NATIONAL RESEARCH CENTRE
KURCHATOV INSTITUTE

НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ
ЦЕНТР «КУРЧАТОВСКИЙ ИНСТИТУТ»

Kurchatov Complex for Fusion Energy &Plasma Technologies

Fusion-Fission Hybrids

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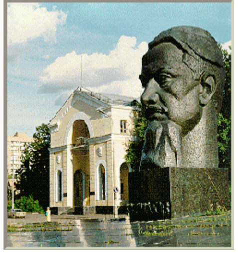
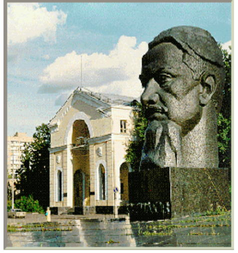
Thanks to DEMO-FNS design team

B.Kuteev, 31 October 2023, IAEA meeting, Vienna, Austria



The status of the problem of materials of hybrid systems

- Modern nuclear power industry faces serious fuel problems
  The problems of the nuclear fuel cycle are particularly significant for ensuring its growth rates
- They are based on: the shortage of free neutrons in fission and fusion reactors, as well as the unexplored behavior of materials in the energy spectrum of 14 MeV neutrons in the reaction of heavy isotopes of hydrogen D+T -> He+n +17.05 MeV
- Neutrons free for the production of fuel nuclides are few in number
- Atomic reactors on thermal neutrons n+U235 -> Fission products +2.1n + 200 MeV
  -0.5n
- Atomic reactors on fast neutrons n+Pu239 -> Fission products +3.0n + 200 MeV
  +0.2n
- Fusion reactors d+t -> He + n + 17.05 MeV
  +0.15n
- The problems can be completely solved if subcritical hybrid synthesis-fission systems are used due to the more efficient use of thermonuclear neutrons in the fast spectrum of their active zones and the possibility of using minor actinides with increased neutron yield values (up to 5n per fission) in them
- The use of thermonuclear neutrons as controlling subcritical active zones significantly (up to 100 times) reduces the loads of 14 MeV neutrons on the structural and functional materials of the reactor, opening the way to a new hybrid energy
- The search for optimal ways to it is being actively conducted today and will be discussed in the report with an emphasis on properties, choice of materials and related problems

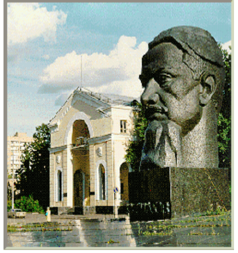


Requirements to materials of FFHS

- **FFHS materials** can be divided into several groups:

1. **structural** (mechanical loads up to 1 MPa/m2, magnetic fields up to 15 T, (steels, vanadium alloys, silicon carbide)
2. **functional** (ensure the operation of technological systems)
   conductors and superconductors
   heat carriers
   insulators
   materials of diagnostic systems and additional heating
   protective coatings that prevent the release of tritium and active gases
3. **special** (forming the composition of fuel nuclides, their fission and transmutation products)

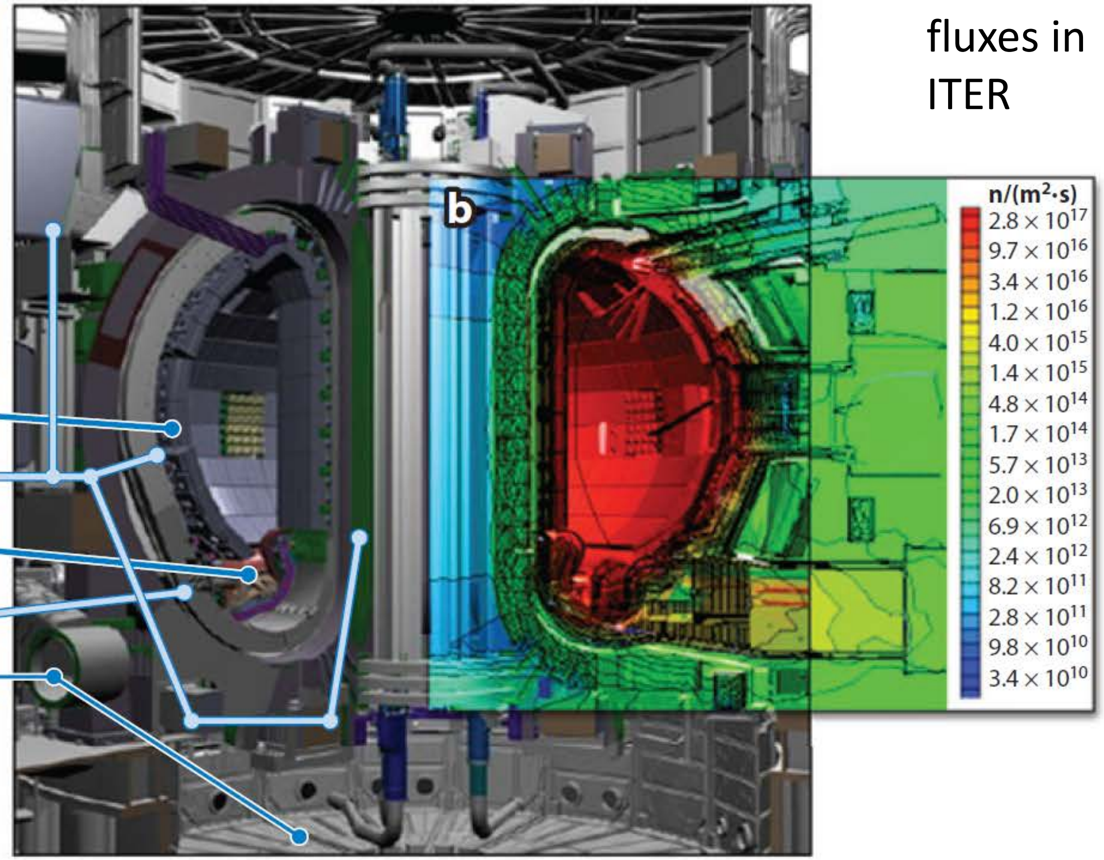
- **Expected radiation loads and damages** include:
- **heat flows** from the plasma to the first wall and divertor up to 5 - 50 MW/m^2 dpa and appm neutrons 0.25 MW/m ^2 and 2 dpa/year and 20 appm/year
- **transmutation** with a change in the chemical composition of materials sputtering and melting by plasma
- **generation of dust** based on high-temperature hydrocarbons and metals
- **destruction of insulators** by gamma radiation and neutrons
- **corrosion** during the interaction of heat carriers with materials



Working conditions in Fusion reactors (Zinkle 2014)

Neutron fluxes in ITER

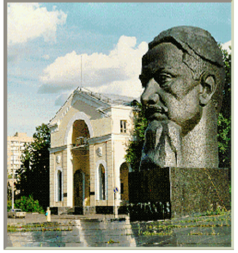
ITER: lifetime fast neutron fluence (n/m^2; $E > 0.1$ MeV)	DEMO fusion power reactor: annual fast neutron fluence (n/m^2; $E > 0.1$ MeV)	Component
3.7×10^{21}	5×10^{22}	Blanket
5.1×10^{14}	7×10^{15}	Magnet
1.9×10^{21}	2.6×10^{22}	Divertor
1.1×10^{19}	1.5×10^{20}	Vacuum vessel
3.4×10^{11}	4.5×10^{12}	Cryostat



