The US Stellarator Program: On the path to a stellarator Fusion Pilot Plant

Fusion Power Associates, 43rd Annual Meeting and Symposium: The Road Ahead – 2022-12-07

Novimir Pablant[a]

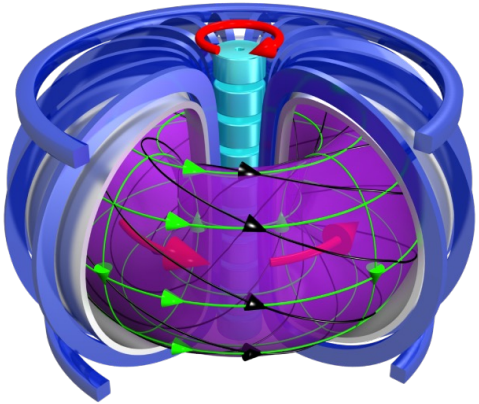
PPPL – Head, Stellarator Experiments Division

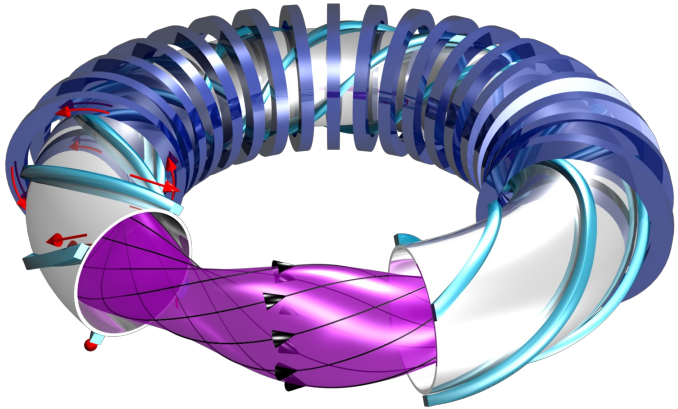
Chair, National Stellarator Coordinating Committee (NSCC)

[a] npablant@pppl.gov

Stellarators are an alternative magnetic configuration to Tokamaks

Stellarators and Tokamaks generate the confining magnetic field differently





Tokamak

magnetic field from plasma current and 'simple' 2D external coils

- **Requires current drive or pulsed operation**

ITER is a tokamak

Stellarator

Magnetic field entirely from 3D external coils

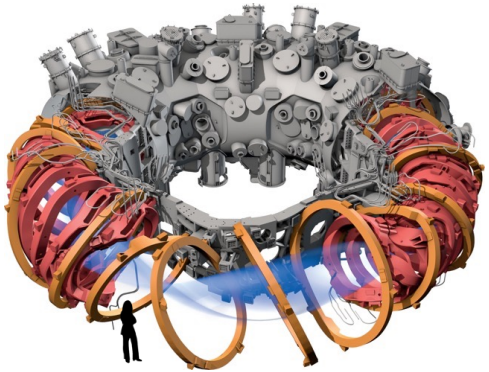
- **Intrinsically steady state, disruption free**

Wendelstein 7-X is a stellarator

Stellarators have several advantages over Tokamaks

Advantages of Stellarators:

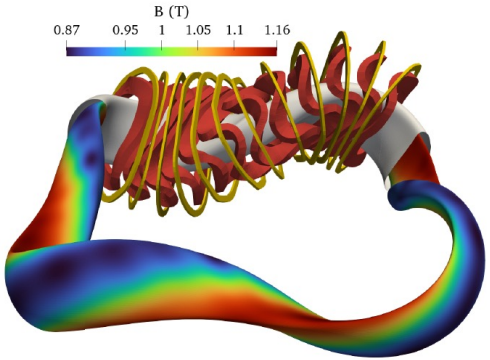
- Intrinsically steady-state
- No disruptions or transient events (ELMs)
- Current drive not required
- High density operation possible
- Improved power handling
  - Advanced 3D divertor concepts possible



W7-X in Greifswald, Germany

Recent advances in Stellarator design make stellarators attractive as a reactor concept

- Optimized stellarators have neo-classical and fast-ion confinement comparable to Tokamaks
- The new frontier in stellarator theory allows for reduction in turbulence by design



HSX in Madison, Wisconsin

Stellarators are part of the US community strategic plan on the path to a Fusion Pilot Plant

The clear advantages of stellarators make them attractive as pathway to a Fusion Power Plant (FPP)

- Part of the Community Strategic Objectives for the US Fusion Science and Technology program

The FESAC long range plan *Powering the Future: Fusion and Plasmas* includes stellarators as a key part of US fusion priorities.

