Plasma Fueling and Implications for FIRE, ITER, ARIES

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Outline

- Fueling system functions
- Fueling program scope
- ITER and FIRE fueling
- Tritium systems
- Fueling efficiency (gas vs. pellets)
- DIII-D results (high field vs. low field, L-to-H mode…)
- Isotopic fueling
- Disruption mitigation technology and experiments on DIII-D

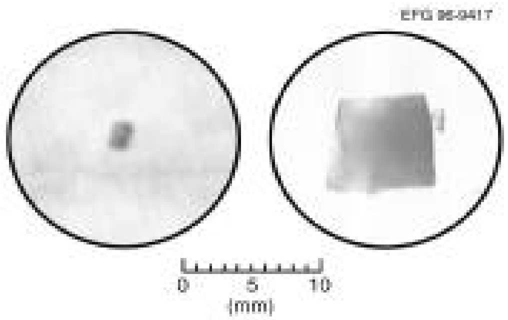
Fueling system functions

- to provide hydrogenic fuel to maintain the plasma density profile for the specified fusion power,
- to replace the deuterium-tritium (D-T) ions consumed in the fusion reaction,
- to establish a density gradient for plasma particle (especially helium ash) flow to the edge,
- to supply hydrogenic edge fueling for increased scrape off layer flow for optimum divertor operation,
- to inject impurity gases at lower flow rates for divertor plasma radiative cooling, wall conditioning, and for plasma discharge termination on demand.

Fueling program scope

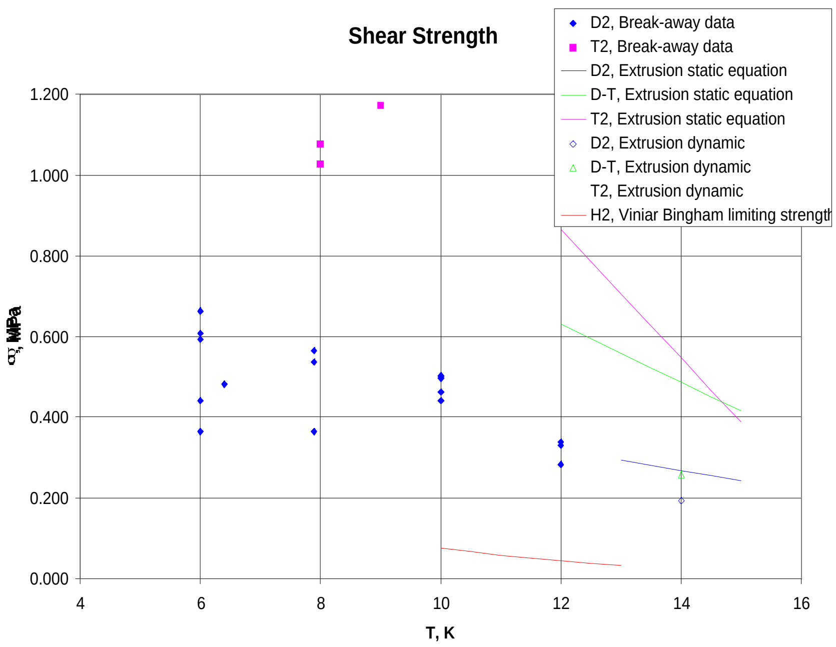
- Gas fueling prototype for ITER
- Pellet fueling development
  - H, D, T, Ne, Ar, Xe cryogenic solid pellets
  - Size from ~0.5 mm to 10 mm
  - feed rates from single shot to 0.26 g/s (ITER)
  - speeds from 100 to ~4000 m/s
- US-related plasma fueling experiments:
  - ORMAK, ISX, PDX, DIII, PLT, TEXT, PBX, TFTR, JET, TORE SUPRA, DIII-D, GAMMA 10, LHD, MST (2001), NSTX (2002)
  - Particle control and fueling physics; example: outside, inside and vertical launch on DIII-D
- Disruption mitigation and impurity fueling development
- Fueling system design for ITER and FIRE

Hydrogenic solids



- Have made hydrogenic pellets in sizes from ~0.5 to 10 mm
- Hydrogen properties:

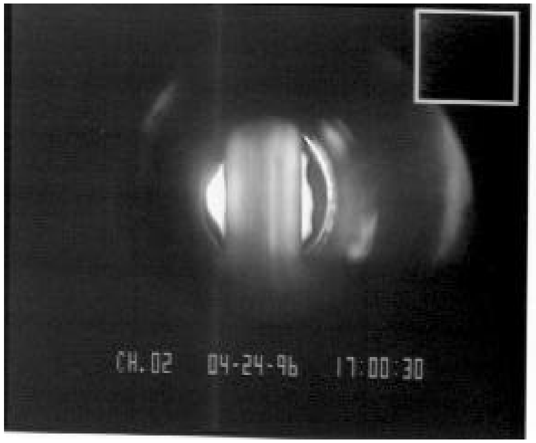
Property	H	D	T
density (g/cc)	.09	.2	0.32
boiling point at 1 atm (K)	20.4	23.7	25
triple point (K)	13.8	18.7	20.6
triple point pressure (torr)	54	129	162

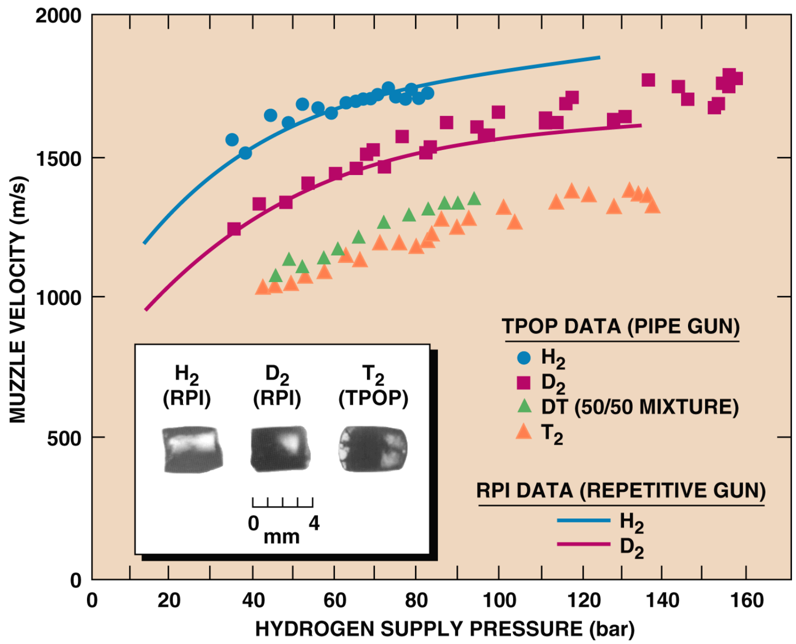


ITER fueling R&D results relevant to FIRE

- Gas fueling prototype testing
  - response time experiments for impurity gas puffing into divertor
- Pellet fueling development
  - world's largest cryogenic pellet ~ 10 mm
  - first extrusions of tritium and DT
  - record extrusion rate of 0.26 g/s (deuterium)
  - pellet feed/rotor dynamics for centrifuge injector (with CEA)
  - piston and screw (RF) extruder development
  - high-field-side launch development

Pure Tritium Extrusion

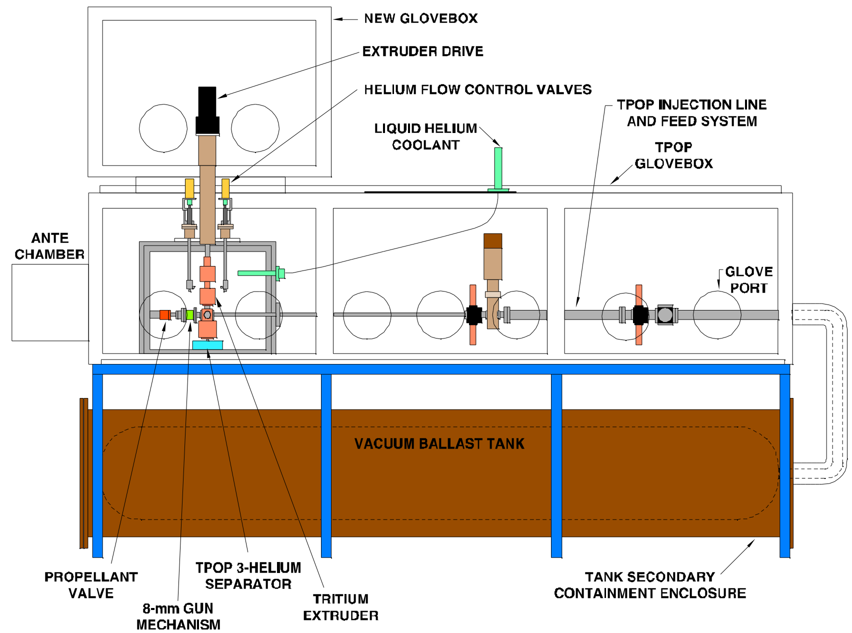


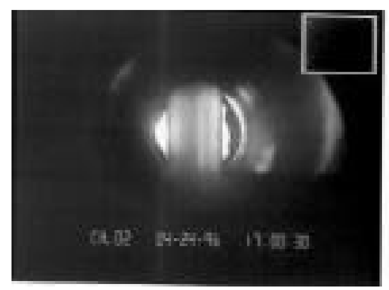


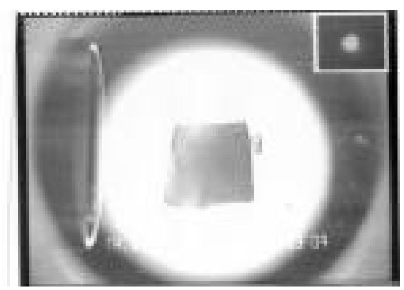
TPOP-II tritium extruder experiments

Highlights

- Demonstrated first extrusions of solid tritium at Tritium Systems Test Assembly Facility at LANL;
- Produced world's largest pellets: 10 mm D, DT and T pellets (full scale for ITER);
- Processed over 40 grams of tritium through TPOP-II;
- Developed isotopic fueling concept to reduce ITER tritium throughputs and inventory.