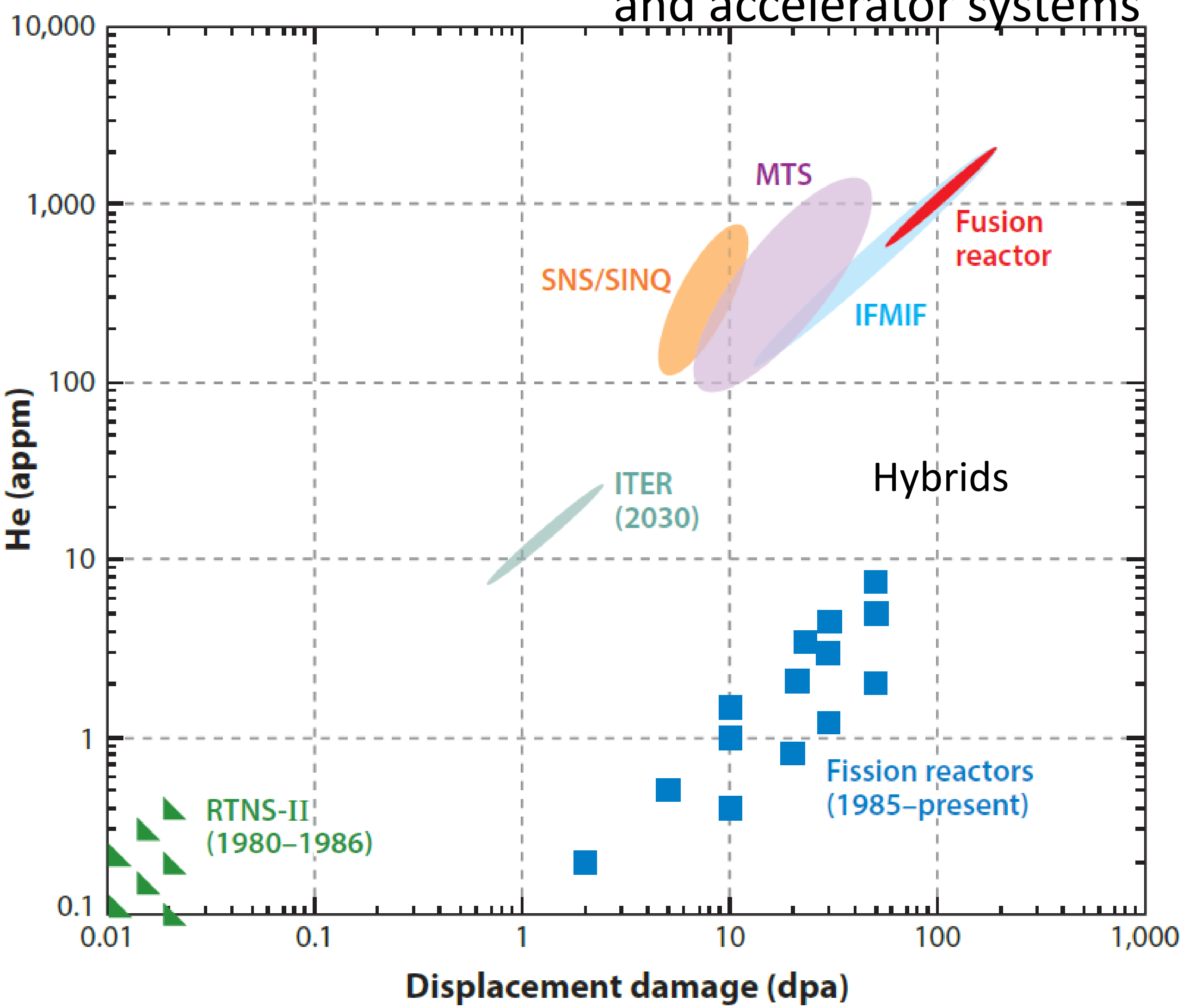
Neutron fluencies within operation time for major components of ITER and DEMO: Blanket, First wall, Magnets, Divertor, Cryostat.

Figure 1

Overview of neutronics and cross section of the ITER tokamak. The inset figure on the right (*b*) highlights the position-dependent total neutron fluxes (based on work of R. Feder & M. Youssef). The table on the left (*a*) compares calculated fast neutron fluences for several key components in ITER and in a demonstration (DEMO) fusion reactor (based on input from M. Sawan).



Materials damage by fusion and fission neutrons due to He generation(appm) versus displacement (dpa) in fission, fission and accelerator systems



The spectrum of nuclear reactors is 100-300 times softer than in tokamaks

The damage in ITER is close to reactor damage. There are no dangerous problems for materials!

Thermonuclear neutron sources are necessary for the certification of materials

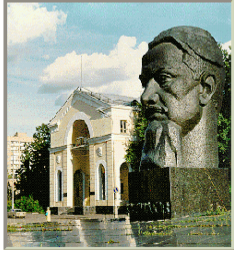
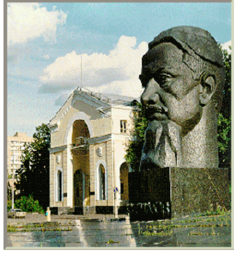


TABLE II Neutrons in Fission and Fusion Systems (FST2020)

System	Neutrons per Fission, ν; Multiplication μ	Residue (Reaction Maintenance and Breeding Subtracted)	Leakage and Volumetric Losses	Free Neutrons Available for Extended Breeding
Critical nuclear reactor 235U, thermal spectrum	ν 2.44	$\nu - 2$ 0.44	1.0	−0.56
Critical nuclear reactor 239Pu, thermal/fast spectrum	ν 2.9/3.05	$\nu - 2$ 0.9/1.05	0.9	0/0.15
Fusion reactor D+T, Be/Pb – multiplier	μ 2/1.8	$\mu - 1$ 1/0.8	0.8	0.2/0
Hybrid reactor D+T and 238U	ν 4.5	$\nu - 1$ 3.5	1.0	2.5
Hybrid reactor D+T and MA, G = 2	$\mu s + 1$	μs		
keff = 0.95	39	38	12.8	25.2
keff = 0.8	9	8	3.0	5.0

Subcritical hybrid system increases the fisile nuclides breeding by ~10 times

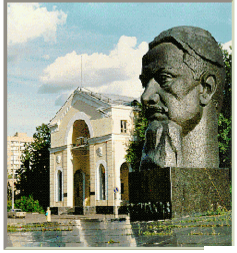


Neutron sources and FFHS

- Sources of DT-fusion neutrons with an energy of 14.1 MeV with an intensity up to 1019 n/s are necessary for the development of innovative materials, components and basic technologies of thermonuclear FFHS). The importance of creating such sources has been repeatedly emphasized by the international thermonuclear community [1,2]. The current state and prospects for the development of sources of thermonuclear neutrons and FFHS in our country and abroad on the time interval of strategic development of FNS by 2040 and FFHS installations until 2060.

[1] Б.В. Кутеев и др. . Физика плазмы, 2010, том 36, № 4, с. 307–346.

[2] Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research. 2018. https://www.goodreads.com/book/show/43328665-final-report-of-the-committee-on-a-strategic-plan-for-u-s-burning-plasm



Energy amplifier (K. Rubbia, 1995)

