Fission-Fusion hybrid - efficient destruction of nuclear waste

From a challenge to an opportunity

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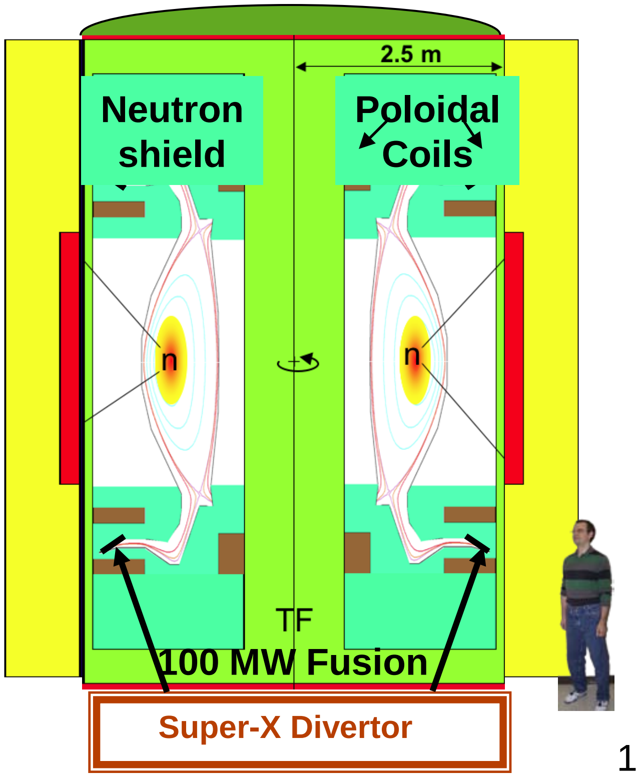

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Desired: a better way to destroy nuclear waste

- Nuclear power is regarded by many as one indispensable element to combat climate change- global stakes are very high
- Surveys: the most important issue for public acceptance of nuclear (fission) power is a satisfactory solution for nuclear waste
  - Geological disposal is very socially unpopular
- Methods of ***destroying*** the most long lived, bio-hazardous wastes have been under development for a long time- but have been deemed too expensive by many
- We have found a new way to use fusion to destroy nuclear waste which seems likely to be **much less expensive** than previous proposed methods
- We believe this is a promising nearer term application of nuclear fusion- which would also symbiotically help in the longer term development of pure fusion power

Recent history of transmutation schemes (non-fusion)

- National Academy of Sciences (NAS) reviewed transmutation schemes: fission only (critical fast reactor FR) and external neutron driven (accelerator ATW)
- Also - recent public congressional testimony (2005-2006) on FR approaches

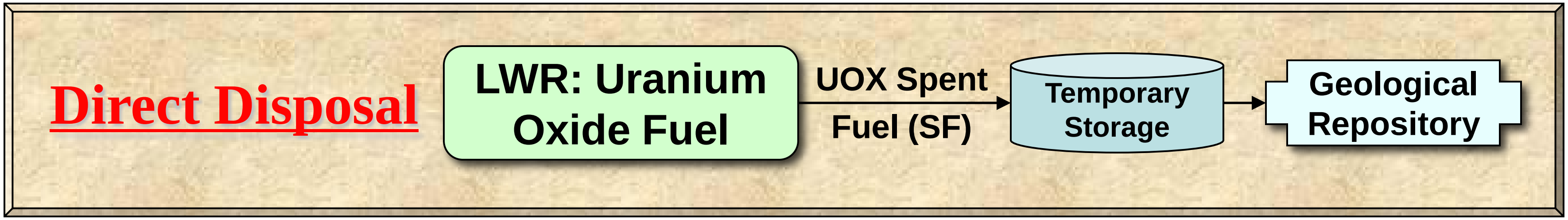
Recommended against transmutation schemes

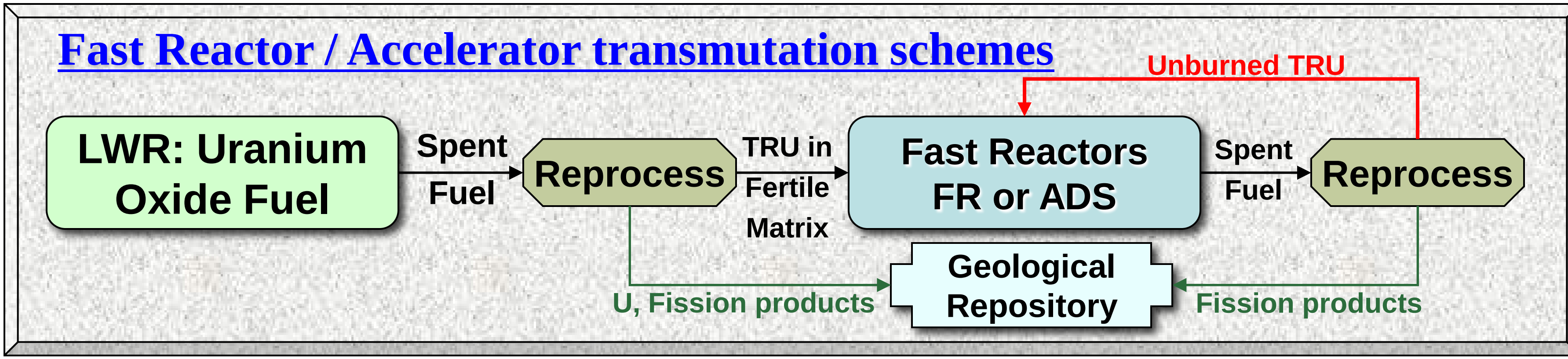
  - They were all **too costly**
  - Most took too long (~ 2 centuries to reduce 99%)
  - Proliferation concerns due to reprocessing

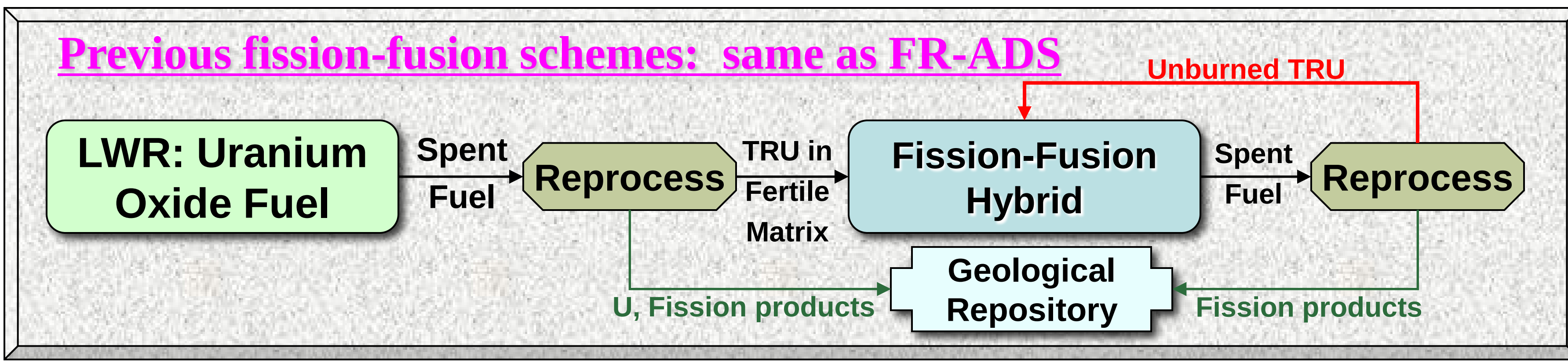
Why too costly? To thoroughly destroy waste-

- Must use reactors more expensive than LWRs- FRs and ATW
- Many were needed
- Total excess cost > $100 billion dollars, perhaps $100's billion

Generic Nuclear Waste Management Schemes







Since hybrid is more costly than FR- same problems as FR & ADS schemes

Devising a “winning” hybrid based scheme

- **“Generic” hybrid scheme has *no major advantage* over proposed FR schemes** in cost, proliferation or time
- However, a generic hybrid has obvious disadvantages; the fusion driver adds
  - Substantial extra cost
  - Major complexity
  - Major new technology development
  - Increased complexity leads to new failure modes and safety issues

A winning Hybrid strategy must

1. find some way of using the hybrid’s advantages to **address system cost**
2. find a way to minimize fusion caused (substantial) disadvantages

What would make a hybrid based scheme attractive?

