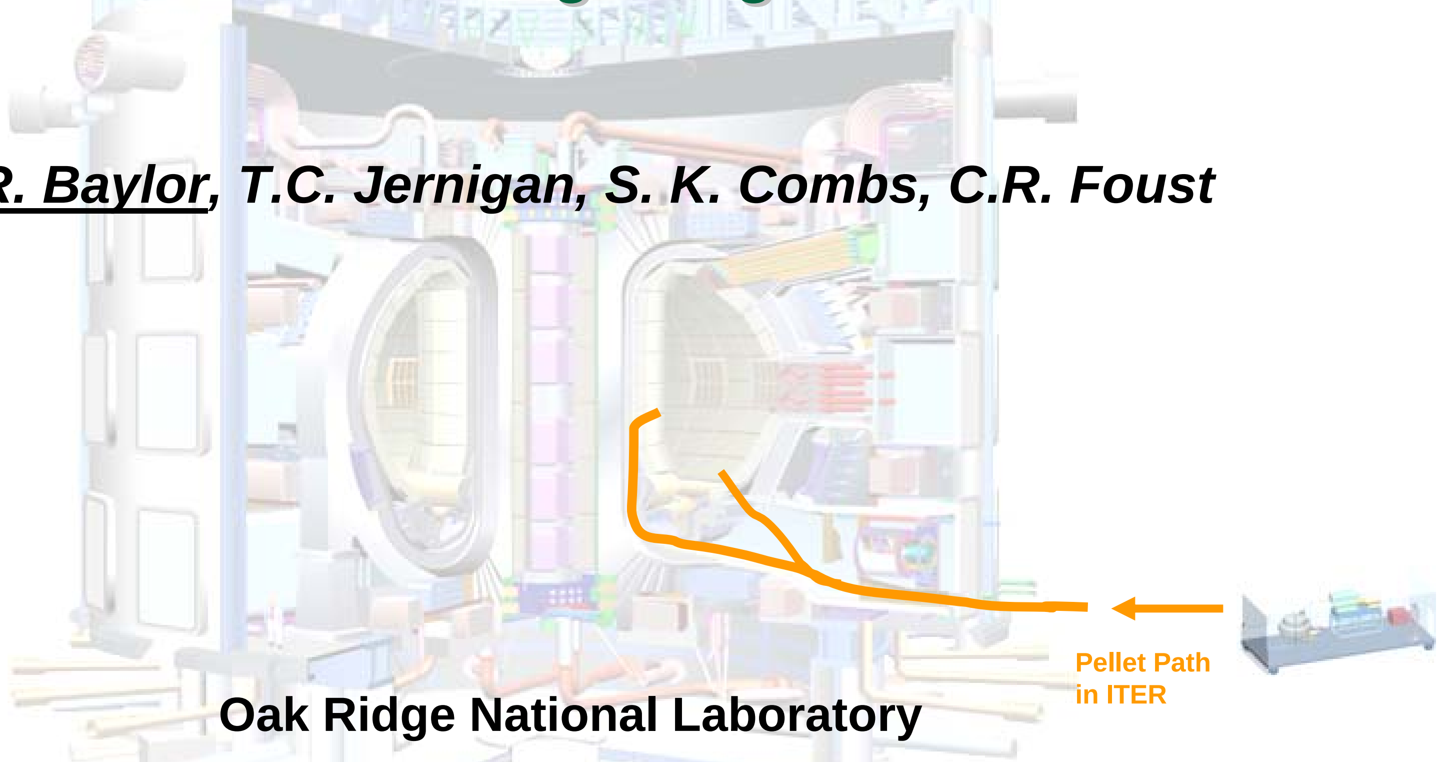
Edge Localized Modes in ITER - Pellet Pacing Mitigation

***L.R. Baylor*, T.C. Jernigan, S. K. Combs, C.R. Foust**



Oak Ridge National Laboratory

VLT Conference Call Highlight

19-Mar-2008

Overview

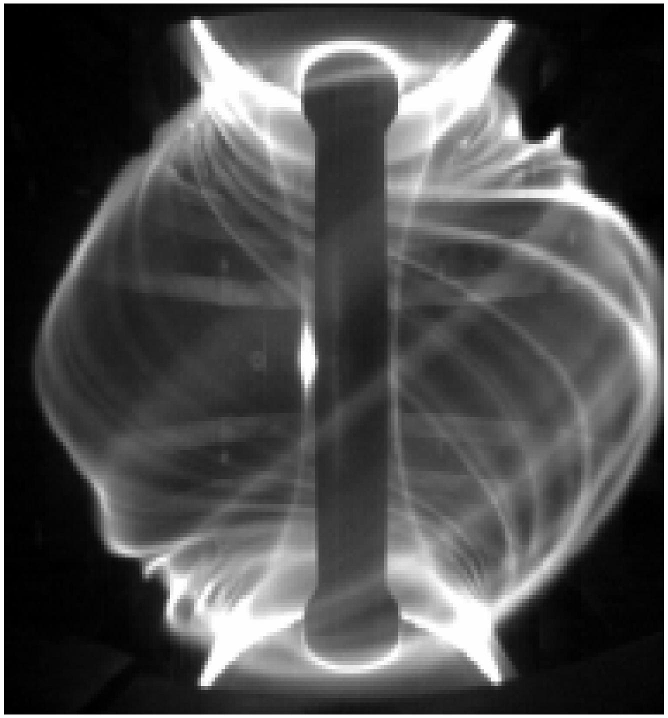
- **ITER has a potential significant ELM problem – erosion of divertor looks serious**
- **Methods to mitigate the ELM problem have been proposed:**
  - Resonant Magnetic Perturbations
  - Pellet ELM pacing
- **RMP suppresses ELMs on DIII-D, but in experiments thus far, ELMs return at high density**
- **Pellets injected from all locations are known to trigger ELMs - Why???**
- **DIII-D Pellet Dropper Installed to Investigate ELM pace making**
- **ELM pacing requirements for ITER are challenging**
- **Further research into pellets for ELM mitigation is ongoing also at JET and AUG.**

ITER ELM Challenge

Edge Localized Mode: periodic instability related to the H-mode edge transport barrier

- ELMs result from edge pressure clamped at ballooning limit – transient breakdowns of edge barrier – filaments are ejected from the plasma
- Significant fraction of the total plasma stored energy ~5% can be expelled by an ELM (>10 MJ on ITER)
- Significant erosion of plasma facing materials will occur for ELM bursts greater than 1 MJ.
- A method to eliminate or induce rapid small ELMs is badly needed for ITER.
- Compatibility of method with pellet fueling needs to be demonstrated.

