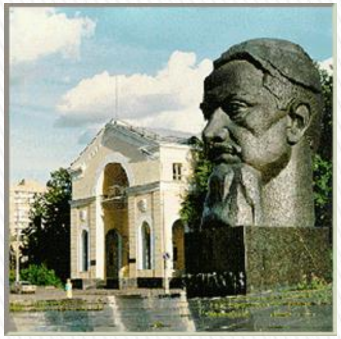
National Research Center “Kurchatov Institute”



# Fusion for Neutrons as a Necessary Step to Commercial Fusion

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MFERW, Princeton, NJ, USA, September 7-10, 2011

# Fusion for Neutrons - F4N – new formula

- Renewal of interest to fusion neutrons
- Growing interest to steady state operations, which are urgently needed for applications of fusion neutrons
- Several concepts of fusion neutron facilities have been formulated (FDF, FNS, FDS, Fusion-Fission Hybrids)

## WHAT IS the REASON?

Demonstration Reactor (DEMO)

Electric Power Generation

~1000 MWe

Fusion for Energy - **F4E** has a threshold of power amplification Q > 30


**F4N** has no efficiency limit, Q << 1 is also needed

Q =30~50

STEADY STATE

$\beta_N$~ 3.5~5.5

**FNS domain**

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

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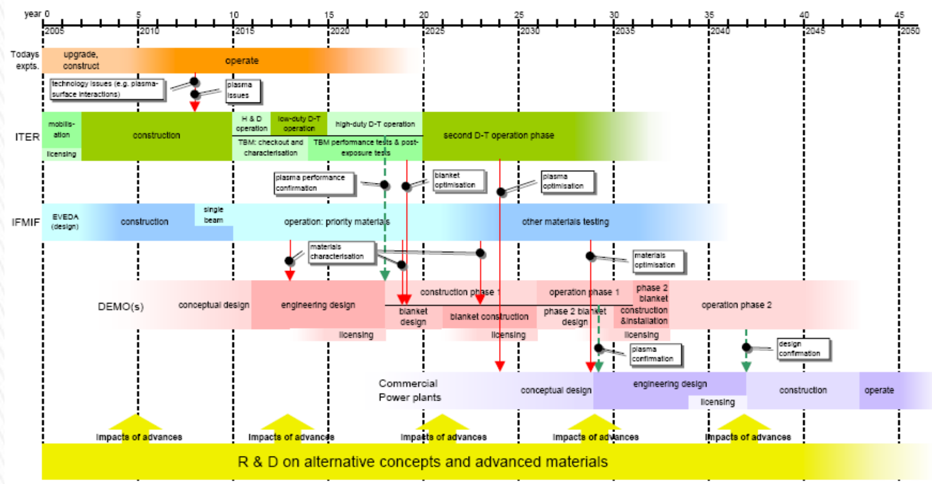
# New products needed to accelerate Fusion

- Fast track to Fusion for Energy is defined:
  ITER ~2020 DEMO ~2035 FPP ~2050

**Reference fast track**




**Fast track to Non-Energy Fusion Applications requires**

- **something that is more valuable than Energy**
- **something that explores unique features of fusion**

