TABLETOP PERMANENT MAGNET STELLARATOR

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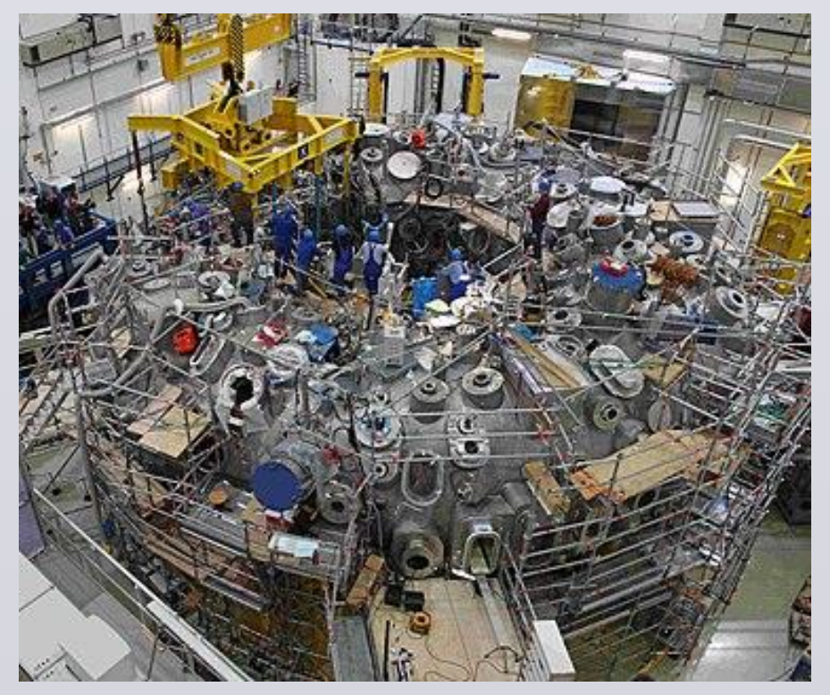
PROJECT GOALS

- As an outreach initiative of the Science Education department at PPPL, this project intends to highlight Stellarators in an easy and accessible device.
- This apparatus could also be used by students to learn about confinement with permanent magnets.

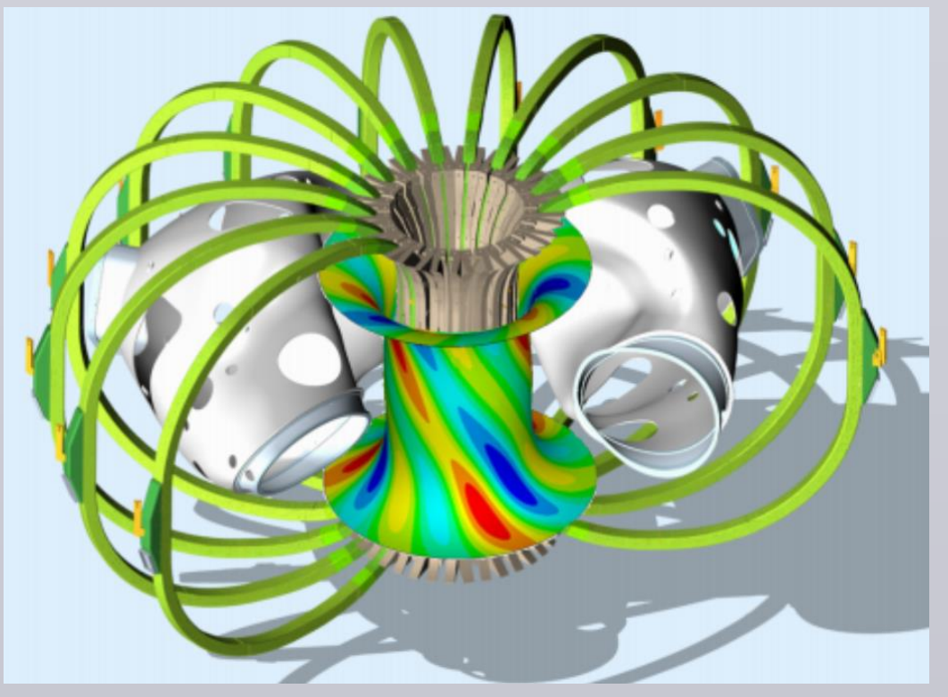
BACKGROUND: STELLARATORS

- Stellarators are one of the contenders for the production of fusion energy. They use their helical shape to confine the plasma without the need of plasma current.



