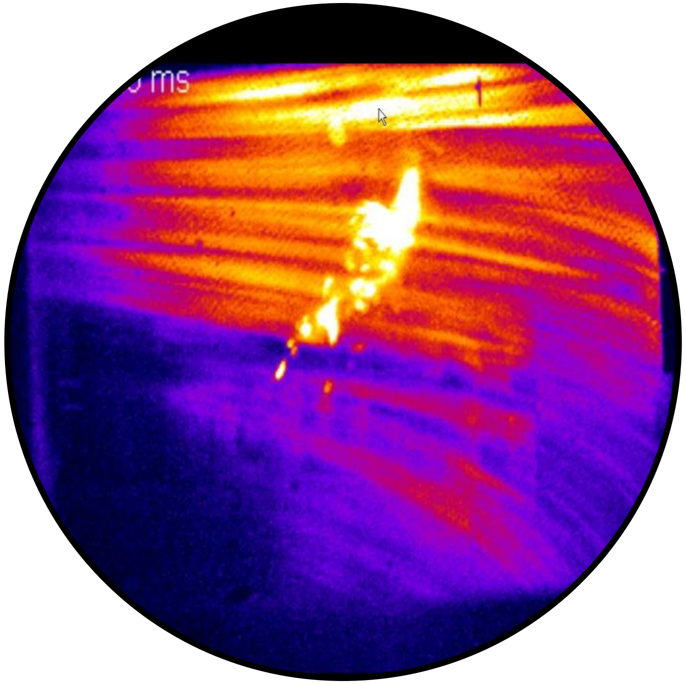
FIRST DISRUPTION MITIGATION EXPERIMENTS ON DIII-D USING THE NEW SHOTGUN PELLET INJECTOR (SPI)

Presented by
N. Commaux

L. Baylor, T.C. Jernigan, E. Hollmann, D. Humphreys, J. Wesley, A. James, J. Yu, P. Parks, C. Foust, S. Combs, S. Meitner



Presented at
APS-DPP Conference 2009
Atlanta, GA

November 2–6, 2009

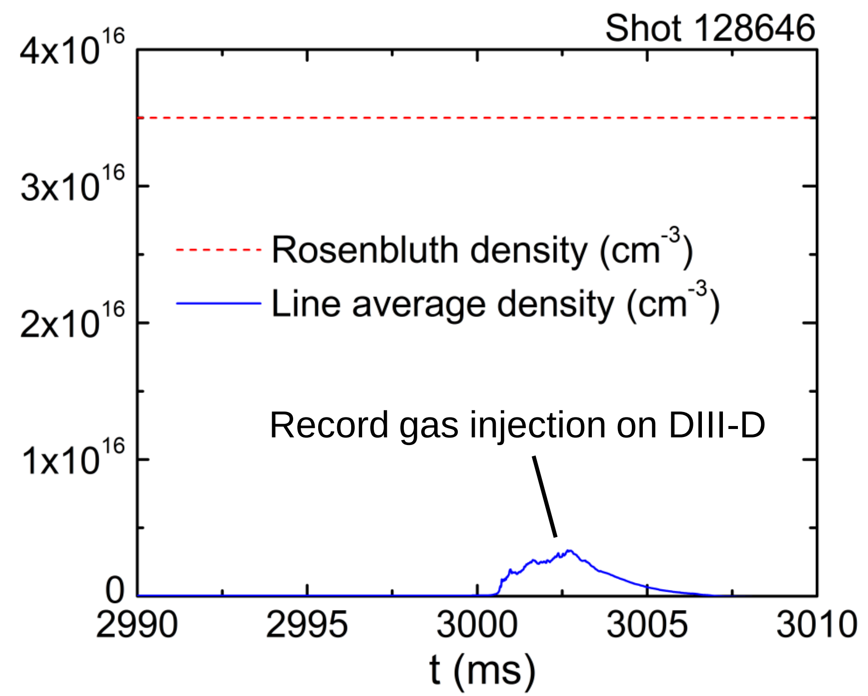
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

OAK RIDGE National Laboratory

High electron density is predicted to suppress runaway electrons in disruptions

- **Runaway electrons can be a major issue for ITER**
- **Runaway electrons in ITER are expected to be generated by an avalanche process**
- **At high densities (~5×10^{16} cm^{-3}), this mechanism would be compensated by collisional losses.**
- **Maximum densities achieved using massive gas injection is ~10 times too low**

$$E_c = \frac{q_e^3 (n_e + n_{tot})}{4\pi\, \varepsilon_0 m_e c^2} \ln\Lambda \;\Rightarrow n_{e\,Rosenbluth} \approx 1\times10^{21} E_c$$

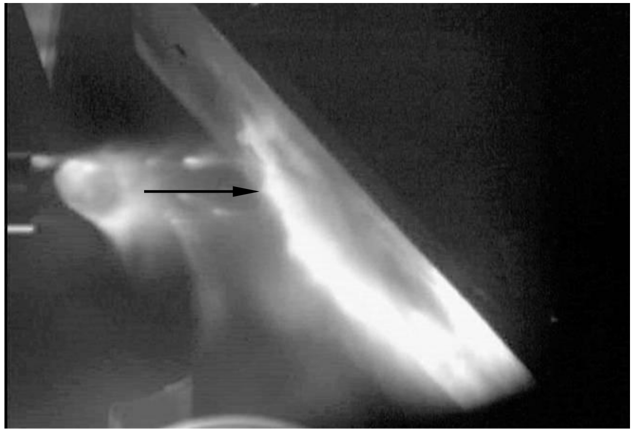


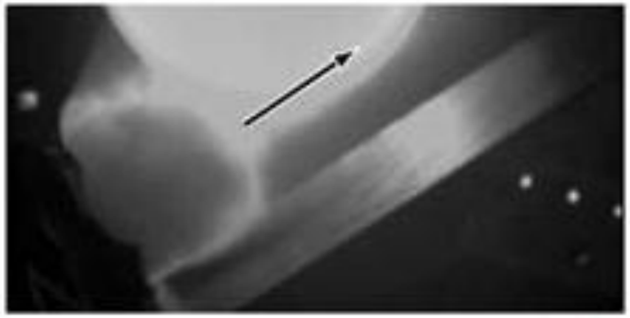
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

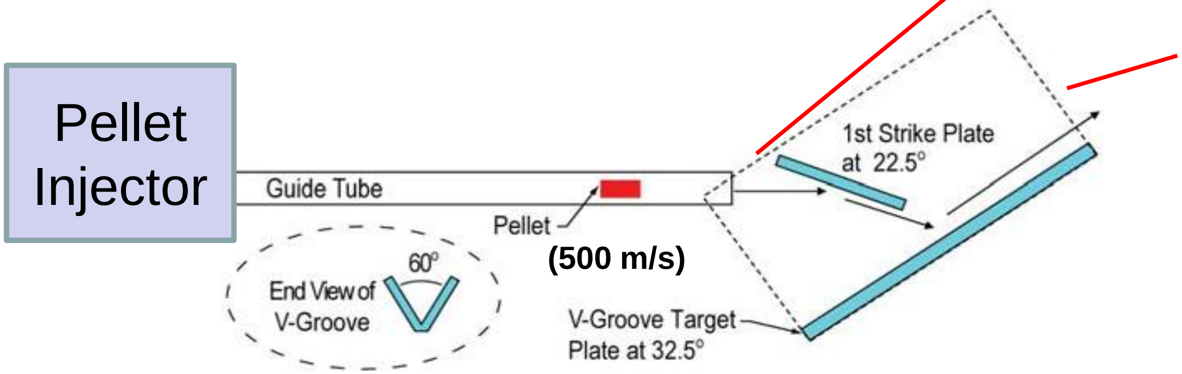
NB: invited talk by E. Hollmann
Post deadline invited XI3.00004

A new method has been designed to increase the density

- **A cryogenic pneumatic pellet injector shooting large pellets (15mm x 20mm cylinders) in DIII-D: the Shotgun Pellet Injector (SPI)**
- **The pellets are shattered before entering the plasma by bouncing on 2 plates to protect the PFCs and increase the surface area for more efficient ablation**



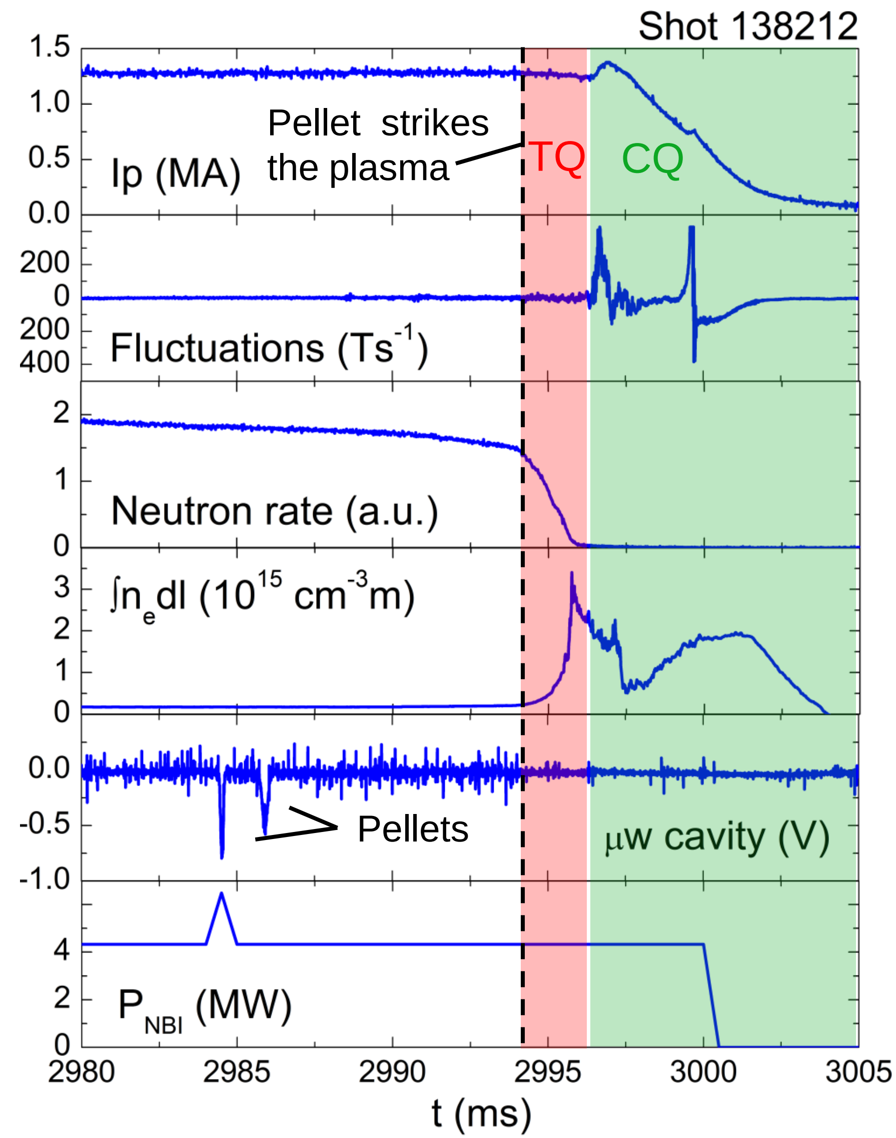




NB: description of the SPI by T. Jernigan (JP8.00090)

