R&D strategy for reliable disruption mitigation in ITER

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ITER Organization

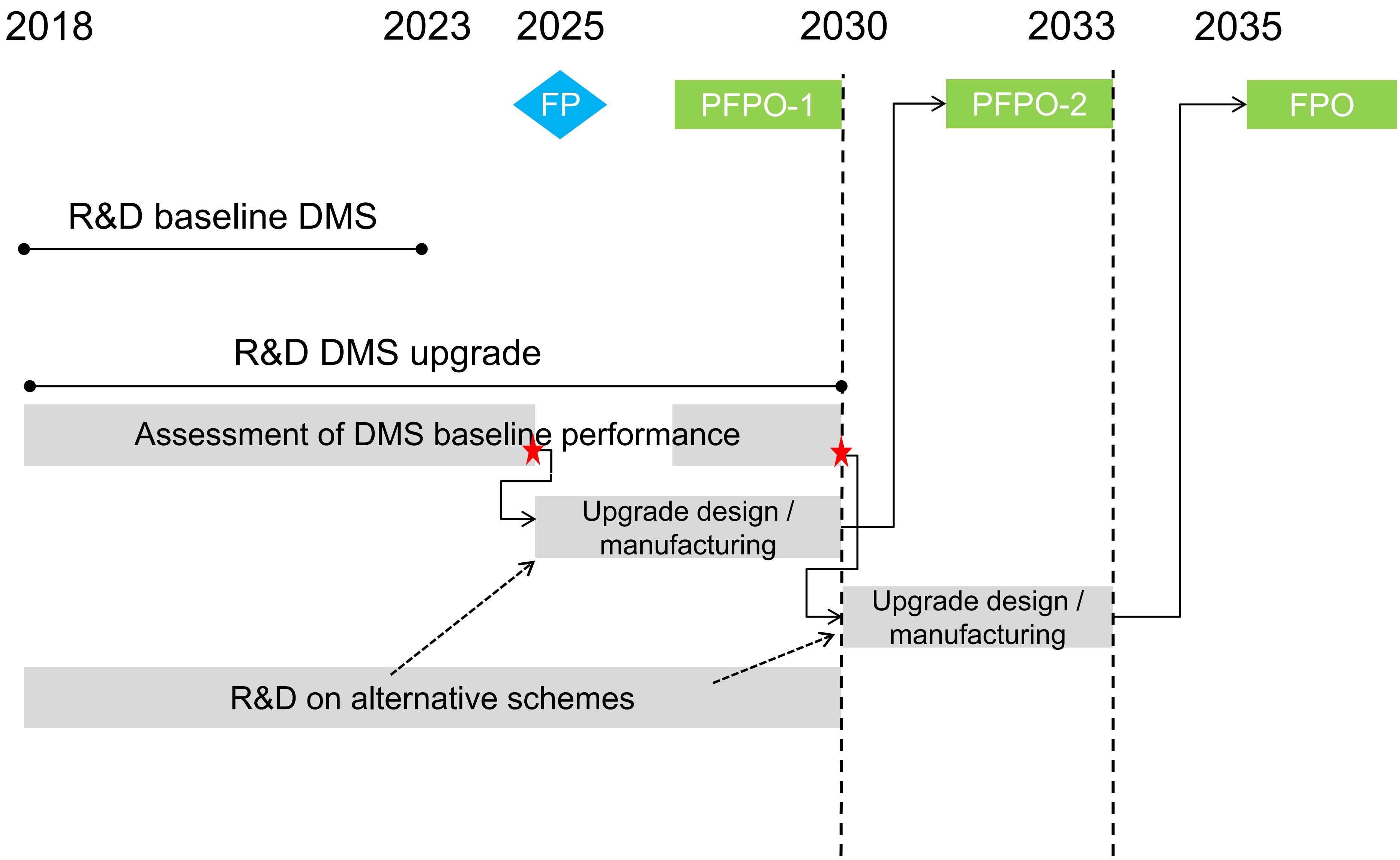
Disclaimer:

ITER is the Nuclear Facility INB no. 174. This presentation explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

- ☐ **Developed DMS R&D plan based on input received at the DMS workshop 2017**
  - ➢ Urgent short term R&D to conclude on baseline DMS design (Shattered Pellet Injection), including JET SPI project
  - ➢ Medium term R&D to address baseline mitigation performance (<u>incl. tokamak experiments</u>)
  - ➢ Long term R&D on alternative technology or mitigation strategy
- ☐ **DMS Task Force established for implementation**
- ☐ **Assessment of ITER DMS injection requirements and allocation of port plugs**

- ❑ **Scope of the DMS TF activity on the R&D plan:**
  - ➢ Physics research to validate baseline DMS concept (SPI) in experiments in present machines and analysis + modelling to assess projections to ITER
  - ➢ R&D to address future upgrades or alternative approaches
  - ➢ R&D leading to industrialization of SPI to reliability needed for asset protection
- ❑ **Out of scope:**
  - ➢ Procurement of the baseline DMS and work related to the change in ITER baseline (MGI → SPI)
  - ➢ Disruption prediction and avoidance and developments of termination scenarios