# Useful Products of DT & DD fusion reactions :

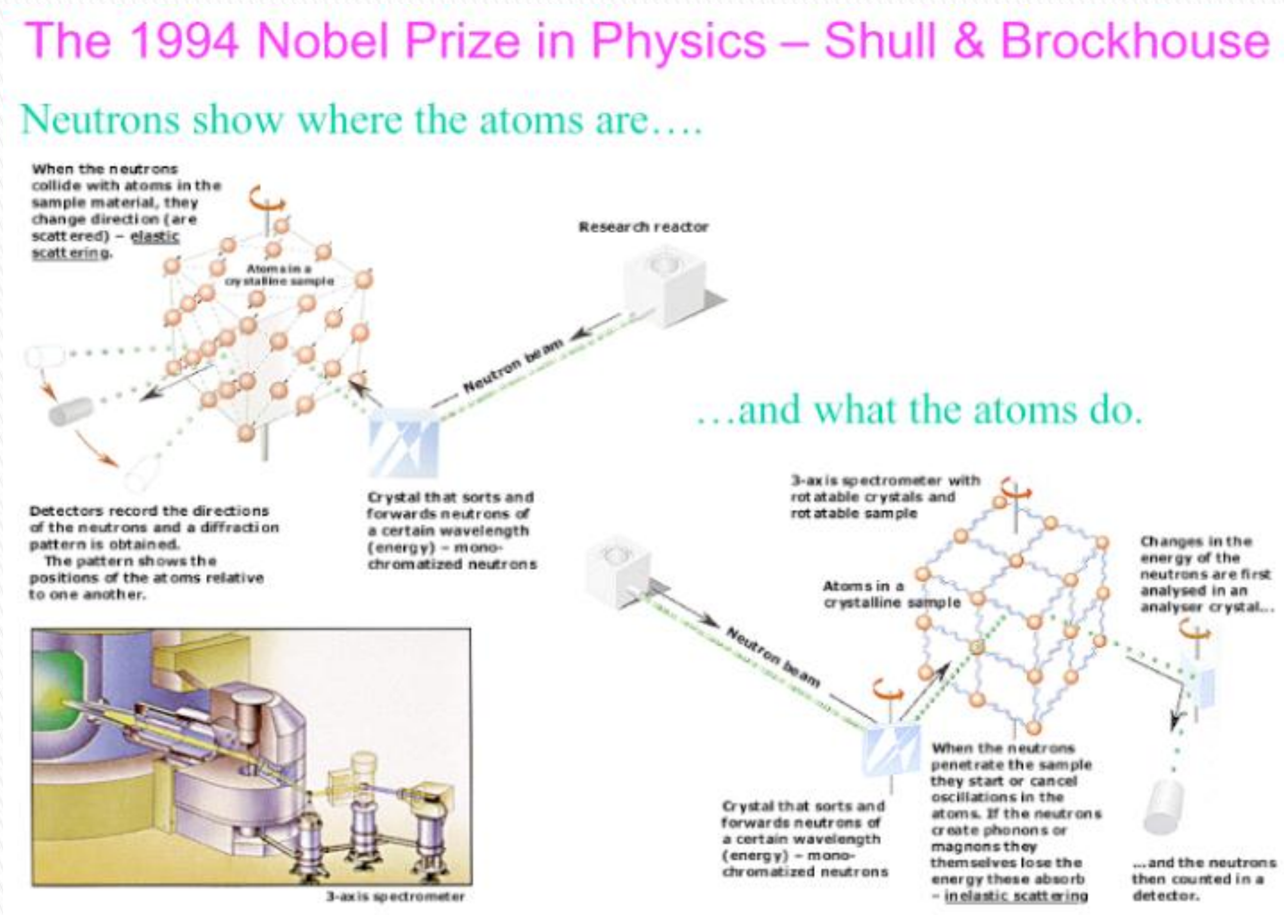
| | DT | DD | |
|---|---|---|---|
| energy, MeV | 17.6 | 3.6 | not much!! |
| neutrons | 1 | 0.5 | plenty!! |
| nuclides | no | $0.5T+0.5\ ^3He$ | |

- **Fusion** creates more free neutrons (per energy released) than **fission** by a factor of **20**
- What is bad for energy production is good for neutron production

## The current trend:

«Neutrons (not energy!) may become the first product of fusion»

# Fusion device for neutron scattering




… is also a nice device for production of **Nobel Prize Winners**

# Fusion Device is needed for National Health Security

Fusion transmutation of waste is at an immature point in technological readiness, and likely such a unit would be more expensive than a FR. However, due to the better support ratio and the elimination of fuel fabrication, there could be some overall cost benefit to the In-Zinerator concept.

