Pellet Fueling Technology Leading to Efficient Fueling of ITER Burning Plasmas

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in collaboration with

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at the

Burning Plasma Workshop

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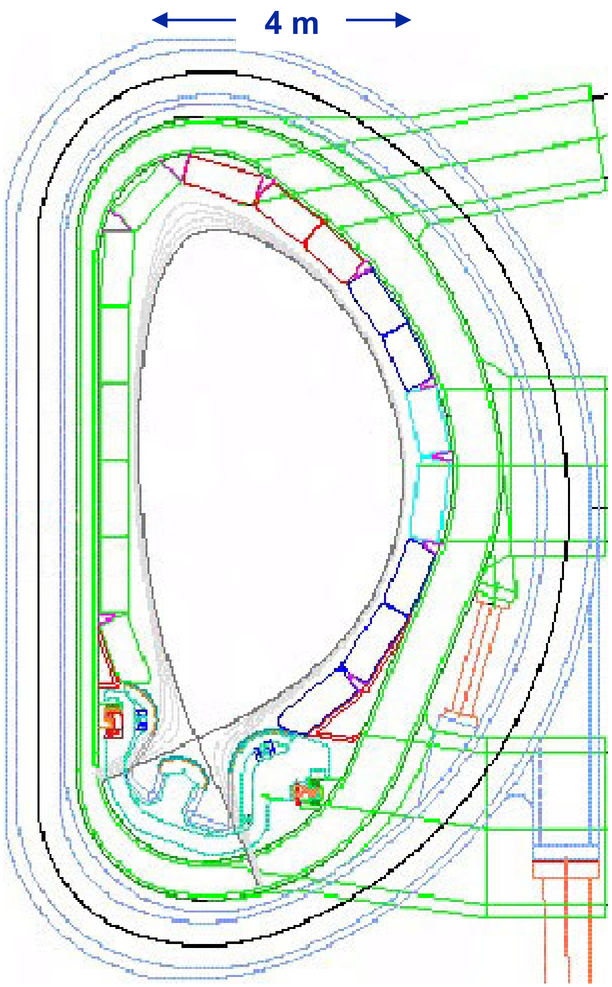
Overview

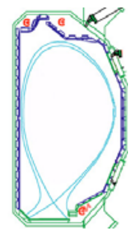
- **ITER requires significant fueling capability to operate at high density for long durations**
- **Gas fueling will not be able to sustain high density in ITER due to limited neutral penetration in the thick dense scrape off layer**
- **Pellet fueling from the inner wall looks promising for core fueling with high efficiency despite limited pellet speeds**
- **The ITER pellet injection system requires capabilities well beyond the current state-of-the-art**
  - Throughput enhancement of nearly an order of magnitude
  - Reliability at high repetition rate is required for BP control
- **The use of pellets for ELM triggering and amelioration remains a possibility for ITER**
  - Understanding pellet interaction with NTMs, ELMs, RWMs etc needed

ITER Fueling Needs are Significant



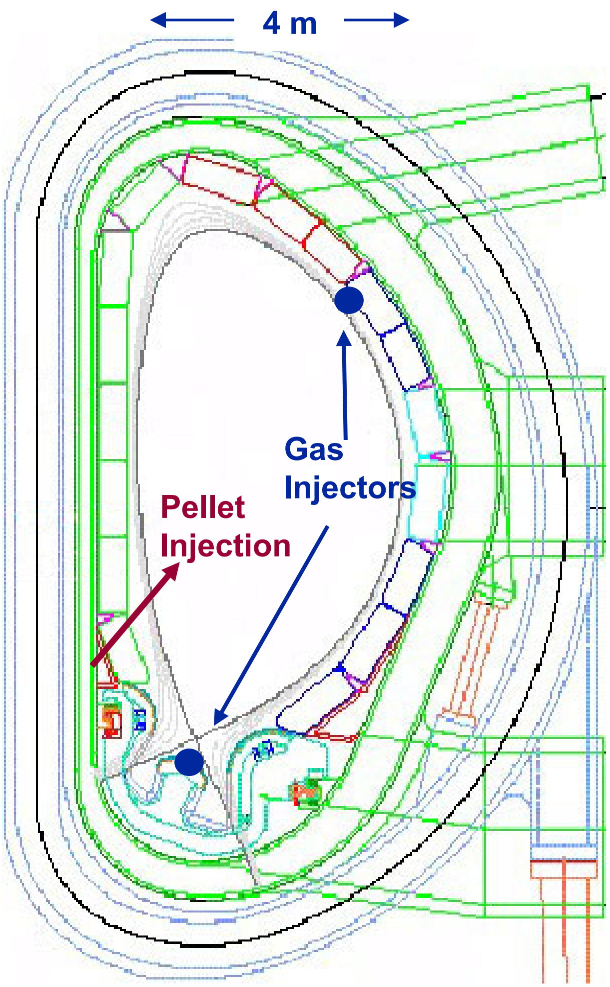
ITER Cross Section

- ITER plasma volume is 840 m^3 and scrape-off layer is ~20 cm thick. This compares to 20 m^3 and ~ 5 cm for DIII-D.



DIII-D Cross Section

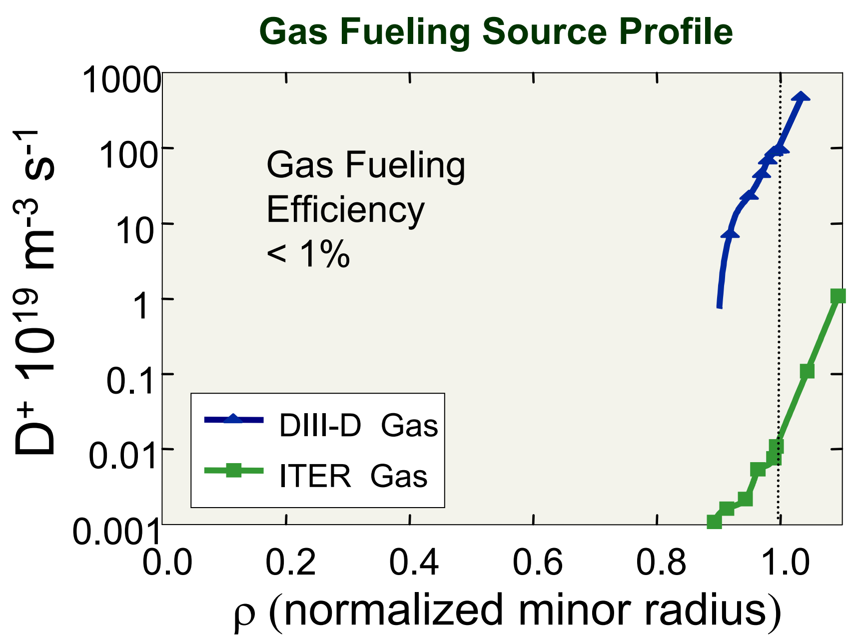
ITER Fueling Needs are Significant



ITER Cross Section

- ITER plasma volume is 840 m^3 and scrape-off layer is ~30 cm thick. This compares to 20 m^3 and ~ 5 cm for DIII-D.
- ITER is designed to operate at high density (> 1x 10^{20} m^{-3}) in order to optimize Q.
- Gas to be introduce from 4 ports on outside and 3 in the divertor region
- NBI fueling to be negligible (< 2 x 10^{20} atoms/s or < 3 torr-L/s)
- Inside wall pellet injection planned for deep fueling and high efficiency. Reliability must be very high.
- Pellet injector must operate for up to 1 hour continuously and produce up to 4500 cm^3 of DT ice per discharge.

