

**Lecture 15: Alternate Concepts (with Darren Sarmer)**

1. In today's lecture we discuss the basic ideas behind the main alternate concepts to the tokamak.
2. These include the following concepts
  - a. The stellarator | externally controlled
  - b. The reversed field pinch (RFP) | self organized (disorganized)
  - c. The spheromak | self organized (disorganized)
  - d. The field reversed configuration (FRC) | self organized (disorganized)
  - e. The levitated dipole experiment (LDX) | novel idea
3. None of these as yet work as well as tokamak
4. The stellarator has (in my opinion) the last chance.
5. The RFP, spheromak, FRC all have serious transport problem
6. LDX is too early to tell – tough to scale up to a reactor.
7. Each of these concepts has been invented with a strong consideration of MHD issues and reactor issues
8. You can judge for yourself, whether you think they will be improvements over the tokamak.

**Stellarator**

1. The stellarator was invented, abandoned, and rediscovered in the US.
2. The idea was picked up in Russia, Japan and Germany.
3. At present there are 2 \$ Billion class experiments, the LHD in Japan and the Wendelstein 7-x under construction in Germany
4. The US is about to begin construction on a \$ 70M, NCSX at Princeton.
5. What is the idea behind the stellarator? What advantages does it have over the tokamak . And disadvantages!
6. A stellarator is a truly 3-D device. Take a straight helical plasma (effectively a cork screw) and bend it into a torus.
7. The stellarator addresses perhaps the most difficult physics problem facing the tokamak – the need for steady state operation with age bootstrap current, and low CD power.

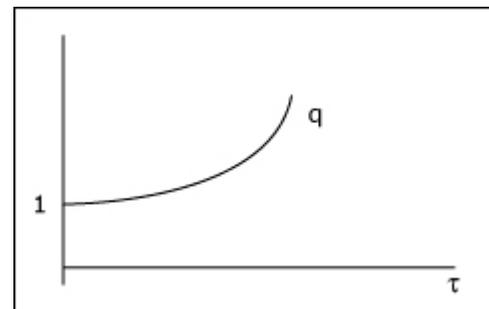
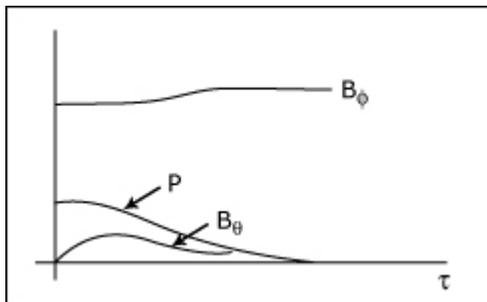
8. The stellarator is inherently a steady state device. There is no need to drive a steady state current.
9. The rotational transform provided by the current in a tokamak is generated externally by means of helical coils
10. The main disadvantage of the stellarator is the engineering complexity and cost of the helical – toroidal coils. Also, high  $\beta$  has not yet been shown.
11. In a reactor these coils must be superconducting. This implies that they must be modular for ease of construction and assembly. Toroidally continuous coils are not feasible.
12. Stellarators come in 31 different plasma configurations. Most are designed with the aim of minimizing neoclassical particle losses. These losses can be prohibitive in a carelessly designed stellarator.
13. There are two approaches to minimizing neoclassical losses. Quasi – Omnigenity and Quasi – Symmetry (QO and QA)
14. Both schemes are based on an observation that the guiding center orbit of a particle can be shown to be a function only of  $|B|$  and not vector  $\underline{B}$ . Thus various helical and toroidal fields can be combined by clever design to achieve either the QO or QA goals.
15. In QO configuration the helical fields are designed to essentially eliminate the bootstrap current.
16. As close as possible, the fields are designed so  $|B|$  surfaces coincide with the flux surfaces – omnigenity. In this way, particles do not drift off flux surfaces and neoclassical effects are small.
17. QO devices tend to be large aspect ratio with low shear:  $\iota(\psi)$  doesn't vary too much. The Wendelstein 7-x is based on the QO idea.
18. The QA idea is to combine toroidal and helical fields to fool the particles into thinking they are moving in a system where  $|B|$  has a particular symmetry – usually helical (QHS) or toroidal axisymmetry (QAS)
19. There is a small QHS experiment at U. Wisconsin and the NCSX at PPPL will be QAS
20. In the QAS, the particles will think they are in an axisymmetric toroidal field like a tokamak. Therefore their neoclassical losses should be similar to those in a tokamak, and these losses would be quite small.
21. In the QAS a bootstrap current is induced as in a tokamak. It is OK, even desirable to have this current flow in steady state, but there is no need to drive any current. Typically  $\iota_{BS} \sim 0.5 \iota_{total}$ .

