Fueling of Reactor-Scale Fusion Plasmas

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Fueling Program Peer Review
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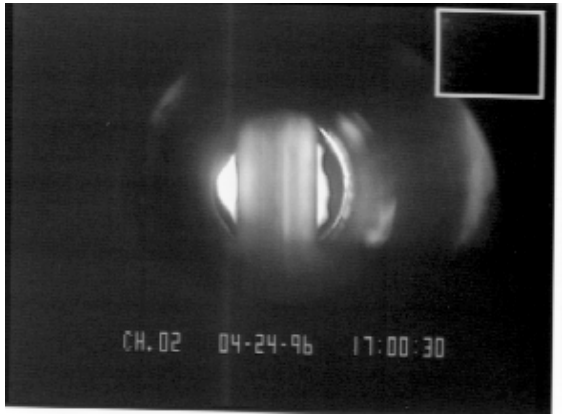
Fueling System Functions

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

ITER fueling R&D results

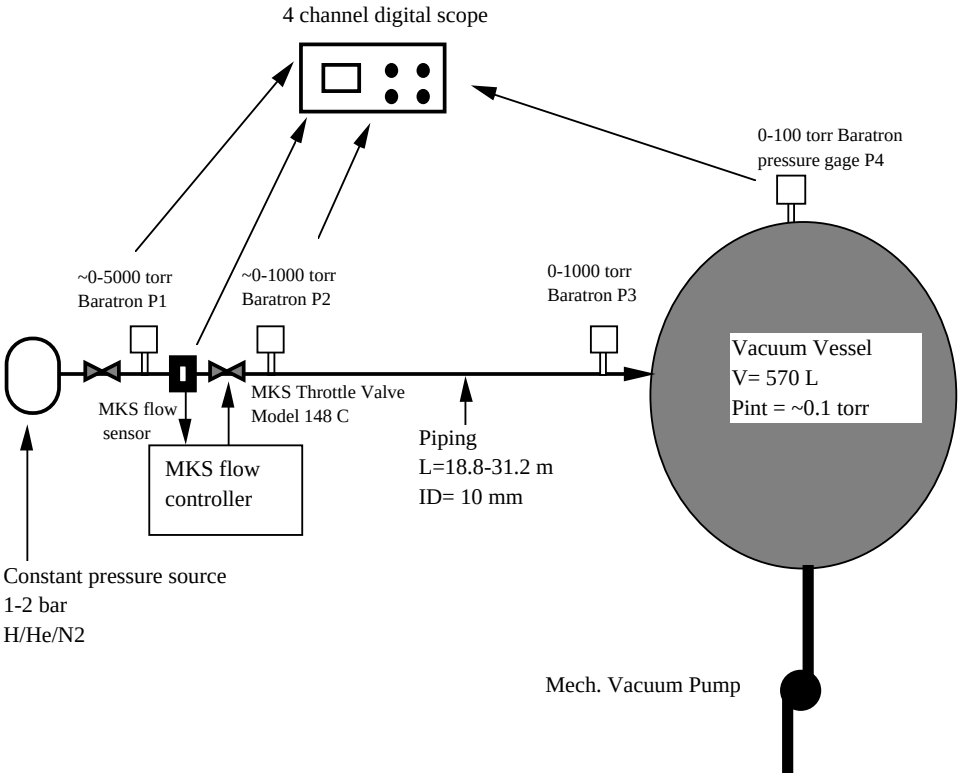
- Gas fueling prototype testing
  - response time experiments for impurity gas puffing into divertor
- Pellet fueling development
  - world's largest cryogenic pellet ~ 10 mm
  - first extrusions of tritium and DT
  - record extrusion rate of 0.26 g/s (deuterium)
  - pellet feed/rotor dynamics for centrifuge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

Pure Tritium Extrusion



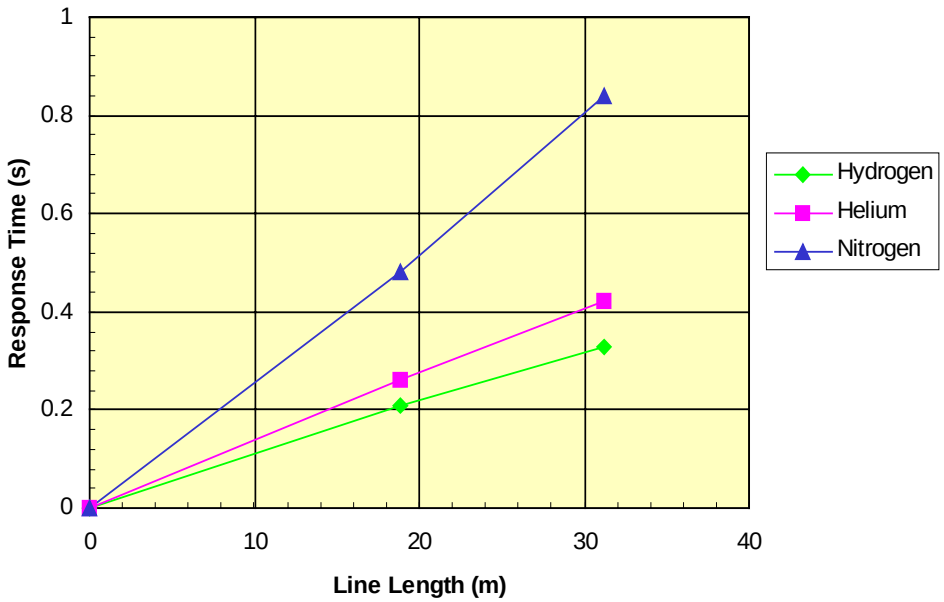
ITER Gas Injection Prototype

- Determine transient performance of ITER gas injection system.
- Vary length of fuel line to the torus from about 18 to 32 m.
- Uses commercial-off-the-shelf components including MKS all-metal dosing valve.
- Feed rates from few-100 Pa-m^3/s
- Transient performance of interest for fusion power control, divertor heat load adjustment and rapid plasma shutdown

