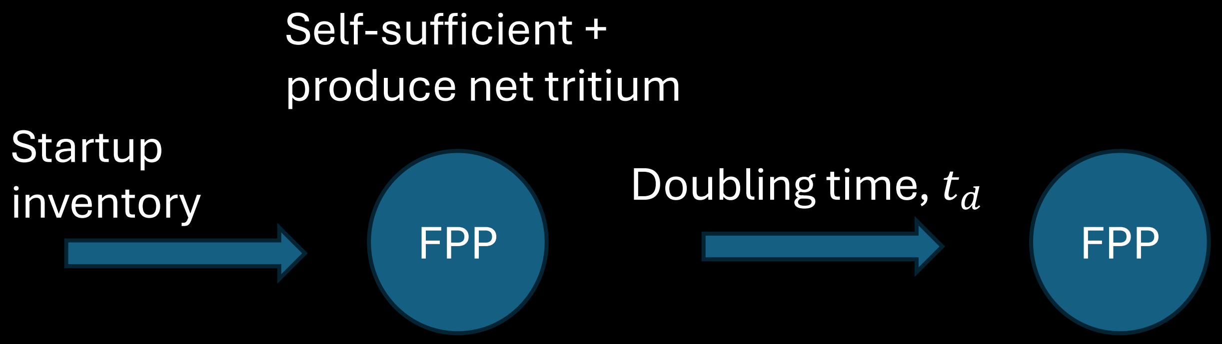
Overview of D-T fuel cycles: the quest for tritium self-sufficiency and the growth of fusion energy

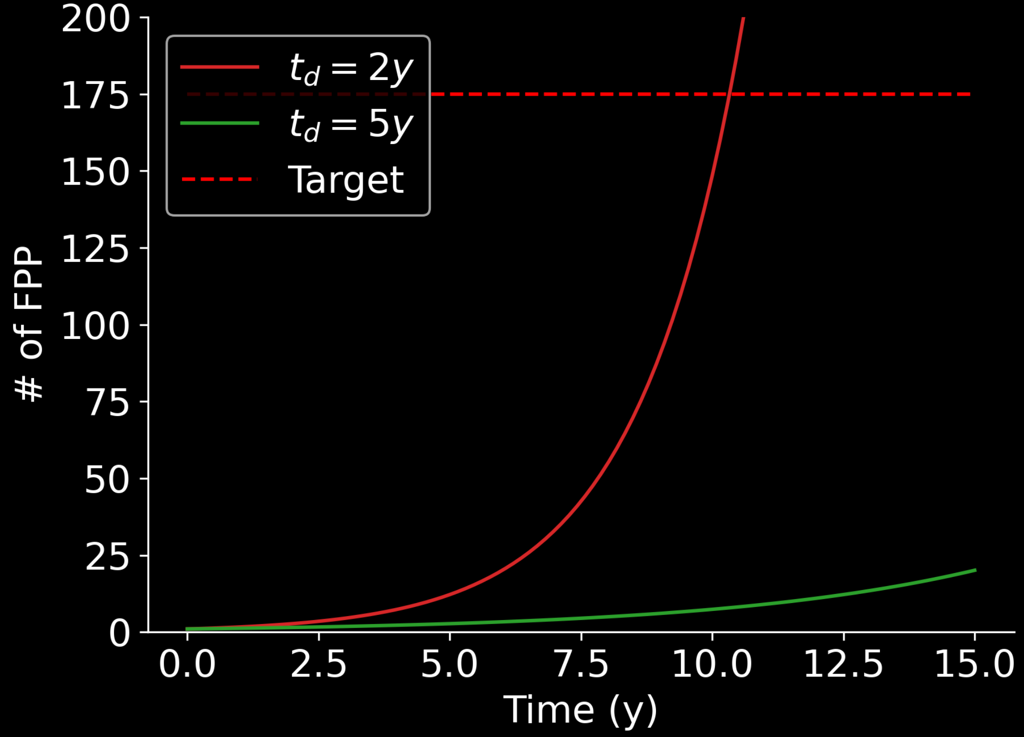
S. Meschini, R. Delaporte-Mathurin, G. Tynan, D. Whyte, S. Ferry
MIT PSFC

MOTIVATIONS



TRITIUM SELF-SUFFICIENCY (TSS)





TBRa > TBRr

SYSTEM-LEVEL MODELING APPROACH

Residence time method

Non-radioactive tritium losses

Radioactive tritium losses

$$\frac{dI_i}{dt} = \sum_{j\neq i}\left(\frac{I_j}{\tau_j}\right)_i - (1+\epsilon_i)\left(\frac{I_i}{\tau_i}\right) - \lambda I_i + S_i$$

Inflow from j-th component

Mean residence time in the i-th component

Tritium generation

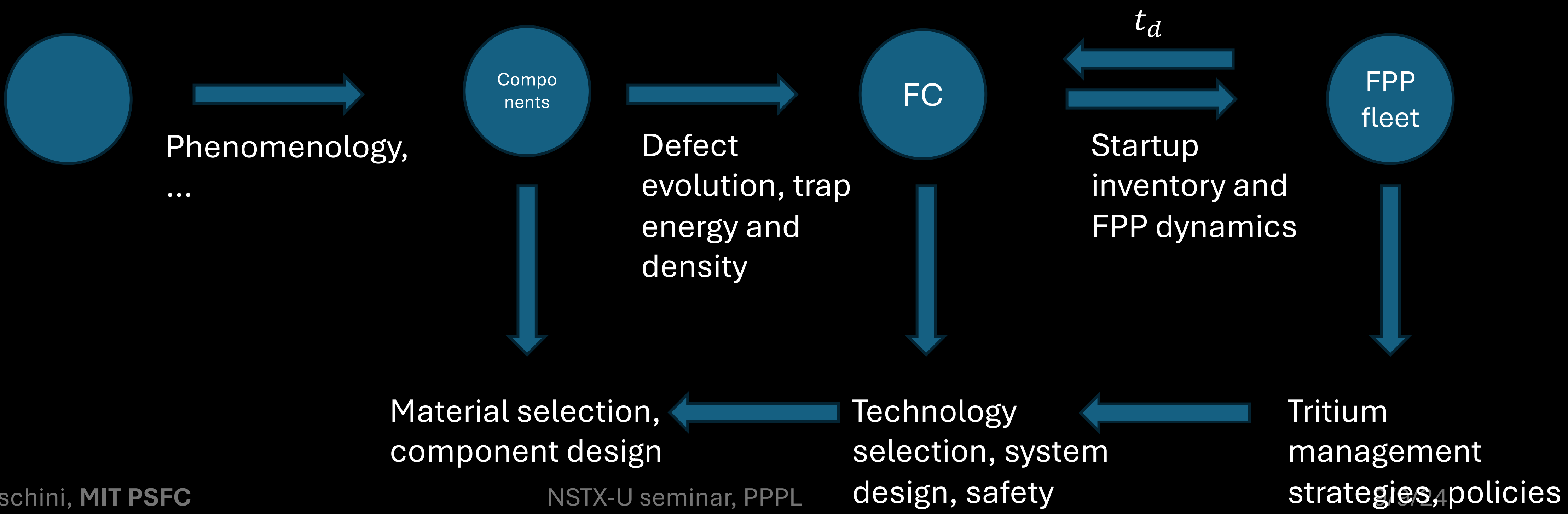
- Tritium systems
  - 1D or 0D + time models for each component

Startup inventory and FC dynamics

Abdou, M., et al., *Nuclear fusion* 61.1 (2020): 013001.
Meschini, S., et al., *Nuclear Fusion* 63.12 (2023): 126005.

TSS IS MULTI-SCALE PROBLEM

- H – lattice interaction
  - Molecular dynamics
  - Density Functional theory
- H transport
  - McNabb – Foster model (3D diffusion + trapping)
- Tritium systems
  - 1D or 0D models
- Global market
  - Tritium reserves
  - Fusion energy penetration



OUTLINE

- Fuel cycle
  - Fuel cycle dynamics
  - Fuel cycle layout
  - Main technologies
- Macroscopic H transport
  - Tritium implantation and trapping
  - Impact of neutron irradiation and material damage on tritium self-sufficiency
- Global market
  - Tritium reserves management
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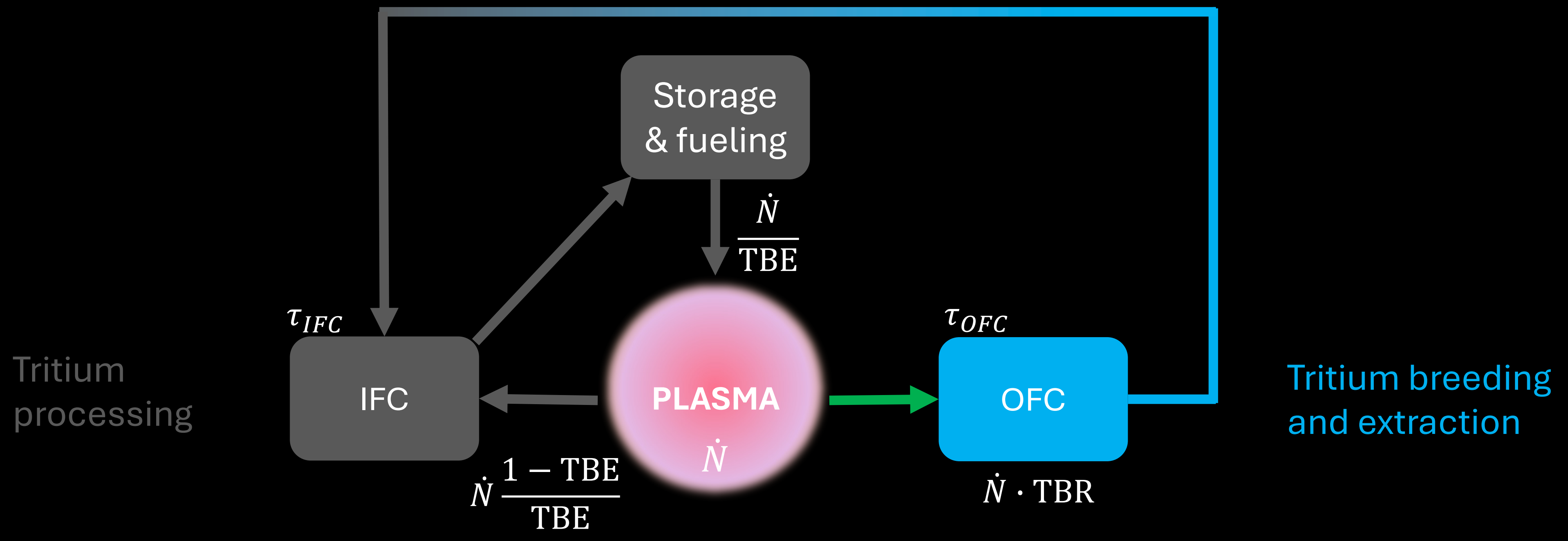
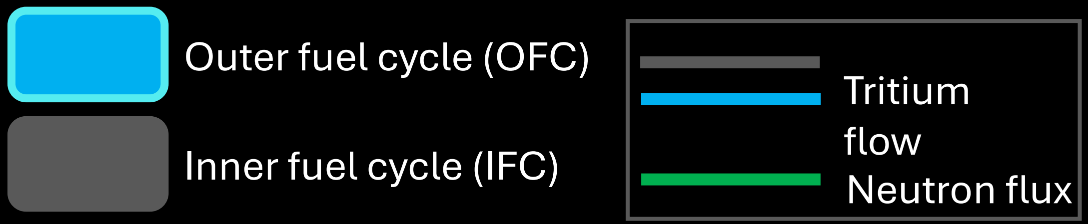
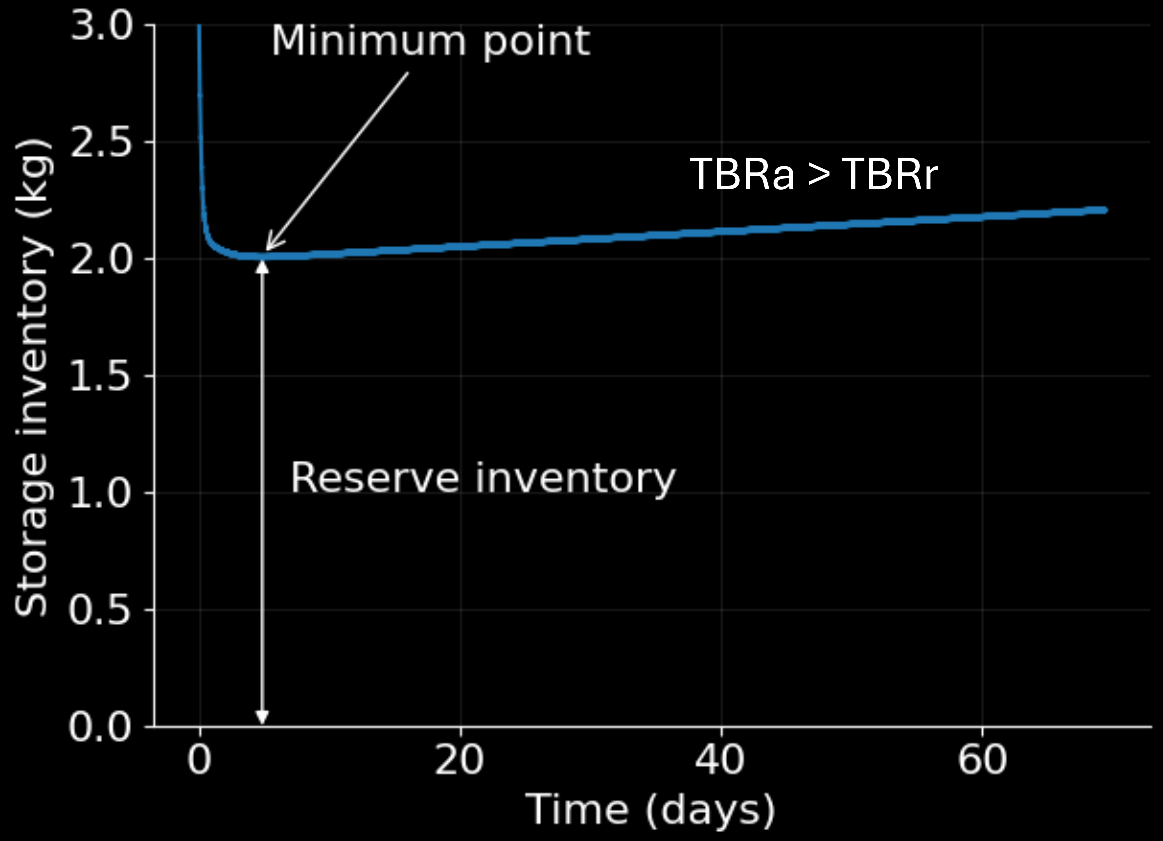
A BASIC FUEL CYCLE MODEL