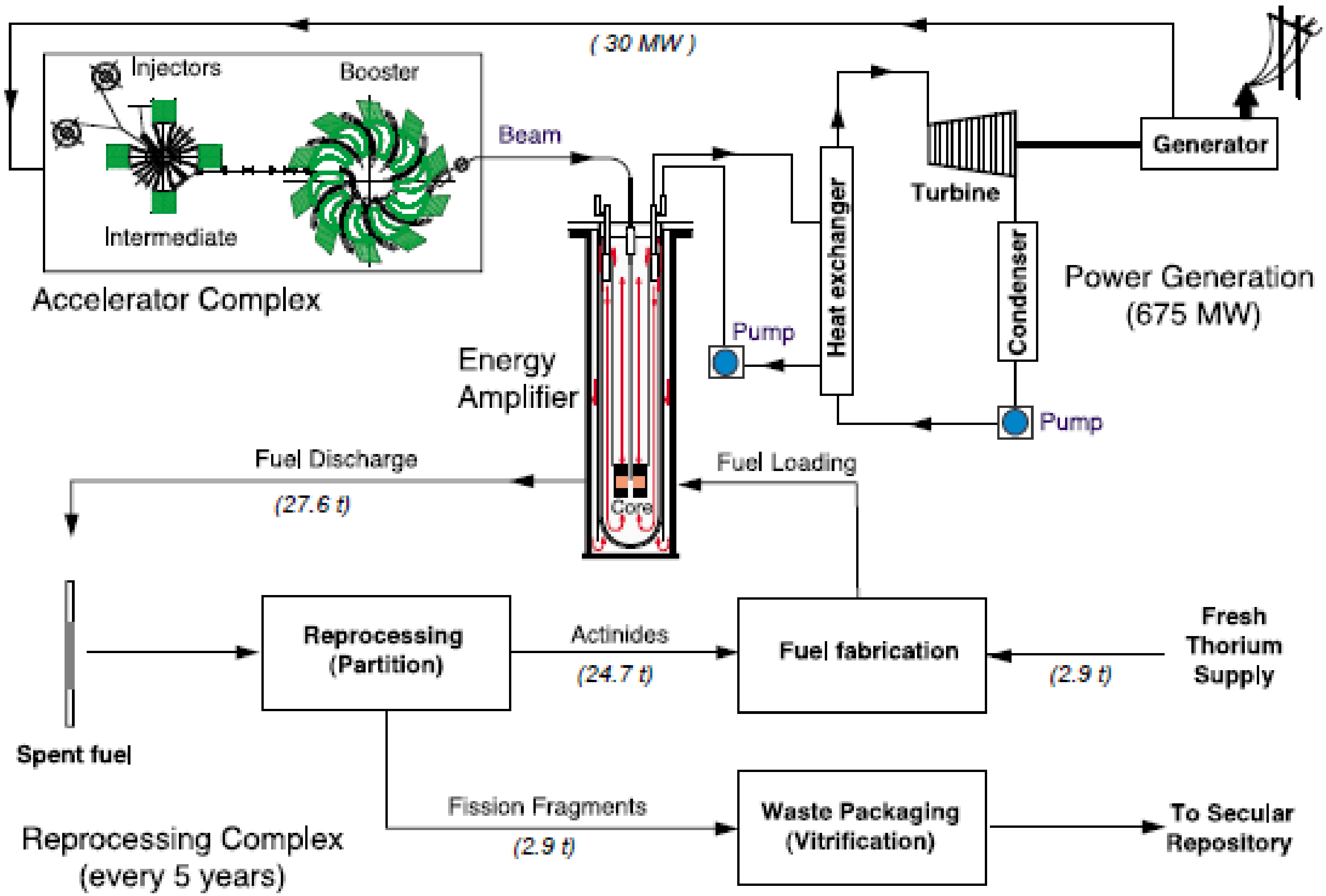
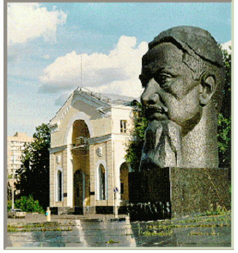
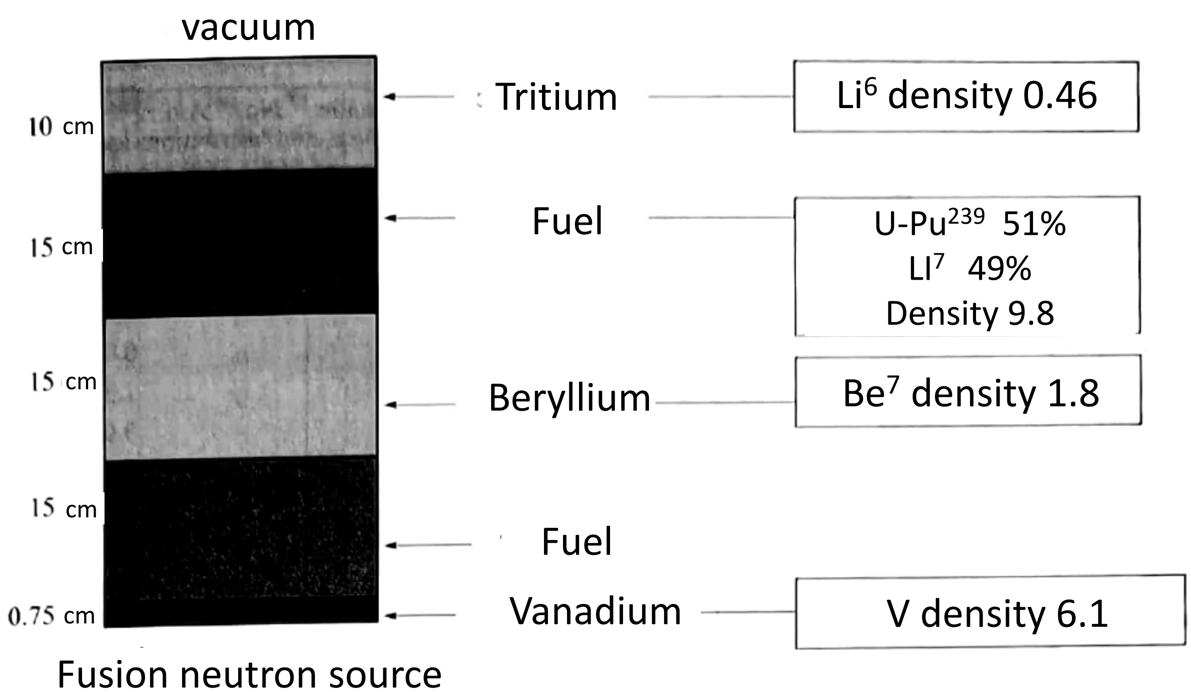


Figure 1.1

A subcritical system with accelerator-generated neutrons is very similar to FFHS



Transmutation using ITER scale FNS, R.I. Ilkaev et al.



- Experiments have shown that 14 MeV neutrons produce the fission rate 1.5-2.5 higher than that of fast fission spectra source [1]
- Confirmed high efficiency of MA transmutation in FFHS with 14 MeV neutrons [2]

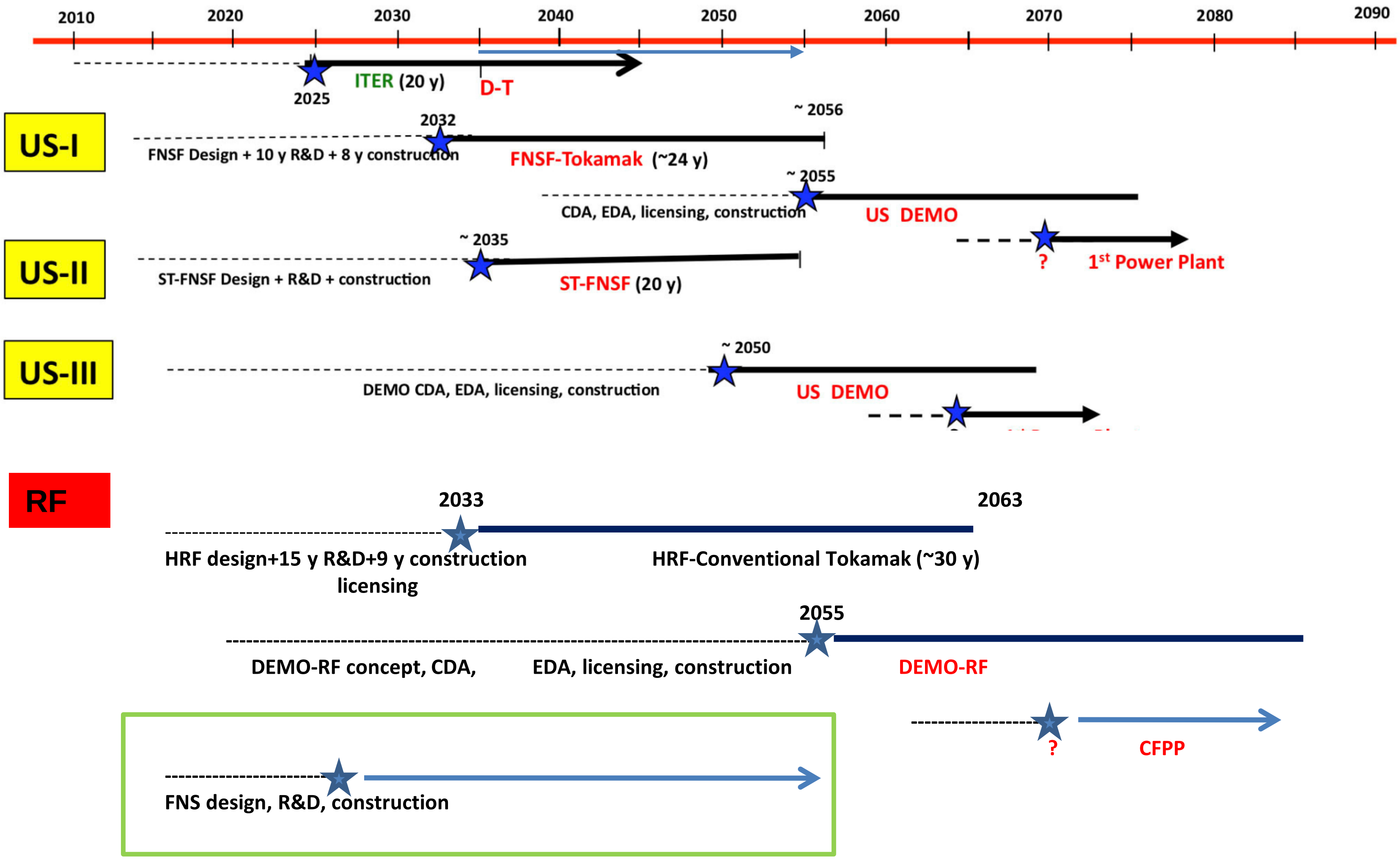
1. R.I. Ilkaev et al., P. Rebut, Hybrid reactor on ITER basis as burner of Pu and MA. Physics and Engineering , 2013,v. 4, № 3, pp. 279-288.