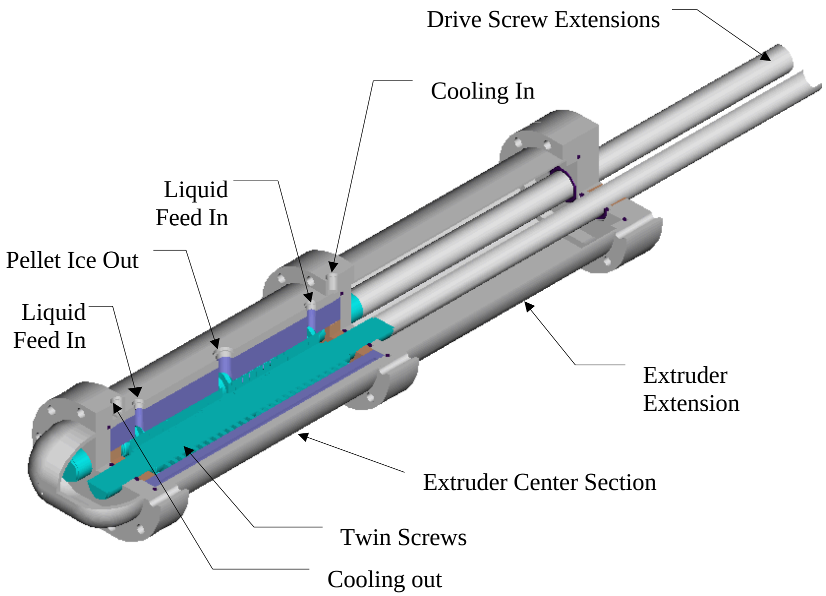


FIRE fueling system

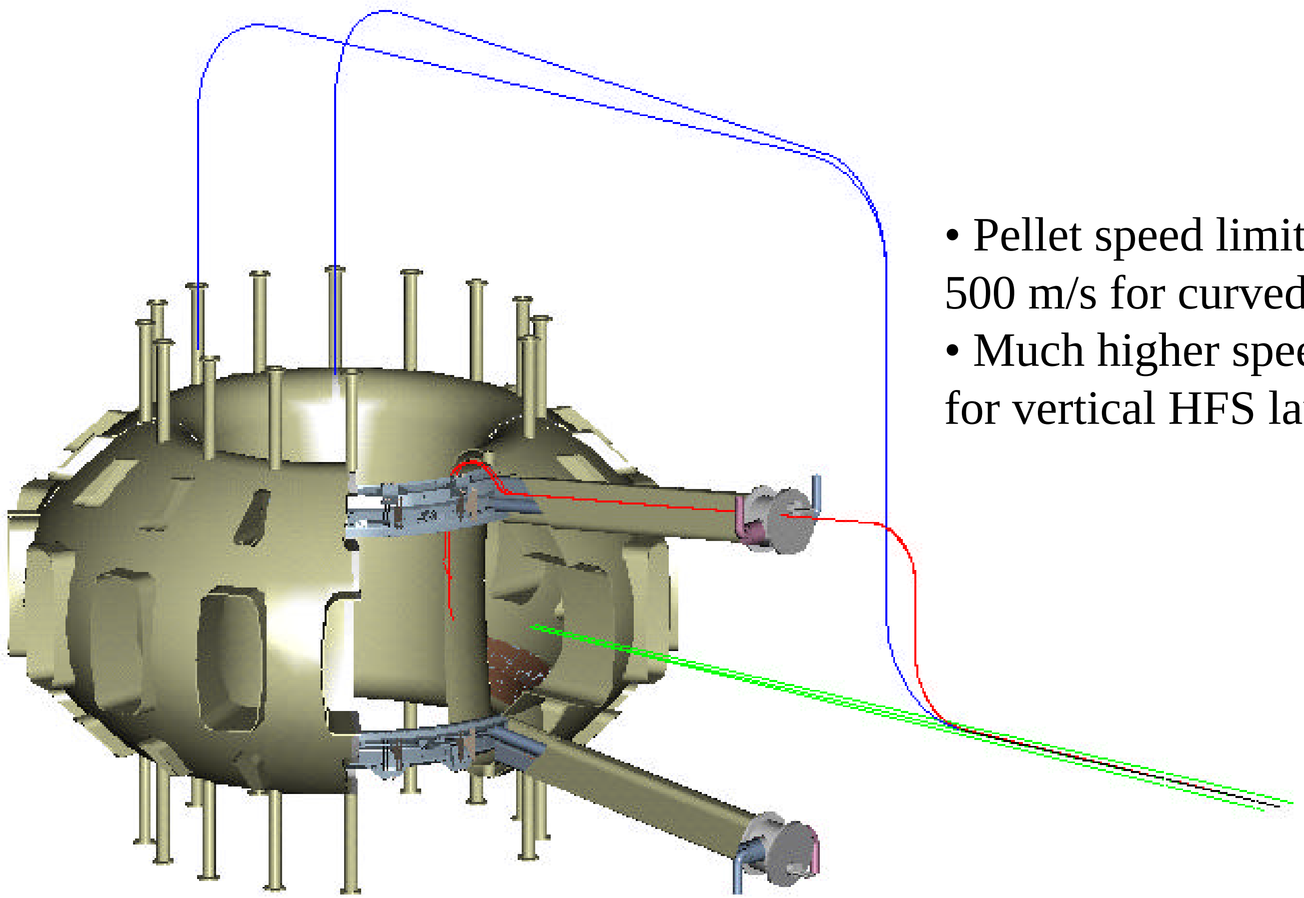
- Baseline is gas (mostly D) + pellets (DT to get 60% D/40%T in the core)
  - Magnetic field magnitude makes CT fueling difficult: ~2 MW just to make up DT fusion losses.
- Use vertical or inside pellet launch
  - Vertical launch allows injection inside major radius at high pellet speeds if the pellet injector is vertically oriented
  - Inside launch fully leverages grad-B ablatant flow but will limit speeds to 100's m/s with a pellet injector located at an arbitrary location (due to guidetube radius of curvature) with modest propellant gas requirements
  - The optimum depends on pellet speed dependence of particle deposition for inside launch which is not quantified.

Double-screw extruder concept
(ORNL STTR with Utron, Inc.)

- Dual, opposed, counter-rotating screws
- Liquid helium is fed into the extruder at one end and flows through cooling channels (alternative is G-M cryocooler)
- Deuterium is fed into the screw chamber and flows to the center of the extruder.
- As the liquid flows it freezes on the inner wall between the screw and the inner housing.
- As the screws rotate they scrape off the deuterium and force the ice to the center of the extruder were it is extruded out the center hole to the feed tube.



Pellet launch paths into FIRE



• Pellet speed limited to about 500 m/s for curved guidetubes.
• Much higher speeds possible for vertical HFS launch

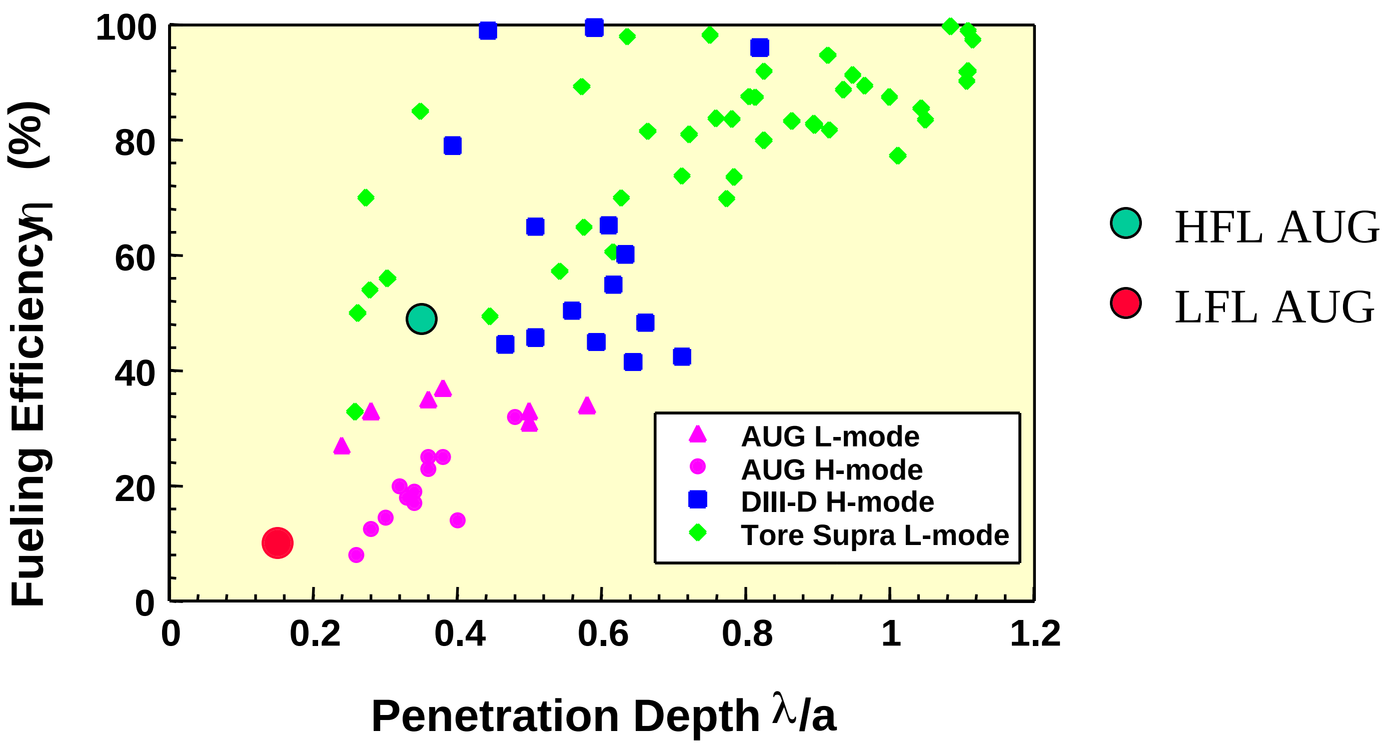
Preliminary FIRE fueling system parameters