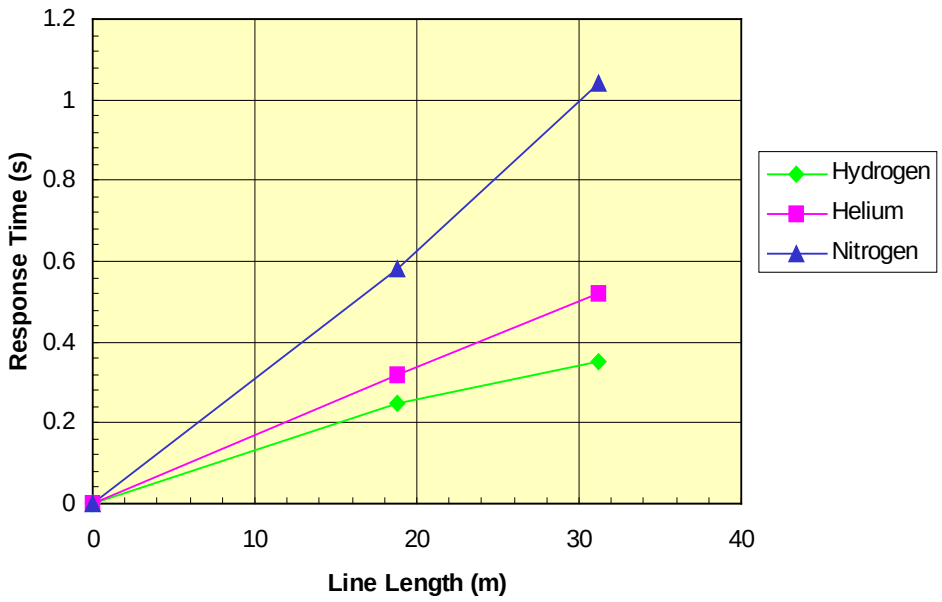


Results of Initial Experiments

Graph 1: Response time to increase flow from 0 to 63.2% of steady-state flow



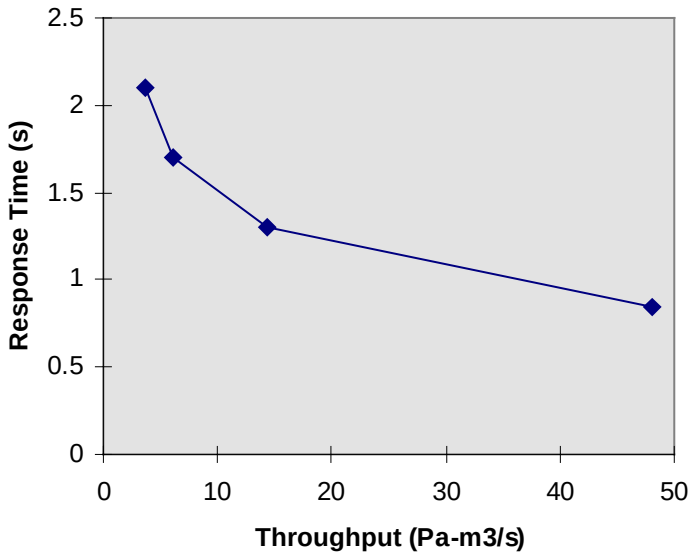
Graph 2: Response time to decrease flow from 100% to 36.8% (1/e)



Fueling rates:
$H_2/He/N_2$: 200/120/50 Pa-m^3/s

Impurity Gas Injection at Low Flow Rates

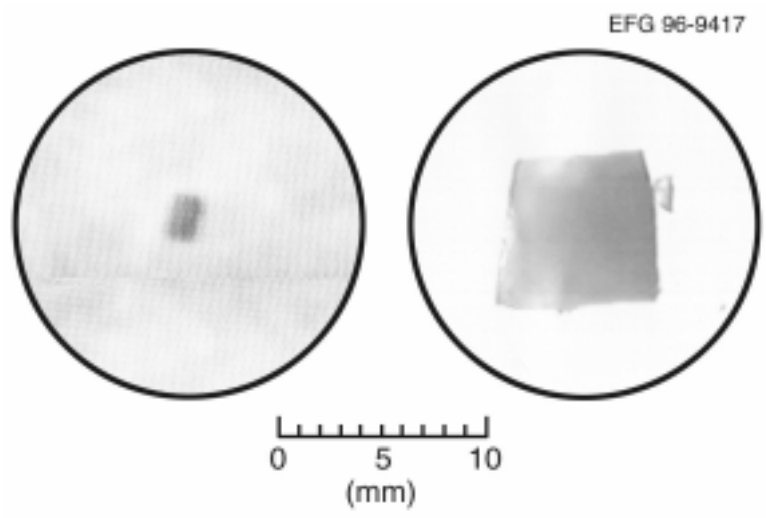
- Low gas flow experiments with nitrogen gas
- 31 m line length, 10 mm line ID, supply pressure 1000 torr (0.13 MPa)
- does not meet spec (0.1 s)
- Solution: place gas dosing valve much closer (1-2 m) to vacuum vessel



Properties of hydrogenic solids

- Have made hydrogenic pellets in sizes from ~0.3 to 10 mm
- Hydrogen properties:

