CNT and Wendelstein 7-X

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PPPL/Simons Stellarator Summer School, July 29, 2024

About me

- 1990: born, Saratoga Springs, NY
- Activities: track, cross-country, trombone
- Wanted (and still want) to do something about climate change and decarbonization
- 2008-2012: majored in physics at Harvard
  - 2011: SULI internship @ PPPL!
- 2012-2017: PhD in applied physics at Columbia University, working on CNT
- 2017-2019: postdoc on W7-X at the Max Planck Inst. for Plasma Physics, Germany
- 2019-present: research physicist, PPPL
  - Continuing to collaborate with W7-X
  - 2024: asked to give talk on CNT and W7-X





The Columbia Non-Neutral Torus (CNT)

Introduction to CNT

- Small, simple stellarator experiment built at Columbia University, New York, NY
- Consists of four circular, planar coils
  - Interlocked (IL)
  - Poloidal field (PF)

Columbia University

Introduction to CNT

- Dimensions
  - R_{major}: 0.2-0.4 m
  - a_{minor}: 0.05-0.15 m
  - World's smallest aspect ratio for a stellarator
- Field strength: 10-300 mT
- Field flexibility
  - Three tilt angles between IL coils
  - Adjustable current ratio between IL and PF coils

Columbia University

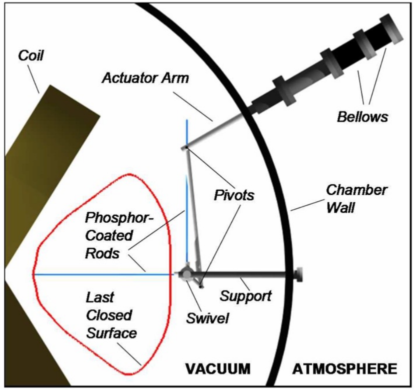
Motivation for a non-neutral stellarator

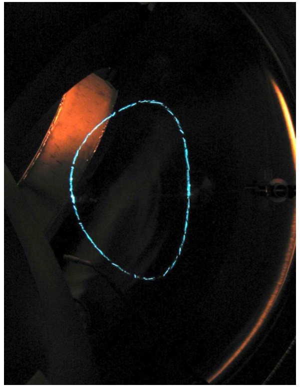
- Electron-positron pair plasmas would be interesting to study in the lab
  - Confirm theoretical models of plasmas with +/- species of equal mass
  - Simulate astrophysical phenomena
  - Validate gyrokinetic codes
- Stellarators are attractive candidates for confining pair plasmas
  - Can confine plasmas of arbitrary degrees of neutrality
  - Steady-state operation
  - Very long confinement times anticipated

Nebula around a pulsar (NASA)

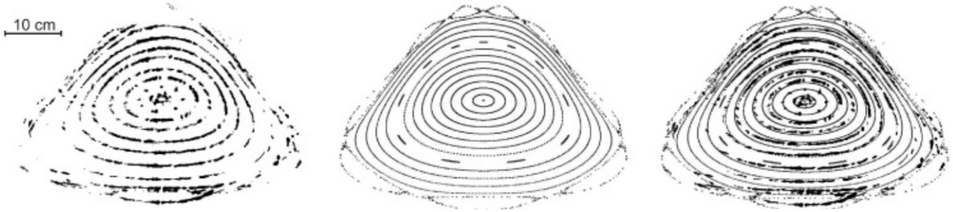
Field line mapping verifies the presence of flux surfaces

- Field line mapping technique
  - Emit a beam of electrons from a filament
  - Sweep a phosphor-coated rod through the flux surfaces
  - Take a long-exposure photo of the rod as it moves
  - Resulting images shows a cross-section of a flux surface
- Confirms lowest aspect ratio of any stellarator ever built





J. P. Kremer (2006)



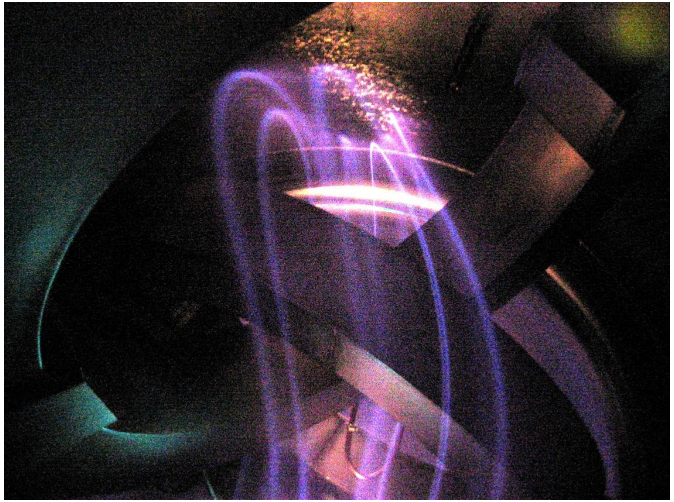
measured   *modeled*   *combined*

T. S. Pedersen et al. (2006)

J. P. Kremer, Ph.D. Thesis, Columbia University (2006)
T. S. Pedersen et al., *Fusion Sci. Technol.* **50**, 372 (2006)

Visualizing field lines and flux surfaces with plasma

- Emitting an electron beam in the presence of neutral gas enables field line/flux surface visualization



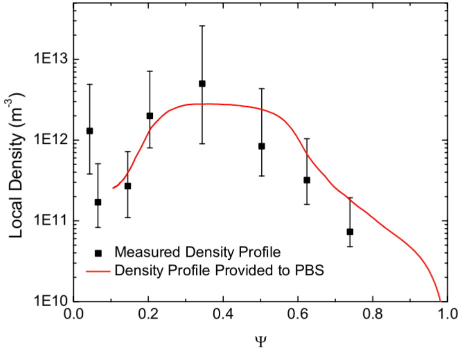
T. S. Pedersen, Columbia University

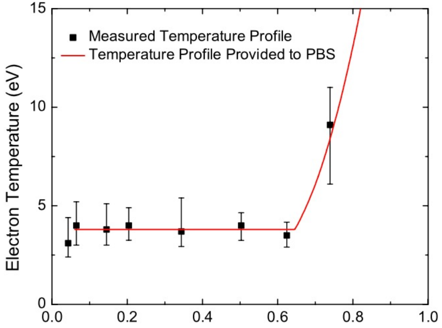
Establishing a pure-electron plasma equilibrium

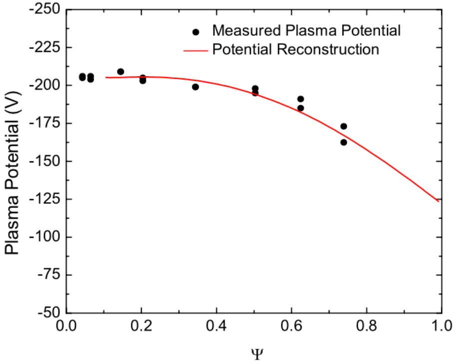
- Prerequisites
  - Very low neutral pressure (< 10^{-8} Torr)
  - Small Debye length
- A pure-electron plasma on flux surfaces satisfies:

$$n_e = \frac{\epsilon_0}{e}\nabla^2\phi = N(\psi)\exp\left[\frac{e\phi}{T_e(\psi)}\right]$$

- Matching measurements with model
  - Profiles of n_e, T_e, and $\boldsymbol{\phi}$ measured with Langmuir probes
  - Model correctly predicts $\boldsymbol{\phi}$ from n_e and T_e





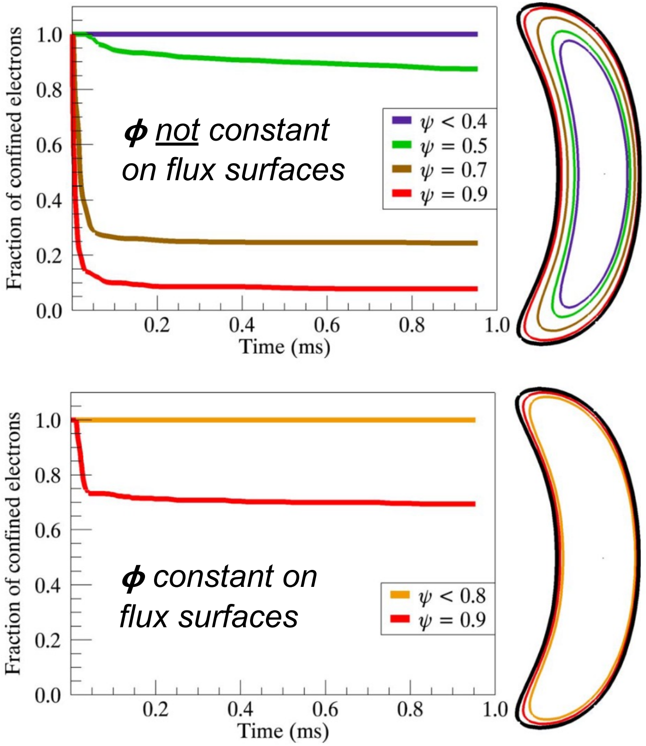


J. P. Kremer et al. (2006)

J. P. Kremer et al., *Phys. Rev. Lett.* **97**, 095003 (2006)

Expectations for confinement in CNT

- CNT is not quasisymmetric
- However, confinement of pure-electron plasmas may still be good
  - Single charge species means strong electric field
  - E×B drift can mitigate losses due to **∇**B drift
- Key requirement: equipotential surfaces should match flux surfaces
  - E×B flows go along equipotential surfaces
  - If equipotential surfaces cross flux surfaces, particles will drift radially (and out of the plasma)

