The Fusion Enterprise

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In a Glimpse

- Pre Basic Physics
- Basic Physics
- Some fundamental recent advances
- Current Fusion landscape- Govt. funded versus privates funded
- How fundamental advances may transform the Landscape
- Is nuclear fusion industry possible- Can it be commercially viable

Recollecting / Building the Magnetic-Fusion Logic

- Dramatis Personae:

  1)$|B|$, the gyro frequency Ω, $\Omega_D \approx 5.10^8$ *for one tesla*

  2)the machine size a, a pressure scale length L

  3) the thermal speed v_{th}, gyroradius $\rho = v_{th}/\Omega$, and the dimensionless measure $\rho^* = \rho/a$

  4)some effective "collision" frequency, in fact, a correlation frequencyγ-generally the growth rate of the "dominant" mocroinstability, $[\gamma \approx v_{th}/a, k\rho \approx 1]$

- The projected turbulence dominated transport:

$$D_t = \gamma(\Delta x)^2 \approx \gamma/|k|^2 \approx \rho^2 v_{th}/a = \rho*^2 a v_{th} \tag{1}$$

implying a confinement time

$$\tau_c = a^2/D_t = \frac{1}{\rho*^2}\frac{a}{v_{th}} \tag{2}$$

"Gyro-Bohm" scaling on which ITER like machines are planned. To get the best confinement time, go to lower ρ^*- totally consistent with the naive ideas of magnetic confinement -Increase the magnetic field- increase the minor radius.

Fusion- Breakeven - Ignition

- Energy produced in a Fusion Reactor

$$E = \frac{1}{4} n^2 < \sigma V > \mathcal{E}, \tag{3}$$

where $\mathcal{E}$= energy released per unit reaction, $< \sigma V >$ will be the reaction rates for D-T reactions.

- For net energy gain, we must demand

$$E > E_{loss} + E_{expended}, \quad define \quad Q = \frac{E}{E_{loss} + E_{expended}} \tag{4}$$

- The more moderate scientific First Ambition is to define $Q_{scientific}$

$$Q_{sc} = 1, \quad when \quad E = E_{loss}, \qquad Q >> Q_{sc} \tag{5}$$

- We are still struggling to get $Q_{sc} = 1$ in any semi steady setting
- Fusion will be an economic reality when $Q \rightarrow$ infinity=Ignition=burning plasma

Is the Fusion Enterprise well grounded- not a chimera

- Two Fusion Systems - The stellar (that works) and terrestrial (our pursuit)

Fusion in the sky - Gravity weak- Size= Big

- Nuclear reaction: A combination of weak and strong; Crudely

$$H + H = D, \quad D + D \to H_e^4 + E_s, \quad at \quad about \quad 1.4KeV$$

- Simple Newtonian hydrostatic balance plus an adiabatic equation of state connects(after solving a Lane-Emden equation) the central temperature, density, and the radius (R= defined to be the distance at which density goes to zero)

$$T \approx m_N \Omega_g^2 R^2, \quad \Omega_g^2 = G\rho_0 = \text{“}frequency\text{”} \tag{6}$$

- A bit of nuclear physics tells us that $T \approx 1KeV$ this gravitating object will shine.
- Then

$$M = 2.10^{23} \to \Omega_g = 5.10^{-4} \Rightarrow R = 7.10^{10} cm$$

Twinkle Twinkle Big star!, oops, Twinkle Twinkle Big star!

Terrestrial Fusion thru Electromagnetic Forces

- A naive replacement of Ω_g by Ω_D at a tesla, will bring R down by 10^{12}- Unfortunately that is not how things work
- needless to say that magnetic forces confine plasmas in a different ways- The Electric fields cannot confine an assembly of electrons and ions (gravity has only one charge)
- It is not my intention to give a tutorial on basic confinement except to state:
  1) since the confinement across the magnetic field is ensured by the strong magnetic field , most ingenuity is needed to close the third direction- let us say we make a set of nested surfaces traced by a field line
  2) However even this confinement is not forever- All magnetic bottles leak - some due to the initial design of the field but mostly because of coulomb collisions and the processes set in by confinement- The instability
  3) If the instability was not overwhelming and only collisional transport pertained , a device size of 25-50 cm will be enough to have fusion at 10 kev
- Euphoric Initial Responses - Fusion is within easy reach
  Bhabha says In Atoms for Peace Conference in 1958 - Fusion is around the corner and Indian Scientists have made fair advances
- Reality, however, was formidably otherwise- The real plasmas lost energy much faster than expected
- So let us examine the ignition condition assuming that the confinement τ_E is determined by anomalous processes (Instability generated). Naturally the efficacy of the fusion furnace is controlled by τ_E

magnetic Fusion- Ignition Condition- The fundamental place for τ_E

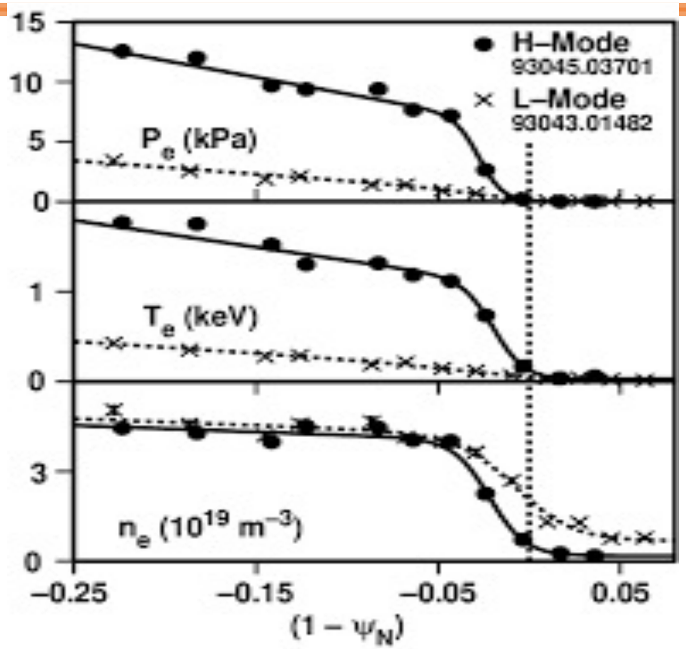
- The heating power that must be supplied to keep a fusion system going is the loss rate minus the production rate

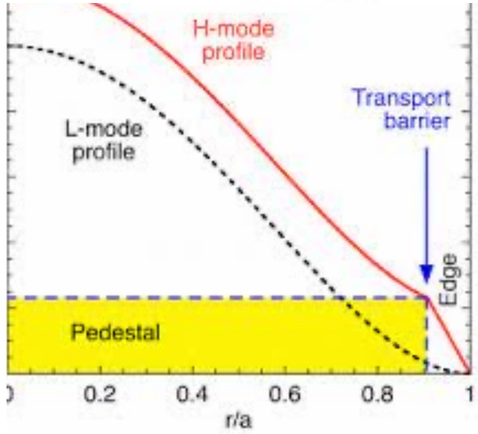
$$P^H_{ext} = \frac{3nT}{\tau_E} - \frac{1}{4}n^2 < \sigma V > \mathcal{E}_\alpha$$

- Notice that I have used $\mathcal{E}_\alpha = .2\mathcal{E}_f$ instead of $\mathcal{E}_f$: The neutron energy is extracted to produce electric power; it is only α energy that is available to balance the losses.
- There is an absolute constraint that limits the Pressure nT- the threshold for instabilities that fully destroy the plasma, not just degrade confinement.
- How the pressure is to be divided into density and temperature has some leeway- Not so much however. Notice that fusion energy scales strongly with density but, through $< \sigma V >$, it scales (in the range of accessible temperatures) even more strongly with temperature. τ_E is almost the only physics parameter that we may play with
- Plasma will ignite - will not need any external power input if $P^H_{ext} < 0 \Rightarrow$ The larger the τ_E, the easier it is to reach ignition
- Let us then graduate to talking about confinement

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 enetrprise
- 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

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 of fundamental-importance- reactors will have very little shear

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

Transport barriers are a HUGE puzzle

Turbulent transport in TBs BEHAVES EXACTLY THE OPPOSITE to a TRULY VAST VARIETY of physical systems outside of magnetic confinement, where:

Increasing some gradient (a "thermodynamic force")

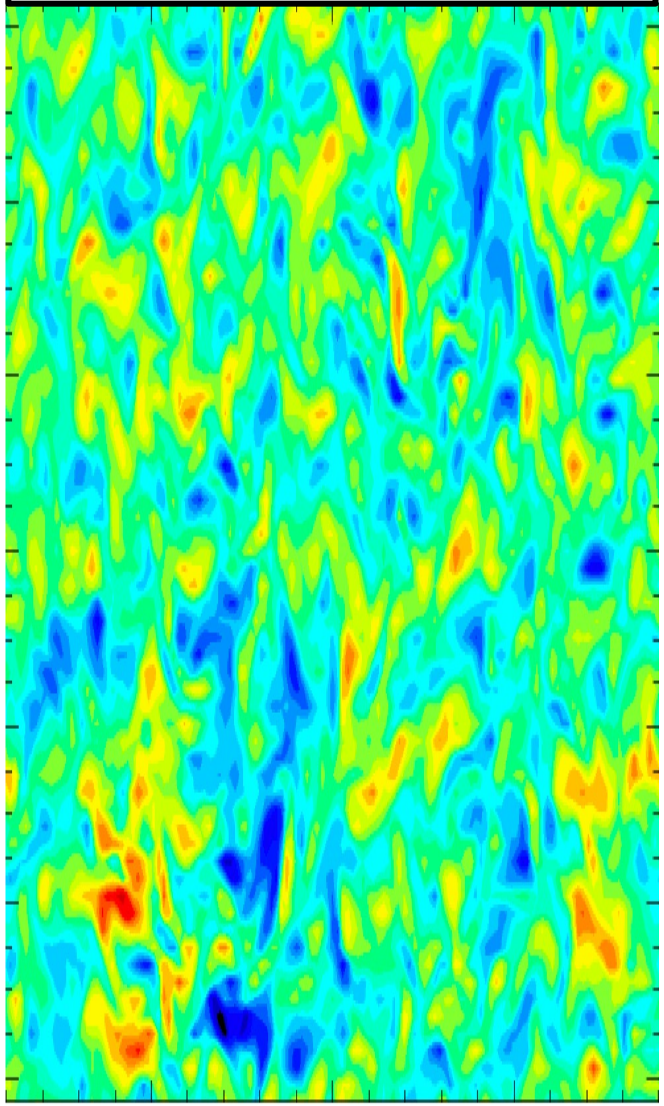
Increases thermodynamic relaxation rate (the corresponding "thermodynamic flux")

In TBs, higher gradients DO NOT lead to higher turbulent fluxes- often, in fact, the opposite

Given the **truly huge** weight of physical systems that behave the "usual" way, we are compelled to ask:

What ***exceptional*** process operates in TBs in magnetically confined plasmas? (**because of history, Specifically, when velocity shear is not crucial.**)

2D contour plot of TB gyrokinetic simulation δn
(the full 5D phase space is far more complex with far more degrees of freedom)



What is needed for a burning plasma 1

- H-Mode will be the generic term for fusion relevant high confinement systems - A Good H-mode confinement

- 1) "Sufficient " MHD Stability The pedestal must have good MHD stability to reach high pressure
- 2) "Enough" velocity shear A good H-mode must also have enough velocity shear at the pedestal top- ??