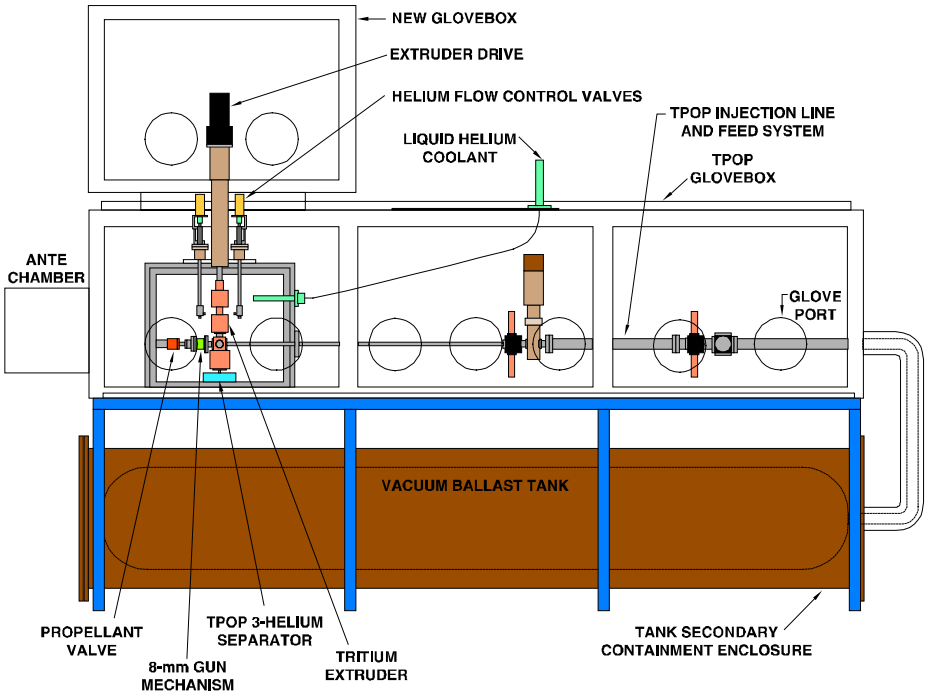
Property	H	D	T
density (g/cc)	.09	.2	0.32
boiling point at 1 atm (K)	20.4	23.7	25
triple point (K)	13.8	18.7	20.6
triple point pressure (torr)	54	129	162

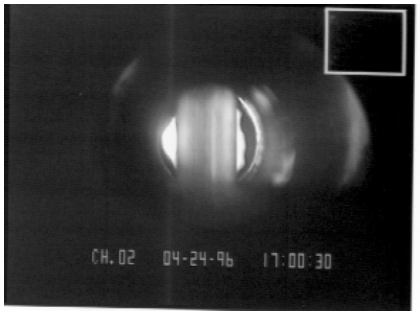


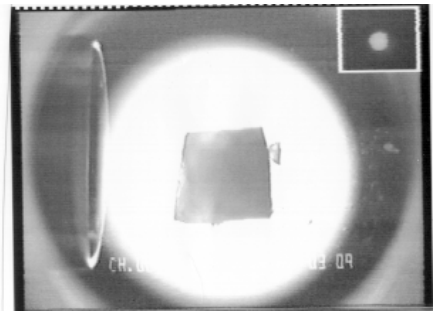
TPOP-II Tritium Extruder Experiments

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 reactors)
- Processed over 40 grams of tritium through TPOP-II
- Developed isotopic fueling concept to reduce reactor tritium throughputs and inventory.





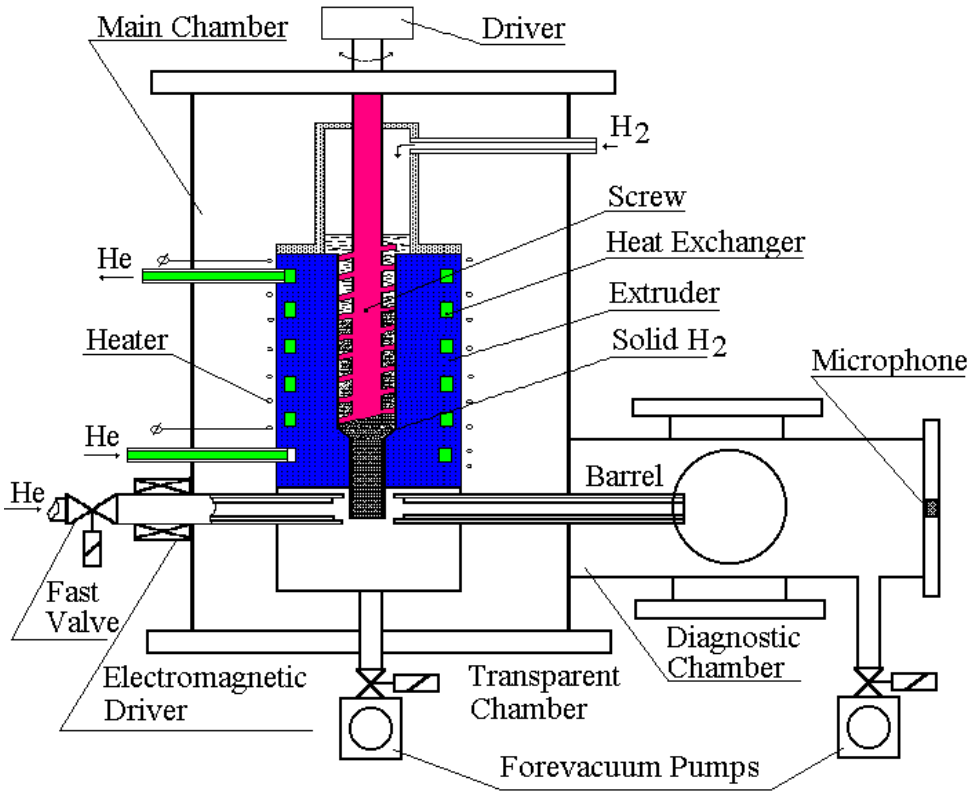


Long Pulse Feed Systems

- The continuous extrusion system using 3 piston-type, linear extruders was developed. It produced hydrogen ice at:
    - 1.3 cm^3/s for moderate pulses (10s)
    - 0.33 cm^3/s for steady-state (1 hour) throughput
- A Russian company (PELIN) has demonstrated about 1 hour continuous operation of a single-screw extruder (2-mm hydrogen extrusions).
- ORNL is exploring (concept design) double-screw and gear-type extruders as variants of the single-screw extruder which have more operational stability and lower LHe cooling requirements.

