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Fusion- Fission Hybrids
Maturing of an old idea

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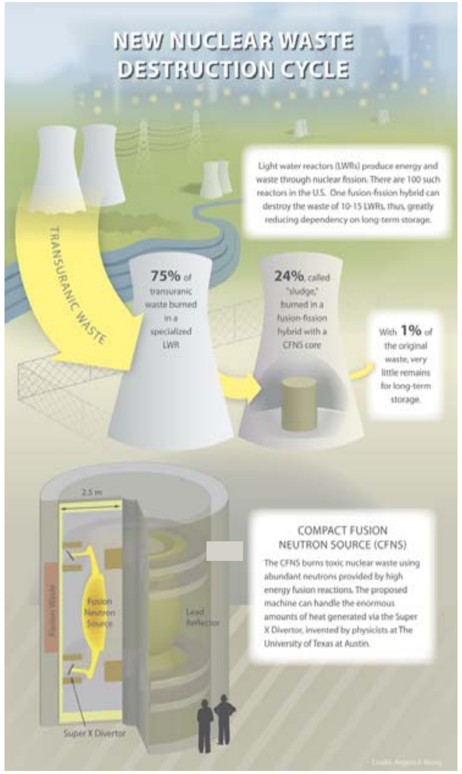
Fusion- Fission Hybrids

Maturing of an old idea



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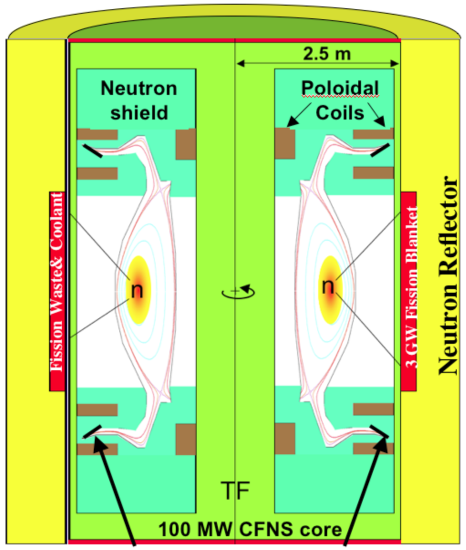
Trieste colloquium, August 13, 2009



UT-IFS Super-X Divertor: The Key

CFNS “Module”-Hybrid Reactor

Binding Energy/nucleon - Origin of Fusion/fission energy

Fusion

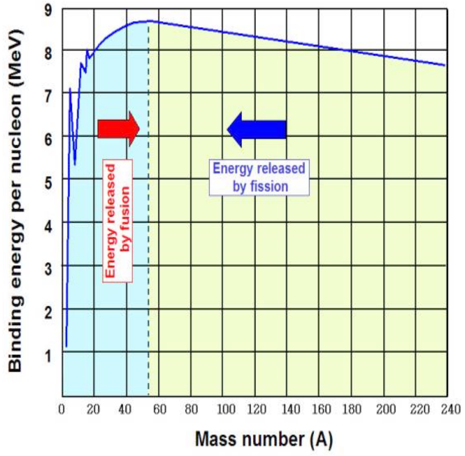
$D^2+T^3 \to H_e^4 + N + 17.6$ MeV

5units=>~20MeV

Fission

$U^{235}+N \to B_a^{144} + K_r^{89} + 3N + 200$ MeV

235units=>~200MeV



Fusion more efficient in converting Mass to Energy

-One of the reasons why fusion holds such fatal attraction

A single fusion event, however, is energy poor but relatively neutron rich as compared to a fission event: $(E/N)_{fu} \sim 20$, $(E/N)_{fi} \sim 200/2=100$.

Wouldn't hybridization, then, work wonders!

D-T fusion neutrons to "fission" U^{235} - will be quite foolish

D-T fusion neutrons to transmute fertile $U^{238}(T_h^{232})$ to fissile $P_u^{239}(U^{233})$- original goal

D-T fusion neutrons for transmutation and fissioning of nuclei that are "difficult" to fission in fission-only systems- perhaps the most important near term goal.

Fission-Fission Energy

- **The Neutron - Neutron Induced nuclear reactions**

  He^4+Be^9 --> C^{12}+n   neutron production Chadwick (1932)

  - Neutron as a projectile to induce nuclear reactions -- Fermi (1932-)
  - Discovery of Uranium fission- Hahn, Strassmann, Meitner, Frisch-1938 with immediate recognition of its practical implications
  - Liquid drop model for fission- Bohr and Wheeler-1939

- Bohr solved a Big initial puzzle-Copious fission reactions for both low energy (< 0.1eV) and relatively high energy(> 1MeV)neutrons but very few in the intermediate range

Thermal neutrons (.025 eV)	Fast neutrons (1 MeV)
U^{235} (~ .72%)	U^{238} (99.275 %)
sigma$_f$ ~ 580 b	sigma$_f$ ~ 0.2b

Def: Nuclei that fission in a thermal neutron spectrum are called fissile

the only naturally occurring fissile nucleus is U^{235} - it is a natural fuel for thermal reactors-

its being such small part of the natural ore (mostly U^{238}) has profound consequences!

Thermal Fission Reactors- Spent Nuclear fuel- Nuclear Waste

- Power producing fission reactors are almost all thermal spectrum and use enriched Uranium (~3-3.75% of U^{235})
  - Since the fission neutrons are produced in the fast range - the spectrum peaks at ~.7 MeV- they have to be slowed down (moderated)
  - The standard work-horse of the nuclear industry is the light water reactor (LWR) in which ordinary water is used both as a coolant and a moderator
  - There is very little fission of U^{238} (96% of the total U) in a typical LWR
  - However by successive neutron captures and beta decays, a whole menagerie of transuranic isotopes (including the well-known P_u^{239}) is built up in the fuel rods
  - These transuranics form the principal component of the so called Waste problem- their longterm radiotoxicity and biohazard

Transuranic content for a 1000 Kg of input fuel (U^{238} = 962, U235= 37.5) after a three year stay in the reactor (~1.2% of the SNF)

Np^{237} ~.65, Pu^{239}+ Pu^{241}~7.1, $Pu^{238-40-42}$ ~3.3, $Am^{241-243}$~ .2, Cm^{244}~ .05

Per year transuranic waste from a current typical 1GWe reactor = 328kg
Total transuranic waste from a fleet of 100 1GWe reactors over 25 years = 800 tonnes
(total SNF~ 60000 tonnes = Yucca mountain)

Criticality, Control, Safety, Fast Reactors

- All fission only energy producing reactors- LWRs or the fast spectrum reactors (FR) run in the critical mode.
  - FRs do not have a moderator and can, in principle, burn anything-U^{238} included. Liquid Na cooled FRs are the most highly investigated
  - The criticality parameter (blanket multiplication factor) $k_{eff} = 1$ for the chain reaction to continue. Most control and safety issues are associated with making sure that the reactor does not go supercritical
  - Though a very complex physics/engineering undertaking, modern reactors do very well on these counts- as long as the fuel is "high quality"
- The worst of transuranics make very "low quality" fuel- control and safety issues for critical reactors, then, are strongly exacerbated-
  - It is this fact more than anything else that creates a unique space for the Hybrid
  - Hybrids, neutronically, are FRs which run sub-critically $k_{eff} < 1$- the chain reaction being maintained by the external supply of neutrons- say, from a fusion source.

Fusion- a modern perspective

- **Promise of Fusion - Unlimited, Low waste and carbon free energy**
  - Promise so attractive that its pursuit had a mandate in spite of difficulties and enormous times expected to be spent in this quest
- Two major approaches
  - Magnetic confinement (MFE)- the object of today's talk
  - Inertial Fusion (IFE)
- A fusion reactor- producing net fusion energy-is way far in the distant future - Both physics and technology challenges are quite staggering- ITER will tackle some of these
- Though ITER is a very ambitious enterprise, it will not, by itself, lay down the foundations of an eventual economic fusion reactor.
- Yet extremely impressive world wide efforts (US, EU, Japan, Russia, China, Korea) have brought considerable sophistication to fusion research- the promise of ITER has been very motivational.
- And Fortunately the current state of fusion, augmented by several new ideas, can indeed lead us to an attractive neutron source- precisely what we may need for a Hybrid.

