Virtual Laboratory for Technology For Fusion Energy Science

ITER Ion Cyclotron Heating and Fueling Systems

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EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

PPPL PRINCETON PLASMA PHYSICS LABORATORY

UT-BATTELLE

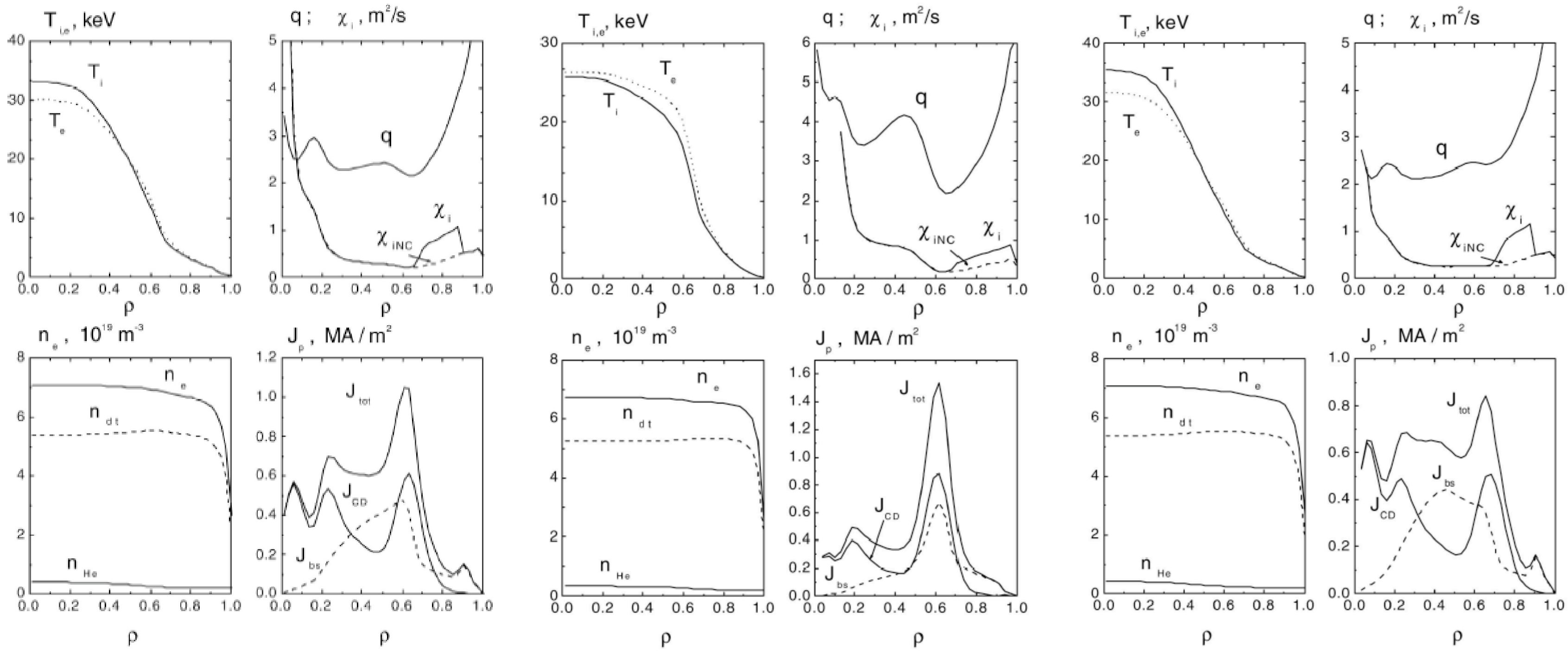
ITER IC H&CD system

- **ITER IC H&CD requirements**
  - The ITER ion cyclotron system offers significant technology challenges.
  - The antenna must operate in a nuclear environment and withstand heat loads and disruption forces beyond present-day designs.
  - The souces and antenna must operate for long pulse lengths and be highly reliable.
  - Antenna and tuning system must deliver power to a plasma load with properties that will change throughout the discharge.
- **IC antenna concepts**
- **Schedule**
- **R&D**

VLT Virtual Laboratory for Technology
For Fusion Energy Science

IC system must provide ion and electron heating and the flexibility for various non-inductive scenarios

q and CD profiles for three heating & CD sceanrios



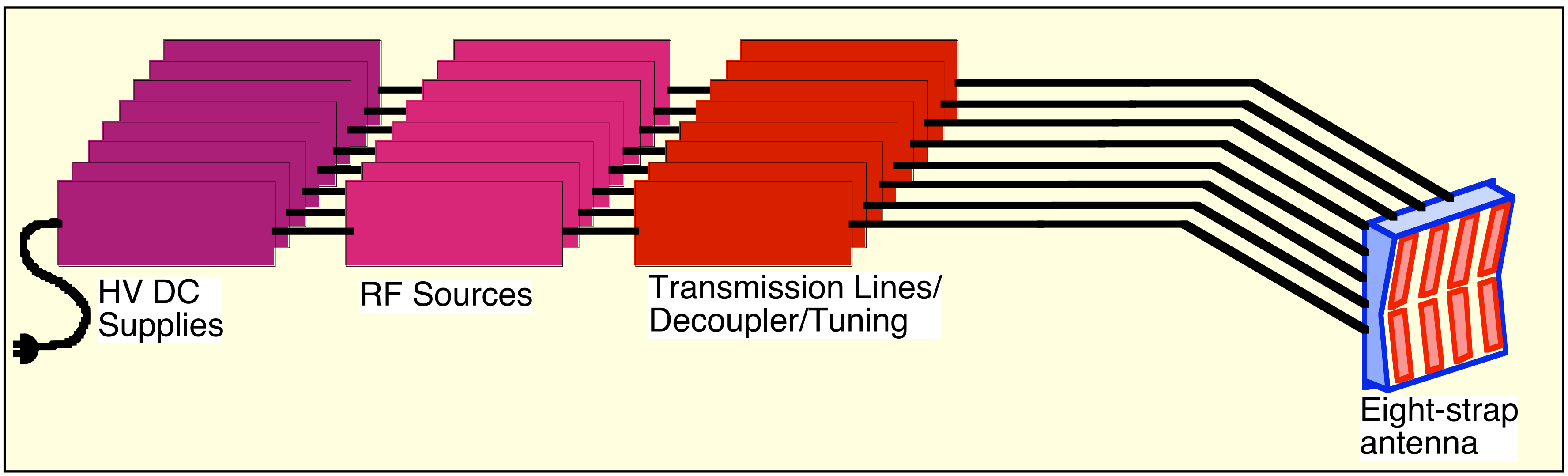
Weak Negative Shear | Strong Negative Shear | Weak Positive Shear

Revised scenarios under development may impact requirements

ITER IC system – overview

- What it is:
  - One antenna, eight current straps
  - Eight rf sources (plus spare), each feeding one antenna strap
  - 20 MW total power to the plasma
  - Variable phasing between straps

ITER ion cyclotron system block diagram

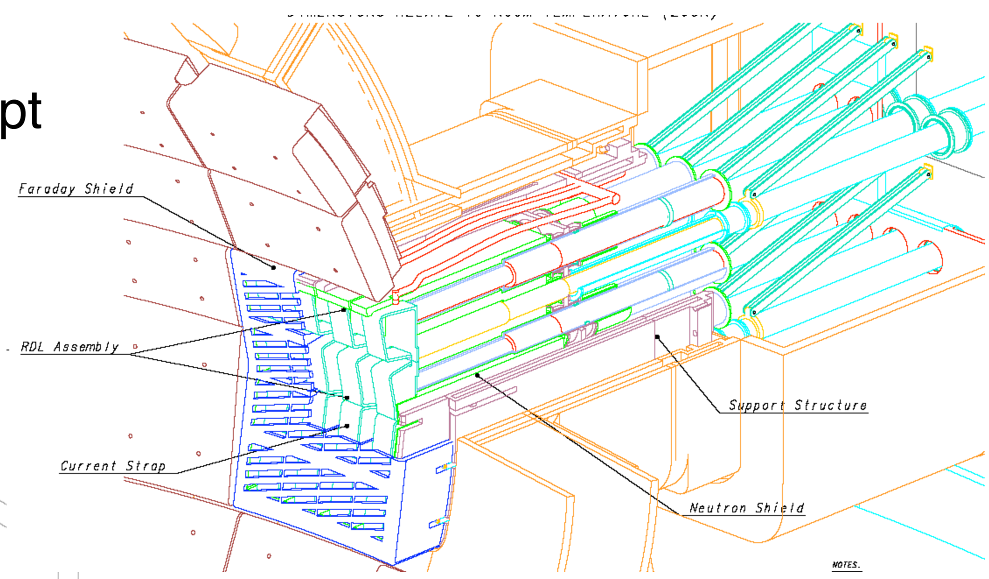


Procurement packages have been developed

- RF Sources
  - Deliver 2.5 MW steady-state into *unmatched* load (VSWR up to 2:1)
  - Operate over 35-65 MHz frequency range (procurement spec)
  - Efficiency of converting DC power to RF power > 65%
  - One prototype source to be built, followed by eight production sources
- Transmission line/decoupler/tuning systems
  - Eight coax lines, ~ 230 mm diameter, water-cooled center and outer conductors with elbows, etc. (≈ 1000 m total length)
  - Matching components (hybrid junctions, stub tuners), instrumentation system
  - 2 High-power dummy loads for system testing
- Antenna
  - One antenna with eight independent current straps, fits in big outer port
    - Long-pulse, cooled, w. neutron shielding, remote maint., tuneable.
  - Frequency range 40-55 MHz - TBD
  - FDR has a design, but EU and US experts agree that improvements are possible.
  - Requires significant design effort and R&D

