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Fusion for Neutrons: Spherical Tokamaks for the development of Fusion Energy

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Fusion for Neutrons: Spherical Tokamaks for the development of Fusion Energy

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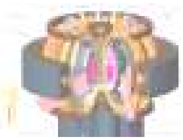
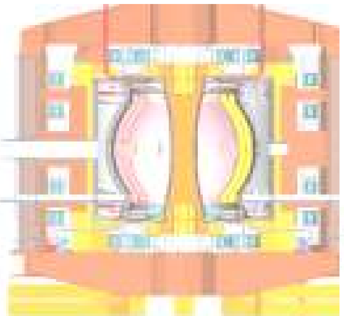
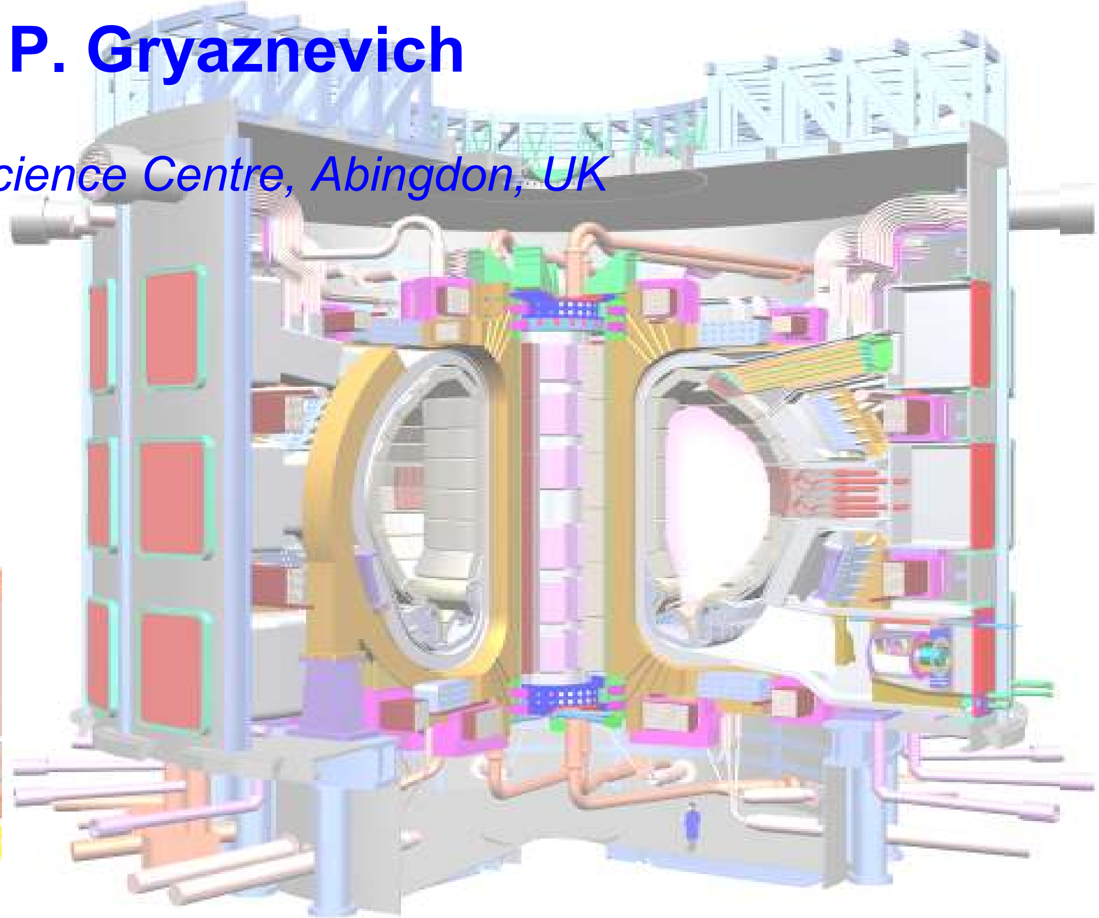






Fusion Reactor as an Advanced Neutron Source: F4N Concept

• High-output neutron sources (NS) are required in fundamental science and many of the modern special and innovative technologies, and by nuclear industry

• Due to the high cost and engineering problems fission reactor and accelerator Neutron Source (ADS) can hardly be expected to appreciably surpass 10^{18} n/s

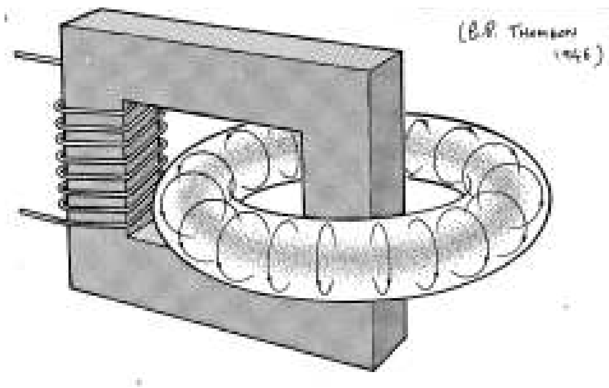
• In near term, **DT fusion** may become the most powerful NS. To date, tokamaks have already demonstrated 5×10^{18} n/s @ 14.1 MeV in DT reaction and 5×10^{16} n/s @ 2.5 MeV in DD reaction. Super Compact Spherical Tokamak Fusion Neutron Source can produce 10^{17}-10^{18}n/s in steady state to become a most intense Neutron Source today

History and Status of Neutron Sources

The Beginning of Fusion

The 1946 Thompson, Blackman patent for a Fusion Reactor

"..a powerful ***neutron source*** *…. Also a powerful source of heat"*



Based on a toroidal Pinch

Parameters were modest:

R / a = 1.3m / 0.3m, I_p = 0.5MA

classical confinement was assumed :

τ = 65s → T = 500keV

Hence D-D fusion would be achievable

(note: Patent includes option of Uranium or Thorium blanket – i.e. a hybrid!)

ZETA at Harwell, 1954-1968 :

R/a=1.5m / 0.48m, I_p = 0.1 – 0.9MA

Confinement was highly anomalous:

τ ~ 1ms → T~ 0.16keV

- Beginning of a long path to Fusion Energy!

F4E vs F4N

Many difficulties of Fusion for ENERGY:

Temperatures ~ few 10's keV needed to maximise D-T reaction

Large size → large cost, high running costs

Large stored energy → damage from disruptions, ELMs

High wall neutron & thermal load – new materials needed

Need to obtain at least **Q = 9** (Q = fusion power / input power), as efficiency of converting P_{fus} to electricity ~ 1/3, and efficiency of auxiliary heating systems also ~1/3.

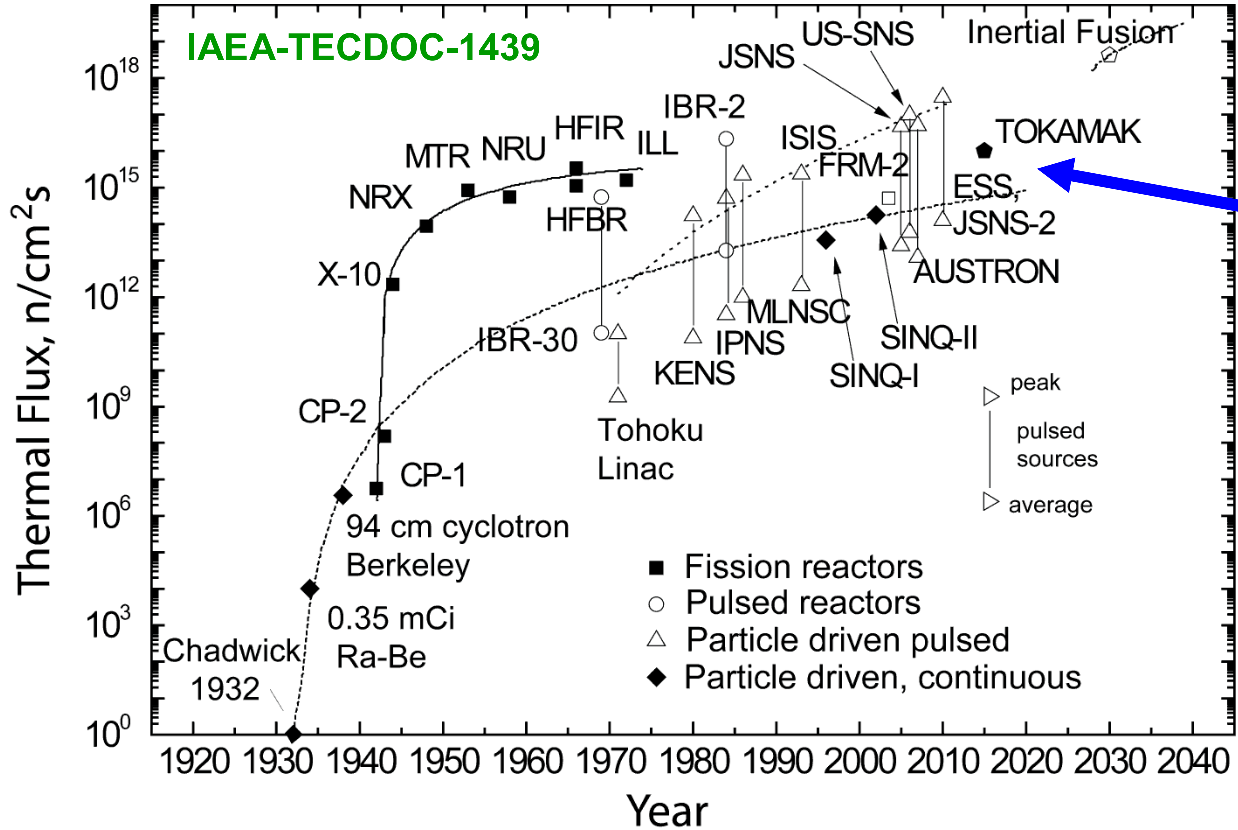
Fusion for NEUTRONS is easier!

- no need in high temperatures, high confinement, high Q
- feasible at very compact size, so low capital and running costs
- low heating power (cheap, available), low stored energy, so no trouble with disruptions, ELMs, neutron wall load, divertor load, alpha confinement

Neutron Sources

Q1: What neutron sources do you know?