- The **main *scientific* advantage** of marrying a fusion neutron source to a fission assembly is that a **hybrid can safely burn extremely "low quality" nuclear fuel; the kind that FRs cannot**

The trick is to turn this scientific advantage of a hybrid into a transmutation scheme with an advantage in

SYSTEM COST

(and advantages in time and proliferation)

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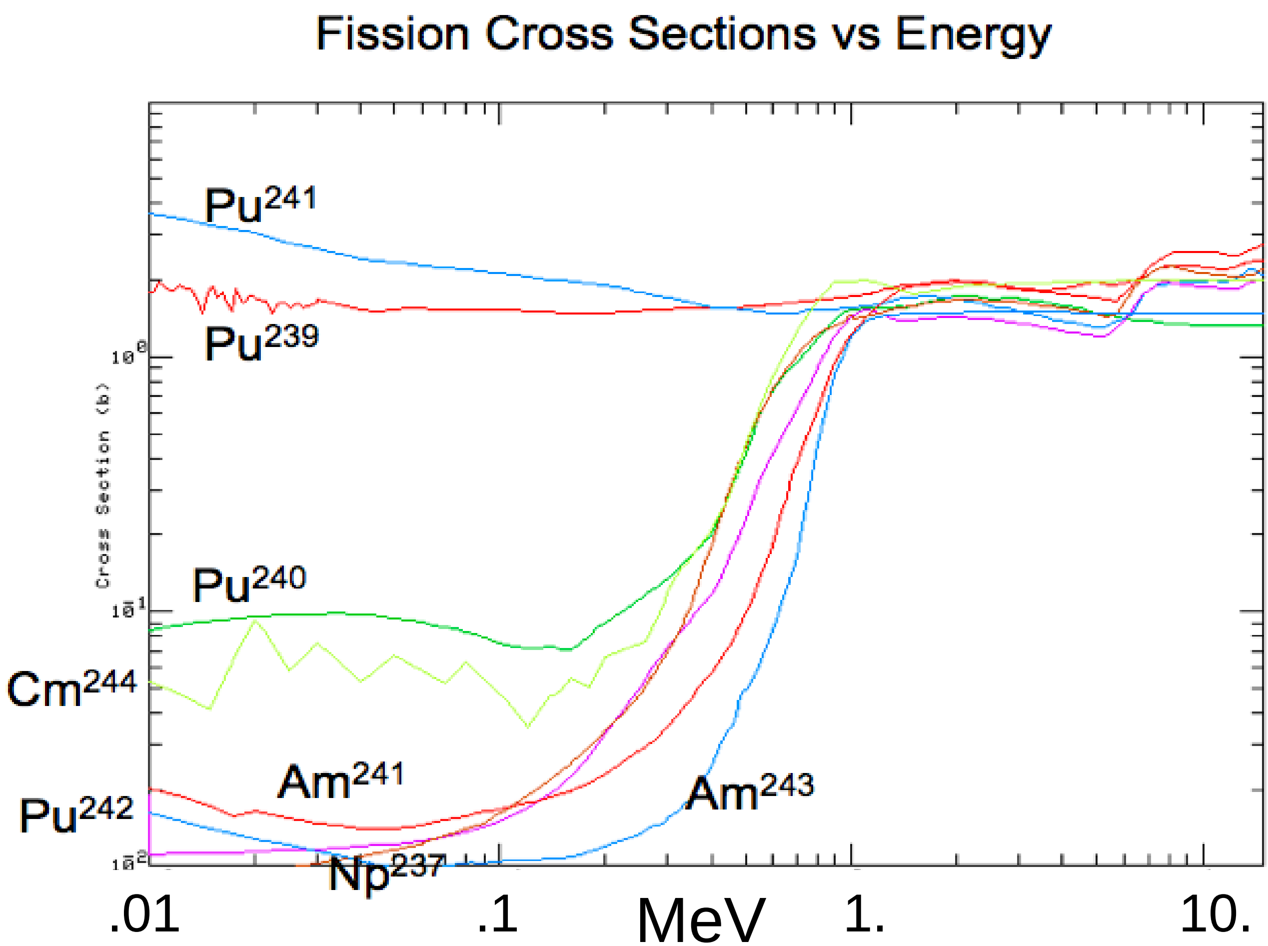
Since only Hybrids can burn very low quality fuel……

- Use a **two step fuel cycle** to exploit hybrid's unique capabilities
- **1st Step - use today's LWRs as much as possible (~75%)**
  - "Deeply" burn as much TRU as possible in *least expensive* reactors - **LWRs**
  - These would entail minimum extra cost- no new reactors must be built!
- **2nd step- use Hybrids to burn only the residue (~25%) that thermal spectrum LWRs cannot**
  - Only "**low quality"** TRU are left- residual cannot be burned in an FR
  - The residual TRU are essentially like minor actinides
  - Such fuel requires sub-critical incineration

Residue from deep burn in LWR: like minor actinides

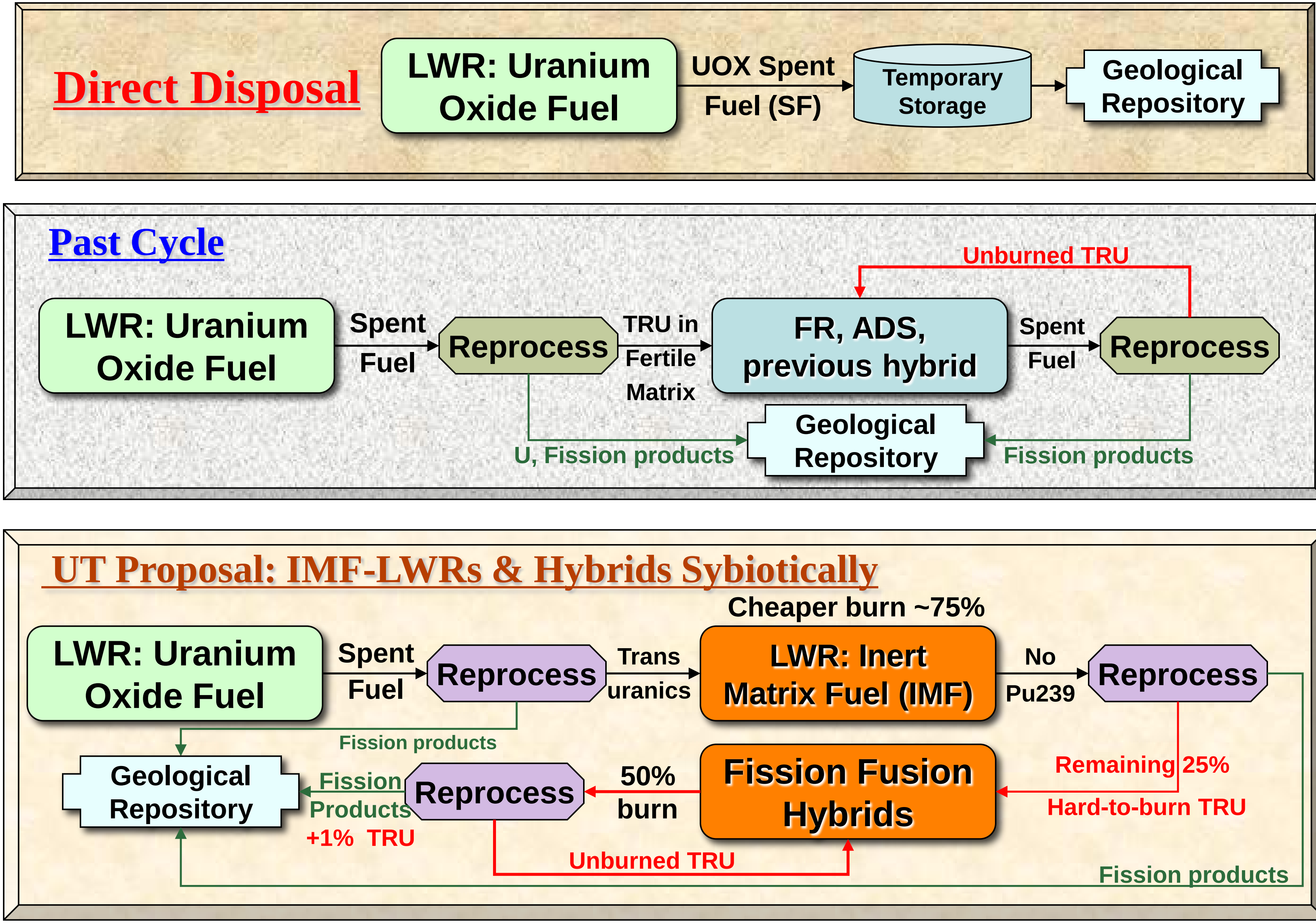
- Dominant minor actinides in spent fuel- Am^{241} and Np^{237}
- Dominant isotopes after deep burn in LWR- Pu^{242}, Am^{243} and Cm^{244}