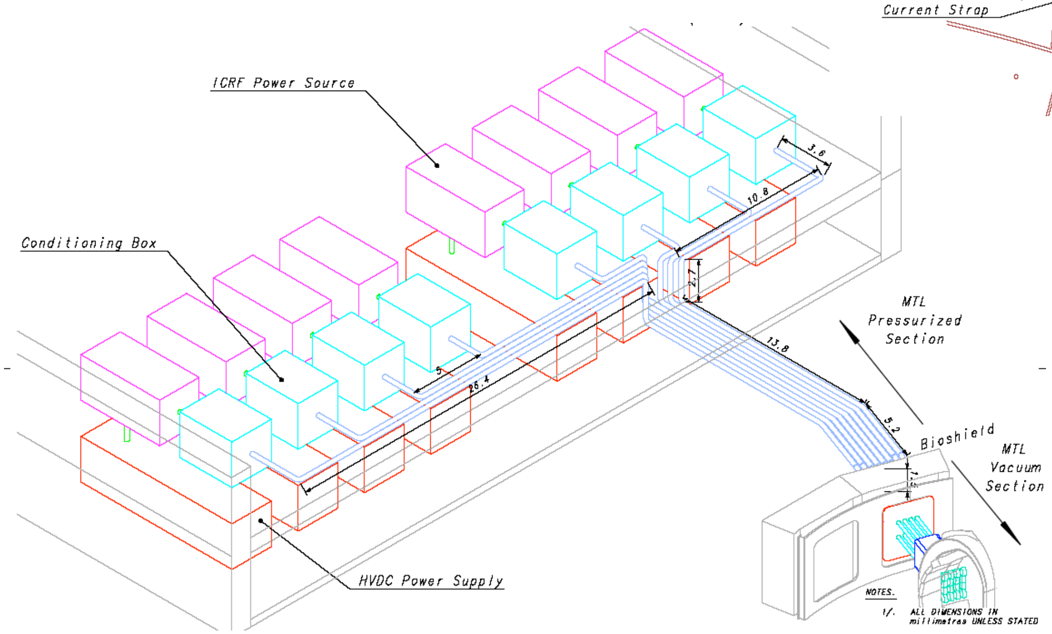
System components

Baseline antenna concept



Power supplies RF sources &

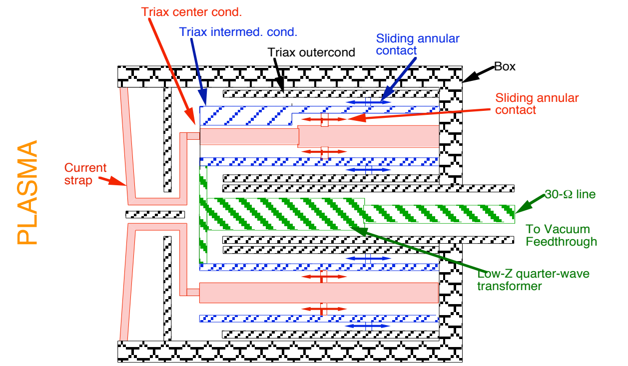
Transmission line

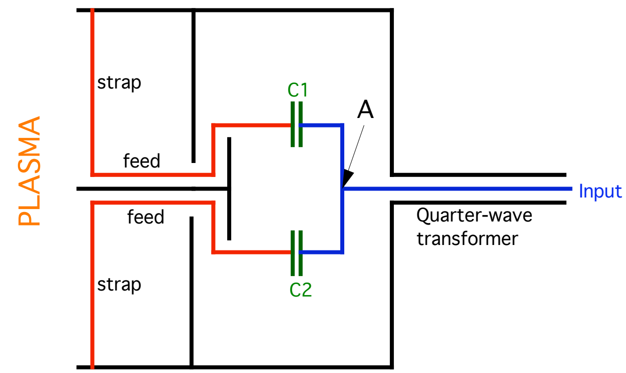


Antenna design and R&D is underway

3 designs are under consideration:

- Baseline design
  - Resonant double loop (RDL) concept
  - Matching inside antenna
  - Triaxial coax sliding stubs for tuning/matching elements
- Internal capacitors
  - RDL
  - Matching inside antenna
  - Ceramic-insulated vacuum capacitors for tuning/matching elements
- External matching
  - RDL
  - Matching outside antenna
  - Matching components on source side of vacuum feedthroughs

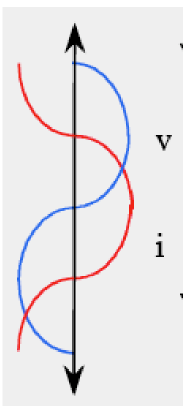


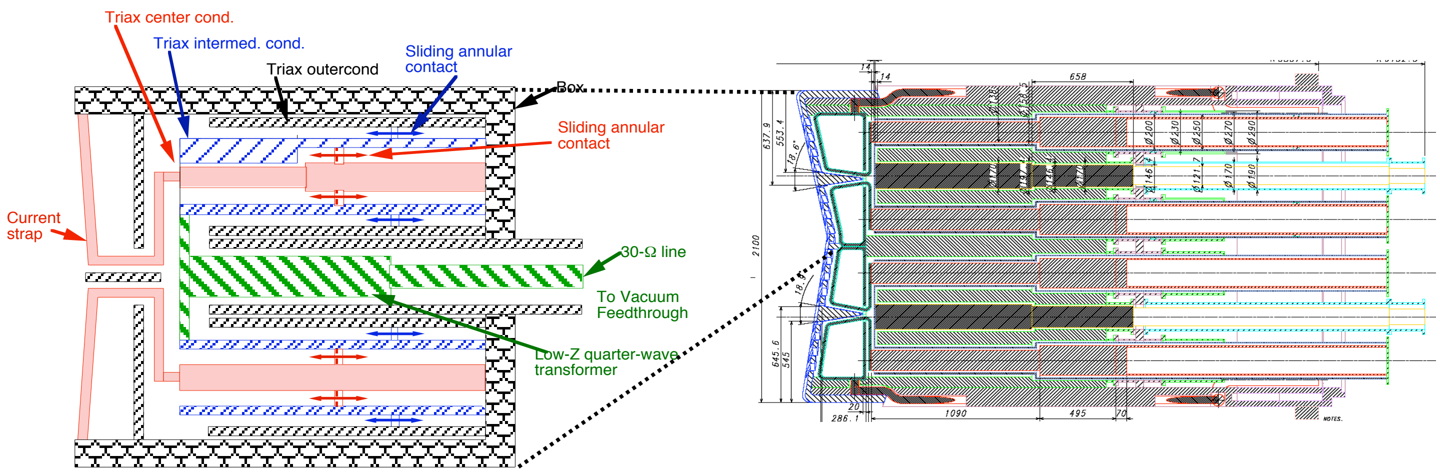


Baseline design has some specific issues

"Baseline design" concept open questions:

- Can reliabile tuners be fabricated?
- Will machine vacuum conditions allow high rf voltage standoff?
- Are mechnical loads adequately supported?





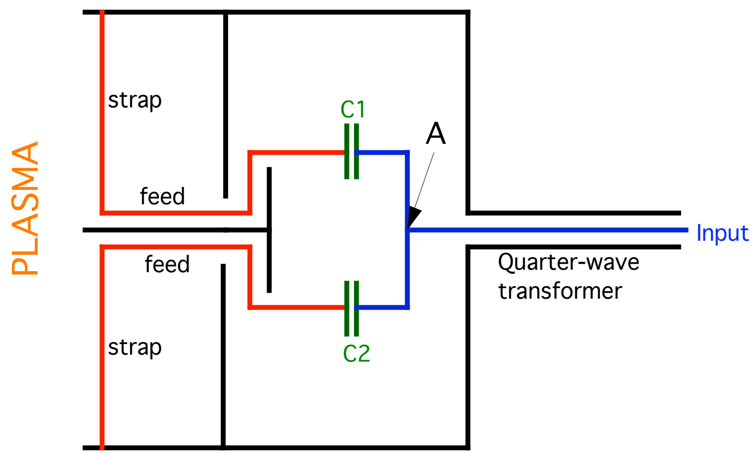
R&D and design tasks:

- Electrical mock-up of one antenna strap and tuners
- R&D version of triaxial tuner
- High-voltage prototype of one antenna strap

R&D for internal vacuum capacitor concept

Key questions:

- Where are capacitors located? / What radiation dose will they see?
  - Close to front means high dose but lower voltages in vacuum TL
  - Farther back means lower dose but higher voltages in vacuum TL



R&D and design tasks

- Evaluate dose and tuning characteristics vs. capacitor location
- Test dose limit of ceramics: loss tangent, mechanical strength, voltage holdoff
- To what extent are fission neutron tests relevant?

R&D for external tuning concept

Key questions:

- Current balance in straps vs. load changes
- Effects of mutual inductance?
- Optimization of design choices
  - Use decouplers?
  - Reduce external space needs?

