Novel Rapid Shutdown Strategies or Runaway Electron Suppression in DIII-D

N. Commaux[1]
in collaboration with
L.R. Baylor[1], N.W. Eidietis[2], T.E. Evans[2], E.M. Hollmann[3],
D.A. Humphreys[2], V.A. Izzo[3], A.N. James[3], T.C. Jernigan[1],
P.B. Parks[2], J.C. Wesley[2], and J.H. Yu[3]

[1]*Oak Ridge National Laboratory*
[2]*General Atomics*
[3]*University of California-San Diego*

Presented at
Twenty-third IAEA Fusion Energy Conference
Daejeon, Republic of Korea

October 11-16, 2010

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

OAK RIDGE
National Laboratory

Overview

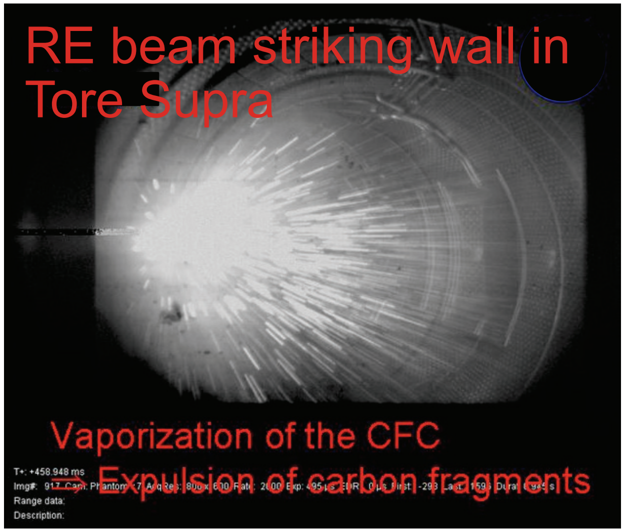
- **Introduction**
- **Massive particle injection**
  - Massive Gas Injection (MGI)
  - Shattered Pellet Injection (SPI)
  - Shell Pellet Injection (SHPI)
- **Active feedback control**
- **Magnetic deconfinement of runaway electrons**
- **Conclusion**

The Danger of Runaway Electrons on ITER

- **ITER is very likely to generate high runaway electrons (RE) currents due to its high plasma current (15 MA). Avalanche multiplication Gain on ITER is $10^{20\text{-}30}$ vs 100 on DIII-D**

$$I_{RE} \approx I_{seed} \exp\left(\frac{I_P}{I_A \ln \Lambda}\right) with\, I_A \approx 0.02 MA$$

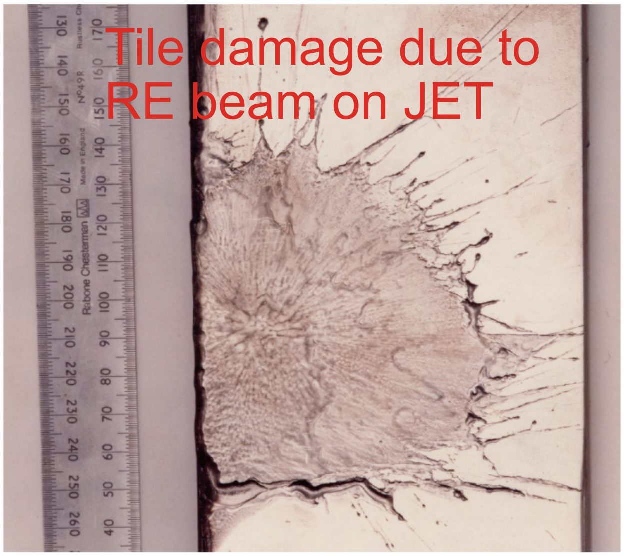
- **These high energy RE beam can damage the plasma facing components**


RE beam striking wall in Tore Supra

Vaporization of the CFC

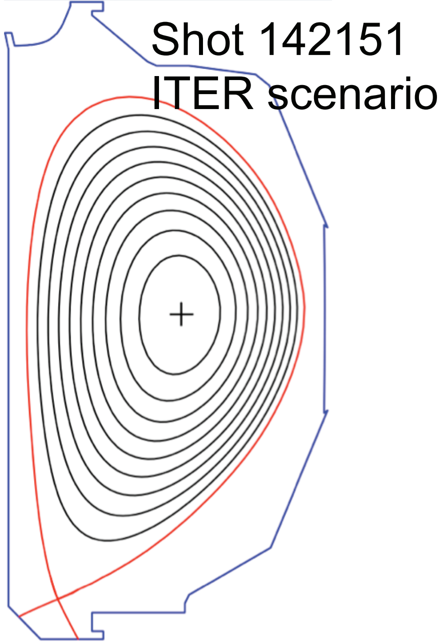
→ Expulsion of carbon fragments

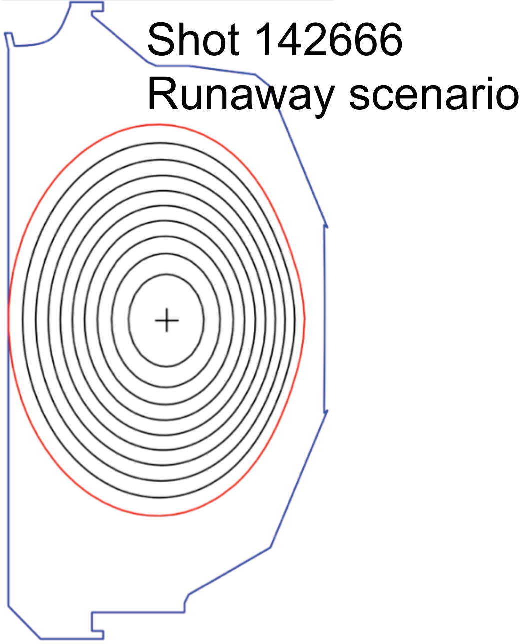
(from F. Saint-Laurent, EPS 2009)

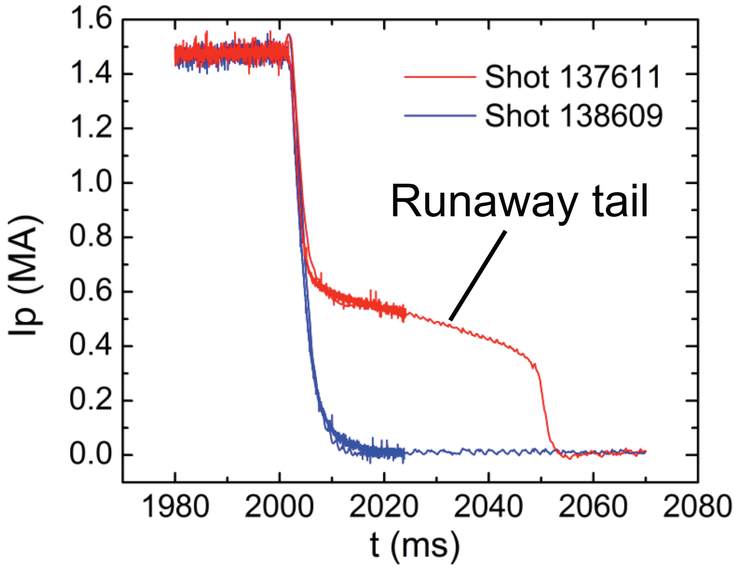

Tile damage due to RE beam on JET

(courtesy of G. Martin)

