The Imperative for Efficient Heating & Current Drive, Core Fueling and Effective Mitigation Methods for Demo

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Startup and Sustainment of a Burning Plasma

H&CD Systems for a Burning Plasma Must:

- Initiate the discharge and provide the bulk of ramp up and ramp down current
- Provide reliable steady state H&CD - ions and electrons to reach and maintain H mode
- Modify bulk and tail distributions to maintain steady state current, pressure, rotation and shear profiles, internal transport barriers and to enhance reactivity
- Suppress and avoid instabilities
- Have all PFCs be resistive to high heat and neutron fluxes with acceptable levels of impurity production

Need High H&CD Efficiency for a Reactor to be Viable

Motivated and Guided by

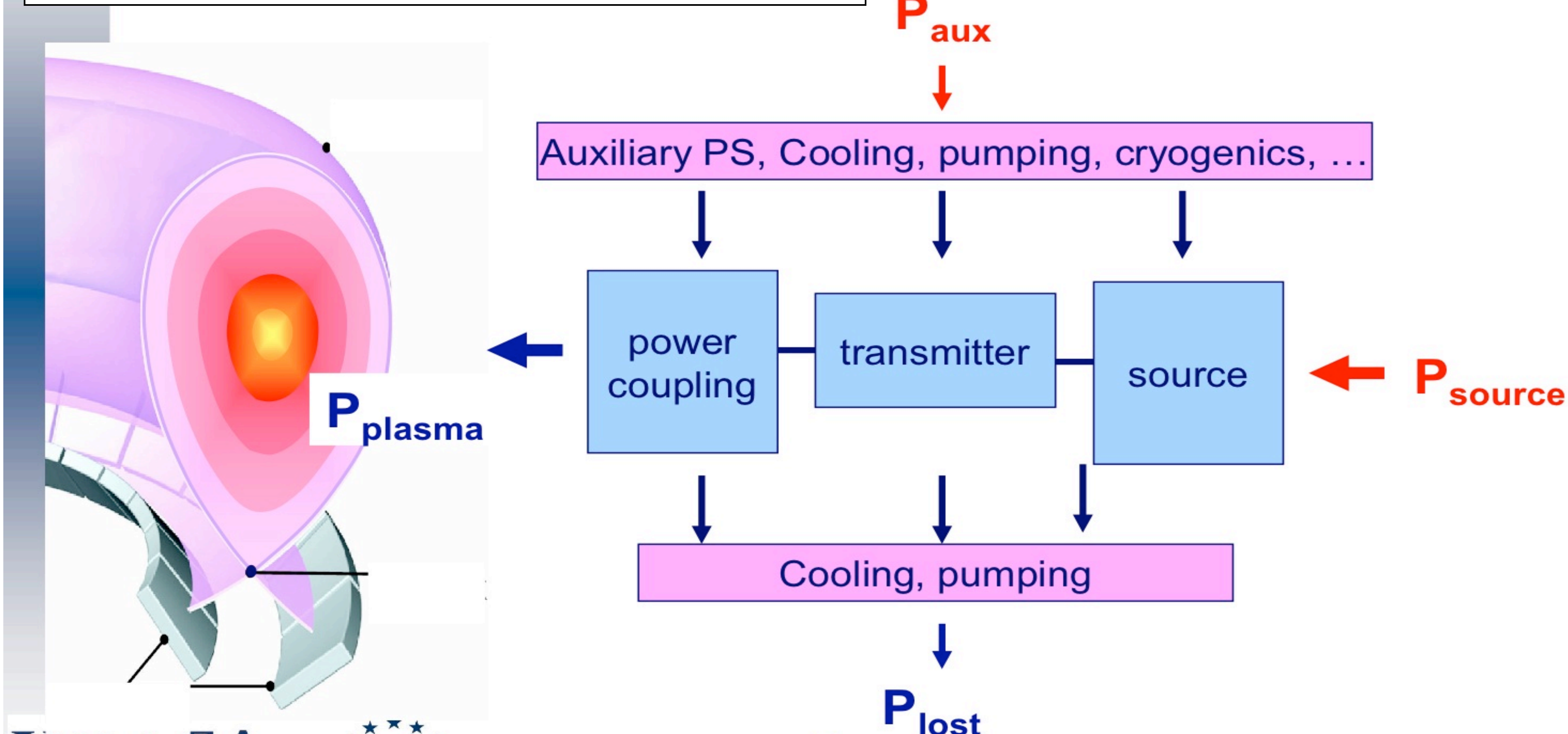
Comprehensive Approach of D. Stork

Heating Efficiency η_{wp} Include all Required Power

$$P_e = (Q_{site} - 1) \cdot P_{in}$$

$$Q_{site} = P_{fus} / \left(P_{wp} / \left(\eta_{wp}\right) + P_{mag} + P_{BOP}\right)$$

$$\eta_{WP} = P_{plasma} / (P_{source} + P_{aux})$$



COE – H&CD Systems Need High Wall Plug and Current Drive Efficiency

- Hence for a machine of **given size,** with low P_{BOP}, P_{mag}

$$\mathrm{CoE} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{\left(\eta_{wp}\gamma_{CD}\right)^{0.4} \beta_N^{0.4} N_{GW}^{0.3}}$$

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$$\gamma = \frac{RI_{CD}}{P} \frac{n}{10^{20}} (m^{-2} A W^{-1})$$

Current Drive Figure of Merit:

Predicted current drive efficiencies extrapolated to DEMO temperatures:

Neutral Beam (1.5 MeV)	$\gamma \sim 0.4 - 0.45$	$\eta_{wp} \sim 0.32$
Electron Cyclotron CD	$\gamma \sim 0.15$	$\eta_{wp} \sim 0.52$
Ion Cyclotron	$\gamma \sim 0.3 - 0.4$	$\eta_{wp} \sim 0.60$
Lower Hybrid CD	$\gamma \sim 0.3 - 0.35$	$\eta_{wp} \sim 0.50$

Negative NBI	$\eta_{WP} \bullet \gamma_{CD} \sim 0.12 – 0.14$
ECCD	$\eta_{WP} \bullet \gamma_{CD} \sim 0.08$
ICRF	$\eta_{WP} \bullet \gamma_{CD} \sim [0.18 – 0.24] \bullet f_{coupled}$
Lower Hybrid CD	$\eta_{WP} \bullet \gamma_{CD} \sim [0.15 – 0.18] \bullet f_{coupled}$

Wall Plug to Launcher Efficiency Improvements?

- **NBI**
  - Higher voltage? Diminishing returns above ~ 1 Mev
  - Higher transmission efficiency
  - Improved neutralization and beam dump
  - Higher current density and/or Lower source density
- **ECH**
  - Higher power per gyrotron tube
  - Multi-stage depressed collector
  - Reduced beam tunnel losses
  - Higher transmission efficiency
  - Improved mode and polarization control
- **ICH**
  - Higher efficiency tubes for long pulse
  - Solid state lower stage amplifiers
  - Higher transmission efficiency (low VSWR)
  - Reduce ohmic losses in tuning and antenna circuits (high VSWR)
- **LH**
  - Higher power per tube
  - Depressed collector klystrons
  - Solid state sources
  - Higher transmission efficiency (oversized guide)

Current Drive Efficiency Improvements?