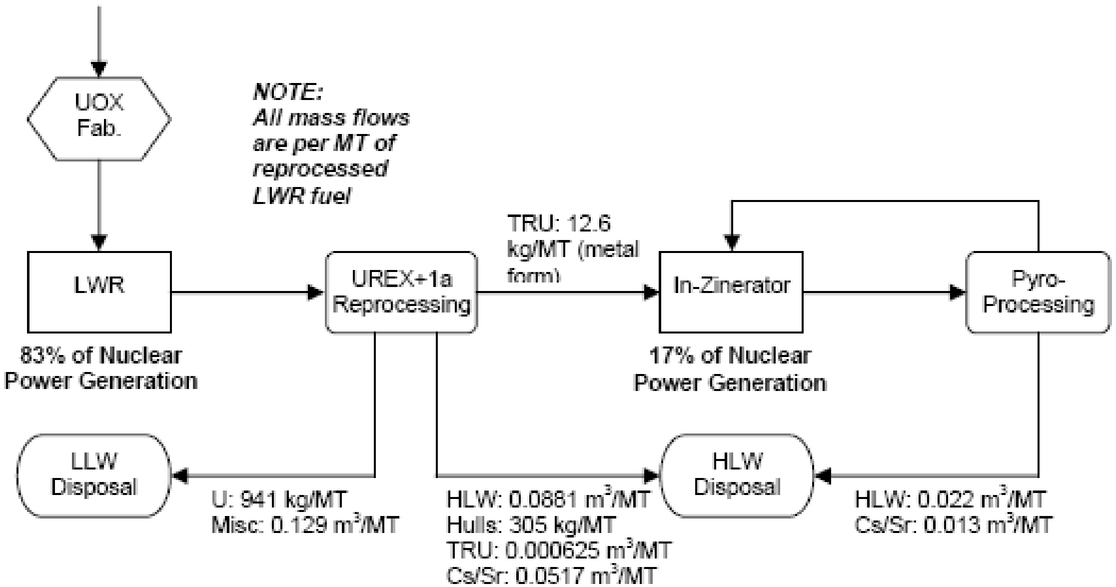



**Figure 8: Scenario 1b**[5,7,12]

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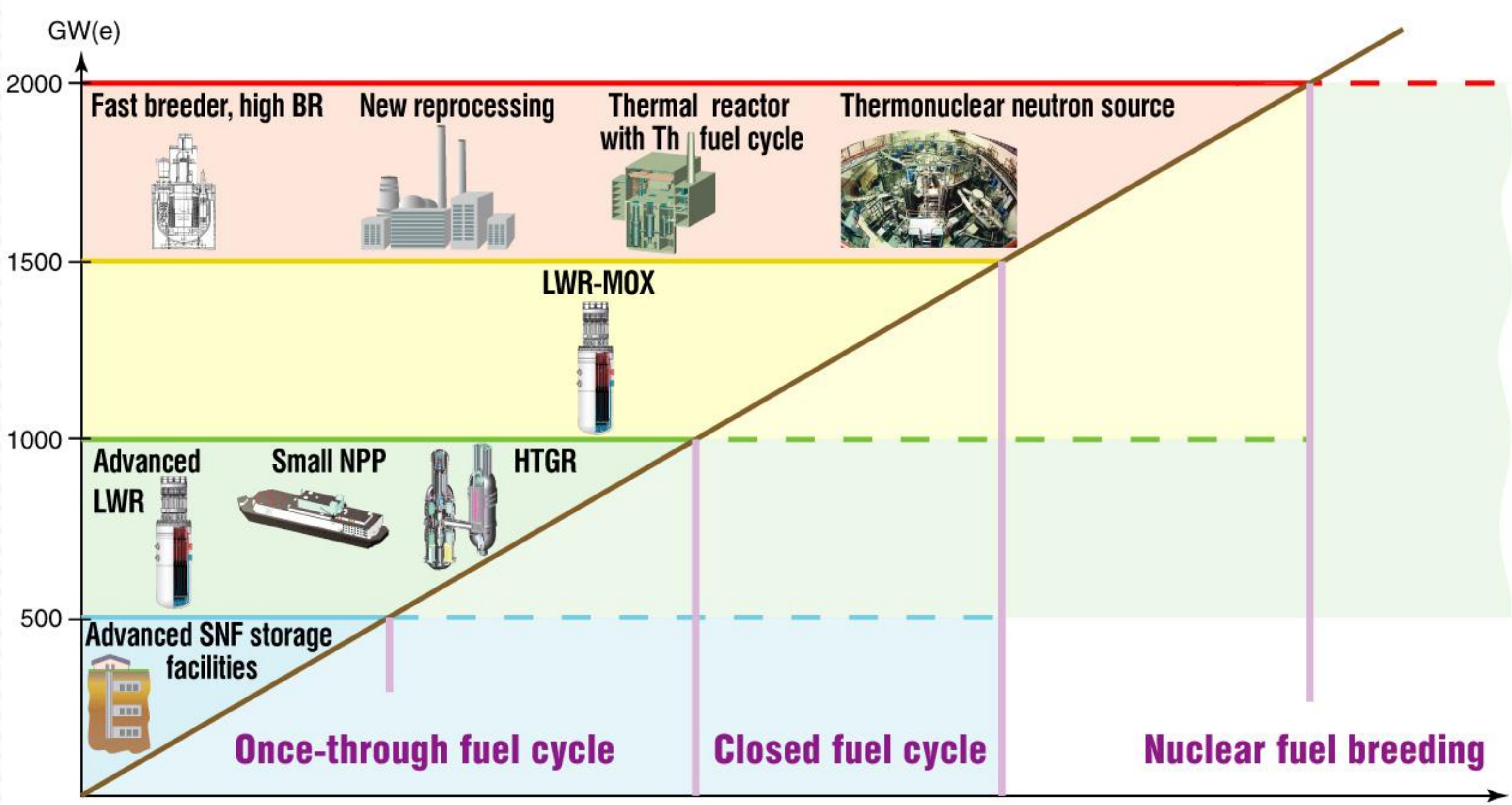
- Nuclear Waste (transuraniums) incineration service

# Device for benign Energy source




Supporting the high growth rate scenario of Nuclear Industry development by nuclear fuel breeding and waste handling

**Fission Energy needs Fusion neutrons**

# Scales for orientation in the problem

**Fission reactor** with heat power 3 GW operates at

**$10^{20}$** fissions per second

**~3 x $10^{20}$** prompt neutrons per second

**$10^{18}$** delayed neutrons per second

Institute Laue-Langevin
57 MW research reactor

**$10^{18}$** useful neutrons per second…

is the Everest!