- Adequacy of shear was supposed to be necessary in earlier understanding- but we have gone for beyond that- Work of our group has been pivotal in demonstrating what physical processes will allow good confinement even without velocity shear-

- *Experiments preceded the theory.*

What is needed for a burning plasma 2

Acceptable Power Exhaust

- Time Average heat flux must be < the engineering limit:
- Transient ELM heat load must be below the melting limit - The restrictions could be even severer
- *The edge conditions must not degrade the main plasma*

- In fact, the smartest strategy will be to make the edge accentuate the main plasma- the simultaneous core-edge optimization

Transport Barriers – Traditional Approach- velocity shear 1

- Transition to H-mode, spontaneously, generates sheared flow
  Shear flow is associated with the appearance of a radial electric field *Er*

- For well developed pedestals, the radial electric field Er is well approximated by the neoclassical estimates

- Neoclassical estimates are abundantly verified in experiments on multiple tokamaks (ASDEX, DIII-D, C-mod, etc.)

- The shearing rate associated with this E × B flow

$$\gamma_E = c\, \partial_r (E_r / B)$$

is a fundamental construct for understanding the pedestal turbulence

Transport Barriers – Traditional Approach- velocity shear 1

- it is intuitive: “high” shearing rates would quench core turbulence (nonlinearly).
- The “usual” core turbulence: primarily “electrostatic modes”- ITG, trapped e-modes-
- The electrostatic turbulent transport is expected to be suppressed when the turbulence eddies are “sheared apart” faster than they are formed
- That is if $\gamma_E > \gamma_L$, the linear growth rate; the latter is a measure of the eddy formation rate . Years of simulations, theory, and experimental benchmarking, find that
- transport -quenching requirements : γ_E several times larger than γ_L- by a factor 2.5-3.
- Till now the fusion community, at large, has assumed that this requirement will be true for burning plasma H-modes.

This, we will soon see, has been a critical oversight

The Shearing Rate/ linear growth rate

- For standard modes , one can simply estimate the ratio $\Gamma = \gamma_E / \gamma_L \approx \rho*$, $\rho*$ being the ratio of the thermal gyro radius to an equilibrium length.

- It is eminently true that Present devices in ELMy H-mode operations have more velocity shear than is needed to suppress the electrostatic transport-the suppression parameter Γ is considerably greater than 1

- it makes sense, then, to examine if the projected *Γ for ITER* that has a much lower $\rho*$, will be large enough to allow such a happy state- a robust H-mode pedestal.

The Shearing Rate/ linear growth rate

- Experimental examination, unfortunately, cannot be done –- ITER- relevant $\rho*$ is unattainable in present devices -especially at relevant collisionality → DIIID pedestal may not accurately reflect the ITER pedestal- they are in different physics regimes!

- Our simulation/ computational abilities have increased tremendously- In particular , the gyro kinetic simulation codes have attained a high level of maturity and reach; the gyro kinetic codes can simulate the pedestal turbulence and its consequences. Our group does it routinely.

- It must be noticed, however, that such powerful investigating tools (to probe Nonlinear fully electromagnetic turbulence, for instance) have just come of age- **They were certainly not available for ITER design**- And really, not for all these interim years

Gyrokinetic Simulations- JET, ITER

- JET: the level of turbulent transport agrees with experiment There is sufficient Γ to suppress the electrostatic transport. Electromagnetic modes, more resistant to velocity shear, predominate

- ITER: At relevant low γ_E, the e.s turbulence produces huge transport- Almost an order of magnitude more turbulent transport losses (many hundreds of MW) than the ITER heating power ≈100MW

→ It appears that the transitional Γ (ρ∗) below which the e.s turbulence may become too high lies somewhere between JET and ITER.

→ with this ITER heating power, the pedestal top will be considerably lower than needed for good core confinement and high enough central temperature.

- The problem is made even worse by strategies that are generally proposed to control divertor heat flux and eliminate ELMs - These considerations are rather sobering – Could we have expected these difficulties with burning plasma pedestals- Did we not grapple with these problems sufficiently and intensively?

Role of turbulent transport in the fate of the pedestal

The crucial fact - Γ is determined by $\rho*$, though clearly known, was not "appreciated" or taken seriously

If Transport threshold was the critical determinant, the pedestal width would scale as ρ_p

Why was this simple fact not an integral part of the pedestal lore?

Missing was the role of turbulent transport in the fate of the pedestal

Let us see why, indeed!

The Influence of EPED-KBM controlled

A Very detailed and intensive/impressive multi- machine experimental effort was undertaken to categorize pedestals- The results were shown not to obey ρ_p but more like sqrt(β_p) *scaling*- which, of course, differs from ρ_p via a density dependence.

Width is not transport controlled, then why fuss about transport?

Experiments , bolstered by a MHD based theoretical model ruled the roost

The EPED model, developed at GA, basically claimed that the pedestal characteristics (crudely, height and width) were set by MHD alone - Micro-turbulence played little role

Broad “consensus” written, inspired, and shepherded by P.Snyder, the originator– led to the net conclusion

ITER pedestal would be broad and high enough for high Q.

Physics Strikes back - Dark Clouds on the ITER horizon

- A high confinement mode (I mode) had an enhanced level of micro-turbulence
- In magnetic field scans, there is considerable departure from EPED for high field
- Several simulations of the JET and some other pedestal see no evidence of a KBM - casting doubts on the KBM engineered pedestal
- Are we beginning to see something different as we travel towards ITER via JET- largest of the current machines with the lowest $\rho*$
- This change from a great match for (DIIID , ASDEX-U —) to not so great a match for current JET experiments creates a serious dilemma? do we believe EPED projections for ITER (quite optimistic) or do we not? Could ITER be in different physics domain - essentially inaccessible to the best diagnosed machines of today?

What will be our new Physics Picture?

Rho* ordering - Resorting to simulations

- Reviving the possibility of micro-turbulent transport as a possible player for larger machines like ITER and high field runs(on current machines). $\rho*$ should be marshalled to enter the battle-field

- It is quite clear that $\rho*$ for ITER will be considerably smaller than for the current machines- Is it conceivable that $\rho*$ for ITER is low enough that micro-turbulence, which is strongly suppressed, say, in DIIID, may end up determining the properties of the ITER pedestal

- A fundamental question for ITER/Fusion: Is $\rho*_{ITER} < \rho*_{crit}$ or $\rho*_{ITER} > \rho*_{crit}$? A vigorous investigation of ITER pedestal must follow- EPED projections may not be reliable

Rho* ordering - Resorting to simulations

- We, at UT, have struggled with these questions for a long time. Finally, we embarked on a somewhat ambitious program on ITER pedestal investigation by employing the *state of the art* code GENE (nonlinear fully electromagnetic simulations) fed by highly resolved full-geometry equilibria
- To the best of our knowledge, this was the very first attempt at this problem at such an encompassing level.
- Most important results of our investigations have shown that ITER, indeed, is not just a larger DIIID; it is in a different physics regime
- There needs to be a paradigm shift in order to understand confinement, i.e, nature of transport barriers especially when the velocity shear is weak

Without much ado, I will introduce you to this new paradigm !

Yes Virginia- Instabilities (the cause of turbulent transport) may not always access the available free energy in gradients!

When there are physics constraints blocking the accessibility!

Example: An atomic transition, though energetically allowed, may be forbidden by angular momentum conservation.

A major discovery of our group, via Theory/Extensive simulations. is that the entire class of possible gyrokinetic motions (essentially the motions that may shorten the “long life” of the hot fusion experiments) must observe a fundamental constraint

The instability induced radial current (charge weighted flux)must vanish

If not, such an instability cannot build despite free energy, even large free energy in the enormous gradients

Simulation results amply demonstrate the efficacy of this constraint

- Principal Physics Result- The dis-association of free energy from instability => free energy does not directly translate to turbulent transport => the biggest barrier to fusion energy is eliminated "in principle"

- Even better- In certain magnetic geometries, in appropriate parameter regimes, we can have very sharp gradients co-existing with reduced transport- far from thermodynamic states

- We have also been able to chart out geometries and parameter regimes(many dimensional) that favor these patently non-thermodynamic fusion-friendly states

- What is equally important is that we have identified the experimental knobs that can be twiddled to initiate and sustain effective transport barriers

