FIRE Fueling and Pumping Design

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Outline

- FIRE Fueling System Design
  - FIRE Requirements and design
  - JET/DIII-D Injector (a good match for FIRE)
  - Curved guidetube systems
  - Tritium pellet experience (TPOP)
  - Disruption mitigation technology
- FIRE Pumping System Design
  - FIRE Requirements and design
  - In-Duct Cryopumping System
  - Nuclear Heat Load
  - General Vacuum System Characteristics
  - Cryopumping and cold duct concept

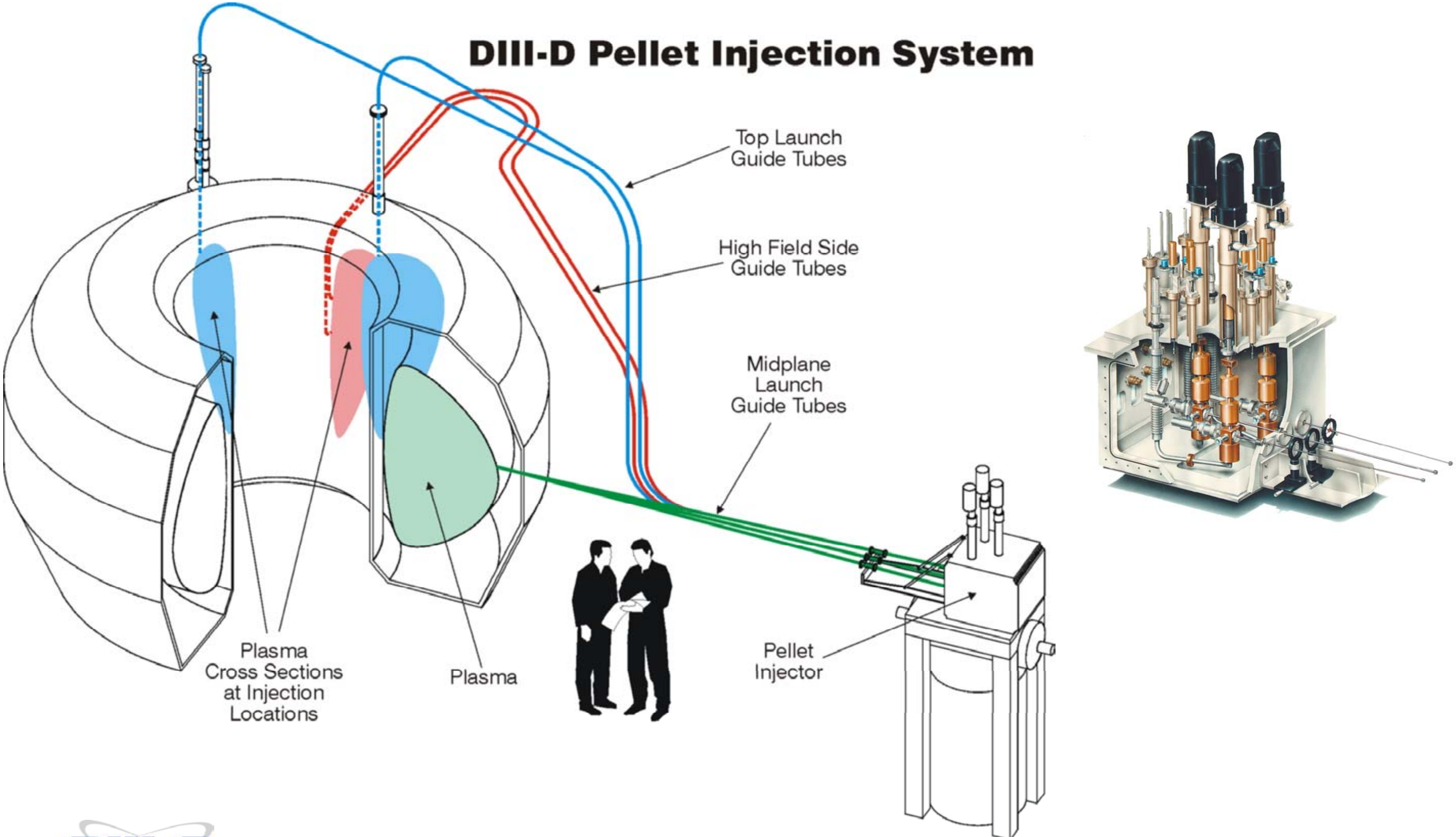
Fueling system functions

- 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.

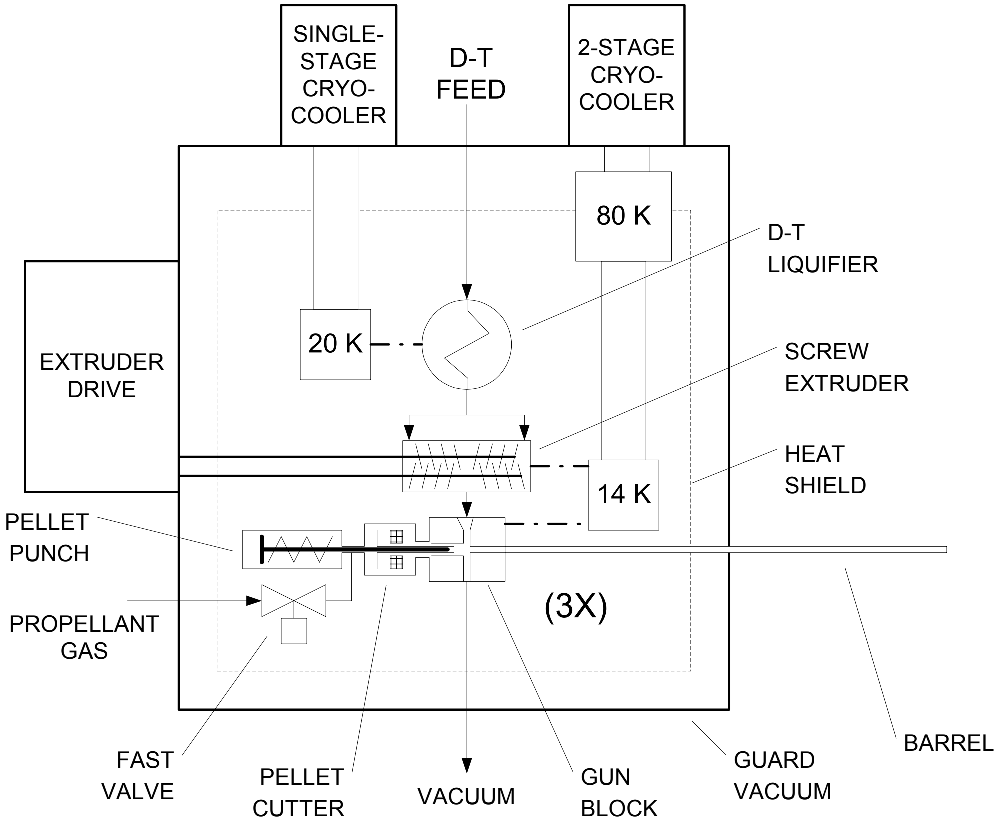
Preliminary FIRE fueling system parameters

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 $\sim 10^6$ 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