Parameter	Gas Fueling System	Pellet Fueling System	Remarks
Design fueling rate	200 torr-l/s for 20 s	200 torr-l/s for 20 s	Torus pumping capacity is 200 torr-l/s
Operational fuel rate	100-175 torr-l/s	100-25 torr-l/s	Isotopic fueling
Normal fuel isotope	D (95-99%) T,H (5-1%)	T (40-99 %) D(60-1%)	D-rich in edge, T-rich in core
Impurity fuel rate	25 torr-l/s	TBD (prefer gas for impurity injection)	25 torr-l/s reduces DT fuel rate due to fixed pumping capacity
Impurity species	Ne, Ar, N_2, other?	TBD	TBD
Rapid shutdown system	Massive gas puff ~10^6 torr-liter/s	"killer" pellet or liquid D jet	For disruption/VDE mitigation
Pellet sizes (cyl. diameter)	N/A	3, 4, 4 mm	3 mm for density rampup, 4 mm for flat-top

Efficiency of gas fueling much less than pellet fueling

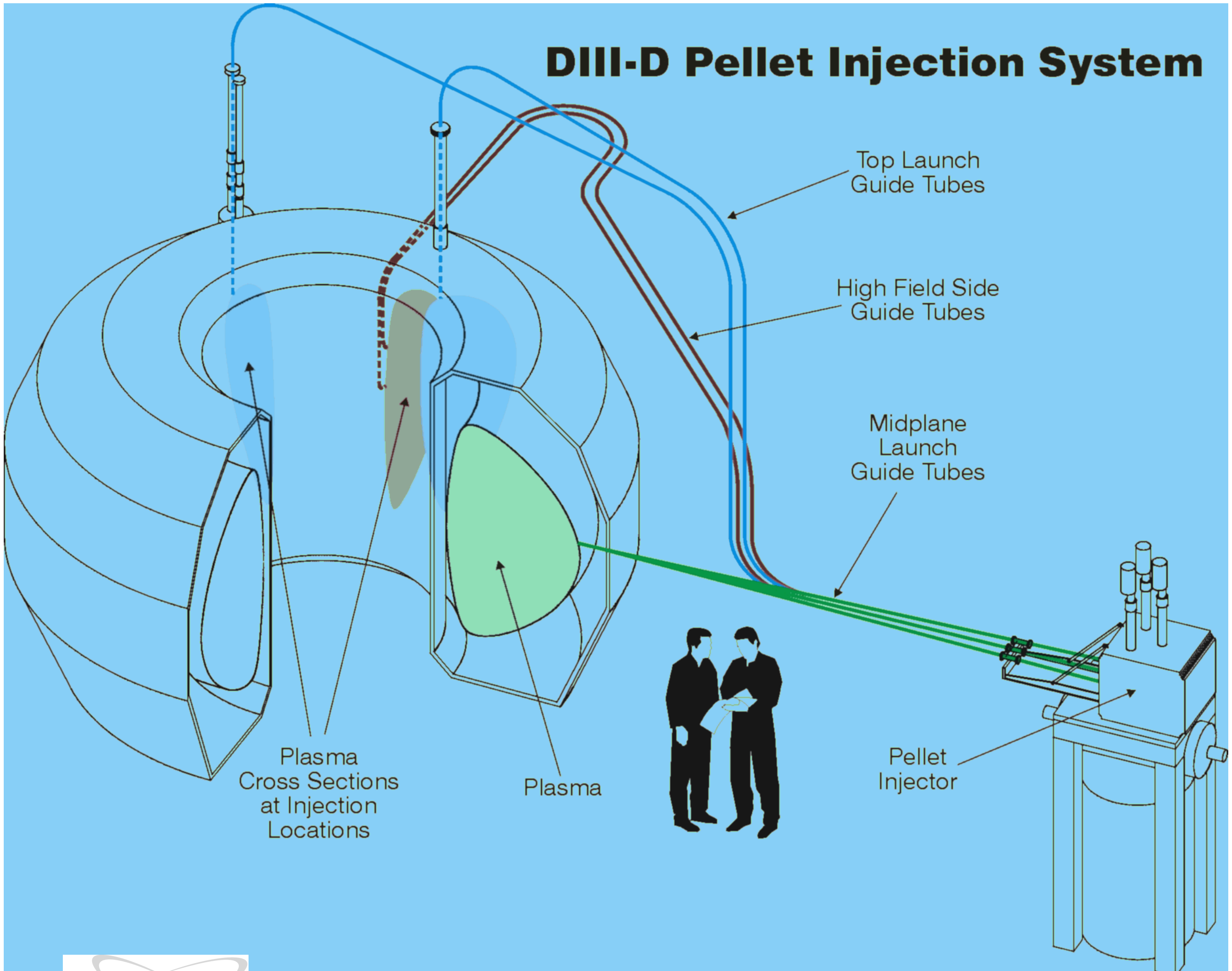
Device	Gas Fuelling Efficiency (%)	Pellet Fuelling Efficiency (%)	Remarks
ASDEX	20	30-100	high density
PDX	10-15		high density
Tore Supra	1	30-100	ergodic divertor for gas fuelling
JET	2-10	20-90	active divertor
JT-60			
JT-60U			
TFTR	15		low density DT
ASDEX-U		8-40	
DIII-D	10	40-100	active divertor

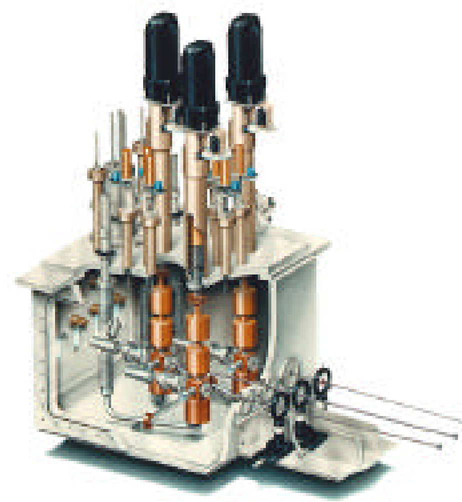
Pellet fueling efficiency has a broad range



- Encouraging initial high field launch experiments on ASDEX-U
  - implications for FIRE
  - ongoing experiments on ASDEX-U, DIII-D, Tore Supra, JET, LHD

Multiple launch locations on DIII-D



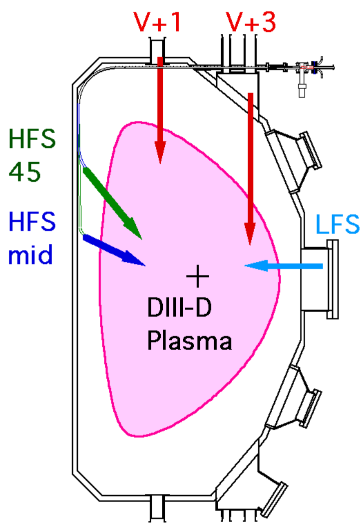


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

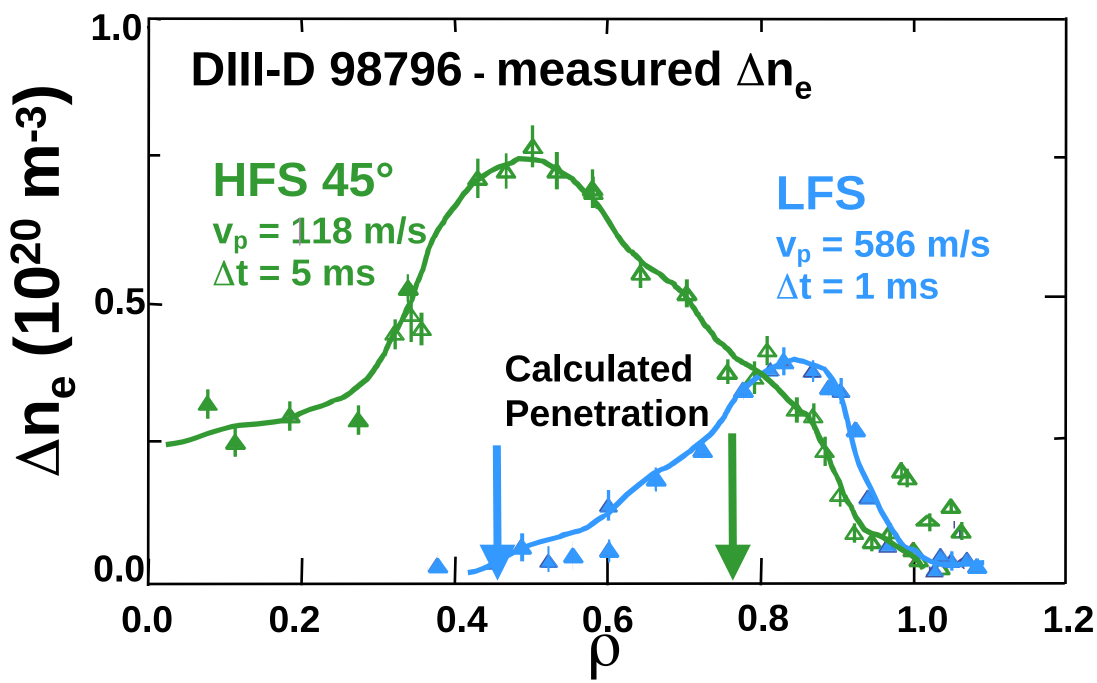
ornl

High Field Side (HFS 45°) Pellet Injection on DIII-D Yields Deeper Particle Deposition than LFS Injection