Plasma Scenarios Used During these Experiments

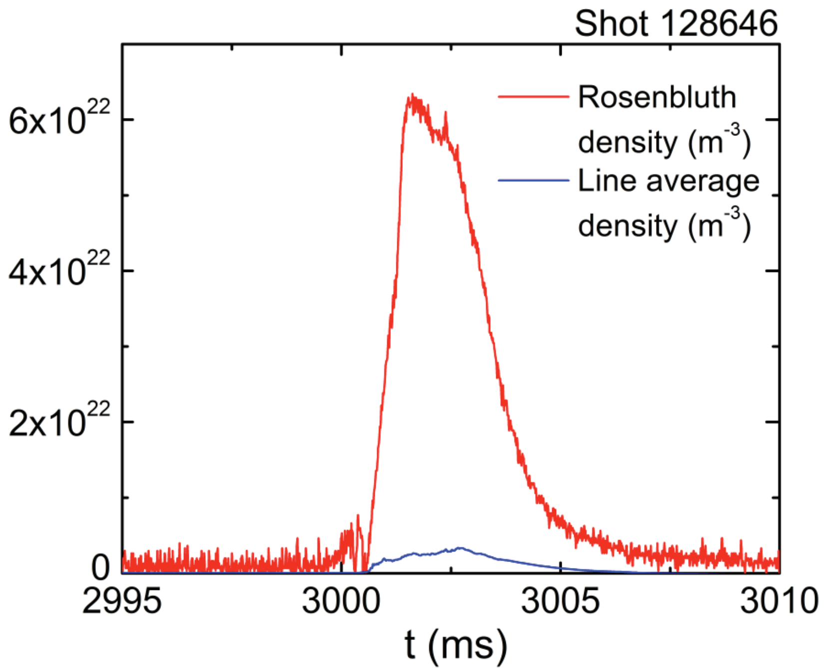


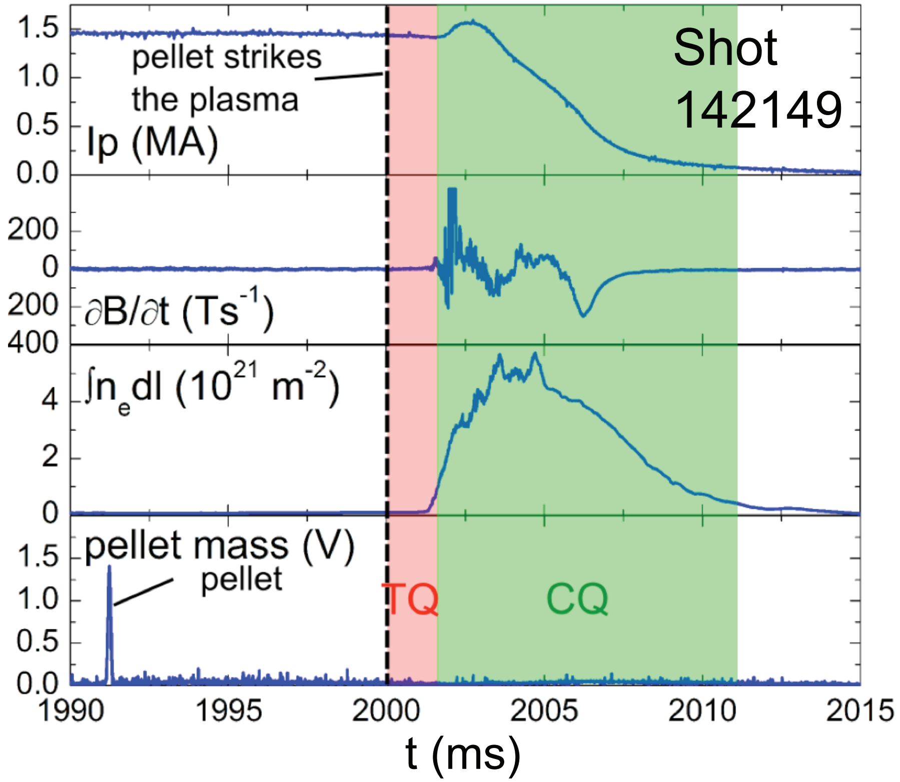




- **2 scenarios were used during the RE mitigation experiments**
- **The ITER relevant scenario: diverted elongated H mode NBI heated. Massive particle injection applied to terminate the discharge**
- **Discovery that low elongation limited can produce reliably significant runaway electrons (10x higher reliability than diverted elongated): used to test mitigation techniques on an existing RE beam**

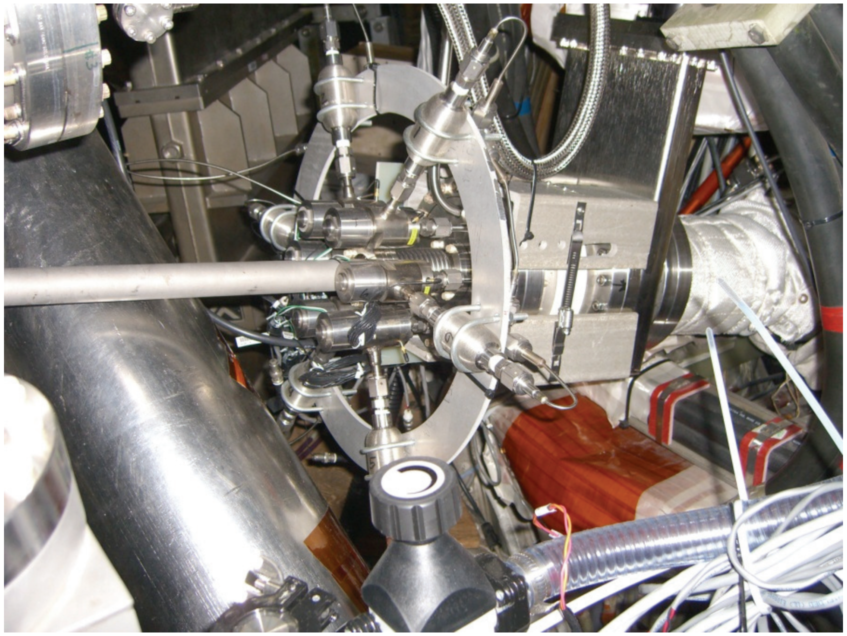
Reaching the Rosenbluth Density



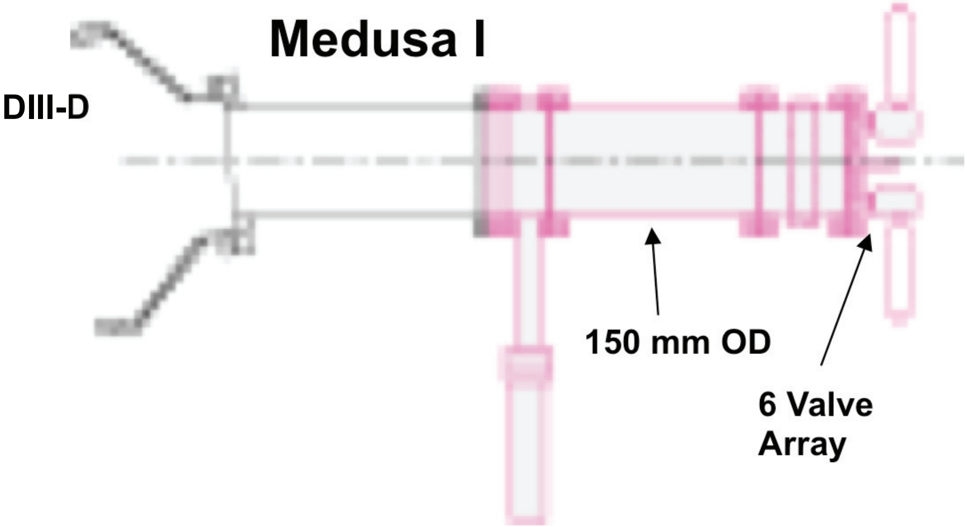


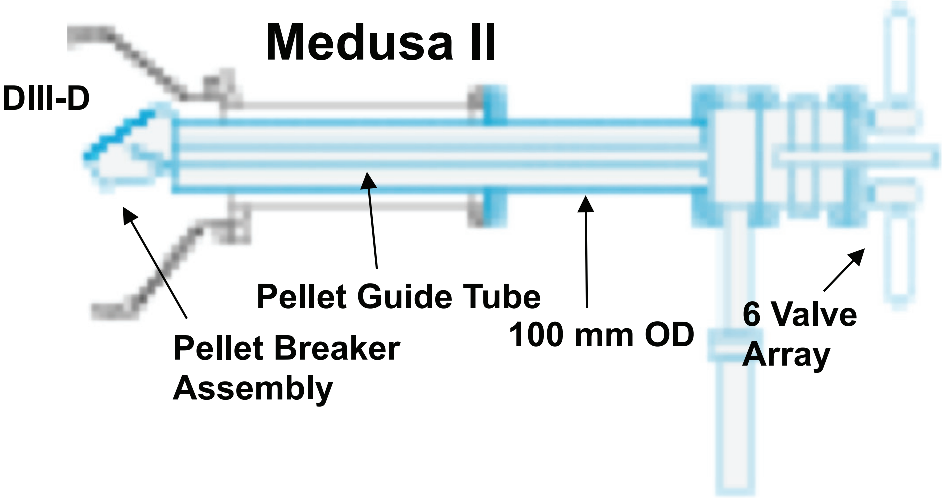
- **The massive particle injection goal is to increase the density where the runaways are generated and the Rosenbluth density**
- **This would prevent the avalanche multiplication process expected to be the main runway generation mechanism in ITER**