Thermal neutron flux available at various neutron sources as a function of time since Chadwick's discovery of the neutron



Spherical Tokamak SCFNS

- Since 1970 reactor sources are close to saturation of the flux reached
- Spallation sources have overcome reactors in 90s, but flux growth is rather slow
- Tokamak FNS reaching 10^{20} n/s may become the leader

Fission & Fusion Neutron Sources

Fission reactor with heat power **3 GW** produces:

10^{20}	fissions per second
~3×10^{20}	prompt neutrons per second
10^{18}	delayed neutrons per second

French Institute Laue-Langevin 56 MW research reactor:

10^{18} useful neutrons per second…

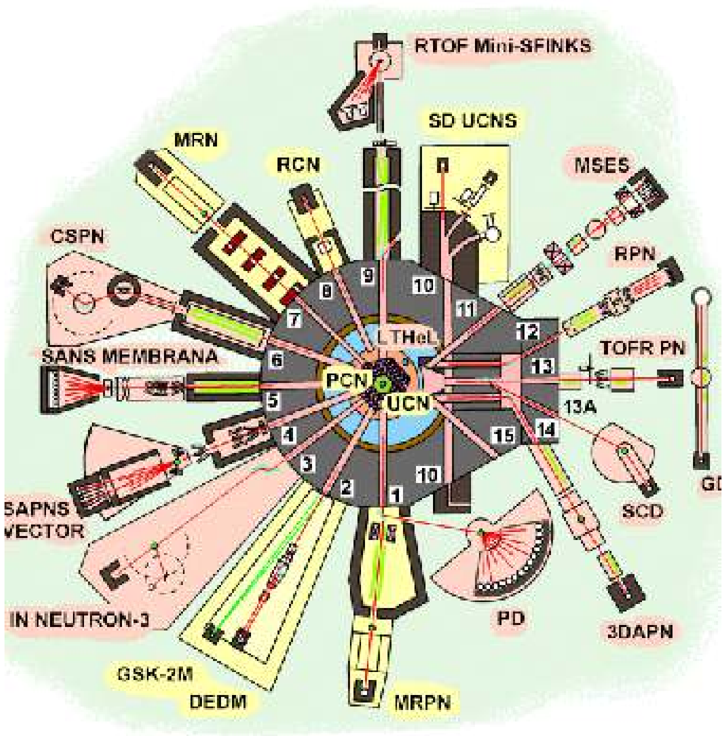
The NRU reactor at Chalk River Laboratories has operated since 1957

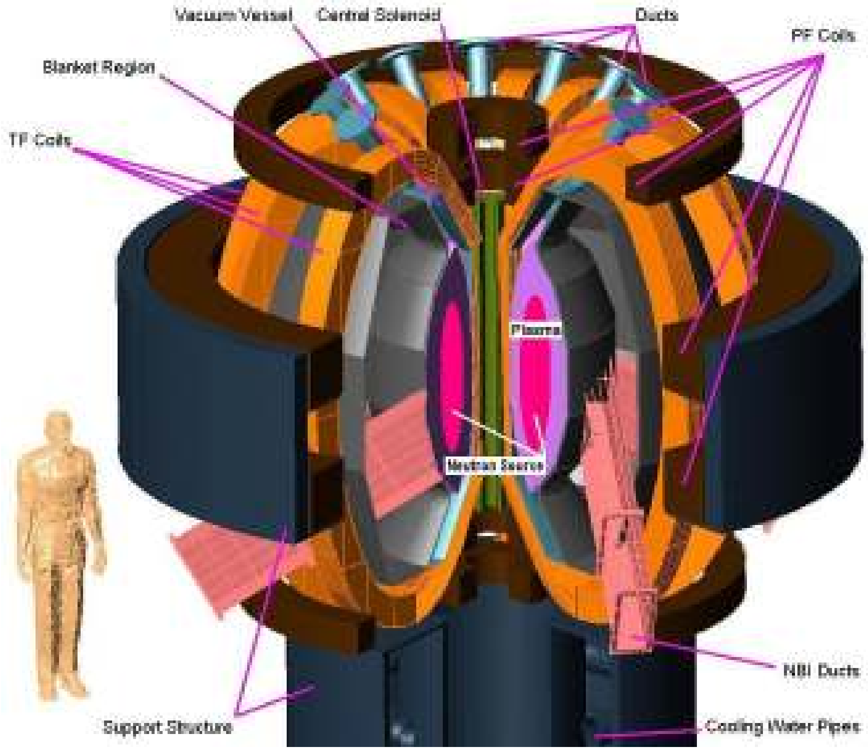
• NRU is the source of the majority of the world's supply of medical isotopes

The peak thermal flux in NRU, 3×10^{14} cm^{-2} sec^{-1}, remains one of the highest in the world.

3 MW of DT fusion produce 10^{18} useful neutrons per second

Fission & Fusion Neutron Sources





Most powerful neutron source based on nuclear reactor gives the same useful neutron production rate as a 3 MW fusion neutron source.

Q2: Why fission neutron source has limits?

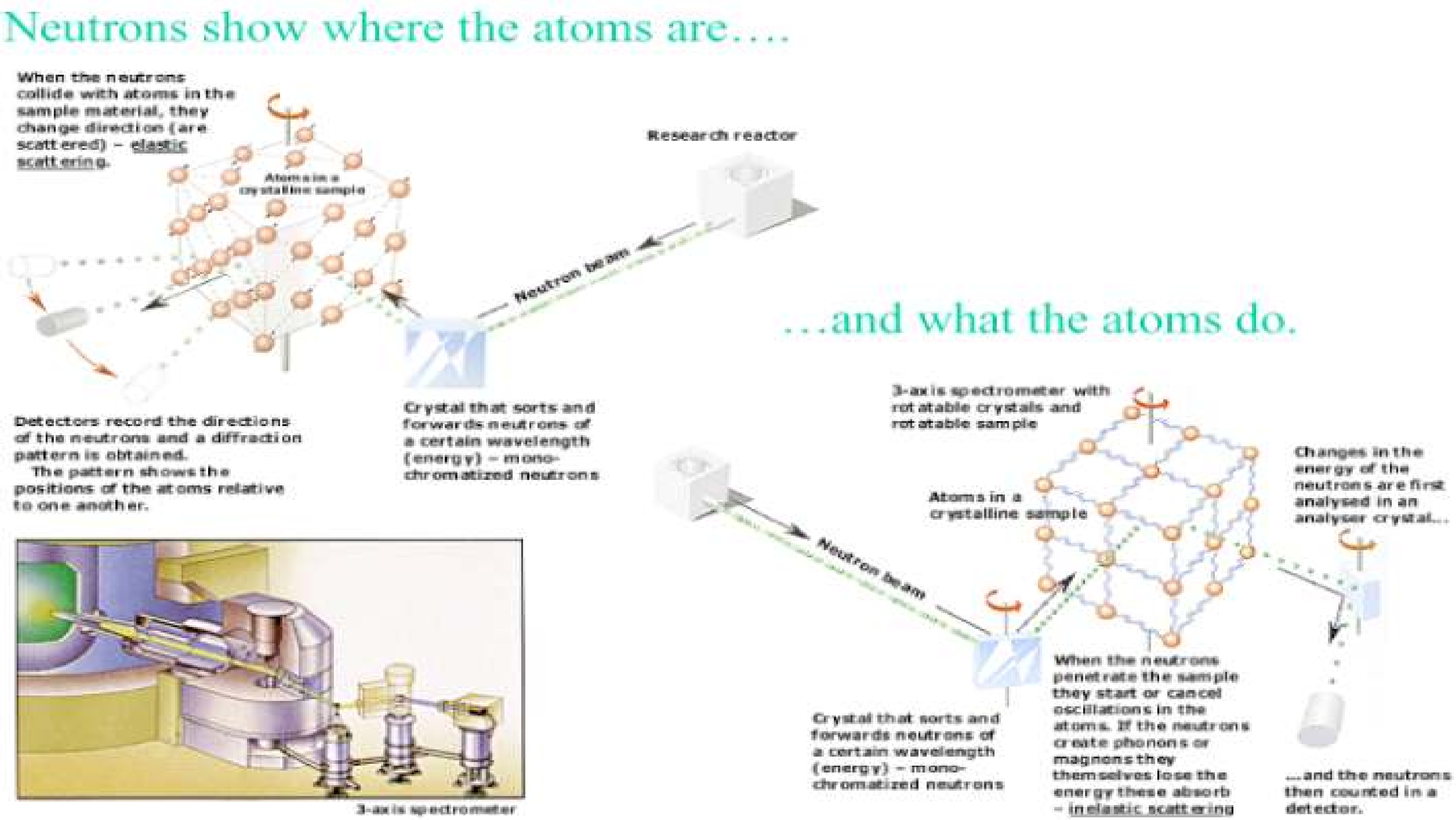
F4N

Most powerful neutron sources in the world (* - projects)

NS Type	Facility (location), used nuclides	Deposited Power, MW S/S (Peak)	Rate, 10^{17} n/s S/S (Peak)	Neutron Power Output, MW S/S (Peak)	Max. Neutron Flux Density, n/cm^2s
1. Fission reactors	ILL (Grenoble, France), U^{235}	56	10	1.5	10^{15}
	PIK (Gatchina, Russia), U^{235}	100	20	3	4.5×10^{15}
	IBR-2 (Dubna, Russia), Pu^{239}	2 (1500)	0.6 (500)	0.03 (25)	10^{16}
2. Accelerators	SNS (ORNL), p, Hg	1 (30000)	1 (30000)	0.3 (10000)	10^{16}
	LANSCE (LLNL), p, W, Pb, Bi	0.1 (10000)	0.1 (10000)	0.03 (3000)	10^{16}
	*IFMIF (being negotiated), D, Li	9	1	1	10^{15}
3. Tokamaks	JET (Abingdon, UK), D, T	0 (16)	0 (60)	0 (13)	10^{13}
	*JT-60SA (Naka, Japan), D	0.01 (0.5)	0.01 (2)	0 (0.4)	10^{11}
	*ITER (Cadarache, France), D, T	500	1800	400	4×10^{13}
	*SCFNS, D, T	2-3	6-10	2-3	10^{14}
4. Stellarators	LHD (Toki, Japan), D	20	*0.2	0.002	10^{10}
5. Muon catalysis	*LAMPF (LLNL), p, Hg, D, T	1	*1.8	1.4	10^{12}
6. Z-pinch	*Z (Albuquerque), D, T	30	(70)	24	10^{17}
7. Laser system	*LIFE (LLNL), D, T	1000	(2100)	800	10^{17}

What Neutron Sources can do?