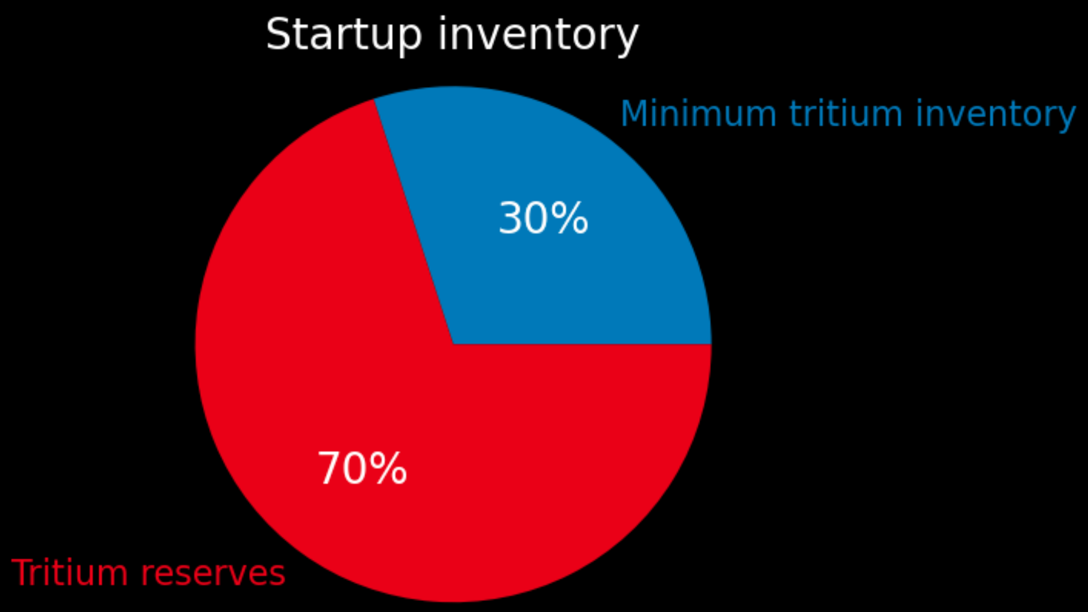
$\dot{N}$: Tritium burn rate
TBE: Tritium Burn Efficiency



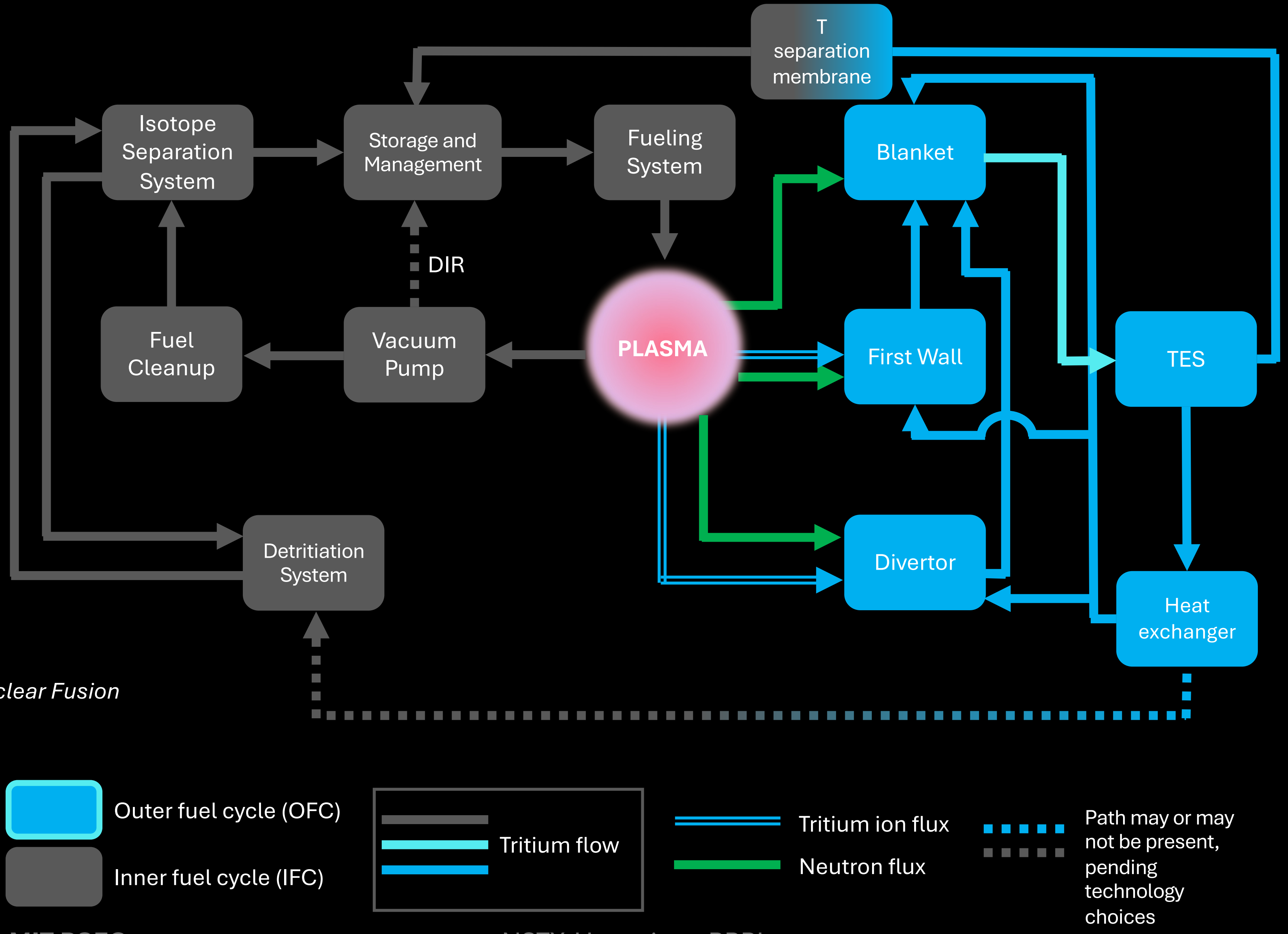
THE INITIAL TRANSIENT SETS THE STARTUP INVENTORY



For 24h tritium reserves



Tritium fuel cycle of an ARC-class fusion power plant

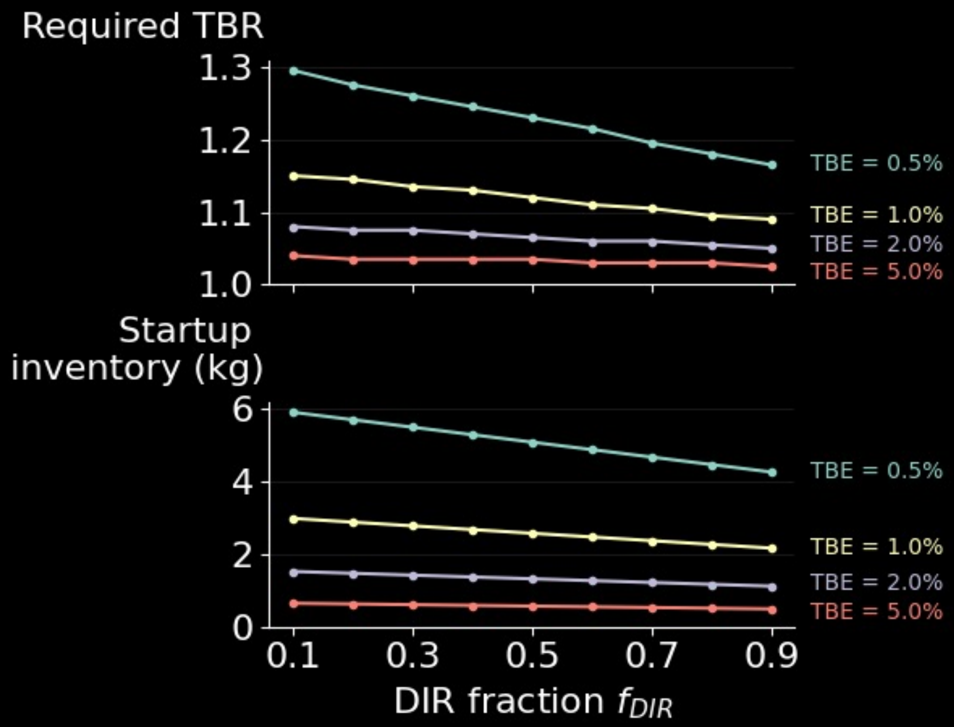


Meschini, S., et al., *Nuclear Fusion* 63.12 (2023): 126005.