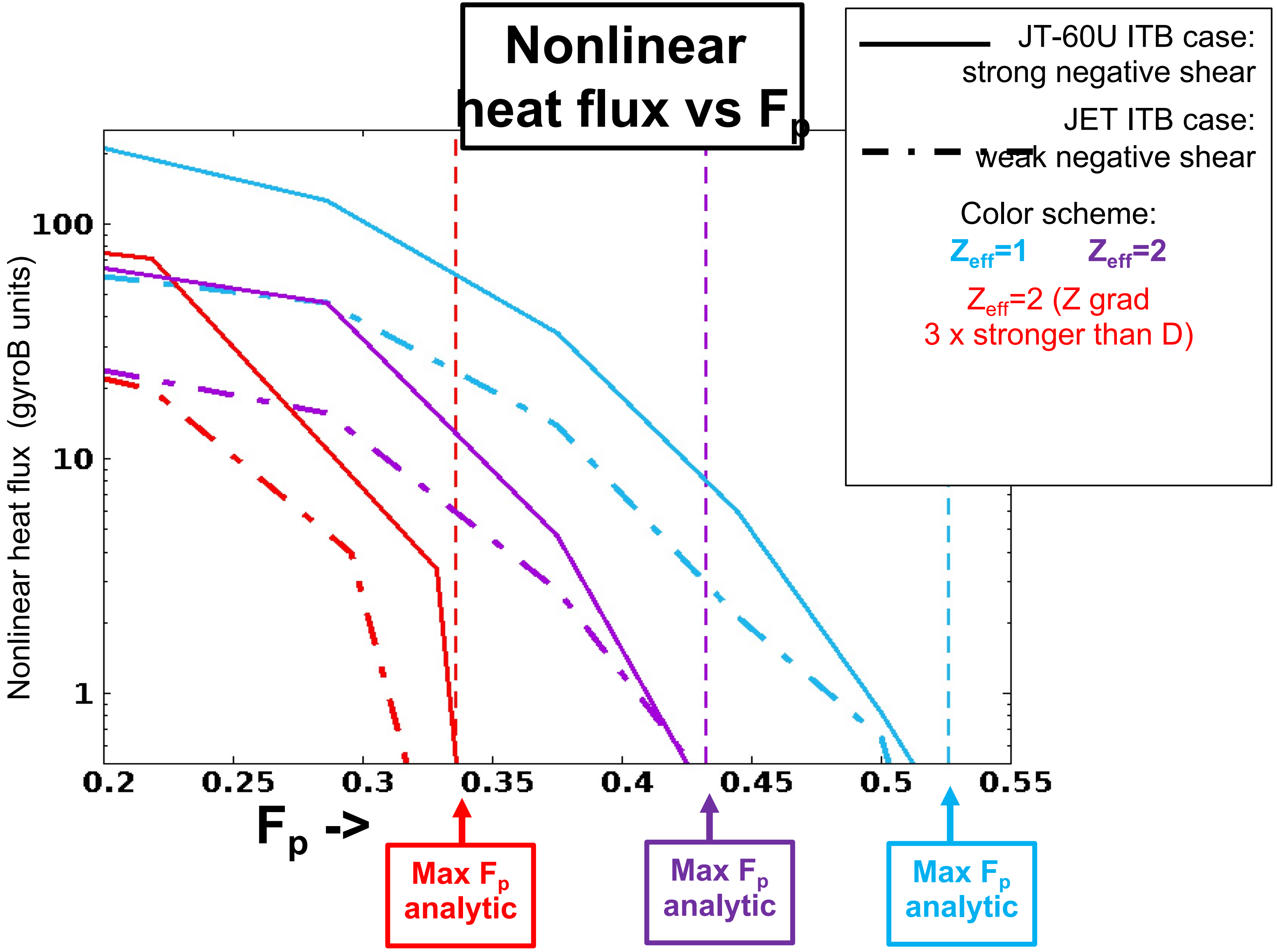
- The most important result is that when density gradients exceed some critical value, the system tends to become instability free despite any amount of free energy!

Nonlinear runs for diverse geometries follow the Constraint

- F_p= ratio of density to pressure gradients- can often be calculated analytically

- For two quite distinct geometries, the heat flux goes down by ~2 orders of magnitude as the analytic F_p boundary is approached

NONLINEAR heat flux follows the impurity modified solubility constraint



How do impurities suppress instabilities

- Unstable modes are not accessible if radial current cannot vanish

- Let us suppose that in the absence of impurities, electrons and ion currents balance- constraint is satisfied-instability will be possible

- Impurities, by enhancing the positive current (strongly because they are multiply charged) destroy this balance and hence push this motion out of the domain of accessibility!

- The more current they cause, the greater the imbalance, the harder to go unstable -- Most effective stabilizing agents- Large Density gradients and Impurities

Optimum Transport Barriers

This aspect of dynamics (stabilization due to inaccessibility) opens new vistas :

New domains in parameter space, and barrier optimization in known domains

We have new control knobs that can give us newer and possibly better barriers than would be found by trial and error.

Amazingly the most important knobs are the ones that are controlled by the Plasma edge- Where the hot plasma meets the somewhat colder world .

Control of edge conditions is crucial

In fact the name of the fusion game, is Core-Edge Optimization

Tail Wagging the Dog- Commercializing Fusion

A daunting fusion issue is how does a hot core plasma remain fusion worthy when it must connect with the cold materials of ordinary life- the walls

This intermediary-edge plasma region is also called a Divertor

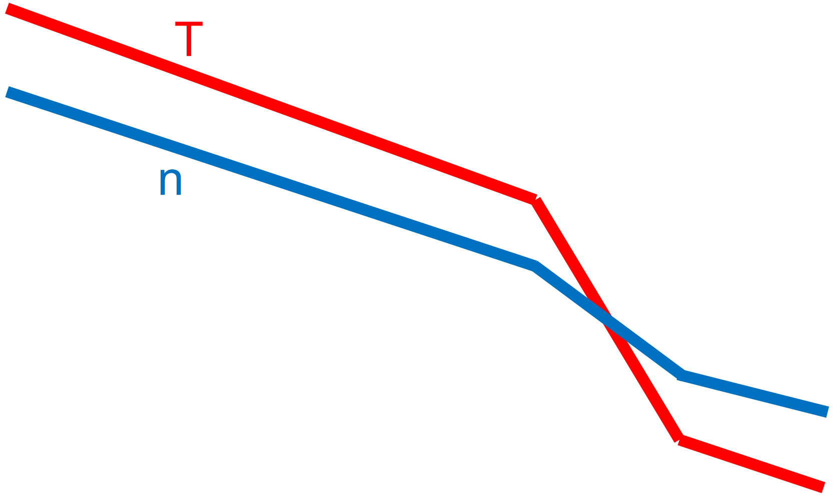
Traditionally all of the burden of confinement is on the core- the edge gives no help, only headaches. With new physics Understanding **This is what we can drastically change**

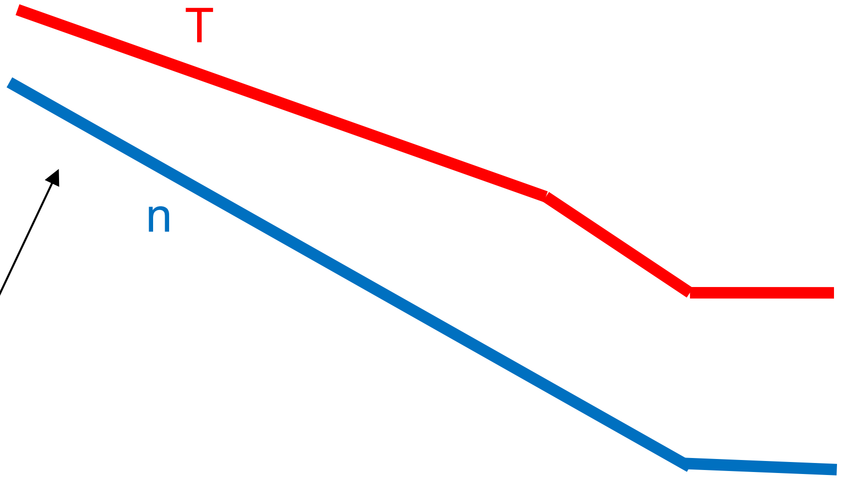
One of our most impactful inventions (time will tell) is to have figured out how to improve the core confinement by suitably engineering the divertor.

The final product is called a Super XT divertor

SXT may be the key to the commercial viability of fusion

Energy Confinement- forever the key issue





Conventional:

Challenges of steep T gradients: ETGs, MTM, ITG/TEM, etc., etc.

We have a lot of experience with these

They'll cause ENORMOUSLY less transport if the profiles looked like this instead

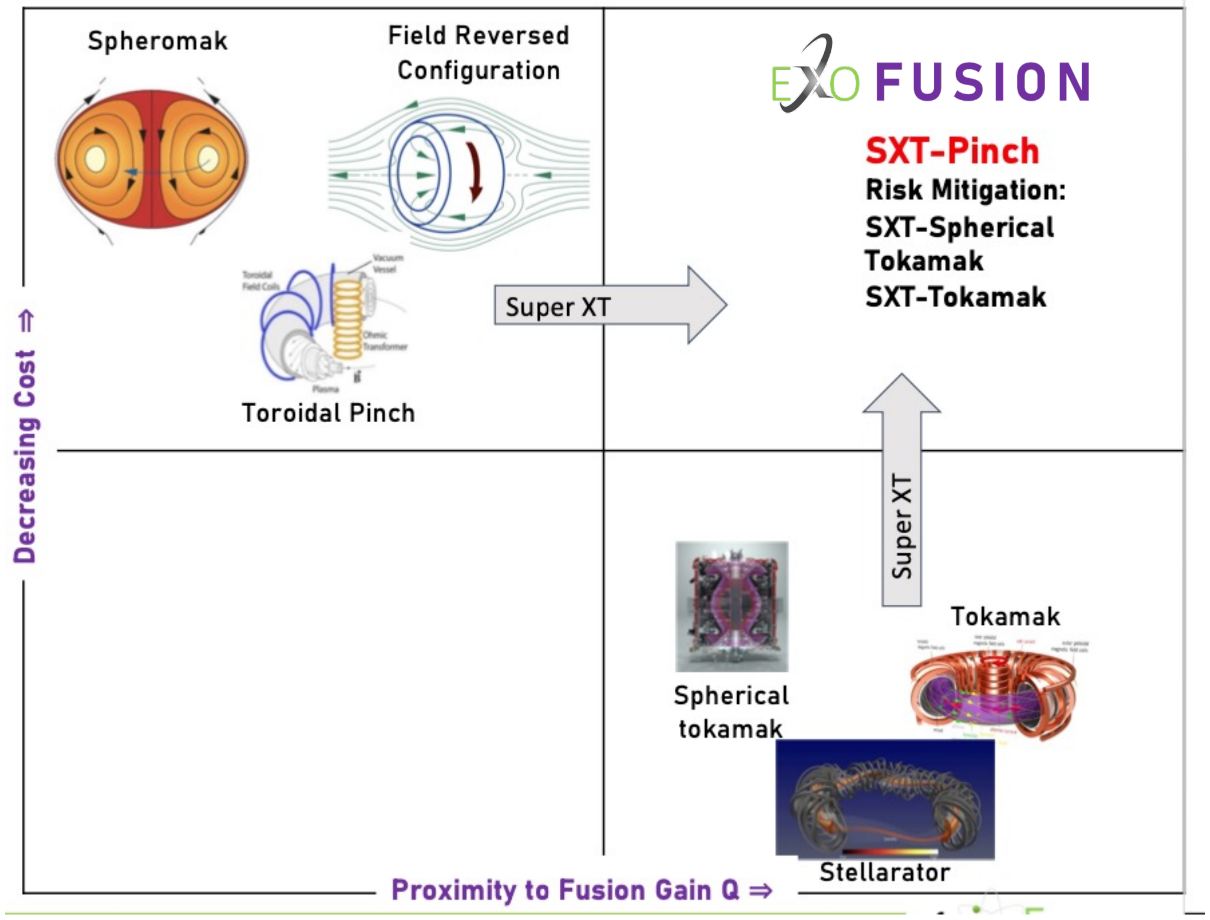
Super-XT divertor:

Much easier to reach fusion T in core: If the SOL is ~ 2 kev, a pedestal at ~ 4 keV is trivial

L-mode core sufficient even in small device

Any improved core confinement is bonus (in fact steeper density gradients will help!)

