

Plasmas- Confinement

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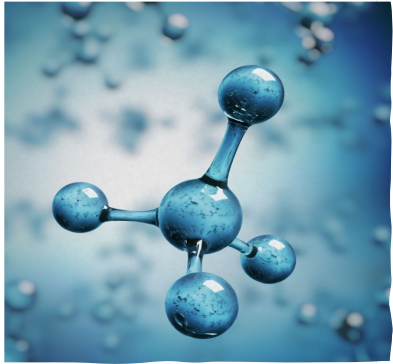


Very Beginning

- Plasma is the 4th state- an ionized gas
-

- Mostly Ions and Electrons interacting via Electromagnetic Forces
- Physics- Mostly Classical Electromagnetism





Plasma Dynamics in a Nutshell

Our Basic Field Equations are Maxwell's:

$$\begin{aligned}\nabla \times \underline{B} &= \frac{4\pi}{c} \underline{J} + \frac{1}{c} \frac{\partial \underline{E}}{\partial t} \\ \nabla \cdot \underline{E} &= 4\pi \rho, \quad \nabla \cdot \underline{B} = 0 \\ \nabla \times \underline{E} &= -\frac{1}{c} \frac{\partial \underline{B}}{\partial t}\end{aligned} \quad (1)$$

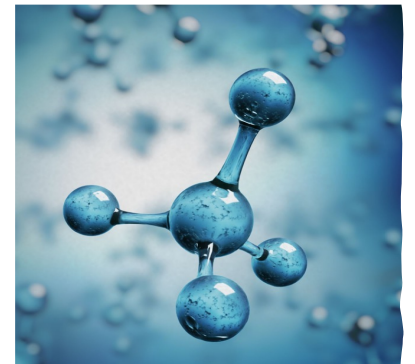
Given (1) \rightarrow all matters e.m are done!

But where is Plasma physics dynamics?

For that matter, barring a few cases (H. Energy physics), much of the physics is covered by (1)

(2)

Basic Notions



Constitutive Relations

$$\begin{cases} \rho = \rho(\underline{E}, \underline{B}) \\ \underline{J} = \underline{J}(\underline{E}, \underline{B}) \end{cases} \text{ Closure}$$

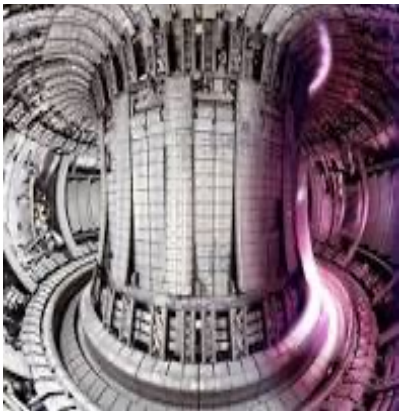
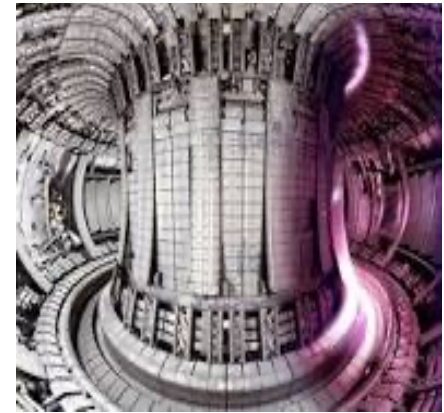
$$J^\mu = (\rho, \underline{J})$$

$$\underline{E}, \underline{B} \implies F^{\mu\nu}$$

$$J^\mu = J^\mu(F^{\mu\nu}) \text{ Rel.}$$

Plasma dynamics is to
simply to derive \square

Then there is algebra!



Completing the picture, $J=J(F)$

- We may use:

single particle responses: orbits, Fluid Descriptions, Kinetic Theory

Plus

Any amount of smartness

- Final Aim: To find $J(F)$ and stick it into Maxwell
- In other fields (condensed Matter, for instance), You may invoke Quantum Mechanics

The holy grail is ever the same- the constitutive Relations

Recognizing the essence of our pursuit fully

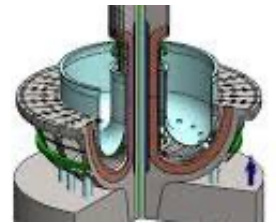
- Maxwell wrote his equations long long ago
- The struggle of a current practitioner is to find the appropriate relations that connect particle motions to E.m fields
- An unwary practitioner may not be fully cognizant
But this cognizance advances our understanding a groat deal!

But we are here today to talk about Confinement- What is it, and why it is needed?

A Nuclear Furnace : Fusing Nuclei

- To overcome the Coulomb repulsion, the reactant nuclei must approach each other with a lot of energy-**To produce enough energy, many nuclear reactions must take place simultaneously in a limited region of space.**
- For a fusion system (star or a terrestrial machine) to qualify as a net source of energy, it must comprise an assembly with **high-density (n)** of nucleons with **sufficiently large average energy (temperature, T)**, **confined** for **sufficiently long time (τ)** in a bounded physical space
 - To which we must add that there **can be no stable, long lived, macroscopic system of positively charged pure nucleons- any fusion relevant assembly of nucleons and electrons must have no net charge.**
 - Also note that at such high temperatures, there will be no atoms- deuterium atoms, for example, will be ionized into deuterons and electrons.
- Such a high temperature, neutral assembly of nucleons and electrons is our Plasma

*And it is this object that one must, creatively, engineer
so that it can generate more energy than is needed to keep it hot.*

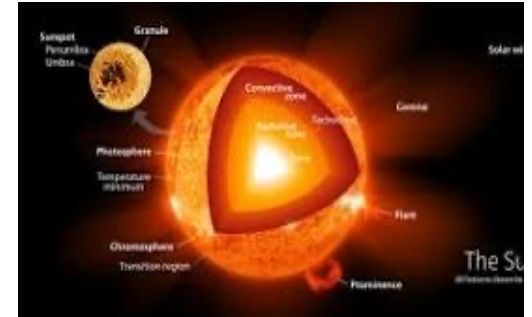


Why Plasma Physics

- It is all prevailing Physics: Barring this unique planet, much of the cosmos is in the plasma-state
- Initial terrestrial Laboratory for plasma Physics-Langmuir
- Particle "scattering" by plasma waves (e-m fields) simulate Momentum-Changing Collisions
- *Such collisions advance thermal equilibration rates by several orders of magnitude*
- Waves and Instabilities- Consequences.

- Plasma physics was launched as a major physics discipline by the promise of thermonuclear fusion.

- Fusion, **powering** the stars, takes place in the celestial Spheres; naturally



- In laboratory, fusion poses a formidable Challenge

- Why ? Very High Temp collection of charged particles must be
Confined for along enough time to react by the strong force

CONFINED ``STABLE'' EQUILIBRIA



Confined Stable equilibria- special challenge of Plasma Physics

- Searching for Confined Equilibria is the hallmark of a plasma physicist
- It is also the biggest challenge and a headache to boot
- Not just the difference between the stars and the lab, it is what distinguishes plasma physics from other fields in physics
- What is the last time you heard a condensed matter physicist worrying about equilibrium?

Confined Equilibria

- Stars confine through gravitation- on earth we lack the mass!
→ Must Seek a (much) stronger force - Magnetic Confinement
- Essential Requirement: Confinement Radius: In Meters
- Good News: If we can make sufficiently strong B and the plasma transport were classical (collisional) to boot, Confinement radius could be as small as 10 cm:



the fusion furnace would be easy to design

We would have had Fusion, then , long ago!!!

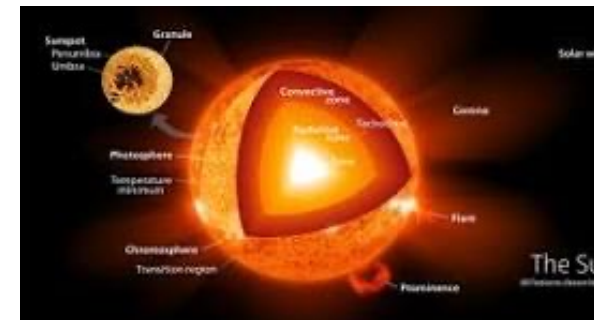
A digression-Functioning Nuclear Furnace: the Stellar Interior

- The stars exploit their **own gravity** to create conditions **in their central regions** that net fusion energy is generated.
- The stars find a state of what is called hydrostatic equilibrium when the gravitational compression balances the forces generated by plasma pressure (which originates in the fusion energy created in the stellar interior).
- **Let me summarize the essence of 100 years of relevant solar physics** : The temperature in the stellar center for a main sequence star in equilibrium is related to its central mass density (ρ) and radius R (m_N is the mass of the nucleon, a D in this case, and G is the universal gravitation constant) by

$$T \sim m_N G^2 \rho^2 R^2$$

- **Nuclear physics** tells us that for **this gravitating object to shine (via fusion)**, the temperature T must be 1KeV or more. Guess what - an object of radius 700000 Km, and mass = $2 \cdot 10^{30}$ K gm- **that is our sun-** will do nicely.
- **Our Sun is just the right size, even Jupiter is too small, earth is tiny**

Again: For Fusion on Earth, we must invoke a force much stronger than gravitation



Imagining a terrestrial magnetic bottle

Long scale- plasma goes to the wall

Fast – it does it quick

As if there is no equilibrium!

Good Magnetic Confinement

(1) Equilibrium: Time Independent accessible solutions of the Maxwell-Plasma system
 Crudely $S_0 = \tilde{B}_0, n_0, T_0, \beta_0 = \frac{n_0 T_0}{B_0^2 / 8\pi}$
 Create \Rightarrow

(2) stability $S = S_0 + \delta(t)$
 $\delta(t) = e^{-\gamma t + i\omega t}$
 $\omega \sim$ good or ok, $\gamma > 0$ bad

(3) Transport:
 Thermal Classical \rightarrow Under Control
 Instability Induced \rightarrow
 Long Scale and Fast: show-stopper

We have to learn to live with short-scale and slow transport

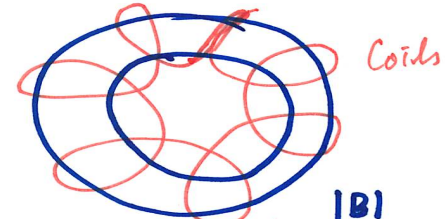
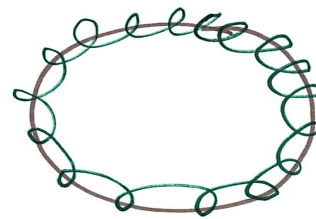
Particles in a
Magnetic field

Purely Toroidal
field not
enough

Magnetic Confinement

Uniform Magnetic field - (2-d) Confined

Close the Field Line



Coils
 $|B|$
Geometry \Rightarrow Inhomogeneous

In hom $\Rightarrow \nabla B$ drifts \Rightarrow charge separation
 \Rightarrow Electric Fields $\Rightarrow \underline{E} \times \underline{B} \Rightarrow$ plasma to the wall



In μs

No Equilibrium from a purely toroidal field.

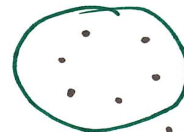
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Helical Twist

Toroidal +
poloidal

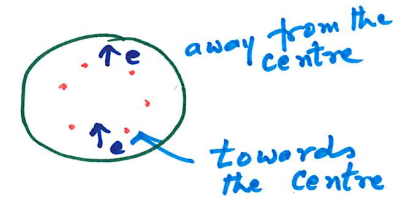
The first step

Magnetic Confinement - Helical Twist



The field lines do not
bite their tail

$$\underline{B} = \underline{B}_T + \underline{B}_\theta$$



No motion on
the average!