DMS R&D plan – overall timeline



2018 2023 2025 2030 2033 2035

FP

PFPO-1

PFPO-2

FPO

R&D baseline DMS

R&D DMS upgrade

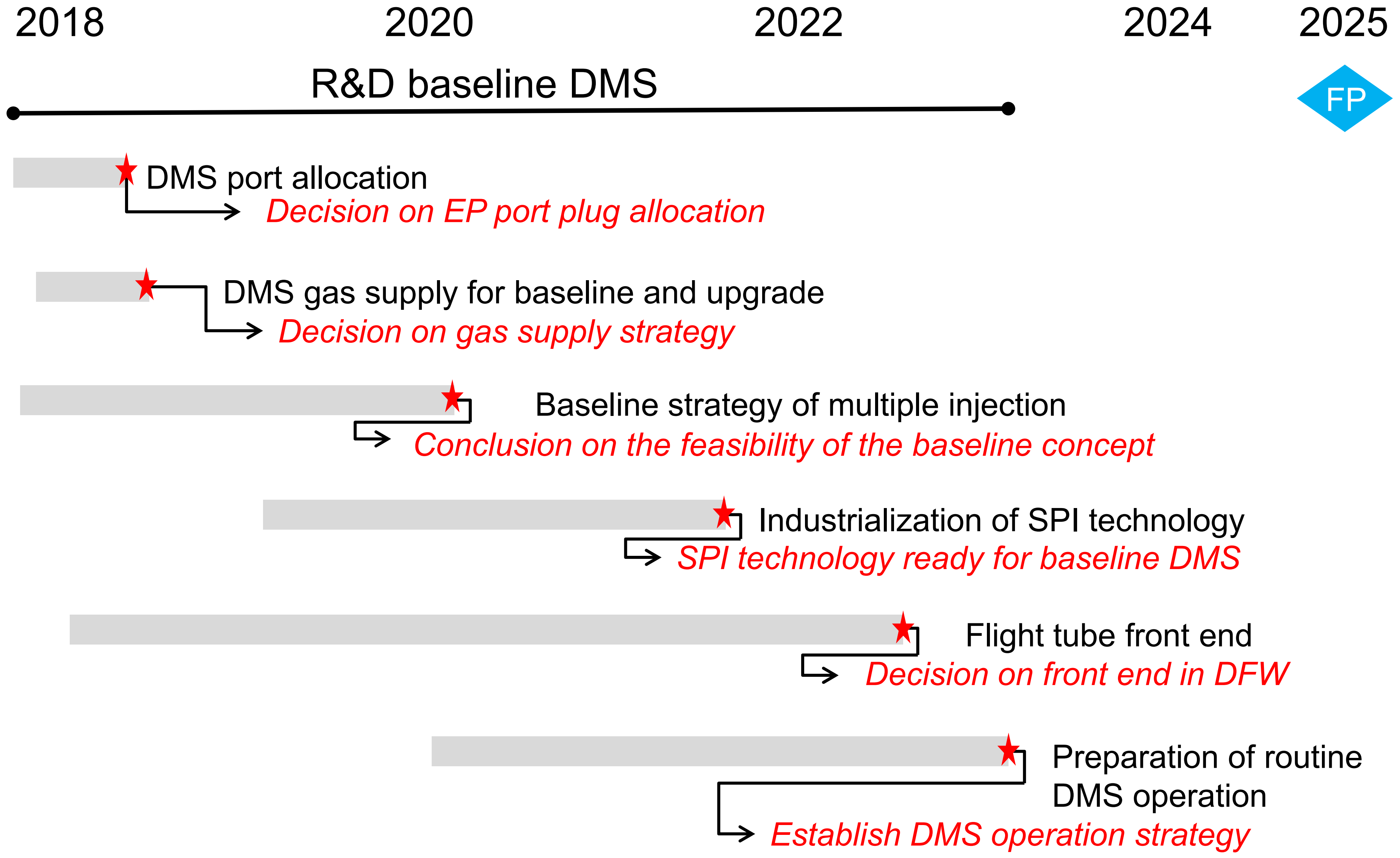
Assessment of DMS baseline performance

Upgrade design / manufacturing

Upgrade design / manufacturing

R&D on alternative schemes

DMS R&D plan – baseline R&D timeline & deliverables



2018 2020 2022 2024 2025

R&D baseline DMS

FP

DMS port allocation

Decision on EP port plug allocation

DMS gas supply for baseline and upgrade

Decision on gas supply strategy

Baseline strategy of multiple injection

Conclusion on the feasibility of the baseline concept

Industrialization of SPI technology

SPI technology ready for baseline DMS

Flight tube front end

Decision on front end in DFW

Preparation of routine DMS operation

Establish DMS operation strategy

Most urgent R&D for the baseline DMS

- Demonstrate that multiple injection is feasible
- Decide on the optimum shard size composition to ensure high assimilation and sufficient core density rise

→ Timeline is tight (~ 2 years)

→ Alternative injection techniques to be explored in parallel to show their potential feasibility for ITER

Risk for PFPO-1 for the baseline DMS to fail is considered low (up to 7.5 MA operation, low E_{th}*)*

Most urgent R&D for a later upgrade decision

- Demonstrate runaway avoidance during TQ mitigation
- Validate runaway energy dissipation scheme (second layer)
- Quantify radiation heat loads from TQ flash

→ Timeline is longer

→ Alternative injection techniques and mitigation schemes to be explored to show their potential feasibility for ITER

Risk for PFPO-2 (up to 15 MA operation) and FPO (high E_{th}*, T decay as RE seed)*

DMS R&D plan – baseline SPI

Decision points	**Priority**	**Work Plan Description**
EP port plug allocation	Design	Assessment alternative design on DMS capability (single barrel)
	Design	Neutron streaming down flight line and activation
	Design	Assess implications of reduced DMS capabilities & additional injection locations.
	Design	Assess implementation of additional barrels in EP17 or other equatorial ports
Gas supply strategy	Design	Assess single containment & separate gas supply
	Design	Assess performance requirements for separate gas supply & impact on DMS ops
	Design	Assess safety implications of separate gas supply
Feasibility of the baseline concept	Design	Modelling of multiple injections
	Risk Mitigation	3D MHD modelling to address rad asymmetry & need for tor/pol distribution
	Design	Tokamak experiment with 2+ injectors at different locations w/variable shard size/velocity

Technology Modelling/Theory Experiments

DMS R&D plan – baseline SPI

Decision Points	Priority	Work Plan Description
SPI technology ready for baseline DMS	Design	Tokamak experiments with varying quantities of propellant
	Design	Lab test & theoretical R&D to establish understanding of pellet formation process
	Design	Lab & theory R&D to understand pellet shear-off & acceleration
	Design	Lab test geometric constraints of all pellet types in funnel/guide tube
	Design	Optimisation of flight tube design
	Risk Mitigation	Develop pellet formation integrity monitor
	Risk Mitigation	Develop & integrate technique to optimise pellet synchronization
	Operational	Impact of broken pellets on mitigation performance, risk of RE generation
	Operational	Effect of impurity inflow on pellet integrity
	Operational	Impact of other gases injected with SPI on mitigation process

Technology Modelling/Theory Experiments

DMS R&D plan – baseline SPI

Decision Points	Priority	Work Plan Description
Flight tube front end	Design	Possible bending angle of shattering section in DFW in UPP
	Design	Simulations to quantify impact of injection angle on assimilation
	Design	Impact of bending angle on fragment sizes
	Design	Simulation of ablation/assimilation vs shard size/composition
	Design	Tokamak experiments w/ flexible shard size.
	Design	Tokamak experiments w/ varying injection angles and ITER shard size distribution
	Risk Mitigation	Alternative shattering techniques
	Risk Mitigation	Tokamak exp’s with pure gas through SPI
Establish DMS operation strategy	Operational	Demonstrate fully automated ITER-like DMS in routine closed-loop operation

Technology Modelling/Theory Experiments

DMS R&D plan – baseline performance / upgrade needs

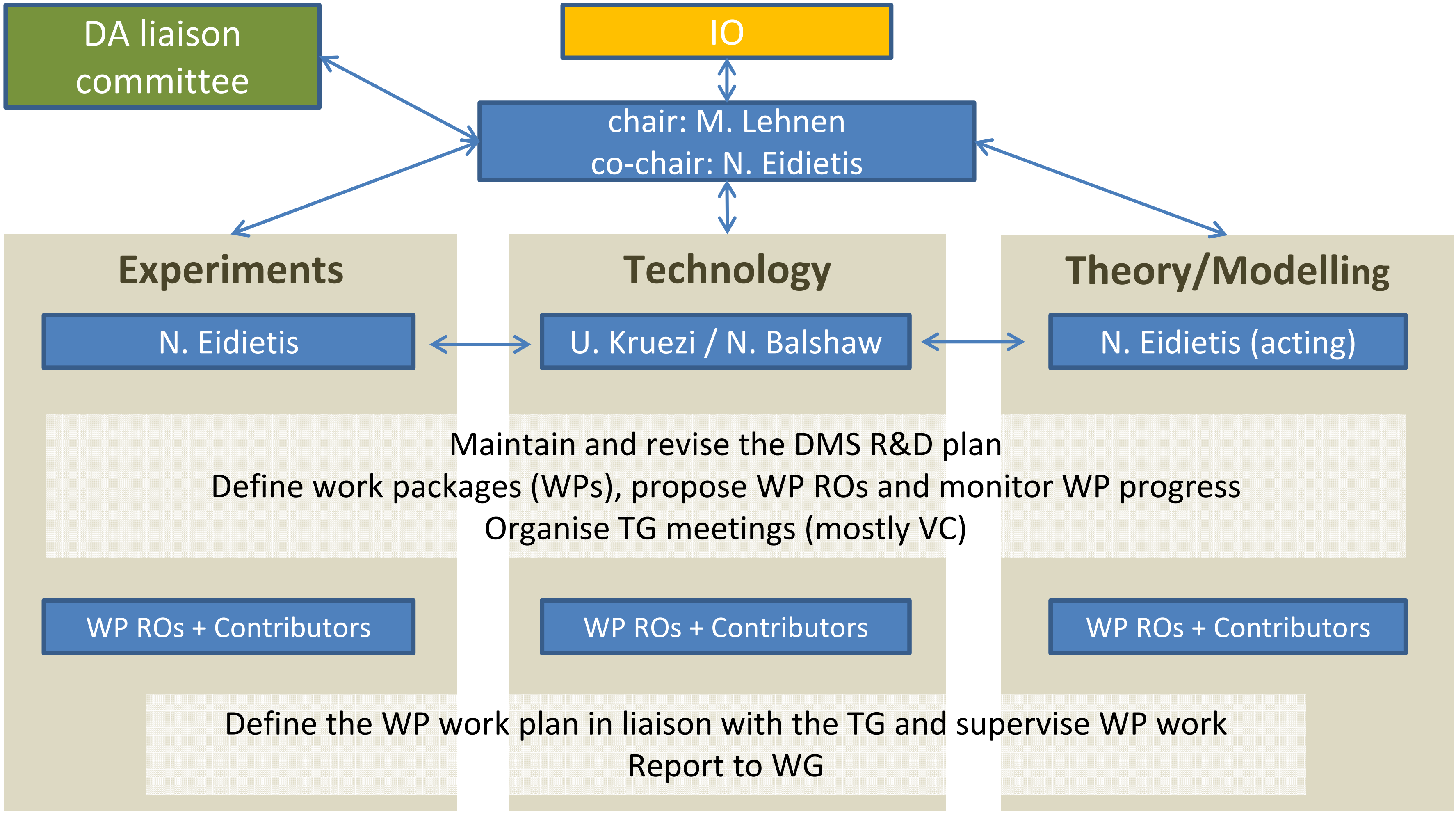
Decision Points	**Priority**	**Work Plan Description**
Upgrade needs	Design	Tokamak Experiments quantifying impact of adding D2 on TQ mitigation efficiency and CQ rate
	Design	RE energy dissipation: quantify required injection quantities & assess improvement of scheme w/ SPI
	Design	Theory/modelling to improve understanding of RE energy dissipation for extrapolation to ITER
	Design	Ip / Z evolution and MHD stability during RE energy dissipation
	Design	Improve models describing RE generation & avoidance during TQ & early CQ
	Design	Tokamak experiments testing baseline scheme for RE avoidance w/baseline DMS geometry
	Operational	Current quench: Develop models to account for all relevant processes for radiative dissipation of magnetic energy & benchmark to XP
	Operational	Lab/Tokamak Experiments of conditions under which arcing between blankets modules may occur