Where do we want them to be



Commercially viable regime

CVF

CVF Reactor - ``small'' size, low magnetic field (possibly with a simple structure) device

with the maximum possible energy confinement time (τ_E)

Extra Slides

The Fusion Energy Landscape- Using Peoples's Money

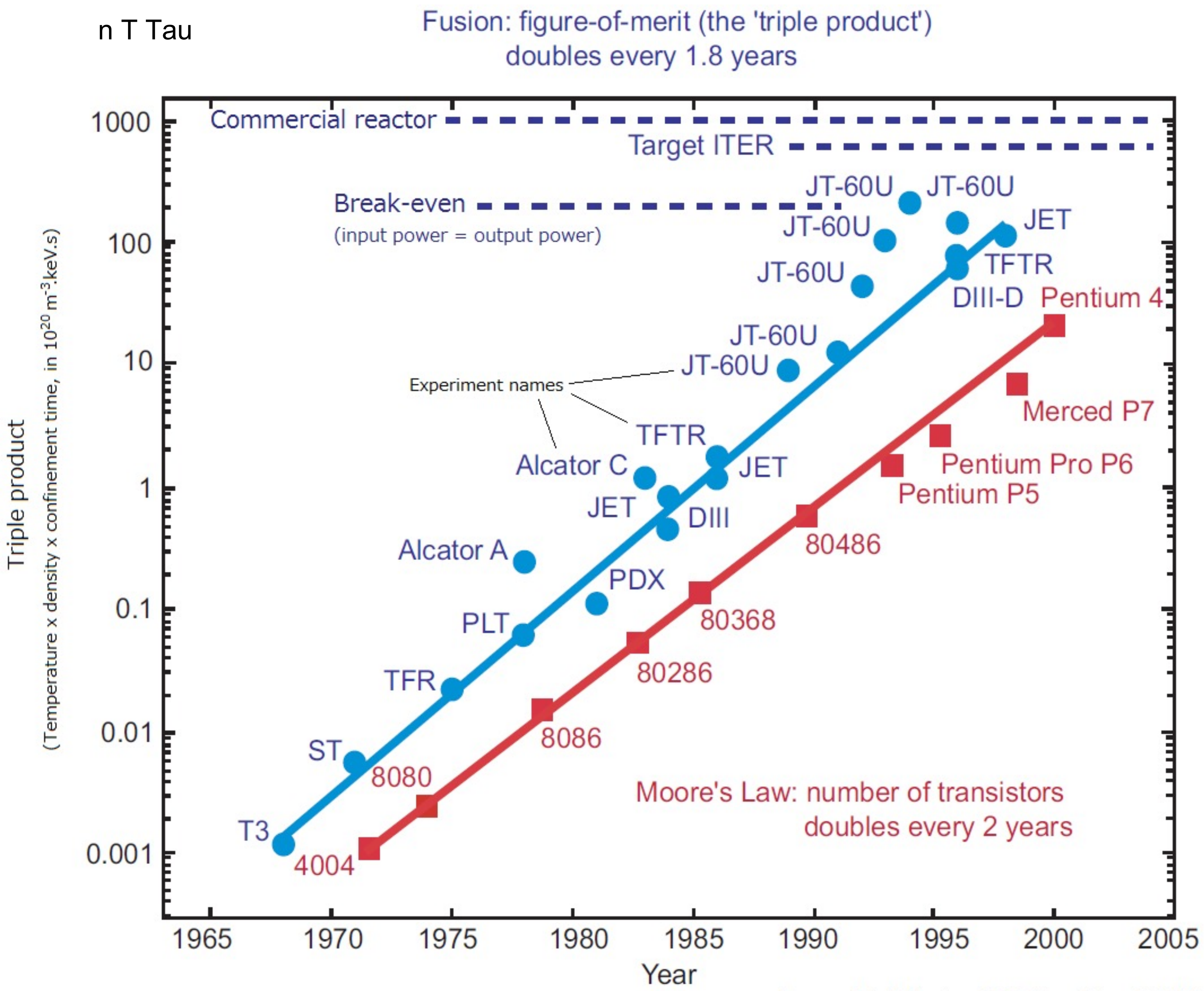
- Fusion Energy – a clean, scalable, non-carbon, non-intermittent, and sustainable energy source–market of $10 trillion *or more*

- About $100 billion already spent to develop fusion- by governments world-wide
  - Still no (real) NET energy output, but finally close to scientific breakeven

- A HUGE scientific/technical infrastructure was developed

- Experience and science led the bulk of programs to ultimately concentrate on magnetic concepts called "tokamaks" and "stellarators"
  - The tokamaks lead the crowd by a big margin

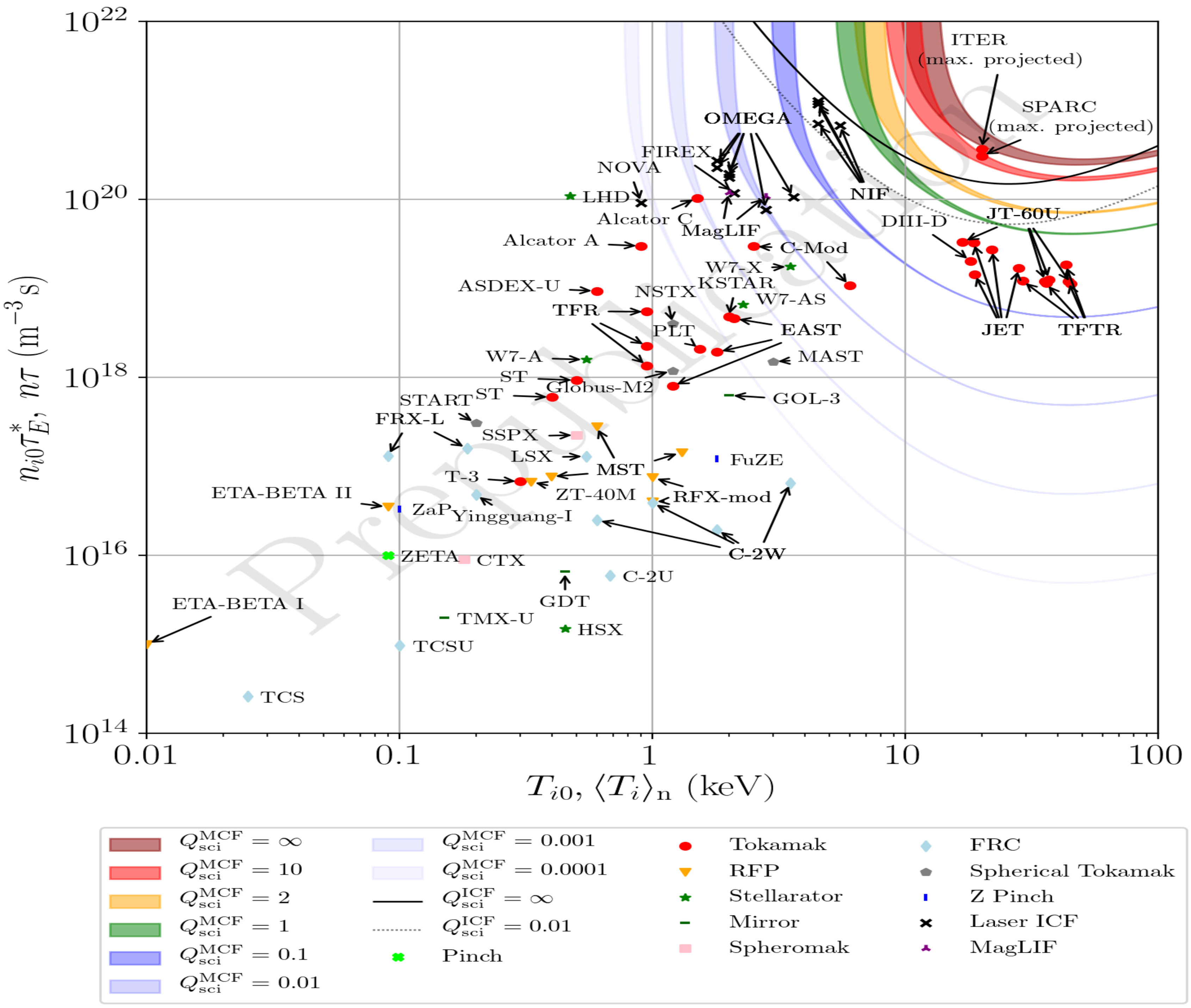
n T Tau



Source: A.J. Webster, 2003 Phys. Educ. 38 135

All machines

n T tau



The Fusion Energy Landscape- Enters Private Money

- Recently, billions have been invested in <u>private fusion start-ups</u>

- Majority use COMPLETELY different magnetic concepts than governments (called “FRC”, ”compact toroid”, “Z pinch”, etc, etc)

- All non tokamak approaches are far expected to lead to a much cheaper reactor than tokamaks

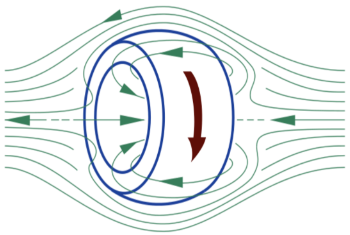
- But all these concepts were initially (for decades) funded by govt at some level of support - ultimately de-prioritized or abandoned

Why this difference?

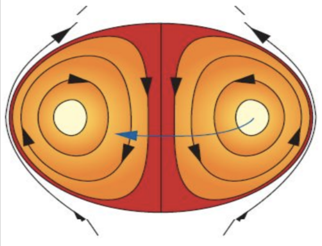
What does that say about the fusion market space?