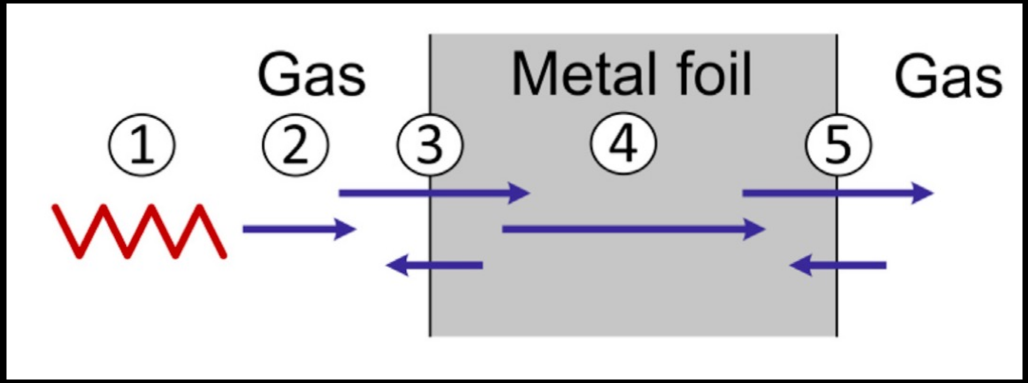
DIRECT INTERNAL RECYCLING

FUNCTIONS:

- Effective pumping
- Sharp H selectivity



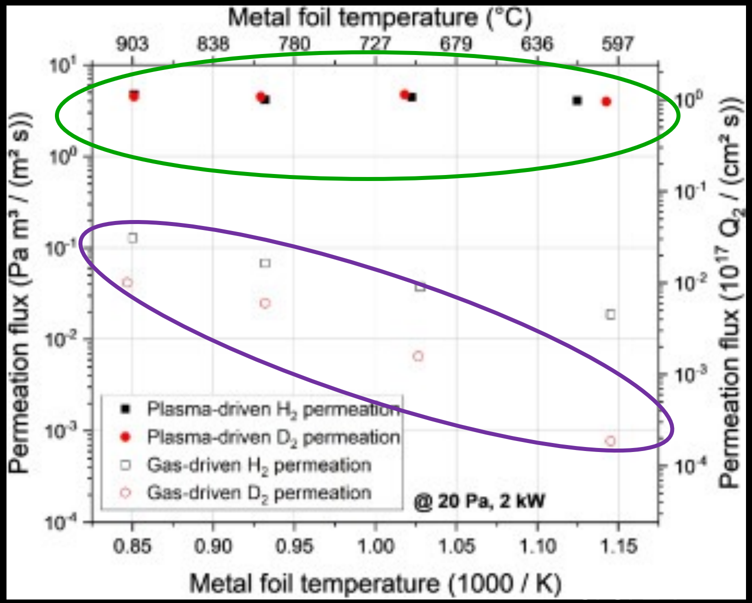
Metal Foil Pumps



SUPERPERMEATION

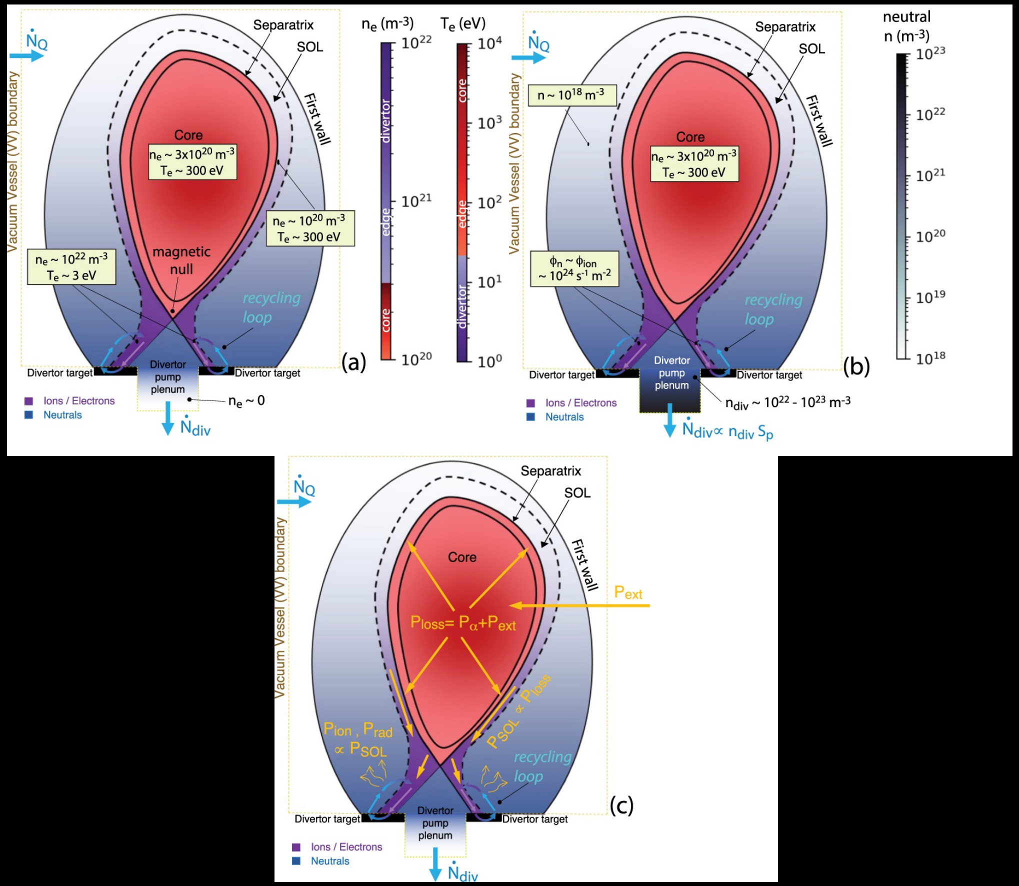
$\times 10^2 - 10^4$

CLASSIC DIFFUSION



Peters, B.J, and Day, C., *FED* 124 (2017): 696-699.

TRITIUM BURN EFFICIENCY



Whyte, D. G., et al, *Nuclear Fusion* 63.12 (2023): 126019.

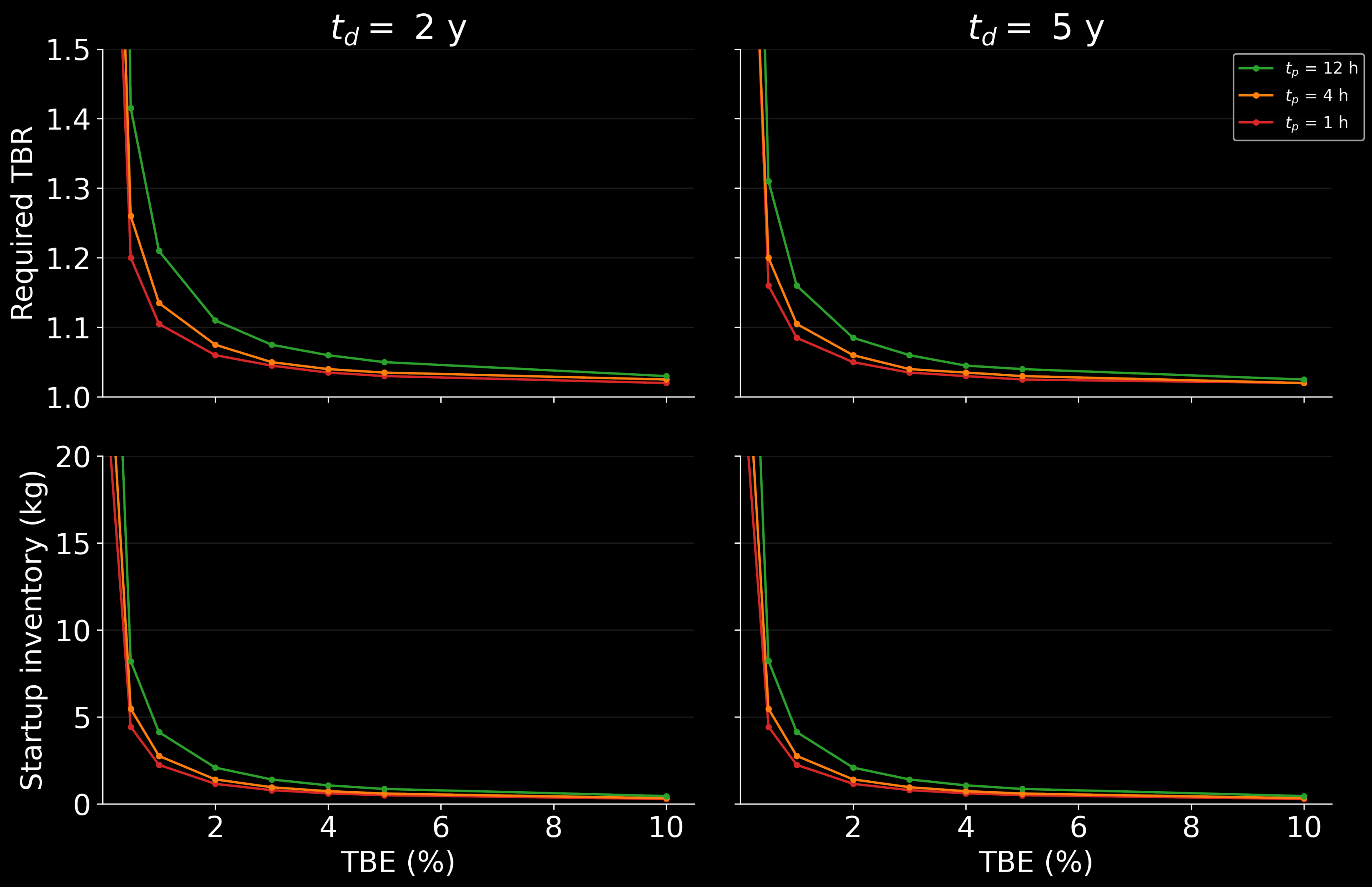
$$\text{TBE} = \frac{\text{T burn rate}}{\text{T input rate}}$$