The MGI Valve on DIII-D: MEDUSA



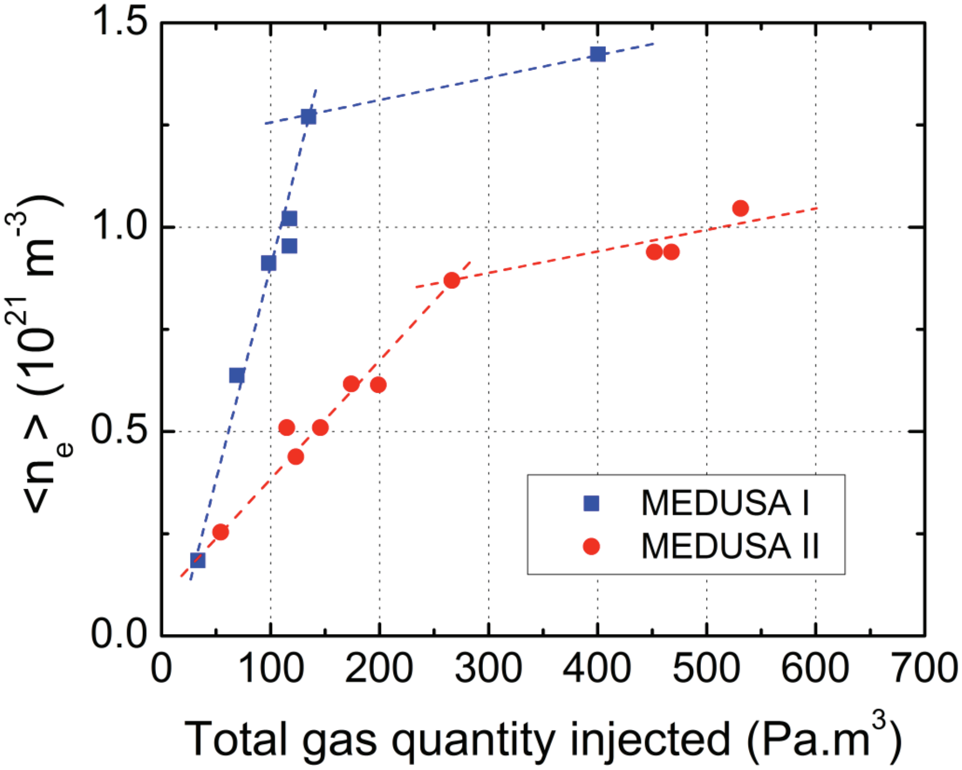
- The MEDUSA valve: array of 6 “small” fast valves (can be actuated faster than one “big valve)
- Can inject up to 400 Pa.m^3 in 1 ms (vs ~10 ms for one “big” valve
- Can dial separately quantity injected and pulse duration





A Direct Duct is Critical for the Efficiency of MGI

- **Significant change in the configuration of the MEDUSA duct slowing down the gas flow**
- **This modification dropped the assimilation efficiency of the MGI system by ~50%**
- **The flow rate has a major impact of the assimilation efficiency**



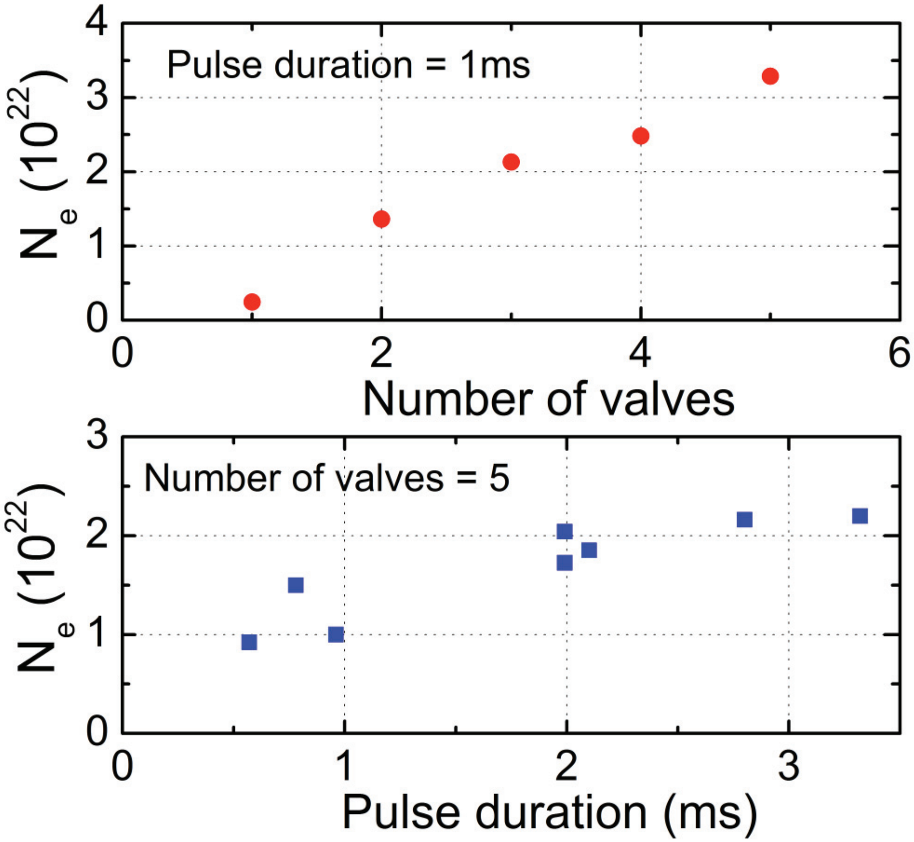
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

The Pulse Duration has an Important Effect on the Assimilation Efficiency of MGI

- **The MEDUSA array allowed to study the assimilation efficiency as a function of the injected quantity of helium gas using 2 methods**
  - Varying the gas pulse duration
  - Varying the number of valves actuated

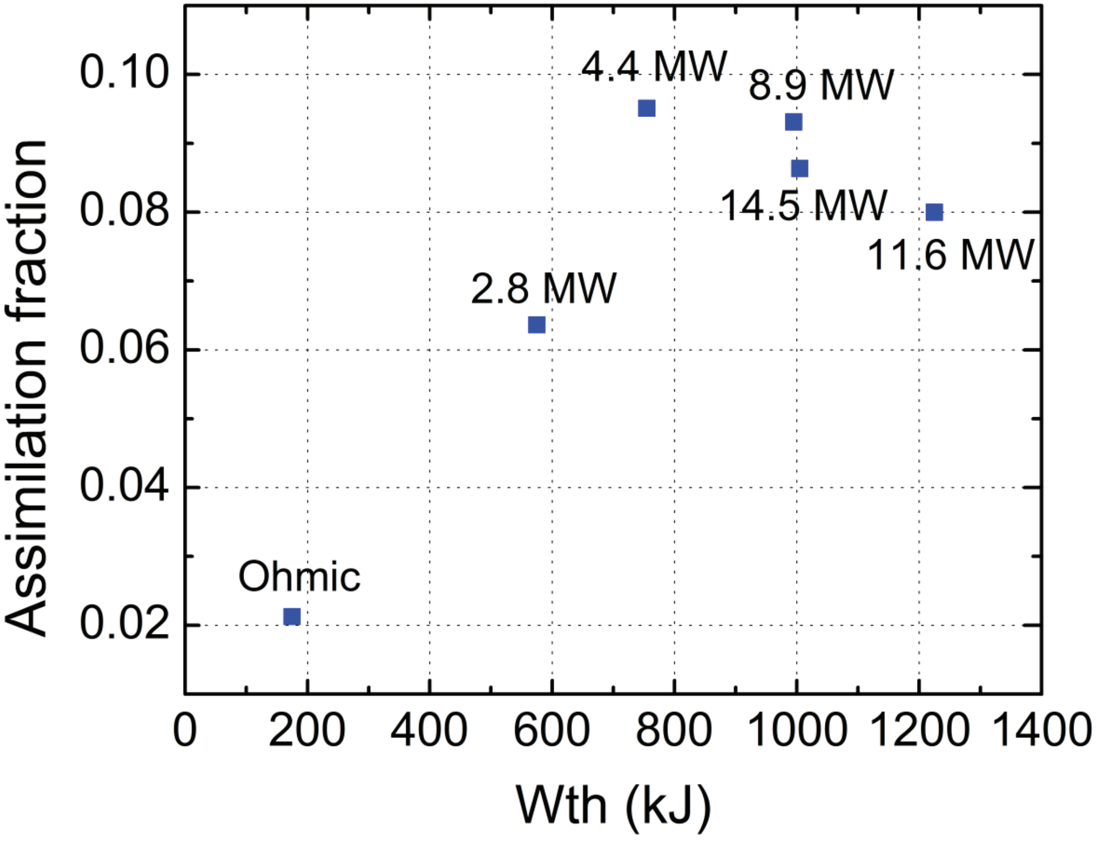
- **A limit observed only on the pulse duration (~1.5-2 ms)**

- **Correlated with the end of the TQ – only particles injected before TQ ends assimilated ?**



The Thermal Energy Content as a Rather Limited Effect on the Assimilation Efficiency for MGI

- **Scan the thermal energy content (180-1220 kJ) by varying the NBI injected power (0-14.5 MW)**
- **A positive dependence is observed but only at low energy content (<800 kJ). Above this value, the assimilation effiency saturates at ~9%**