R&D and design tasks

- Electrical analysis to answer some of above questions
- Electrical prototypes
- Tests on an existing experiment

Antenna schedule – *Preliminary*

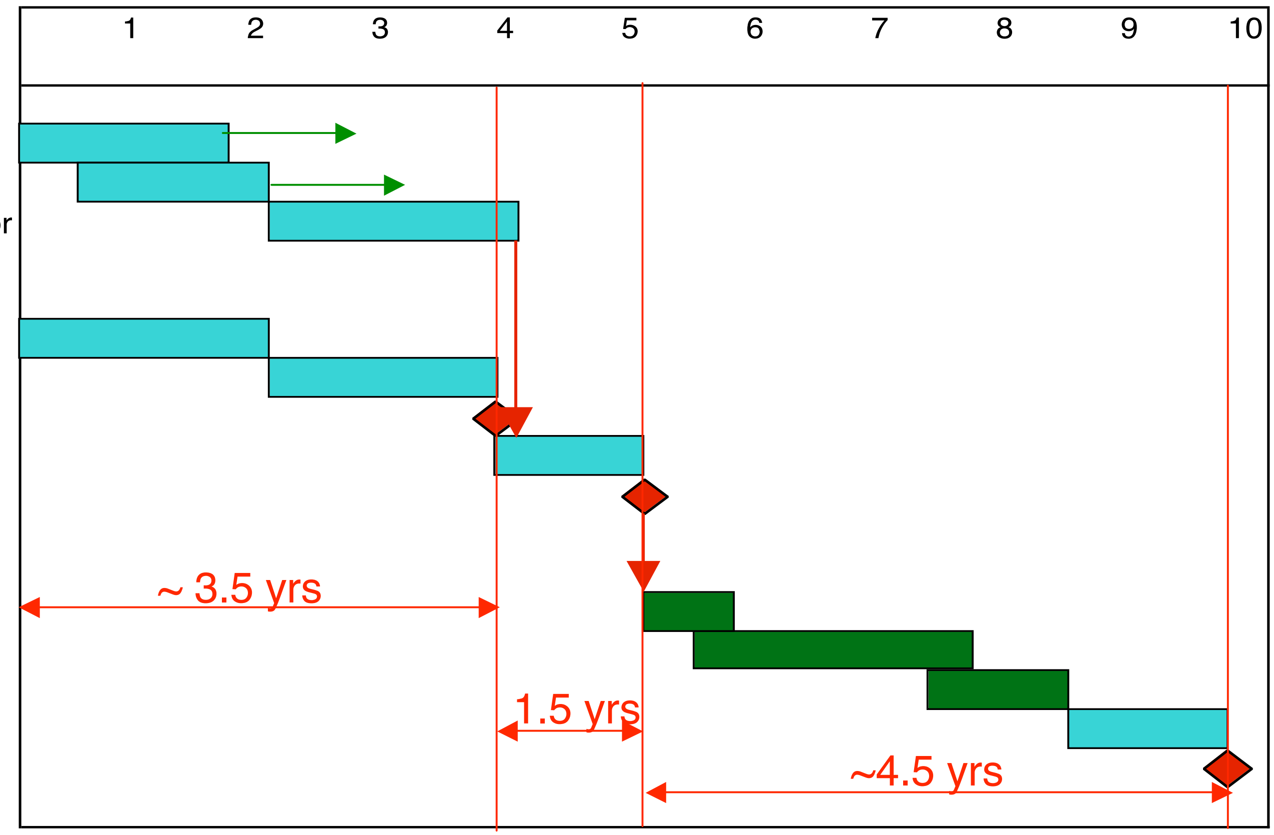
We have about 3 years to carry out design and R&D to decide on the antenna concept for ITER.

Schedule for ITER ICRF Antenna

Direct R&D
Low-power elec. Mockup
Tuning element prototype
High-power prototype -1/8 sector

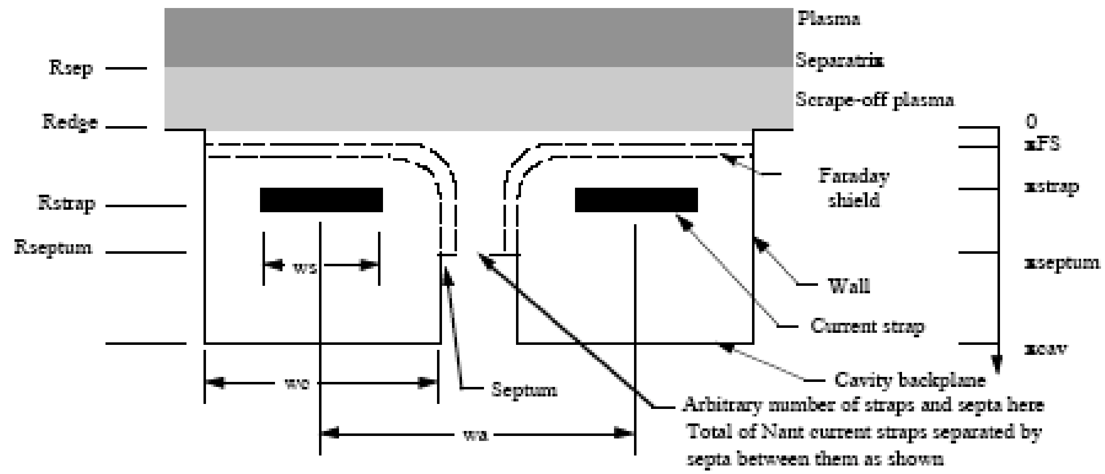
Design
Conceptual Design
Prelim. Design
PDR
Final Design
FDR

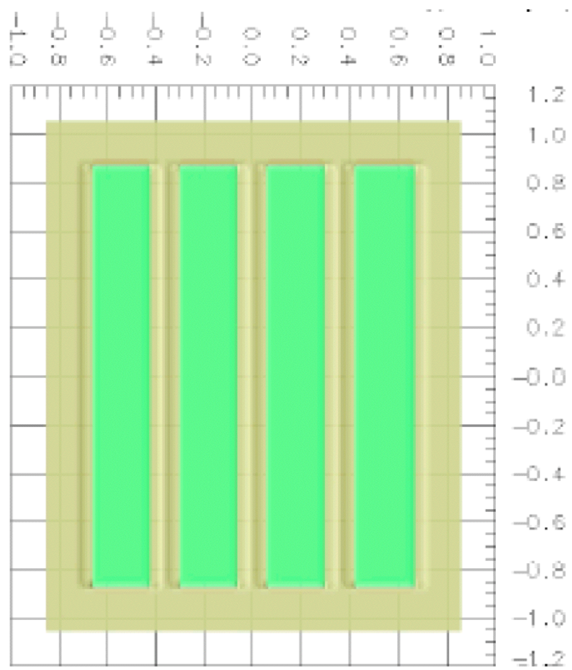
Fabrication
Let contracts
Fabricate antenna parts
Assemble antenna
Test on-site in test stand
Ready to install in ITER



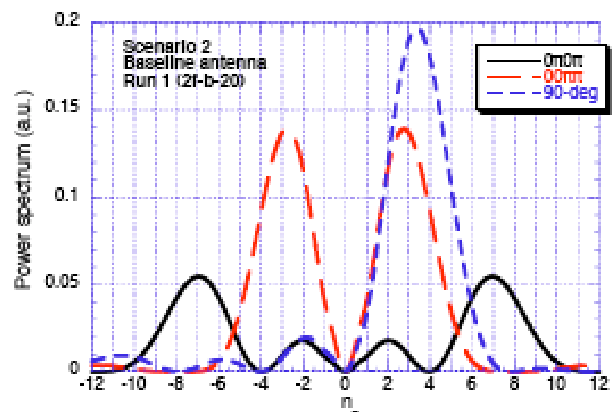
Modeling of ITER antenna spectrum is underway

Calculations of the spectra and loading are done with the GLOSI and RANT3D codes coupled with a transmission line model





Front view of the antenna configuration used by RANT3D



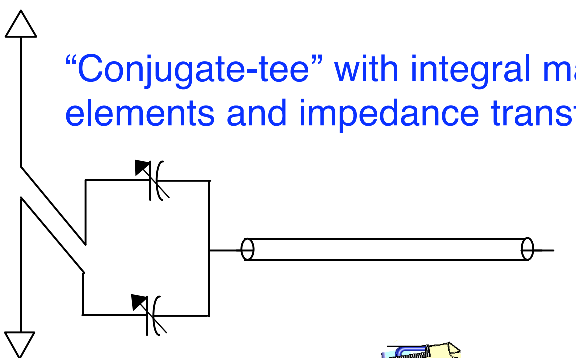
Spectra launched by the antenna for different phasings

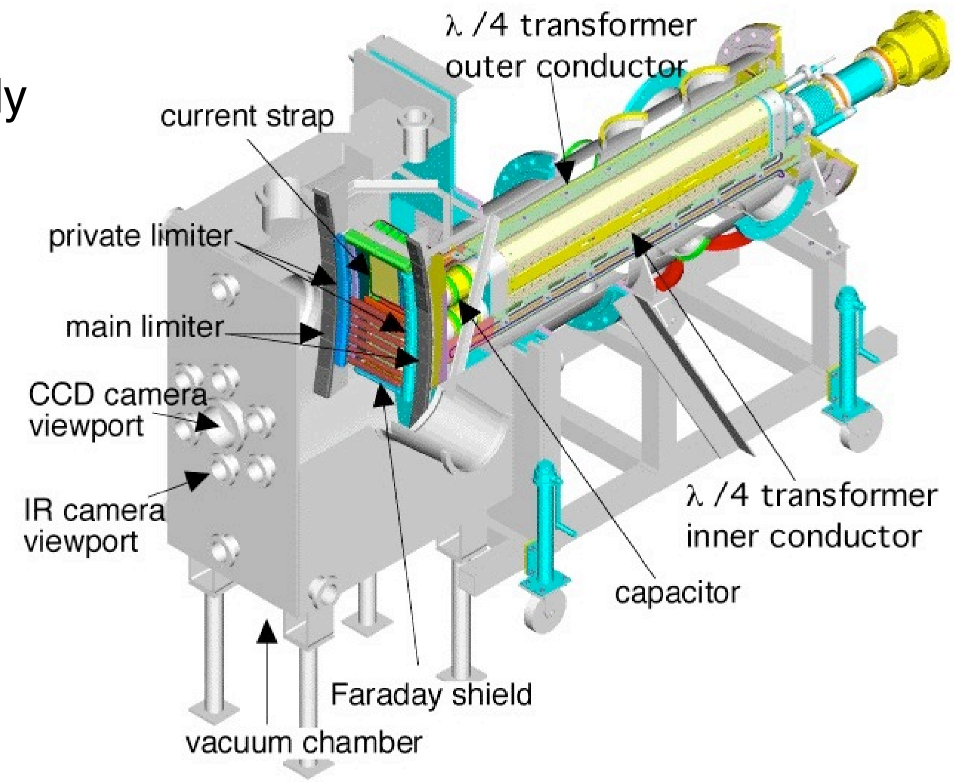
Carter and Swain

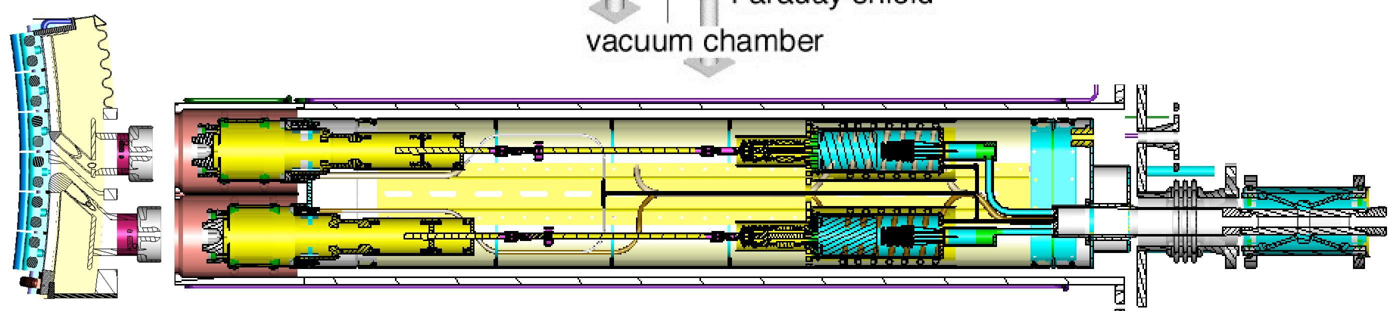
High Power Prototype (HPP) of JET "ITER-like" antenna