2.7 mm Pellets - HFS 45° vs LFS

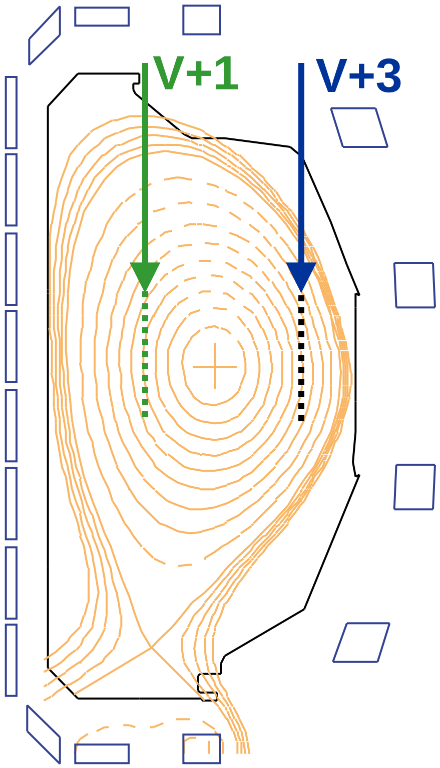


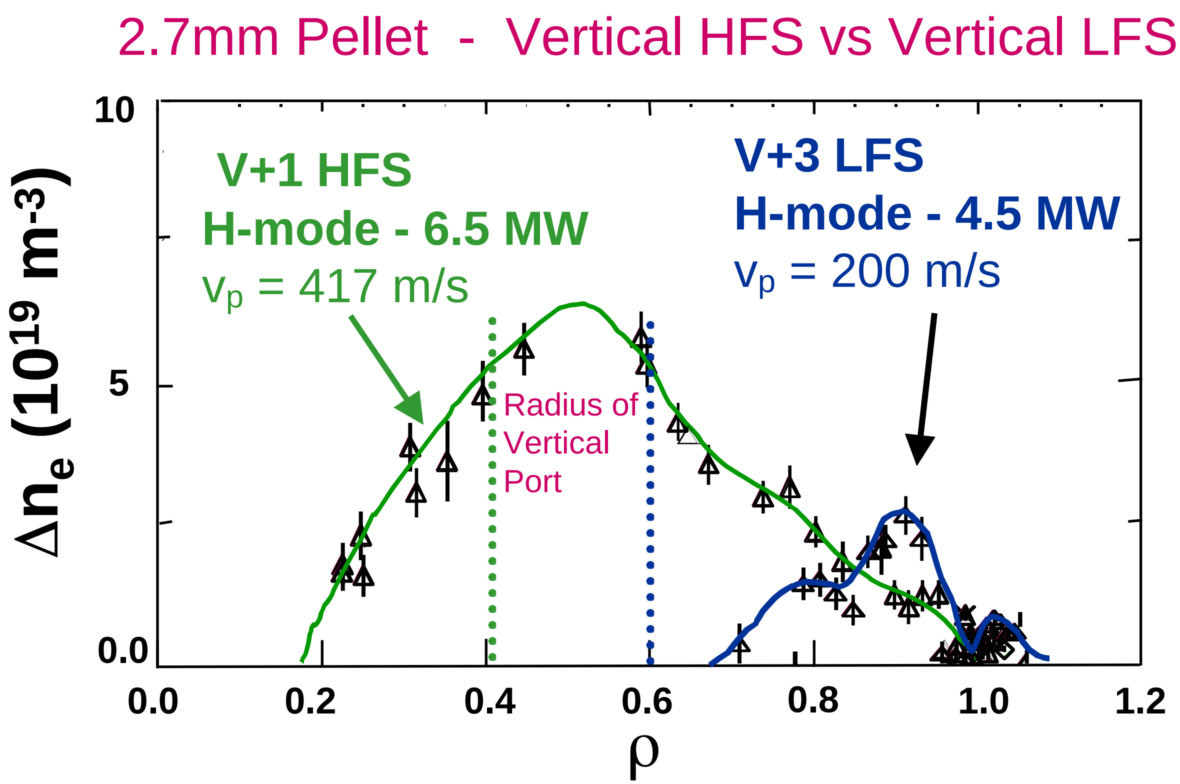
Four positions of pellet injection guide tubes installed on DIII-D



- Net deposition is much deeper for the lower velocity HFS 45° pellets.
- The pellets were injected into the same discharge under the same conditions (ELMing H-mode, 4.5 MW NBI, $T_e(0)$ = 3 keV).
- L. R. Baylor, P. Gohil et al., ***Physics of Plasmas***, page 1878 (2000)

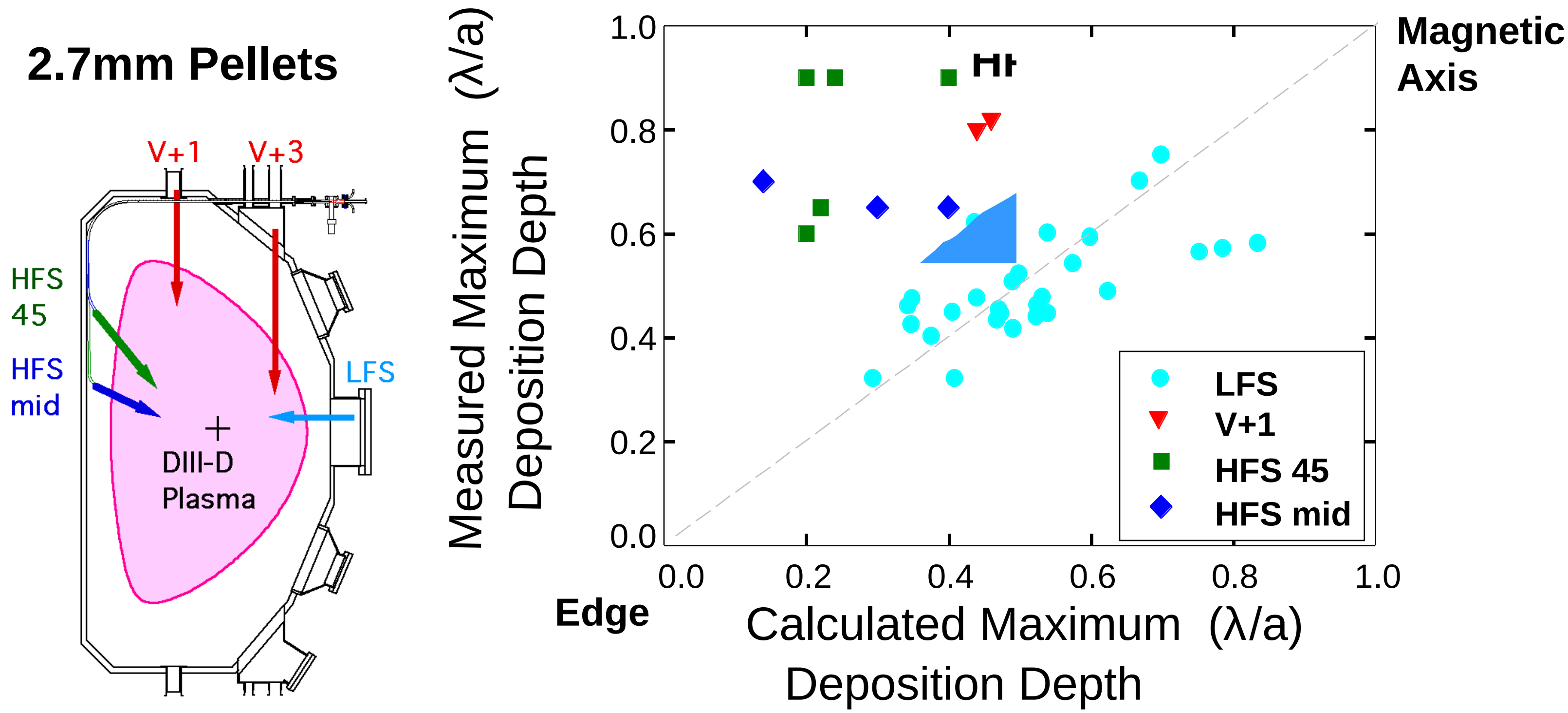
Both vertical HFS and LFS pellet injection are consistent with an uutward major radius drift of pellet mass





- The net deposition profile measured by Thomson scattering 2-4 ms after pellet injection on DIII-D. V+1 HFS indicates drift toward magnetic axis while V+3 LFS suggests drift away from axis.