Technology

Modelling/Theory

Experiments

DMS Task Force Structure



DA liaison committee

IO

chair: M. Lehnen
co-chair: N. Eidietis

Experiments

N. Eidietis

Technology

U. Kruezi / N. Balshaw

Theory/Modelling

N. Eidietis (acting)

Maintain and revise the DMS R&D plan
Define work packages (WPs), propose WP ROs and monitor WP progress
Organise TG meetings (mostly VC)

WP ROs + Contributors

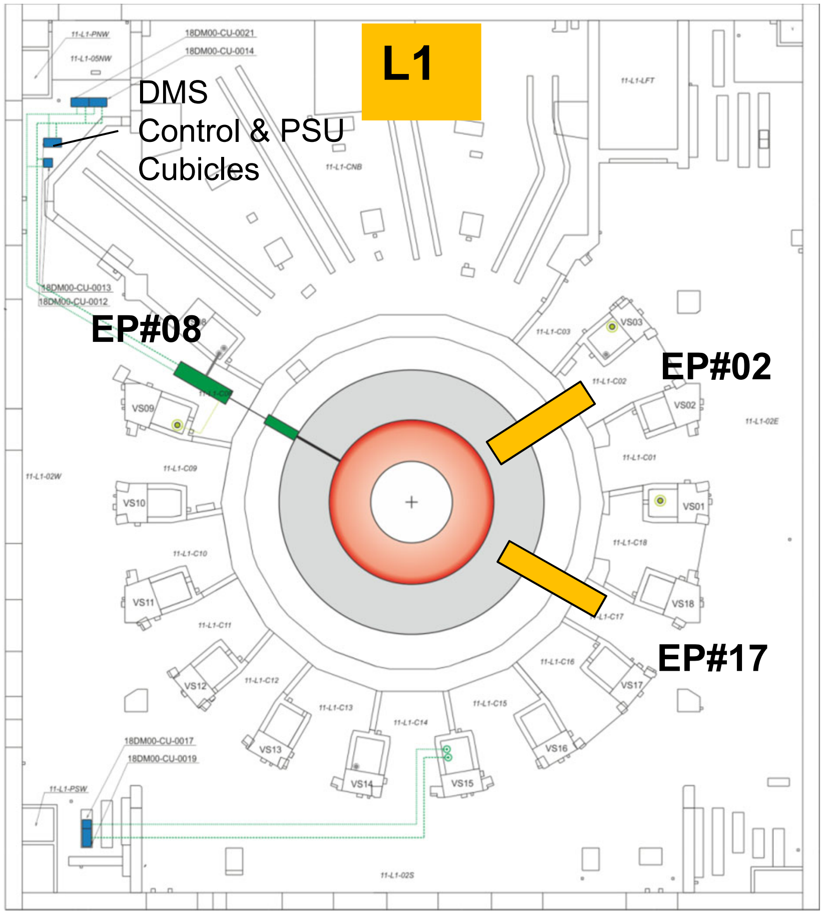
WP ROs + Contributors

WP ROs + Contributors

Define the WP work plan in liaison with the TG and supervise WP work
Report to WG

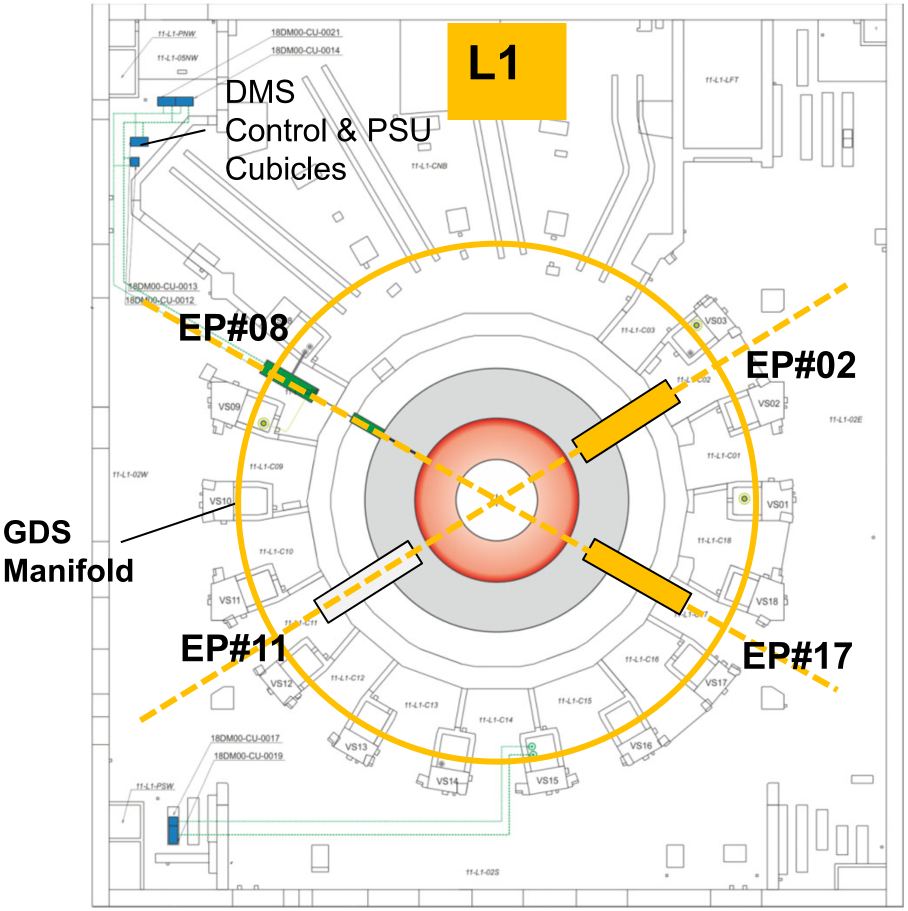
Change in port plug allocation

- Original port plug allocation on upper ports is kept (3 ports)
- 3 additional drawers in equatorial port plugs to become available:
  1 in EP8 and EP17, 2 in EP2 (redistribution of diagnostic port plugs and changes in TBM program)
- 8 barrels / drawer possible (design work ongoing)