- Prototype designed collaboratively between US and EU
- ORNL and PPPL built prototype, tested at ORNL in 2003-2004

"Conjugate-tee" with integral matching elements and impedance transformer







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LPP ERM-KMS

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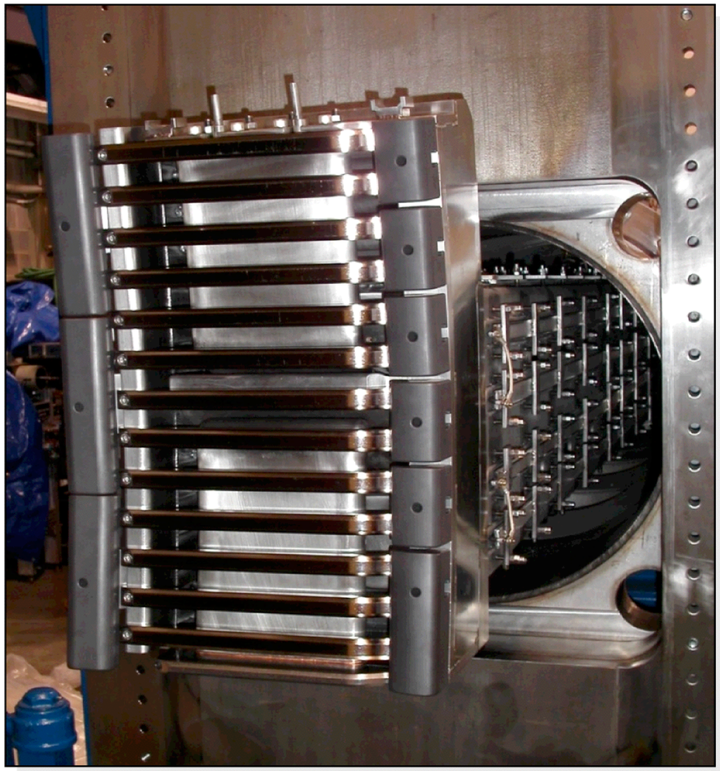
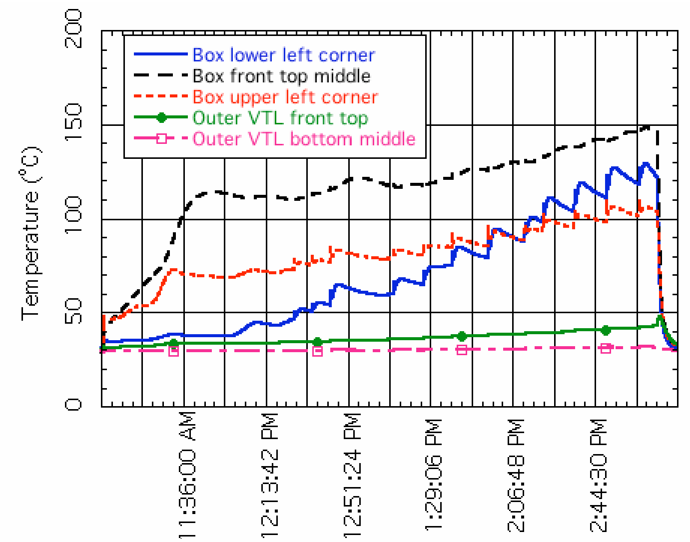
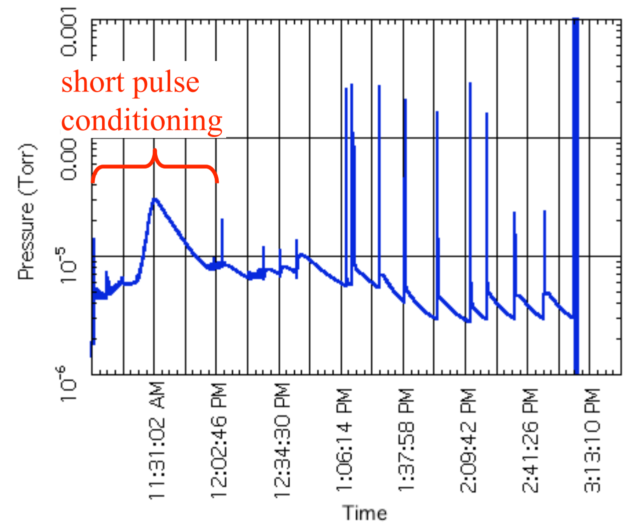
HPP Fully Assembled



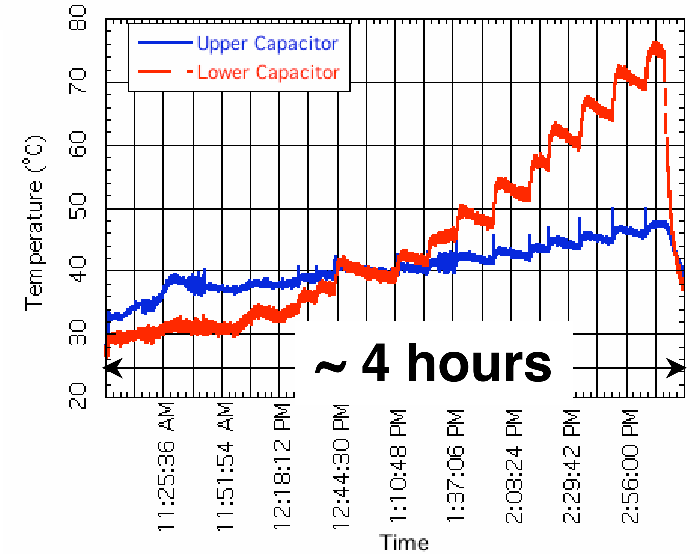
Temperature and pressure data for long (10 s) pulses



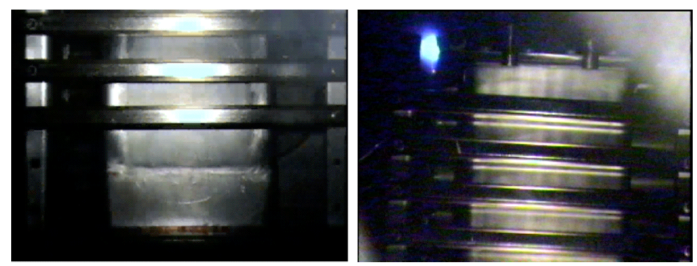
Antenna box and impedance transformer temperatures