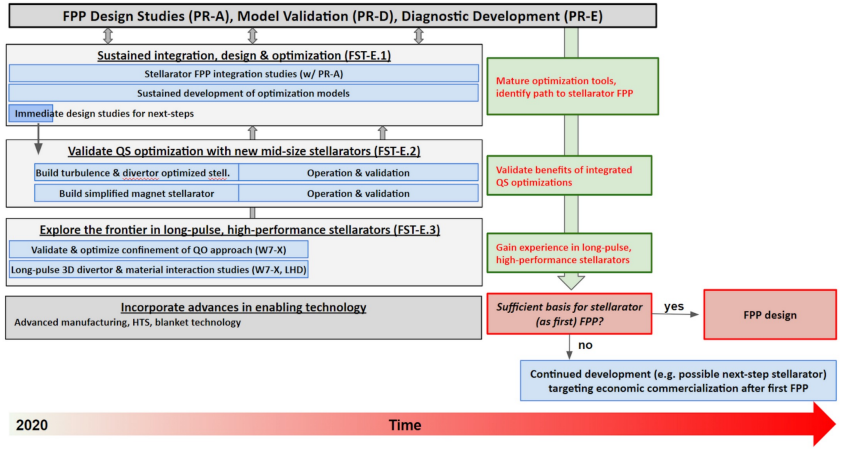
The *National Academy of Sciences: Bringing Fusion to the U.S. Grid* report was made independent of confinement concept.

- The most promising configuration for a FPP should be chosen based on scientific and technological readiness

A Community Plan for Fusion Energy and Discovery Plasma Sciences

FST Strategic Objective E: Advance the stellarator physics basis sufficiently to design a low cost fusion pilot plant

The stellarator has unique features that make it attractive as a fusion energy reactor. It is intrinsically steady state, can operate at high plasma density to achieve high gain while potentially relaxing plasma exhaust constraints, has relatively benign responses to magnetohydrodynamic instabilities, avoids current-driven disruptions, and has low recirculating power needs. These benefits all provide an opportunity to develop a net electric pilot plant at low capital cost.



Development of the scientific and technological basis for a stellarator FPP

The US stellarator research program aims to:

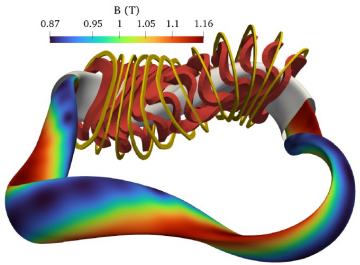
- Close remaining scientific and technological gaps
- Validate and expand the suite of predictive codes
- Develop the next generation of design tools

To achieve these goals a broad program exists including:

- Universities, National Laboratories & Private Industry
- Domestic experiments & International Collaborations
- Collaborations on theory and tool development

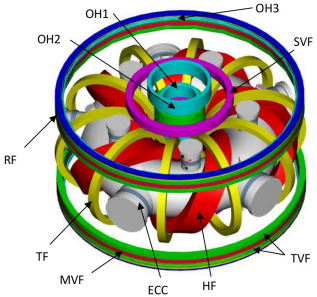
There are Several Domestic (or US) Stellarator Experiments

HSX
Madison, Wisconsin



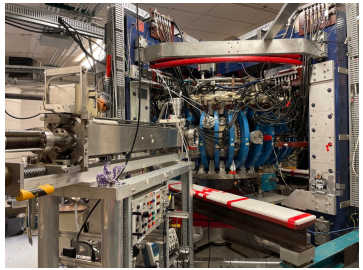
quasi-helical symmetry; turbulence reduction through plasma shaping