Germany's W7-X Stellarator, Max-Planck-Institut für Plasmaphysik.

- PPPL, in collaboration with the Simons Foundation, is on its way to design and build a operational stellarator that incorporates the use of permanent magnets (PM).



Simon Advanced Stellarator (SAS), M. Zarnstorff

TABLETOP PM STELLARATOR

- Stellarators are a novel concept with a promising future. However, they are very complex and difficult to design. That is why we want to simplify the concept in a tangible fashion.
- Ideally, we want to display the concept in outreach activities and for that, the stellarator must be simplified to be portable. For this, some constraints were established:
    - stellarator must be portable;
    - its size must roughly 1m x 1m x 1m;
    - It must be lightweight; and
    - It must produce visible plasma for display purposes.
- It would use permanent magnets for non-axisymmetric magnetic fields.

PHYSICAL DESIGN

Specifications

- Following the size constraint, we arrived to the approximately 0.3m major radius for the torus.
- We want an aspect ratio of 2, so we chose the minor radius ("width" of vessel's tube) to be 0.15m.
- It is recommended for the gyroradius (ρ) to be 1/10th of the minor radius (Rm), thus
    - $\rho <$ Rm/10 mm → $\rho \approx$ 1mm

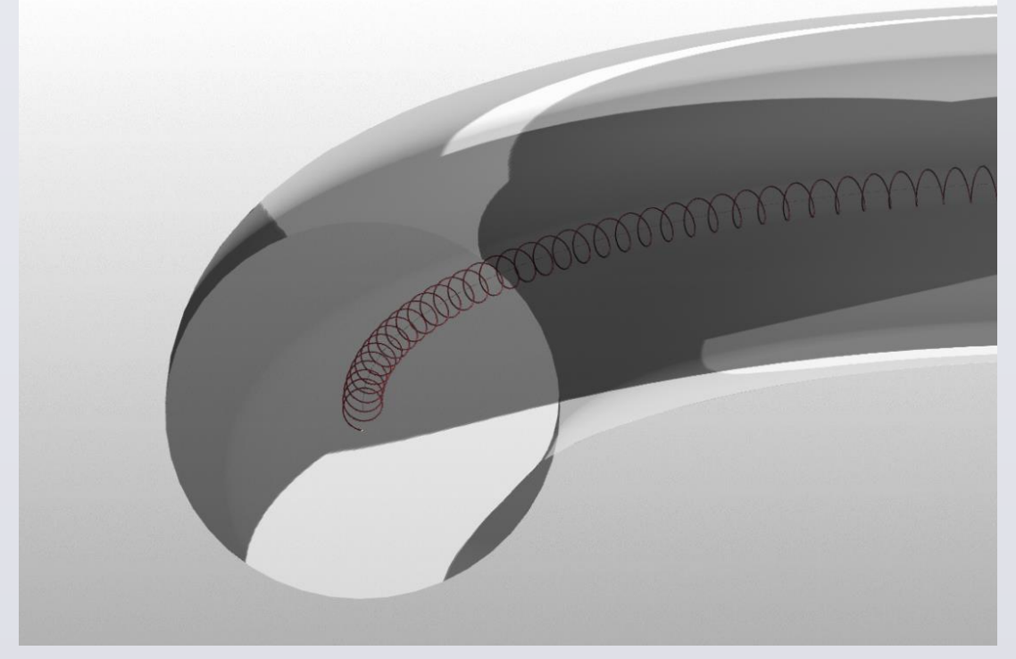


Diagram exemplifying the gyroradius of a particle in a torus to scale.