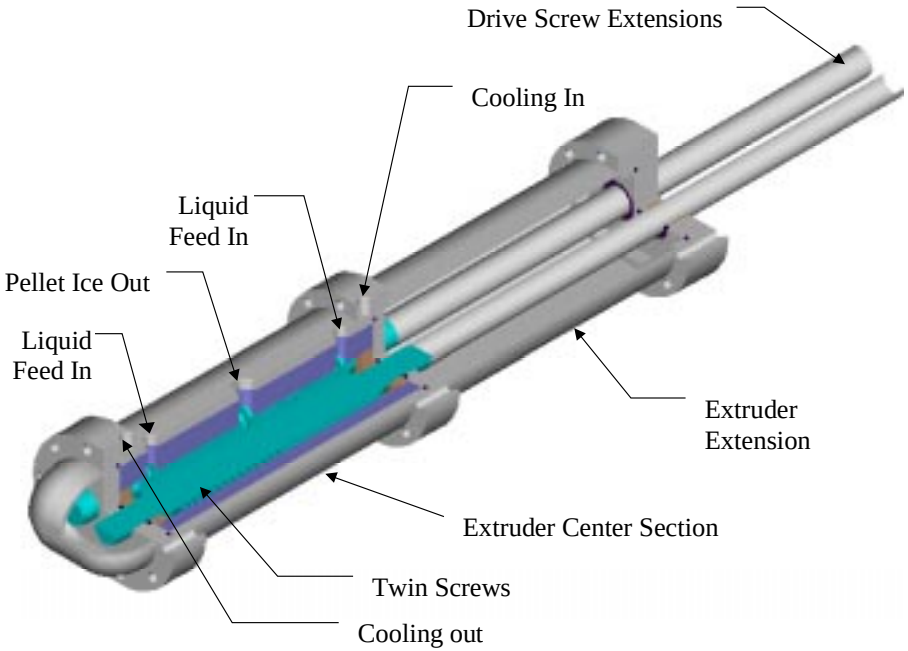
Continuous Screw Extruder (RF)

- A new technique of continuous pellet formation using an extrusion produced by a screw extruder.
- A prototype screw extruder with 5 cm^3 working volume produced a continuous extrusion of a 160 cm^3 solid hydrogen rod with a diameter of 2 mm and with an average volume flow rate of 65 mm^3/s.
- In August 97, Dr. Igor Viniar from the Russia visited ORNL and developed a feasibility study for this technology scaled to 10-mm DT pellets.

