High Pressure Gas Injection for Suppression of Runaway Electrons in Disruptions*

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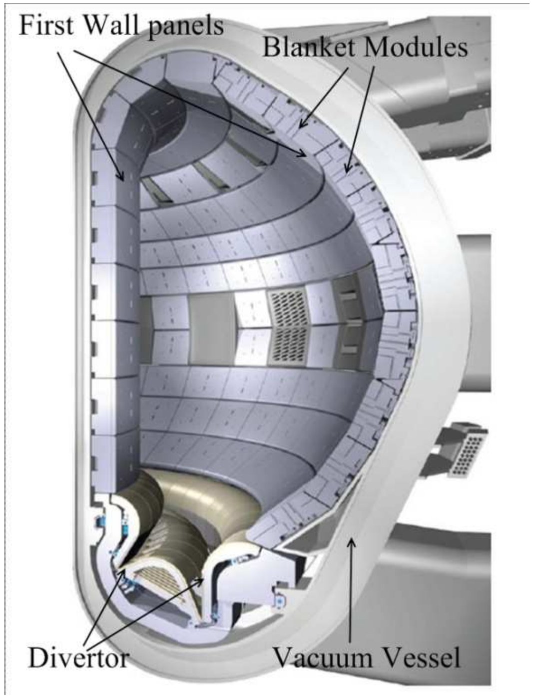
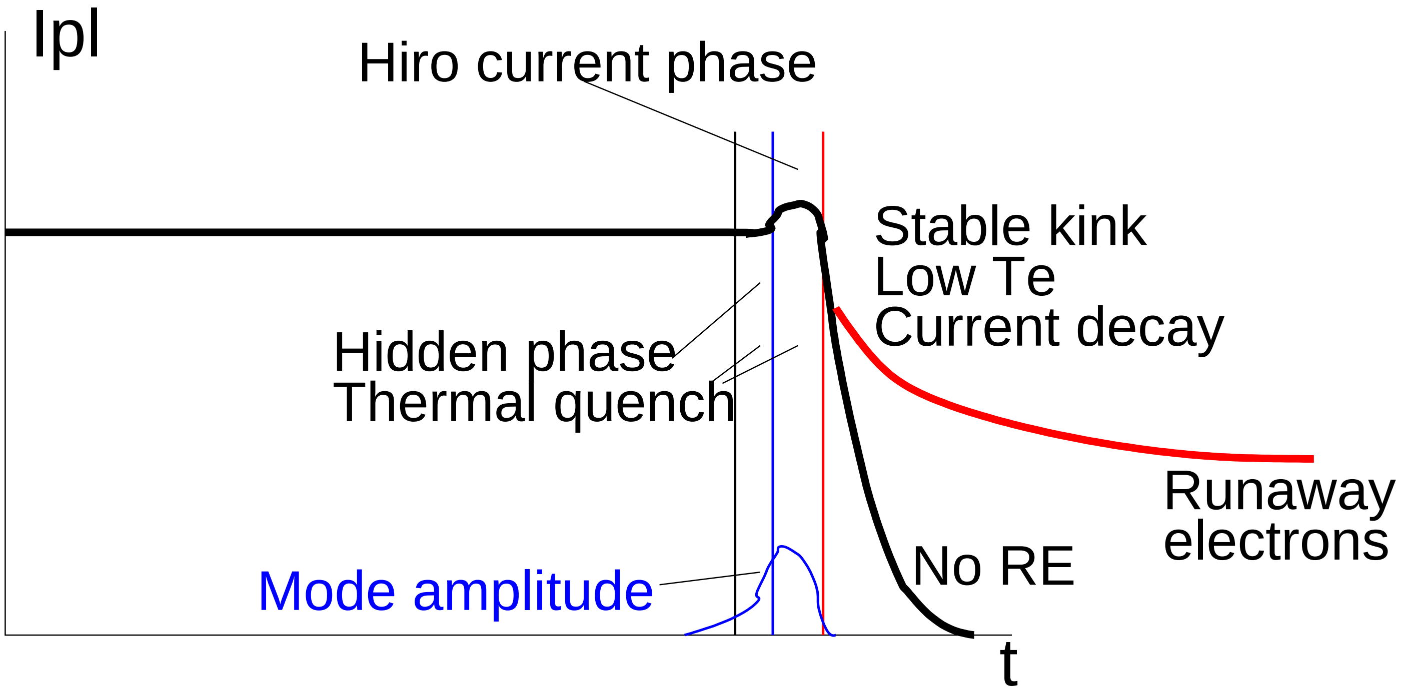
1 Introduction

- ***ITER vacuum vessel and in-vessel components are designed mechanically to withstand EM loads from the expected 2600 typical 15 MA disruptions (current quench time 50-150 ms) and 400 typical VDE***
- ***However, local thermal loads during plasma disruptions significantly exceed melting thresholds of materials of divertor targets and FW panels***
- ***A reliable Disruption Mitigations System (DMS) must be developed and installed in ITER prior to the full scale operation which will start in 2022. Presently it is at conceptual design phase***

Stages of disruptions





- ***The largest thermal loads occur during Thermal Quench (MGI might mitigate the effect);***
- ***Major mechanical forces act on plasma facing components during Current Quench (addressed by design requirements);***
- ***Runaway electrons can be generated during Current Quench (not yet addressed properly).***

Now, we have, at least, theoretical interpretation of disruption stages which allows to suggest some potential schemes.