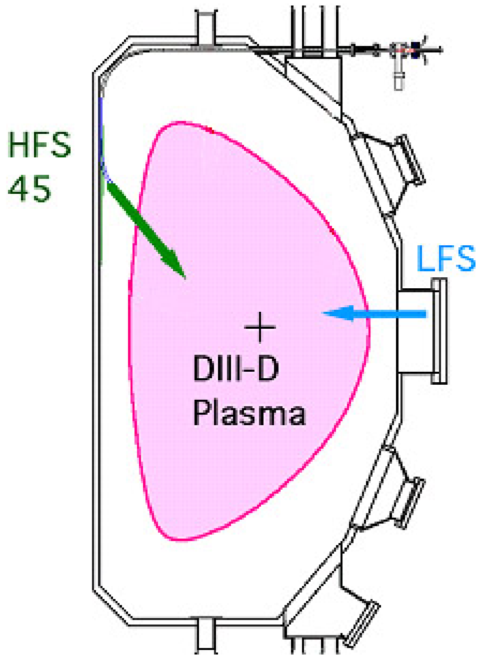
Gas Fueling in ITER is Much Less Efficient than in Current Machines

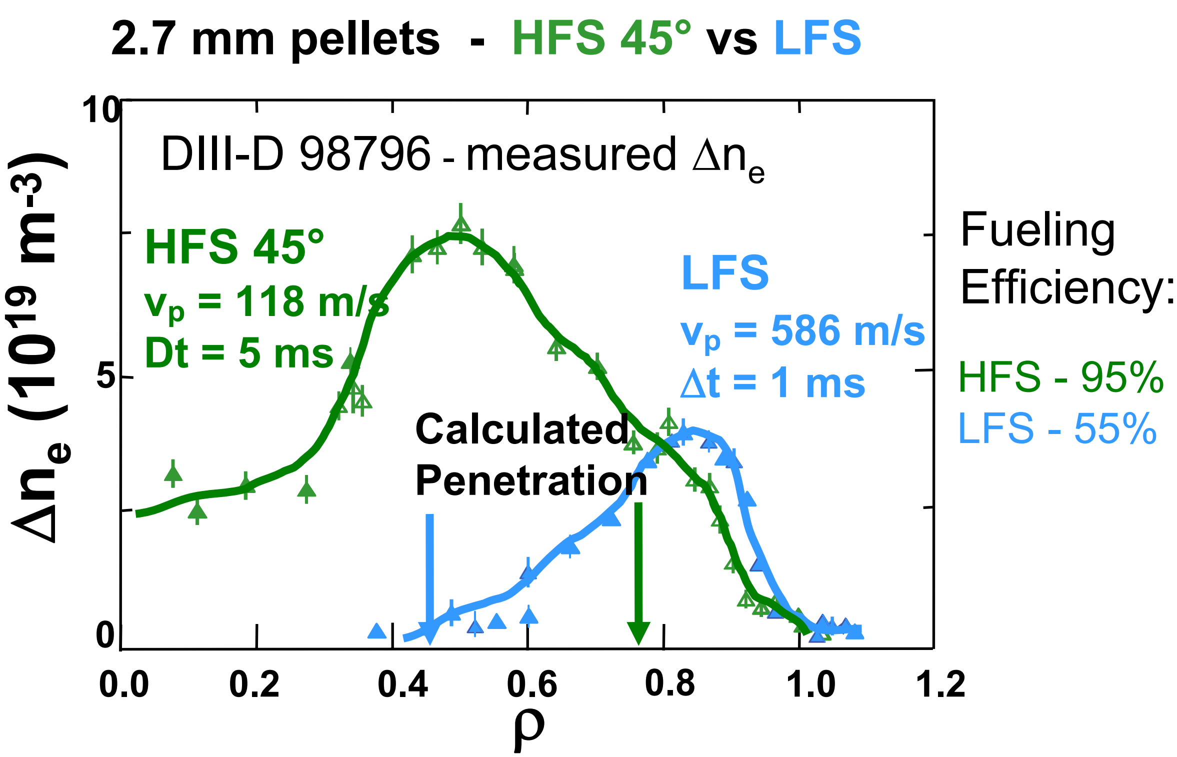


Fueling efficiency is $\Delta N_{plasma} / N_{source}$

- **This B2-Eirene slab calculation shows that gas puff core fueling in ITER will be much less effective than in current experiments such as DIII-D.**
  - **Gas fueling rate of 100 torr-L/s for DIII-D**
  - **Gas fueling rate of ~1000 torr-L/s for ITER case** **(L. Owen and A. Kukushkin)**
    (see also Kukushkin & Pacher, Plasma Phys. Control. Fusion 44, 931, 2002)

Pellet Injection from Inner Wall Looks Very Promising for Tokamak Plasma Fueling

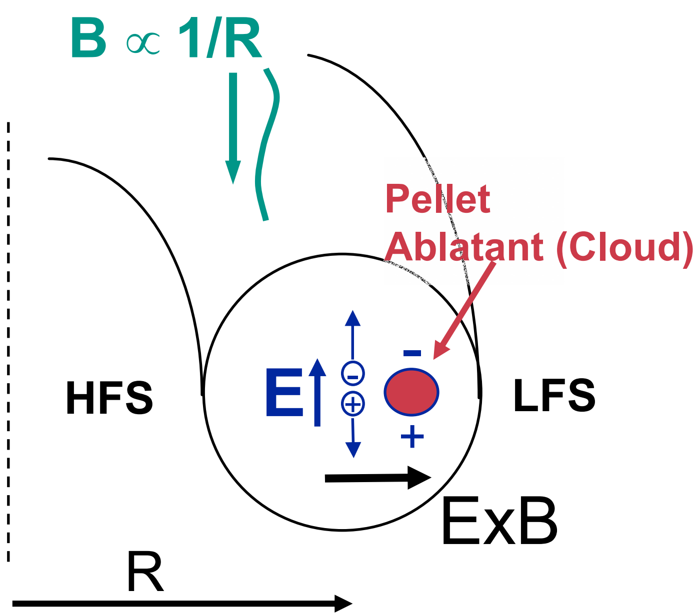




- Net deposition is much deeper for HFS pellet in spite of the lower pellet velocity used to survive curved guide tube
- Pellets injected into the same discharge and conditions (ELMing H-mode, 4.5 MW NBI, $T_e(0)$ = 3 keV)