Is a Hybrid needed?

Fusion - a bend in the road

Two major developments in the last decade have redefined the overall "energy debate":

- Broader recognition of the specter of anthropogenic global warming, caused by carbon-based fuels, haunting our civilization
- Drastic boosts in energy consumption due to rapidly increasing affluence in sections of developing societies

=>We must produce lot more energy while our conventional sources of energy production (coal, natural gas …) have proved unfriendly to the planet

=> => All carbon-free energy sources must be marshaled in near term

⇒ => => Nuclear Energy must be in this desirable energy mix which contains renewables (some of them with their inherent intermittency)

Is there a near term role for fusion in the fight against global warming even though Direct production of Net energy is not a near-term option

Fusion neutron source driving a Hybrid-augmenting fission- a near term goal and strategy

- **Fusion finds near term bliss - can advance carbon-free energy by assisting and augmenting fission**:
  - By providing an efficient, fast, and economic solution of the Nuclear Waste Problem
    - Perhaps the biggest social roadblock to social /environmental acceptance
  - Fusion neutrons, can be a most efficient means for incinerating the transuranic nuclei - the principal cause of longtime radioactivity and biohazard of the fission aftermath
  - By burning the long lived transuranics to ~1% of the original, the UT fusion-fission transmutation system effectively solves two fundamental “fission problems”:
    - Burn all the bomb-making isotopes like Pu^{239} - minimizing proliferation risk
    - Drastically reduce the number of geological repositories (Yucca) for storing waste
- **The fusion-based waste destruction scheme (based on a fusion-fission hybrid) provides an attractive and viable technical solution to the nuclear waste menace**

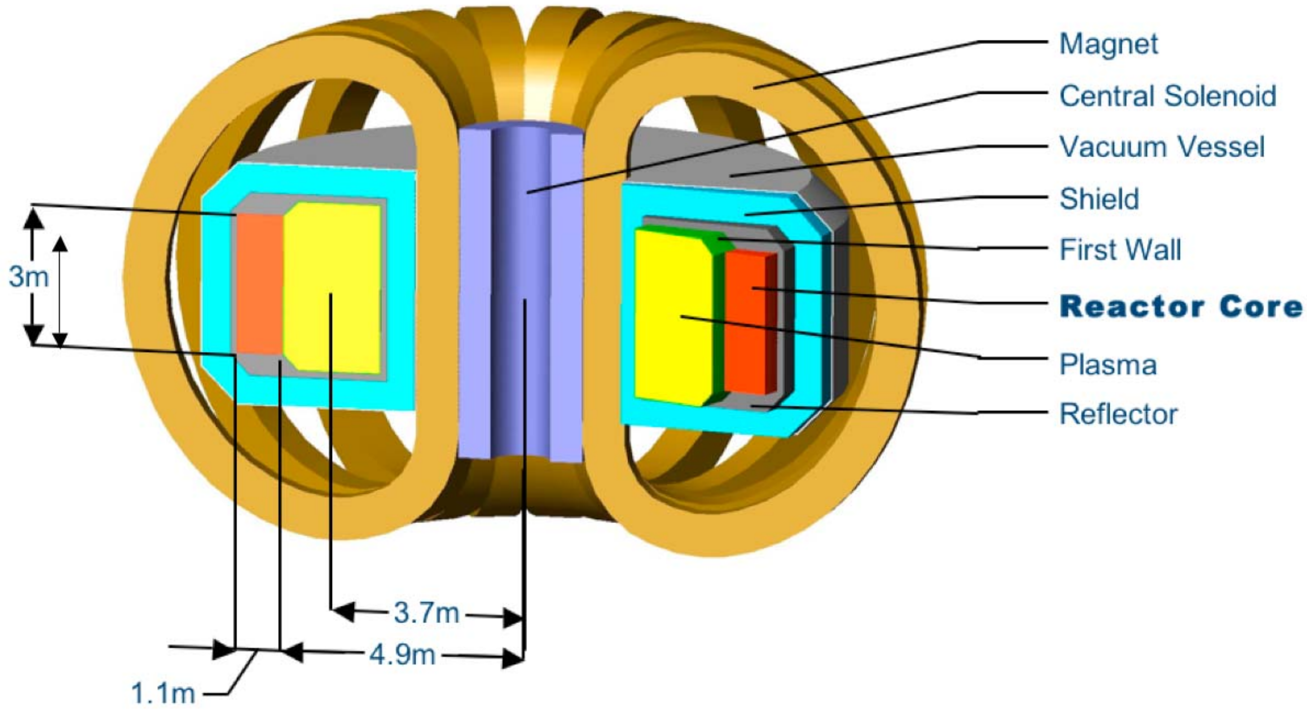
Will this technical solution translate into a social mandate for a nuclear renaissance?

It better, since the fate of the planet is at stake!

Hybrid- An old idea

- It is an old idea but with precious little history
- It was first broached in 1950s- extra neutrons (non-fission) could augment the nuclear reactions to maintain criticality when enough neutron- absorbing fission products are accumulated
- Fusion was an obvious theoretical source of such extra neutrons
  - Attention- the reactor engineers thought of it first!
  - Unfortunately one could not go shopping for fusion neutrons
- Energy crisis of 1970s catapulted Hans Bethe to write his famous paper in 1979- a fusion fission hybrid to breed fuel (extending the fuel supply for a long long time) so that “one could be free of the OPEC menace”
- A Google search on timeline for fusion fission hybrid history shows a few headings before 2009.
- There was (and is), however, a persistent warrior for the Hybrid cause- Weston M Stacey of Georgia Tech. His design is what we will call the Generic Hybrid.

The Generic Hybrid



Large and Complex
Fusion and Fission systems intricately connected

Generic Hybrid vs critical FRs - A Critique

- **A Generic Fusion driven Hybrid adds**
  - Substantial extra cost per reactor (a third of ITER price, for example)
  - Substantial additional complexity and reliability and maintenance issues
  - Substantial new technology development
  - Increased complexity leading to new failure modes and safety issues
- **Engineering Challenges since Fission assembly is *connected to* the fusion driver:**
  - ***Mechanical*** => new coupled failure modes, difficult to license
  - ***Electro-magnetic*** => plasma disruptions cause mechanical EM loads- what happens to the fission blanket
  - ***Magnetic*** => coolant flow "impeded" by MHD effects

Generic Hybrid and critical FRs - A Critique

- A generic hybrid does bring following advantages:
  - Longer burn time - criticality constraints reduced.
    - Material damage limits burn time - advantage is modest
  - Can use fuel with no U^{238} for breeding-no new TRU produced
    - modestly reduces the number of reactors- by a factor of 4/3 to 2 compared to FRs with breeding ratio of 0.25- 0.5- low support ratio

> Support Ratio S= Number of LWRs whose waste can be burnt by a single advanced reactor (Hybrid or FR)

  - Chance of criticality accidents reduced- But Hybrids introduce new accident scenarios due to the marriage of two technologies
  - Hybrids uniquely equipped to burn particularly “problematic” minor actinides-This must be fully exploited

Advantages few- Problems many

A digression- Scale of the Nuclear Waste Problem-1

- A geological repository for storing "Non-transmuted" reactor waste - Yucca mountain (~$90 Billion for accumulated waste) - Recently abandoned
- With a nuclear expansion (enough to make a dent against global warming), US alone would need a Yucca mountain every 10 years in the coming century
- Estimated cost ~ $900 billion in this century for US alone?
  - World wide nuclear waste production ~ 5-10 times the US
  - Not just the cost, but where and how do we find so many sites?
  - Every such site is a future Pu mine to boot
- Transmute waste to reduce its radio-toxicity by orders of magnitude
  - Great reduction in the number of needed geological repositories
  - whittle nuclear waste problem down to the realm of environmental, political, and social reality

A digression- History of Transmutation schemes-2

- National Academy of Sciences (NAS) studied transmutation schemes(1990s): Fission only (critical fast reactor FR) and the ADS "hybrid" in which external neutron are accelerator based.

  Fusion driven Hybrids were not even considered

- Recent public congressional testimony (2005-2006) on FR approaches

Recommendation negative - Transmutation schemes

- all **too costly**
- too slow(~ 2 centuries to reduce 99%)*
- Proliferation concerns due to many rounds of reprocessing

Why so expensive?