$\underline{B}_\theta \Rightarrow \text{Twist} \equiv \text{Rotational Transform} \equiv i$

Two different methods of 'Twisting'
Two different fusion paths

Stellarators

i from outside currents
No Current-driven Disruptions
the bane of a putative
tokamak reactor!

Tokamaks

i from the plasma
automatic heating (ohmic)
axi-symmetric
easier to build / theorize

(12)

Helical Twist to avert
charge
separation

poloidal field = parallel
current in a tokamak

A More Sophisticated View

The $|\nabla B|$ drifts $\rightarrow \perp$ Current \underline{J}_\perp

To Avoid charge separation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \underline{J} = 0$$

$$\nabla \cdot \underline{J} = \nabla_\perp \cdot \underline{J}_\perp + \nabla_\parallel J_\parallel = 0$$

not zero \Rightarrow must be nonzero

Plasma Induced Current is the required
 J_\parallel in a Tokamak

It is essential to understand:

The Large B_T
Needed for Gross
level stability

Much Smaller B_T
Equilibrium

Point to Ponder: When does stability
is really equilibrium!

How do we find Equilibria
How do we calculate Gross stability

For a closed system (tokamak, st..)

MHD - Magnetohydrodynamics - Good

$$\underline{\underline{J}} \times \underline{\underline{B}} = c \nabla \phi$$

$$\underline{\underline{\nabla}} \times \underline{\underline{B}} = \frac{4\pi}{c} \underline{\underline{J}}$$

$$\underline{\underline{\nabla}} \cdot \underline{\underline{B}} = 0$$

Challenge : Find $\underline{\underline{B}}$ such that
 $\nabla \phi \neq 0$ is possible

That is the region of Confinement

$|\nabla \phi|$ is the figure of merit.

(14)

Pressure confining
states-

what class of magnetic
fields

Confinement

Existence of
Magnetic Surfaces
that

neither intersect

nor go to infinity

Variety of Equilibria - Interesting/Not So

~~⊗~~ Not all fields are confining

(1) Vacuum field $\nabla \times \underline{B} = 0 \Rightarrow \underline{J}_{\text{plasma}} = 0$
 $\nabla p \equiv 0$

(2) Simple Force-Free Field

$$\nabla \times \underline{B} = \lambda \underline{B} \Rightarrow \underline{J} \parallel \underline{B} \Rightarrow$$
$$\nabla p = 0$$

What we are seeking is a region in which $p(\underline{x})$ is a smooth function
We need isobaric surfaces that are nested



they can neither intersect nor go to infinity

MHD provides such states

$$\underline{B} \cdot \nabla p = 0 \quad \underline{J} \cdot \nabla p = 0$$

Isobaric Surfaces are both Magnetic Surfaces and the Current Surfaces. (15)

Nested Surfaces

- Magnetic Confinement = Existence of a set of isobaric nested surfaces
 - The particles are constrained to move on the surfaces
 - Any Movement across the surface spells trouble! In fact, the movement across the surfaces is the so-called **Turbulent Transport** which all of us investigate so that it can be minimized!- **Turbulent transport is what limits confinement!**
- What are the constraints on the class of such Desirable surfaces that magnetic fields can generate?

Let us have some fun looking-investigating

Stars in the cosmos



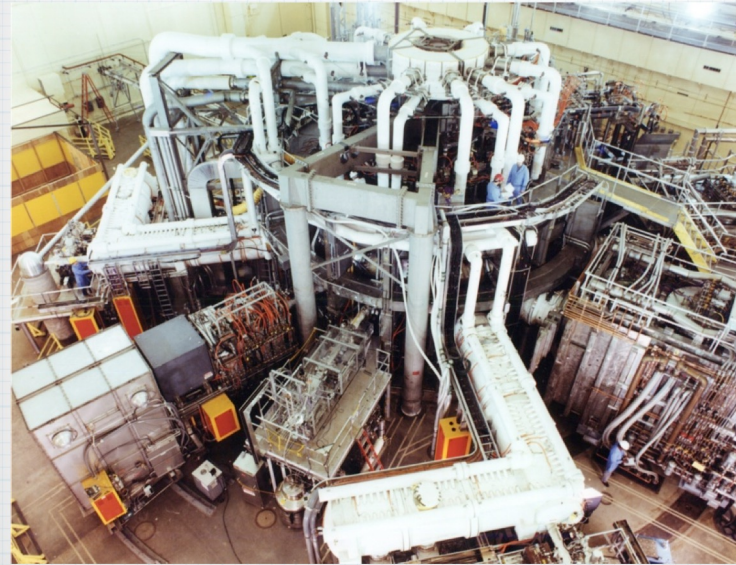
We are looking at...

1. A hot **plasma**,
2. Held together ("**confined**") by gravity,
3. Powered by nuclear **fusion**.

Expected
Breakeven that
did not happen

Star on earth is
just an inspiring
metaphor

Some laboratory stars:

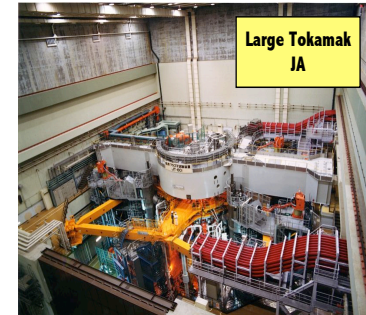
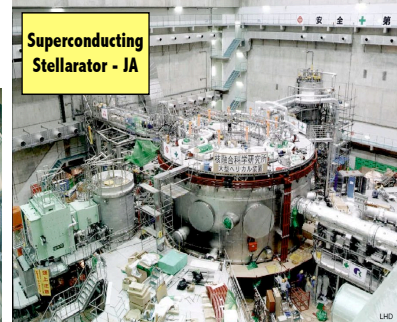
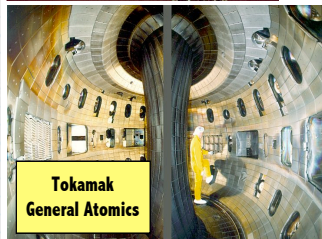
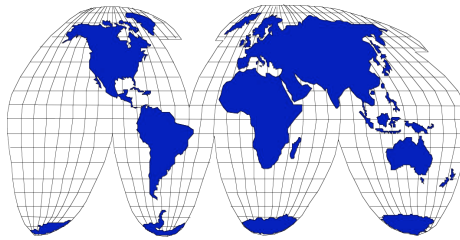
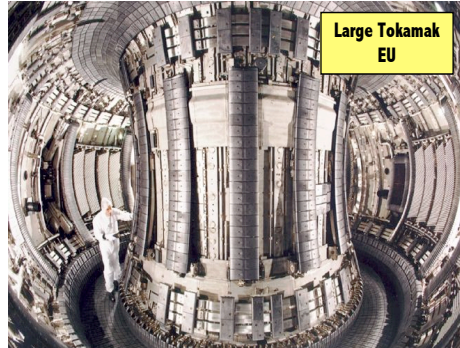


**TFTR device at
Princeton**

**Break-even
fusion energy
production,
1994.**

Tokamaks and Stellarators

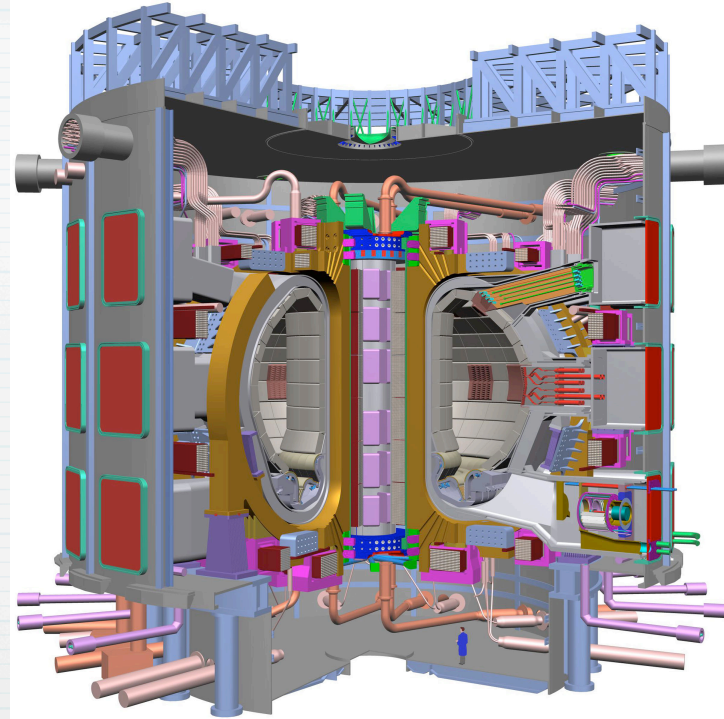
Toroidal proliferation: samples



And, Of course

ITER ("The Way")

Joint project of
EU, Japan,
Russia, US,
China, Korea,
India



Construction begins in 2008, in France

Some say it is
certainly not **the way**

For Smaller
Size/Cost of
the Fusion
Furnace

Increase B

Control
turbulent
transport

Soonest/smallest ARC

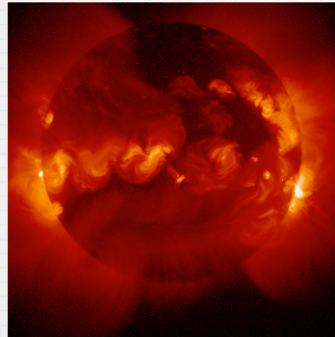


Comparing confinements

Cooler plasmas are easier to confine

Fusion Plasmas can quench with walls – hard to confine

Two plasmas:



A hot plasma, **confined** by gravity: long lifetime.

A cooler plasma, **not confined**: very short lifetime.



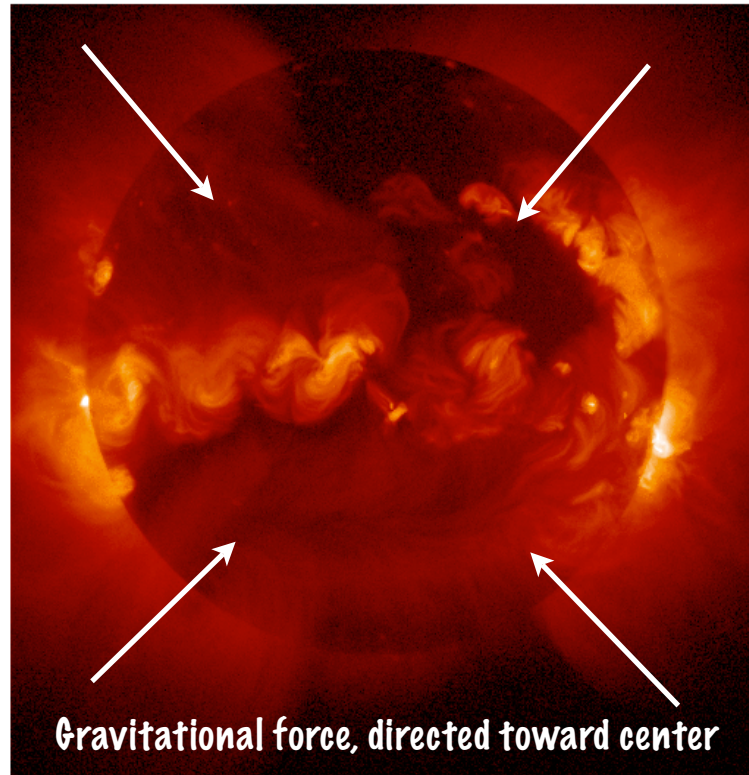
Unconfined plasmas **disperse** and **quench**.