2. *Kotschenreuther M., Valanju P.M., Mahajan S.M., Schneider E.A.* Fusion-fission transmutation scheme – efficient destruction of nuclear waste. Fusion Eng. Des. 2009. V. 84. P. 83–88.

Fusion Strategies

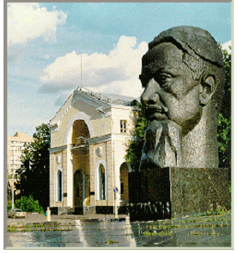
US Final Report 2018

ITER shift today

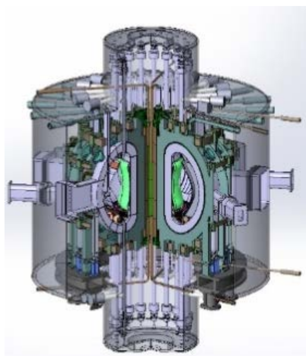


Justification of the construction of facilities of the Fusion and FFHS program requires urgent creation of sources of thermonuclear neutrons for the development and certification of materials and components

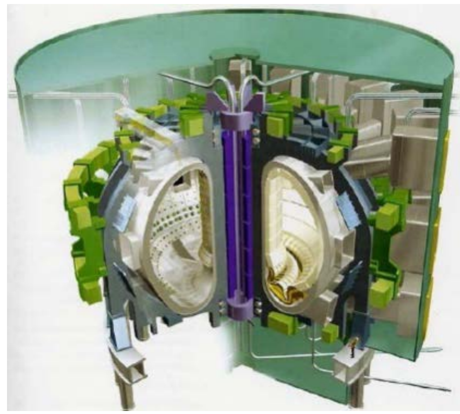
IAEA CRP on Compact FNS in since 2012



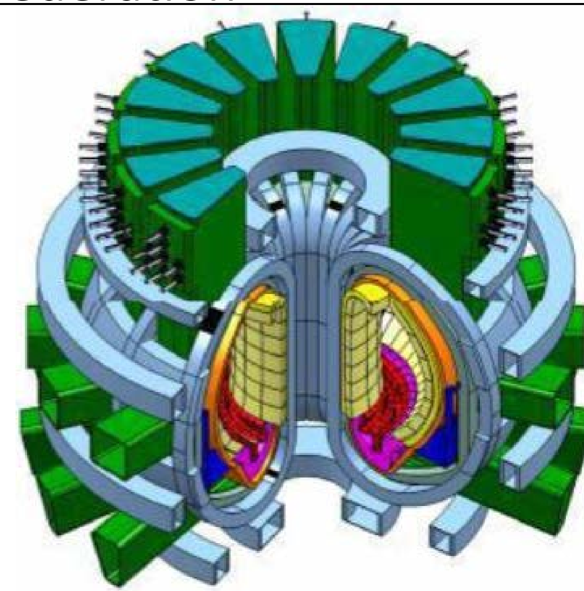
The program of development of thermonuclear and hybrid systems of the Russian Federation



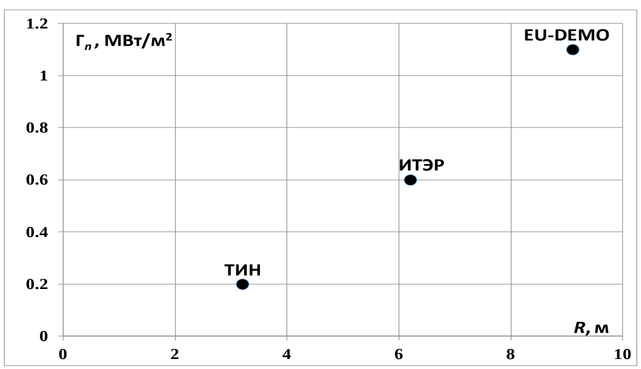
DEMO FNS 3/2 m



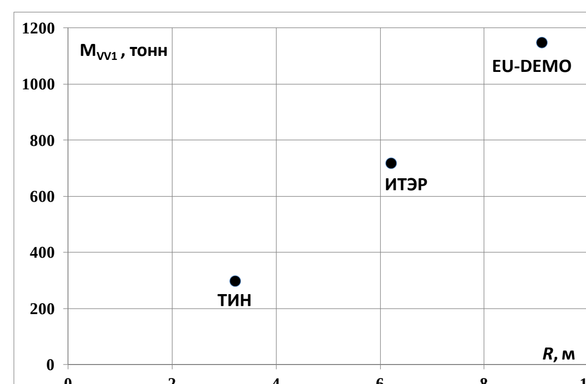
ITER 6/2 m



DEMO-RF 7.8 m

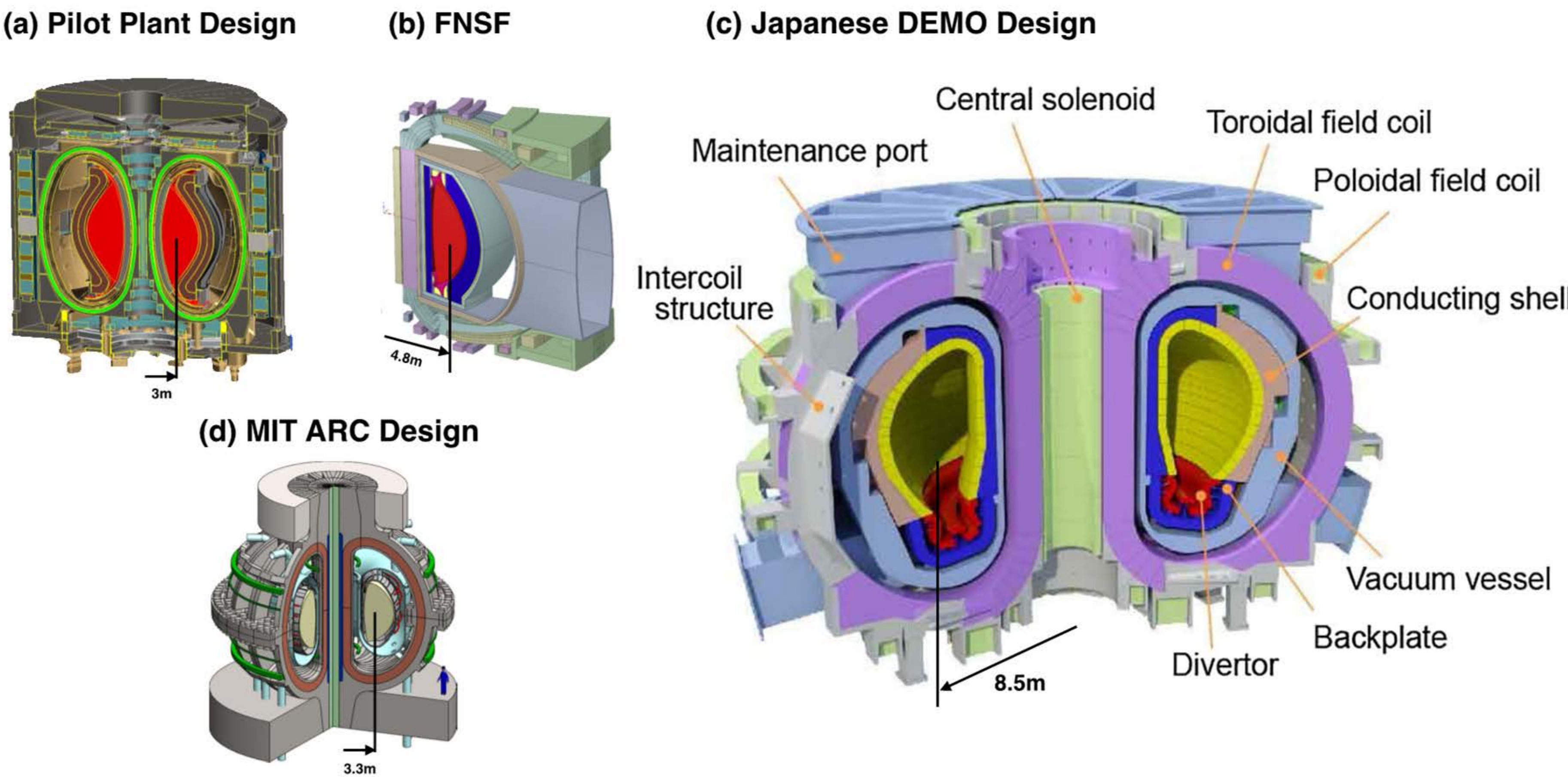


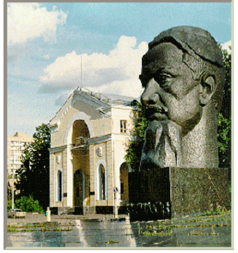
The program for the development of thermonuclear and hybrid systems RF Hybrid DEMO-TIN plans a neutron load 3 times less than in ITER and 5.5 times than DEMO-RF