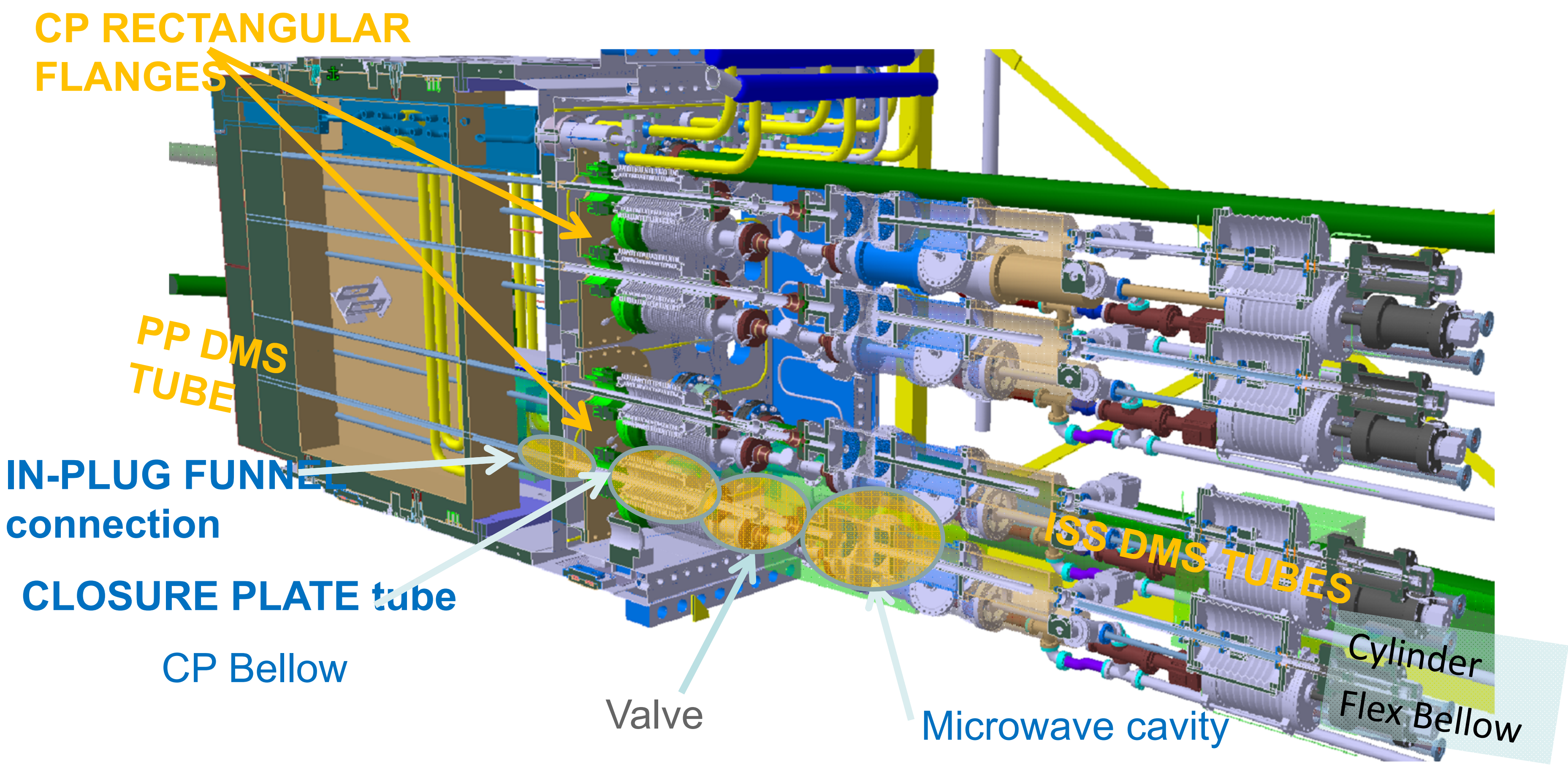
Change in port plug allocation

- **Provisions planned to allow possible reconfiguration**
    - Radiation heat loads may require more uniform toroidal distribution
    - Safety limit for inflammable gases presently under assessment
- **Captive components:**
    - Gas Supply Manifold for the DMS (in present configuration)
    - Cryogenic supply for possible upgrade in e.g. EP#11 (to be specified)



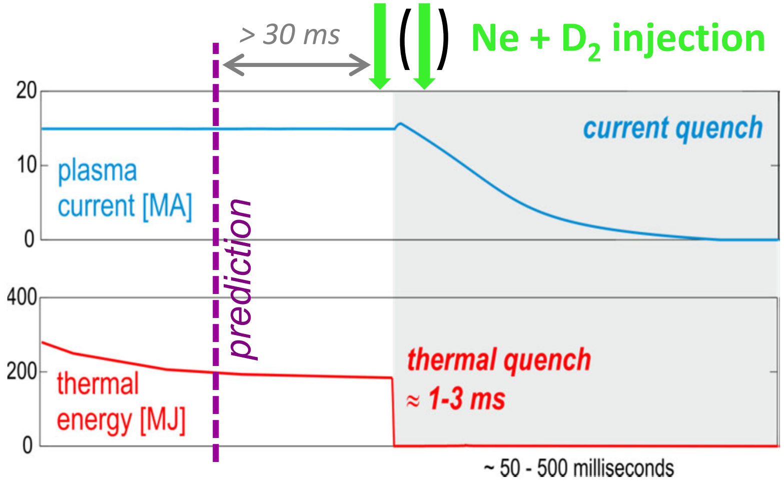
Port plug integration

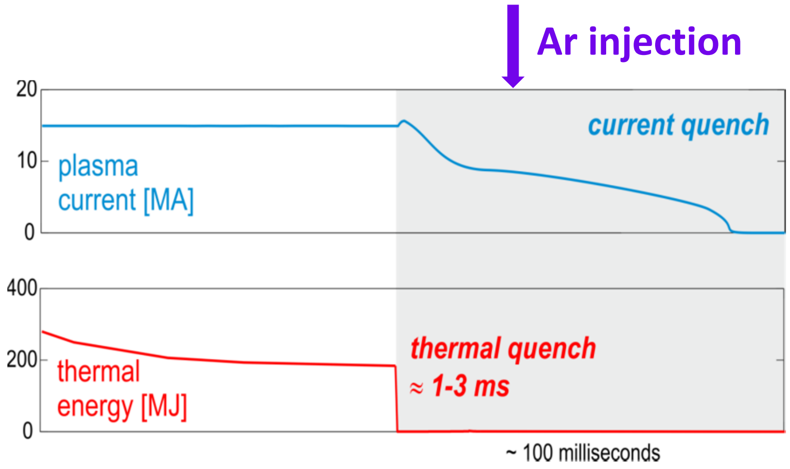
Integration of 8 barrels in one drawer of an equatorial port plug



Present Disruption Mitigation Strategy

- **Thermal + current quench mitigation:**
  Ne injection pre-TQ
  (mainly pellet fragments)
- **Current quench mitigation:**
  Ne injection post-TQ (only if TQ missed)
  (mainly gas)
- **Runaway electron avoidance:**
  D_2 injection pre-TQ
- **Runaway electron energy dissipation:**
  Ar injection post-TQ





DMS capability needs

- ❑ **Required DMS capabilities for TQ, CQ and RE avoidance and mitigation**

Pellet diameter [mm]	species	quantity/pellet [particles]	quantities required* [particles]	# pellets
Equatorial ports (RE mitigation)				
28.5	Ar	0.9×10^{24}	10^{25}	**12**
28.5	D_2	1.1×10^{24}	10^{25}	**10**
Equatorial ports (TQ mitigation)				
13.4/16.6/19.7	Ne	$1.2/2.3/3.9 \times 10^{23}$	5×10^{22}	**4** 1)
Upper ports (CQ mitigation)				
13.4/16.6/19.7	Ne	$1.2/2.3/3.9 \times 10^{23}$	5×10^{22}	**3** 1)

