Progress in validating the ITER Disruption Mitigation Strategy

M. Lehnen

ITER Organization

Content

- Update on the Disruption Mitigation System
- DMS Task Force Activities
- Highlight issues

Progress with the ITER Disruption Mitigation System

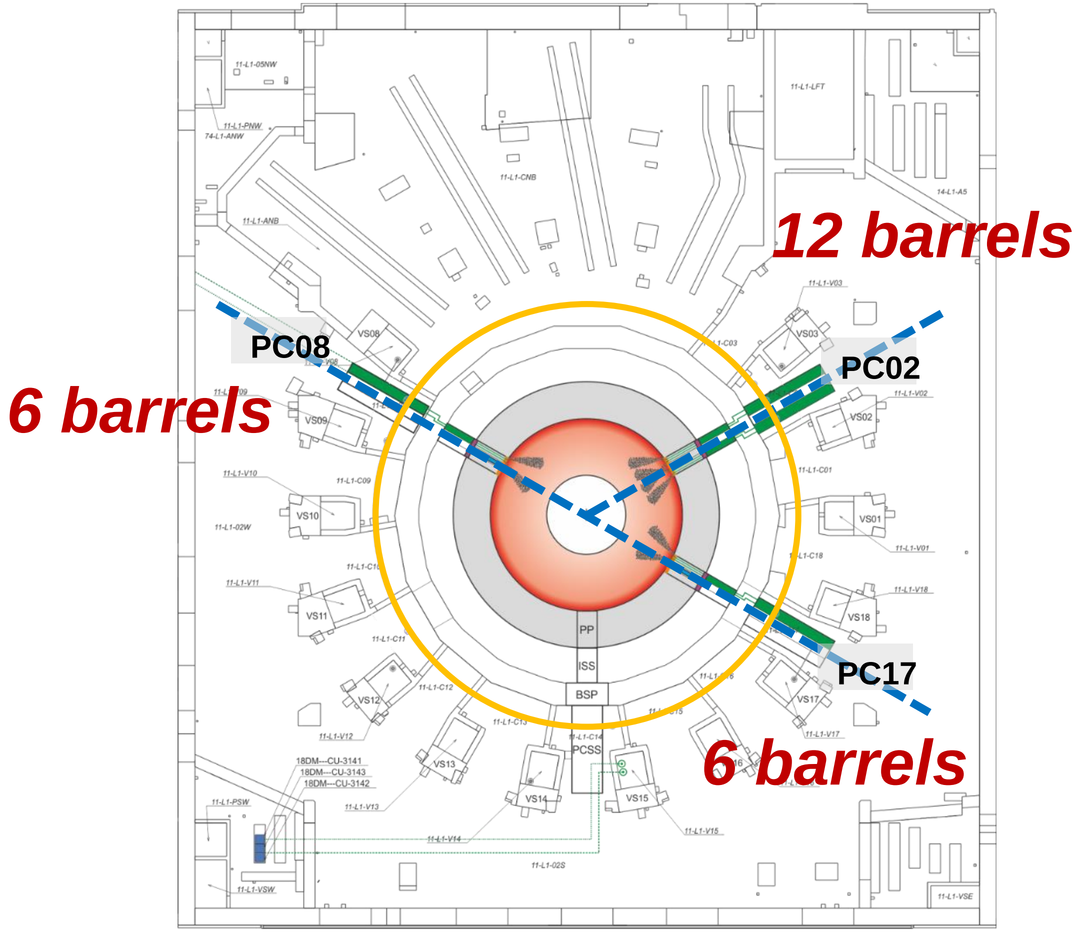
The DMS design, procurement and integration is now the responsibility of the ITER Organization (was US DA)

The plan for Design Validation, Technology Development, and Procurement has been approved by IC-24 and is presently implemented

The DMS has been re-configured providing more injection locations and overall more injection capability

DMS port plug allocation

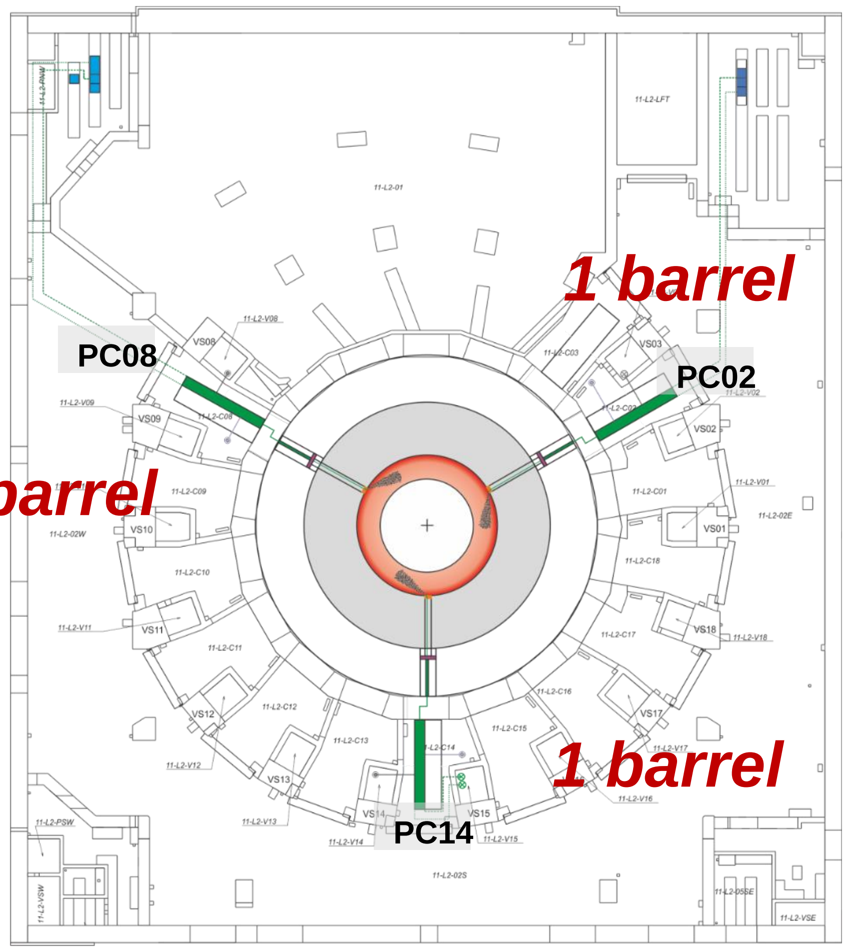
Equatorial ports



Allows evaluation of the need for further toroidal distribution after PFPO-1 (services will be available in port #11)