Minimum number of expensive hybrids are needed

- Transmutation is dominated by inexpensive LWRs, so system cost is minimized
  - Hybrids have a high support ratio to LWRs- ~ 15-20
- A symbiotic relationship - each reactor type does what it does best
  - LWR- burns high & medium quality TRU with large thermal cross sections cheaply and quickly
  - Hybrid- burns very problematic material safely- the worst TRU- that even FRs cannot burn safely in undiluted form

New hybrid transmutation scheme



Optimal in several senses

- First step: destroy ~ 75% of TRU in LWRs in Inert Matrix Fuel (IMF)
  - Limited by physics: cross sections of ~ 25% of the isotopes are too small in an LWR neutron spectrum (close to thermal) for destruction
  - Cross sections of easily fissile isotopes are much larger in a thermal spectrum system
  - use of Inert matrix fuel (IMF) avoids generating new TRU (unlike MOX)
  - Destruction of most TRU is rapid, significantly reducing time for destruction
- Thermal spectrum systems also destroy a much larger percentage of fuel in a single pass- and virtually all weaponizable Pu^{239} -
  - Easily weaponizable isotopes (Pu^{239}, etc.) quickly eliminated in the very first step- and do not propagate through multiple remaining steps
- The remaining 25% residue must be "incinerated" in a sub-critical assembly for safety
  - A relatively inexpensive, prolific external neutron source is needed- **fusion!**
  - Hybrid also uses fertile free fuel (unlike FRs)- no new TRU or weaponizable Pu^{239} is generated during destruction

25% residue- Abode of much of the original long term radioactivity and biohazard

- Isotopes that grossly dominate the long lived biohazards of fission waste are not destroyed in the LWR -IMF step:
  - Pu^{242} half life 4×10^5 years
  - Np^{237} half life 2×10^6 years
- Geologic disposal is difficult precisely because these specific isotopes must be isolated from the biosphere for **very** long times
  - Example: DOE analysis of Yucca Mountain:
  - **these isotopes dominate surface doses** of radiation
  - Doses much higher than allowed by other man-made source
  - At 2-4 x 10^5 years: less than legislated time horizon 10^6 yrs
- **The hybrid is NEEDED to eliminate the very long lived TRU isotopes that make geological isolation difficult to insure- perhaps the fundamental public concern**

UT-Hybrid vs Fission-only Cycle

Required Reactor fleets for zero net transuranic nuclear waste production from the current ~100 US utility reactors

	Hybrid Route	Fission-only (AFCI)
US Light Water Reactors	100	100
Fast-spectrum waste destruction reactors	4-6	25-56

Under our proposal

4-6 new utility-scale hybrid reactors would suffice

Total reprocessing for fast-spectrum reactors will also be reduced by roughly an order of magnitude

This hybrid based scheme has a major *system cost advantage* over other schemes

- First fission-fusion hybrid based scheme with this advantage
  - (to our knowledge)--- perhaps several times cheaper?
  - The advantage appears easily more than enough to overcome the cost disadvantage of *individual* hybrid vs an *individual* FR
- **The system cost advantage may be enough to overcome the obvious disadvantages of the hybrid:**
  - Complexity, stage of development, novel failure modes
  - We turn to these **technological challenges** momentarily

Reactor Requirements for Waste Transmutation for different schemes

Reactors needed to destroy waste from 100 LWRs

	Fast Reactors BR= 0.25-0.5	Hybrids burning all TRU	Hybrids burning only Np & Am	IMF pre-burn followed by hybrids
Number of FRs	25-56	0	20	0
Number of Hybrids		28	5	4-6
Total # of Fast systems	25-56	28	25	4-6
Cost (excess) (LWR equivalents)	32-70 (6-13)	56 (28)	35 (20)	8-12 (4-6)

FR cost = 1.25 LWR, Hybrid = 2 LWR

How sub-critical is necessary?

- **Fission blanket must maintain k_{eff} <1 even in an accident scenario**
- Severe accident: complete voiding of the coolant in the core
- With coolant present (normal operation) the k_{eff} is somewhat less than 1
- This determines the number of external neutrons needed to reach a given fission blanket power level- and hence the power level of the fusion source

The size of the k_{eff} swing upon voiding depends on the fission blanket coolant and configuration

- The k_{eff} swing is strongly dependent on the fission blanket design
- **Developing fission blankets to minimize the k_{eff} swing in a hybrid (and hence minimze fusion power) is a crucial area of research**
- We have emphasized sodium cooled blankets to maintain continuity with the largest US FR program
- Other blanket coolants would have many advantages
- Consistent hybrid blanket designs with other coolants is an crucial area of research
  - Pb alloys, gas (He or CO_2), liquid salts, etc.
  - Neutronics, thermo-hydraulics, MHD, material lifetimes, etc.

Breeding Tritium

- At present, Li^6 is used for both breeding and neutron shielding of important components
  - copper magnets, PF coils, divertor plate region
- A fission blanket with keff > 0.9 is phenomenal neutron multiplier
  - Leakage of neutrons from the fission blanket into the areas above (plus fusion neutrons) appears adequate for tritium self-sufficiency
- A better optimized tritium breeding/shielding blanket design and configuration is an important area for research
  - Minimize development issues, use wider temperature window (power conversion unnecessary), etc.

The Fusion Driver

A Compact High Power Density Fusion Neutron Source

(CFNS)

What may constitute a reference fusion driver?