SPI was installed and tested on DIII-D in 2009

- **1 run day obtained 7 shots ending with a SPI injection of deuterium pellets**
- **Very fast density increase (too fast for interferometry: no reliable data)**
- **Preliminary scans:**
  - Quantity:
    - 2500 torr.L
    - 3000 torr.L
    - 3500 torr.L
  - injected power
    - 2.3 MW
    - 4.5 MW
    - 6.5 MW



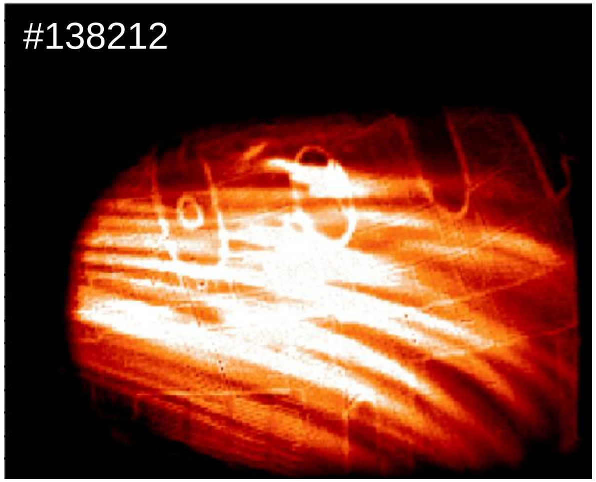
Fast visible camera shows the pellet cloud penetrating deeper than Massive Gas Injection (MGI)

MGI

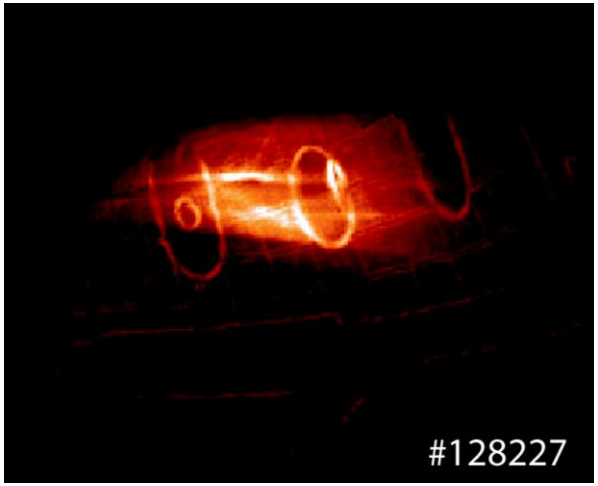
SPI

TQ

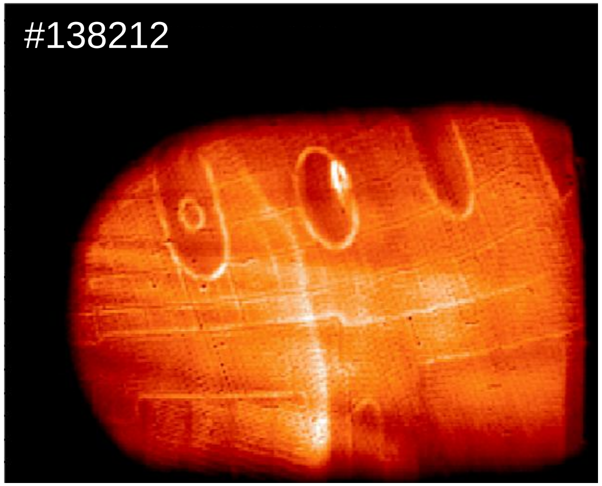
TQ



CQ



CQ

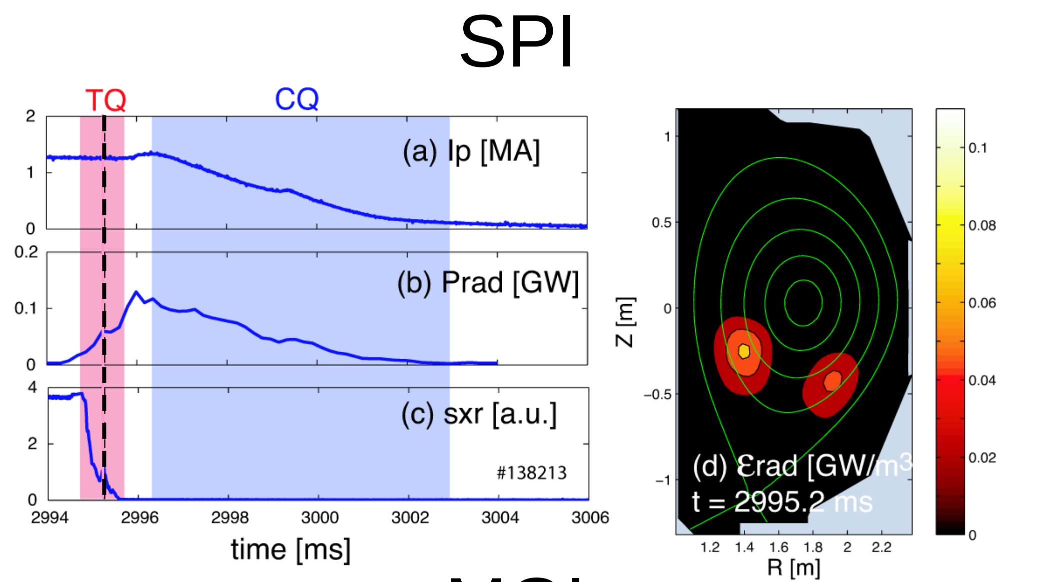


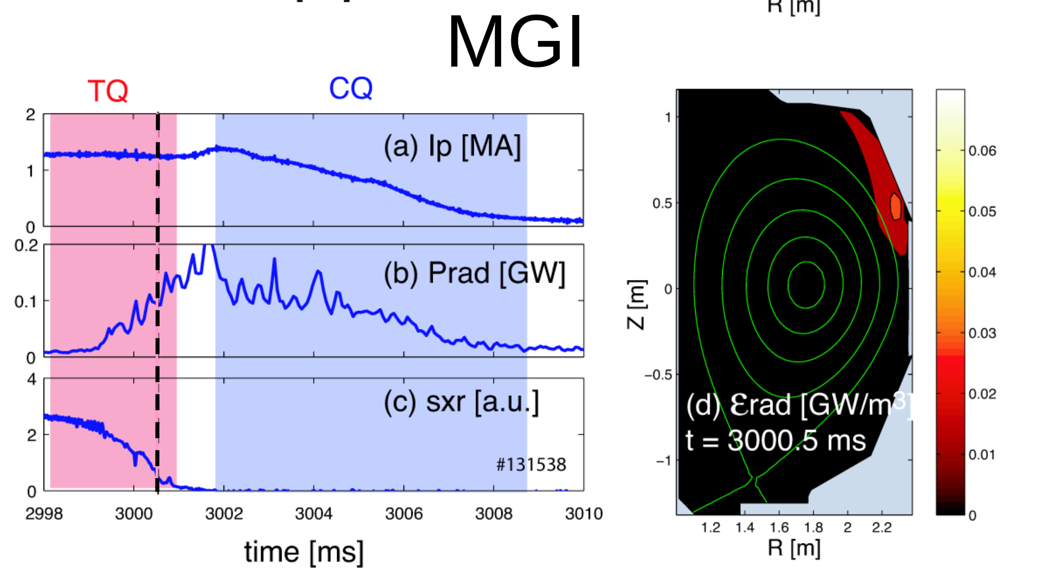
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Bolometry shows evidence for deeper impurity penetration for SPI

- **Bolometer tomography gives indication about particle deposition**
- **The deposition pattern is different between SPI and MGI**
- **The deposition appears much deeper for the pellet case**