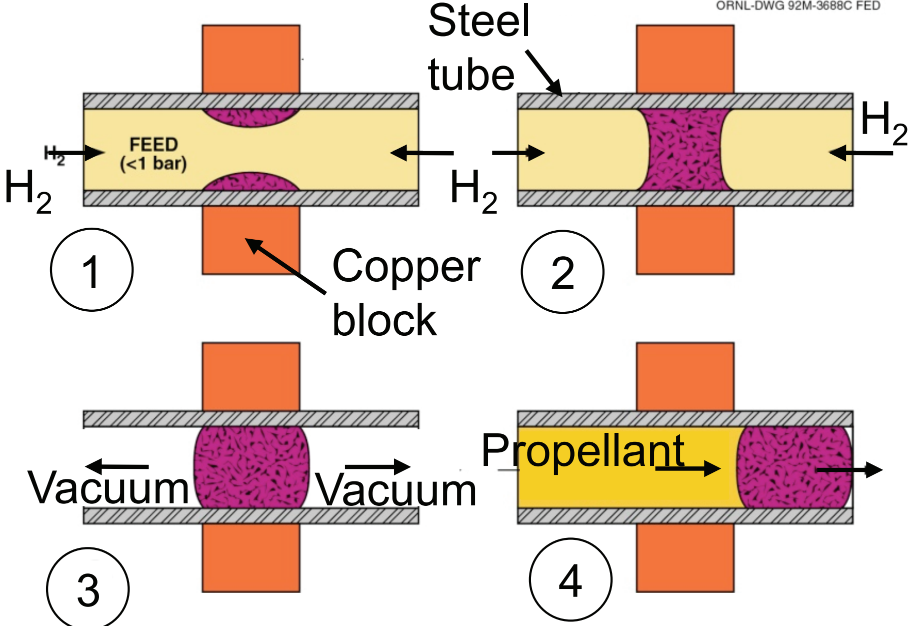


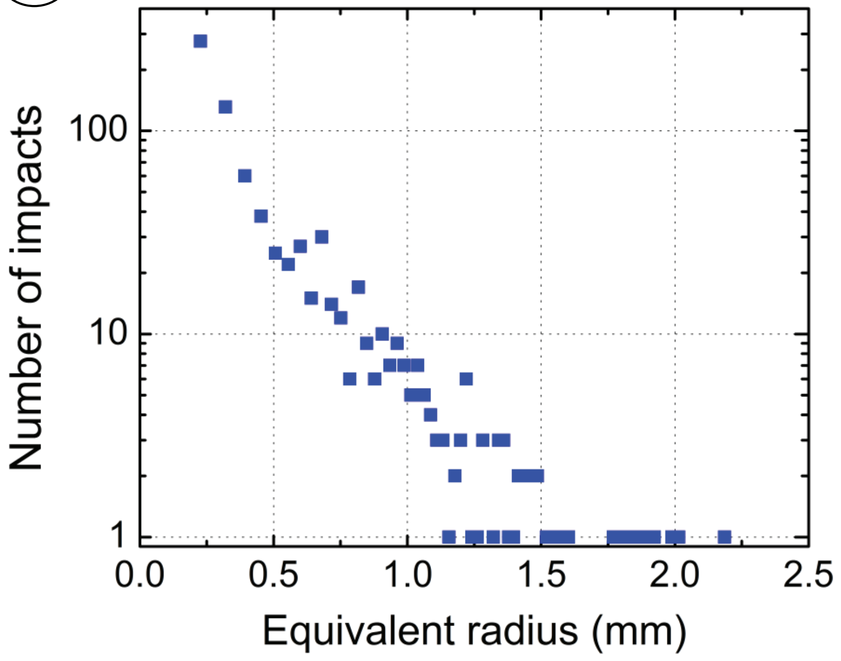
Principle of the SPI

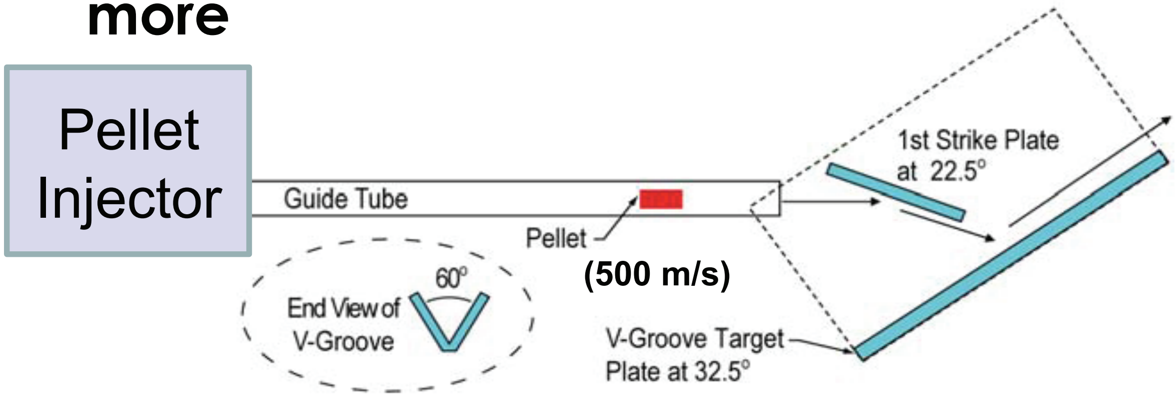
- **A cryogenic pneumatic pellet injector shooting big pellets (~15 mm x 20 mm cylinders)**

- **The pellets are shattered before entering the plasma by bouncing on 2 plates**

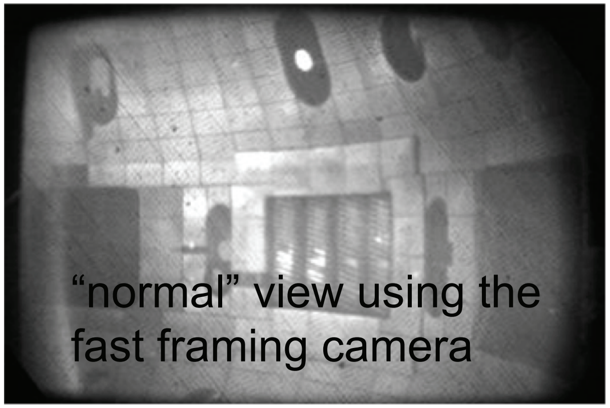
- **The small shards are no danger for the PFCs and increase the surface area for more**

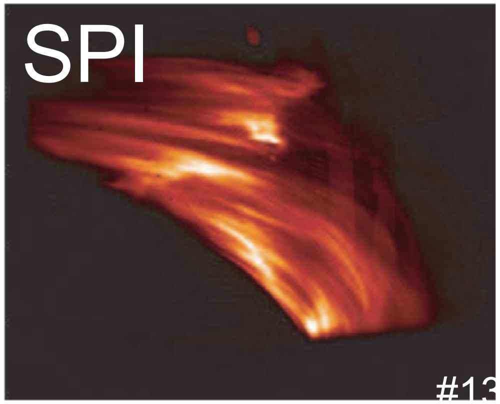




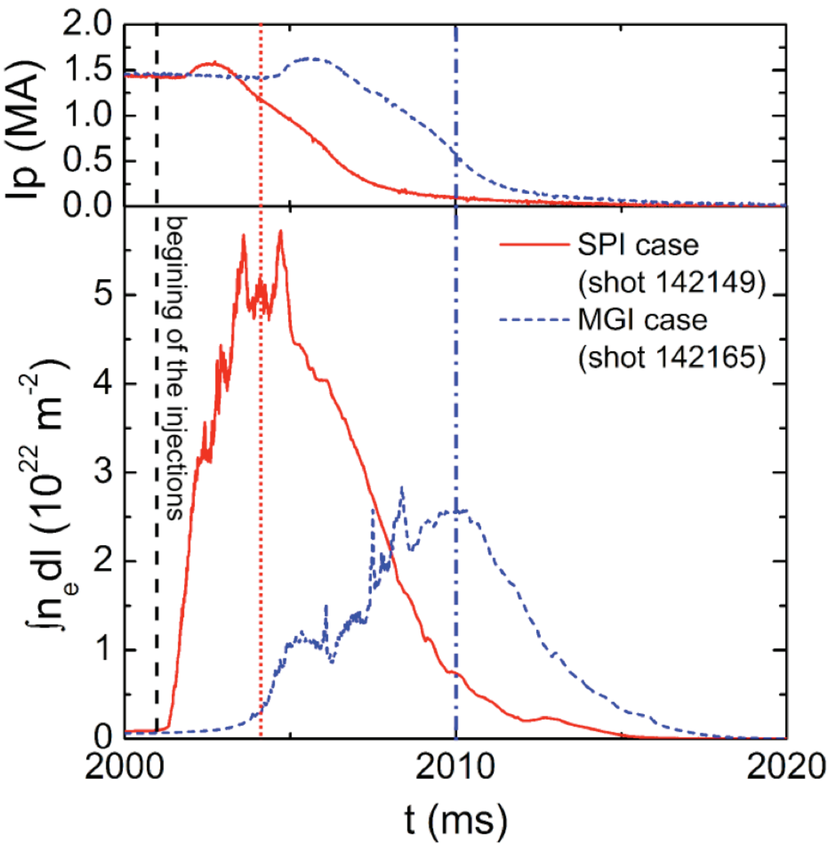


Better and Faster Assimilation for the SPI in Similar Conditions Due to the Deeper Penetration