Multiple launch locations on DIII-D

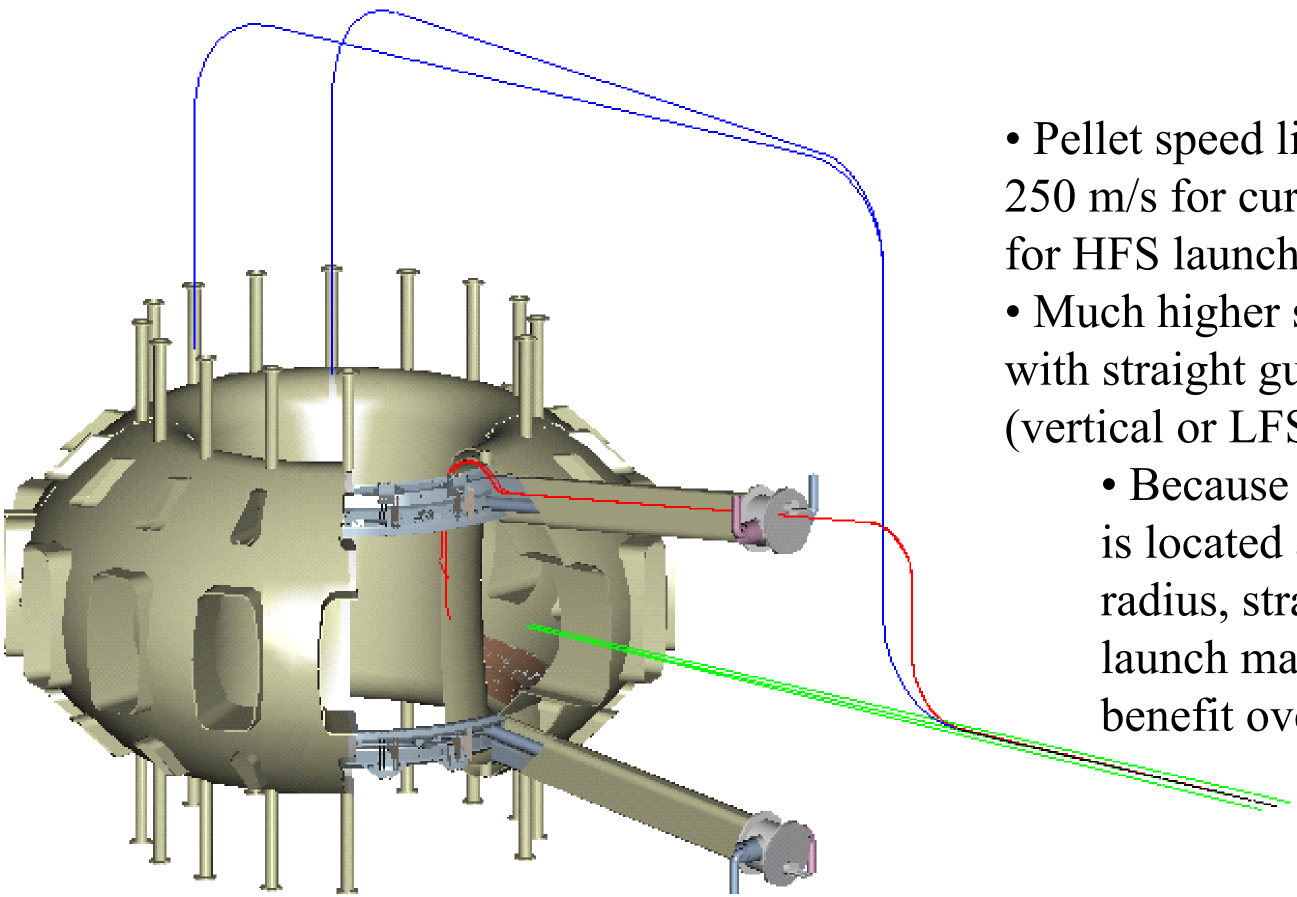


FIRE pellet fueling system



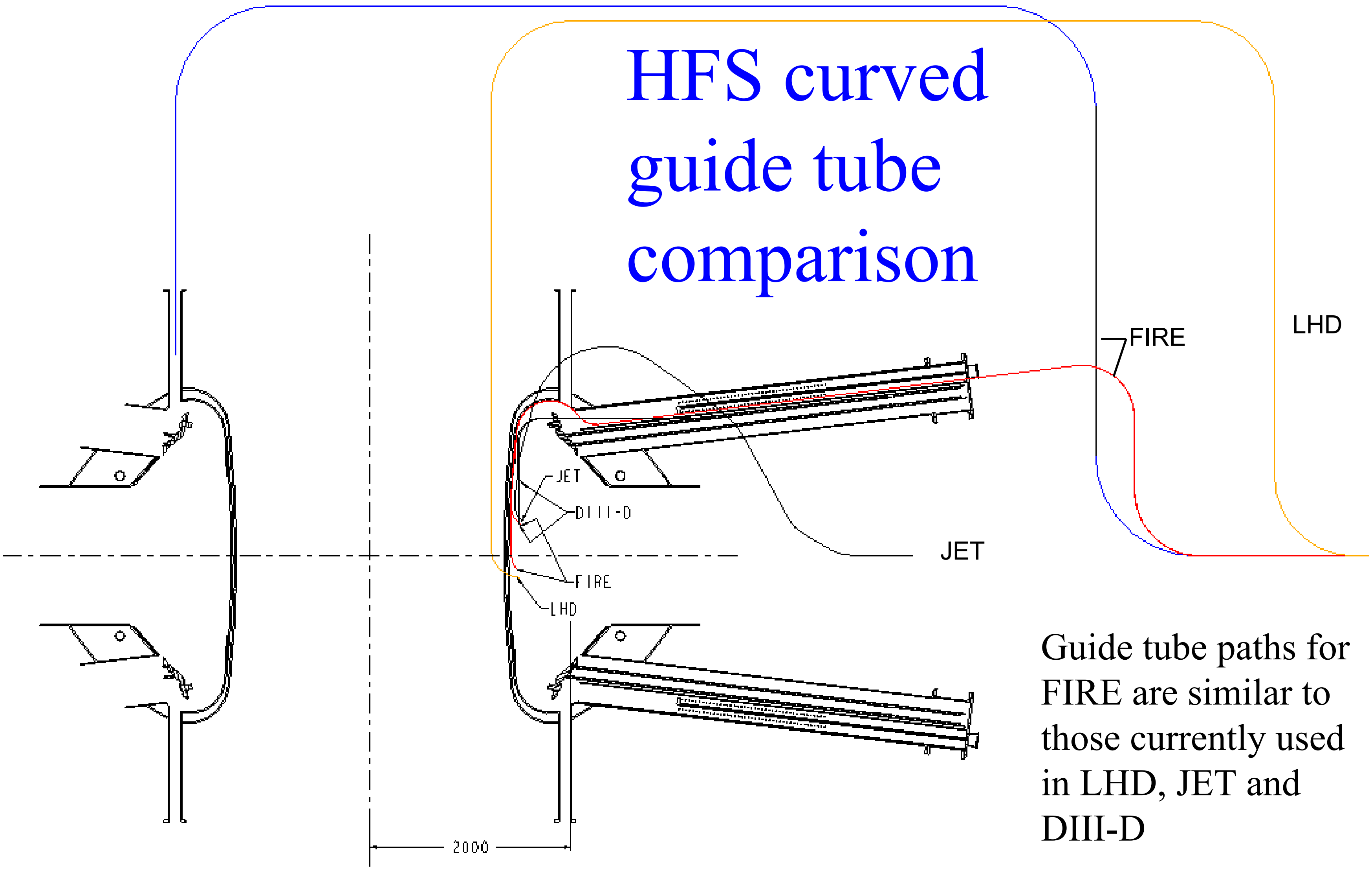
- •Repeating pneumatic injectors (3)
- •D-T 200 torr-L/s for 20 s, 3-4 mm pellets @~4 Hz, 200-1200 m/s
- •Pellet diagnostics, injection line, guide tubes, secondary containment
- •Based on JET/DIII-D injector
- •Employing new cryocooler and continuous extruder technology