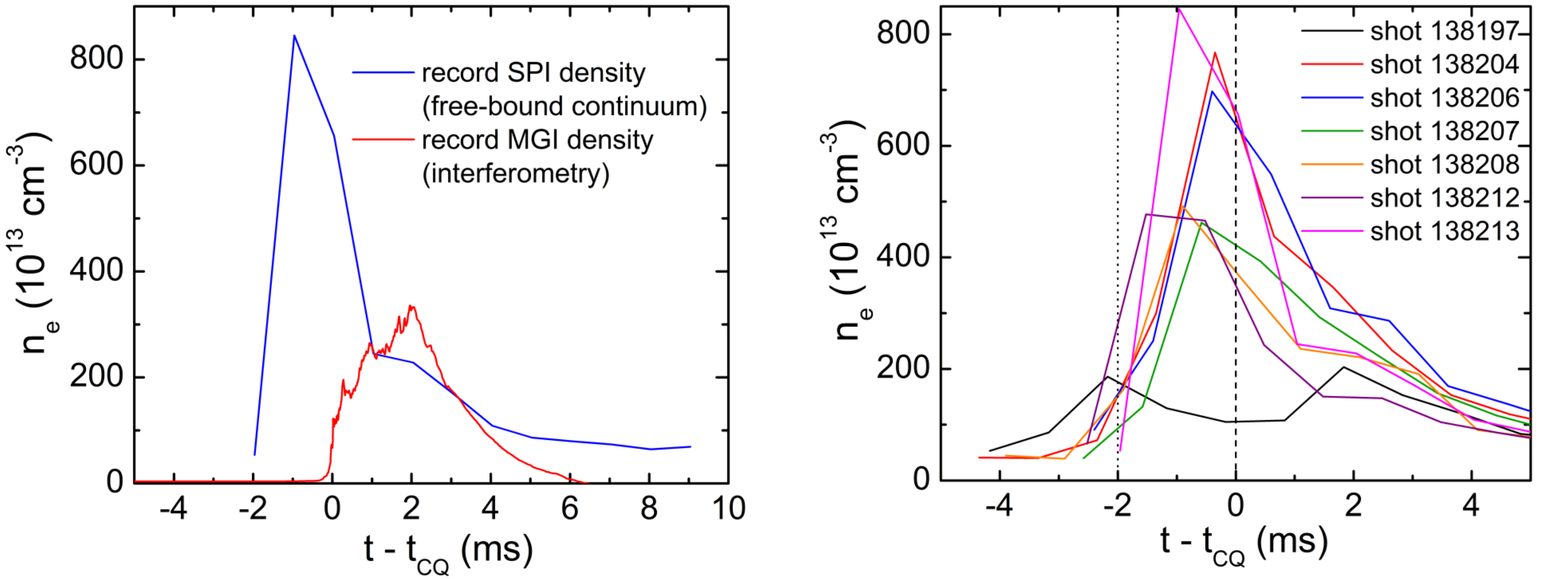
NB: shattered pellet ablation model by P. Parks (TP8.00036)





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

SPI reliably produced high local densities

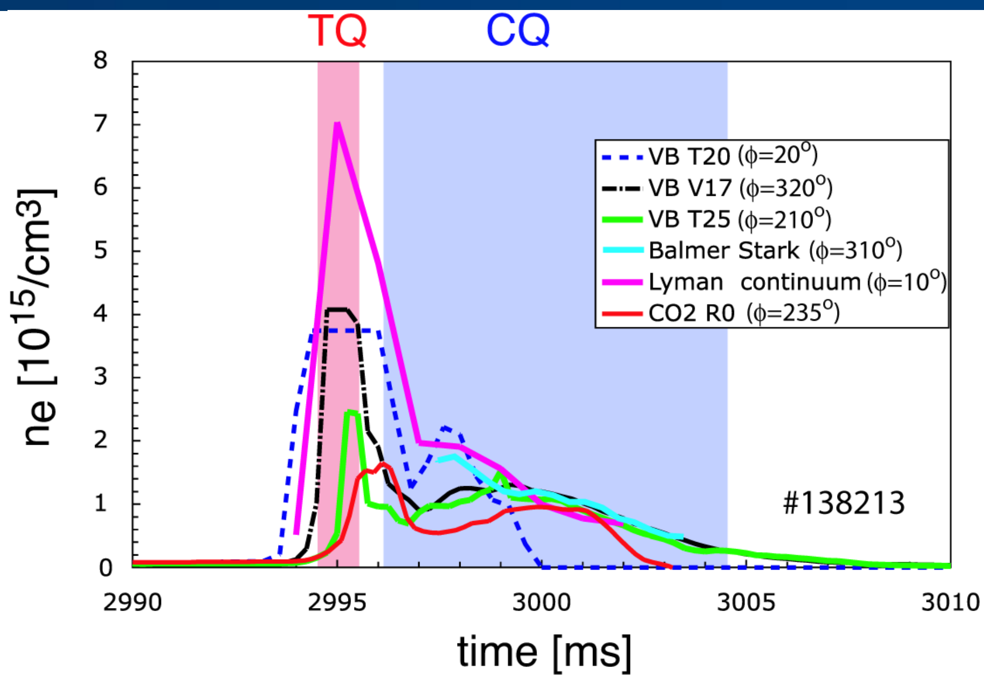


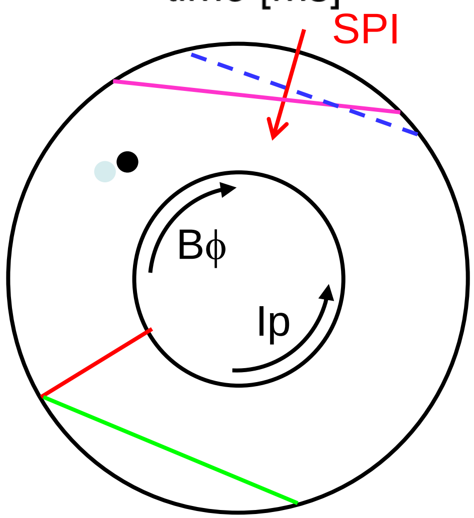
- **The spectral analysis provided the only available density measurements during the pellet injection and the disruption**
- **The local densities reached during the injection are very high (up to 8×10^{15} cm^{-3})**
- **Every shot but one reached local densities > 4×10^{21} m^{-3} (good reliability)**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Strong toroidal density asymmetry is observed during the Thermal Quench

- **Spectroscopic measurements are available in several toroidal angles in DIII-D**
- **After the TQ, strong toroidal density asymmetry is observed**
- **During the CQ, the density measurements show that the toroidal symmetry is achieved when $n_e \sim 2\times10^{15}$ cm^{-3}**
- **The assimilation efficiency is ~17% (lower bound)**

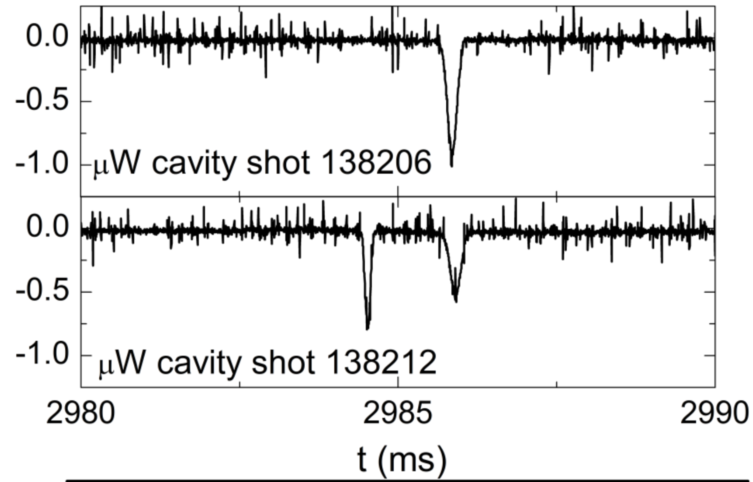


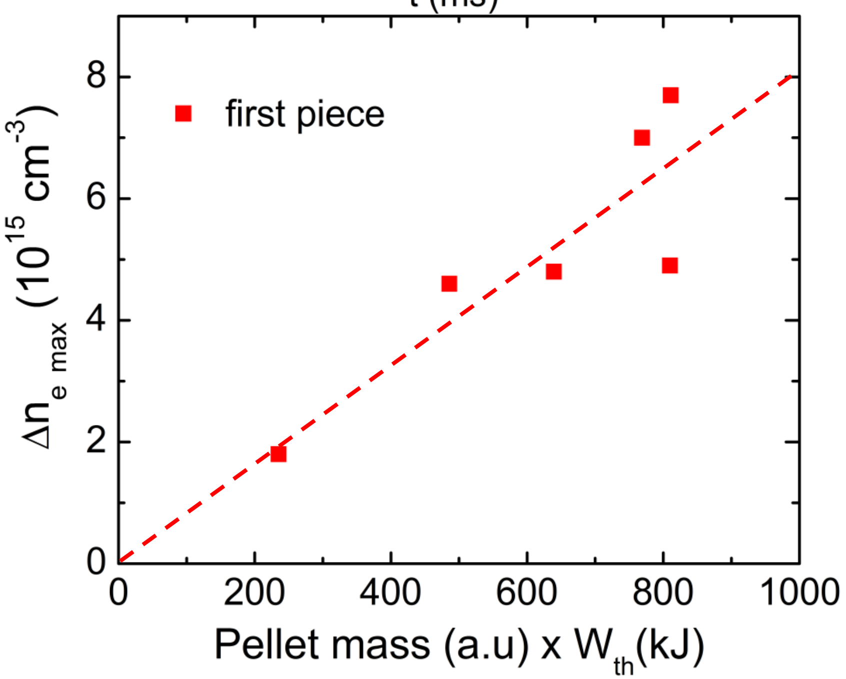


NATIONAL FUSION FACILITY SAN DIEGO

Density perturbation is a function of the size of the first large pellet piece

- **In several cases, the pellet broke in the barrel in 2 pieces: 2 clouds of fragments hit the plasma several ms apart**
- **Density perturbation due to SPI increases with:**
  - The thermal energy of the plasma
  - The amount of mass injected
- **The density perturbation appears to be a function of W_{th}x size of the first fragment hitting the plasma**
- **The second piece appears to arrive "too late": not enough energy left to ionize the particles**
- **Similar effects are also observed with MGI**