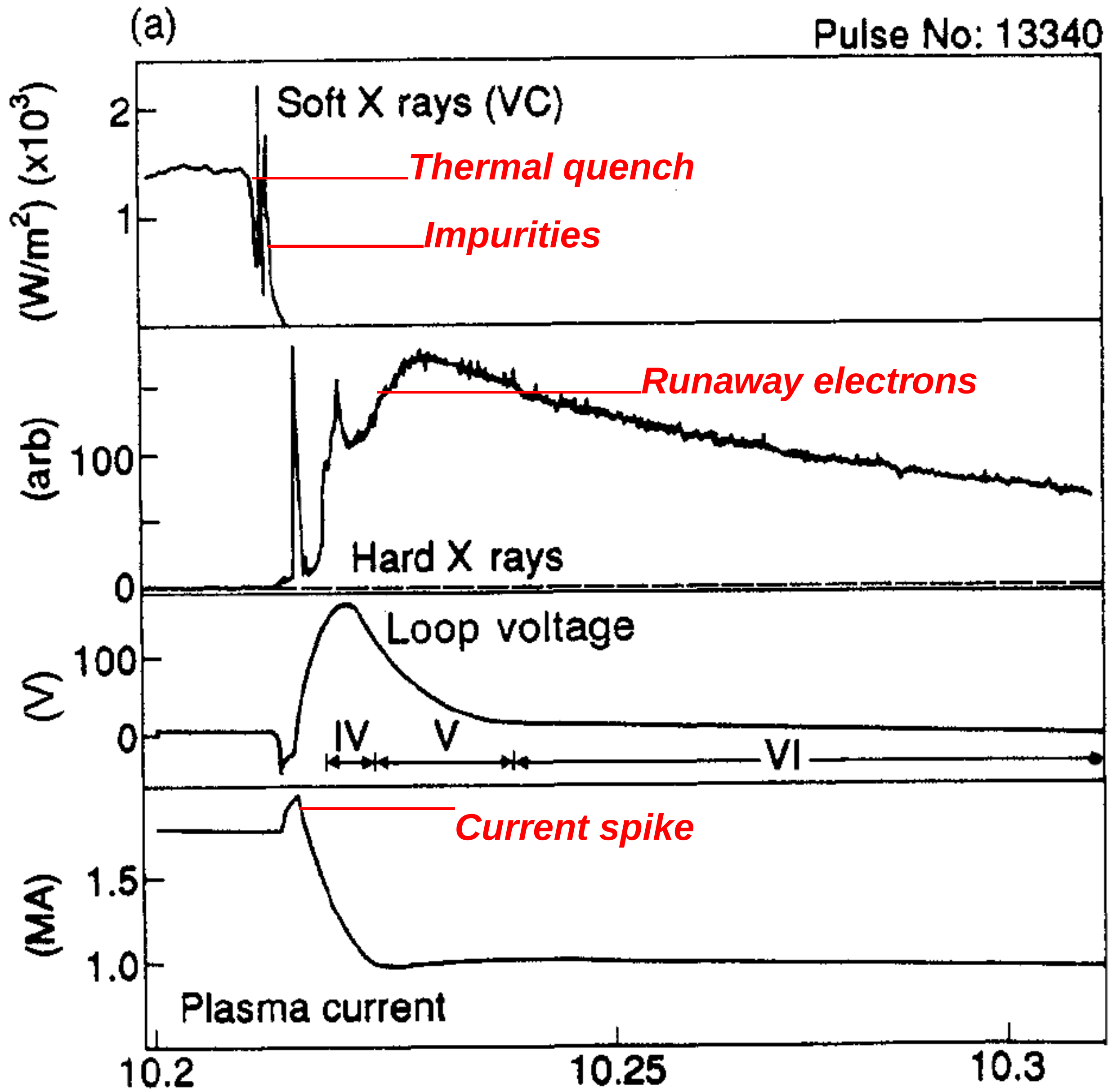


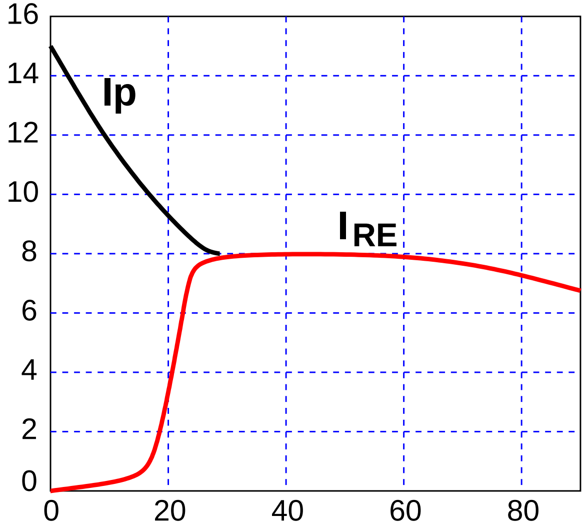
Fig.2. from R.D.Gill. Nucl. Fusion, Vol.33, p. 1613 (1993)

The concept of DMS for ITER is not yet complete

1. ***The largest thermal loads occur during Thermal Quench (MGI might mitigate the heat load). Prediction of disruptions is required.;***

Gas for DMS	Required amount, kPa$\times$m^3	Pumping system limit kPa$\times$m^3
D_2	500	100
He	500	40-50
Ne	100-200	200
Ar	100	100