The Fusion Energy Landscape-Some Landmarks

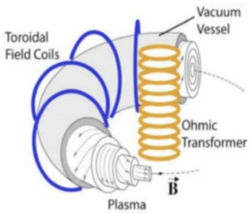
FRC
Tri Alpha Energy
Helion



Spheromak
CT Fusion

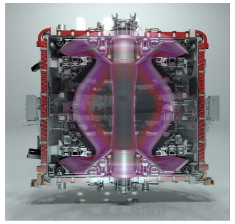


Toroidal Pinch



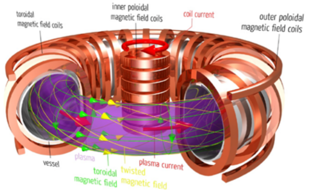
Lower guiding magnetic fields

Spherical tokamak
STEP (UK)
Tokamak Energy



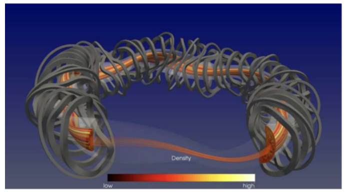
Low, Not so low

Tokamak
ITER
Commonwealth Fusion Systems



High to very high

Stellarator
Type One Energy
Renaissance Fusion



High and highly controlled
Very complex

Increasing magnetic field and/or engineering complexity and/or cost

The differences arise from prioritizing two <u>different but crucial</u> aspects

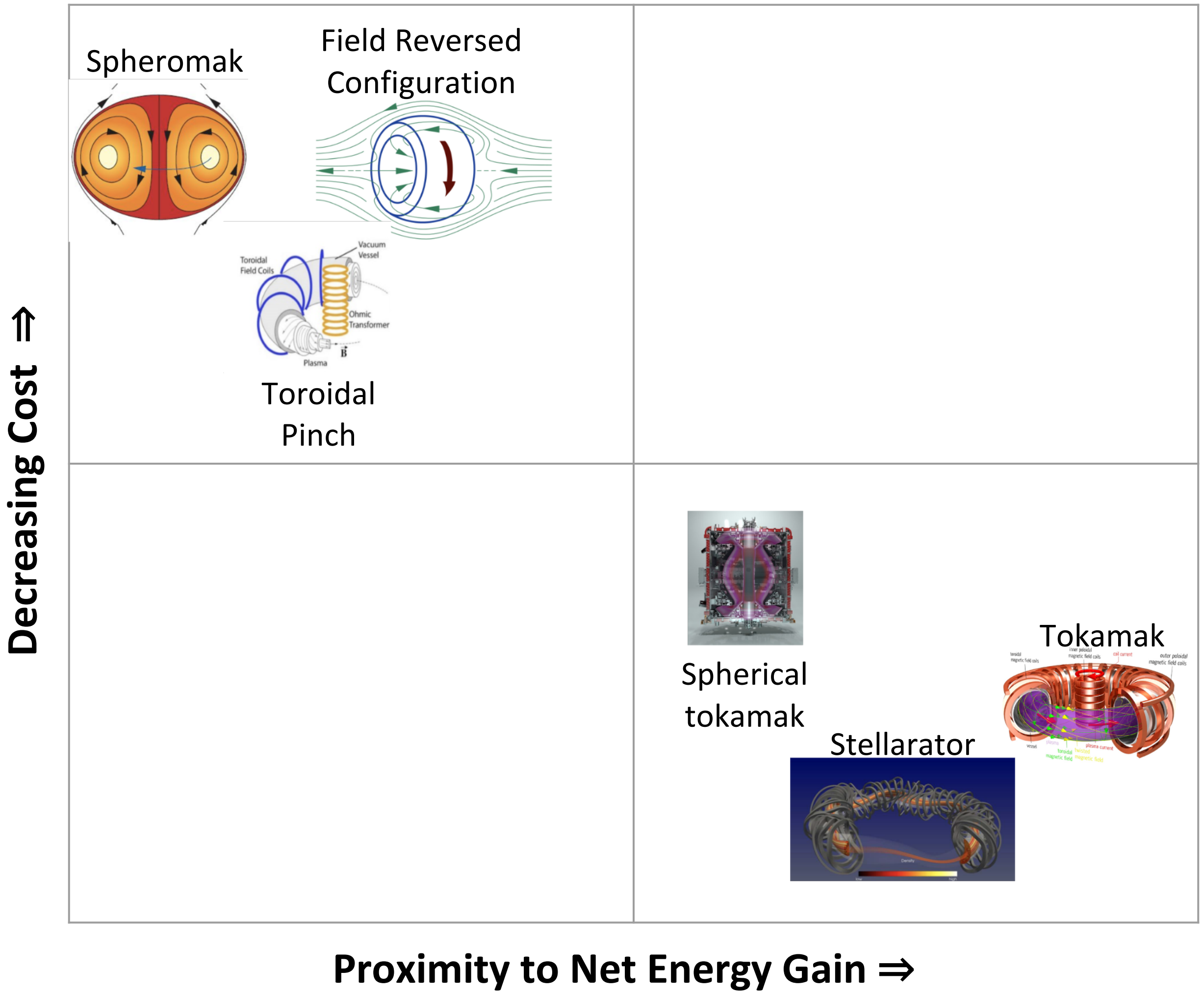
Government research emphasizes NET ENERGY Gain- a natural requirement for an energy *source*…

- Boosted Q_{sc} from nearly zero to near one
- Main Message: strong and expensive magnetic fields needed to GET NET ENERGY

Start-ups emphasize commercial viability

- Strong magnetic fields are just way too expensive- tokamaks can't compete
- start-ups use much lower/cheaper magnetic fields- emphasize innovation-Often speculative
- If they succeed, their cheaper reactors will win in the marketplace

But they are currently orders of magnitude behind the energy gain of tokamaks



Beware – what follows is

Science ginned with propaganda

The suggested Third Way: ExoFusion Approach

- Though not ready for commercial reactors, tokamak research has been impressive
  - It has stimulated enormous experimental and theoretical/computational capability and understanding in fusion science and technology. After years of progress, however, the pace of advancing net energy gain has stalled

- As one understand Magnetic Fields, one also understands the lack of commercial tenability of current approaches.

- The answer is to identify **key new technologies** and **key variations** on confinement concepts (some recently discovered by us) that enables

  a fundamentally resolution of the dichotomy just described

  in years, not decades

- The ExoFusion principals have a unique and proven track record of making similar things work…

The Third Way that revolutionizes magnetic fusion

Enormously reduce the cost of the magnetic fields *by reducing their part in the burden of confining high temperature fusion fuel* (for example, magnetic field reduction by a factor of 3 cuts the cost down by about 9)

Transfer that burden: to modifying the geometry and materials of the wall to harmoniously interact with ten-million- degree temperatures (like the sun's interior)

The scientific jargon for this is a "low recycling divertor"- a dream in the fusion world for 25 years, but making only glacial headway in government programs

<u>ExoFusion has patents pending on how to reify the sought after "low recycling divertor"</u>

<u>the Super-XT divertor</u>

Uniquely ExoFusion: the Super-X Divertor, our forerunner to the Super-XT

Our previous invention, the Super-X divertor was a major breakthrough.

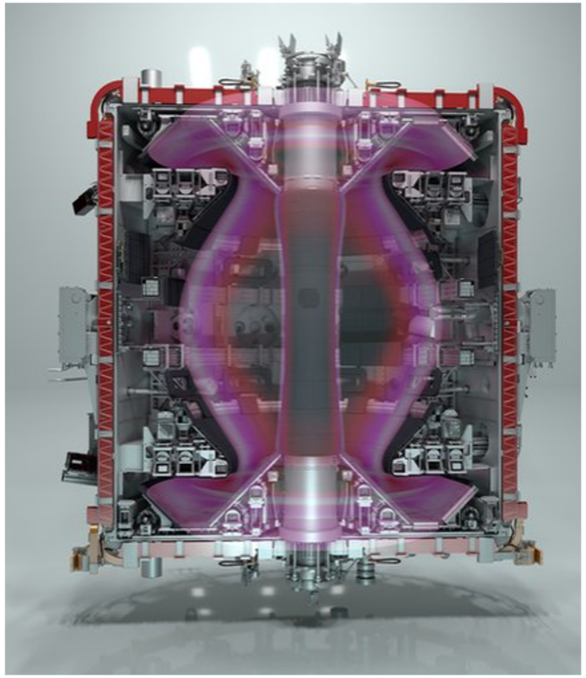
The U.K. gov't flagship experiment was upgraded to test it - £50-100 million
Spectacular experimental verification in 2021

But the Super-X operates in the conventional mode (cold edge).

Exo-Fusion has patents pending on crucial, non-obvious modifications of the Super-X divertor so it will become the uniquely successful configuration for a "low recycling divertor" (hot edge).

The Super-XT (XT for eXtreme Temperature) allows an enormous boost to magnetic concepts it is connected to

Super-X Divertor UK experiment



"I think the Super-X Divertor is a big step forwards. A huge step forwards"

"The Super-X Divertor could certainly enable the high-power devices that the Texas group want… It will be the model of the kind of divertor that we will have on any demo reactor."

—Sir Steve Cowley, then director of the UK Atomic Energy Agency fusion program, now director of the largest U.S. fusion lab (Princeton Plasma Physics Laboratory).

Quotes in Nature, the most prestigious physics journal in the world

Strategy: Low initial capital for a possible (most likely) huge win later

Fusion experiments are expensive, one can't waste time and money in lots of trial and error with expensive hardware

Expertise in the most revolutionary modern advance in science: simulations of the principles of physics to predict behavior of matter in new conditions via software- One well-known expertise of ExoFusion that encompasses entire device (not just divertors).