USA&Japan development set of facilities

US Final Report 2018





Requirements for neutron sources for materials science research

- **Stages of FFHS development correspond to 3 levels of fusion power**

  3 (FNC-C), 40 (DEMO-FNS), 500 (ITER) MW

  and neutron yield of

  $1x10^{18}$ n/s, 10^{19} n/s и 10^{20} n/s (the last one not needed for materials studues)

- **Neutron Yield**

  10^{18} n/s – testing of materials and components (SSO+T+RH)

  10^{19} n/s – control of subcritical zones, transmutation and breeding T and fissile nuclides (SSO+T+RH+Blanket+Molten Salts+Hybrid Fuel Cycle)

  10^{20} n/s – breeding of fissile nuclides using thermal and fast neutrons

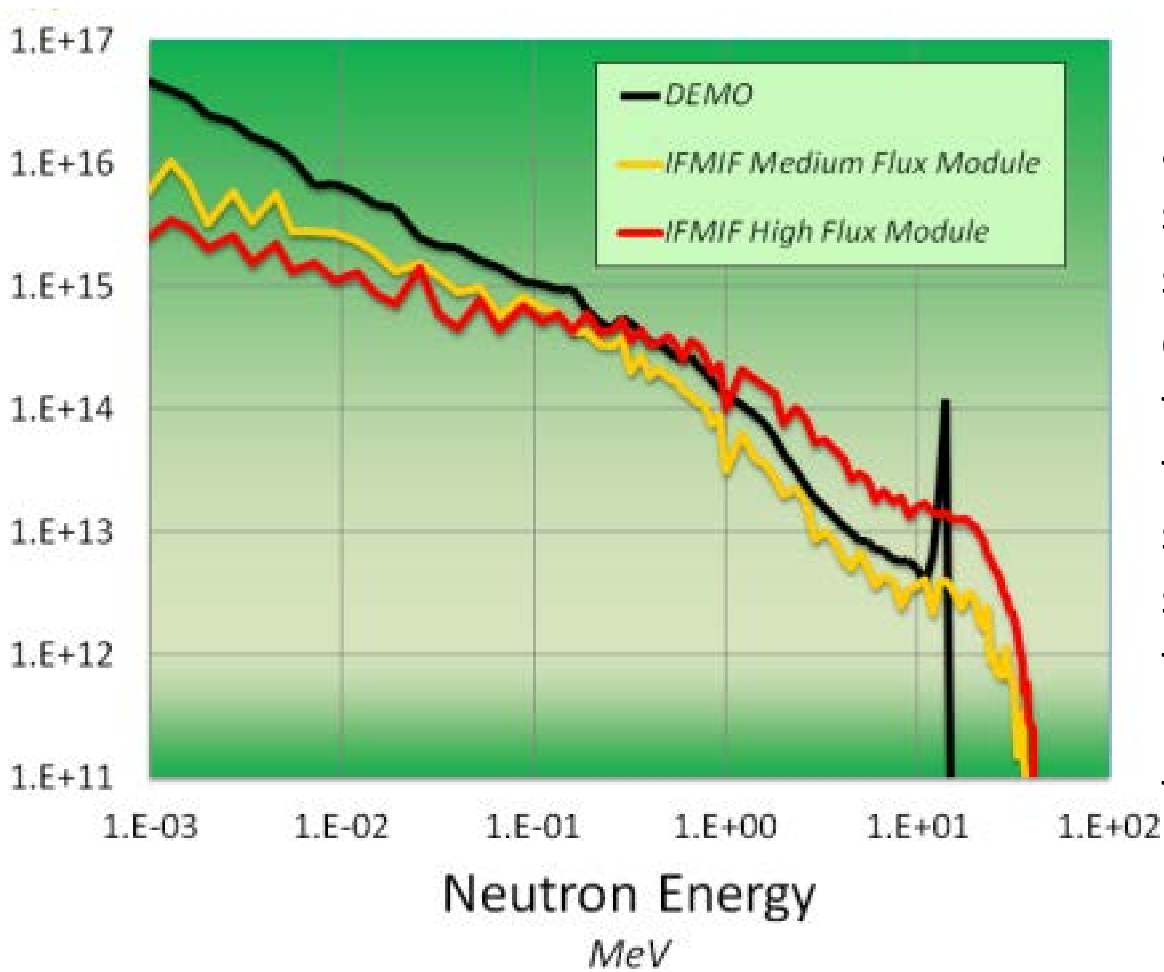
- **Lifetime longer than 10 years** is needed for reaching

  20 dpa and 200 appm по He

- **This level opens new effects in properties of structural and functional materials under loading by**

  neutrons, gases generation, chemical composition and structure variation, additional nuclear reactions on artificial nuclides

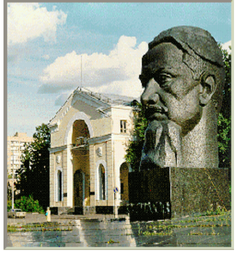
Steels damage by neutrons is sensitive to its spectra



Unfortunately, intensive accelerator sources form a spectrum different from the thermonuclear spectrum and a small volume for the placement of test samples

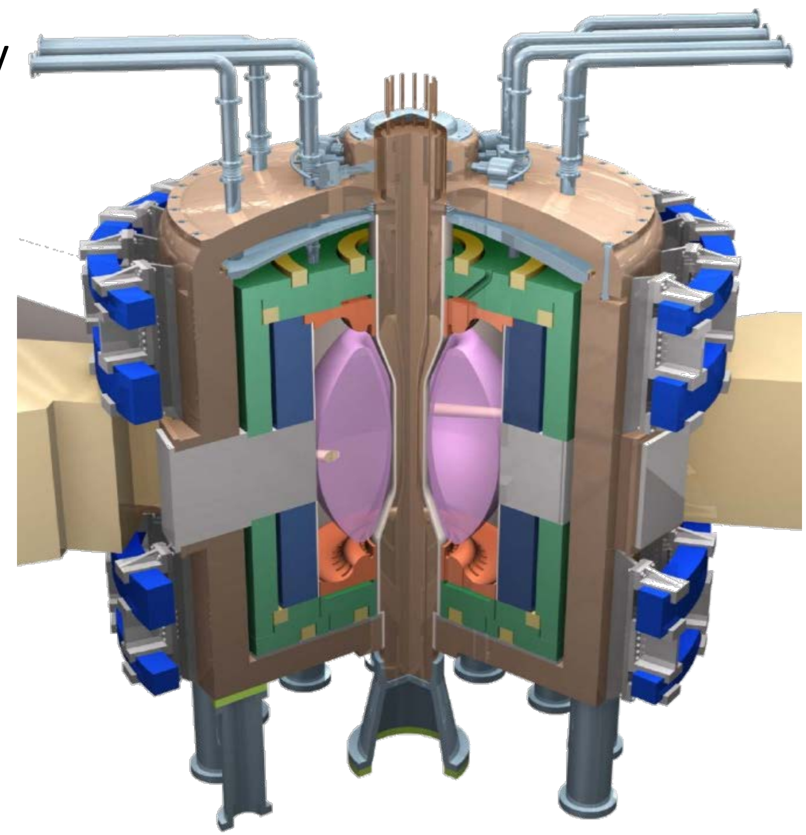
Neutron flux in IFMIF is up to 10^{18} n/sec*cm^2

https://tnenergy.livejournal.com/15900.html



Fusion Nuclear Science Facility

- Mission: Provide an integrated, continuously driven fusion nuclear environment of neutrons that can be used to test multiscale interacting phenomena involving:
  - plasma material interactions
  - tritium fuel cycle
  - power extraction
  - nuclear effects on materials
- 1 MW-yr/m^2 & 10 dpa @ ≤10% duty cycle
- Allows upgrade to CTF (≤6 MW-yr/m^2 & 60 dpa; ≤30%)
- Tests material synergies to 2-6 MW-yr/m^2, 20-60 dpa

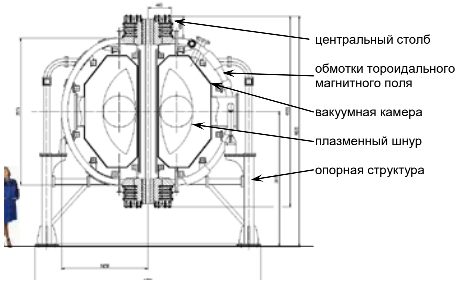


US Final report, 2019

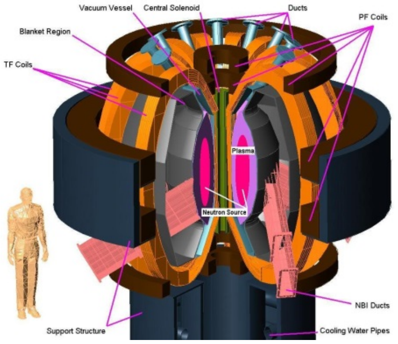
Major facilities on the path to Commercial Hybrid Plant

Investment	$1 B	$0.1 B	$1 B	$5 B
	SSO&MS	Globus-3	FNS-ST	DEMO-HF
	Steady State Technologies		DT neutrons	MS blankets

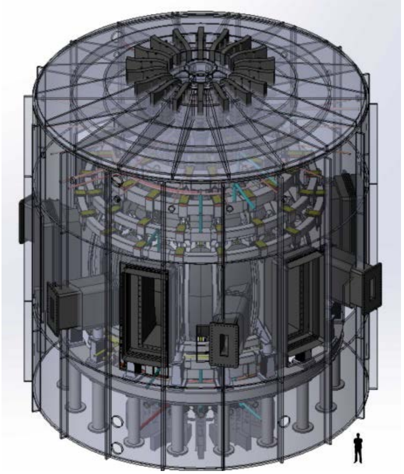
- Magnetic system
- Vacuum chamber
- Divertor
- Blanket
- Remote handling
- Heating and current drive
- Fuelling and pumping
- Diadnostics
- Safety
- Molten salts



•Integration



•Materials



•Hybrid Tech

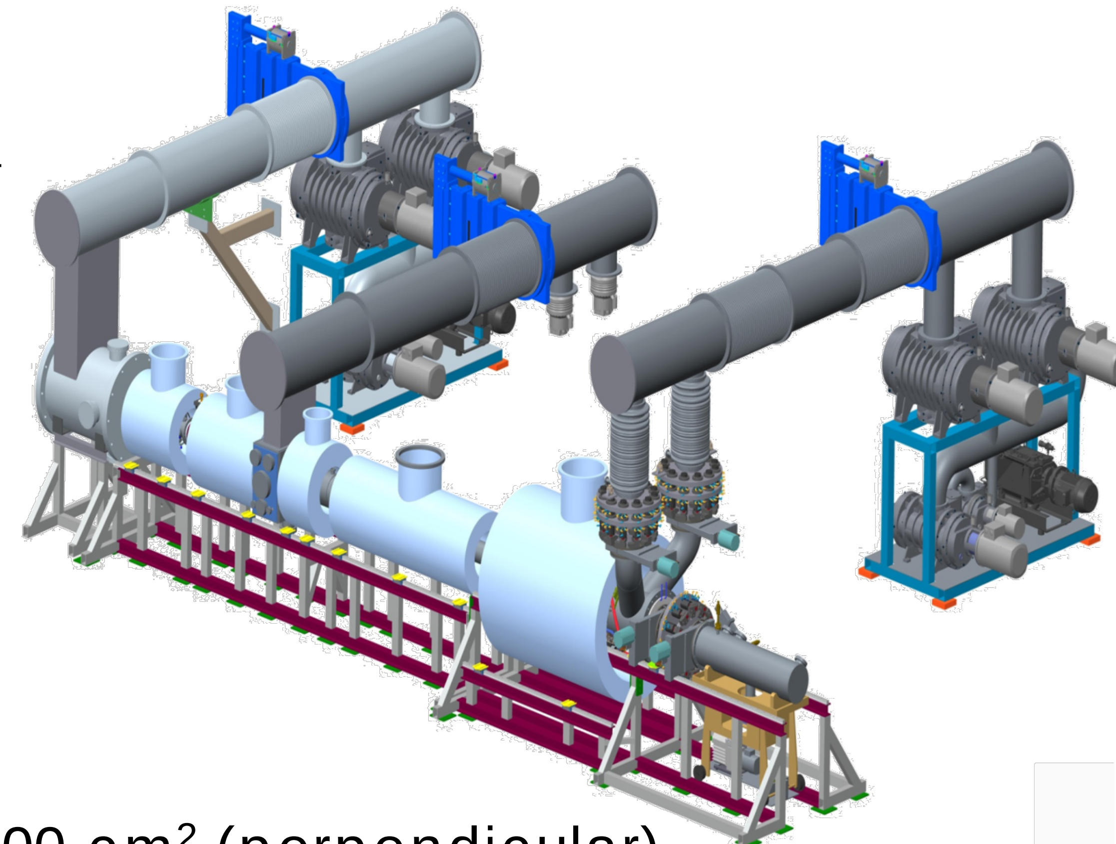
$10 B Pilot Hybrid Plant construction by 2045 P=500 MWt, Q_{eng} ~1

$100 B Commercial Hybrid Plant construction by 2055 P=3 GWt, Q_{eng} ~6.5 P=1.3 GWe, P=1.1 GWn, MA=1t/a, FN=1.1 t/a

Last design activity confirms the time and cost scales

MPEX Overview

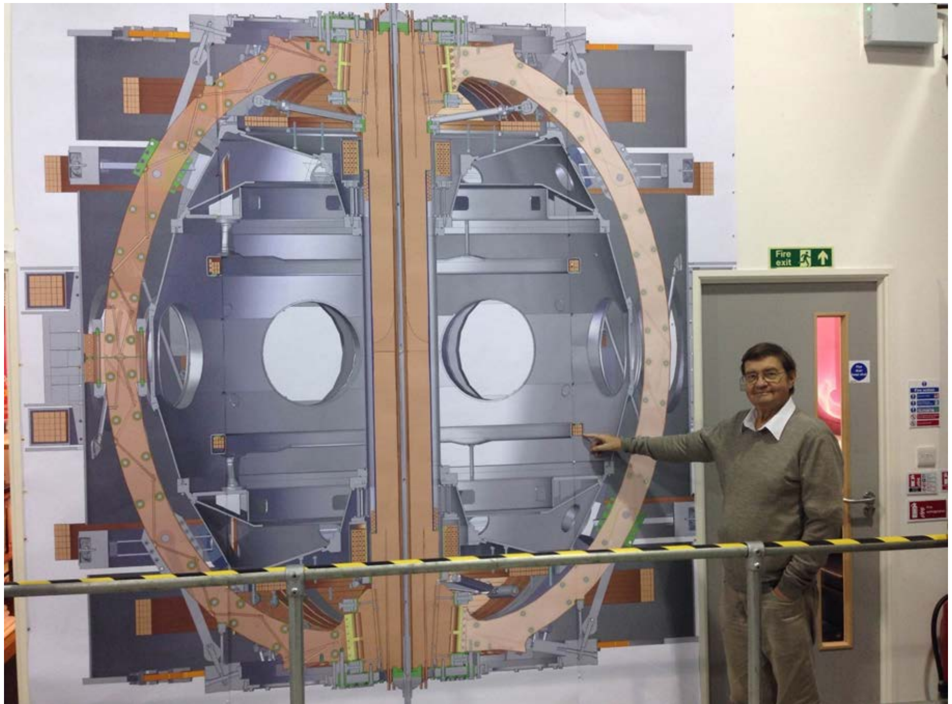
FUNFI3, 2018
Arnold Lumsdaine,

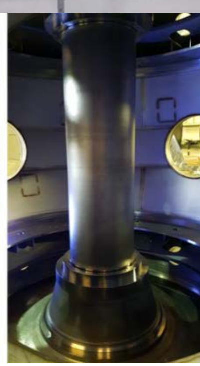


- RF plasma source
- Ion fluxes Γ > 10^{23} $m^{-2}s^{-1}$
- Power flux on target 10 MW / m^2
- Normal or inclined target
- B_{target} > 1 T
- Steady state > 10^6 s
- Large plasma area ~ 100 cm^2 (perpendicular)
- Capable of handling neutron irradiated samples (low activation)

For studies of PSI in neutron environment special mockups are developed!