- **NBI**
  - Increase off axis NBCD γ_{CD} by aligning poloidal and toroidal injection angle with field pitch to reduce trapped particles
  - Synergistic effects with ICH
- **ECH**
  - Increase ECCD midprofile γ_{CD} with larger poloidal injection angle for midplane launch
  - Increase ECCD γ_{CD} with larger toroidal angle for upper launch
  - EBW and/or high field launch for overdense ECCD
  - Synergistic effects with ICH
- **ICH**
  - Higher coupling with control of local density and density gradient
  - Optimize launched spectra from strap currents and image currents of surrounding structures
  - Reduce parasitic coupling
  - Minimize $E_{//}$ and impact of resultant RF sheaths
  - Utilize decouplers to minimize strap voltages and balance/maximize power flows
  - Synergistic effects with LH, ECH, NBI and alphas
- **LH**
  - Higher coupling with control of local density and density gradient
  - Optimize launched spectra and upshift
  - Synergistic effects with ICH

Long Pulse H&CD with High Bootstrap & Driven Current Needed for Steady State ITER and DEMO

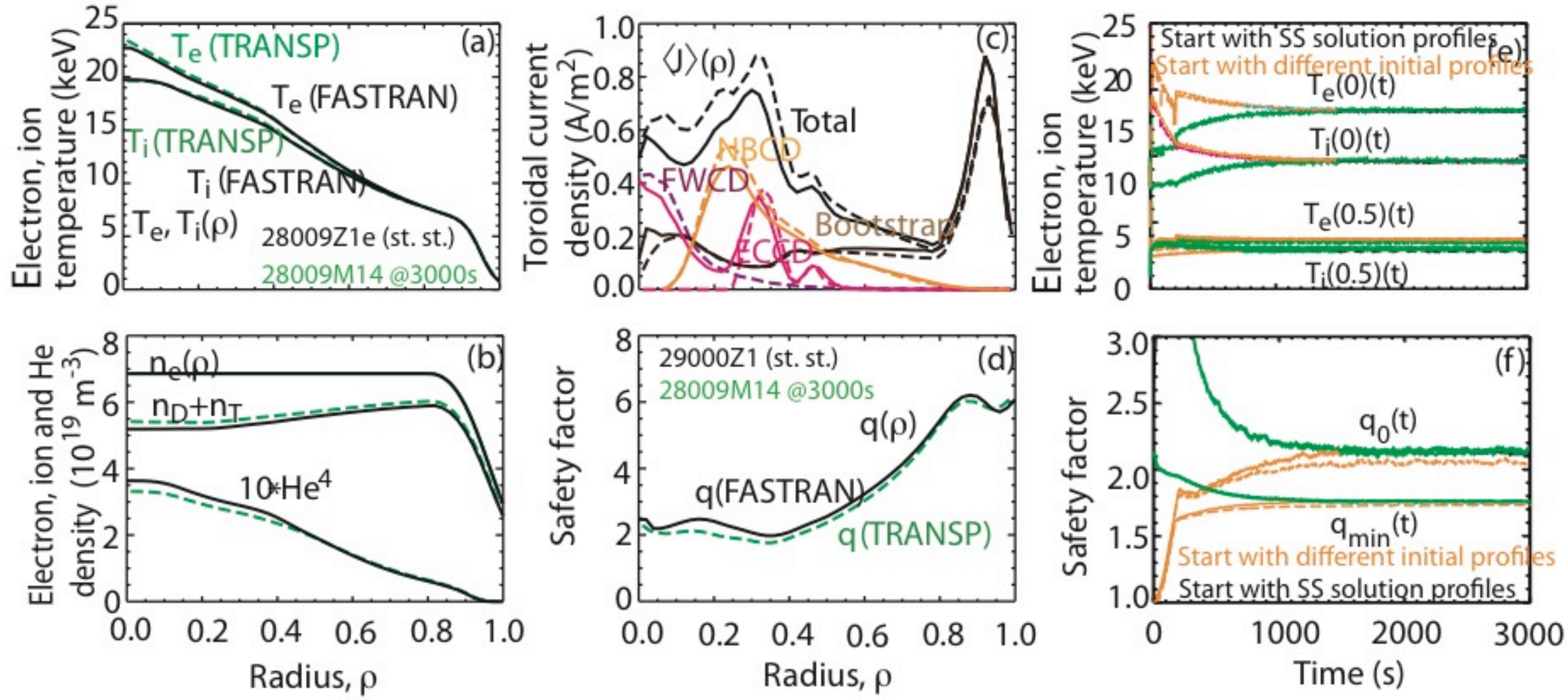

Figure 4. ITER weak-shear **steady state** profiles using the GLF model with the experimental boundary conditions at ρ = 0.8–1.0 from a DIII-D ITER demonstration discharge. Full noninductive fraction (102%) and fusion gain Q = 3.4 are obtained with 63% bootstrap fraction with a normalized β_N of 2.7. The profiles of the steady state solution procedure agree well with the profiles from time-dependent TRANSP (t = 3000 s) runs, as shown in (e) and (f), independent of initial conditions (close to (green) and further away from (orange) the equilibrium value).

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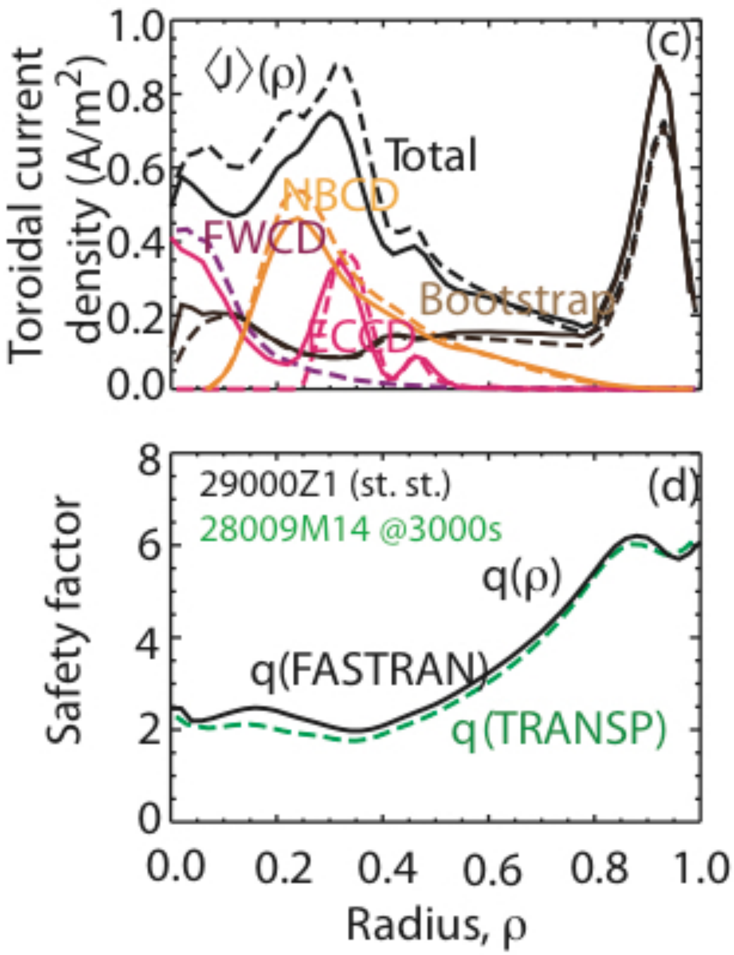
Mix of H&CD Systems (NBCD, ECCD, FWCD) Needed for Steady State ITER and DEMO

Role of H&CD in Steady State – Provide steep pressure gradients and drive global current



Fully non-inductive (102%)
Large bootstrap current fraction (63%) peaks at internal transport barrier and at temperature pedestal