Similar methods have been used in many fields to affect an incredible compression in the time and cost to develop highly innovative products

The task is to translate this experience (in two years perhaps) to

- Refine the design of the Super-XT
- Integrated into promising confinement concepts

The next step: test the Super-XT in a reduced scale fusion device

We want something cheap, fast, and with a lot of *UPSIDES*

- This brings us to the second key variation: a magnetic concept called a "toroidal pinch"
- Pinches are over an order of magnitude cheaper than tokamaks/stella
- But they have a lot of trouble keeping the fusion fuel hot-Poor energy confinement
- The Super-XT is precisely the medicine for this illness.
- No other start-up employs a toroidal pinch –Super-XT is the possible key

The next step: test the Super-XT in a reduced scale fusion device

By testing the Super-XT with a pinch, we:

- Test the Super-XT fast and cheap, showing that ten-million-degree matter *actually does* interact harmoniously with ordinary matter under specified conditions

- If, in addition, the pinch fuel stays hot for long enough time, the Super XT pinch would rocket into the lead of the fusion race

- Hugely cheaper and/or higher Q than competitors!--100x improvement on other concepts - This will be our preferred path

However, the Super XT experiment goes beyond catapulting a toroidal pinch

- if testing shows that pinch is not improved enough despite the success of the Super-XT, then SXT can be applied to tokamak variants–still 10x improvement on other concepts

How the New invention Changes the Fusion Energy Landscape

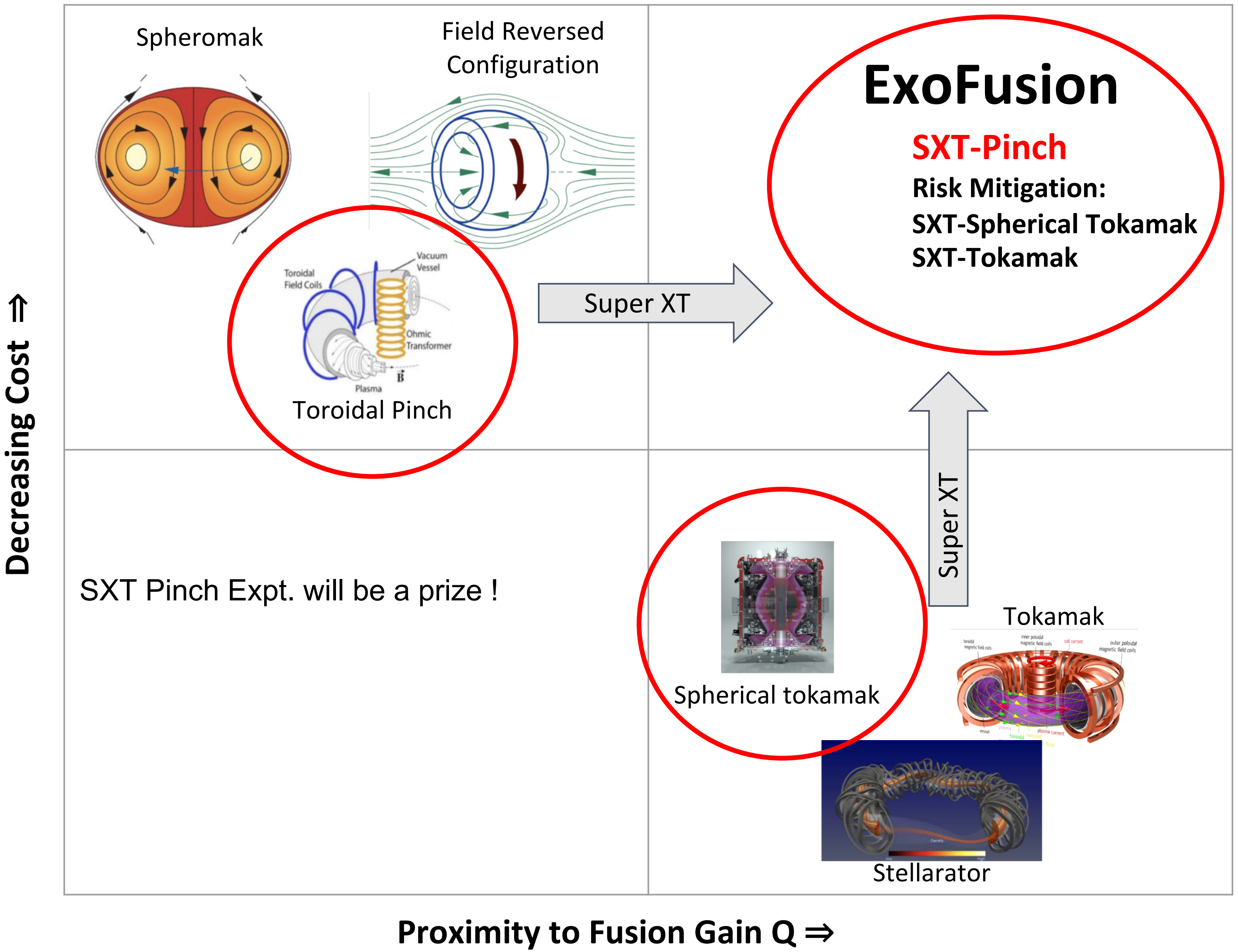
The Super-XT can bring cheap concepts vastly closer to fusion gain.

The Super-XT can make mainline (expensive) concepts vastly cheaper.

Plan: First two years:
Refine design of Super-XT divertor
Design SXT-Pinch
Design SXT-Spherical Tokamak

Next five years:
Build and operate SXT-Pinch
Test viability of SXT-Pinch for fusion
Demonstrate the Super-XT divertor (applicable to other concepts)-
Who will build the SXT-Pinch ?

Multiple routes to success. The Super-XT floats all boats in the magnetic confinement ecosystem.



Can Fusion be ever made Economic- Is it even a legitimate question-1
Surely, it depends on who you ask

- Three main components of a reactor
  - The furnace (fusion)- F
  - the auxiliary fusion stuff (blankets etc.)- A
  - Balance of Plant- B- essentially same for all power producing systems
- The EU Demo reactor : It is the most developed Reactor study – The EU demo is a bigger and more butteresed ITER- seriously overdesigned
  - It assigns F=.5, A=.5 - "reduce" F by a factor of ten, there is a cost reduction of 45%
  - It is good but it is still too expensive especially for monstrously expensive ITER line.
- The Commonwealth Fusion Systems: F=.9, A=.1 ➔ reduction by a factor of 5- Huge decrease by a factor of 5 for already much cheaper device- magnetic fields are lot larger

Can Fusion be ever made Economic-Is it even a legitimate question-2

- Both these systems are designed on the physics of 1980s – CFS has the magnet technology of today but dated physics- robust risk free

- Private enterprise is , perhaps, essential- to create a somewhat riskier/diverse landscape – Let hundred flowers bloom

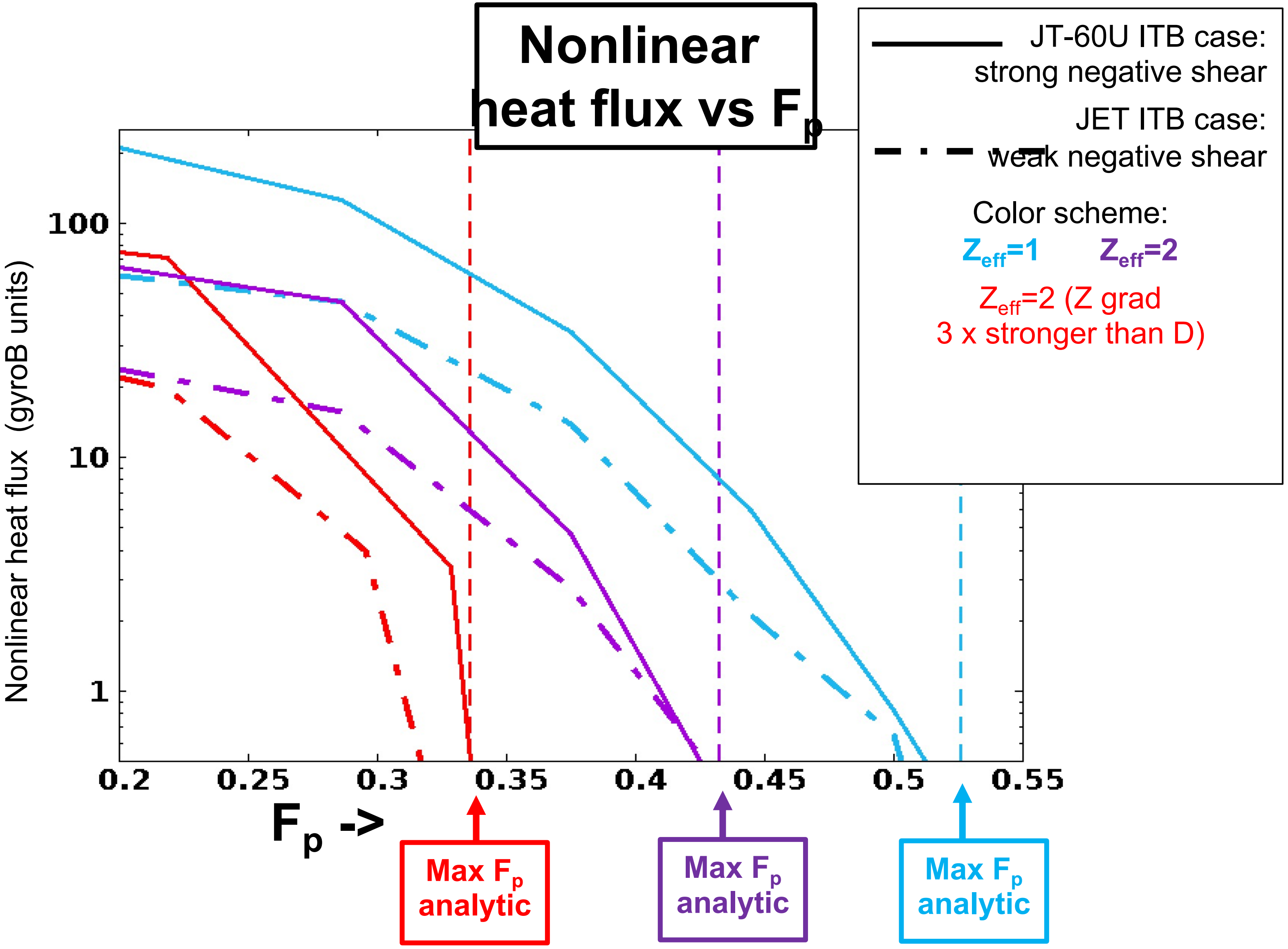
- The Physics of 2Ist century (all the way to 2022) and commensurate engineering, in my opinion, is the minimum it will take

To Bring Fusion Power to Home and to H(earth)