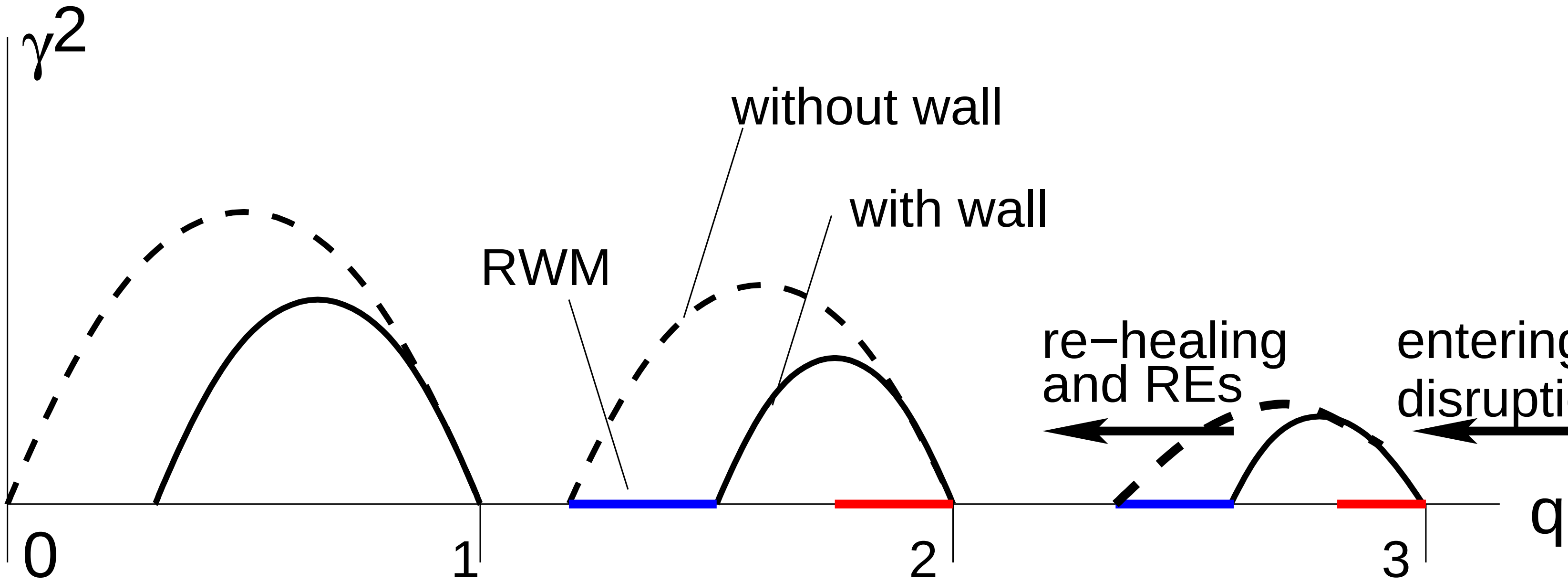
2. ***Major mechanical forces act on plasma facing components during Current Quench (addressed by design requirements for VV);***



- ***Massive runaway electrons, up to 10 MA (from DINA simulations), might be expected during current quench;***
- ***Avalanche is the primary mechanism for ITER, MGI is not expected to help much;***
- ***RE are NOT produced during the thermal quench phase of the current spike;***
- ***Healing magnetic surfaces is a necessary condition for RE generation.***

Prevention of re-healing during the current quench might be a practical approach for suppression of RE generation. The idea is to use plasma instabilities as a helper.

Resonant free boundary kink mode initiates the disruption. Wall plays no role.

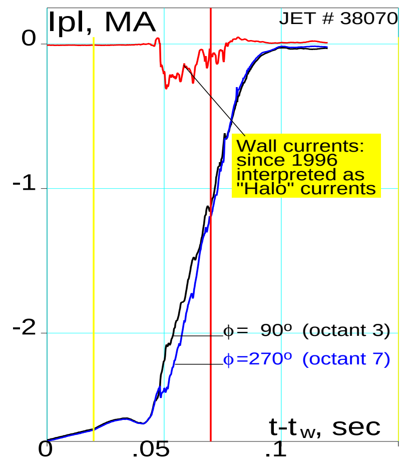


When $q(a,t)$ is going down toward $q = m$, the kink mode excited with no effect of the shell. The kink mode grows at a fast, MHD, time scale, leading to disruption.

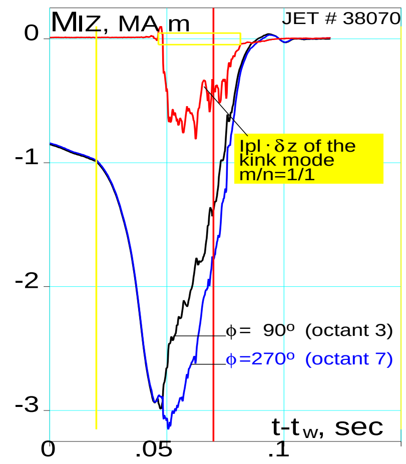
- ***Wall Touching Kink Mode is a primary candidate for driving thermal quench;***
- ***WTKM is related to the current spike;***
- ***Re-healing occurs due to transition into another stability window.***

The idea is to close the stability window by shrinking plasma cross-section and excite the next MHD mode