Weak reverse shear q profile

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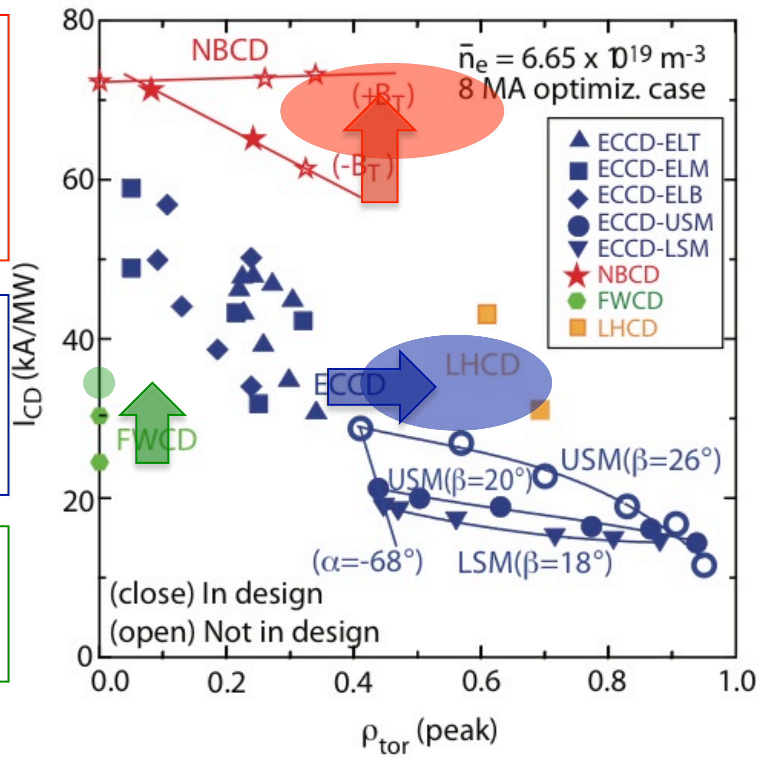
Optimized Launch can Improve Current Drive Efficiency

Increase off axis NBCD γ_{CD} by aligning poloidal and toroidal injection angle with field pitch to reduce trapped particles

Increase midprofile ECCD γ_{CD} with larger poloidal injection angle from midplane launch

Increase central FWCD γ_{CD} by optimizing launched spectra



B field direction +/- B_T

Equatorial Launch Top (ELT)
Equatorial Launch Middle (ELM)
Equatorial Launch Bottom (ELB)
Upper Steering Mirror (USM)
Lower Steering Mirror (LSM)

Fast wave CD (FWCD)

Poloidal and Toroidal steering angles (α, β)

Figure 5. Ratio of driven current to absorbed power as a function of peak CD radius for various CD sources for the ITER SS scenario discussed (baseline shown in figure 4). NBCD is calculated in two toroidal field directions: ITER normal B_T and the hypothetical reversed B_T direction. ECCD is calculated by taking the momentum conserving effect using the TORAY/CQL3D code. The ECCD upper launcher (USM) poloidal scan with β = 26◦ is beyond the present-design capability, but will provide higher CD and cover the radial gap between the equatorial and upper launches. ELT, ELH and ELB represent the equatorial launcher top, middle and bottom. LSM represents the lower steering mirror, part of the upper launcher system.

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COE – H&CD PFCs Operating at High Temperature

- Hence for a machine of **given size,** with low P_{BOP}, P_{mag}

$$CoE \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{\left(\eta_{wp}\gamma_{CD}\right)^{0.4} \beta_N^{0.4} N_{GW}^{0.3}}$$

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- High temperature metal walls, divertor and launch structures
- Operating temperature ~ 600 C with gas-cooling
- High heat and neutron fluxes
- High RF and microwave heating of launchers and ducts
- H&CD systems and synergistic or deliterious effects compatible with acceptable levels of impurity production?
- H&CD systems and deliterious effects compatible with power production and tritium breeding and recovery?

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COE – H&CD Must Have High Availability

- Hence for a machine of **given size,** with low P_{BOP}, P_{mag}

$$\mathrm{CoE} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{\left(\eta_{wp}\gamma_{CD}\right)^{0.4} \beta_N^{0.4} N_{GW}^{0.3}}$$

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- System optimization and simplification
- Improved reliability and maintainability of subsystems
- Longer lifetime sources and launchers
- Evaluate system or subsystem compatibility with RH and time to remove and replace components
- Evaluate impact of each H&CD system on other plant systems availability

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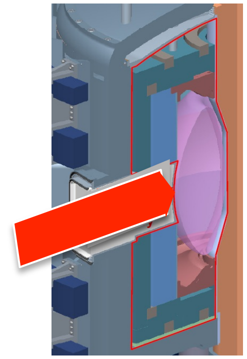
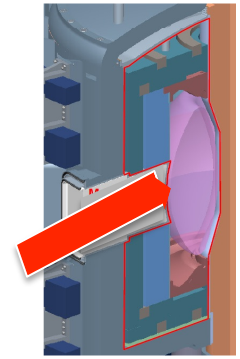
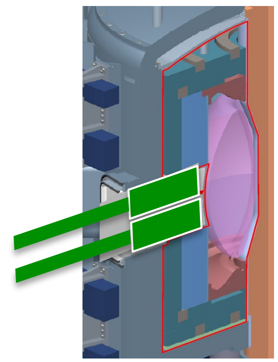
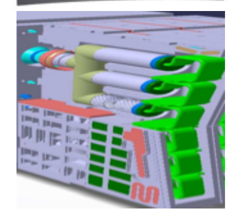
Robust “Workhorse” Plasma Heating and Current Drive

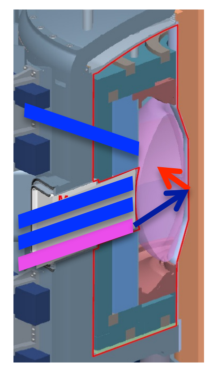
- NBI – electron and ion H&CD, rotation
  - 1-1.5 Mev
  - Fixed toroidal and poloidal angle (upward injection) with sufficient duct clearance
  - RF plasma source without seeding or with continuous seeding
  - Improved neutralizer and ion beam dump power and particle handling
- ECH and EBW – electron H&CD, startup, ramp up, mode suppression
  - > 170 GHz ECH H&CD – optimized poloidal and toroidal launch angles from midplane and above midplane
  - Overdense H&CD –weak 1st pass reflection off inner wall with strong 2nd pass absorption
  - Fixed front mirrors with <u>rear remote steering</u> and polarization control
- ICRF - electron, ion and tail ion H&CD, flow, mode suppression
  - 2 fixed frequencies for minority and/or mode conversion heating or HHFW
  - Fixed toroidal and poloidal phasing
  - External tuning with “set and forget” prematch
  - Passive “ELM tolerant” 3 dB hybrid matching
  - Strap array rotated to minimize E// fields
  - Local edge gas injection to improve coupling and reduce rf sheath/impurities
- LH - edge CD
  - ~ 5 GHz PAM grill
  - Local edge gas injection to improve coupling
  - Access In high density plasma?