- ❑ **Most likely solution: 28.5 mm D2 pellets doped with Ne (injection of 10 pellets: 0.5% Ne)**

*Numbers based on present knowledge; reduction of uncertainty high priority of DMS R&D plan

1) Number determined by the objective to minimize toroidal radiation peaking

Runaway avoidance through D2 admixture

Presently only simplified models:

- 1D current evolution, but no self-consistent seed mechanism
  J.R. Martín-Solís et al., Nucl. Fusion 2017

- Hot tail model with self-consistent thermal quench duration from radiation power balance
  P. Aleynikov & B.N. Breizman , Nucl. Fusion 2017

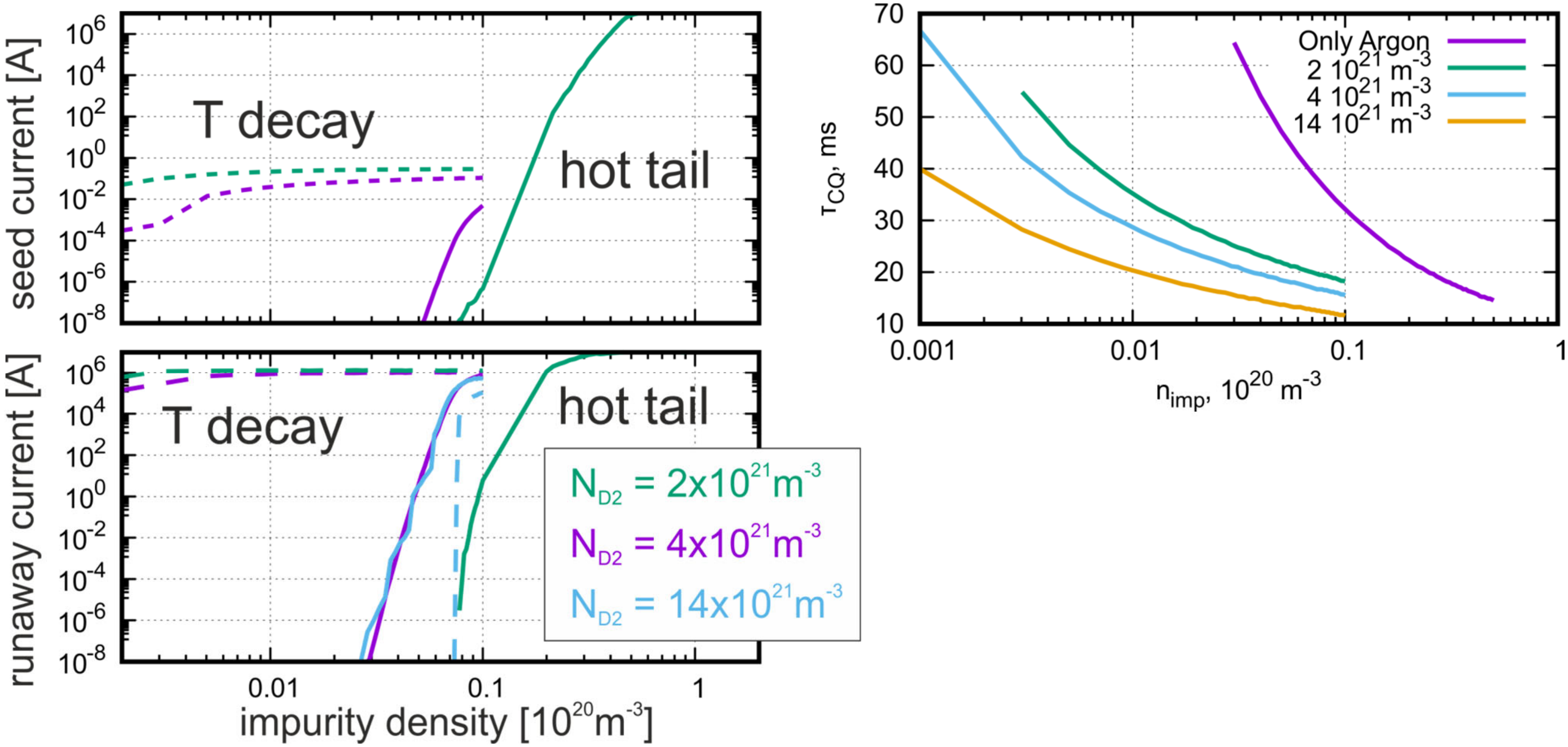
What is needed to move forward:

- *Characterise density rise over the entire cross-section and the related RE seed formation*
- *3D MHD (island formation, stochasticity)*
- *Self-consistent ion source from appropriate pellet model*
- *Self-consistent RE seed mechanism implemented*

→ Presentations by P. Parks (last workshop), D. Hu (this workshop), and work by C. Kim (NIMROD)

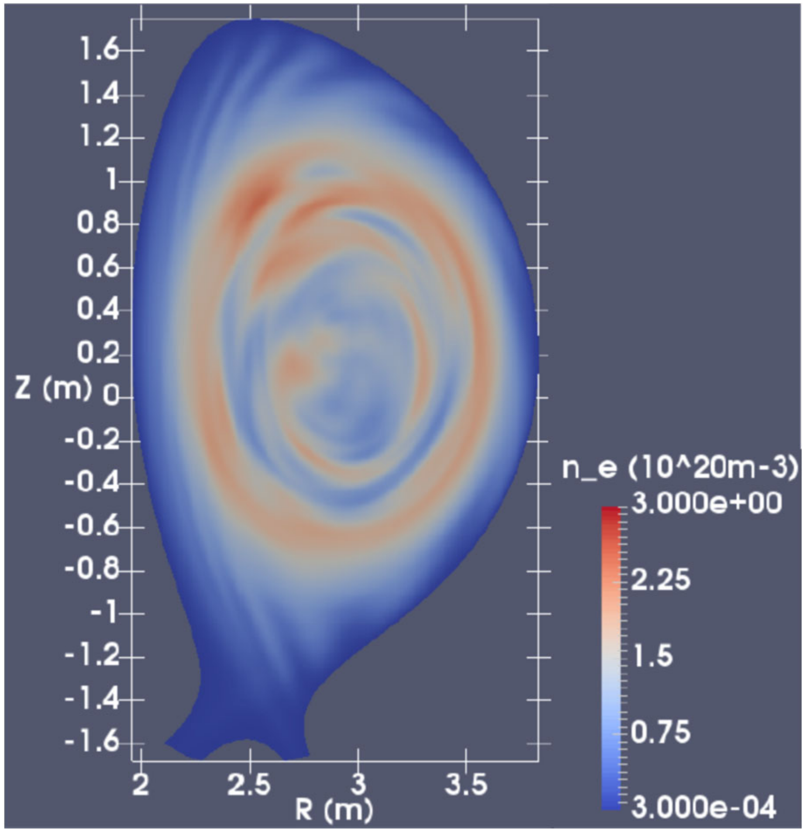
Runaway avoidance through D2 admixture

- Aleynikov et al.: TQ self-consistent ($dE_{th}/dt = P_{rad}$)
- Addition of D2 reduces final RE current through:
  - Increased radiation by higher n_e (less Ar at same CQ time)
  - Lower E/E_C preventing hot tail acceleration