The 1994 Nobel Prize in Physics – Shull & Brockhouse

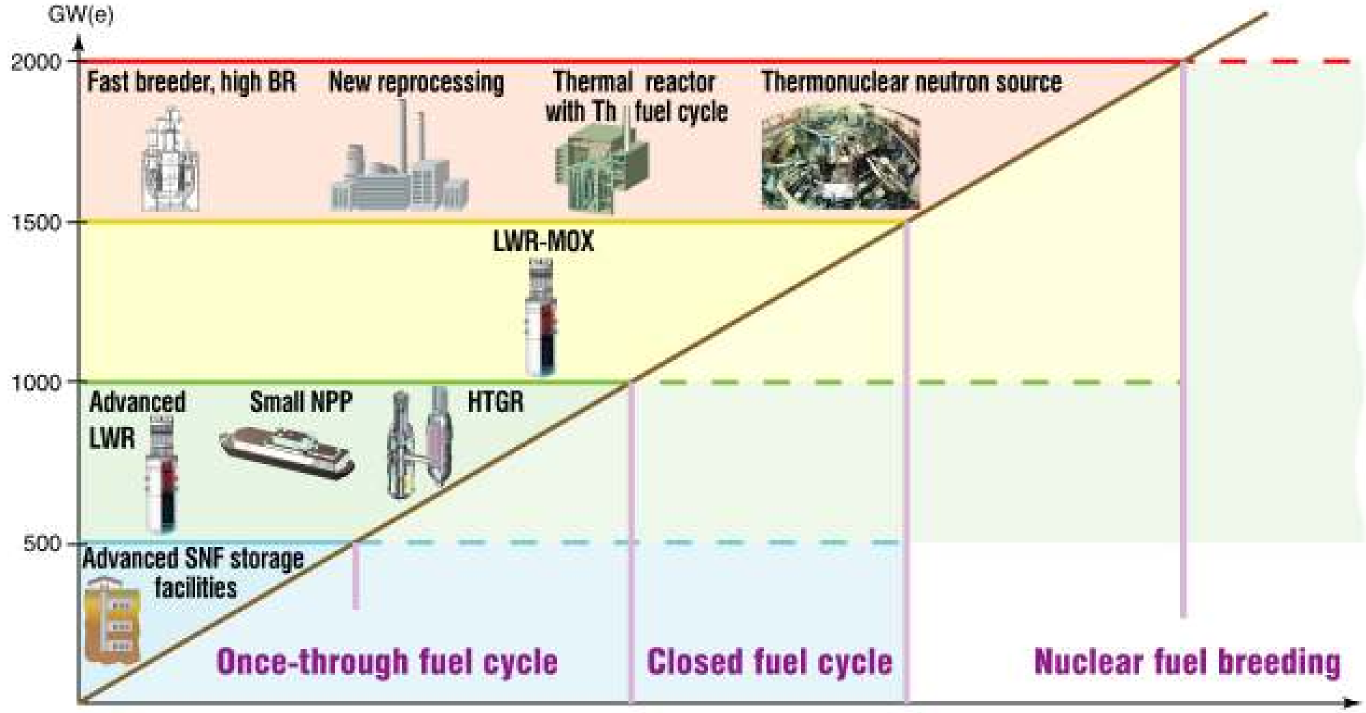


Neutron Source is a nice device to show where the atoms are…

… and also a nice device to show where you can get a **Nobel Prize!**

F4N

What Neutron Sources can do?



Supporting the high growth rate scenario of **Nuclear Industry** development:

- *Materials studies and development (e.g. for Fast Reactors)*
- *Nuclear fuel* ***breeding*** *and* ***waste handling***

- **Nuclear Energy needs Fusion neutrons**

Q3: What is the "greenest" energy source?

Q4: What is the safest energy source?

F4N for Nuclear Industry

• Fusion with 60 years of R&D is now ready to help in resolving main problems of Nuclear Power production: fuel, waste, proliferation

Combination of "fission + fusion" reactors becomes self-sufficient and environmentally clean, which dramatically improves both the safety and economics of nuclear energy production

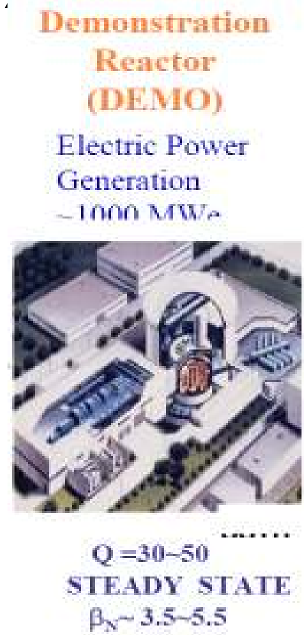
New Approach
"F4N"
"Fusion for Neutrons"

Fusion for Neutrons - F4N - new formula

- Renewal of interest to fusion neutrons
- Growing interest to steady state technologies urgently needed for applications of fusion neutrons
- Several concepts of fusion neutron facilities have been proposed (FDF, FNS, FDS, Fusion-fission hybrids)

*Fusion for energy – **“F4E”** has a threshold of power amplification **Q >> 9***

F4N has **no** efficiency limit, Q << 1 is also very useful and efficient



← **FNS domain** →

10^{-6} 10^{0} 10^{2} **Q**

Challenges for “Fusion for Neutrons”

Medical isotopes, materials, diagnostics	> **10^{15} n/s**
Transmutation	> **10^{18} n/s**
Fuel breeding	> **10^{20} n/s**

Compact tokamaks with a few MW fusion power may compete with contemporary neutron sources (fission reactors and spallation neutron sources)

Steady State Operations in neutron environment is the basic requirement for FNS

Options for Fusion Neutron Source

• Auxiliary heating, T consumption and magnetic systems set the cost of a demonstration experiment

• **Classical tokamaks R/a > 2.5:**

Running costs > $500 M/year-100%

- superconducting coils are possible for providing high TF ~6 T, but leads to high T consumption (big device size)

• **Spherical tokamaks R/a < 2.0:**

Capital cost as low as $50M
Running cost < $50 M/year-100%

- copper coils with water cooling are possible, only power dissipation (running costs) constrains TF in ST FNS

- stress limit (TF) favours the lowest aspect ratio

- high beta in ST ensures no physics limitations

- neutron balance of ST is optimal at R/a ~ 1.6

Q5: What is “Spherical Tokamak”?

Fusion Reactor as an Advanced Neutron Source

- Many proposals of **FNS** have been considered:

  - **conventional tokamaks:** FDF (Stambaugh); ITER-type (SABR Stacey, Rebut); FDS-1 (Wu); FEB (Feng)

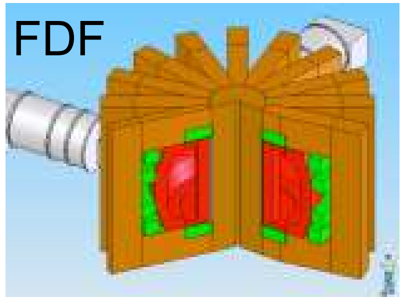
  - mainly considered as prototypes of fusion-fission hybrids

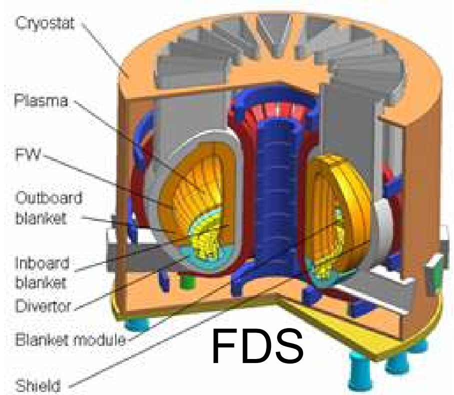
  - superconductive (big, expensive to build) or Cu (pulsed, high operating costs)

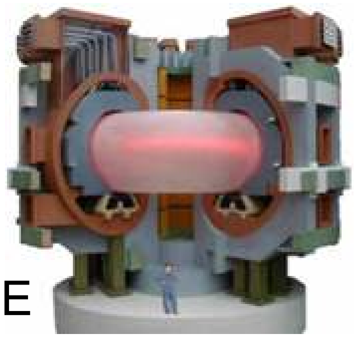
  - need to breed tritium

  - high divertor and wall load, high NB power

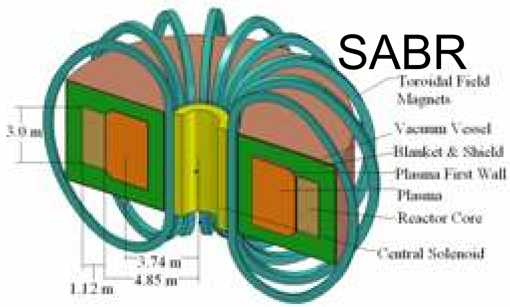
  - rely on ITER technologies







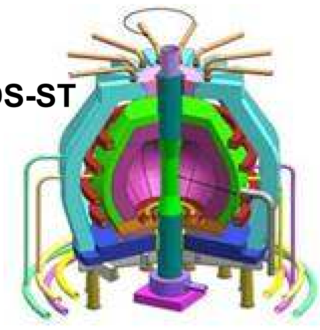
FEB-E



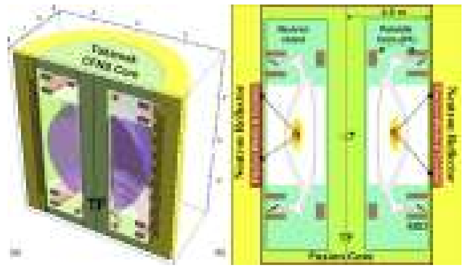
Spherical tokamak as an Advanced Neutron Source