HFS pellet injection on DIII-D yields deeper particle deposition than predicted

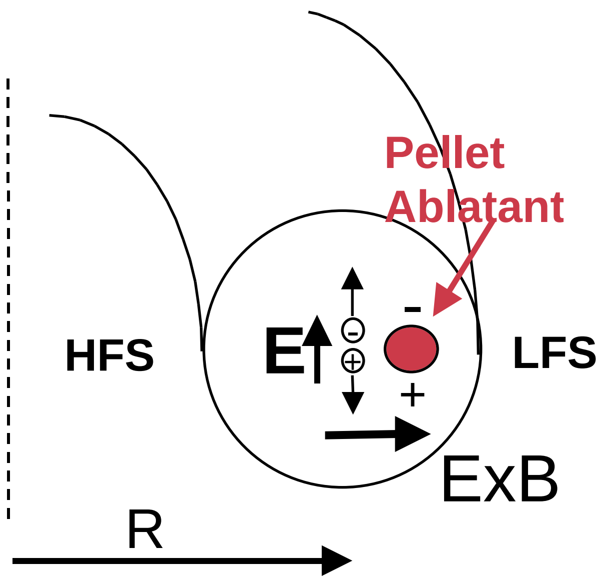


- The net deposition depth measured by Thomson scattering after pellet injection on DIII-D is compared with the calculated pellet penetration depth. The high field side (inner wall and vertical injection) locations all show deeper than expected depth of the deposition of the pellet mass.

Theoretical model for pellet radial drift predicts strong inward drift for reactor

ExB Polarization Drift Model of Pellet Mass Deposition

(Rozhansky, Parks)



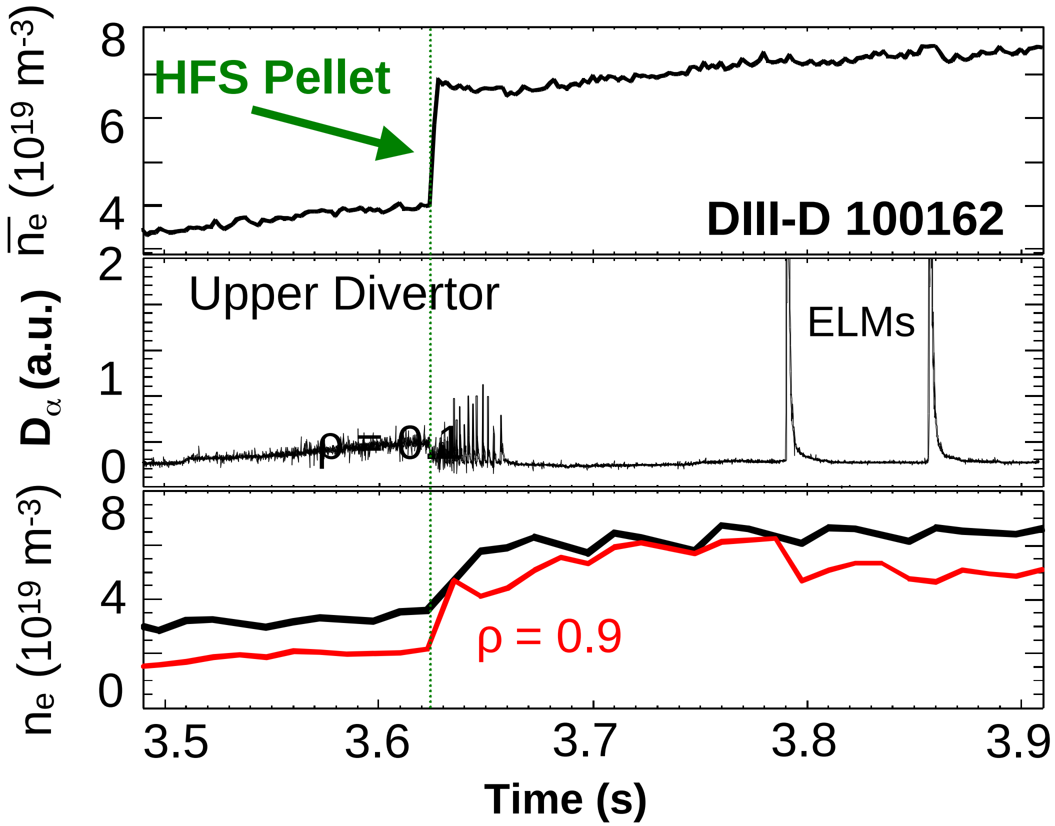
- Polarization of the pellet cloud occurs from B and curvature drift in the non-uniform tokamak field:

$$\vec{\mathbf{v}}_{B} = \frac{W \;\; + 2W_{\parallel}}{eB^{3}} \vec{\mathbf{B}} \leftrightarrow \overrightarrow{\;\mathbf{B}\;}$$

- The resulting E causes an ExB drift in the major radius direction
- Drift ΔR is a strong function of local T_e (Parks et al. Physics of Plasmas, p. 1968 (2000)):
  - For ITER-FEAT with Te(0) of 20 keV and r_p = 6mm, the drift ΔR is ~2m, all the way to the axis.

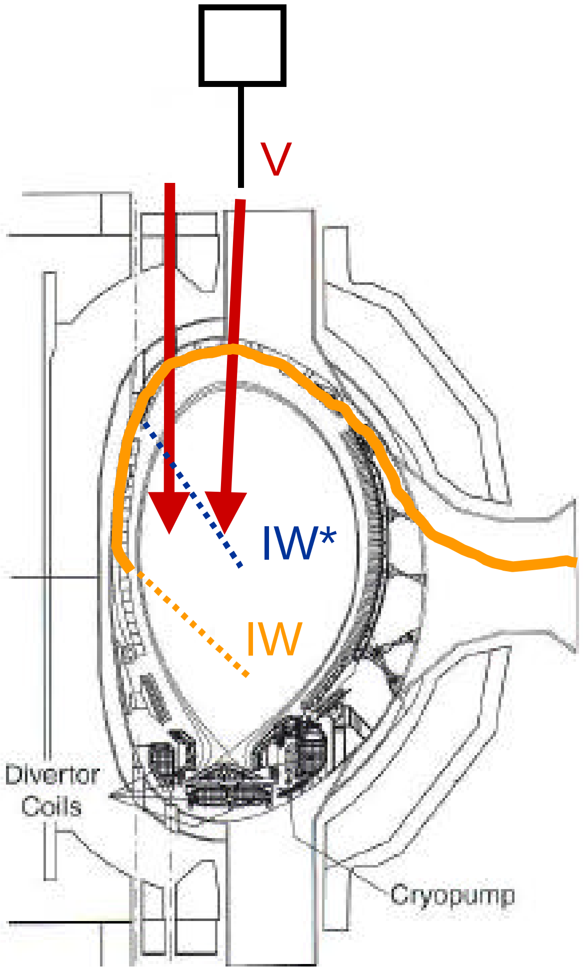
L-to-H Mode transition triggered by single D pellet

(P. Gohil et al., Phys. Rev. Lett., p. 644, (2001))

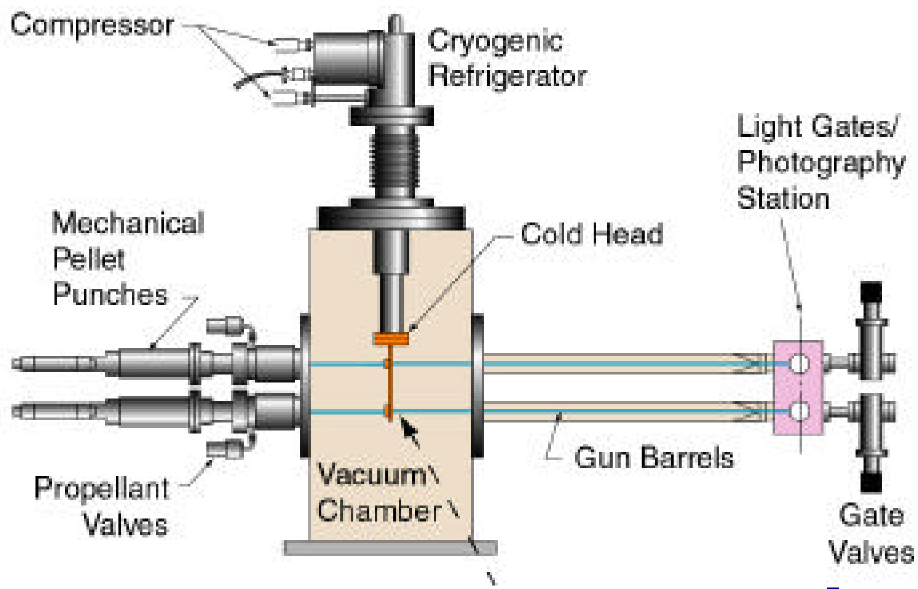


- HFS pellet induces H-mode transition that is maintained
- H-mode power threshold reduced by 2.4MW (up to 33%) using pellet injection