CTH
Auburn, Alabama



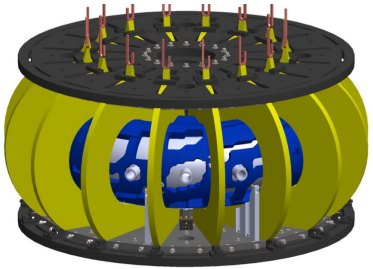
Steady-state operation; operational limits; equilibrium reconstruction

HIDRA
Champaign, Illinois



Plasma–wall interactions; wall conditioning; lithium wall concepts

MUSE
Princeton, New Jersey



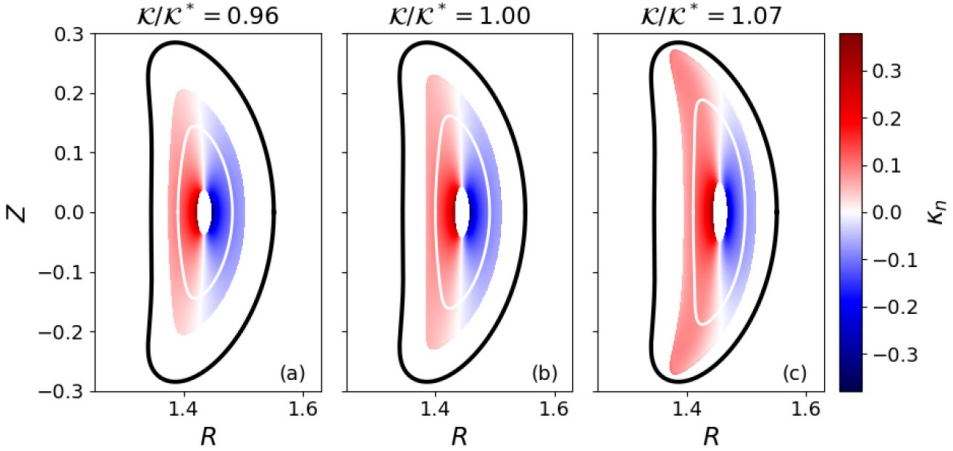
Quasi-axial symmetry; permanent magnets; advance manufacturing

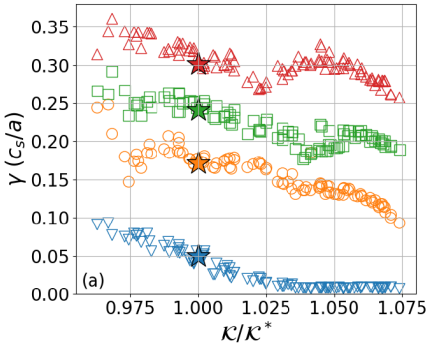
These institutions (along with others) are the bedrock of the US workforce development for stellarator physics

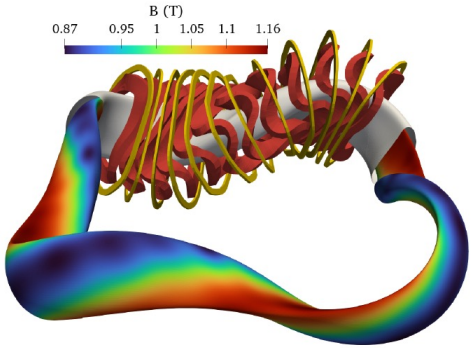
Optimizing the HSX Stellarator for Micro-instabilities (turbulence) by Coil-Current Adjustments

M. J. Gerard, B. Geiger et al, submitted to NF

- **Changes to individual coil currents in HSX allows for modification of the magnetic field geometry while maintaining comparable quasi-symmetry**
- **Linear gyrokinetic growth rates of Trapped Electron Modes are strongly reduced for configurations with increased elongation**