Pellet launch paths into FIRE



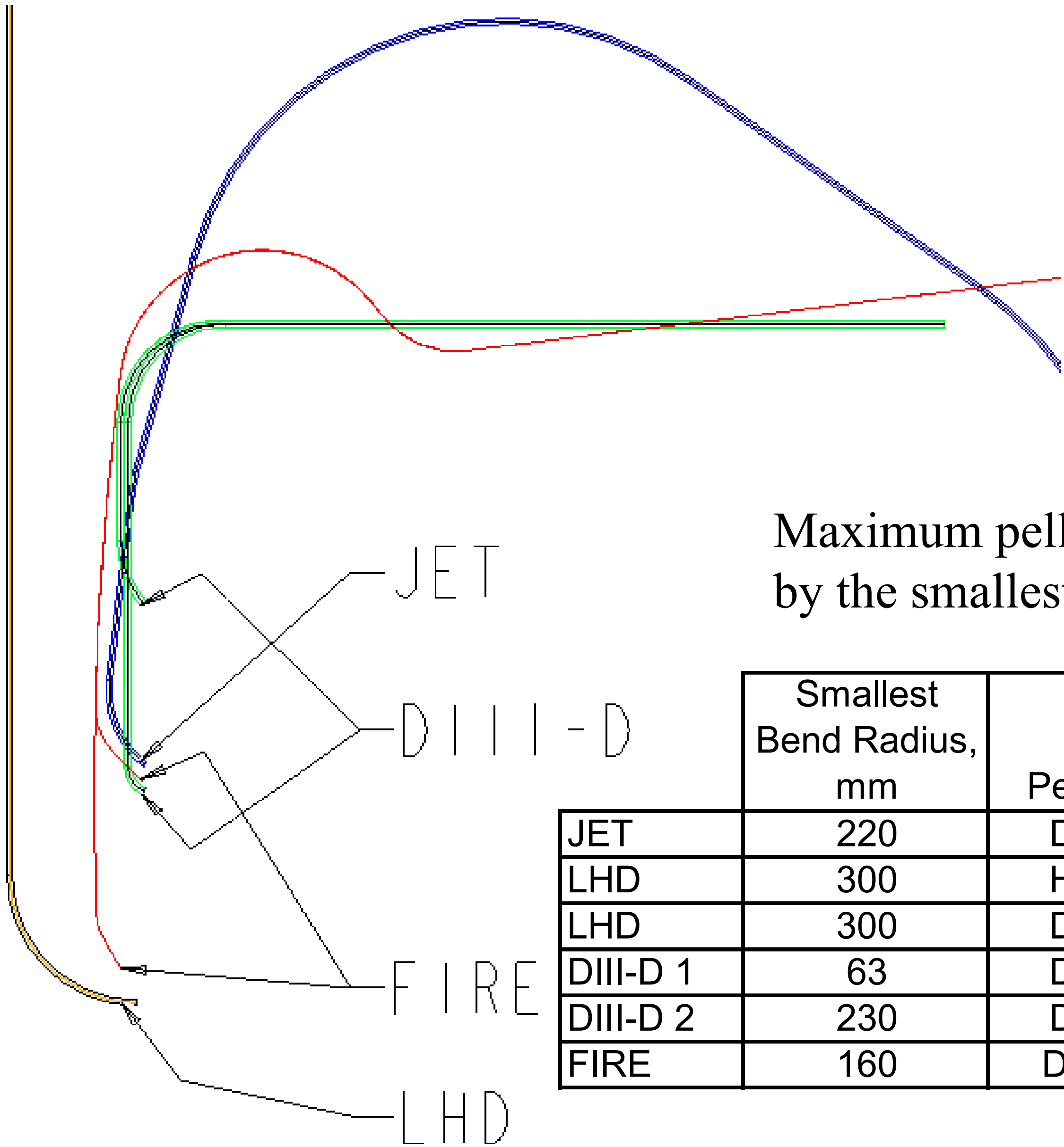
- Pellet speed limited to about 250 m/s for curved guide tubes for HFS launch
- Much higher speeds possible with straight guide tubes (vertical or LFS launch)
  - Because the vertical port is located at the major radius, straight vertical launch may have little benefit over LFS launch

HFS curved guide tube comparison



Guide tube paths for FIRE are similar to those currently used in LHD, JET and DIII-D

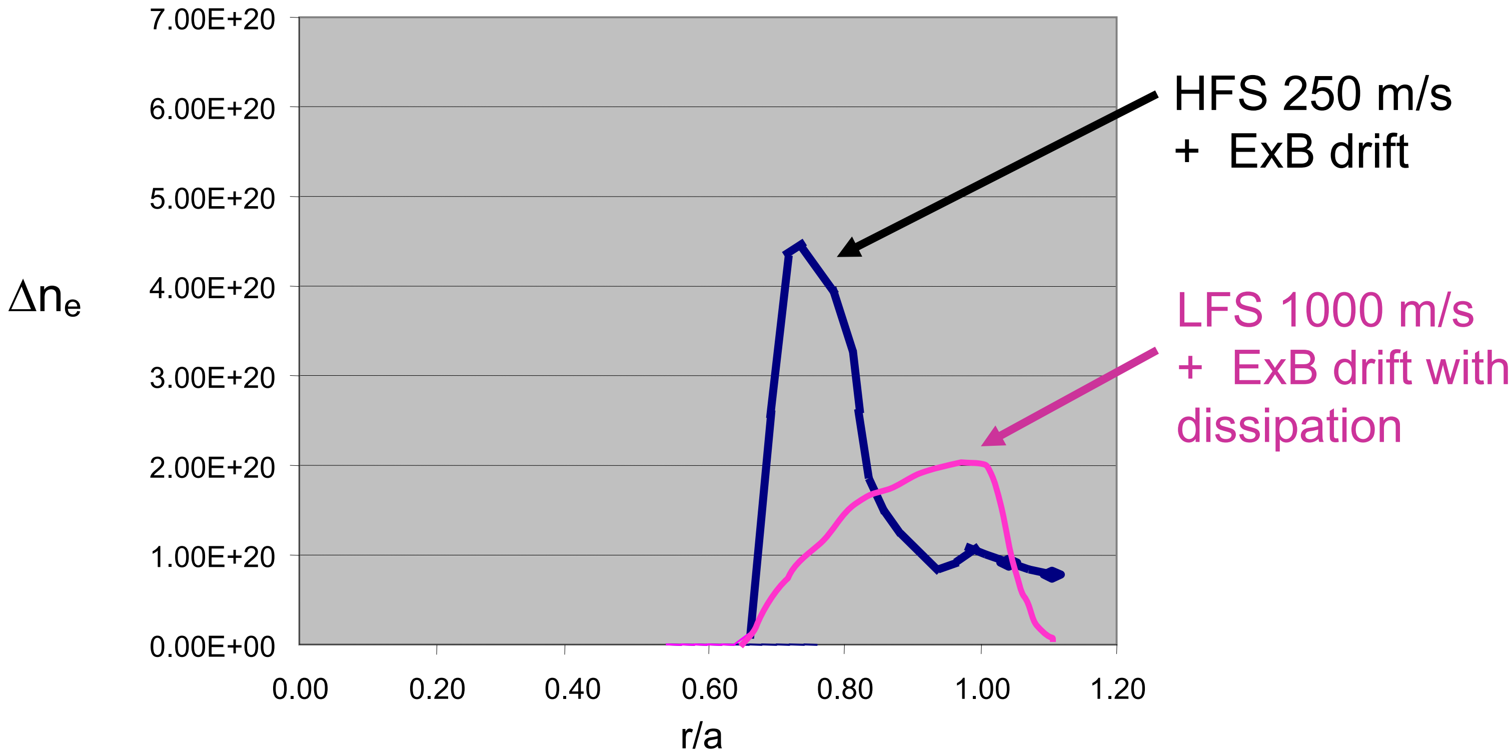
HFS curved guide tube comparison



Maximum pellet speed is limited by the smallest bend radius

	Smallest Bend Radius, mm	Pellet	Diameter, mm	Pellet Speed Limit, m/s
JET	220	D2	4	160-250
LHD	300	H2	2.7	270-470
LHD	300	D2	2.7	265-360
DIII-D 1	63	D2	2.7	220-300
DIII-D 2	230	D2	2.7	260-300
FIRE	160	D-T	3-4	<250

FIRE - Pellet Deposition with Parks ExB Drift Model (Apr 2001)

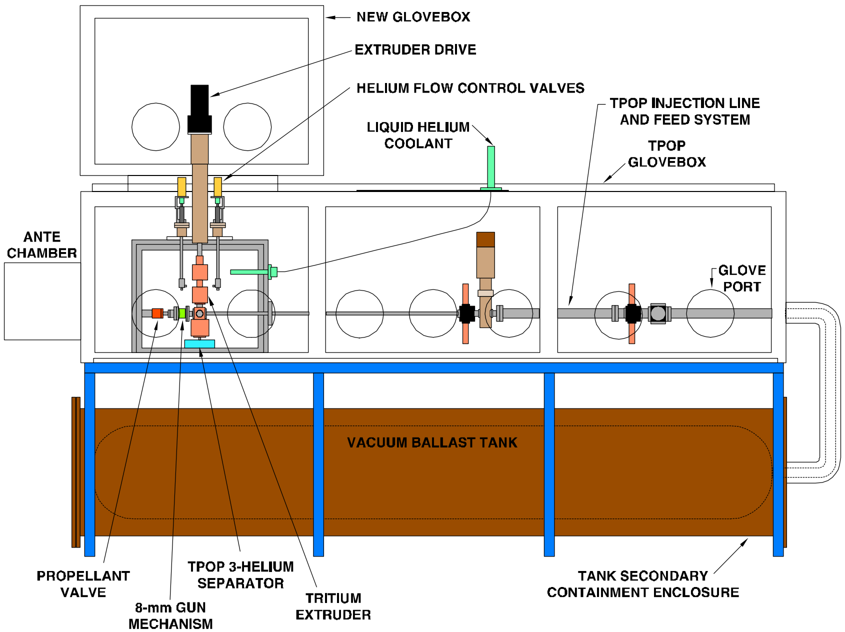


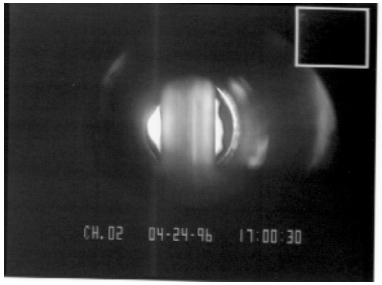
The resulting deposition from a 4 mm pellet injected from the outside midplane (LFS) and inner wall (HFS) including ExB drift effects to NGS pellet ablation. The calculation uses the Pellet Relaxation Lagrangian code to model the cloudlet displacement from ExB drift. Dissipation is ad hoc scaled from DIII-D results.