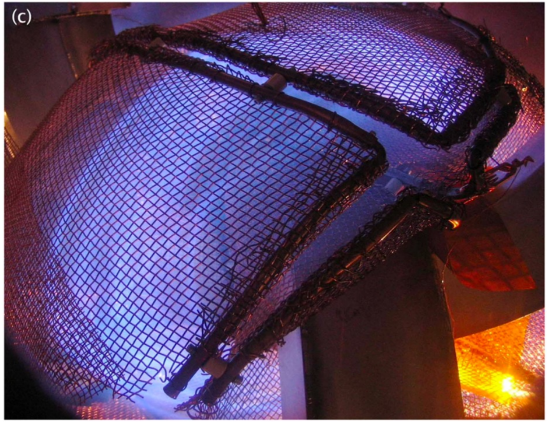


B. Durand de Gevigney et al. (2009)

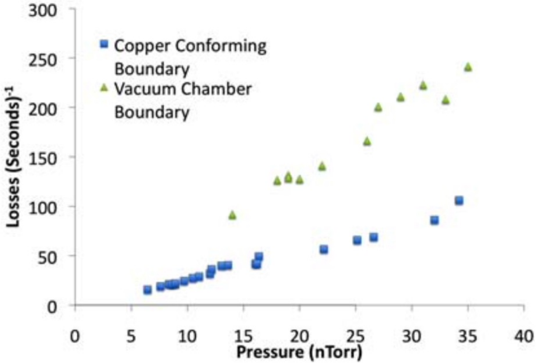
B. Durand de Gevigney et al., *Phys. Plasmas* **16**, 122502 (2009)

Installing a conducting boundary to improve confinement

- Copper mesh build to conform to last closed flux surface
- Imposing equipotential on LCFS would lead to better agreement between equipotential surfaces and flux surfaces
- Confinement improved by a factor of 2, but less than expected
  - Misalignments detected in the boundary



P. W. Brenner et al. (2008)

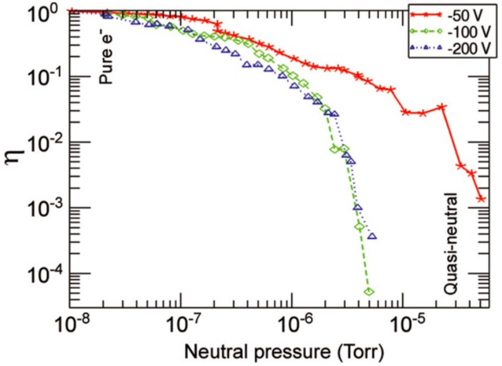


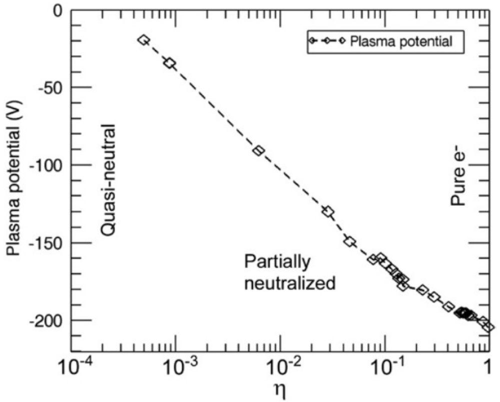
P. W. Brenner et al. (2010)

P. W. Brenner et al., *IEEE Trans. Plasma. Sci.* **36**, 1108 (2008)
P. W. Brenner et al., *Contrib. Plasma Phys.* **50**, 678 (2010)

Adjusting the degree of neutrality

- Degree of non-neutrality ***η*** could be varied continuously by adjusting the neutral gas density
- Plasmas could be maintained indefinitely at any degree of non-neutrality
- Key changes as ***η*** decreases
  - Decoupling of plasma potential from bias of emitter (electron source)
  - Characteristics of modes and fluctuations



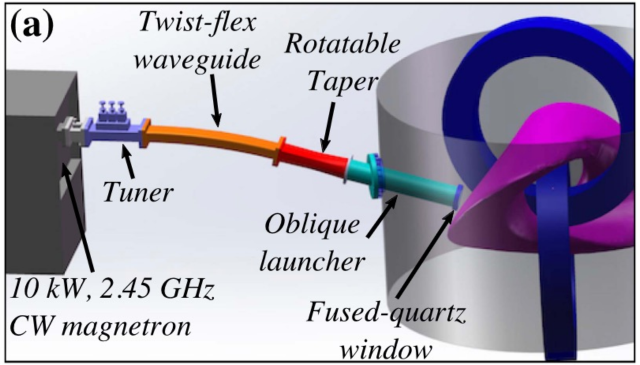


X. Sarasola and T. S. Pedersen (2013)

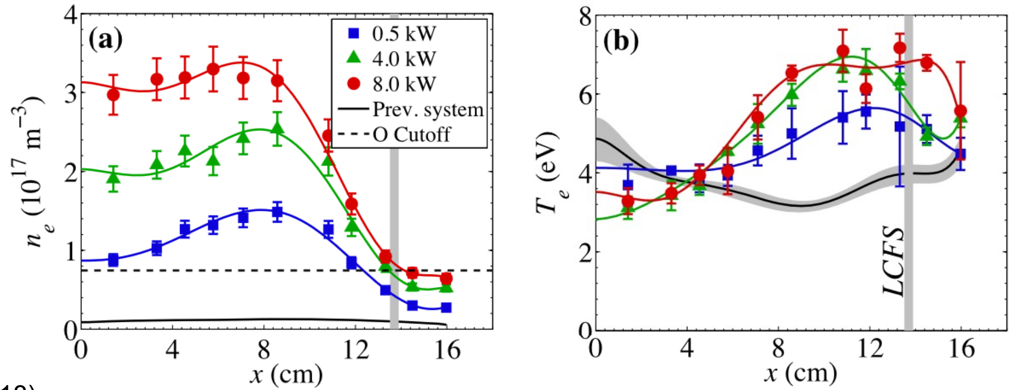
X. Sarasola and T. S. Pedersen, *Plasma Phys. Control. Fusion* **55**, 049601 (2013)

Transitioning to higher-power quasineutral plasmas

- 10 kW, 2.45 GHz microwave generator and launcher installed
  - 2.45 GHz resonates with electron cyclotron motion at 87.5 mT
- Increase in power brought about a substantial increase in density
  - Above nominal cutoff for 2.45 GHz in many cases
  - Cutoff assumes uniform plasma, which is not the case for CNT where $a_{minor} \sim \lambda$



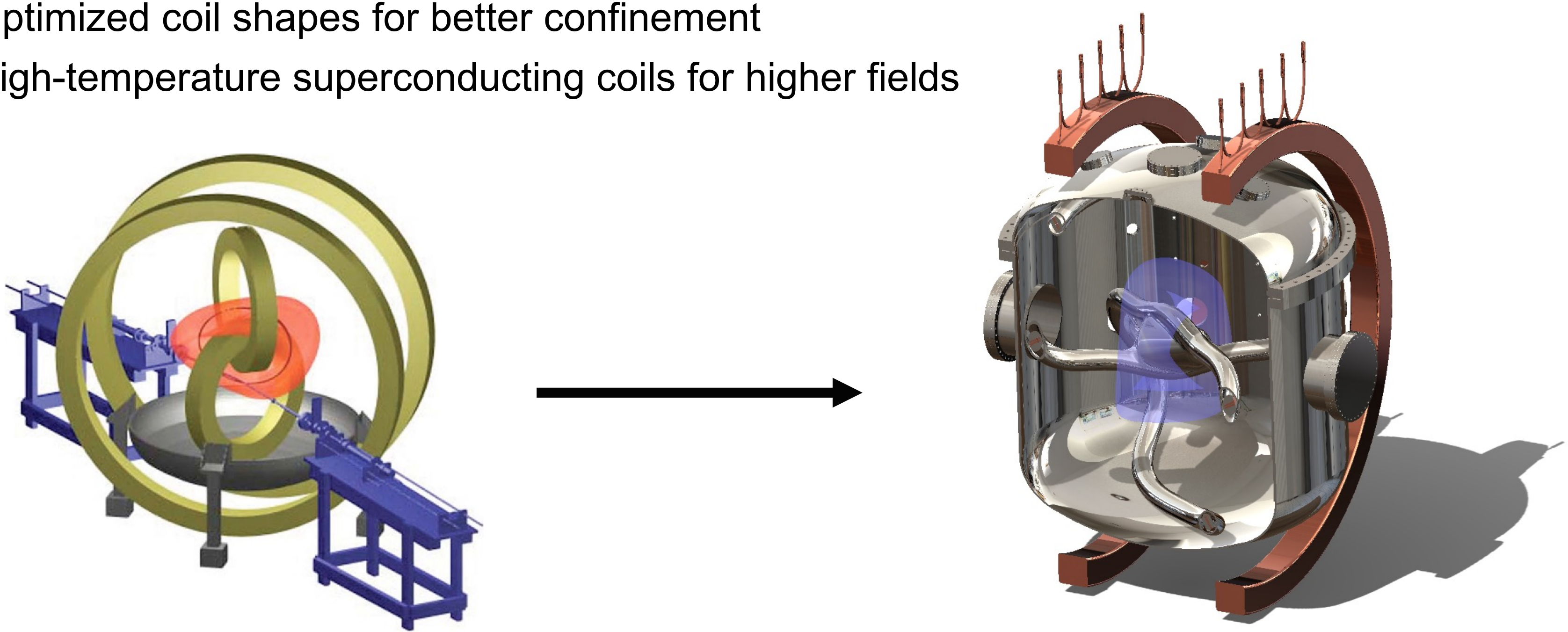
K. C. Hammond et al. (2018)