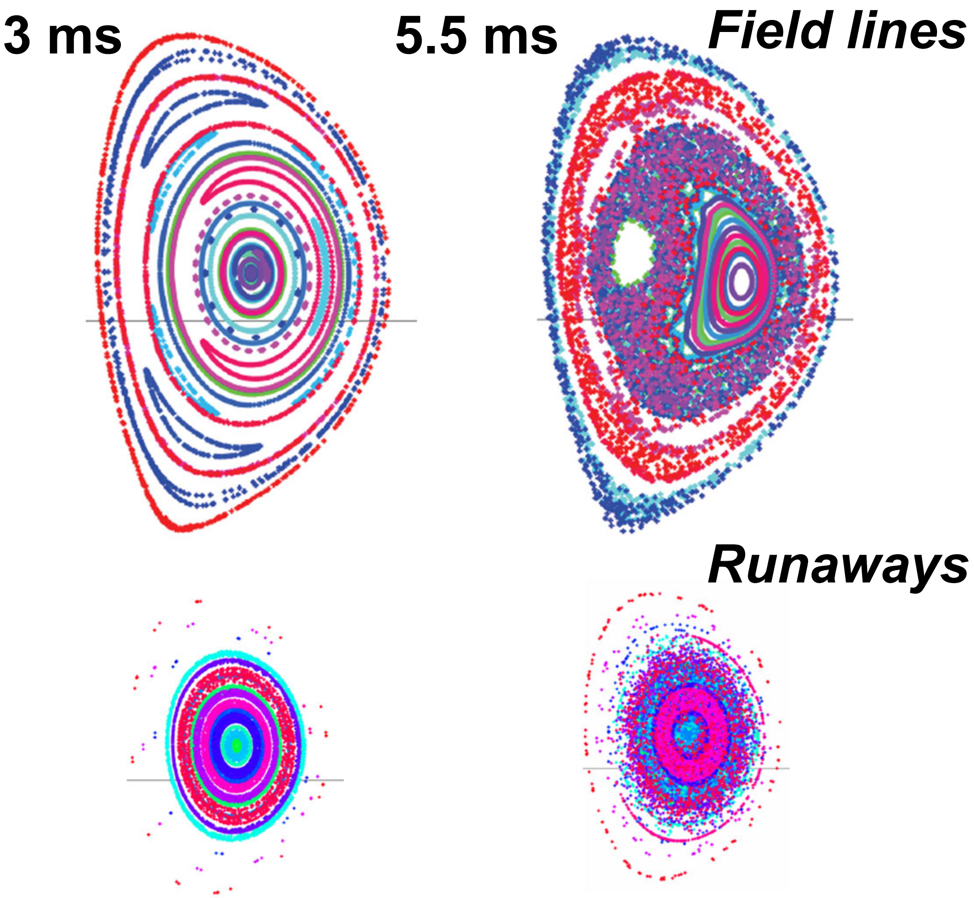
Runaway avoidance through D2 admixture

JOREK D2 SPI simulation for JET shows non-uniform density rise



→ *Presentation by D. Hu*

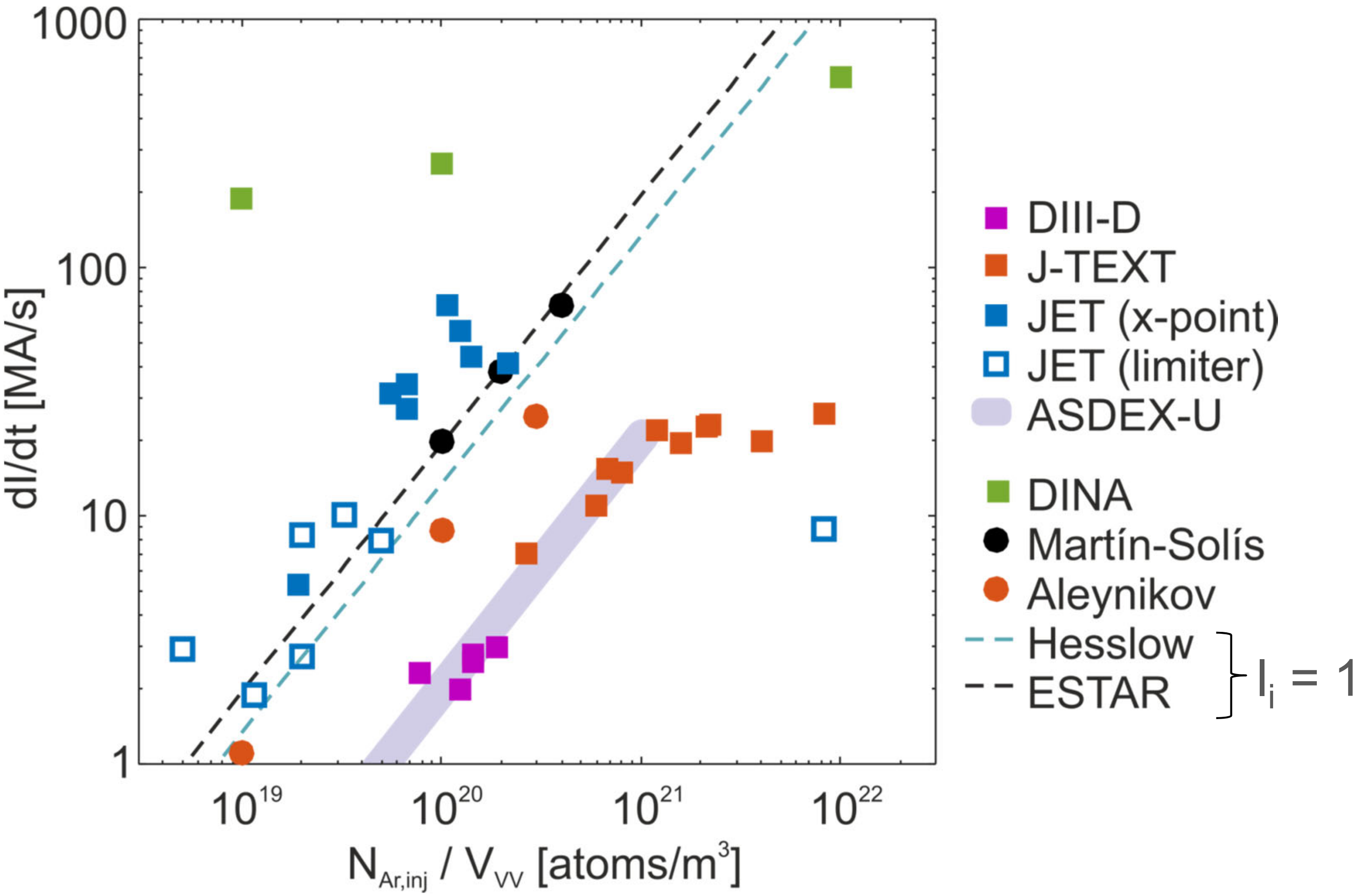
NIMROD (C. Kim et al.):
10^{23} Ne atoms, 1/1 kink drives TQ, E_{th} almost fully radiated, RE still confined