JET initiated breakthrough in understanding disruptions



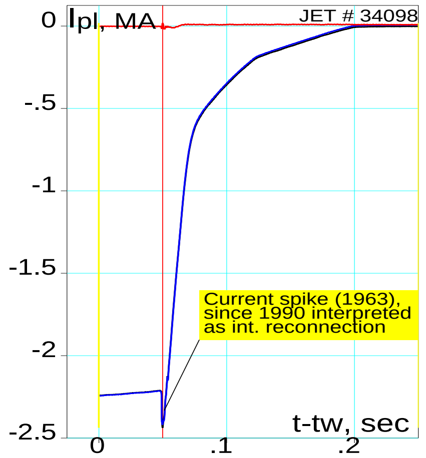
Plasma current I_{pl}



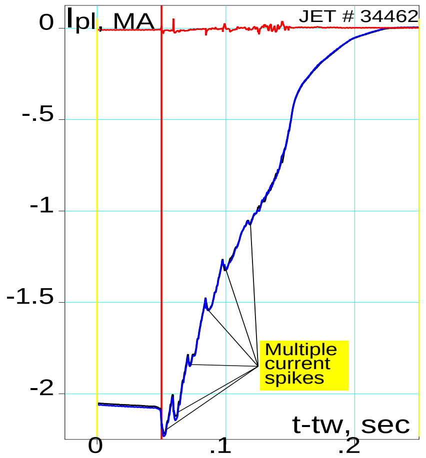
First vertical moment M_{IZ}

I. Vertical disruption event (VDE):

- Long lasting kink and toroidal asymmetry in magnetic measurements are found on JET (1996). Explained in 2007 (L.E.Zakharov. Phys. of Plasmas, v.15, 062507 (2008))
- Noll's formula for sideways force was justified
$$F_x^{Noll} = \frac{\pi}{2} B_\varphi (M_{IZ,7} - M_{IZ,3}), \quad M_{IZ} \propto I_{pl} \Delta_z .$$
- Projections to ITER have been made
$$F_{x,JET}^{Noll} = 2.4\, MN \quad \rightarrow \quad F_{x,ITER}^{Noll} = 40 - 50\, MN$$



Single current spike



Multiple current spikes

II. Conventional disruptions (known since 1963):

Current spike (although reproduced by simulations) remains a puzzle for theory.

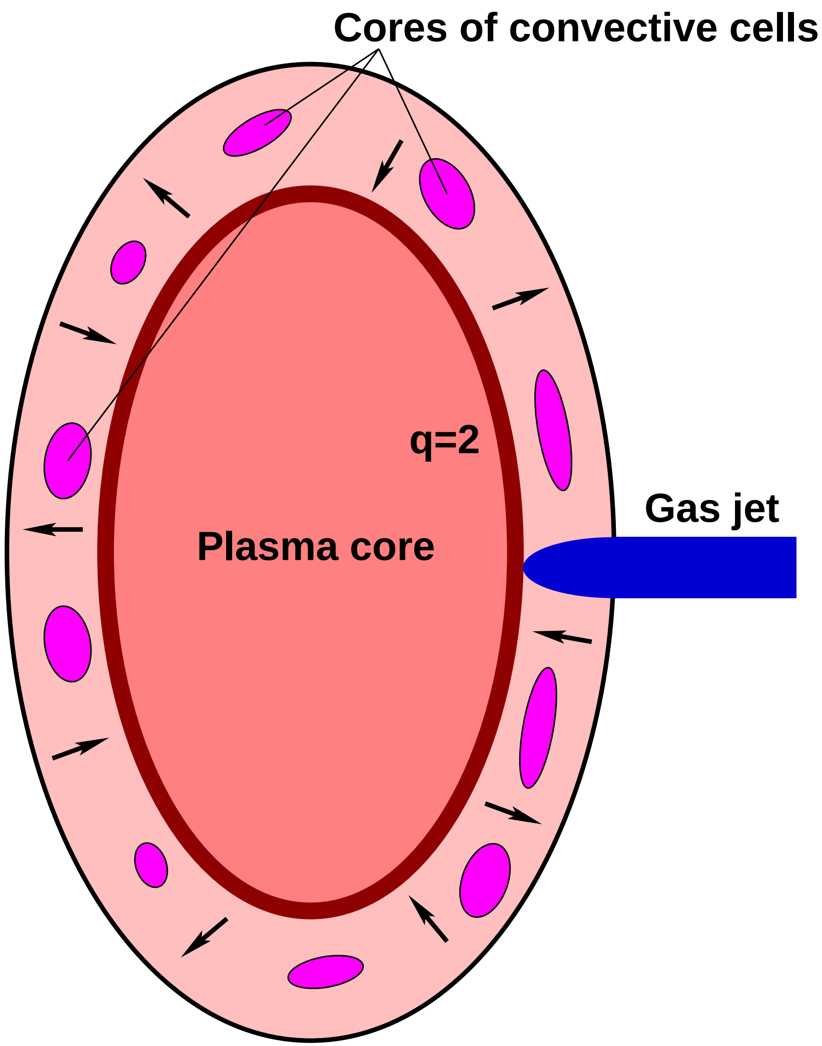
"Low L_i" interpretation adopted after Wesson, Ward, Rosenbluth (NF, 1990)

New interpretation was given in 2008

New scheme (instead of Massive Gas Injection) was suggested for ITER (2009)

Yes, kink modes can be excited repetitively during the Current Quench

3 High pressure jet might excite kink modes at CQ



Cold dense jet is expected to shrink the plasma cross-section and reduce the q-value at the edge.

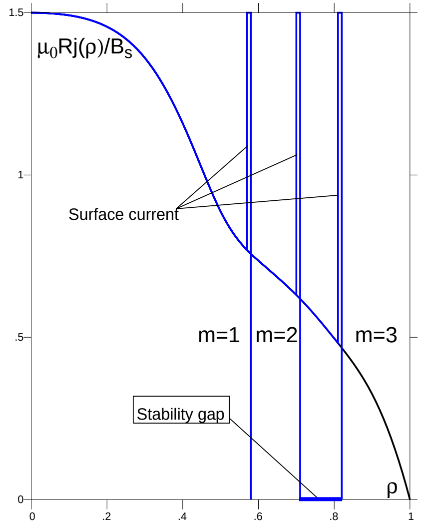
- ***High electrical resistance of the jet produces*** $\mathrm{E} \times \mathrm{B}$ ***convective cells;***
- ***A substantial fraction of plasma's magnetic energy can be dissipated on jet.***
- ***Jet generates a skin current, creates magnetic islands near the q=m/n (***$m < a/D \simeq 10$***) surfaces;***
- ***As soon as the q=2 surface is exposed, the major MHD event will be triggered.***

The physics of jet-plasma interaction is complicated.