K. C. Hammond et al., *Plasma Phys. Control. Fusion* **60**, 025022 (2018)

The Columbia Stellarator Experiment (CSX)

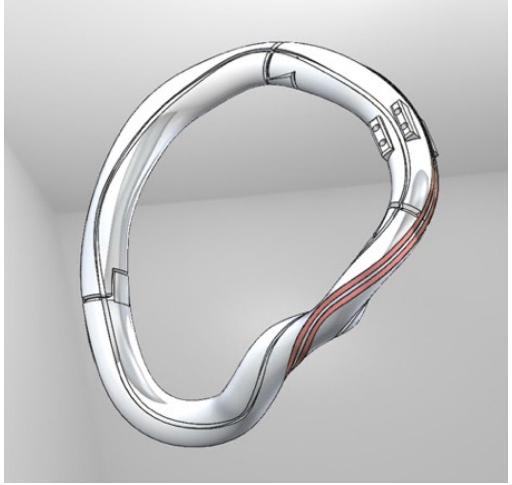
- CNT is now undergoing a major upgrade
  - Optimized coil shapes for better confinement
  - High-temperature superconducting coils for higher fields



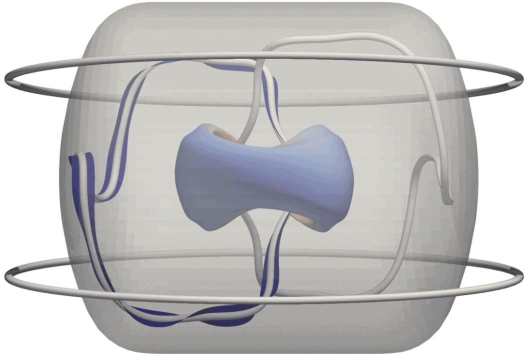
E. J. Paul et al.

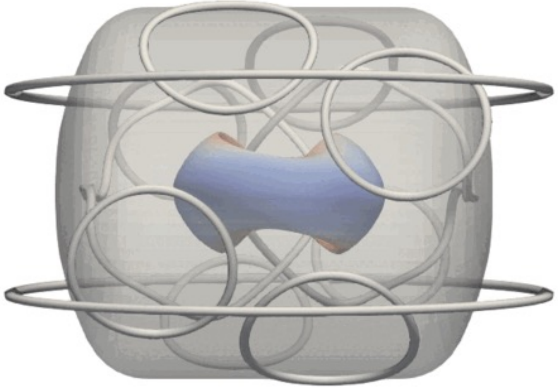
Optimizing the coil shapes for CSX

- Single-stage optimization approach employed
  - Plasma and IL coil shapes optimized together
  - Adding external coils improves quasisymmetry
- Winding pack geometry optimized to minimize strain on HTS tape



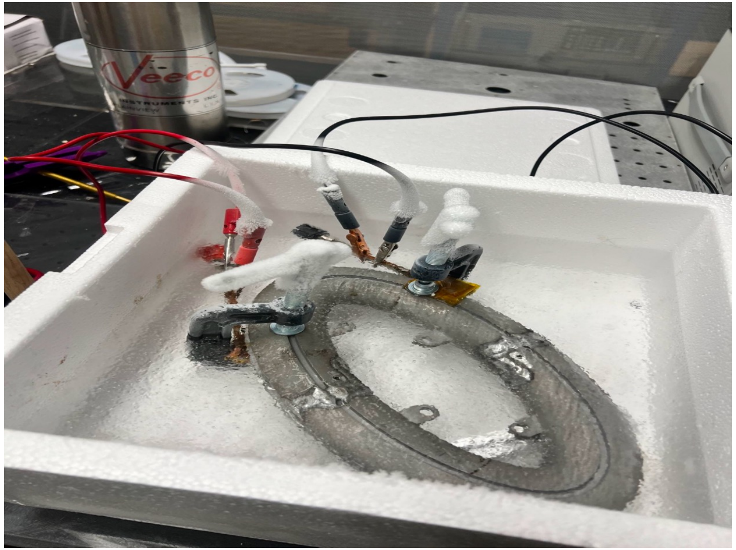
E. J. Paul, A. Baillod, et al.





Making coils out of high-temperature superconducting tape

- Test coils have been wound in the lab
- Test stand under development for cryogenic testing



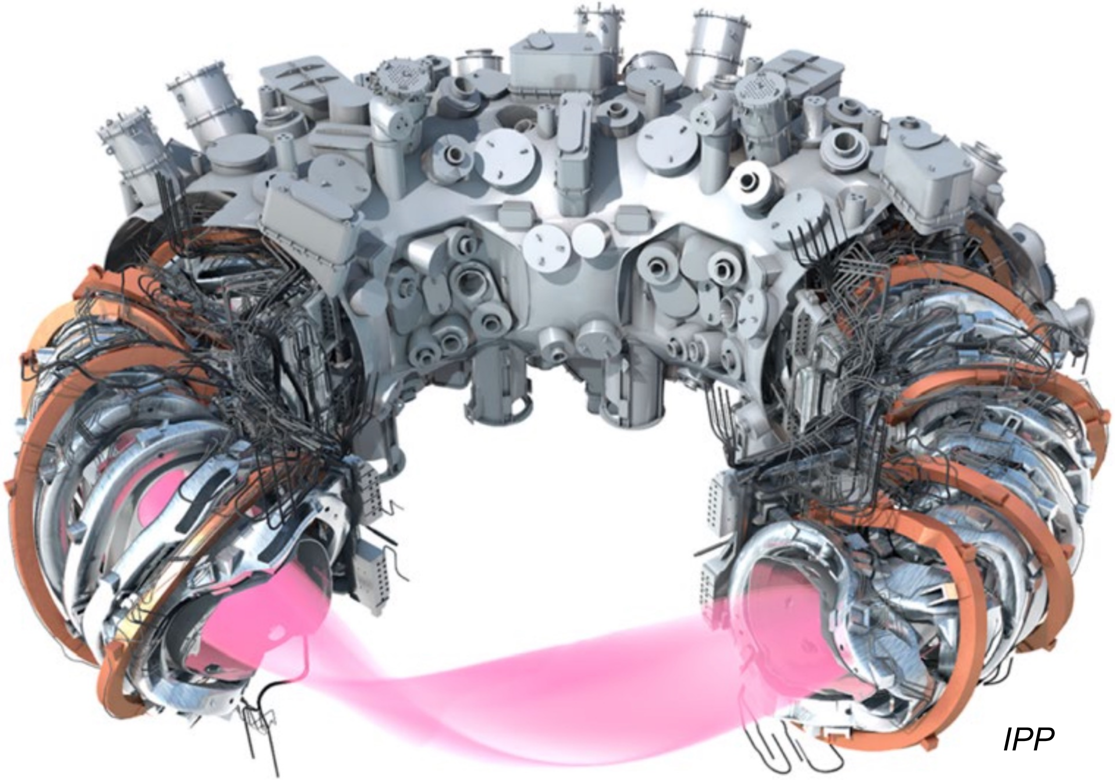
E. J. Paul et al.