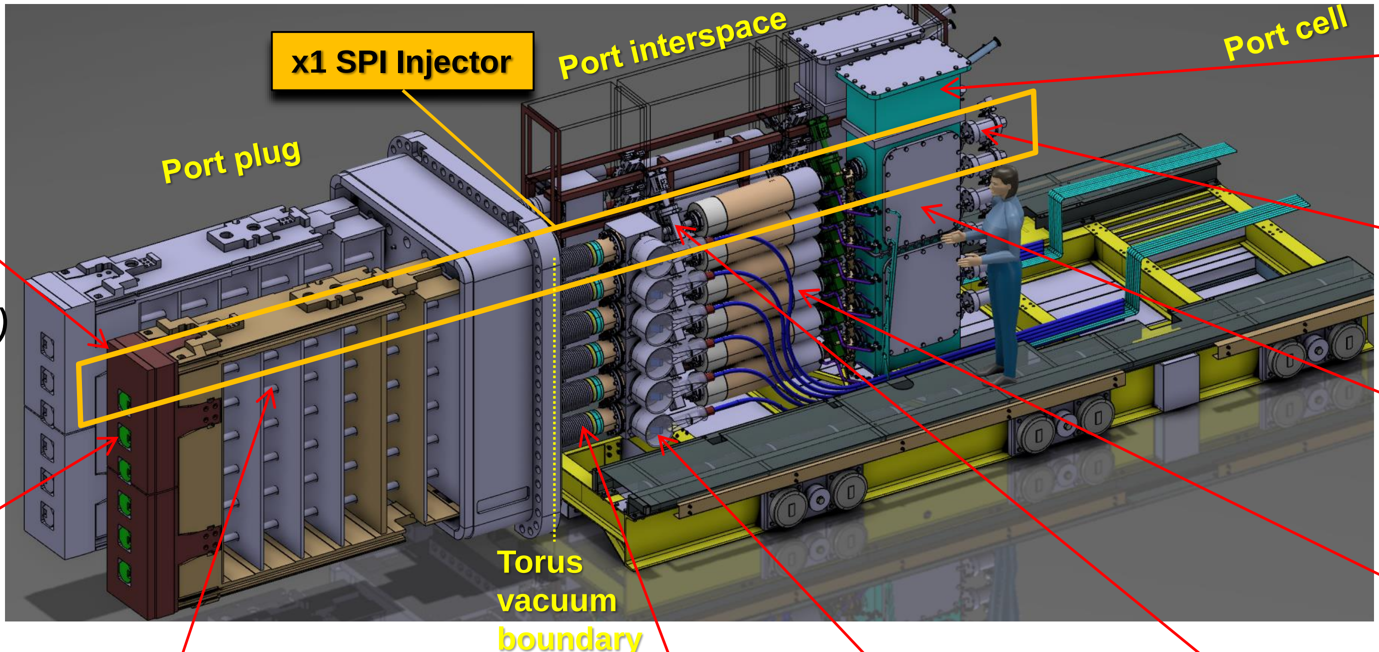
DMS port plug allocation

Upper ports



Upper port injection presently foreseen for post-TQ injection with high conversion to gas

Preliminary design studies of SPI integration in one drawer of the equatorial port



SPI cryostat (prismatic)

Diagnostic first wall *(Plasma facing Component)*

Flyerplate propellant valve

Cold head

Pellet shatter exit segment

Propellant gas recovery

Pellet guide tube

Double bellows

Optical pellet diagnostic

Vacuum valve

ITER DMS injection scheme

***Pre-TQ* Ne/D2 injection from equatorial ports**

- Thermal load mitigation *(TQ and CQ)*
- Electromagnetic load mitigation *(CQ)*
- Runaway electron avoidance *(TQ)*

***Post-TQ* Ar injection from equatorial ports**

- Runaway energy dissipation *(CQ)*

***Post-TQ* Ne (+D?) injection from upper ports**

- Thermal load mitigation *(CQ)*
- Electromagnetic load mitigation *(CQ)*
- Runaway electron avoidance (?) *(CQ)*

DMS injection capabilities

	Species	Required assimilated quantity*
RE energy dissipation	Ar	10^{25}
RE avoidance	D_2	10^{25}
TQ + CQ mitigation	Ne	$5x10^{22}$

28.5 mm pellet contains ~ 10^{24} atoms

Injection scheme under discussion:

- Ne/D mixtures or separate injection of Ne and D?
- Assimilation of multiple pellets efficient?
- Injection trains of D after TQ to target on early runaways?
- Injection of D pre-TQ for dilution cooling?

*Numbers based on present knowledge, to be addressed

Scope of the ITER DMS Taskforce

- **Scientific validation** (experiment and theory) of DMS requirements
- **Technology development** to ensure required DMS reliability
- Studies to address future upgrades or **alternative approaches**

Main focus next 2-3 years

Coordinate activities across the ITER members

Identify needs beyond those covered by ongoing efforts

Establish collaboration agreements / contracts to fill these and to support SPI experiments

ITPA is the framework for coordinating joint SPI experiments → new JEX MDC-24

DMS final design review planned late 2022

DMS Task Force – Topics addressed

Experiments

N. Eidietis

Tokamak experiments

- multiple injection
- size scaling
- radiation flash
- pellet parameters
- runaway avoidance
- broken pellets / impurities
- ITER-like DMS in routine closed-loop
- alternative shattering techniques

Technology

U. Kruezi / N. Balshaw

Lab experiments

- pellet formation
- integrity monitor
- pellet shear-off, acceleration, synchronisation
- geometric constraints
- impurity inflow
- controlling shard sizes