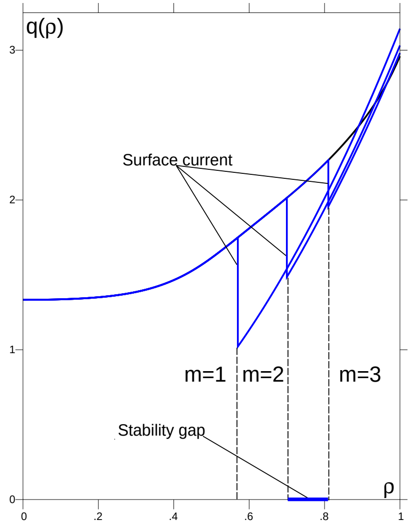
Theory can give only a guidance for amount of gas, plenum gas pressure, timing, the number of injection points, etc.

The real experiments are necessary for calibrating the understanding.

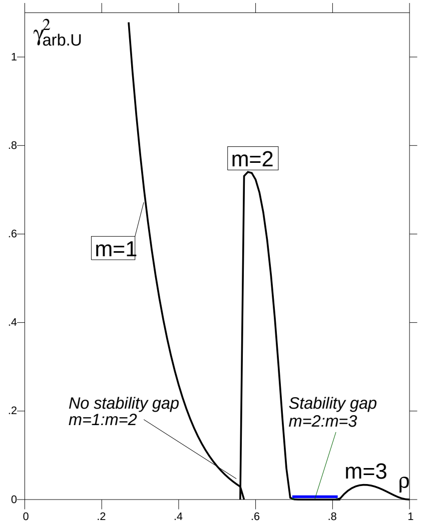
Repetitive Triggering Minor Disruptions (RTMD)



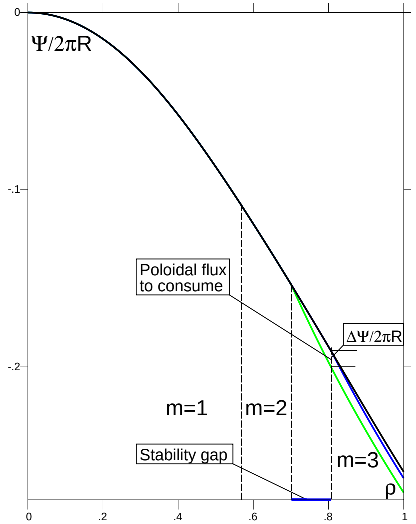
Current density $j(r)$ profile



$q(r)$-profile



Instability zones



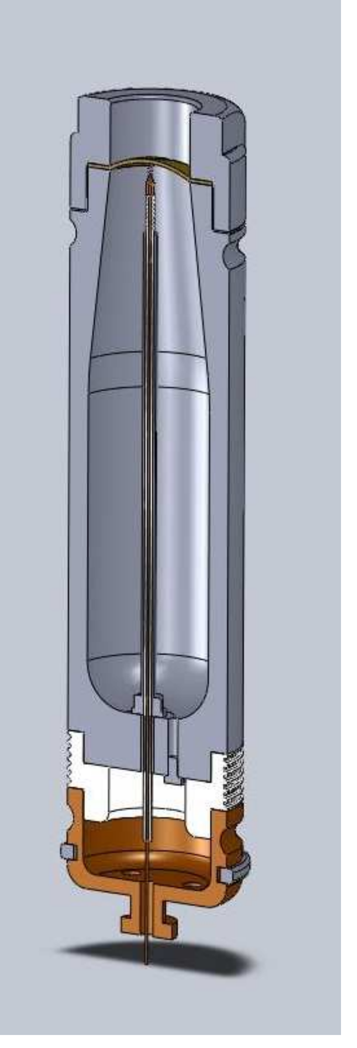
Volt-second consumption

RTMD has to consume only 1.5 Vsec of poloidal flux and may work for RE suppression.

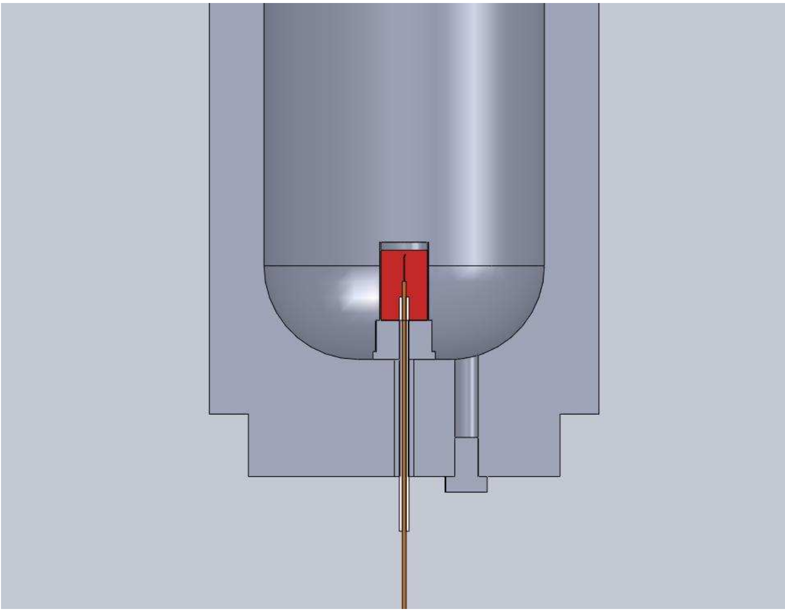
Using plasma MHD as an ally may lead to acceptable level of gas injection.