- Must use reactors more expensive than LWRs- FRs and ATW
- Many reactors were needed- low support ratio S of the studied schemes
- Total excess cost in $100 billions

What will make an attractive waste destruction scheme-1

- The answers to this question will define the operating space for the Hybrids- Three major ideas to create this space

1. High Support ratio S- fuel cycles

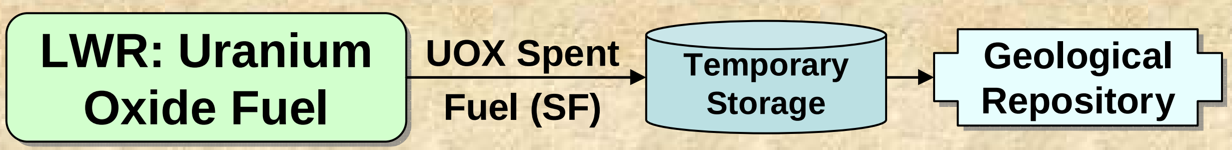
- Let us first first assume that a “desirable fusion source” is available
  - It is not a technological horror like the generic hybrid
- Then for an economically attractive scheme the system support ratio S must be as high as possible
  - The higher the S, the fewer the advanced and more expensive reactors- the fewer such reactors, the lower the excess cost

The support ratio is determined, primarily, by the fuel cycle choices

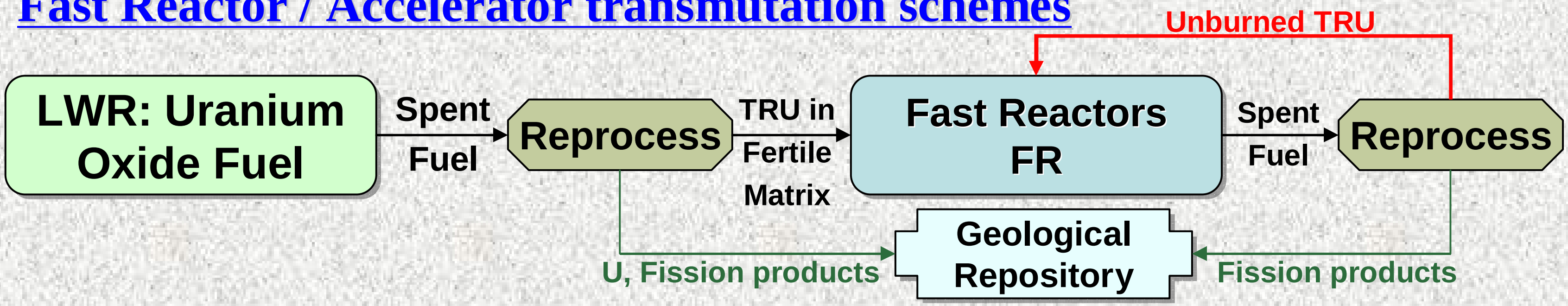
What is a fuel cycle

Generic Nuclear Waste Management Fuel Cycles

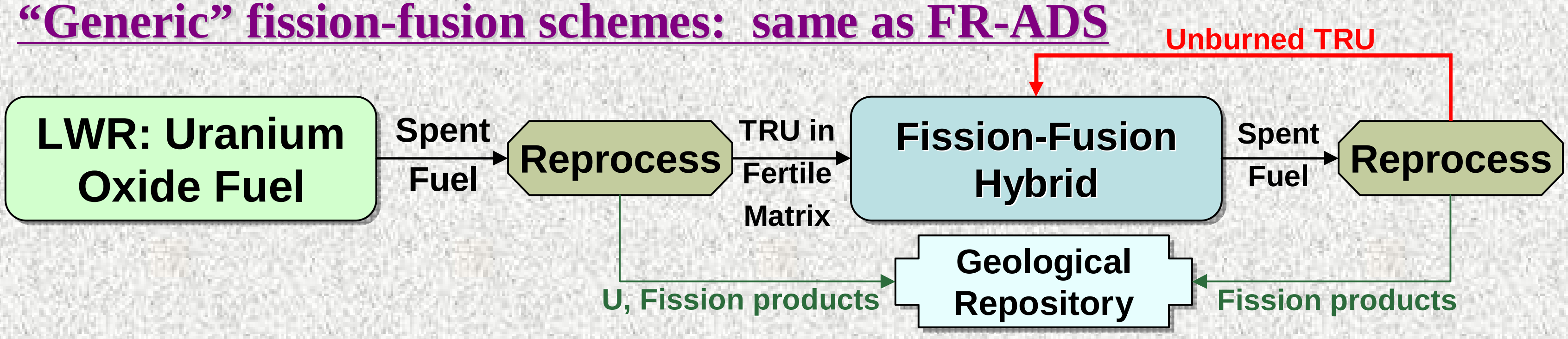
Direct Disposal



Fast Reactor / Accelerator transmutation schemes



"Generic" fission-fusion schemes: same as FR-ADS



Fertile matrix contains U_{238} - creating more TRU while destroying TRU.
Inert matrix fuel(IMF) does not create new TRU as TRUs are incinerated

Inert Matrix Fuel(IMF)-High S fuel cycle

The Texas reference two-step fuel cycle suggested by nuclear physics:

- 1-The LWR-IMF pre burn step: Burn as much of TRU as possible in an LWR using

an Inert Matrix fuel (IMF)- thermal cross sections are large for several TRU isotopes

  - Calculations indicate that as much as 75% TRU destruction may be feasible, in one or two passes- no new transuranics are generated in this process

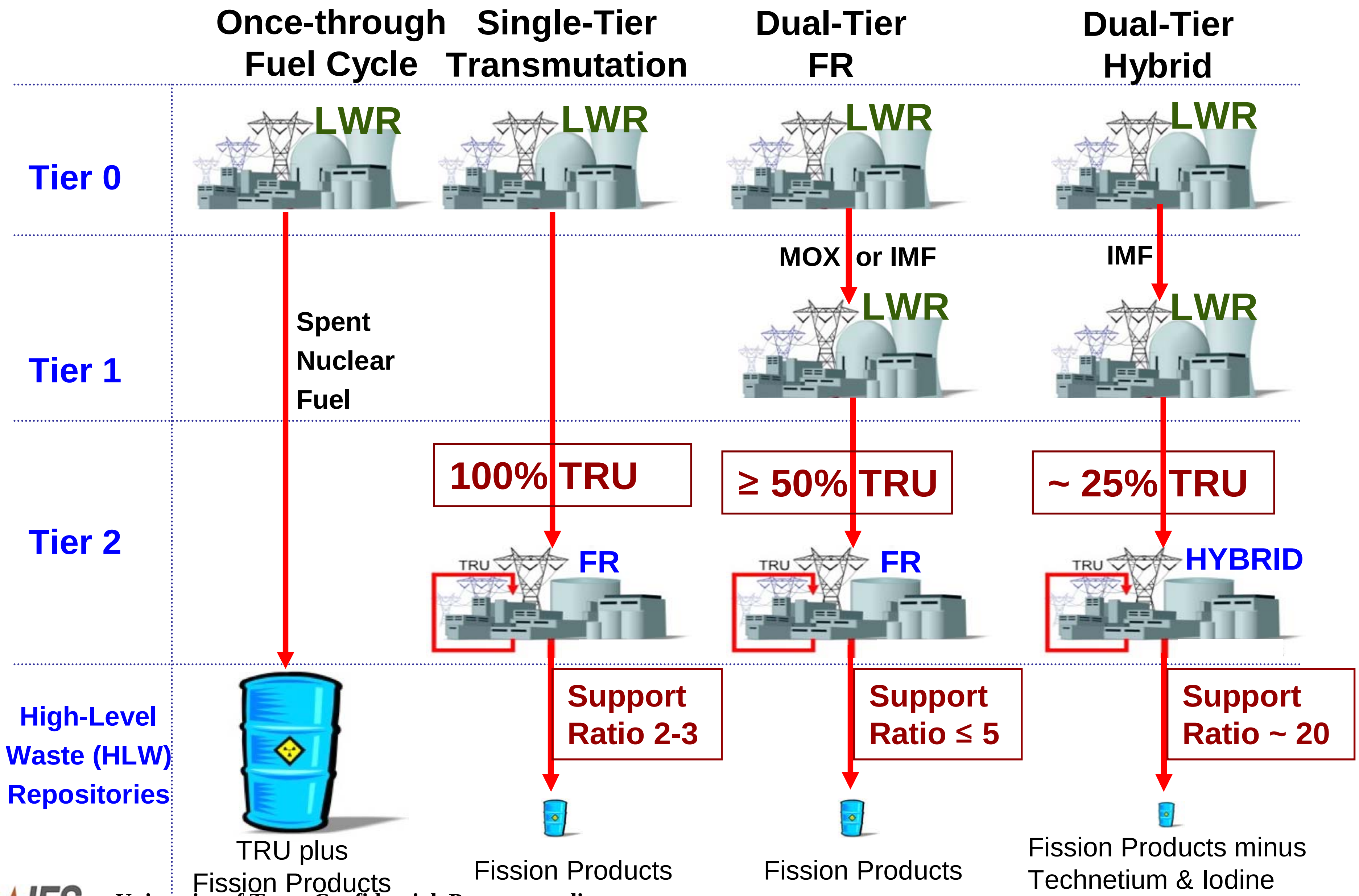
- 2- The Hybrid Step (H)
  - Burn the vastly reduced (~25% TRU) residue in a small number of Hybrids
  - The post LWR-IMF TRU constitute "very low quality"fuel - many are threshold fissioners - these cannot be safely burned in critical FRs
  - The LWR-IMF step-Shifting 75% of the burden on the cheap LWR strongly boosts S
- The two-step fuel cycle, uniquely suited to a Hybrid (with an external neutron source), is not accessible to critical fast reactor approaches
- The IMF-LWR-H fuel cycle is the UT reference cycle