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

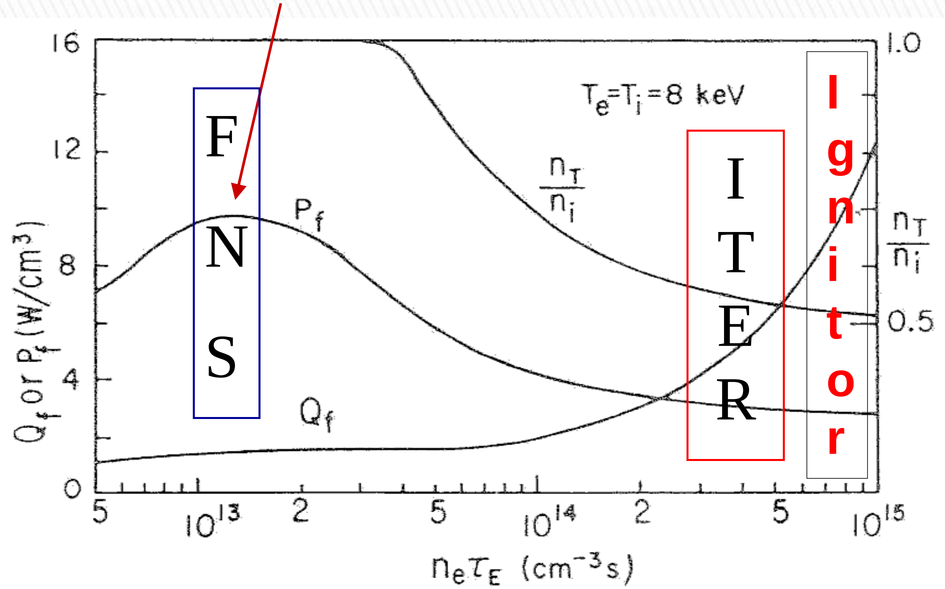
# Most powerful neutron sources in the world (* - projects)

| NS Type | Facility (location), used nuclides | Deposited Power, MW SS (Peak) | Rate, $10^{17}$ n/s SS (Peak) | Neutron Power Output, MW SS (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 | $4.5\times10^{15}$ |
| | 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 | $4\times10^{13}$ |
| 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 | $10^{17}$ |

# Beam-plasma interaction is a good source of neutrons

- Optimal **fusion energy** and **neutron** production are realized at **different** plasma conditions:

**Beam-plasma fusion rate has maximum at lower $n\tau_E \sim 10^{13}\ cm^{-3}\ s$**




*D.L. Jassby, Nucl. Fusion,* ***15*** *(1975)*

Dependence of $P_f$ and $Q_f$ on $n_e\tau_E$ for an 8-keV D-T plasma heated by 200-keV D beams. Maximum $Q_f$ is attained for the plasma composition given by $n_T/n_i$, where $n_i$ is the bulk-ion density. $p = 0.655$ J/cm$^3$. Radiation loss is included in $\tau_E$. Alpha-particle effects are neglected.

# Challenges for "Fusion for Neutrons"

- Free neutrons thermal n-flux $> 10^{15}$ **n/cm²s**
- Transmutation n-source rate $> 10^{18}$ **n/s**
- Fuel breeding n-source rate $> 10^{20}$ **n/s**

Compact tokamaks with copper coils and 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 for hybrids

Pulsed Operation acceptable for research

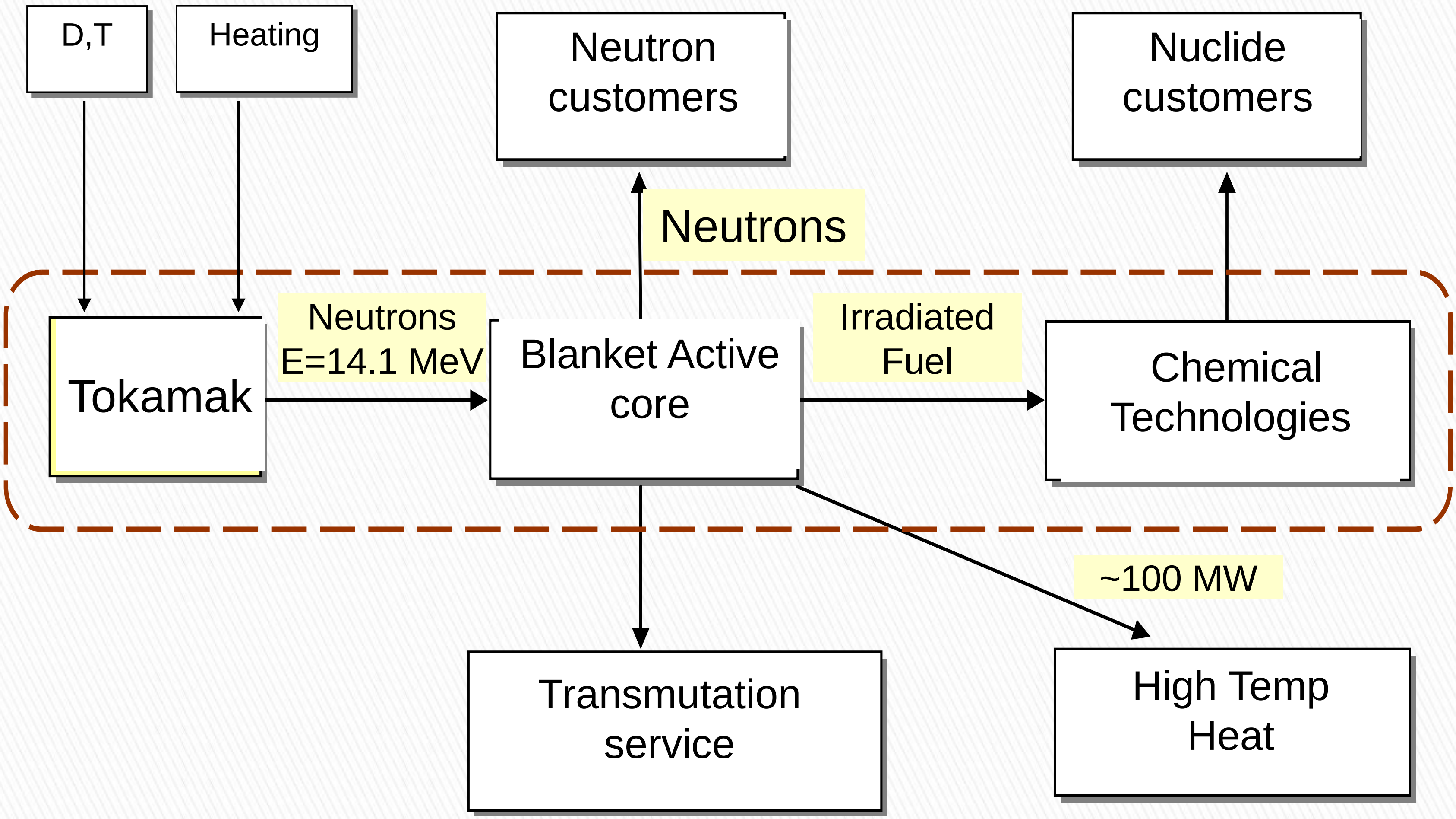
# Interest to hybrid systems in Russia came back because:

- Resources of U-235 for development of power generation by thermal reactors are limited

- Fast reactors as the basis for future large-scale nuclear industry with acceptable economy are at a stage of concept selection and still have unclear prospects due to technological difficulties

- A part of Russian fission community considers fusion-fission hybrid systems based on fusion neutron source (FNS) as a possible solution of the fission power problems

# Schematic diagram of a Fusion-Fission Hybrid



# Time scale of hybrids development

**Current activity:**

Development the physical prototype T-15 and demonstration FNS for hybrid systems

Several options for demonstration tokamak- FNS with warm and superconducting electromagnetic system have been considered to ensure the maintenance of steady-state mode at conceptual level since 2009

**Plans:**

Facilities to be constructed and put into operation:

| | |
|---|---|
| Physical prototype of FNS (T-15, Globus MU) | 2013 |
| TIN-1 (demonstration tokamak-FNS) | 2018 |
| Pilot plant | 2022 |
| Industrial hybrid reactor | 2030 |

# Basic goals of FNS-ST design

- To formulate a concept of a MW range fusion neutron source as small in size as possible
- To optimize beam-plasma fusion regime
- To determine the device SS Operation domains
- To define key physical issues of the device
- To outline the R&D needed to support the project

# FNS-ST project

- The mission of the FNS-ST is to be a prototype of a fusion-fission hybrid system with the fusion power below 10 MW and fission power below 100 MW, being capable to produce neutrons with fast/thermal spectra with the plant life time of several decades.

- **Main design constraints:**

 - Minimization of the device size is desirable to reach highest neutron flux density

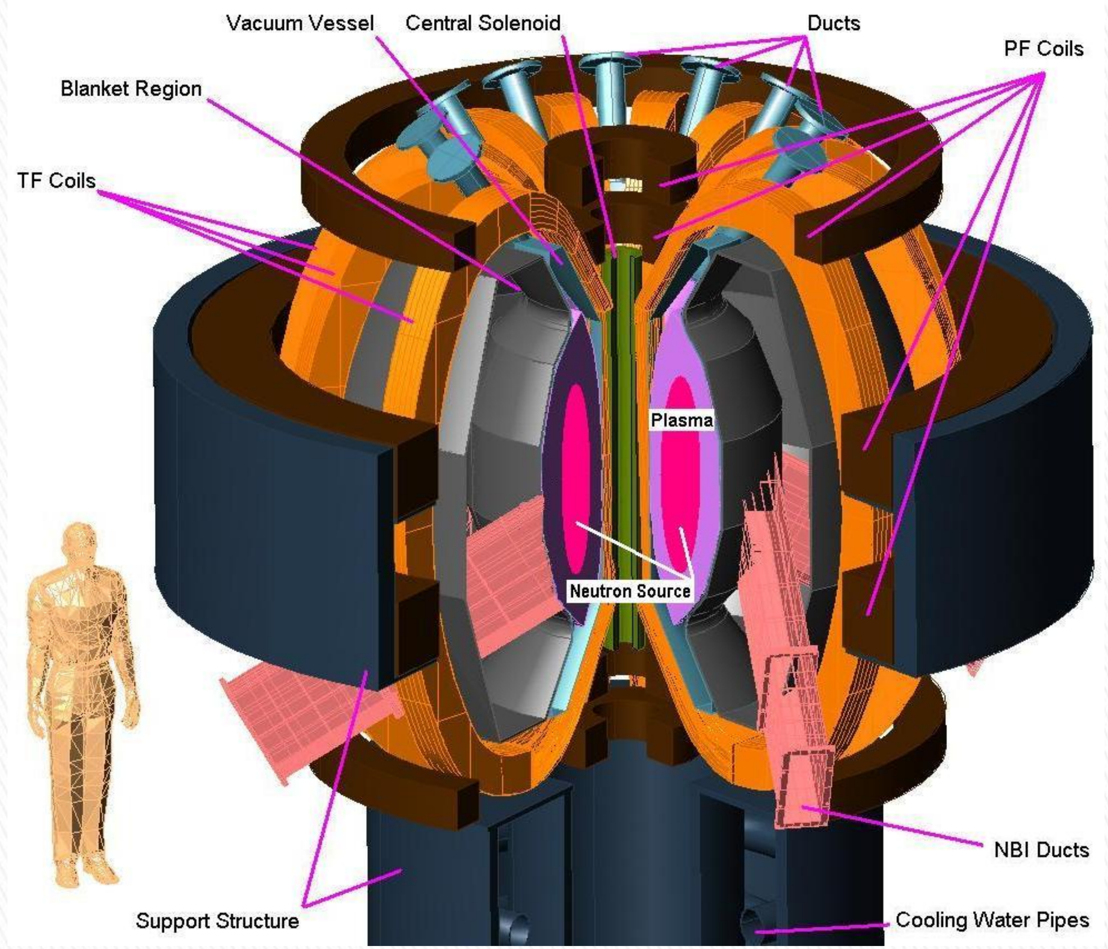
 - Reducing the total electric power consumption below 50 MW follows from the desire to keep the capital cost <200 M$ and operation cost <30 M$ with the duty factor of 0.3