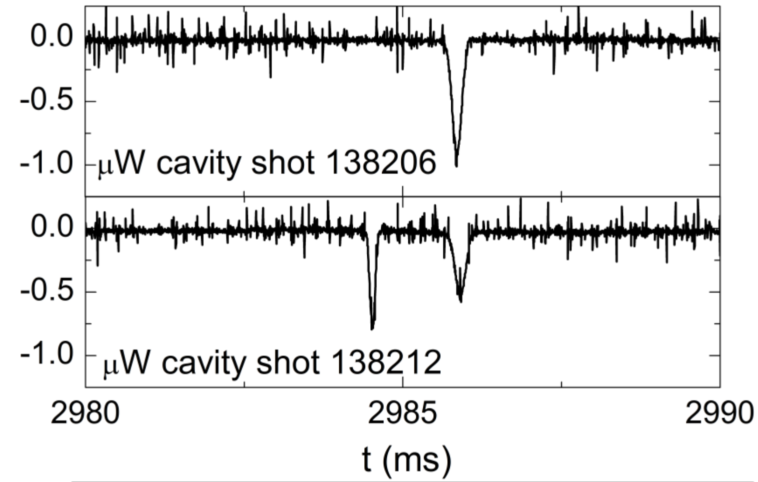


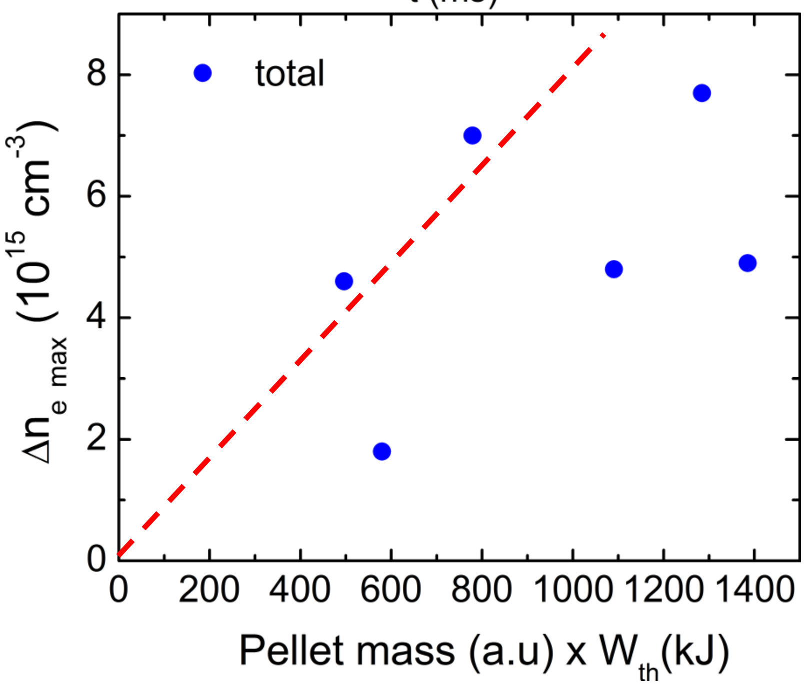


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Density perturbation is a function of the size of the first large pellet piece

- **In several cases, the pellet broke in the barrel in 2 pieces: 2 clouds of fragments hit the plasma several ms apart**
- **Density perturbation due to SPI increases with:**
  - The thermal energy of the plasma
  - The amount of mass injected
- **The density perturbation appears to be a function of W_{th}x size of the first fragment hitting the plasma**
- **The second piece appears to arrive "too late": not enough energy left to ionize the particles**
- **Similar effects are also observed with MGI**





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

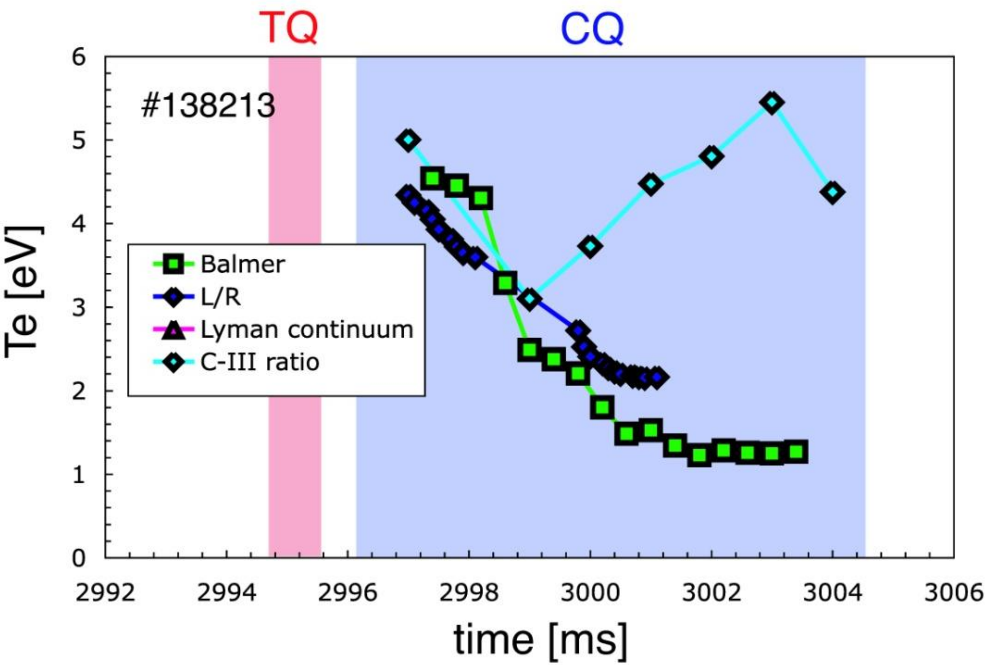
There is no significant contribution of the bound electrons to the runaway mitigation

- **Neutral particles are also important for runaway mitigation: free and bound electrons mitigate the runaways**

- **Measuring the neutral gas pressure during the disruption is challenging**

- **Spectra acquired during the current quench give some information through the electron temperature**

- **The different methods yield Te ~ few eV: the ionization fraction should be close to 1**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Summary

- The first 1.5cm x 2cm shattered deuterium pellet were injected in DIII-D
- Fast camera data show deeper penetration with shattered pellet than with massive gas
- Local electron densities observed appear to be very high (~18×10^{15} cm^{-3})
- Cases with a pellet broken in the barrel show that only the first “cloud” impacting the plasma contributes to the density increase
- These preliminary promising results motivate proposed 2010 experiments on DIII-D with higher power, higher Z material, improved diagnostics…

For more information

- *Invited talk summarizing the disruption mitigation experiments on DIII-D by E. Hollmann (Post deadline invited XI3.00004) Friday morning*
- *Description of the SPI by T. Jernigan (JP8.00090) Tuesday afternoon*
- *Shattered pellet ablation model by P. Parks (TP8.00036) Thursday morning*

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Prospects

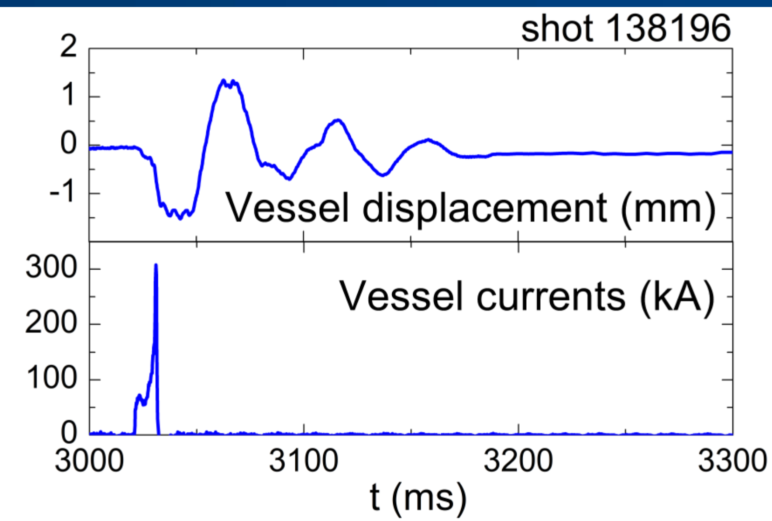
- **A new run day is scheduled during the next campaign of DIII-D in order to test Neon pellets (which would contain enough electrons to reach an average density higher than the Rosenbluth density)**
  - assimilation (as good as for D_2 ?)
  - The energy losses due to impurity radiation

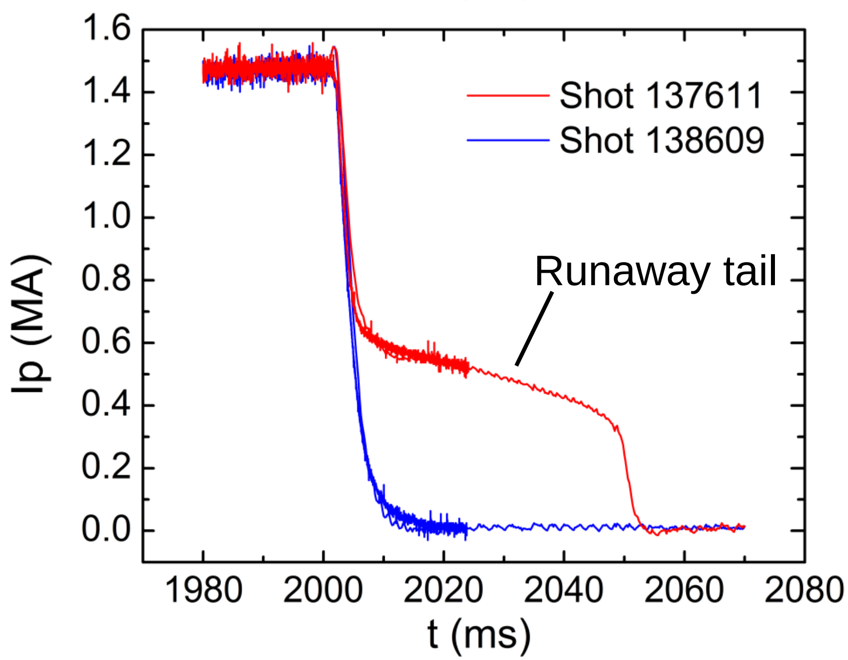
- **The assimilation of the particles injected through several pellets or pellet+MGI is important to be addressed:**
  - for ITER, 1 pellet containing enough electrons would be the size of a grapefruit
  - Is it possible to use several pellets injected with several injectors ?