- Many proposals of **ST FNS** have been considered with main parameters in the range:
  - R_0 ~ 0.7 – 2.9 m
  - R/a ~ 1.3 – 2.0
  - I_p ~ 5 – 18 MA
  - B_t ~ 1.5 – 6 T
  - P_{NB} ~ 30 – 130 MW
- As a hybrid fusion core, also as a **VHS, CTF**
- ARIES analysis (2000) considered **only** STs as FNS
- However, most of proposed devices have **serious unresolved issues**

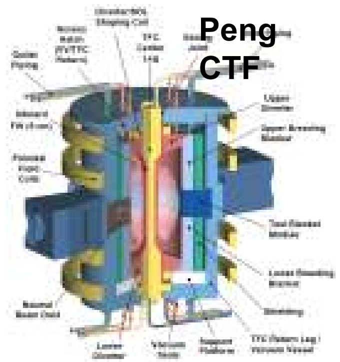
FDS-ST



Texas CFNS



Peng CTF



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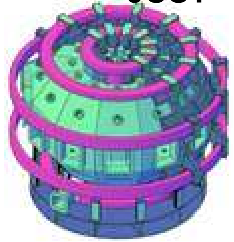
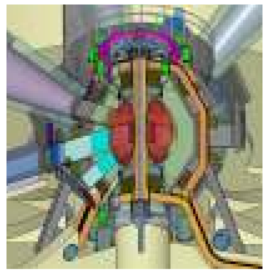




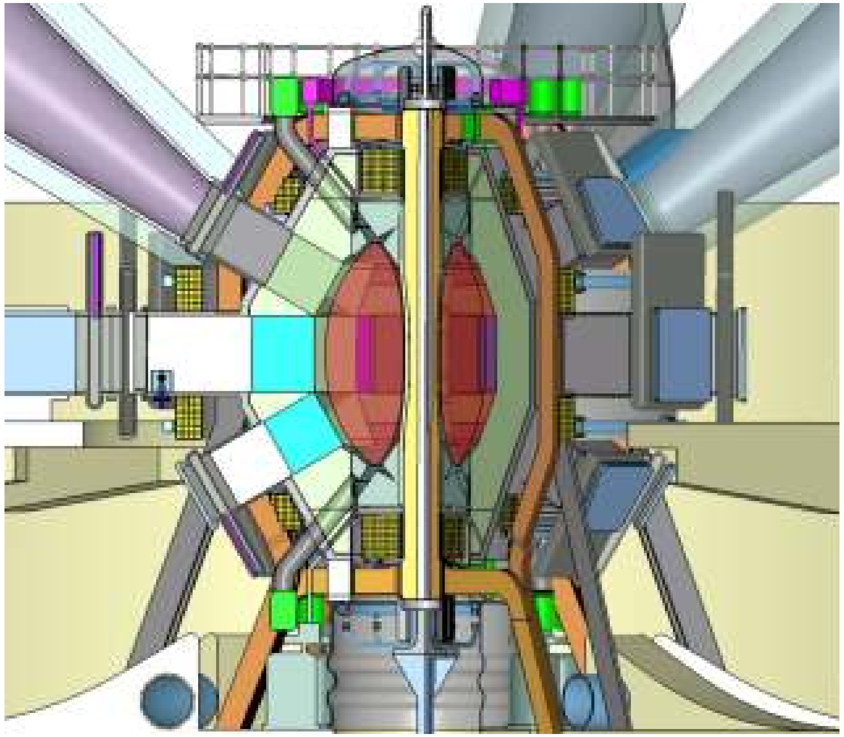
UKAEA CTF

F4N

Culham CTF design parameters

Parameter	ST-CTF
Major / minor radius	85/55cm
Elongation / triangularity	2.4/0.4
Plasma current/rod current	6.5/10.5MA
β_N	3.5
Average density	1.8×10^{20} m^{-3}
Average temperature	Te=6.5keV Ti=8keV
Confinement H98(y,2)	1.3
Auxiliary power	40MW
Fusion power (thermal + b-p)	35MW
Neutron wall loading	$1MWm^{-2}$
Power consumption	390 MW

G Voss, Nov. 2010

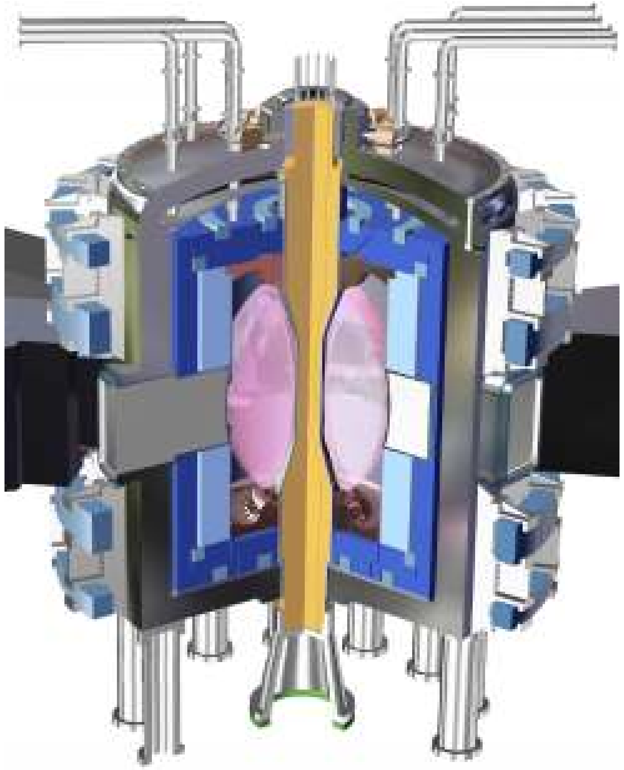


Tritium consumption ~ 0.6 kg/y

Features:

- *does not need to breed tritium*
- *retractable small solenoid for start-up*
- *2.5cm steel shield for c/col*
- *option for HTS PF coils*

FNSF-ST* (Peng, 2010)



Stage-Fuel	I-DD	II-DT	III-DT	IV-DT
Current, I_p (MA)	4.2	4.2	6.7	8.4
Plasma pressure (MPa)	0.16	0.16	0.43	0.70
W_L (MW/m^2)	0.005	0.25	1.0	2.0
Fusion gain Q	0.01	0.86	1.7	2.5
Fusion power (MW)	0.2	19	76	152
Tritium burn rate (g/yr)	0	≤105	≤420	≤840
Field, B_T (T)	2.7	2.7	2.9	3.6
Safety factor, q_{cyl}	6.0	6.0	4.1	4.1
Toroidal beta, β_T (%)	4.4	4.4	10.1	10.8
Normal beta, β_N	2.1	2.1	3.3	3.5
Avg density, n_e ($10^{20}/m^3$)	0.54	0.54	1.1	1.5
Avg ion T_i (keV)	7.7	7.6	10.2	11.8
Avg electron T_e (keV)	4.2	4.3	5.7	7.2
BS current fraction	0.45	0.47	0.50	0.53
NBI H&CD power (MW)	26	22	44	61
NBI energy to core (kV)	120	120	235	330

FNSF-ST R=1.3, a=0.75 vol ~ $42m^3$ S~$75m^2$ P_{NBI} = 26 MW P/vol ~ $0.6MW/m^3$ P/S ~ 0.3

SCFNS R=0.5 a=0.3 vol ~ $2.5m^3$ S~$12m^2$ P_{NBI} ~ 6 MW P/vol ~ $2.4MW/m^3$ P/S ~ 0.5

*Fusion Nuclear Science Facility *meetings.aps.org/Meeting/DPP10/Event/130935*

Cost estimates (2002 USD)

	Peng CTF (2002) R=1.2	SCFNS R=0.5	comment
Toroidal device	$190M	$15M	~ 1/15 volume
Ancillary systems (inc. remote handling)	$190M	$45M	
Gas, coolant	$90M	$20M	
Power supply, control	£120M	£30M	~ ¼ NBI, ¼ current
Heating, Current Drive	$210M	$20M	~ ¼ NBI, ¼ current
Site, facilities	$250	$70M	
TOTAL	**> $1.0B**	**< $200M**	

Super Compact ST FNS, New Approach

- **Constraints:**
  - Materials and heating systems **availability**
  - Capital and operating **costs**
  - Uncertainties in **physics** extrapolation to burning plasma

These issues were enough to delay realisation of the previous proposals

- **New concept:**
  - Low wall load
  - NBI power at the commercially available level
  - Low running costs
  - Rely on new (or well-forgotten) physics

Super Compact Fusion Neutron Source

Mission of Super Compact FNS

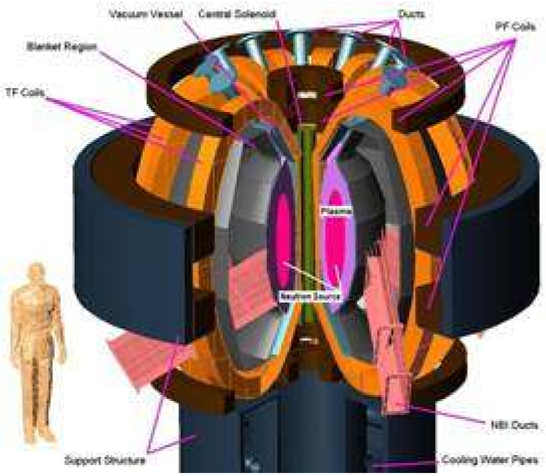
- To show feasibility and advantages of the ST concept as a powerful neutron source
- To demonstrate and use steady-state fully non-inductive regime
- To operate with tritium, contributing with this to the mainstream Fusion research in many areas (T handling, material/component testing, diagnostics, safety, remote handling etc.)
- To be the first demonstration of possibility for commercial application of Fusion today

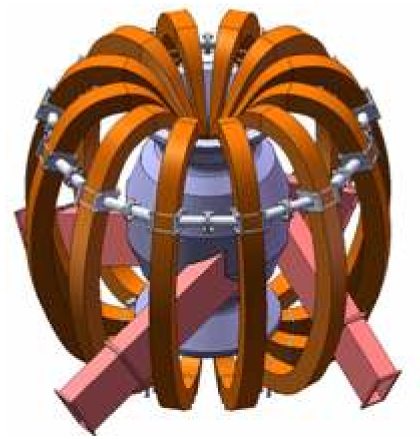
How the simplest SCFNS looks like?