 - Tritium consumption to be less than 100 grams per year

B.V. Kuteev et. Al. “Plasma Physics Reports, 2010, vol.36, pp.281

# FNS-ST: basic parameters and cut-view

| | |
|---|---|
| R, m | 0.5 |
| R/a | 1.67 |
| k | 2.75 |
| δ | 0.5 |
| $I_p$, MA | 1.5 |
| $B_T$, T | 1.5 |
| n, $10^{20}m^{-3}$ | 1 |
| $P_{wall}$, MW/m$^2$ | 0.2 |
| $E_b$, keV | 130 |
| $P_b$, MW | 10 |
| Angle NBI, deg | 30 |
| $P_{EC}$, MW | 5 |
| H-factor | 1-2 |
| $\beta_N$ | 5 |
| $f_{non-ind}$ | 1.0 |
| $P_{diss}$, TF, MW | 14 |
| $P_{diss}$, PF, MW | 6.0 |
| $S_{wall}$, m2 | 13 |
| $V_{pl}$, m3 | 2.5 |



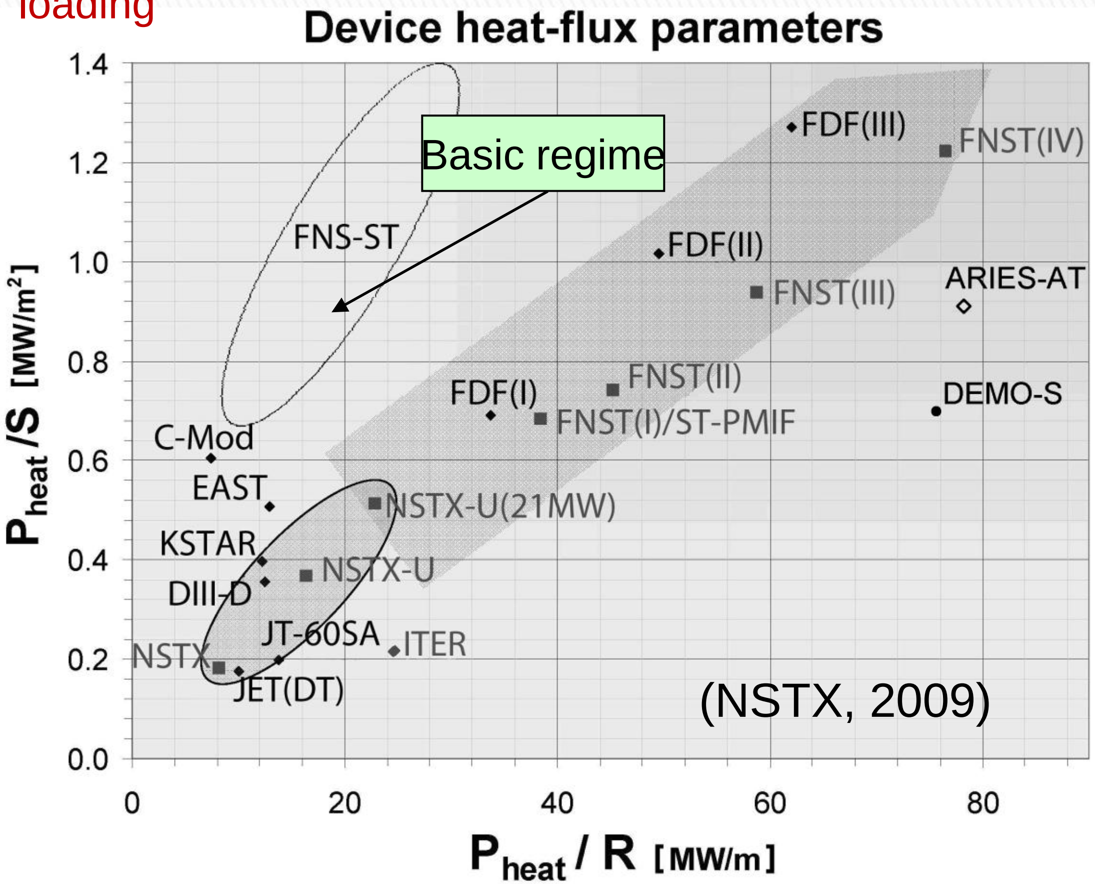

High shape device

$$S = \frac{I_p}{aB_T} q_{95} \sim \frac{1}{A}\left[1 + k^2(1+2\delta^2)\right] \sim 30$$

B. V. Kuteev et al. Nuclear Fusion **51** (2011) 073013

# Wall and divertor thermal loads

FW loading

