PART 1 OF NONLINEAR SCIENCE SEMINAR PRESENTATION: FINDING OUR WAY ON THE GREEN SIDE OF THE NUCLEAR VALLEY

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1. Title slide: Nonlinear plasma physics for fusion:

finding our way on the green side of the nuclear valley

I'd like to thank Professor Yoshida for inviting me back to Kashiwanoha to participate in this interesting multidisciplinary three-day seminar. I have tried to rise to the challenge of presenting lectures to an audience more than half of whom are not very familiar with plasma physics, or perhaps not at all, and yet try to give an idea of some open research questions in the field.

2. Abstract

Negotiating the path to fusion power requires understanding and controlling a very complex system: a plasma sustaining an enormous thermal gradient that drives many emergent nonlinear phenomena through a variety of self-organization mechanisms. After a very brief overview of the magnetic confinement approach to fusion power, some theoretical approaches to understanding and modeling these phenomena will be reviewed.

3. Plan

In this lecture I attempt to cover a lot of territory quickly, starting with the Big Bang and ending with an illustration of self organization — not the greatest one, the evolution of human life, but one that may help we humans sustain our way of life without destroying the planet.

The story will necessarily be incomplete and superficial, but I shall try to suggest a few research problems that some of you will perhaps solve in your future careers.

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4. Plasma physics and fusion power

The word "plasma" comes from the same greek root as "plastic" — a substance that can change its shape, but is not an ordinary fluid. In physics Irving Langmuir used it as the word for a gas that is sufficiently hot that it becomes electrically conducting and thus becomes subject to Maxwell's equations as well as those of gas kinetics.

Much of the gas in the universe is ionized, including that in *stars*, so when astrophysicists say "gas" they often mean "plasma"!

Plasma has found a lot of industrial applications, e.g. television plasma screens, but the biggest *research challenge* is to find a way to use it in the generation of fusion power, like in the sun but on earth, providing a safer alternative to fission power. (Some of you may have seen the movie "Monty Python and the Holy Grail," which refers to the search for a difficult-to-find object with miraculous powers.)

5. The Nuclear Valley

So, let's begin at the beginning — the Big Bang. After the universe cooled sufficiently, neutrons and protons condensed out of the primordial quark gluon plasma and bonded via the nuclear force to each other, and electrostatically to electrons to form neutral atoms — mainly isotopes of hydrogen (^{1}H, and ^{2}H — deuterium), helium and small amounts of other light elements like lithium. Although these nucleus-electrons systems were *electromagnetically* stable it turns out they still had a huge amount of *nuclear* energy locked up waiting to be released!

This can be seen from the plot of binding energy/nucleon (E/A) vs. atomic number (number of nucleons, A) showing the "nuclear valley" — rolling down the green side of the valley by combining (fusing) light elements releases nuclear energy, while rolling down the black side by splitting (fissioning) heavy elements also releases energy until we get down to iron at the bottom.

The Universe solved the problem of fusion power by using the *gravitational* force to condense the neutral gas clouds into stars. Fusion reactions started turning the hydrogen and helium into iron until there was no more nuclear energy to provide sufficient pressure to stop the stars collapsing; which they did, before exploding into supernovae. The small amounts of elements in the earth heavier than iron were produced in these explosions, explaining why elements like uranium are remnants of these rare events, while most of the hydrogen dates back to the Big Bang and is still waiting to be fused to release its nuclear free energy!

6. Two approaches to fusion power: inertial & *magnetic* confinement

The gravitational force is too weak confine hydrogen at the densities and temperatures needed to create fusion power on Earth, as seen by the "triple product" curve — there can be a thermonuclear fusion burn only *above* the curve, which for a deuterium and tritium (^{3}H) mix has its minimum at a thermal energy of the order of 10^4eV and pressure×(confinement time) about 10 atmosphere seconds.

There are two strategies to meet this criterion:

(1) Inertial "confinement" : make a mini-hydrogen bomb using extremely powerful lasers to provide high density for a short time ($\leq 10^{-9}$s);
(2) Magnetic confinement : make a very strong magnetic field to confine a plasma at around atmospheric pressure (but extremely high temperature, so it is a high vacuum before heating), with each ion confined for a long time (> 10s).

7. Magnetic field geometry

Most approaches to magnetic confinement use toroidal geometries to avoid end losses. The aim (not always quite achieved, but on this slide I assume it is) is to design the magnetic field so all field lines lie on tori that foliate (i.e. fill in a nested manner) the plasma volume. These tori are called "magnetic flux surfaces" because the magnetic flux ψ they enclose at one cross section of the plasma is the same through any other section of the same surface, making it a good "label" for the surface. (Sometimes they are called "magnetic surfaces" or "flux surfaces" for short.)

Topologically a torus does not have to be axisymmetric like an anchor ring, it just needs to have two directions that are periodic and one that isn't. The periodic one the "long way around" is called the *toroidal* direction and that the "short way round" is the *poloidal direction* (quotes because "long" and "short" are metric concepts rather than topological ... for a bit more about the "toroidal and poloidal" terminology, see the Wikipedia entry I wrote it).

I have denoted the poloidal angle on each magnetic surface by θ and the toroidal angle by ζ. (I'll say a bit more on these curvilinear coordinates later.) A field line is the locus of a moving point as it traces out a curve on its magnetic surface, that either closes on itself or wraps infinitely many times, covering the surface ergodically.

Which of these two alternatives applies on a given magnetic surface depends on ι, the *rotational transform*: the average increment in the θ as ζ increases by 2π.