Fuel cycle overview and rationale

- (LWR-IMF) step -destroying 75% of TRU in LWRs in a single pass
  - Cross sections of ~ 25% of the isotopes are too small in an LWR neutron spectrum (close to thermal) for destruction - would take for ever!
- Thermal spectrum systems destroy a larger percentage of fuel in a single pass- and use of the Inert matrix fuel (IMF) prevents any generation of *new* TRU waste
  - Cross sections of easily fissile isotopes ($Pu^{239\text{-}241}$ etc.)are much larger in a thermal spectrum system- they are better fissioned in LWRs.
  - Destruction of most TRU is rapid, significantly reducing time for destruction
  - Easily weaponizable isotopes (Pu^{239}, etc.) quickly eliminated in the very first step
- Incineration of the recalcitrant 25% TRU - Sub-critical Hybrid assembly due to stability
  - Virtually all the residue isotopes are threshold fissioners (like minor actinides)-leading to very high void reactivity, low Doppler stability, etc.
  - A relatively inexpensive, prolific external neutron source is needed- **fusion!**

High Support ratio is the minimal required Hybrid passport to win competition

Nuclear Waste Management Schemes



Residual TRU post LWR- IMF PreBurn

- **The more transmutation that is accomplished in LWRs, the fewer fast spectrum systems that will be required.**

- It is plausible to achieve 75% TRU burnup in a single IMF pass given small perturbations from existing single pass schemes (e.g. increased ^{235}U enrichment, 4/3 IMF-bearing / all-UOX assembly cycle reload pattern)

- The isotopic content (a/o) of the residual TRU after 75% burn is shown in the table at right. **This is the feed to the Hybrid.**

Np-237	2.1
Pu-238	7.0
Pu-239	2.0
Pu-240	4.0
Pu-241	2.2
Pu-242	43.8
Am-241	0.0
Am-243	13.2
Cm-242	1.0
Cm-244	23.0
Cm-245	0.5
Cm-246	1.1

Where is the fusion Neutron Source- what does it look like

General Features of a reference fusion driver

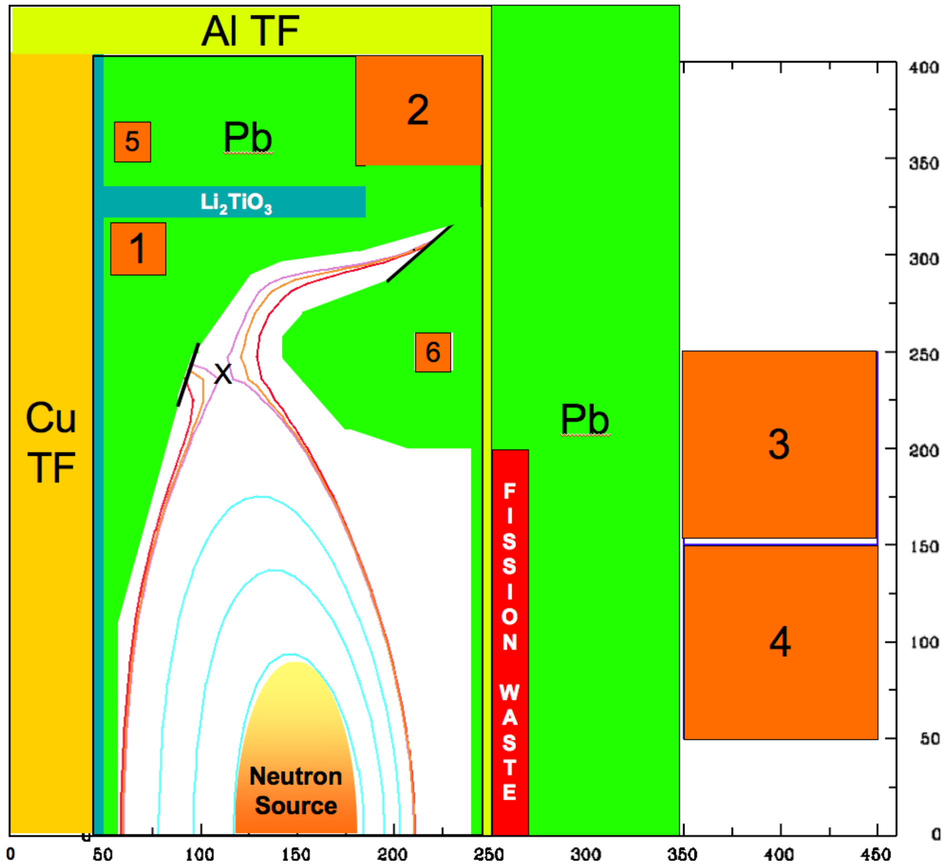
- **For neutron fluxes needed for Hybrid applications, Fusion power levels ~ similar to a CTF in a similarly COMPACT device**
  - 50~100 MW with ~ 1.5 MW/m^2 - compactness => high power density*
- **Credibility for near - term operation - choose a tokamak**
  - well developed physics basis
- **Choose a spherical tokamak for engineering advantages**
  - High power density, low coil mass, low capitol cost- easy maintenance

Reference compact high power density fusion driver will be called CFNS.

CFNS-Hybrid better look and behave very different from the generic one

CFNS gross parameters

R (m)	1.35
A	1.8
κ	3
P_{CD} (MW)	50
n_e (m^{-3})	1.3-2 x 10^{20}
$\Gamma_{neutron}$	1.1 MW/m^2
n_e (m^{-3})	1.2-2 x 10^{20}
n/n_G	0.14-0.3
β	15-18%
I_p (MA)	10-14
B_{coil}	7 T
B_{plasma}	2.9 T