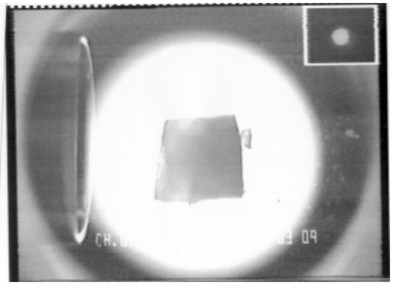
TPOP-II tritium extruder experiments

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.



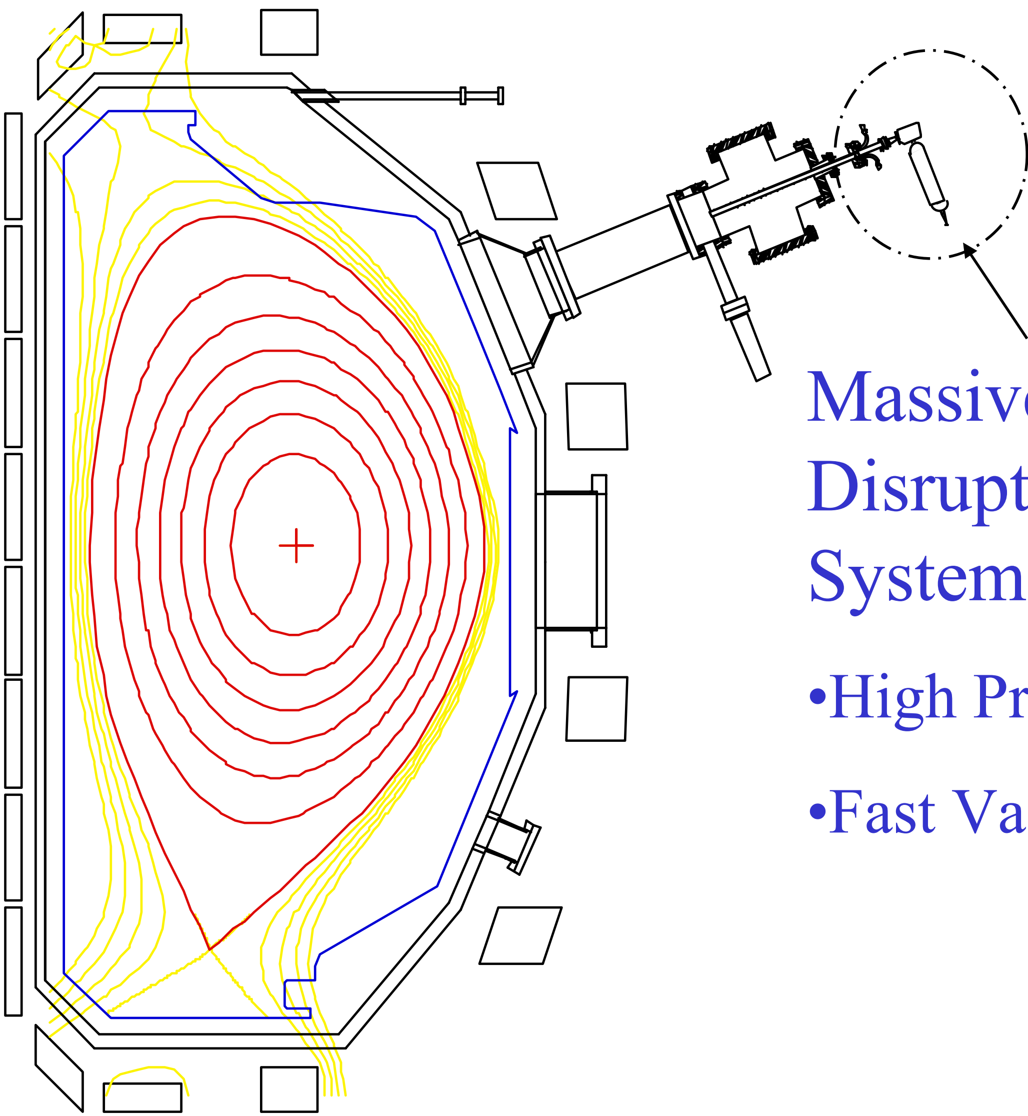




Fueling technology for mitigating disruptions and VDEs

- 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

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



Massive Gas Puff Disruption Mitigation System for FIRE

- High Pressure Gas Supply
- Fast Valve

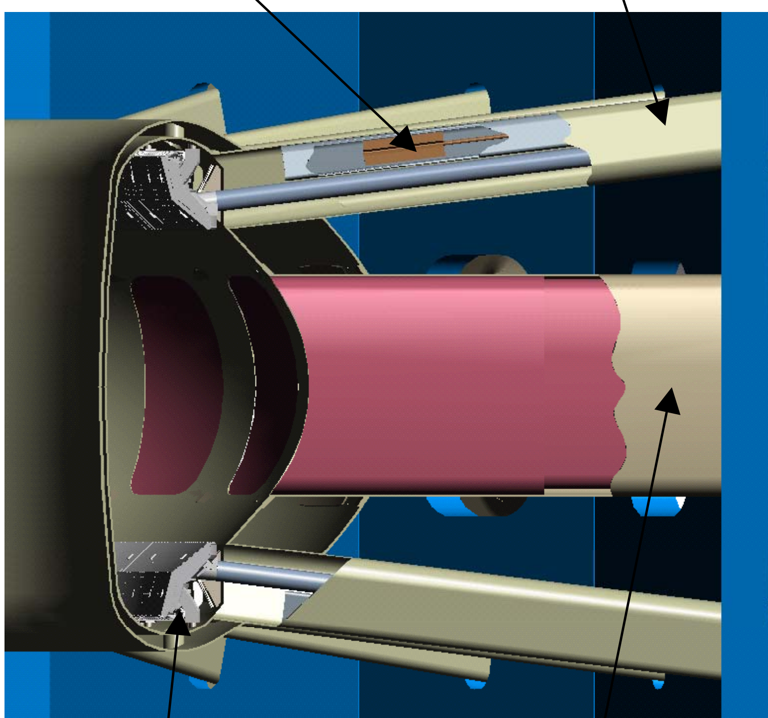
FIRE Pumping System

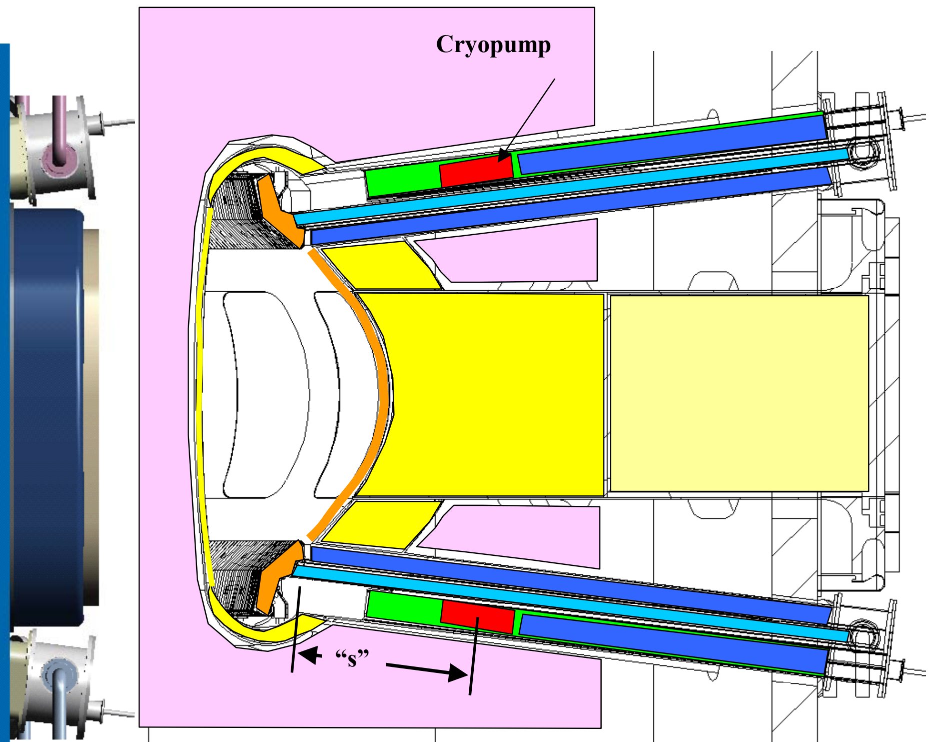
- Provide all vacuum pumping for torus during
  - bakeout
  - normal operation
  - discharge cleaning
- Base pressure:
  - 10^{-7} torr, for fuel gases (H, D, T)
  - 10^{-9} torr for impurities
- Gas load: ~ 200 torr-l/s of H, D, T and some He
- Operating pressure ~ 0.02 torr
- Must be compatible with tritium (oil free, all metal)
- H, D, T inventory must remain below deflagration (a non-issue with FIRE's daily shot limits) and tritium limits

FIRE Vacuum Vessel Pumping

- Current baseline is cryopumps: 16 total 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