$\iota$  is an increasing function of flux opposite that in a tokamak  
 $\iota(0) = .4 < \iota < \iota(a) = .66$

22. The only difficulty is that if the bootstrap current is not in the value predicted, the magnetic field changes and the QAS symmetry may break down.
23. Neither QO or QA stellarator are designed with  $\beta$  as their primary goal. Secondary optimization on  $\beta$  lead to values of a few percent but that may increase with experience.
24. Another major advantage (with some degree of creditability) is that since there is zero or small toroidal current, stellarators should not observe disruptions. This is true at low  $\beta$ , but must be demonstrated experimentally at higher  $\beta$ .
25. The NSCX proposal has some interesting diagrams showing the variation of plasma cross section around the torus and the modular coil set needed to generate the QAS fields.

### RFP, Spheromak, and FRC

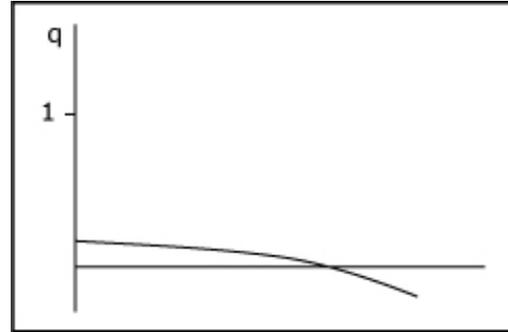
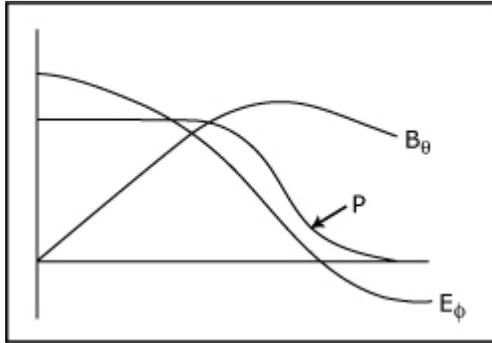
1. These three concepts are usually referred to as self organized configuration.
2. Actually a more accurate name would be self-disorganized
3. Their justification is as follows. They recognize that a tokamak reactor, even as RS reactor, is still very expensive and difficult technologically, because of the high field magnets and large size
4. Each of these concepts addresses the issue of making a more attractive reactor – more compact, simpler magnet system.
5. They do not address the tokamak physics issues particularly steady state. In fact, their physics is far less attractive than in a tokamak
6. They address the reactor system with a simpler magnet system, using lower fields.
7. Temporarily putting plasma physics aside consider the RFP. Spheromak and FRC configurations
8. Reference case – tokamak



9. RFP ( MST as Wisconsin, RFX as Padua Italy). As I said earlier in the term

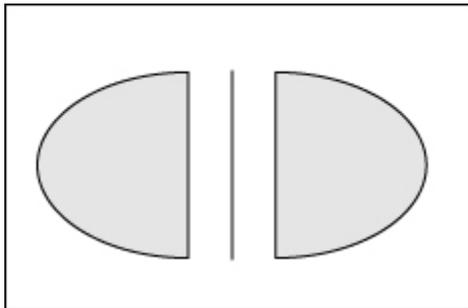
$$\frac{\text{tokamak}}{\text{Budveiser}} = \frac{\text{RFP}}{\text{DomPerignon}}$$

10.

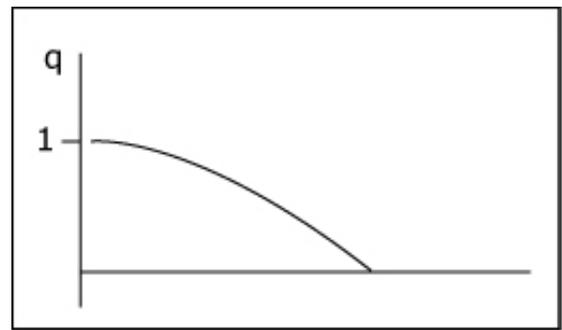
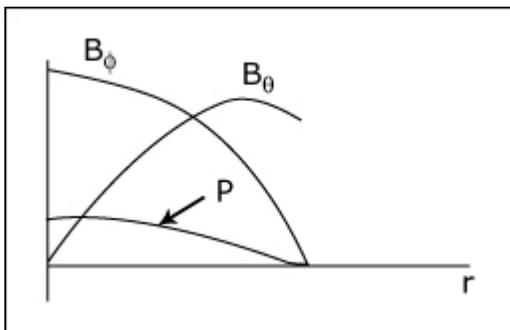


11. RFP has low  $q$ ,  $B_z$  reversal, flat pressure profile, large aspect ratio  $R_0/a \sim 6$ , circular cross section.