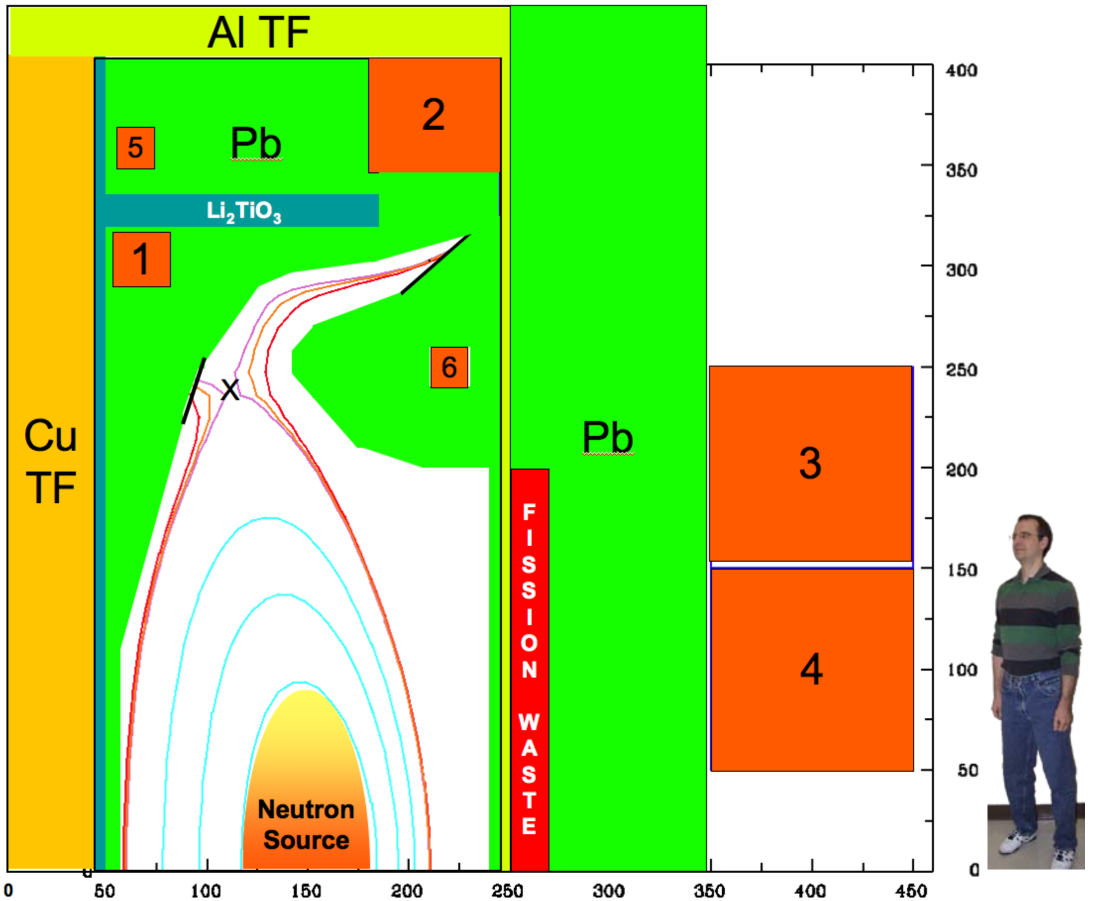
- **Fusion power levels similar to a CTF in a similarly COMPACT device**
  - ~100 MW
- **For credibility for near term operation, choose a concept which the larger world will believe is plausible**
  - Tokamak with conservative physics has best credibility, adequate performance
- **Choose an ST for engineering advantages when marrying to fission**
  - High power density, low coil mass, low capitol cost
  - Easy maintenance - a much more important consideration
- **Slight neutron shielding on center TF to extend life to ~ 1-2 years**
  - To make room, aspect ratio A~ 1.8 is on high side for ST

Core physics operation conservative for credibility

- **Below No-wall limit**
  - estimates by Jon Menard quoted in Jeff Freidberg's MHD book:
  - use TROYON definition $<\beta>_N$ with correction for q*
- **H-mode confinement (H ~ 1)**
- **Densities far below Greenwald limit (< 0.3), and minimum q above 2 (avoids worst NTMs) to minimize disruptions**
- **RF current drive only (trying to avoid neutral beams)**
  - Want to avoid any penetration of the fission blanket surronding the driver
  - Both Electron cyclotron and Fast Wave appear to have adequate efficiency
  - RF power can be routed through top or botton- avoiding sides

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



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Conservative Core Physics Demands

- **CFNS** can use operating modes and **dimensionless performance parameters** where experiments operate reliably on present tokamaks

  - **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

Hybrid closer to Today's experimental achievements than ITER or a pure fusion reactor

Device	Outer radius (R + a)	Fusion Power	Q = Fusion power/ Heating power
JET, JT-60U (exist)	**4 m**	**16 MW (achieved)**	**Close to 1 (achieved)**
Fusion driver for Hybrid (Transmutation)	**2.5 m** Fits inside fission blanket	**100 MW** (~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**

The Hybrid fusion source has a higher *power density* compared to current experiments and ITER - need SXD

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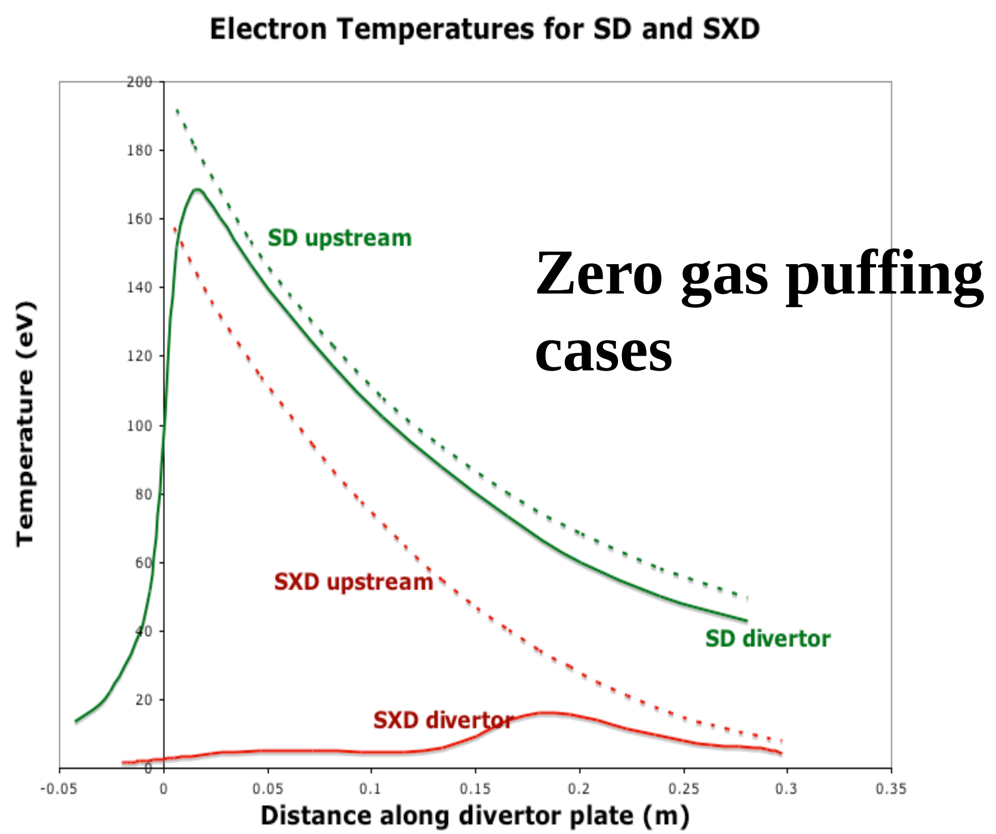
Super-X Divertor (SXD)- makes CFNS feasible

- Analysis using best available simulation (SOLPS - as for ITER)
- Standard divertor - exhausted high power plasma is unacceptably hot and damaging -**"sheath limited"**
  - No cooling of plasma in SOL
- SXD- exhausted plasma is **"partially detached"**- what ITER design aims for
  - Strong cooling of plasma in SOL
- **SXD reduces peak heat flux by factor of FOUR- to 3 MW/m^2**



Calculations by John Canik ORNL

The challenge of making a hybrid a nearer - term technological task

Technology issues of a hybrid compared to FR

Fusion driver technology issues:

- Complexity- a long time to develop to be reliable
- Internal maintenance, with TF coils and vacuum vessel- “Like disassembling a ship in a bottle”
- Damage from 14 MeV neutrons is greater than fission neutrons due to He generation