PRINCETON
PLASMA PHYSICS
LABORATORY

Wendelstein 7-X

Introduction to Wendelstein 7-X

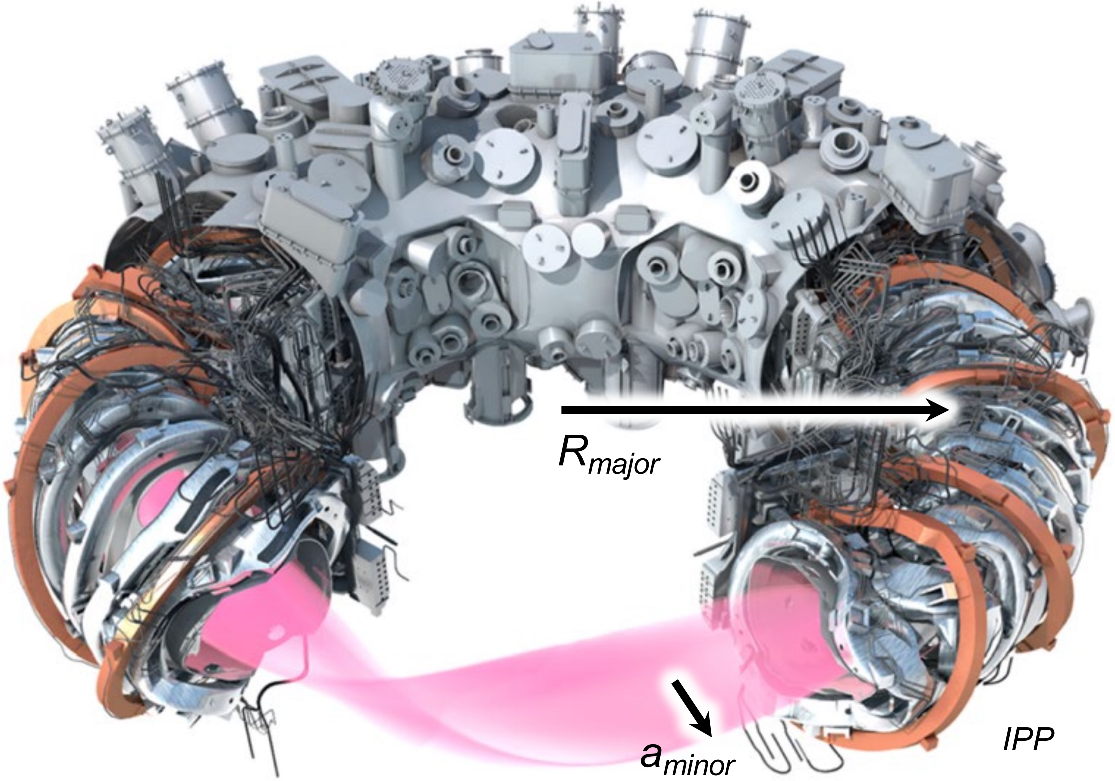
- World's largest and most advanced stellarator
- Located at the Max Planck Institute for Plasma Physics in Greifswald, Germany
- Design activities began in the late 1980s/early 1990s
- First plasma in 2015



IPP

Key characteristics

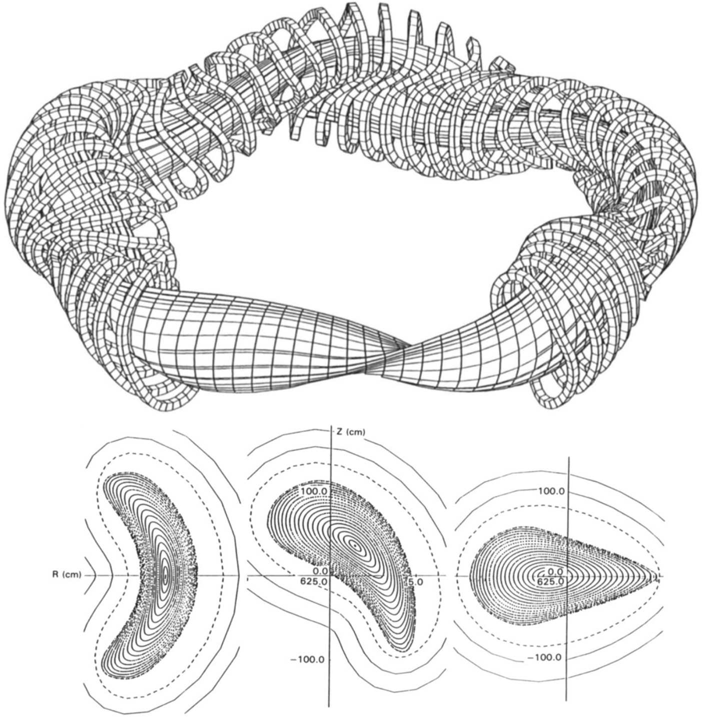
- R_{major}: 5.5 m
- a_{minor}: 0.55 m
- Field periods: 5
- Field strength: 2.5 T
- Heating power: ~10 MW
- Pulse length:
  - Up to ~10 min (to date)
  - Up to 30 min (long-term)



IPP

Designing the plasma

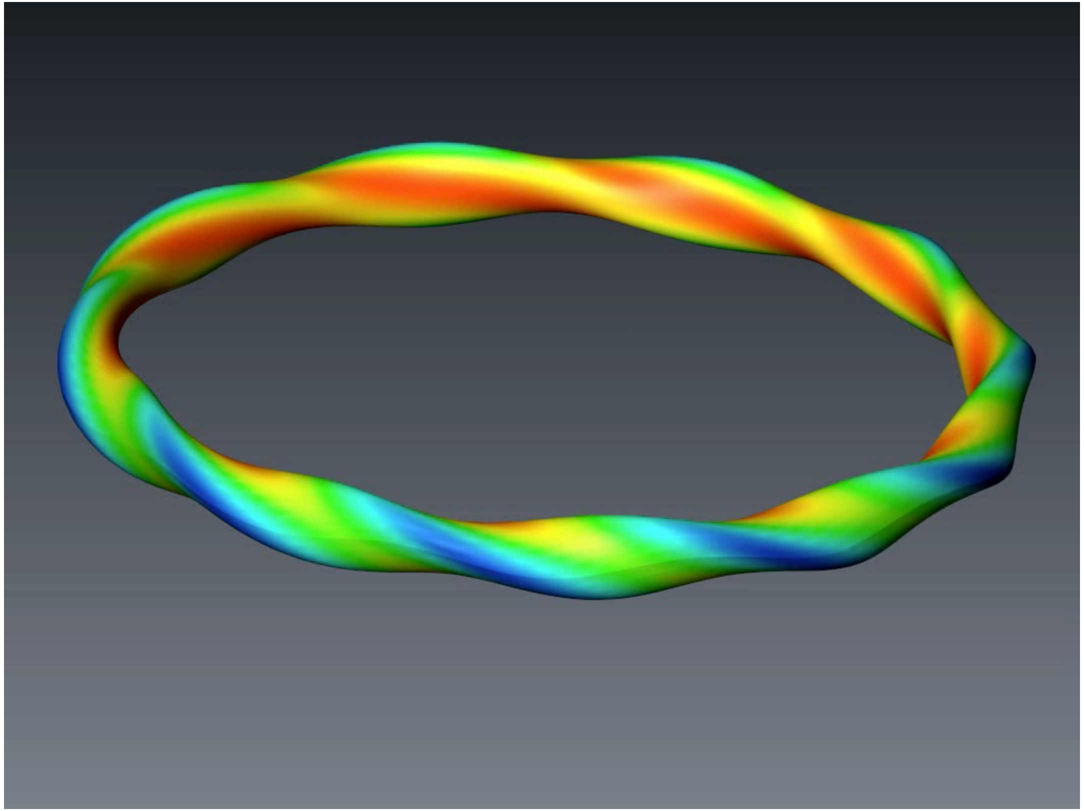
- Optimization criteria
  - High-quality magnetic surfaces
  - Good equilibrium properties up to $\beta = 5\%$
  - Magnetohydrodynamic stability up to $\beta = 5\%$
  - Reduced neoclassical transport
  - Improved fast-ion confinement
  - Small bootstrap current
  - Good modular coil feasibility



C. Beidler et al. (1990)

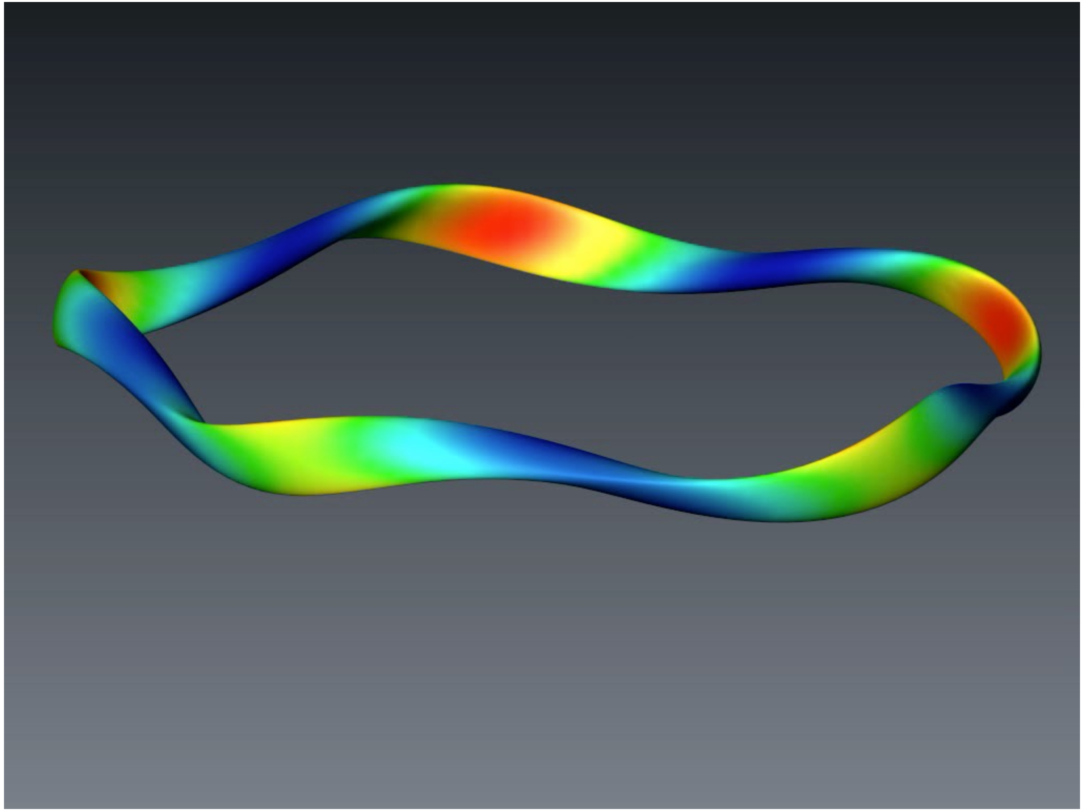
C. Beidler et al., *Fusion Technol.* **17**, 148 (1990)