http://www.jet.efda.org/pages/focus/elms/index.html

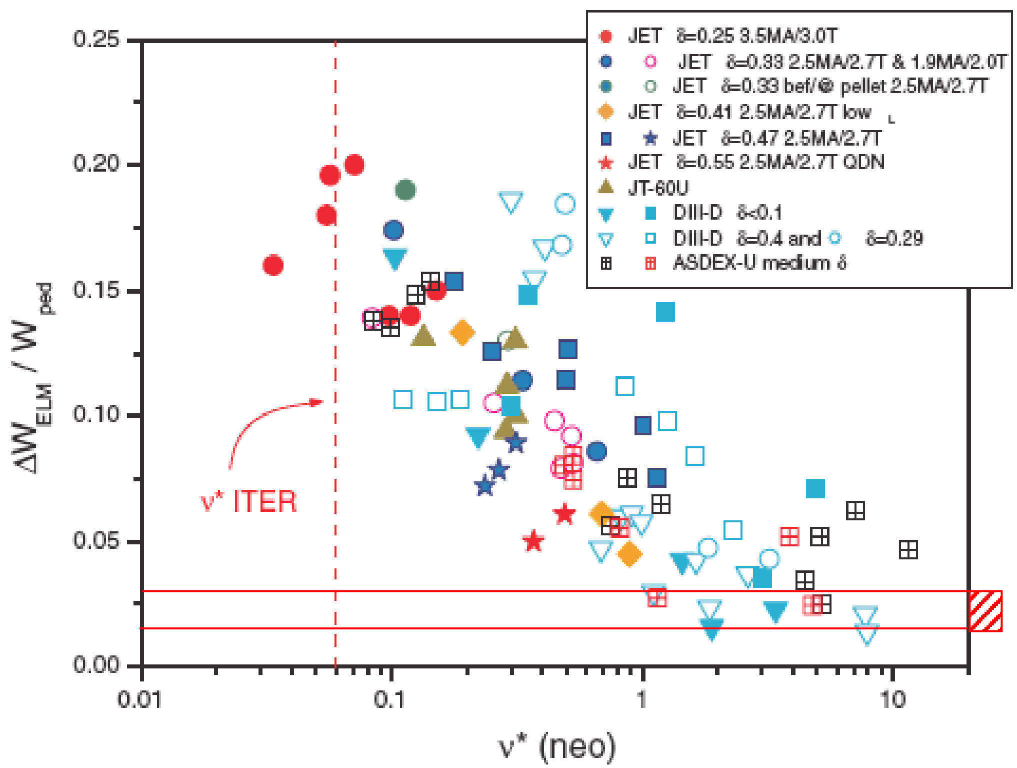


Filaments evolving during ELM on MAST. Kirk, et al. PRL 2004.

VLT Virtual Laboratory for Technology For Fusion Energy Science

Oak Ridge National Laboratory

Size of ELM Loss Predicted for ITER as much as 20 MJ



Loarte et al., Nuclear Fusion, ITER Physics Basis,Chapter 4

Minimum Acceptable Value (?)

Full performance ITER plasma W pedestal can be as much as 100 MJ leading to ~20 MJ ELM loss if ν^*_{ped} is the controlling parameter.

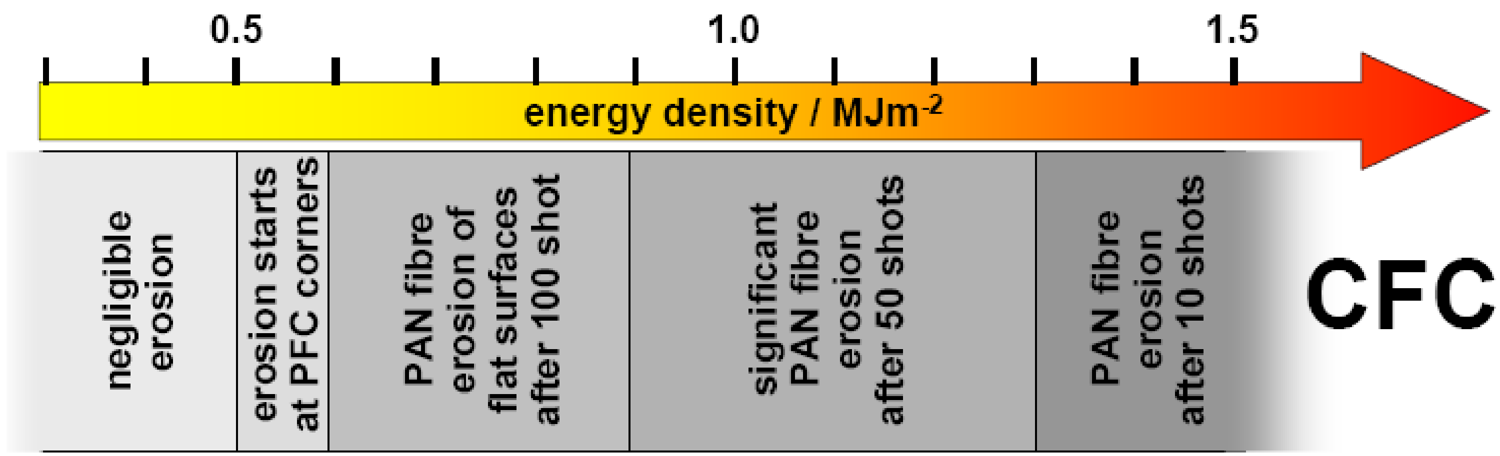
VLT Virtual Laboratory for Technology For Fusion Energy Science

OAK RIDGE National Laboratory

Erosion of ITER Divertor Tiles

CFC erosion is negligible for Q_{ELM} < 0.5 MJ/m²

[Zhitlukhin et al., JNM, 2007]



Noticeable mass losses of a sample took place at an energy density of 1.4 MJ/m²

Severe crack formation was observed at energy densities **≥ 0.7 MJ/m²** (cracking of pitch fibre bundles)

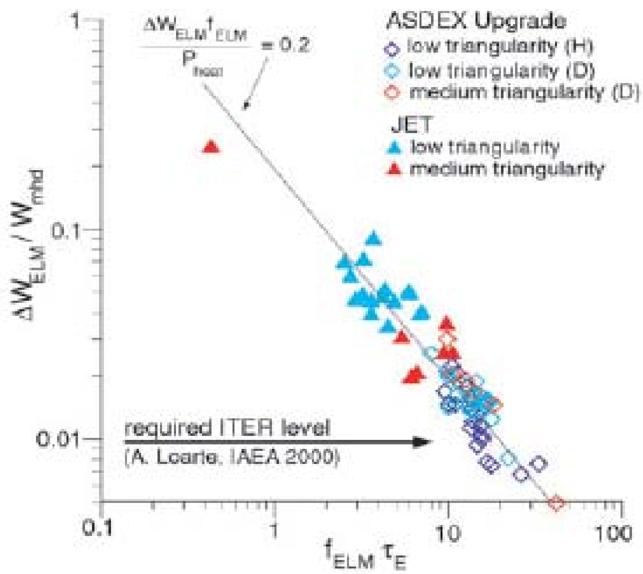
ITER SOL projection on the divertor plates is 3.0 m²

→ **ITER ELM size needs to be < 1.5 MJ for low erosion**

Tolerable ELM Energy Loss Dictates at Least 15 Hz ELMs

Scaling from JET and AUG shows:

$$\frac{\Delta W_{ELM}}{W_{tot}} = \frac{0.2}{f_{ELM}\ \tau_E} \quad \textbf{or} \quad \frac{\Delta W_{ELM}\ f_{ELM}}{P_{heat}} = 0.2$$



Hermann, PPCF 2002

If ΔW_{ELM} max = 1.5 MJ , then

$$f_{ELM} = \frac{0.2\, W_{tot}}{\Delta W_{ELM,\max}\ \tau_E}$$

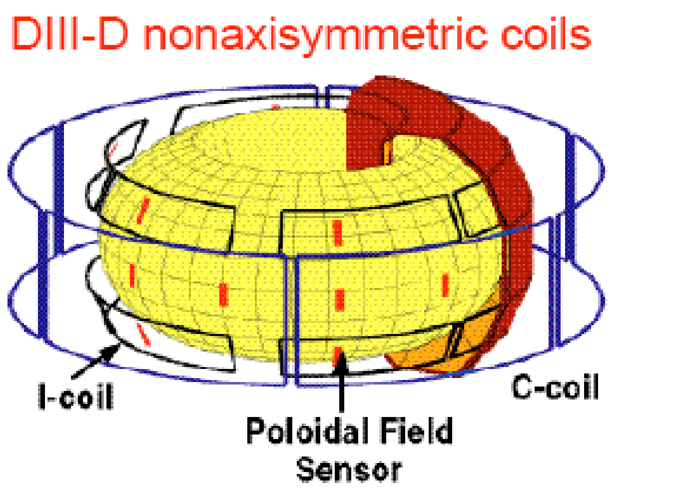
W_{TOT} / τ_E is expected in the range of 80-100 MW, therefore

