Long Pulse Physics via International Stellarator Collaboration

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& the US stellarator community*

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US Collaboration on overseas stellarators leverages substantial world investment

- Stellarator research addresses high priority Greenwald gaps
  - 3D plasma exhaust solutions compatible with high-performance core
  - Extending high-performance plasmas to long pulses.
- Stable commitment to long term collaborations with Germany and Japan will yield important physics that will help fill the gaps
  - Required for the design of stellarator FNSF and reactor concepts

* See the Stellarator White Paper: **Control of High-Performance Steady-State Plasmas: Status of Gaps and Stellarator Solutions**

LHD and W7-X, the world's two superconducting long-pulse stellarator experiments

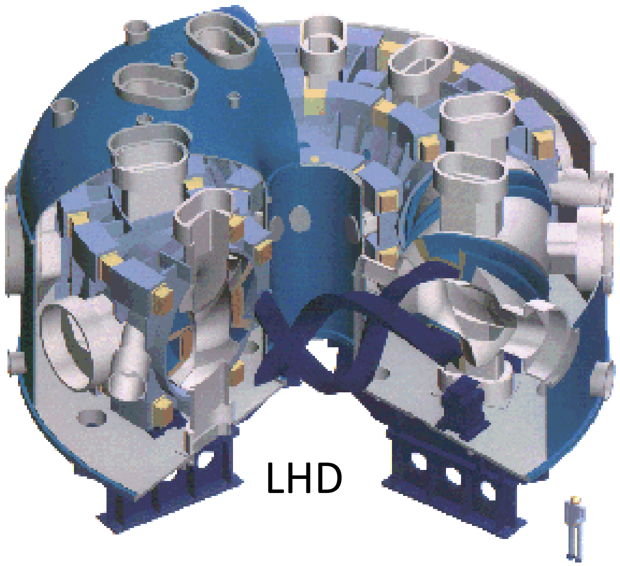

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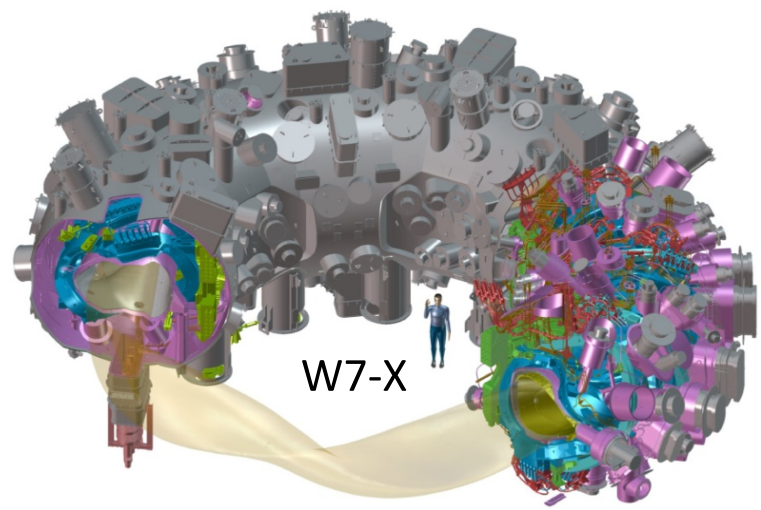
Figure 1 from H.-S. Bosch et al 2013 Nucl. Fusion 53 126001



Max Planck Institute for Plasma Physics, Greifswald, Germany

- W7-X begins operation in 2015, will have
  - SC magnets, high-power heating systems
  - Magnetic island divertor
  - 30 minute pulse at full power
- LHD has been operating since 1998
  - well equipped with heating, diagnostics
  - helical divertor
  - Achieved 1 hour long pulse at reduced power