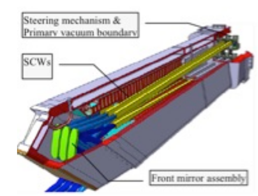


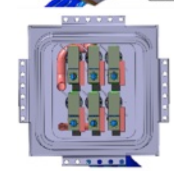








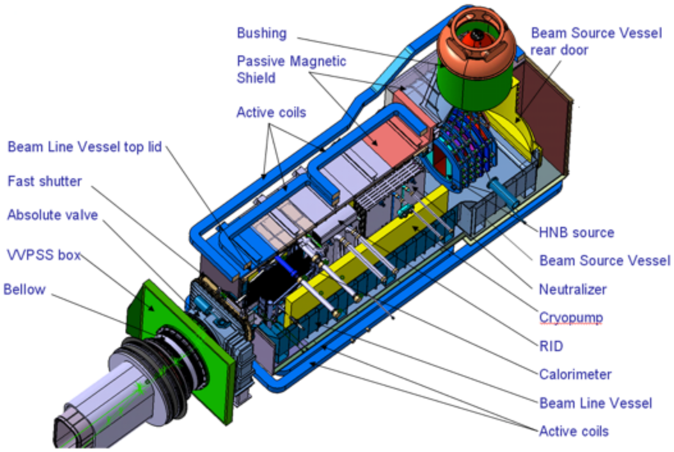




Roadmap for Improving and Qualifying H&CD Systems

- *Utilize FNS facility, appropriate test stands (PMI, RF) and modeling tools to identify and overcome operational, reliability and lifetime limitations of H&CD designs.*
- *Develop operational and materials database needed to enable reliable and adequate capability for DEMO.*
- *Develop suite of codes and integrated self consistent codes to model plasma dynamics, H&CD system designs, performance and materials.*
- *Model, bench test and deploy traditional and novel H&CD systems compatible with DEMO environment on existing and future devices.*
- *Evaluate impact of current and alternate sets of H&CD systems on DEMO and reactor plant designs*
- *Evaluate subsystems and components of all H&CD systems to identify opportunities for significant improvements in wall plug to CD efficiency*

NBI Issues and Candidate Research goals



- **Present large volume gas neutralizers impose an inventory and cryo panel regeneration limit and hence a pulse limit.** ***Develop alternative neutralizers (Li jet or laser photodetachment) to reduce gas load and achieve continuous beam operation.***

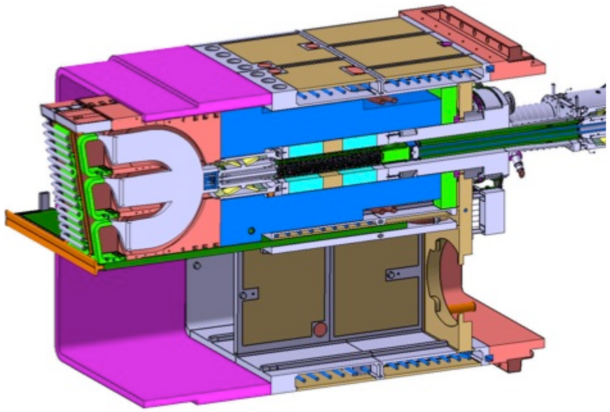
- **Present negative ion sources have insufficient cathode filament lifetimes. RF-driven negative ion sources are under development but not mature.** ***Understand present and improved RF-driven negative ion sources*****.**

- **High voltage accelerator grid materials, permanent magnets (Samarium Cobalt), and some insulators experience line of sight irradiation.** ***Understand present and improved materials in the source environment under substantial irradiation*****.**

- **Neutral beam openings reduce tritium breeding area and beam lines extend the nuclear boundary.** ***Evaluate impact of NBI footprint on T breeding and power generation and explore strategies to minimize impact.***

- **Tritium migrates into the beam duct and beam dump systems and can mix with cryopump streams.** ***Measure and model trace T deposition and migration in beam dump dominated by energetic D^+ in chosen materials of interest.***

ICH Antenna & System Issues and Candidate Research goals

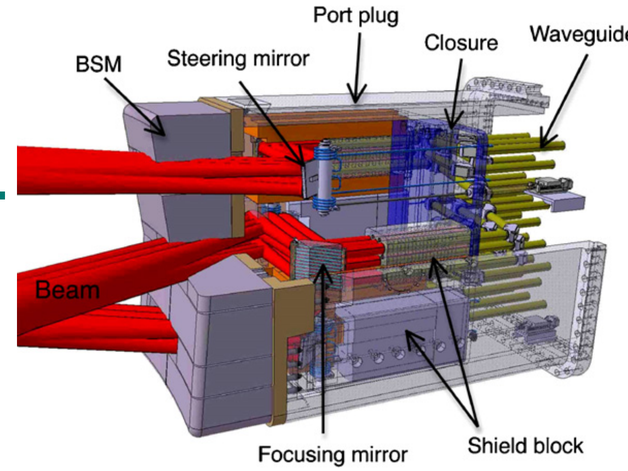


- **ICH coupling and absorption efficiency is dominated by scrape off layer density and density gradient at plasma antenna interface. There is always a design tradeoff of antenna-to-plasma coupling gap and heat flux to antenna.** ***Develop a self consistent predictive capability for far SOL density profile. Complement with experimental program to use local gas puffing to fill in profile and impurity injection to reduce RF sheaths. The modeling effort requires integration and improvement of many existing RF codes and extending them into the SOL volume***

- **Faraday shield and antenna straps are irradiated PFCs with the addition of high RF voltages, RF sheaths/hot spots and high internal RF currents. Present long pulse antennas are water-cooled while future antennas will operate with gas coolant at ~ 600 C. They will likely be constructed from layered or coated materials.** ***Develop the experimental, operational and materials database needed to enable reliable ICRF capability in a DEMO. Model, bench test and deploy antennas with conducting and insulating materials compatible with this environment and high temperature gas-cooling.***

- **High RF breakdown/arcing is one of the main power limiting issues with operating ICH antennas in the plasma environment and is poorly understood.** ***Extend present basic studies of breakdown mechanisms and avoidance to include advanced materials designed for RF, high heat flux and irradiation environment*.**

ECH/EBW Launcher & System Issues and Candidate Research goals



- **ECH launchers utilize fixed or moveable final mirrors. There are ECCD and EBWCD coverage and efficiency tradeoffs with remote steering and front steering designs.** ***Develop and deploy remote steering designs that optimizes current drive efficiency and also the broad spatial coverage with good directivity required for NTM suppression.***
- **ECH launchers are remote from plasma but final mirrors and shield blocks are irradiated PFCs with the addition of microwave resistive losses. Present long pulse launchers are water-cooled while future launchers will operate with gas coolant at ~ 600 C. They must maintain high reflectivity and directivity.** ***Develop the experimental, operational and materials database needed to enable reliable ECH and/or EBW capability in a DEMO. Model, bench test and deploy launchers with mirror and shield materials compatible with this environment and high temperature gas-cooling.***
- **Single frequency gyrotrons limit the operational flexibility of ECH and EBW systems to a narrow band of B field. Multifrequency sources may improve current ramp up sequences and reduce required mirror steering range.** ***Expand gyrotron research efforts to develop multi-frequency gyrotrons while maintaining high efficiency*. Study possible operational space and launcher design trade offs.**

LH Launcher & System Issues and Candidate Research goals

- **LH coupling and absorption efficiency is dominated by scrape off layer density and density gradient at plasma launcher interface.** ***Develop a self consistent predictive capability for far SOL density profile. Complement with experimental program to use local gas puffing to fill in profile and impurity injection to reduce heat loads. The modeling effort requires integration and improvement of many existing RF codes and extending them into the SOL volume***

- **LH grills are irradiated PFCs with the addition of high RF voltages, possible ICRF driven sheaths/hot spots and high resistive losses in guides. Present long pulse LH launchers are water-cooled while future launchers will operate with gas coolant at ~ 600 C. They will likely be constructed from layered or coated materials.** ***Develop the experimental, operational and materials database needed to enable reliable LH capability in a DEMO. Model, bench test and deploy LH launchers with conducting and window materials compatible with this environment and high temperature gas-cooling.***

Fueling/Pumping of a Burning Plasma

Fueling/Pumping System for a Burning Plasma Must:

- 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
- Be a closed loop that recovers and controls T inventory
- 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.
- Have pumping and processing capacity compatible with ELM and disruption mitigation systems