Particle orbits in a non-optimized plasma



IPP

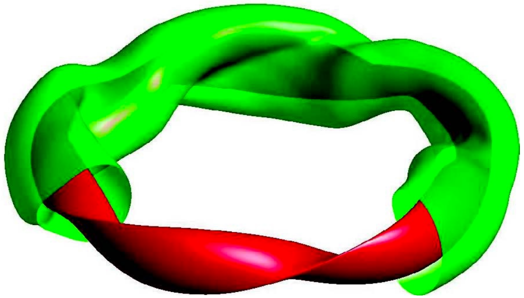
Particle orbits in Wendelstein 7-X



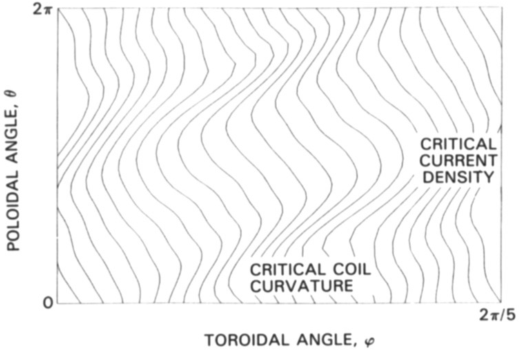
IPP

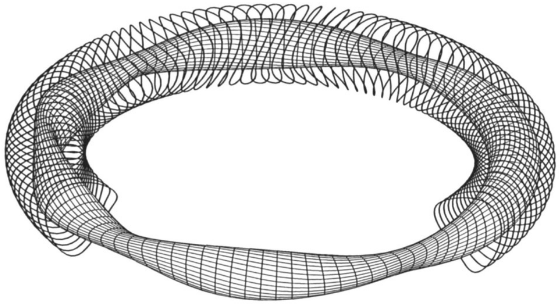
Determining the coil geometry

- Winding surface approach (using NESCOIL code)
  - Define a surface enclosing the plasma
  - Optimize 2D current distribution on surface to achieve desired field on plasma boundary
  - Calculate streamlines of current
    - Ensure not too close
    - Ensure curves not too tight
  - Streamlines form discrete coils



M. Landreman (2017)

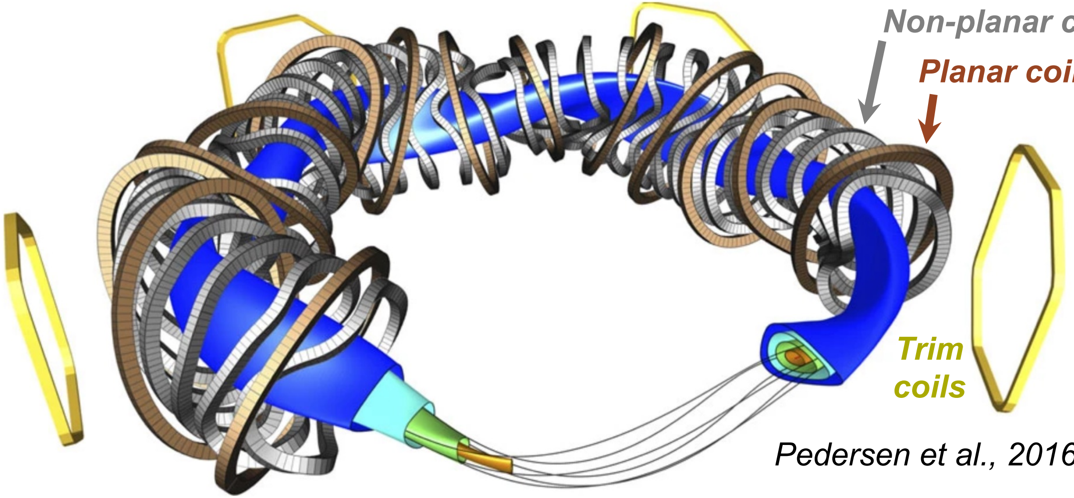




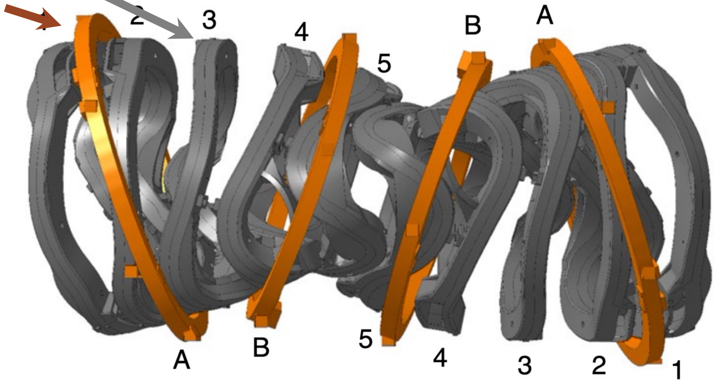
C. Beidler et al. (1990)

M. Landreman et al., *Nucl. Fusion* **57**, 046003 (2017)
C. Beidler et al., *Fusion Technol.* **17**, 148 (1990)

Coil set consists of 70 superconducting coils and 15 copper coils



Pedersen et al., 2016



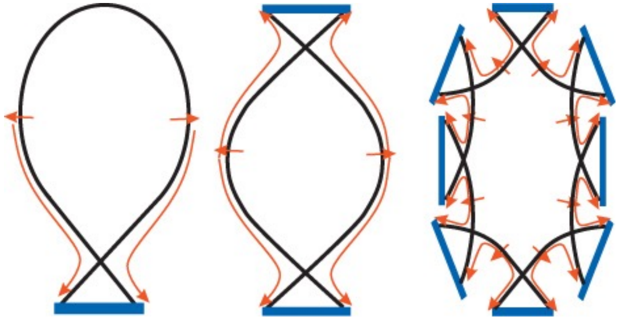
Dinklage et al., 2018

- 50 non-planar coils: primary source of field
- 20 planar coils: adjust rotational transform
- 5 trim coils: correct resonant error fields
- 10 control coils: modify edge fields (not shown)

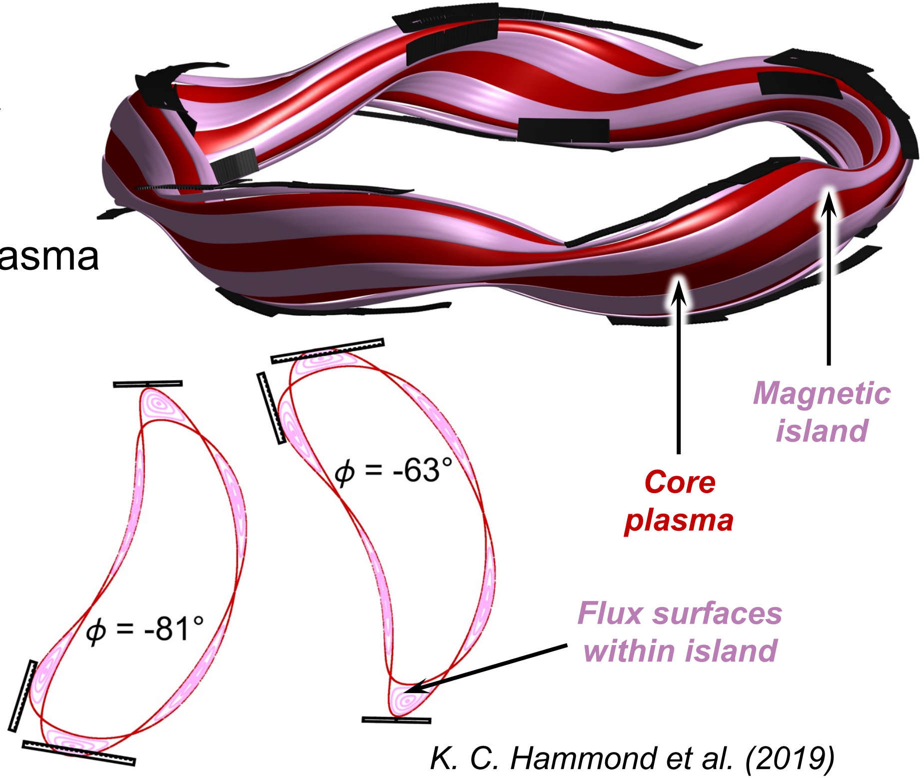
T. S. Pedersen et al., *Nature Comms.* **7**, 13493 (2016)
A. Dinklage et al., *Nature Phys.* **14**, 855 (2018)

The island divertor concept

- W7-X has naturally-occurring *magnetic islands* at the edge of the core boundary
- Divertor targets intersect islands
  - Divertor targets are protected from core plasma
  - Plasma flows into islands only via (slower) perpendicular transport