Possible vertical pellet injection test at JET

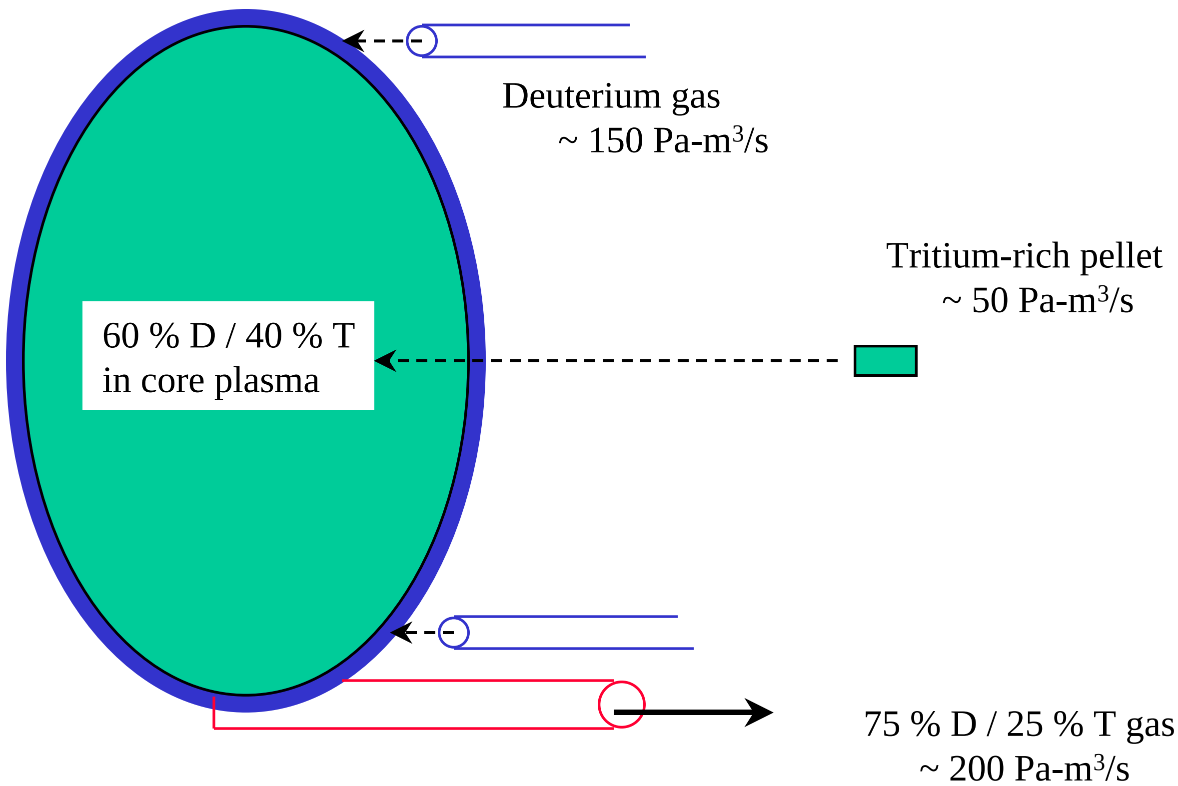


- **Pipe-gun injector for vertical pellet injection on JET**
  - **Complements existing JET inner wall injection with high-speed vertical pellets.**
  - **Simple “pellet injector in a suitcase” for flexible installation. 1-4 pellets.**
  - **Self contained cryorefrigerator for simple operation.**
  - **For characterization of pellet drift physics in a large device.**



Isotopic Fueling:

- minimize tritium introduced into torus
- but maintain P_{fusion} (fuel rates shown typical of reactor)



Isotopic fueling model results are promising

- Isotopic fueling provides a radial gradient in the T and D densities.
- The magnitude of the effect depends on the separation of the two fueling sources.
- In-vessel tritium throughputs and wall inventories can be reduced by about a factor of two or more.
- This can ease requirements on the tritium breeding ratio.
- M. J. Gouge et al., *Fusion Technology*, **28**, p. 1644, (1995)

Figure 1

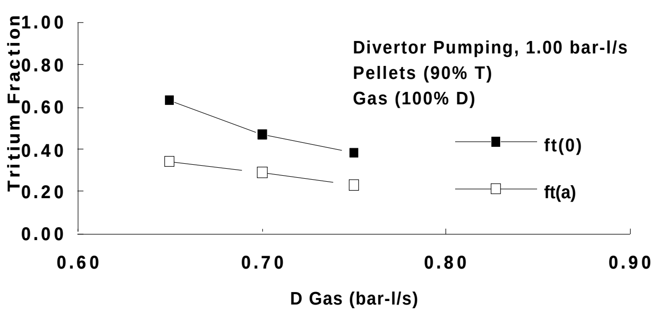
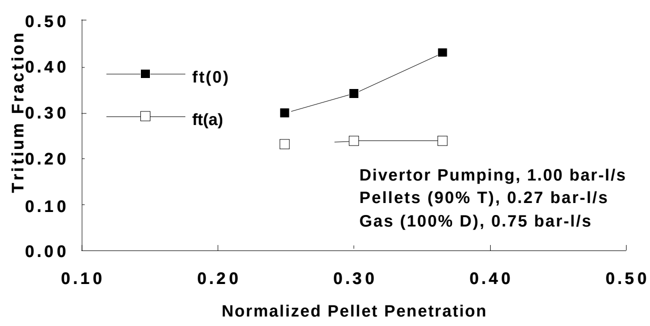


Figure 2



Fueling technology for mitigating disruptions and VDEs

- Massive gas puff into DIII-D (T. C. Jernigan et al.)
  - Peak halo currents were reduced up to about 50% by the massive He and D puffing.
  - Toroidal spatial nonuniformity was also reduced by the He puffs.
- Ne, Ar and methane pellets into DIII-D(Todd Evans et al.)
  - Peak halo current amplitudes are reduced by up to 50% in triggered VDEs with both neon and argon killer pellets.
  - Halo current toroidal peaking factors are reduced from 3 to 1.1 for these discharges.
- Cryogenic liquid jet modeling (Paul Parks, GA et al.) and development (P. W. Fisher, ORNL)
- Low Z impurity pellets (e.g. LiD) may be option if no runaway electron issue

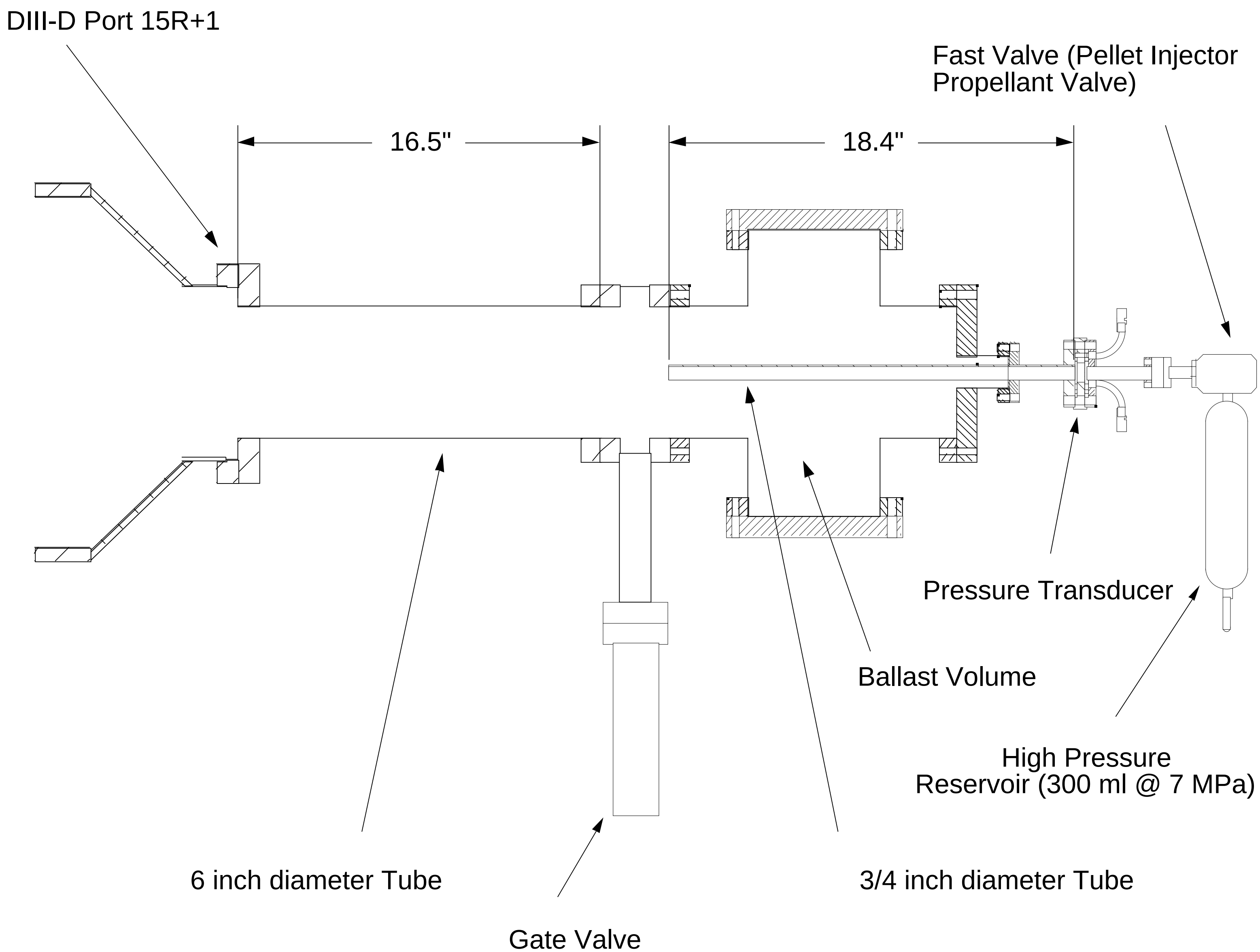
Disruption mitigation systems by a massive gas puff