A little more on magnetic bottles



- A magnetic bottle must contend with fundamental laws/processes of physics
- the most harmful originate in the very act of confinement- that make them leak both particles and energy. *Resistance to confinement*
- Let all the losses be lumped together to define what is called **the time of (energy) confinement** τ_E - an integrated measure of the fusion worthiness of the central magnetic bottle; τ_E is a major concept.
- The second trying fact is that eventually the bottles must ``see'' the material walls.
- The physics and engineering of the region between the edge of the magnetic bottle and material walls (which must limit the fusion machine) is very complicated. One must work out how an energetic edge plasma can coexist with material walls without ``destroying'' them.
- *The solution of the plasma-wall problem can have a profound effect on the quality of the core plasma where bulk of fusion reactions take place.*
- **A simultaneous optimization of the core-edge system is so much more challenging than individual optimization**

Comparing confinement



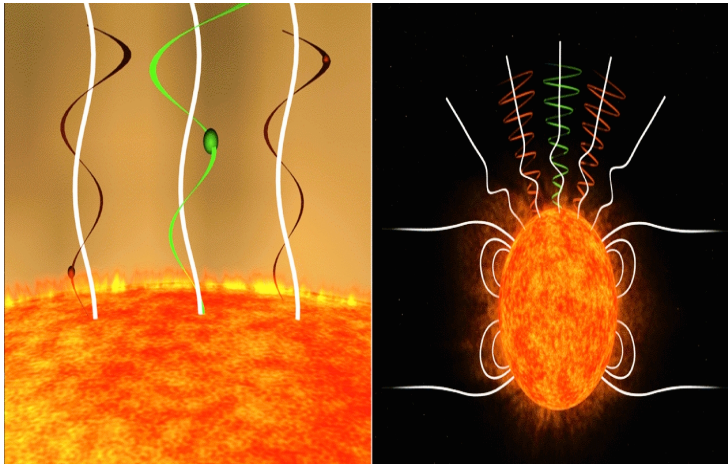
Solar plasma confinement:

Gravity holds plasma
together for fusion to
occur

But gravitational force
is proportional to mass:

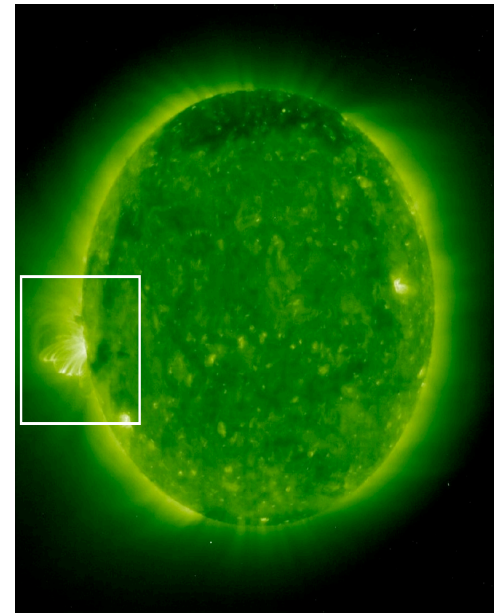
Solar confinement works because sun is large and massive

Magnetic force links plasma (charged particles) to "field lines"



Motion across field lines is tightly constrained; but motion along field lines is not affected. ("2-D confinement.")

Solar corona: a different sort of confinement



Filaments and loops reveal charged particles trapped on magnetic field lines

Magnetic force is independent of mass: acts equally on large and small scales

Coronal confinement is magnetic

Repeat

Essence of magnetic confinement

Magnetic field lines must lie on (everywhere tangent to) a surface. This **magnetic surface** must be

1. Closed: no edges
2. Bounded: fits inside a building

Magnetic force will confine charged nuclei inside such a surface; if hot enough, they will collide at high speed to eventually **fuse**.

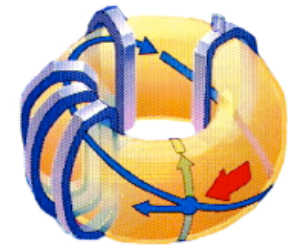


This some of you may not have heard about

Poincare Theorem:

A vector field that is **nonzero and finite everywhere** must trace a **torus in three-space**

Closed magnetic surface must be **toroidal**



Krispy Kreme

Tokamak

No ends to cap: field lines cover surface

Summarize: confinement and topology

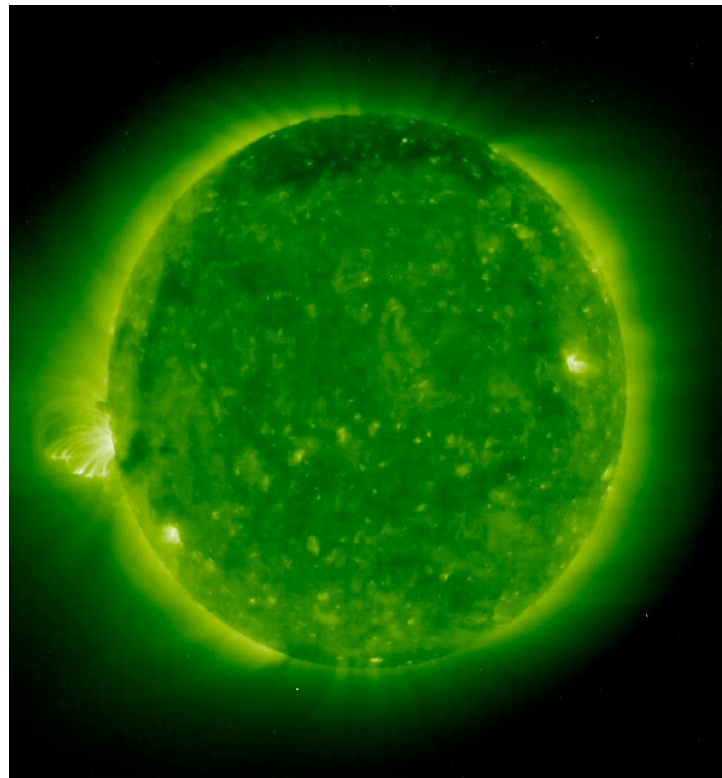
Defining difference:

gravitational

and

magnetic

confinement



Gravity → sphere

Magnetism → torus

A confined
equilibrium is

the first step

in the fusion
enterprise

Confinement is the main thing, not the only thing...

Equilibrium must be **stable**

-historically, the hardest puzzle

Plasma must be **heated** (energy investment)

-induction heating, plus microwave heating

Fuel must be supplied

-**breeding tritium** is an engineering challenge

Etc.

Magnetic confinement is not perfect

Collisions between particles cause occasional jumps between neighboring field lines

→ gradual loss of particle and heat

Magnetic curvature (inter alia) causes slow **drifts** of particles off field lines

→ enhanced losses

Residual instabilities cause fluctuating electric fields

→ more serious **turbulent** heat loss

Few Comments on Stability

Confined Equilibria are, by def, not thermal Equilibria $\nabla p \neq 0$

There is always free energy

⇒ drive the system to a thermal state

Instability is a mechanism by which a system seeks a lower energy state

All the thermonuclear fusion attempts can state access states with a finite

Life Time τ = Confinement time

The larger the τ , the better the chances of eventual fusion.

$n T \tau \rightarrow$ triple product - Metric

State of Confinement: Macro/micro physics



At this time, the Tokamaks, in particular, while operating in the so called H-mode, are the most established/ best confining devices. But there are many more stellarator companies in private sector

We are just in the process of understanding the physical processes that are the determinants of "good" confinement

Confinement, and therefore fusion is not yet an Engineering project- far from it. We cannot just extrapolate to high Q fusion machines of the future from our experimental investigations on the current machines.

Simple scaling laws may be not just inadequate, they could positively lead us astray- So Physics needs to be understood, tried and tested on current machines and then applied to the appropriate regimes of future machines- ITER and beyond

Our group at IFS (like some other groups) is head over heels involved in this process of unearthing the physics that will give us the ontology and anatomy of H-modes – we have identified some of the knobs that will give the best confining configurations: the results to date are encouraging but we have ways to go



Elevating Confinement: The Key to Commercial Viability

Still a quintessential Scientific project

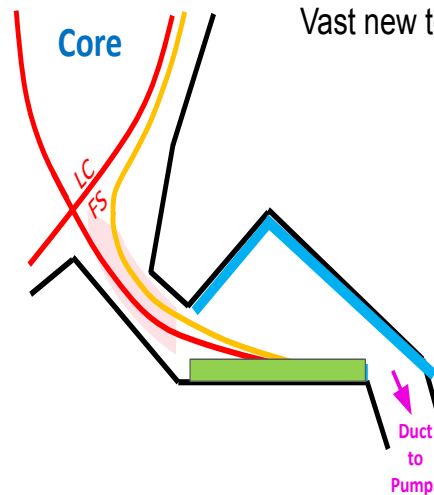
Additional

Extras

The Super-XT Divertor: Ultimate Flexibility

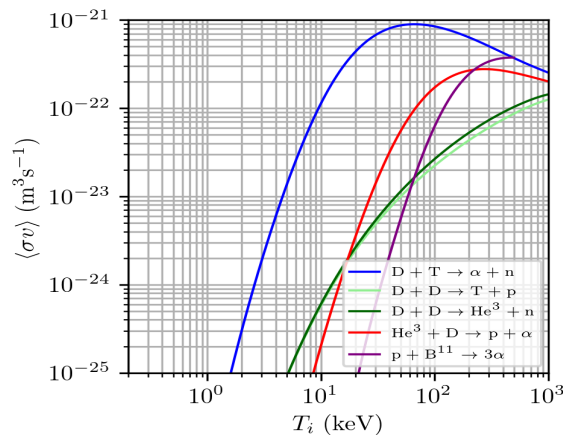
High recycling, low recycling or anything in between

Vast new territory in which to optimize $T_{div} = 10-1000eV$



Some elements of the Super-X, but crucial new aspects are needed. The outboard target is in a region of reduced magnetic field strength, like the Super-X. Additional critical elements include 1) in long mean free path (LMFP), regimes, an electrostatic potential arises on the outboard and the inboard, which strongly shields the core from impurities 2) Due to the strong erosion of the plasma facing surface from sputtering, in high duty cycle operation, the entire region near the target must be coated by LM that is slowly replenished (low-Z sputtering but not lithium) 3) novel heat flux mitigation using magnetic geometry, without requiring rapid LM flows 4) configurations to greatly improve helium exhaust.

A terrestrial fusion furnace – Basic minimum Physics



Comparing Fuel Reactance-
Choosing the best initial fuel

At 10 KeV, the DT intrinsic reaction rates are at least a factor of hundred more than other fusion fuels

Ceteris paribus, demonstration of fusion with DT fuel will be the least challenging

- The fusion power produced in a unit volume of the system (a D-T plasma) is estimated as

$$P_f \sim n^2 \langle \sigma v \rangle E_f \quad E_f = E_\alpha + E_N$$

n = density of each species, $\langle \sigma v \rangle$ is a measure of the probability of a DT fusion event taking place.