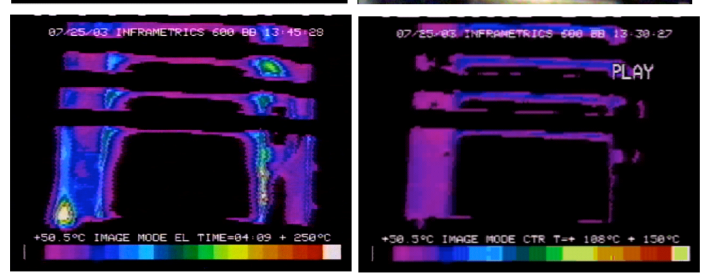
Vacuum chamber pressure



Capacitor temperatures

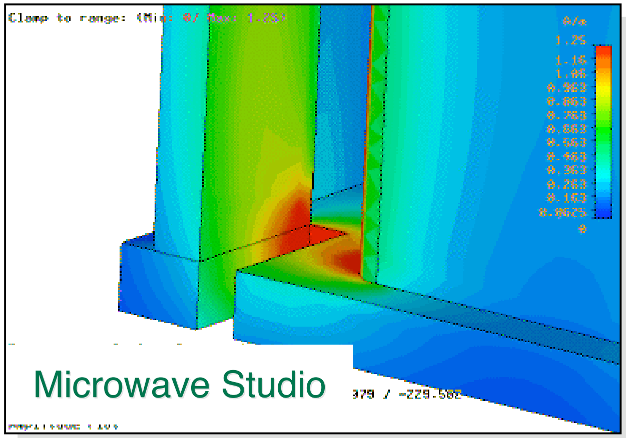


Glows& arcs



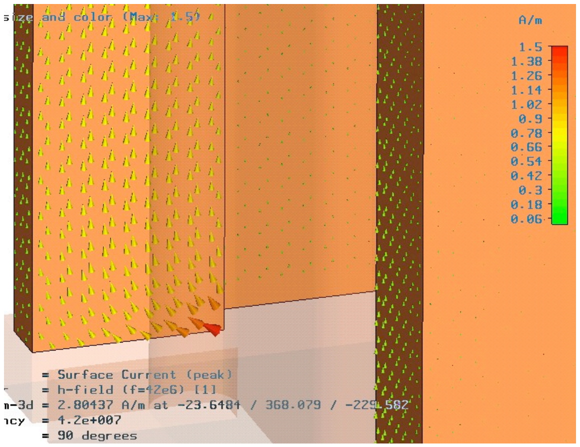
IR images

Significant damage in "Flexipivot" region limited long pulse operation

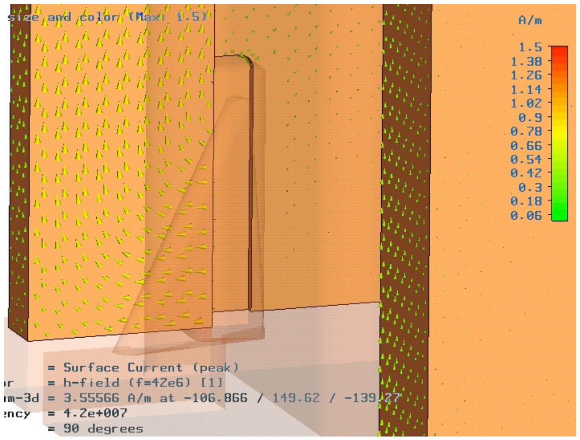


A "fix" was developed using EM modeling

no wedge



with wedge



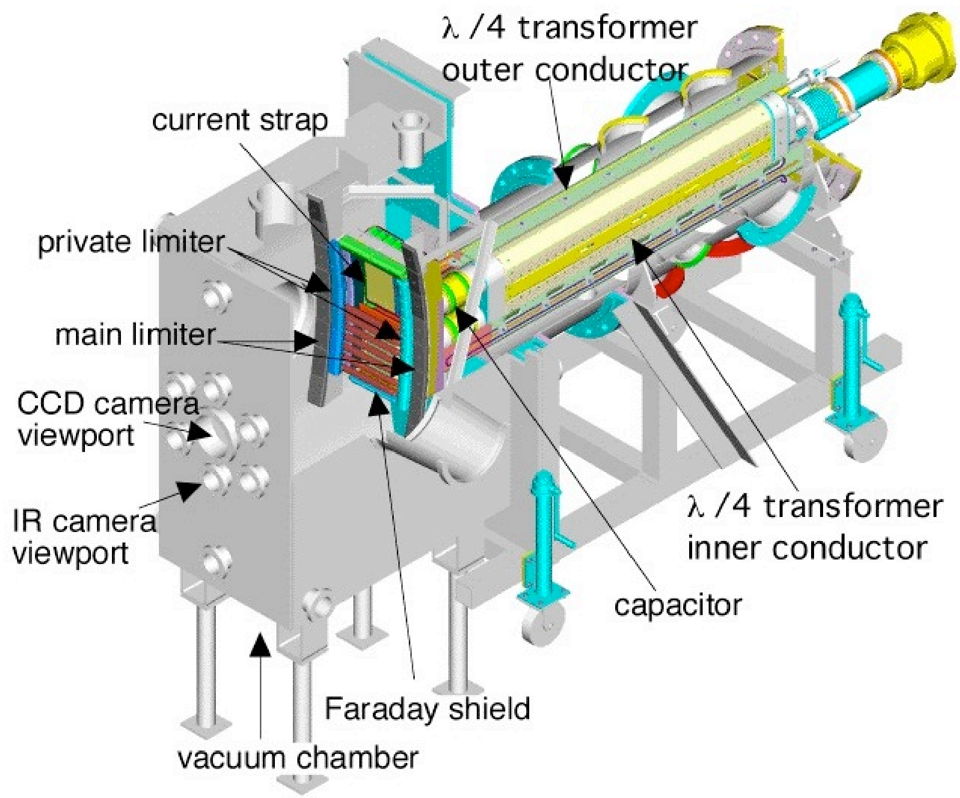
High Power Prototype (HPP) Plans

Initial tests achieved original objectives, found ways to improve antenna

- Tested voltage limits in vacuum
- Tested thermal & electrical behavior of components during long-pulse operation

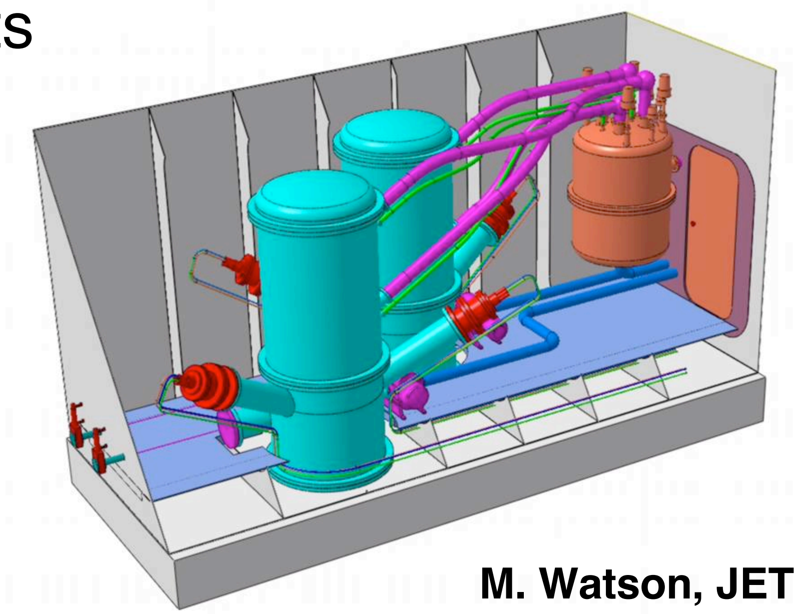
New test program underway

- Test new current strap design to improve power-handling capability
- Show modified antenna can operate for full-current 10-s pulses.
- Test new capacitors with stainless steel internal components.
- Determine operating limits for the JET "ITER-like" antenna



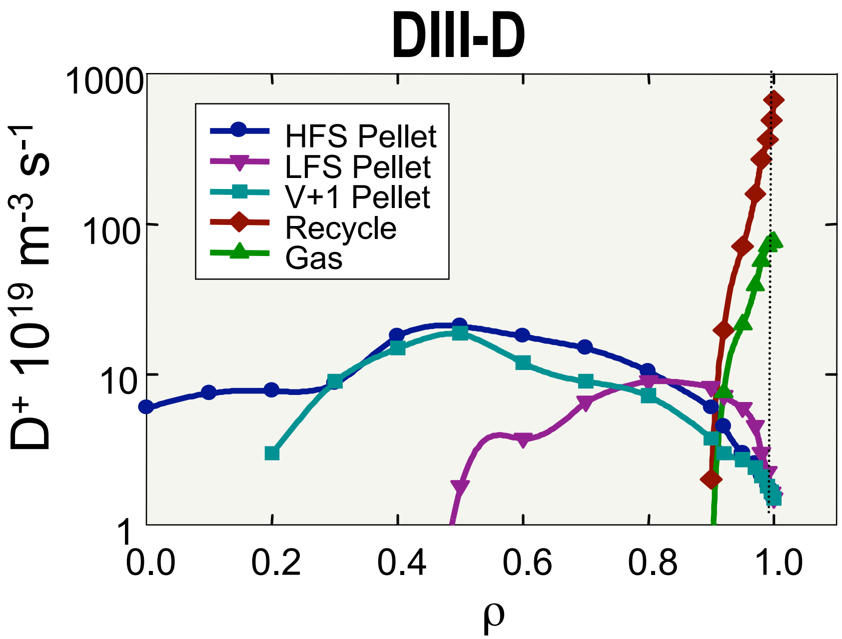
ITER fueling system

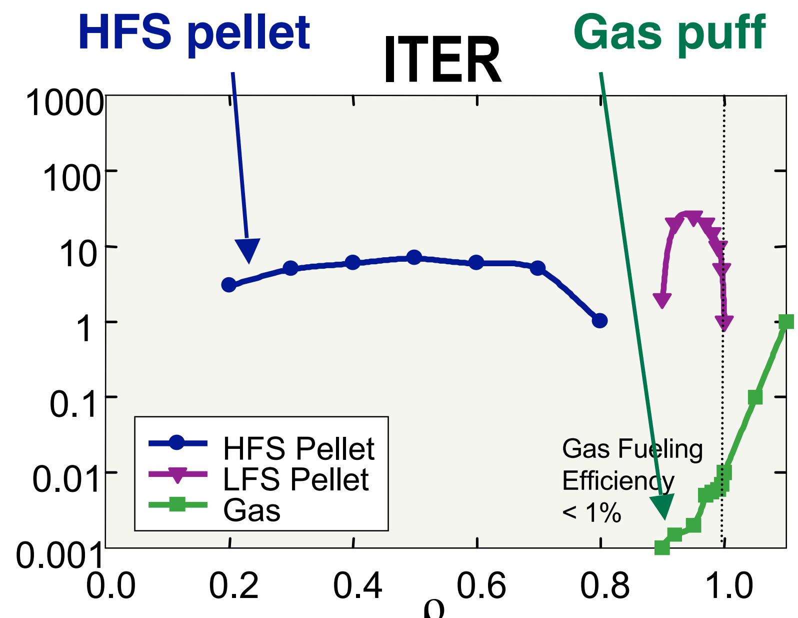
- Gas injection system for edge fueling
- Multiple pellet injectors for deep core fueling, are the primary ITER fuel delivery system.
- Requires long pulse, highly reliable, high throughput, tritium rich pellets
  - Significant extension of present-day designs.
  - Centrifuge accelerator with a continuous screw extruder.
  - Inner wall pellet injection with curved guide tubes