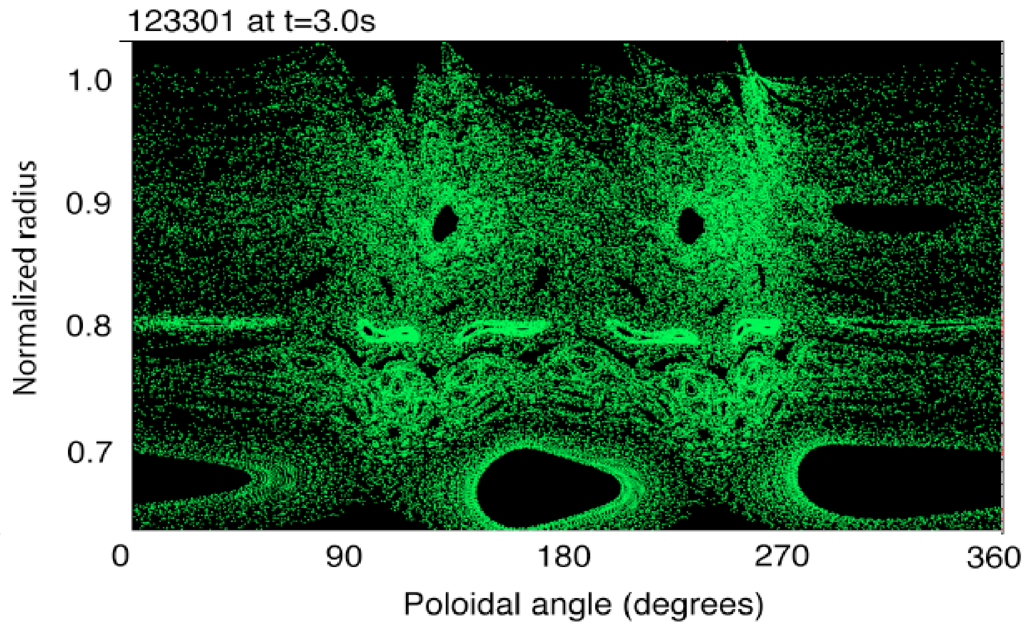
$$f_{ELM} \approx 15 - 20\ Hz$$

Overview

- **ITER has a potential significant ELM problem – erosion of divertor looks serious**
- **Methods to mitigate the ELM problem have been proposed:**
  - Resonant Magnetic Perturbations
  - Pellet ELM pacing
- **RMP suppresses ELMs on DIII-D, but in experiments thus far, ELMs return at high density**
- **Pellets injected from all locations are known to trigger ELMs - Why???**
- **DIII-D Pellet Dropper Installed to Investigate ELM pace making**
- **ELM pacing requirements for ITER are challenging**
- **Further research into pellets for ELM mitigation is ongoing also at JET and AUG.**

Resonant Magnetic Perturbation



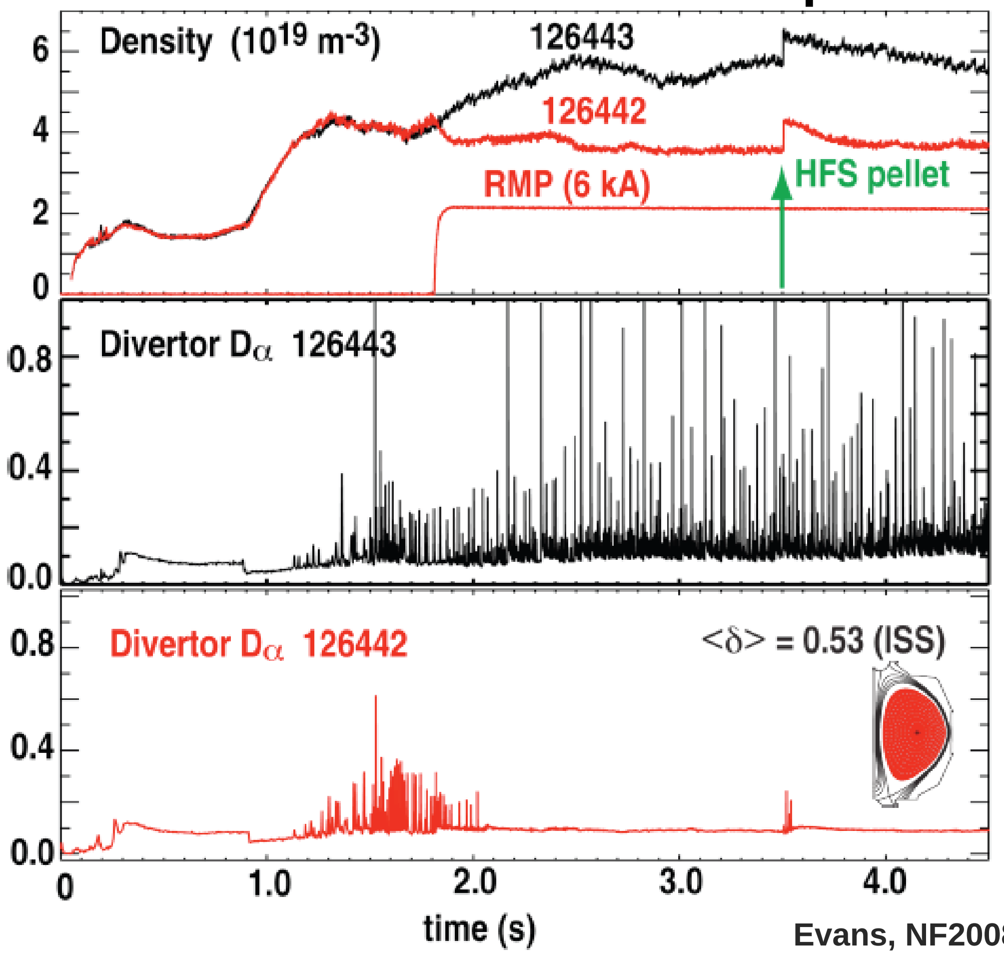


Evans, NF2008

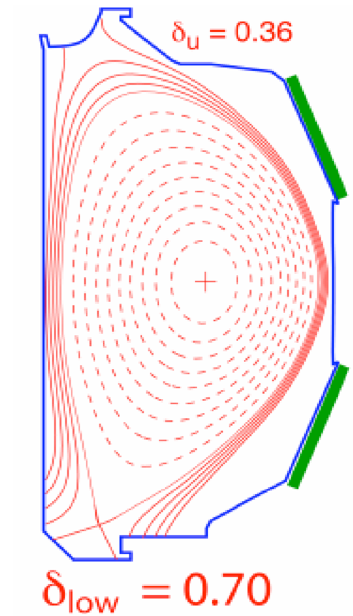
- RMP created by currents in external coils (I-coil on DIII-D) and results in stochastic magnetic fields in the plasma edge that affect the plasma edge profiles and can keep the edge pressure below the ballooning limit.

RMP Using Internal Coils Developed by Evans et al. is Successful at Eliminating ELMs with Reduced Density