Y. Feng et al., (2006)

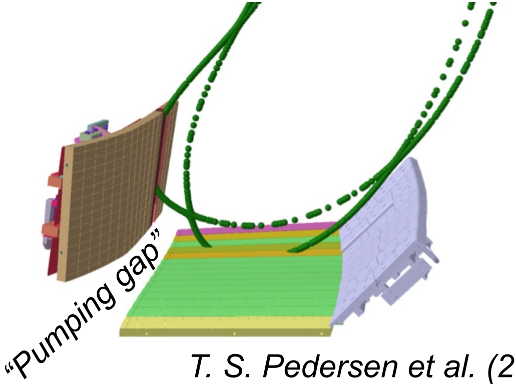


K. C. Hammond et al. (2019)

K. C.. Hammond et al., *Plasma Phys. Control. Fusion* **61**, 125001 (2019)
Y. Feng et al., *Nucl. Fusion* **46**, 807 (2006)

Functions of the divertor

- Protect other wall components from escaping core plasma
- Enable efficient pump-out of exhaust gases



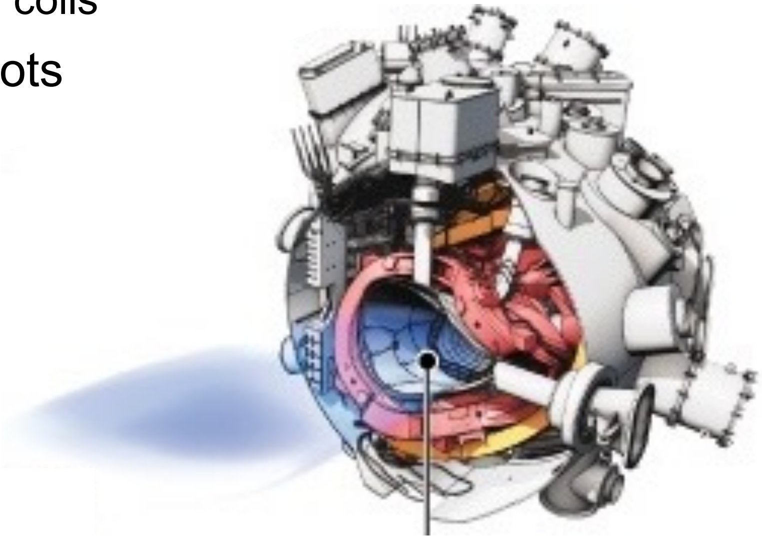
T. S. Pedersen et al. (2019)

H.-S. Bosch et al. (2020)

H.-S. Bosch et al., *IEEE Trans. Plasma Sci.* **48**, 1370 (2020)
T. S. Pedersen et al., *Plasma Phys. Control. Fusion* **61**, 014035 (2019)

Challenges with construction

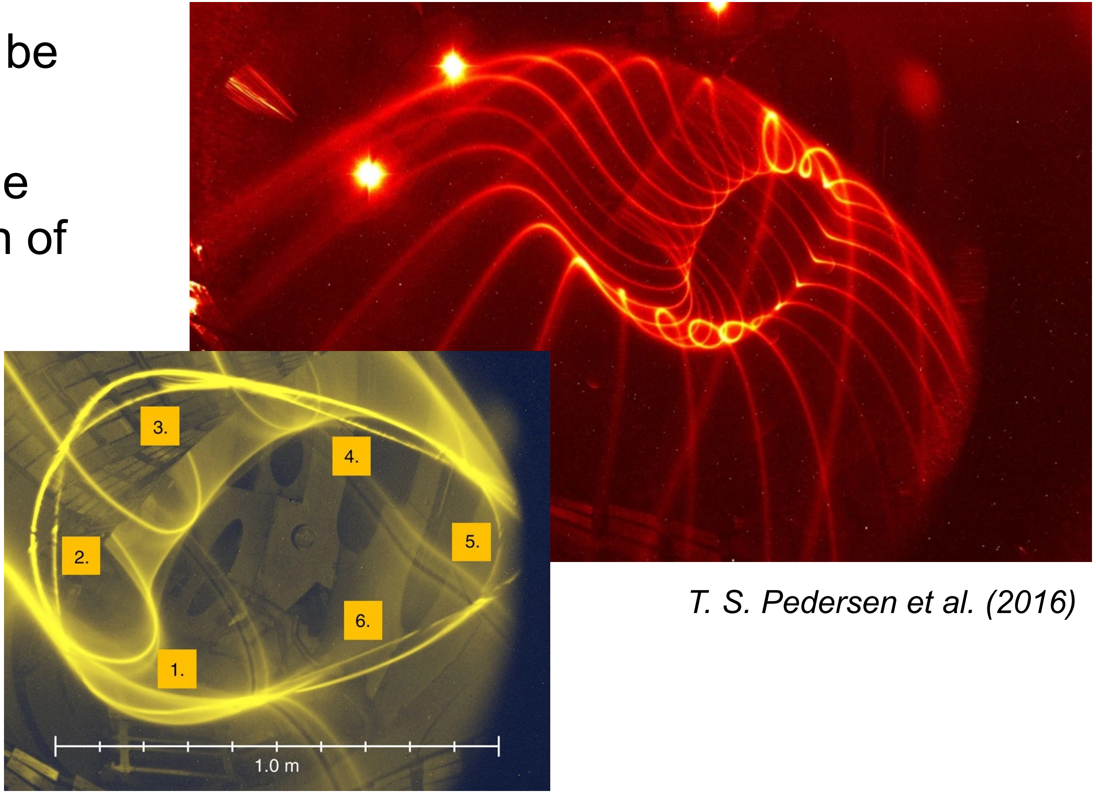
- Tight engineering tolerances
  - Coil shapes and positions accurate to ~1 mm (< 0.1% tolerance)
  - Divertor target positions accurate to ~10 mm (< 1% tolerance)
  - Plasma vessel and cryostat must snugly enclose coils
- Forces up to 4.4 MN (990,000 lbs) in some spots
- Cooling the coils to 3.9 K is "hell on Earth" (T. Klinger, director of W7-X)
- Organizational issues
  - 1/3 of manufactured coils rejected (failed tests)
  - One coil manufacturer went bankrupt



H.-S. Bosch et al., *Nucl. Fusion* **53**, 126001 (2013)
D. Clery., *Science News* (2015), doi.org/10.1126/science.aad4746

Verifying the field accuracy

- Field lines and flux surfaces can be measured with electron beams
- Observing magnetic islands in the cross-section enables calculation of resonant error field harmonic
  - Error field harmonic with mode numbers m=n=2 is 1.1 × 10^{-4}
  - Can be corrected by trim coils