  - Water is pumped on the ID of the 160 mm diameter by 1 meter long, 30 K entrance duct which connects the divertor to the cryocondensation pump
  - Other impurity gases are pumped on a 0.5 m long 15K shield
  - Hydrogen is pumped by cryocondensation by a liquid helium cooled in-duct pump
  - 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 pumped by a turbo/drag pump located outside the biological shield through the divertor duct
  - cryogenic cooling requirement for the 16 pumps at a pumping rate of 200 torr-l/s and the nuclear heating loading (estimated at 0.03 watt/cm^3 at the proposed cryopump location) is 3 watts per pump. The liquid helium cooling rate required during a shot is 200 l/h for the 16 pumps.

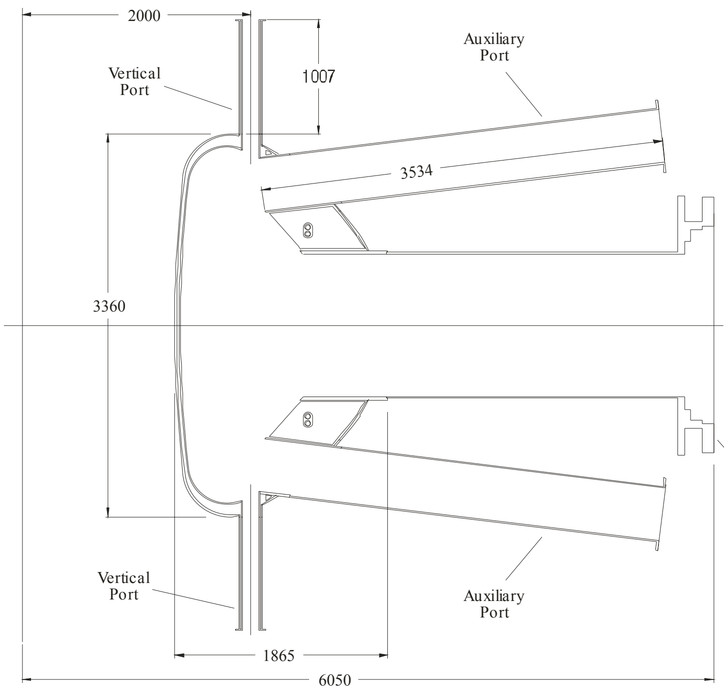
In-Duct Cryopumping System for FIRE

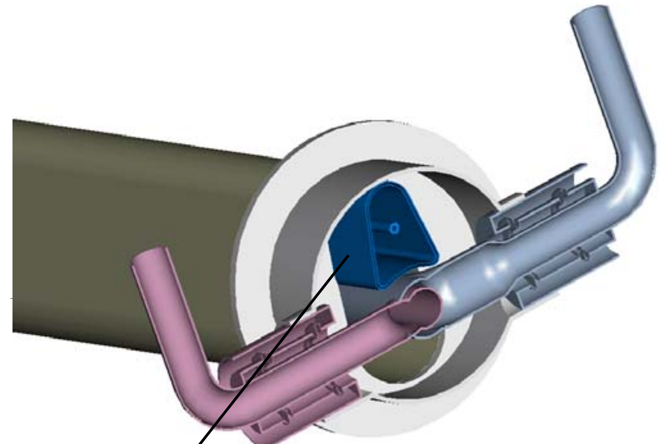


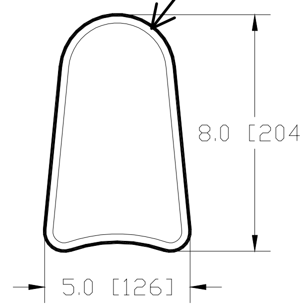


Green = thermal shroud for cryopump.
Red = cryopump located inside thermal shroud
Light purple=TF coil and intercoil structure (filled with polyetheline shielding)
Yellow, dark blue = “good” steel / water shielding
Blue = divertor piping (mostly water)
Orange = FW / passive plates, mostly copper