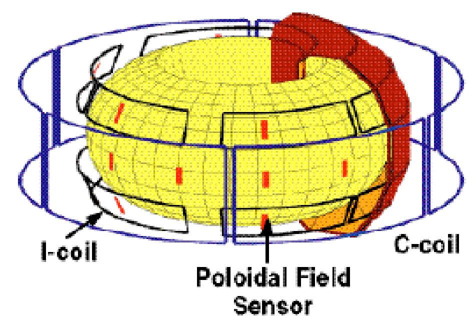
DIII-D RMP and non-RMP Comparison



Evans, NF2008



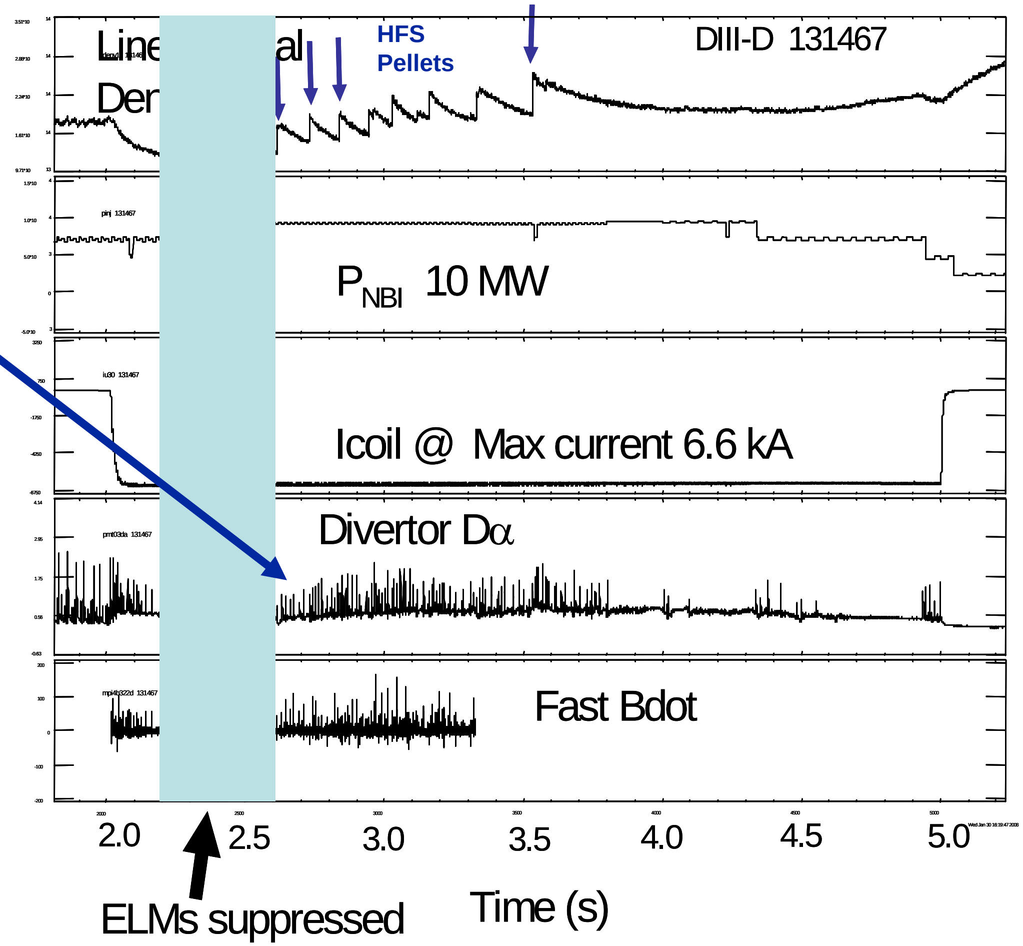
DIII-D nonaxisymmetric coils



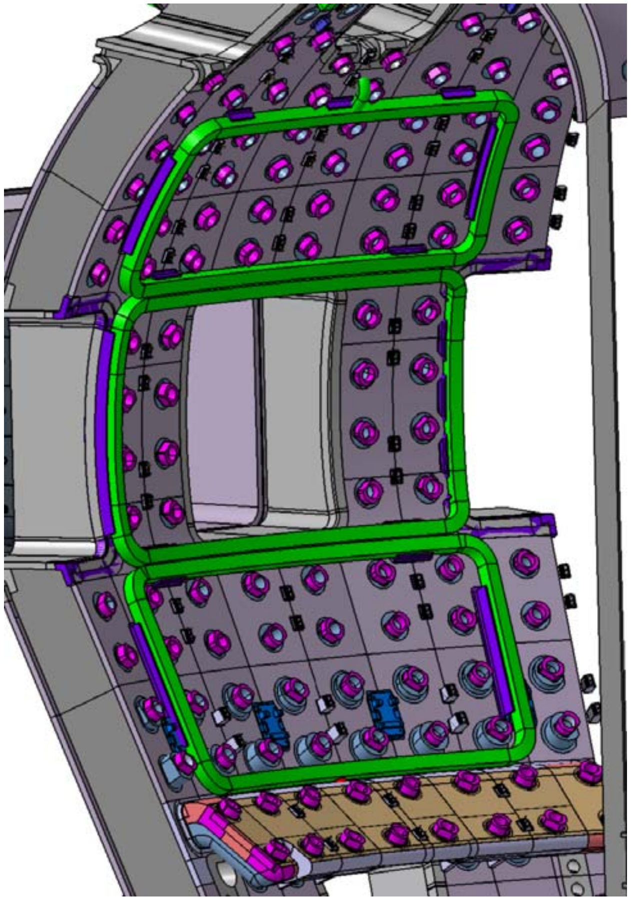
- RMP technique developed by Evans et al. is successful in ITER like collisionality and shape at eliminating ELMs.

Pellet Fueling During RMP Leads to ELMs when Density Increased

- Pellet Fueling (and gas fueling) into RMP ELM Suppressed plasmas can lead to a return to ELMs when high density is reached. (DIII-D result from Feb. 2008)
- In lower density cases with fewer pellets only a few ELMs are triggered by the pellets.
- Further research needed to demonstrate RMP ELM suppression at high density needed for ITER high Q_{DT}.



ITER RMP Coil Concept for Inside Vacuum Vessel

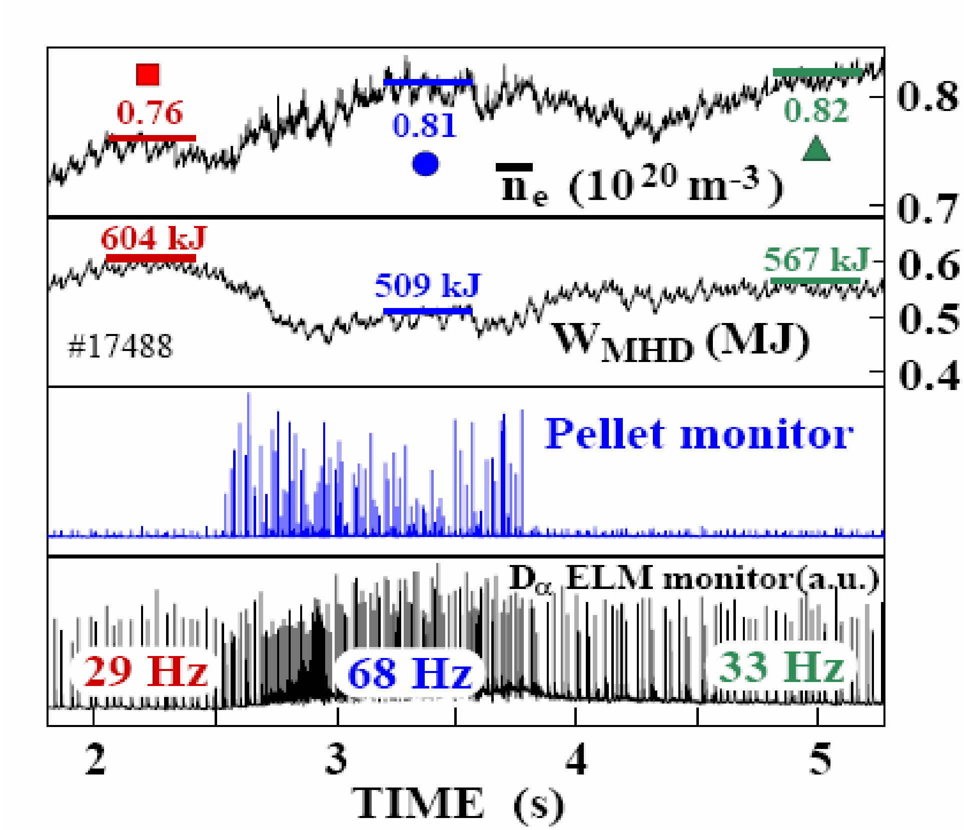


- Most likely scenario now looks like RMP Coils inside the vacuum vessel behind the blanket modules.
- Design Change /Fabrication may delay the VV delivery.
- RMP coils may also serve to add to vertical plasma stability and for RWM stabilization.