M. Watson, JET

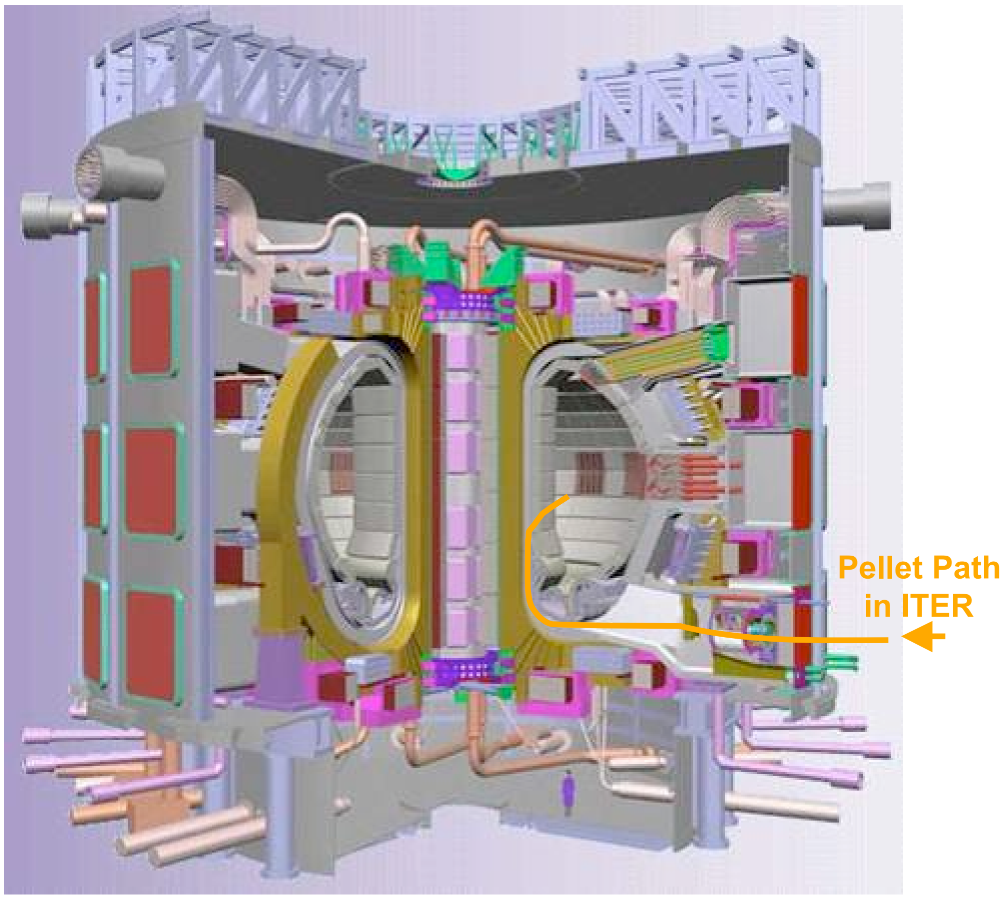
Pellet Injection is Crucial for Effective Core Fueling in ITER as Shown in H-mode Fueling Source Profile Comparison with DIII-D





- **Gas puff core fueling in ITER will be much less effective than in DIII-D**
  - **ITER pellet profiles are from PRL (P. Parks) (10-mm, 1 Hz)**
  - **gas fueling rate of ~1000 torr-L/s for ITER case (L. Owen and A. Kukushkin) B2-Eirene slab calculation**

ITER Pellet Fueling Requirements



- Inside wall pellet injection for deep fueling and high efficiency.
- Pellet injectors will provide D-T pellets (5-mm 16 Hz typical).
- Reliability must be very high
- Pellet injector must operate for up to 1 hour continuously and produce ~ 1 cc/s of D-T ice.
- ITER guide tube mockup tests are underway at ORNL. Initial tests show speed limit of less than 300 m/s with ~ 10% erosion.

ITER Fueling Systems Requirements & Present Design

- Requirements developed at ITER Pellet Injector Workshop in Garching, May 17,18

Plasma Density (n_{GW})	0.4 - 1
Fuel Isotope	Pellet (90%T/10%D)
3-5 mm diam => 1.25-6 x10^{21} particles	$\Delta n/n$ ~ 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)	120 for D_2, DT (~900 torr-L/s) 70 for T_2 (~525 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
  - 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 6 mm diam (50 to 7 Hz, respectively)
  - Only at pre-conceptual design level and significant R&D support still needed

ITER Pellet Injection System

- Pellet speeds 0.3 - 0.5 km/s, from the inner wall, are considered necessary to achieve a penetration beyond the ELM-affected zone (expected to be ~ 15% of minor radius).
- Two injectors will be installed, for redundancy and flexibility. Pellet injectors are specified for steady-state operation and consist of the following major hardware:
  - centrifuge pellet injector;
  - screw extruder, for pellet production;
  - gas feed manifold and supply;
  - pellet injector cask for injector assembly (~ 6 m L x 4 m H x 3 m W);
  - single guide tube, through a divertor port;
  - diagnostic, control and data acquisition system.

New Technical Challenges

- Systems must be able to operate reliably in tritium environment and be readily maintained
- High throughput requirements are significantly greater than achieved in experiments to date (3mm @50 Hz, 6mm @7Hz)
  - Continuous screw extruders are the ITER baseline design, to date have achieved flow rates that are a factor of ~5-10 lower than required (I. Viniar, R.F.)
  - Highest ice flow rates to date (~50% of ITER design value) used three prototype extruders operating in sequence (Combs et al., ORNL)
- Centrifuges have not achieved the overall reliability objective (~100% intact pellets); pneumatic injectors may meet reliability requirements, but could have a propellant gas load issue
- Significant R&D effort required before final design; development and testing program will be needed to validate proposed ITER design
- Evolution of the system may permit new technologies such as high-speed vertical injector and supersonic gas jet

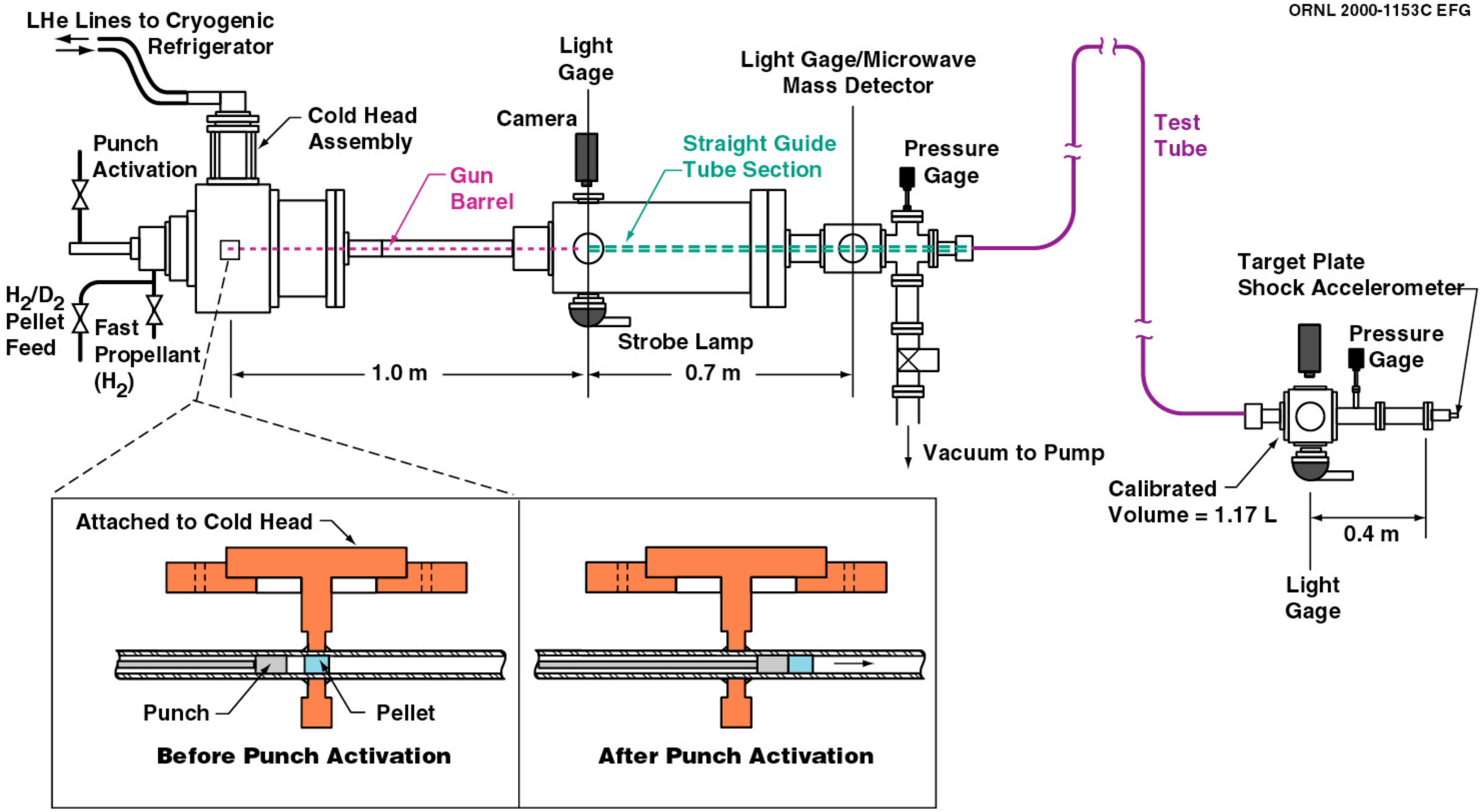
Experimental Studies of Curved Guide Tube Pellet Delivery Systems

- Basic experiments with D_2 (or H_2) pellets in lab
  - Pellet impacts on solid surfaces and speed limits
  - Pellet survivability through single and multiple bends