“normal” view using the fast framing camera

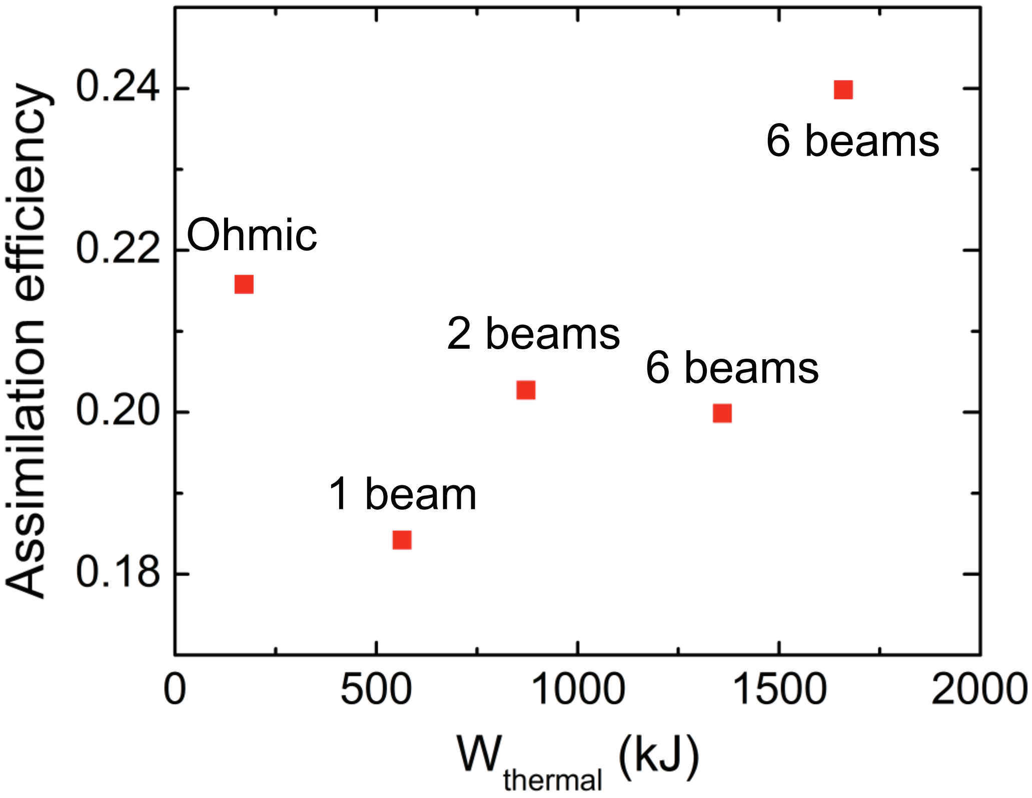


- **The density after transport and homogenization is 2 times higher for the SPI (same amount injected: ~400 Pa.m^3)**
- **Fast visible camera shows SPI cloud penetrating deeper than MGI**
- **The maximum density is reached earlier in the CQ: on DIII-D the RE flattop is already existing at that stage**



Weak Dependence of the Assimilation with the Thermal Energy of the Plasma for the SPI

- **The assimilation efficiency increases with the thermal energy content of the plasma**
- **The ohmic shot allows a higher assimilation efficiency: longer TQ ?**
- **Ionization limit reached ?**

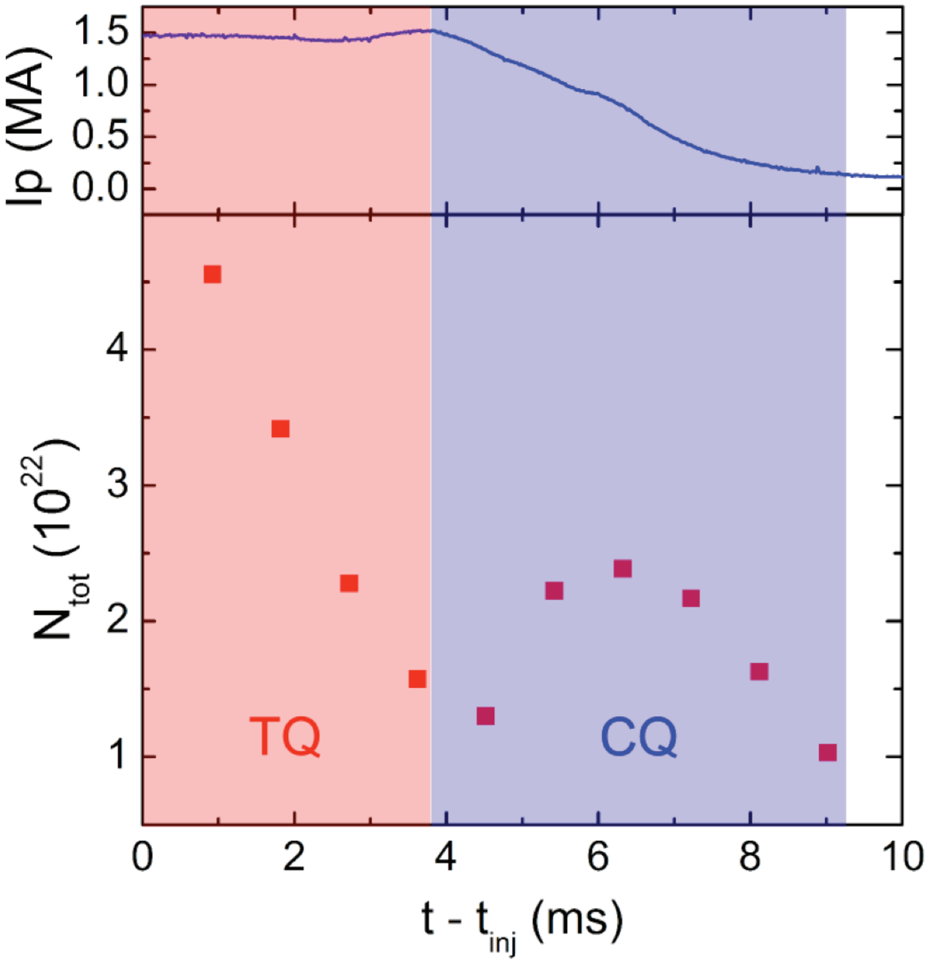


Total Number of Electrons During a SPI Fast Shutdown Varies Significantly

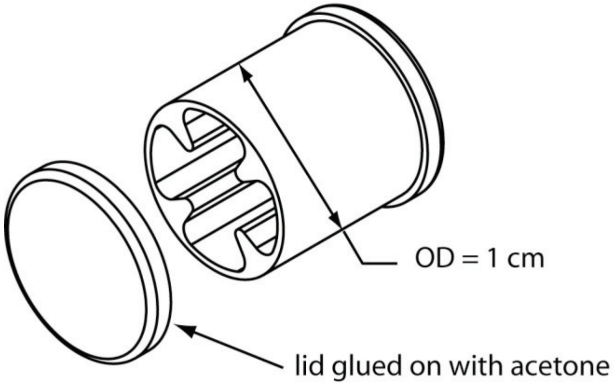
- **Using the different local density measurements to get the total number of electrons N_{tot}**

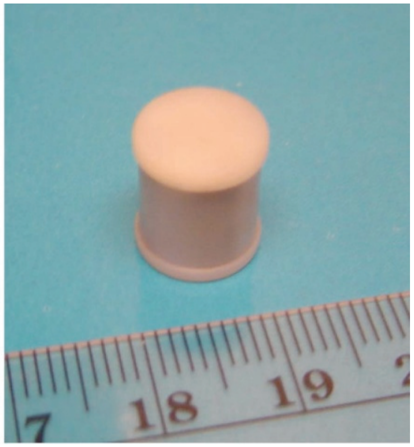
- **After an initial decrease of N_{tot} during the TQ. Increases again at the beginning of the CQ**