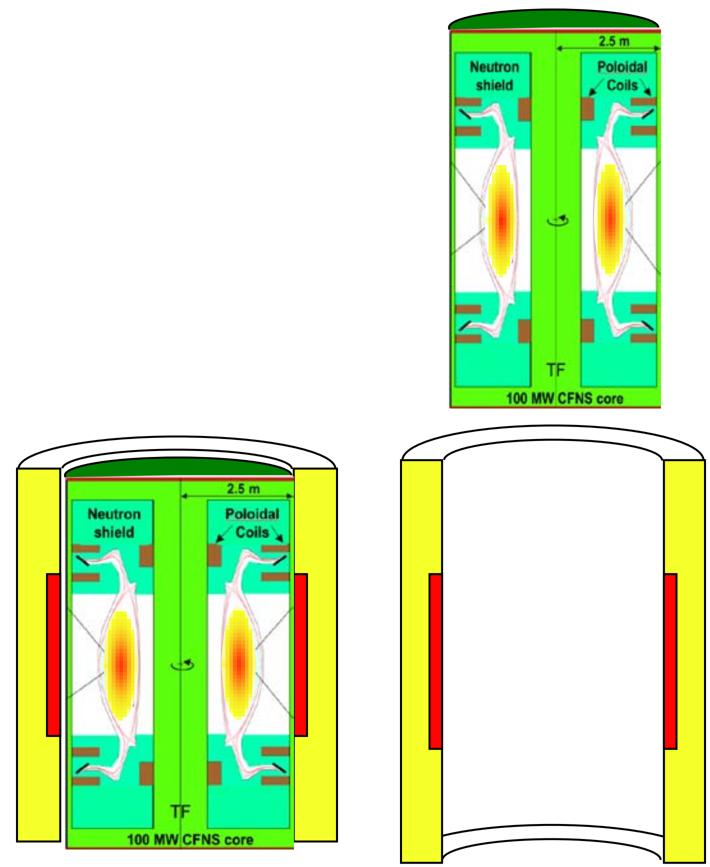
Fission assembly is *connected to* fusion driver:

- ***Mechanically*** => new coupled failure modes, difficult to license
- ***Electro-magnetically*** => plasma disruptions cause mechanical EM loads
- ***Magnetically*** => coolant flow impeded by MHD effects

Replaceable Module concept to address all these issues

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)**



We shall now spell these out

Electromagnetic disruption effects on blanket

- The L/R time of the fairly thick, highly conducting TF is

~ 1 second

(even with substantial holes to let neutrons through)

- Disruptions: as fast as

~ 1 ms

- TF slows down EM transients in the fission blanket by orders of magnitude

Eddy currents and forces in fission assembly are reduced orders of magnitude

MHD coolant effects

- **Fission blanket power density is ~ 1 1/2 orders of magnitude higher than pure fusion-** MHD coolant problems could be very severe for a hybrid
- Magnetic field outside the TF coils is only from PF, and is almost exactly vertical- **aligns almost perfectly with the coolant flow direction**

MHD drag effects reduced by orders of magnitude from previous tokamak hybrids

Physical separation of Driver and fission blanket

Failures that arise inside the complex fusion driver have

much less affect

on the fission assembly where safety is paramount

- The fission assembly can consist of conventional fission technology and fuel rods
- Licensing safety analysis is substantially simplified

"Cost of this strategy"- neutrons go through outer slotted TF coil

- The "fusion blanket" is 10-20 cm of Pb to multiply and reduce the energy of the neutrons to ~ 1-2 Mev
  - Much closer to fission spectrum
- Reduces energy of neutrons going between coils so large majority are below parisitic loss threshholds for Al, Fe, etc.
  - (n,p), (n,α) reactions
  - Only loss about 20-30% of neutrons
- Damage rates ~ 10 dpa/yr, much reduced He generation- several year lifetime of outboard components?

CFNS: easier than CTF

- Driver is exposed to as little as **1.5** year of damage:

  ~ 1.5 Mwyr/m^2

- CTF requirement for DEMO components

  ~ 6 MWyr/m^2

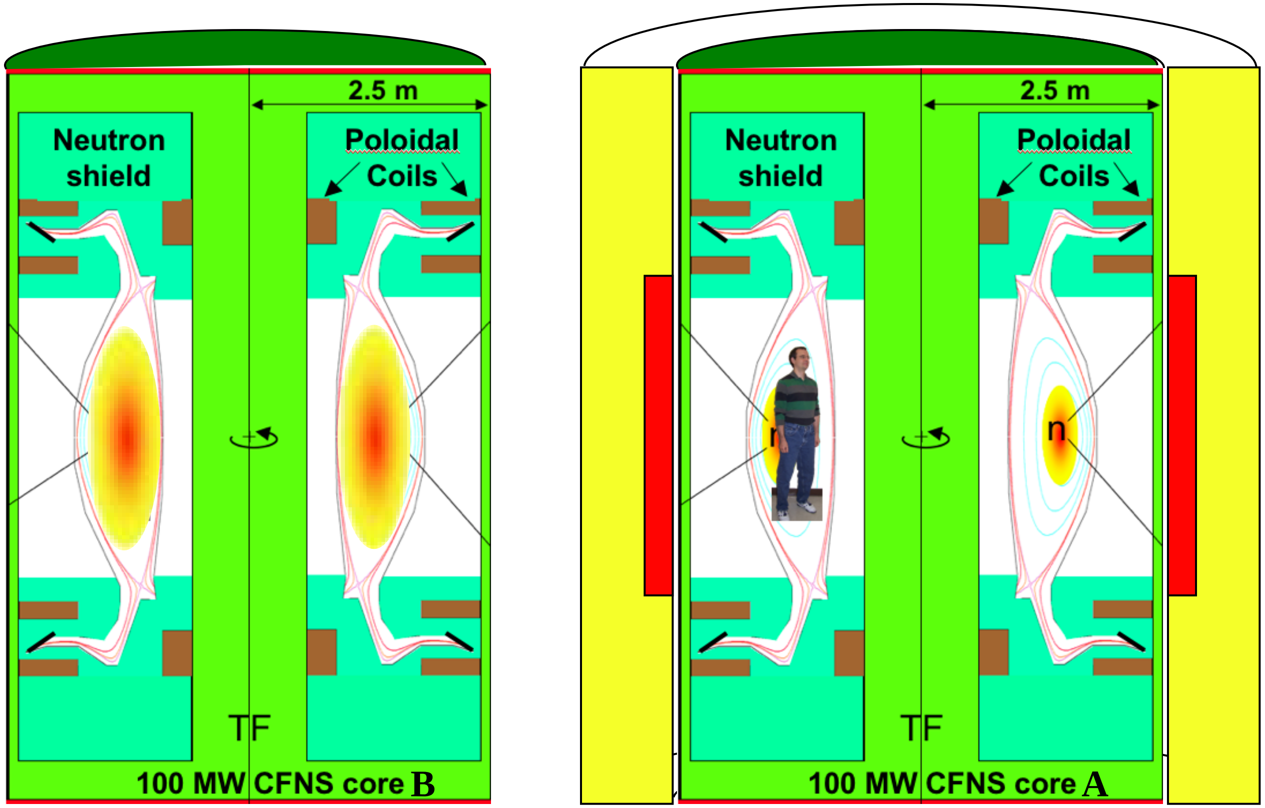
- **CFNS mission could be much easier than CTF mission because**
  - Components are much less damaged
  - A testing cycle is 4 times shorter, so development to obtain high reliability is faster

Maintenance scheme: similarities to ARIES-ST

- Replace entire ST, fusion blankets and copper center post all as one unit
  - Weight of thei assembly for ASRIES-ST : ~ 4000 tons
- CFNS is much smaller
  - Entire device including TF coils ~ 300-400 tons
- Hence, replace entire CFNS as a unit
- However, most of the device has low neutron damage
- Hence, refurbish used CFNS in a remote maintenance bay by replacing only damaged components
- Meanwhile, a new CFNS is inserted inside the fission blanket for continued operation