- $E_f = 17.6 \text{ MeV}$ is the amount of energy liberated in each reaction the latter is the sum of two terms: $E_\alpha = 3.5 \text{ MeV}$ and $E_N = 14.1 \text{ MeV}$, carried, respectively, by the alpha particle and the neutron. The alpha energy is about 1/5 of the total energy liberated; this is an important detail.
- $\langle \sigma v \rangle$ has all nuclear physics built-in, and varies strongly with T
- Attention: the effective $\langle \sigma v \rangle$ for D-D and many advanced fuels considered by various researchers is much lower than that of D-T in the multiple KeV temperature range. With substantial reaction rates only at much higher temperatures, *fusion via such fuels will be even more daunting!*

Further towards a fusion furnace- Q and Ignition-1

- An equilibrium plasma of density n and temperature T has an energy content $E_p = 3nT$
- All magnetic bottles are leaky- plasmas will continuously lose energy by a variety of processes - radiation, convection, conduction, **more advanced processes called turbulent transport induced by the instabilities that result from the very process of confinement.**
- In terms of the already introduced confinement time τ_E (the time in which the plasma loses much of its energy due to the collective action of all effects), we define

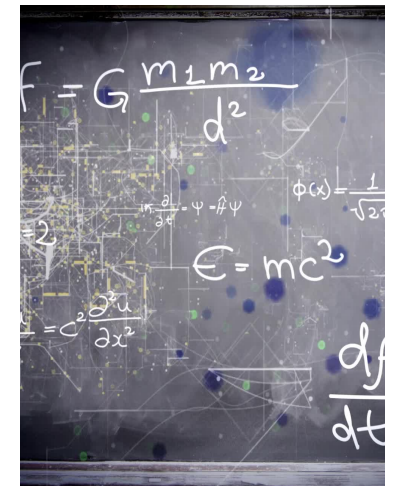
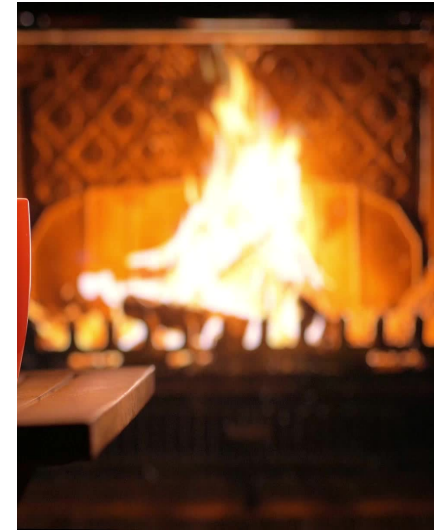
$$P_{loss} = \frac{E_p}{\tau_E} = \frac{3nT}{\tau_E} \quad (4)$$

- If P_h is the heating power needed to compensate this loss, then an obvious figure of merit

$$Q_{scientific} \equiv Q_{sci} = \frac{\text{Fusion Power}}{\text{heating power}} = \frac{n^2 \langle \sigma v \rangle E_f}{P_h}$$

- $P_h \ll P_t$, the real $Q = \text{Fusion Power} / P_t$, $Q \ll Q_{sci}$
- *No magnetic confinement machine has yet achieved $Q_{sci} = 1$. Reaching $Q_{sci} = 1$, though, is the first grand milestone on the road to fusion energy-*

we are almost there



Q and Ignition

- Remember that fusion energy is shared between an alpha (E_α) and a neutron (E_N)
- In all designs of magnetic fusion systems, it is expected that the energy E_α will be fed back - absorbed to internally heat DT .
- The alpha particle will be confined by the same magnetic field as confines DT. It is the Neutron energy alone that will appear as the net fusion energy (to be converted to electricity, for example).
- Thus, we recognize a new internal source of heating,

$$P_{h\alpha} = n^2 \langle \sigma v \rangle E_\alpha = \frac{E_f}{5}$$

- The fusion furnace is self sustaining if

$$P_{hext} + n^2 \langle \sigma v \rangle E_\alpha \geq \frac{3nT}{\tau_E}$$

- When $P_{hext} \Rightarrow 0$, the system is ignited-burns without external help

And we reach the holy grail of fusion Power



The Lawson Criterion

- Ignition is one of the most important words in the fusion vocabulary
- The nuclear burn (like the chemical burn of fossils) happens when

$$n^2 \langle \sigma v \rangle E_\alpha \geq \frac{3nT}{\tau_E}$$

- And by using appropriate formulas for $\langle \sigma v \rangle$ in the multiple KeV range (these are known to great accuracy), the **ignition condition** translates into, perhaps, the most famous equation in nuclear fusion,

$$nT\tau_E \geq 4.10^{22} m^{-3} KeV.sec \equiv L$$

- Pushing $nT\tau_E$ past L is the overriding goal of all fusion experiments.
- L, in general, is a function of T- the number given here is one that will pertain when we run the DT system at optimal temperature.
- **Lawson criterion is the lighthouse to assess the fusion readiness of fusion systems**



Variety of Magnetic Bottles- Fusion Machines

- It is almost trivial to state that the fundamental difference between various magnetic fusion schemes originates in just what kind of magnetic field they employ:

How Much

How Complicated

What Geometry

How much from plasma currents and how much from external coils

- The magnitude and structure of the confining magnetic fields as well as the mode of generation has strong bearings on the characteristics of the plasma they confine.
- It is surely presumed by each devotee that their chosen path has advantages over others: engineering simplicity, efficacy, freedom from catastrophic instabilities, low cost to name a few.
- Large and complicated fields through external coils tends to be more expensive – But they also have consistently shown much better confinement
- What will make the best reactor is all up in the air- Today's most advanced system is not guaranteed to be the best reactor of the future



Dipping into Patrimony 2
qualitative summary

Nuclear Fusion

Energy via Controlled
Thermonuclear Program

Extremely High Energy Density
The fatal attraction of Fusion

Creating a Sun on Earth*

*An inspiring metaphor

- A few grams of D-T has more *latent nuclear energy* than the *latent chemical energy* in a truck load of coal
- This principal supplier of visible energy in the universe, however, is so hard to replicate on earth despite ready availability of fusion fuel and all the **anthropic resourcefulness**.

Scientific Needs and Challenge:

- An extremely energetic (high temperature **T**) collection of nuclei with sufficiently large density (**n**) confined together for a sufficiently long time (**tau**).
- The figure of merit for such a plasma of nuclei and electrons $L = (nT)^* \tau$
- L is what we must chase!!

For a solar plasma tau is essentially infinite

Magnetic Field to the Rescue

recruit the strong force of the magnetic fields on charged nucleons/ electrons-

Magnetic Bottle better be in meters rather than kilometers



Heating a dense plasma to high temperatures is, by no means, easy

But it is **confining** a hot plasmas into a limited region **away from material walls** that really constitutes both the excitement and formidable challenge of controlled thermo-nuclear fusion.

Such bottles can never be perfect-they are always leaky

The very laws of physics militate against such bottles

The story of controlled fusion is the story of trying a whole variety of magnetic bottles- always driven by special understanding of physics, and often by partial success- improving those that seem to work, discarding those that do not seem to – **And Coming back to discarded ones with a new understanding of physics and HOPE**

The Tokamak line has been the most successful yet

Hark, the fusion landscape of today is populated with **EVERY** Magnetic bottle ever conceived

The triple product

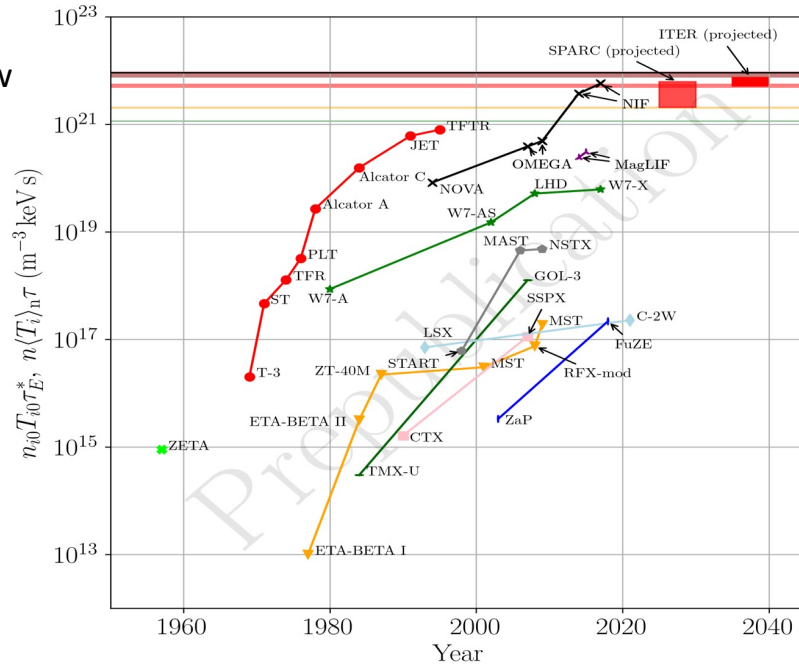
$$nT\tau_E$$

Spectacular Rise

Slowdown and stagnation

Resurgence in the air

Faster than Moore's law



ITER/CFS are bland extrapolations



The nT tau revolution upto 2000 has slowed down

A big idea needed for another big boost

*Tokamak central temperatures are much much higher than the solar interior

Fusion on Earth- Government versus Private- Contrasting Prioritizations-1

Government: Most research, till now, was in govt. labs or govt. sponsored labs

- Dedicated to Understanding the science and technology of fusion
 - lip service was paid to commercialization, it was, by no reckoning, the compelling goal.
 - What really drove fusion research was the fundamental goal of demonstrating that fusion, ``in principle'', is possible; cost and time spent did not enter the equation-
 - the sheer grandeur of replicating on earth what stars do in the Heavens served as the aphrodisiac
-
- It is my firm belief that this awe/wonder will stir folks to pursue fusion to the very successful end.

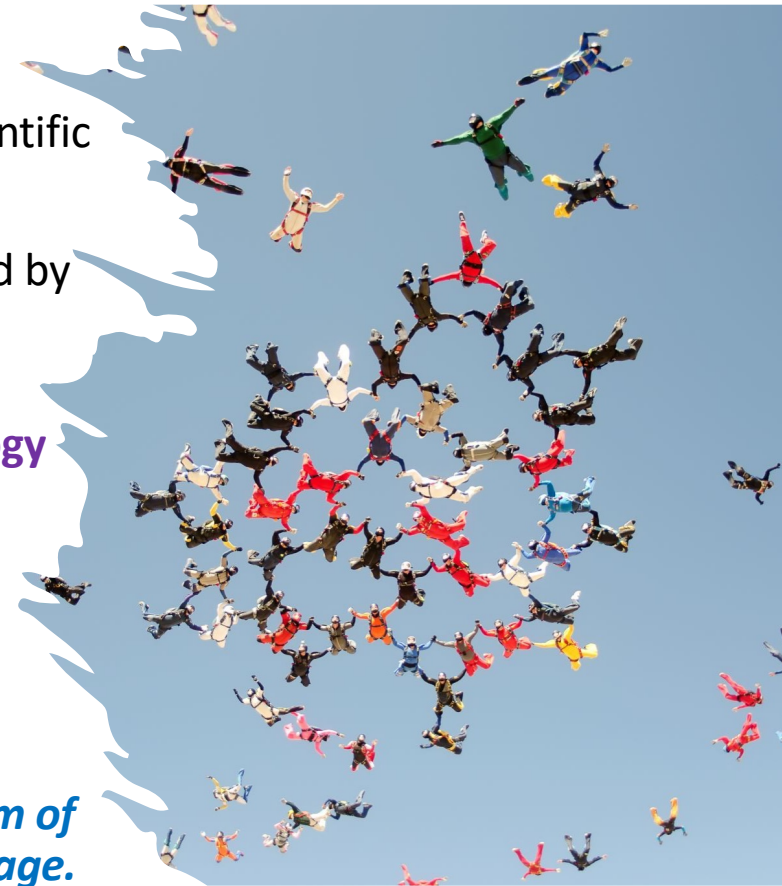


Fusion on Earth- Government versus Private- Contrasting Prioritizations-2

- The Govt research, fortunately, has brought us near the scientific breakeven ($Q_{sc}=1$).
- It is my equal firm belief that the next synthetic stage, fueled by a combination of

**steady path breaking innovations in fusion science/ technology
plus
entry of more and more highly innovative private companies
will be qualitatively different.**

Riding on the shoulders of the Govt sponsored research, and relentlessly pushed by the profit-motive, vision and dynamism of the private sector, the fusion enterprise has, finally, come of age.