- **The possibility of "killing" an existing runaway beam has also to be addressed (SPI, MGI, magnetic control…)**

The Disruptions on ITER

- **ITER will contain ~ 350 MJ of thermal energy and ~1 GJ of poloidal magnetic energy**
- **ITER can sustain important damage due to disruptions during high performance discharges**
- **The hazardous effects of the disruptions on ITER are:**
  - High heat fluxes on plasma facing components less susceptible to tolerate such effects (metal walls)
  - High halo currents generating strong mechanical stress in the structures
  - "runaway" electrons

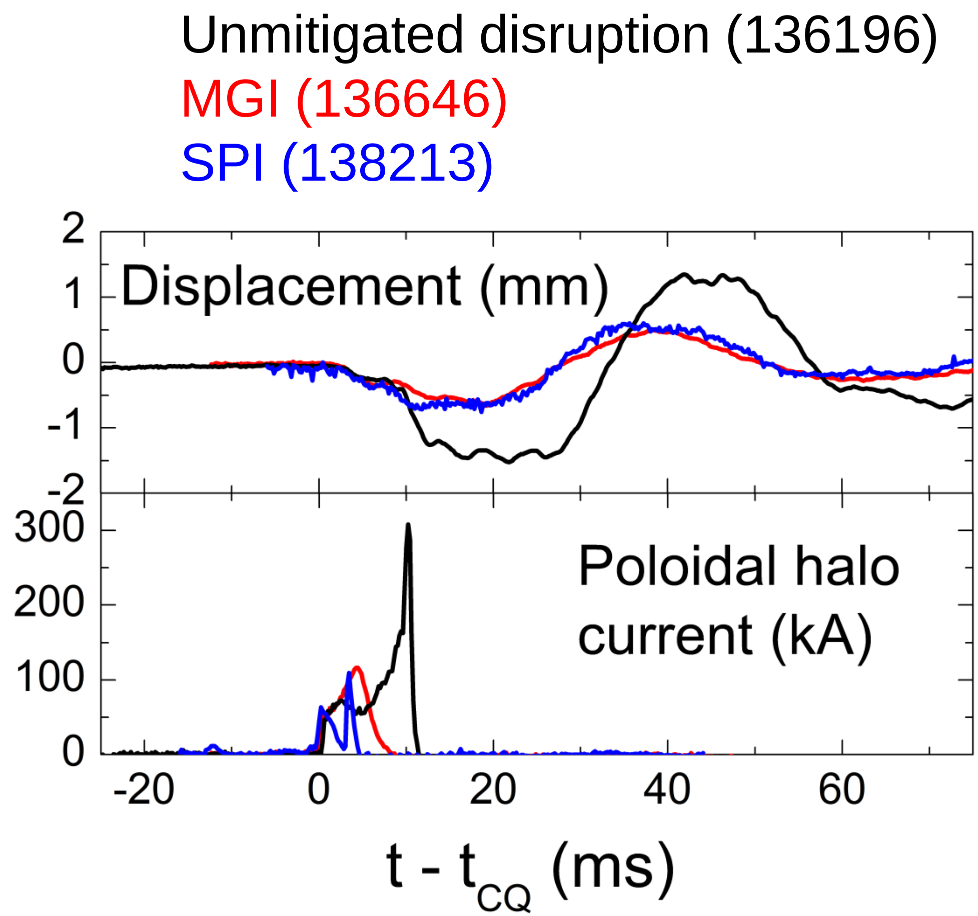




NATIONAL FUSION FACILITY
SAN DIEGO

Mitigation of Vessel forces and currents

- **The halo currents and displacements generated by a MGI triggered disruption are 2 to 3 times smaller than the one occurring during unmitigated disruption**
- **The SPI mitigation allows the same level of mitigation on DIII-D in terms of vertical displacements (~vertical forces) and halo currents**
- **The horizontal forces are not (yet) monitored during these experiments**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

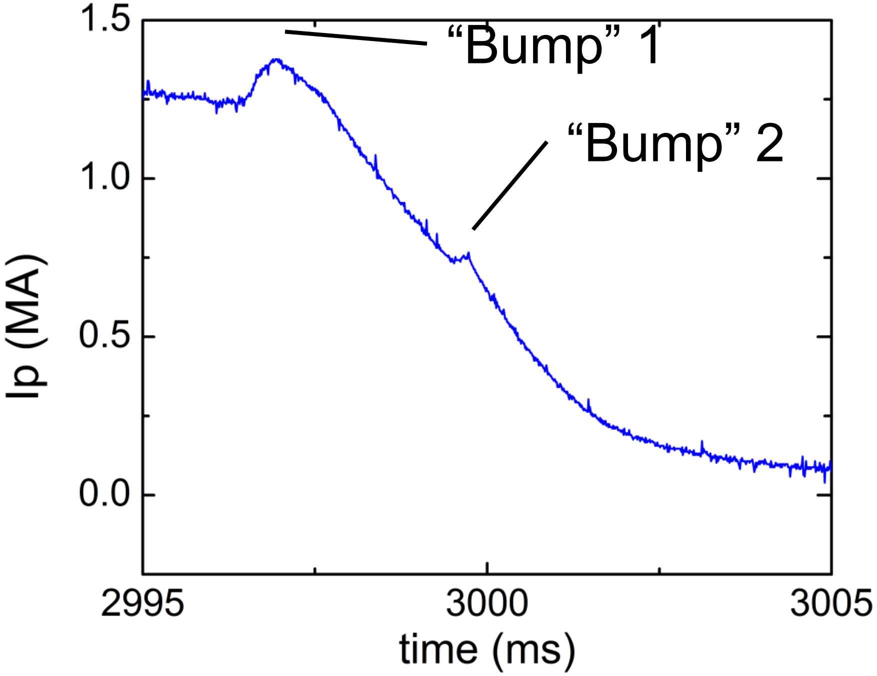
The "bump" on the current decay: a runaway beam?

- **Almost all the disruptions triggered by an SPI injection exhibit 2 plasma current bumps during the current decay**

- **The first bump is well documented (very common feature: magnetic reconnection (kink mode ?) dropping the plasma inductance.**

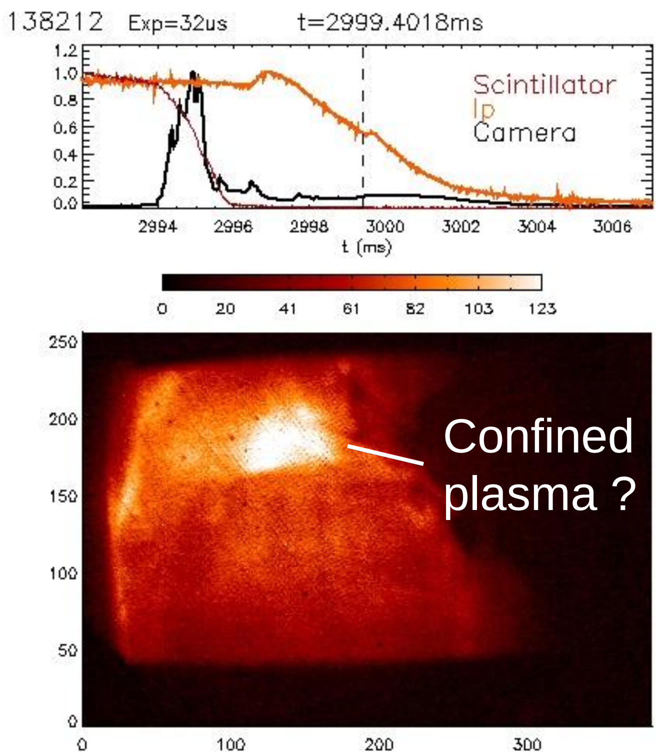
- **The second bump is rare during unmitigated and/or MGI disruptions. Not runaway electrons (no plastic scintillator signal)**

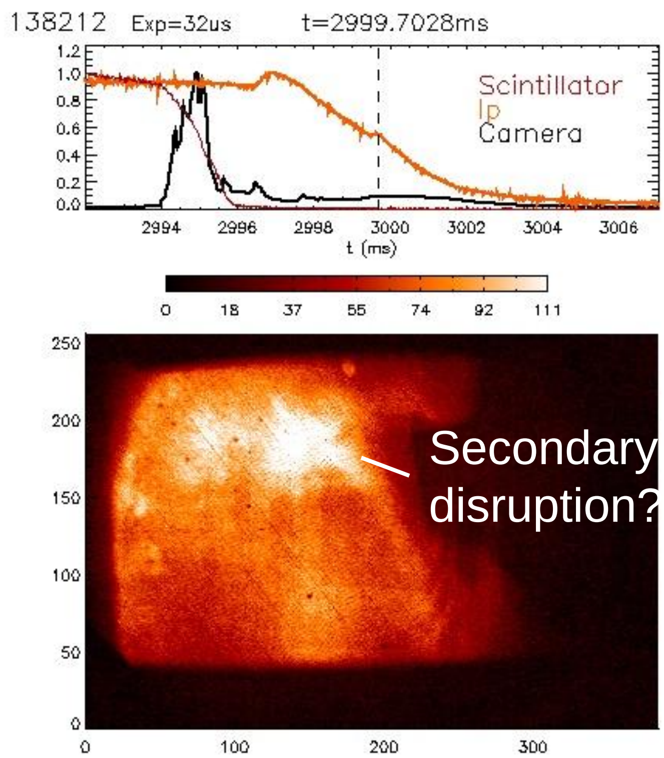
- **Hypothesis: while the plasma shrinks, q_{edge} drops and crosses an integral value (2 ?) triggering another kink mode**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