Tritium removal is a collateral effect of He ash removal

ITER TBE = 0.36%

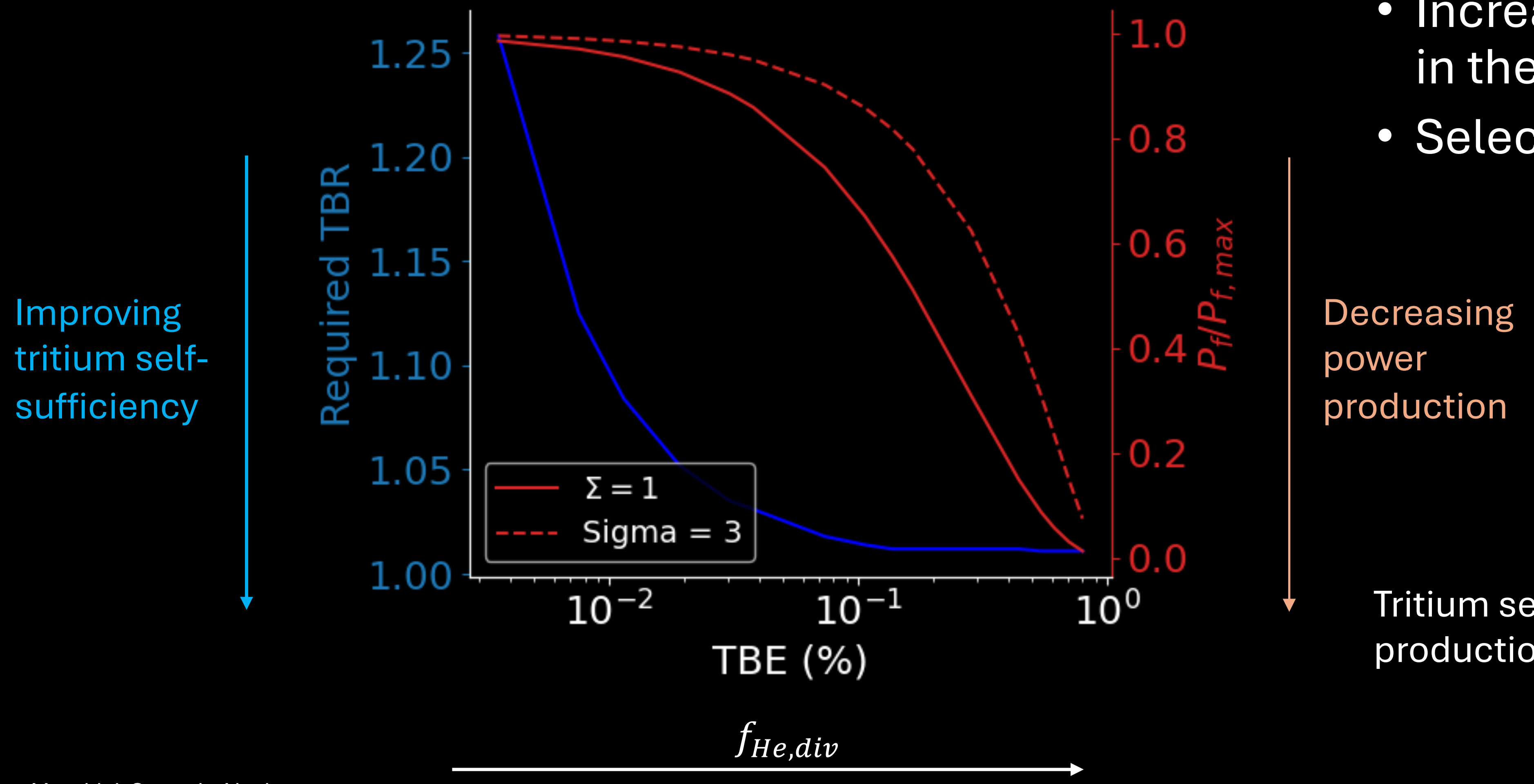
TBE and TSS

TSS is virtually impossible at low TBE



Meschini, S., et al., *Nuclear Fusion* 63.12 (2023): 126005.

TBE and FUSION POWER



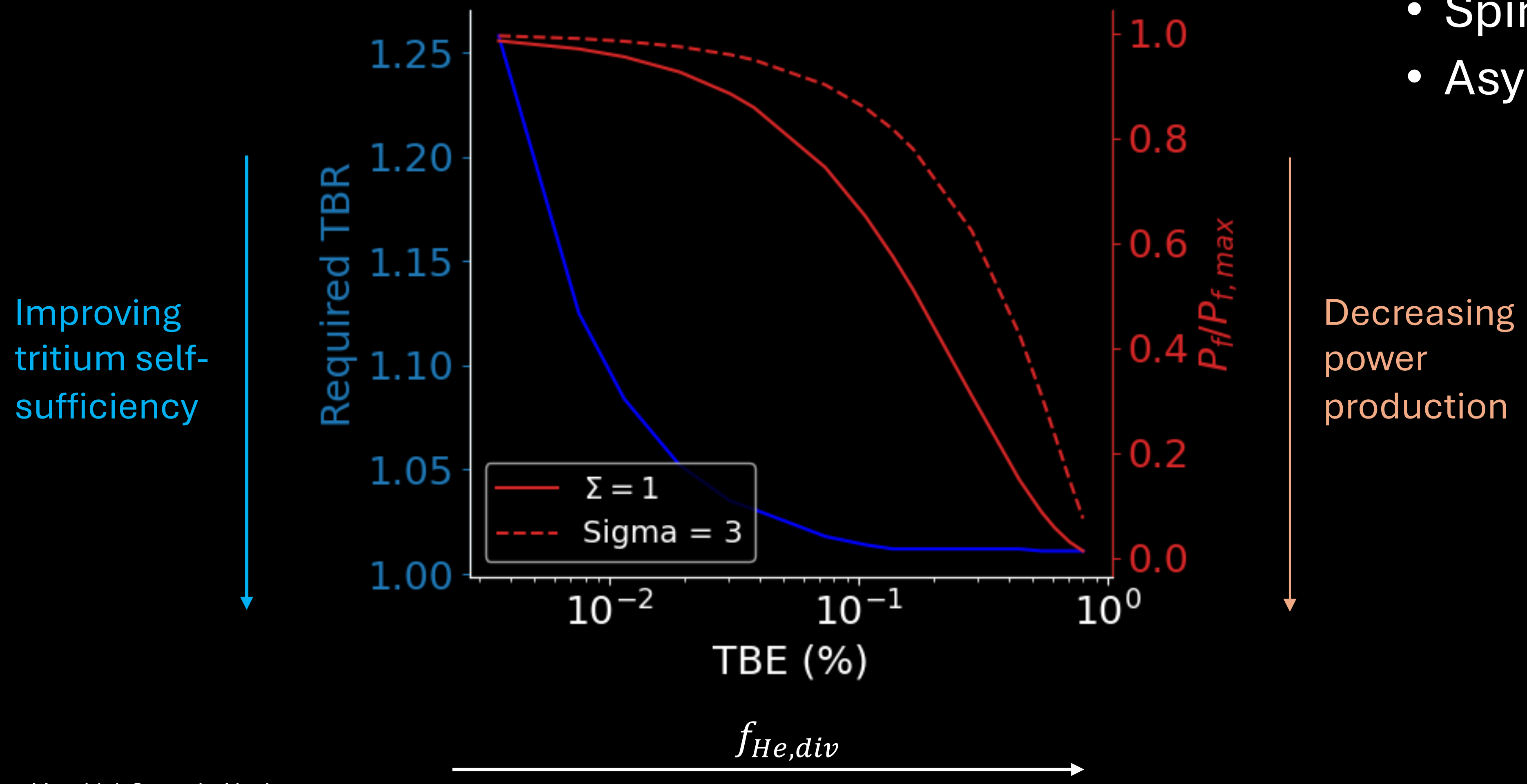
TBE can be improved by:

- Increasing the He fraction in the divertor, $f_{He,div}$
- Selective He pumping, Σ

Tritium self-sufficiency and power production are competing goals!

Meschini, S., et al., *Nuclear Fusion* 63.12 (2023): 126005.

TBE and FUSION POWER



Possible strategies to improve TBE and P_{fus}

- Selective He pumping
- Spin polarized fuels
- Asymmetric transport

Meschini, S., et al., *Nuclear Fusion* 63.12 (2023): 126005.

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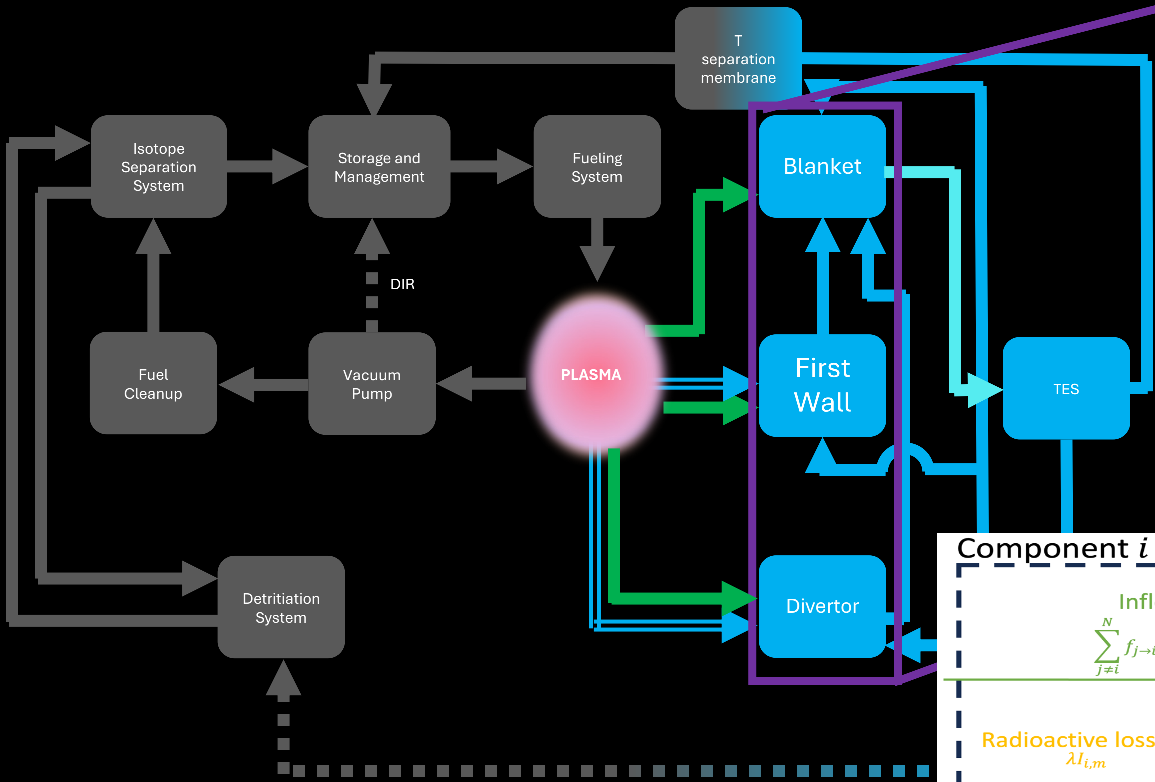
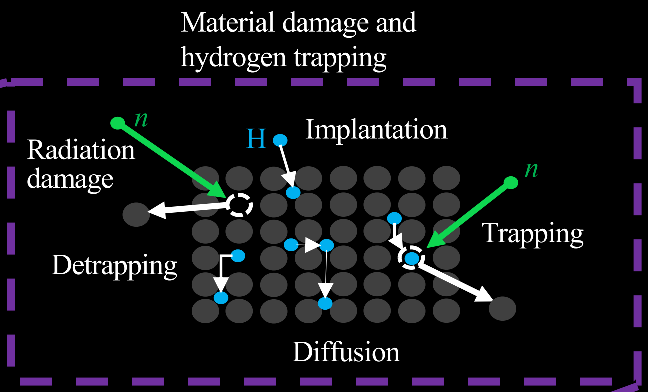
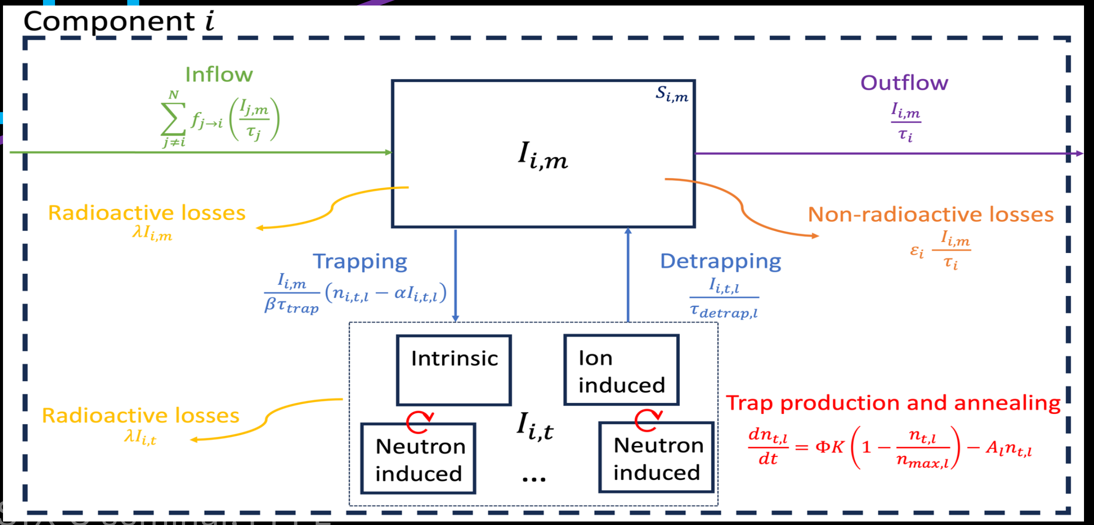
NEUTRON-INDUCED DAMAGE IN MATERIALS