Runaway energy dissipation scheme

WG-13 in ITPA MHD is assessing the efficiency of this scheme

*Experiments versus modelling / theory**



** Preliminary data analysis, JET is pre-TQ injection*

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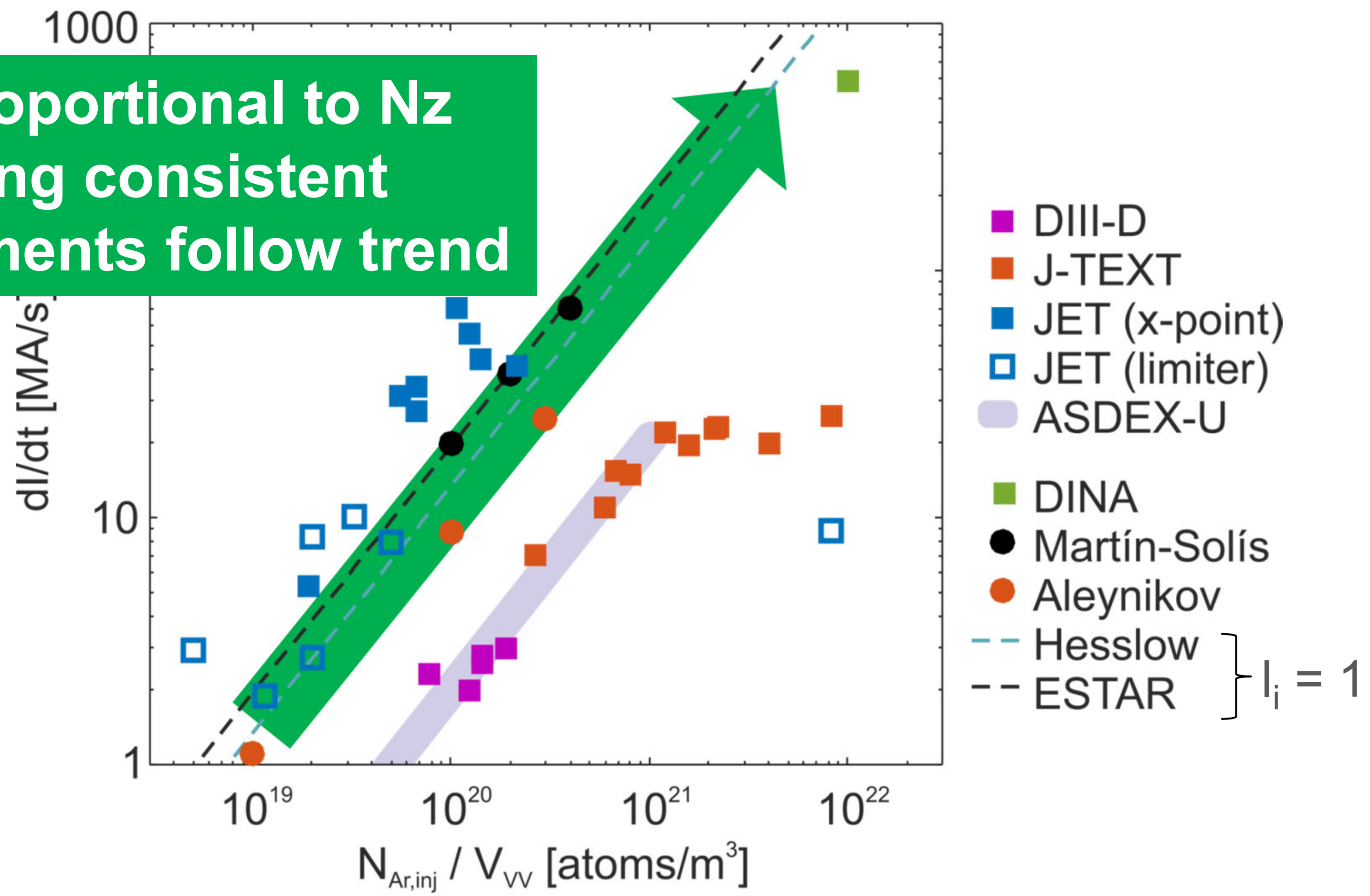
dI/dt proportional to Nz
Modelling consistent
Experiments follow trend

* *Preliminary data analysis, JET is pre-TQ injection*

Runaway energy dissipation scheme

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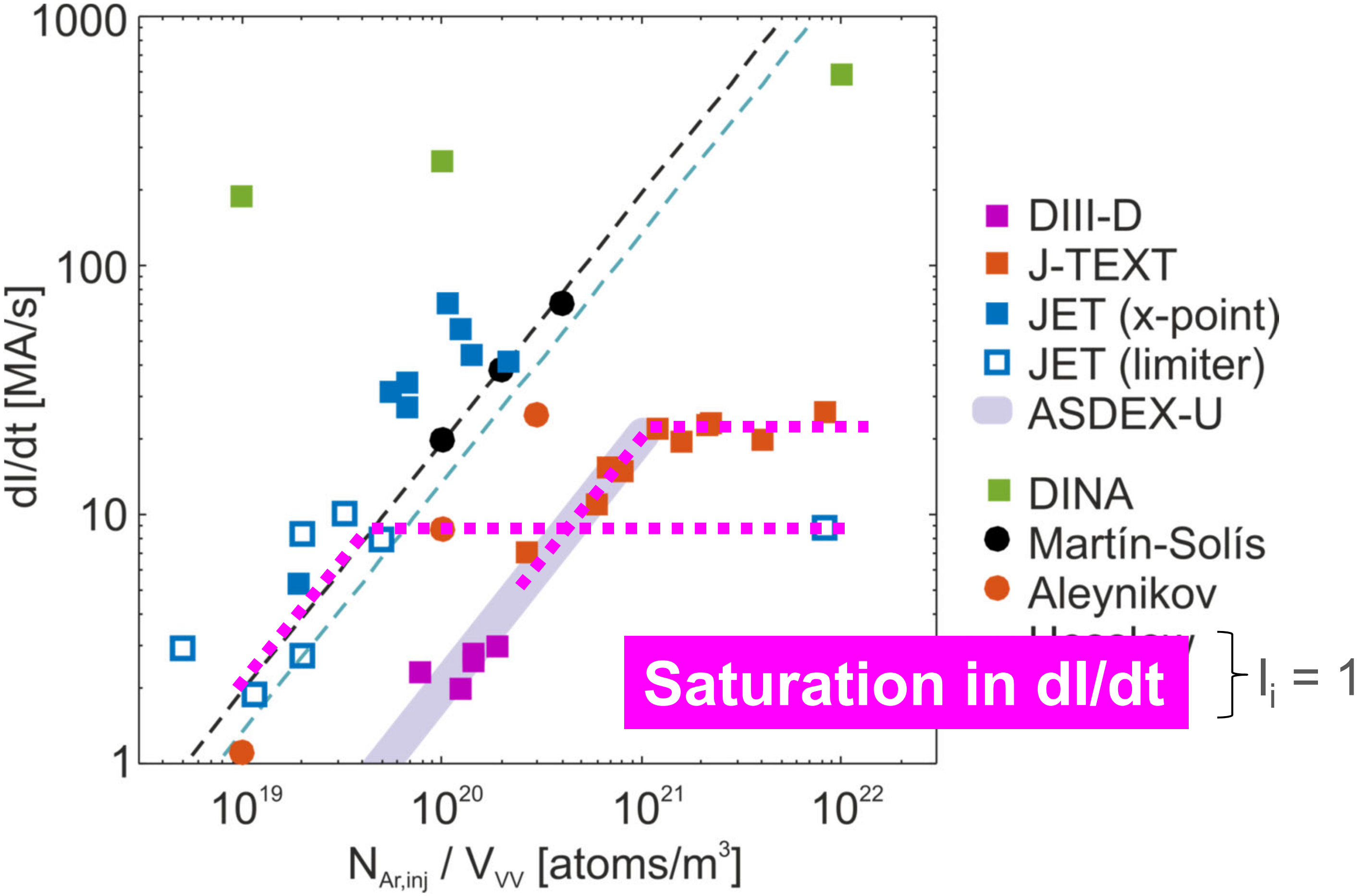
*Experiments versus modelling / theory**