Theoretical Model for Pellet Radial Mass Drift

ExB Polarization Drift Model of Pellet Mass Deposition (Rozhansky, Parks)



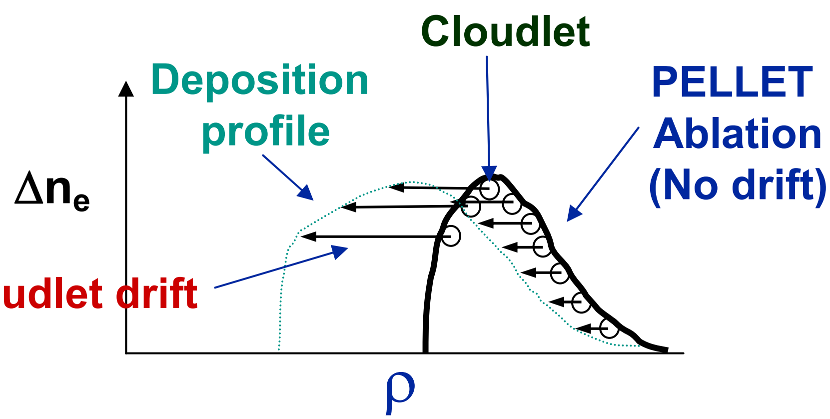
- Polarization of the ablatant occurs from ∇B and curvature drift in the non-uniform tokamak field:

$$\vec{v}_{\nabla B} = \frac{W_\perp + 2W_\parallel}{eB^3}\vec{B}\times\overrightarrow{\nabla B}$$

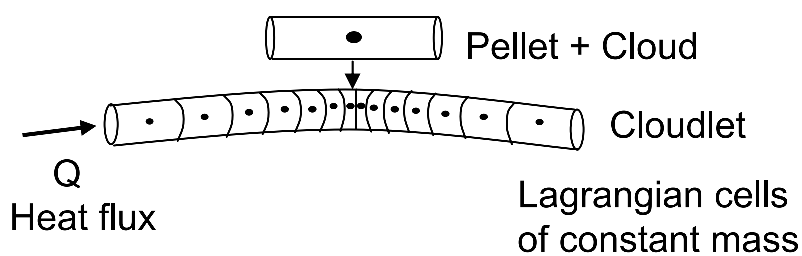
- The resulting E yields an ExB drift in the major radius direction, $V_\perp = (ExB)/B^2$
- $J_{\nabla B} = -2p/RB$ and this balances the polarization return current $J_p = (\rho/B^2)\ dE/dt$. (p is cloud pressure and ρ is cloud density)
- Therefore the pellet cloud motion equation is $dV_\perp/dt = 2p/\rho R$
- ΔR drift distance is stronger at higher plasma β due to higher cloud pressure
- Detailed model by P.B. Parks, [Phys. Rev. Lett. 94, 125002 (2005)].

Pressure Relaxation Lagrangian (PRL) Code Solves Coupled Drift and Parallel Dynamics for a Series of Cloudlets

- The PRL code uses the pellet size and plasma parameters at each point along the ablation track determined by PELLET code [Houlberg, Nucl. Fusion 1988] to initialize the cloudlet parameters using model of Parks, et al. 10-20 cloudlets are assumed per pellet. [see Phys. Rev. Lett. 94, 125002 (2005)].



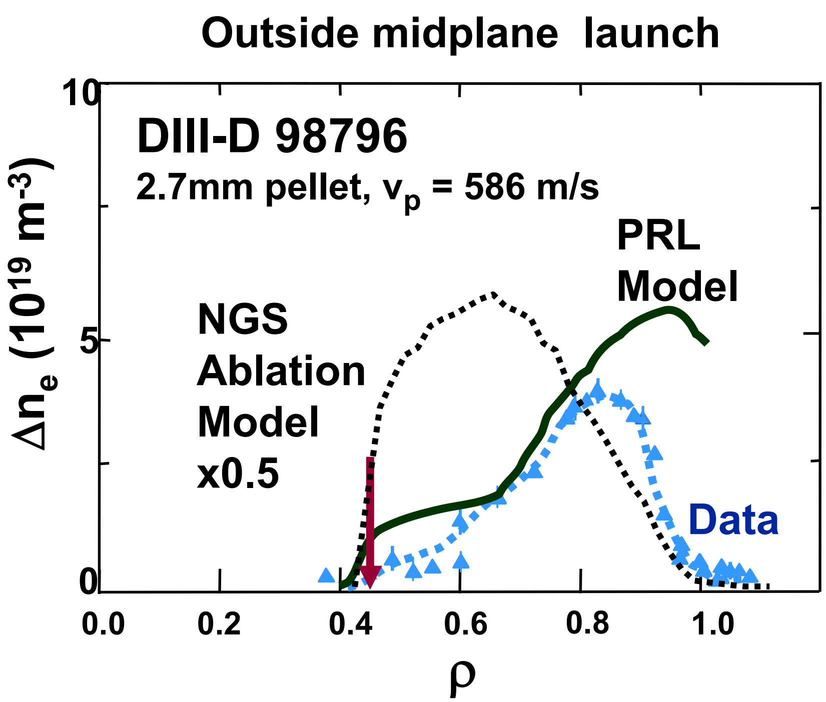
- The cloudlets form a tube of high density plasma along the field lines. The ends of the cloudlet are sheared off as it drifts inward (mass shedding).

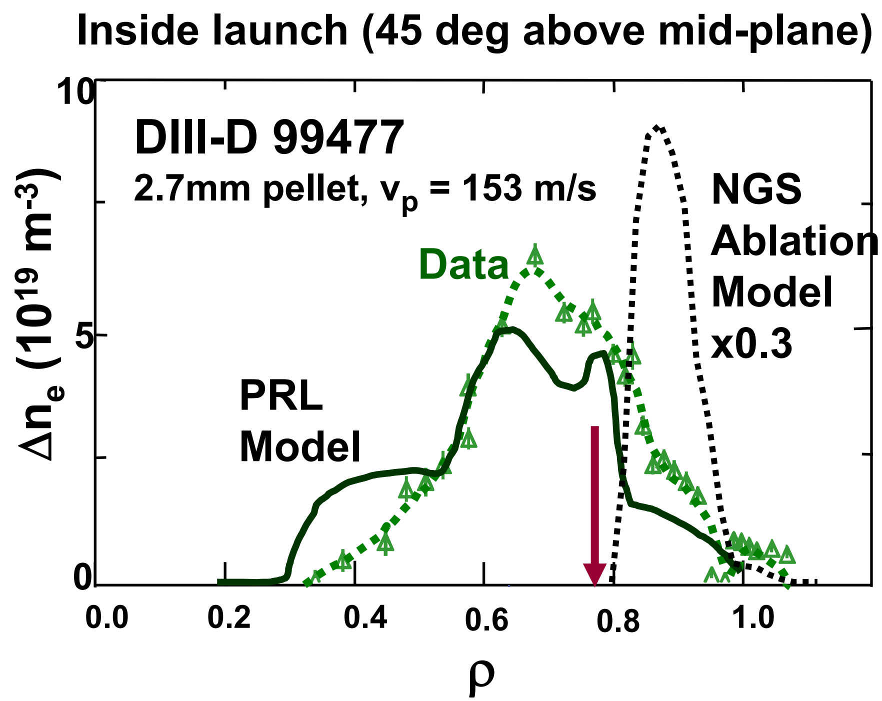


- The experimental plasma profiles are used by PRL to calculate the cloudlet pressure relaxation, drift velocity, and shedding location.