Overview

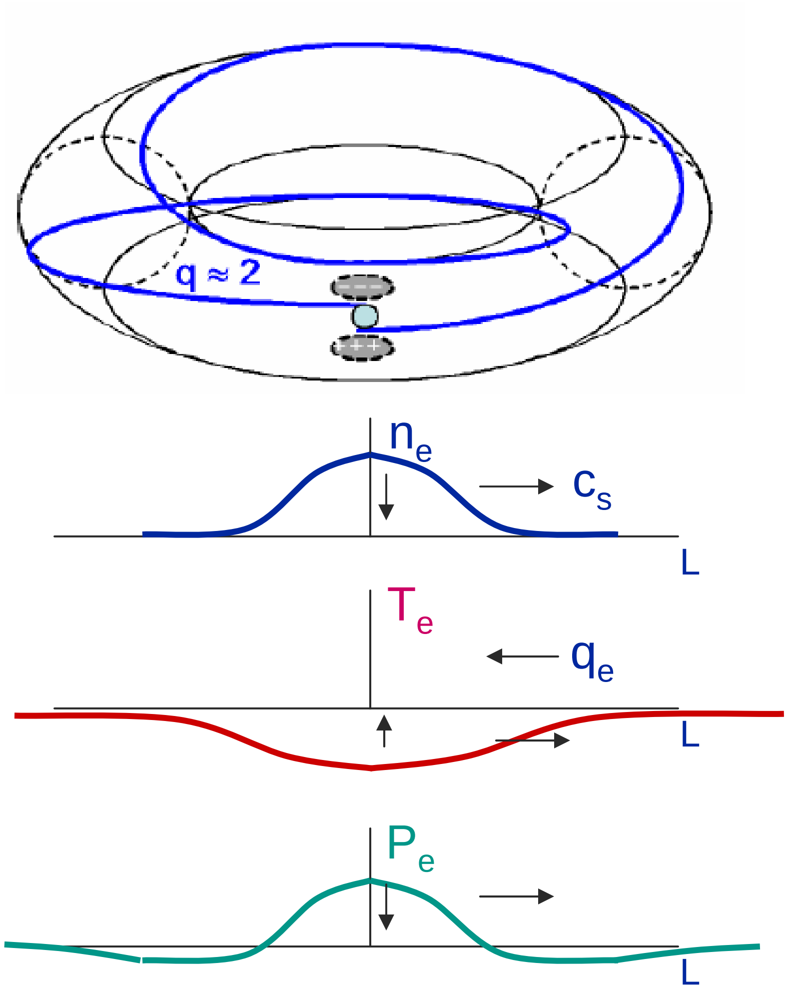
- **ITER has a potential significant ELM problem – erosion of divertor looks serious**
- **Methods to mitigate the ELM problem have been proposed:**
  - Resonant Magnetic Perturbations
  - Pellet ELM pacing
- **RMP suppresses ELMs on DIII-D, but in experiments thus far, ELMs return at high density**
- **Pellets injected from all locations are known to trigger ELMs - Why???**
- **DIII-D Pellet Dropper Installed to Investigate ELM pace making**
- **ELM pacing requirements for ITER are challenging**
- **Further research into pellets for ELM mitigation is ongoing also at JET and AUG.**

Pellet ELM Pacing Led to Higher ELM Frequency on AUG

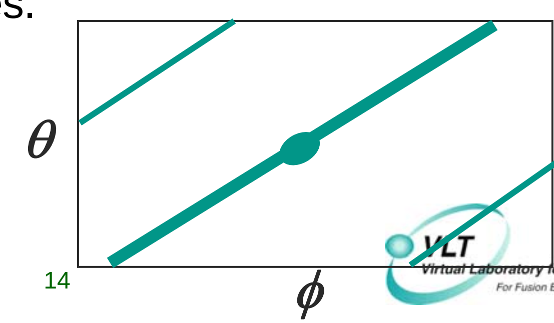


- Initial pellet ELM pacing shown for 1 second on AUG. (Lang et al NF 2004). Small fueling pellets injected from HFS doubled the natural ELM frequency.
- Further optimization needed to reduce strong fueling induced confinement decay and greatly increase the natural ELM frequency.

What Causes an ELM Trigger from a Pellet?



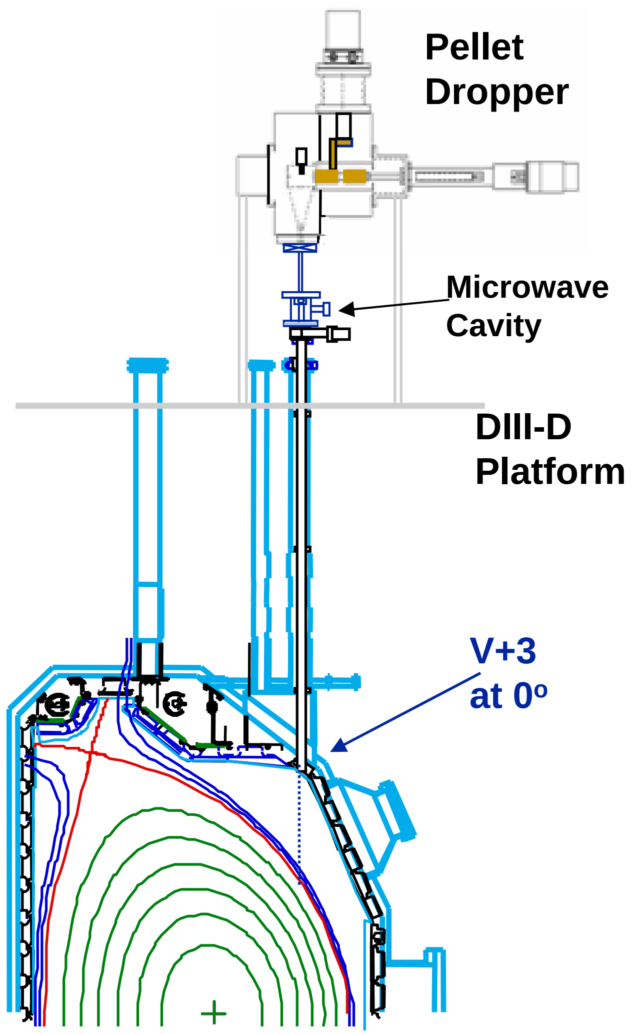
- Pellet cloud releases from pellet and expands along a flux tube.
- Density from the cloud expands along flux tube at the sound speed c_s.
- Temperature 'cold wave' travels along the flux tube at the thermal speed. Heat is absorbed in the cloud resulting in a temperature deficit far from the cloud.
- Pressure decays and expands along the flux tube with a lower pressure far from the cloud.
- Strong local cross field pressure gradients result along the flux tube that form on μs time scales.



Overview

- **ITER has a potential significant ELM problem – erosion of divertor looks serious**
- **Methods to mitigate the ELM problem have been proposed:**
  - Resonant Magnetic Perturbations
  - Pellet ELM pacing
- **RMP suppresses ELMs on DIII-D, but in experiments thus far, ELMs return at high density**
- **Pellets injected from all locations are known to trigger ELMs - Why???**
- **DIII-D Pellet Dropper Installed to Investigate ELM pace making**
- **ELM pacing requirements for ITER are challenging**
- **Further research into pellets for ELM mitigation is ongoing also at JET and AUG.**

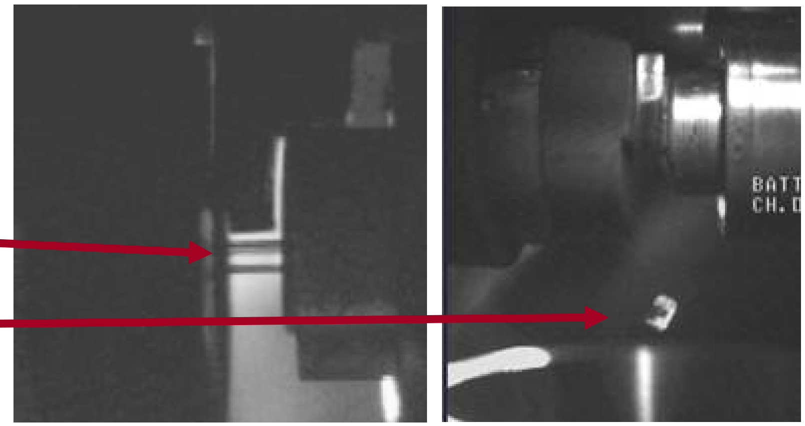
Pellet Dropper for ELM Triggering on DIII-D