Targeted research Opportunities on LHD

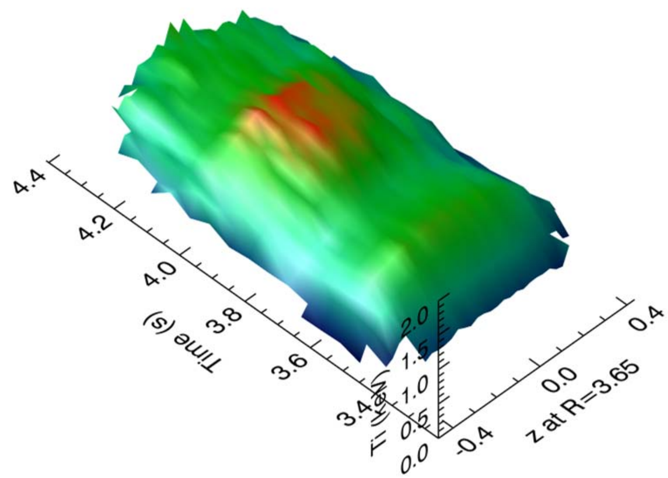
- Support US developed X-ray Imaging Crystal Spectrometer (XICS) on LHD
  - Minimal investment to restart this collaboration $0.3 million/year
- Argon Impurity transport studies
- Island physics studies
- Confinement studies at high density

US XICS diagnostic provides profile measurements of:

Ion Temperature
Electron Temperature
Poloidal Flow Velocity

Time resolution: 20ms, Spatial resolution: 2cm.
Non-perturbative to the plasma (no NBI).

Time resolved ion temperature profiles
From XICS on LHD

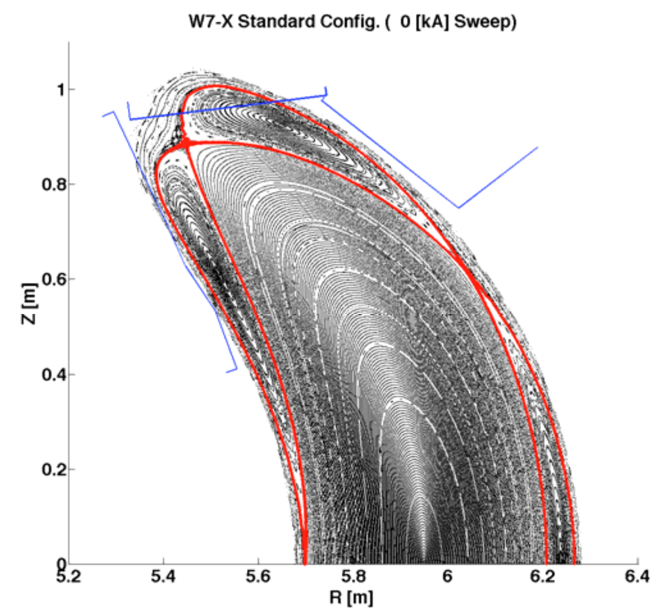


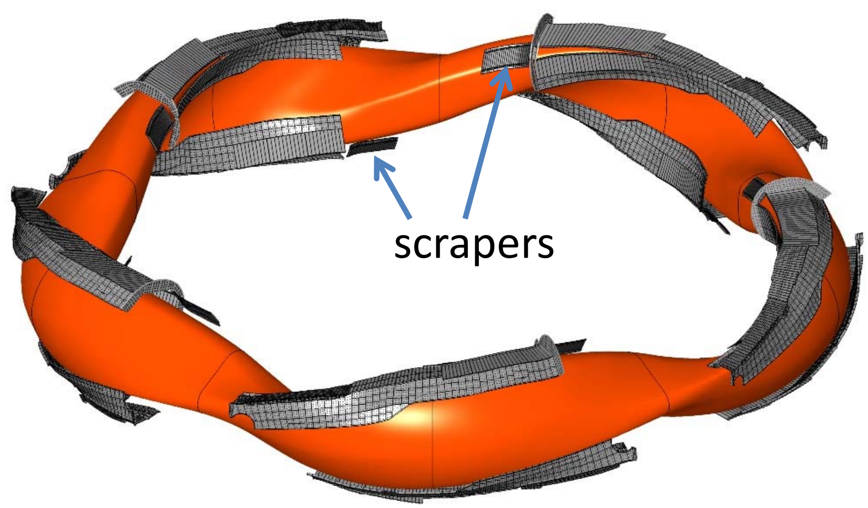
W7-X: opportunities/challenges

- **W7-X will become a world-class fusion facility**.
  - ITER-like high-heat-flux and steady-state operation (before ITER)
  - Valuable supplement to tokamak program
- **US contributions to W7-X (>$10M) have made a real difference.**
  - Added important capabilities (trim coils, scrapers, imaging . . .for plasma control and power exhaust management) beyond scope of IPP budget.
  - Strengthened position of W7-X, both inside and outside Germany
- **US has earned partnership opportunity in W7-X . . .**
  - US contributions are deeply integrated into W7-X. Interest in/competition from other countries is growing.
  - Any US stellarator strategy will benefit from partnership in W7-X.