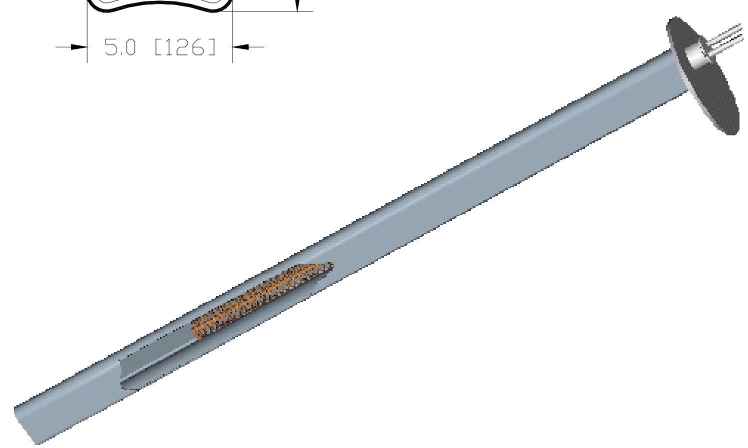
FIRE vessel and port dimensions



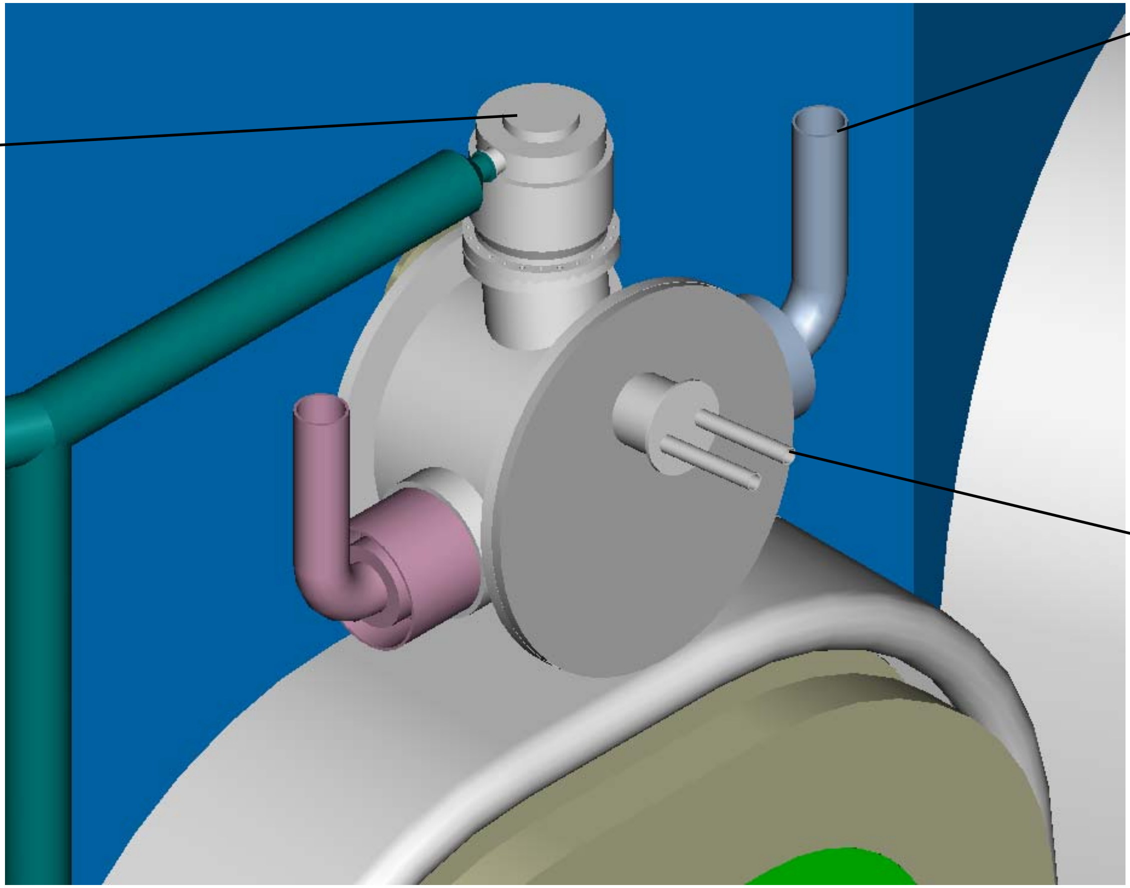




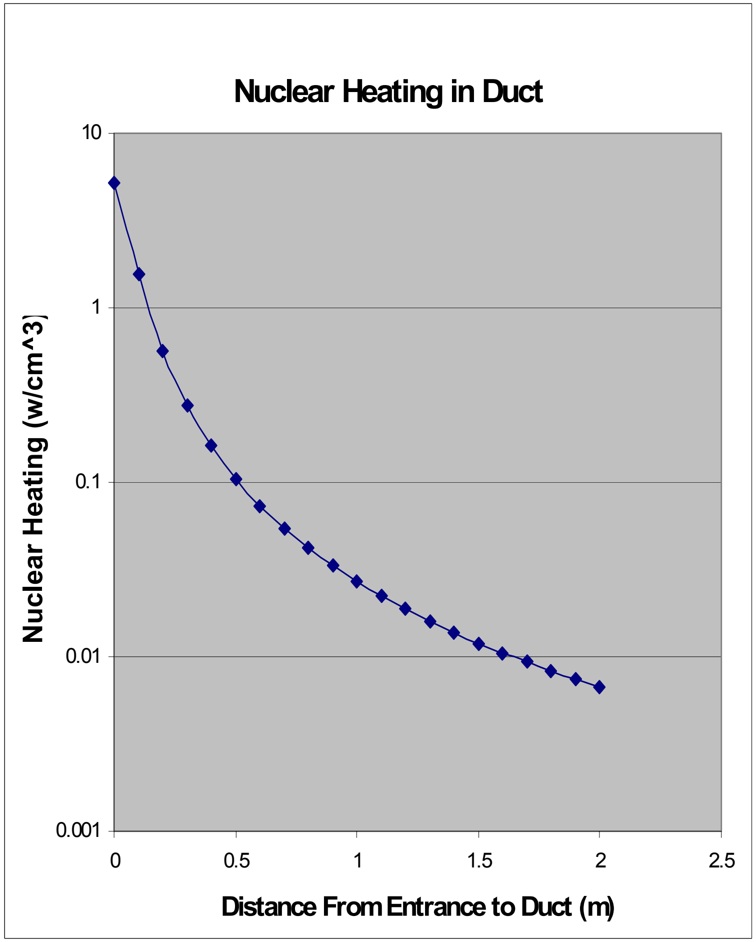
D_h	5.7 in	0.14 m
CSA	32 in^2	0.021 m^2

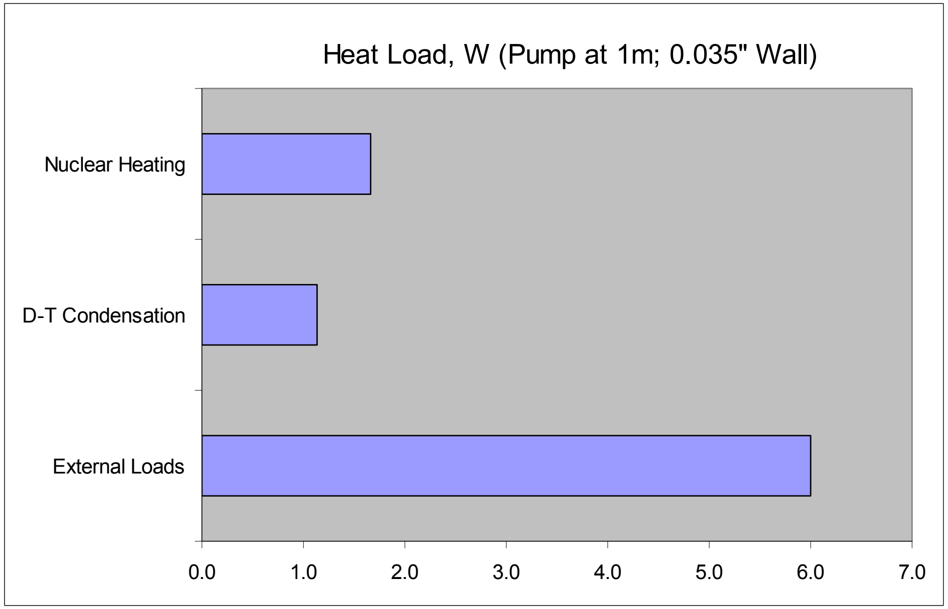


FIRE Vacuum Port



Nuclear Heating





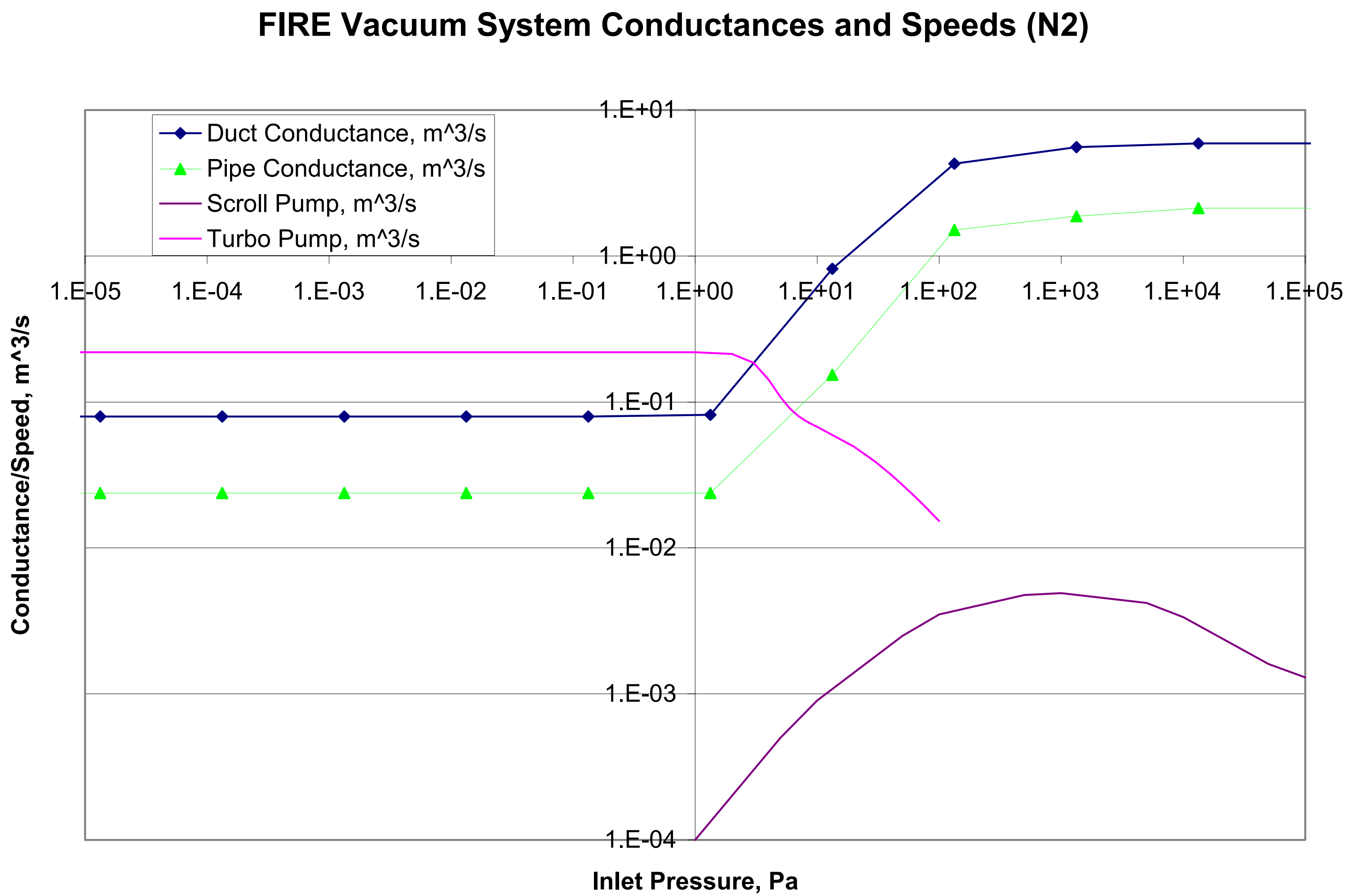
LHe Consumption for16 Cryopumps

- 200 L/h during pulse
- 170 L/h during dwell

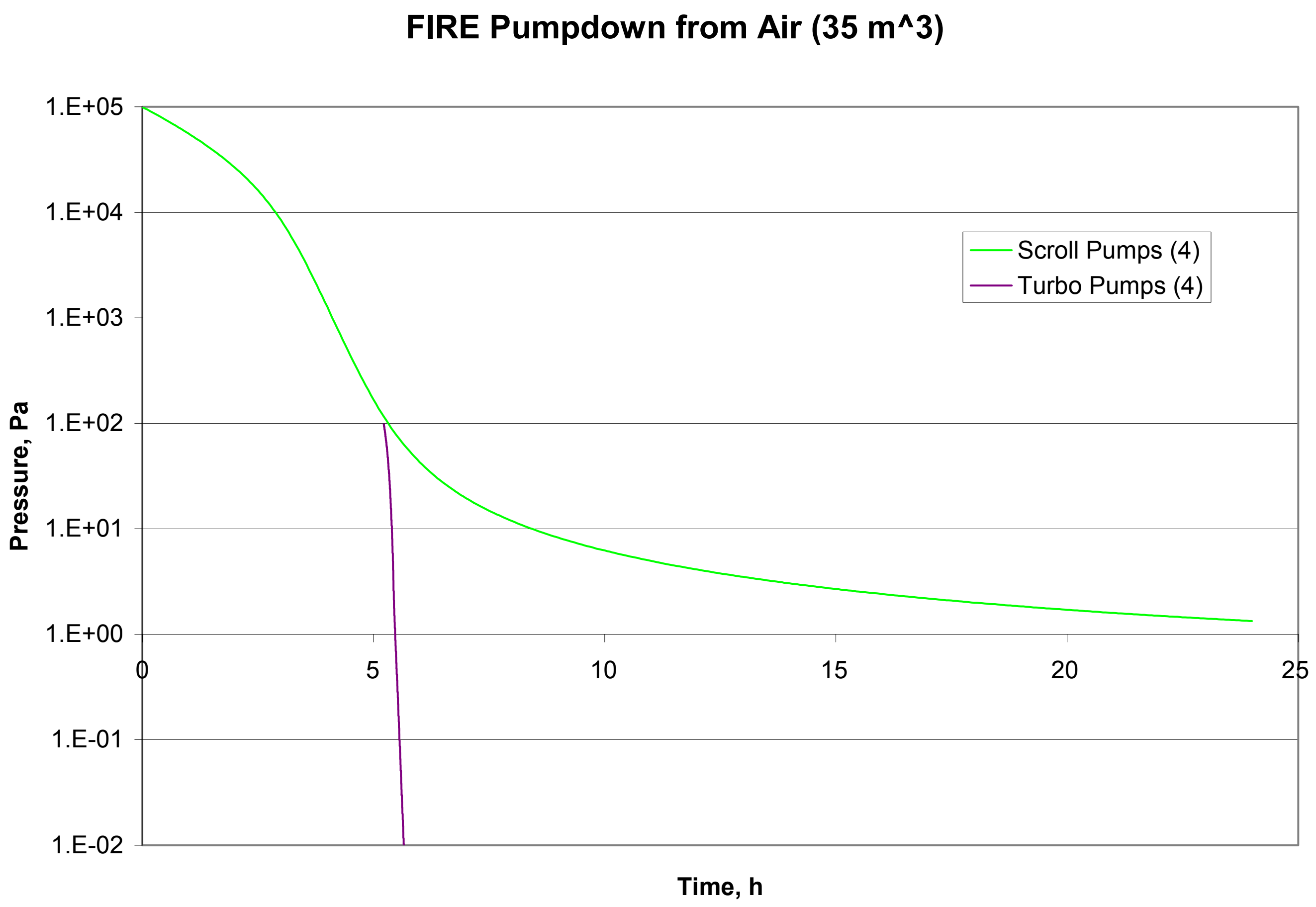
FIRE Vacuum Pumping Options

- Option to minimize in-vessel tritium inventory by cryopump regeneration between pulses:
  - between shots the LHe flow may be stopped to allow the pumps to regenerate into the compound turbo/drag pumps
  - the 4,000 torr-l of DT pumped during the shot will raise the 35 m^3 torus chamber to 0.1 torr. The pumping time constant for the 16 turbo-drag pumps with 3,200 l/s combined speed will be 12 seconds
  - multiple turbo/drag pumps may be backed with a single 3.3 l/s scroll pump backed with a metal diaphragm pump
  - this will limit the tritium contained on the cryopumps to less than 1 gram for a 20 sec. discharge

Comparison of Conductances and Speeds

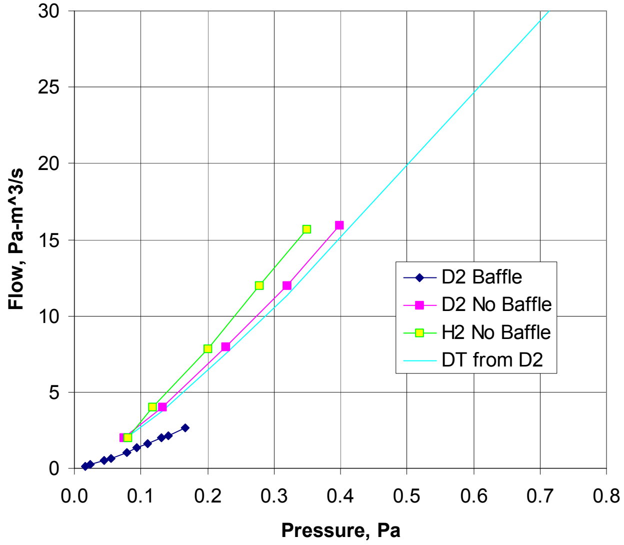


Rough Pump Performance

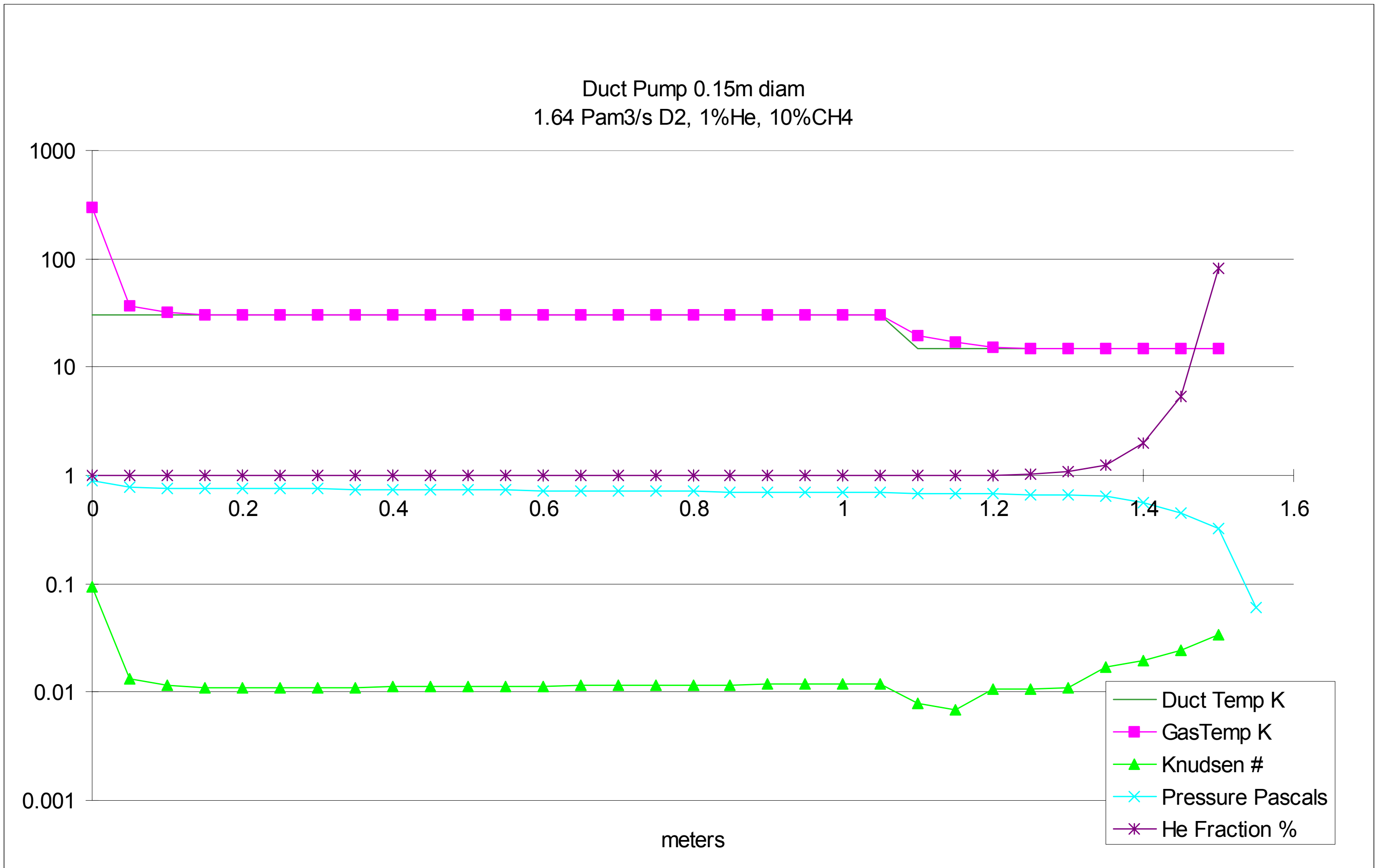


Continuous cryopump: developed under DOE SBIR program

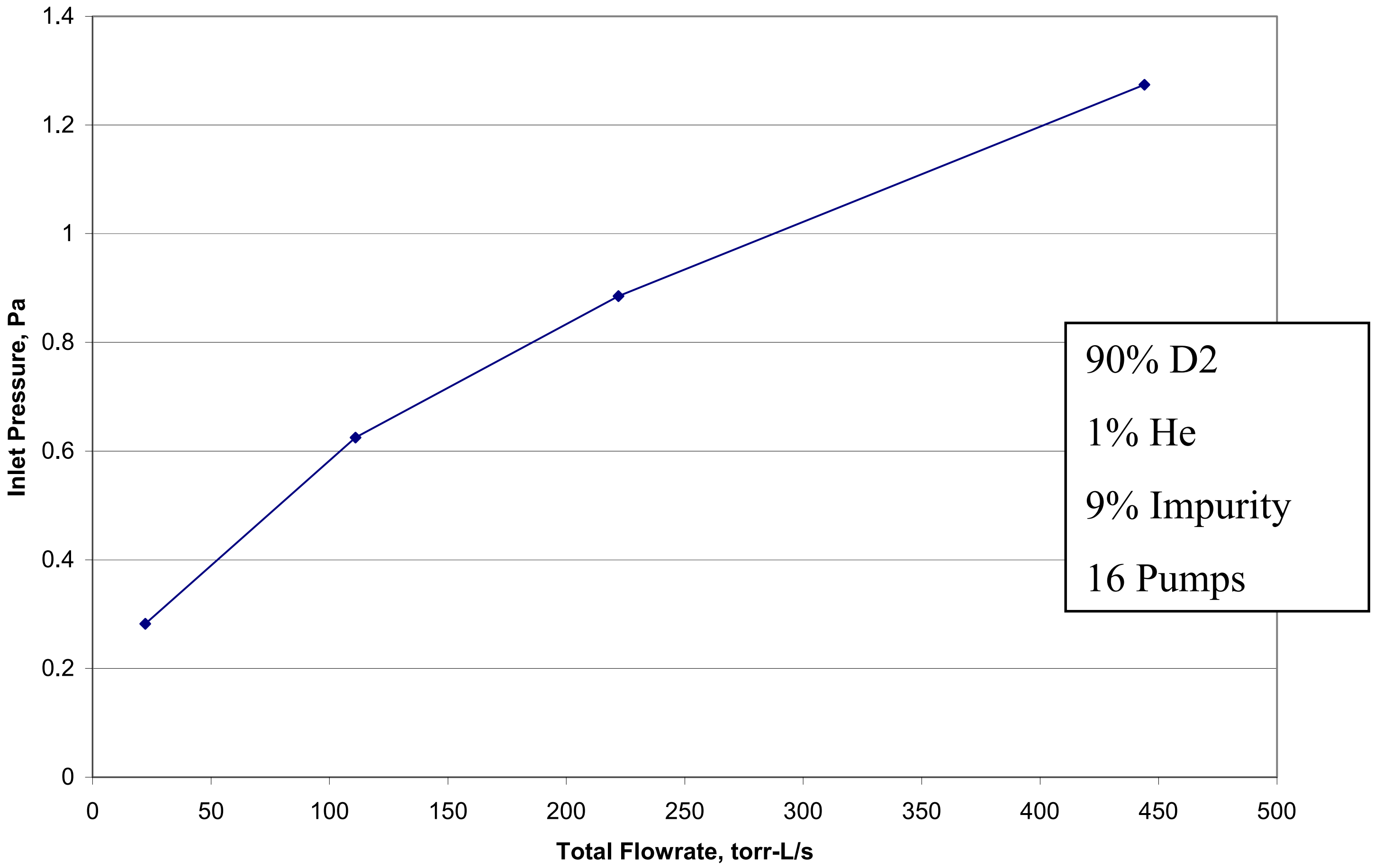
- A prototype pump has been developed and tested with deuterium gas.
- It has a 0.5 m inlet diameter and continuously regenerates via a snail regeneration head with a regeneration cycle time of 270 s.
- The pump has demonstrated a speed of 40,000 litter/s (D) with 0.4 Pa inlet pressure (throughput of 16 Pa-m^3/s).
- Points on the plot are data for 300 K gas feed for two cases: D_2 and H_2 into an open throat pump with no chevron or cooling baffle and D_2 into the pump with a 77 K baffle.
- The line shown for DT was extrapolated from the D_2 curve.
- 30 Pa-m^3/s appears to be achievable with this pump. The pump inlet pressure at this feed rate would be about 0.73 Pa without a baffle and about twice this value with a baffle.



Cold Duct Performance 200 torr-L/s Thru 16-Ducts



Cold Duct Response to Flowrate



Conclusions

- Innovation and R&D in plasma fueling systems provides a sound basis for design of the FIRE fueling system
  - Three gun repeating pneumatic injector (RPI) similar to the JET/DIII-D gun (in service > 10 years)
  - Curved guide tube system is similar to those presently in use
  - Extruded D-T pellets have been demonstrated in TPOP experiments
- FIRE vacuum requirements are met using an innovative cryopumping system
  - Cold ducts make it possible to pump in the viscous regime
  - In-duct cryopumping of DT compresses helium making it possible to pump it with an external pump