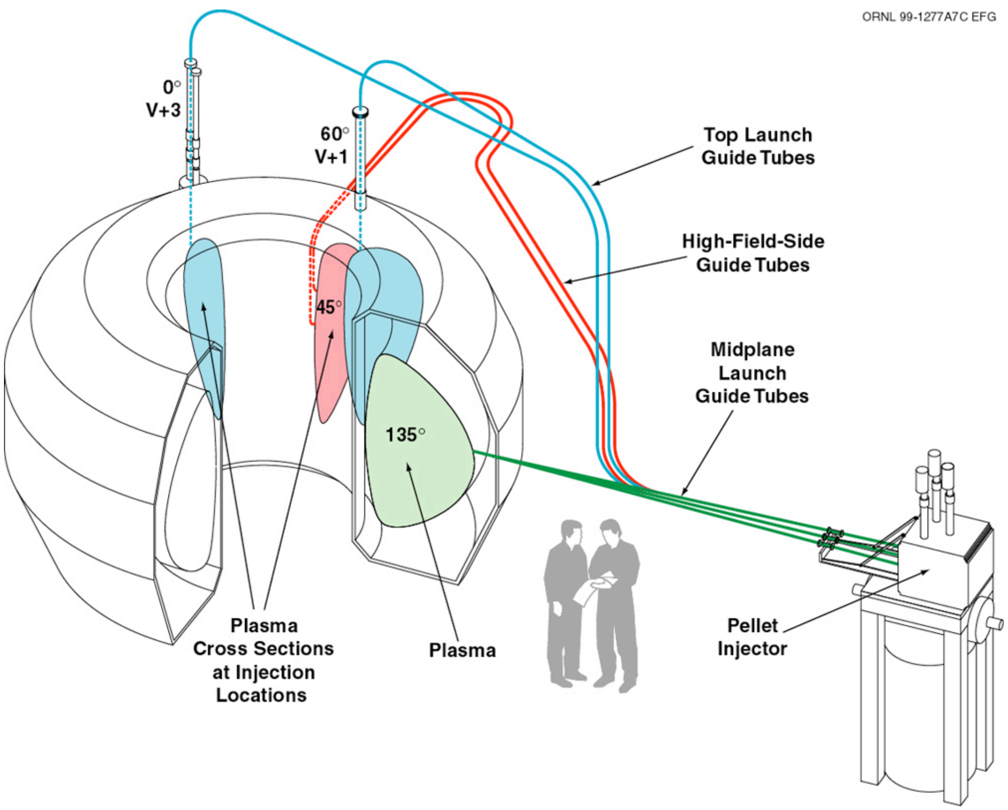
- Mock-up tests of guide tube installations in lab
  - DIII-D (two inner wall and two vertical)
  - JET (one inner wall and three vertical)
  - LHD (inner wall)
  - FIRE (inner wall)
  - ITER (inner wall)

- Pellet speed limits observed in active fusion experiments above are in good agreement with data from mock-up tests

Pipe-Gun Facility Used for Testing Curved Guide Tubes and Mock-Ups of Pellet Injection Schemes for DIII-D, JET, LHD, FIRE and ITER

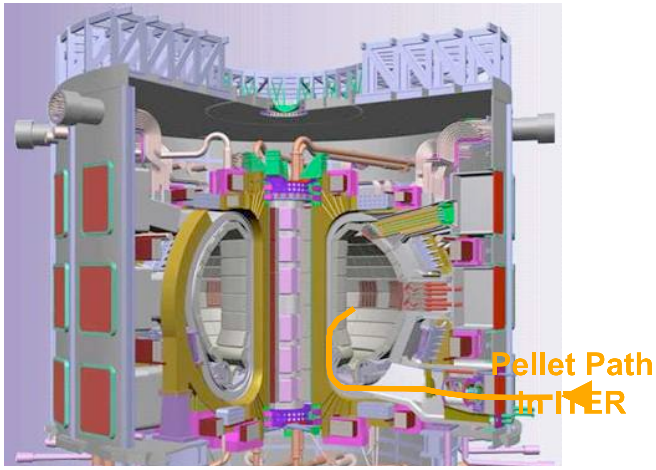


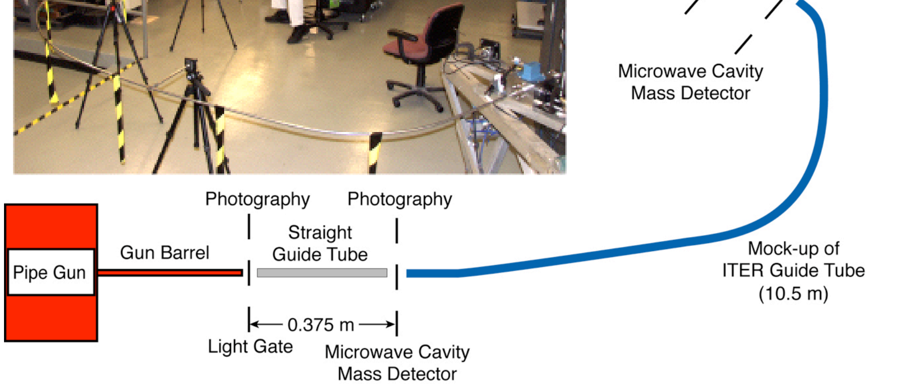
DIII-D Pellet Injection System – Transport Guide Tubes



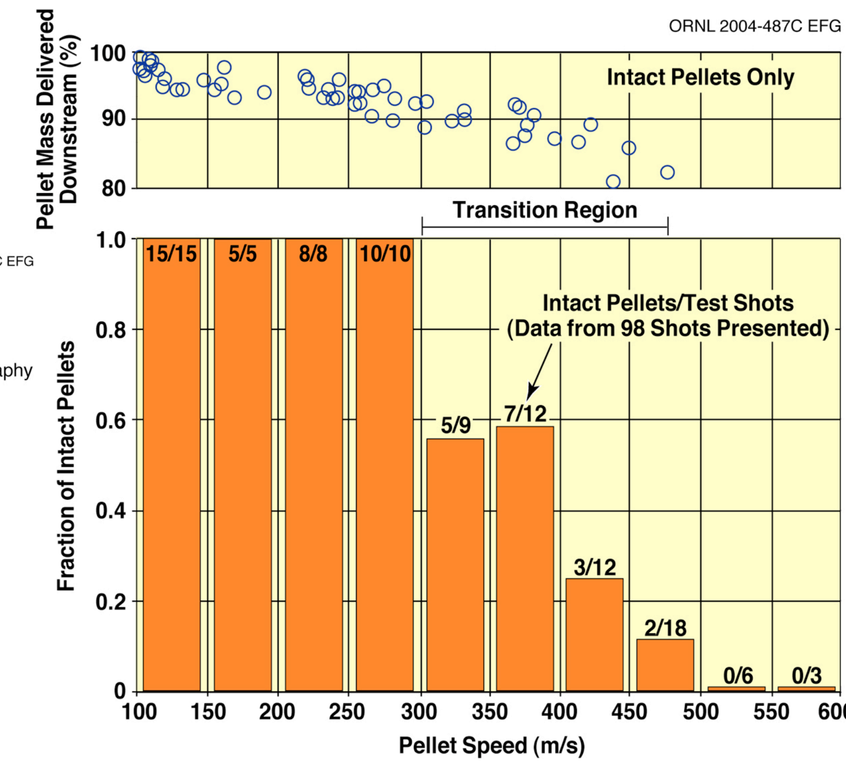
- Performance tests were done at ORNL on simulations of DIII-D "roller-coaster" tube runs
- Pellet speeds limited to ≈200 m/s for survival with inner wall injection and ≈400 m/s for vertical injection
- DIII-D Inner Wall Mock-ups tests indicate Pellet Mass Losses of ≈20%

Mock-up of ITER Inner Wall Guide Tube Was Tested at ORNL





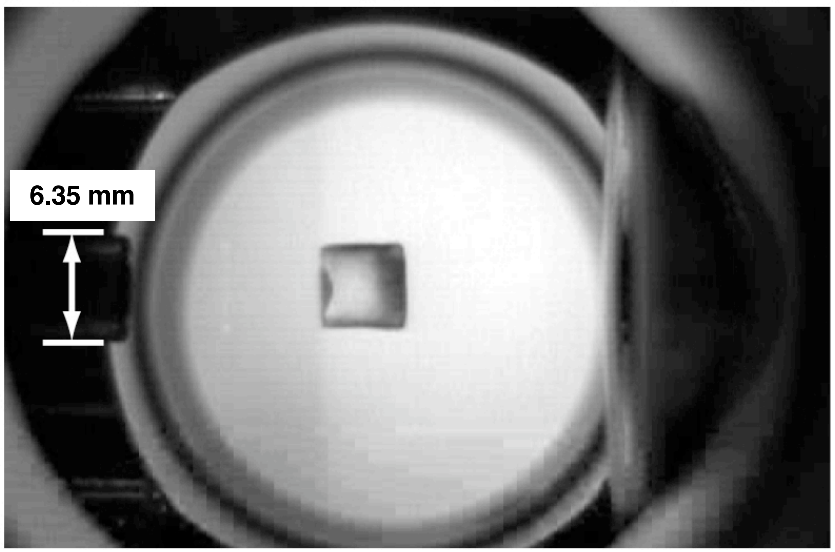
- Initial tests with 5.3 mm pellets
- Pellet speeds limited to ≈300 m/s
- Guide tube mass loss ≈10% at speed limit



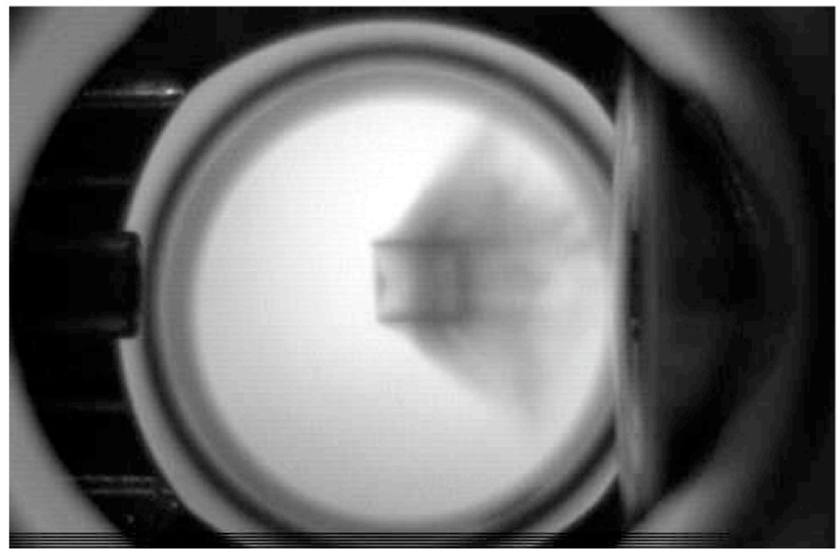
5.3 mm D2 Pellets at Gun Muzzle and Guide Tube Exit from Mock-up Test of ITER Inner Wall Pellet Injection