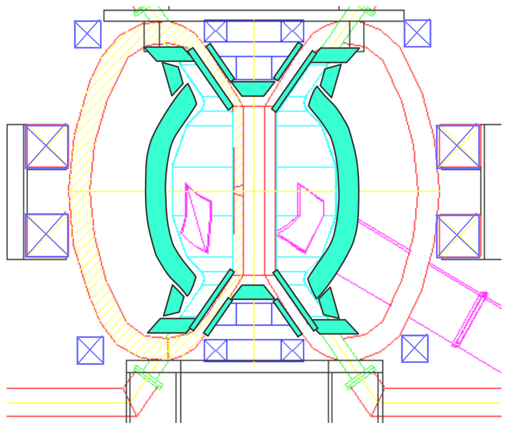
- Main **SCFNS** parameters, mainly interpolation:

R/a = 0.5m/0.3m, k = 2.75, I_{pl}=1.5MA, B_t=1.5T, P_{NBI} ~5-10MW, E_{NBI} ~100-130keV

- **Size:** between START and MAST. Same as QUEST, Pegasus
- Elongation: NSTX/MAST-U
- **Plasma current**: NSTX/MAST-U level. Three times higher toroidal field
- NSTX/MAST-U **heating power**, but up to two times higher beam energy







Comparison with present STs and Proposals

	MAST/ MAST-U UK	NSTX/ NSTX-U US	Globus-M/ Globus-MU RF	QUEST Jap	KTM Kaz.	SCFNS TSUK
R, m	0.8	0.85/0.93	0.36/0.6	0.68	1.0	**0.5**
R/a	1.4	1.4/1.5	1.5	1.7	2.0	**1.6**
k	2.7/2.75	3.0	1.6/2.5	2.5	2	**2.7**
I_p, MA	1.4/2	1.5/2	0.35/0.5	0.3	0.5	**1-2**
B_t, T	0.6/0.8	0.5/1.0	0.5/1.0	0.25	1	**1.5**
P_{NB}, MW	4/10	7/10	1.5	-	-	**5-10**
t_{pulse}, s	0.8/5.0	1.8/5.0	0.5	s/s	0.5	**s/s**

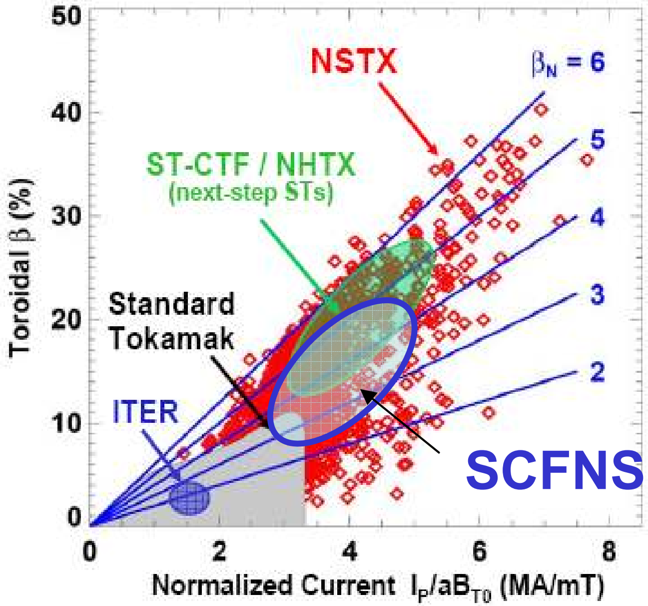
Operating devices and upgrades

Next-step proposals

	R, m	B_T, T	I_p, MA	P_{aux}, MW
CTF UKAEA	0.8	2.5	6	30
CTF US	1.2	1.1-6	3.4-10	15-43
STEP	1.2	3.5	5	10-40
JUST	2	3.9	5.3	45
VNS UKAEA*	0.57	1.5	6	25
ST Pilot Plant GA*	0.47	4.4-9.6	10-14	50
SCFNS	0.5	1.5	1-2	5-10

*Smallest version

Comparison with present STs and Proposals

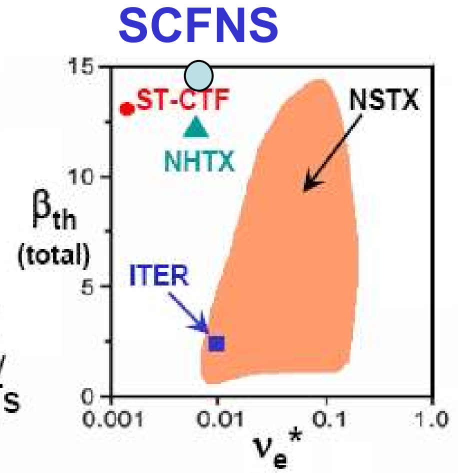


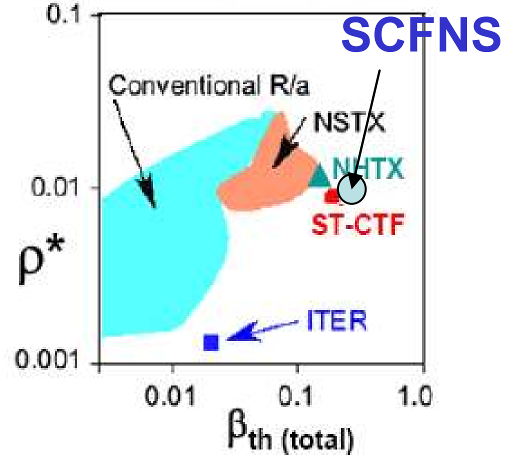
- ST accesses higher normalized current & higher normalized β

➡ higher $\beta_{Toroidal}$

(High β_N results in part from rotational stabilization of resistive wall mode)

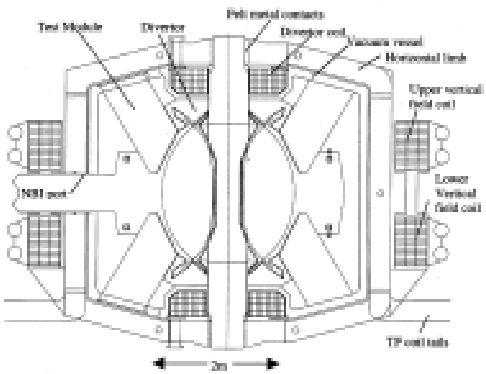
- Access ITER-level ν*, extending confinement understanding to high β
- Next-step STs expected to operate at significantly lower ν* than present STs
- ST operates at higher ρ* than tokamaks / ITER - impacts thermal and fast-ion transport, MHD
- Extrapolation in ρ* from present STs to next-step STs is small

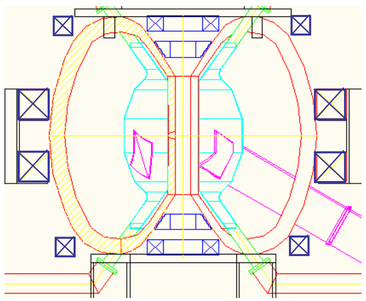




Other Super Compact designs

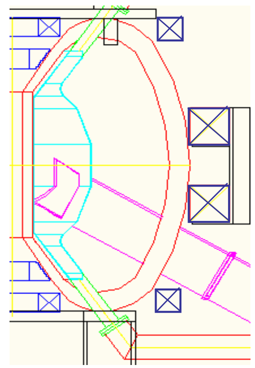
• We analyse two ST FNS designs closest in size (R < 0.6 m) and compare them with SCFNS





UKAEA VNS, *T C Hender et al, FED 45 (1999)*

R = 0.57 m, B_t= 1.5 T, I_p= 6.8 MA, k = 2.3, P_{NB}= 25 MW

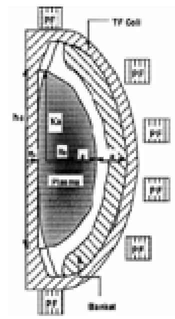


GA ST Pilot Plant,

R Stambaugh et al, FT 33 (1998)

R = 0.47 m, B_t= 9.6 T, I_p= 14 MA,

k = 3.0, P_{NB}= 50 MW



UKAEA VNS

- **Motivation for compact design and main issues:**

- neutron shielding of central post increases the size, which results in unacceptable high T consumption

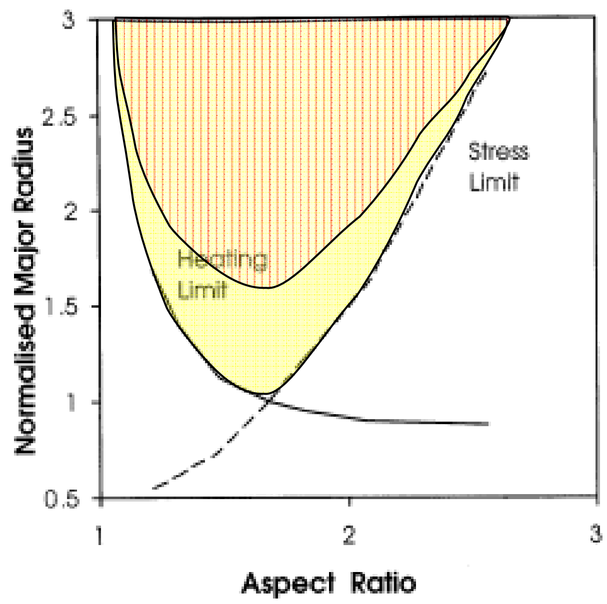
- unshielded central post constrained by heating limit (dissipation in TF magnet) and stress limit

- stress limit favours low R/a, low R

- limit on β_N => low R/a, but:

- requested fluence of 6 MWa/m^2 resulted in very high H-factor, which required an increase in size to R = 0.8m

- prompt α-losses favour high I_p, bigger size



Normalised (on R=0.57m) device size as a function of aspect ratio at fixed neutron wall load, β_N and q_c =3