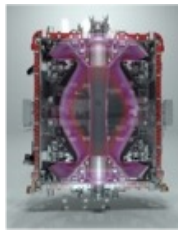
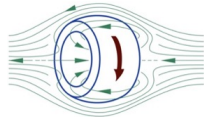
The Fusion Market-Place - Government and Private –let Hundred Flowers Bloom

all contenders claim relative advantages in a possible fusion energy economy

Lower magnetic field systems- simpler, cheaper (1-3)

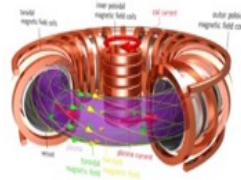
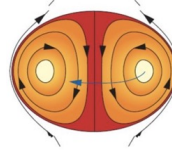
FRC (1)

Tri Alpha Energy, Helion

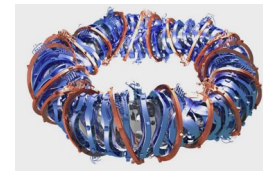
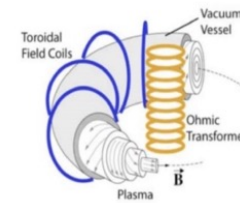


Spheromak (2)

CT Fusion



Toroidal Pinch (3)



Spherical Tokamak (4)

STEP -UKAEA
Tokamak Energy
ENN, --

Tokamak (5)

ITER-EU
CFS

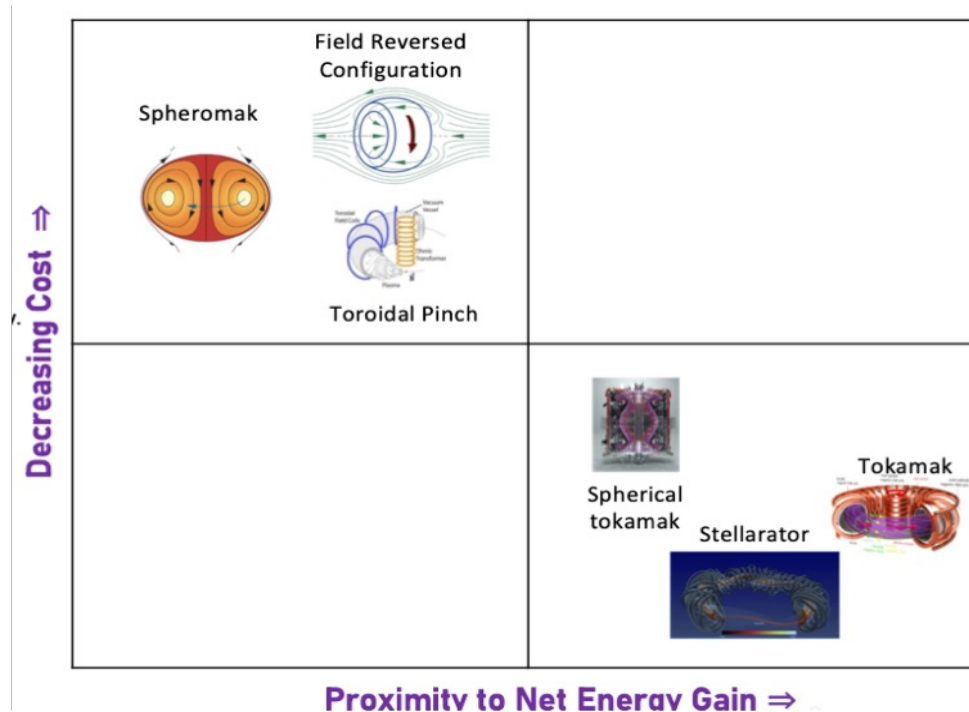
Stellarator (6)

Type One Energy, Proxima
Renaissance Fusion, Realta

Much larger magnetic fields, complex, expensive (4-6)

Where are these various contenders Located Cost versus proximity to breakeven

The Fusion Quandary



Stratups opt for smaller magnetic field- cheaper systems

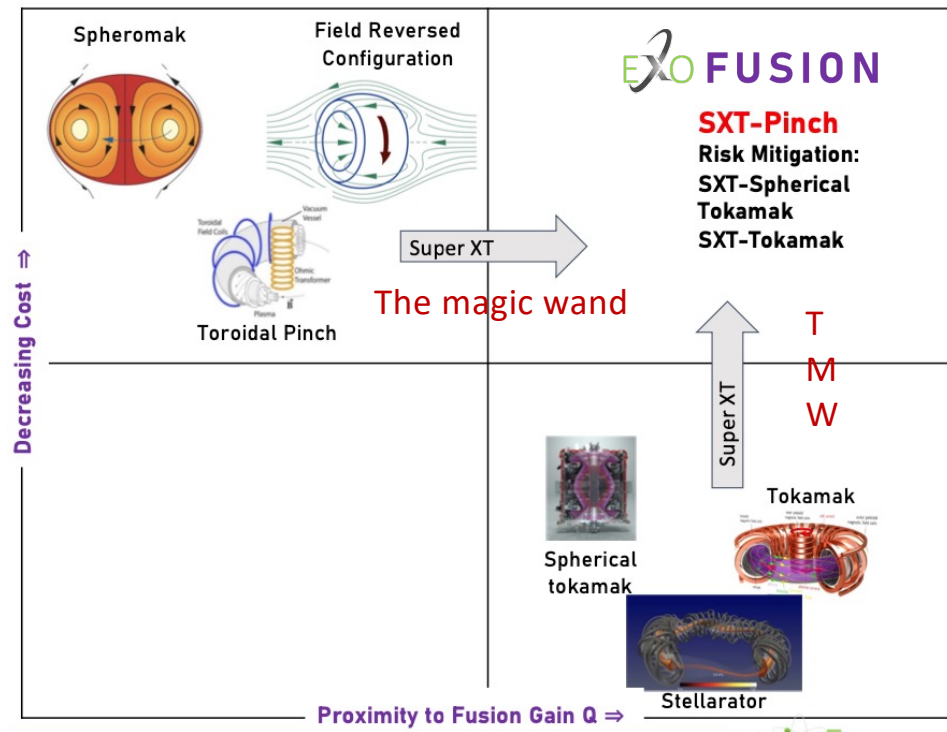
But they are orders of magnitude below tokamaks
In $nT\tau_E$

Already at the threshold of breakeven

??
Strong magnetic fields too expensive- great for research and giving proof of principle

Magnetic field Cost: Magnitude, complexity, and the size of the device
A smaller device with comparable performance is road to Heaven

Where do we want them to be



CVF Reactor - "small" size, low magnetic field (possibly with a simple structure) device with the maximum possible energy confinement time (τ_E)

How do we get there- In principle

- Figure of Merit: $F = n T \tau_E = (n T) \tau_E = (P) \tau_E$
P=Pressure
- The Fusion categorical Imperative : For a given B, maximize $P \tau_E$
- From totally elementary physics (of fusion), For a given B, $(n T)= P$ is fully constrained, it cannot go beyond P_{\max} - Otherwise fast instabilities set in and plasma is “ lost”
- Maximizing $P_{\max}(B)$ by shaping the structure of the magnetic field is one of the signature quests of all innovative magnetic bottles
- After all the shaping/engineering is done , the only way F can be increased is by **increasing** τ_E
- The confinement time τ_E is set by what is called turbulent transport (loss of heat)

Suppress turbulent transport and march to CVF

Confinement is the key



Boosting Confinement the new Frontier

Glimpses of Twenty first century physics (TFP)

There exist plasma regimes defined by the structure of the magnetic fields, and the profiles of density and temperature that manage to suppress plasma instabilities and hence the concomitant turbulent transport, the main culprit for heat loss.

Such regimes are ideal with boosted confinement.

TFP=Deeper theoretical analysis in conjunction with State-of-the-Art simulations

There are yet unexplored regimes of higher confinement - we can simulate them

We can also devise pathways through to access these regimes in experiments- it is possible to identify the knobs that control entry into these regimes.

Some such regimes have been reached in experiments, through trial and error. But TFP can help us understand why and how of these experiments.

One of the most exciting routes to high confinement is via redesigning the relatively cold edge of the magnetic bottle so that it works to improve the core confinement (where fusion reactions are taking place)

This is where ExoFusion contributes most fundamentally to Commercially Viable Fusion - Our magic wand is the **Super XT divertor**- Exofusion principals also invented the highly successful Super X divertor

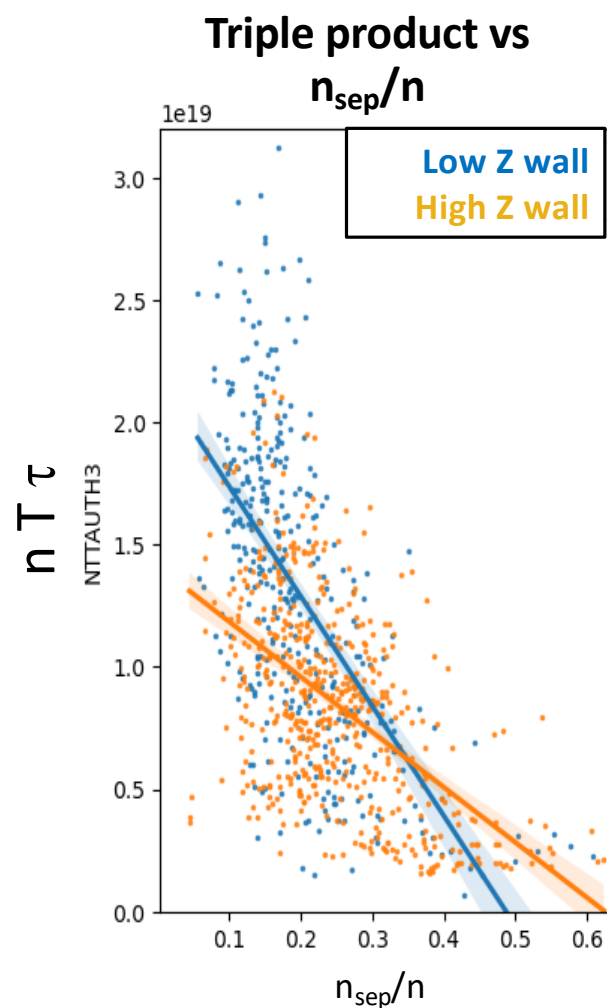
Though born of advanced physics, it requires tremendous engineering and technology ideas that we have been systematically developing