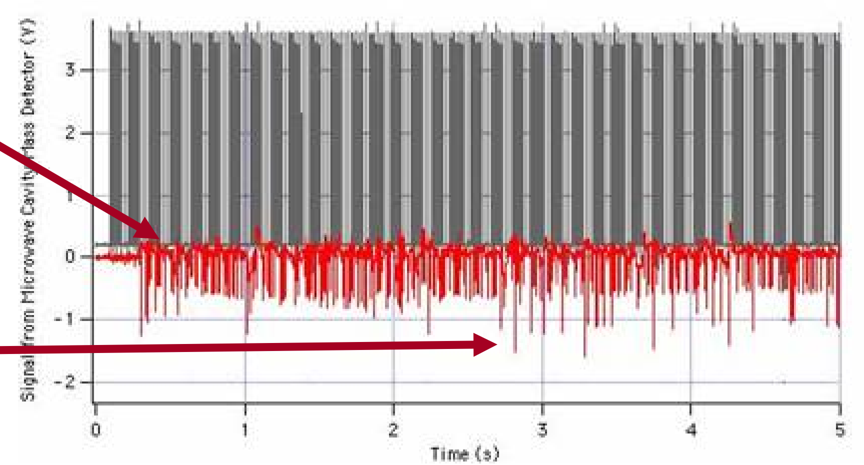
- The pellet dropper was developed from existing equipment to make a simple ELM trigger tool.
- It uses a batch extruder with pellet cutter to supply sub 1mm D_2 pellets at up to 50 Hz for triggering ELMs on DIII-D
- Natural ELM frequency on DIII-D can be as low as 10 Hz
- The extruder is cooled with a G-M cryocooler and LN_2 for simplified installation
- Gravity acceleration limits pellet speeds to ~ 10 m/s
- Low speed and small pellet size minimize fueling, but should make strong enough density perturbations to trigger ELMs

Test Results of Pellet Dropper Show 50 Hz Operation for 5 Sec

- The Pellet Dropper has been optimized DIII-D environment
  - Careful thermal design and gas handling required
  - Extrusions of 5+ sec duration routinely produced
  - ~1mm pellets dropped at 5 m/s

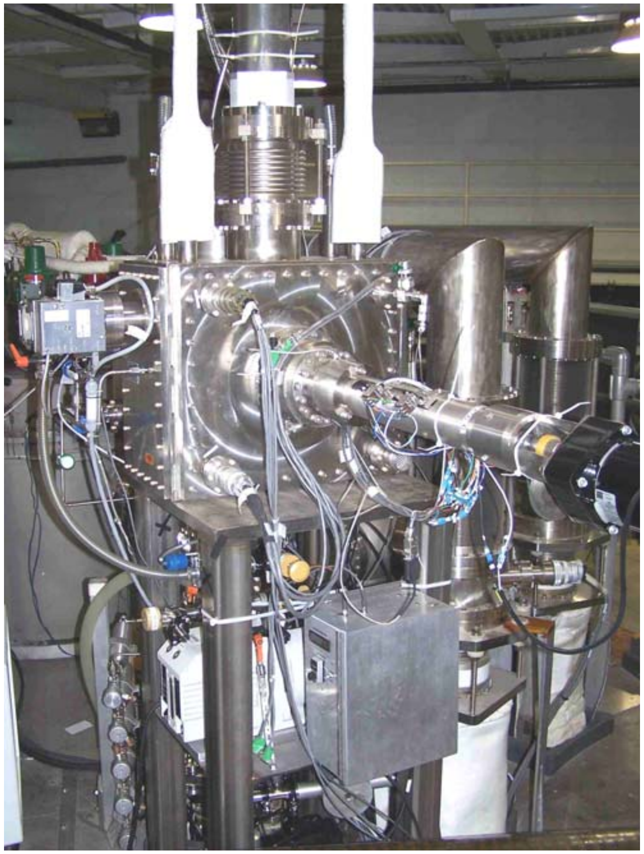


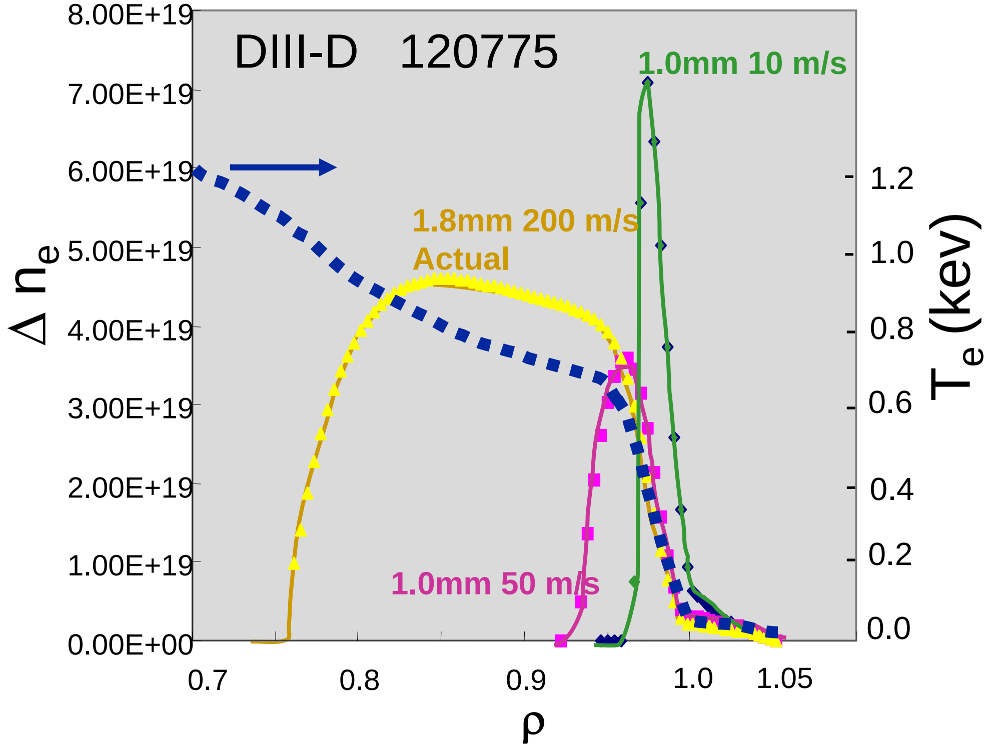
- Pellet cutting and dropping at 50 Hz achieved
  - Vertical negative going spikes are pellets dropping through a microwave cavity. Signal level proportional to mass.
  - Some clumping of pellets producing larger signals and uneven spacing occurs. Pellets are less than 1 mg!