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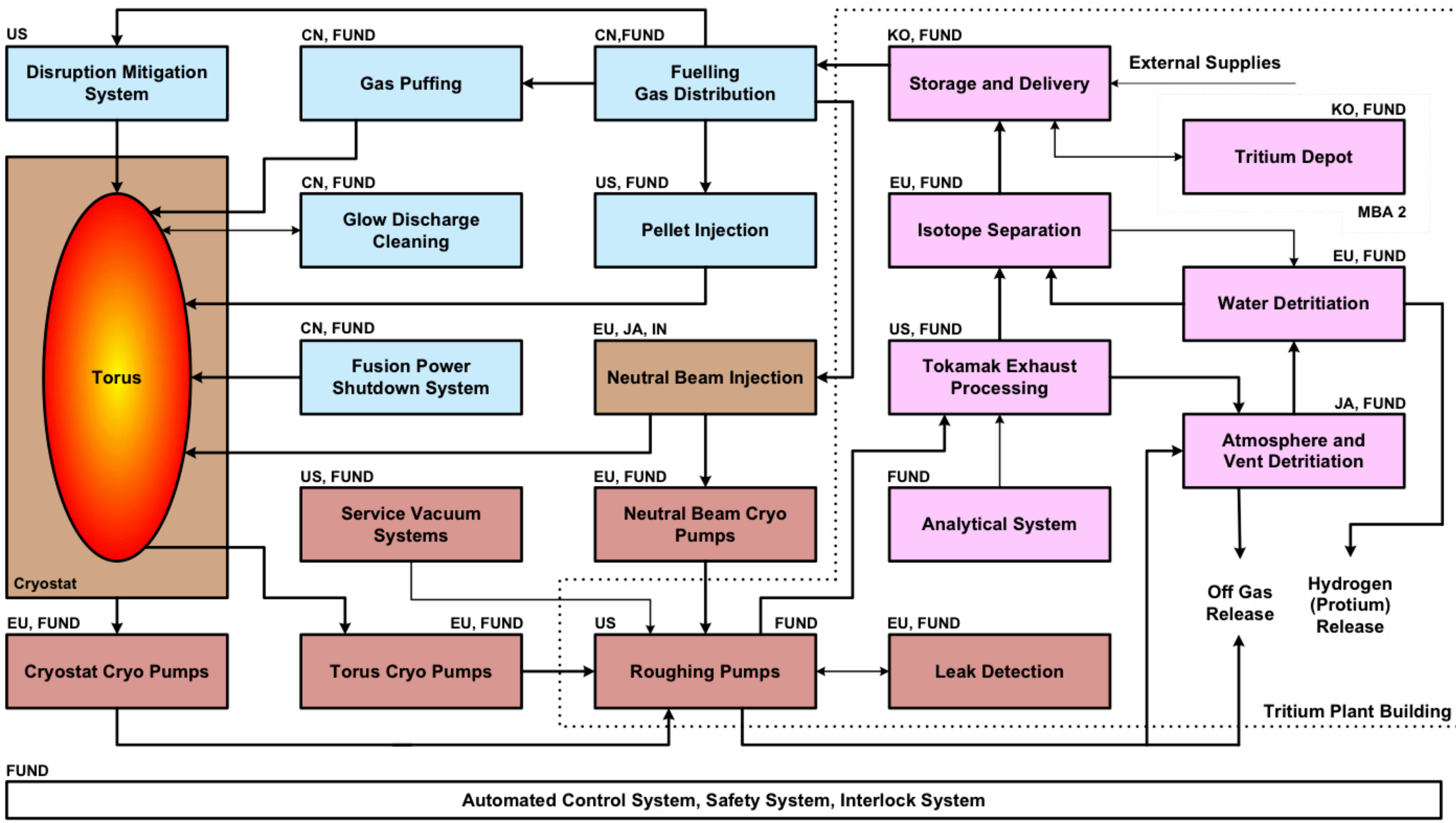
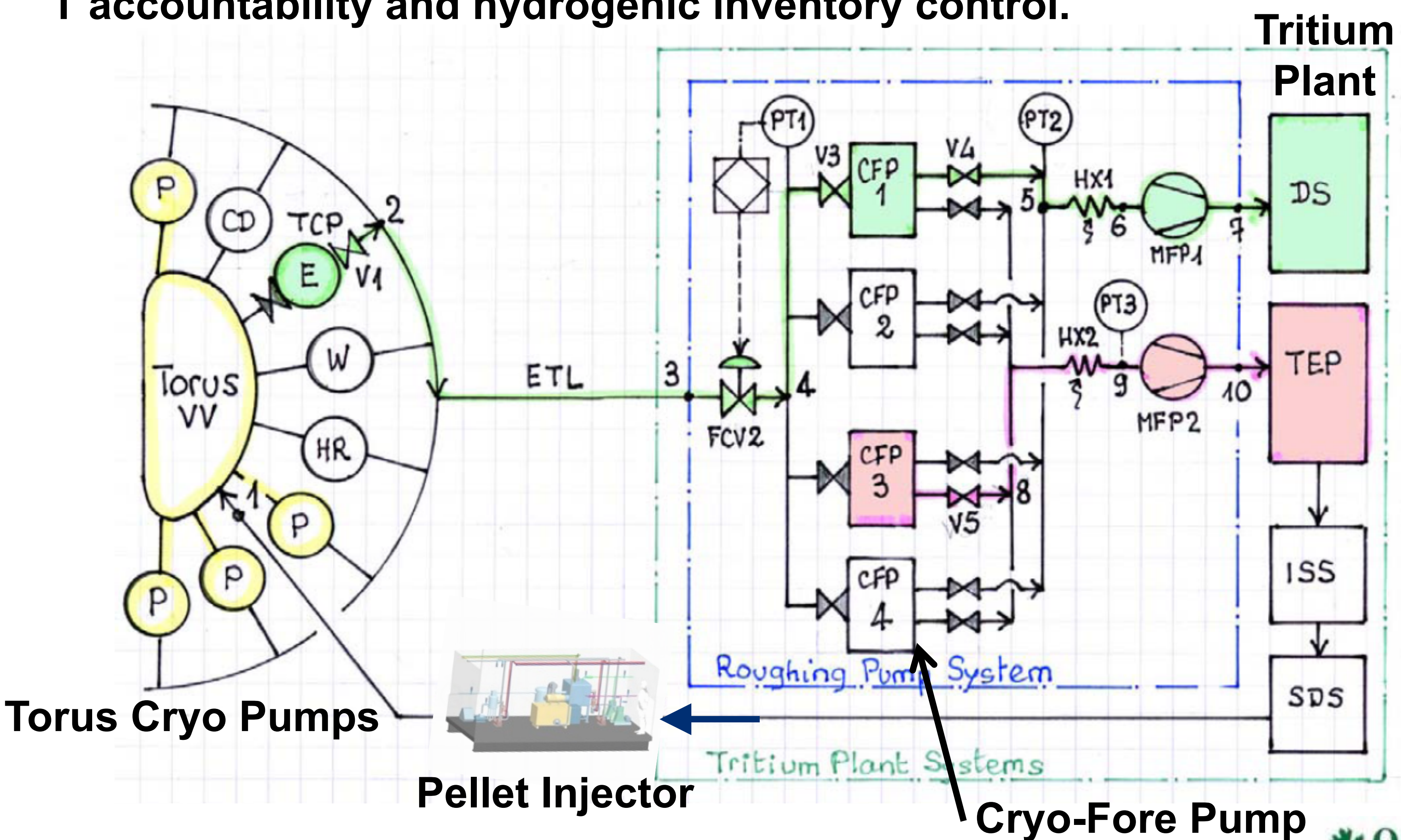
Fueling/Pumping of a Burning Plasma