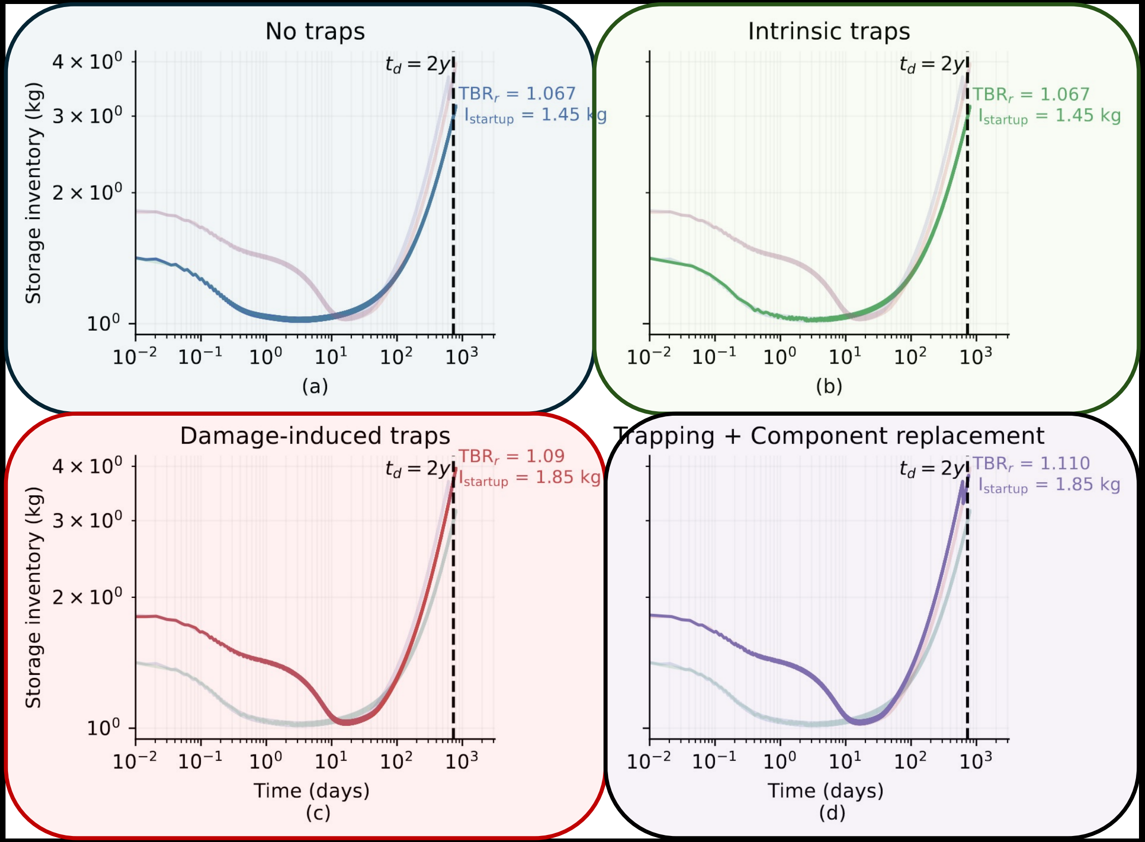


+ COMPONENT REPLACEMENT

TRAPPING AND COMPONENT REPLACEMENT STRONGLY IMPACT TSS

No traps
As before

Intrinsic traps
- Trapping energy negligible at blanket operating temperatures
- Negligible (constant) trap density



Damage-induced traps
- High trapping energy
- Non-negligible, increasing trap density

+ 3% TBRr and + 20% startup inventory

Trapping + component replacement
- Periodic tritium sink
- Must recover trapped tritium before disposal

Meschini et al., Submitted to NF

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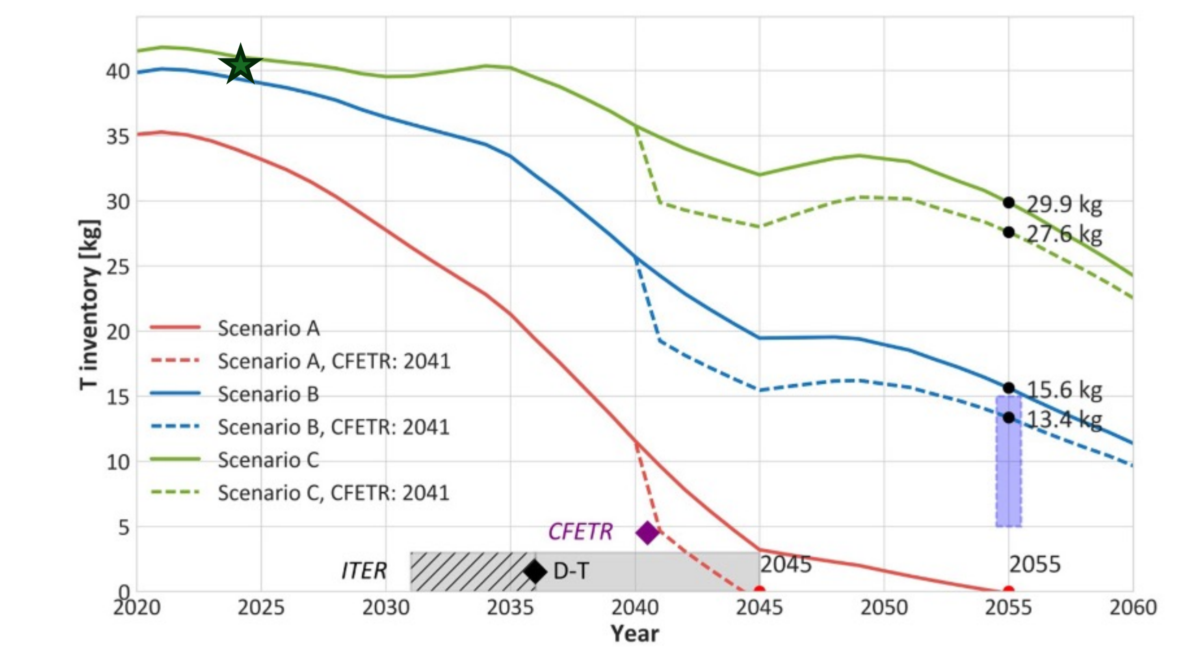
TRITIUM RESOURCES AVAILABLE



Kovari, M., et al. "Tritium resources available for fusion reactors." *Nuclear Fusion* 58.2 (2017): 026010.
See also: Pearson, R., et al., *Fusion Engineering and Design* 136 (2018): 1140-1148.

Private companies might deploy FPPs[2] even before ITER starts D-T operations (delayed to 2039[1])

Goal:
375 TWh of electricity production by 2050

MIT Energy Initiative

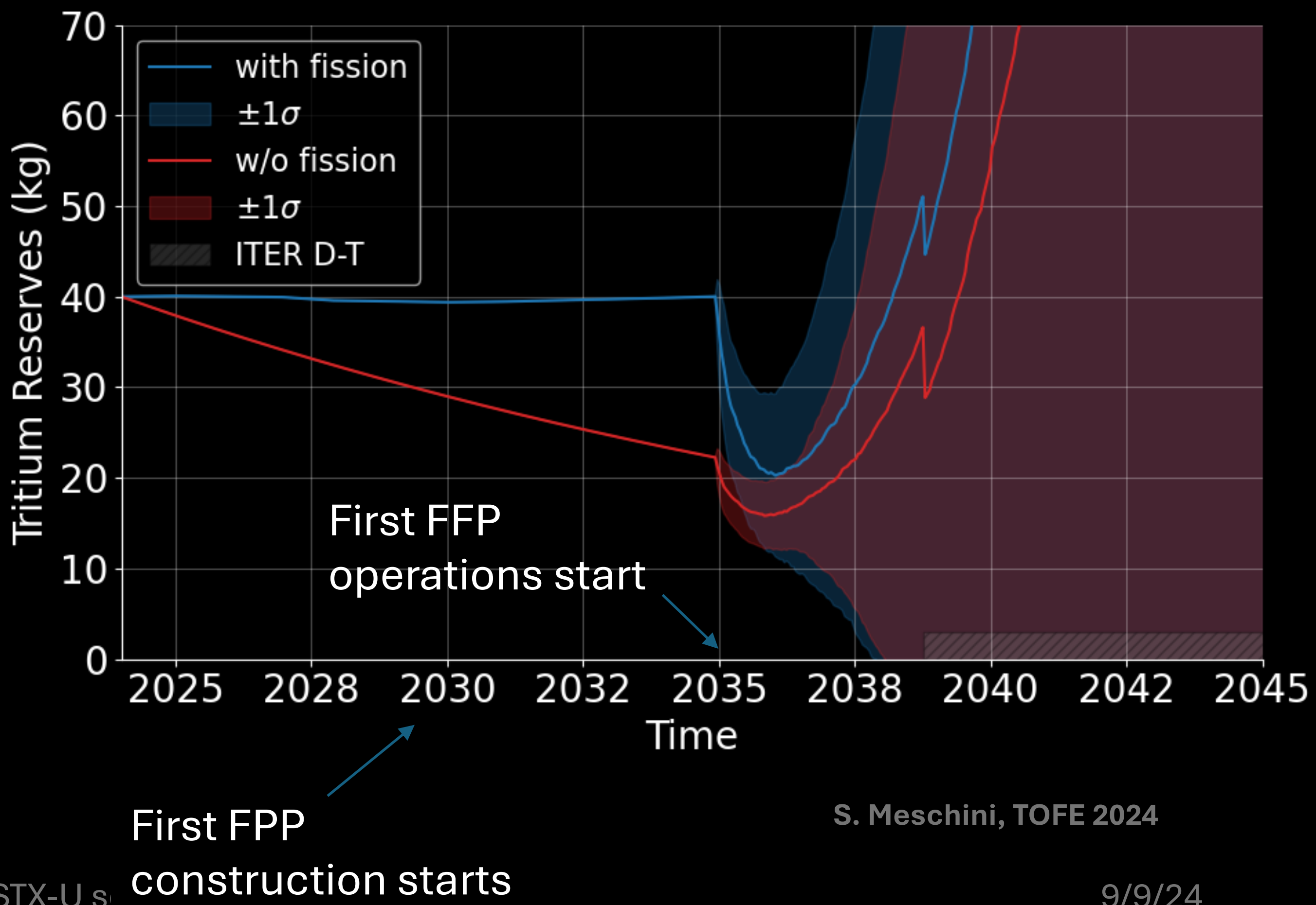
$N_{FPP} = 175$ with
$P_{fus} = 1000\ \mathrm{MW_{th}}$