ORNL 2004-490C EFG

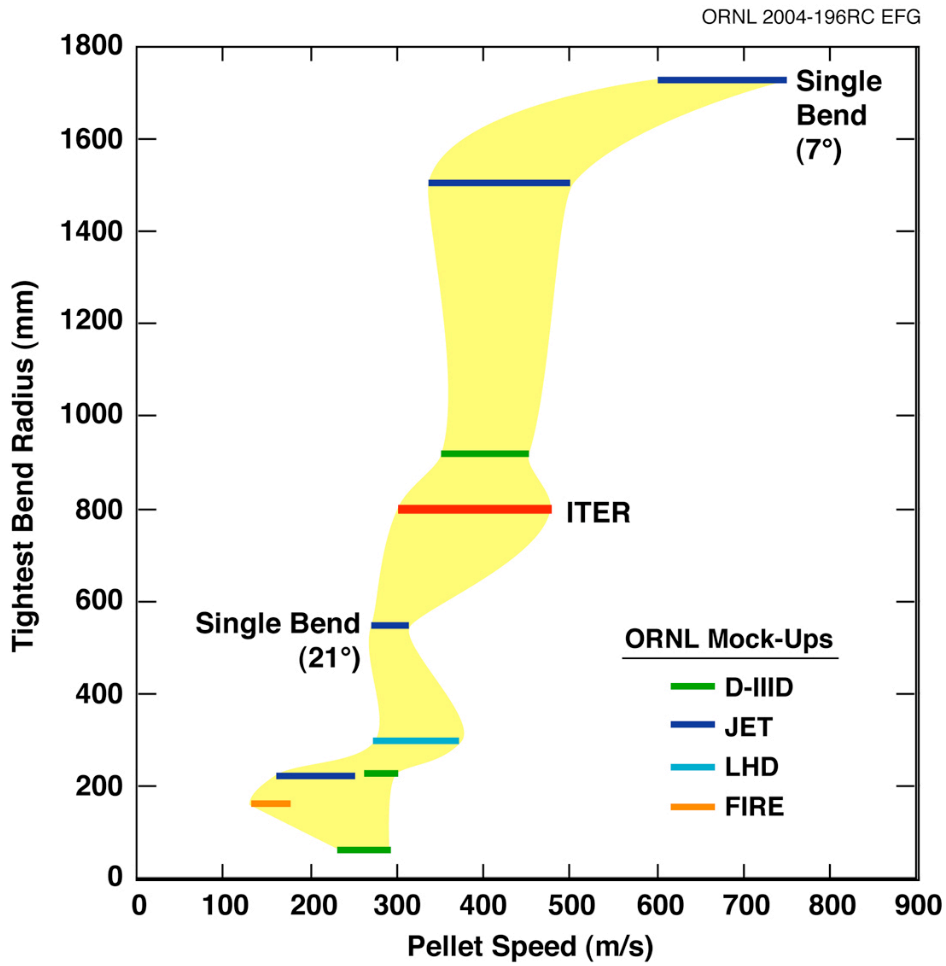
Shot 3 105 m/s 8/9/2004



Shot 100 416 m/s 8/12/2004

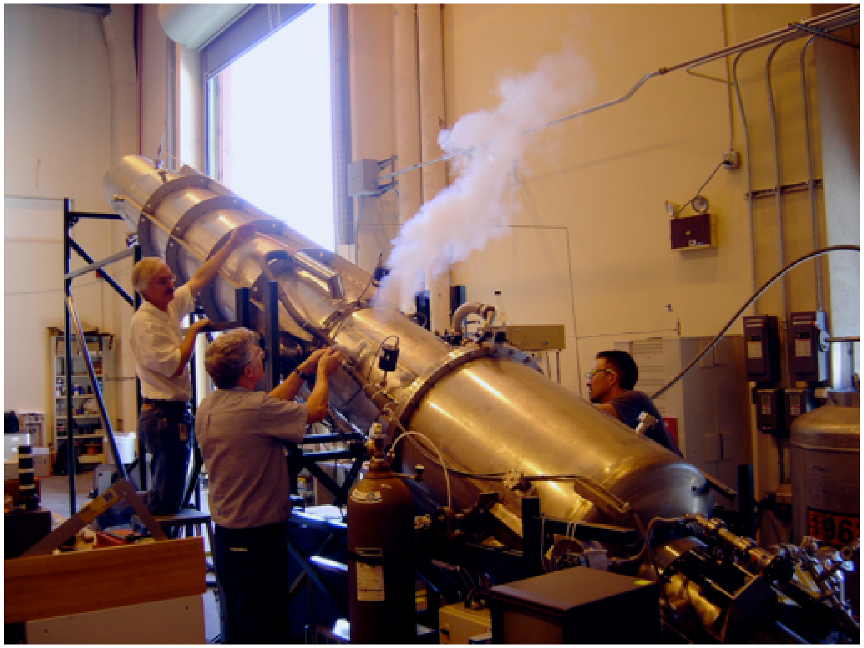


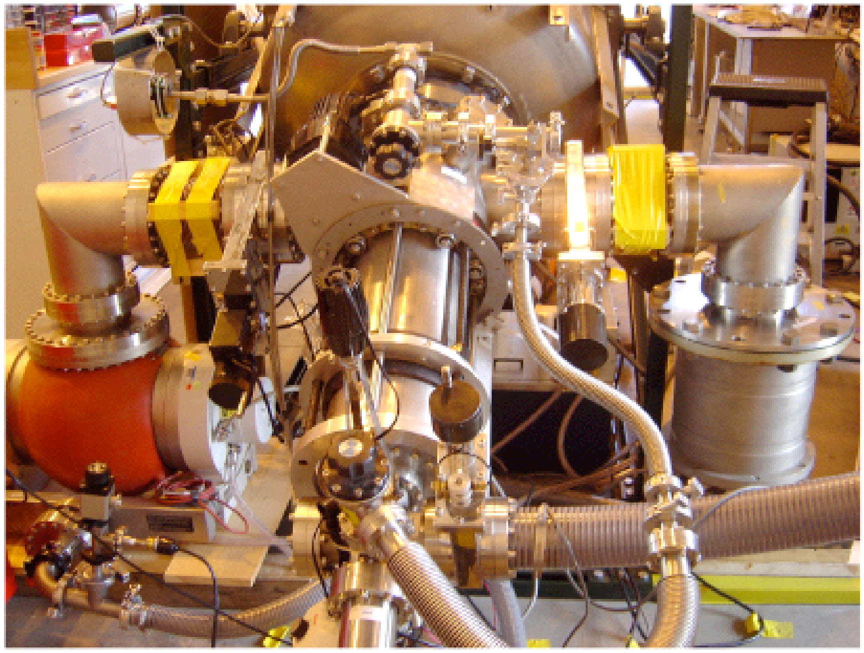
ORNL Mock-up Data for Pellet Delivery Systems and Implications for ITER Inside Launch Pellet Survivability



- Overall ITER guide tube length of ≈7.2 m; includes 5 major bends with tightest radius of 800 mm
- Data suggest speed transition range of ≈330 to 430 m/s

120,000 L/s Snail pump has been tested at LANL



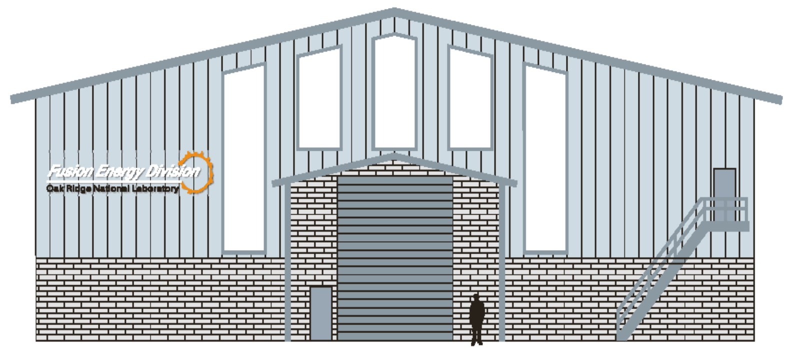


Chris Foster (Cryogenics Applications F, Inc.)

Scott Willms , Dave Dogruel (LANL), Larry Baylor (ORNL)

A smaller version without the He compression section is under consideration for the pellet injector pumping system

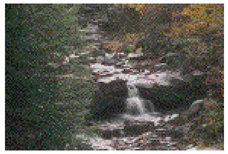
ORNL Fusion Energy Division has new office and laboratory facilities



See you at the
21st IEEE/NPSS Symposium on Fusion Engineering
SOFE_2005
September 26-29, 2005
Knoxville, TN USA
http://ornl.gov/sci/fed/sofe05/

NUCLEAR & PLASMA SCIENCES SOCIETY

21st IEEE/NPSS Symposium On Fusion Engineering 2005



Hilton Hotel
Knoxville, TN
September 26 - 29, 2005

First Announcement

The 21st IEEE Symposium on Fusion Engineering will be held Sept. 26 - 29, 2005 in Knoxville, Tennessee at the downtown Hilton Hotel. The Symposium is dedicated to the scientific, technological and engineering issues of fusion energy research and is a mixture of oral presentations and poster sessions allowing for extensive interactions among the participants.

Submissions are requested in all areas of MFE & IFE engineering including:

- Experimental devices
- New device design and reactor studies
- Divertors and plasma materials interactions
- Targets, chambers, vacuum vessels, blankets, and shields
- Diagnostics, data acquisition, and plasma control systems
- Safety and environmental engineering
- Materials assembly, fabrication, and maintenance
- Heating and current drive
- IFE drivers
- Power systems
- Magnet engineering
- Electromagnetics and electromechanics

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Deadline for Abstracts April 30, 2005