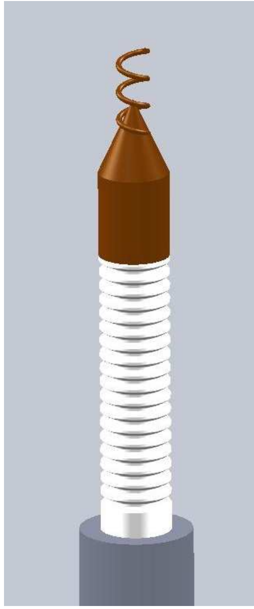
4 Potential gas cartridge design for ITER

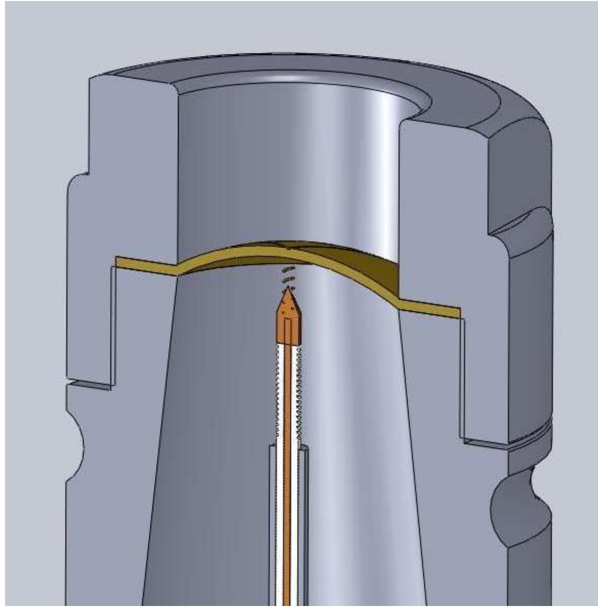
- *Cartridge consists of high pressure cylinder, rupture disk at the plasma end, electrode at the rear end, and triggering device*
- *Rupture disks operational pressure is up to 90% of rupture pressure. The one used in the design is from Fike company: http://www.fike.com/products/rdscrd.asp. It has rupture pressure 240 atm*
- *Front nut compress rupture disk and protect it from damage*
- *Wall thickness has to be sufficient to contain 200 atm CW and pressure pulses up to 400 atm. At 400 atm tensile stress in the wall is 120 MPa.*
- *Cylinder is filled with the gas and the gas feedthrough is sealed*
- *The rupture disk is opened by exploding wire, arc, or small chemical charge*
- *Hot lead of the trigger is connected to the electrode in the rear end of the cartridge*
- *Mass of the assembly 1.7 kg*