[1] https://www.iter.org/newsline/-/4056
[2] The global fusion industry in 2024, Fusion Companies Survey by the Fusion Industry Association

UNCERTAINTY IN FC DESIGN MAKES THE RESERVES EVOLUTION *VERY* UNCERTAIN

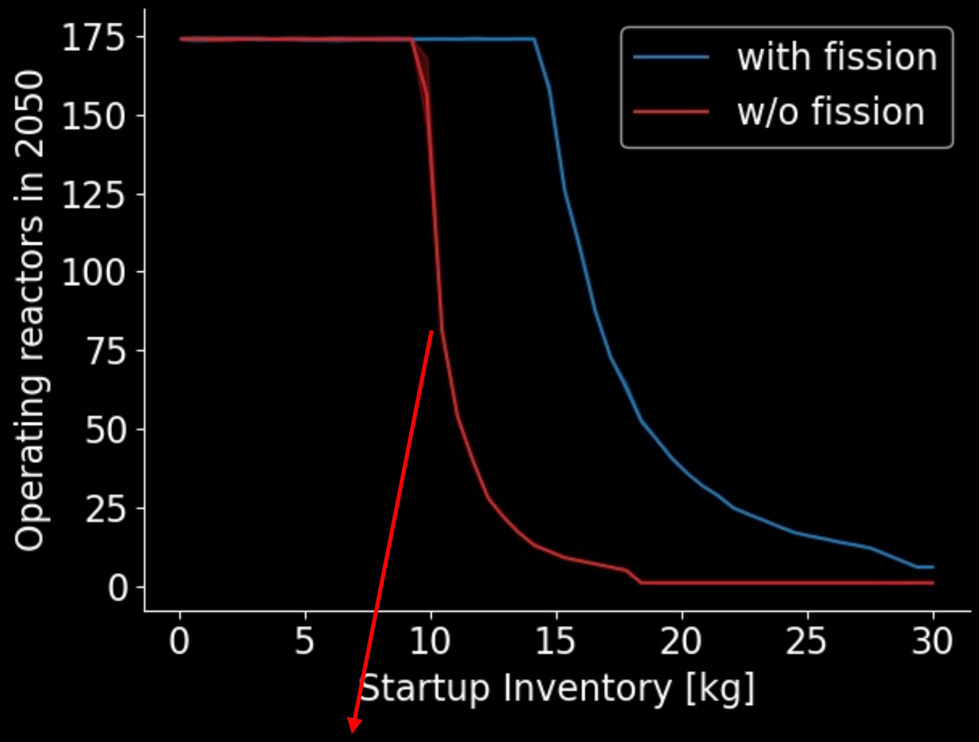
Multiple factors impact tritium reserve evolution:

- TBR
- Startup inventory
- FPP construction time
- FPP availability
- …



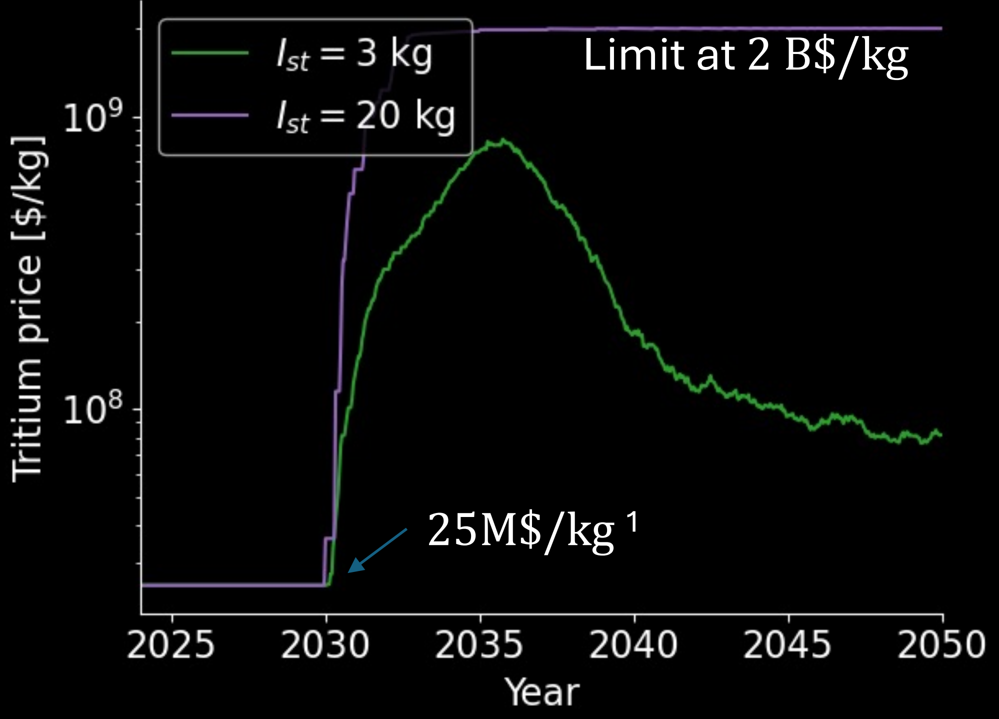
S. Meschini, TOFE 2024

STARTUP INVENTORY DRIVES FUSION ENERGY GROWTH AND TRITIUM ECONOMY



Tritium reserves chocked by too high, scattered demand

Assuming a regulated market as for He3



S. Meschini, TOFE 2024

[1] Kovari, M., et al. "Tritium resources available for fusion reactors." *Nuclear Fusion* 58.2 (2017): 026010.

CONCLUSIONS

- Tritium self-sufficiency is a multiscale problem. Lack of coordination and experiments to connect the scales.
- Technology development (DIR) and ‘tritium efficient’ plasma operations (TBE) can revolutionize fuel cycle designs
- Tritium retention in tritium facing components (structural materials) dominates the reactor tritium inventory
- Very high operating temperatures may worsen retention due to trapping

CONCLUSIONS

- Tritium reserves might easily approach 0 for $\mathrm{I}_{st} > 5\ \mathrm{kg}$
  - Regulated or unregulated market?
- If the operations of FPPs start between 2035 and 2040, ITER T consumption will be easily covered by surplus production from FPP
- T price is likely to spike, then fall - might be a valuable revenue stream for 1st generation FPPs

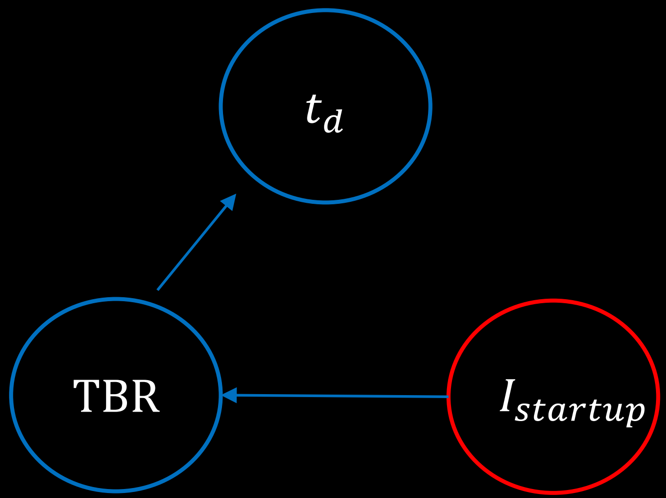
BACKUP SLIDES

R&D H TRAPPING

- Trap energy and density data is scarce and unreliable for structural materials (V alloys, Eurofer, HEA, Nikel superalloys)
- Defect production and dynamics need deeper understanding, especially at high fluences and high neutron energies
- Tungsten is *assumed* to be a good proxy for fusion neutrons (demonstrated for fission neutrons only). None of the available facilities can achieve FPP-relevant fluences (or dpa) with 14 MeV neutrons
- Computational material science (DFT and MD) might be pivotal to speed up R&D in this field

RELATION BETWEEN TSS FIGURES OF MERIT

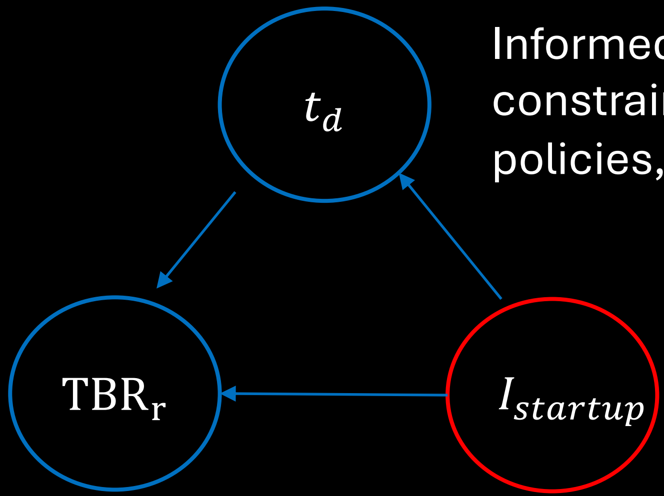
Uninformed approach



Set by FC design and reserves

From blanket design

Informed approach

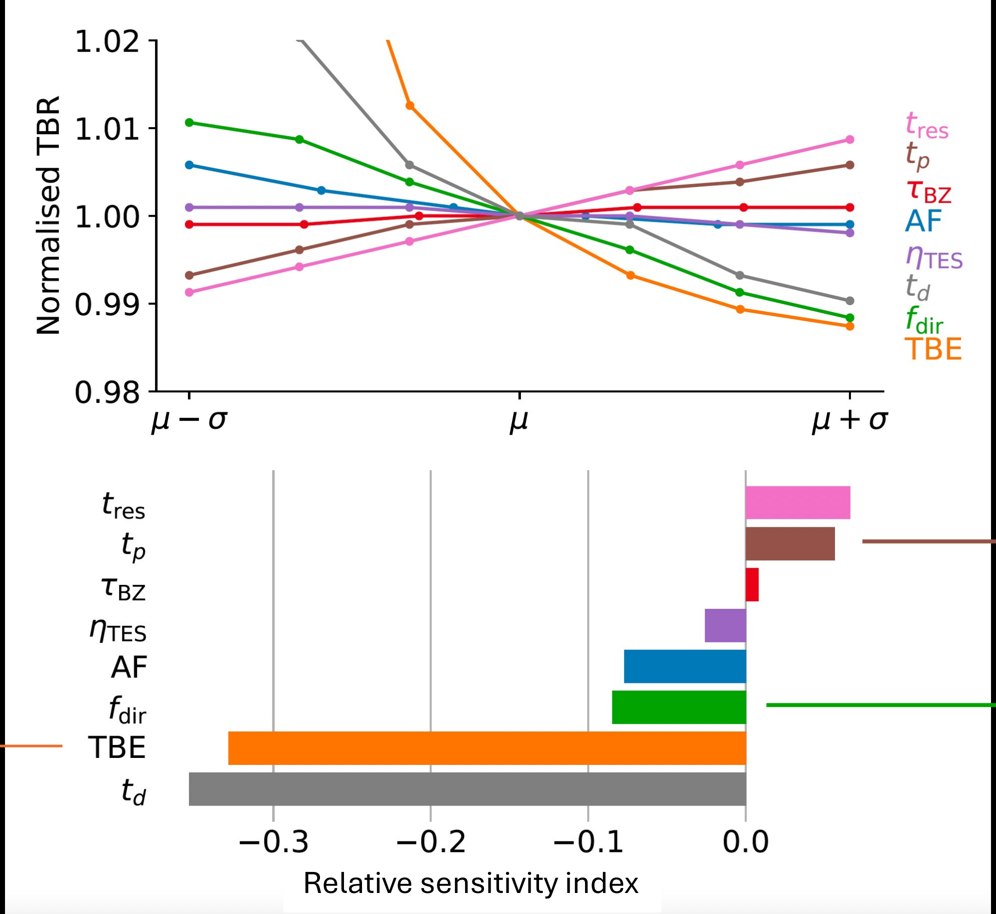


Informed by global scale constraints (economics, policies, T supply)