Hender et al, FED 45 1999

UKAEA VNS vs SC FNS

	SCFNS	UKAEA VNS	SCFNS vs UKAEA VNS
R, m	0.5	0.57	similar
R/a	1.66	1.6	similar
k	2.75-3	2.3	higher bootstrap, longer NB path
I_p, MA	1 – 2	6.8	less, no α confinement
B_t, T	1.5	2.5	less stress, dissipation
P_{wall}, MW/m^2	0.1 – 0.3	1.5	acceptable wall load
P_{NBI}, MW	5 – 10	25	realistic supply availability
H-factor	1.2 – 1.4	> 2	confirmed on MAST, NSTX
β_N	4.3	4.4	similar, below limit
$P_{diss, TF}$, MW	10	30	much less
$P_{diss, PF}$, MW	5	45	much less

SCFNS is much more realistic, cheaper in capital and running costs, and still produces multi-MW neutron rates

UKAEA VNS vs SC FNS

- Main issues of R=0.57 m UKAEA VNS resolved in SCFNS:

  - reduction of fusion power from 25MW to 1-3MW results in acceptable neutron wall load

  - reduction in heating power results in less thermal wall and divertor loads

  - higher availability as no need to replace central rod, divertor targets and induction coils

UKAEA VNS vs SC FNS

• Main issues of R=0.57 m UKAEA VNS resolved in SCFNS:

- no need in increased confinement and so device size as most neutrons are from beam-plasma DT reaction, so much lower confinement is needed, H-factor ~ 1.4 is sufficient

- lower I_p, so much less dissipation in PF coils, much less NBI power for CD, contribution from optimised NB launch

- α-particles lost on 1st orbit, so no ash, no danger from fast particles MHD

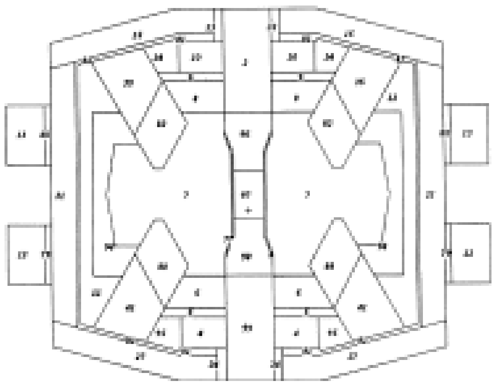
UKAEA VNS studies support SCFNS design

• Similarity of UKAEA VNS and SCFNS allows using many results of VNS studies for SCFNS

• Feasibility studies of UKAEA VNS provide optimistic feasibility predictions for SCFNS:

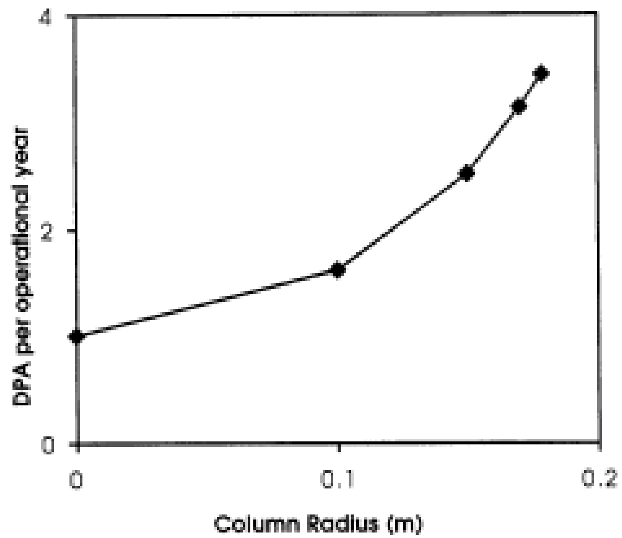
- stress analysis of VNS with NASTRAN code shows stress levels within ASME III allowable values, even lower for SCFNS

- MCNP neutrotics analysis suggest VNS magnets will survive for several years, much longer for SCFNS



MNCP model

DPA in VNS TF centre column for 1 operational year (0.44 full power years) at fusion power of 25 MW - x0.1 for SCFNS



General Atomics ST Pilot Plant

• Motivation for compact GA ST confirms feasibility of ST path to commercial application as an FNS:

- ST approach can progress from Pilot Plant to Power Plant just by doubling or tripling the linear dimensions of the device with no changes in technology

- ST approach has the two key features of an executable commercialization strategy: - a low-cost pilot plant that can attract commercial cost sharing at an affordable level and with minimal financial risks; - and a strong economy of scale leading to compact Power Plants

- The fact that a viable concept for a Pilot Plant exists is the principal attraction to government of the compact ST approach to commercial transition.

GA ST Pilot Plant

• Aggressive design suggests doubled heating limit compared with UKAEA VNS, so higher TF at smaller size

• An increase in elongation from 2 to 3 allows a factor of 2 saving in the plasma size

• This GA design shows device only constrained by heat and stress limits and the aggressive wall load of $8MW/m^2$

• Only beta limit, not confinement, determines performance:

"High beta potential of the ST is so great that the physics of this device will not determine its size".

• Recently found favourable dependence of confinement on B_t confirms this optimistic assessment of Stambaugh.

GA Pilot Plant vs SC FNS

	SCFNS	GA Pilot Plant	SCFNS vs GA Pilot Plant
R, m	0.5	0.47	similar
R/a	1.66	1.4	higher
k	2.75-3	3	same
I_p, MA	1 – 2	14	much less
B_t, T	1.5	4.4	less stress, less dissipation
P_{wall}, MW/m^2	0.1 – 0.3	8	acceptable wall load
β_N	4.3	6.9	lower, below limit
$P_{diss,\ TF}$, MW	10	63	much less

- The proposed GA ST Pilot Plant is not a CTF or FNS, but a prototype of an ST Power Plant for energy

- SCFNS is much more realistic, cheaper in capital and running costs than GA Pilot Plant, and still produces multi-MW neutron rates

Advantages of Super Compact STs as a Steady-state FNS

- Some of the big issues of large high-power and higher aspect ratio devices are resolved in SCFNS :
  - disruptions (much lower I_p than required for bigger device)
  - ELMs – low total energy in ELMs in SCFNS
  - high beta in STs – no AEs, less EPMs
  - low T consumption in SCFNS, no need to breed
  - small size – less problems with plasma formation
  - small size, high elongation – less CD requirements for SSO

Known fusion physics & technologies show feasibility of Super Contact FNS with R as low as 0.5m

Q6: When we will have Fusion as an energy source?

Q7: When we will have Fusion as a Neutron Source?

Super Compact Fusion Neutron Source (F4N) Concept is based on the latest developments in Fusion and Nuclear Physics & Technologies

Design principles

- Goals/features
  - ST more efficient user of neutrons than large R/a - little absorption in centre column
  - Minimum size (low cost, low T consumption)
  - “Conventional” physics - minimise risk
  - Strongly driven, Q</~1 (minimise uncertainty)
  - Simple design (availability, maintainability)
  - Use ITER technology where possible
- Freedom (within reason)
  - Low running costs and power consumption
  - Minimum/no long-live waste, low activation
  - Variable output power, and, possibly, neutron energy
  - Level of T breeding (default is no breeding)
  - Long component lifetime (but, availability)

How will we build the SCFNS?

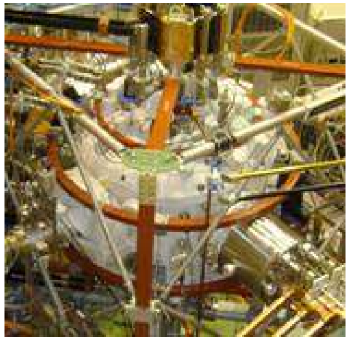
• The engineering is now standard practice in fusion laboratories and with their component suppliers, but now needs to be brought to commercial levels of reliability, safety, cost and volume.

• 20 prototypes of the CFR, which is based on the novel spherical tokamak design, are currently operational.

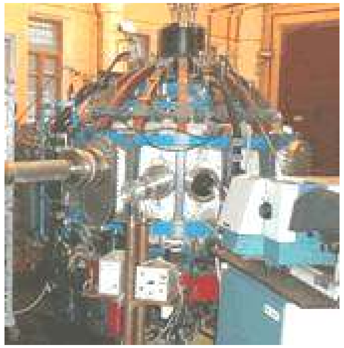
• The construction venture will work with the current best suppliers and industries from several countries, including Hitachi, Toshiba, Mitsubishi, Fuji (Japan), Northern Plant, Efremov (Russia), Princeton (US), Culham (UK).

How will we build the SCFNS?

• 20 Spherical Tokamaks built in last 15 years by leading Nuclear and Fusion Industries