- The deposition profiles from each cloudlet are summed, yielding a net Δn deposition profile.

Experiment and PRL Model Compare Well





- Vertical arrows indicate pellet burnout location

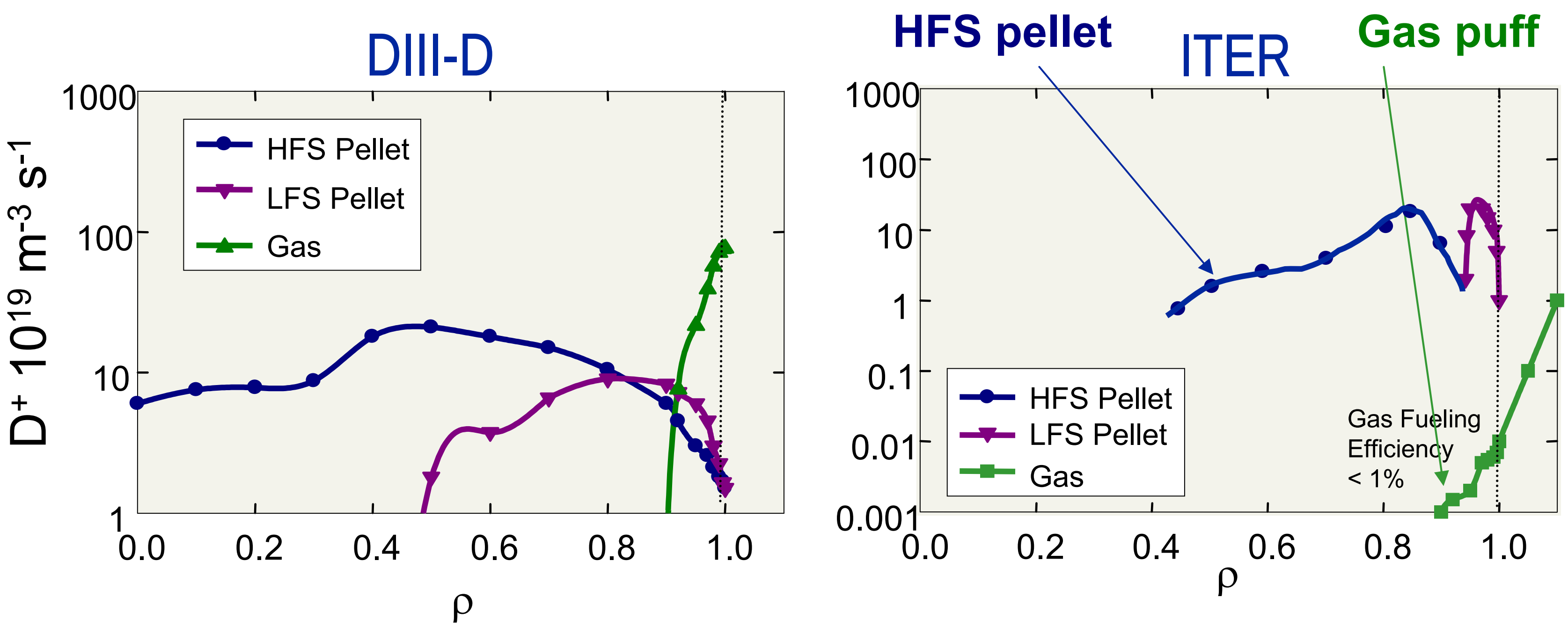
- Fueling efficiency for inside launch is much higher (even with slower pellets)

outside launch ηtheory = 66% , ηexp = 46% (discrepancy due to strong ELM)

inside launch ηtheory = 100% , ηexp = 92% (discrepancy due to weak ELM)

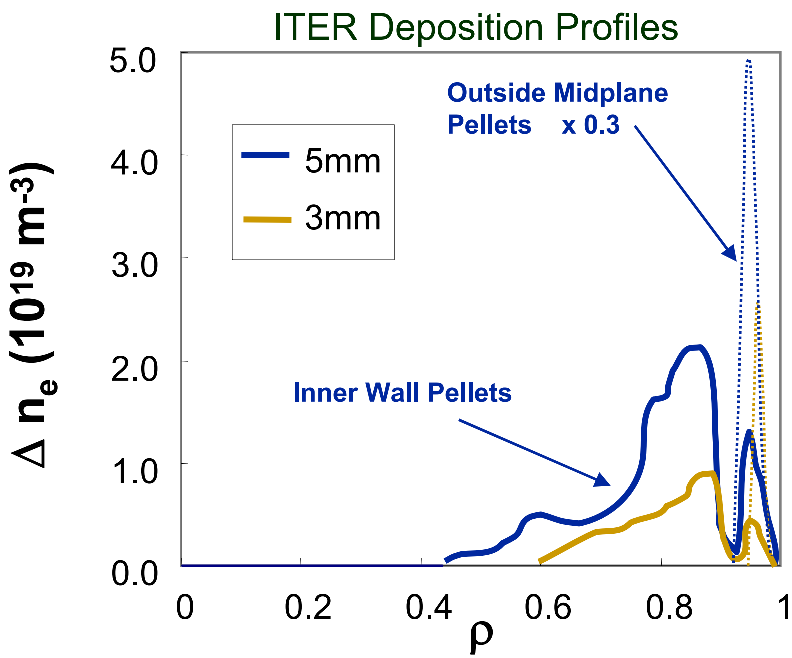
- PRL model is a major breakthrough in understanding the physics of pellet mass drift

Pellet Injection is Crucial for Effective Core Fueling in ITER as Shown in H-mode Fueling Source Profile Comparison