3D Magnetics on W7-X : Island Divertors

- Exhaust heat from the W7-X plasma is carried by hot particles flowing along 5/5 island chain
- Divertor targets (5-fold symmetry) are placed so as to intersect the islands
  - Field lines are mostly toroidal, so they intersect targets at a shallow angle.
- As bootstrap current changes, so does the magnetic geometry of the islands at the plasma edge
- US designed “scraper element” protects parts of each divertor
  - Science program studies the effect of this divertor structure





W7-X US Collaboration

- The driving themes of the existing collaboration are: Edge plasma/divertor physics in 3D geometry, core transport in 3D, and plasma control in long pulse operation. This includes simulation/modeling, diagnostics, and planning for experiments.
- We have a seat on the W7-X council. Up to a dozen US scientists and engineers are presently working back/forth with IPP Greifswald, with increasing efforts coming as operations begin next year.
- Ongoing activities
  - Deploying an X-ray imaging crystal spectrometer (ion temp and rotation profiles)
  - Field line mapping with US supplied trim coils (modeling support)
  - IR imaging and analysis, optical access periscope for Scraper (heat-load mapping)
  - Design and build Test Divertor Unit Scraper Element (island divertor studies)

Exciting opportunities for expanded collaborations

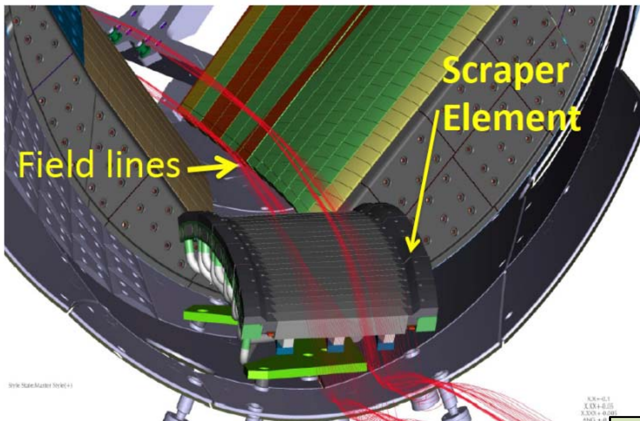
- Proposed areas for expansion of US partnership on W7-X
  - Formation of university/laboratory W7-X science partnership
  - TDU scraper element fabrication.
  - Detailed divertor/scraper imaging, fast data processing.
  - Energetic particle physics
  - Fluctuation measurements, turbulence simulation
  - Steady-state pellet injector preparation

- These research areas would further leverage W7-X into our overall long-pulse, edge/plasma, 3D divertor development strategy.

Scraper element is a target for <u>future</u> expanded joint U.S. University and National Laboratory program in edge physics

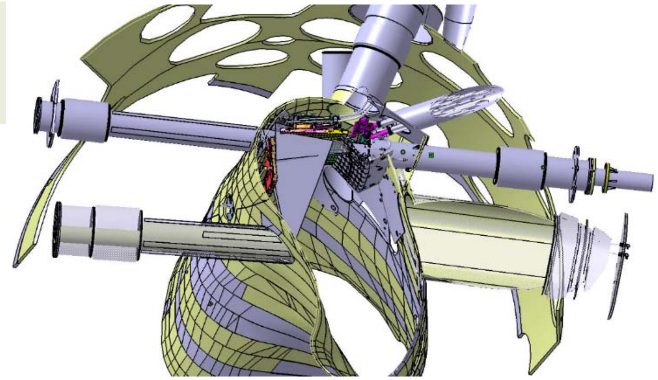
Proposal: Fabricate scraper element

Proposal: Support divertor endoscope development



TDU Scraper observation and physics exploitation

All topics proposed for startup phase are relevant



National Laboratory goals

Scraper with endoscope offers multiple opportunities to exploit university strength in resonance with nat. labs

University contributions

Magnetic Structure Optimization

- Control of current profiles
- Island control with Trim coils
- Impact on scraper heat flux of both