Exploding wire as a trigger for rapture disk



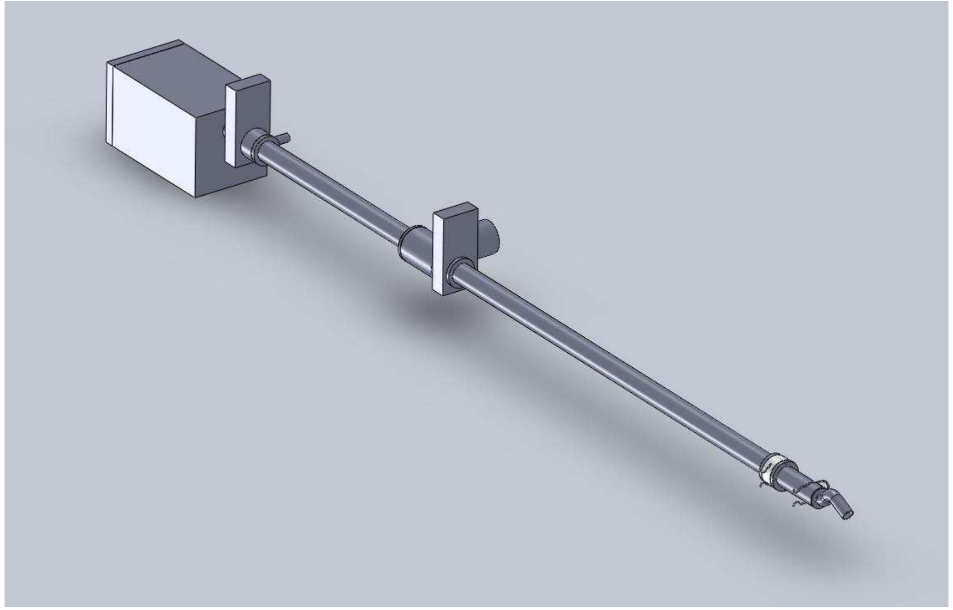


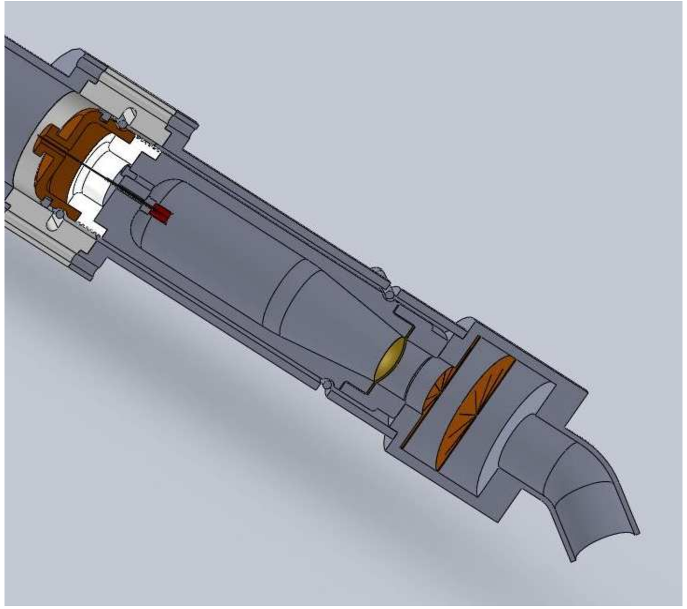


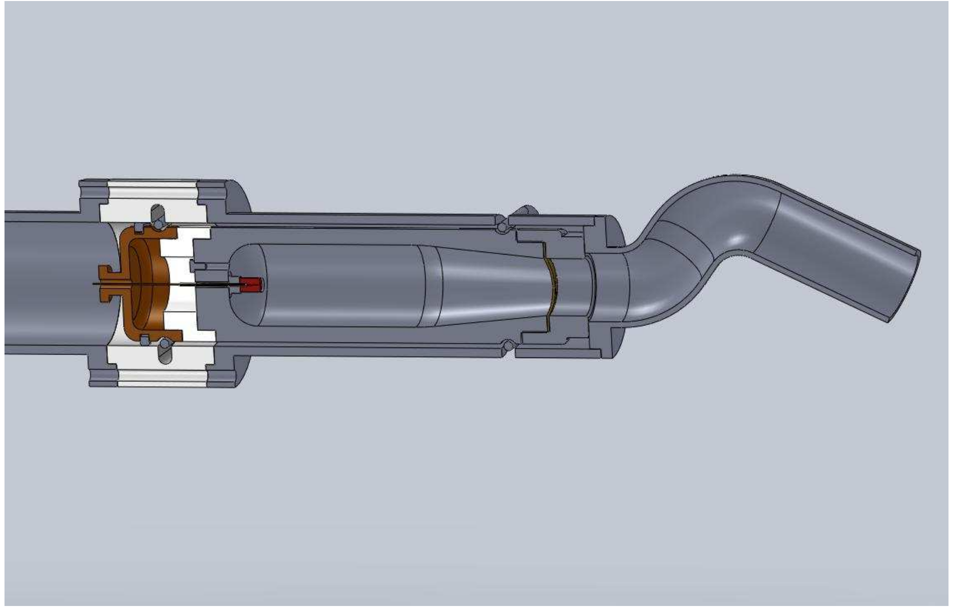
- *If the gas breakdown will be not reliable then chemical charge can be used to open the rupture disk*
- *Small charge of TNT or other explosive (0.5 g « 13 g of gas) is sufficient to generate shock wave with front pressure 400 atm*
- *Bridge wire with electrical feedthrough shall be used for detonation.*

- *Arc or exploding wire can be used for opening the rupture disk*
- *Required energy < 1 kJ. Capacitor 100 mF x 4 kV has sufficient power to open the disk.*
- *Discharge time* $1\ \mu$*s is too short for any significant deflection of the electrode*
- *Effect of magnetic field should be small,* $\omega_e \tau_e \ll 1$ *at p* $\simeq$ *100-200 atm*
- *A thin spring can be used to reduce the gap and facilitate gas breakdown*
- *Required voltage and energy should be optimized experimentally to minimize fragmentation*

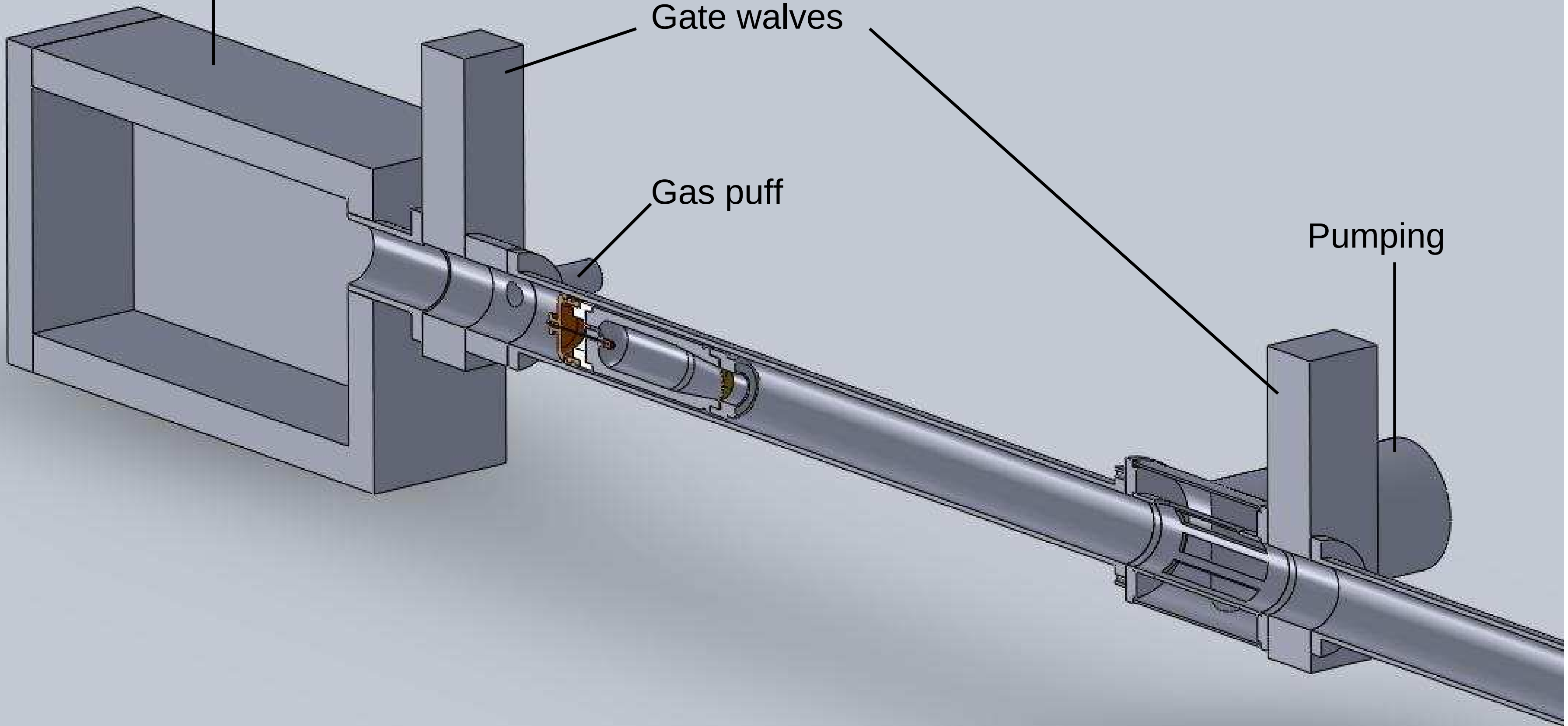
Loading system







Loading scheme



- Pneumatic loading section consists of two gate valves, gas puff and gas pumping port
- Cartridge is inserted in the loading tube and then accelerated by high pressure gas puff

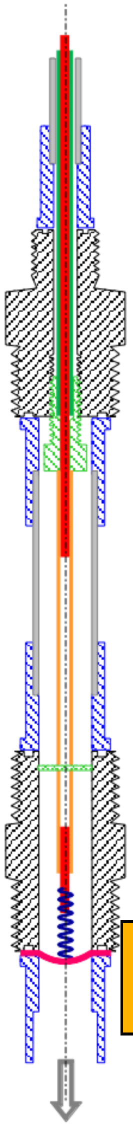
Reference parameters of the gas cylinder for ITER

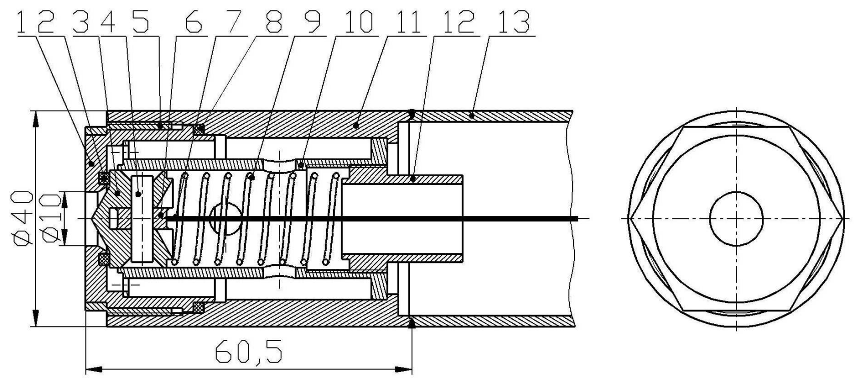
- *Multiple injector shall be installed and put on stand by during operation. The number of injectors for RE suppression shall be 5-7*
- *The injectors shall operate in machine gun regime. The injector can be triggered by TQ of disruption. Rep time between consecutive shots shall be preset to 4-6 ms*
- *The response time (including triggering, gas exhaust, and gas propagation in the plasma) of individual injectors shall be not larger then 2 ms.*
- *The reloading time shall not be longer then dwell time between pulses after major disruption (few hours)*

Amount of Ne (kPa*m3)	1.00
Gas pressure (atm)	180
Number of cylinders	5
Repetition time (ms)	6
Inner diameter (cm)	3
Outer diameter (cm)	4
Length (cm)	11
Wall thickness (mm)	5
Initial temperature (K)	400
Tube mass (g)	620
Wire diameter (mm)	0.50
Wire length (m)	0.06
Wire resistance (Ohm)	0.15
Evaporation time (μs)	30
Pressure after evaporation (atm)	420
Energy in capacitor bank (kJ)	2.1
Current in the wire (kA)	21
Voltage on the wire (kV)	3.23

5 Experiments in progress on Tore Supra, AUG, and T-10

In 2009-2010 experimental verification of the idea were motivated on DIII-D, T-10, Tore Supra, ASDEX-U, JET machines by S.Putvinski





- *Tore Supra successfully tested 100 atm with rapture disks and exploding wires as a trigger;*
- *18 cartridges were installed recently for actual experiments;*
- *6 successful high pressure jet injections were performed.*

Jet do generate the secondary current spikes as expected

- *The T-10 design is based on conventional valve with electromagnetic activation through a long string outside the VV.*
- *So far, the plenum pressure is insufficient ($\simeq 10$ atm) on both T-10 and AUG*

6 Summary

- ***It is suggested to de-couple mitigation of thermal and mechanical loads from RE suppression;***
- ***Repetitive triggering of MHD events during CQ will likely prevent magnetic surfaces from re-healing and thus prevent generation of RE s ;***
- ***The triggering of RE suppression system can be done by TQ and does not rely on precursors (100% probability of detection);***
- ***Based on estimates the total amount of gas required for the triggering is about 10 times less then the net amount for Rosenbluth s density;***
- ***Fast gas injectors based on rupture disks can provide the necessary response time and gas amount for RE mitigation in ITER***

Experimental verification of the presented scheme is now on the way on Tore Supra, T-10, Asdex-U.