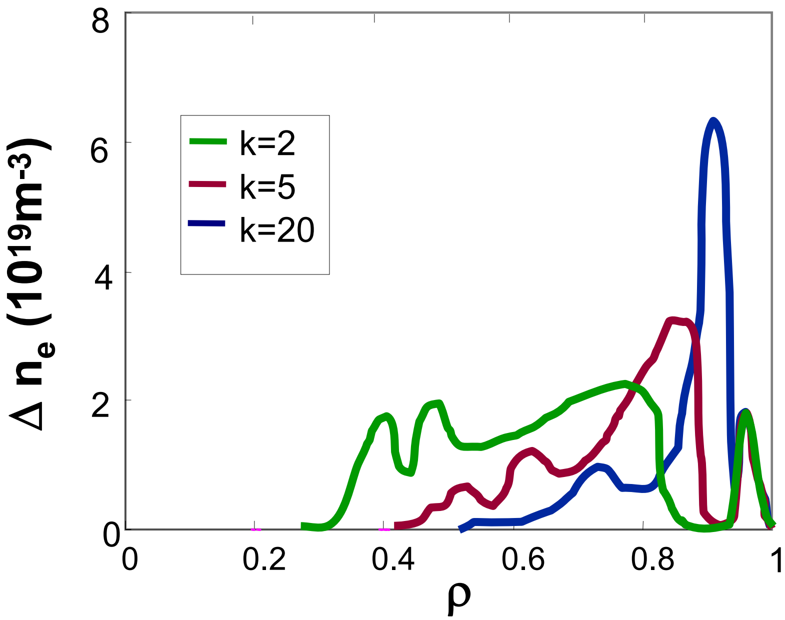
- **Gas puff core fueling in ITER will be much less effective than in DIII-D**
  - **ITER pellet profiles are from PRL** **(P. Parks)** **(5-mm @ 16 Hz)**
  - **gas fueling rate of ~1000 torr-L/s for ITER case B2-Eirene slab calculation** **(L. Owen and A. Kukushkin)**

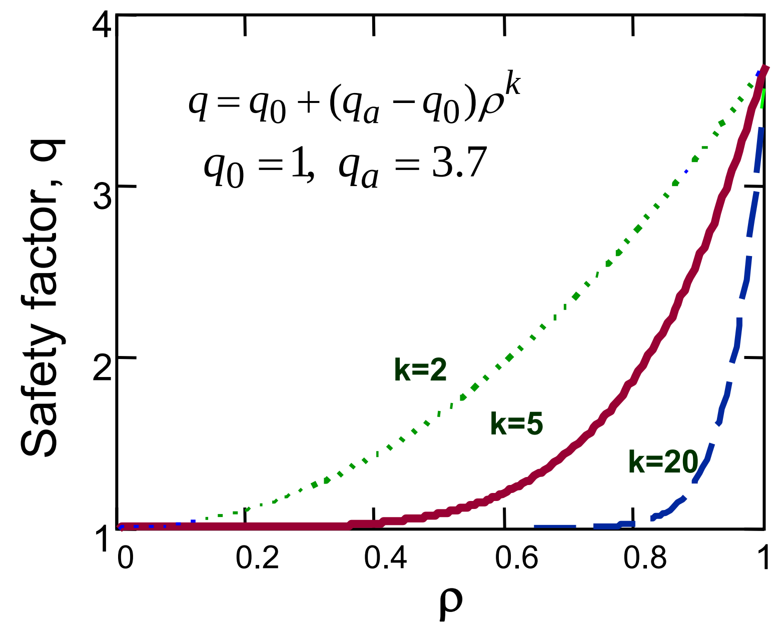
Density Change in ITER as a Function of Inner Wall Pellet Size



- Pellet fueling deposition calculations from PRL for ITER with different size pellets. Larger pellet size yields marginally deeper mass penetration. Mass drifts well beyond the pedestal for all pellet sizes. Outside midplane injection deposition profiles (dashed) with no drift are shown for comparison.
- Pellets injected into the same discharge conditions from the inner wall guide tube port. (H-mode, $T_e(0)$ = 20 keV, T_{ped} = 4 keV, Δ_{ped}=0.04)

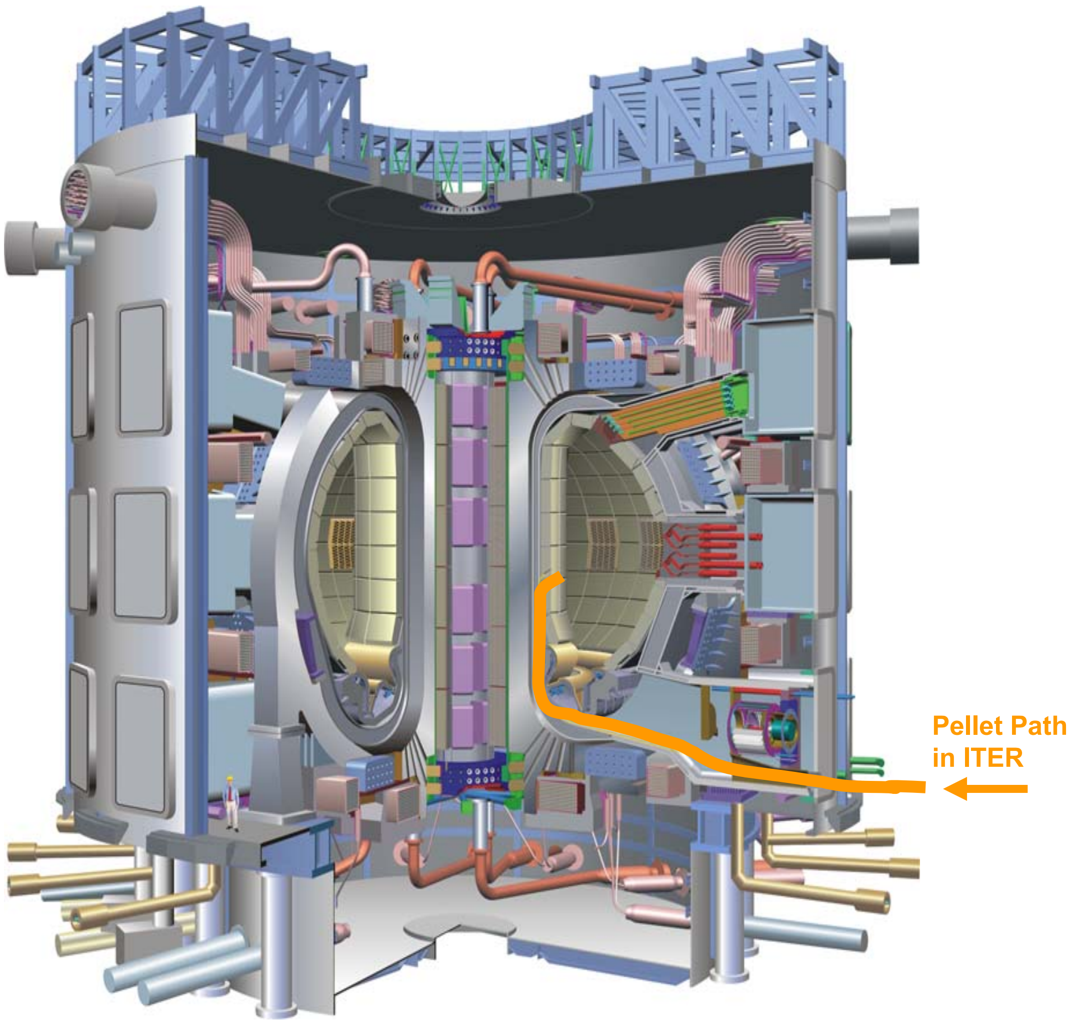
Weaker Shear Leads to Deeper Mass Deposition for ITER Inner Wall Pellet Injection