Saturation in dI/dt

** Preliminary data analysis, JET is pre-TQ injection*

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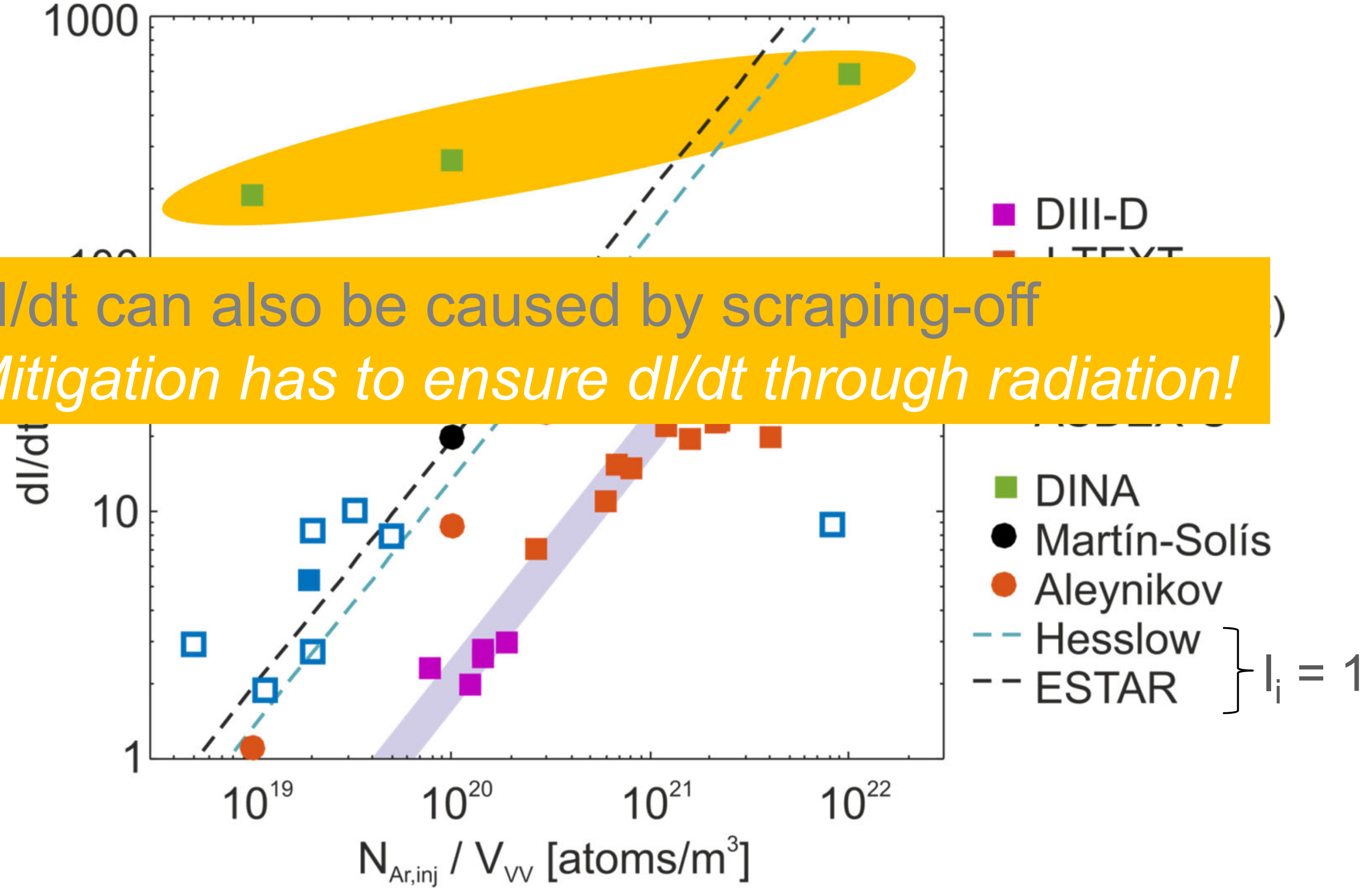
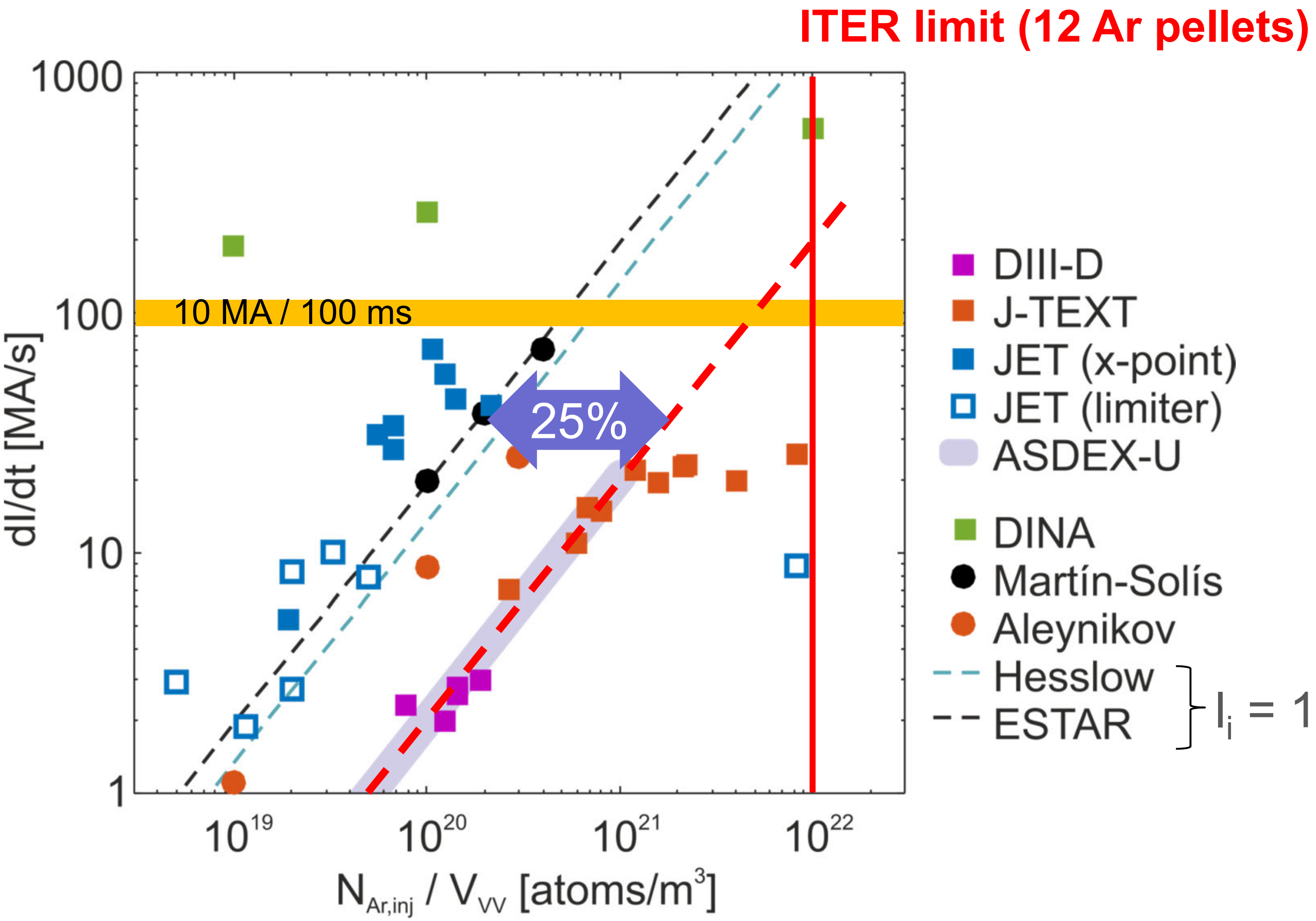


dI/dt can also be caused by scraping-off

Mitigation has to ensure dI/dt through radiation!

** Preliminary data analysis, JET is pre-TQ injection*

Runaway energy dissipation scheme



Final Remarks

- Most urgent physics R&D:
  - Test efficiency of multiple injection (up to 10 pellets for TQ in ITER!)
  - Optimise density rise in the plasma centre (shard size distribution)
- SPI will be available in several devices:
  - DIII-D to continue with SPI (pure Ar injection, eliminate propellant gas)
  - JET ready for operation in November
  - J-TEXT first experiments done
  - KSTAR in planning (two injectors for multiple injection)
  - HL-2A ?
- Diagnostic coverage to be enhanced for code validation and to have quantitative answers (e.g. bolometer coverage, space resolved density measurements)