- Once the gyroradius is known, we can now proceed to calculate the required magnetic field using the following equation, with *m* and *q* as the mass charge of electron, respectively and *V* as the velocity attained at 100 eV:

$$B = \frac{m * V}{q * \rho_{Gyroradius}}$$

The resulting magnetic field is of 400 Gauss, and now we can proceed to design the coils needed to satisfy that field. A code was developed to determine the optimal number of turns per coil versus the types of wire and mass, using input from sellers and suppliers. For the code, equations such as Amp-turns (shown below), power dissipated by a resistor, Kirchhoff's laws and heat transfer, just to name a few, were used.

$$B2\pi r = \mu_0 NI$$

It was then determined that the best configuration is with Copper water line tubes. These are readily available since they are a standard size of ½". 32 turns with a bending radius of 0.10m in eight coils should be enough. The wires will be insulated with Kapton tape and then a fiberglass cloth hardened with epoxy will encase the coils.

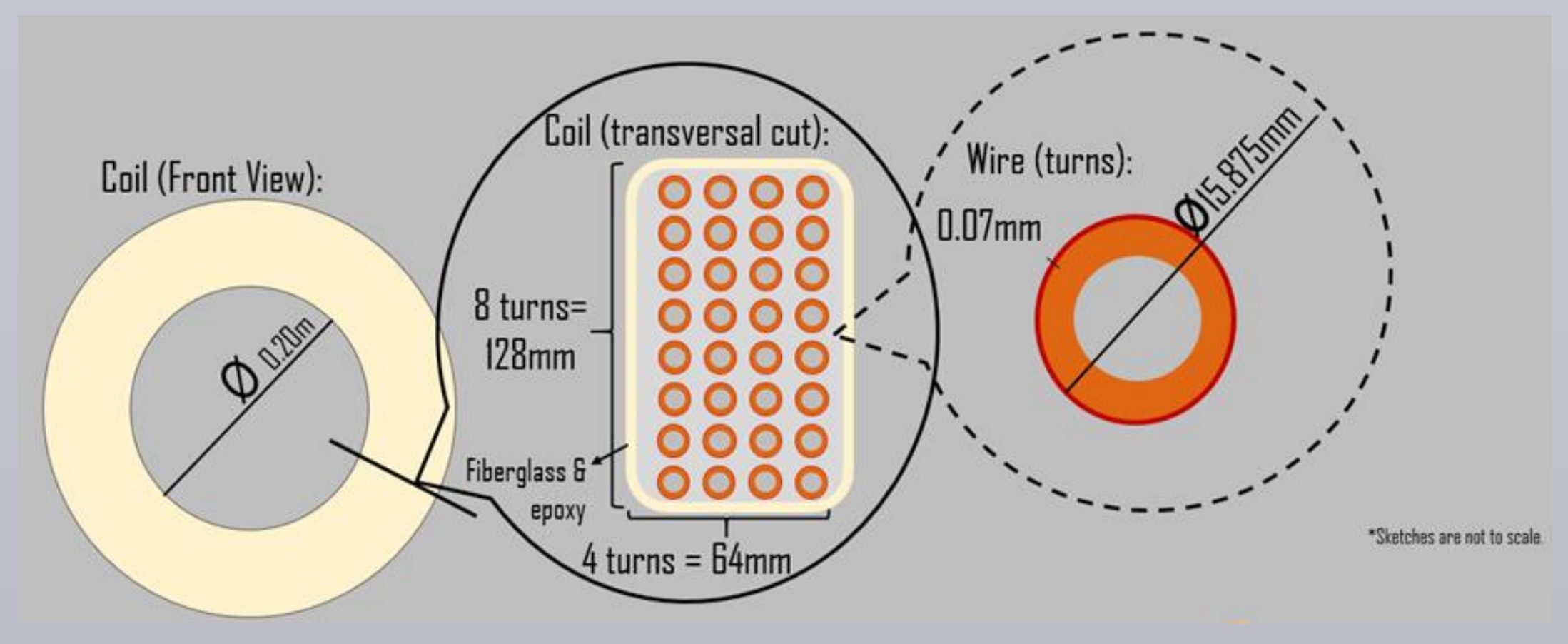


Diagram of coils. They will be made with ½" copper water line.

The vessel must be strong, lightweight, and most importantly, transparent. Given these, we considered two material options: glass or plastic. For glass we could use borosilicate (Pyrex®). Otherwise, a polycarbonate (Lexan®) structure could function as a strong plastic. Confirmed by suppliers, the vacuum vessel will be four 90 degrees elbow tube with a diameter of 6in and a bend radius of 12in.