CFNS-driven Hybrid-to scale

2nd major idea

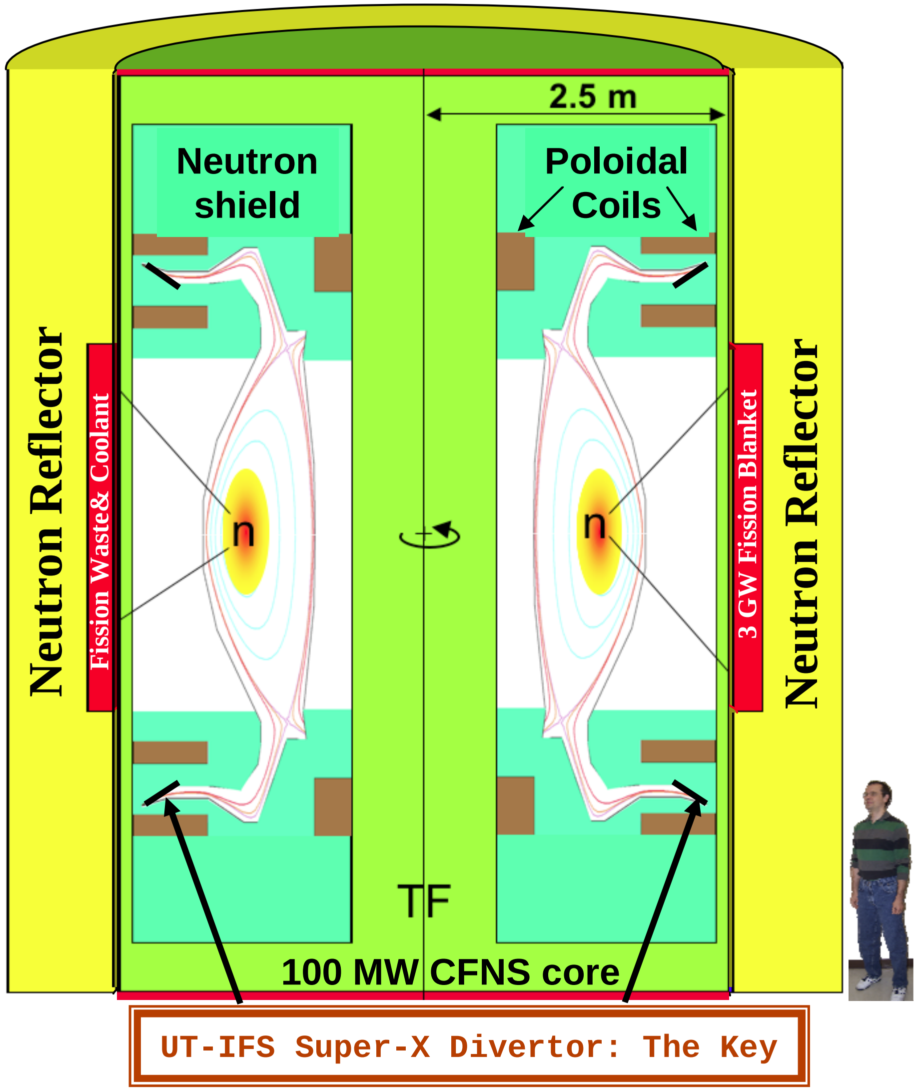
The Super-X divertor magnetic geometry

to solve the enormous heat exhaust problem peculiar to all high power density machines

Power density in CFNS~ 5 times that of ITER

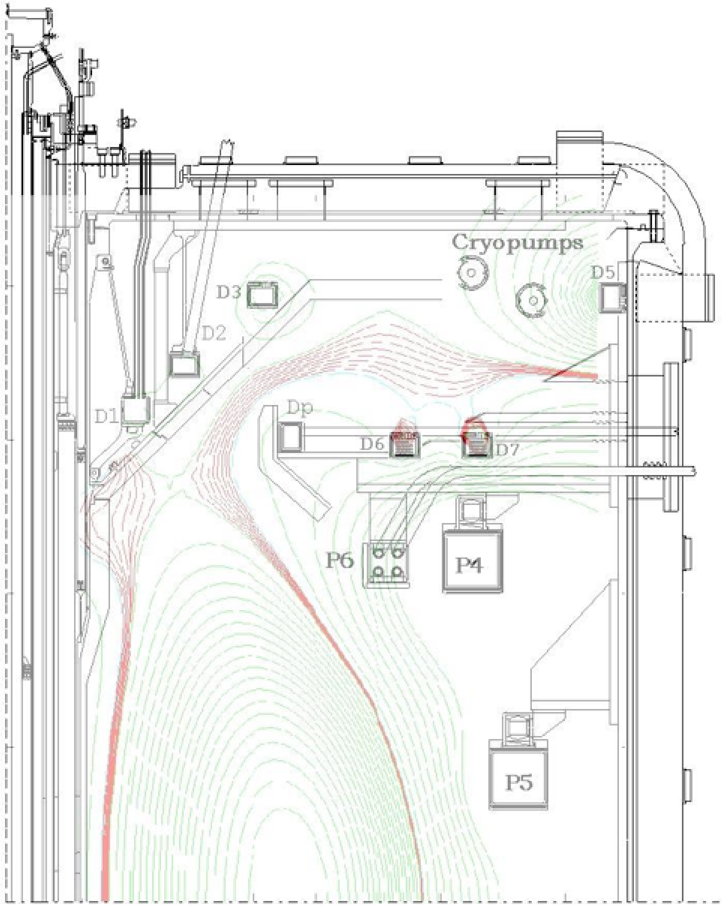
High power density is the essence- to match fusion and fission power densities for excellent coupling.

SXD dividend- neutron shielding ,boosting up core physics performance----.



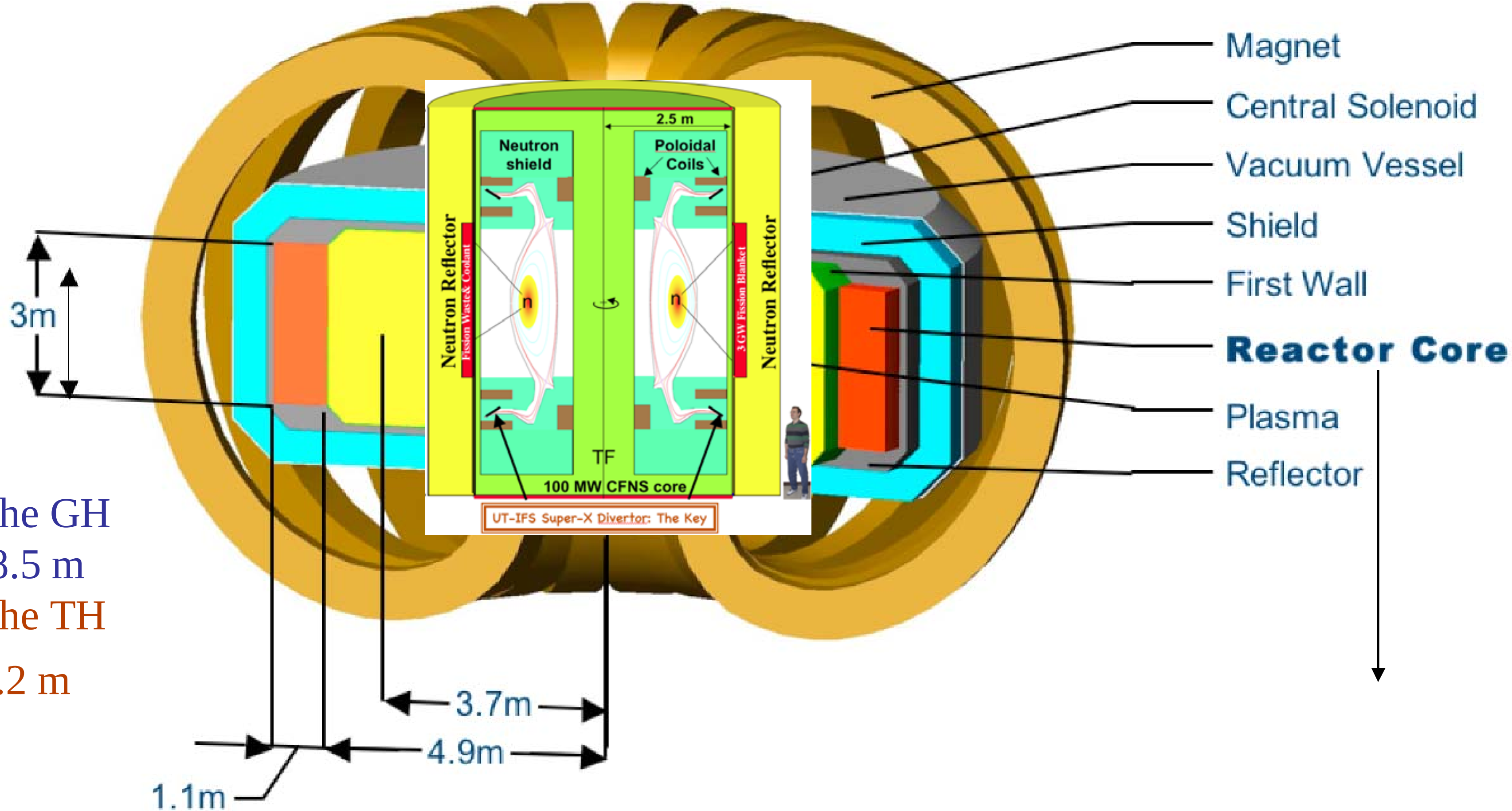
Super X Divertor: Experiments in progress