Confinement Doubles => Size Halves => cost down by a factor 5-8

Triple product following predicted trends

Maximum fusion performance ($n T t$) is obtained at low n_{sep} , particularly, for low Z walls

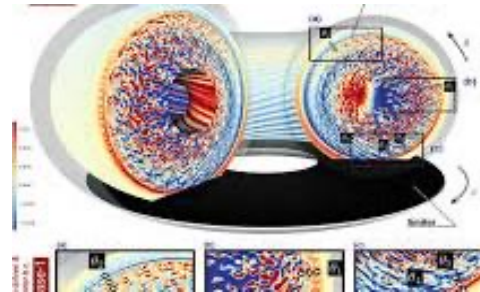
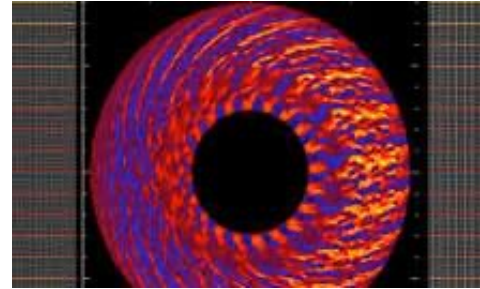
- Such low n_{sep} (and correspondingly high $T_{\text{sep}} \sim$ hundreds of EVs) edges are rather problematic :
- Demand novel divertor solutions
 - New geometries
 - New materials
 - New Kinetic codes to model/analyze the new edge
- Most enterprises are exploring new geometries, new materials needed to enable exceptional confinement



Glimpses of Twenty first century physics (TFP)

Physics of confinement

If the transport were classical
diffusion, fusion would be
a household word long ago.

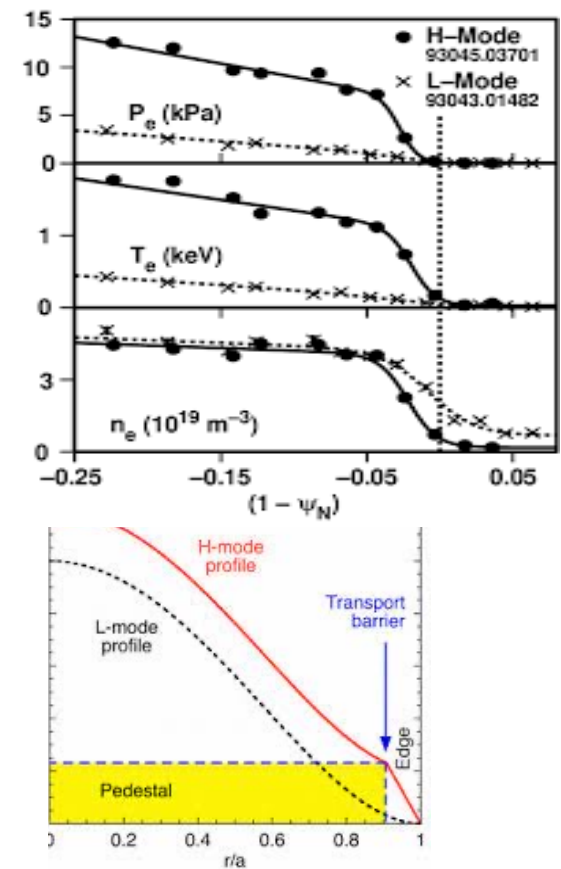


Probing Turbulent Transport

Essence of Magnetic Confinement

- Keeping Highest plasma pressure for longest periods of time
 - **Creating and sustaining sharp pressure gradients**
- Experimental manifestation is a transport barrier (TB)
 - 2nd savior of the enterprise
- **Edge Pedestals** or **Internal Transport Barriers**
- **Manipulating the edge turns out to be crucial**
- It is naturally believed (with experimental support) that TBs are created in experimental configurations where the dominant instability causing turbulent transport is suppressed (linearly and/or nonlinearly)

\$\$\$. Notice how the big jump near the edge boosts the central temperature- Stiff core transport\$\$\$



First Experimental Transport Barrier- The H- Mode Pedestal Experimental Serendipity 1982- ASDEX

The CTR program got a lease of life when the ASDEX team found the H-mode - large boost in confinement

It was (and is) believed that this remarkable **self-organization** of the plasma took place when the source of turbulent transport- the ITG-TEM instability is tamed by velocity shear

However, **theory predicts**, and **experiments do show** barrier formation even without velocity shear – **This is fundamental- proposed reactors will have very little velocity shear!**

Why , How- a detailed and deep understanding of this very interesting and important phenomenon is the TFP.



Qualitative Understanding of Transport Barriers

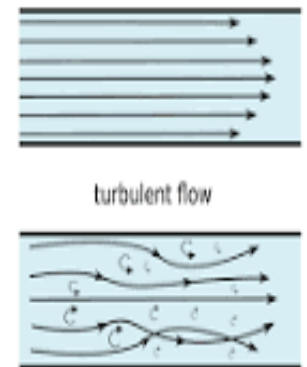
- Turbulent transport in TBs BEHAVES EXACTLY OPPOSITE to most physical systems outside of magnetic confinement:
- Standard behavior - increase a gradient and faster flows the physical quantity- heat will flow more rapidly for sharper temperature gradients

In MCTBs, higher gradients , in fact, lead to lower turbulent fluxes

- What *exceptional* process operates in magnetically confined plasmas ?
- What prevents the enormous free energy from driving the system towards an equilibrium- The dis-association of free energy from instability !
- **A Constraint that forbids the conversion of free energy into turbulence??**
- Finding that constraint, and finding out conditions when it operates most effectively, and figuring out the route to those states is the twenty-first century physics of fusion



Laminar
&
Turbulent
Flow



Heat Flux and Impurity problem

High Z impurities degrade confinement

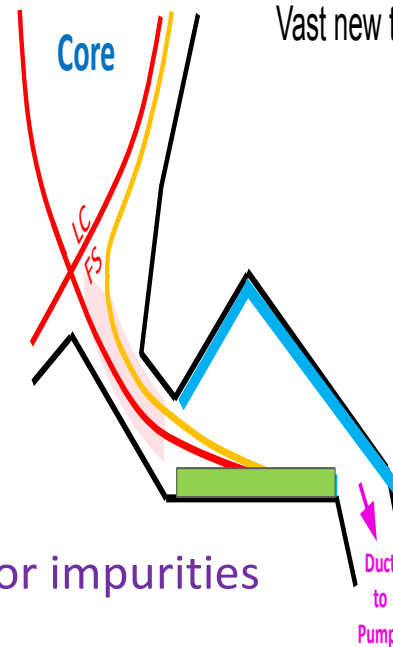


Ideal PFC=High Z for heat handling and low Z For impurities

The Super-XT Divertor: Ultimate Flexibility

High recycling, low recycling or anything in between

Vast new territory in which to optimize $T_{div} = 10-1000eV$



Some elements of the Super-X, but crucial new aspects are needed. The outboard target is in a region of reduced magnetic field strength, like the Super-X. Additional critical elements include 1) in long mean free path (LMFP), regimes, an electrostatic potential arises on the outboard and the inboard, which strongly shields the core from impurities 2) Due to the strong erosion of the plasma facing surface from sputtering, in high duty cycle operation, the entire region near the target must be coated by LM that is slowly replenished (low-Z sputtering but not lithium) 3) novel heat flux mitigation using magnetic geometry, without requiring rapid LM flows 4) configurations to greatly improve helium exhaust.

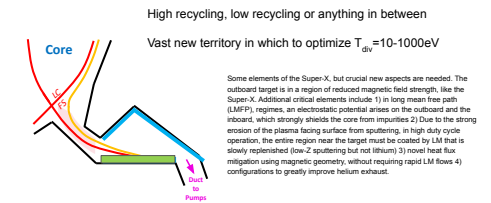
Guards against disruptive transients, accidents and other loss events

Liquid metal can be replaced



An optimum PFC solution must not be built on the constraint that the main plasma must adjust (in fact be degraded) to be compatible with the PFC. It should, in fact, be the other way around; the PFC technology should be so chosen that it will be able to handle the best possible core conditions that physics allows.

The Super-XT Divertor: Ultimate Flexibility



Taking Stock

there are ideas and inventions driven by recent advances in Physics and incorporation of newer technologies, that could grow into a well-defined program for boosting confinement to needed levels.

i



- Though the highway to the destination -Commercially Viable Fusion- is partially constructed (through scientifically brilliant, sustained and dogged research), we still have miles to build
- Soon we will have $Q_{sci} = 1$, the first grand step in the grand pursuit- fusion on earth. **But much work still needs to be done to ensure that the star on earth, we create, does not remain just a prize museum ornament.**
- Confinement must be boosted for both set of contenders:
 - 1) currently cheaper but low confinement systems –essential... period!
 - 2) currently moderate/good confinement systems => smaller and lower magnetic fields => **reduce cost- realm of commercial viability**
- With the literal formation of the united community of Government Researchers, private companies and the private-public partnerships, the fusion enterprise will surely graduate from scientific breakeven to a regime of commercial viability.

A Quintessential Scientific Quest



Engineering challenges galore, and yet

- It will be unwise to declare Fusion to be an Engineering and development program only
- Without periodic scientific injection of new ideas , CVF may remain distant
- Boosting Confinement today, new Fuels tomorrow, neutron Free fusion day after- This will keep scientists busy for a while



Extra Slides

Elevating Confinement: The Key to Commercial Viability

Fusion- a Quintessential Scientific Pursuit

Swadesh Mitter Mahajan,

Professor, University of Texas | Chief Scientific Advisor ExoFusion

FPA, Dec.19, 2023



Bending the Directives!

This talk is not about a particular FPP design, its technological readiness, costs and schedules—etc.

At this time, ExoFusion does not have a “marked” horse in the race

We will, instead, focus on scientific investigations that have helped us to identify the defining characteristics of a commercially viable FPP.

Science also identifies/defines technologies crucial for the success of a fusion reactor

Boosting confinement will be key for every magnetic fusion approach
our approach is both catholic and agnostic.

Why dwell on Confinement (energy confinement time τ_E)?

- Scientifically - Fusion Enterprise must maximize $n T \tau_E$
- Commercially speaking, smaller, cheaper reactors are necessary
- The higher the τ_E , the smaller and cheaper the fusion relevant machines
- ExoFusion's Defining Philosophy and Key Challenge :

Develop modes of boosting confinement

So that high fusion gain in a small device becomes possible

To do that we've designed suitable exhaust systems (divertors, for instance) that are compatible with most high gain configurations

Deeper Look into Confinement- Turbulent Transport

- It turns out even if conventionally understood mechanisms (like velocity shear) are strong enough to stabilize MHD and some other vicious modes, they are not adequate to stabilize all fluctuations (like ETG and MTM)
- The residual turbulence due to these fluctuations can/does degrade confinement . To push confinement beyond the conventional values, one must investigate the physics of the Residual Turbulent Transport
- This twenty first century physics (developed, in part, by the principals of ExoFusion), in fact, supplies us with enough understanding on how to control the turbulent transport, and in the process, strongly boost confinement.
- We have, in fact, found regimes where turbulence suppression takes place without velocity shear.