The “bump” on the current decay



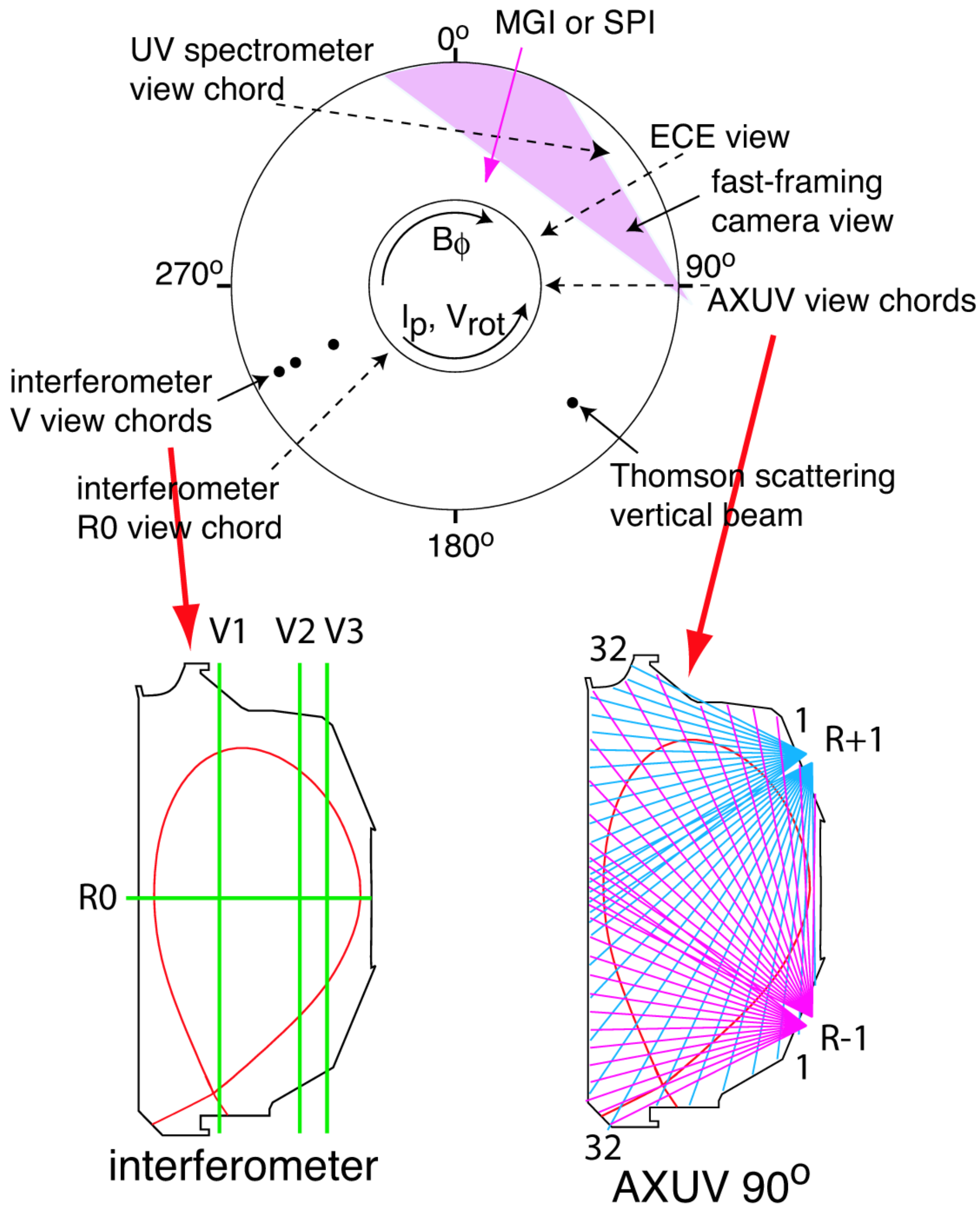


- **The images of the UCSD fast camera show a bright spot before the second bump that could be a confined plasma**

- **When the bump occurs, the bright spot warps and get larger (MHD mode destroying the flux surfaces ?)**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Diagnostics



Detailed theory (1)

- **Assume**: **Identical** initial pellet radii r_{p0} and **uniform** concentration n_c , low enough to ensure that each pellet within a given slice of flux surface receives nearly the same electron heat flux.

•INSERT a sketch of the stream showing x = distance from plasma boundary and stream length, radius, velocity Lc,Rc, Vc respectively.

$$\partial r_p/\partial t + V_c \partial r_p/\partial x = -C n_e^{1/3} T_e^{5/3} r_p^{-2/3}/(4\pi n_s)$$

$$\partial n_e/\partial x = C n_e^{1/3} T_e^{5/3} r_p^{4/3} n_c R_c^2/(4\pi r R)$$

- Assume dilution cooling during penetration: $n_e(r,t)T_e(r,t) = n_e(r,0)T_e(r,0) = w(r) n_{e0} T_{e0}$
- Transform to 2 coupled universal ODES

$$dY/d\xi = (4/7\xi)Z^{-4/7},\ dZ/d\xi = Y^{4/5},\ \text{where}: \xi = (t/t_* - x/V_c t_*)[(a/V_c t_*)F(\rho)]^{-7/4},\ Y = (r_p/r_{p0})^{5/3}$$

$$Z = \rho w^{-5/3}(n_e/n_*)^{7/3}[(a/V_c t_*)F(\rho)]^{-7/4},\ F(\chi) = \int_\chi^1 w(\rho)^{5/7}\rho^{4/7}d\rho,\ \ \rho = r/a$$

- **Boundary Conditions:**

Entrance: $\xi = \infty,\ Y = 1,\ Z = \infty$ Stream Front: $\xi = \xi_0,\ Y = 0,\ Z \approx 0$

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Detailed theory (2)

- Solve ODEs to find ξ_0 = 6.5. Then Stream front trajectory ρ_{front} is given implicitly:

$$\rho_{front} = 1 - V_c t/a + \left(\frac{a\xi_0^{4/3}}{V_c t_*} \right)^{3/4} F(\rho_{front})^{7/4}$$

- Optimal case: want pellet stream **completely burned up**, “back” reaches “front” at moment $t = t_{burn} = L_c/V_c + a/V_c$, when $\rho_{front} = 0$

$$\longrightarrow \quad V_c = \frac{5^{7/3}\xi_0^{4/3} C_{sph} a F(0)^{7/3}}{2^{2/3}3^{7/3}\pi n_s (\Delta n_e)^{4/3}} \left(\frac{T_{e0} n_{e0}}{r_{p0}} \right)^{5/3} \quad \text{(cm/s)}$$

- Compare with range of DIII-D experimental values $V_{c,exp}$ ~ 200 - 400 m/s

$$T_{e0} = 2.8 \text{ keV},\ n_{e0} = 9\times10^{13} \text{ cm}^{-3},\ a = 66 \text{ cm},\ r_{p0} = 0.09 \text{ cm},\ F(0) = 0.34,\ \Delta n_e = 5\times10^{15} \text{ cm}^{-3}$$

↑ $\sim (1/4) n_{crit}$

→ V_c = 322 m/s, consistent with experiment!

- Prediction for ITER with $\Delta n_e = n_{crit} \sim 2\times10^{16} \text{ cm}^{-3}$ requires higher velocity

$$T_{e0} = 20 \text{ keV},\ n_{e0} = 10^{14} \text{ cm}^{-3},\ a = 200 \text{ cm},\ r_{p0} = 0.35 \text{ cm},\ F(0) = 0.34$$

→ V_c = 505 m/s

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Pellet cluster stream penetration theory: the assumptions

- **1D model assuming a cylindrical homogeneous cloud of small identical pellets (pellets density n_c and radius r_0)**

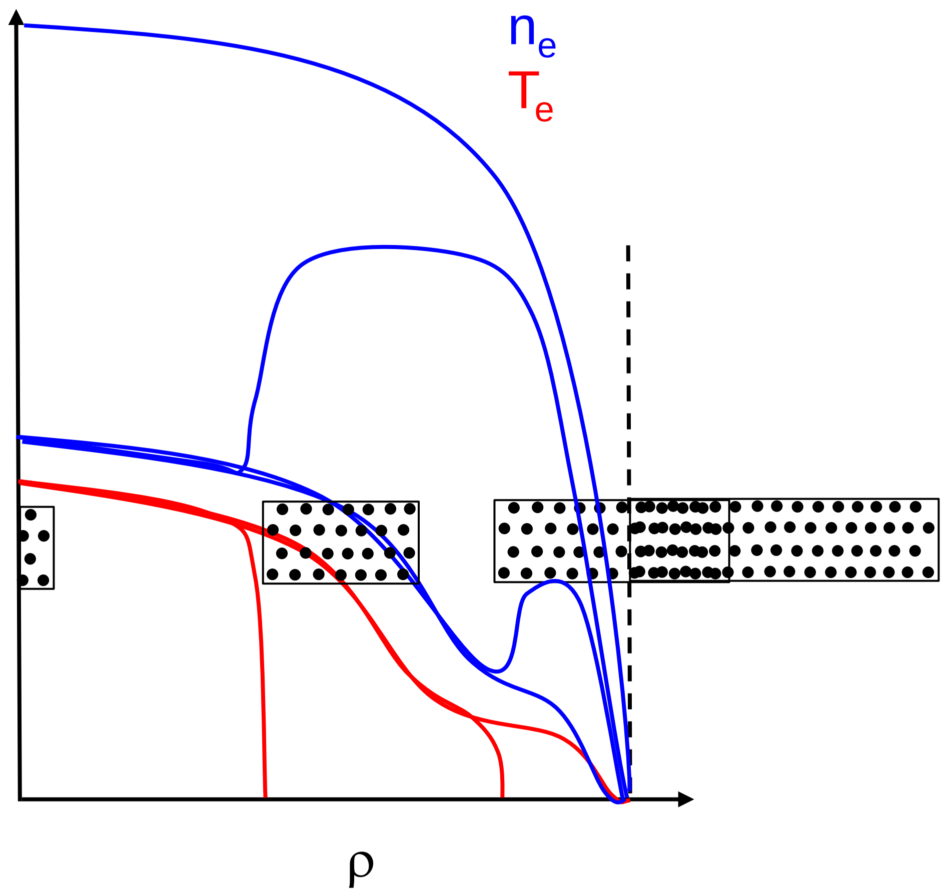
- **Assume dilution cooling during the penetration of the cloud (adiabatic ablation)**