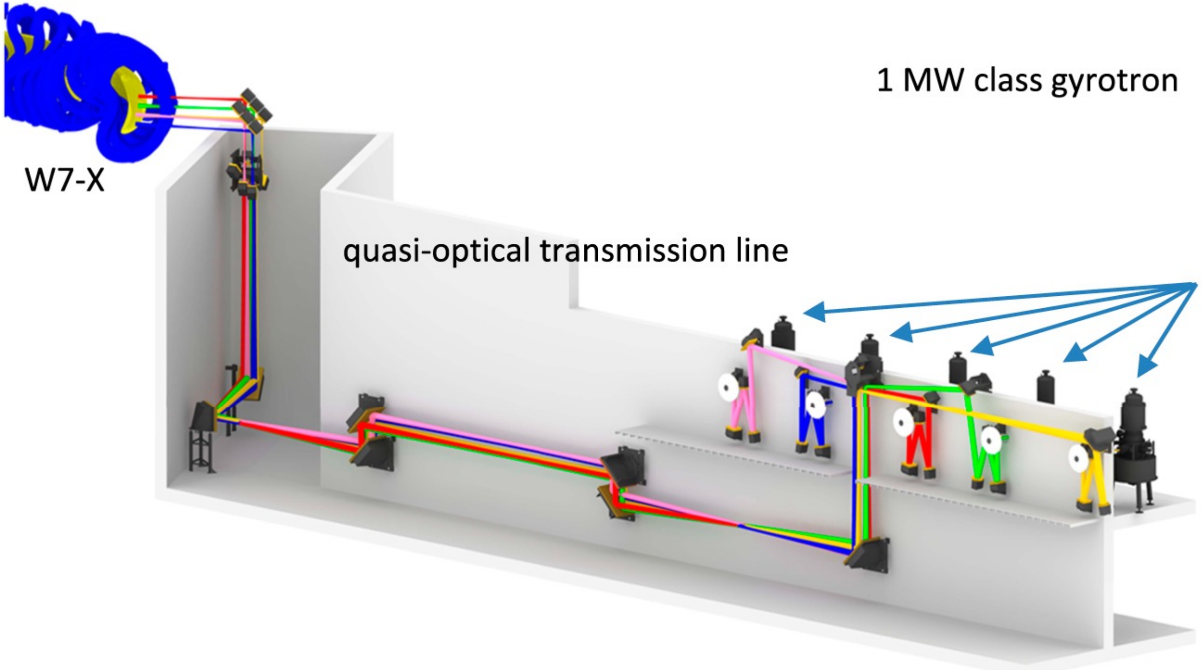


T. S. Pedersen et al. (2016)

T. S. Pedersen et al., *Nature Comms.* **7**, 13493 (2016)

Heating sources

- Electron cyclotron resonant heating

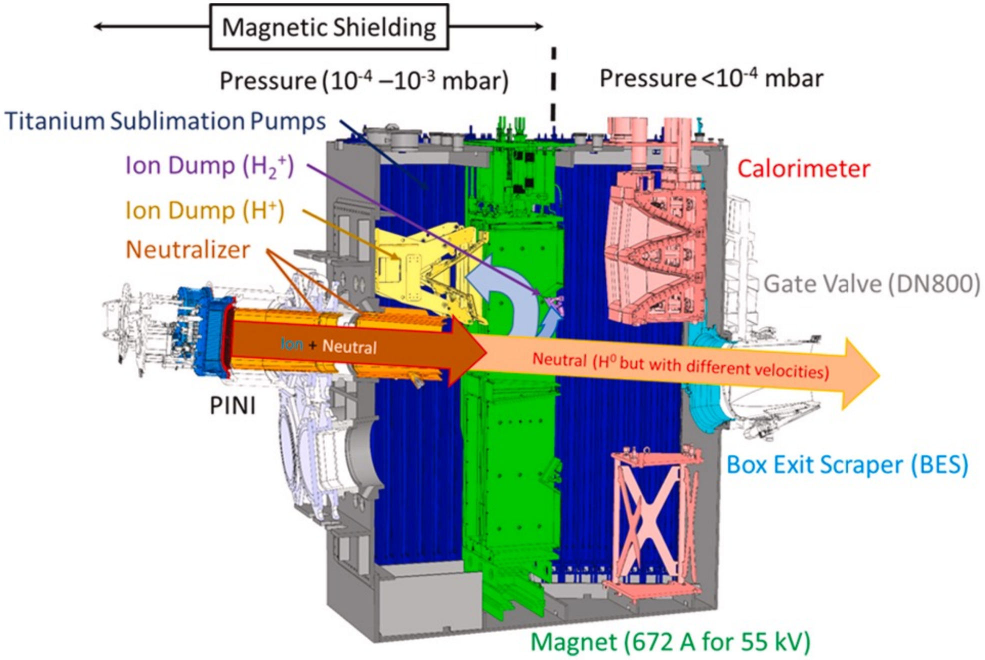


H. Laqua et al. (2021)

H. Laqua et al., *Nucl. Fusion* **61**, 106005 (2021)

Heating sources

- Electron cyclotron resonant heating
  - Gyrotrons
- Neutral beam injection
- Ion cyclotron resonant heating

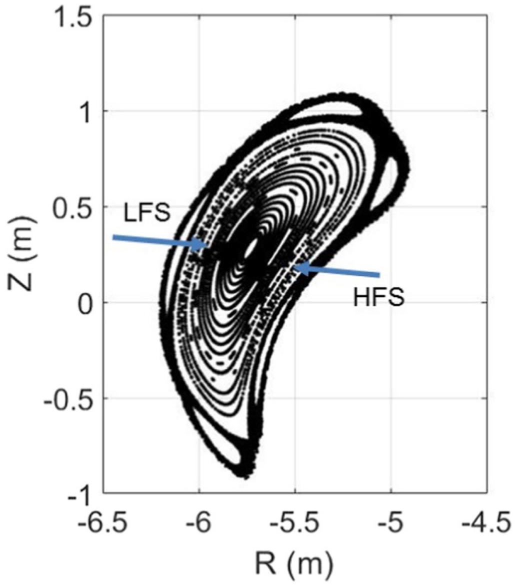


P. McNeely et al. (2020)

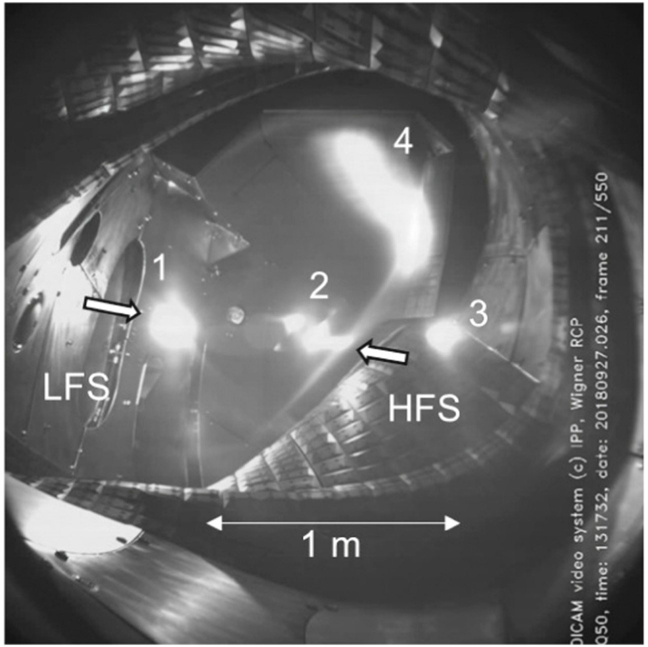
P. McNeely et al., *Fusion Eng. Des.* **161**, 111997 (2020)

Fueling

- Gas injection: injects particles in the plasma edge
- Pellet injection: injects particles in the plasma core
    - Pellets made of frozen H_2 or D_2
    - Launched into plasma at 200-1000 m/s
    - Ice ablates as pellet propagates through plasma



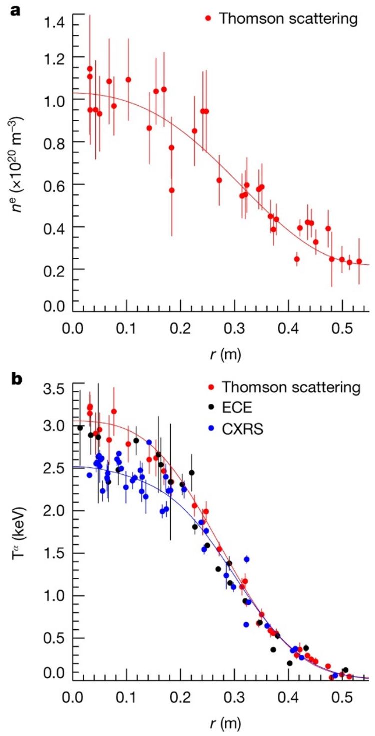
J. Baldzuhn et al. (2019)



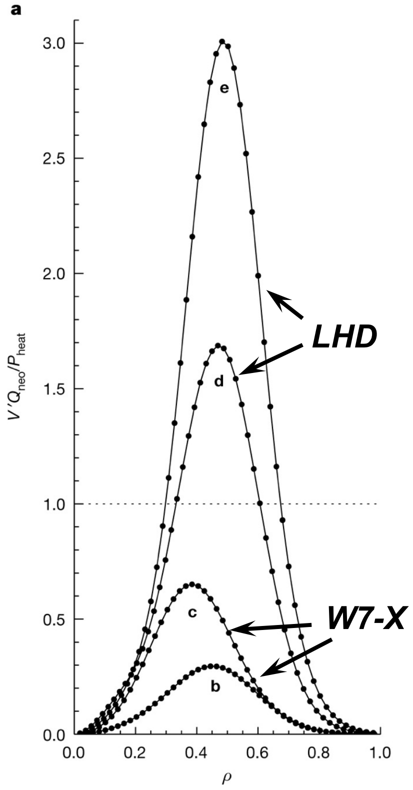
J. Baldzuhn et al., *Nucl. Fusion* **61**, 095012 (2019)

Confirmation of good neoclassical confinement

- Neoclassical heat flux can be calculated given:
  - Temperature and density profiles
  - Magnetic field configuration
- Calculated neoclassical heat flux for exemplary W7-X discharges is less than the total heating power
- For a non-optimized (e.g. in the Large Helical Device), the same profiles could not be sustained with the same heating power



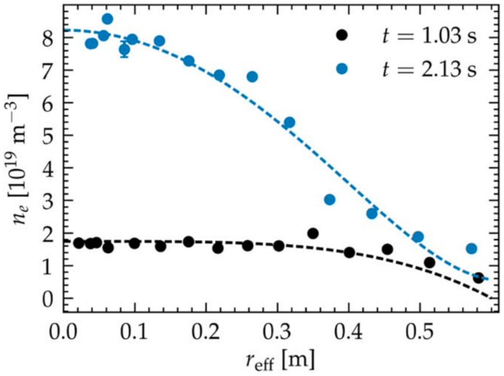
C. Beidler et al. (2021)