- Joint VMEC efforts
- STELOPT & V3FIT
- Expertise in 3D equilibrium

Edge physics and exhaust

- Impact of scraper on exhaust
- Scraper heat and particle flux
- SOL width with scraper

- EMC3-Eirene modeling
- Exhaust measurements
- Probe diagnostics

Plasma material interaction

- Scraper as high heat flux test surface
- Localized erosion/deposition

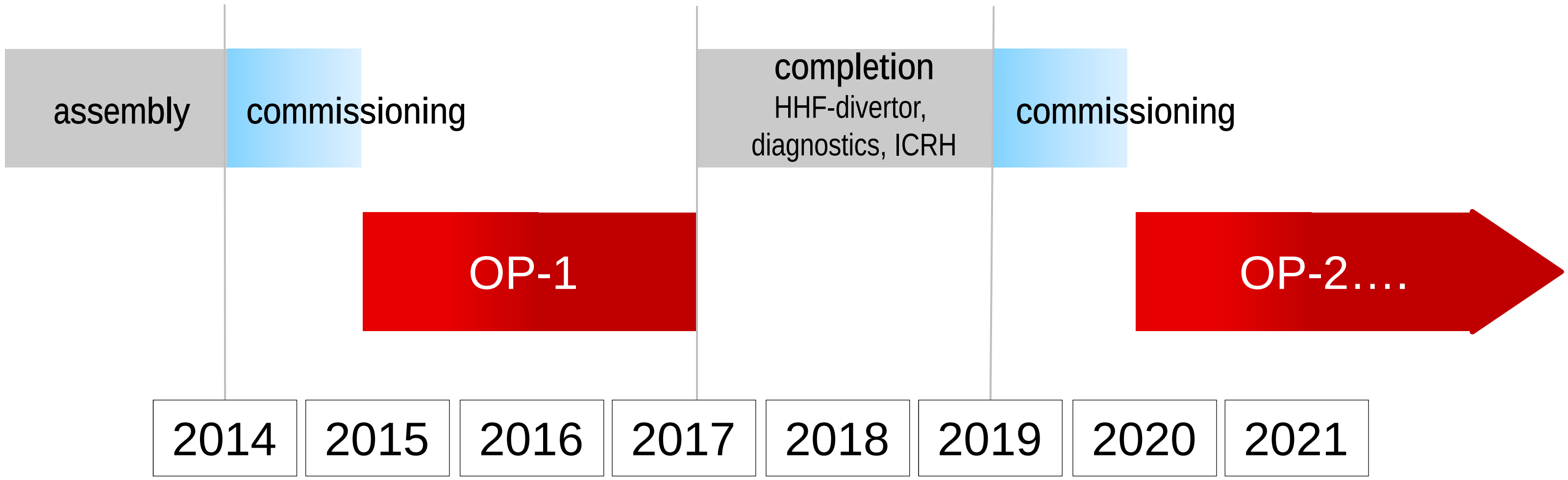
- Spectroscopy
- Atomic models for emission
- Optical design expertise

International collaboration on stellarators is a high leverage opportunity that can fill Greenwald gaps

- Integral component of a coherent US stellarator program
  - Broad participation with Universities and laboratories
- US is already engaged in an exciting productive program
- Taking full advantage of new opportunities require added investment, $10-12 million/year
  - e.g. 10% partnership on W7-X
  - Renewing targeted LHD collaboration
  - US participation is welcomed on both LHD and W7-X
- Urgency for action is high as W7-X starts operation in 2015

Backup Slides

We need to work within the W7-X Schedule



Operational phase 1 (OP-1)

- inertially cooled divertor, only partial cooling of in-vessel components
- up to 10 s at 10 MW, 50 s at 1 MW heating power
- development of steady state scenarios

Operational phase 2 (OP-2)

- high heat flux divertor, water cooling of in-vessel components
- steady state at 10 MW, 10 s at 18 MW heating power
- transition to high power steady state operation (30 min)