T. Jernigan ORNL

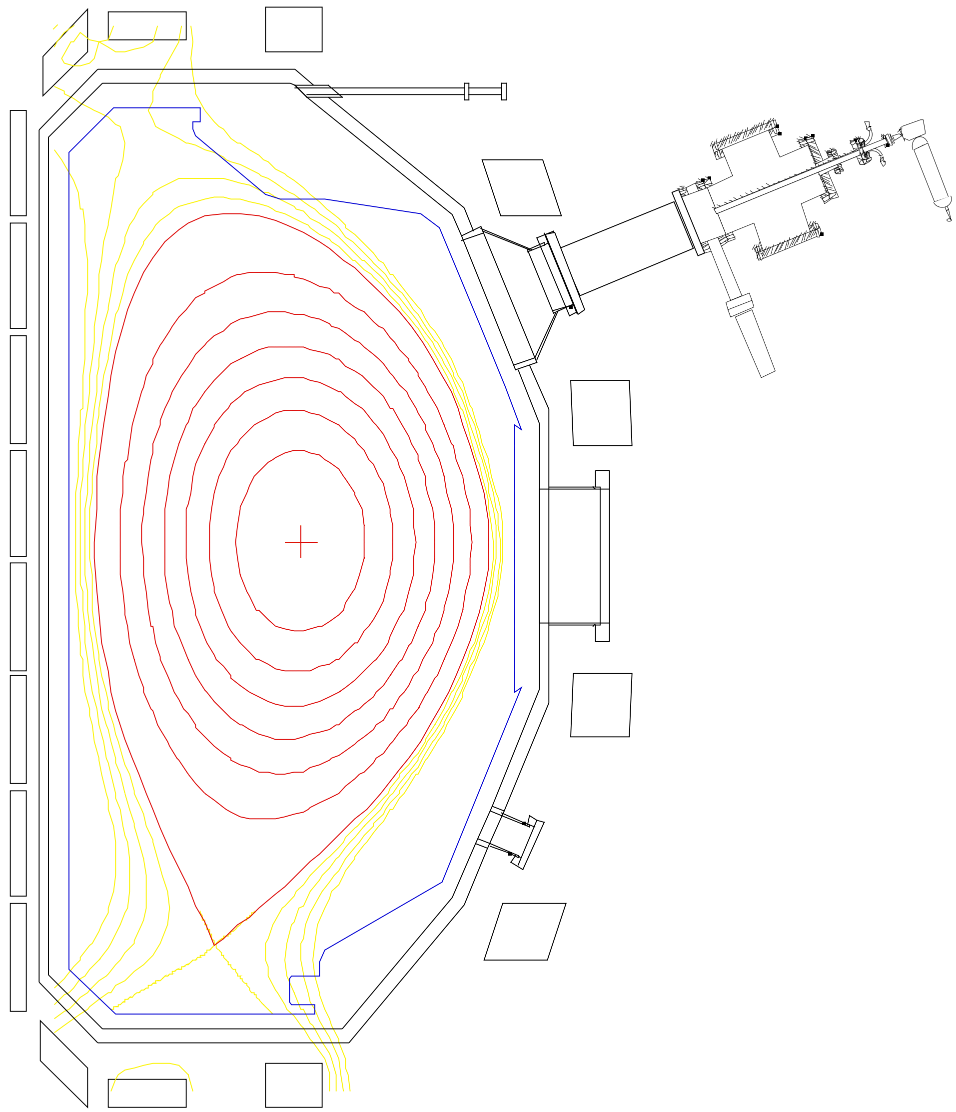
- Conceived as a “quick and dirty” test of a simple mitigation technique to overcome potential runaway electron problems with impurity pellets in ITER class devices
- Uses existing hardware developed for pellet injector program at ORNL
- Model for gas penetration assumes that the sufficient density can be obtained in the gas puff to shield the interior from plasma electrons thus allowing deep, rapid penetration of the neutrals.
- Very successful in preliminary tests on DIII-D in mitigating vertical displacement event (VDE) discharges with no runaway electrons using helium
- Recently results extended to deuterium gas

Objectives of massive gas puff

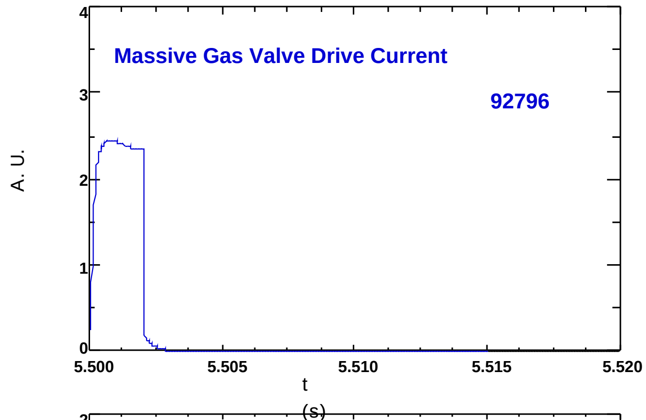
- Mitigate disruption forces and heat flux to the first wall as effectively as impurity pellets using electromagnetic radiation to dissipate the plasma energy
- Eliminate runaway electron generation by using low-Z (D_2 or He) and high density (10^{15} cm^{-3})

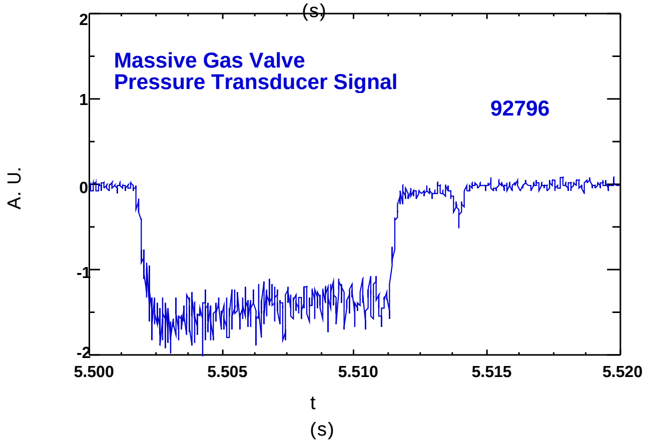

DIII-D Port 15R+1
16.5"
18.4"
Fast Valve (Pellet Injector Propellant Valve)
Pressure Transducer
Ballast Volume
High Pressure Reservoir (300 ml @ 7 MPa)
6 inch diameter Tube
3/4 inch diameter Tube
Gate Valve

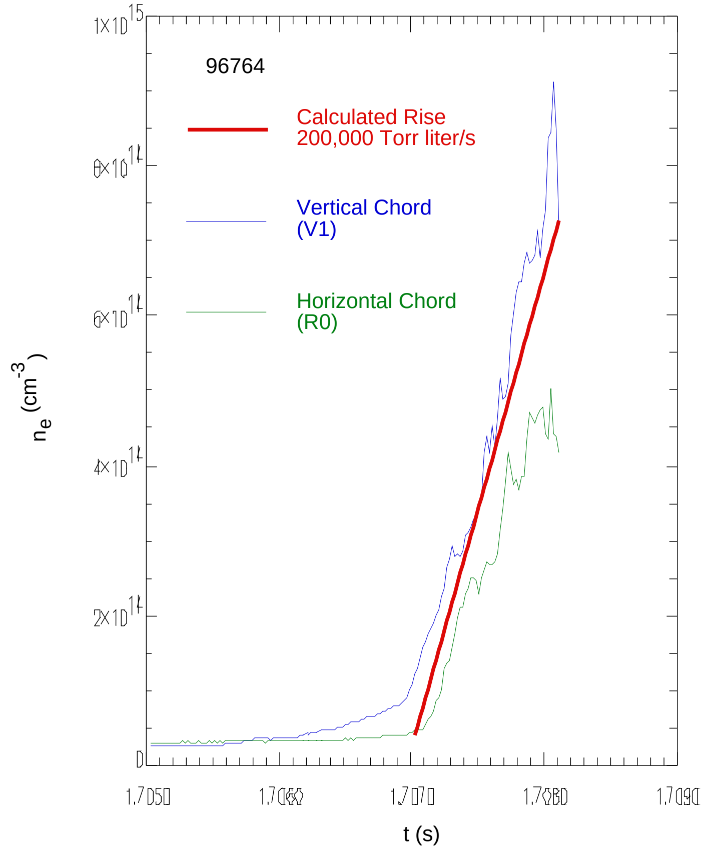
DIII-D with Massive Gas Puff Valve
Flux Surfaces for Shot 95195 at 1.700 s



