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Disruption mitigation in tokamak by Fast Gas and Macroparticles Injection

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IAEA
International Atomic Energy Agency
Atoms for Peace

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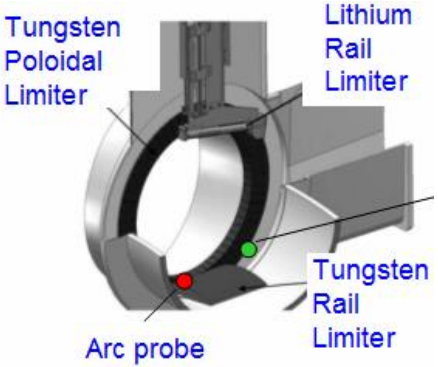
“BASELINE” Disruption/Runaway Mitigation System (DMS) for ITER

- Massive Gas Injection (MGI) // Shattered Pellet Injection (SPI)

T-10 experiments

R0/a=1.5/0.3m
Bt up to 2.5T
W (Li) limiters

L mode DLD
n_e up to 5e19m^{-3}



1. Trigger:

- MHD modes
- Limits -> & Dynamic Neural Networks
- **Arcs**

2. “BASIC” mitigation concepts:

- Forced plasma rotation to prevent MHD wall locking;
- Localized heating/current drive to shrink the islands;
- Plasma re-heating, gas and position control for safe shutdown;
- Stohastization of the magnetic field for runaway electron losses;
- Electromagnetically launched liquid “flyer plates” or “rail sabot gun”
- Self-sacrificing elements
- **Biasing - forced arcs initiation**

3. “SPARE” concept:

- EXplosive INjection (EXIN) by Chemical blasting

Energy quench could be associated with interaction of the low m/n modes

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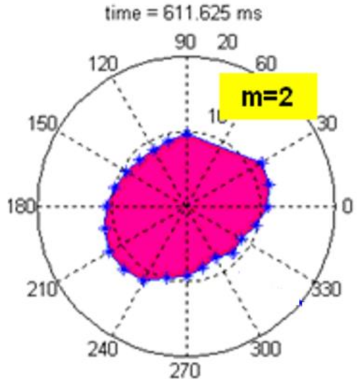
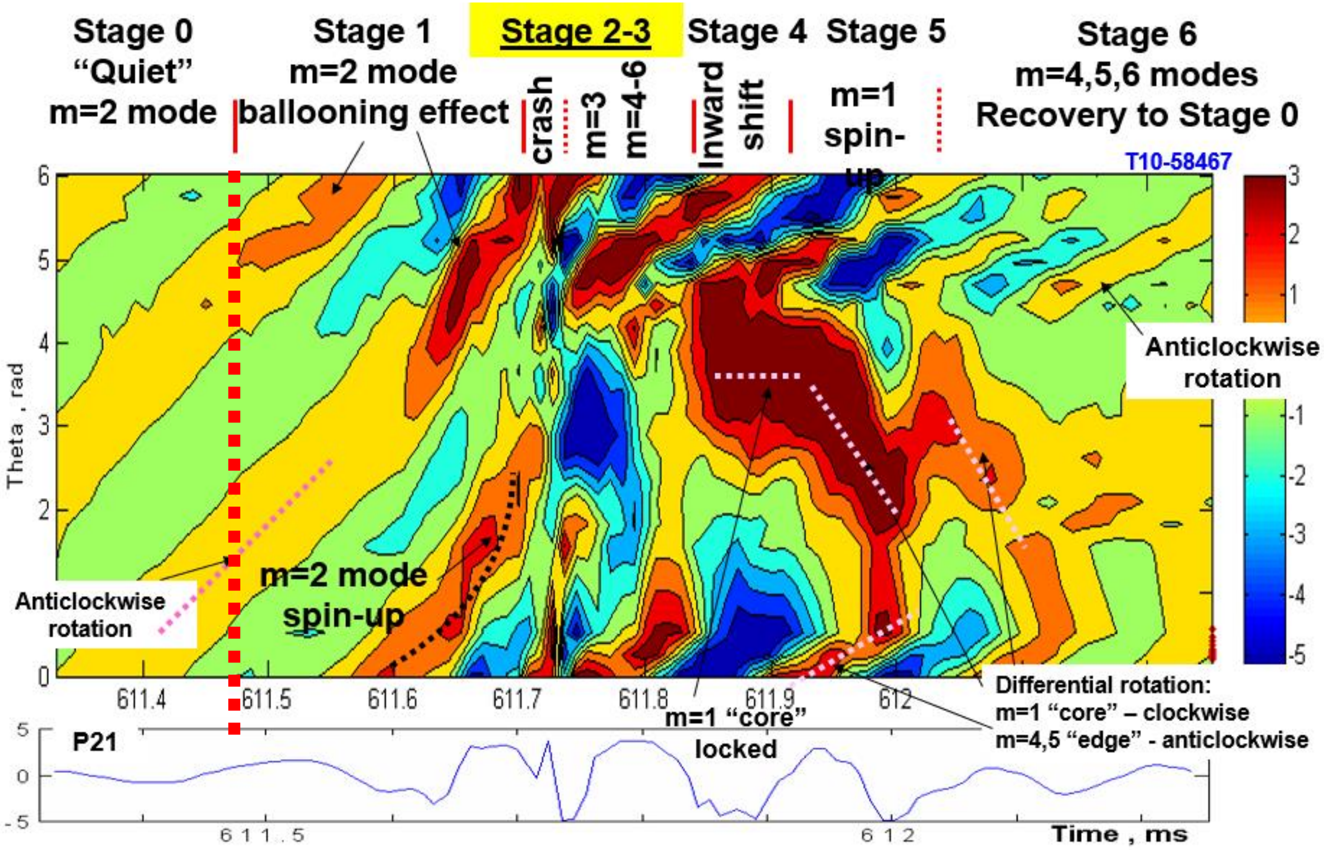


“Quiet”
m=2 mode

Density limit

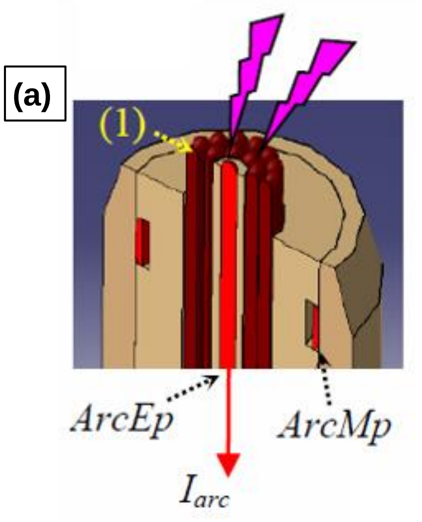


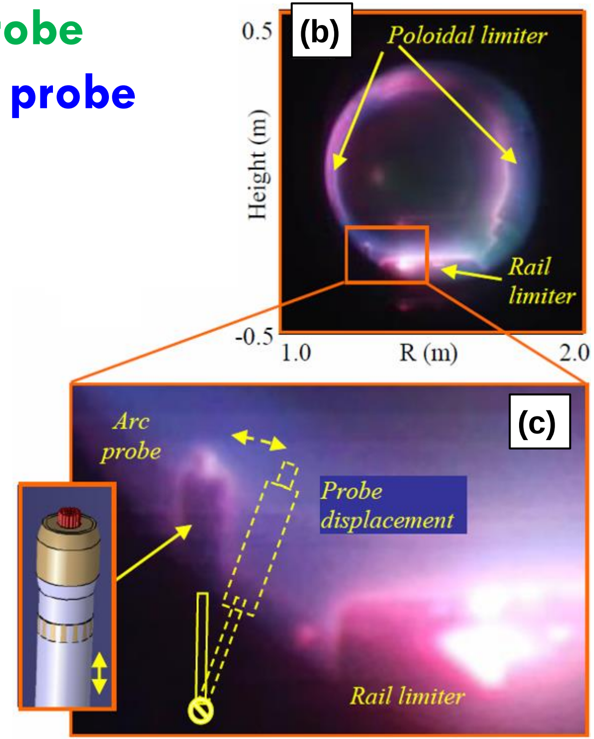
Trigger conditions based on MHD modes - not clear for at least 100 μs before disruption

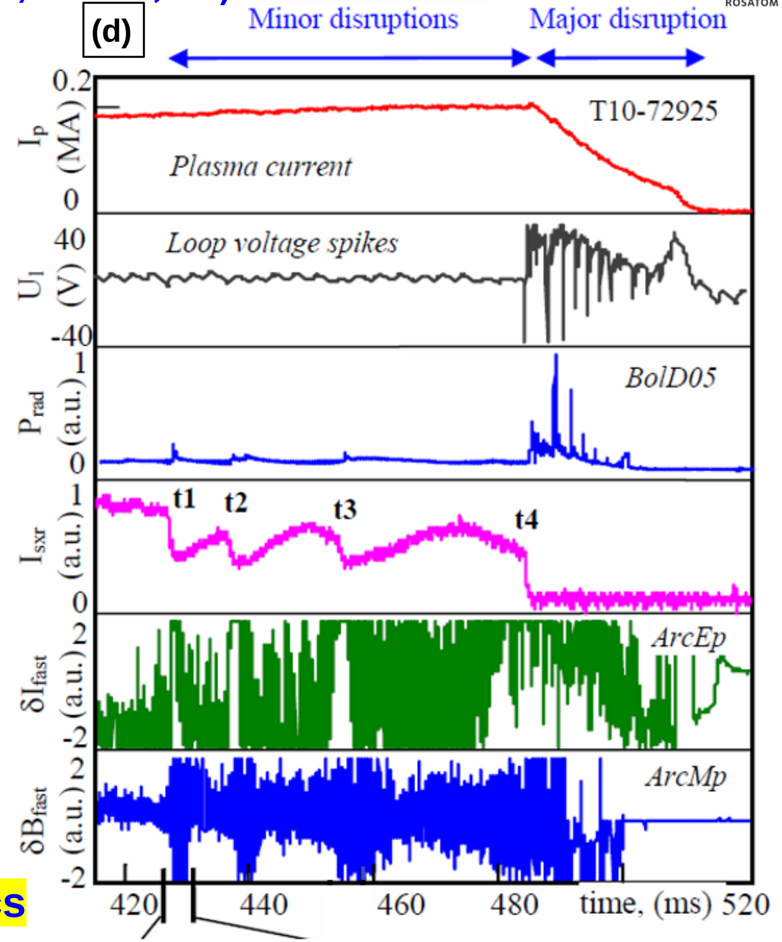
Arc discharges are observed during disruptions (DITE, JFT-2, …)

In vessel probe for arcs studies in T-10:

- set of electrodes (1) for arc initiation
- electric (*ArcEp*) probe
- magnetic (*ArcMp*) probe







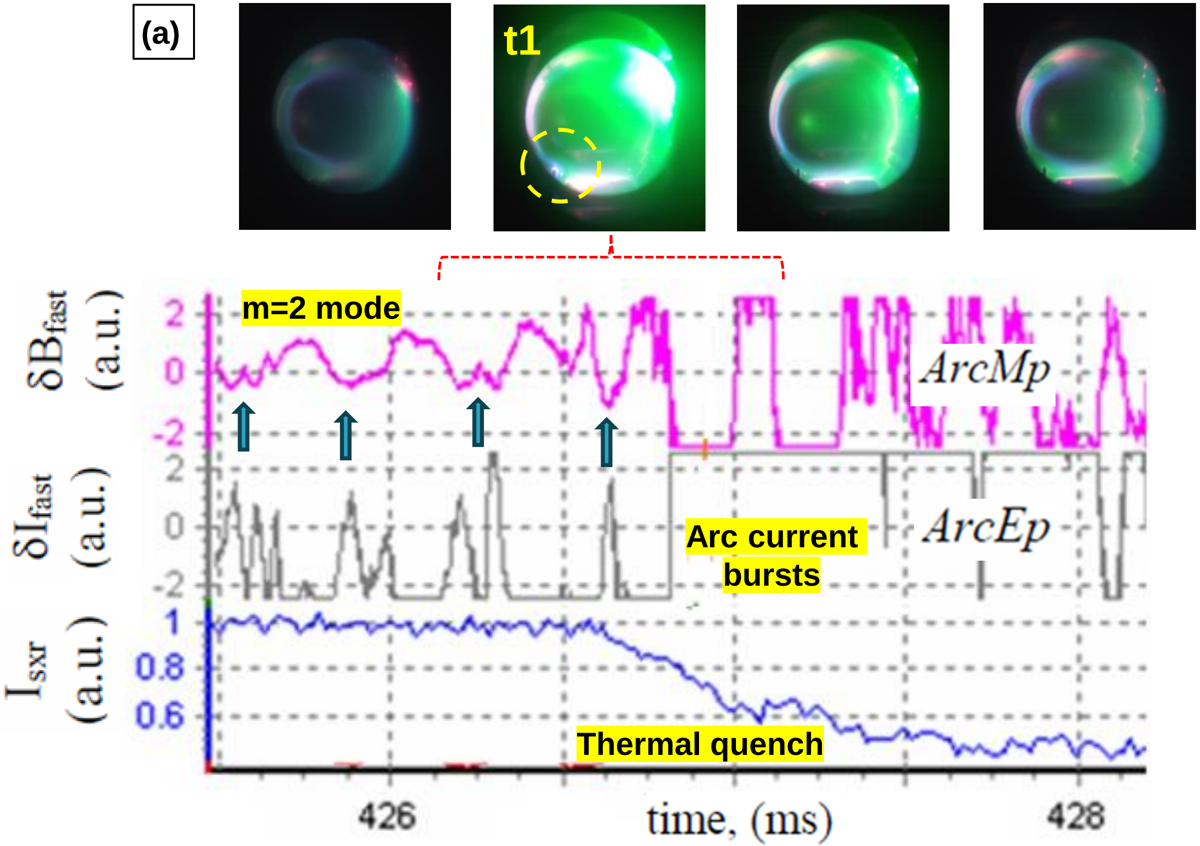
Fast stage of disruption could be associated with Arcs

See next page for extended view

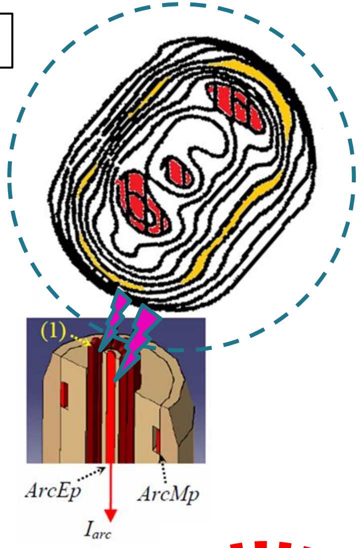
Savrukhin Physics of Plasmas 26, 092505 (2019)

Arc bursts observed during rotation of the 2/1 mode and thermal quench in T-10

(a)



(b)

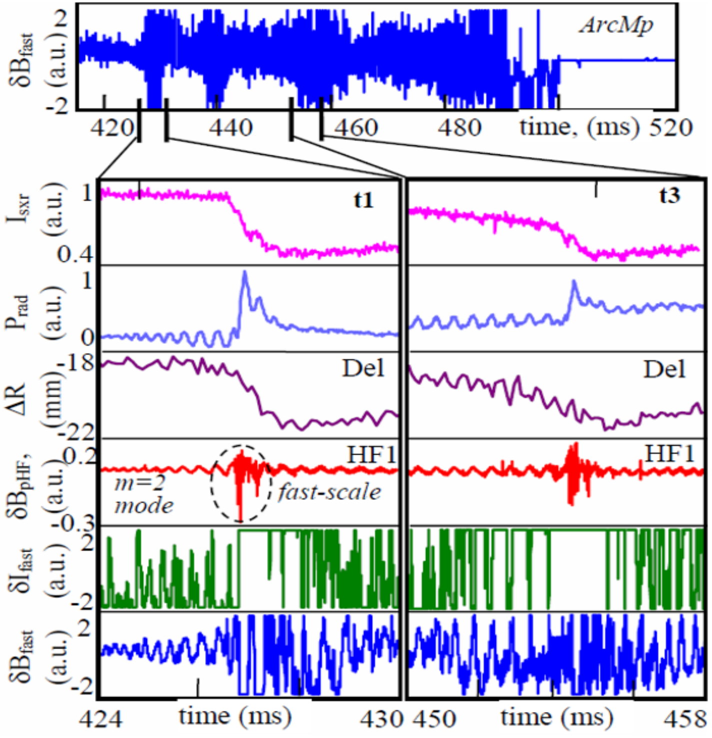


Sparks at the probe tip

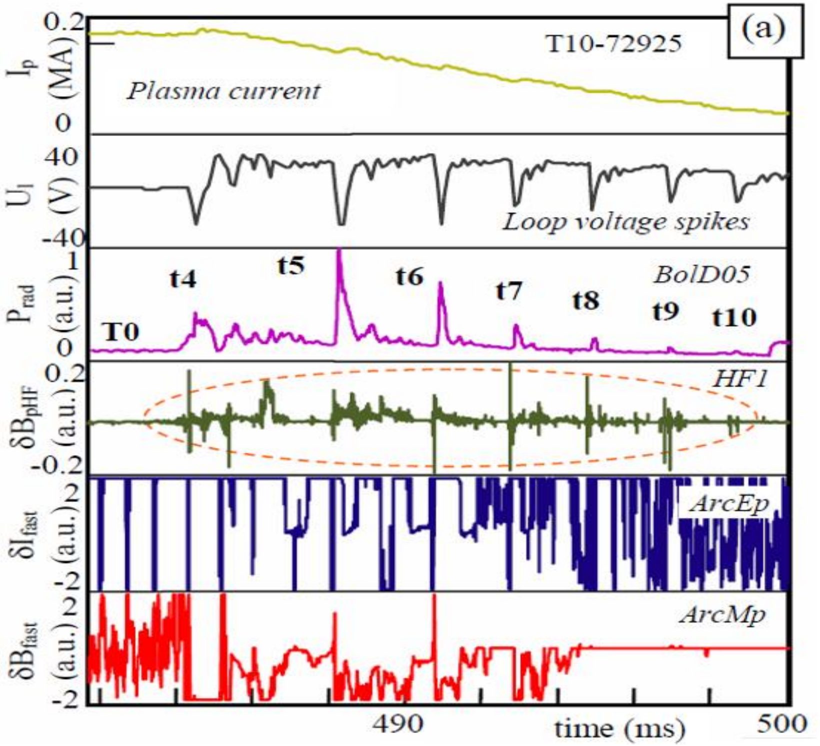
Arc Currents ~ 100A/mm²

~ Correlates with rotation of the m=2 mode

Arc's intensity increases in series of thermal quenches



Current decay stage of disruption is associated with continues arc bursts



Arc Currents could be an additional trigger for the disruption mitigation systems

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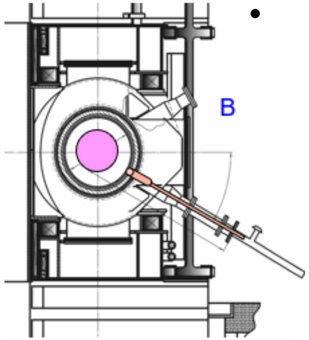
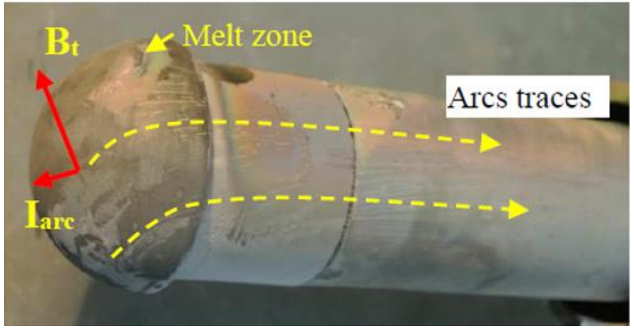
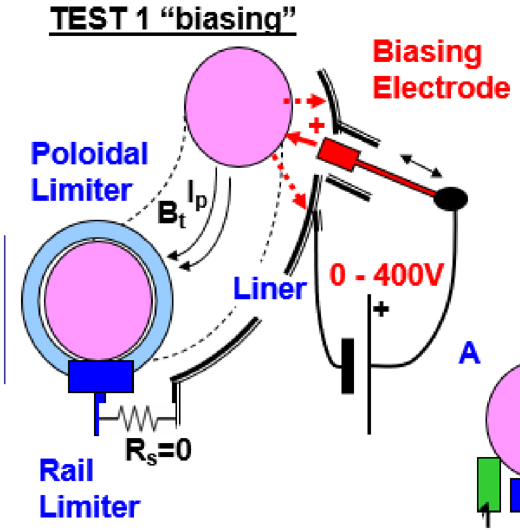
3. T-10 biasing experiments - forced arcs initiation

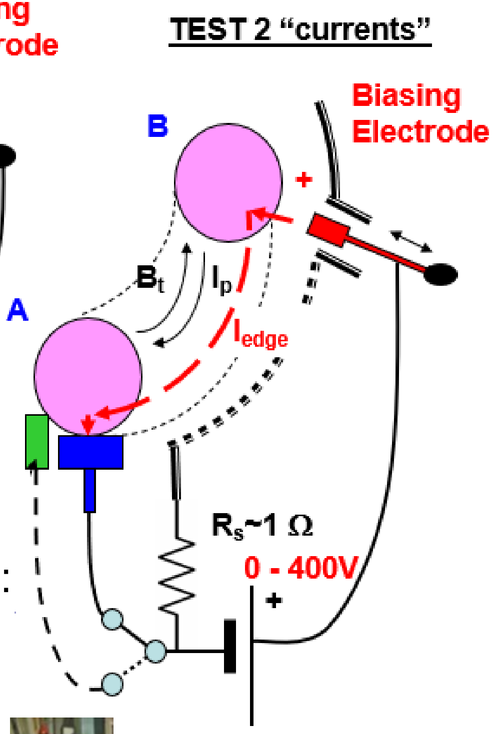


- W electrode (d=50mm)



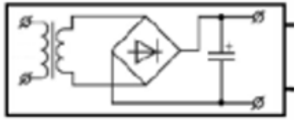
- Arc traces are observed starting at the electrode hemispherical head and moving in the "retrograde" direction.
- The arc traces are stretched along the top surface of the rod up to 100 - 150 mm.





Capacitors & thyristor switches:

$U_b = 0 \div 400V$
$C_b = 0.4$ F
$W_b = 40.5$ kJ



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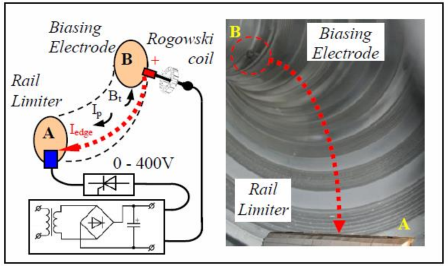
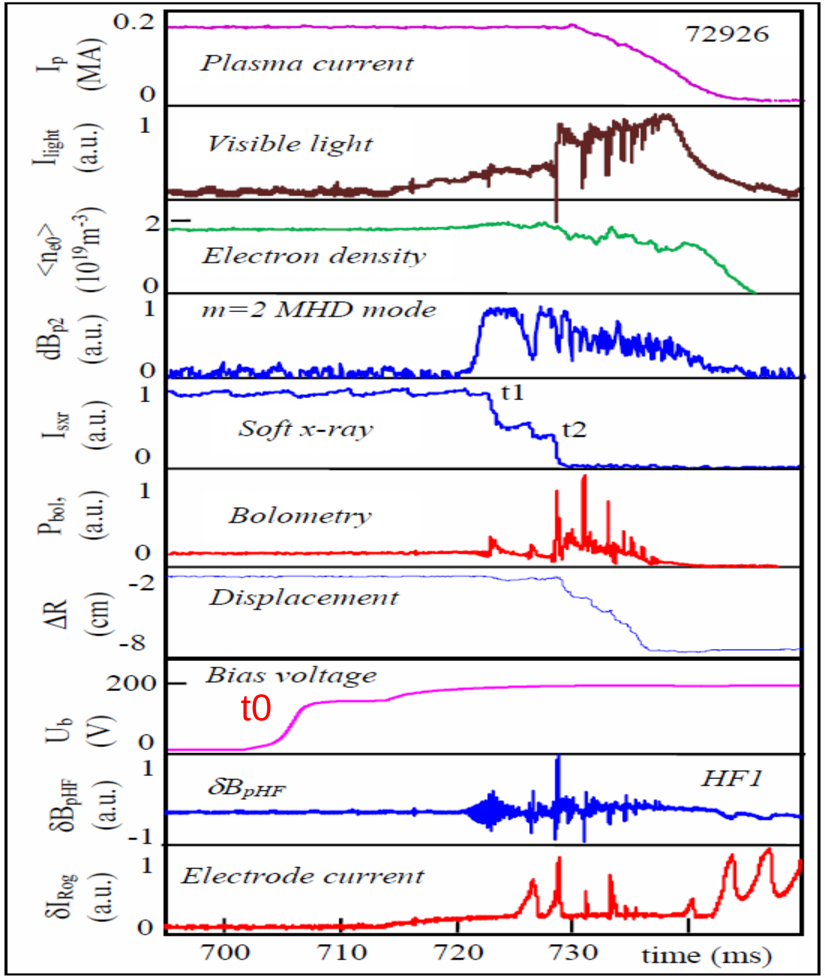
Disruption induced by biasing between the W electrode and rail limiter

- t0 = 703 ms
- Biasing switch-on
- t > t0
- Density growth
- Light around the biasing rod
- Increase of the “arc” current to the rob
- t1 = 722 ms Start Thermal quench
- MHD burst // Bolometer bursts
- Soft X-ray decay
- t3 = 728 ms Start “Major” disruption
- t > t3   Current decay



U_b = 200 V



Time to disruption Δt ~ 15ms

Voltage & currents thresholds

Reduced effect with liquid Li conditioning

No strong effect with Graphite rod

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Experimental test of runaway electron suppression by means of dense gas jet injection in the 'fast' stage of current quench

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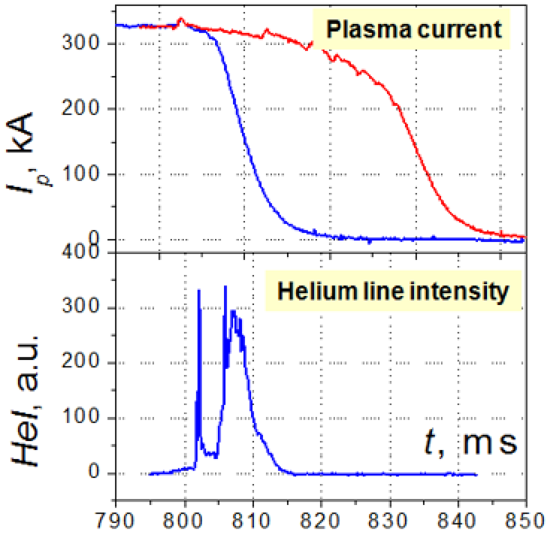
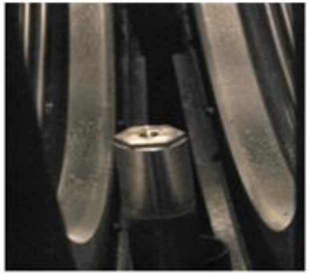
EM valve	V1	V2
Distance to plasma, cm	80	8
P, Atm	20	5(70)
Gas	He	He
Flux, p/sec	10^{23}	$5x10^{23}$
Pulse, ms	2-3	2-3
Time delay*	~1.6ms	~6ms

(*) Time delay between the valve power supply control pulse and the start of gas jet injection



- ***The gas valve head inside tokamak vacuum vessel***



- **Triggered by negative voltage spike**

- The helium gas jet injection with $(1,5 \div 2)\times10^{22}$ particle/sec converts the 'slow' current quench phase into the 'fast' one;
- Secondary Hard X-ray burst are suppressed by the helium gas jet injection with $\geq10^{23}$ particle/sec
- MHD activity initiation - not clear

M.M. Dremin, Problems of Atomic Science and Technology, Ser. Thermonuclear Fusion 4 (2012) 54

“Spare” concept: Chemical blasting

Ultra fast plasma discharge shutdown

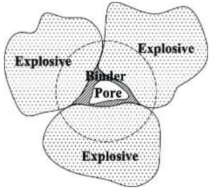
- Detonation of a small chemical charge
- Local gas pressure increases faster than the gas can expand
- Shock wave propagation inside the plasma
- MHD burst
- Thermal quench
- Discharge termination

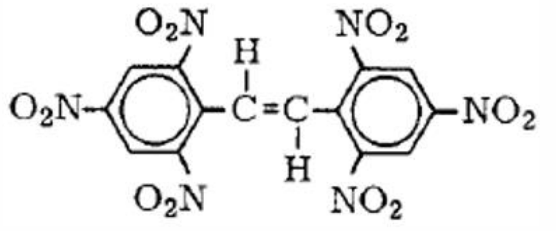
Technology & Safety ???

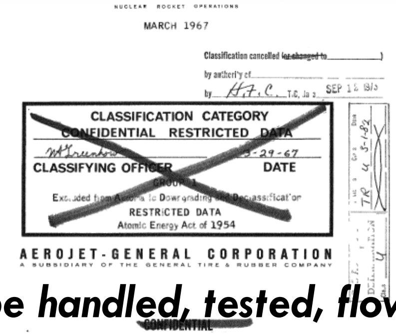
S.Putvinski 2011 ~~TNT~~

PBX - Polymeric Binder Explosives

The explosive used in eight charges placed on the moon during Apollo 17 was discovered and developed at he Naval Ordnance Laboratory at White Oak, Maryland.
The substance used was hexanitrostilbene (HNS).





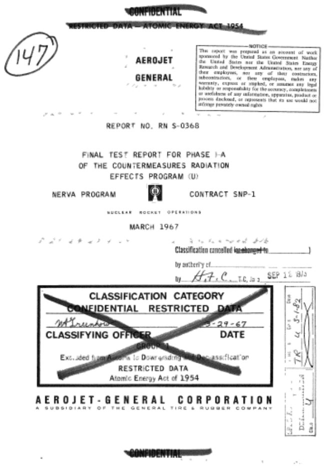


yellow crystals
empirical formula: $C_{14}H_6N_6O_{12}$
molecular weight: 450.1
energy of formation: +57.3 kcal/kg = +239.8 kJ/kg
enthalpy of formation: +41.5 kcal/kg = +173.8 kJ/kg
oxygen balance: –67.6 %
nitrogen content: 18.67 %
volume of explosion gases: 766 l/kg
heat of explosion
(H_2O liq.): 977 kcal/kg = 4088 kJ/kg
(H_2O gas): 958 kcal/kg = 4008 kJ/kg
density: 1.74 g/cm^3
melting point: 318 °C = 604 °F (decomposition)
lead block test: 301 cm^3/10 g
impact sensitivity: 0.5 kp m = 5 N m
friction sensitivity:
over 24 kp = 240 N pistil load crackling

It was concluded that HNS could be handled, tested, flown on a spacecraft, and deployed by astronauts with relative safety

	HNS properties
vacuum stability	**The material does not decompose in a vacuum, prolonged exposure resulting in a weight loss of less than 0.06 percent, and this due primarily to evaporation of residual solvents**
thermal stability	**It does not begin to melt until exposed to temperatures well above 500ºF for prolonged periods, making it extremely safe to handle in any normal temperature environment.**
friction sensitivity	**It is in no way sensitive to friction,**
impact (shock) sensitivity	**As a raw material it is very insensitive to impact shock. It has been dropped from great heights onto solid concrete without detonating; its impact sensitivity as measured in Military Standard Laboratory tests is well above the minimum military standard of 60 centimeters.**
shelf life	**With respect to shelf life, military tests predict a decomposition of only 1 percent over a 500-year period at 212ºF**
radiation sensitivity	**Radiation sensitivity tests indicate that material is in no way sensitive to radiation.**

Increased radiation resistance to fast neutron flows E°>°1°MeV, F°~°7.5°e12°neutron/cm2/sec


CONFIDENTIAL
RESTRICTED DATA — ATOMIC ENERGY ACT 1954
AEROJET GENERAL
REPORT NO. RN S-0368
FINAL TEST REPORT FOR PHASE I-A OF THE COUNTERMEASURES RADIATION EFFECTS PROGRAM (U)
NERVA PROGRAM CONTRACT SNP-1
NUCLEAR ROCKET OPERATIONS
MARCH 1967
CLASSIFICATION CATEGORY
CONFIDENTIAL RESTRICTED DATA
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RESTRICTED DATA
Atomic Energy Act of 1954
AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY
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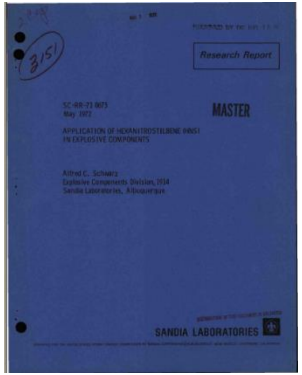
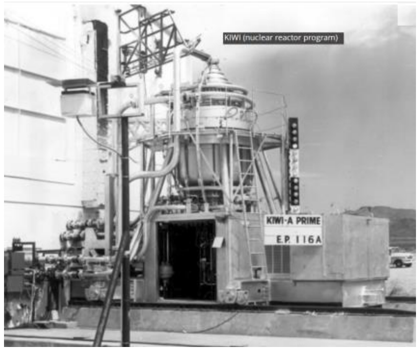

Research Report
MASTER
May 1972
APPLICATION OF HEXANITROSTILBENE (HNS) IN EXPLOSIVE COMPONENTS
Alfred C. Schwarz
Sandia Laboratories, Albuquerque
SANDIA LABORATORIES



4. Thermal Decomposition/Nuclear Radiation Damage

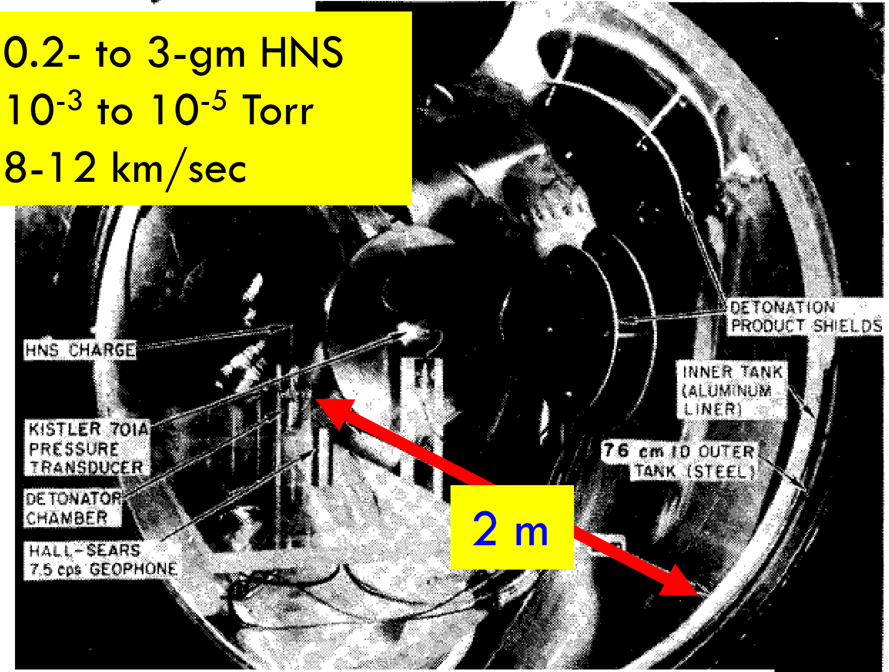
HNS was subjected[40] to neutron and gamma radiation from a power reactor at flux levels of about $3.85 \times 10^8 r$ per hour and 7.5×10^{12} neutrons/cm^2/sec. fast neutron flux, unchanged compound remaining after irradiation was determined by thin layer chromatography. Similar samples heated at 280°C were analysed for residual compound (Table 3). Ratios of unchanged samples to solid products proved nearly the same for irradiated and heated samples at each of three levels of degradation for corresponding equivalent weight losses.

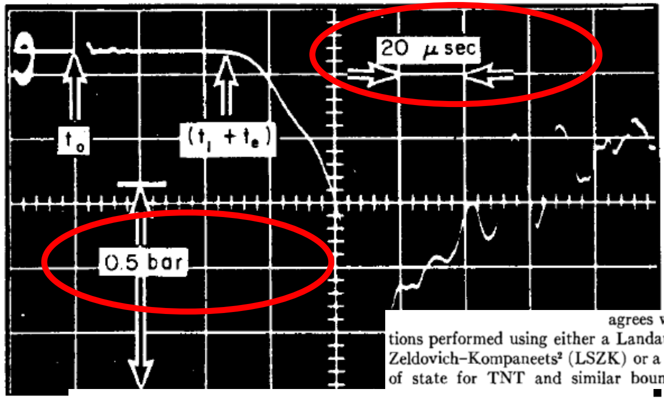
Explosive Gas Blast: The Expansion of Detonation Products in Vacuum

JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 2 FEBRUARY 1971

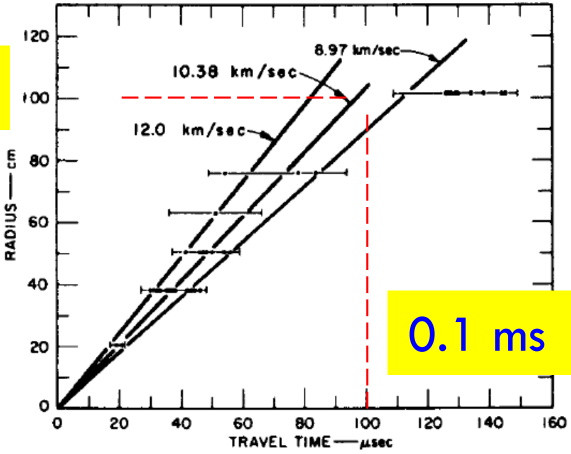
THOMAS J. AHRENS CHARLES F. ALLEN ROBERT L. KOVACH

0.2- to 3-gm HNS
10^{-3} to 10^{-5} Torr
8-12 km/sec





agrees well with calculations performed using either a Landau–Stanyukovich–Zeldovich–Kompaneets[2] (LSZK) or a Wilkins equation of state for TNT and similar boundary conditions.



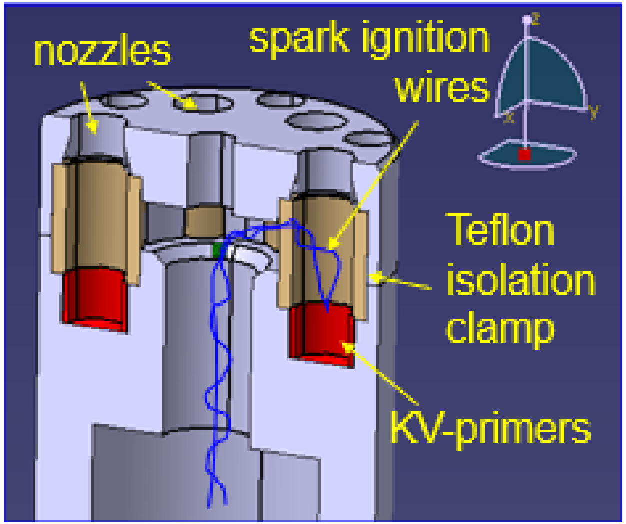
$$p = 6.5 \times 10^5 \text{ (bar) } r'^{-3.5}$$

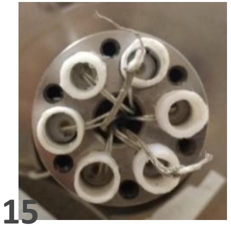
p – reflected shock pressure //

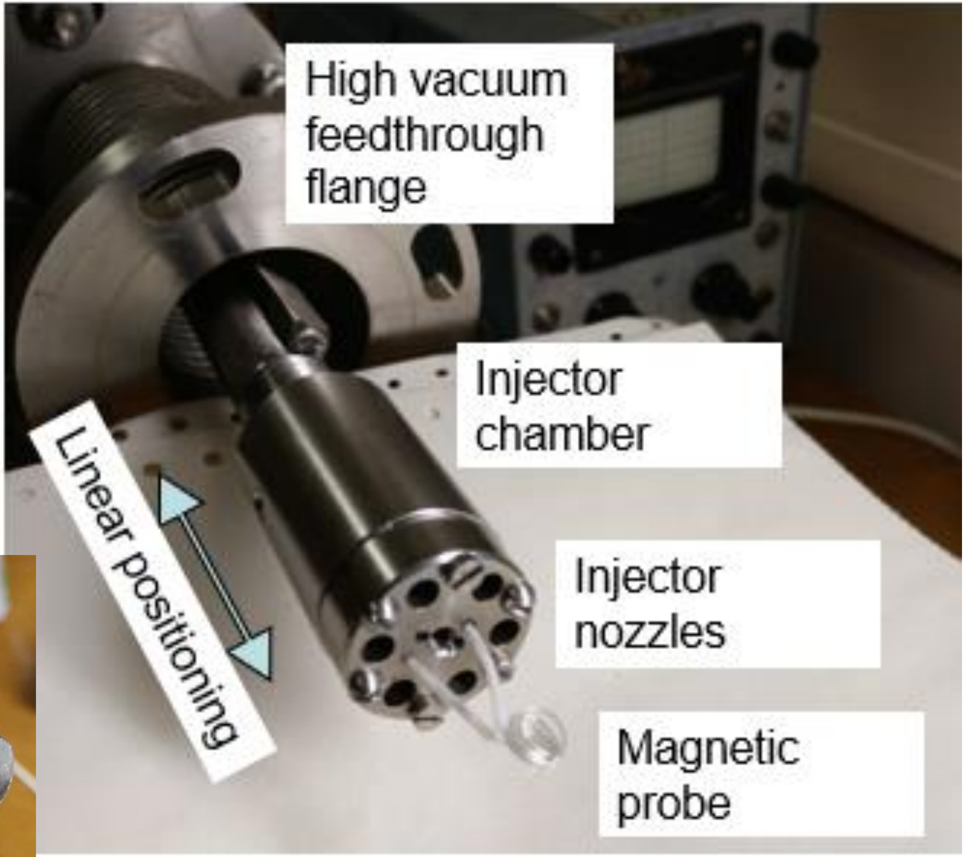
r' – ratio of distance from the charge center/radius of the charge

KV primers injection system in T-10

KV-209
20 - 80 mg







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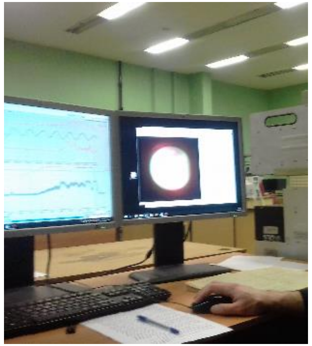
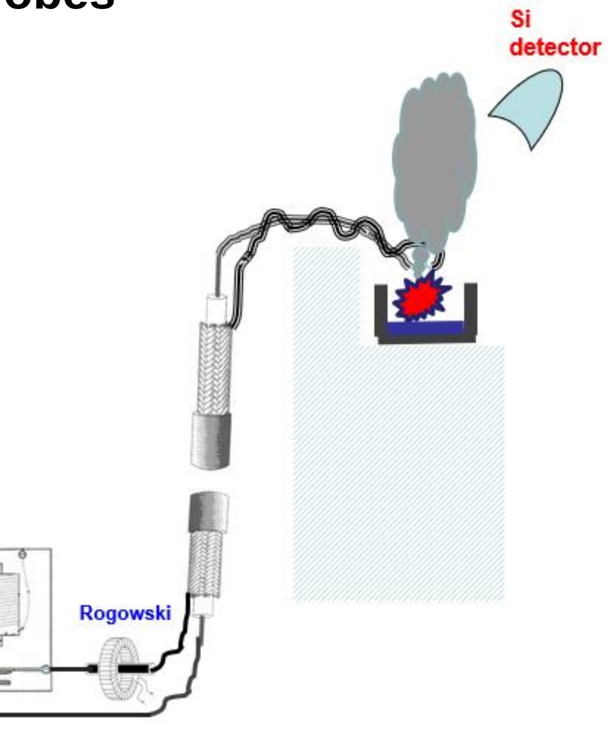
Diagnostics:

Rogowski, Si diode, MotionPro Camera, Magnetic probes





Two bridge-wire Electric initiation schemes tested

- 180 VAC transformer
- 30 kV capacitor bank

Spark ignition wires:

low-alloyed copper bronze

+ Ag covering + Teflon isolation

30 kV

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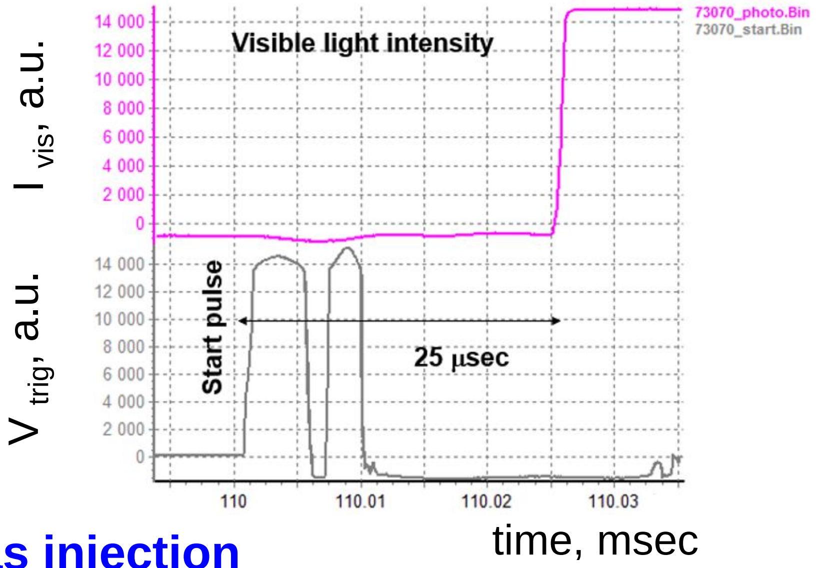
KV injection system - Laboratory test



laboratory

vacuum

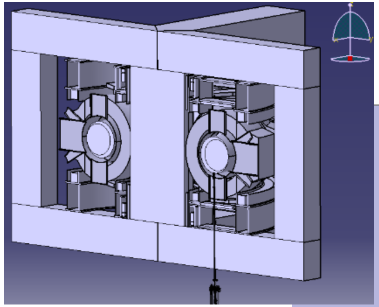
- **Fast gas injection**
- **Gas flow in the forward direction / vacuum**

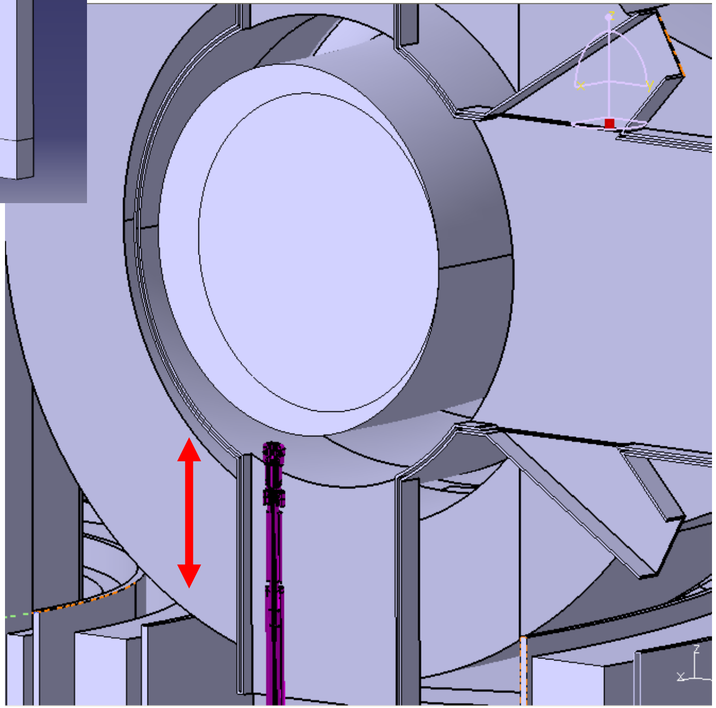
KV-209 (20 mg) for T-10 $5m^3$ VV

Carbon monoxide CO 17mg $4.5e19\ m^{-3}$

(+1% atoms impurities) $1.6\ Pa/m^3$

KV injection system in T-10





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Density limit disruption in the T-10 tokamak

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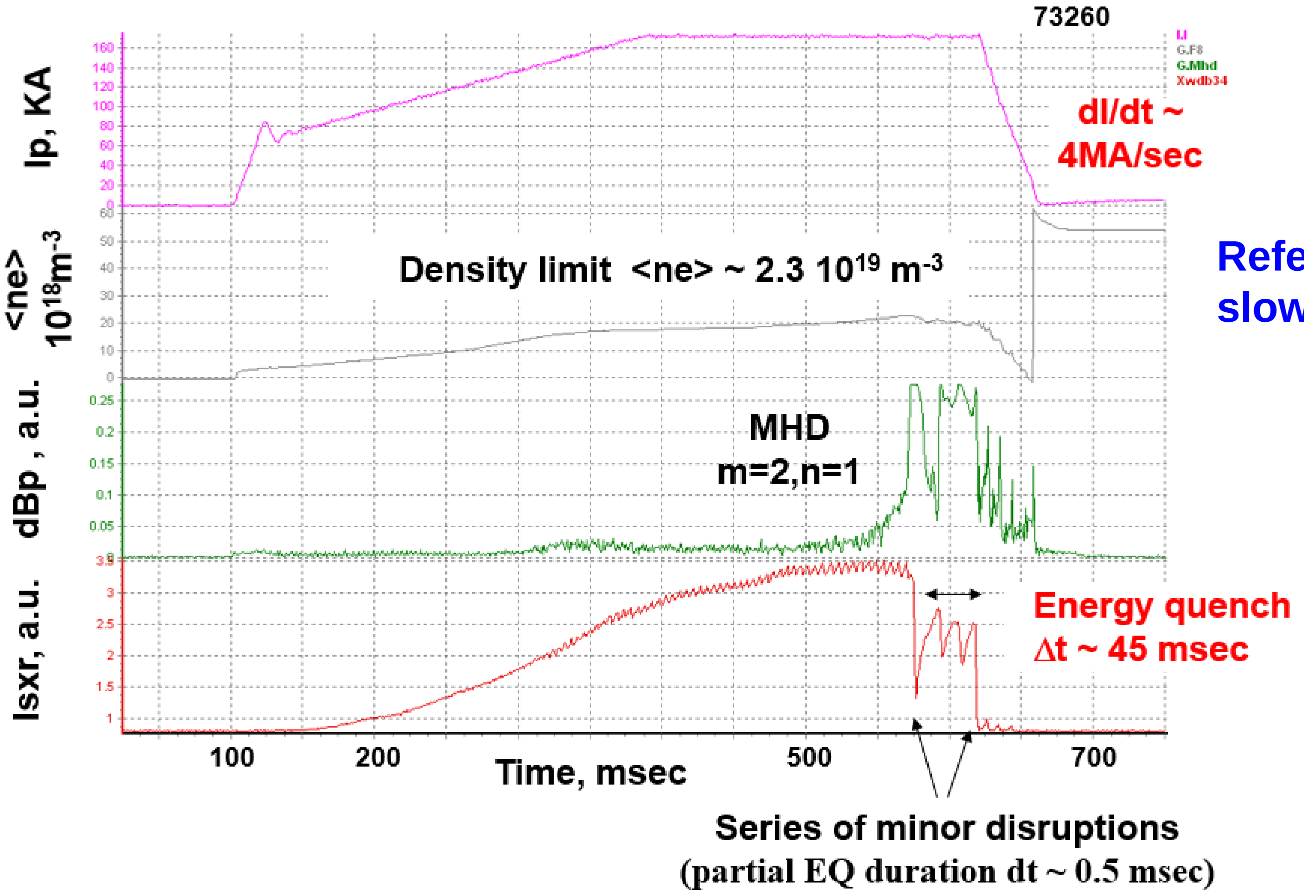

Reference discharge – slow disruption

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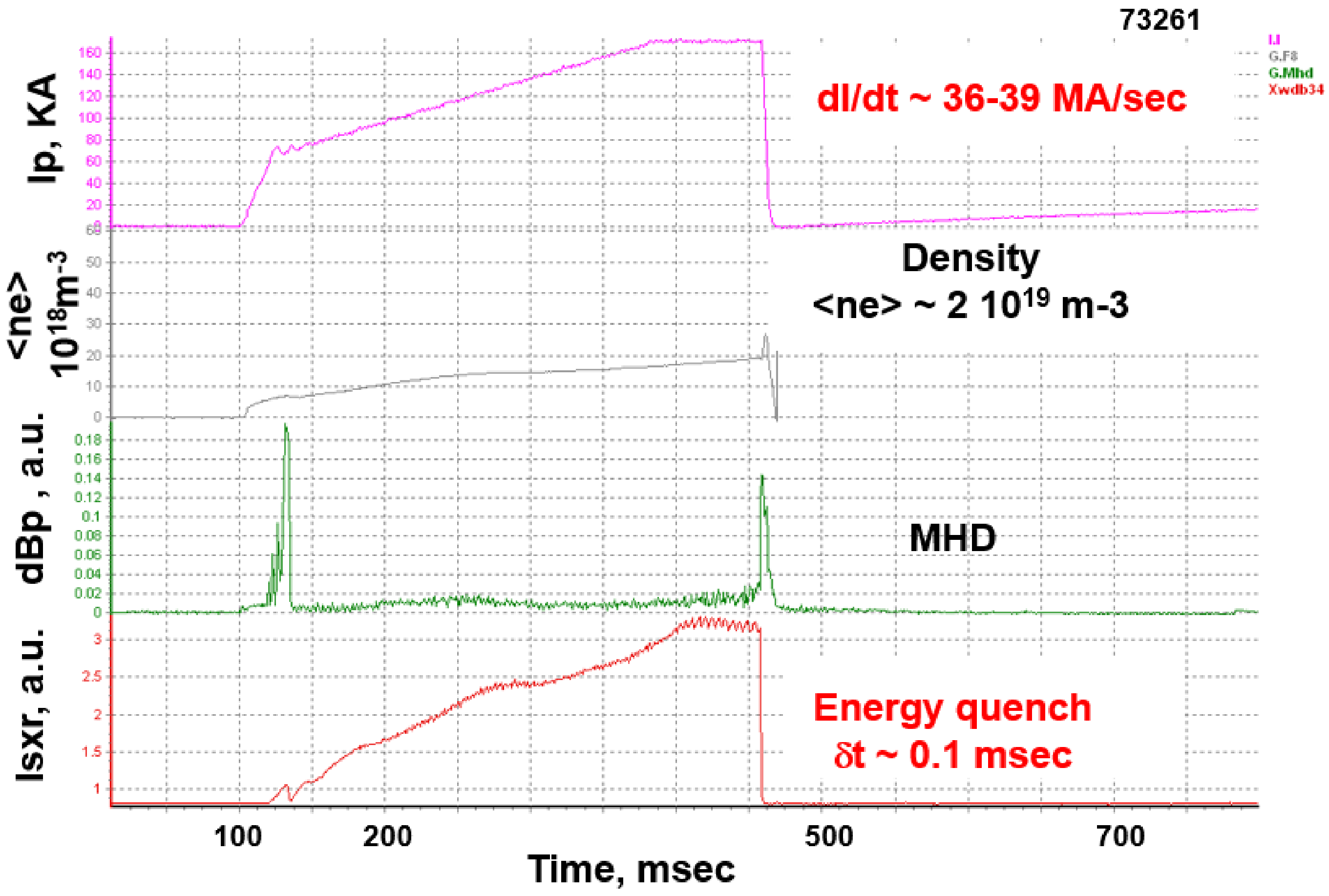
Discharge shut-down by Primers Injection in T-10



Fast thermal quench and current decay

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Radiation Light Images during Discharge shut-down in T-10

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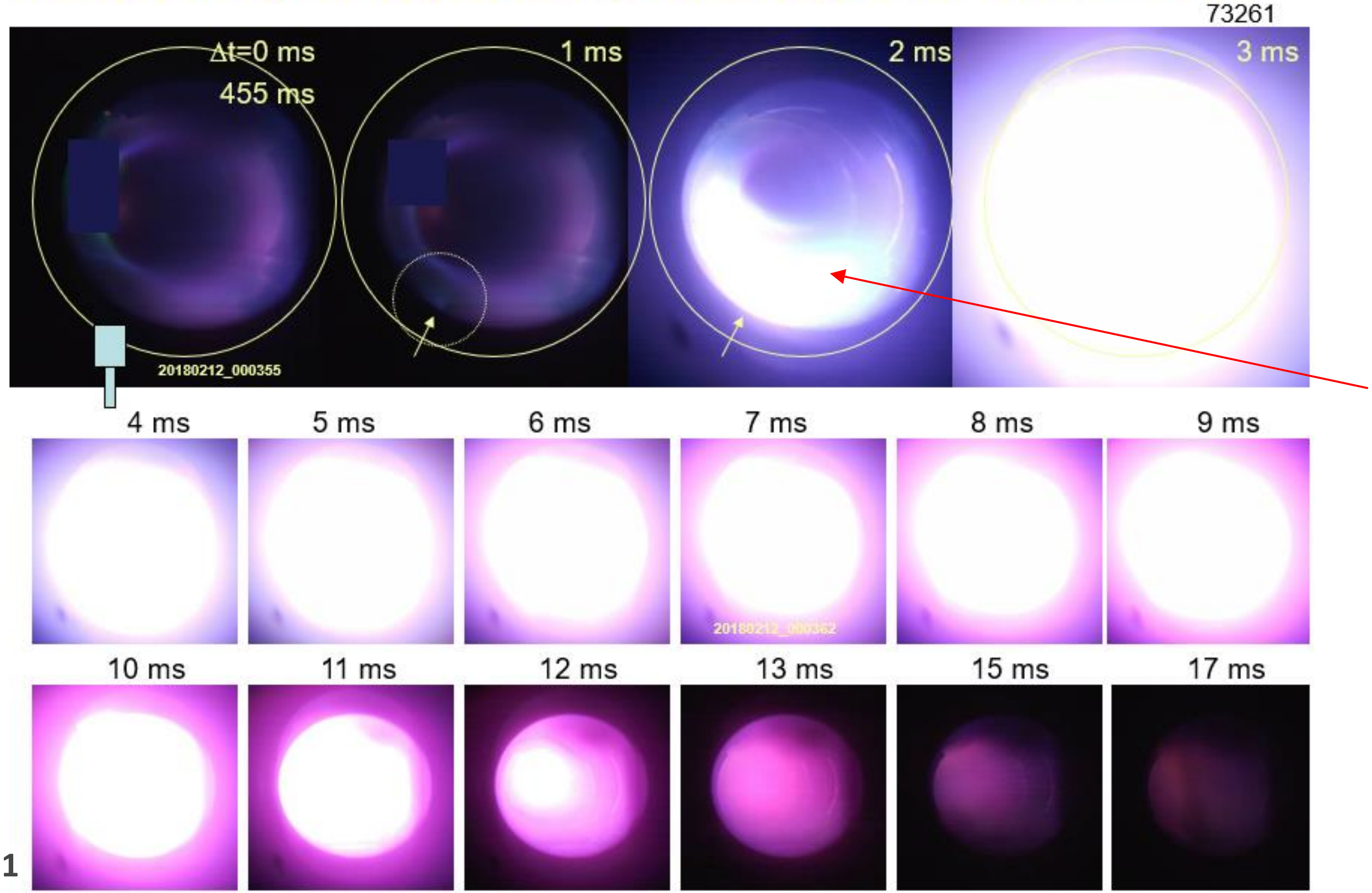

Gas flow in poloidal direction

Shutdown in 15 ms

Discharge shut-down by Primers Injection in T-10

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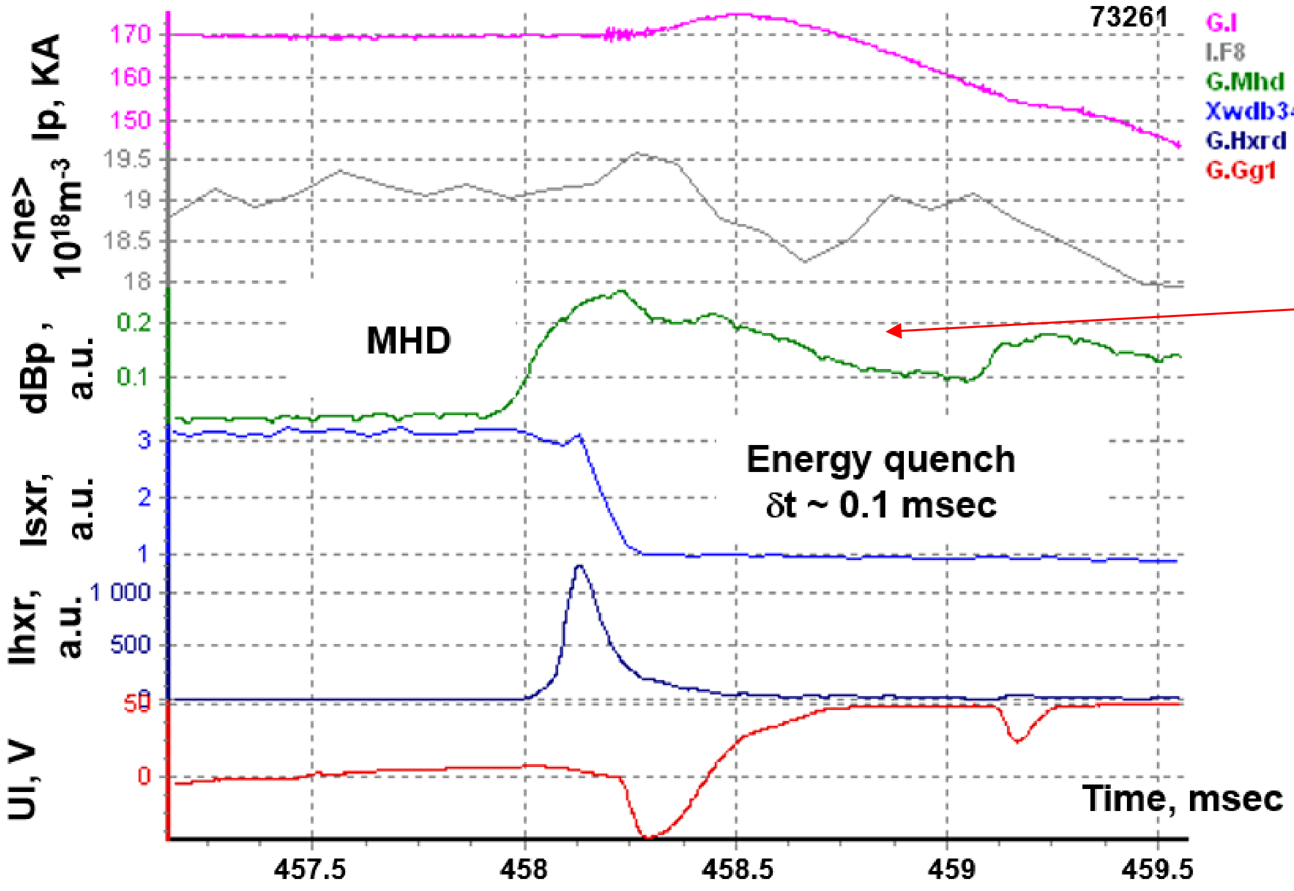

Start of injection at T0 ≈ 455ms

Disruption starts from growth of the m=2 MHD mode

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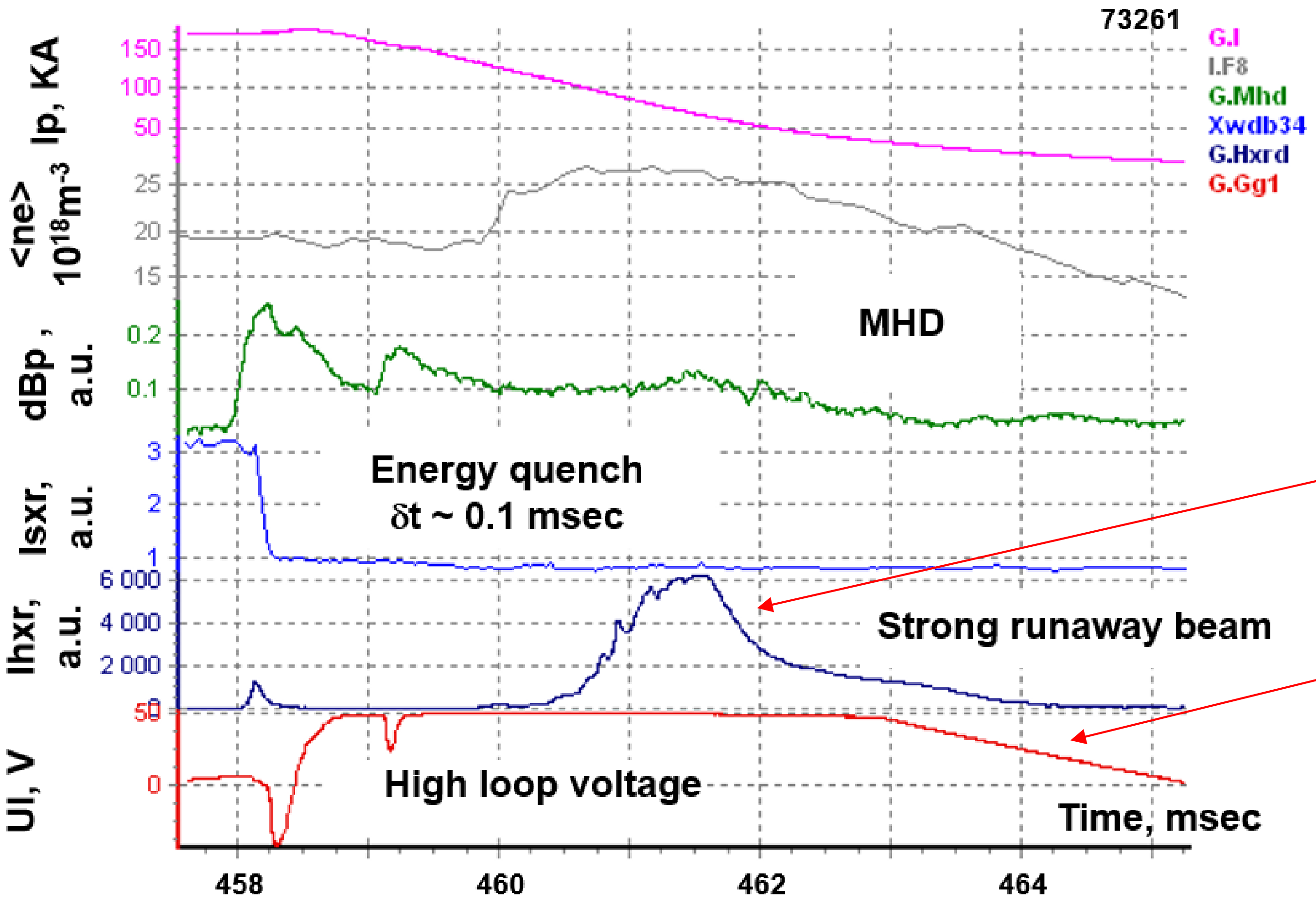
Discharge shut-down by Primers Injection in T-10



Formation of secondary runaway beam due to High induced loop voltage

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Conclusions:

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- Analysis of the T-10 experiments with W (and Li) in-vessel limiters can confirm appearance of the arc discharges during disruption instability.
- Monitoring of the arc discharges at the plasma periphery could provide important trigger for the disruption mitigation systems in tokamaks.

Several “Spare” concepts of the Disruption Mitigation System are analyzed T-10, including:

- Biasing for forced arcs initiation
- Explosive Gas Injection with Chemical Blasting - fast gas and microparticles injection

Preliminary experiments demonstrated possibility of the fast plasma shutdown based on Explosive Gas Injection with Chemical Blasting:

- Fast trigger and disruption initiation
- Fast thermal quench
- Fast plasma current decay
- Generation of the runaway electrons

Thank you for your attention!