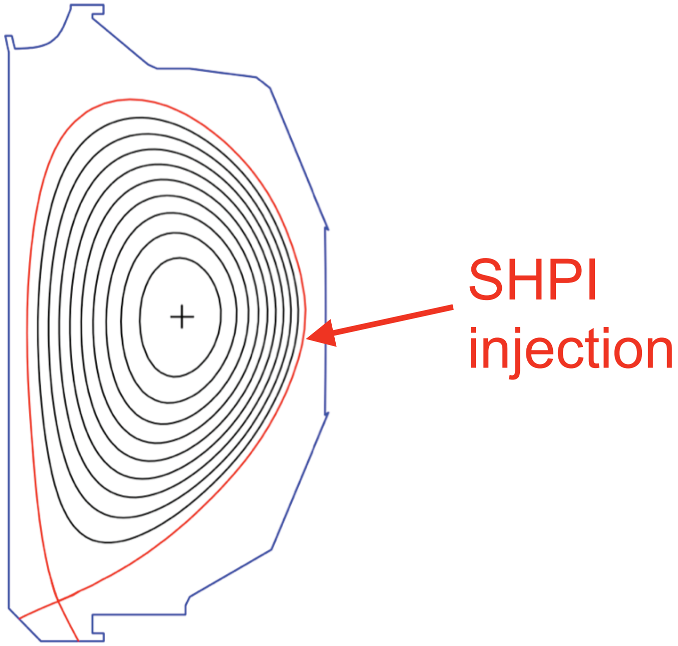
- **Possible explanations**
  - Heat transport
  - Wall recycling



The SHPI Concept



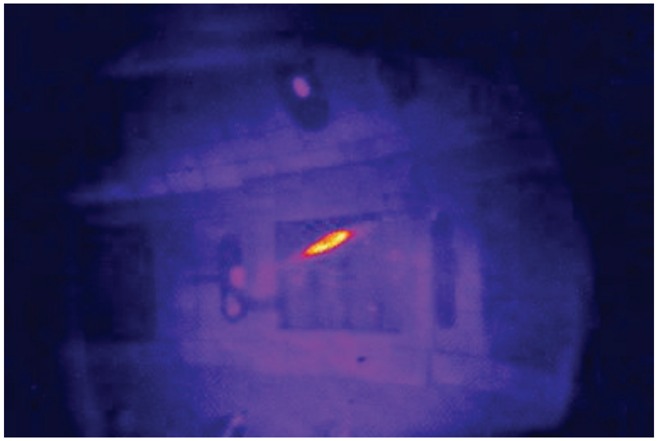


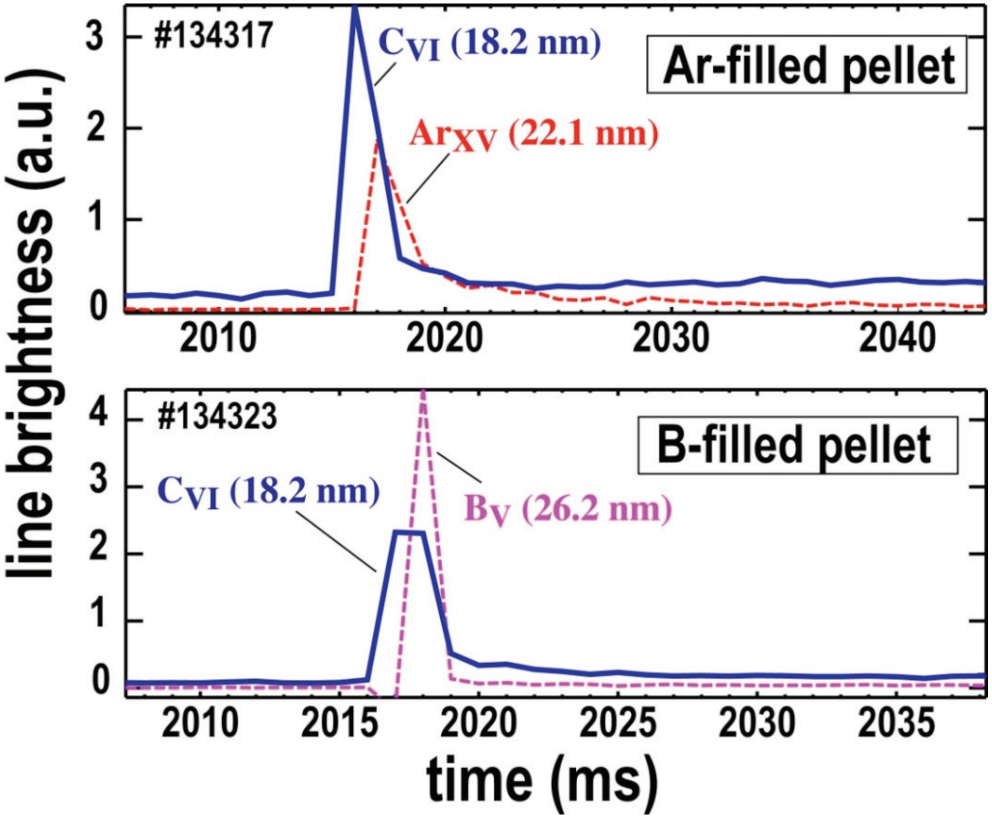


- **Would like to achieve core total electron densities n_{tot} ~ $4x10^{16}/cm^3$ in DIII-D to demonstrate total collisional suppression of runaway electrons deep in the core**
- **Requires of order 1 g ~ 1 cm^3 of material deposited in core of DIII-D**
- **First large shell pellet experiments were attempted in 2009 using D = 1 cm, t = 0.4 mm polystyrene shells filled with boron powder**

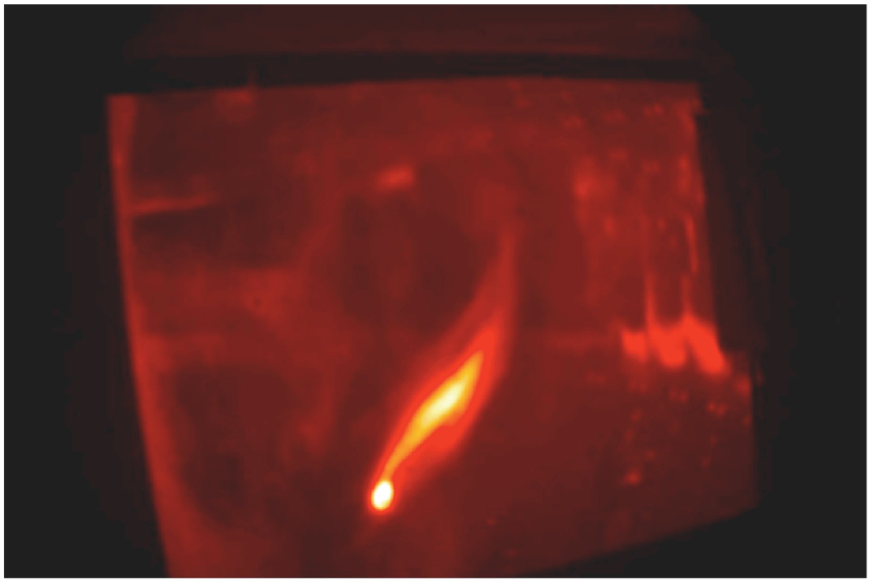
Successful Proof of Principle of the SHPI Using Small 2 mm Shells

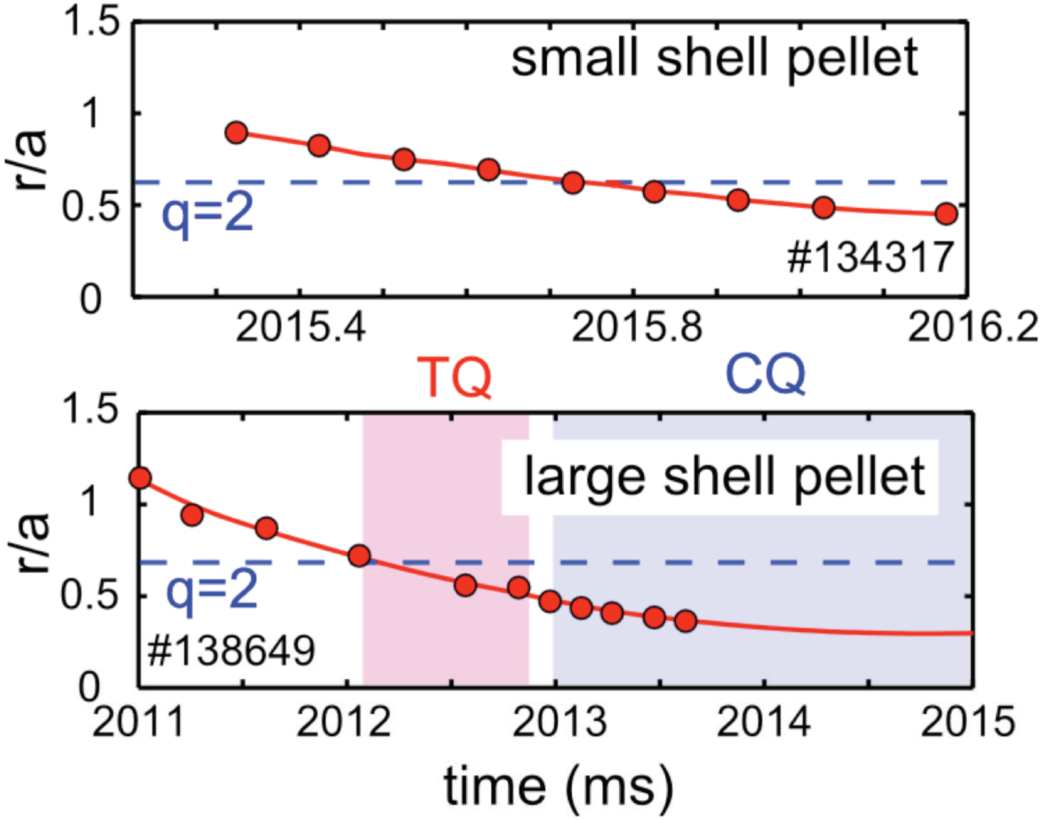
- **Fast camera data show the small shell penetrating deep in the plasma and releasing its payload (boron powder or argon gas)**
- **UV spectrometer shows carbon spike from polystyrene shell**
- **Then highly-charged argon or boron ion spike, consistent with payload release into plasma**
- **No fast shutdown triggered: the amount of particles in the payload is too small**