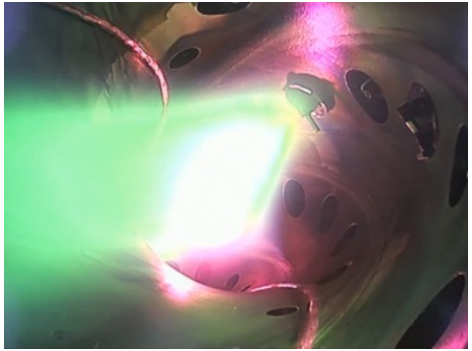




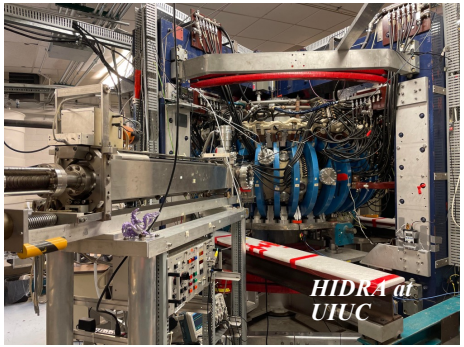
- **Upgrades of HSX (recently completed) provide substantial new capabilities including the ability to validate these theoretical predictions**

WISCONSIN
UNIVERSITY OF WISCONSIN · MADISON

Hybrid Illinois Device for Research and Applications (HIDRA)



Result of evaporating lithium into a helium plasma in HIDRA

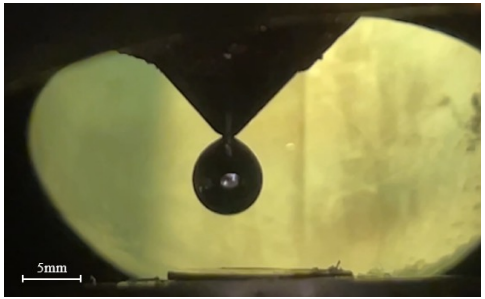


Functions as an experimental plasma-material interaction research device to help develop plasma-facing components (PFCs)

Long-pulse plasmas have been demonstrated up to 5400 seconds

Current research projects in both public and private fusion collaborations focus on lithium's beneficial effects on plasma parameters and PFCs

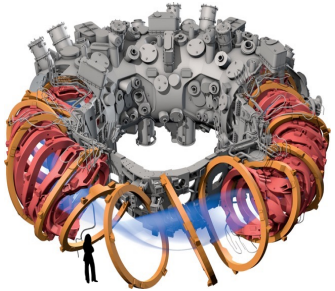
Results are relevant to long pulse Operation and PFC development for both tokamaks and stellarators



Application of a lithium droplet to a tungsten sample in HIDRA-MAT

International collaborations form a critical part of the US stellarator program

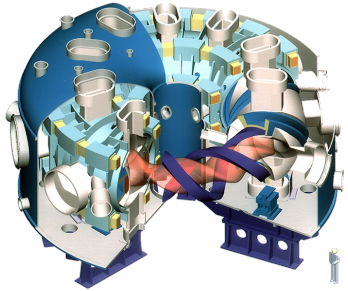
W7-X
Greifswald, Germany



Optimized Stellarator

Development of scenarios for Long-pulse, high-power, steady-state operation

LHD
Toki, Japan



Classical Heliotron

Theory validation; steady-state wall conditioning

Participation in international experiments allows the US to benefit from research on these world class facilities while also substantially contributing to the success of these experiments.