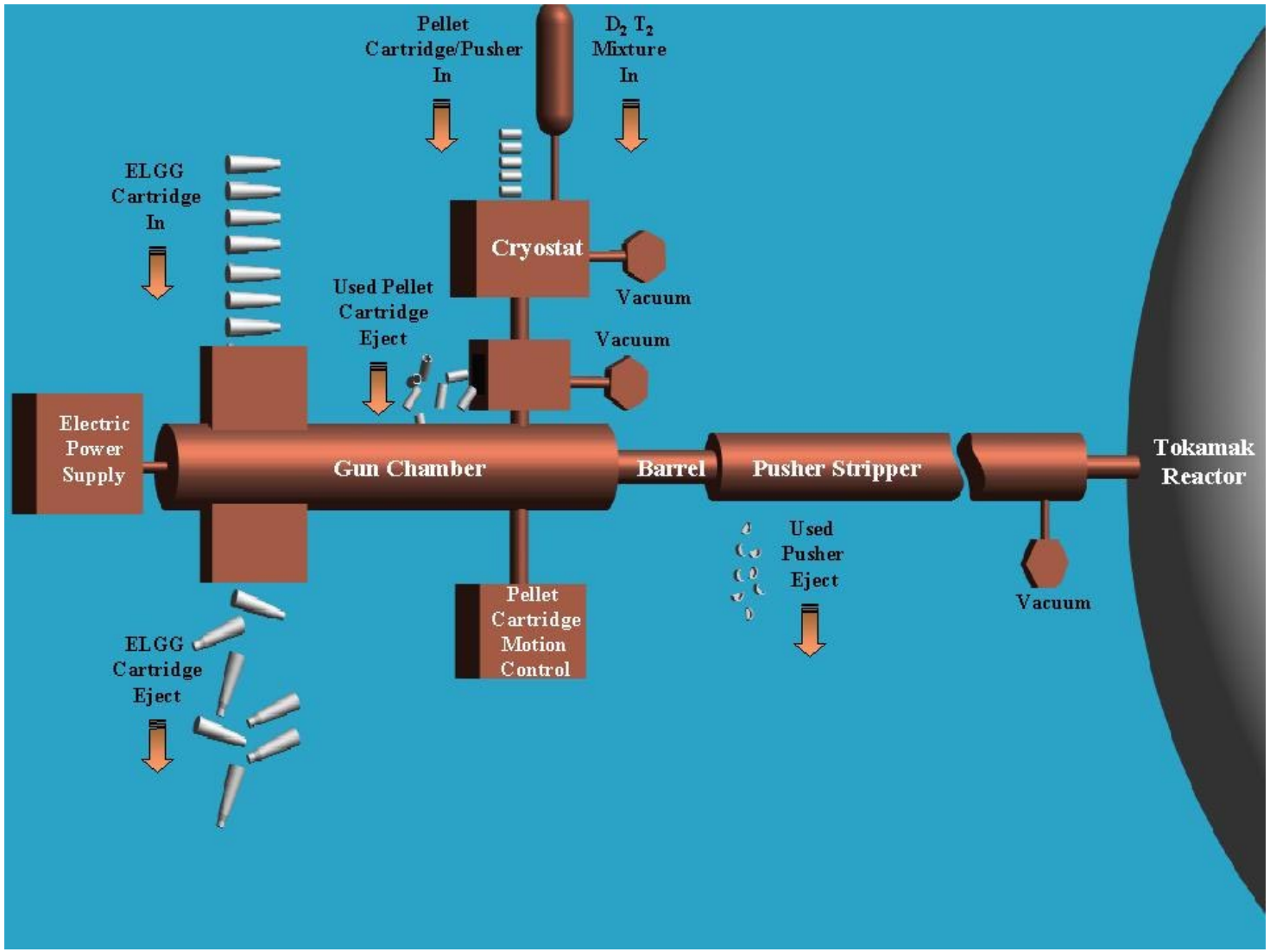


Double-screw extruder concept (ORNL STTR with Utron, Inc.)

- Dual, opposed, counter-rotating screws
- Liquid helium is fed into the extruder at one end and flows through cooling channels
- 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.



Repeating, high-speed, electrothermal gun
(STTR with Utron, Inc; prototype to 6 km/s)

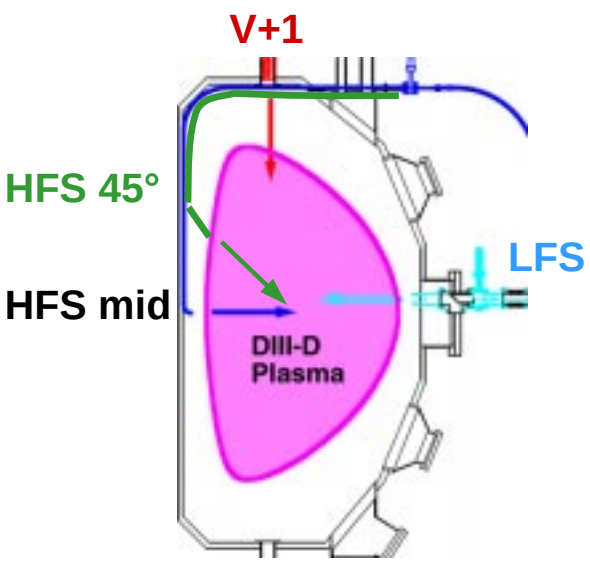


Efficiency of gas fueling much less than pellet fueling:

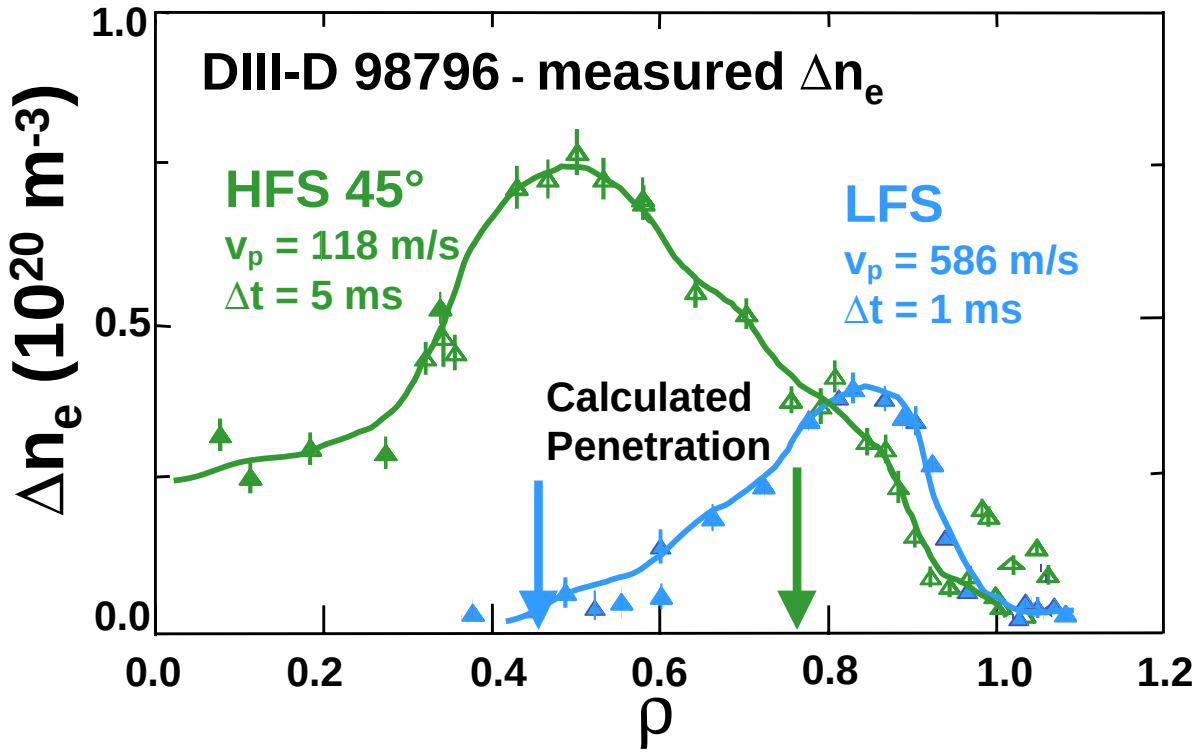
Device	Gas Fuelling Efficiency (%)	Pellet Fuelling Efficiency (%)	Remarks
ASDEX	20	30-100	high density
PDX	10-15		high density
Tore Supra	1	30-100	ergodic divertor for gas fuelling
JET	2-10	20-90	active divertor
TFTR	15		low density DT
ASDEX-U		8-40	
DIII-D	10	10-100 (LFS)	active divertor
DIII-D		80-100 (HFS)	active divertor
Reactor	~0	25-100	HFS