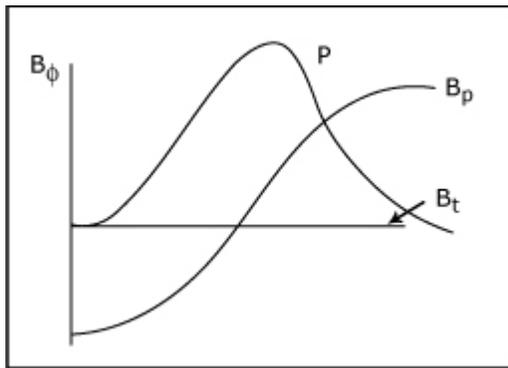
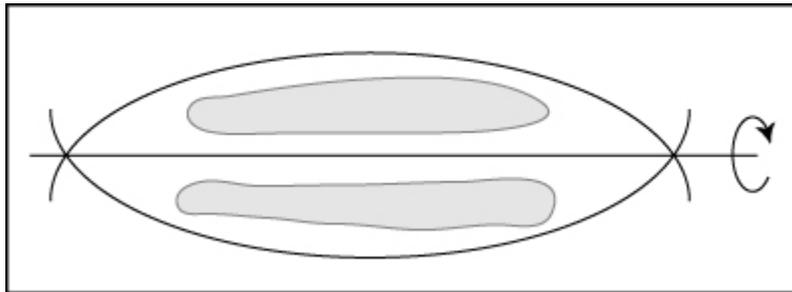
12. The spheromak is a tight aspect ratio RFP, without a TF coil. This eliminates the need for a TF structure down the middle.



There is a spheromak at LLNL



13. The FRC is a 4:1 elongated tokamak, without a toroidal field (MTF)

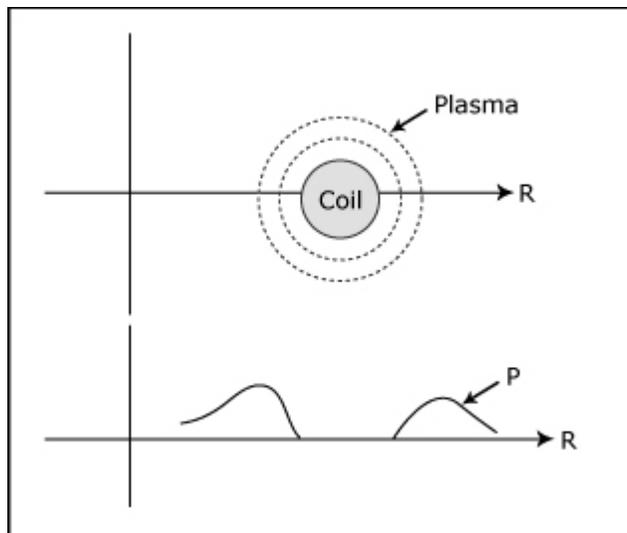


$q$  has no significance

14. All three configurations have small or zero toroidal field at the edge.
15. All three rely on the Taylor relaxation process to establish and maintain their profiles.
16. How does their relaxation work. All these configurations are unstable to fine scale resistive instabilities. This allows tearing and reconnection of magnetic field lines which occurs because of turbulence driven by the instabilities.
17. The turbulence causes the plasma to "relax" to its lowest energy state. IS this self organization or self disorganization?
18. The main physics problem is that the relaxation is so effective that their isn't that much plasma at height  $T$  left afterwards. In other words the anomalous transport is much worse than that in a tokamak by factors 10 – 100.
19. All these configurations are also tremendously unstable to MHD resistive wall modes. However, transport is usually so poor that MHD is not the main issue.
20. These are very interesting physics experiments. They do scale to attractive reactors, they probably will have very tough time overcoming the physics, none of them really have an effective way to drive current in steady state.

## The LDX

1. The LDX is a novel idea for confining plasmas.
2. It has a very simple magnetic field configuration with good MHD equilibrium and stability.
3. Its biggest difficulty is associated with the technology of the levitated coil, which is super conducting.
4. Basically, LDX is a Z pinch with a hard core current flowing along the axis, bent into a torus.
5. Schematic



6. We will show later that their configuration has good MHD stability proportion because of the hard core.
7. The coil must be levitated. Any connection to the outside wall would make contact with the plasma. This is bad for the connectors, and bad for the plasma.
8. MIT has an LDX and expect it to be operational very shortly.