One possible new effort: W7-X pellet fueling

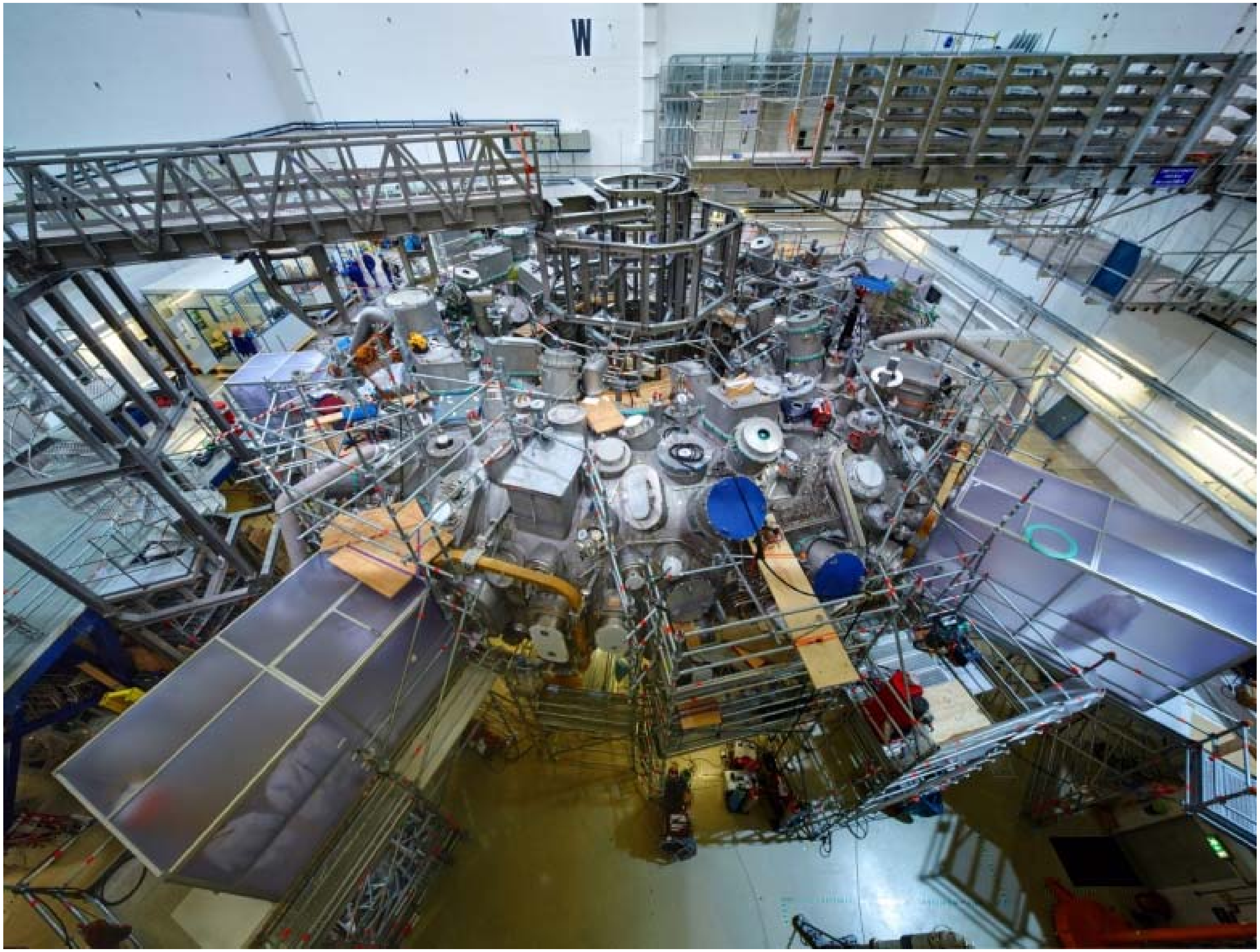
Stellarators heated with ECH exhibit hollow n(r)

- Serious risk in W7-X of edge density rising to ECH cut-off and limiting heating.
- Verified in 30 years of experiments on ATF, Heliotron-E, CHS, W7-AS, LHD
- Ware pinch, which transports particles to axis in tokamaks, vanishes for $I_{pl} = 0$
- Solution: repetitive pellet fueling as demonstrated on ATF(1990).

Planning for W7-X pellet fueling

- Staged capabilities:
  5-10 pellets for TDU phase (20 s)
  Continuous pellet injection for steady-state operation (>2017)
- **Synergy with ITER R&D** (and on nearer term time-scale)
  ORNL is developing continuous pellet system for ITER
  Pinch effect much reduced in non-inductive tokamaks: turbulent pinch?
- Strategy meeting of pellet experts from IPP, ORNL, and NIFS at IPP was in April 2013
  Multi-faceted international collaboration plan has emerged: more leverage.