The Large Shell Pellet Triggers a TQ when Reaching q=2 (SHPI)

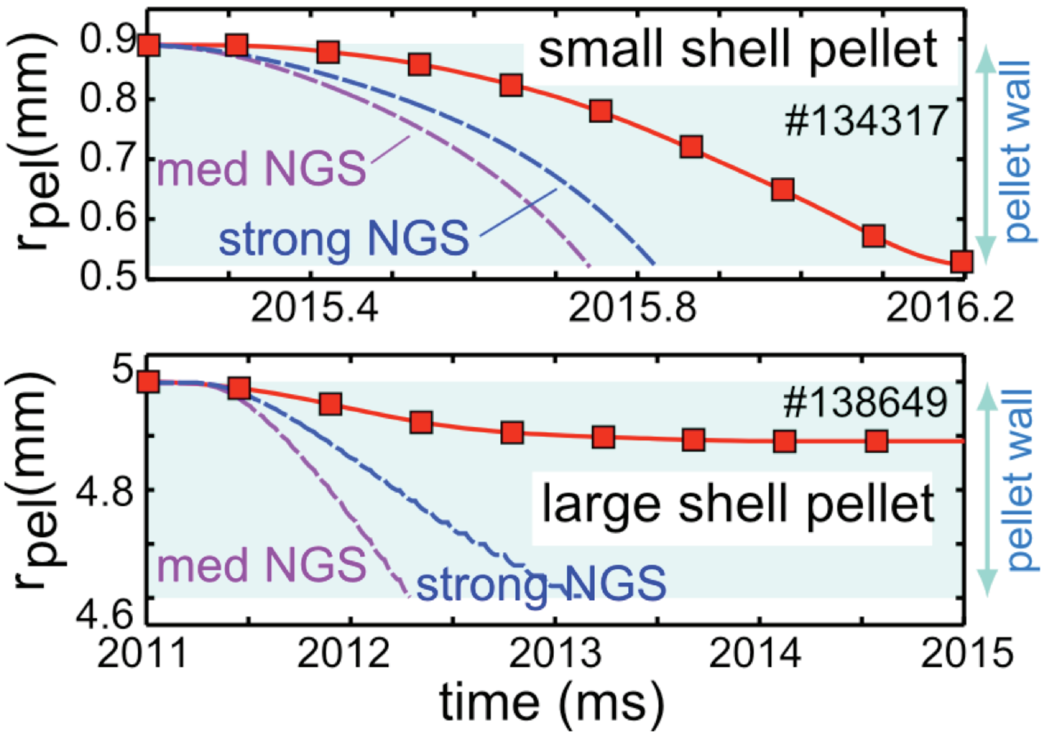




- The large shell pellet did trigger a disruption
- The TQ is initiated when the pellet reaches q=2
- Strong local cooling on q=2 initiate major instabilities
- No indication that the payload has been released

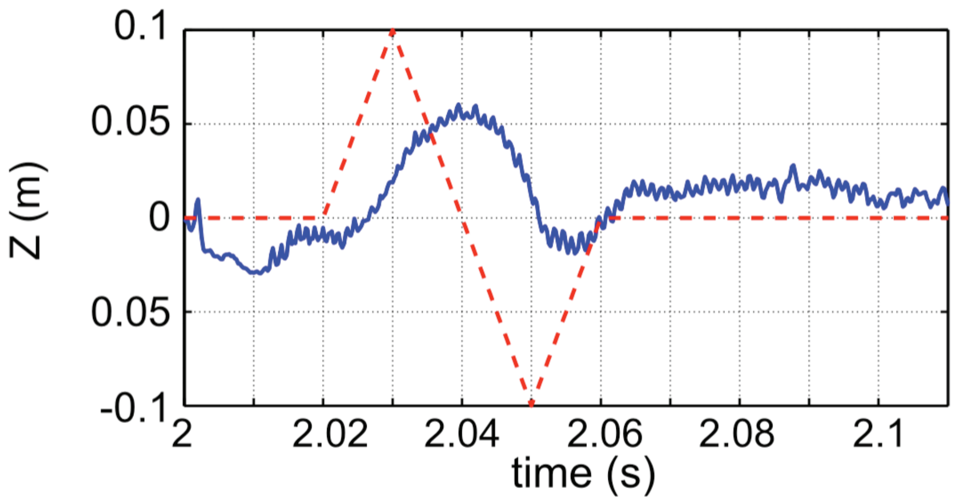
The Big Shell did not Burn all the Way Through (SHPI)

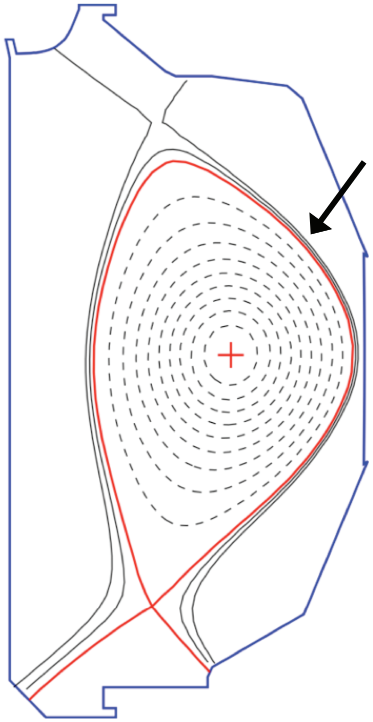
- **The modeling using a modified version of NGS (Neutral Gas Shielding) theory applied to polystyrene predicts breakoff at the center**
- **The measured ablation rate at least 50% lower than expected : pre-cooling effect ?**



Position Feedback Control of the RE Channel Achieved

- **Vertical position controlled**
  - Rather low performance
  - Response to an arbitrary target
- **Radial position control still needs improvement**
  - Requires HFS and LFS control coils
  - Results in an elongated separatrix: risk of VDE ?
  - Achievement of diverted separatrix: no direct contact with the wall
- **Duration of the RE beam still limited by fast instabilities**
  - Sudden loss of the RE beam always observed (kink ?)
  - Loss of vertical position control because of elongation (VDE ?)