- Pellet fueling deposition calculations from PRL for ITER with different plasma q profiles. Stronger shear at the edge leads to more rapid mass shedding of the cloudlets and hence shallower mass penetration.
- Pellets (6mm from inner wall) injected into the same discharge conditions (H-mode, $T_e(0)$ = 20 keV, T_{ped} = 4 keV, Δ_{ped}=0.04)

ITER Pellet Fueling Requirements



- ITER will initially have 2 pellet injectors that each provide D_2, DT, T_2 pellets (5mm @ 16Hz, 3mm @ 32Hz).
- Inside wall pellet injection for deep fueling beyond the pedestal and high efficiency. Reliability must be very high.
- Guide tubes bring the pellets in from divertor ports and routes them to the inner wall.
- Pellet injector must operate for up to 1 hour continuously and produce ~ 1.5 cm^3/s of ice.

ITER Fueling Systems Requirements & Present Design

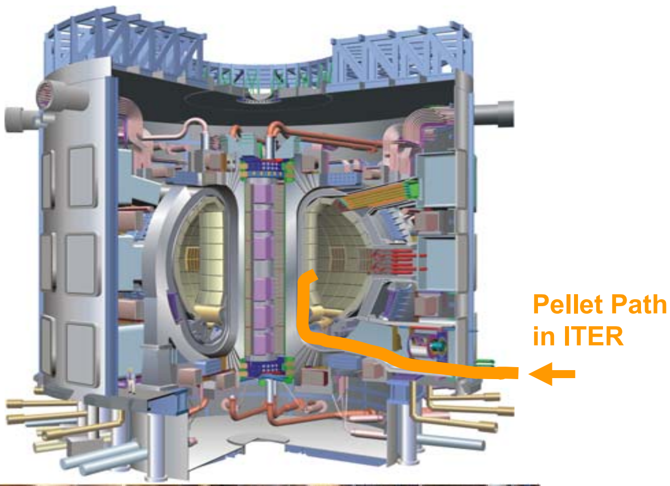
Requirements refined at ITER Pellet Injector Workshop in Garching, May 2004

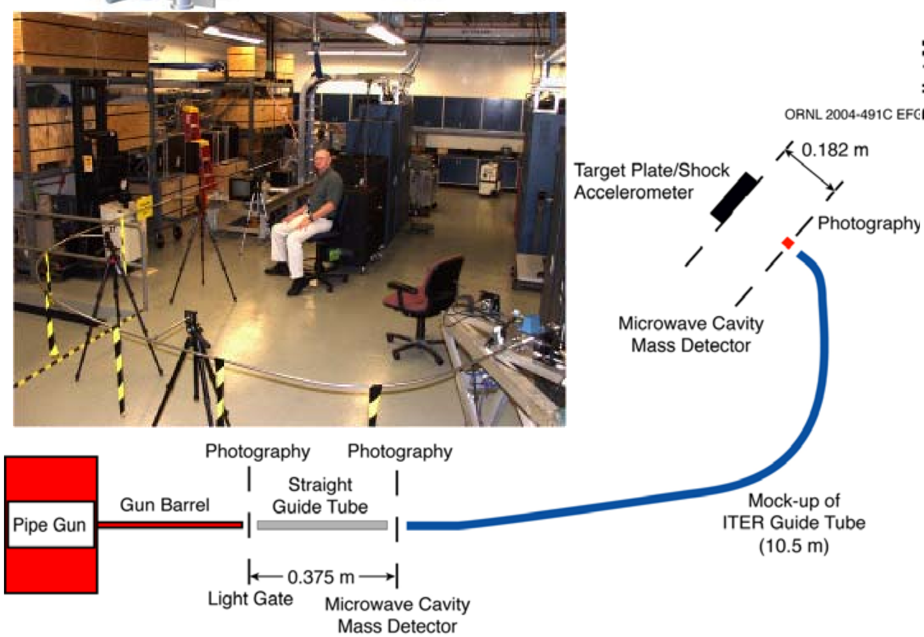
Plasma Density (n_{GW})	**0.4 – 1 (0.5-1.2 x 10^{20} m^{-3})**
Fuel Isotope	**Pellet D_2, DT , T_2(80%T/20%D)**
3-5 mm diam => 1.25 - 6 x10^{21} atoms	**$\Delta n/n$ ~ 1.3%-6.6%**
Gas Fueling Rate (Pa-m^3/s)	**Up to 400 (~3000 torr-L/s)**
Pellet Fueling Rate (Pa-m^3/s)	**100 for D_2, DT (~800 torr-L/s) 50 for T_2 (~400 torr-L/s)**
Pulse length (s)	**Up to 3000**

- **Gas injection system**
  - » Supplies H_2, D_2, T_2, DT, Ar, Ne, and He via a gas manifold
  - » Primary use for initial gas fill, control of SOL, and flushing impurities to divertor
  - » Makes use of conventional gas handling hardware and requires minimal R&D

- **Pellet injection system**
  - » Supplies H_2, D_2, and DT pellets: 3 to 5 mm diam. (32 to 16 Hz, respectively)
  - » Only at pre-conceptual design level and some R&D still needed

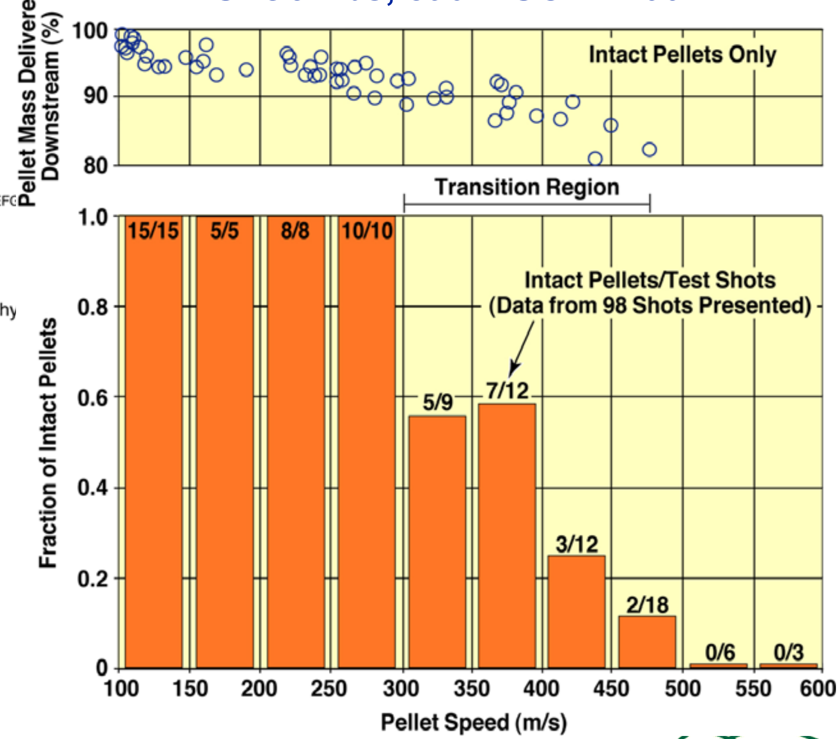
ITER Inner Wall Guide Tube Tests Indicate 300 m/s Speed Limit