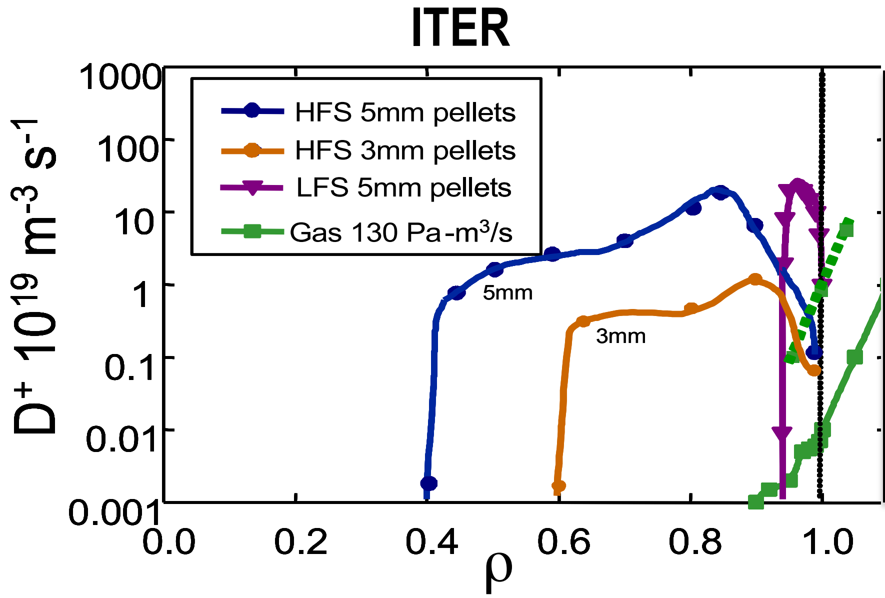
Simplified ITER Fuel Cycle Flow Diagram

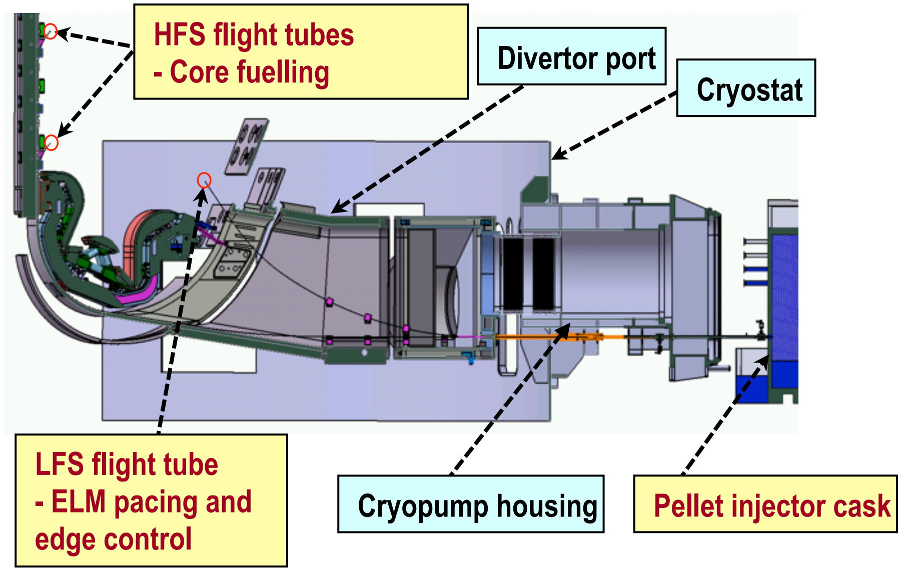
Closed fuel cycle - T fueling, pumping, recovery and recycle.
T accountability and hydrogenic inventory control.

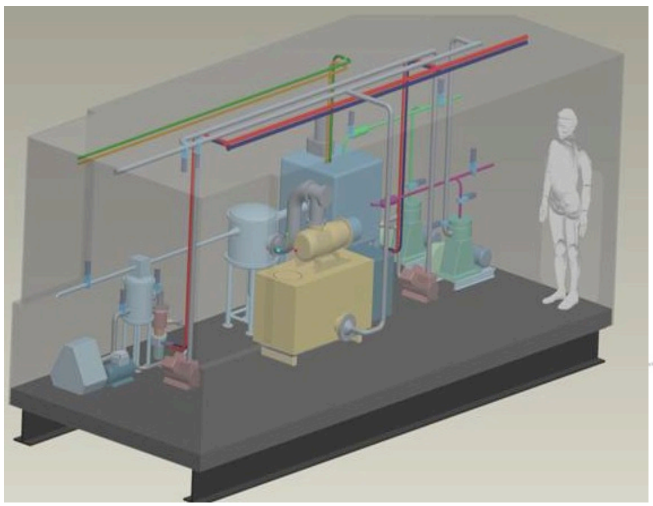


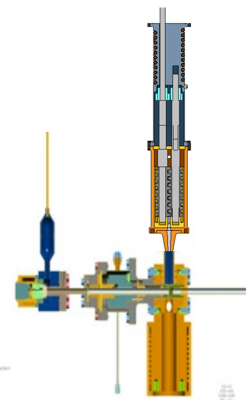
Fuel Cycle Technology Development - Fueling

- **Pellet and gas Fueling**
  - **Continuous fueling – plasma gun, NBI, gas and inner wall pellet injection (core fueling, isotopic control)**
  - **Impurity injection**
  - **Tritium recycle inside pellet injector cask**
  - **Batch cleanup/recovery in tritium plant**



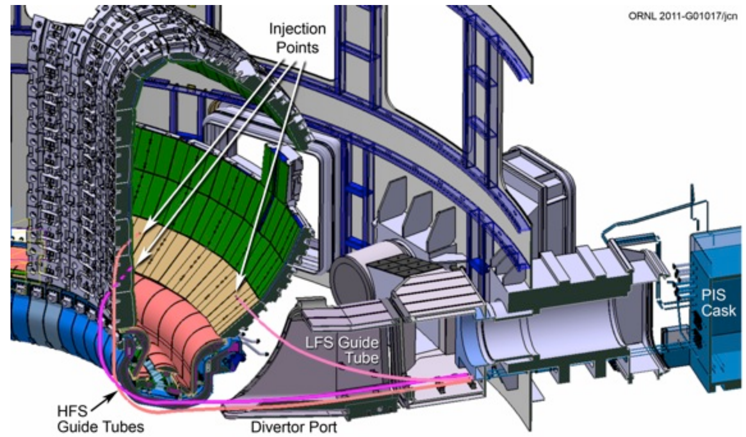


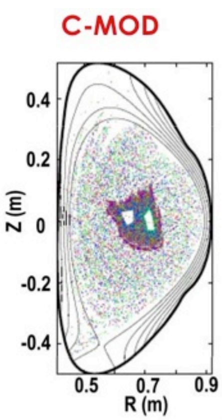


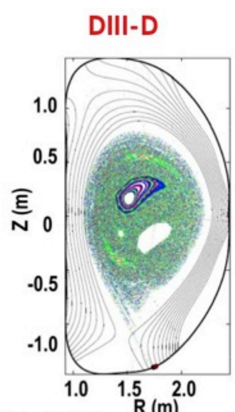


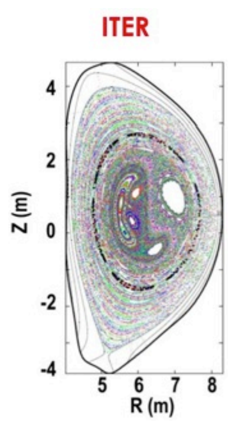
Fuel Cycle Technology Development - ELM Mitigation, Disruption Mitigation and Runaway Suppression