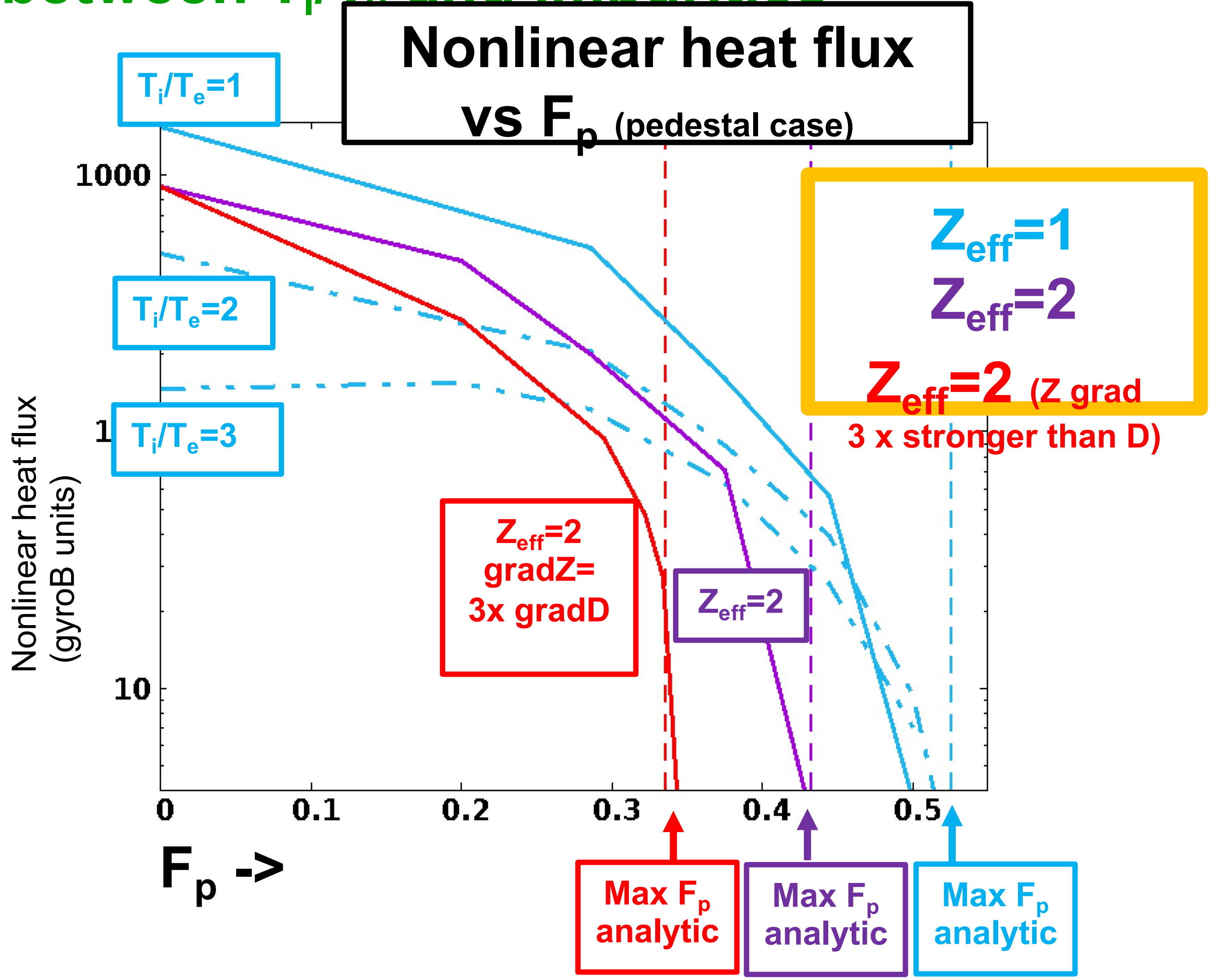
Nonlinear runs for diverse geometries follow the constraint boundary with Z: ITBs

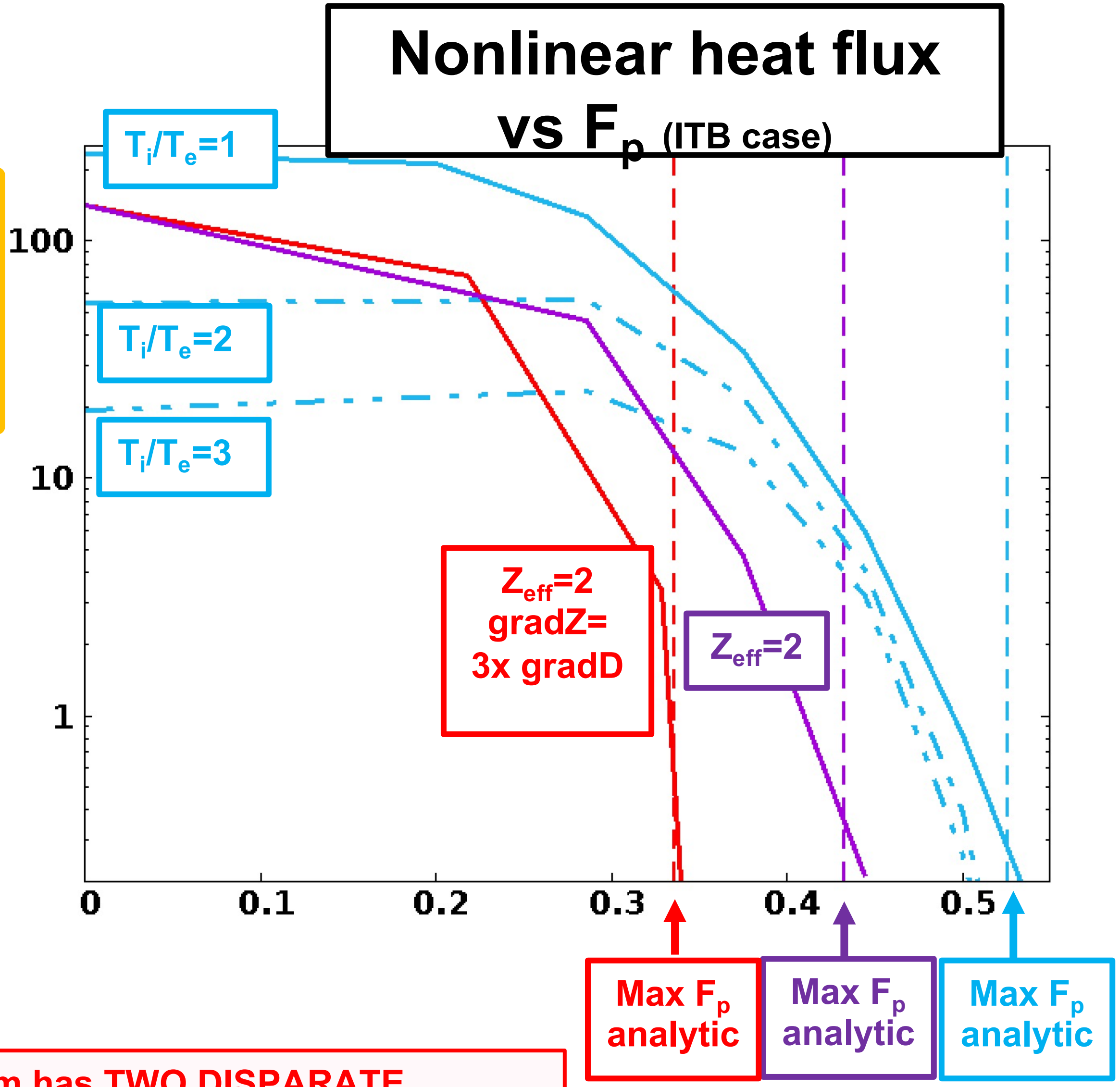
- For the previous ITB geometries:
- the heat flux goes down by ~2 orders of magnitude as the analytic F_p boundary in approached, and

NONLINEAR heat flux follows the impurity modified FC solubility condition



The T_i/T_e can severely alter the energetics, but not the FC solubility. The nonlinear simulations reflect this fundamental physical difference between T_i/T_e and impurities



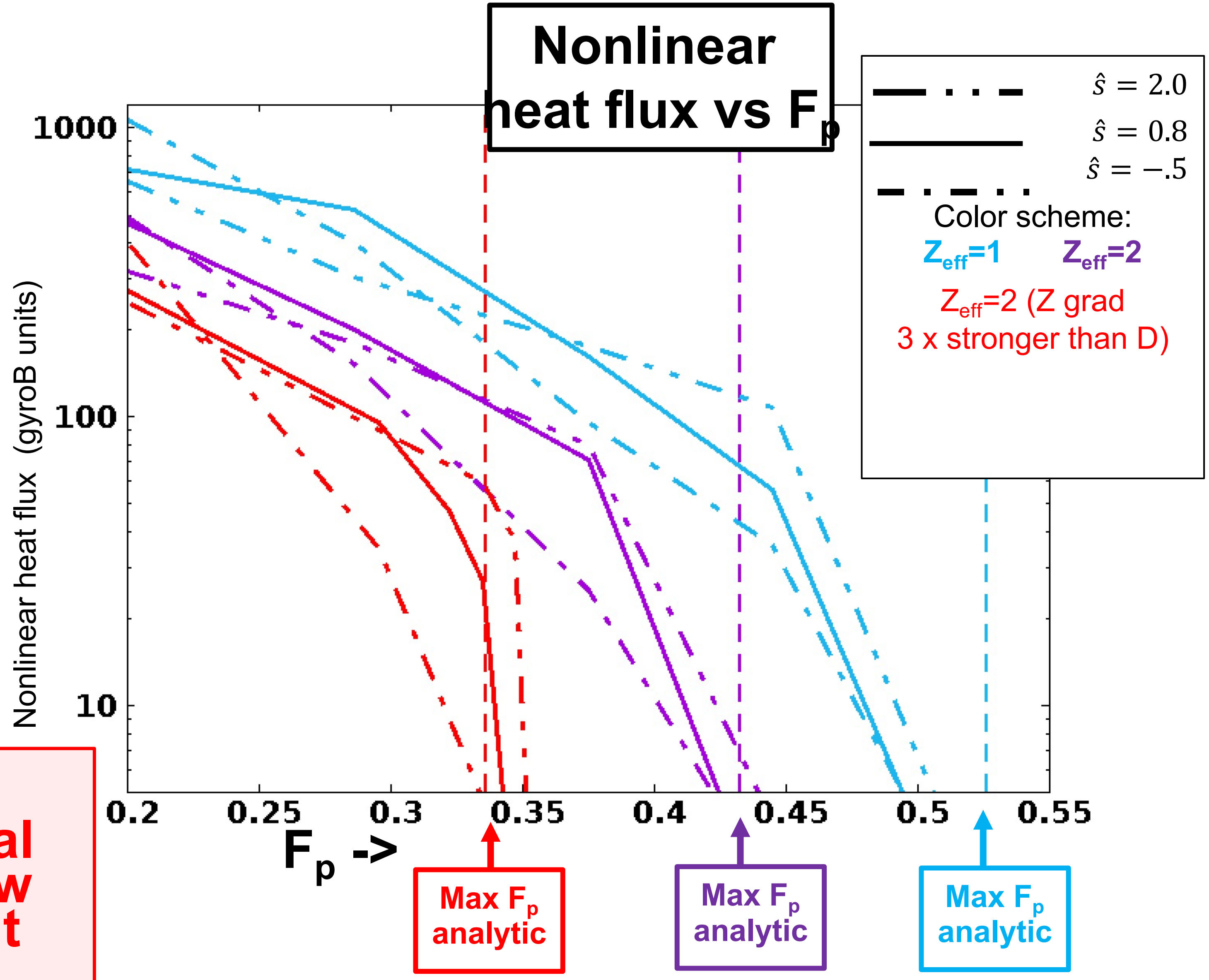


Yet another demonstration that the gyrokinetic system has TWO DISPARATE controlling dynamcs: free energy drive and the flux constriant