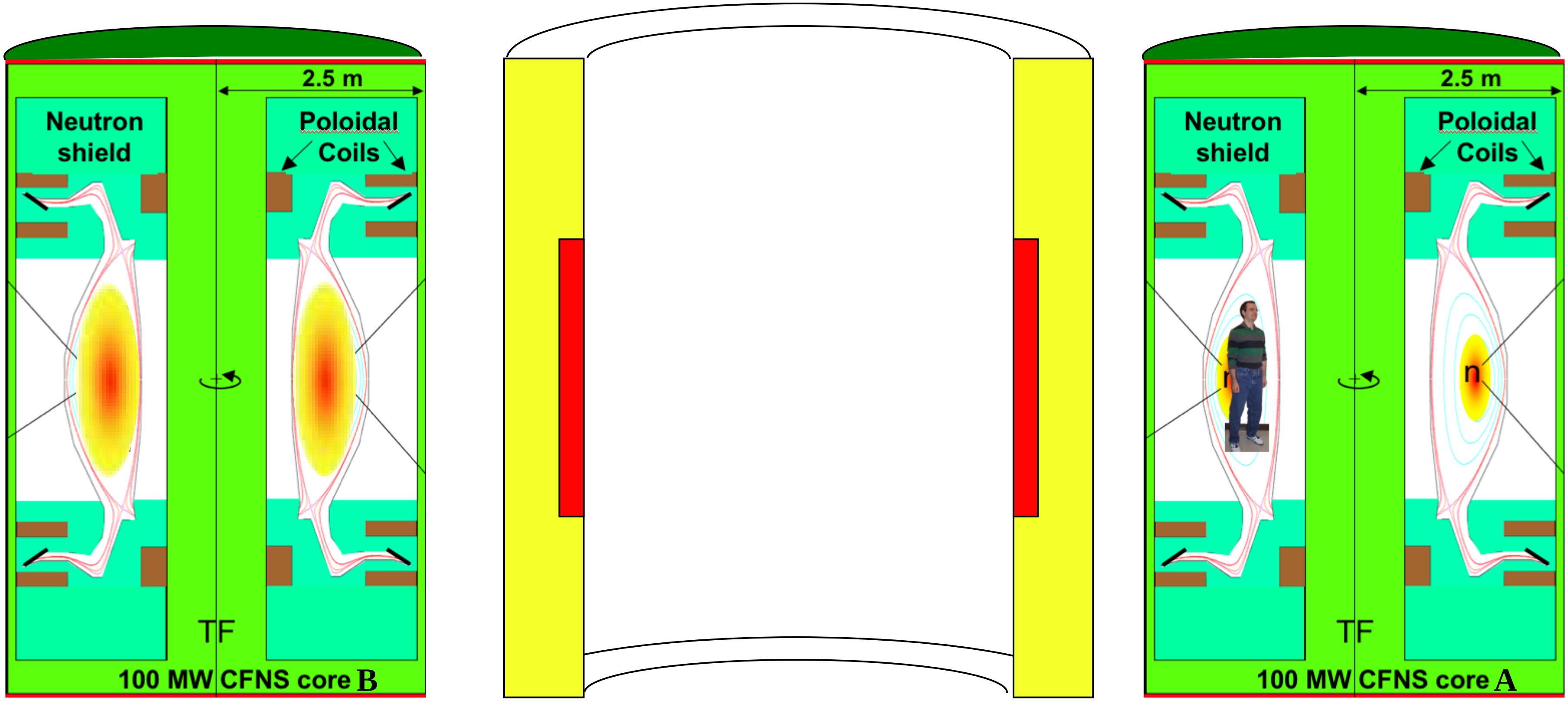
Replaceable Fusion Module Concept

- **Due to SXD, the whole CFNS is small enough to fit inside fission blanket**
- CFNS driver to last about 1-2 full power years
- It can be replaced by another CFNS driver and refurbished away from hybrid
- **CFNS driver itself is small fraction of cost, so a spare is affordable**



Replaceable Fusion Module Concept

- **Pull CFNS driver A out to service bay once every 1-2 years or so - at the same time when fission blanket maintenance is usually done**
- Refurbish driver A in service bay - much easier than in-situ repairs



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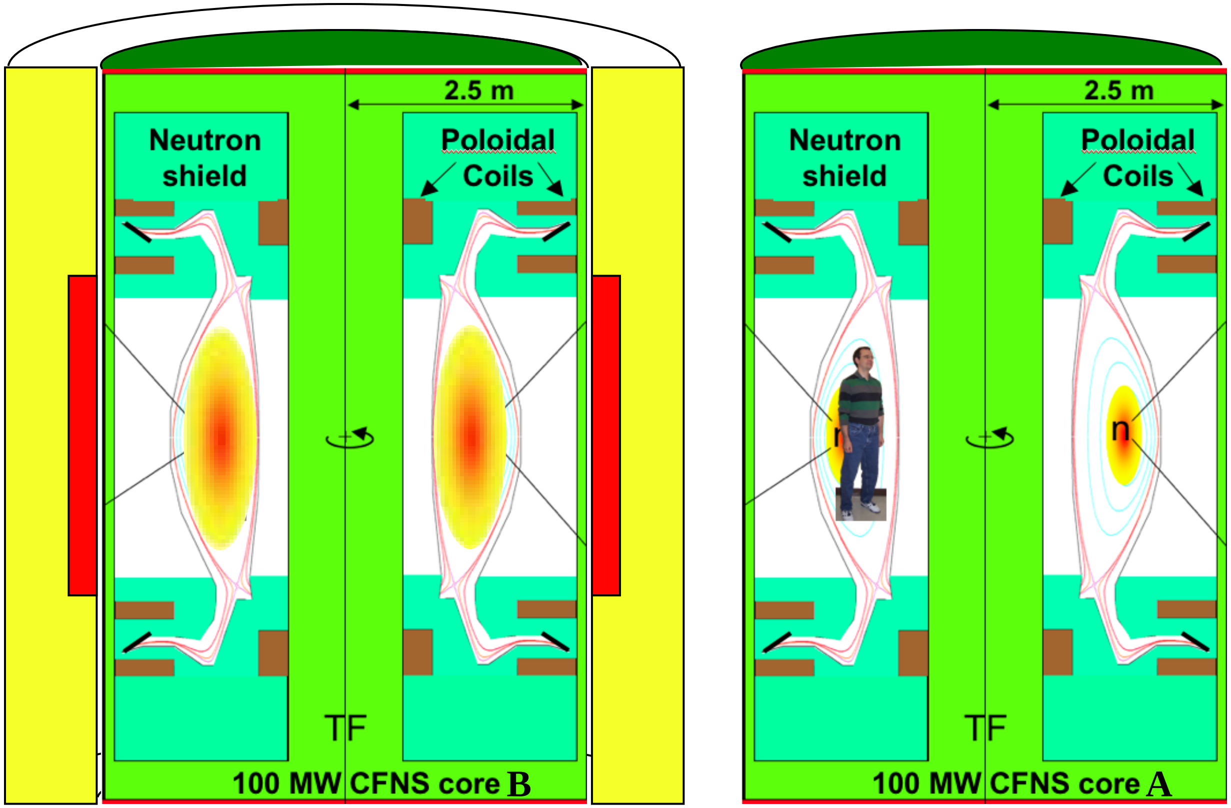
Replaceable Fusion Module Concept

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



Hybrid in the context of fusion research - an intermediate milestone

- Development of a hybrid would tremendously advance fusion technology - hybrid-fusion are symbiotic
- **The performance/cost of a hybrid improve as the physics and technology improves towards the requirements of pure fusion**

The demands (both physics and technology)

for initial operation of an *attractive* hybrid

are low enough

that an attractive application of fusion

may become possible more quickly

Back-up slides

CFNS Unknowns - Plasma wall interaction

- SXD is promising, but needs *testing*
- Success of SXD still leaves further PMI issues
  - Tritium retention
  - Effect of loss of wall conditioning on plasma performance?
  - Will material surfaces evolve acceptably at long times (e.g., will erosion / re-deposition lead to wall flaking & plasma disruptions?)
  - Will surfaces survive a rare disruption without unacceptable damage?
- Liquid metal on porous substrate looks like a promising potential solution to all of these
  - NSTX might be able to test it sometime in the future?