COMBS, SOFE 2007

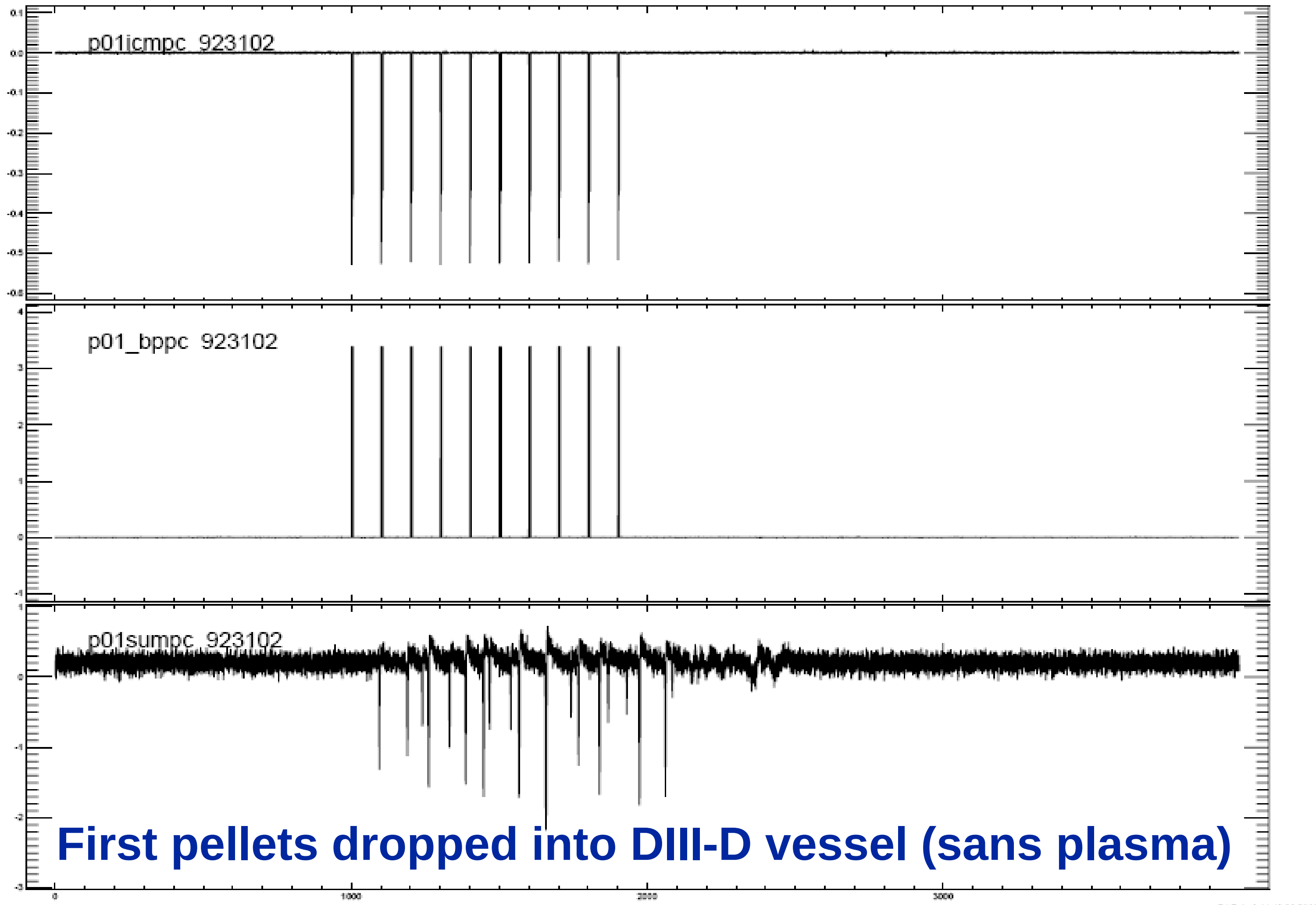
Pellet Dropper Now Mounted on DIII-D





- **NGS ablation model shows pellets should nearly reach T_e pedestal in DIII-D H-mode. Good simulation of expected ITER 3mm pellet penetration depth.**
- **Initial operation will be to determine penetration depth and ELM triggering.**

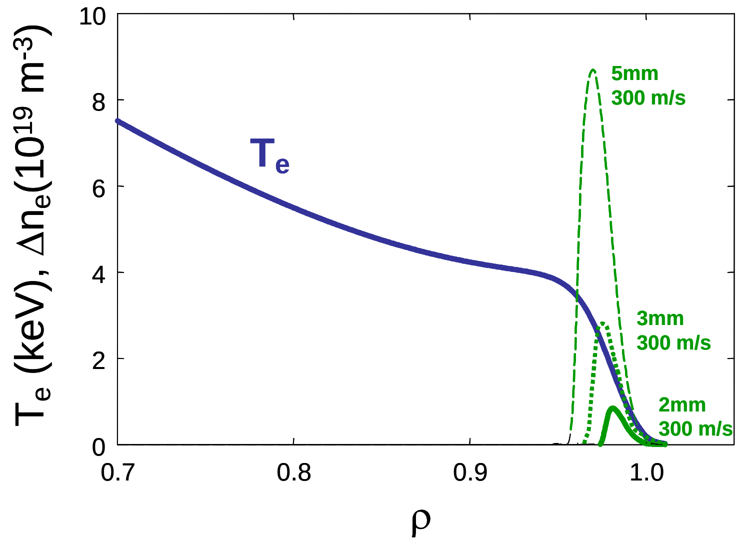
Pellet Dropper Operational on DIII-D

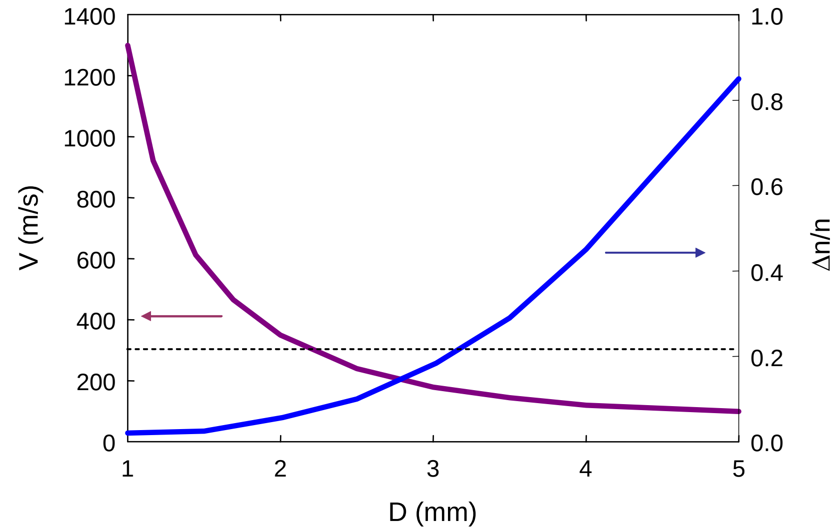


Overview

- **ITER has a potential significant ELM problem – erosion of divertor looks serious**
- **Methods to mitigate the ELM problem have been proposed:**
  - Resonant Magnetic Perturbations
  - Pellet ELM pacing
- **RMP suppresses ELMs on DIII-D, but in experiments thus far, ELMs return at high density**
- **Pellets injected from all locations are known to trigger ELMs - Why???**
- **DIII-D Pellet Dropper Installed to Investigate ELM pace making**
- **ELM pacing requirements for ITER are challenging**
- **Further research into pellets for ELM mitigation is ongoing also at JET and AUG.**

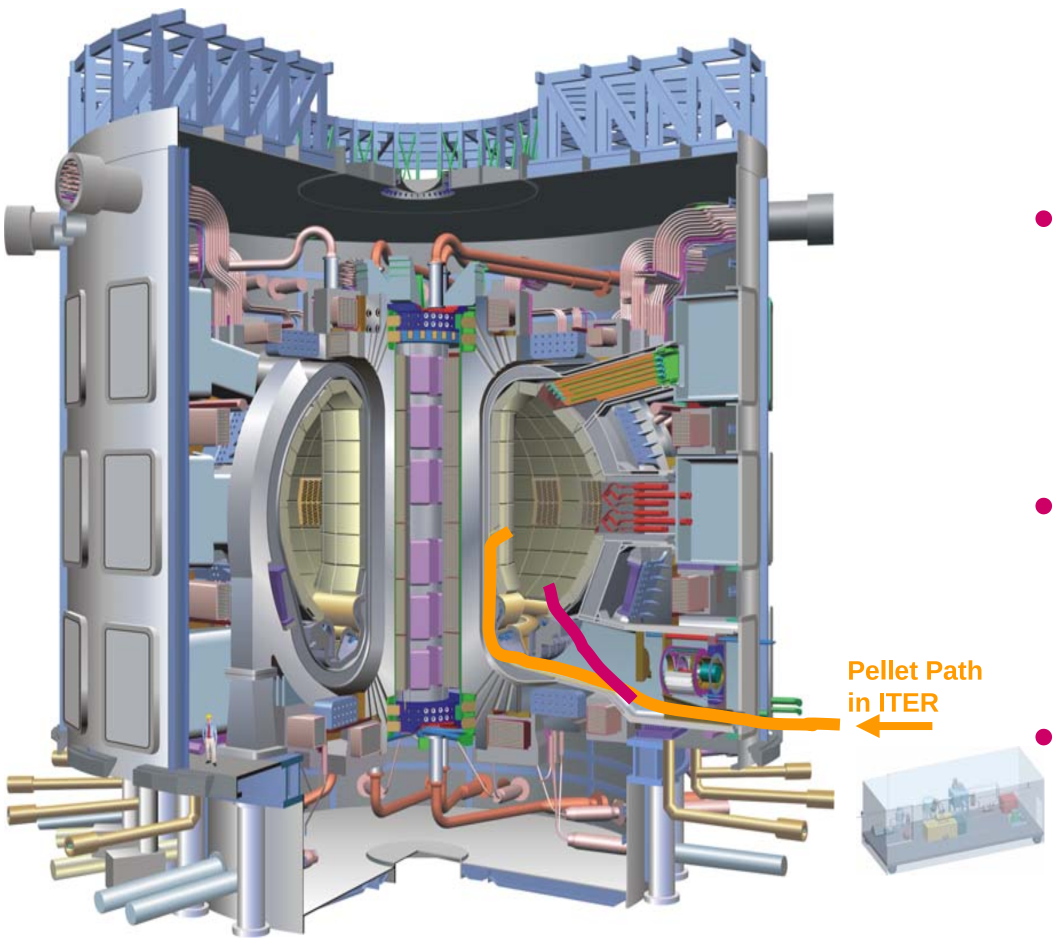
ITER Pellet ELM Triggering May Provide Tool for ELM Amelioration