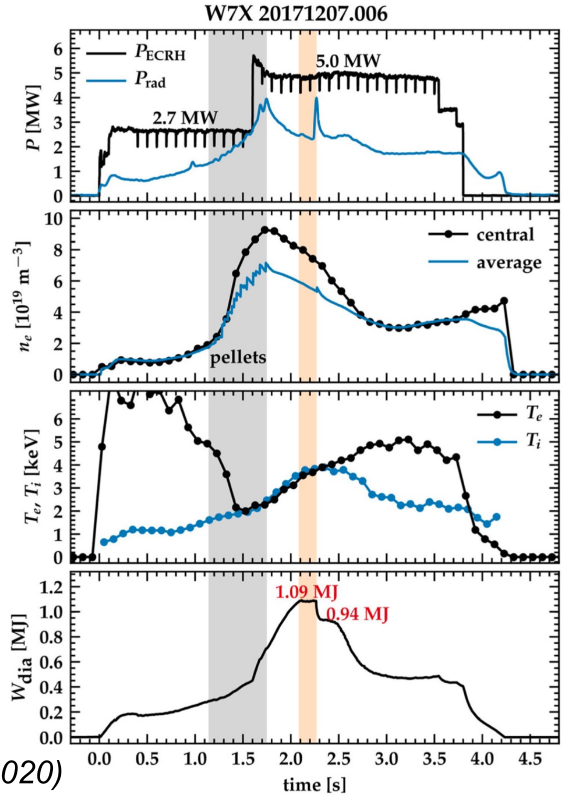
C. Beidler et al., *Nature* **596**, 221 (2021)

Achieving a record fusion triple product

- Higher triple product ($nT\tau$)
  → better conditions for fusion
- W7-X holds the record for triple product achieved in stellarators
- Key characteristics
  - Achieved with pellet injection and ECRH
  - Didn't last long – pellet injection was transient
  - Peaked profile of density
  - Low turbulence



T. S. Pedersen et al. (2019)

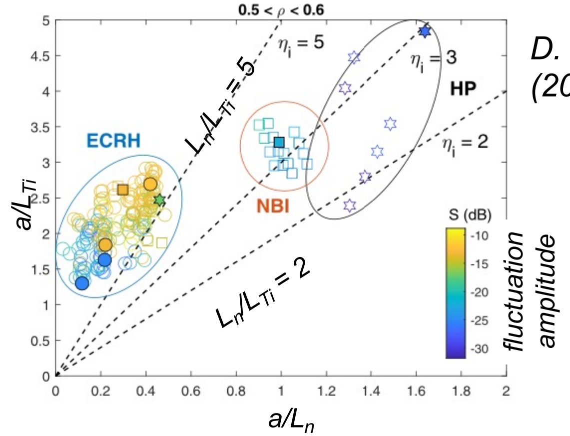


R. C. Wolf et al. (2020)

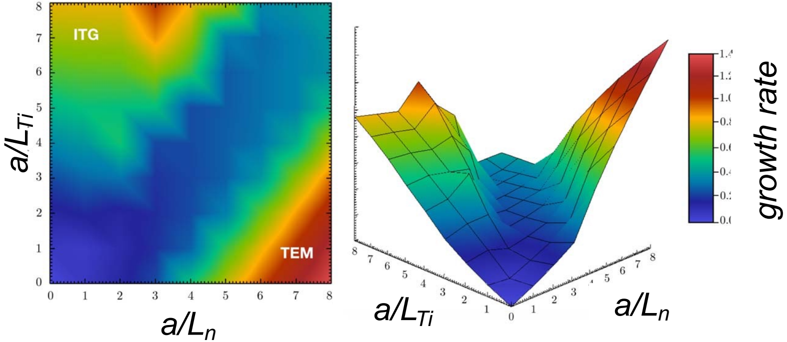
T. S. Pedersen et al., *Plasma Phys. Control. Fusion* **61**, 014035 (2019)
R. C. Wolf et al., *Phys. Plasmas* **26**, 082504 (2019)

Reducing turbulent transport with profile shaping

- Density and temperature gradients impact micro-instabilities
  - Trapped-Electron Mode (TEM)
  - Ion Temperature Gradient (ITG)
- W7-X can avoid both TEM and ITG if normalized T_i and n_e gradients are equal
  - Highest performance discharge exhibited gradient ratio L_n/L_{Ti} closest to 1
  - Observed turbulent fluctuations tend to be lower for L_n/L_{Ti} closer to 1
  - When L_n/L_{Ti} plasma is in a “stability valley” according to linear gyrokinetic calculations



D. Carallero et al. (2021)



J. Alcusón et al. (2020)

D. A. Carallero et al., *Nucl. Fusion* **61**, 096015 (2021)
J. Alcusón et al., *Plasma Phys. Control. Fusion* **62**, 035005 (2020)

Future goals for Wendelstein 7-X

- Run long-pulse discharges (30 minutes)
- Control plasma profiles in real time for high performance
- Combine high core performance with a safe edge scenario
- Operate at high beta (5%)
- Install a tungsten divertor

CNT and Wendelstein 7-X

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PPPL/Simons Stellarator Summer School, July 29, 2024

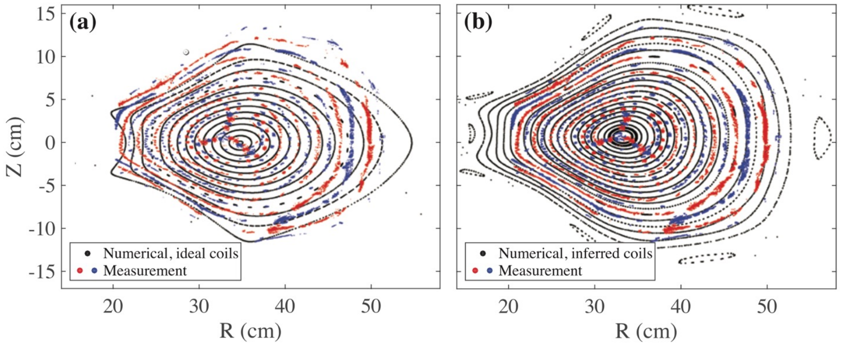
Flux surface measurements indicated presence of error fields

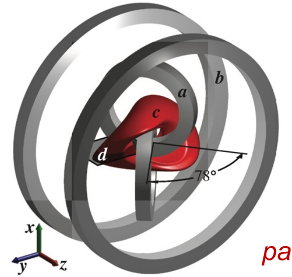
- Following a change of the IL tilt angle, discrepancies observed between measured and modeled flux surfaces
- Inferring rigid coil displacements
  - Defined discrete parametrization of surface geometry
  - Implemented inverse method to infer coil offsets for model to match measurement
- Discrepancies explained by ~1º offset in tilt angle and ~3 mm excess IL coil separation

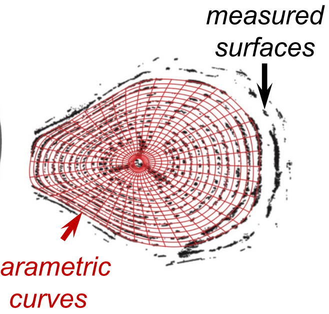
Comparisons with measurement:

without *inferred coil offsets in calculation*

with *inferred coil offsets in calculation*





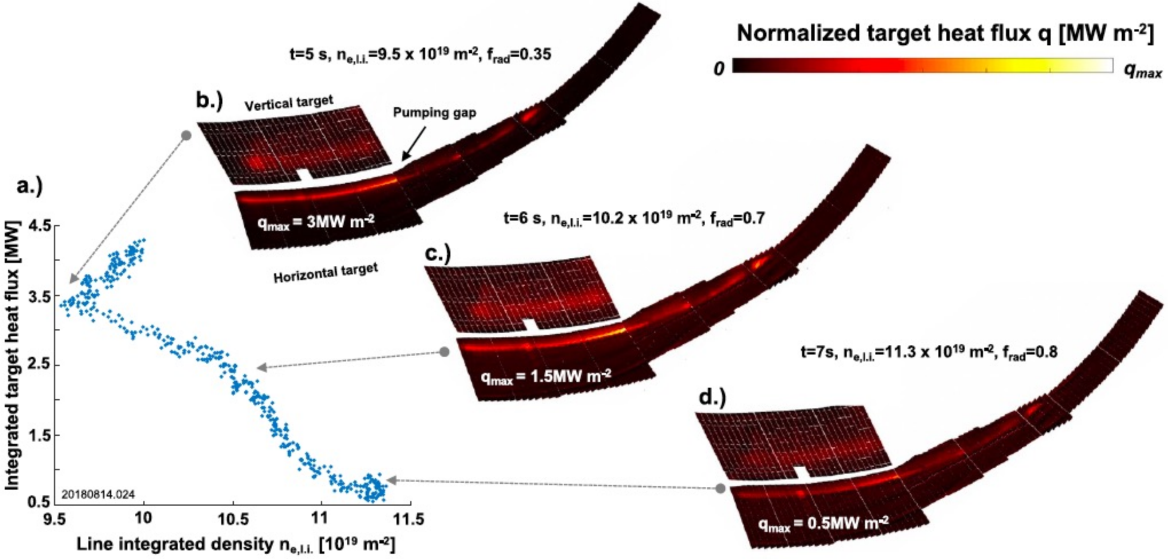

measured surfaces

parametric curves

K. C. Hammond *Plasma Phys. Control. Fusion* **58**, 074002 (2016)

Keeping the edge cool

- Impurity seeding
    - Impurity gases cool edge plasma by radiating
    - Cooler edge plasma reduces loads on divertor targets
- Detachment: nearly all exhaust power radiated
    - Minimal loads on divertor targets
    - Achieved by seeding and/or divertor erosion
- W7-X can maintain detached discharges for > 30 s



O. Schmitz et al. (2021)

O. Schmitz et al., *Nucl. Fusion* **61**, 016026 (2021)