CPD, TOSHIBA, Japan, 2005



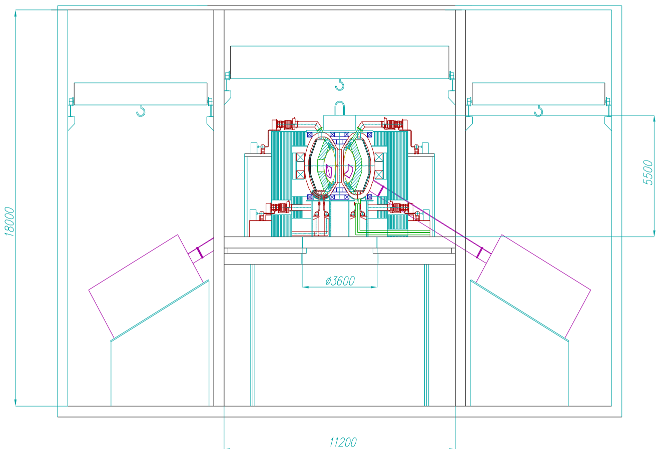
Globus-M, North Plant, Russia, 2000

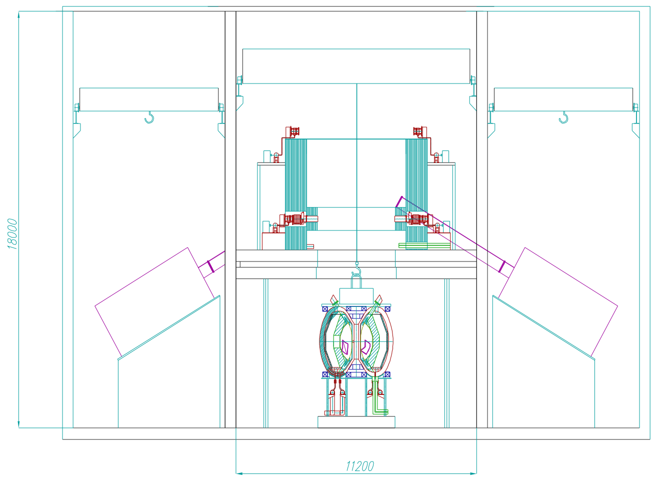
UTST, Fuji, Japan, 2008

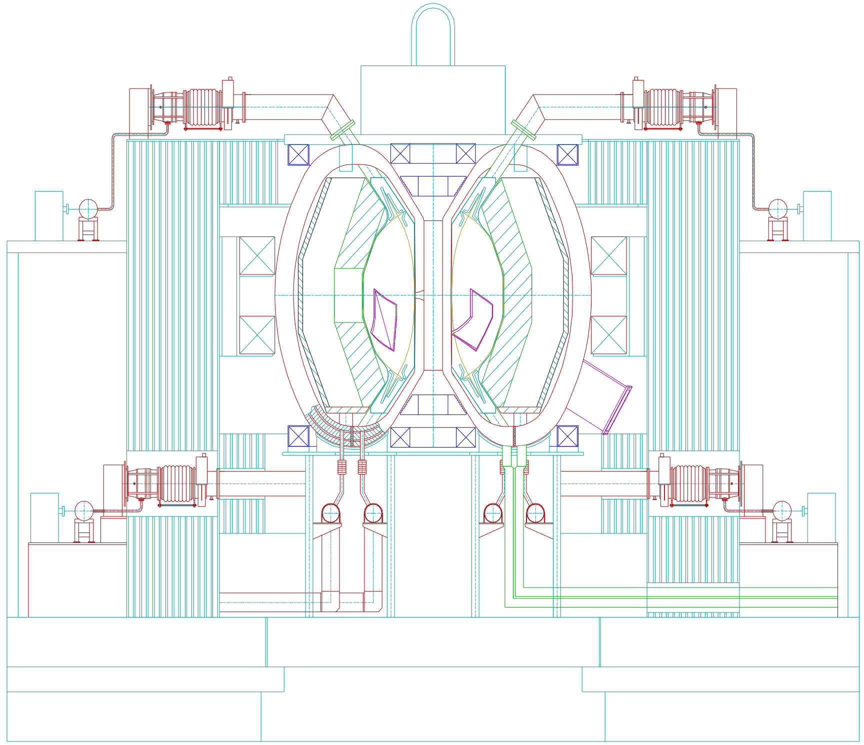
QUEST, TOSHIBA, Japan, 2008

KTM, Efremov Institute, Russia, 2007

How will we build the SCFNS?







Both VV and TFC are changed after reaching the fluence limit or in a case of accident

Changing the vacuum vessel and TF coils

Physics of Compact Fusion Reactor as a Powerful Neutron Source

SSO vs Advanced Inductive

- **SSO** is not required in FNS, but may be more economical

  *- however, **SSO** requires good confinement, neutron output does not*
  *- Optimal NBI Energy for **SSO** is lower than the optimum for beam-plasma fusion*

- Optimisation is needed to reduce fluence cost:

  - NBI energy, power and launch geometry
  - availability more important than pulse duration
  - AI scenario gives better opportunity for optimisation – easier to optimise for neutron production

- A I scenario may be simpler and gives more flexibility, but will force increase in device size (central solenoid shielding)

  - coming back to earlier ST FNS proposals…

Confinement vs Neutrons

- In compact devices beam-plasma dominates over thermal D-T

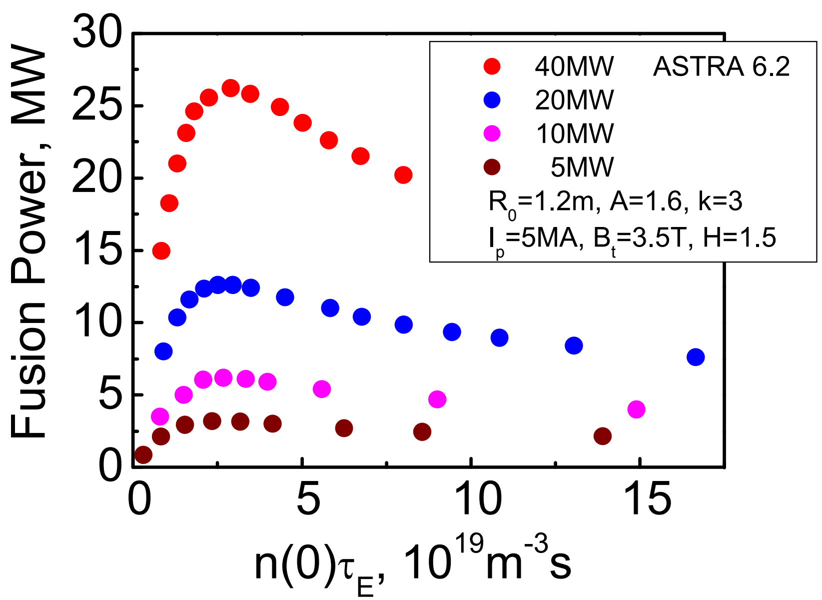
  - also important for large devices: 50/50 predicted for JET DT 2015

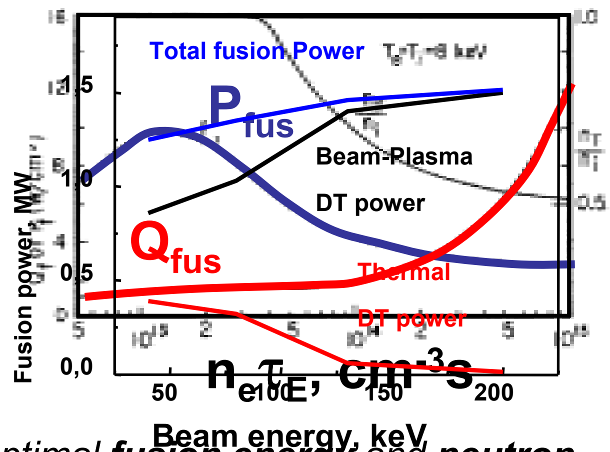
- This changes requirements for confinement:

  - satisfy CD requirements (high confinement)

  - form good target for beam-plasma interaction (moderate confinement)

… and requirements for beam energy and launch geometry





*Optimal **fusion energy** and **neutron** production are realized at different plasma conditions,* ***D Jassby, Nucl. Fus., 15 (1975)***

Increase of beam-DT power with beam energy, SCFNS

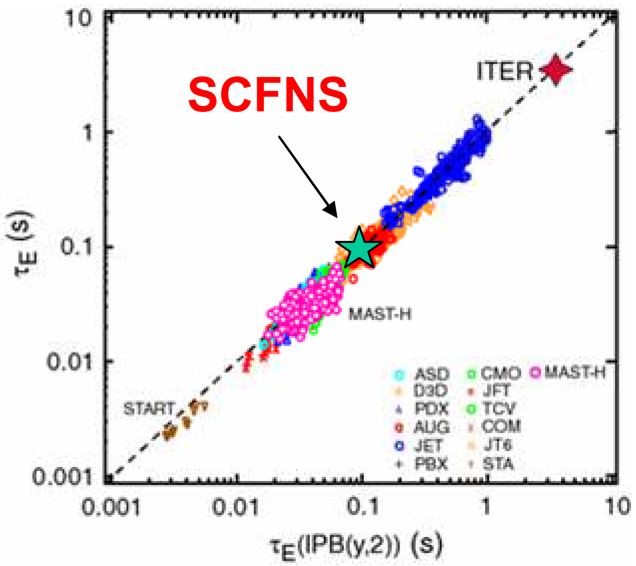
Confinement in SCFNS

- Good confinement opens promising opportunities for STs:

  - ITER IPB(y,2) indicates confinement

$$\tau_E \sim B_T^{0.15}\, I_p^{0.93}\, R^{1.97}\, n^{0.4}\, k^{0.78}$$

	B_t, T	I_p, MA	R, m	$n_e e^{19} m^{-3}$	k	tot
MAST/NSTX	0.45	0.7	0.8	4	2.2	
SCFNS	1.5	2	0.5	20	3.0	
τ gain	x1.2	x2	x0.4	x1.9	x1.27	**x2.3**



- Is this scaling valid for STs?

  - *MAST-NSTX scaling suggests x5.5 gain*

M Valovic scaling, *Nucl. Fusion, **49** 2000:*

$$\tau_E = 0.252\, B_t^{1.4}\, I_p^{0.59}\, R^{1.97}\, (a/R)^{0.58}\, M^{0.19}\, n_e^{0.00}\, k^{0.78}\, P_{in}^{-0.73}$$

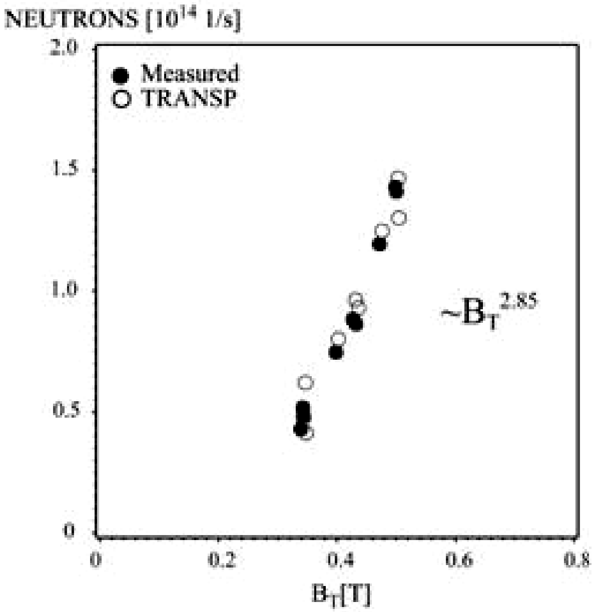
Confinement vs Neutrons

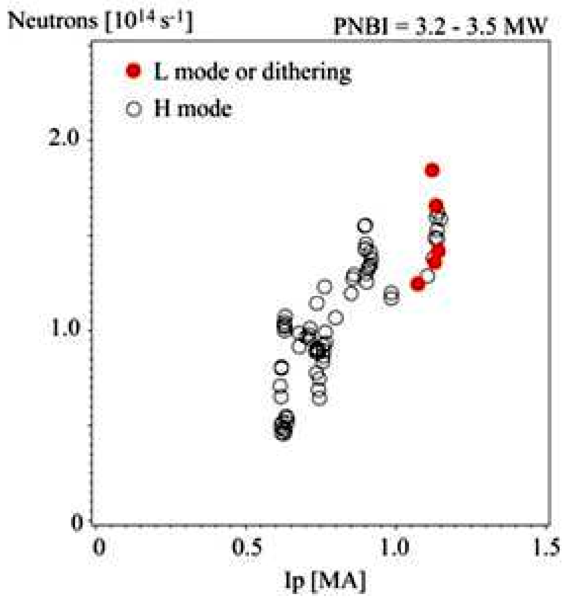
• Physics of new concept requires re-assessment of confinement requirements:

- *increase in neutron rate with* ***TF*** *on MAST*
- *but* ***L-mode*** *may give more neutrons*

• Confinement should be optimised for neutron production

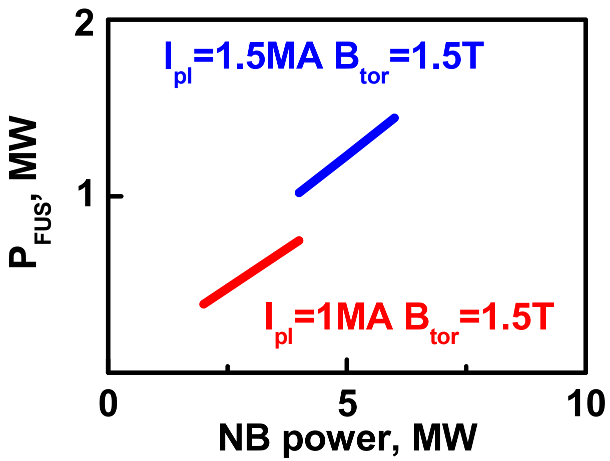
- *increase in P_{fus} with TF and reduction at increased $n_e \tau_E$*



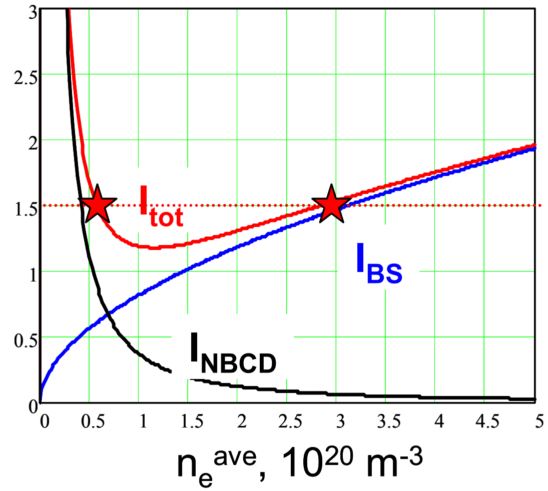


Steady-state Operations of SCFNS

• ASTRA-NUBEAM modelling confirms feasibility of SSO
• Steady-state conditions can be obtained at a wide range of density, while producing a MW-level of fusion output:



Fusion output *in the SCFNS vs injected power at 130keV with D/T 50/50 mixture in steady-state for plasma current 1 MA (red) and 1.5 MA (blue),* n_e^{ave}*=* $10^{20}m^{-3}$

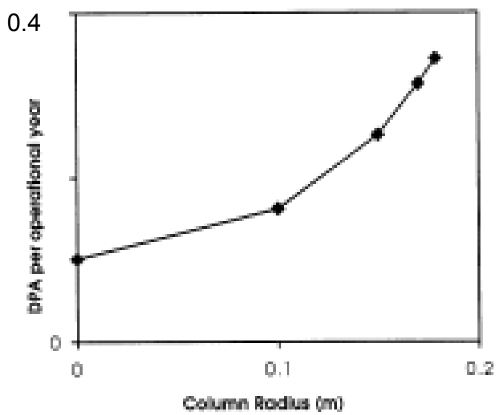


Density dependence of ***NBCD, bootstrap*** *current and total non-inductive current for* P_{NB} *= 6 MW, 130keV and H-factor H = 1.4. Stars show two possible operating points.*

More constraints for SSO

• Power load, both neutron and thermal, on the vessel wall and divertor:

- wall area in SCFNS is ~ 10 m², => low P_n^{wall}< 0.25 MW/m²



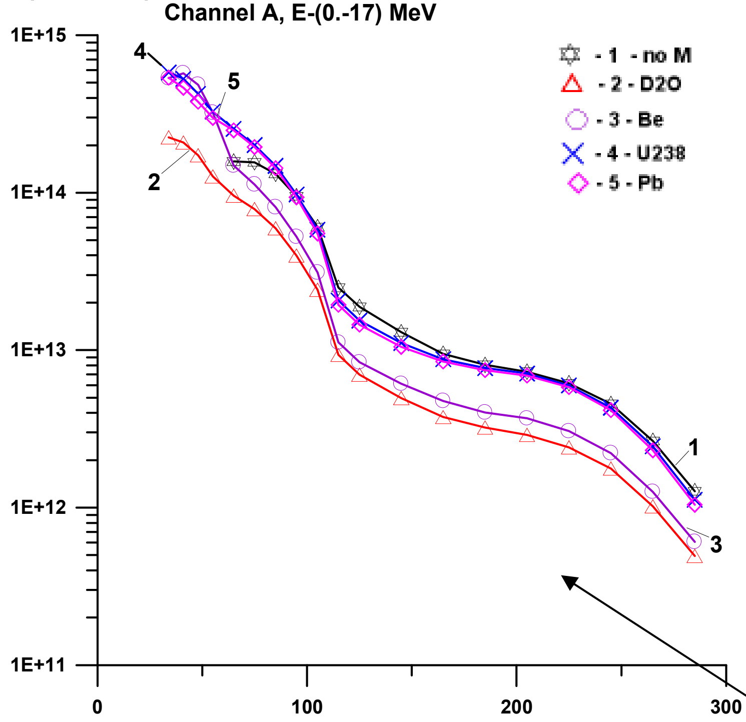
DPA in the SCFNS central post for 1 ops year (44% availability) at P_{fus}=2.5MW

• Engineering (stress, heat, neutron damage etc.) does not obstruct reduction in the size of FNS to as low as 0.5m

• P_{th}^{wall} ~ 1 MW/m² is within the ITER range, ANSYS analysis has shown that removal of the heat with water cooling should not by a problem. Similar analysis shows feasibility of the divertor.

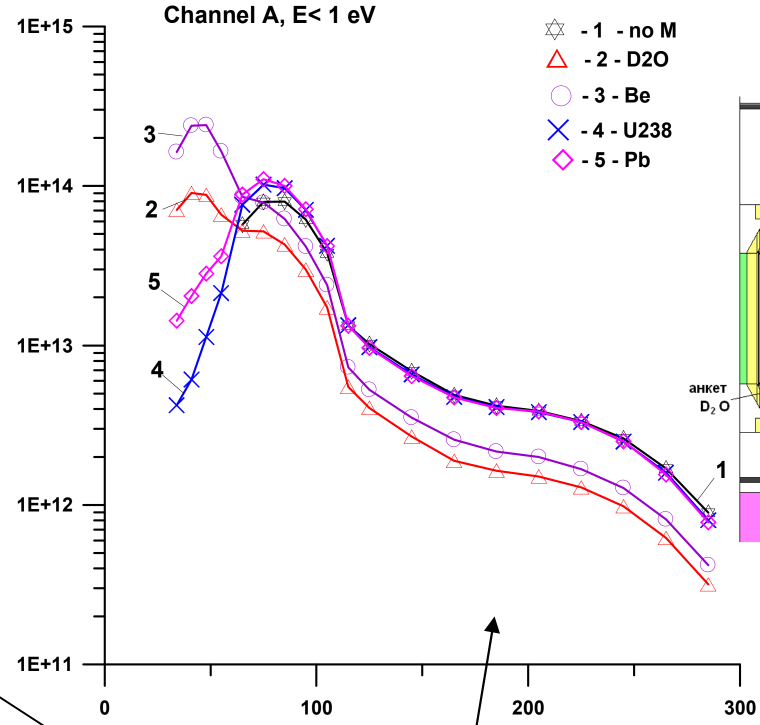
How much neutrons will be produced?

n/(cm²s)



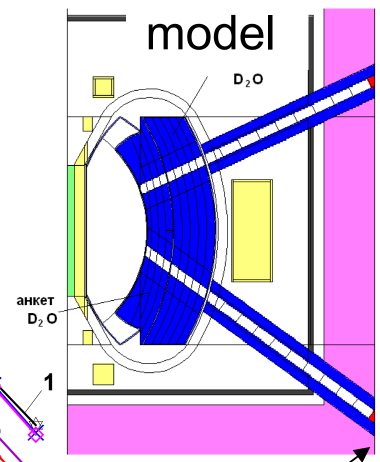
cm

n/(cm²s)



cm

MCNP model



Maximum total neutron flux	~ $5 \cdot 10^{14}$ n/(cm²s)
Cold neutrons -	~ $2 \cdot 10^{14}$ n/(cm²s)
Beyond shielding	~ $1 \cdot 10^{12}$ n/(cm²s)

Source strength 10^{18} n/s (3 MW) provides thermal neutron flux 5 10^{14} n/cm²s

F4N

CONCLUSIONS

- **High-output Neutron Sources** are required in fundamental science and commercial applications, including isotope production and nuclear industry

- In near term, **DT fusion** may become the most powerful **NS**

- **FNS** with Mega-Watt rates *(10^{17-18}n/s)* will have strong influence on the global energy production strategy as well as on the development of fusion & nuclear science and technologies

- **Compact ST** may become the most efficient and feasible Fusion Neutron Source

CONCLUSIONS

• Development of a **steady-state** reliable Neutron Source in the **nearest task for Fusion**

• **The ST path** to commercial application of Fusion can start from a **Compact ST** with R as low as 0.5 m and NBP 5-10 MW

"It seems important to have an achievable goal in the not too distant future in order to encourage the large goal, in this case pure fusion" ***H Bethe, Physics Today 1979***