Modern, Innovative Physics

- In magnetically confined plasmas, there is a constraint on gyrokinetic fluctuations that prevents them from accessing free energy in the equilibrium. General physics principles, then, can be invoked to find regimes of strongly suppressed turbulent transport – of boosted confinement (BC).
- Via detailed investigations, Exo Fusion has mapped out these regimes. Though demonstrated primarily for tokamaks, BC is accessible to all magnetic configurations.
- Equally important is the fact that Theory and Simulations identify ***the knobs that we must turn*** to access the BC states.
- *In systems as complex as magnetically confinement plasmas, it is amazing that High confinement regimes are often accessible when density gradients become large.*

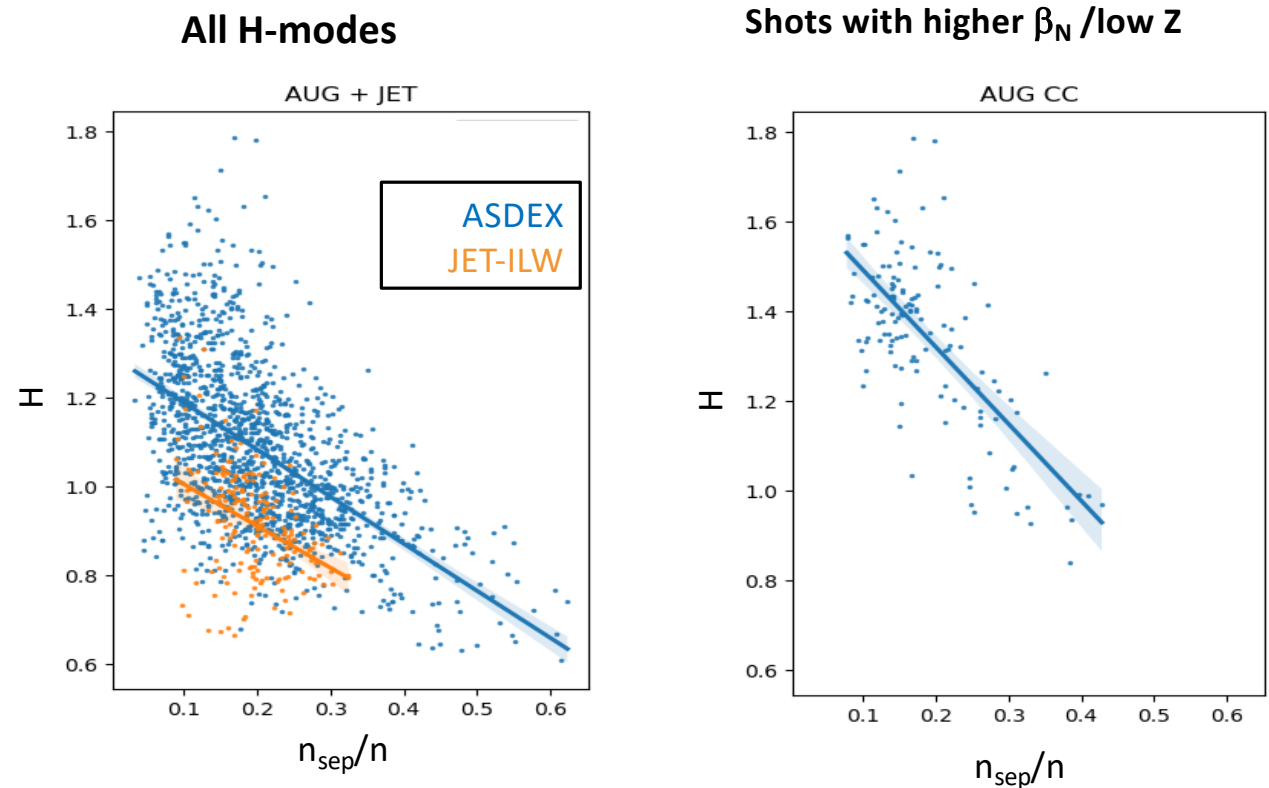
Larger density gradients = smaller n_{sep}/n , n_{sep} = separatrix density

Experiments show the trend expected from gyrokinetic theory: low edge density greatly improves confinement

- From the ITPA database:

Confinement relative to the H-mode scaling law (“H factor”) increases as separatrix density n_{sep} is lowered

Confinement up to 1.8 times higher than normal is possible with low n_{sep}

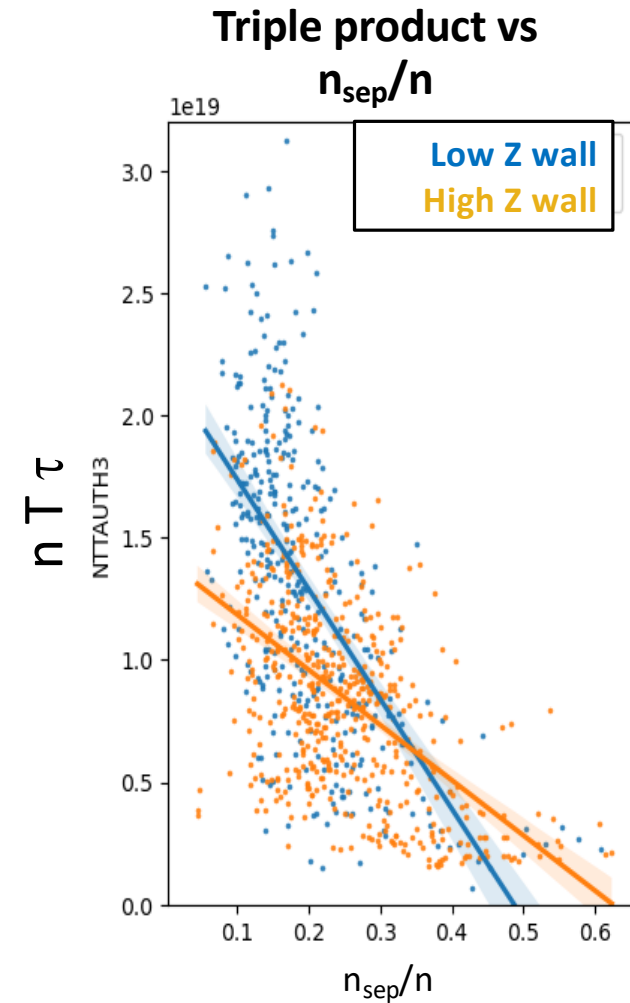


Heating power needed for the same stored energy falls to 1/3- sure signature of suppressed transport

Triple product follows these trends

Maximum fusion performance ($n T t$) is obtained at low n_{sep}
particularly, for low Z walls

- Such low n_{sep} (and correspondingly high $T_{\text{sep}} \sim$ hundreds of EVs) edges are rather problematic :
- Demand novel divertor solutions
 - New geometries
 - New materials
 - New Kinetic codes to model/analyze the new edge
- ExoFusion has patents pending on new geometries, new materials needed to enable exceptional confinement



What must we do to reify high confinement regimes

- *ExoFusion has been working vigorously to create pathways to access and maintain the high confinement regime implied by the basic structure of the gyrokinetic equations (epitomizing the physics of turbulent transport)*
- *It is a multidimensional space in which we have to find working solutions- has required innovations on several fronts*
- The most salient expression of this persistent investigation is what may be called a **Liquid Metal SUPER XT divertor (T is for high temperature)**, a very advanced version of the well-known SuperX divertor (invented by ExoFusion principals years ago) whose efficacy has been so well demonstrated by MAST-U experiments.
- *ExoFusion has also been occupied in developing appropriate computational tools to further understand and predict confinement in general, and in the regimes of choice.*

Super-XT Divertor: Ultimate Flexibility to Optimize

Integrated solution: Efficiency in handling heat exhaust , Sputtering/erosion, impurity entrainment, alpha pumping---

Employ self-healing liquid metals creatively + manipulation of divertor magnetic geometry

Originally designed for low recycling conditions- separate the absorbing and the heat handling functions- each becomes more effective (Lithium not needed at all)

However the exhaust part is applicable to all edge conditions-including the high recycling ones

The best of both worlds- The Miracle Liquid Metal : An alloy with high Z metal with a “segregated” low Z surface- Combining the high heat handling capacity of the high Z with limiting sputtering to only low Z (Exo Patent Pending) .

This is an important technical solution invented by ExoFusion- likely applicable to most if not all fusion worthy concepts.

How Could ExoFusion enrich the vibrant Fusion Ecosystem

- ExoFusion is a relatively small company developing novel solutions to problems of confinement, divertors and Liquid metal PFCs. Creating exploitable intellectual property has been our main pursuit.
- Design and analyze SuperX - Super XT divertors for superior quality ETBs and ITBs-Coupled with Miracle Liquid Metal walls, these will handle problems of erosion and limiting impurities to only low Z
- Provide novel simulation tools to analyze kinetic divertor regimes. One of the code, necessary for all burning plasma edges, is being developed along with PPPL -- *STEP divertor design will be its first application*
- Our abilities (theoretical- state of the art computational tools) equip us to do Confinement projections in multiple geometries (our codes are global – a crucial advance upon local tools like TGLF)
- We already have experience in engineering TBs in tokamaks- we designed an ITB for EAST in conjunction with GA - invited talk. All our tools are applicable to other geometries

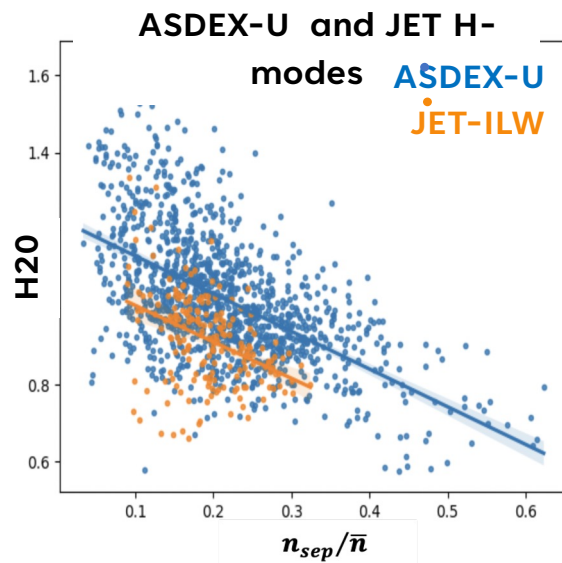
ExoFusion Ready to Work for advancing fusion

Making it cheaper, less risky, nearer term

- Even If your system already has good confinement, we can work out ways to enhance it and help you design a system that is smaller and cheaper
- For systems struggling towards adequate confinement, we will work out scenarios to boost it to fusion worthy values
- More generally, through our well-developed investigative tool kit, we can help avoid costly delays by anticipating and correcting confinement shortfalls
- We can always give you the best in PFCs if that is all you need