ST40 project Tokamak Energy Ltd, UK
M. Gryaznevich





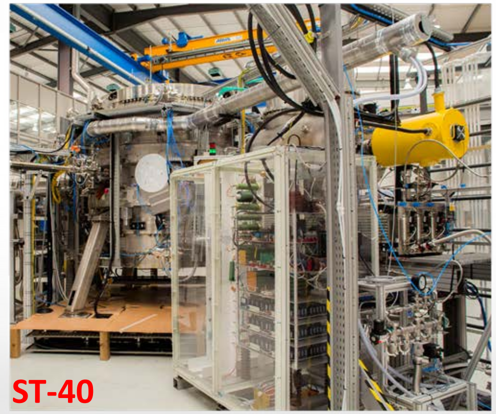
Main features:

- High toroidal field up to 3T, water or LN2 cooled (phase 2) copper magnet
- Plasma major radius 0.4 - 0.6m, R/a = 1.6-1.8
- Moderate elongation (κ~2.5) and triangularity (δ~0.3), DND
- Plasma current up to 2MA, merging/compression plasma formation
- NBI and EBW/ECRH heating
- Possibility of **DT** ops

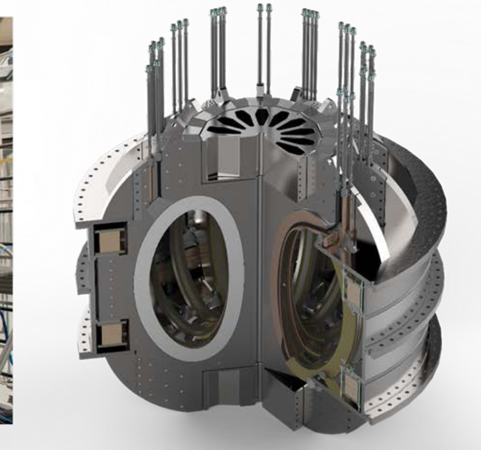
- To be constructed in 2017 at Milton Park TE Ltd site

Tokamak Energy Limited (& Inc.)
GB actively realizes ST-40 tokamak project
(10 000 shots with duration 0.2 s)

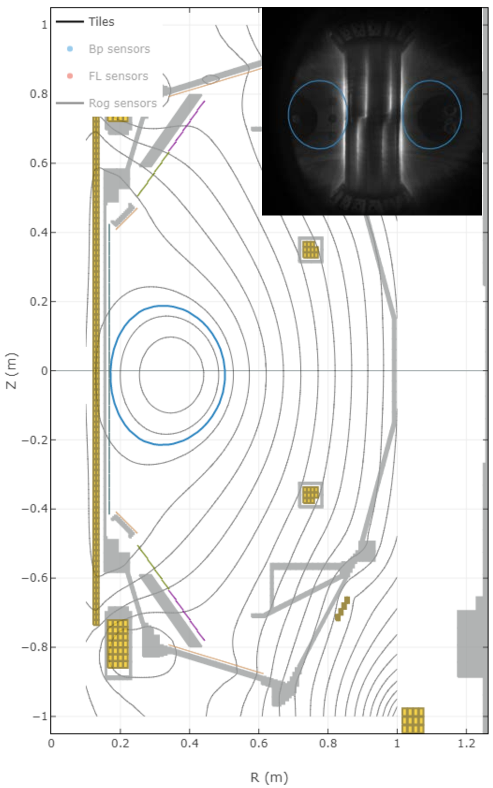
- Established in 2009 with a mission to develop a faster route to fusion energy
- Engineering centre in Milton Park, Oxfordshire, UK
- Over £115M investment with £40M of grants and R&D subsidies
- Team of over 220 and growing fast!
- Operating the ST40 compact high field spherical tokamak
- World leading high temperature superconducting magnet facility

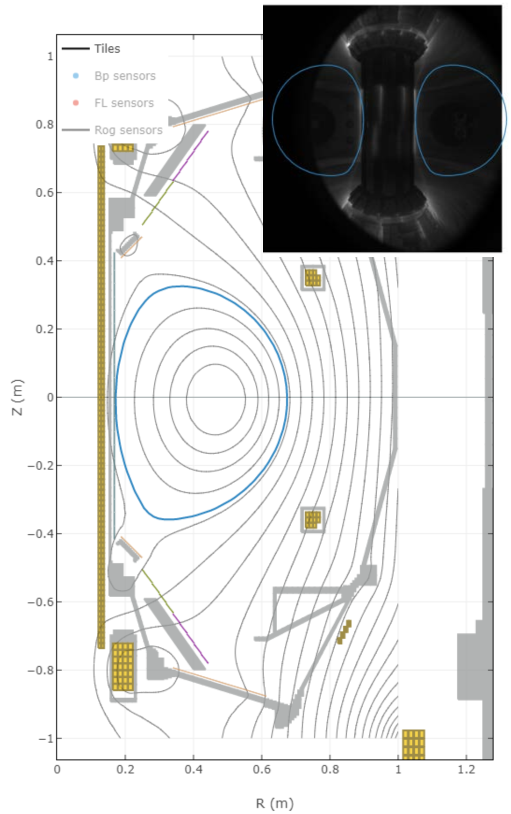


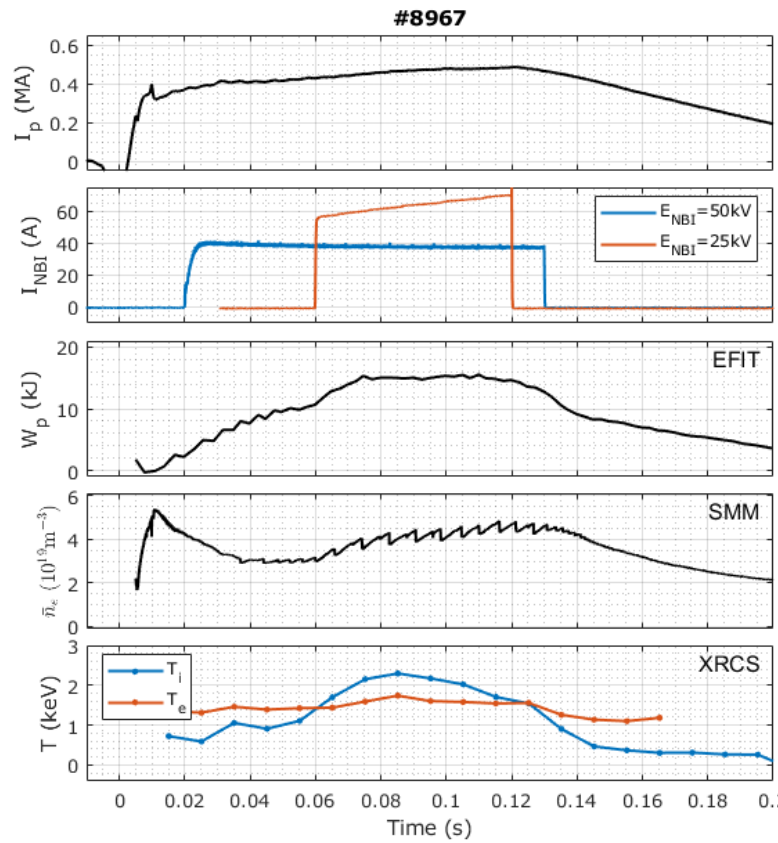
DEMO-4

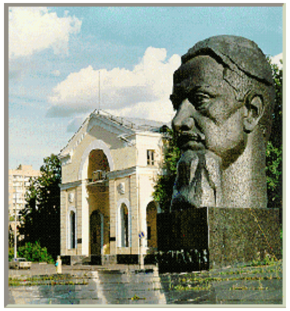


Typical 09/21 $H^0 \Rightarrow H^+$ pulse









Fusion Neutron Applications

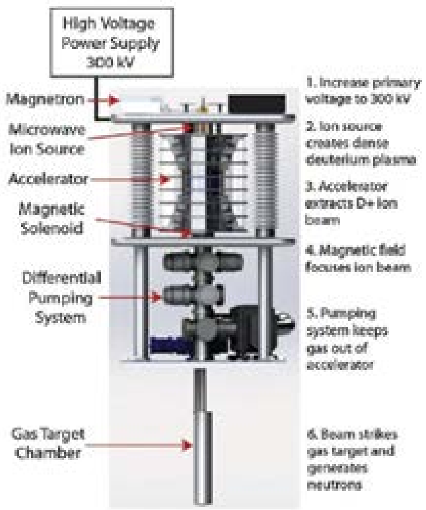


Fig. 4. Schematic of SHINE neutron generator prototype.