- **Worldwide plans to test Super X Divertor- designs are underway**
  - MAST upgrade (Culham, UK), NSTX (PPPL)- a partner for general realization of CFNS, DIII-D, possibly this year (GA), China, India have both shown interest
- ****SXD: enables power exhaust into much lower neutron damage region**
  - Much of ITER divertor technology be used (H_2O cooled Cu substrate- steady Q < 10MW/m^2, 20 MW/m^2 transient)**



Super X Divertor
for MAST Upgrade

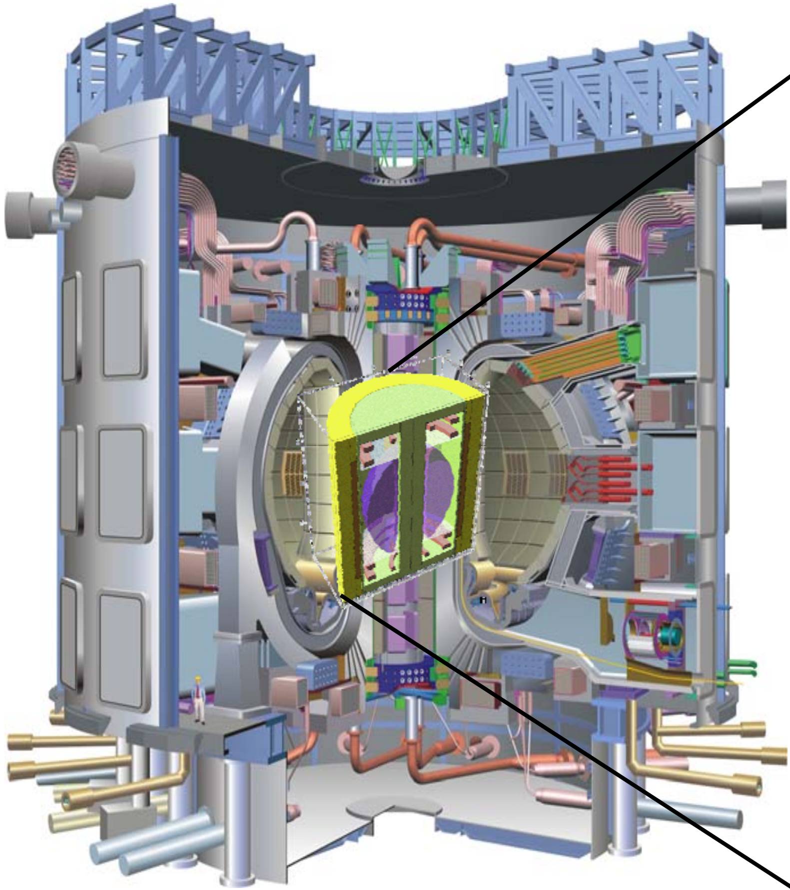
Generic (Stacey) and Texas Hybrids



For the GH
L ~ 8.5 m
For the TH
L ~3.2 m

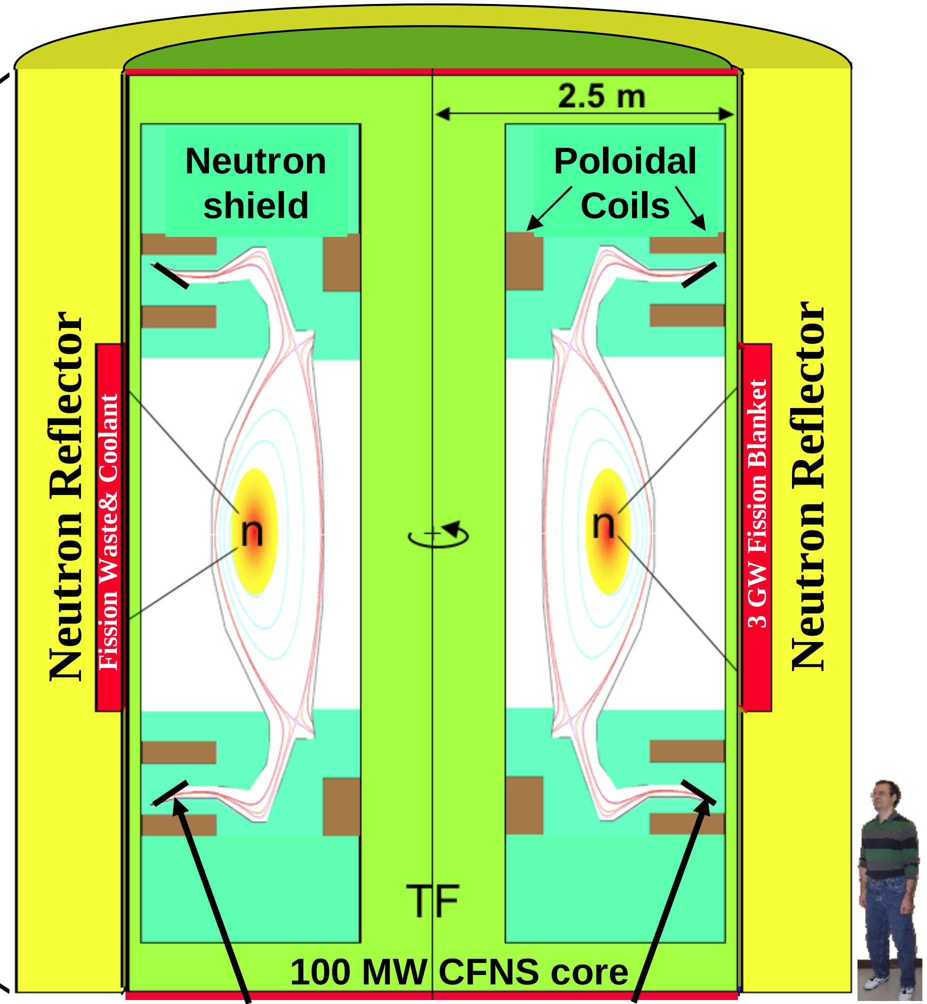
GH:Fission blanket (reactor core)is inside the magnetic field coils- strong mechanical and electromagnetic Fu-Fi coupling
TH:Fission blanket outside toroidal coils- fusion module removable- Fu-Fi coupling primarily neutronic

How compact is compact?



ITER (the next fusion flagship)

and Hybrid (on same scale)



UT-IFS Super-X Divertor: The Key

CFNS "Module" in Hybrid Reactor

CFNS- Modest Core Physics Demands

- Operating modes and **dimensionless performance parameters** for **CFNS** are reliably reproduced everyday in present tokamak experiments

  - only because SXD allows high power density without degrading the core

Device	Normalized confinement H	Gross stability β_N	Poloidal ρ / minor radius
Today's experiments- Routine operation	1	< 3	~ 0.05-0.1
Today's experiments- Advanced operation	< 1.5	< 4.5	~ 0.05-0.1
Hybrid - CFNS	**1**	**2-3**	**~0.05**
ITER- basic	1	2	~0.02
ITER-advanced	1.5	< 3.5	~0.03
"Economic" pure fusion reactor	1.2 -1.5	4-6	~0.02

Current machines, CFNS , ITER and a pure fusion reactor

Device	Outer radius	Fusion Power	Q = Fusion power/ Heating power
JET, JT-60U (exist)	**4 m**	**16 MW** **(achieved)**	**1** **(achieved)**
Fusion driver for Hybrid (Transmutation)	**2 - 3 m** Fits inside fission blanket	**50-100 MW** (2000-3000 MW fission)	**1-2**
ITER (being built)	**8 m**	**400 MW** **(expected ~ 2020)**	**10** **(expected ~ 2020)**
Pure fusion reactor	**7-10 m**	**2000-3500 MW**	**10-30**