8. Tokamak plasmas are often said to be *doughnut shaped*

... because they are approximately axisymmetric, and used to have circular cross sections. However this may not impress as an opening gambit at a cocktail party!

9. Magnetic field "dynamics"

This slide presents a different view of the field line geometry I talked it about in slide 7. It uses a device called the Poincaré section after the famous dynamicist Henri Poincaré. It is simply a surface (e.g. the one in slide 7) that cuts the phase-space flow so that an orbit (a field line in our case)"punctures" the surface many times. This allows some delicate features of dynamics to be discussed with more precision than is easily done in a 3-D view like I used before.

It allows us to see the clearly the difference between the cases when the rotation number $\iota\!\!\!-\equiv \iota/2\pi$ is a rational number and when $\iota\!\!\!-$ is an irrational number.

- $\iota\!\!\!-$ rational: In an axisymmetric system, where the magnetic flux surfaces do indeed foliate the volume, all the field lines on the rational surface are closed loops foliating the surface, but in non-axisymmetric ("3-D") systems many of these closed field lines are dynamically unstable and instead wander chaotically in chaotic orbits around the separatrices of "magnetic islands."
- $\iota\!\!\!-$ irrational: If $\iota\!\!\!-$ is sufficiently strongly irrational (by a Diophantine approximation criterion I don't have time to go into) the field lines may still be confined to a magnetic surface. This possibility follows from the famous KAM (Kolmogorov, Arn'old and Moser) theorem.

10. Particle dynamics

Particle confinement is a bigger subject than field-line dynamics. In this slide I illustrate just two concepts — *particle trapping* and *drift orbits.*

Trapping is related to the concept of island formation referred to in slide 9, referring to the particles inside an island (ones outside are called "passing particles"). Trapping and island formation can occur in both electrostatic and magnetically dominated dynamics as illustrated in the slide.

The concept of particle drift is intrinsic to magnetic confinement physics because a large magnetic field creates a large anisotropy in the dynamics — dynamics along field lines is a bit like the electrostatic problem illustrated, whereas cross field-dynamics has a separation of time scales between the fast gyromotion and the slow *drifts* of the gyrocenters. The figure shows the result of this in a tokamak, where there is a trapping effect along field lines and a grad-B drift across them that causes the peculiar "banana orbits" illustrated.

11. The need for helical twist

The $\boldsymbol{\nabla} B$ drift (combined with the $\mathbf{E}\times\mathbf{B}/B^2$ drift) is also the reason why we need both toroidal and poloidal field, because electrons and ions drift in opposite directions under the $\boldsymbol{\nabla} B$ drift. So, without poloidal field, charge separation occurs, causing a vertical electric field that crosses with the horizontal toroidal field to make the plasma drift rapidlyt o the wall Adding poloidal field makes field lines helical so, as conductivity is high along field lines, this shorts out the charge separation and makes magnetic surfaces equipotentials, so only $\mathbf{E}\times\mathbf{B}$ drifts are tangential to the magnetic surfaces.

This was understood very early on in the history of fusion research, so in the 1950-60s the Russians (and Australians in the '60-70s!) developed Tokamaks, using a high toroidal current to generate the poloidal field. However, this can cause dangerous *disruptions* that can kill the plasma and damage the vacuum vessel.

On the other hand, the American astrophysicist Lyman Spitzer Jr. invented the *stellarator* concept, to use 3-D geometric effects instead of large toroidal current, thus making stellarators much more robust against disruption at the cost of greater technical complexity to design and build.

12. Largest current magnetic-confinement-fusion experiment: ITER

Encouraged by empirical scaling laws that indicate that simply building a magnetic confinement experiment *bigger* will eventually enable us to meet the triple product criterion, a number of nations have contributed to perhaps the greatest international collaboration in the history of science — the building of the ITER experiment being at Cadarache built in the south of France (instead of the other leading candidate site, Rokkasho).

It is expected that first plasma will be obtained around 2025 and tritium will be introduced around 2035 to create a fusion burn — fusion research proceeds slowly and cautiously, but, if we need baseload power for a stable electricity grid, it is the best hope for coming centuries.

In the meantime it is source of many interesting plasma physics research problems!

13. Alternative: Large Stellarators/Torsatrons

As mentioned in slide 11, stellarators *break* the continuous rotational symmetry of the (ideal, as opposed to real) tokamak in order to operate with low toroidal current. This is much stabler and safer, but poses many mathematical challenges!

Japan, where stellarators are usually called *torsatrons*, has been for many years a leader in stellarator research. The Large Helical Device (LHD), a torsatron with superconducting magnetic field coils at the National Institute for Fusion Science (NIFS), between Tajimi and Toki-shi on the Chuo line near Nagoya, achieved first plasma in March 1997 — Happy 20th birthday LHD! It has a discrete,10-fold symmetry, which is high enough in that much theoretical work can be using the method averaging over the ripples, making it Quasi-axisymmetric.

The other large stellarator/torsatron in the world is the quasi-helically-symmetric superconducting stellarator Wendelstein 7X (W7X), at the Max Planck Institute for Plasma Physics (MPIPP), in Greifswald on the Baltic sea in Germany. This was built using a great deal of sophisticated theoretical analysis, which resulted in a machine that has taken nearly 20 years to build! It achieved first plasma only in December 2015. It has 5-fold symmetry and is Quasi helically symmetric in a physically important curvilinear coordinate system called Boozer coordinates.