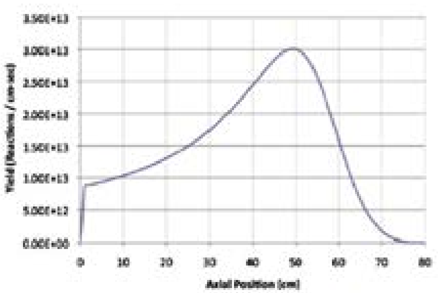


Fig. 5. Calculated neutron production rate for D⁺ stopping in 4 kPa (30 Torr) tritium target gas [4–7].

•DT-fusion

commercially available in

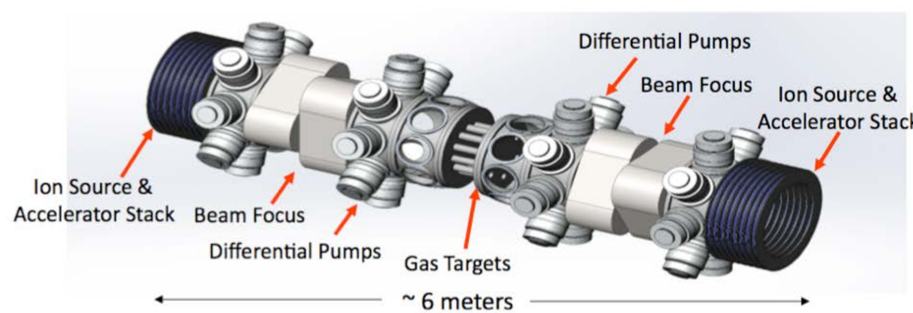
-accelerator – solid target version 10^{11}-10^{13} neutron per second and 1 month resource in cw-mode

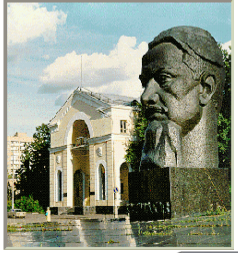
-plasma focus pulse mode with a similar neutron yield

next future (DOE supported)

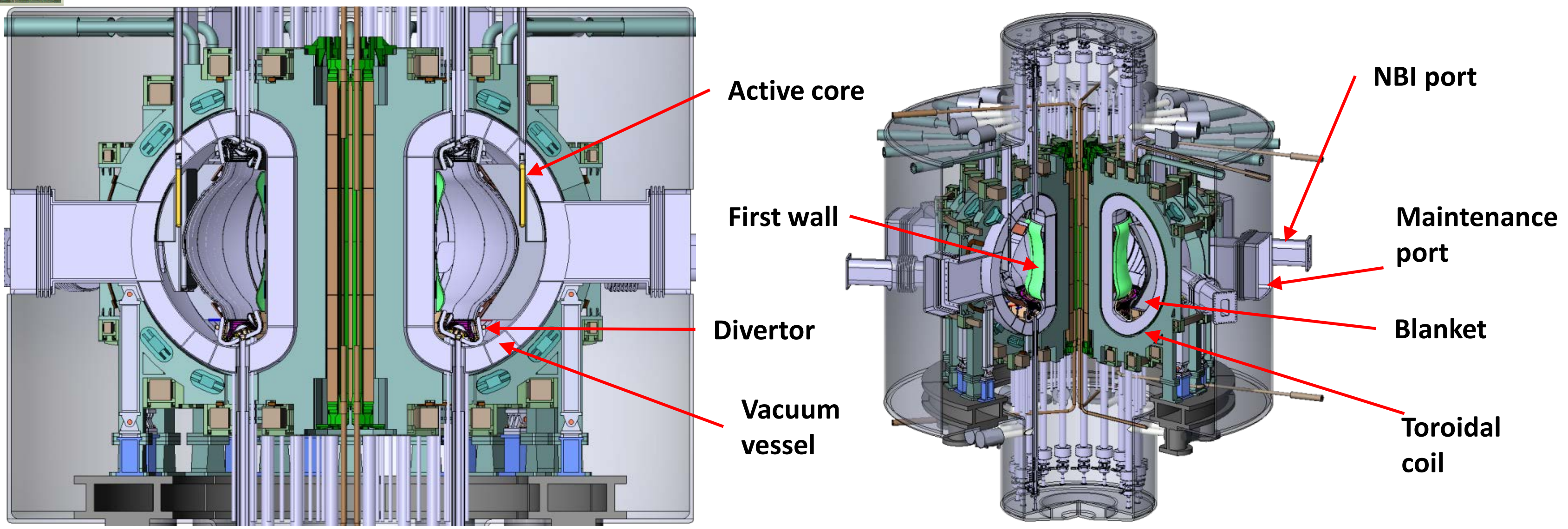
-accelerator – gas target version (G. Kulcinski) 10^{14} n/s

The DT-fusion neutrons may control subcritical system. 110 W of DT-fusion power drives 75 kW fission for ^{99m}Tc production, which is used in 50,000 medical procedures per day in USA





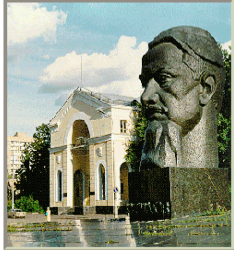
Tokamak and plasma parameters



Major radius,	**m**	**3.2**
Minor radius,	**m**	**1.0**
Toroidal field,	**T**	**5.0**
Plasma current,	**MA**	**5**
NBI power,	**MW**	**30**
ECRH power,	**MW**	**6**
Electron/ion temperature,	**keV**	**11.5/10.7**

β_N		**2.1**
β_p		**0.96**
Neutron yield,	**n/s**	**$>10^{19}$**
Thermal power F+F	**MW**	**500**
Consumed/generated electric power,	**MW**	**up to 200**
Discharge time,	**h**	**up to 5000**
Capacity factor		**0.3**
Life time,	**years**	**30**

DEMO-FNS tokamak general views with vertical ports for active cores



Requirements for neutron sources in FFHS

Sources of thermonuclear neutrons DT 14 MeV are necessary for testing and certification of FFHS materials:

1. Sources based on particle accelerators (D+Li) IFMIF and DONES have been developed, the latter is being built in Spain.

    Problems: a more rigid spectrum (up to 40 MeV) and a small test volume of ~0.5 liters; only micro samples are possible

2. Kulcinsky's source is deuterium beams with a tritium gas target.

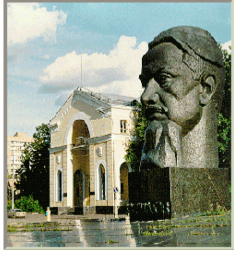
    The spectrum of 14-MeV neutrons is provided. The test volume is significantly larger. Samples of cm-scale are possible. Problems: stationary tritium technologies and remote handling.

3. Sources based on spherical tokamaks FNS-ST/C and ST-40 with a beam thermonuclear.

    FNS-C design and construction is required.

Problems: implementation of stationary and pulsed tokamak technologies in the conditions of the FNS-C neutron load.

New technologies for maintaining a stationary discharge using the magnetization reversal of the solenoid by the generated current in ST-40.



Conclusion

- Materials research forms by the world scientific community an important R&D direction for the development of thermonuclear and hybrid systems, as well as their basic technologies.
- The interaction of plasma with irradiated materials and compact neutron sources is a modern trend of research and development.
- The spectral characteristics of n-sources and fluxes of more than 0.2 MW/m2 are achievable within 7-10 years with the immediate start of work. Level 1 MW/m2 seems later > 2050.
- When implementing long-term induction-free DT discharges, compact tokamaks are able to ensure the development of FNS-ST-level by 2030 and DEMO-FNS by 2050.
- FNS based on plasma-beam discharge is a promising system if the problems of working with tritium are solved. The system seems real by 2030.
- The successful implementation of the Controlled Fusion and Plasma Technology programs in the Russian Federation in the field of materials will require not only the creation of FNS, but also effective coordination of all research works.
- The importance of the task of developing and certifying materials requires appropriate correction of RF federal project on Fusion.
- A significant contribution to the RTTN program should be done also by research in the field of nuclear cross sections and material properties.