- **Ablation model for each individual pellet similar to the NGS fueling pellet ablation model**

$$\partial r_p / \partial t + V_c \partial r_p / \partial x = -C n_e^{1/3} T_e^{5/3} r_p^{-2/3} / (4 \pi n_s)$$

$$\partial n_e / \partial x = C n_e^{1/3} T_e^{5/3} r_p^{4/3} n_c R_c^2 / (4 \pi r R)$$

- **Goal: calculate the speed of cloud in order to get a full ablation when the cloud reaches the center of the plasma (ideal scenario)**



Results: the SPI is in the right ball park for DIII-D

$$V_c = \frac{5^{7/3}\xi_0^{4/3} C_{sph} a F(0)^{7/3}}{2^{2/3}3^{7/3}\pi n_s (\Delta n_e)^{4/3}} \left(\frac{T_{e0} n_{e0}}{r_{p0}} \right)^{5/3} \text{ (cm/s)}$$

- For DIII-D: T_{e0} = 2.8keV ; n_{e0} = $9x10^{13}cm^{-3}$; a = 66cm ; rp0 = 0.9 mm ; Δn_e = $5x10^{15}cm^{-3}$

  The speed should be 322 m/s (speed of the fragments evaluated between 200 and 400 m/s)

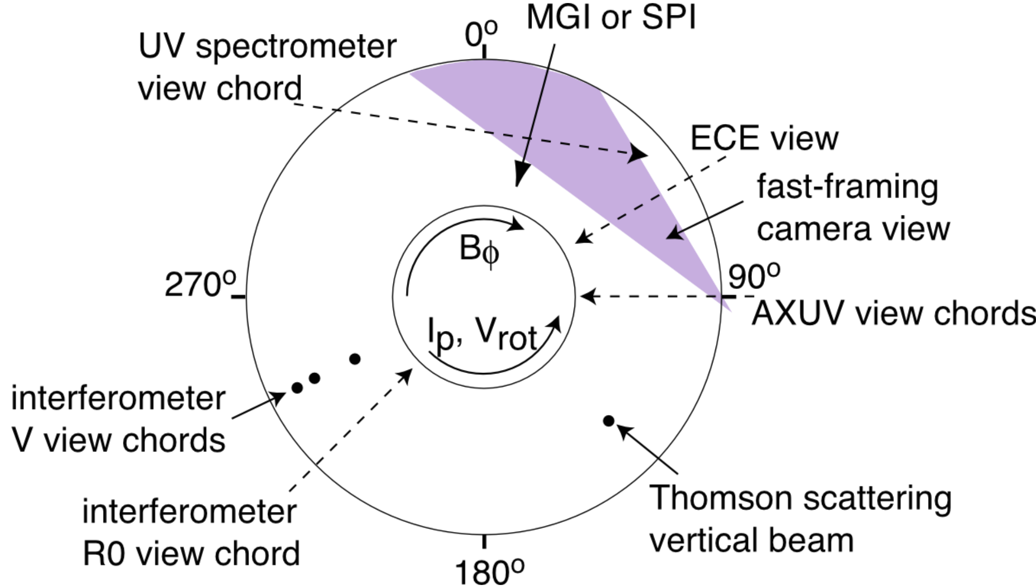
- For ITER: T_{e0} = 20keV ; n_{e0} = $1x10^{14}cm^{-3}$; a = 2 m ; rp0 = 3.5 mm ; Δn_e = $1x10^{16}cm^{-3}$

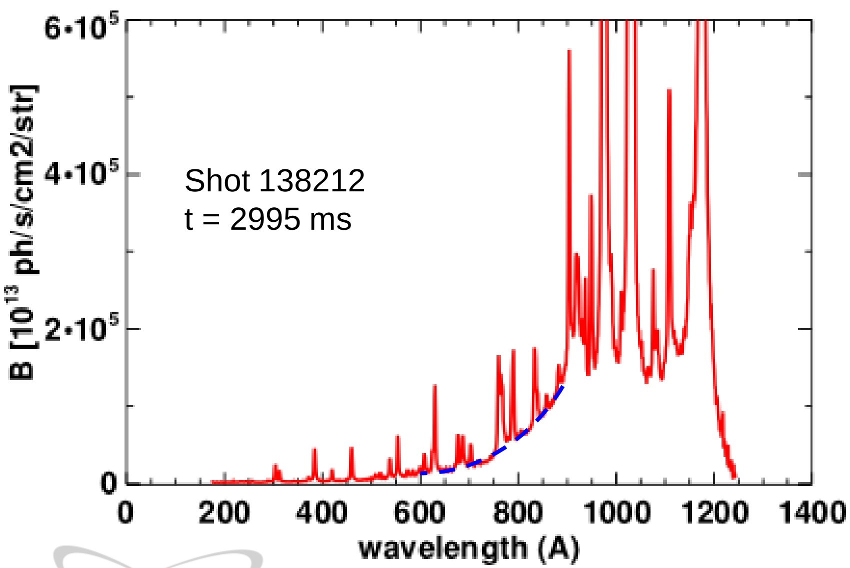
  The speed should be 505 m/s (realistic value)

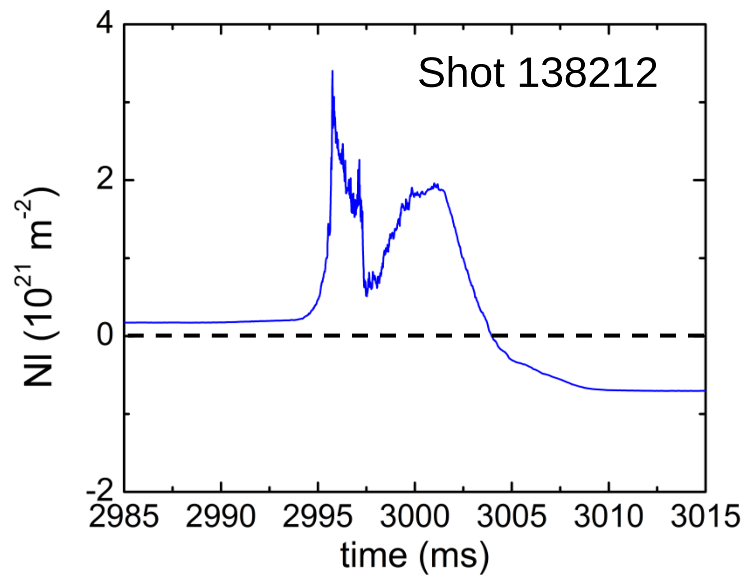
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Measuring the density: a real challenge

- **The interferometers are too slow for the density perturbation induced by the SPI: fringe skipping**
- **The only available density measurements are through spectrum analysis**







DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Several mitigation systems are available

Massive Gas Injection (MGI)

- Reduces both halo currents and heat loads
- **BUT**: weak assimilation (~15% on DIII-D) and penetration of the particles

Impurity pellet injection ("killer pellet")

- Reduces both halo currents and heat loads
- **BUT:** generates runaway electrons

Magnetic perturbation (RMP):

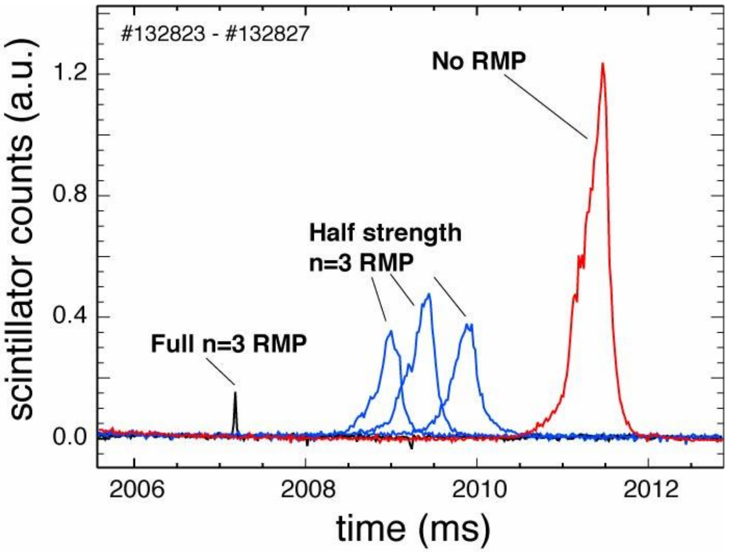
- Intended to de-confine the runaways before they reach dangerous energy levels

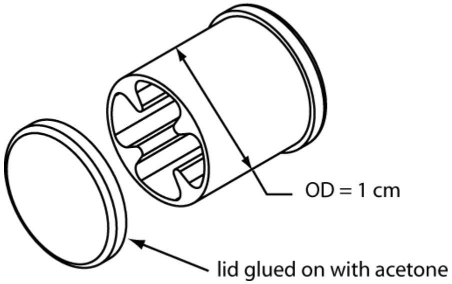
Shell pellet (plastic shell filled with impurity powder)

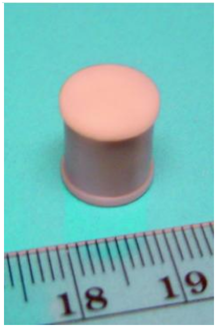
- Intended to disperse its payload in the core