Theory/Modelling

E. Nardon/A. Matsuyama

3D MHD / fluid / simplified modelling theory development

- multiple injections
- ablation/assimilation
- radiation distribution
- injection angle
- RE avoidance (TQ)
- RE energy dissipation (instabilities, I_P/Z)

DMS Task Force – Topics addressed

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Theory/Modelling

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3D MHD / fluid / simplified modelling theory development

Expert groups

- Tokamak experiments – assessing needs for new SPI experiments
- 3D MHD modelling (kick-off January 2019)
- Runaway electron theory & modelling (kick-off February 2019)
- Pellet ablation and assimilation (kick-off September 2019)

Theory and Modelling – work plan of 3D MHD group

NIMROD	M3D-C1	JOREK		
			Code development and benchmarking	Code-code benchmark on fictitious radiative collapse cases (atomic models); Development of SPI ablation models, benchmark with more simplistic models
			Code validation and Experiment interpretation	KSTAR, AUG, JET, D3D, J-TEXT
			ITER-like configuration (multiple injection)	Focus on radiation and density distribution; Simplified ablation models; Resolving SPI plume limited for toroidal Fourier expansion
			RE seeds during SPI in ITER	Assess RE extraction from Maxwellian; One-way coupling to kinetic codes sufficient for $j_{RE} << j_{thermal}$

Theory and Modelling – work plan of runaway electron group

Runaway formation and avoidance

Simplified integrated ITER simulations of baseline strategy
(in the spirit of Martin-Solis+, NF2017)

Minimal requirements on models:

- Primary and secondary RE generation mechanisms
- Self-consistent E-field

Acceptable simplifications:

- No SPI physics (prescribed material deposition)
- No self-consistent MHD

- Assess domain of parameters for RE avoidance (required quantities, Ne/D_2 ratio)
- Include scans in uncertain factors (e.g. material deposition profile, stochastic losses, TQ duration…) to assess robustness of RE avoidance

KORC | EXTREMe | RAMc

GO | CODE/NORSE

Theory and Modelling – work plan of runaway electron group

Runaway formation and avoidance

Complex integrated simulations

- Include self-consistent SPI physics, MHD and electron kinetics

NIMROD + PIC + test particles + CQL3D

M3D-C1 + KORC

EXTREMe + test particles

- Validate and benchmark integrated models (“simplified” versus “complex”)
- Integrated ITER simulations of baseline strategy

Investigate alternative RE avoidance strategies

- RF current drive
- RF waves

Theory and Modelling – work plan of runaway electron group

Runaway energy dissipation

Develop a model for the RE beam and its background plasma

- Need a self-consistent description of the BG plasma including interaction with RE, diffusion time, neutral penetration

Integrated ITER simulations of the evolution and termination of a RE beam

- Assess tolerable RE current
- Assess the effect of a 2nd injection
- Quantification of magnetic energy conversion at instability and of remaining kinetic energy

ITER target plasmas for mitigation studies

Corsica simulation chosen as target plasmas for SPI simulations

Scenarios	DT H-mode	H L-mode	He H-mode	H H-mode
Ip [MA]	15	15	7.5	5
Bt [T]	5.3	5.3	2.65	5.3
Max E_{th} (MJ)	370	54	55	30
main ions	D-T	H	He	H
reference name	DThmode24	H26	He56	H123
shot	130506	100506	110509	100507
last run	1	1	1	1
Selected time (s)	400	60	400	100

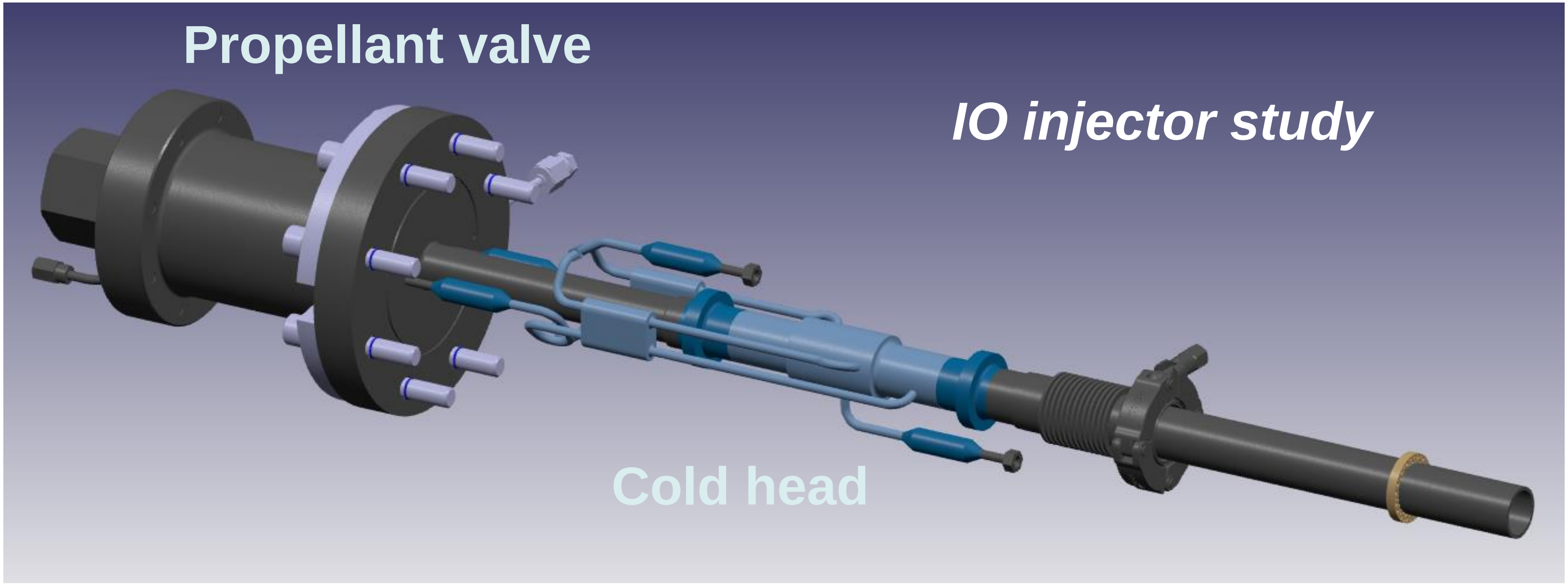
Available through IMAS → contact Simon Pinches for IMAS support, simon.pinches@iter.org
or through G,P,T files → contact Eric Nardon, Eric.NARDON@cea.fr

Technology projects

The system must be robust with respect to availability, timing jitter, fragment size distribution

- Punch and fast valve development
- Pellet release and shattering studies
- Size scaling to 28 mm pellets

Many aspects covered by ORNL SPI program
IO DMS TF will launch complementary activities



International JET SPI project

First experiments took place in the last 2 weeks
More experiments scheduled for September and November

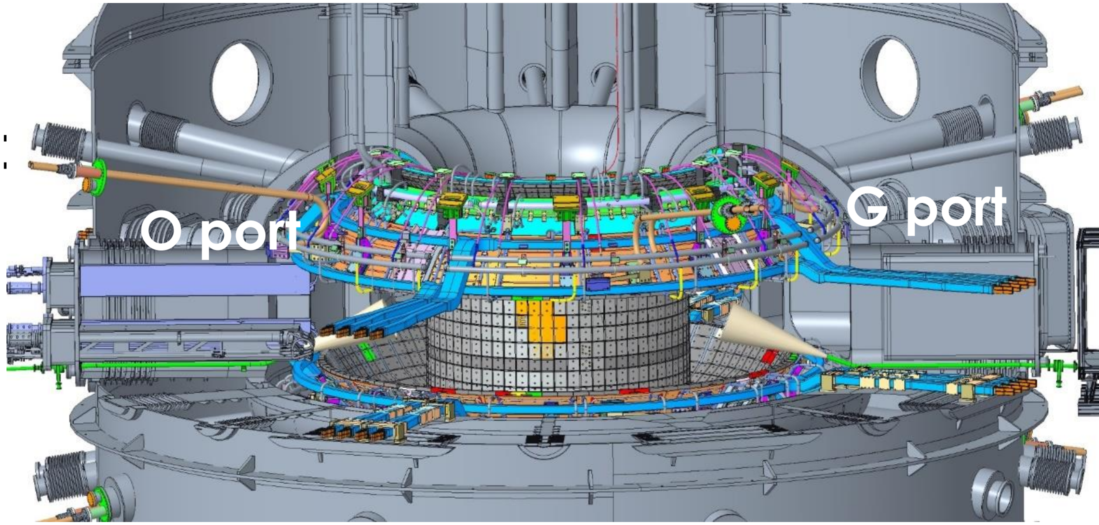
Focus on RE avoidance, mitigation, thermal and current quench mitigation
4.6, 8, 12.5 mm pellets available with quantities from ~$5x10^{20}$ to ~$9x10^{21}$

Experimental DMS TF projects

Dual injection in KSTAR

ORNL provides the injectors: first ready for 2019, both available in 2020

Radiation distribution and effectiveness of assimilation



SPI in ASDEX Upgrade (under discussion)

Studies of the impact of different fragment sizes using three different flight tubes

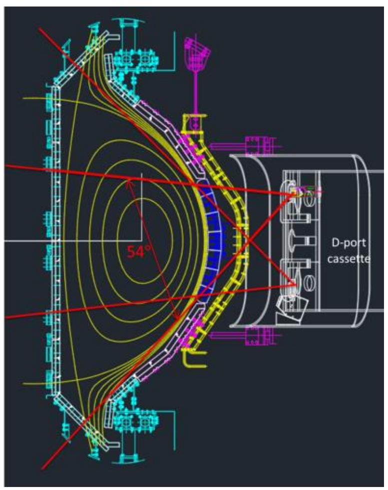
2nd SPI on JET (under discussion for JET extension > 2020)

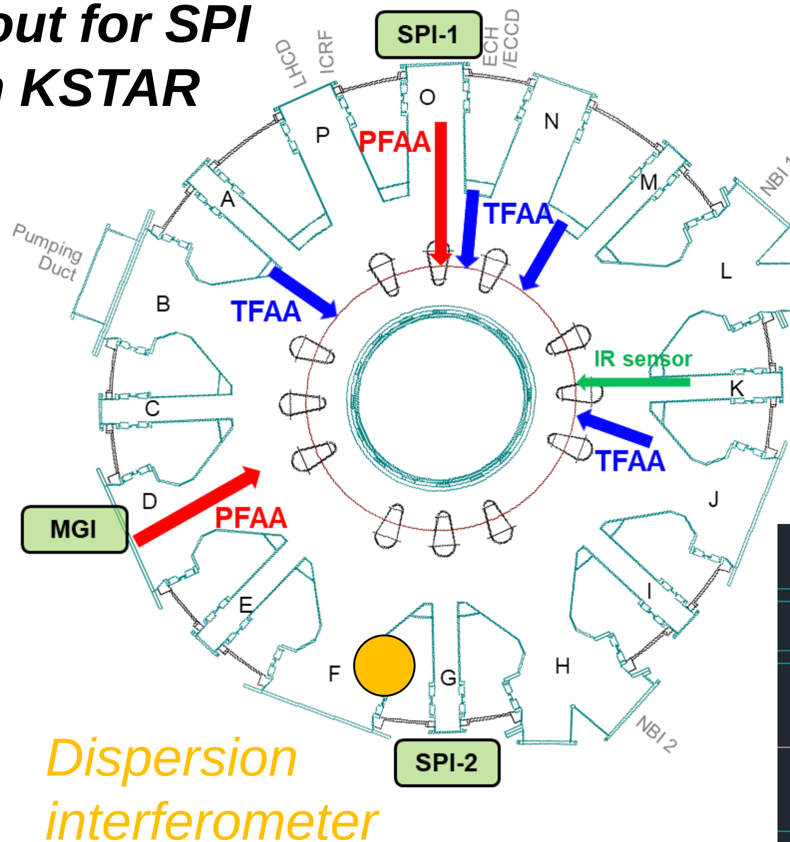
Would allow size scaling from KSTAR

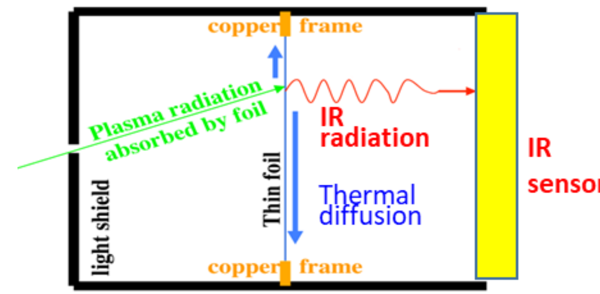
Experimental DMS TF projects – KSTAR Diagnostic upgrades

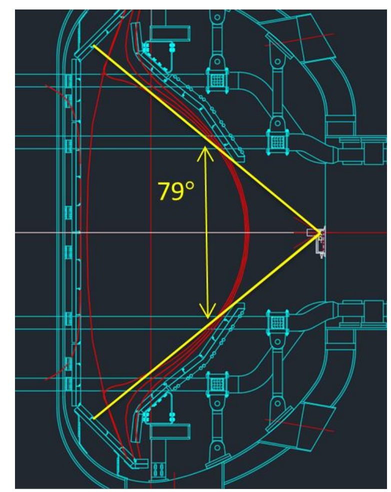
Tokamak diagnostics are in general not optimised to study disruption mitigation

Bolometer layout for SPI experiments in KSTAR









+ fast cameras for both SPI locations

High priority issues – Multiple injections

Multiple injection is required for

- runaway avoidance
- runaway energy dissipation
- reduction of heat loads from the radiation flash

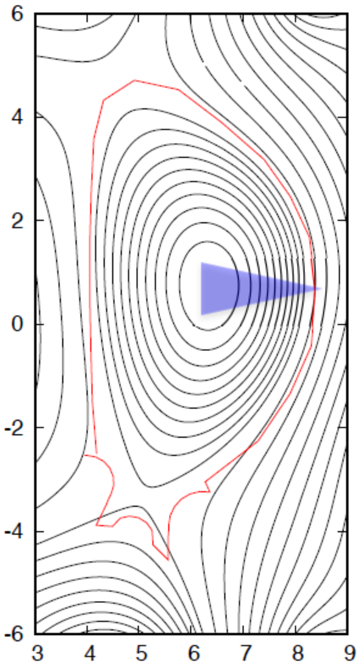
Critical questions are

- Is the achievable density proportional to $N_{pellets}$
- Is the density increasing where needed (uniformity?)
- How are the timescales (e.g. time until TQ onset) related to injection sequence and geometry
- Is the peak radiation heat flux proportional to $N_{injection\ locations}$

High priority issues – Multiple injections

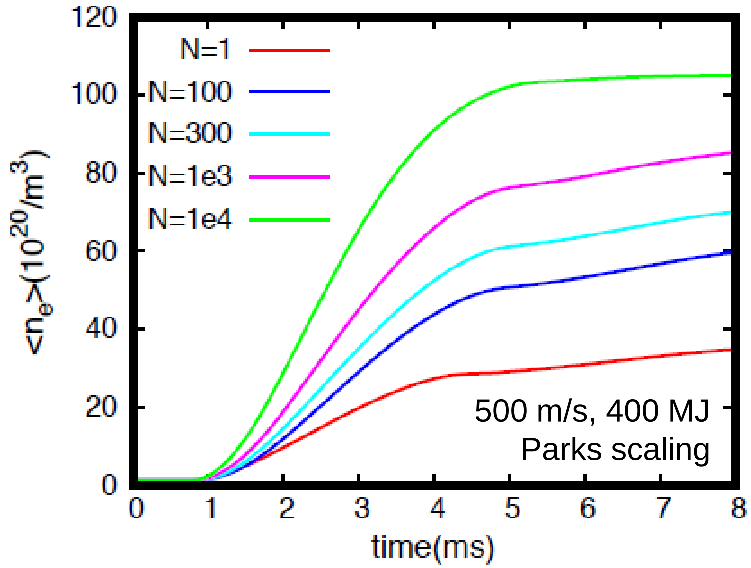
Initial simulations with 1.5D code **INDEX**
[A. Matsuyama+, JSPF Conf. 2018]

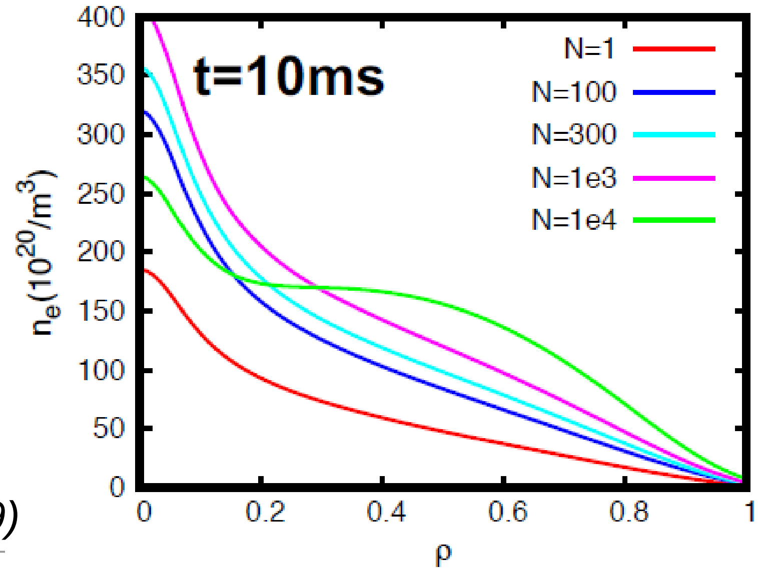
D_2 28.5 mm x 4



- Divergence 20 degree
- Velocity dispersion 20%
- Injection plume spread over 1ms for each pellet
- Pellets injected simultaneously
- Fragment size distribution according to P. Parks
- Independent fragment ablation

N = number of fragments





Courtesy of A. Matsuyama, QST
(extract from presentation at the ISFN meeting June 2019)

High priority issues – Multiple injections

Initial simulations with 1.5D code **INDEX**
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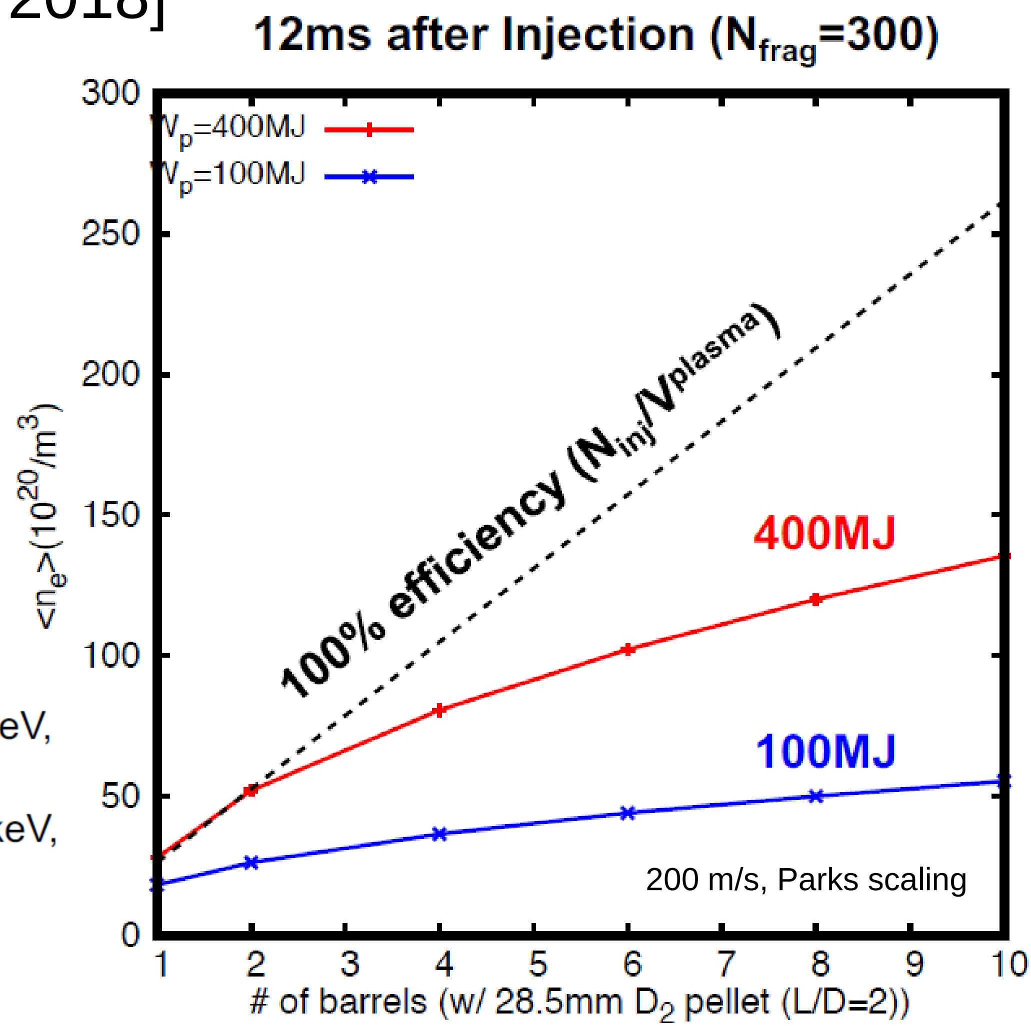


- **400MJ (H-mode like):** I_p = 15 MA, $<T_e>$=8.3keV, $<n_e>$ =1.2x$10^{20}/m^3$, W_p = 400 MJ, Z_{eff}=1.5 (O)
- **100MJ (L-mode like):** I_p = 15 MA, $<T_e>$=4.3 keV, $<n_e>$=0.5x$10^{20}/m^3$, W_p = 100MJ , Z_{eff}=1.5 (O)

Courtesy of A. Matsuyama, QST
(extract from presentation at the ISFN meeting June 2019)

High priority issues – Runaway energy dissipation

Runaway current decays as expected with impurity quantity for modest injections

But there are substantial issues:

Next slides

- Significant current carried by RE at the final loss
- Scraping-off effect increases required argon quantity and could lead to early RE energy deposition

Konovalov+ IAEA 2014

- Limited fuelling efficiency
  - Pellets are not better than MGI (in this respect)
  - Slow particle transport times prevent fast penetration