W7-X at the beginning of 2014



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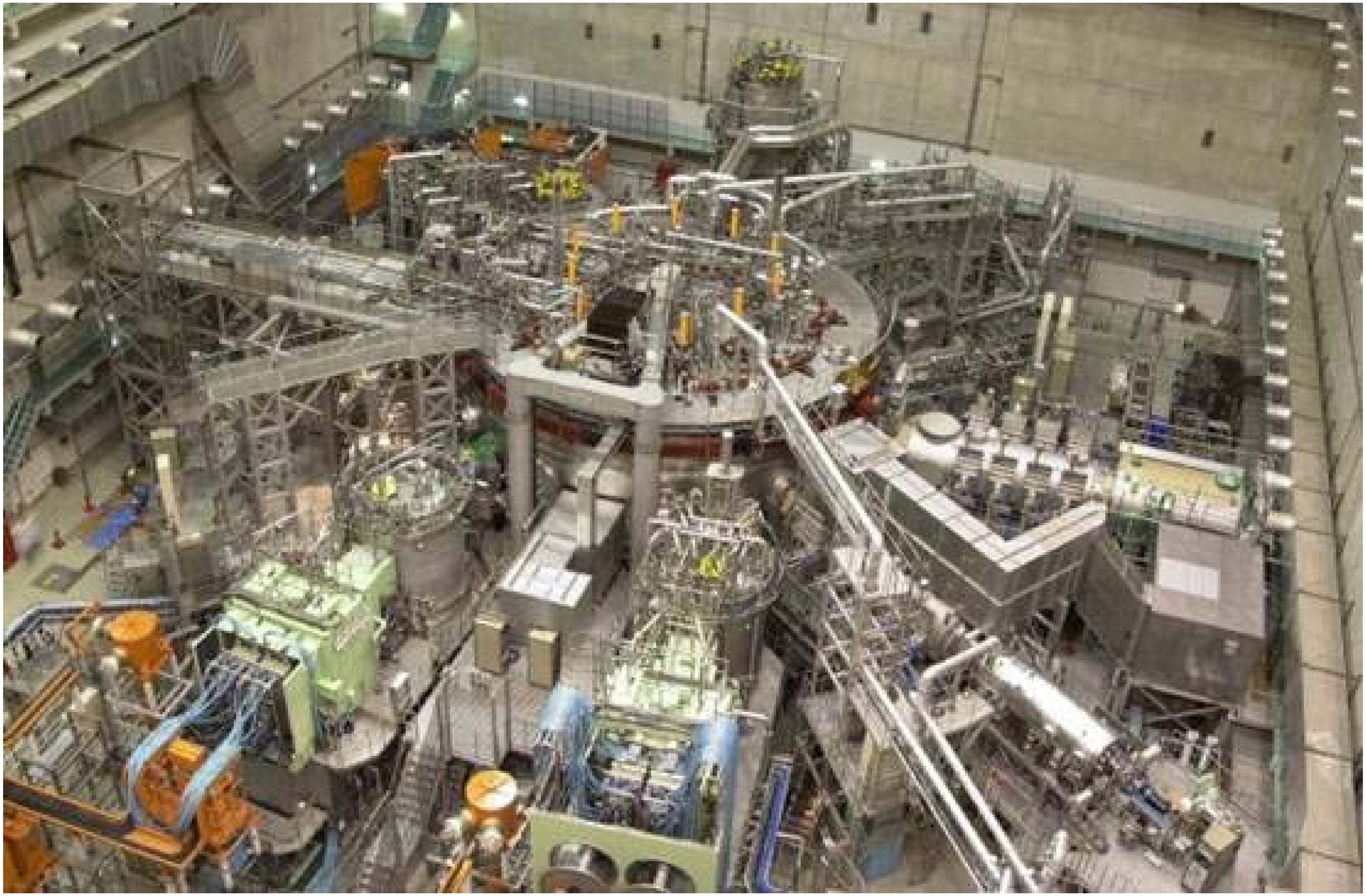
The LHD torus hall



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