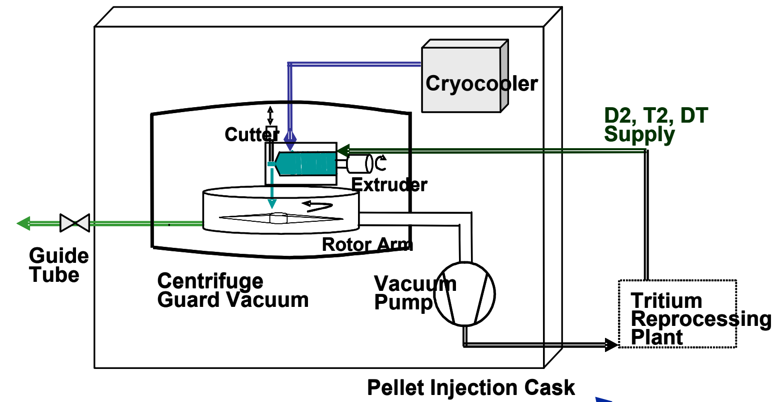
- **Initial tests with 5.3 mm pellets**
- **Pellet speeds limited to ≈300 m/s for intact pellets**
- **Guide tube mass loss ≈10% at speed limit**

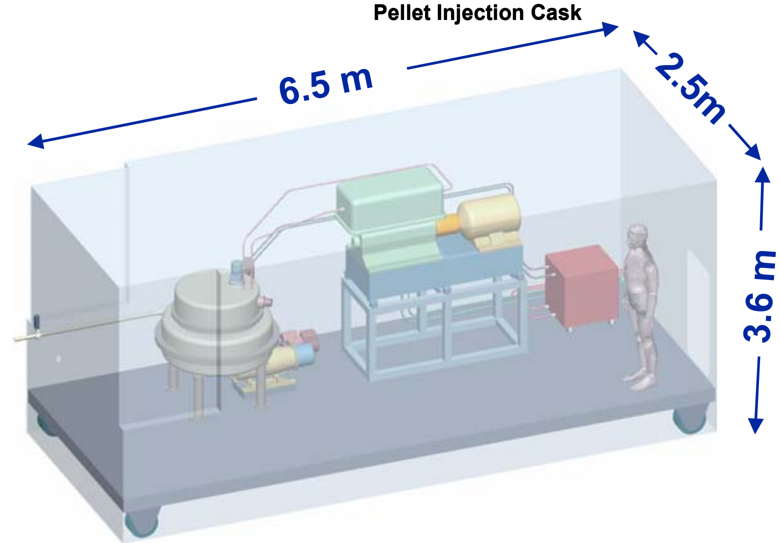
S. Combs, et al. SOFT 2004



ITER Pellet Injection System Conceptual Design

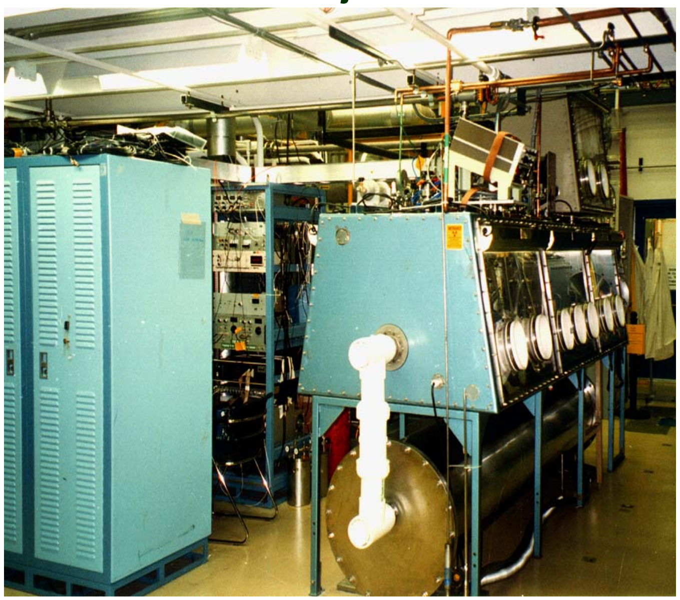
- **ITER initially will have 2 pellet injectors for deep core fueling as the primary fuel delivery system.**
  - » Up to 6 injectors planned for future
- **Requires continuous, highly reliable, high throughput, tritium rich pellets**
  - » significant throughput extension of present-day designs
  - » Centrifuge accelerator with a continuous screw extruder
  - » Inner wall pellet injection with curved guide tubes
  - » Maximum T concentration is ~80% due to tritium processing plant limitation
- **PIS to be enclosed in cask that rolls up to a divertor port**

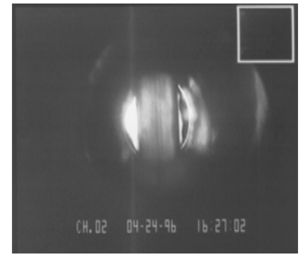




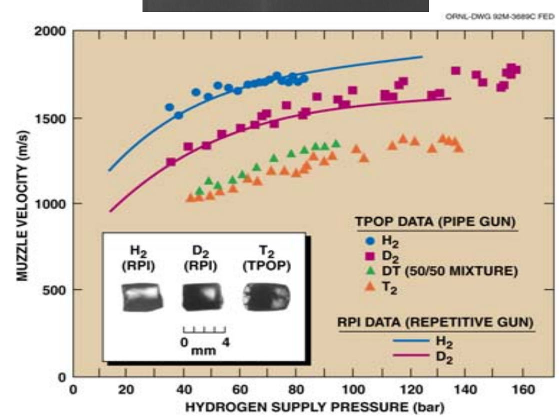
Tritium Pellet Formation has been Proven and Can Be Used to Control Plasma Burn