For CFNS higher *power* -SXD indispensable

Is the Texas CFNS-Hybrid

a nearer - term technology

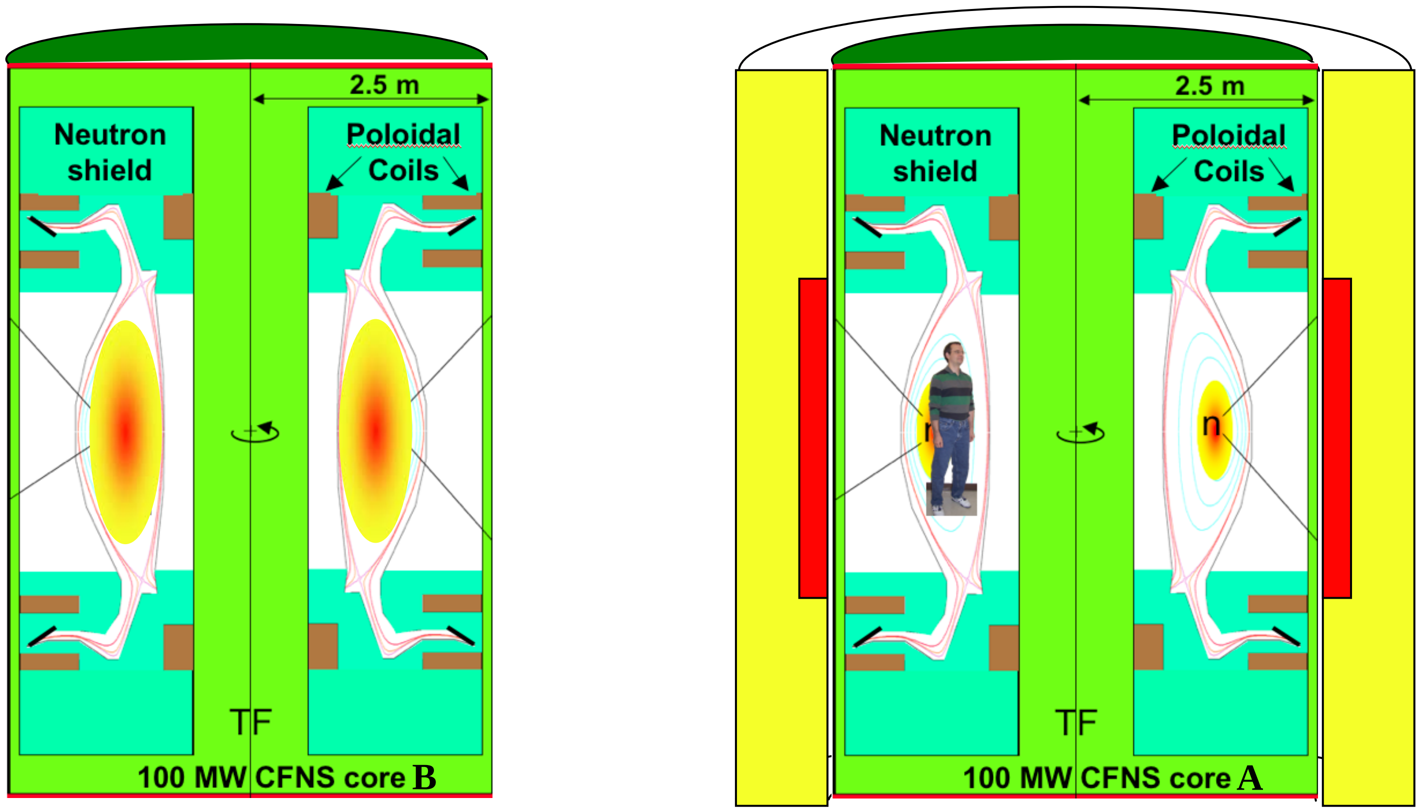
Generic Hybrid- a critique

Fusion driver technology issues:

- Complexity- a long time to develop to be reliable
- Difficult maintenance
- Damage from 14 MeV neutrons is greater than fission neutrons (He generation) **Fission assembly is *connected to* fusion driver:**
- ***Mechanically*** => new coupled failure modes, difficult to license
- ***Electro-magnetically*** => plasma disruptions cause mechanical EM loads
- ***Magnetically*** => coolant flow impeded by MHD effects

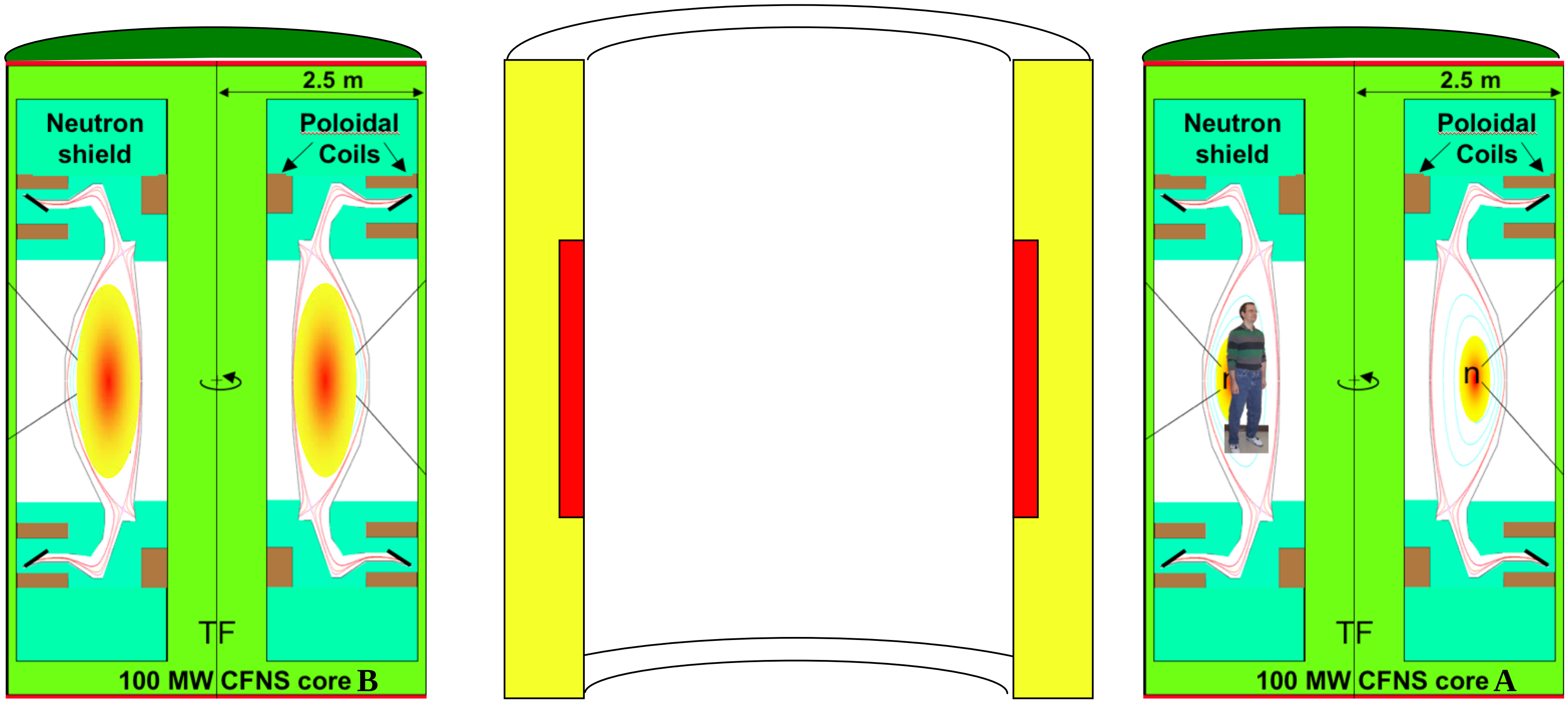
Replaceable Fusion Module Concept- the 3rd. major idea

- **SXD-insured compactness => CFNS fits inside the fission blanket**
- CFNS driver to last about 1-2 full power years- No known materials for the first wall that could take greater neutron fluences.