Set by FC design and reserves

Design requirement for blankets

MAJOR DRIVERS ARE IFC RESIDENCE TIME AND TRITIUM BURN EFFICIENCY

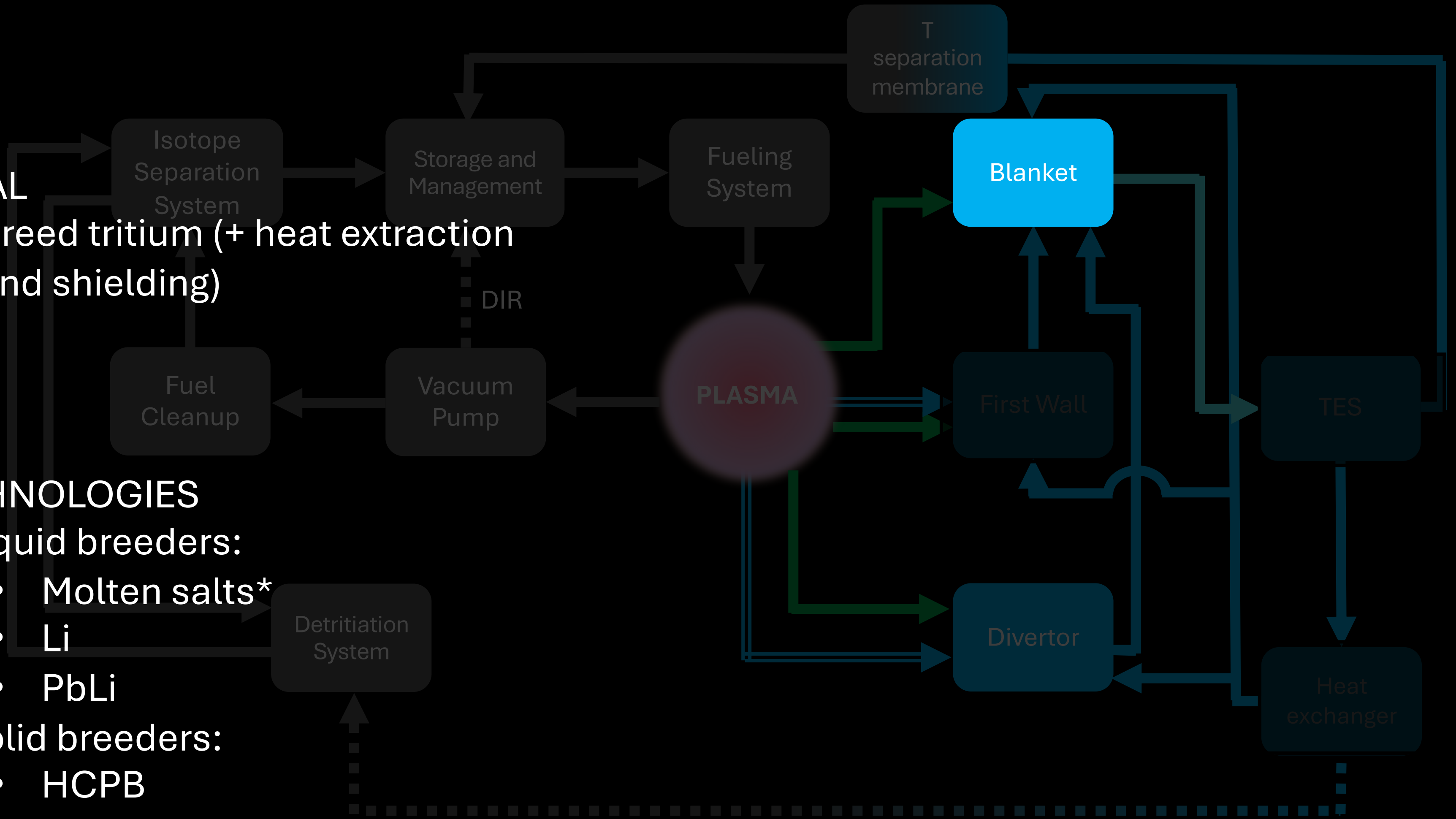


Better fuel usage

Faster T processing time

BREEDING BLANKETS

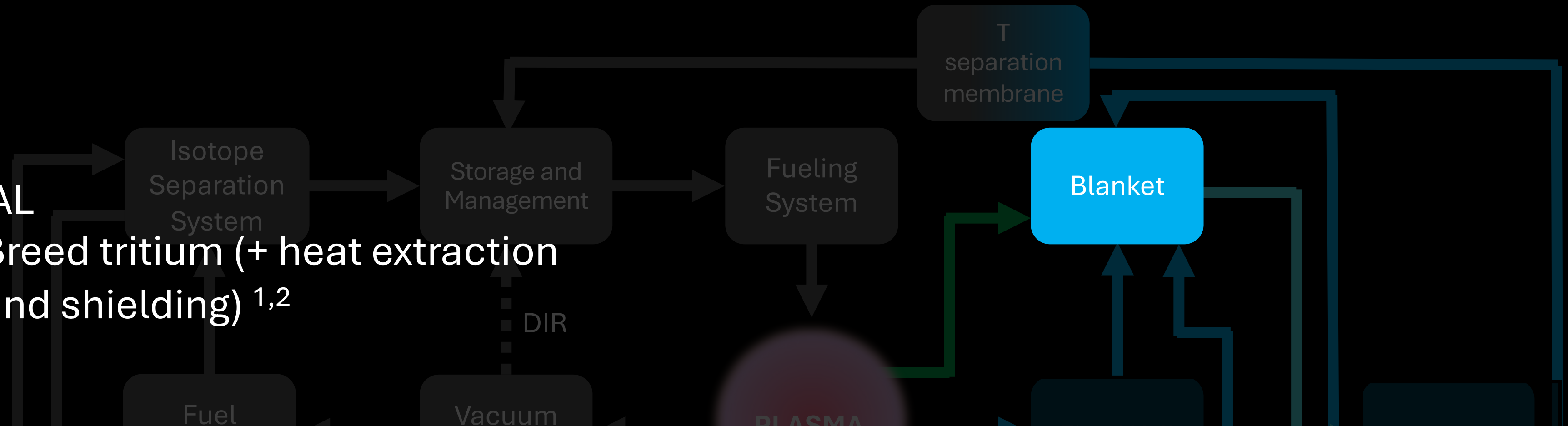
GOAL
- Breed tritium (+ heat extraction and shielding)



TECHNOLOGIES
- Liquid breeders:
  - Molten salts*
  - Li
  - PbLi
- Solid breeders:
  - HCPB

*LIBRA experiment at MIT

BREEDING BLANKETS



GOAL

- Breed tritium (+ heat extraction and shielding) [1,2]

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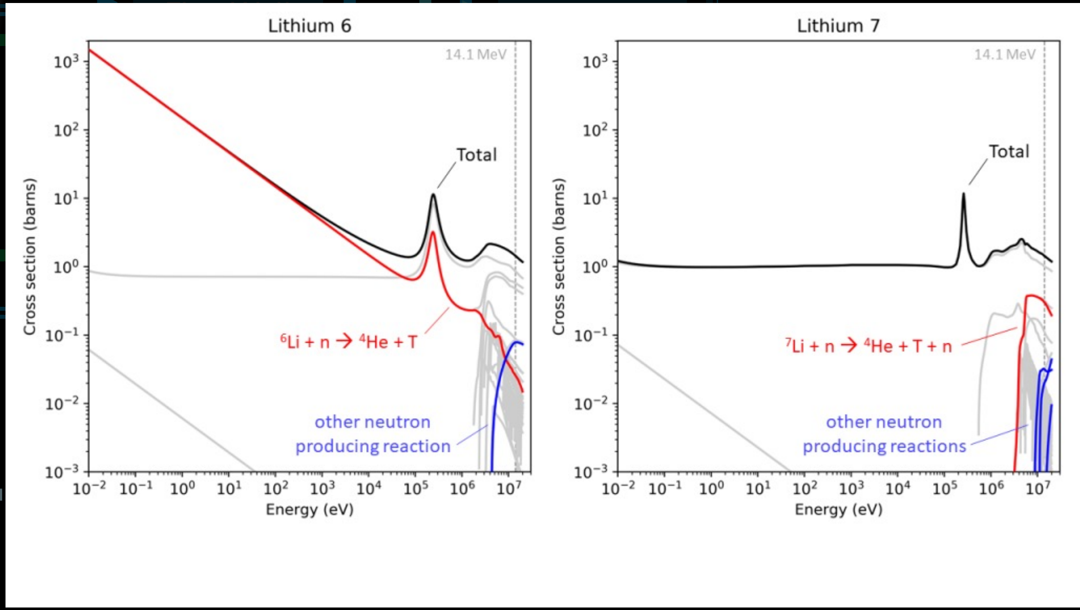


Shimwell, J., https://xsplot.com/

[1]Di Giacomo, M., Master Thesis, PoliTo, 2024.
[2]Bae, Jin Whan, et al., *Nuclear Fusion* 64.5 (2024): 056013.