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 cannot imagine the US 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 emerging as a global imperative - everyone is talking!

A believable technical solution to the nuclear waste problem- a scientific imperative

Issue: Maintenance of highly radioactive driver

- Driver is removed as a unit relatively quickly
- Refurbishment of a “spent” driver is done relatively slowly in a remote maintenance bay
- Rapid inspection/replacement of components of the “ship in a bottle” method- which we don’t know how to do- is avoided

Credible inspection/maintenance improves the credibility of high availability

New Hybrid versus Generic Hybrid

- The new hybrid is **technologically much more credible**

Together with the advantages of the IMF-hybrid fuel cycle,

the new hybrid emerges as a potentially

attractive and credible endeavor

Why is the hybrid needed for the residue?

- Safety issue for the FR: stability of the fission chain reaction
- Consensus of many previous analysis of FRs: too high a fraction of low quality fuel - minor actinides - is unacceptable

Only a smallish minority fraction of minor actinides is tolerable in FRs

- The residue from the LWR step: about half minor actinides
- Even the isotopes which aren't minor actinides, but are left after the 75% LWR burn, behave like minor actinides for an FR

Fuel quality of residue is like ~ 100% minor actinides

- The consensus is that safely burning such fuel requires an external neutron source

Safety requires that such fuel must be burned "subcritically",

with the help of non-fission neutrons

Fusion appears to be several times cheaper per neutron than an accelerator, so it would be the cheapest/safest way of burning this low quality fuel

Usual advantage claimed for a hybrid: safety

- Hybrid is said to be "safer"- the fission blanket operates sub-critically

BUT: FR community claims good passive safety while burning TRU from LWRs - using advanced geometry, materials

- FR safety (criticality accidents)- not raised as the major issue in the NAS study or recent congressional testimony
  - Major issues with FR approach - **COST**, reprocessing, time
  - Hybrid makes cost worse, slightly improves time
- Safety advantage of hybrid is hard to argue persuasively- whereas disadvantages are clear-cut

Analysis of TRU from LWR which must be burned

- FR safety is made problematic by **particular** TRU isotopes which *only* fission from *very fast* neutrons (~ 1 Mev)
- Problematic fuel- low fission cross section at lower energy ~ 100 keV
  - Such fuel leads to unacceptable controllability of the chain reaction- high void reactivity, low Doppler stability, low delayed neutrons, etc.
- A qualitiative measure of fuel quality: fission cross section σ_f at ~ 100 keV

Highly problematic isotopes are a minority- so FR operation can be made acceptable

Quality	σ_f(100keV)- barns	Isotopes in LWR TRU	Total %
High	~ 1	Pu^{239}, Pu^{241}, Pu^{238}	54%
Medium	~ 0.1	Pu^{240}	22%
Low	~ 0.01	Am^{241}, Np^{237}, Pu^{242}, Am^{243}	24%

This *mixture* of TRU can, indeed, be burnt in an FR
Its just that the cost is deemed too high

Basis of rough costing- consistent with DOE

- FR capitol cost ~ 1.3 LWR
- Reprocessing cost of FR ~ 15% FR capitol cost~ 0.2 LWR
- Single FR cost with reprocessing~ 1.3+ 0.2 ~ 1.5 LWR
- => excess cost of FR = 0.5 LWR

- Cost of hybrid = cost of FR + cost of CFNS
- CFNS cost (100 MW fusion- CTF studies) ~ $1.5B ~ 0.5 LWR
- Reprocessing cost of hybrid ~ same as FR
- Hybrid cost ~ 1.3 + 0.5 + 0.2 ~ 2.
- => excess cost of hybrid = 1 LWR

The CFNS divertor is implausible without the Super-X divertor

- From Stangeby: sheath limited if $S' = Q_{||u} / n^{1.75} L^{0.75} > 1 \times 10^{-27}$
- Benchmark with SOLPS- define

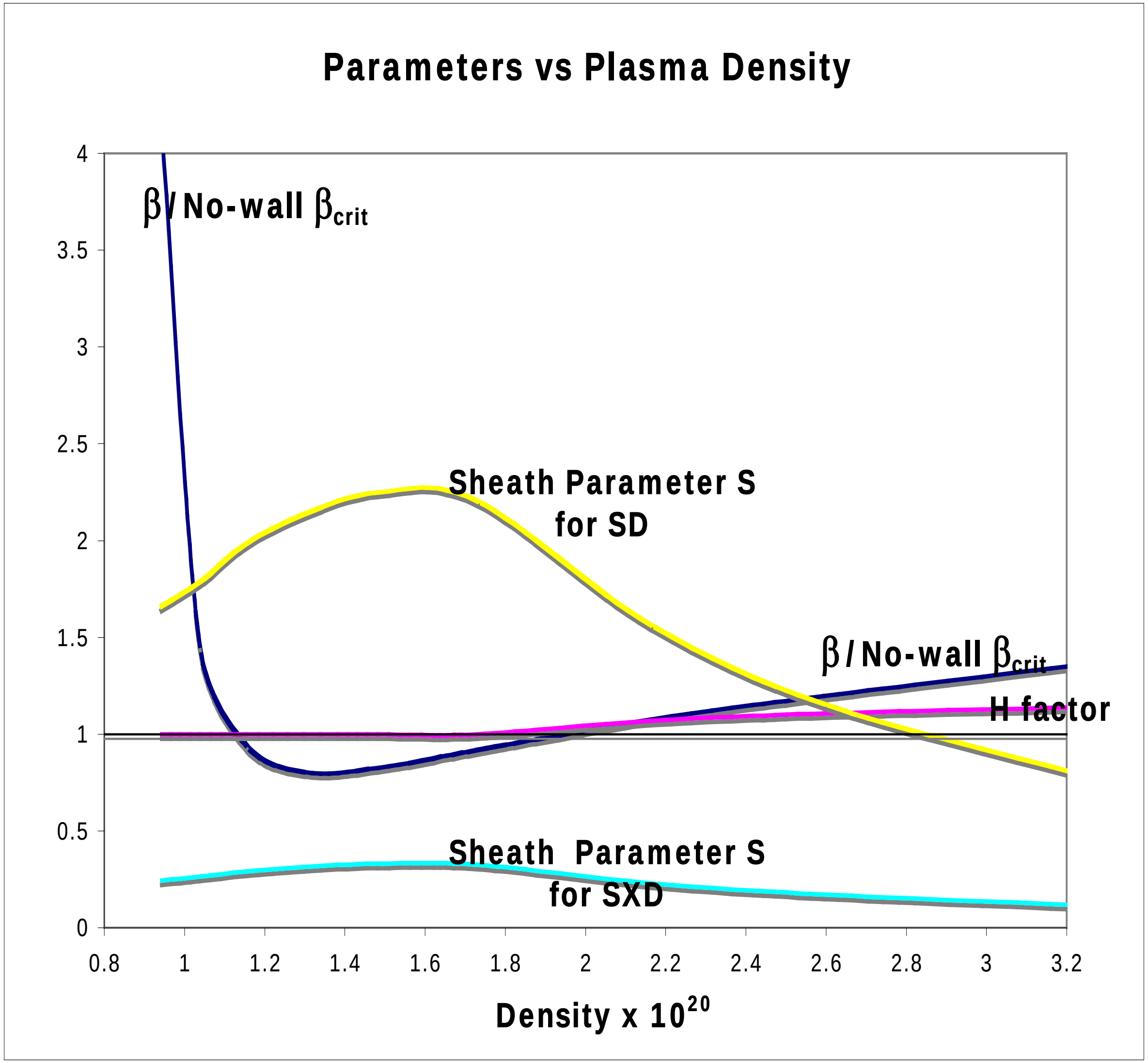
$$S = Q_{||u} (B_{div}/B_u) / n^{1.75} L^{0.75} / 3 \times 10^{-27}$$