Continuous Pellet Fueling System (CFPS) for W7-X

International team has developed CPFS for W7-X at Max-Planck IPP, Greifswald, Germany

- **Prototype for ITER pellet fueling system (in development at ORNL)**

ORNL: **pellet extruder, accelerator, mass detector, system integration**
PPPL: **controller, vacuum components**
NIFS: **cryocoolers**
IPP: **physical and control system integration with W7-X facility**

Features: continuous injection of 10 pellets per second for 30-minutes

Status: installed at W7-X; control system integration in progress

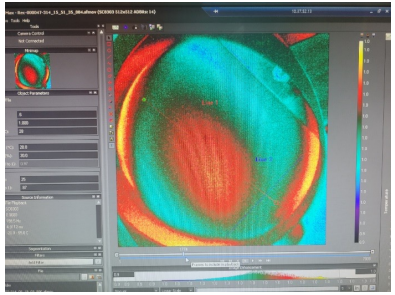
- **Goal: steady-state density profile control to optimize confinement (reduce turbulence)**

The US is a key collaborator in the W7-X program

New: Infrared Imaging Bolometer

Los Alamos NATIONAL LABORATORY EST. 1943

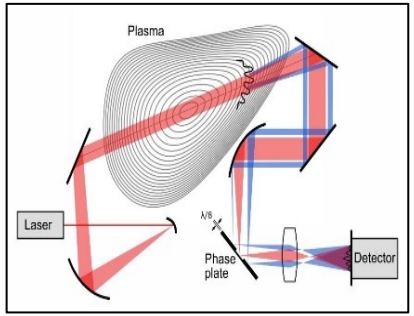
Sensitive, new tool to study divertor heat handling and thermal detachment during high-power steady-state operation.



Phase Contrast Imaging

MIT PSFC Cortland SUNY

Primary diagnostic for measurements of core turbulence; key to understanding improved confinement regimes and for validation of theory

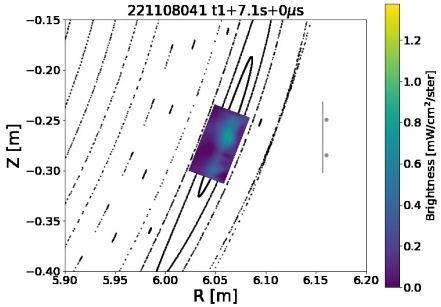


New: Gas Puff Imaging

MIT PSFC

Enables measurement of edge turbulence;

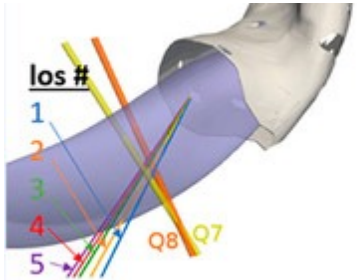
Will enable entirely new physics of edge and island transport to be studied in W7-X



New: Impurity Charge Exchange

WISCONSIN

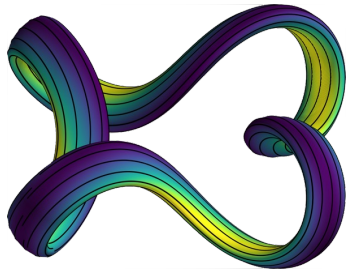
Highly tunable charge-exchange spectrometer enabling measurement of impurity densities; key diagnostic to impurity control, a critical reactor topic



Predictive Theory and Stellarator Design Tool Development

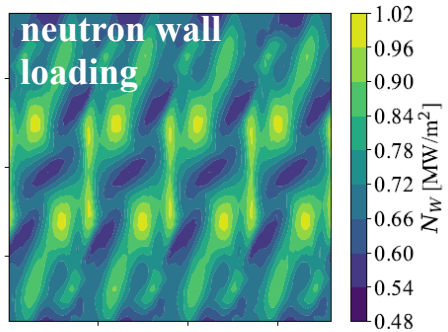
Several collaborative efforts are underway to develop tools for reactor design

Hidden Symmetries



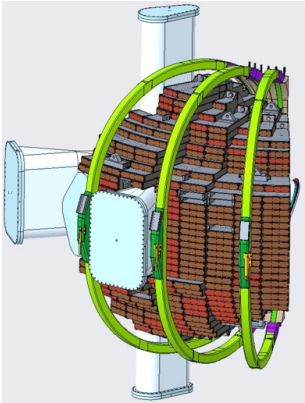
Develop mathematical and programmatic tools to design advanced stellarators

Reactor Design



Develop tools for stellarator reactor design incorporating advanced predictive tools