Shattered pellet

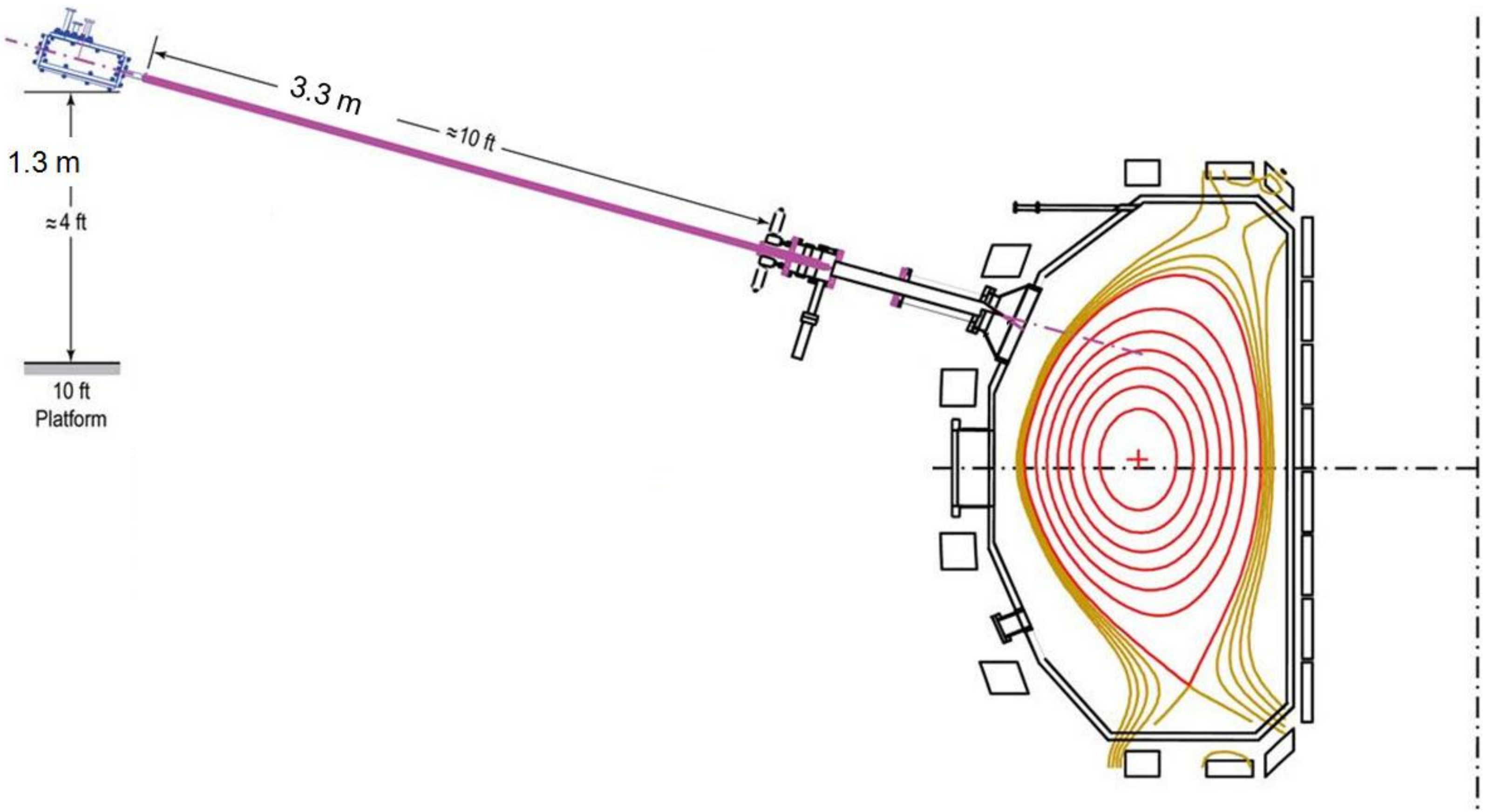
- Expected to improve the assimilation to damp the avalanche multiplication of the runaways by reaching the Rosenbluth density







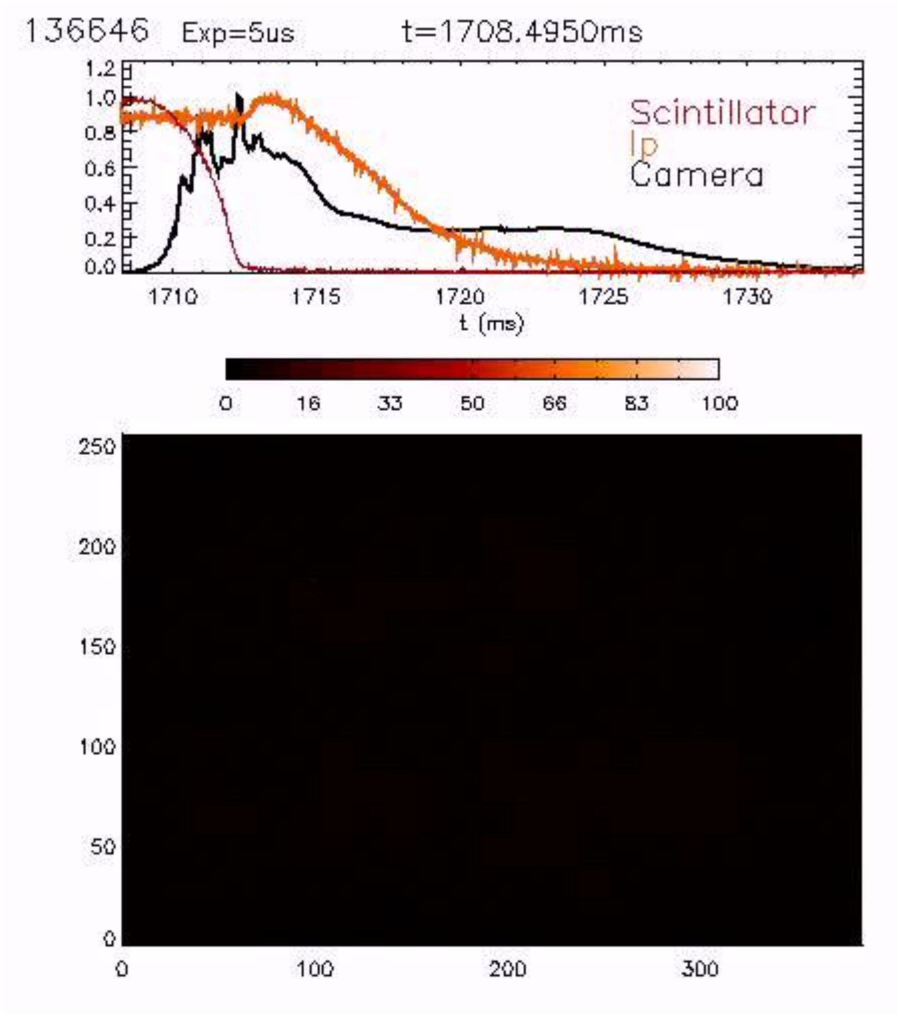
Implementation of the SPI on DIII-D



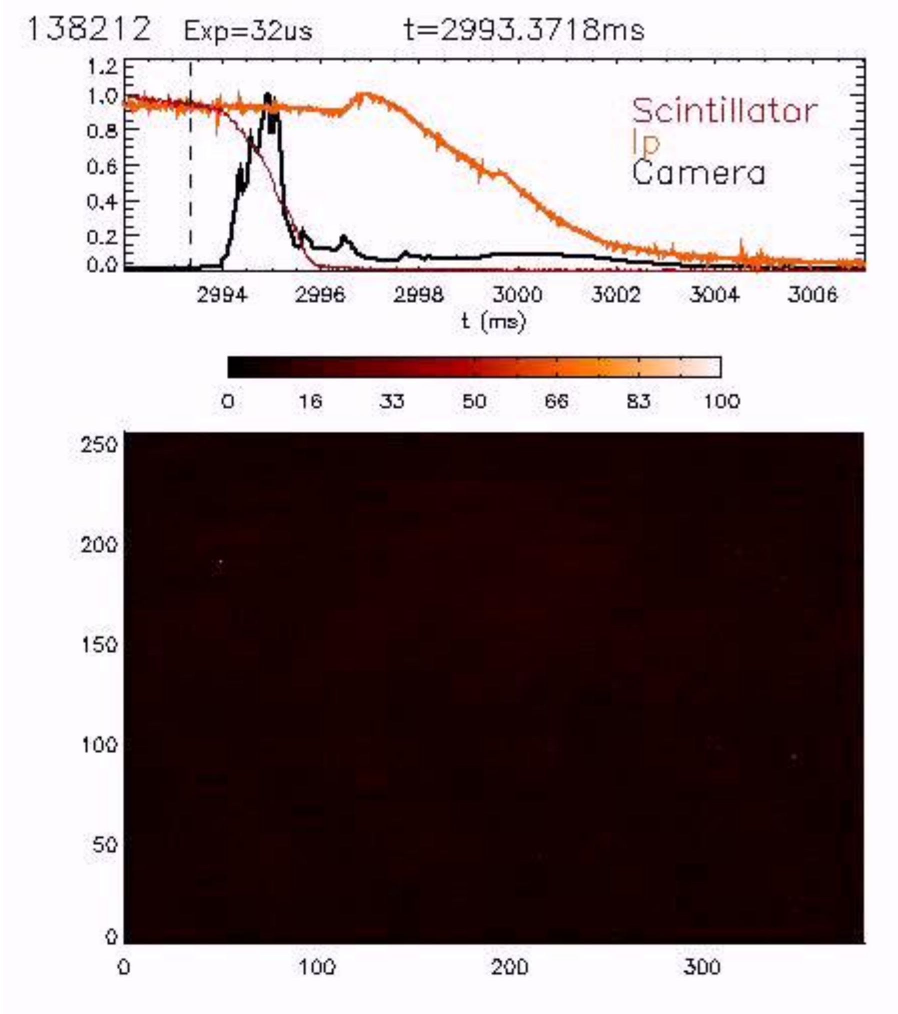
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Fast visible camera shows the pellet cloud penetrating deeper than Massive Gas Injection (MGI)

MGI



SPI



DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO