Pellet Fueling Technology Development

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Peer Review: Plasma Fueling Program

Oak Ridge National Laboratory

Oak Ridge, Tennessee

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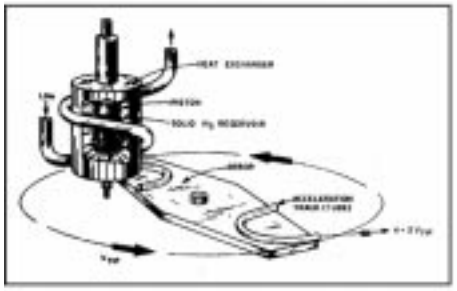
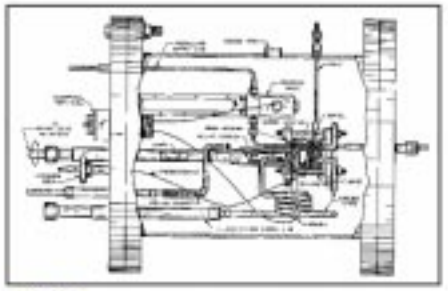
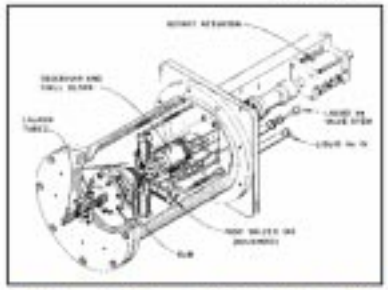
ornl

Main Objective of Plasma Fueling R&D Has Been to Develop Systems for Fusion Experiments





• ISX-A

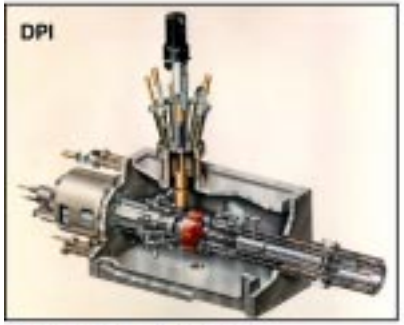


• PDX • ISX-B • Alcator-C • TEXT

• D-III

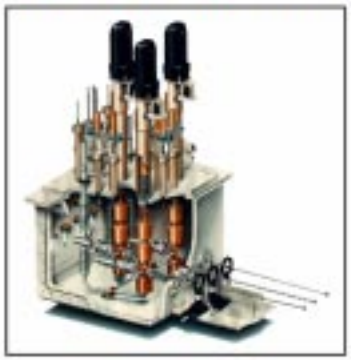
Since First-Generation Injectors, Significant Developments Have Been Made in Performance Parameters and Reliability

• ATF • PBX • GAMMA-10



• TFTR (RPI, DPI, and TPI)

• Tore Supra

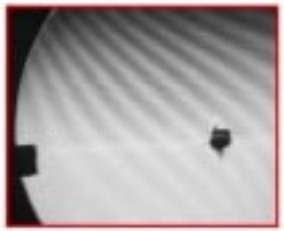


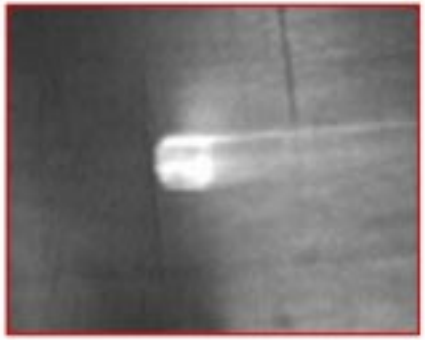
• JET • DIII-D

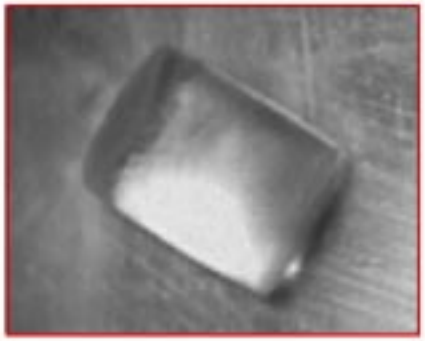
Pellet Sizes Are Relevant for Fueling Applications on Any Present Experimental Fusion Device and Future Fusion Reactors

ORNL 2000-1170C EFG

Small Innovative Confinement Experiments	1-mm-diam ~5 x 10^{19} D^o
DIII-D	2.7-mm-diam ~10^{21} D^o
Reactor	10-mm-diam ~5 x 10^{22} D^o







Damage from 6-mm pellet

(Photographs of In-flight D_2 Pellets; Nominal Sizes Are Listed)

Outline

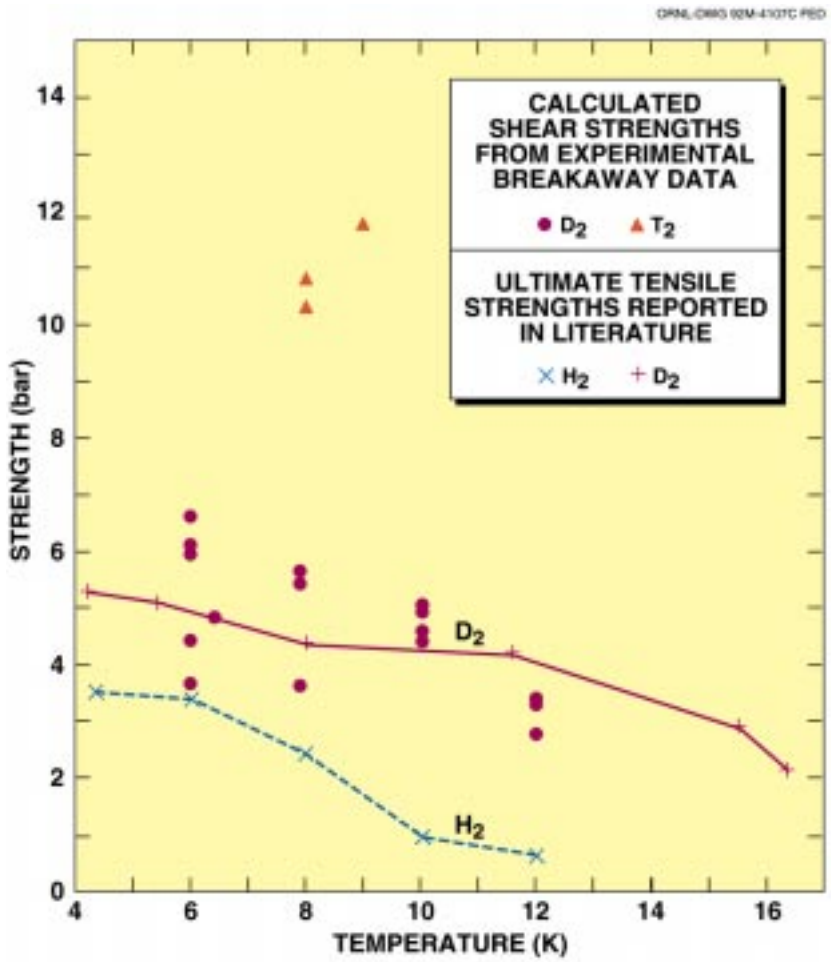
- Background and basic pellet injector technology
  - Hydrogen properties
  - Ice/pellet formation techniques
  - Acceleration techniques
- Selected R&D topics
  - Three-barrel repeating pneumatic injector
  - Centrifuge injector
  - Two-stage light gas gun
  - Long-pulse/steady-state pellet feed system
  - High-field-side (HFS)/inside launch pellet injection technology
- Present and future activities

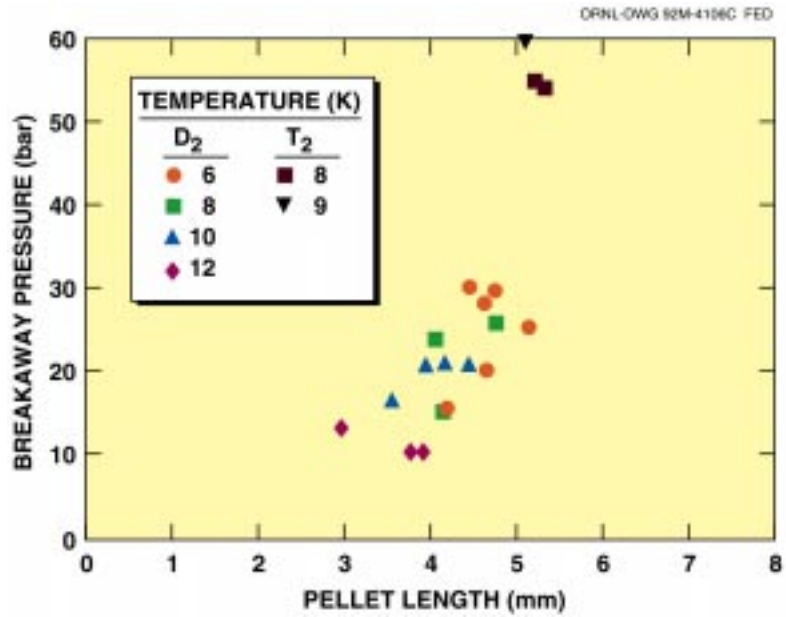
Properties of Hydrogen Isotopes

Isotope	Molecular weight (g/mol)	Critical-point temperature (K)	Triple-point temperature (K)	Triple-point pressure (bar)	Solid parameters	
					Density (g/cm^3)	Ultimate yield strength (bar)
H_2	2.016	33.2	13.9	0.072	0.087	0.7–3.5 (12.0 to 4.2 K)
D_2	4.028	38.3	18.7	0.172	0.20	2.1–5.3 (16.4 to 4.2 K)
T_2	6.032	40.4	20.6	0.216	0.32	10.3 (8.0 K) 11.7 (9.0 K)

- Reported strengths for hydrogen and deuterium at 8 K are 2.4 and 4.4 bar, respectively
- Tritium strength is estimated from breakaway pressures for tritium pellets in pipe-gun experiments (Fisher et al.)

Strength Data for Hydrogen Ice

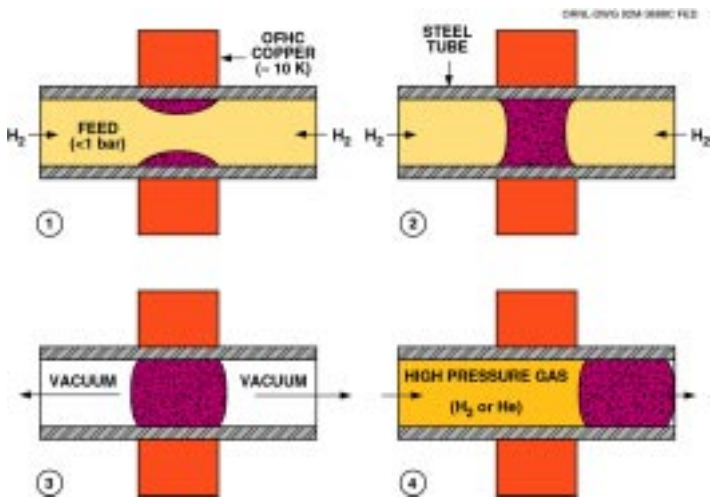




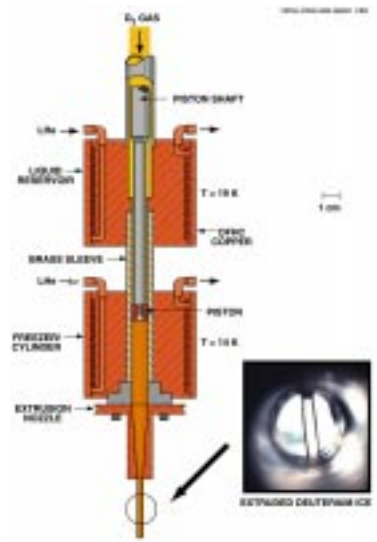
$$\sigma = \frac{P_b D_p}{4 L_p}$$

σ = Pellet shear strength
P_b = Breakaway pressure
D_p = Pellet diameter
L_p = Pellet length

Ice/Pellet Formation Techniques

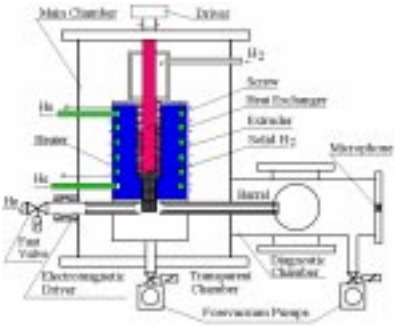


Pipe Gun – Simplest Pellet Injector (Limited Number of Pellets)

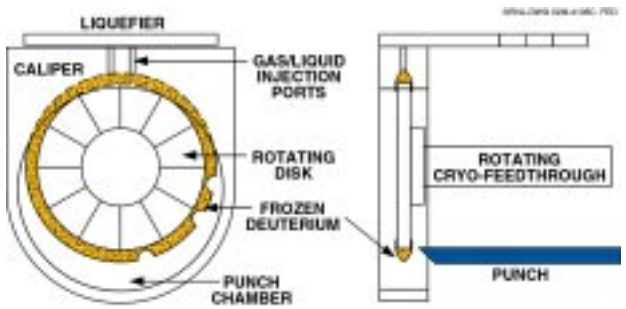


Basic Extruder – Long-Pulse Applications (Multiple Units – Steady-State Applications)

Russian Company: (I. Viniar)



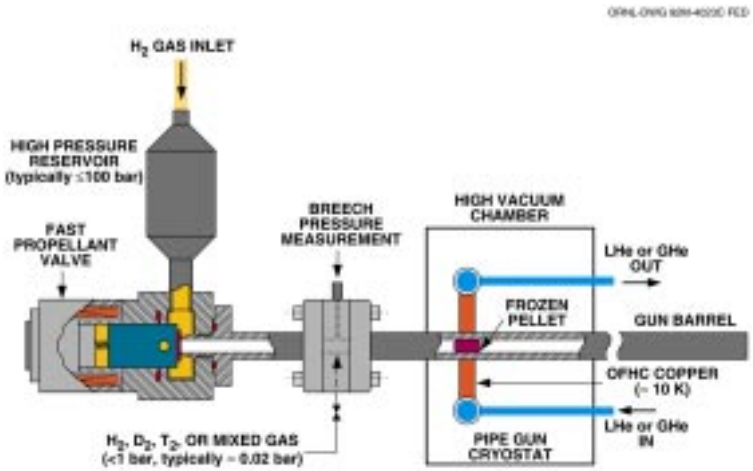
Screw Extruder – Steady-State Applications (ORNL Has Investigated a Double-Screw Extruder Design)



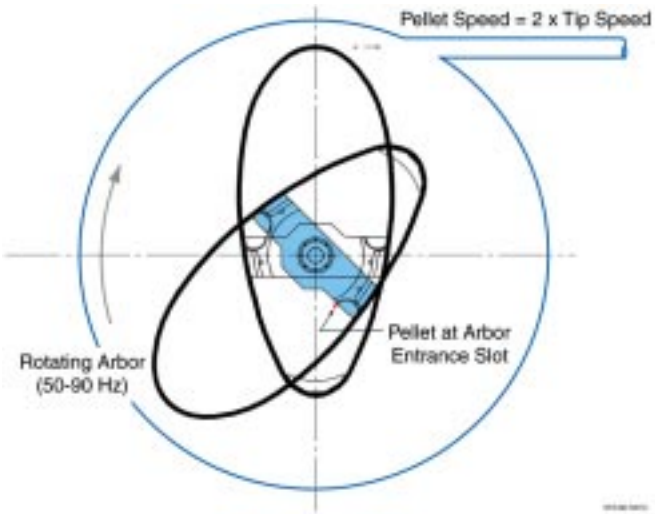
Zamboni Machine – Long-Pulse Applications

Acceleration Techniques

- **Standard injectors**
  - **Light gas gun (single-stage pneumatic device); speeds up to 2 km/s**

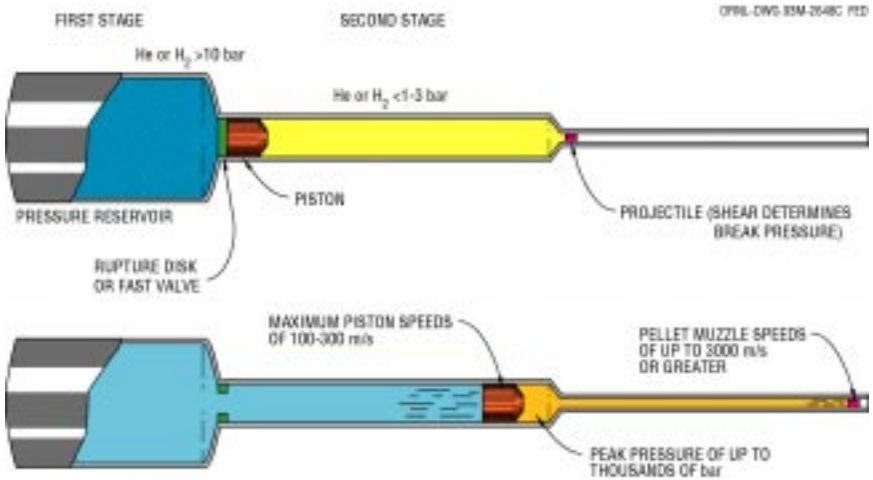


  - **Centrifuge (mechanical device); speeds up to 1.2 km/s**

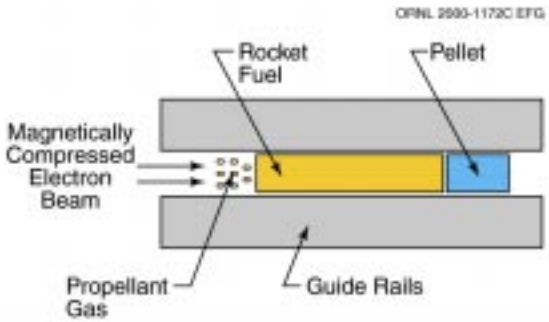


Acceleration Techniques (continued)

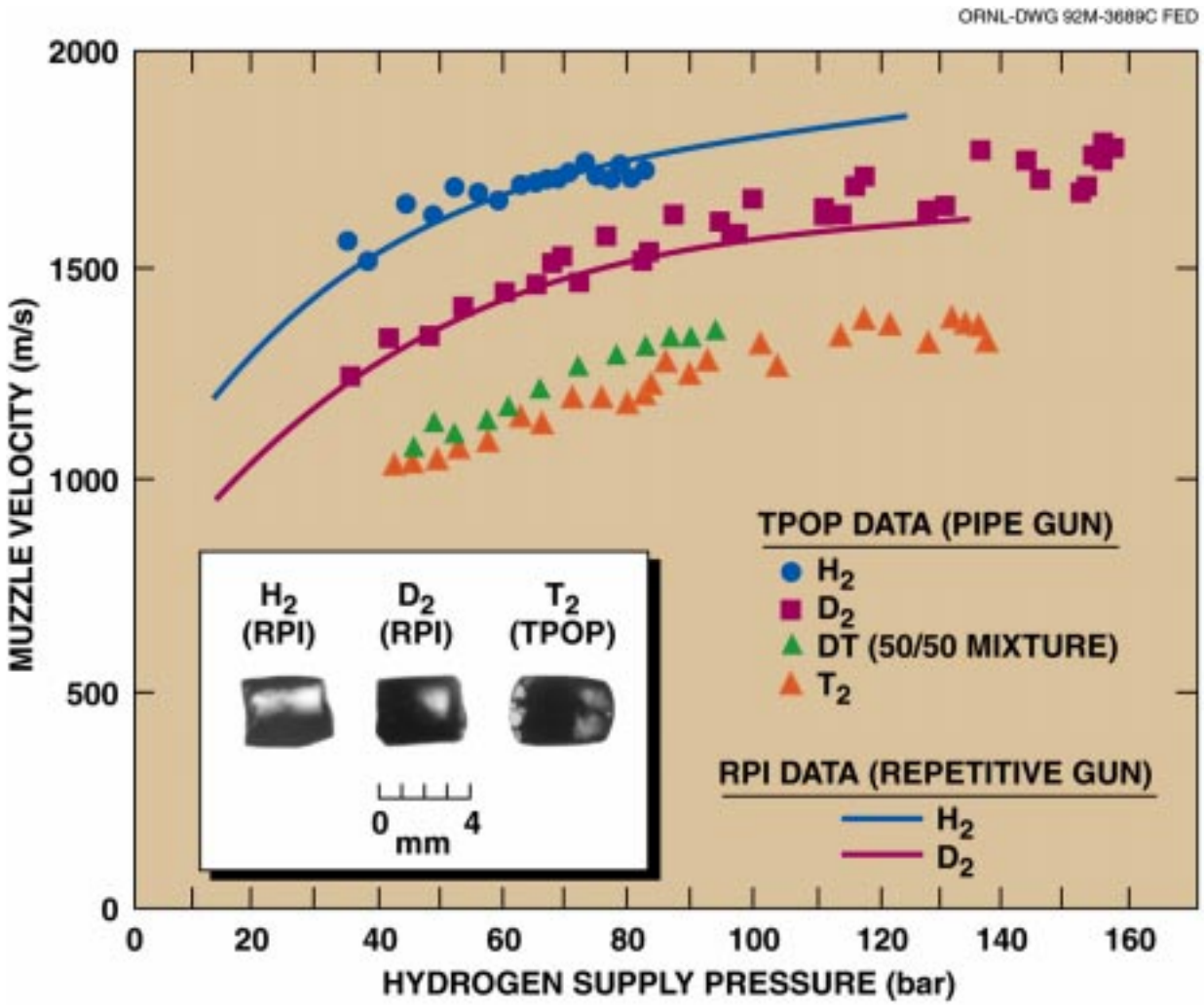
- **High-speed injectors**
  - **Two-stage light gas gun (two-stage pneumatic device); speeds >4 km/s routinely achieved at Tore Supra**



  - **Electrothermal (CRADA with UTRON, Inc.)**
  - **Rail gun (University of Illinois, K. Kim)**
  - **Electron-beam heated rocket pioneered at ORNL (no activity since 1992)**

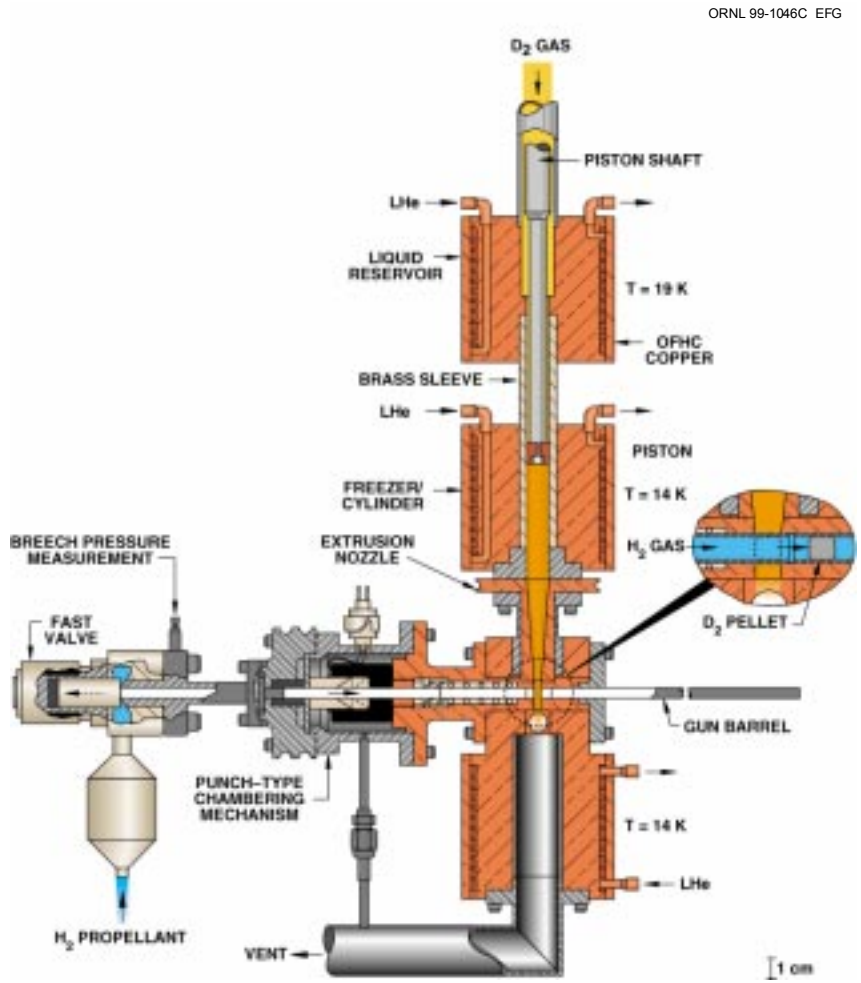


Pellet Speed Data for Hydrogen Ice Accelerated with Light Gas Guns



Repeating Pneumatic Injector – Operations

- Injector comprised of cryogenic extruder and gun assembly
- Normal sequence (up to 10 Hz)
  - Extruder provides filament of D_2 ice to gun assembly (≈14 K)
  - Activation of punch-type cutter mechanism chambers pellet
  - Firing of propellant valve admits He/H_2 gas (≈70 bar) for acceleration of pellet in barrel (up to ≈1500 m/s)
  - Reliability of delivering intact pellets to the plasma during fueling experiments has been ≈100% for standard mode of operation

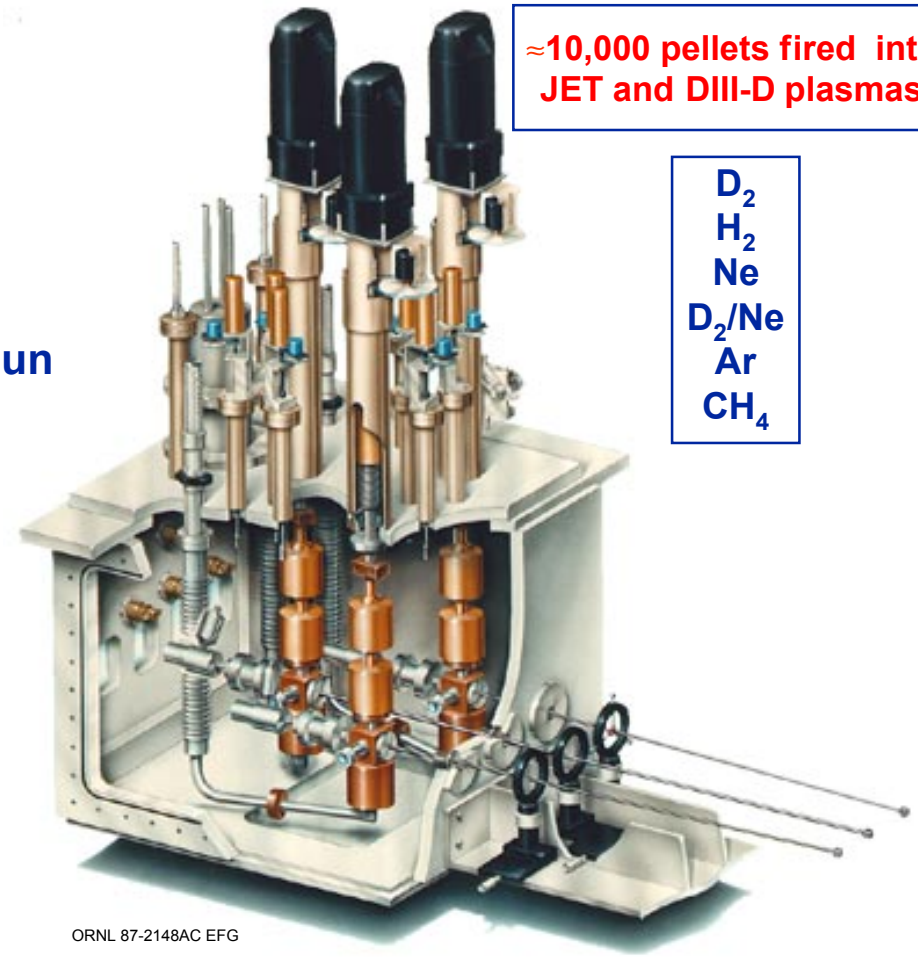


Three-Barrel Repeating Pneumatic Injector

- Fabricated 1986-1987
- Three independent single-stage guns/extruders
  - Standard speed: 1-1.5 km/s
  - Nominal pellet sizes: 2.7, 4.0 and 6.0 mm
  - Repetition rates: 1 to 10 Hz for each gun
  - Total pellets: 10 to 100 per gun
- Installed on JET in 1987 and used for experiments until 1991
- Returned to ORNL in 1992 and modified/ reconfigured for DIII-D (1.8-mm size added); installed on DIII-D in 1994 and used in experiments since
- Recent improvements include higher repetition rates (up to ≈20 Hz) and capability to operate at slower speeds (≈100 to 300 m/s)

≈10,000 pellets fired into JET and DIII-D plasmas

D_2
H_2
Ne
D_2/Ne
Ar
CH_4

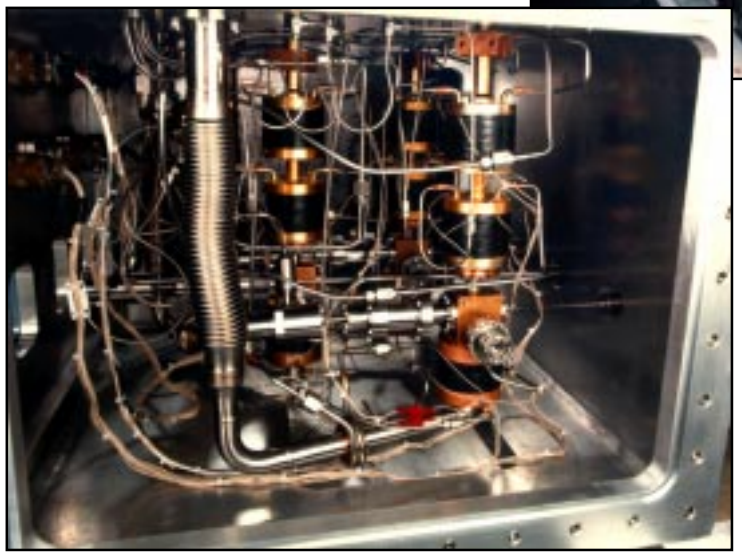


ORNL 87-2148AC EFG

Three-Barrel Repeating Pneumatic Injector – Major Components/Systems

Injector and Control/Data Acquisition Systems

Cryogenic Extruders/ Gun Assemblies

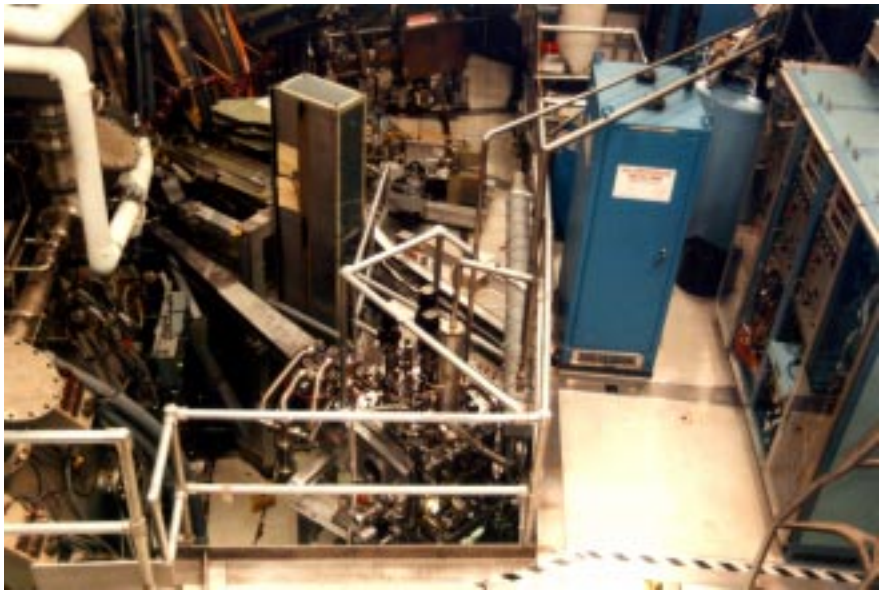


Gas Manifold System

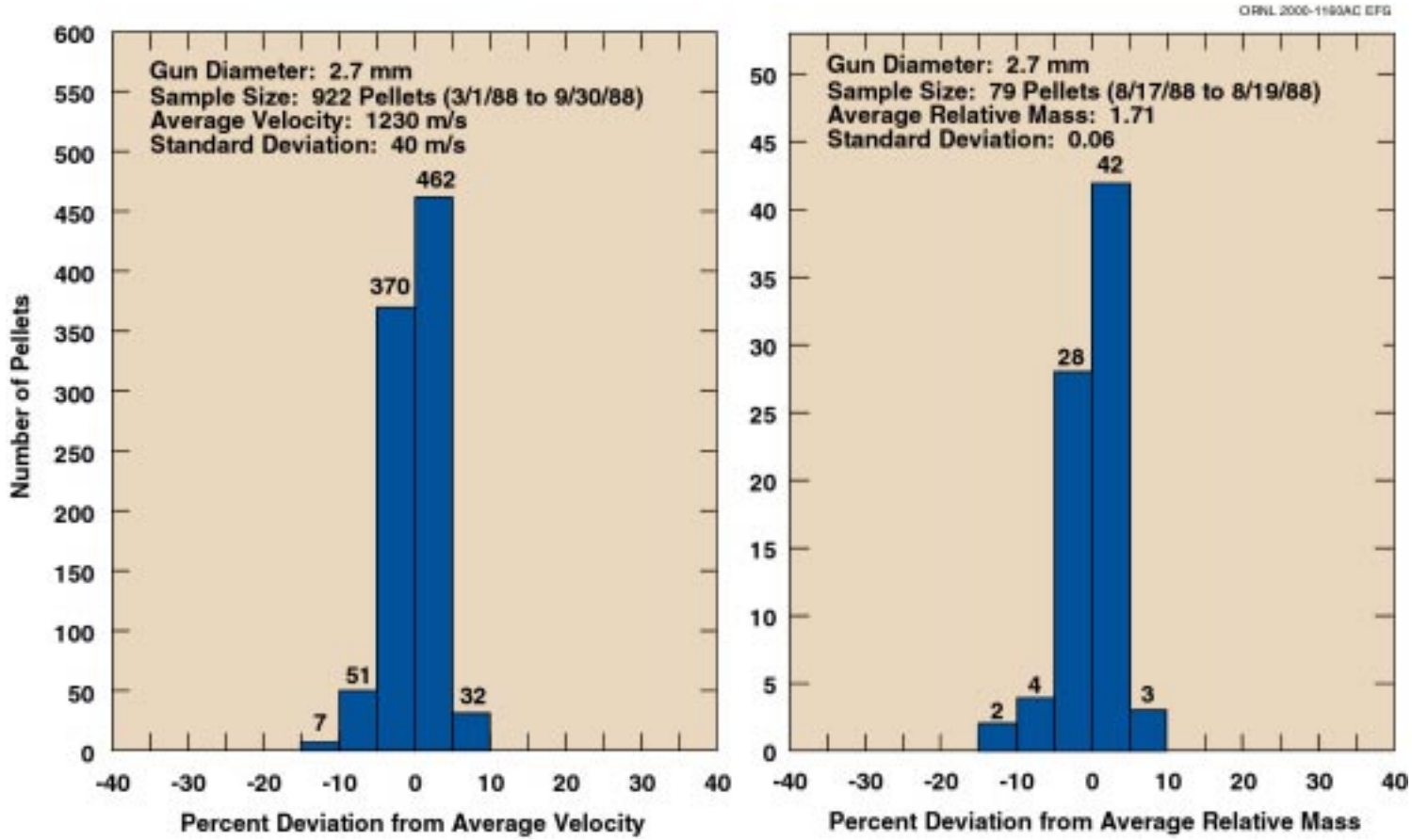
Three-Barrel Repeating Pneumatic Injector – Installations on JET and DIII-D

JET

DIII-D

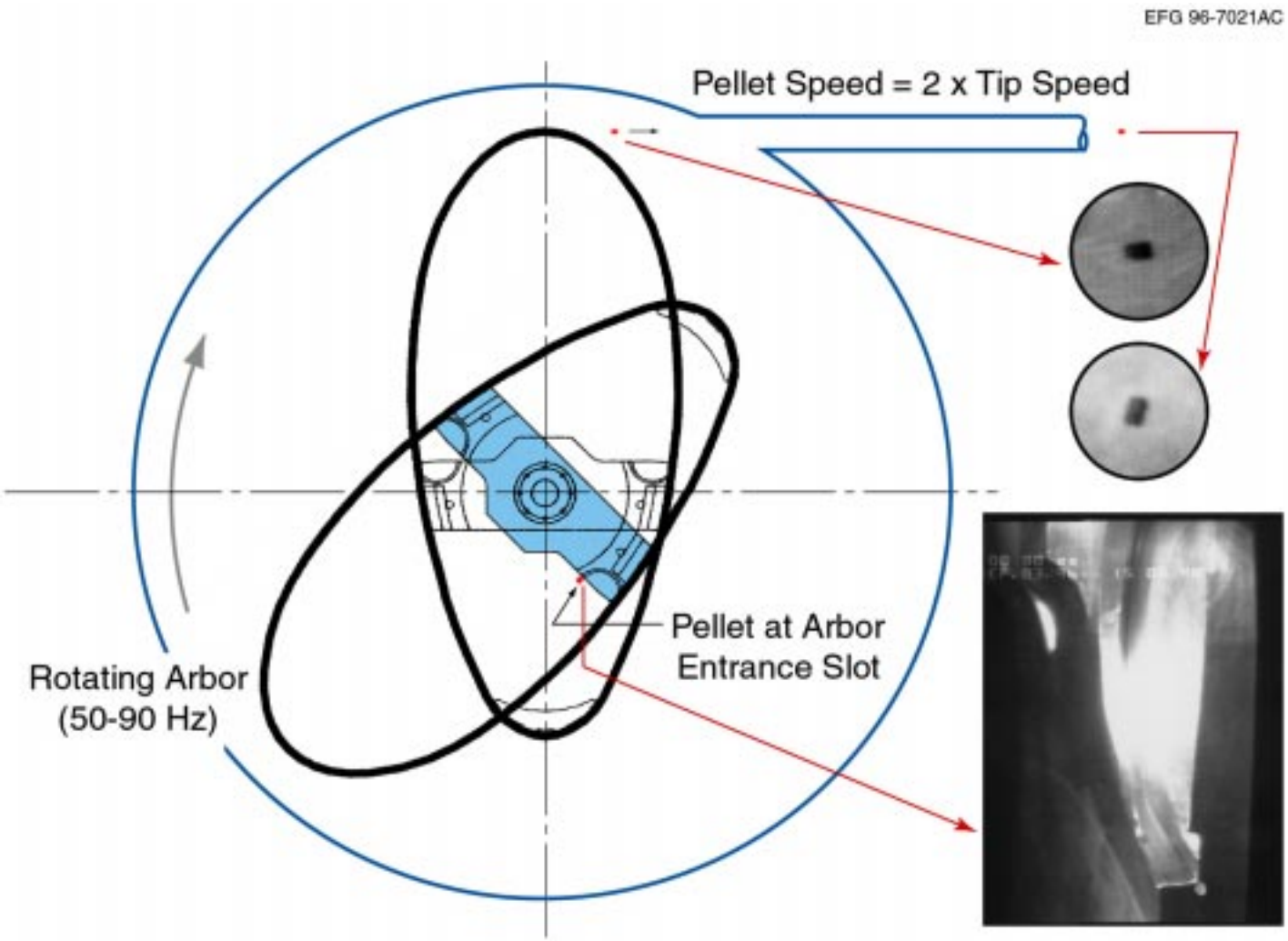


Three-Barrel Repeating Pneumatic Injector – Delivered Pellets with Consistent Speed and Mass in Fueling Experiments on JET



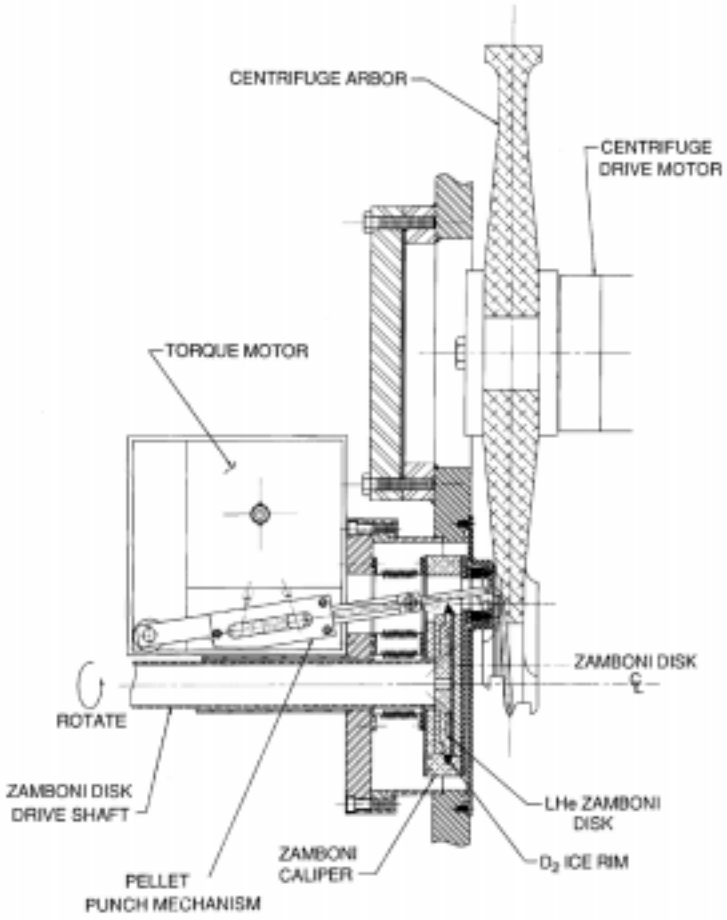
- **90.2% of Pellets with Velocities within ±5% of Average and 99.2% within ±10%**
- **88.6% of Pellets with Masses within ±5% of Average and 97.5% within ±10%**

Basic Operating Principle of the ORNL Centrifuge Pellet Injector

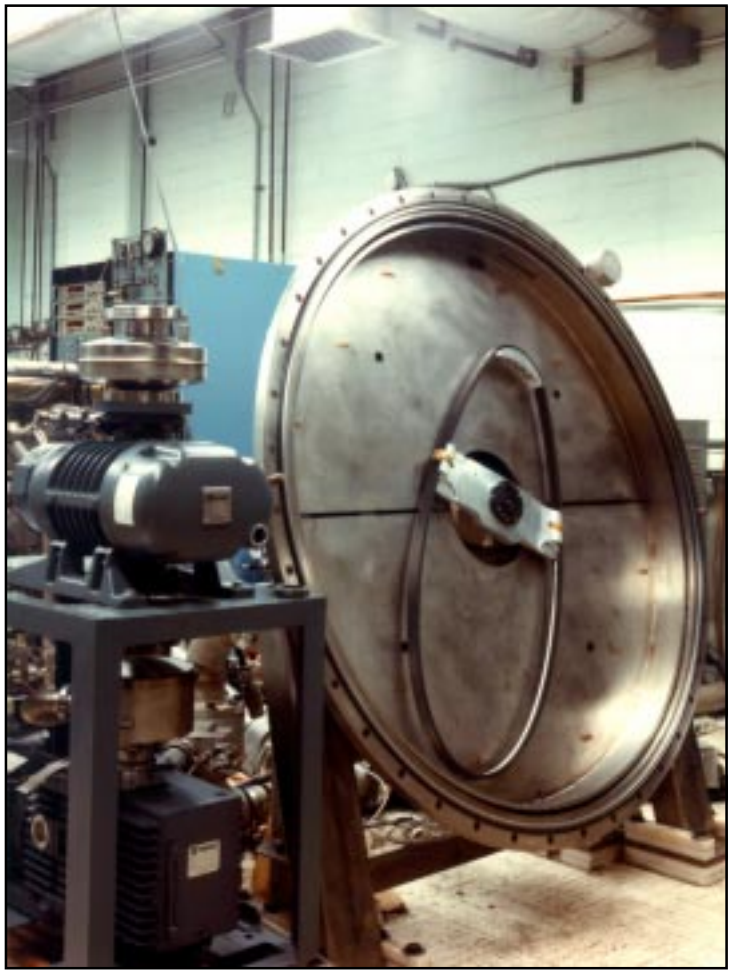


Centrifuge Injector – Tore Supra Application

- Developed/fabricated late 1980s
- Installed on Tore Supra in 1989 and used for experiments since
- Zamboni feed system and high-speed rotating arbor (≈50-90 Hz)
  - Standard pellet speed: 450 to 800 m/s
  - Nominal pellet sizes (D_2): 3 to 10 Torr-L
  - Repetition rates: up to 10 pellet/s
  - Total pellets: 100
- Pellet delivery reliability: ≈70-80% intact pellets
- New extruder-based feed system developed/fabricated and tested on duplicate spin task at ORNL (1995-1996); delivered to Tore Supra and tested on a test stand with original injector (1997-1998)

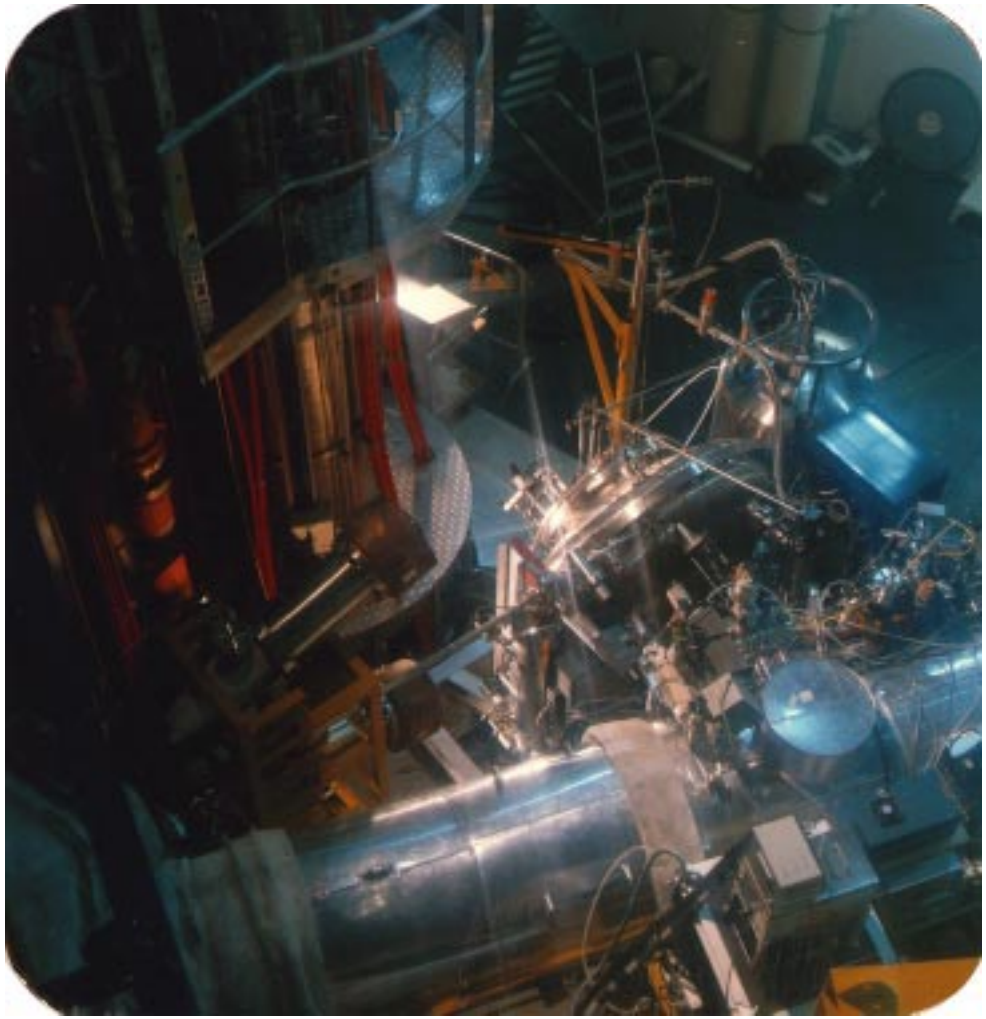


Centrifuge Injector – Assembly Photographs

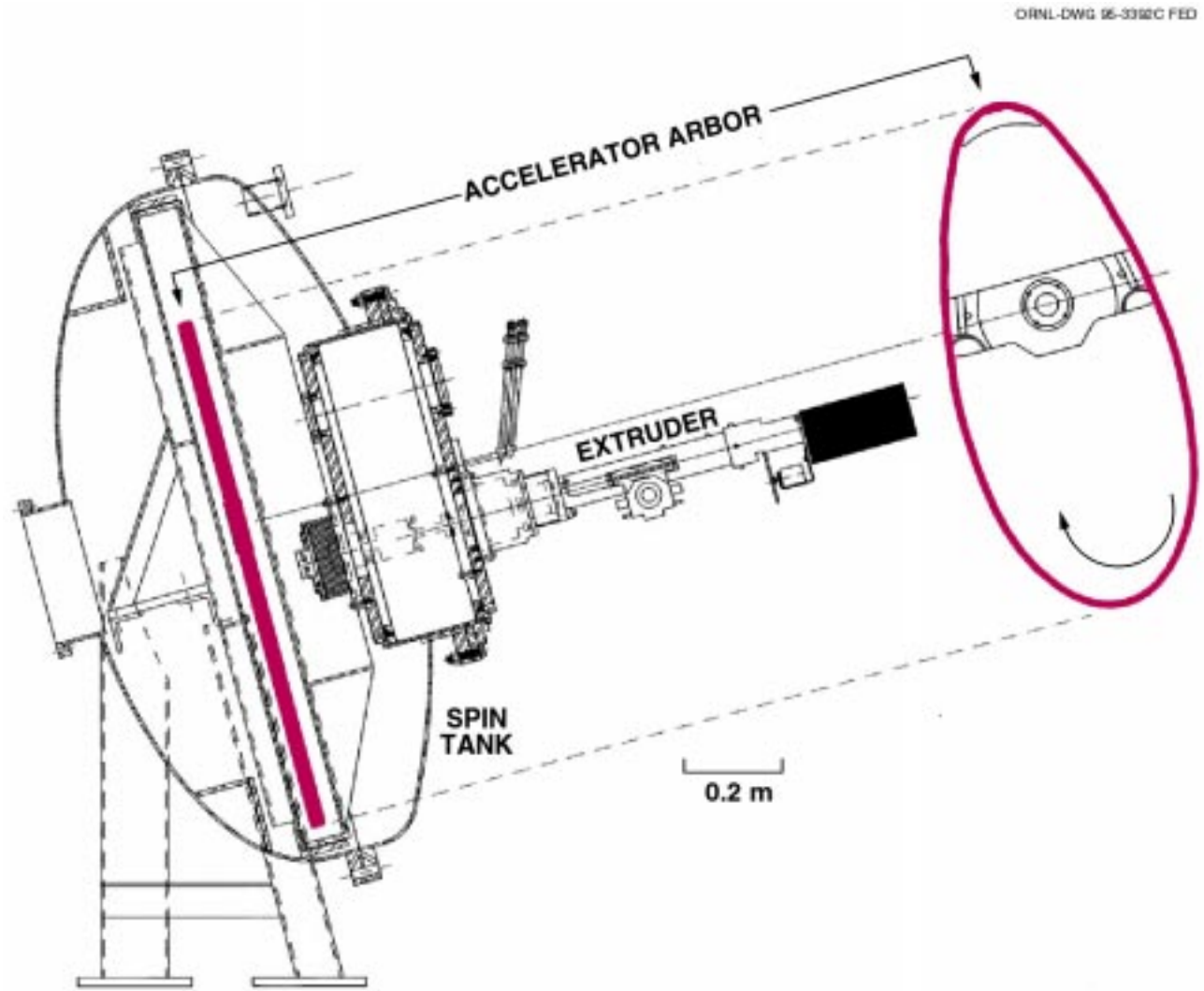


Centrifuge Injector – Aerial View of Installation on Tore Supra

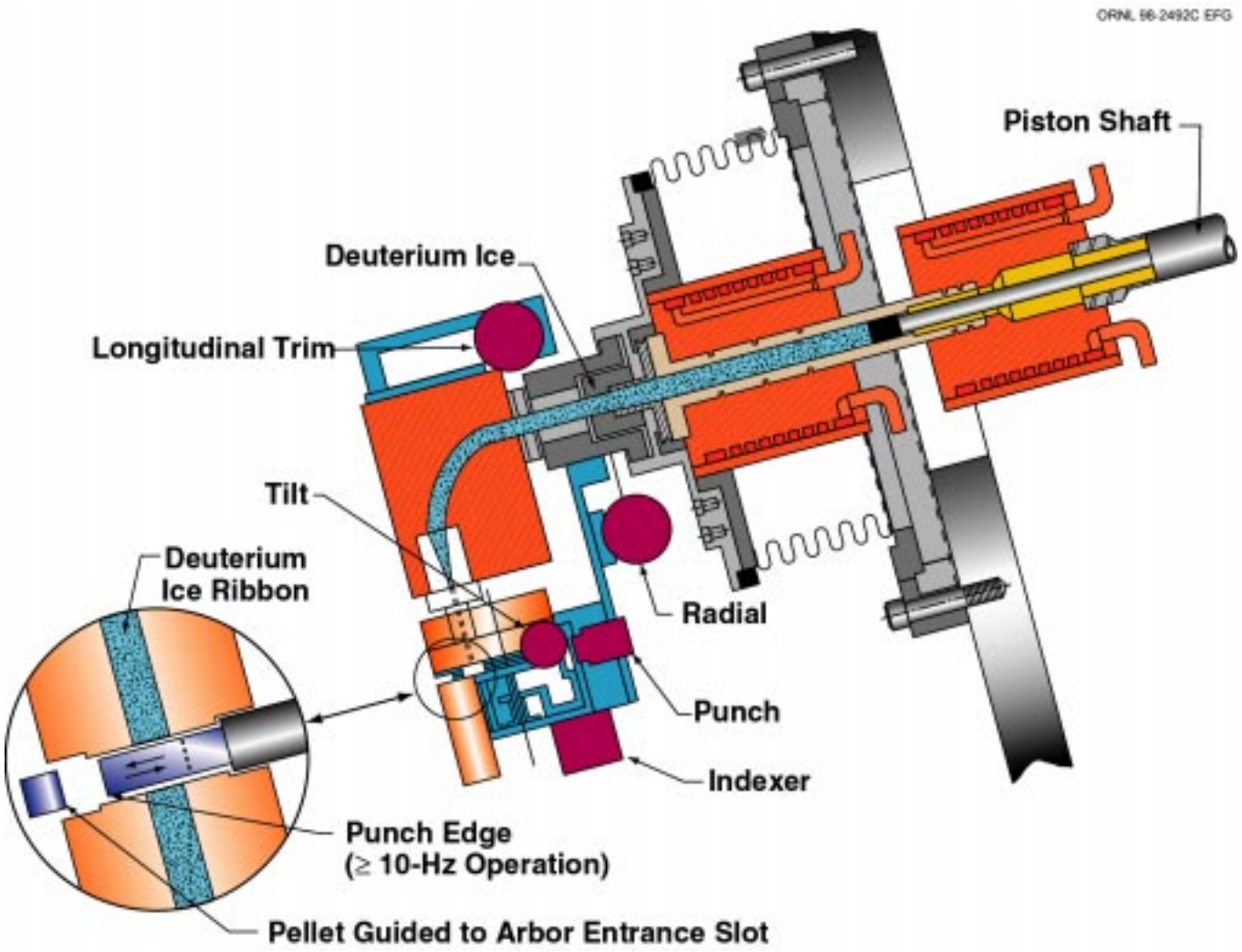
ORNL-DWG 94M-3316C FED



Side Elevation View of ORNL Centrifuge Pellet Injector with New Extruder Pellet Feed System



Close-Up View of Extruder Feed and Pellet Punch Components



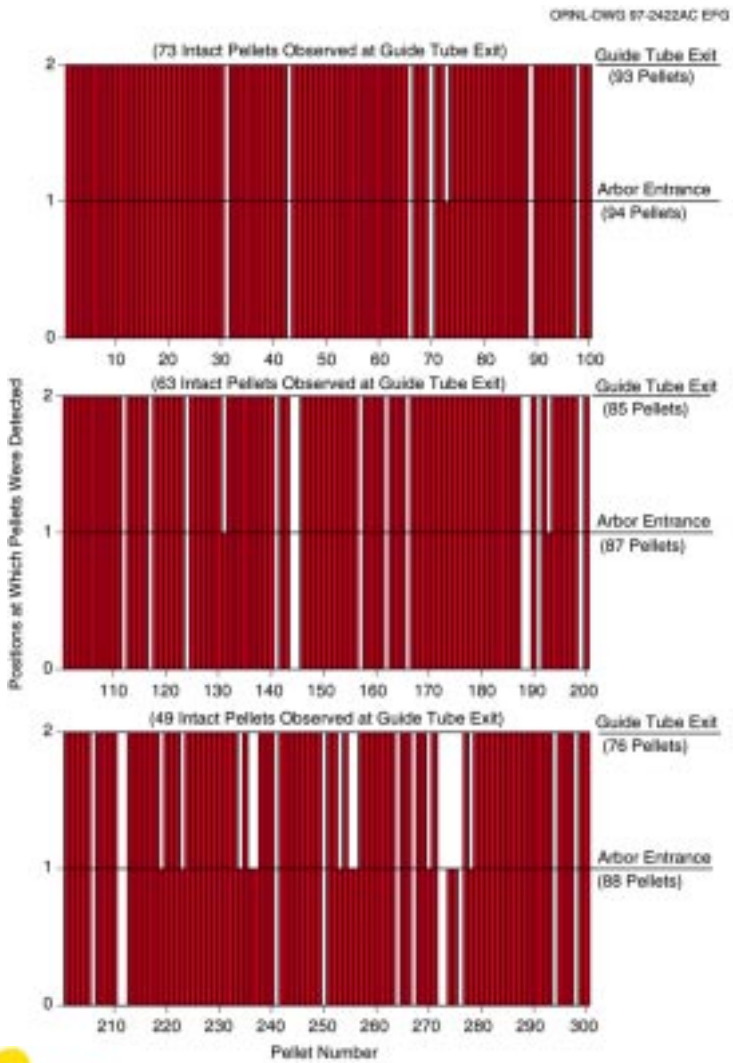
Operating Parameters Achieved in Testing of New Feed System at ORNL; Experiments on Tore Supra Test Stand Confirmed Results

EFG 96-7454

Pellet speed	~430 m/s @ 50 Hz arbor speed
Pellet shape	Right circular cylinders
Pellet diameter	2.3-mm diam (3.2-mm diam also available)
Pellet length	Variable (1.6 to 2.8 mm in 0.2-mm increments)
Pellet frequency	Up to 10 Hz for routine operation (20-Hz operation probable with improved power supply to drive punch solenoid)
Number of pellets	Up to ~1000 per pulse
Reliability	Objective of ~90%; in experiments to date, up to 85% of the pellets requested have been observed exiting guide tube (>70% fully intact)

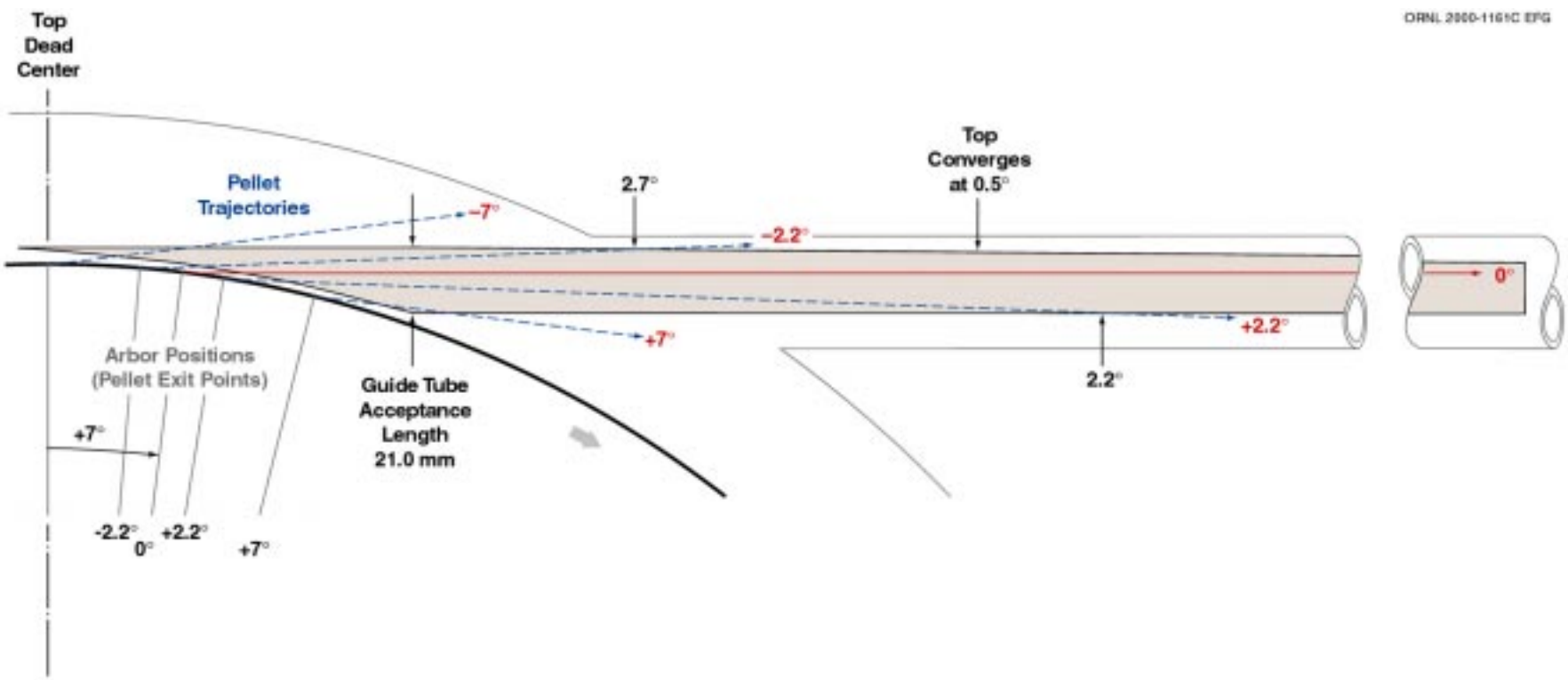
- **Reliability of delivering intact pellets was essentially the same as the original centrifuge injector; number of pellets available per batch was increased significantly (factor of 10)**

Test Results of 300-Pellet Test Sequence (10 Pellets/s and 50-Hz Arbor Speed; Pellet Velocity = 430 m/s); Positions 1 and 2 Refer to Arbor Entrance and Guide Tube Exit, Respectively

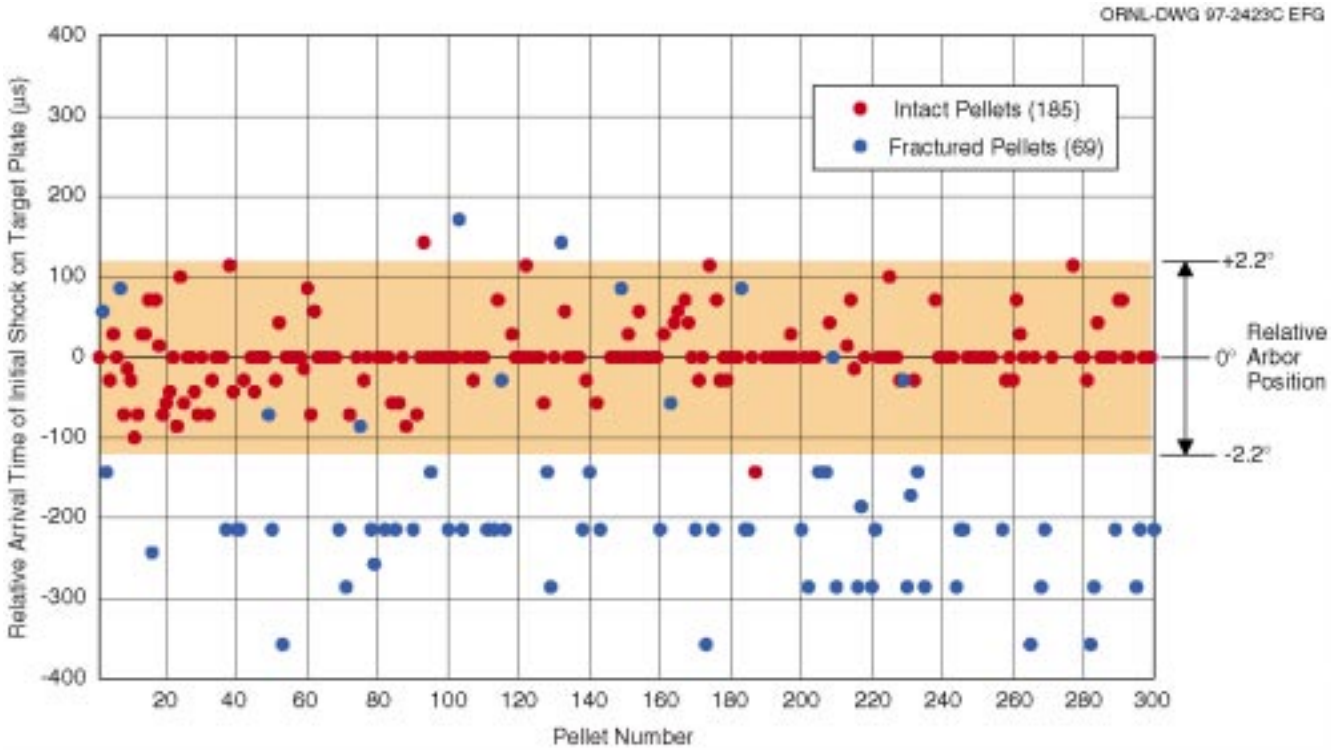


- ≈10% of pellets not in proper space/time window for capture by arbor (inherent problem with pellet free-flight method)
- Pellets almost never fracture during acceleration on arbor (only 2 out of 149 pellets photographed at the arbor exit were fractured)
- Normal dispersion of pellets from arbor results in some pellet fractures upon impact with the guide tube surfaces

Pellet Trajectories for Different Arbor Exit Points
(Rectangular Guide Tube with a 21.0-mm Acceptance Height and 550 mm Length)

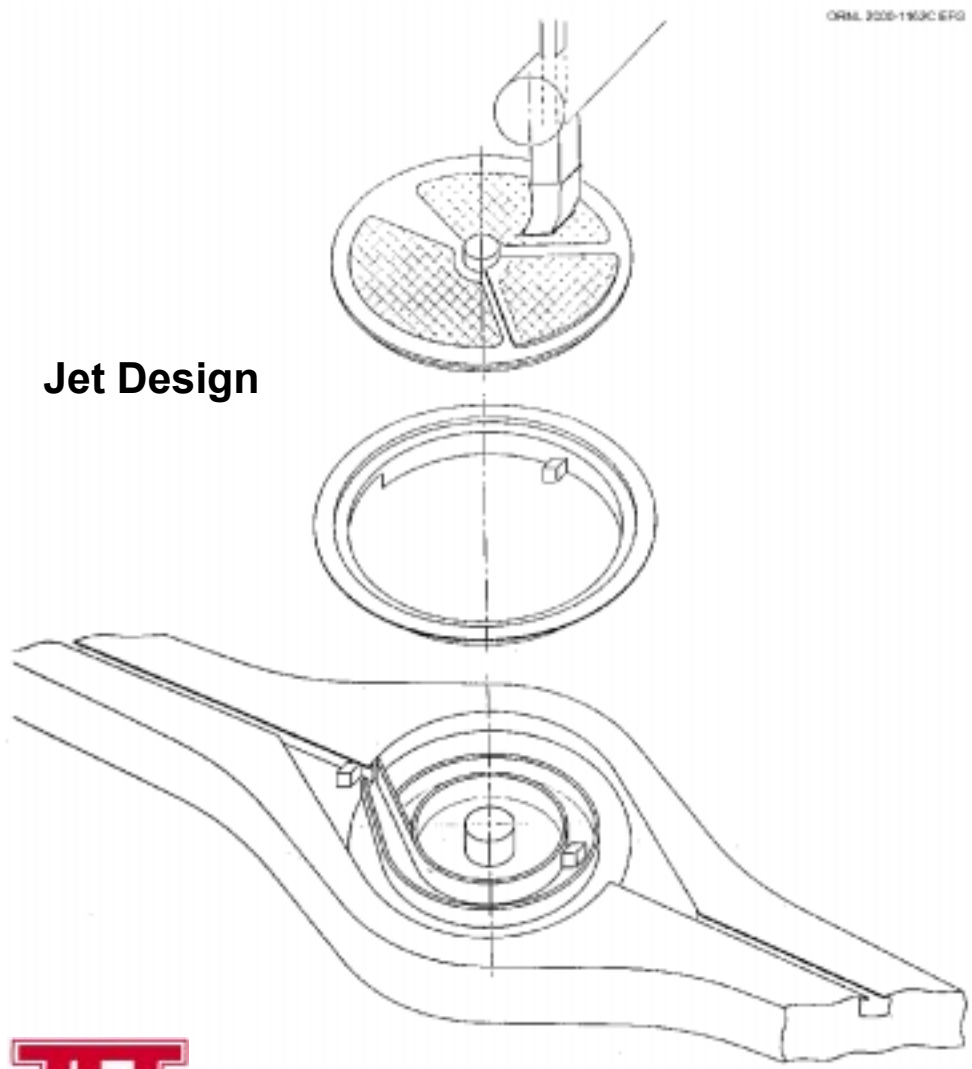


Data Suggests that Pellet Fractures Can Almost Always Be Attributed to the Impacts on the Guide Tube Surface



- **With effective impact angle of 2.7° (top wall converges at 0.5°), the normal velocity to wall is ≈20 m/s**
- **In testing at Tore Supra, this dispersion and speed limit was confirmed with more extensive diagnostics**

Centrifuge Injectors – Reliability Issue

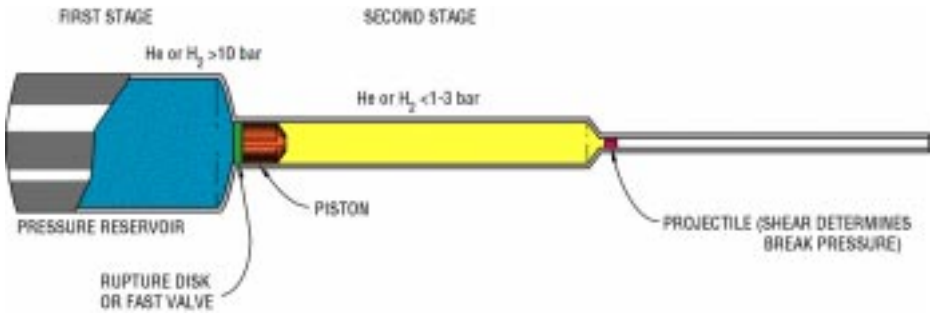


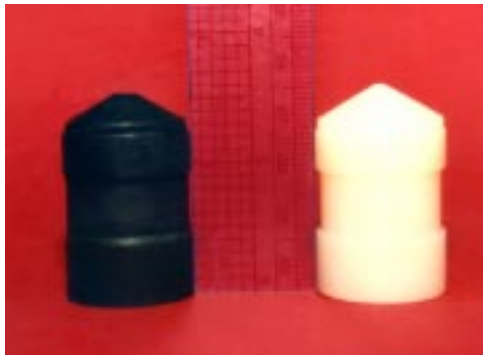
- Improvements like those recently implemented on the JET Centrifuge Injector result in improved reliability
- As part of ITER support, ORNL performed initial design and tests of a new rotor/feed system for higher reliability

Two-Stage Light Gas Gun Development – ORNL Highlights

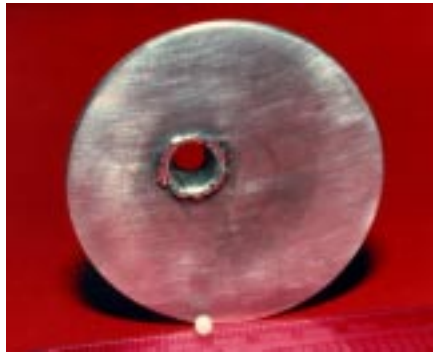
- Accelerated plastic projectiles (4 and 6 mm) up to 5 km/s (single pellets)
- QUICKGUN Algorithm for estimating the performance of two-stage guns developed by Milora et. al
- Accelerated D_2 pellets (4 mm) up to 3 km/s (single pellets)
- Operation of repetitive two-stage gun demonstrated at 1 Hz and 3 km/s with plastic projectiles (4 mm)
- Two-stage light gas gun developed for TPI and installed/operated on TFTR in 1992
- In an ORNL/ENEA Frascati collaboration, operation of repetitive two-stage gun demonstrated at 1 Hz and up to 2.5 km/s with D_2 pellets (2.7 mm)
- Sabot separation technique demonstrated with plastic pusher/pellet arrangement (6 mm) at speeds of >3 km/s

Two-Stage Light Gas Gun Development – Test Results

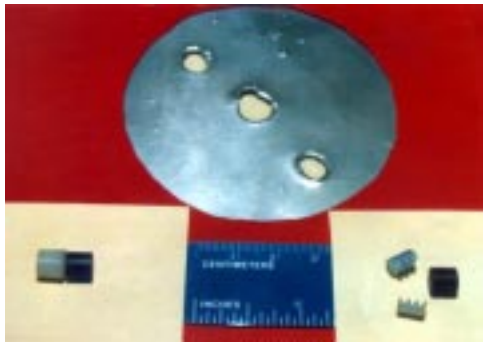




Condition of Nylon Piston Before (Right) and After Shot (Left)

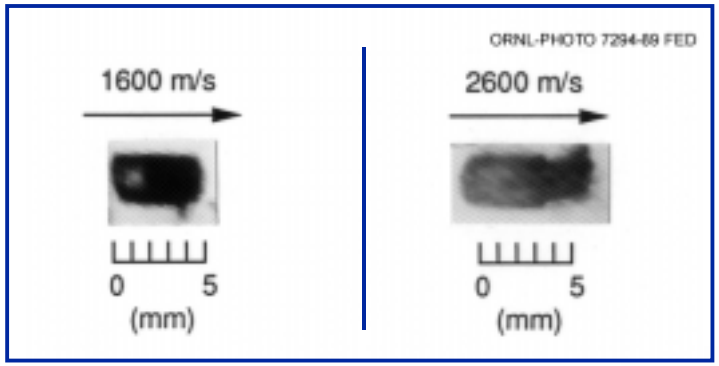


Al Target Plate (4.5-mm Thick) After Impact of 35 mg Nylon Projectile at 4.5 km/s

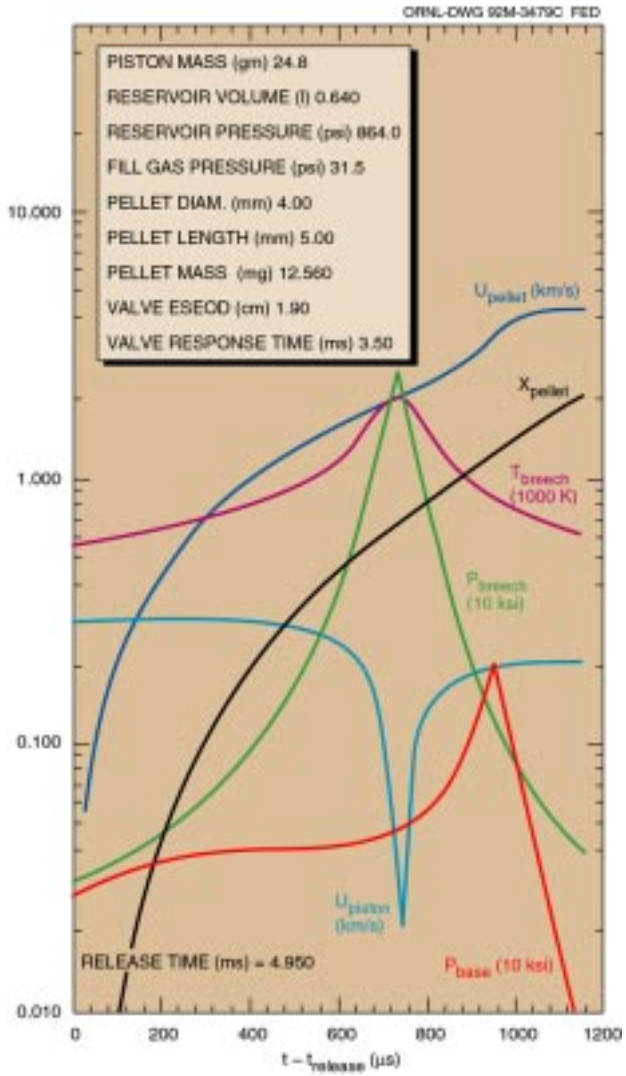


Sabot Separation with 6-mm-Bore Rifled Gun Barrel and Pusher/ Pellet Arrangement

D_2 Pellets

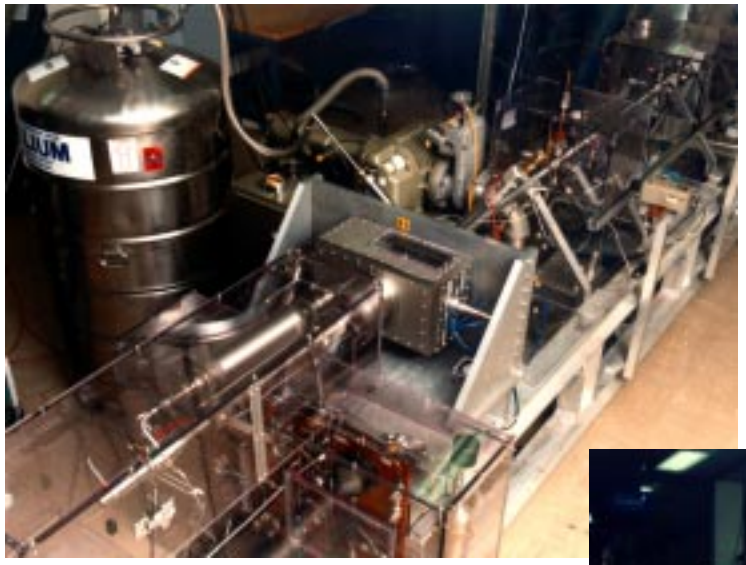


Two-Stage Light Gas Gun Development – QUICKGUN Calculations for 4-mm D_2 Pellet

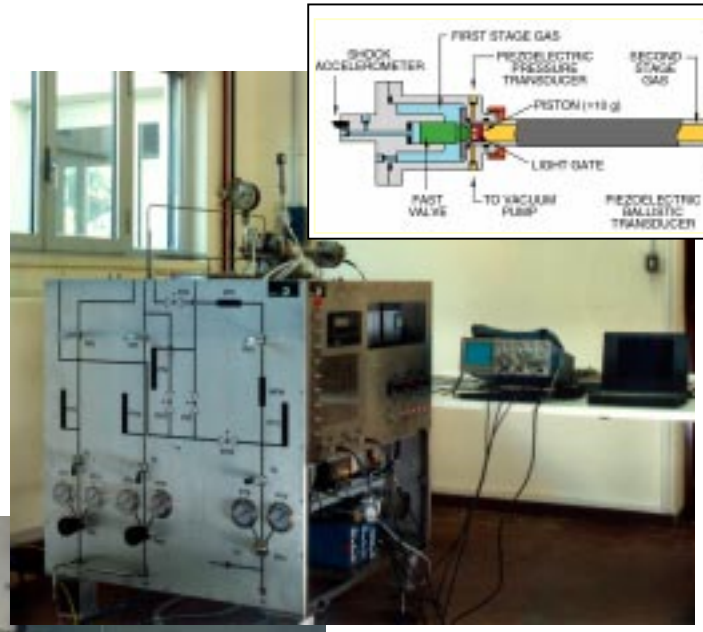


- Code runs on PCs and used by researchers around the world
- Modeling efforts like this are crucial to help guide the R&D

Two-Stage Light Gas Gun Development – Test Apparatus and Systems



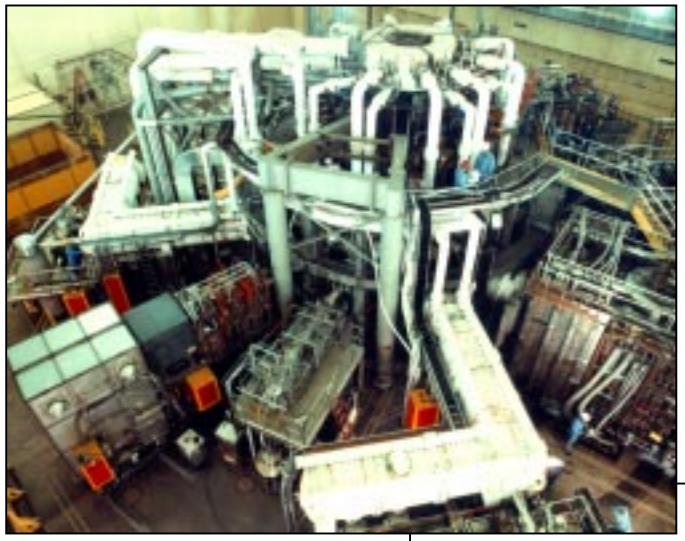
Two-Stage Gun (4-mm Plastic and D_2 Projectiles); 6-mm rifled gun also available for plastic projectiles



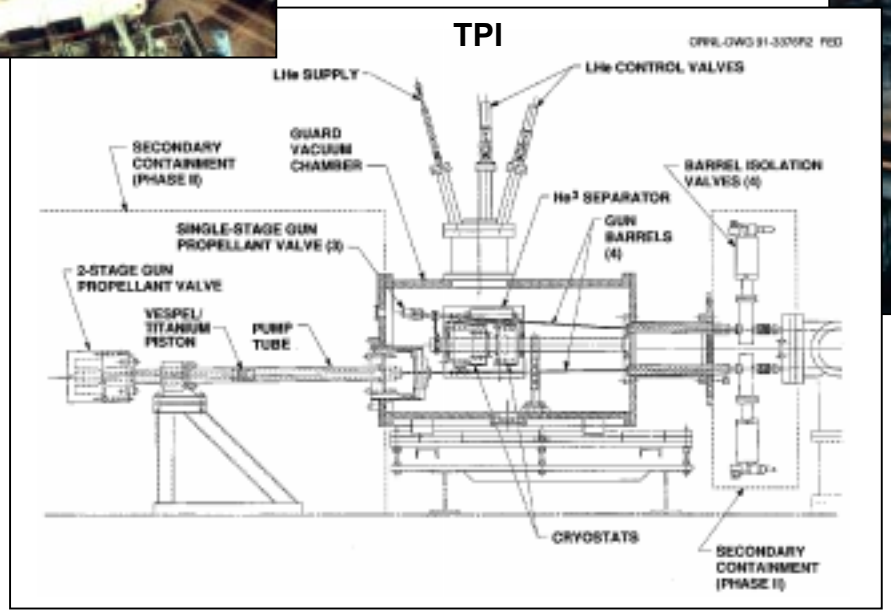
Frascati Two-Stage Gun

Experiments at ORNL (ORNL/Frascati Collaboration)

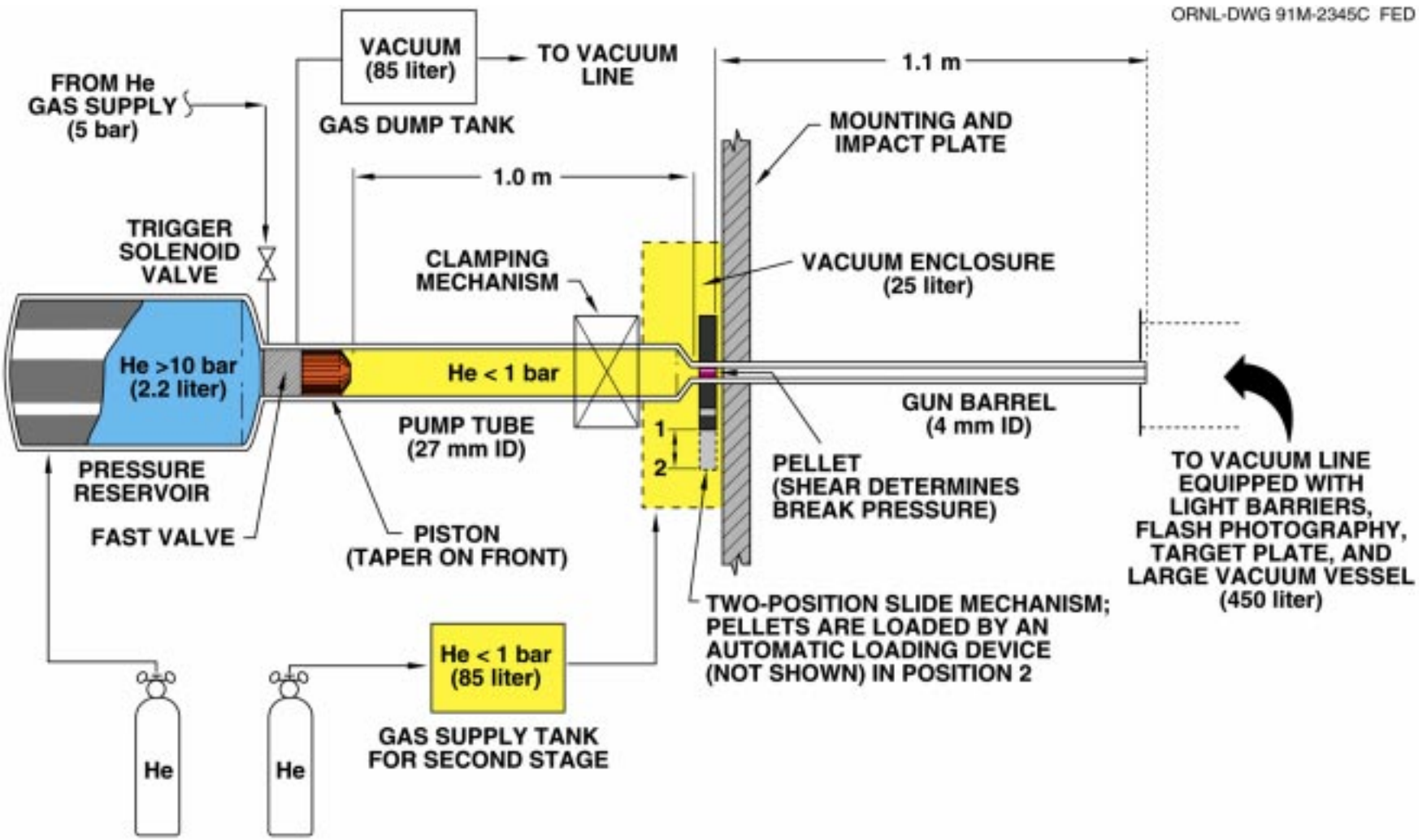
A Two-Stage Gun Was Incorporated in the Upgrade from DPI to TPI in 1991 and Installed on TFTR in 1992



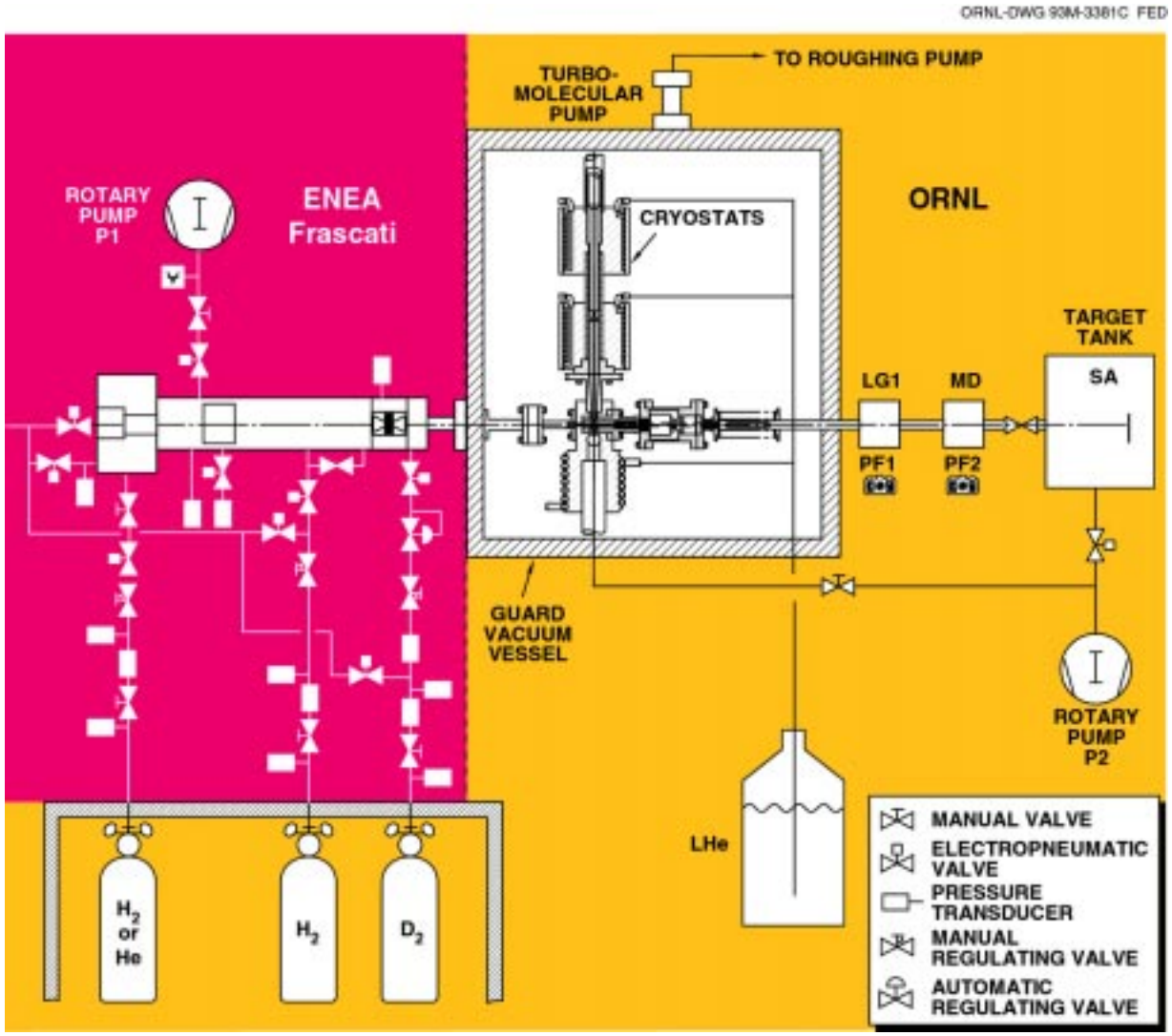
DPI on TFTR



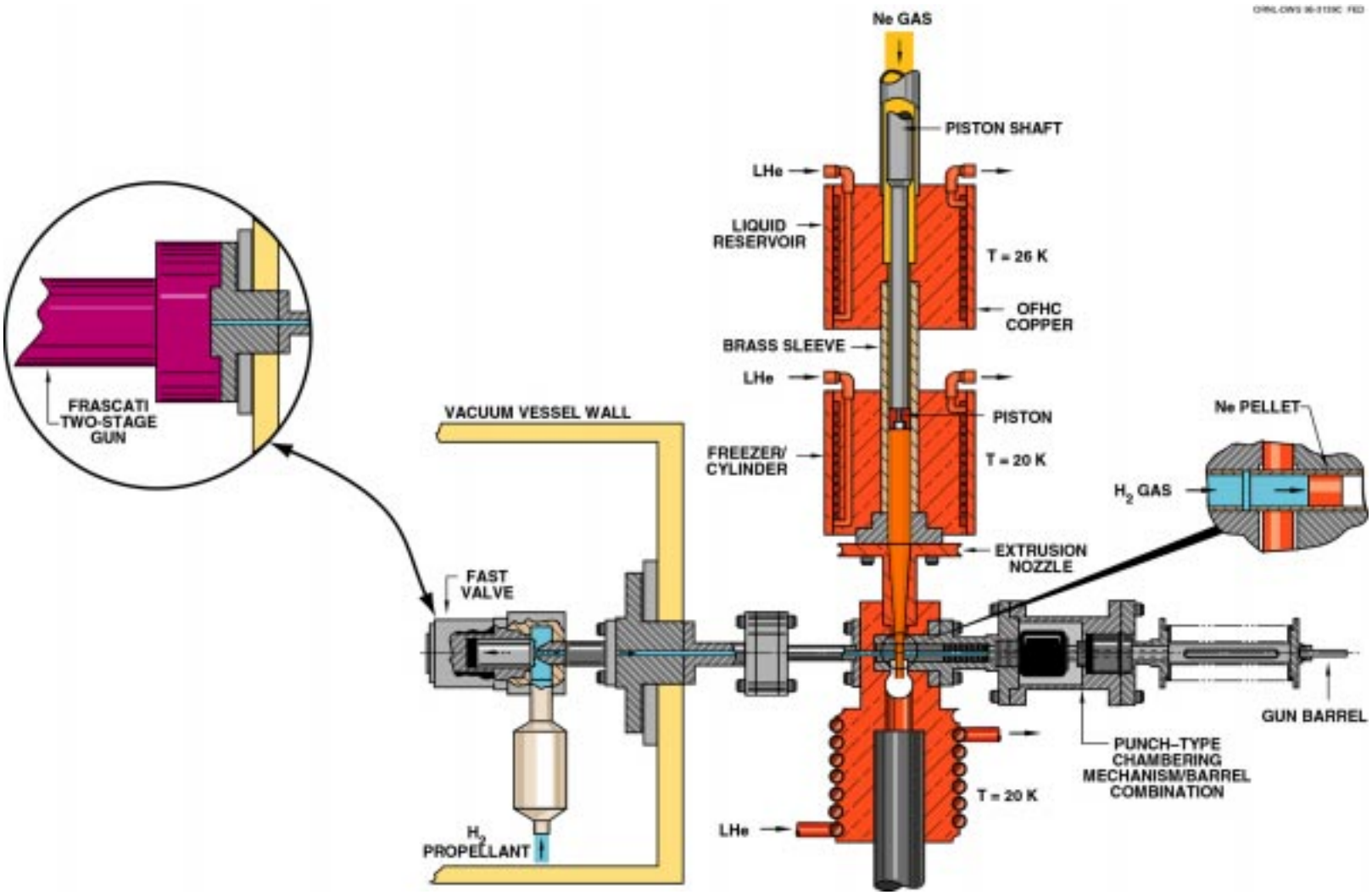
Two-Stage Light Gas Gun Development – Repetitive Two-Stage Gun (4-mm Plastic Projectiles at 1 Hz and 3 km/s)



Schematic of Repeating Pneumatic Injector (RPI) Test Facility for the ORNL/ENEA Frascati Collaboration



Original Repeating Pneumatic Injector Was Modified to Accept the Frascati Two-Stage Light Gas Gun

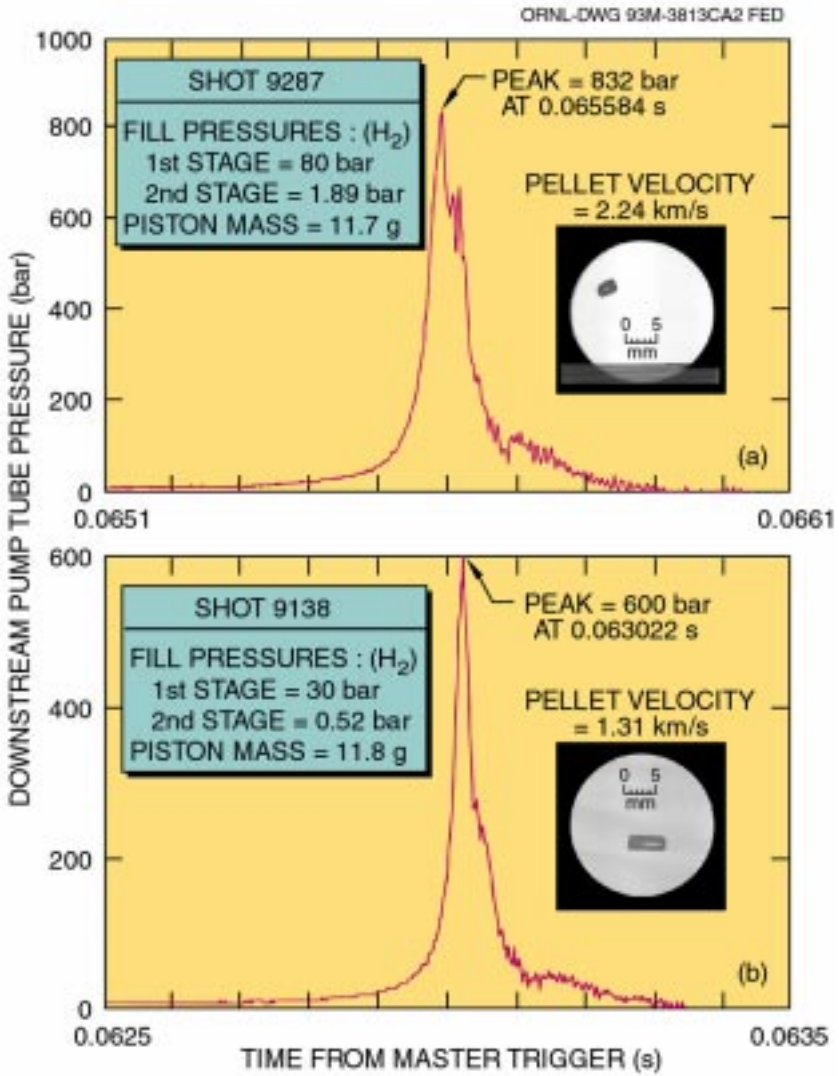


Main Parameters of the ORNL/Frascati Injector

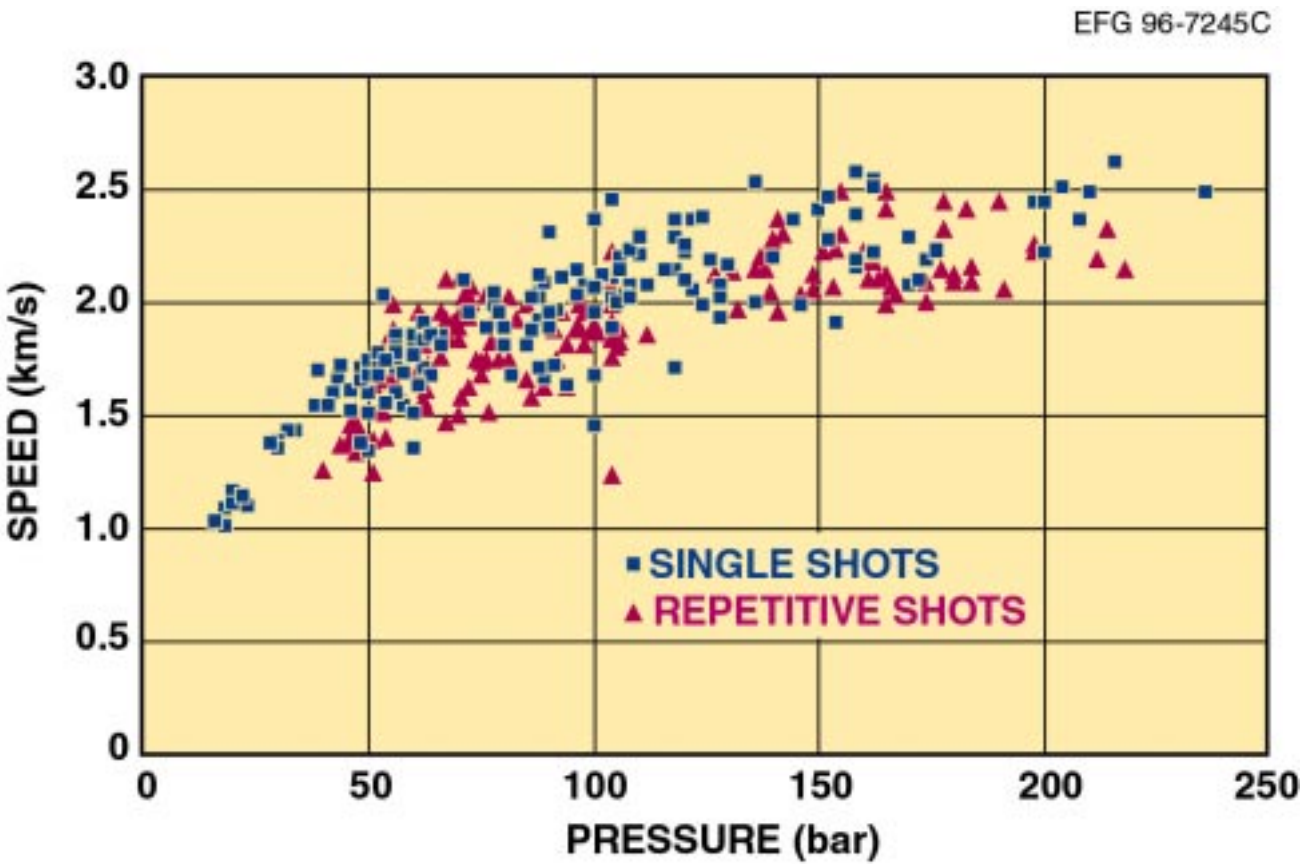
ORNL-DWG 93M-3876C FED

Frascati two-stage gun	
First stage reservoir volume (cm^3)	325
Pump tube ID (mm)	25.03
Pump tube length (mm)	350
Piston material	Al alloy (ergal)
Piston mass (g)	~10
Piston length (mm)	~14
Piston diameter (mm)	24.97
Operating gases	H_2 or He
ORNL extruder/gun assembly	
Pellet material	D_2
Barrel length (mm)	800
Barrel ID (mm)	2.7
Pellet nominal length (mm)	2.7 (x 2 and 3)
Pellet nominal mass (mg)	3 (x 2 and 3)

Test Shot Data from the ORNL/Frascati Two-Stage Gun Experiments

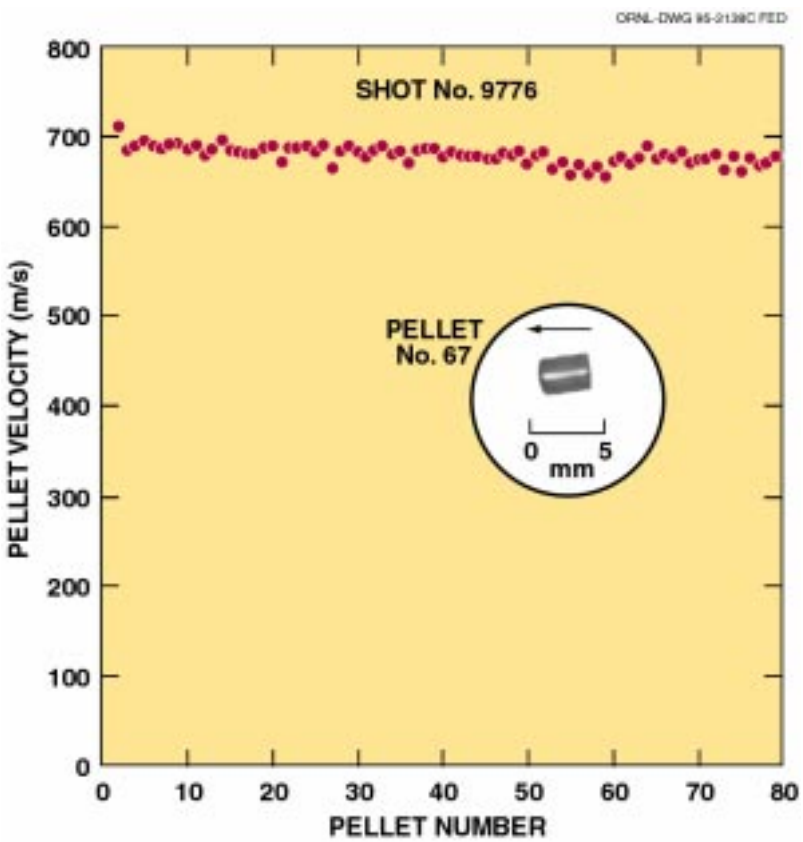


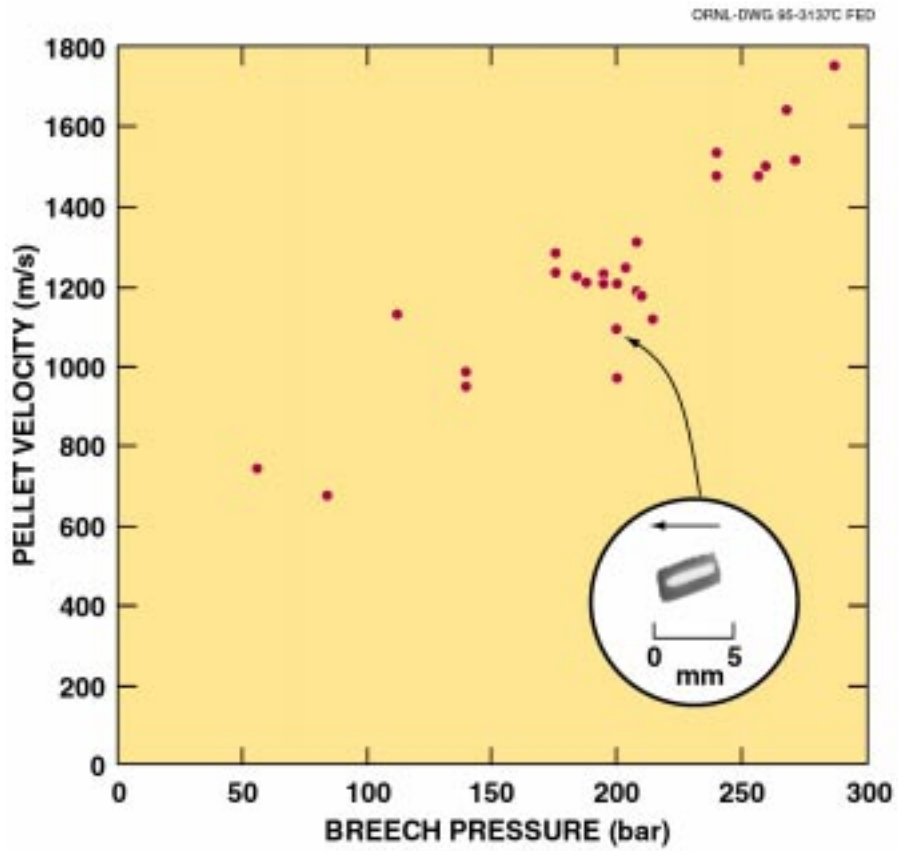
Comparison of Data from Single-Shot and Repetitive-Mode Operation of the ORNL/Frascati Two-Stage Gun



- In three experimental campaigns between September 1993 and May 1995, original objectives of the collaboration were met

Speed Data for Neon Pellets Accelerated with Single-Stage and Two-Stage Light Gas Guns During ORNL/Frascati Collaboration



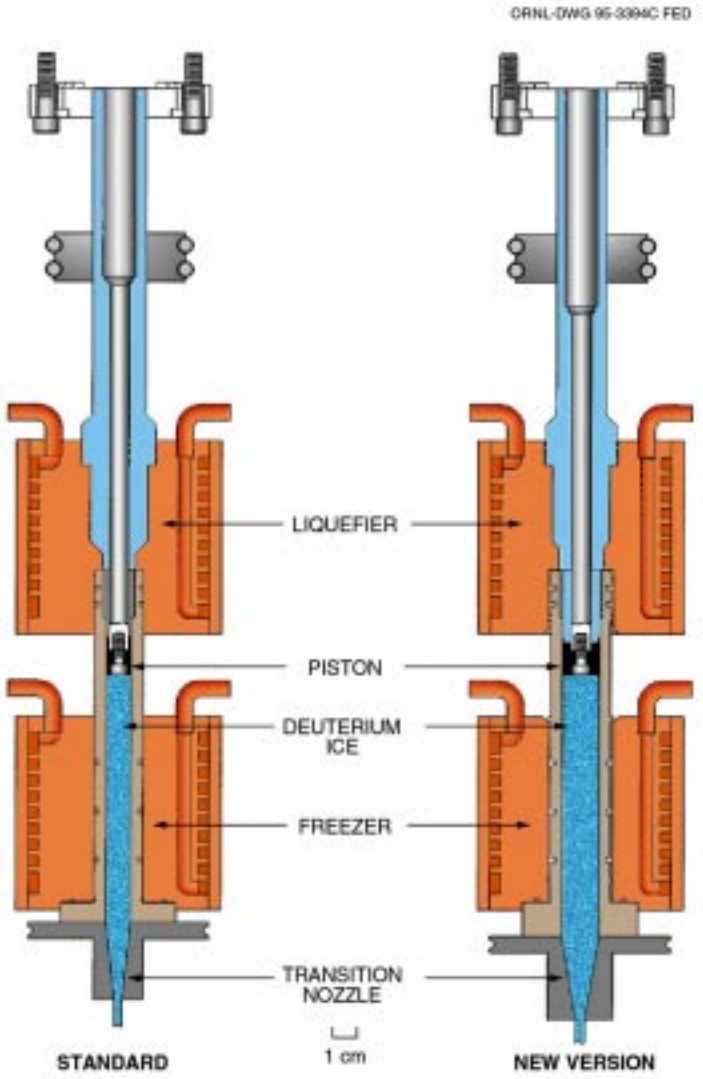


- **Single-stage light gas gun (78 consecutive pellets fired at 1 Hz; ≈50 bar breech pressure)**
- **Frascati two-stage light gas gun (H_2 gas used in both stages)**

Long-Pulse/Steady-State Pellet Feed System

- Straightforward concept in which multiple extruders operate in tandem
- New double-volume extruder design
- New Operating scenario discovered
- Prototype developed and tested at reactor-relevant parameters

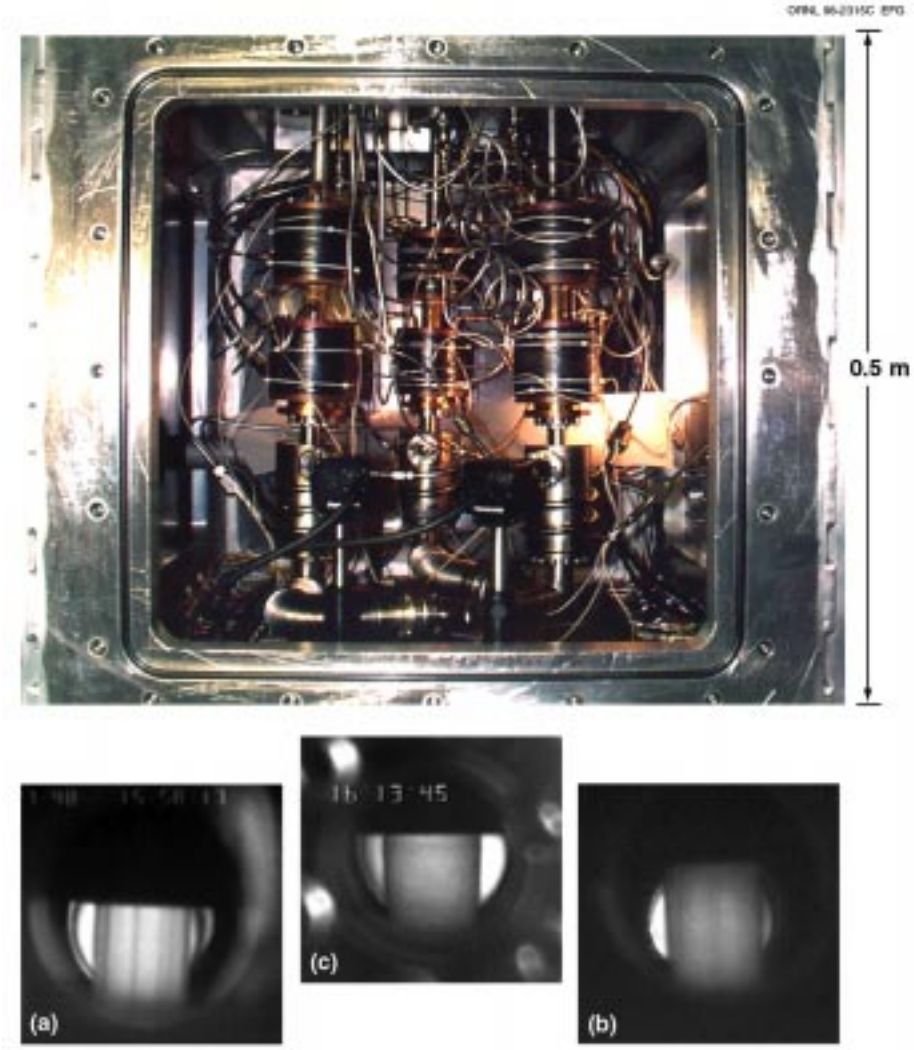
Designs of Standard ORNL Extruder and New Version with Twice the Deuterium Ice Volume



- In experiments, a new operating scenario was discovered that also doubled the volume of ice per batch; this was accomplished by simply lowering the liquefier temperature to that of the freezer before initiating extrusion
- In tests with D_2, it was found that the extruder could provide ice flow rates of up to ≈1.3 cm^3/s for ≈10s, which is sufficient for fueling reactors at the gigawatt power level

Multiple Extruder Units Can be Operated in Sequence to Provide a Steady-State Supply of Hydrogen Ice for Feeding a Pellet Injector

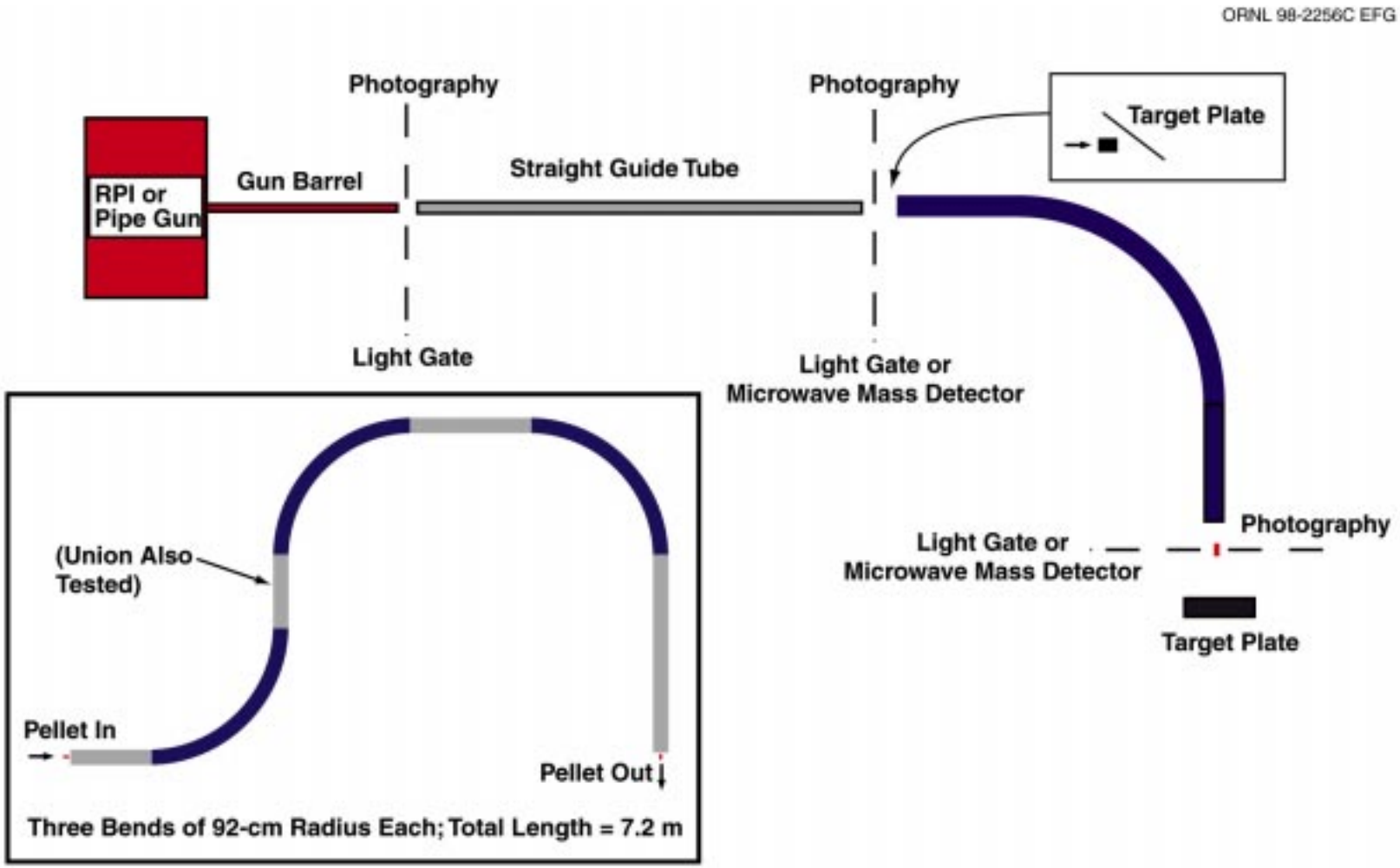
- With the three-extruder prototype, a steady rate of ≈0.33 cm^3/s was maintained for a duration of 1 h
- Operation of prototype at 1 cm^3/s is feasible, but additional extruder units (1-3) would facilitate operations at higher throughputs and reduce the duty cycle of each unit
- Prototype can easily accommodate steady-state fueling of present large tokamaks or other near-term experiments



HFS/Inside Launch Pellet Injection Technology

- Basic impact studies to determine speed limits for pellet collisions with hard surfaces
- Curved guide tube experiments to determine the pellet speed limit for different pellet/tube parameters
- Mock-up of alternative injection schemes for large fusion experiments (supportive data required before proceeding with installations)
  - DIII-D (inside launch and vertical injection)
  - JET (inside launch)
  - LHD (inside launch)

Test Configurations for Experiments with RPI and Pipe Gun Insets Show Special Setups for Multiple Bends and Impact Tests (Pipe Gun Only)



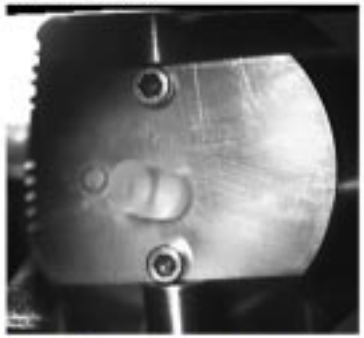
Photographs of 10-mm D_2 Pellets after Impact on Inclined Flat Plate

ORNL 98-2265A2C EFG

Shot 1067

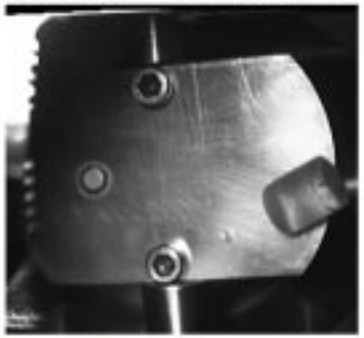
Pellet Speed = 82.1 m/s
Impact Angle = 15°
Normal Velocity = 21.2 m/s

Shot 1069



Pellet Speed = 77 m/s
Impact Angle = 15°
Normal Velocity = 20 m/s

Shot 1070 10 mm

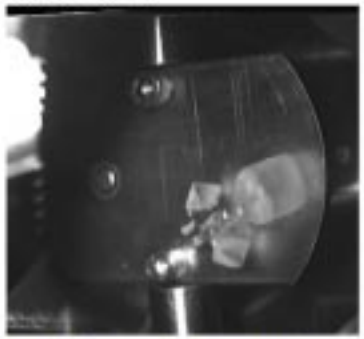


Pellet Speed = 47.8 m/s
Impact Angle = 15°
Normal Velocity = 12.4 m/s

Shot 1072

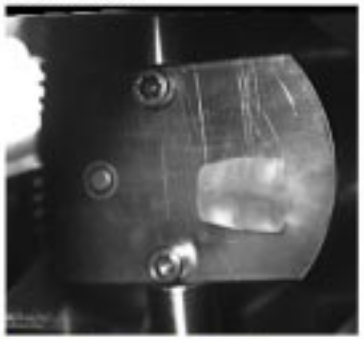
Pellet Speed = 81.1 m/s
Impact Angle = 30°
Normal Velocity = 40.6 m/s

Shot 1074



Pellet Speed = 61.5 m/s
Impact Angle = 30°
Normal Velocity = 30.8 m/s

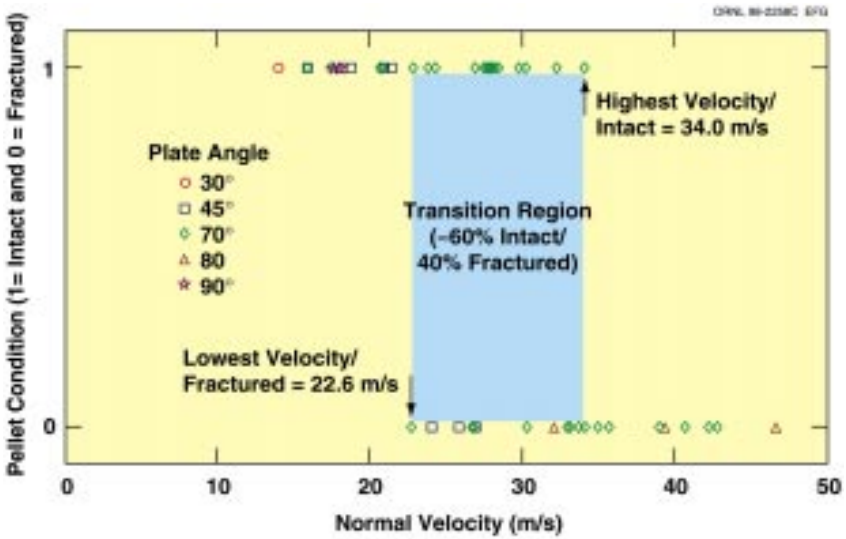
Shot 1076



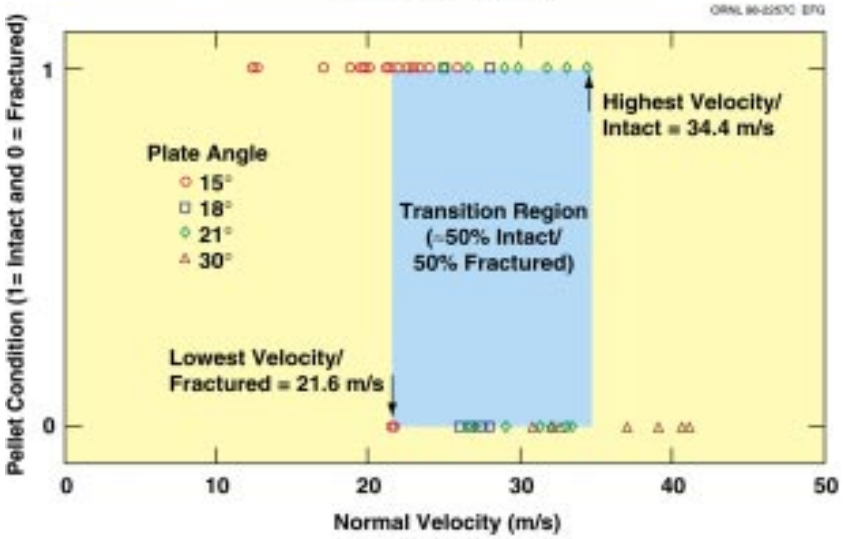
Pellet Speed = 74 m/s
Impact Angle = 21°
Normal Velocity = 26.5 m/s

Impact Test Results for D_2 Pellets on Inclined Stainless Steel Plate

2.7 mm



10 mm



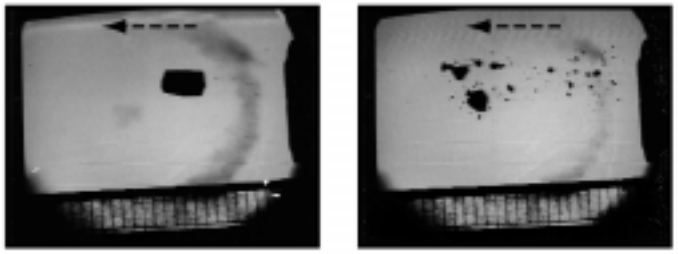
- Almost no difference observed in the speed limit for the two pellet sizes
- Pellets with speeds <22 m/s were intact; pellets with speeds >34 m/s were fractured
- In the transition region, about half of the pellets were fractured

Test Data Summary for 2.7-mm D_2 Pellets Shot through Curved Guide Tubes of Different Radii (90° Bends)

- ORNL curved guide tube tests with repeating pneumatic injector
  - For sharp bends (≤20-cm radius), pellet integrity appears to follow simple stress limit model that considers only centrifugal forces
  - For weaker bends, pellet speed limit is significantly less than expected from simple model; absolute limit of 400–500 m/s recorded in lab tests
  - Indications are that low-speed limits are due to multiple collisions with tube walls
- New model by Artaud and Géraud accounts for pellet/tube surface collisions and predicts trends in test data quite well (1998 SOFT, Marseille)

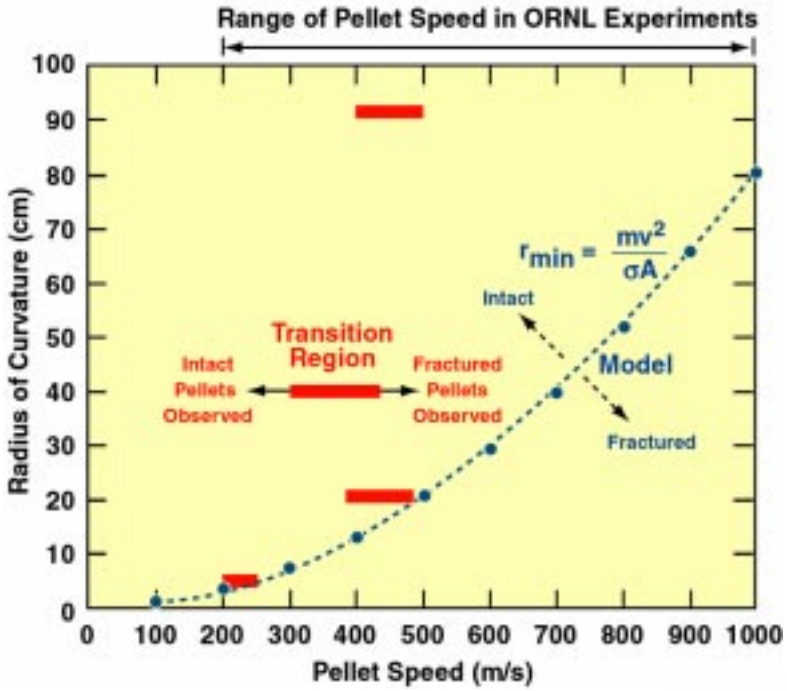
Pellets Exiting 40-cm Radius Curved Guide at 440 m/s

ORNL-DWG 97-3278 EFG



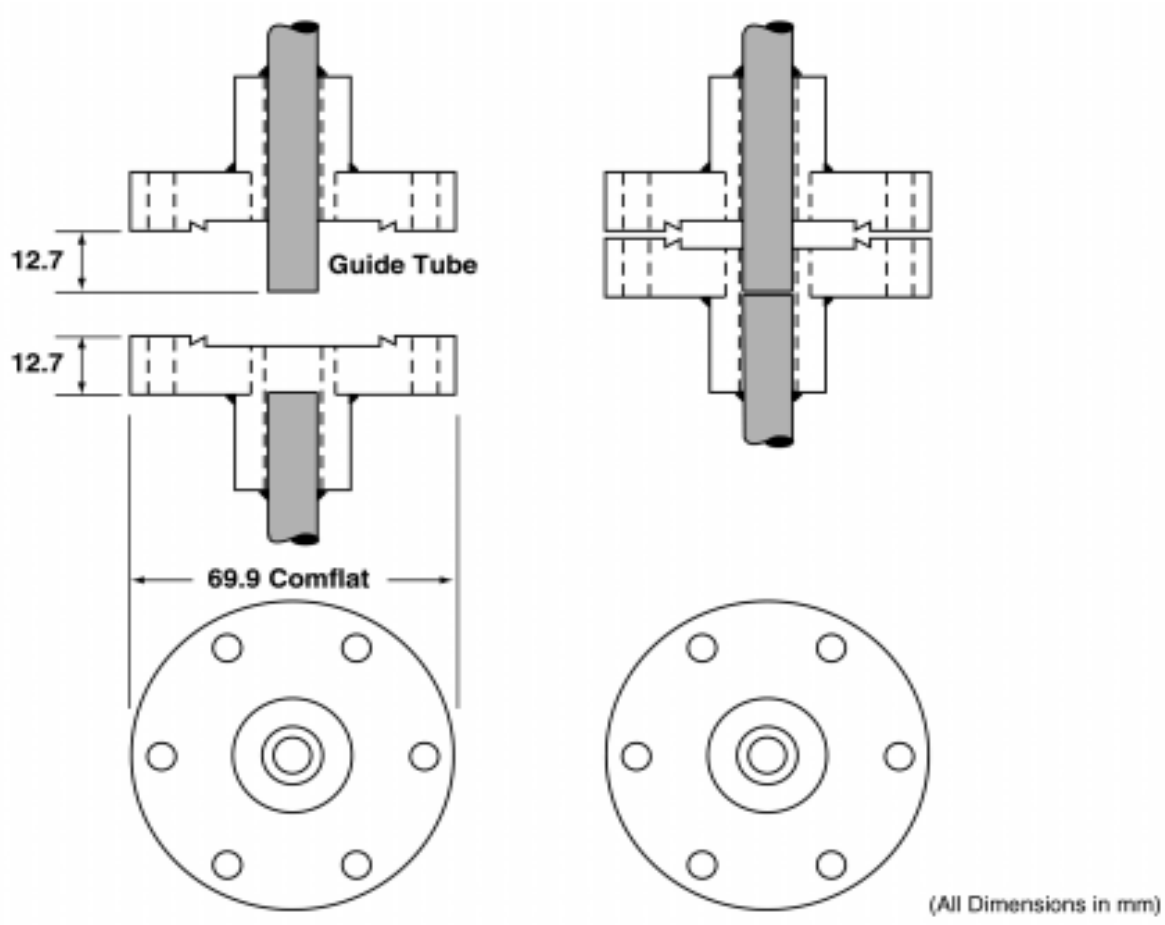
Intact Pellet Fractured Pellet

ORNL 2000-1171C EFG

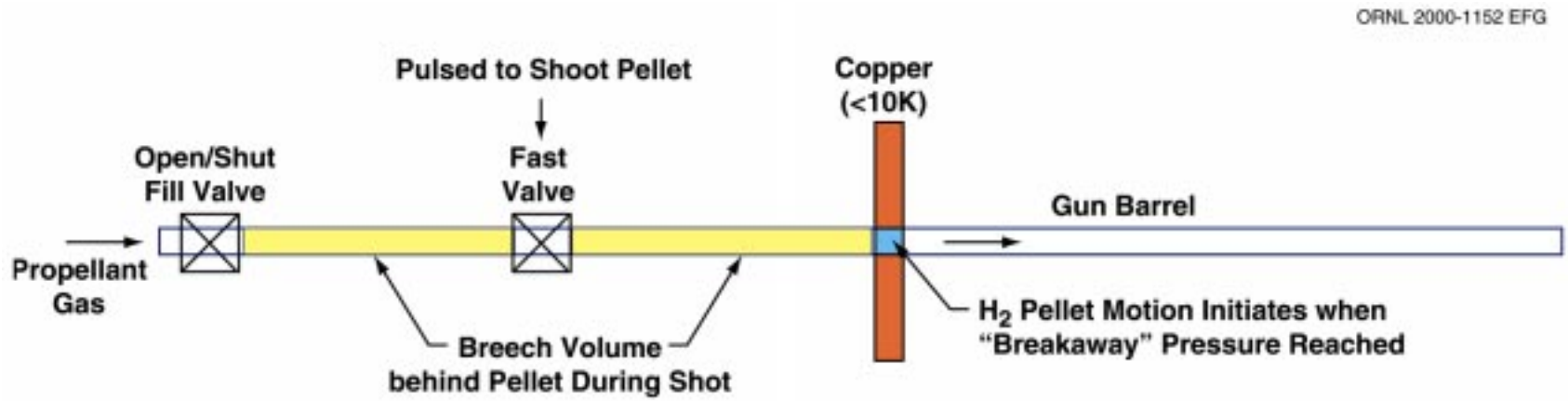


ORNL Union Design for Connecting Multiple Tubes to Transport Pellets through Long Runs; Extensive Testing with D_2 Pellets Indicated No Deleterious Effects on Pellet Integrity or Speed

ORNL 99-1604 EFG

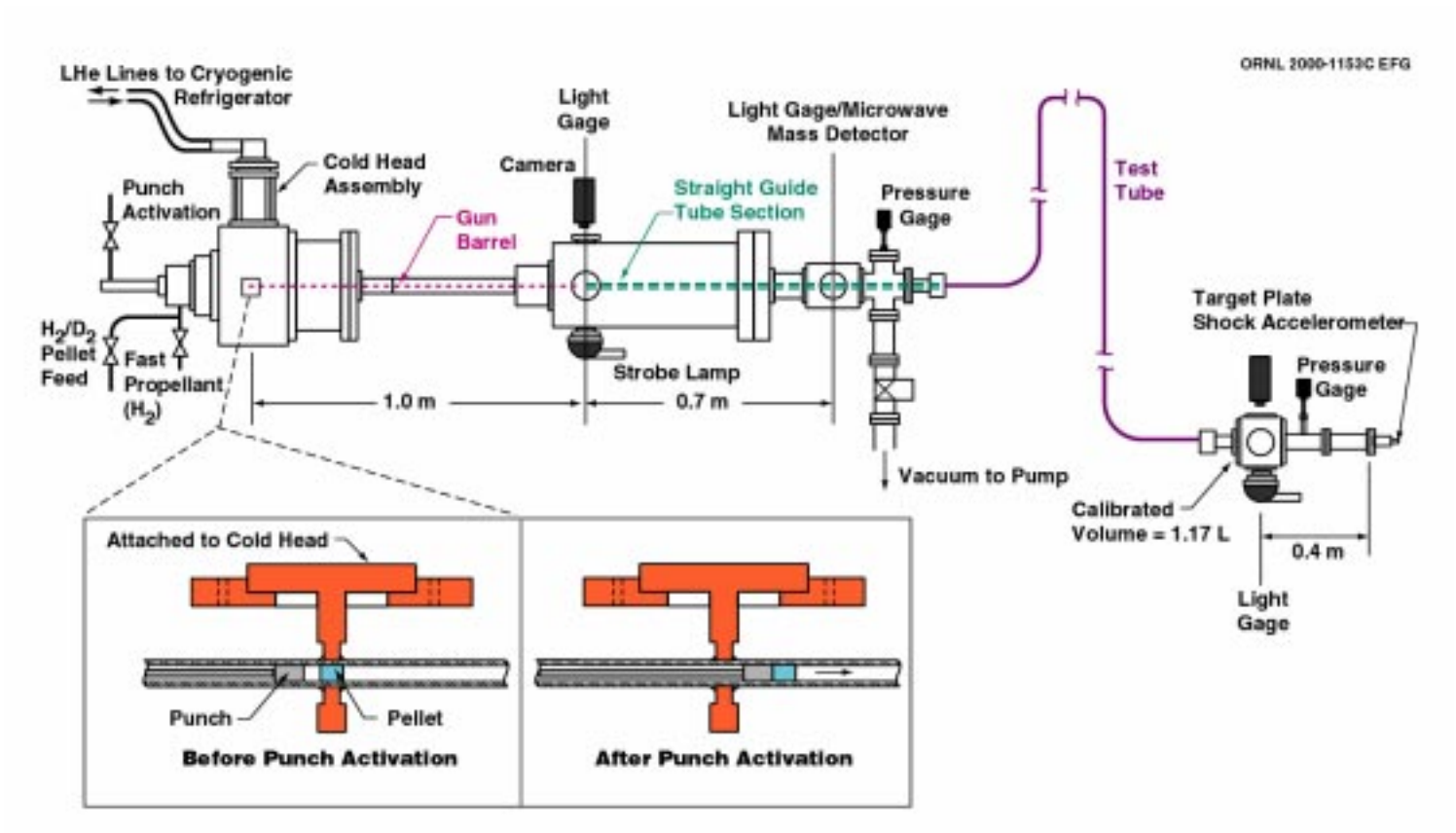


Issue with Guns – Reliable Operation at Low Speed



- Pellet "breakaway" pressure is ≈5 to 15 bar (function of temperature)
- Breech volume behind pellet rises to "breakaway" pressure before pellet initiates motion/acceleration; volume can be relatively large
- PV product results in relatively high speeds with standard guns (especially pipe guns)
- Simply lowering the operating pressure does not work
  - No pellet motion if "breakaway" pressure not reached
  - Speeds >400-500 m/s attained if "breakaway" pressure reached
- With a mechanical punch initiating pellet motion, the fast valve can be pulsed to provide minimal gas for low pellet speeds

ORNL Pipe-Gun Facility Was Modified and Used for Testing Curved Guide Tubes and Mock-Ups of Inside Launch Pellet Injection on DIII-D, JET, and LHD



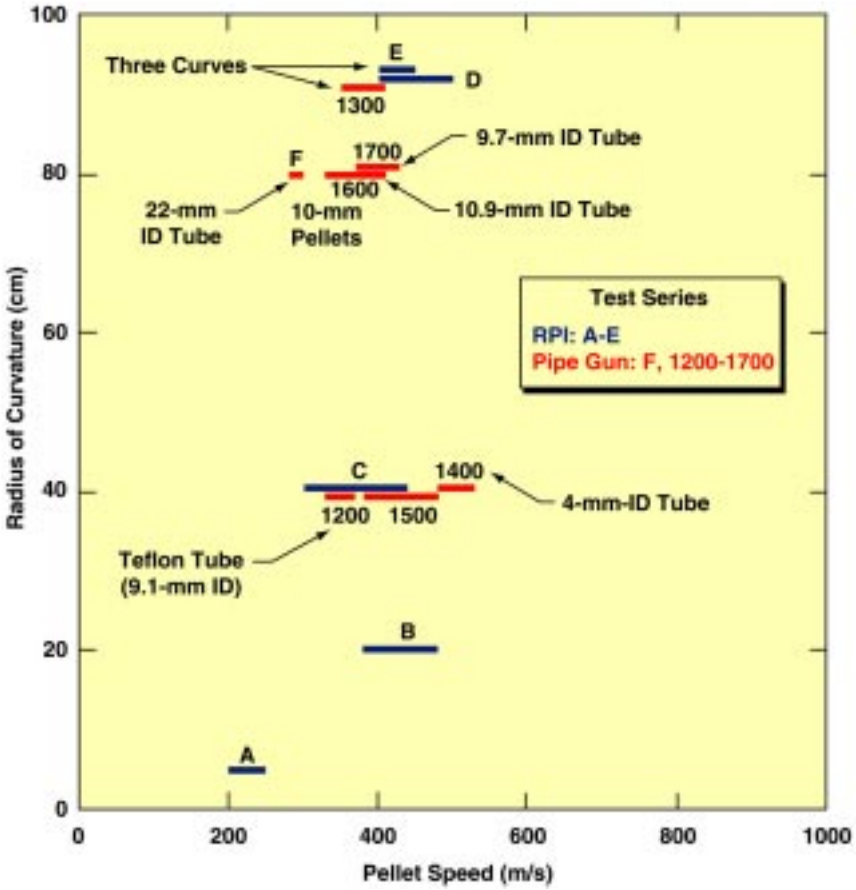
Experimental Data for D_2 Pellets Shot through Curved Guide Tubes (90° Sections); A Speed Transition Region Is Identified for Each Test Series (Unless Marked, Pellet Size Was 2.7 mm, and Tube ID Was ~8 mm)

Summary of Parameters for Curved Guide Tube Tests
(D_2 pellets shot through 90° sections)

ORNL 98-2264C EFG

Test series	Guide tube parameters: Curve radius (cm)	ID (mm)	Material	Pellet parameters: Diameter[a] (mm)	Length/ diameter	Temperature (K)	Speed: Transition range[b] (m/s)
			RPI				
A	5	7.9	Stainless steel	2.7	1 to 2	12	200 to 250
B	20	7.9	Stainless steel	2.7	1 to 2	12	380 to 480
C	40	7.9 and 8.5	Stainless steel	2.7	1 to 2	12	300 to 440
D	92	8.5	Stainless steel	2.7	1 to 2	12	400 to 500
E	92 (×3)	8.5	Stainless steel	2.7	1 to 2	12	400 to 450
			Pipe gun				
F	80	22.0	Stainless steel	9.7	1	8[c]	280 to 300
1200	40	9.1	Teflon	2.7	1	9[d]	330 to 370
1300	92 (×3)	8.5	Stainless steel	2.7	1	9[d]	350 to 410
1400	40	4.0	Carbon steel	2.7	1	9[d]	480 to 530
1500	40	8.5	Stainless steel	2.7	1	9[d]	380 to 480
1600	80	10.9	Stainless steel	9.7	1	8[d]	330 to 410
1700	80	9.7	Stainless steel	9.7	1	8[d]	370 to 430

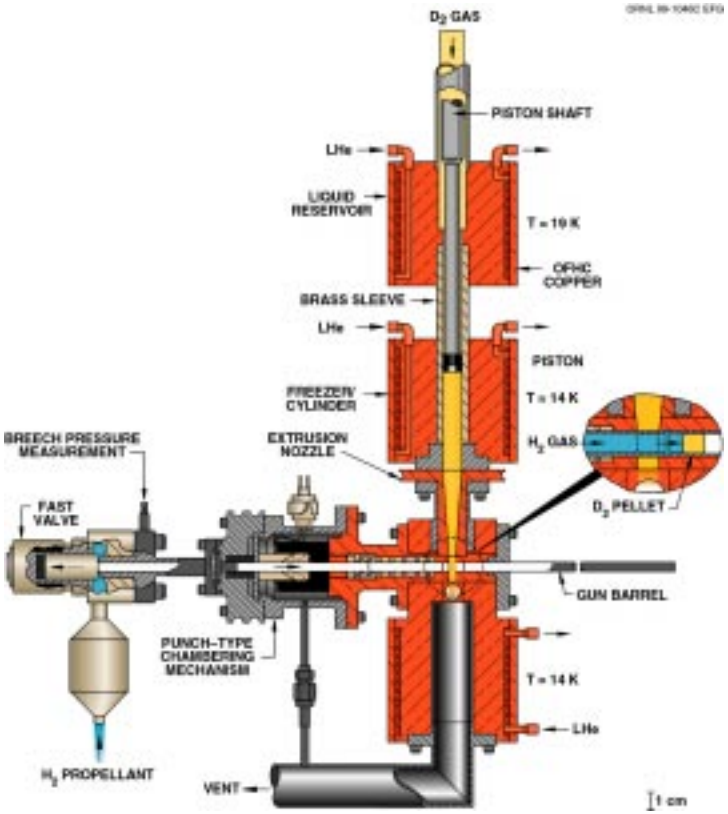
[a]Nominal pellet diameter is taken as the gun barrel ID.
[b]In the transition range, intact and fractured pellets were observed; below the minimum velocity, pellets were always intact; and above the maximum velocity, pellets were always fractured or severely eroded.
[c]Pellet was frozen at 8 K; however, cryostat was warmed up to ~15 K to attain slower speeds.
[d]Punch was used to initiate pellet motion.



DIII-D Pellet Injection System – Recent Injector Modifications

- All three guns now fire 2.7-mm pellets (1.8- and 4.0-mm sizes also used in previous experiments)

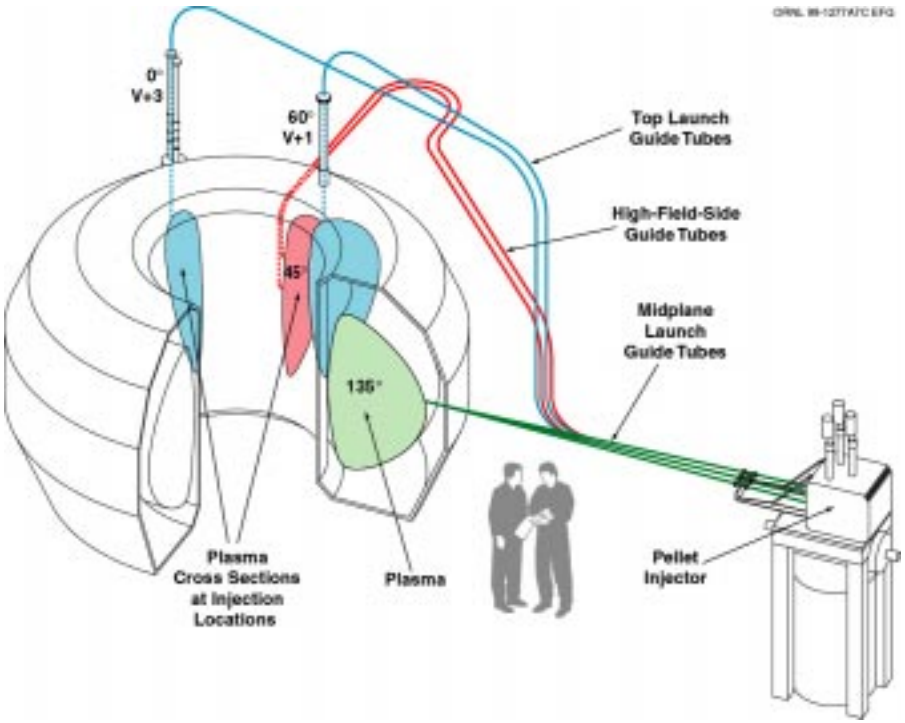
- New pellet punch mechanisms installed on two guns for reliable slow-pellet operation; these guns are also equipped with oversized gun barrels to further limit pellet speed (<200 m/s)



New Pellet Punch (Not Shown) Initiates Pellet Motion; It Was Developed and Tested at ORNL before Installation on DIII-D

DIII-D Pellet Injection System – Transport Guide Tubes

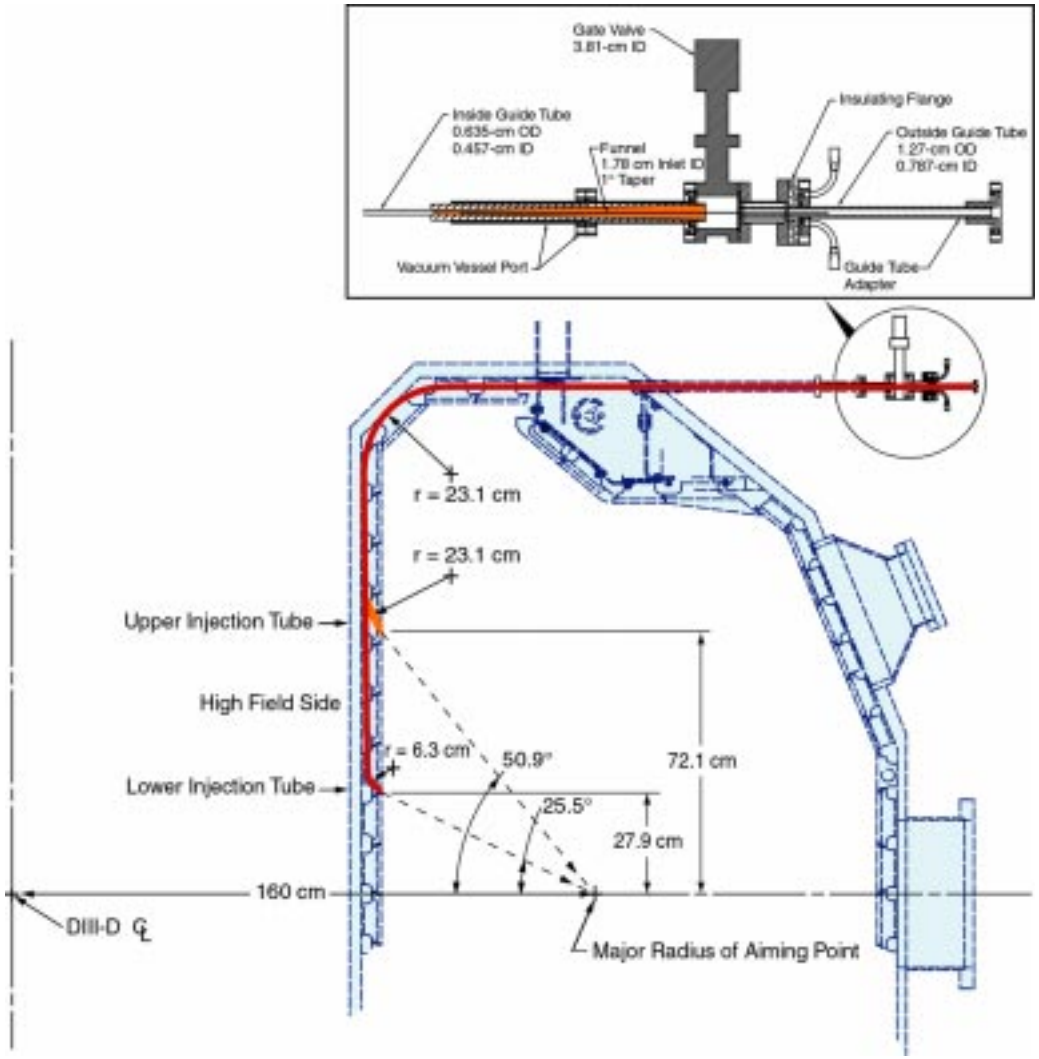
- Straight guide tubes (≈4 m)
  - Three independent standard low-field-side (LFS) injection tubes: 135º port
- Curved guide tubes (≈12.5 m)
  - Two independent vertical injection tubes: 0º (V+3) and 60º (V+1) ports
  - Two independent HFS injection tubes on inner wall: 45º upper and lower ports
  - Special tube with tight bend radius for LFS injection experiments with fractured pellets
- Performance tests were done at ORNL on simulations of DIII-D "roller-coaster" tube runs
  - Special ORNL components were developed for attaching multiple tube sections and size transitions
  - Pellet speeds are limited to ≈200 m/s for survival in HFS tube runs and ≈400 m/s for vertical installations



Any guide tube can be connected to any pellet gun (or a gas valve)

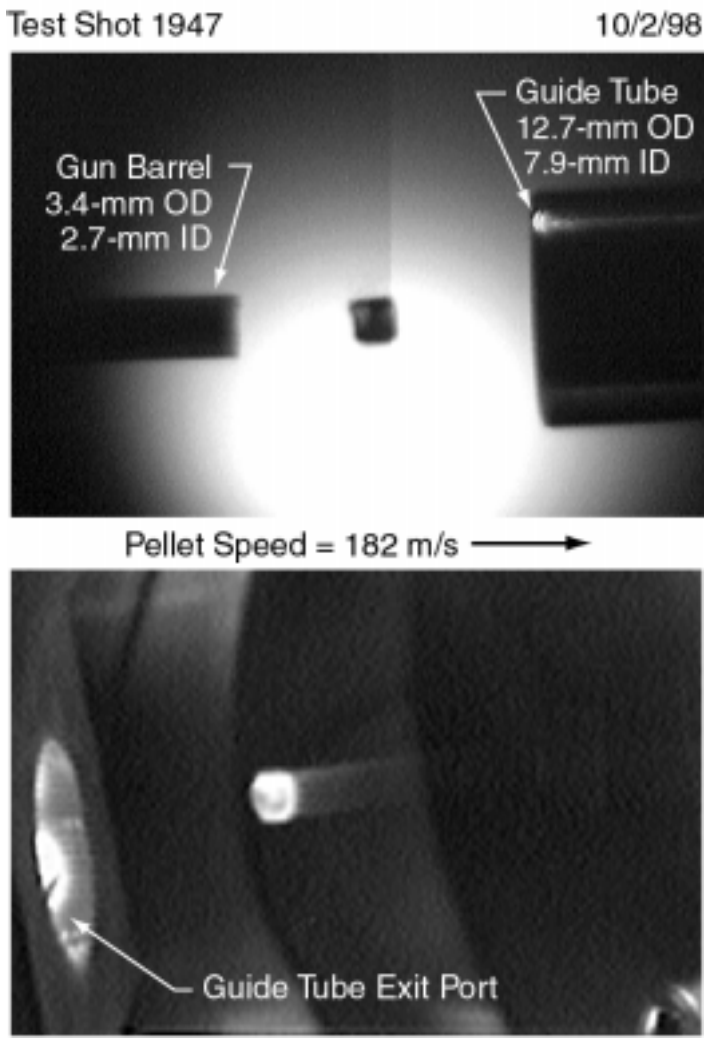
HFS Pellet Injection Tubes on DIII-D

ORNL 99-1470C EFG

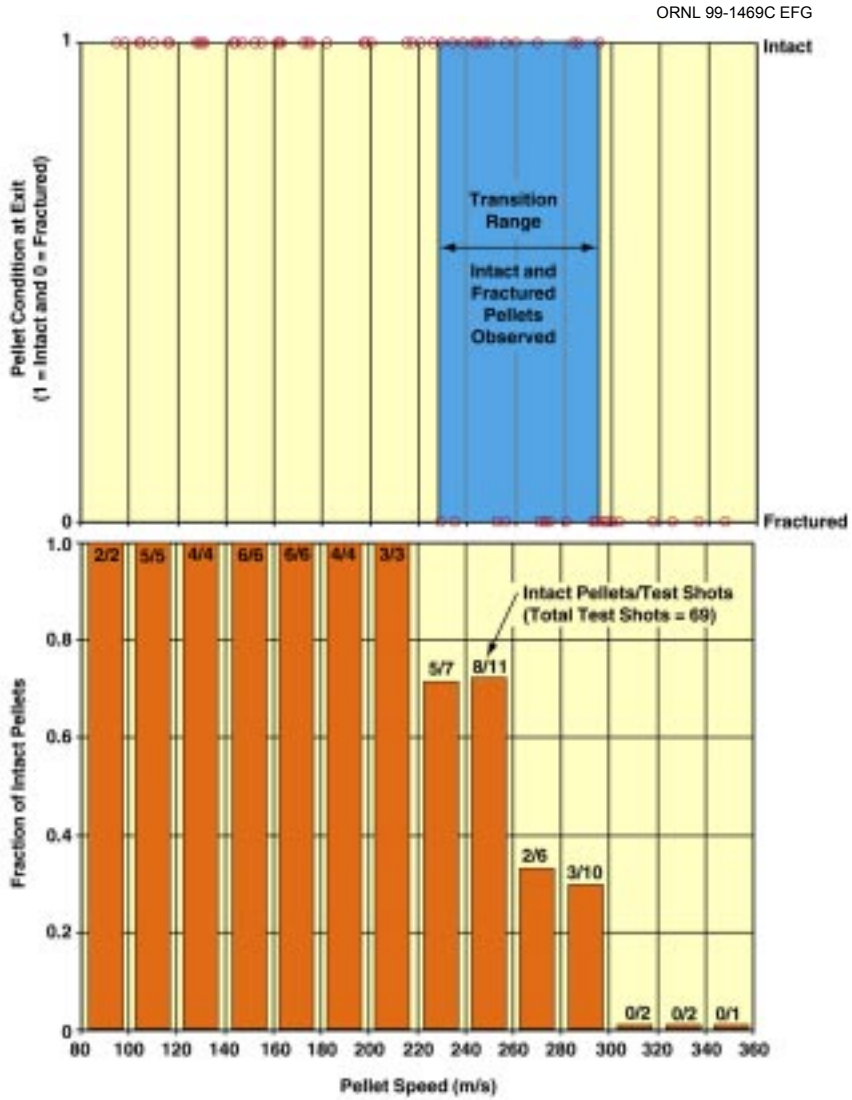


D_2 Pellet at Gun Muzzle and Guide Tube Exit from Simulation Test of DIII-D Lower HFS Pellet Injection

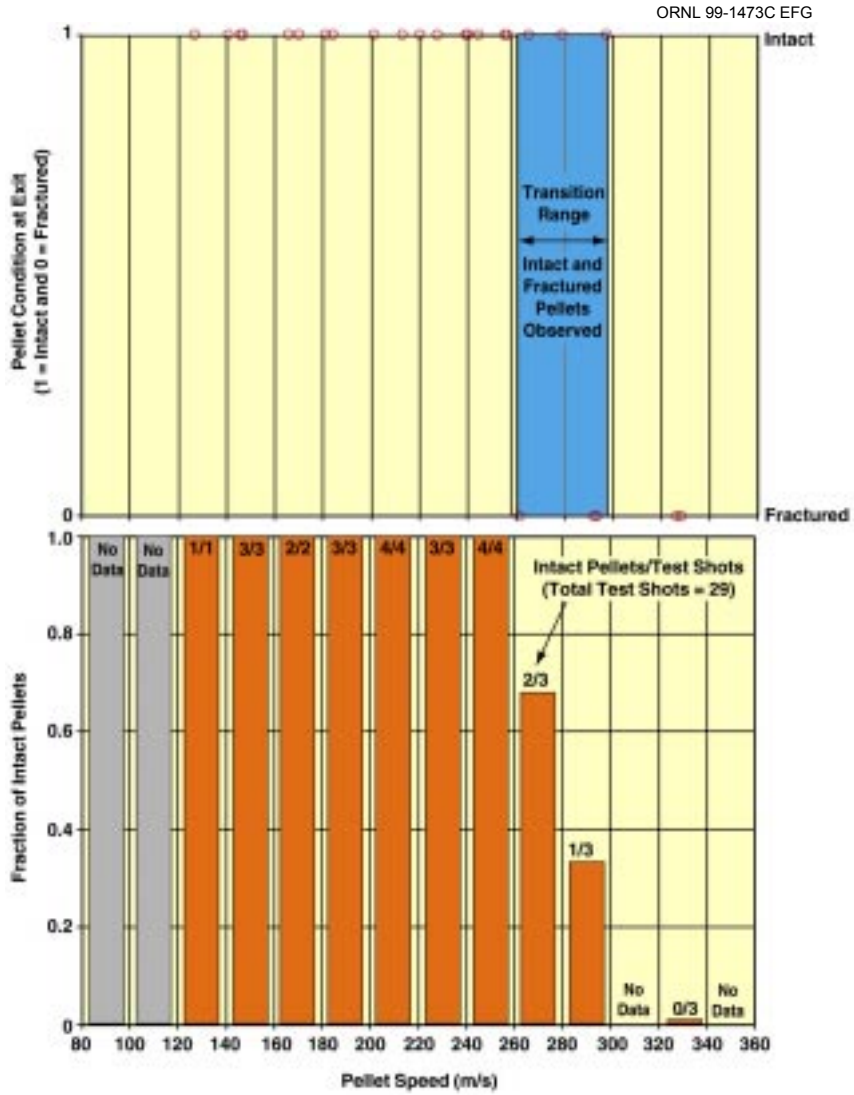
ORNL 99-1472 EFG



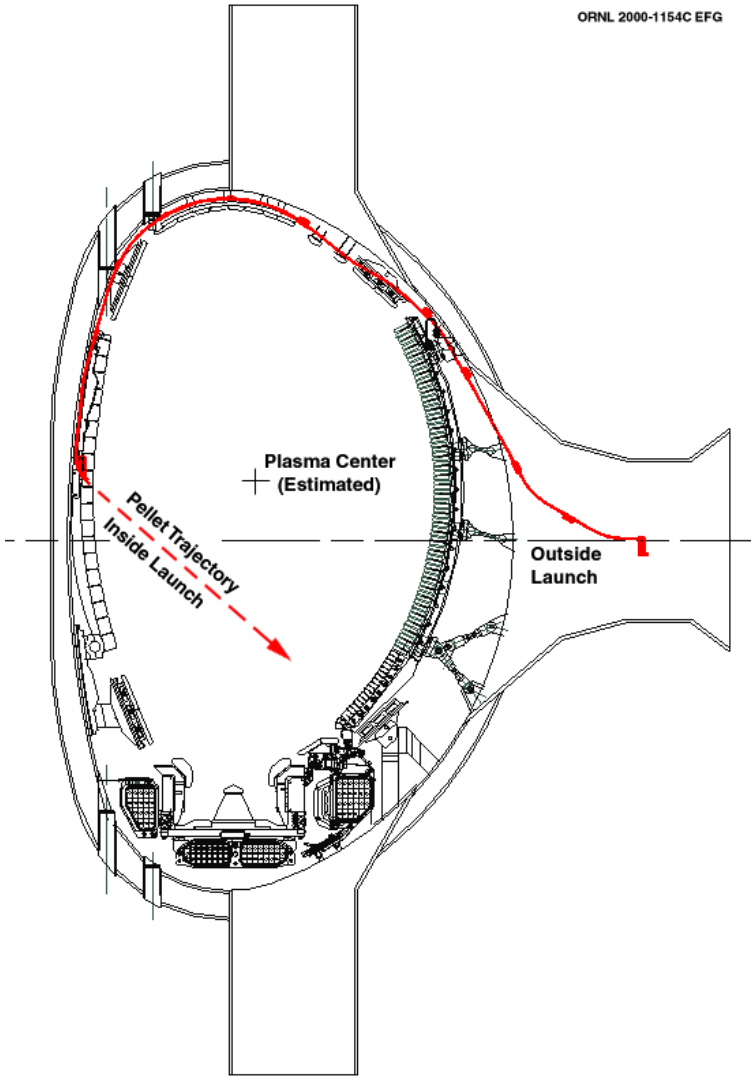
Results from ORNL Simulation of DIII-D Guide Tube Geometry for Lower HFS Pellet Injection (Test Shots with 2.7-mm D_2 Pellets)



Results from ORNL Simulation of DIII-D Guide Tube Geometry for Upper HFS Pellet Injection (Test Shots with 2.7-mm D_2 Pellets)

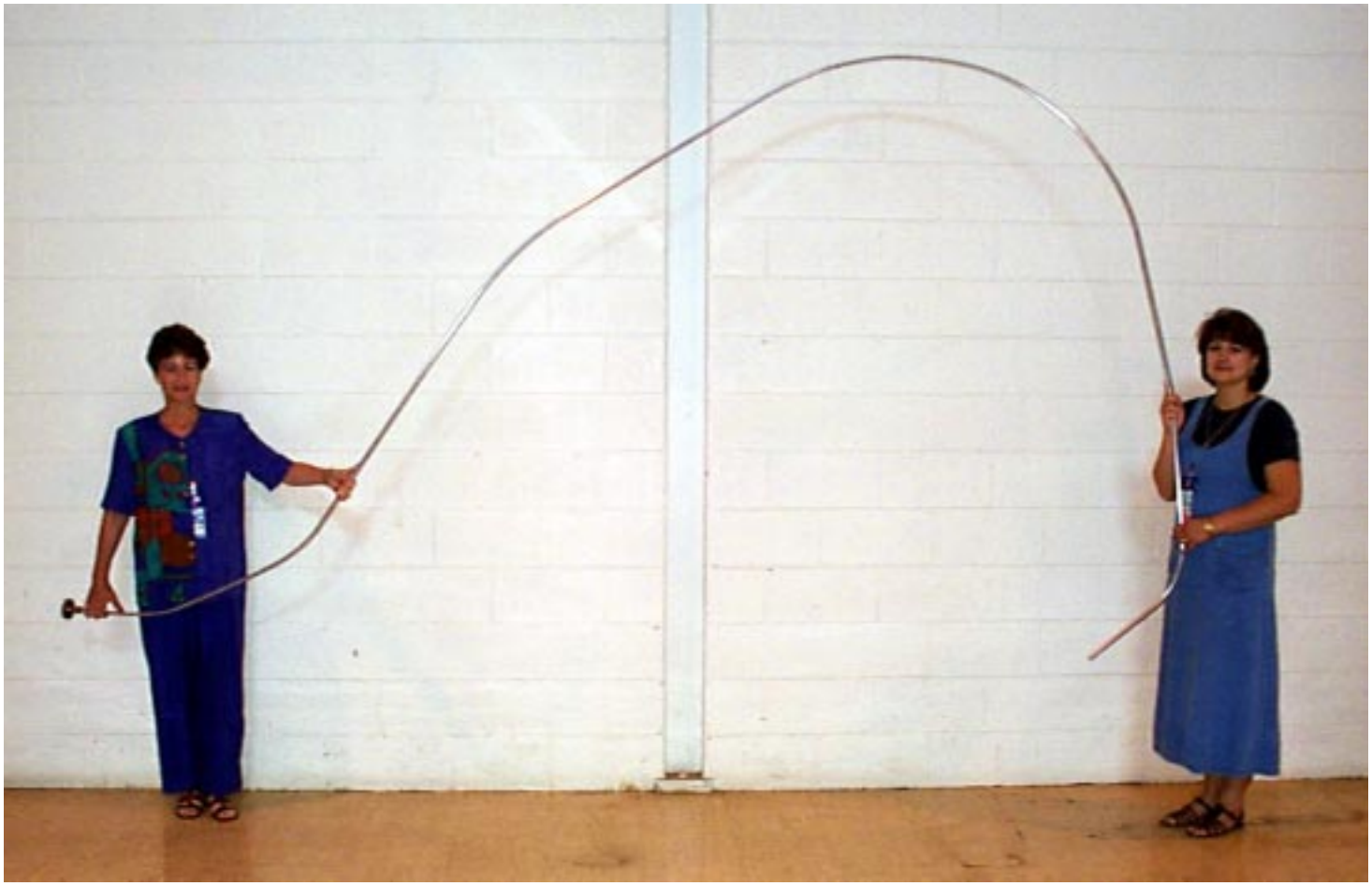


Guide Tube for Inside Launch Pellet Injection on JET Is Highlighted in Red (Stainless Steel Tube; Length = 6.2 m; and ID = 10 mm)



Guide Tube for ORNL Simulation of JET High-Field-Side Pellet Launch

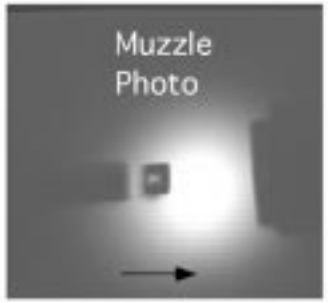
ORNL 99-1068C EFG



Pellet Photos and Speed Measurements Were Collected for Each Test Shot

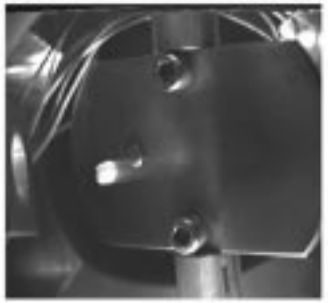
ORNL 99-1605C EFG

Pellets at Gun Muzzle Were in Excellent Condition and Essentially Indistinguishable from Each Other



Pellets at Exit of Guide Tube

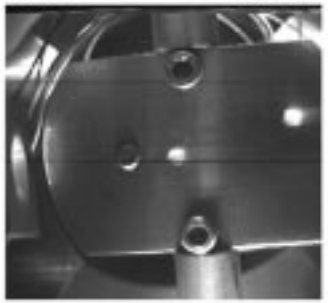
3044 246 m/s



3048 183 m/s

3057 233 m/s

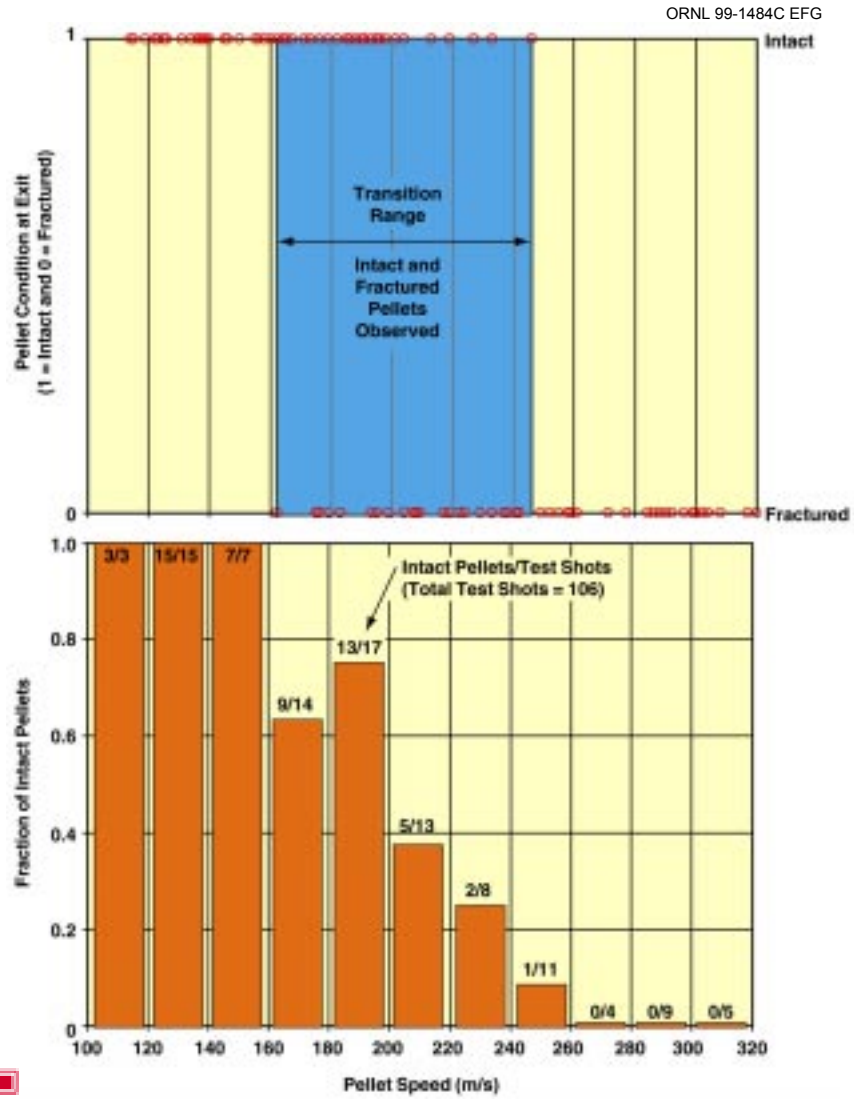
3059 258 m/s



3062 126 m/s

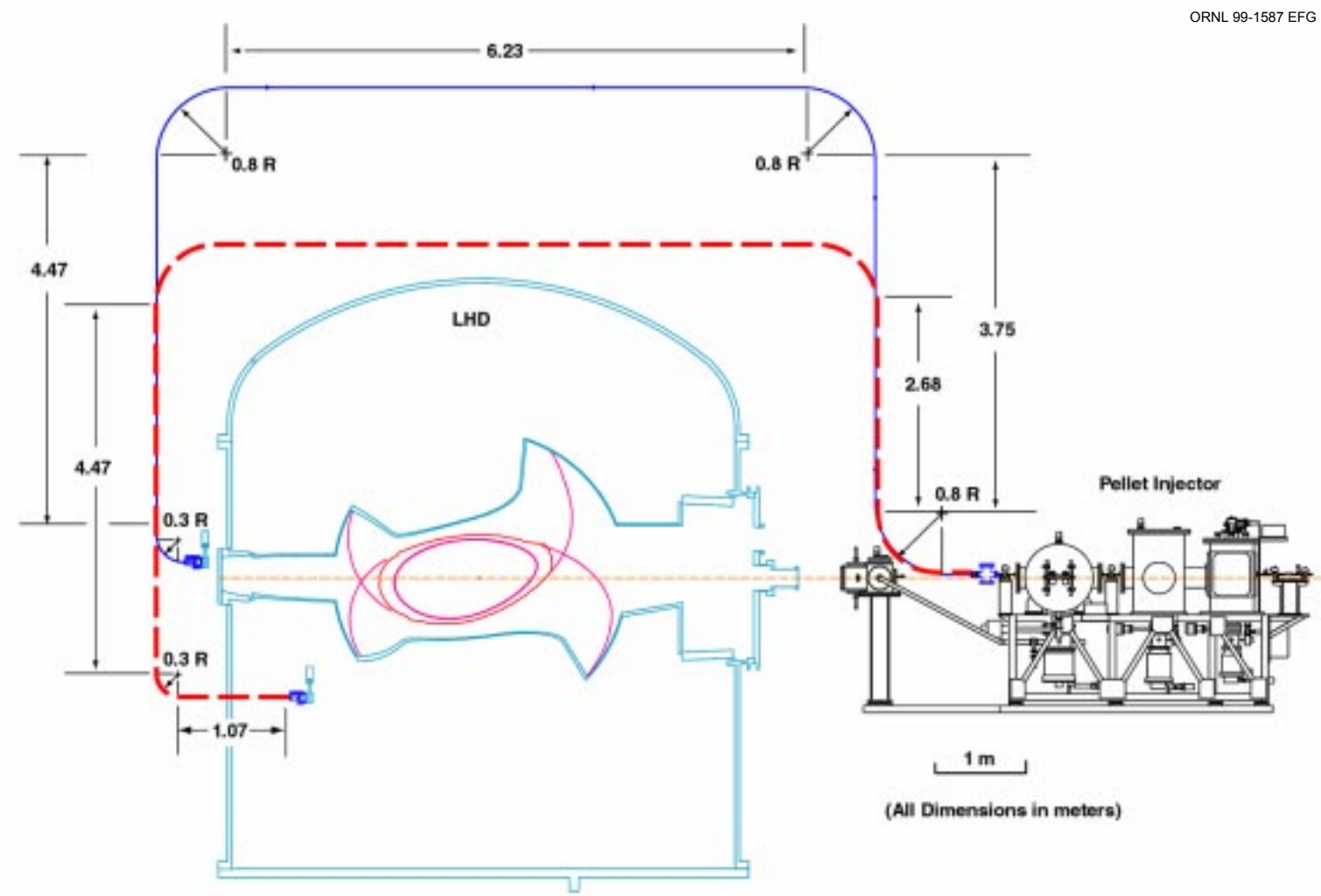
3092 207 m/s

Results from ORNL Simulation of JET Guide Tube Geometry for HFS Pellet Injection (Test Shots with 4-mm D_2 Pellets)



Speed limit confirmed in JET pellet fueling experiments in fall 1999

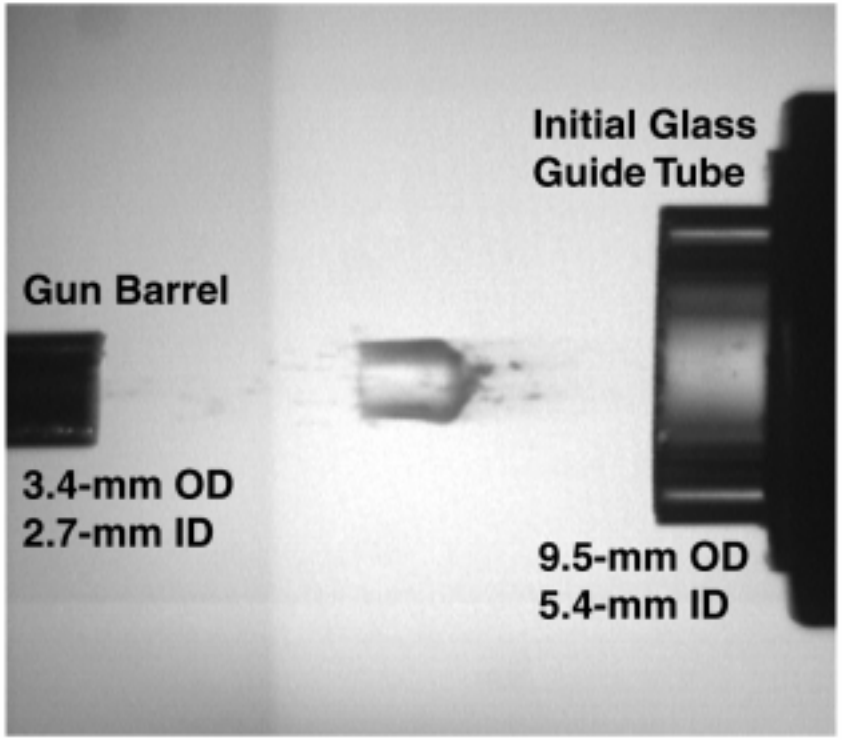
Guide Tube for Inside Launch Pellet Injection on Large Helical Device (LHD); ORNL Simulation is Shown with Dashed Line (Stainless Steel Tube; Length = 19 m; and ID = 7.7 mm)



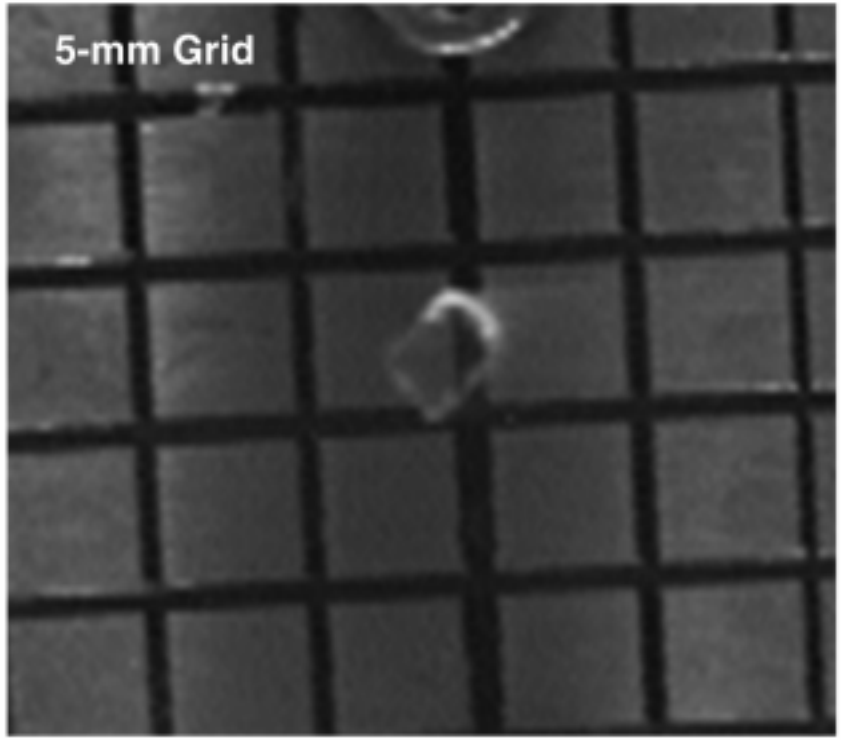
Photos of Hydrogen Pellets from ORNL Simulation of LHD High-Field-Side Pellet Injection; Pellets Travel 19 m through Curved Stainless Steel Guide Tube (7.7-mm ID by 9.5-mm OD)

ORNL 99-1588A3C EFG

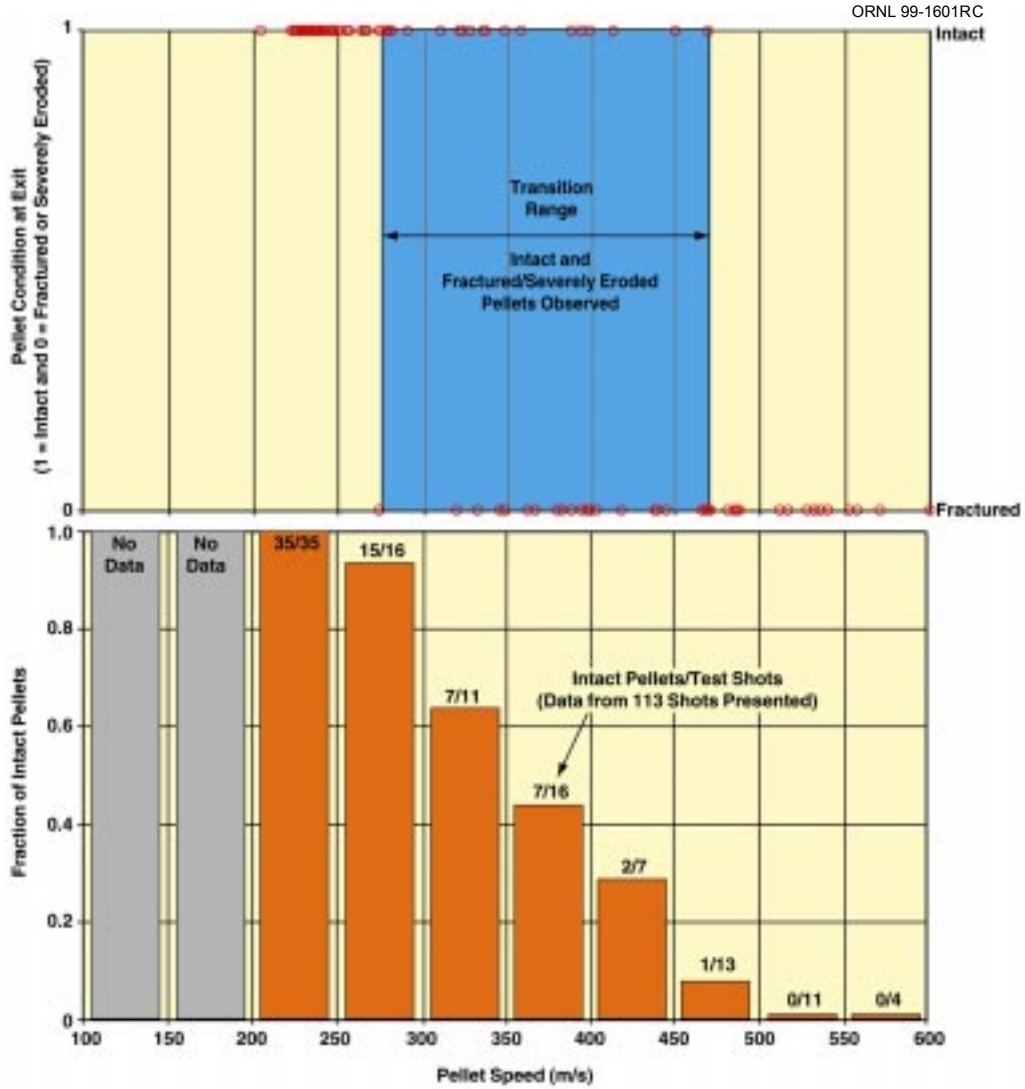
Gun Muzzle Speed = 231 m/s



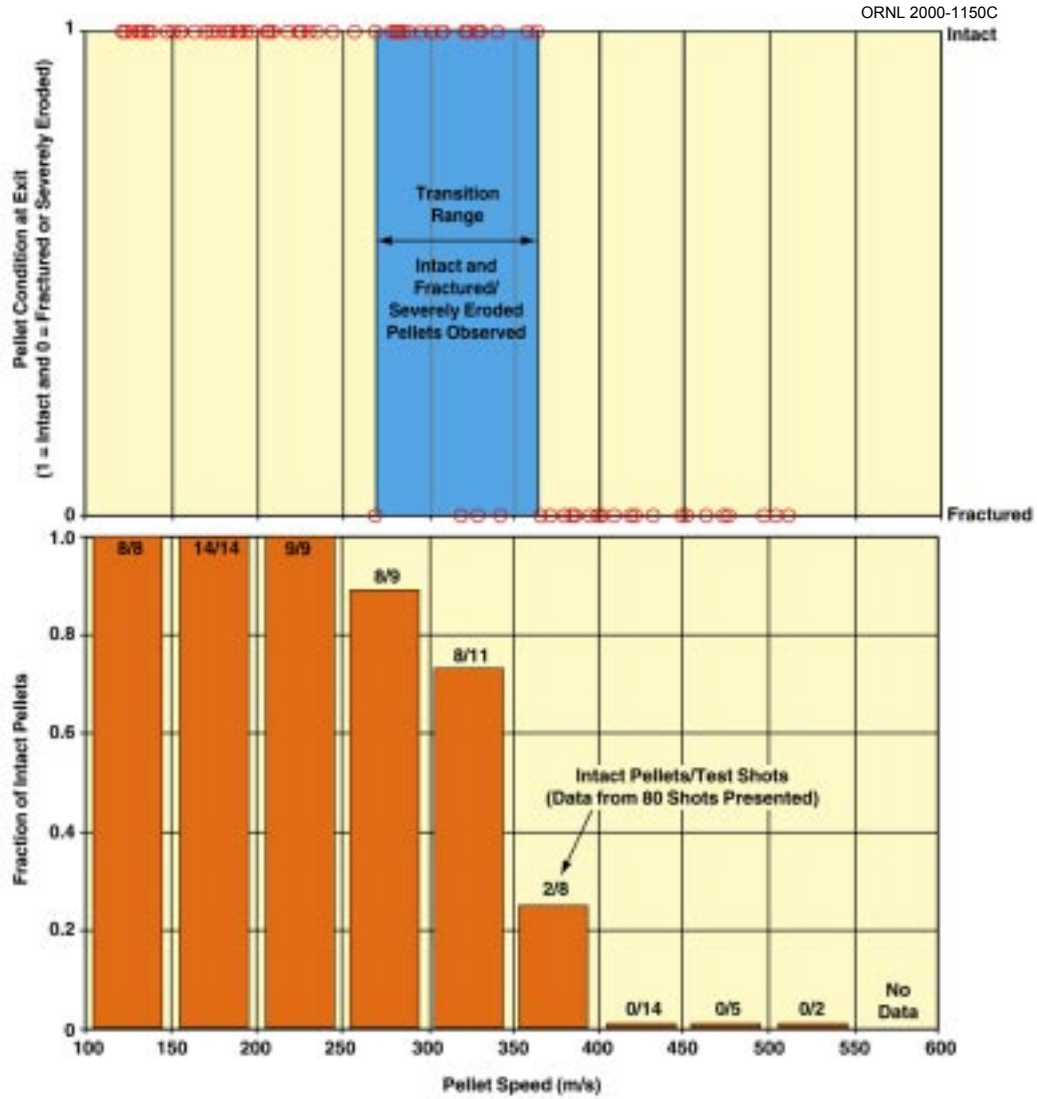
Guide Tube Outlet Speed = 213 m/s



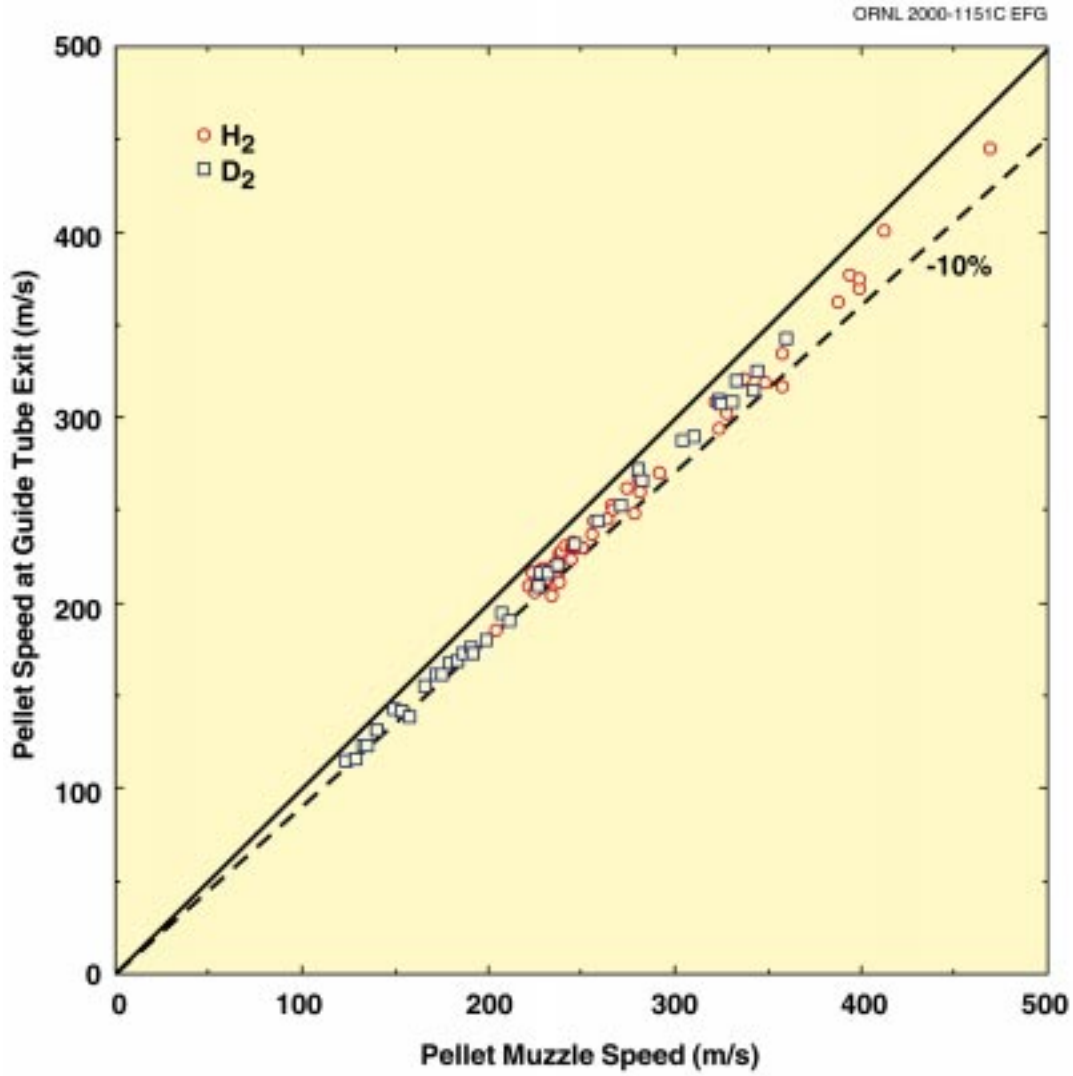
Results from ORNL Mock-Up Tests of Inside Launch Pellet Injection on LHD (Test Shots with 2.7-mm H_2 Pellets)



An Additional Data Set Was Taken with the LHD Mock-Up and 2.7-mm D_2 Pellets; Only a Small Difference Was Observed in the Results



Upstream and Downstream Pellet Speed Measurements in the LHD Mock-Up Tests Showed that Pellets Slow Down at Most by ~5-10%



Present and Future R&D Activities

- Continue studies of HFS/inside launch pellet injection technology
  - LHD – provide a punch for slow pellets
  - JET
  - TEXTOR
  - DIII-D – high-speed vertical pellet injection (two-stage gun)
- Four-shot pellet injector in a "suitcase"
  - Simple, compact design
  - Equipped with pellet punches for slow pellets
  - Steerable guide tube to control pellet trajectory into plasma
- New extruder design for operation with cryogenic refrigerators (and demonstration tests) and continue development of double-screw extruder
- Propellant gas minimization and recycling for repetitive gas guns
- Develop improved rotor/feed system for reliable centrifuge operation