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

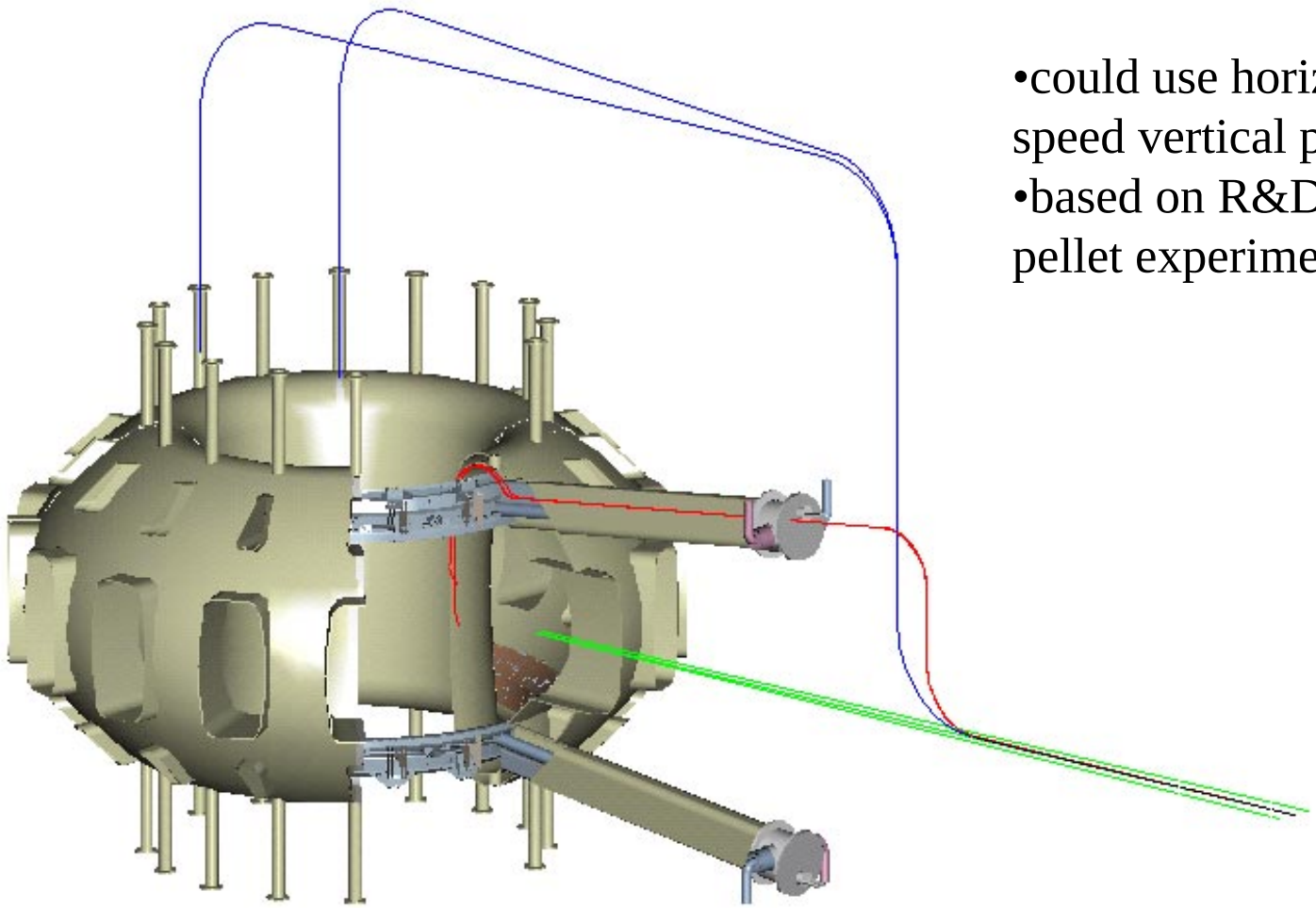


Four positions of pellet injection guide tubes installed on DIII-D



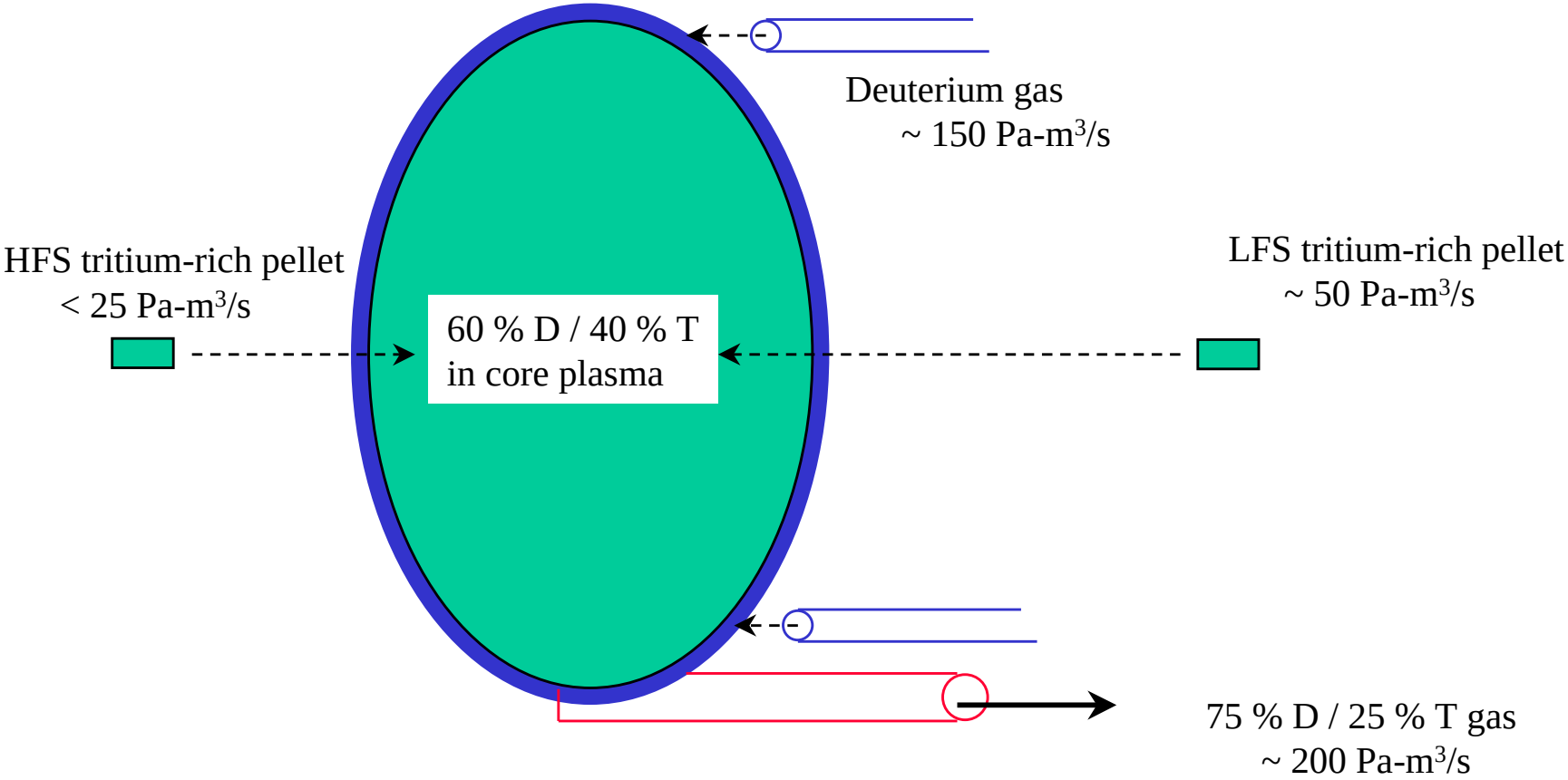
- Net deposition is much deeper for the lower velocity HFS 45° pellets.
- The pellets were injected into the same discharge under the same conditions (ELMing H-mode, 4.5 MW NBI, $T_e(0)$ = 3 keV).

Pellet launch paths into FIRE



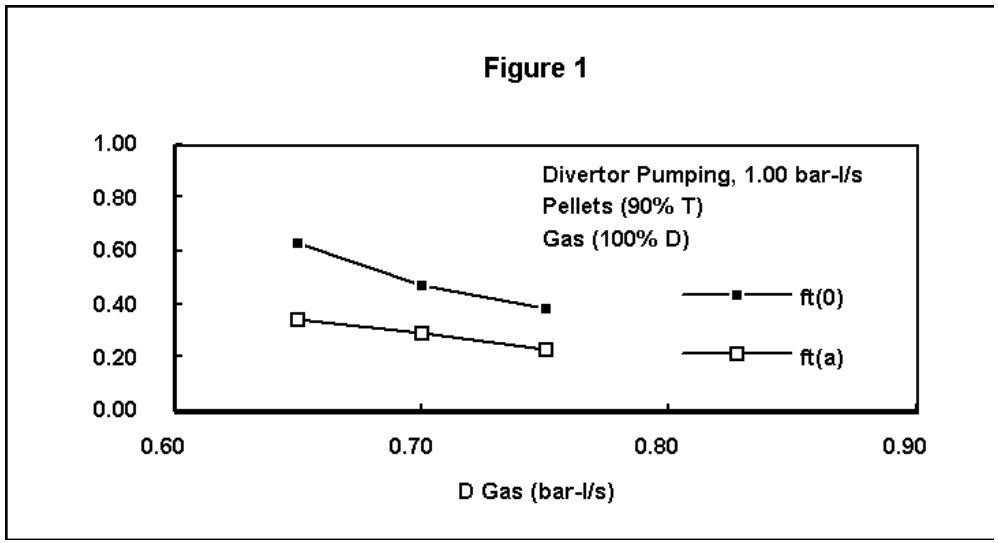