Parameters

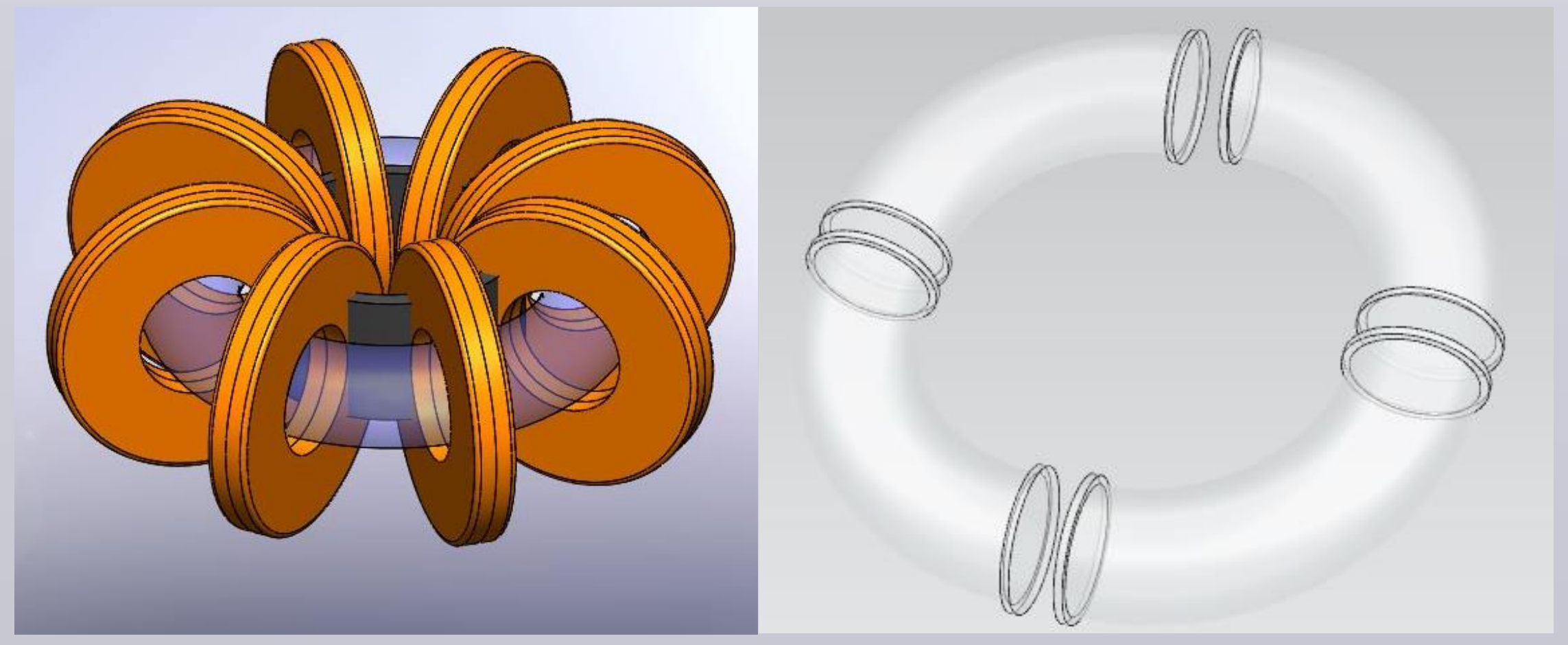
After defining the coils and the vessel, we worked on the rest of the project and we got these parameters:

Criteria	Value
Size	0.3 m Do, 76.2 mm R_{minor}
Mass	500 kg
Generated Heat	2,800 W
Current (magnets)	240 A
Voltage (coils)	12 V
Vacuum	10-3 Torr

The tabletop stellarator is a complex project with many components that perform unique actions in order to produce and confine the plasma. The main ones are the support structure, cooling units, vacuum pump, batteries, and the electron beam.