Plasma ionizes ~50% of input gas before the thermal collapse





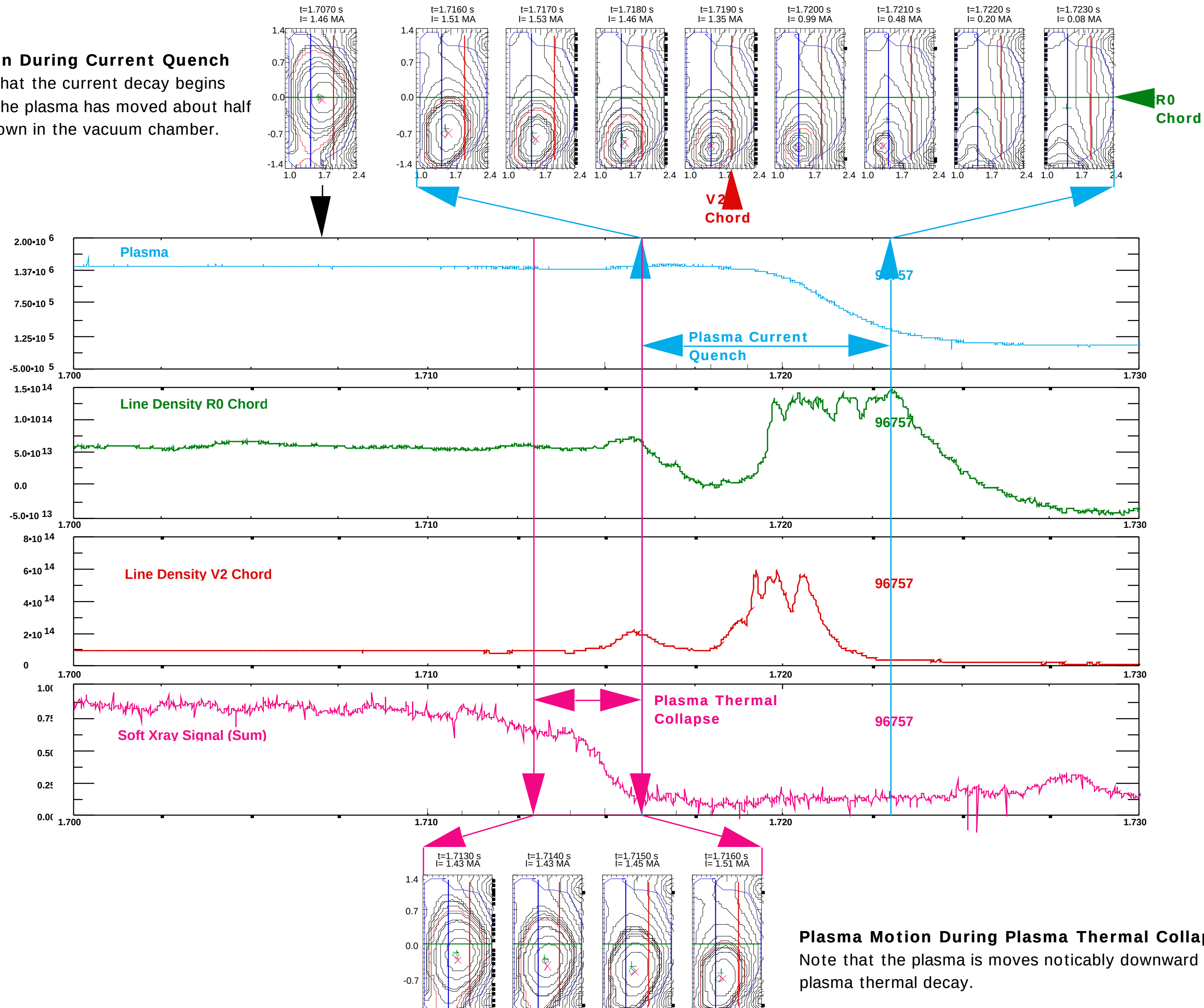


9 ms wide pulse gives pressure rise of 3.2 torr in 1200 liter volume which implies the flow = 400,000 torr-liters/s

Slope of density rise matches flow of 200,000 torr-liter/s until thermal collapse (fully ionized helium)

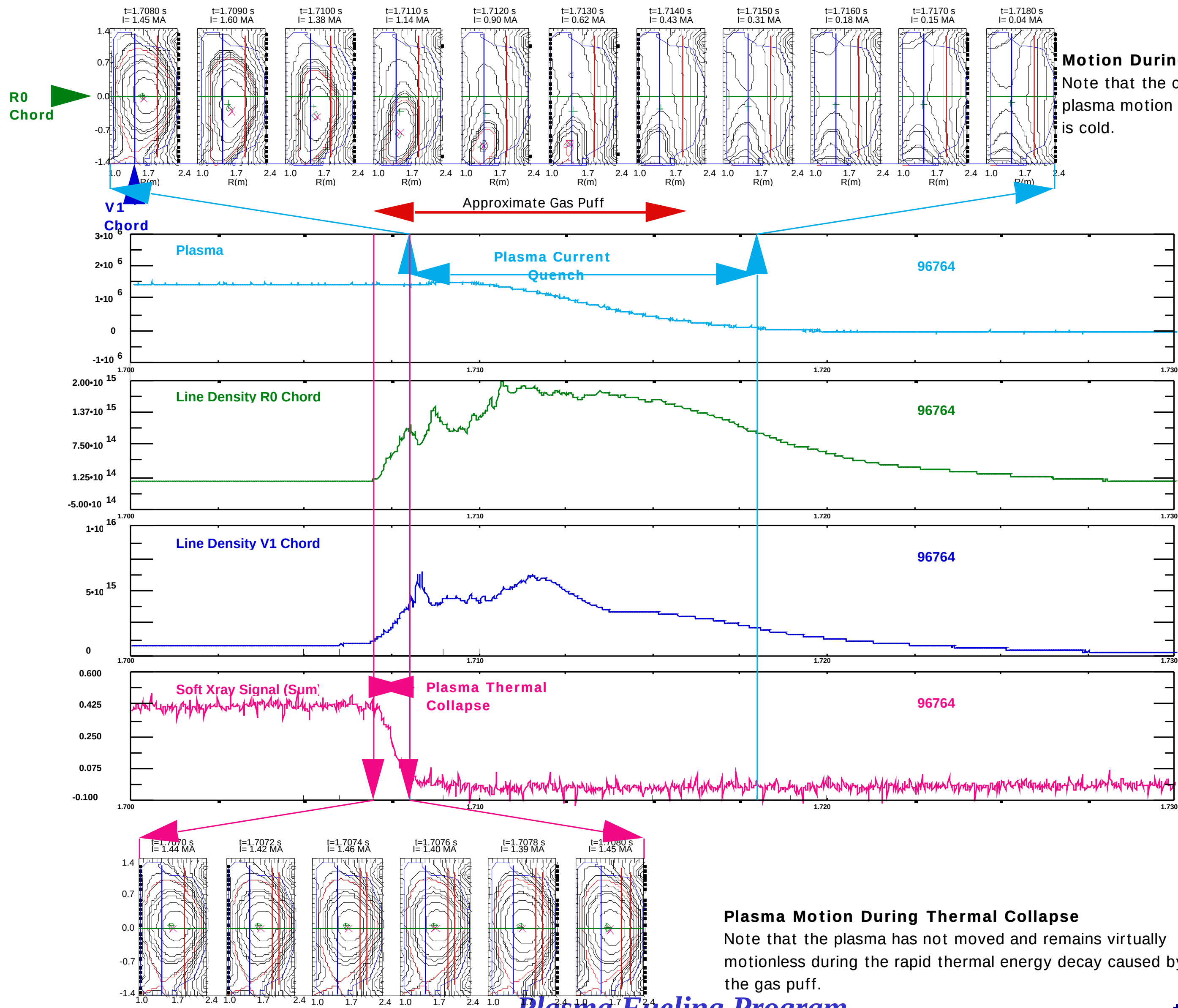
Triggered Vertical Displacement Event Disruption with no Mitigation

Motion During Current Quench
Note that the current decay begins after the plasma has moved about half way down in the vacuum chamber.



Plasma Motion During Plasma Thermal Collapse .
Note that the plasma is moves noticably downward during the plasma thermal decay.

Triggered Vertical Displacement Event Disruption Mitigated with Massive Gas Puff



Motion During Current Quench
Note that the current decay and plasma motion begin after the plasma is cold.

Plasma Motion During Thermal Collapse
Note that the plasma has not moved and remains virtually motionless during the rapid thermal energy decay caused by the gas puff.

Mitigation with massive gas puff

- Halo currents: both magnitude and toroidal peaking factor reduced by factor of 2 which means a factor of 4 reduction in peak forces to the first wall
- Radiated power: virtually all the energy (both thermal and magnetic) is dissipated as radiation
- Power to divertor: could not be measured due to high radiation levels in infrared
- Still have not been able to use Thomson scattering to determine density profiles during the density rise - density measured by multiple chord far-infrared interferometers.

Disruption mitigation conclusions

- Mitigation by massive gas puff test in DIII-D with helium and deuterium gas
  - Rapid penetration of density
  - Rapid energy collapse
  - Mitigation as effective as medium-Z pellets
  - No runaway electrons
  - Deuterium just as effective as helium
  - Extra electrons from helium not required for penetration thus reducing the source for runaway electrons
  - Density rise is uniform across plasma cross-section lending support to the self–shielding model thus enabling deep penetration of the gas
  - Simple, reliable implementation
  - Strong candidate for next step devices

Liquid jets for disruption control status: March 2001

Shown below is a water jet produced using a nozzle that is being considered for use in a liquid deuterium disruption control device for DIII-D. The liquid core of the jet is clouded by mist that surrounds the jet.

This water jet with the same Reynolds number and Weber number as the proposed cryogenic jet is being used to develop the system. The first phase of the work injected jets into air; this jet is traveling into a vacuum.

Parameter	DIII-D Goal	Achieved to Date
Reynolds No.	1.2E6	8.2E5
Weber No.	7.6E6	3.7E6
Jet L/D	2000	1800

5 ms after burst disk rupture

Conclusions

- Innovation and R&D in plasma fueling systems continues to positively impact future MFE devices
  - high-field-side launch: increased fueling efficiency, profile peaking for approach to ignition and high-Q burn
  - pellet-triggered L-H mode: required power threshold reduced ~ 30%
  - isotopic DT fueling: reduced tritium throughput, wall inventories
  - disruption mitigation: exploit performance base of advanced tokamaks while having credible mitigation scheme for disruptions or fast plasma shutdown