•could use horizontal or higher speed vertical pellet injector
•based on R&D from ITER and HFS pellet experiments

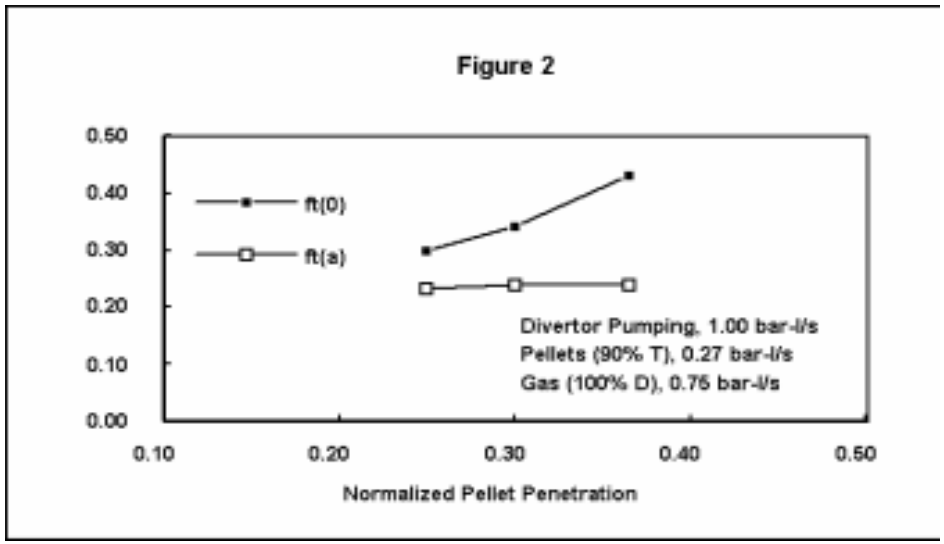
Isotopic Fueling: An innovation to minimize tritium introduced into reactor but maintain P_{fusion}



Isotopic fueling model results are promising (even for LFS launch)

- 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.
- Reactor in-vessel tritium throughputs and wall inventories can be reduced by about a factor of two (LFS) or more (HFS).