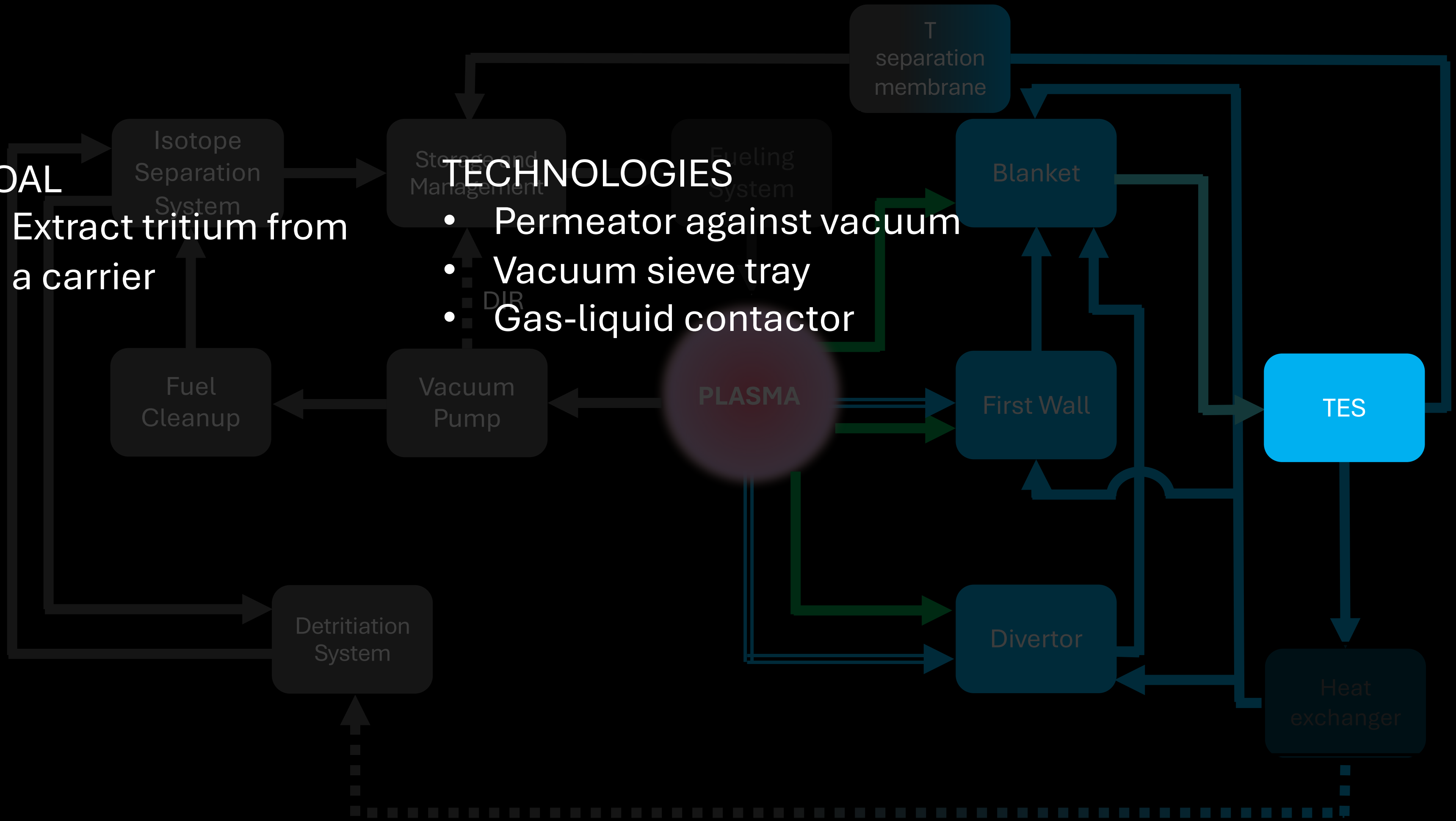
TRITIUM EXTRACTORS

GOAL

- Extract tritium from a carrier

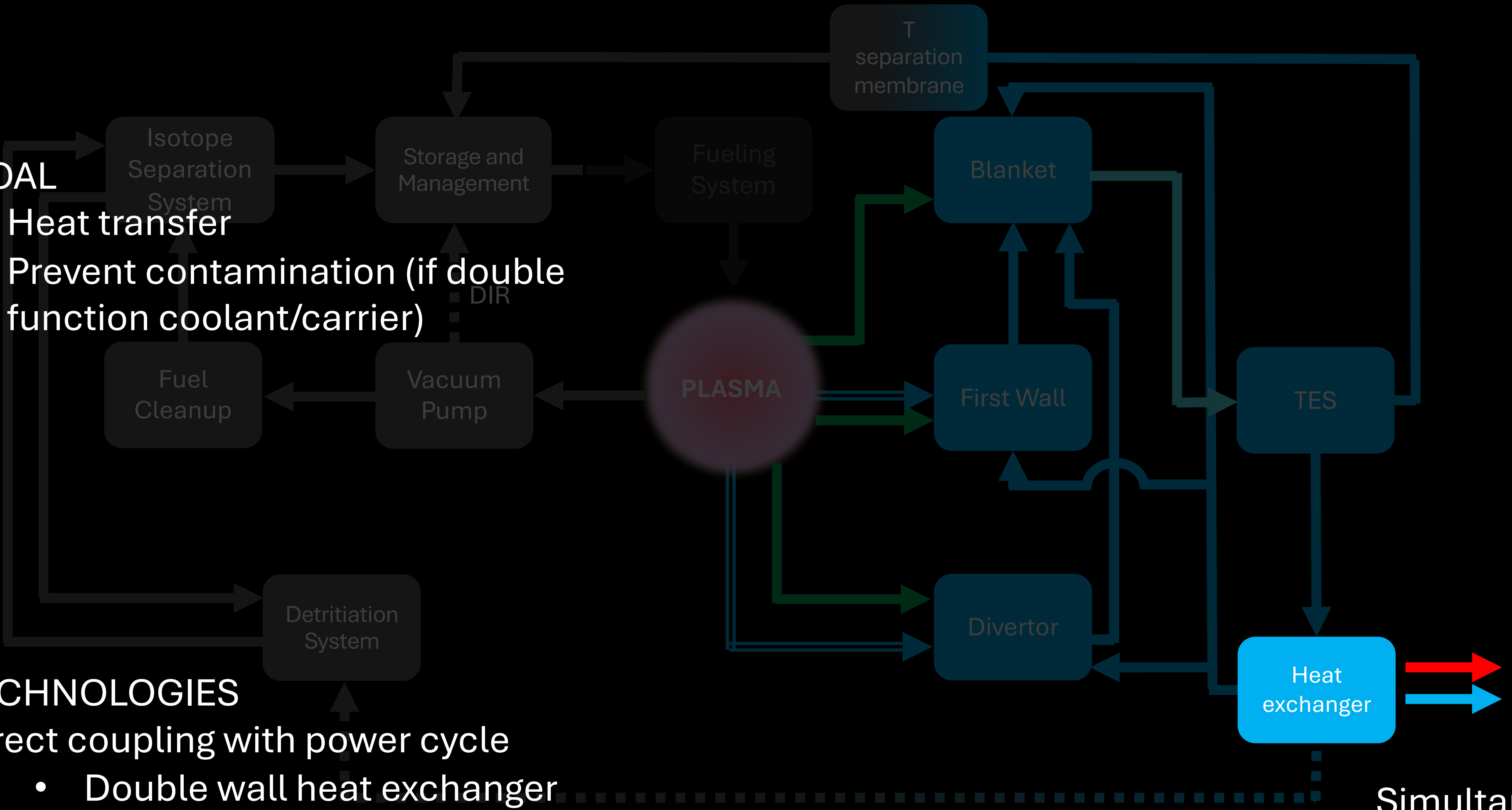
TECHNOLOGIES

- Permeator against vacuum
- Vacuum sieve tray
- Gas-liquid contactor



HEAT EXCHANGERS

GOAL
- Heat transfer
- Prevent contamination (if double function coolant/carrier)



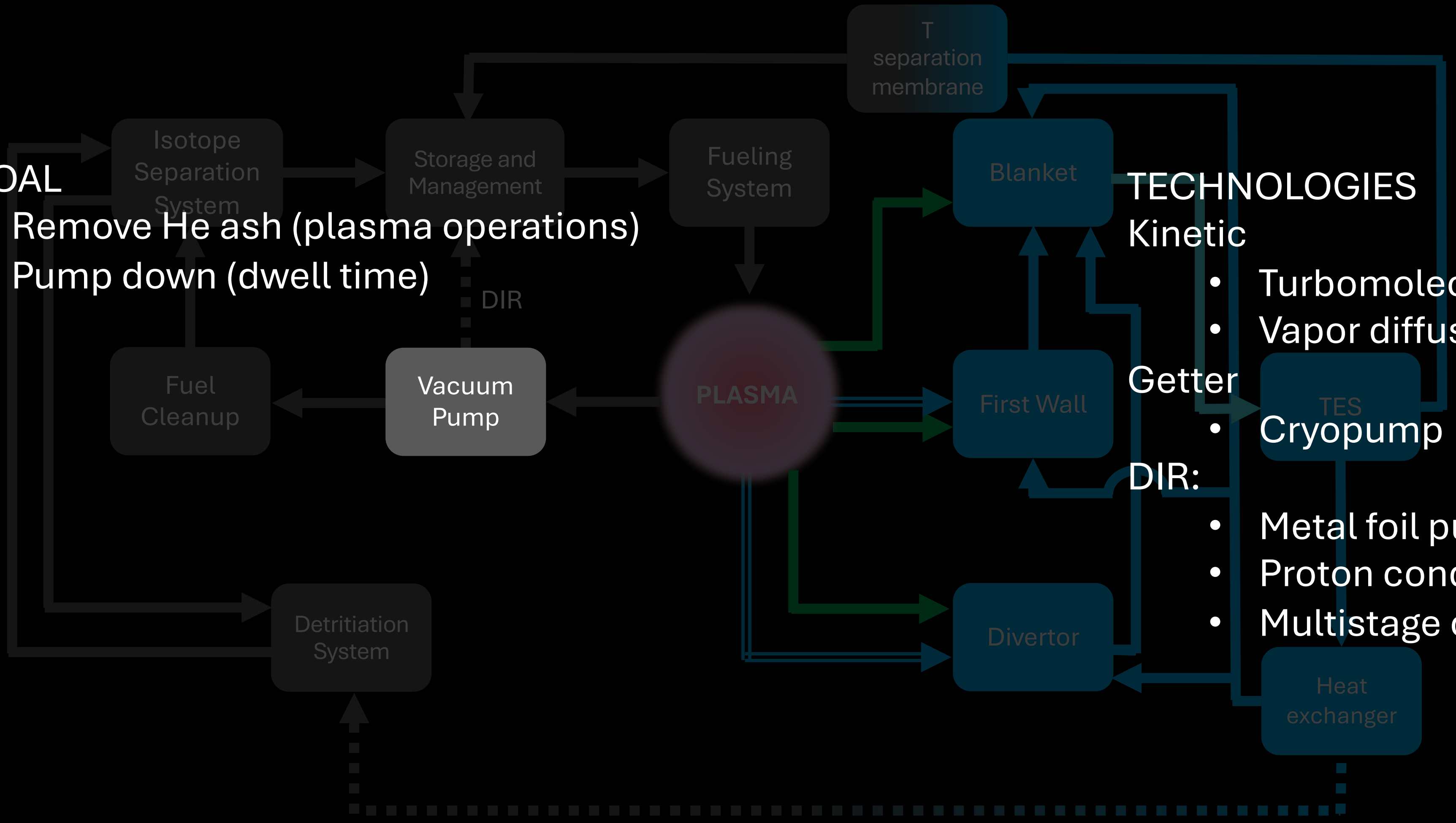
TECHNOLOGIES
Direct coupling with power cycle
- Double wall heat exchanger

Indirect coupling
- Intermediate loop (+storage)

Simultaneous extraction of heat and tritium?

Colliva, Francesco, et al., *FED* 201 (2024): 114261.

VACUUM PUMPS



GOAL
- Remove He ash (plasma operations)
- Pump down (dwell time)

TECHNOLOGIES

Kinetic
- Turbomolecular
- Vapor diffusion

Getter
- Cryopump

DIR:
- Metal foil pumps
- Proton conducting pumps
- Multistage cryopumps

DESIGN CONSIDERATIONS DUE TO TRAPPING

- Tritium retention in tritium facing components (structural materials) dominates the reactor tritium inventory
- Tritium retention in plasma facing components still important but less relevant (compare an FPP vs experimental device)
- Very high operating temperatures may worsen retention due to trapping
- Frequent replacement of in-vessel components requires fast and efficient tritium removal techniques
- Standard tritium removal techniques are not effective to remove tritium from high energy traps