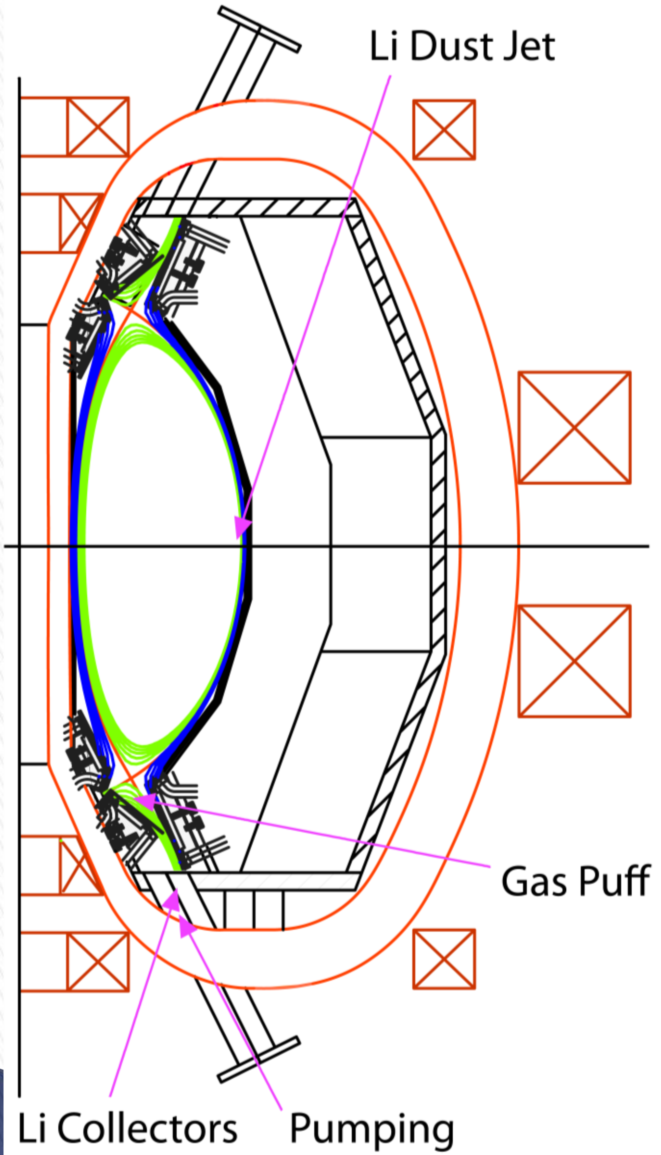



- ***$P_{heat}$/R and $P_{heat}$/S determine divertor plate and wall loads correspondingly***
- ***$P_{heat}$/R is of the order of ITER values,*** *therefore ITER divertor technologies may be used*
- ***$P_{heat}$/S is very high exceeding ITER values by factor of 3,*** *therefore ITER divertor technologies should be used for the first wall as well*

Divertor loading

- ***In basic FNS-ST regime $P_{heat}$/S is close to Alcator C-MOD values***

# FNS-ST divertor concept




Main divertor components are:

- ***Magnetic coils***
- ***Divertor cassettes; W tiles protected by lithium films***
- ***Lithium dust injectors and collectors*** *for plasma-wall interaction control*

B. V. Kuteev et al. Nuclear Fusion **50** (2010) 075001

- ***Pumping and gas supply systems***
- ***Local gas puffing for detachment (or partial detachment)***