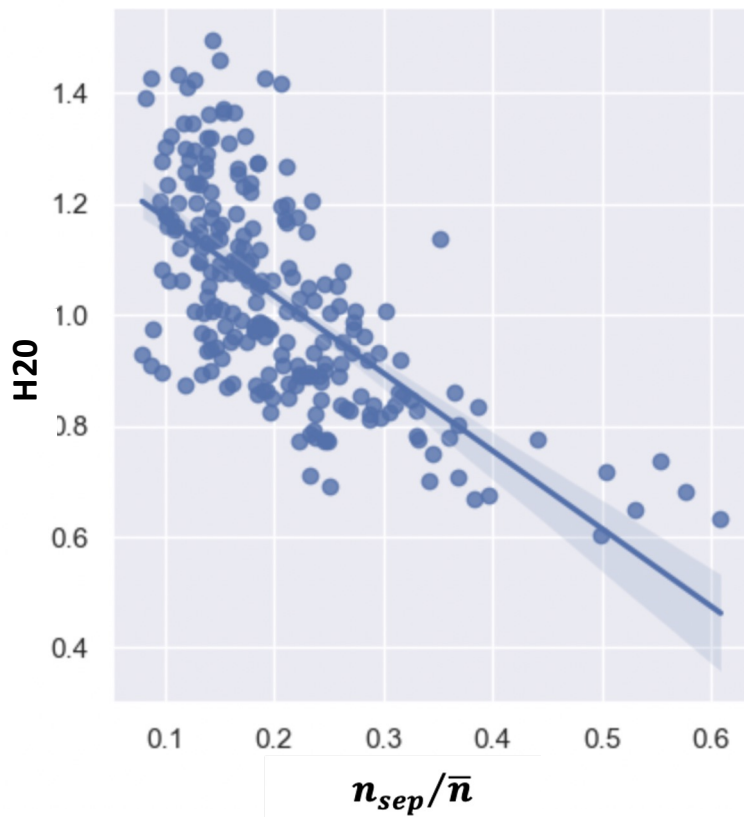
Experimental Evidence - Confinement goes up with lower edge density

Most spectacular effects are seen when both the divertor and wall are low Z



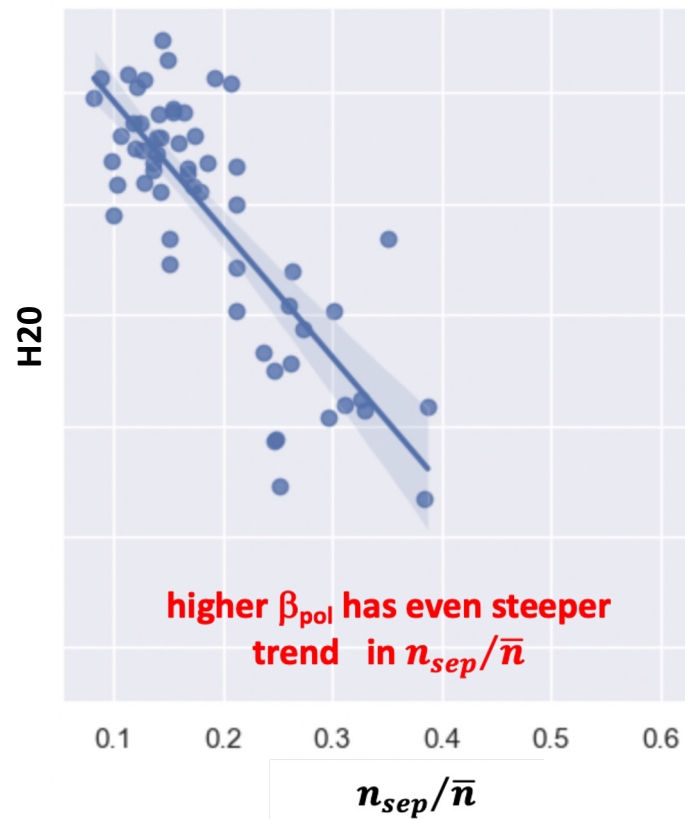
Although the tokamak data is available and clear, the physics is common to gyrokinetic instabilities in diverse geometries. And for a given geometry to all Variations in plasma properties.

ASDEX-U wall-C div-C
(like DIII-D)



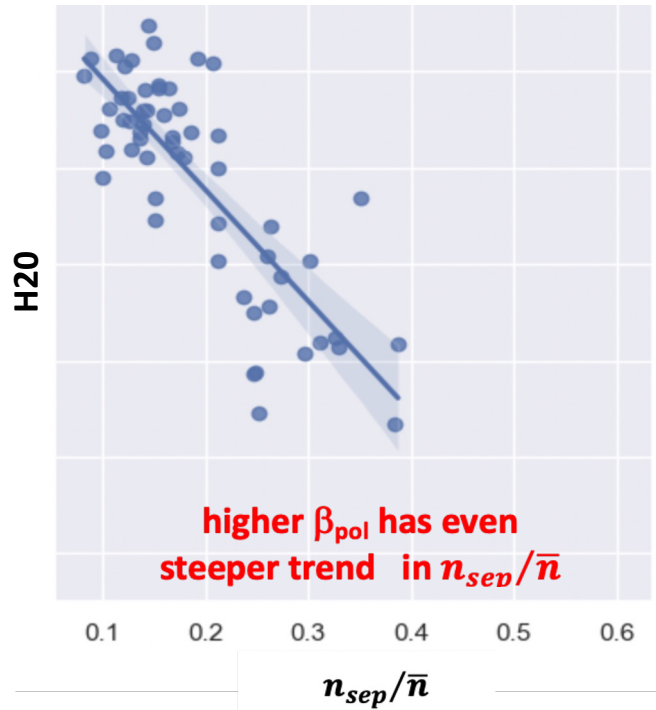
Holds for both
ITBs / pedestals

ASDEX-U wall-C div-C:
highest β_{pol} quartile

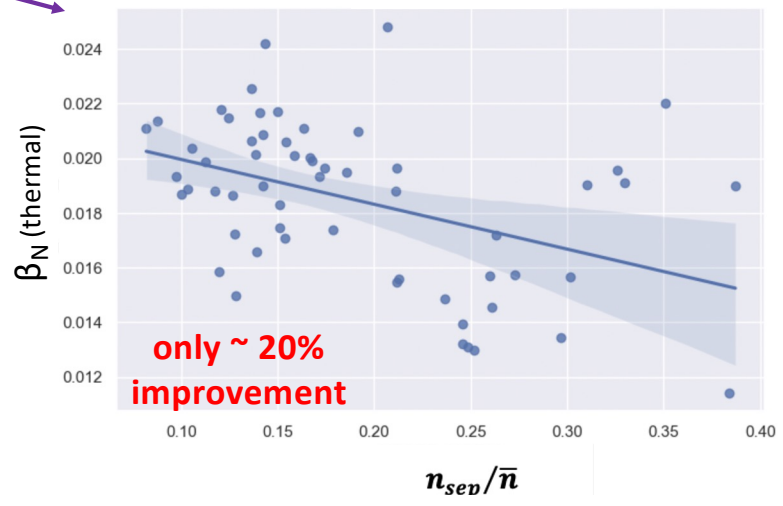
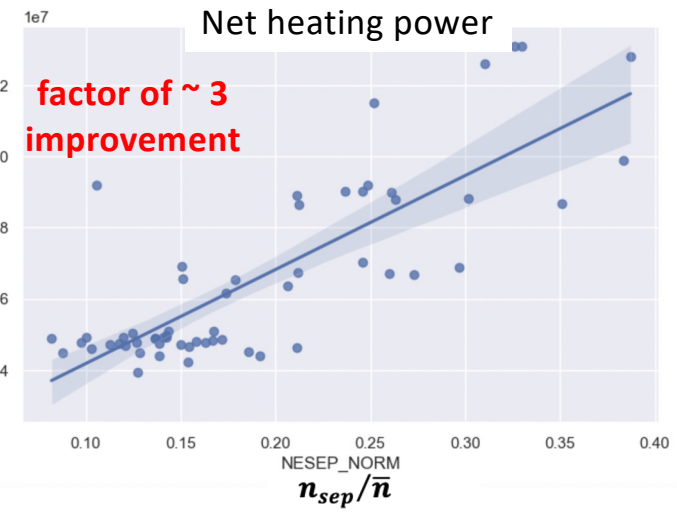


Where does this confinement improvement come from?

ASDEX-U wall-C div-C:
highest β_{pol} quartile

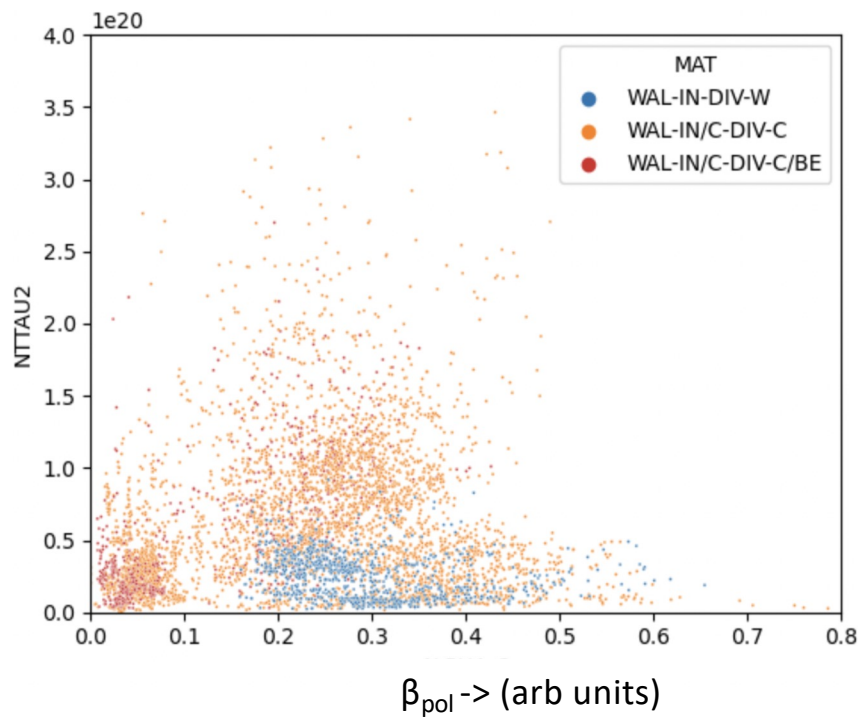


- Almost factor of 3 reduction in heating to get the same stored energy
- NOT from pedestal MHD stability improvement
- Further analysis: reduced pedestal transport allows pedestal to get to MHD limit with much less heating



As the Constraint Dynamics would predict !

On JET low Z divertor (C and C-Be) much higher $n\tau_{\text{avg}}\tau$ than W



At higher β_{pol} C much better than W

This and earlier pictures gives us a Profound message that plasmas are much more fusion worthy if they are “polluted” by low Z impurities. Exo incorporates this fully into the design of Super XT liquid metal divertors.

Fusion on Earth

Government versus Private

Contrasting Priorities

- **Government:** Most research in govt. labs or govt. sponsored labs
 - Dedicated to Understanding the science and technology of fusion
 - lip service was paid to commercialization, it was, by no reckoning, the compelling goal.
 - What really drove fusion research was the fundamental goal of demonstrating that fusion, ``in principle'', is possible; cost and time spent did not enter the equation- the sheer grandeur of replicating on earth what stars do in the Heavens.
- It is my firm belief that this awe/wonder will ever stir folks to pursue fusion to the very successful end.
- The Govt research that has brought us to the stage where we are near what is called scientific breakeven ($Q_{sc} = 1$).
- It is my equal firm belief that the next synthetic stage, fueled by a combination of

steady plus path breaking innovations in fusion science and technology
plus
entry of more and more highly innovative private companies

Will be qualitatively different. Riding on the shoulders of the Govt sponsored research, and relentlessly pushed by the profit-motive, vision and dynamism of the private sector, the fusion enterprise has, finally, come of age.