MECHANICAL ANALYSIS

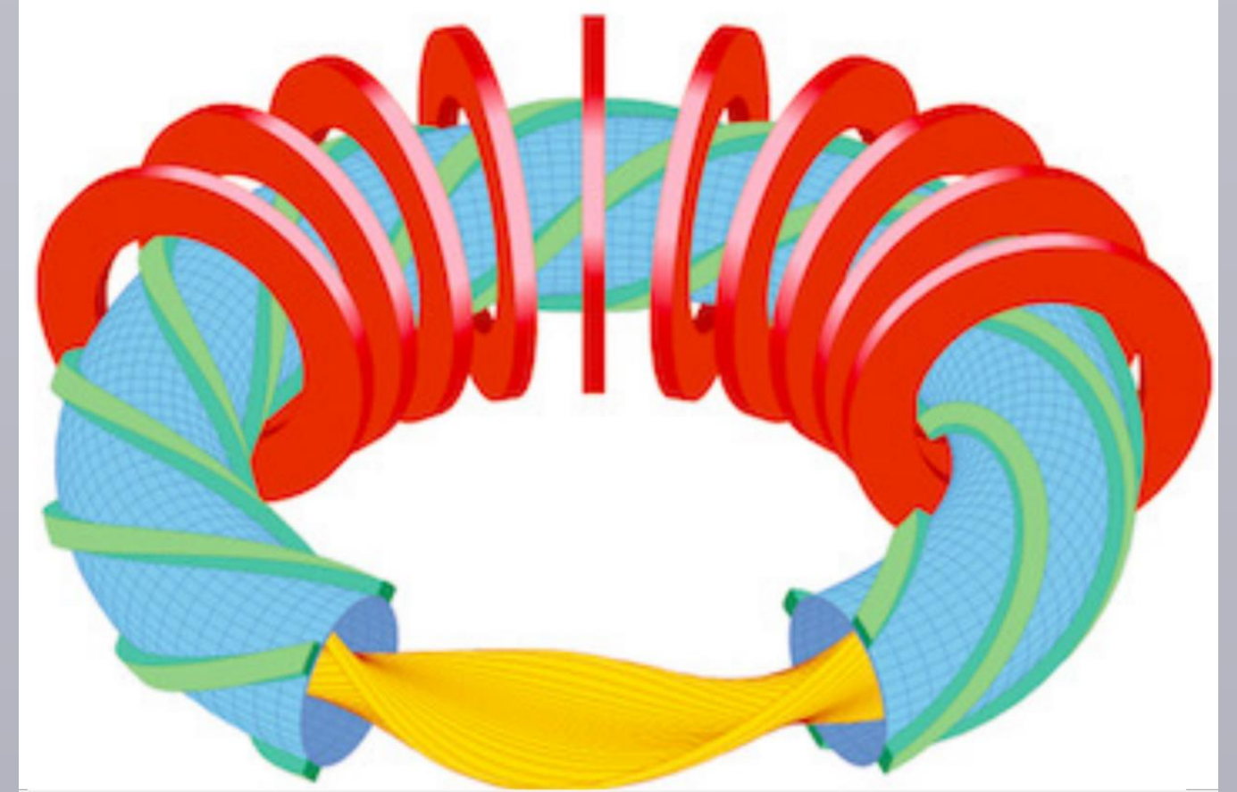
- Thermal Analysis: Because the coils are resistances, they generate excess heat, and we must keep it from melting the insulator or other components. With a heat generation of over 2.7kW, we will use two CPU cooling units to radiate out the heat from the water that will flow through the coils.
- Because the magnets are so close to each other, the attractive forces they experience could change their position, and this is detrimental. We modeled the magnets as dipoles in order to approximate their forces, so we then could design the support structure.



Left to right: Stand-alone CAD of vessel, center structure and coils, to scale. Sketch of manufacturing concept. Joining techniques could be with the use of O-rings.

Electron Gun

- The electron beam is necessary for the generation of plasma. In practice, this consists of a Tungsten lightbulb filament on a small rod that will be biased in a circuit of 10 V and 100 V in order to generate a steady state source of the electron emitter.