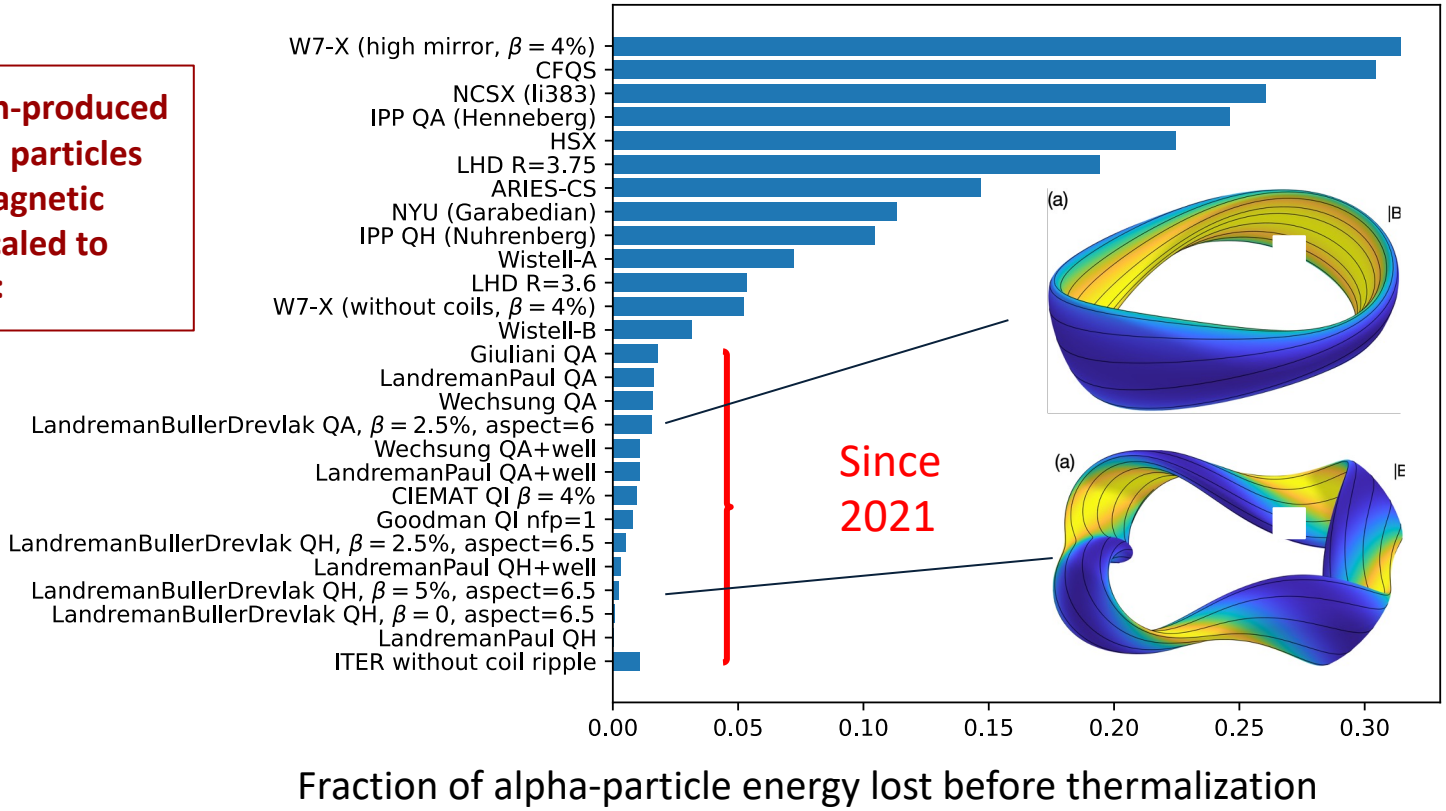
Permanent Magnets



Novel developments for magnetic field shaping to simplify stellarator reactor construction

Stellarators can now be designed with comparable or lower α-particle losses to tokamaks