If S > 1, reliably sheath limited (typically $T_{e\ plate} > 100$ eV)

- This would give:
  - Negligible radiation/high heat flux
  - Unacceptable erosion sputtering
  - Low neutral pressure and very likely unacceptable He exhaust

Operating window becomes substantial only with SXD

CFNS: SXD allows conservative core physics



CD power = 50MW

P_{fus} = 100 MW

- **At moderate density, no wall stable regime**
- **At very low density:**
  - ***too much* current =>**
  - **poor MHD stability**
- **Add core radiation to make H = 1 and “save” divertor when possible**

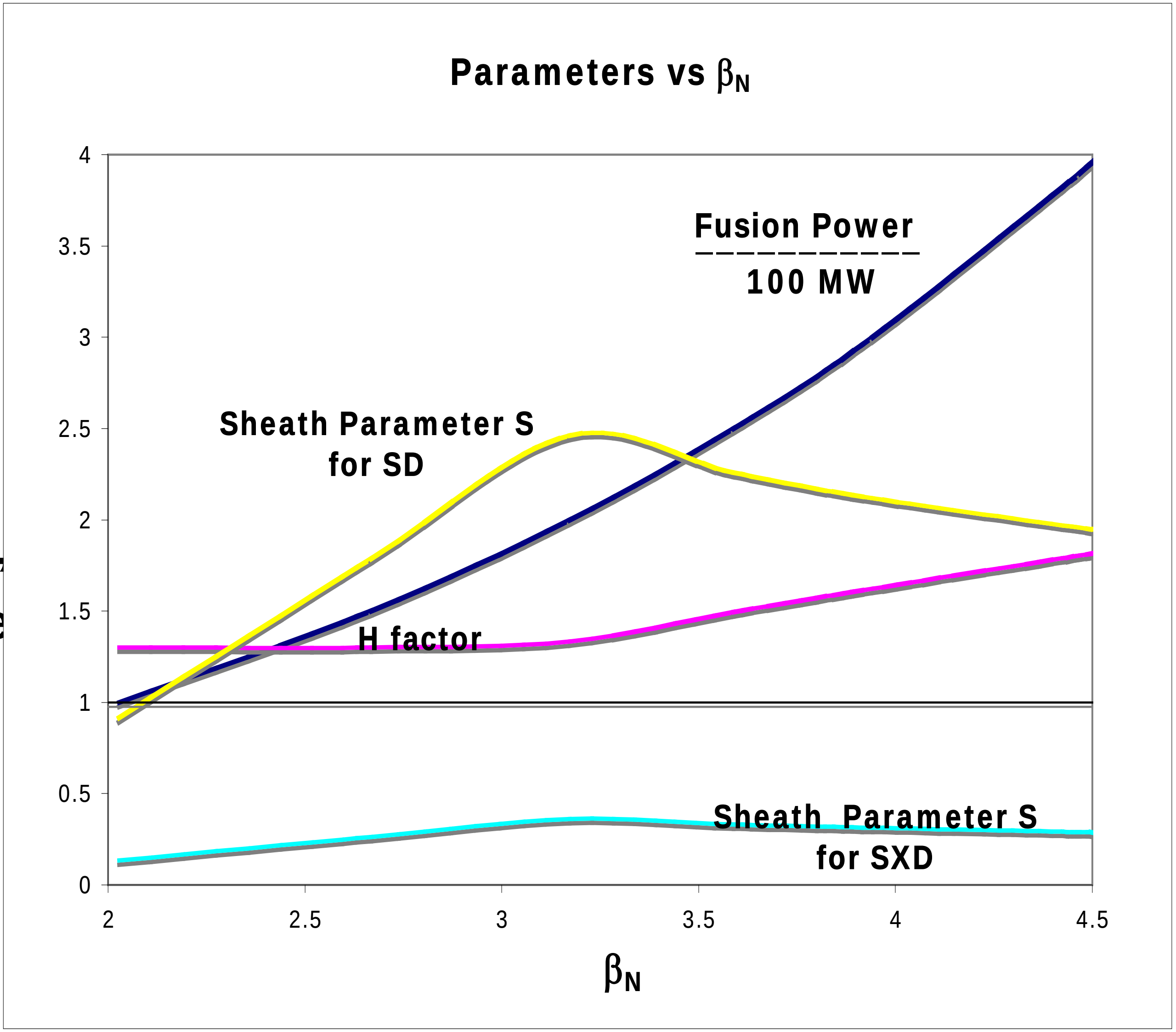
Only SXD has

S ~ 1/3 <<1

CFNS: SXD enables more advanced scenarios

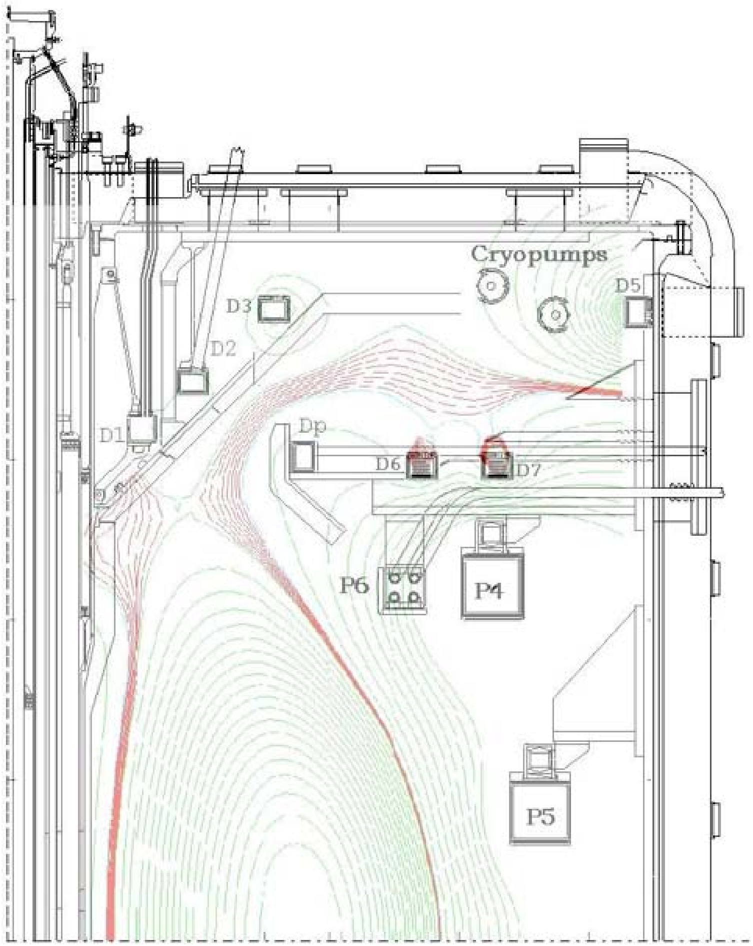
CD power= 50MW

- Only SXD has S<1
- 400 MW fusion at $\langle\beta_N\rangle \sim 4.5$
- Assume H = 1.3 attainable
  - More core radiation to "save" divertor if possible
- Advanced operation H ~ 1.5 enables
- ~ 300 MW fusion



SXD-from theory to experiment

- **Worldwide plans are in motion to test SXD**
  - MAST upgrade now includes SXD
  - NSTX: XD and future SXD?
  - DIII-D SXD test experiments, possibly next year
  - Long-pulse superconducting tokamak SST in India designing SXD
- **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)



SXD for MAST Upgrade