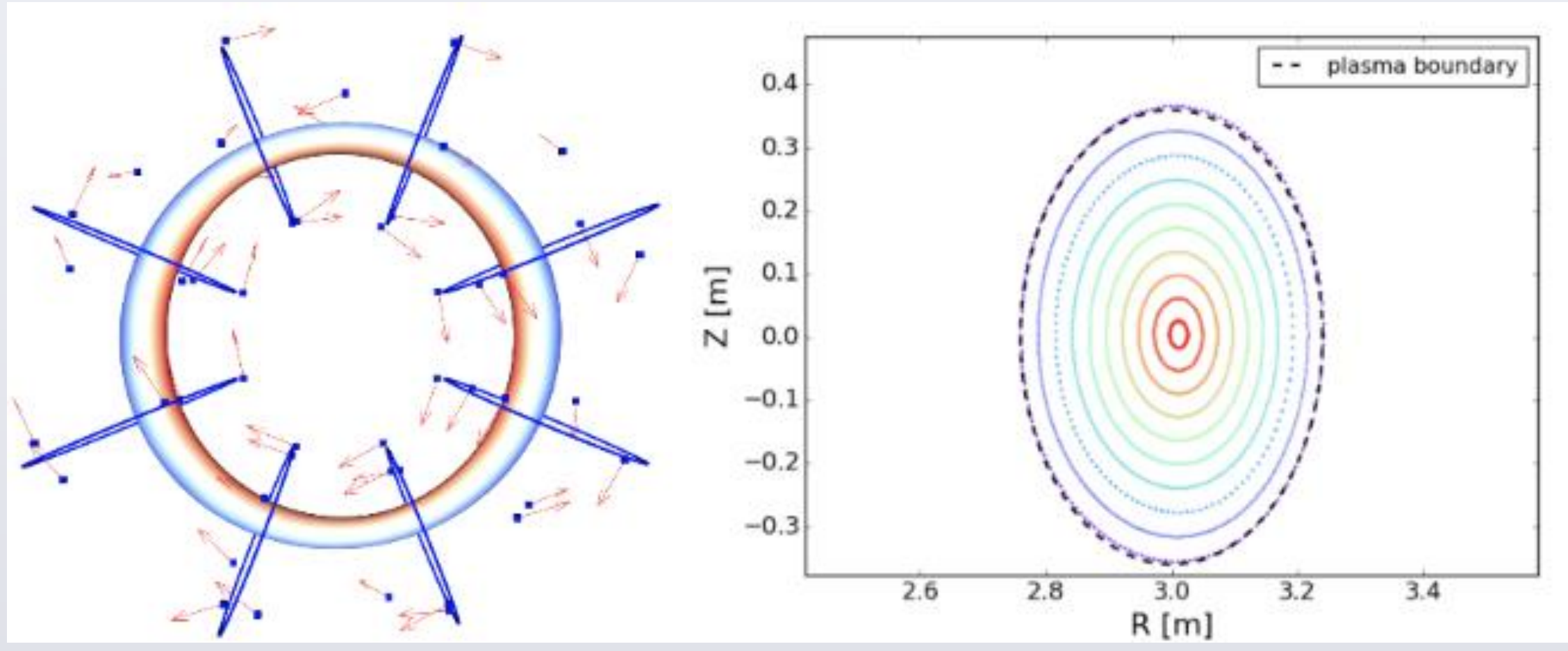


Sketch of magnetic field lines of a stellarator, note the helical field lines. Max-Planck-Institut für Plasmaphysik.

- The rod will be in an adjustable joint so that the users could change the direction of the beam to study its effect.
- The installation will be through a flange with a vacuum seal port.

MAGNETIC SURFACES

- Plasma confinement is reached by the toroidal magnetic field generated by the 8 coils and the helical magnetic field generated by the permanent magnets. These would be placed in an arrangement similar to the one on the image below on the left.



Left to right: Position of permanent magnets. Plot of flux surfaces. Caoxiang Zhu, for SAS.

The image on the left shows the placement of the magnetic dipoles from the permanent magnets for a stellarator with elliptical coils. Our stellarator would have a similar configuration. On the right, a Poincare plot displays the magnetic flux surfaces of such a configuration.

CONCLUSIONS

- **Designing a portable plasma generating and confining device is complex, thus we had to optimize between visibility and portability constraints.**
- **This project represents a novel concept of confinement by integrating the use of permanent magnets.**
- **Experimental procedure with the copper wires is a recommended next step.**

FUTURE WORK

- Analyze the stresses on the vessel and the support structure caused by vacuum pressures, its weight and the magnetic forces.
- Use software like ANSYS to confirm data and results.
- Following interns could work on the system integration of the apparatus.

REFERENCES

CADs and sketches were drawn by Carlos A. Catalano unless otherwise specified. Sources are available if requested.

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