Shiraki+ NF 2018

Hollmann+ NF 2019

Reducing current at final RE loss in DIII-D

$\tau_{wall} \leq \tau_{CQ}$

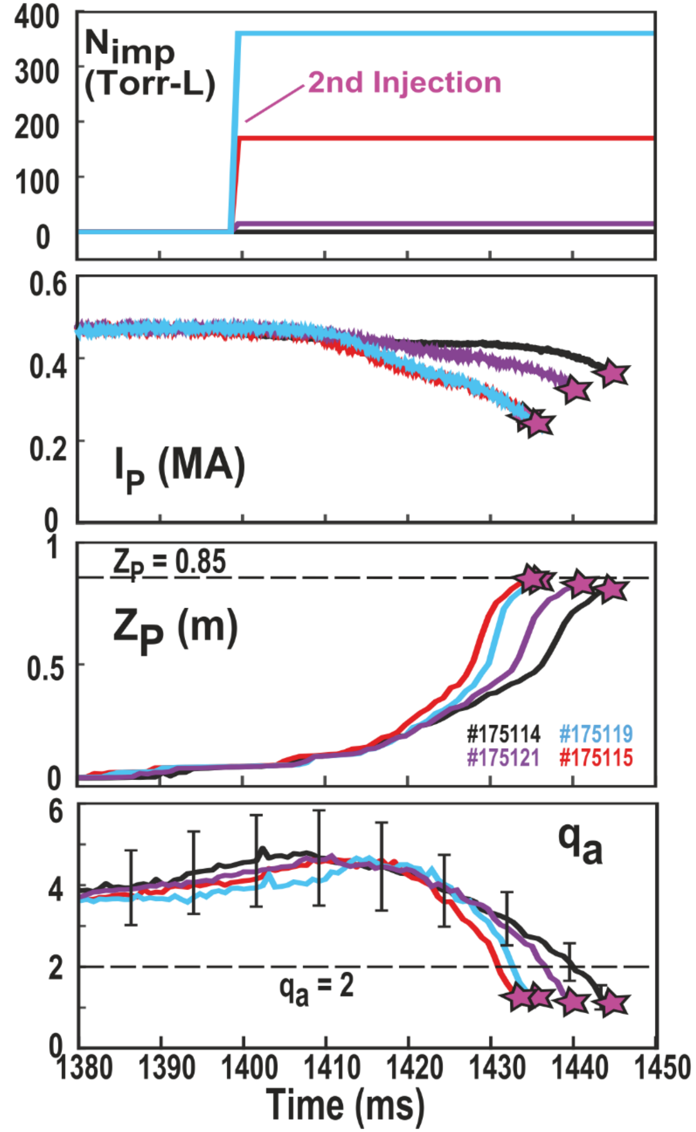
Vertical position control switched off

Second injection accelerates the RE current decay

The remaining current at the final RE loss can be reduced by

a) Increasing injected quantity

b) Earlier injection

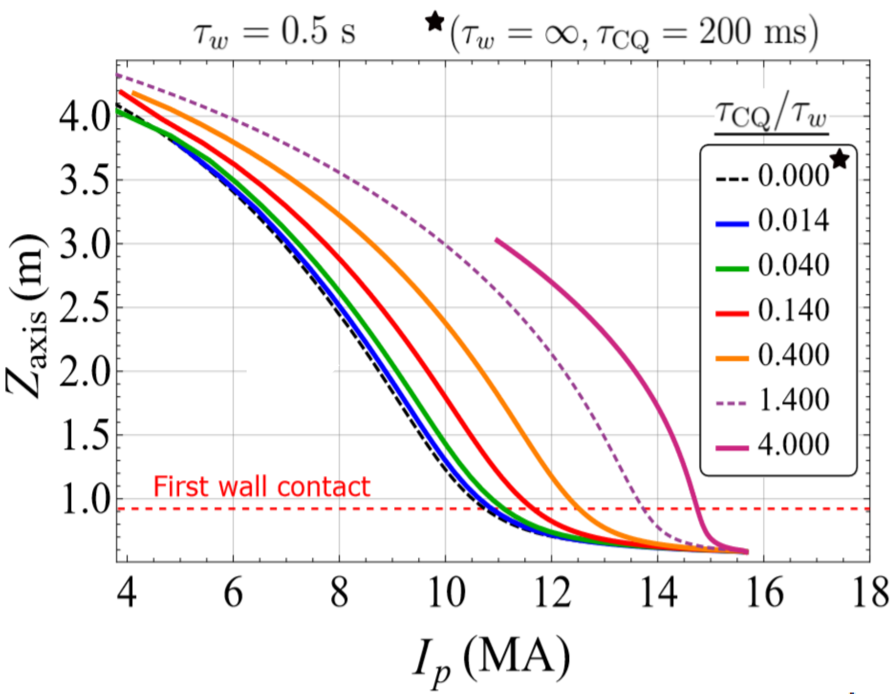


Hollmann *et al* 2019 *Nucl. Fusion* in press
https://doi.org/10.1088/1741-4326/ab32b2

Current and vertical position linked in ITER

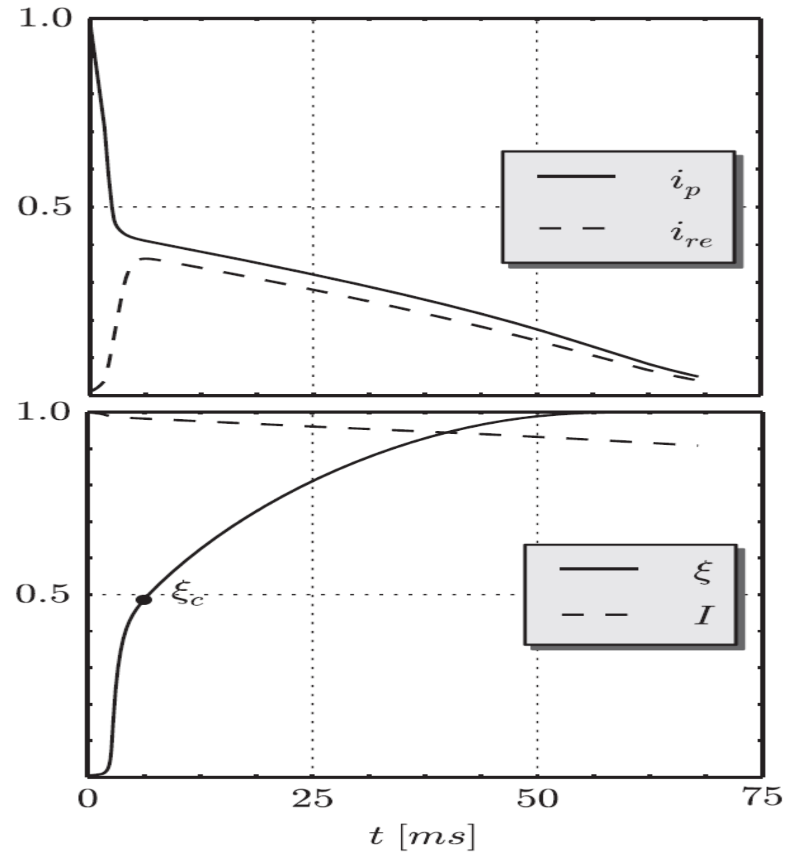
$\tau_{wall} > \tau_{CQ}$

JOREK 2D VDE simulation
I_P at FW contact cannot be reduced below ~11 MA



J. Artola, ITPA MHD, October 2018

Wire model: ideal wall → vertical motion determined by I_P drop



$$i_p = -2\frac{i_e(L_w - L_{12})[\xi(t) - \xi(0)] + i_p(0)L_{wp}[\beta\xi(0) + L\xi(t)]}{L_{wp}(l_1(\xi) - L\xi l_2(\xi))}$$