- **ELM mitigation**
  - Injection of “small” pellets at~15 Hz can trigger small ELMs
  - Minimize harmful effects on the divertor from the larger natural ELMs
- **Disruption Mitigation and Runaway Electron Suppression**
  - Massive pellet injection for Disruption mitigation and massive gas injection for Runaway Electron Suppression
  - Pre-programmed controlled ramp down with VF and auxiliary H&CD to avoid Runaway Electron formation

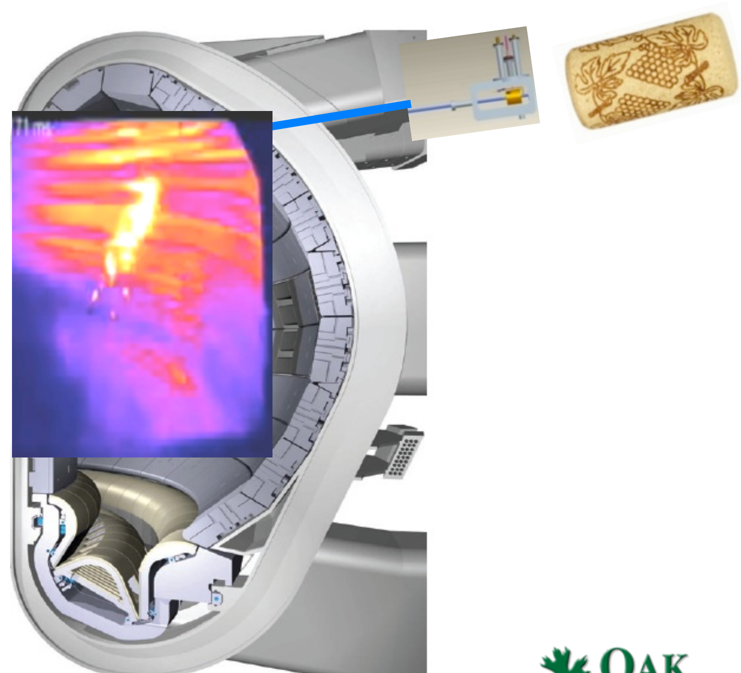






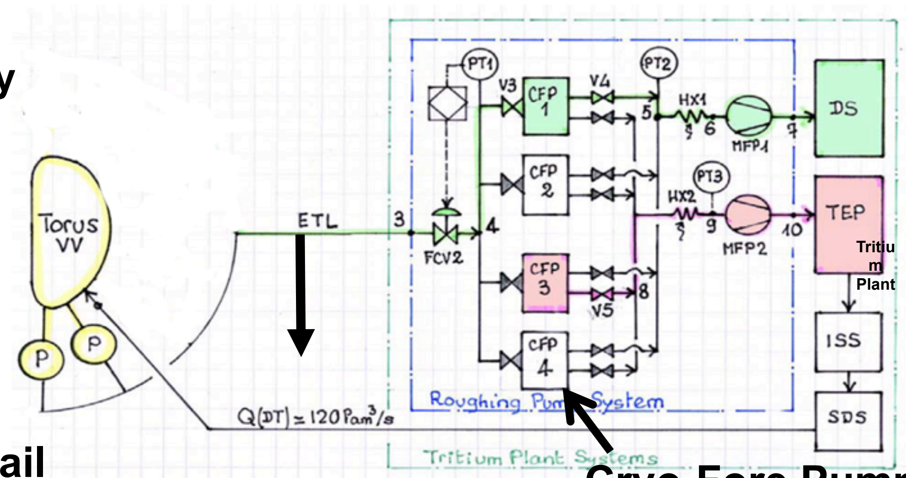


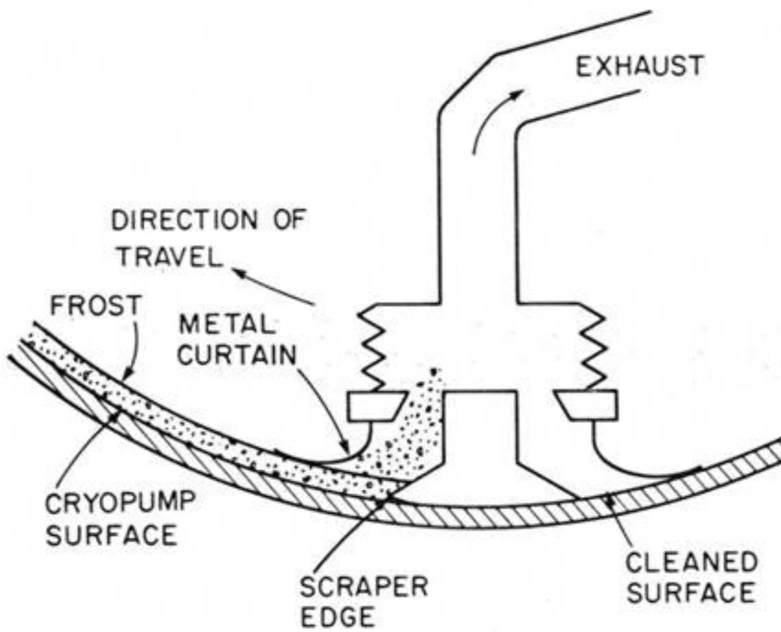
(V. Izzo, IAEA 2010)



Fuel Cycle Technology Development - Pumping

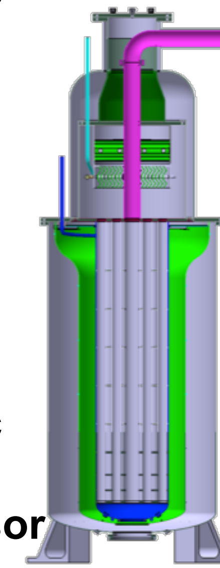
- **Fueling, Pumping & Tritium Recovery**
  - Closed fuel cycle - T recovery, accountability and hydrogenic inventory control
  - Continuous cryo-pumping
  - Downstream cryo-separation of He and D/T streams





Snail Cryo-Pumps

Cryo-Fore Pump



Cryogenic Viscous Compressor

Roadmap for Improving and Qualifying Fuel Cycle and Plasma Instability Mitigation Systems

- ***Utilize FNS facility, appropriate test stands and modeling tools to identify and overcome operational, reliability, capacity, inventory and lifetime limitations of fuel cycle designs.***
- ***Develop operational and materials database to needed to enable reliable and adequate plasma instability mitigation capability in a DEMO.***
- ***Model, bench test and deploy fuel cycle and mitigation systems compatible with DEMO environment and safety considerations.***
- ***Evaluate impact of current and alternate sets of <u>fuel cycle</u> systems on DEMO and reactor plant designs***
- ***Evaluate impact of current and alternate sets of <u>mitigation</u> systems on DEMO and reactor plant designs***

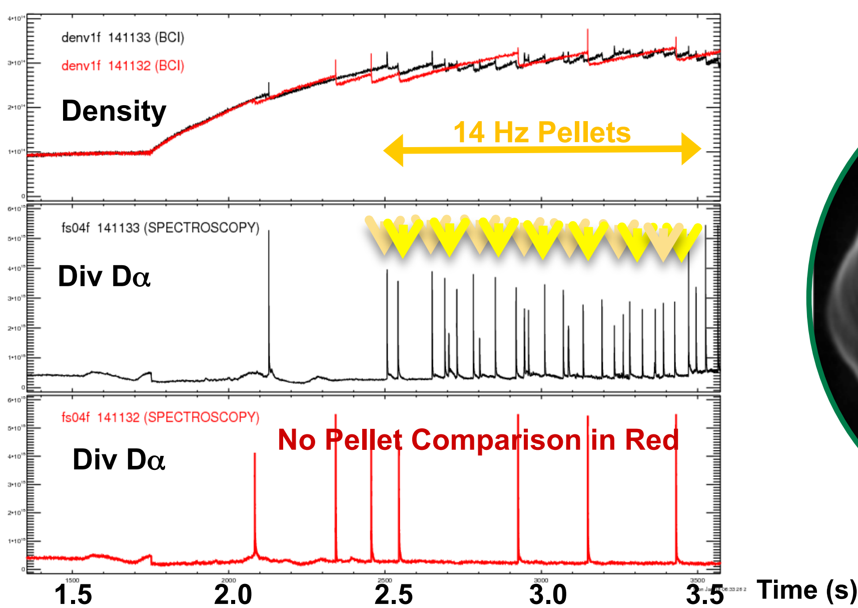
Fuel Cycle Issues and Candidate Research goals