Trajectories of fusion-produced distribution of alpha particles followed in many magnetic configurations, all scaled to reactor size and |B|:



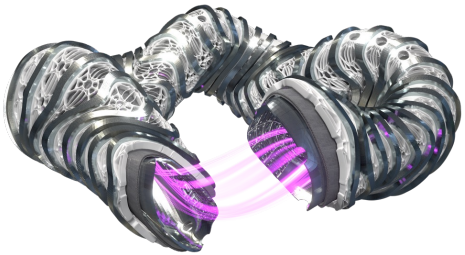
Landreman & Paul PRL (2022), Wechsung et al PNAS (2022), Giuliani et al JPP (2022), Landreman, Buller & Drevlak PoP (2022)

Private Investment in Stellarator Fusion Concepts

Several private companies have been formed with a goal of developing a stellarator fusion reactor

- Close collaboration with National Laboratories and Universities is being pursued

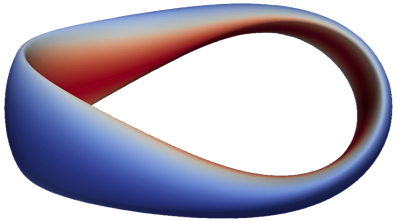
TYPE ONE ENERGY



Princeton Stellarators

psi

STELLAREX



Princeton Stellarators Inc. (PSI)

PSI spun out IP and team from Princeton University / PPPL in 2022

- Founded in April 2022 by David Gates, Brian Berzin, and Matt Miller.
- Exclusive license executed with Princeton University for key stellarator IP.
- PSI's proprietary architecture eliminates complicated, modular stellarator coils by utilizing high-fidelity arrays of High Temperature Superconducting planar coils.
- Raised $3M seed round in July 2022 (Lowercarbon Capital, 11.2 Capital, Mercator Partners, among others).
- As of December 2022, 10 employees, and will be growing rapidly in 2023.
- Pre-conceptual design underway for PSI's first stellarator system.

TYPE ONE ENERGY

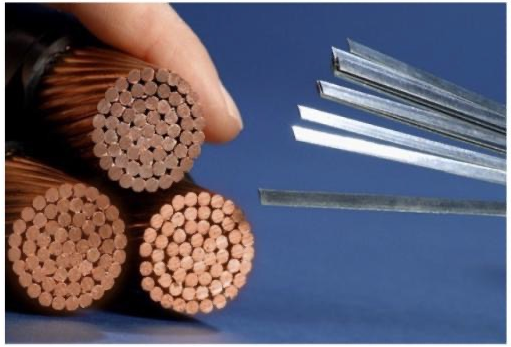
Type One Energy's vision is to make the ultimate clean energy source using the stellarator.

Type One Energy Officers: David Anderson, John Canik, Paul Harris, Chris Hegna, Thomas Sunn Pedersen, Randall Volberg

Website: https://www.typeoneenergy.com

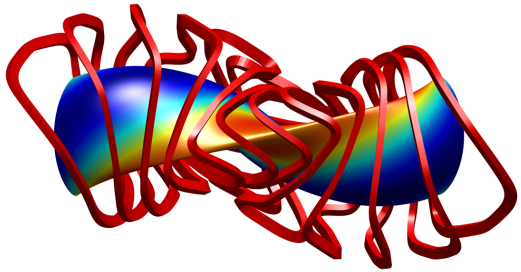
Key technology elements:

High Temperature Superconducting Magnets



Advanced Design, Manufacturing and Materials

Plasma Physics Optimization



Stellarators: The Road Ahead

New upgrades in domestic and international stellarator experiments are now coming online

- Expect another leap in the stellarator Scientific and Technological basis!

Theoretical predictive tools continue to improve

- Validation against experiments provides confidence in predictive capability
- New opportunities for optimization and improved concepts continue to be found

A completely new generation of stellarator design tools is now reaching maturity

- Theses effort will form the basis for the generation of a next step experiment or FPP

Private industry is poised to accelerate stellarator development

- With close ties to University and National Laboratory programs to leverage scientific advances