Kiramov and Breizman, NF 2017

Current and vertical position linked in ITER

$\tau_{wall} > \tau_{CQ}$

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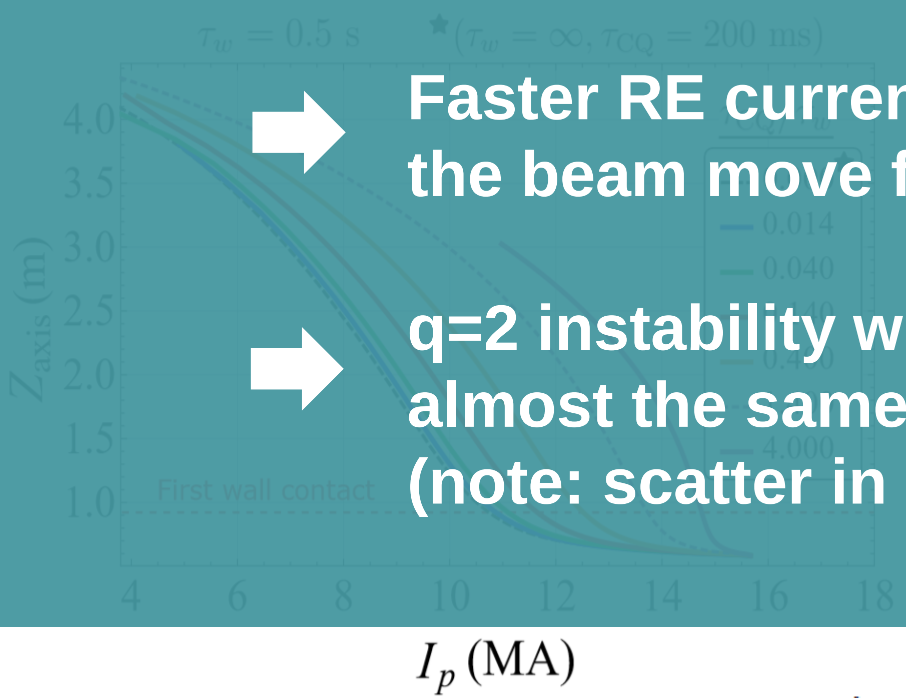

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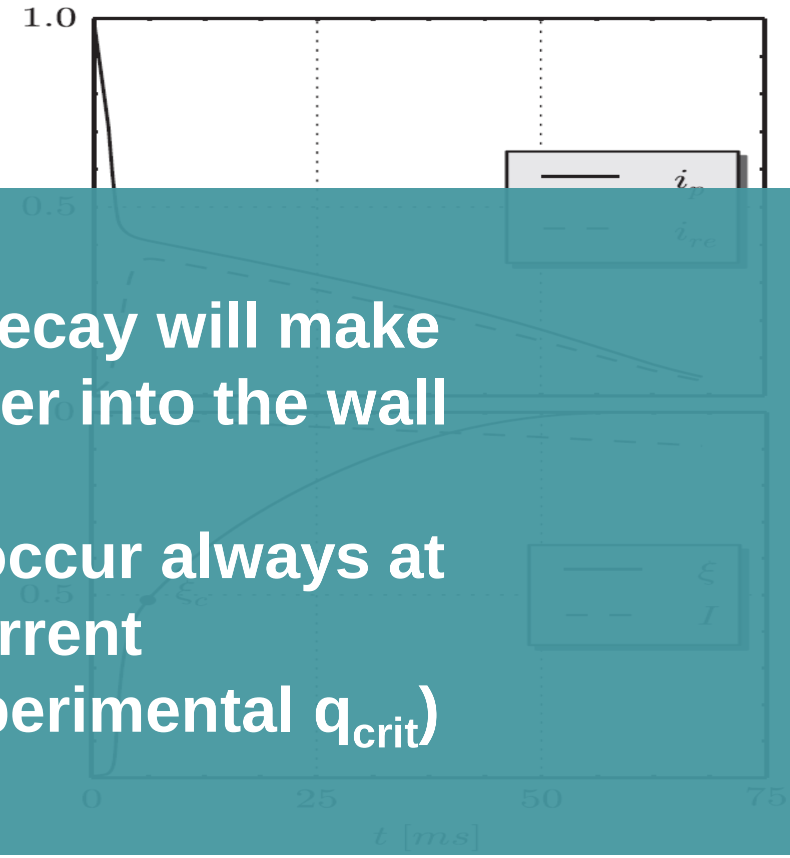

Faster RE current decay will make the beam move faster into the wall

q=2 instability will occur always at almost the same current (note: scatter in experimental q_{crit})

$$i_p = -2\frac{i_e(L_w - L_{12})\left[\xi(t) - \xi(0)\right] + i_p(0)L_{wp}\left[\beta\xi(0) + L\xi(t)\right]}{L_{wp}(l_1(\xi) - L\xi l_2(\xi))}$$

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Kiramov and Breizman, NF 2017

Summary

The **DMS** has now significant injection capabilities. The focus in the next 2-3 years must be on how to use these most efficiently.

Identifying deficiencies of the mitigation scheme (through modelling and experiments) has to lead to development of *alternative schemes* → beyond the next 2-3 years

The DMS Task force

- provides an umbrella to coordinate information exchange in the field of theory and modelling; *many activities are already planned through domestic programs like SCIDACs and E-TASCs, the TF provides support to fill gaps and to perform ITER specific simulations*
- motivates and provides support for new SPI experiments and appropriate diagnostics equipment
- promotes technology development towards a robust injection system

DMS TF material e.g. from meetings can be found here (ITER account required)