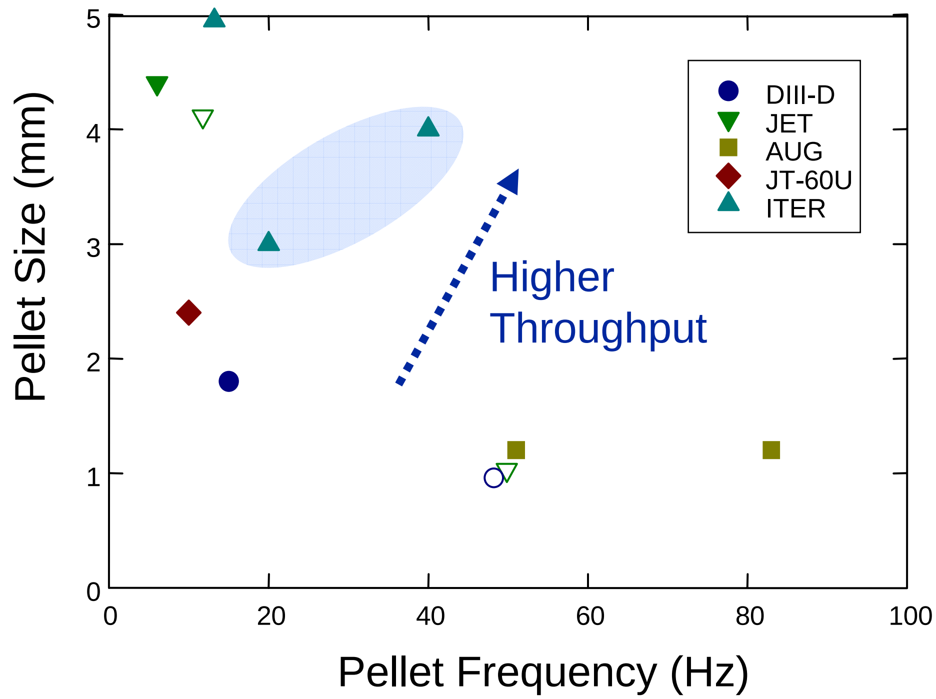
- NGS ablation model in PELLET code shows 300 m/s 3mm pellets should nearly reach T pedestal in ITER H-mode (4 keV pedestal T_e).
- Figure on right shows pellet size necessary to reach half of pedestal height as a function of cylindrical pellet size. The local pellet density perturbation size is shown in blue curve.

ITER Pellet Fueling and ELM Pacing Challenges



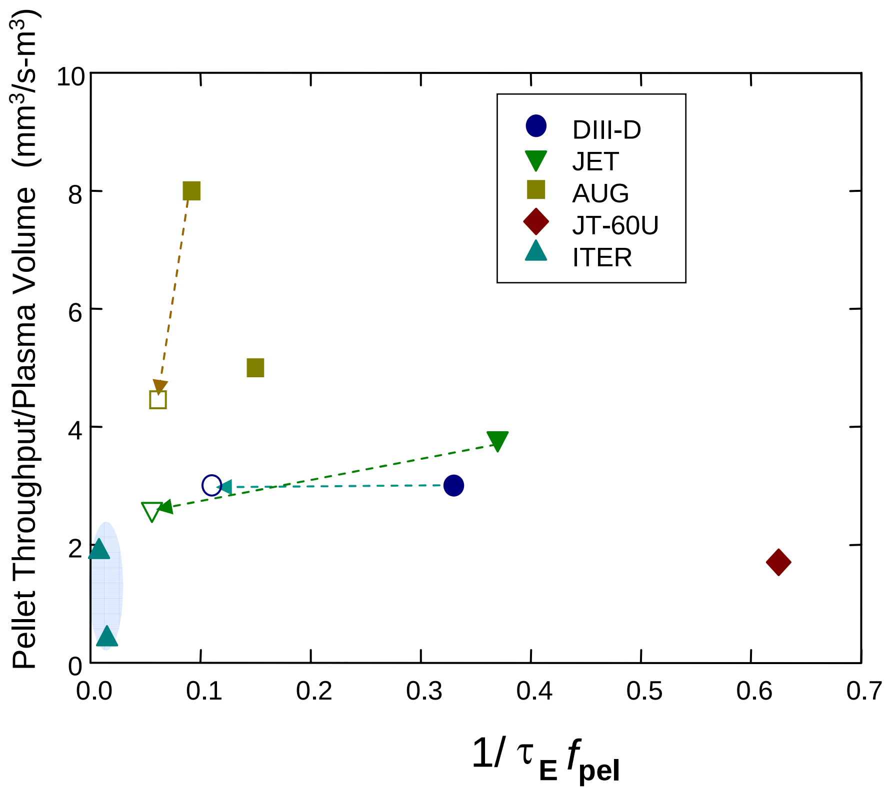
- **ITER will have 2 pellet injectors that each provide D_2, DT, T_2 pellets (5mm @ ~10Hz, 3mm @ ~30Hz).**
- **Inside wall pellet injection for efficient fueling beyond the pedestal utilizing a curved guide tube. Maximum pellet survival speed is 300 m/s.**
- **Pellet injector must operate for up to 1 hour continuously and produce ~ 1.5 cm^3/s (0.3 g/s) of ice.**
- **A LFS tube is being added for pellet ELM pacing. Pellet speed maximum probably ~500 m/s.**

Pellet Throughput in Present Experiments Well Below That Projected for ITER Pellet ELM Pacing



- The anticipated pellet throughput for ITER pellet ELM pacing is well above that in present day experiments. (Technically challenging)
- A multi-barrel injection system is likely needed to meet this high ITER throughput requirement.
  (Pellet sizes are cylindrical equivalent)

Pellet Normalized Throughput in Present Experiments is Heading Toward Projected ITER Pellet ELM Pacing Conditions



ITER range covers: 3mm@20 Hz – 4mm@40Hz

- The normalized pellet throughput from current pacing and fueling experiments is far from the projected operating point.
- The planned pellet ELM pacing experiments on JET, DIII-D, and AUG are all planning to be in a regime that is more ITER relevant in terms of normalized throughput and pellet time scaled to energy confinement time.

Summary

- **ITER will require ELM mitigation in order to complete its mission**
- **RMP for ELM suppression needs further optimization to be compatible with high density operation and pellet fueling**
- **ELM triggering by small LFS pellets a promising but unproven technique for ITER**
  - Further research to optimize and understand physics of pellet induced ELMs and ELM energy loss is required
  - ELM pacing research is ongoing on DIII-D, JET, and AUG and should provide data to extrapolate to ITER
- **The pellet injection system for ITER fueling and ELM pacing presents challenges for the technology in throughput and reliability**
  - Development is underway and expected to take ~ 4 yrs
  - Extruder and accelerator prototypes will be produced which can be available to test on existing tokamak devices