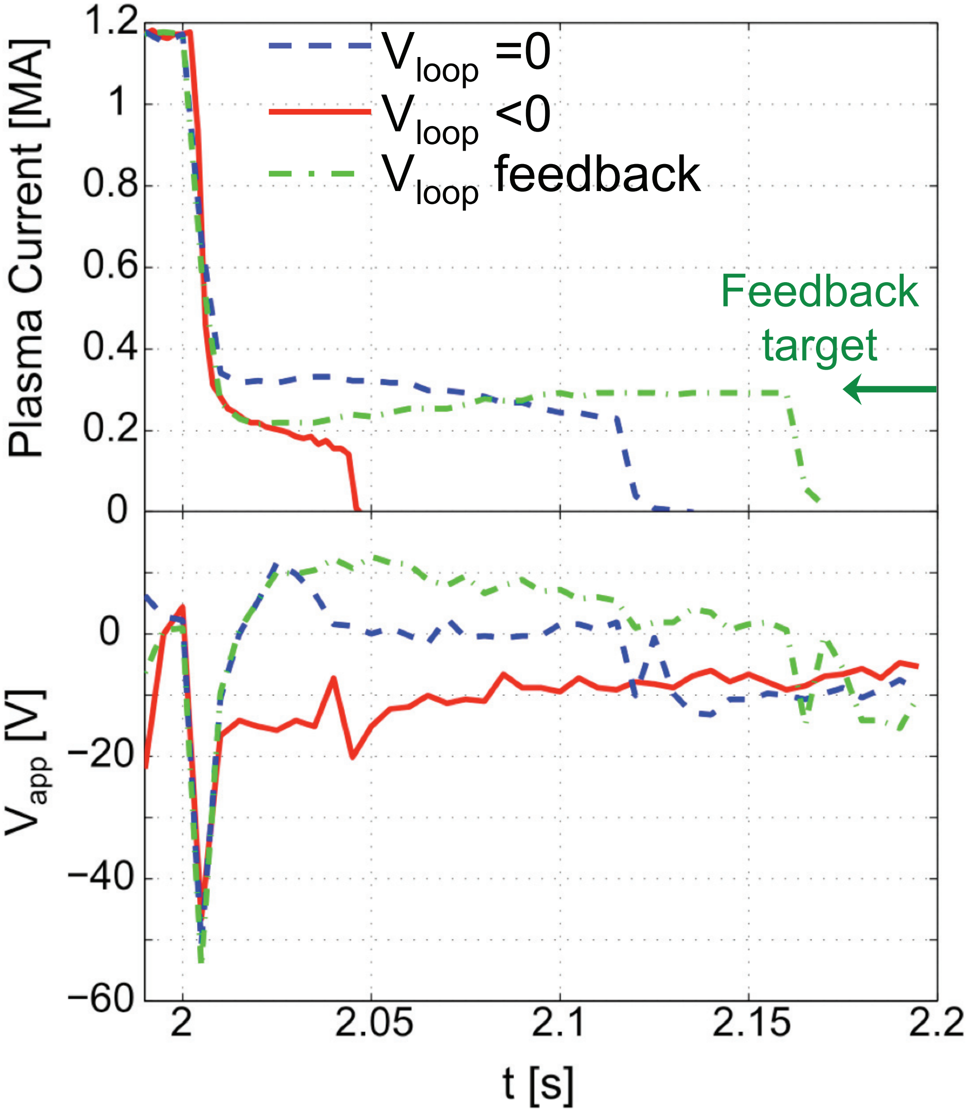




RE beam EFIT reconstruction

Control of the RE Current Amplitude Achieved

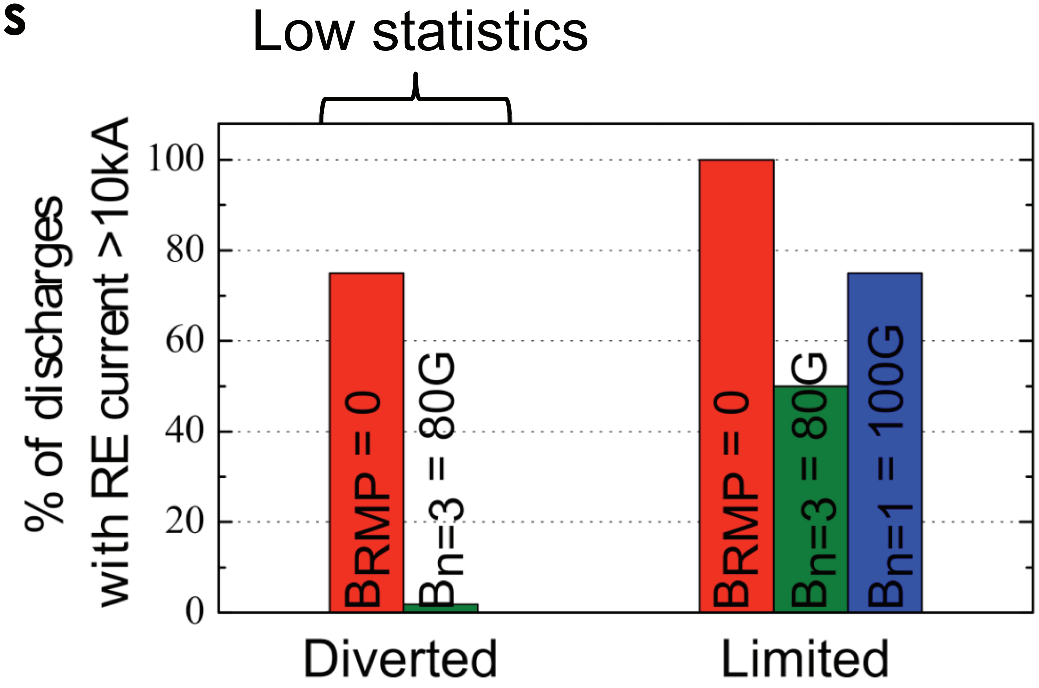
- **Comparison shots with different external loop voltage V_{app} applied**
  - V_{app}<0 lowers the RE current
  - V_{app}=0 induces a slow "natural" decay
  - V_{app} >0 increases the RE current
- **Demonstration of RE current feedback control using the central solenoid**
- **But the beam is systematically lost during a final fast event (VDE, kink … ?)**



NATIONAL FUSION FACILITY SAN DIEGO

Applying a Non-axisymmetric Field Appears to Suppress the Runaways

- **Experiments achieved to test the effect of n=3 and n=1 fields (19 shots) applied with internal coils**
  - Field applied on the existing beam
  - Field applied during the TQ (before the beam appears)
- **The probabity of getting a runaway beam drops by 50%**
- **No observable effect on an existing beam: the RMP field would affect the seed population before the avalanche process can take place**

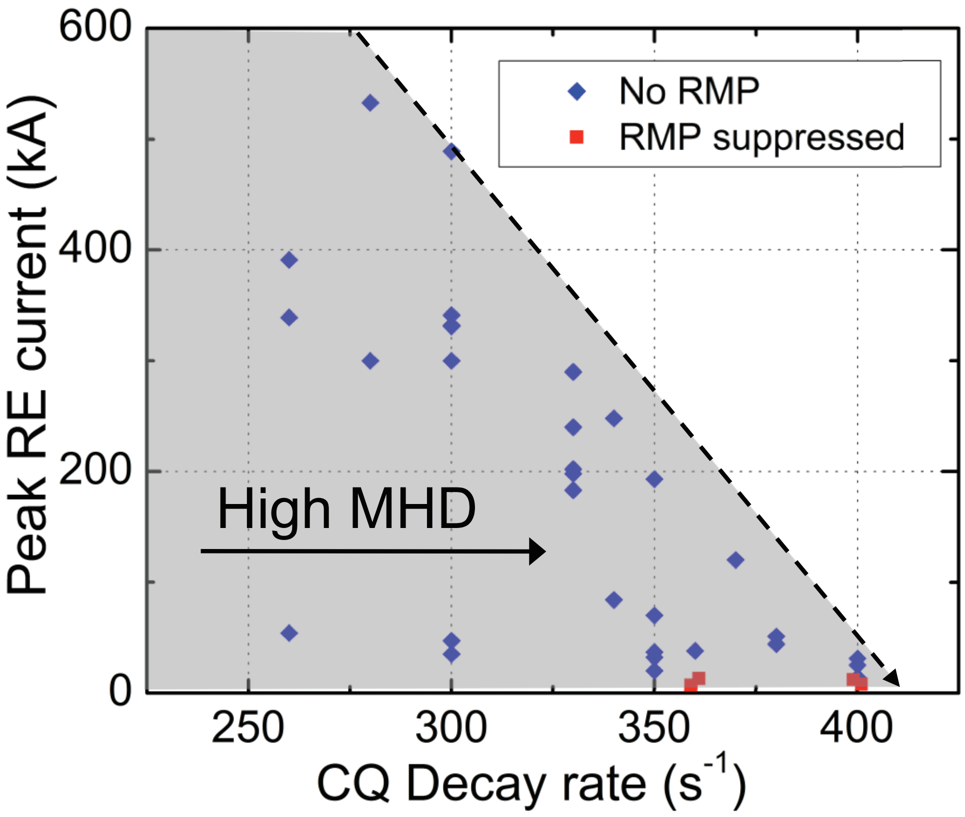


Link Between the Initial Runaway Seed and the MHD Activity During the TQ?

- **Correlation observed between the peak runaway current and the initial I_p decay rate**

- **I_p decay rate characterize the TQ MHD activity:**
  - MHD amplitudes determines the convected heat flux to the wall during the TQ
  - Induces also the deconfinement of the initial runaway seed: lower seed would result in lower final runaway current

- **The RMP would increase the initial MHD activity, which would explain the mitigation observed**



Conclusion

- The new SPI technique shows promising results: good penetration and assimilation
- The parameters scan showed that the initial flow rate of MGI is critical for its efficiency
- The SHPI technique requires fine tuning to be efficient
- The runaways control technique appears efficient and provides an opportunity to apply other mitigation techniques on an existing runaway beam
- The RMP showed some efficiency in mitigating the initial runaway seed but requires further studies to improve its efficiency