Nonlinear runs for diverse geometries follow the constraint boundary with Z: pedestals

- For three different pedestal geometries
- the heat flux goes down by ~2 orders of magnitude as the analytic F_p boundary in approached

NONLINEAR heat flux follows the impurity modified FC solubility condition

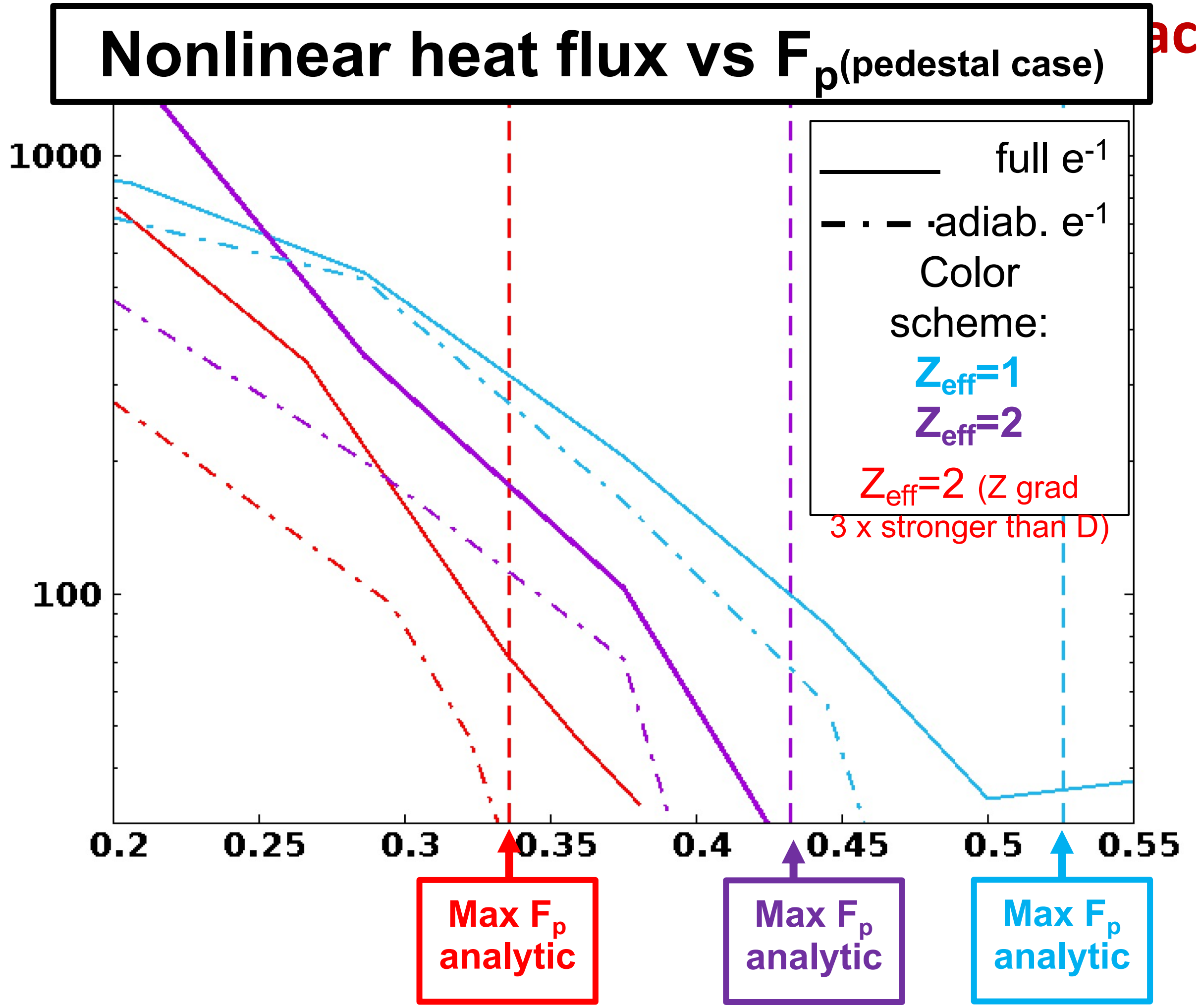


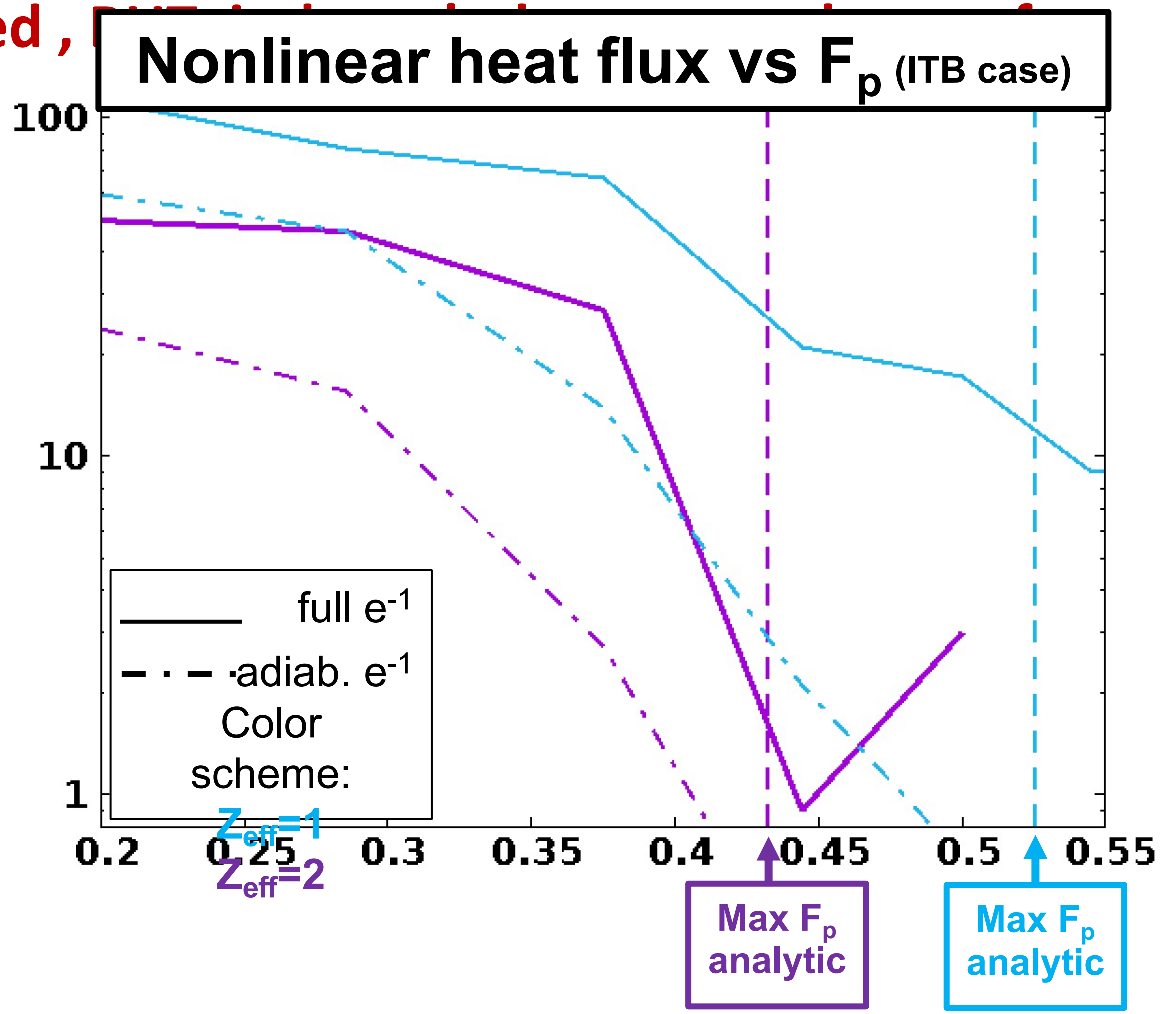
Despite HUGE parameter differences between pedestal and ITB cases, they all follow the same analytic constraint bounds

Simulations with full electrons and electromagnetic effects for TB cases behave similarly to ITG_{ae}, but the electrons reduce the stabilization

- The electrostatic part of the heat flux behaves similarly to the ITG_{ae} for both pedestal and ITB cases:

ached ,





ExoFusion

A recently founded LLC

Scientific Principals :

Mike Kotschenreuter, Swadesh Mahajan, David Hatch

Interim CEO - Romi Mahajan

Currently advising

United Kingdom Atomic Energy Agency, and General Atomics

Why and wherefore of ExoFusion

An Explosive Growth in Private Investments in Nuclear Fusion

$ 4 Billions already committed, and rapidly increasing PLUS
Mushrooming of resources for Private-Public Partnerships (Govt Funds)

However, the most important reason why we got into this game is Scientific - again an explosive growth

We have recently made fundamental scientific discoveries/understandings, and
inventions which can , in principle, change the trajectory of fusion power - make it
Faster and way cheaper

Three slides for bare-bones Physics- Total emphasis on the recent physics created by the ExoFusion folks

Desiderata

IFS , Department of Physics, University of Texas

In the context of a Spectacular Nuclear Fusion Renaissance

(my perspective)

Plus

ExoFusion

a UT originated Company with grand plans

ExoFusion

Commercially Viable Fusion Leadership

Mike Kotschenreuther, Swadesh Mahajan, David Hatch