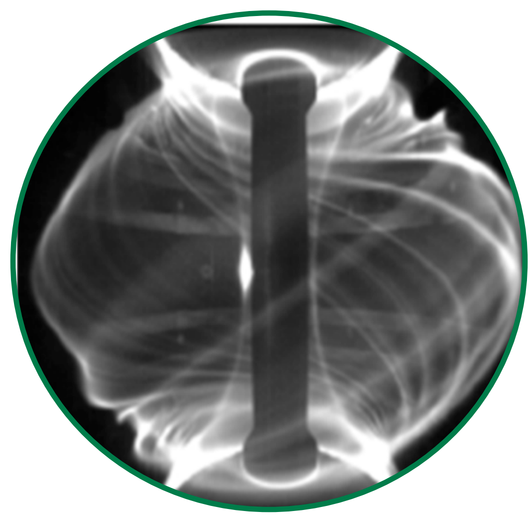
- **ITER fuel cycle is semi continuous. Torus cryopumps, T roughing pumps and T recovery operations include batch regeneration** ***Develop and deploy continuous pumping and recovery designs that maintain inventory, accountability and reliability requirements***
- **Present roughing pump designs employ materials that are not fully tritium compatible.** ***Qualify new materials and new designs and deploy pumps with T compatible components.***
- **High field side launch guide tubes have curves that impose a pellet speed limit. Low field side launch tubes can be straight, with resultant high pellet speeds but ExB drives ablated mass outward. This can reduce the penetration depth in plasmas with high pedestal temperatures.** ***Develop very high speed launchers for low field side launch. Integrate FNSF and DEMO designs with optimized high field guide tube routings with only large radius bends.***

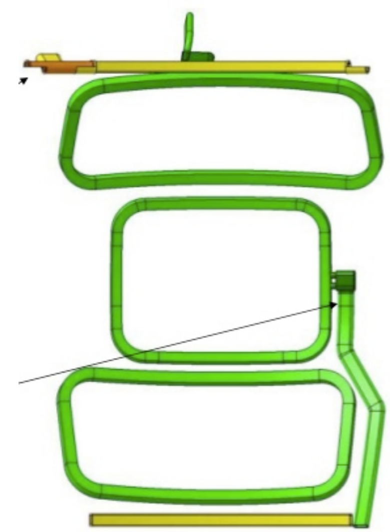
Plasma Instability Mitigation Issues and Candidate Research goals

- **Disruption Mitigation and Runaway Suppression systems require injection and plasma assimilation of large volumes of hydrogenic and/or noble gas. Multiple synchronized injectors and subsequent vessel pumping recovery methods will need to be employed.** ***Conduct experiments to determine requirements for both DM and RE suppression. Design and verify capability of fuel cycle systems to accommodate these non-routine events.***

- **ELM mitigation has been achieved with ELM coil arrays and with pellet pacing. Design and operational limits of these techniques have been explored in a <u>limited</u> set of experiments.** ***To the extent possible, test these alternative systems in DEMO-like environments and operating ranges.***







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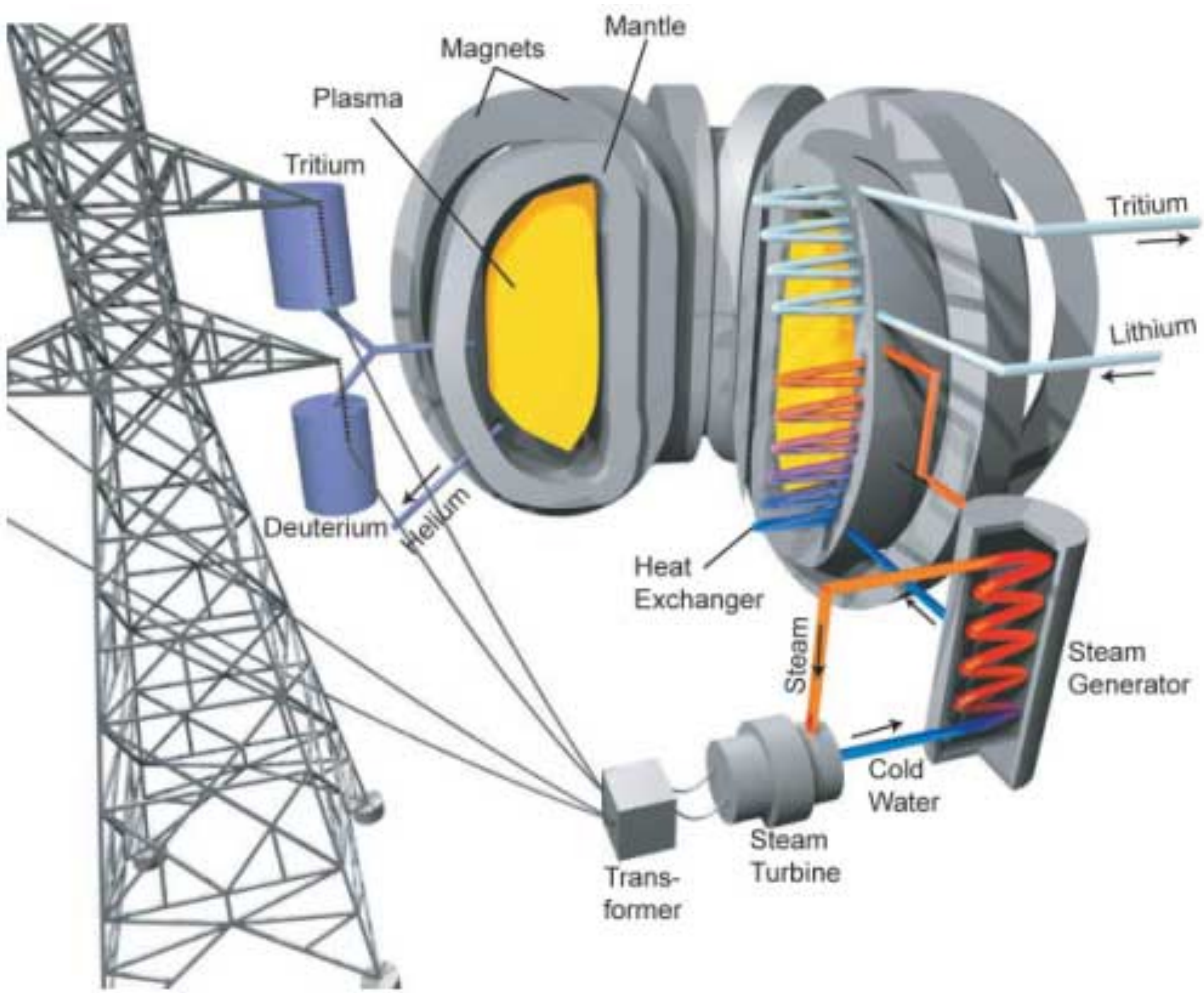

We can hardly wait to get started!