Tritium Pellet Injector at TSTA





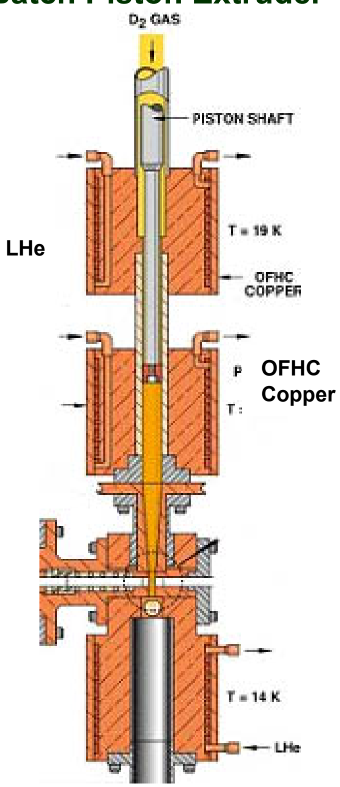
Tritium Extrusion (≈8 mm)

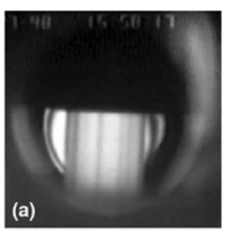


- **Tritium pellet formation and acceleration were found to be readily achievable with present technology.**
- **Pellets with high T_2 concentration are envisioned for fueling ITER using the isotopic tailoring scheme**
  - T_2 rich pellets combined with D_2 gas puffing (Gouge, et al., Fusion Tech. 1995)
- **Multiple pellet injectors with different T fractions can be used to control fusion power**

Batch Piston and Continuous Screw Extruders are Possible to Meet the Needs for the ITER Pellet Injection System

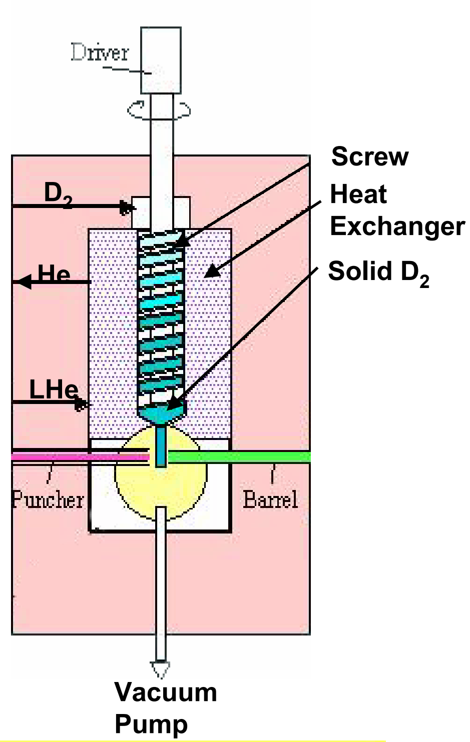
Batch Piston Extruder





8mm H_2 ice extrusion

Continuous Screw Extruder

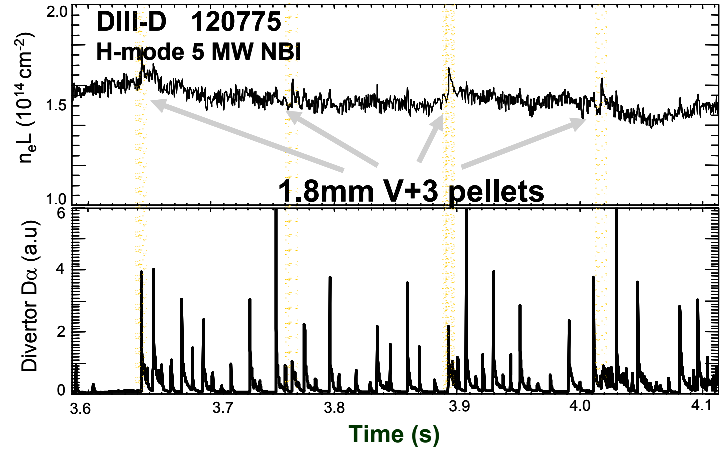


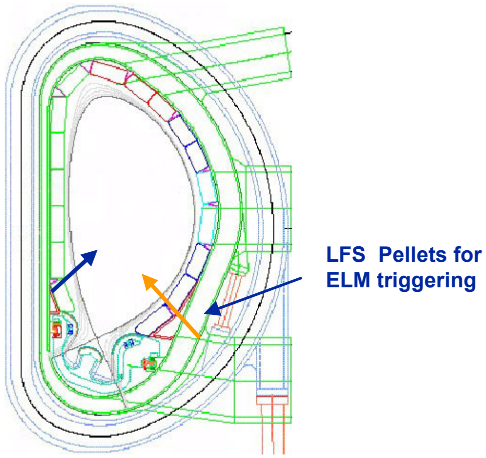
PELIN Laboratory, Ltd. (Russia)

- Both batch piston and continuous screw extruders have been developed as possible ITER ice sources
- Multiple batch extruders have produced 1.3 cm^3/s **(S. Combs, et al, RSI (1998)** while a continuous screw extruder by PELIN has produced steady-state H_2 ice up to 0.3 cm^3/s. (~1/5 of rate needed for ITER) **(I. Viniar, SOFT 2004)**.
- Throughput enhancement may be possible or multiple such extruders could be used on the ITER pellet injection system.
- Simpler operation makes the screw extruder preferable over a batch extruder.

Pellet ELM Triggering May Provide Tool for ELM Amelioration

- Pellet injection has been found to trigger ELMs in ELMing H-mode plasmas (AUG, DIII-D, JET).
- LFS pellets trigger larger ELMs than the same pellets from the inner wall, leading to a possible sensitive LFS pellet ELM trigger.
- AUG has succeeded in increasing the ELM frequency and lowering the ELM size using small pellet triggers. (P. Lang et al., Nuc. Fusion 2004)
- ITER 3mm size pellet is for ELM triggering using a LFS guide tube.
- Further research is needed to investigate the pellet induced ELM mechanism and its scaling to ITER.
- Interaction of pellets with NTMs, RWMs, ELMs, etc. needs better understanding.





Summary

- **ITER will require significant fueling beyond that provided by gas**
  - » Gas fueling and recycling expected to be very inefficient
- **Inner wall injection port will allow up to 300 m/s pellet injection**
- **Modeling of the proposed ITER pellet injection scenario looks promising for core fueling well beyond the H-mode pedestal**
  - » Further validation of the ExB polarization drift model is needed with diagnostics and scaling studies
- **The pellet fueling system for ITER presents challenges for the technology developers in throughput and reliability, concepts look promising**
  - » Development is underway and expected to take ~ 5 yrs
  - » Centrifuge and extruder prototypes will be produced which can be available to test on existing tokamak devices
- **ELM triggering by small LFS pellets also a promising technique for ITER**
  - » Further research to optimize and understand physics of pellet induced ELMs and ELM amelioration is required as well as other MHD interactions.