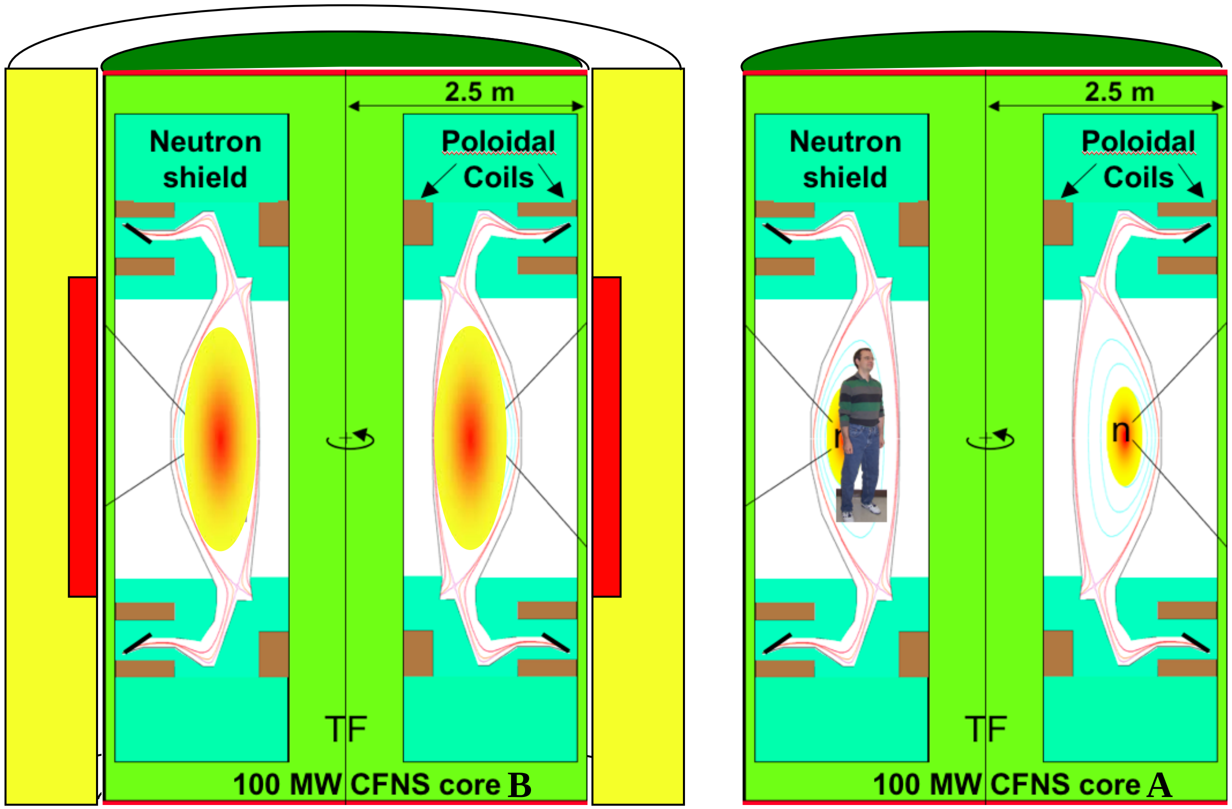
Replaceable Fusion Module

- **Pull CFNS driver A out to service bay once every 1-2 years or so.**
- Refurbish driver A in service bay - much easier than in-situ repairs



Replaceable Fusion Module

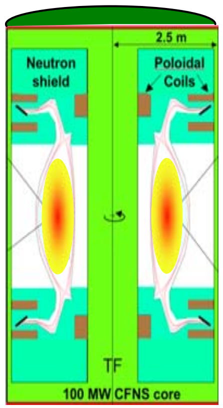
- **Put driver B into fission blanket**
- This can coincide with fission blanket maintenance
- Use driver B while driver A is being repaired

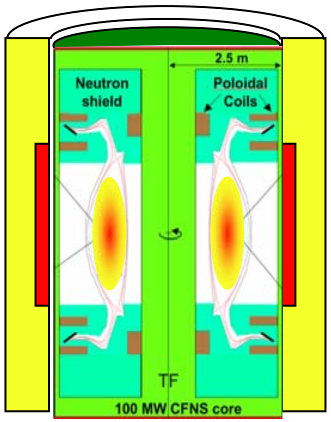


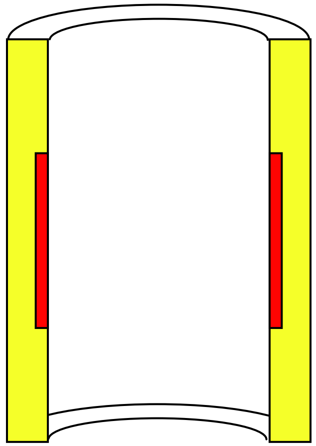
Replaceable Module -Solution to severe technical problems

Replaceable fusion driver

- Driver replaced up to yearly while fuel rods reshuffled **(development time, neutron damage)**
- Damaged driver refurbished in remote maintenance bay **(maintenance)**
- Fission assembly is physically separate from fusion driver **(failure interactions minimized)**
- Fission assembly is electro-magnetically shielded from plasma transients by TF coils **(disruption effects greatly reduced)**
- Fission blanket is outside TF coils **(coolant MHD drastically reduced)**







Fusion and fission systems are coupled only neutronically

Physical separation of Driver and fission blanket

- The fission assembly can consist of conventional fission technology and fuel rods

Maximum exploitation of known critical FR technology

- Licensing safety analysis is substantially simplified-

Failures that arise inside the complex fusion driver have much less affect on the fission assembly

CFNS-minimum development time

- Driver is exposed to one-two year of damage: **~ 1 Mwyr/m^2**
- CTF requirement for DEMO components **~ 6 MWyr/m^2**

- **CFNS technical mission much easier and cheaper than**
  - **A CTF**
  - A full pure fusion power plant (way easier)
  - Experiments at the full fusion power plant size (ITER)

- **Most Significantly, the testing cycle is 6 times shorter - development to obtain high reliability lot faster.**
- Physics and power-level demands of a CFNS are much less challenging than for a power producing pure fusion reactor.

CFNS-Hybrid vs DOE Fission-only Cycle

Reactor fleet that would result in ~ zero net transuranic nuclear waste production from the current ~100 US utility reactors

	Hybrids	FR route
US Light Water Reactors	100	100
Fast-spectrum waste destruction reactors	4-6	20-54

Under our proposal

4-6 new utility-scale CFNS-hybrid reactors would suffice

Waste reprocessing for fast reactors less by order of magnitude

Time for destruction reduced from ~200 to ~50 years

Summary

- **The fusion-Fission Hybrid has a fusion part and a fission part**

1. **A high energy density Compact Fusion Neutron Source (CFNS)**
   - The CFNS is made credible and near-term feasible by:
   - Significant demonstrated advances in overall Fusion research, and
   - Super X Divertor : a recent key idea
   - The concept of a replaceable fusion module

- **An optimum high S fuel cycle* enabled by the CFNS- LWRs doing what they are best at and the Hybrid doing only what others (LWRs and FRs) cannot do**
   - Uses existing, cheaper Light Water Reactors (LWRs) for 75% destruction
   - Works in synergy with the CFNS-driven Fusion-Fission Hybrid*
   - Much cheaper and faster than the standard Fast Reactor (FR) approach

- **Architectural plan for efficient, economic (lots issue to be settled yet), near- term, scientifically/ technologically feasible fusion-fission hybrid waste burning system.**

Nuclear Energy Renaissance
Scientist and Businessman - A rare meeting of minds

Jim Hansen - Tell Obama the Truth-The Whole Truth:

- However, the greatest threat to the planet may be the potential gap between that presumption (100% "soft"energy) and reality, with the gap filled by continued use of coal-fired power. Therefore it is important to undertake urgent focused R&D programs in both next generation nuclear power and ---
- However, it would be exceedingly dangerous to make the presumption today that we will soon have all-renewable electric power. Also it would be inappropriate to impose a similar presumption on China and India.

Exelon CEO John Rowe Interview - Bulletin of American Scientists:

- We virtually cannot imagine the United States dealing with the climate issue, let alone the climate and international security issues without a substantial increment to the nation's nuclear fleet
- I think you have to have some federal solution to the waste problem. If it (the Federal Government) ultimately cannot, I do not see this technology fulfilling a major role

Renaissance of Fission Energy is a global imperative - everyone is talking!

Developing a believable technical solution to the nuclear waste problem would, then, seems like a scientific imperative