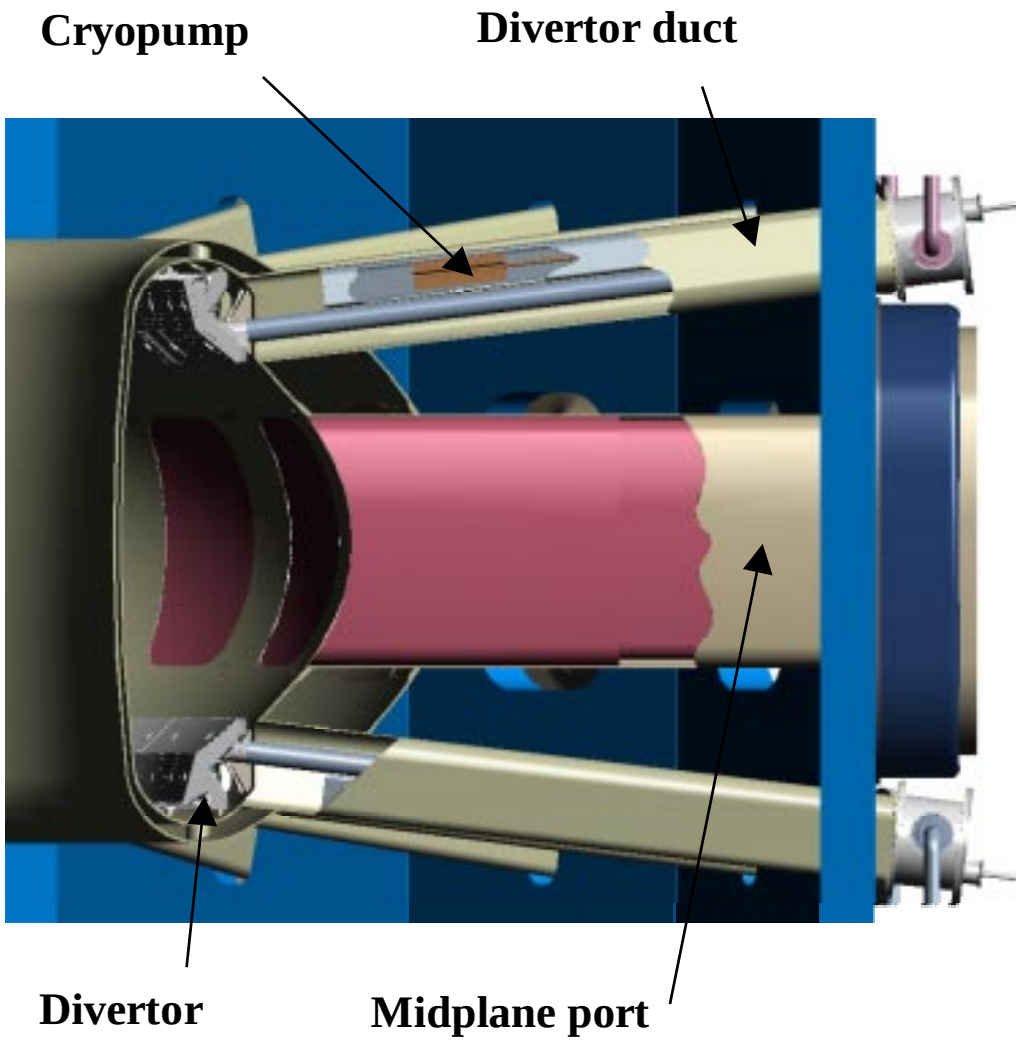


Pumping and exhaust system for reactors

- OFES-VLT does not have an active development program element in the vacuum pumping and exhaust area:
  - typically there are modest resources under NSO-type activities for design and analysis
  - more hardware development in Europe/Japan (innovation is limited)
- Almost all MFE development work in U. S. is via the SBIR/STTR program with several projects by Cryogenics Applications F, Inc. (CAFI)
- CAFI has developed continuously-regenerating, primary pumps ("snail") backed by pellet-type pump (talk by Chris Foster)
  - active phase II STTR in this area
  - potential to simplify fuel cycle, reduce tritium inventories, reduce sizes
  - ITER pellet injector pumping system used this technology

Pumping system for FIRE

- baseline is 16 cryopumps with 8 each top and bottom, close coupled to torus, no interface valve (i.e. regenerate to torus):
- cryocondensation/diffusion pumps backed by turbo/drag pumps
- designed to pump in both the free-molecular and viscous flow regimes
- the 2 torr-l/s helium gas produced by the D-T fusion reaction is compressed by viscous drag in the entrance duct by a factor of up to 100.
- the compressed helium gas is carried from the cryopump to a turbo/drag pump located outside the biological shield through the divertor duct



Summary

- Have designed fueling systems for a succession of future fusion devices: CIT, BPX, TPX, ITER, FIRE, ARIES…
- The results from the VLT development program and from our enabling technology on plasma experiments have been applied to reactor-scale fueling and pumping systems:
  - innovations like tritium pellets, PEP mode, high field side pellet launch, isotopic fueling and L-H transitions are making our reactor designs more attractive
  - operational experience on large devices improves reliability of future systems through feedback to developers (also FMEAs)
  - related technology such as impurity injection for plasma radiation control and mass injection systems for disruption mitigation and rapid plasma shutdown also support more attractive MFE reactors.