V.Yu. Sergeev et al. Plasma Physics Reports, 2011 TBP

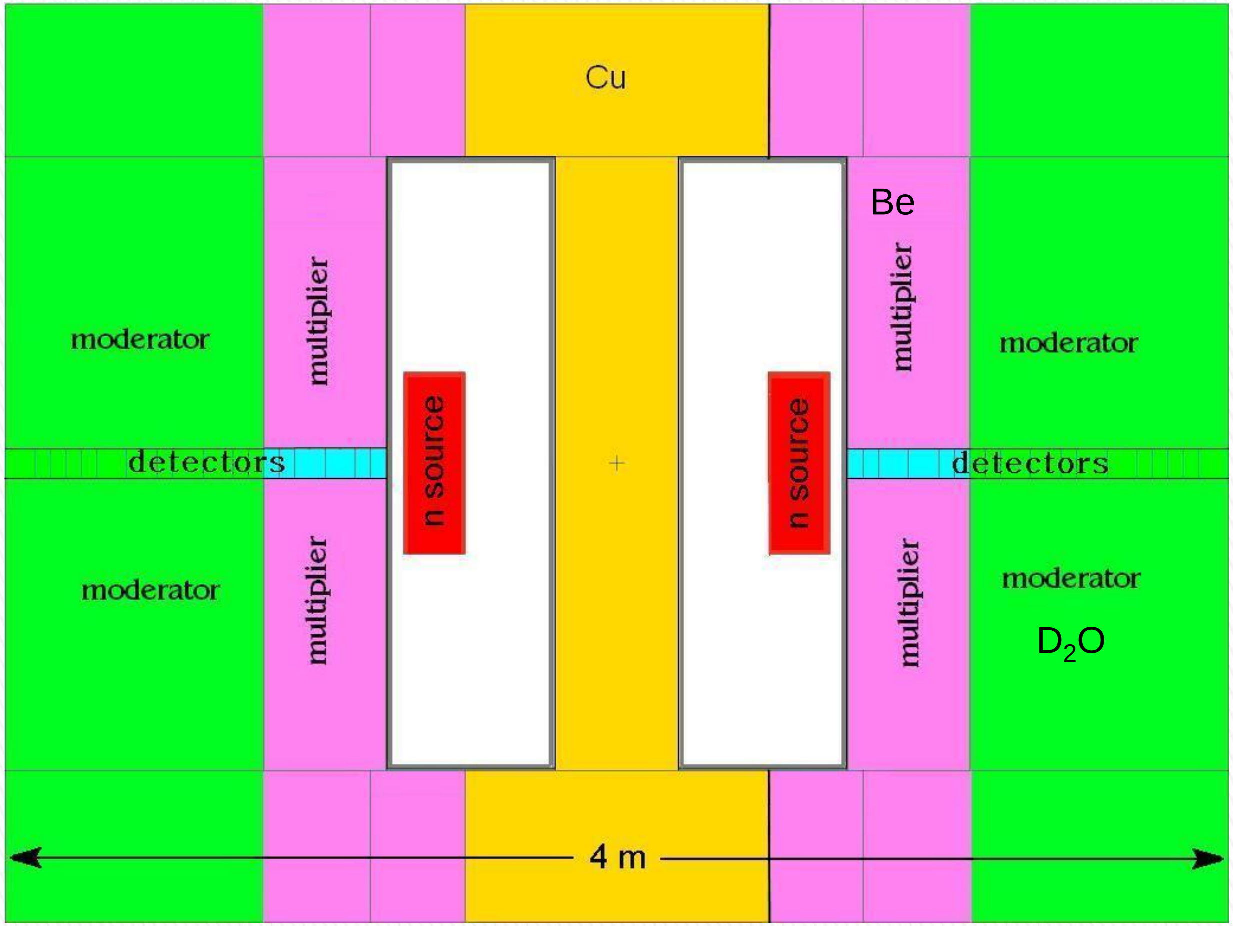
# Magnet system with twisted central pole

a) b) c)

The toroidal magnet system: Cu alloy, 20 tons, 80 m length, 250 kA current, 46.8 V, 11.7 MW, $T_{max}$ = 142° C (a) with twisted central pole (b).

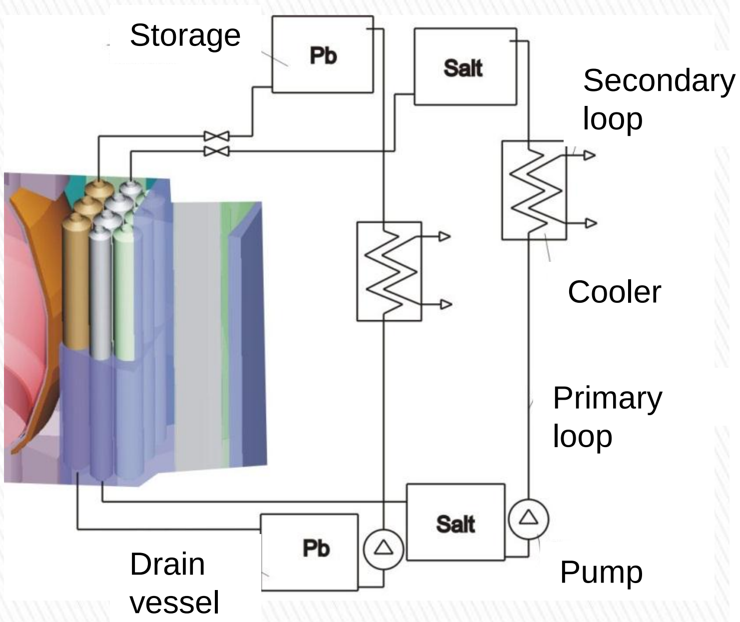
The vacuum vessel assembly is inside the TF magnet (c).

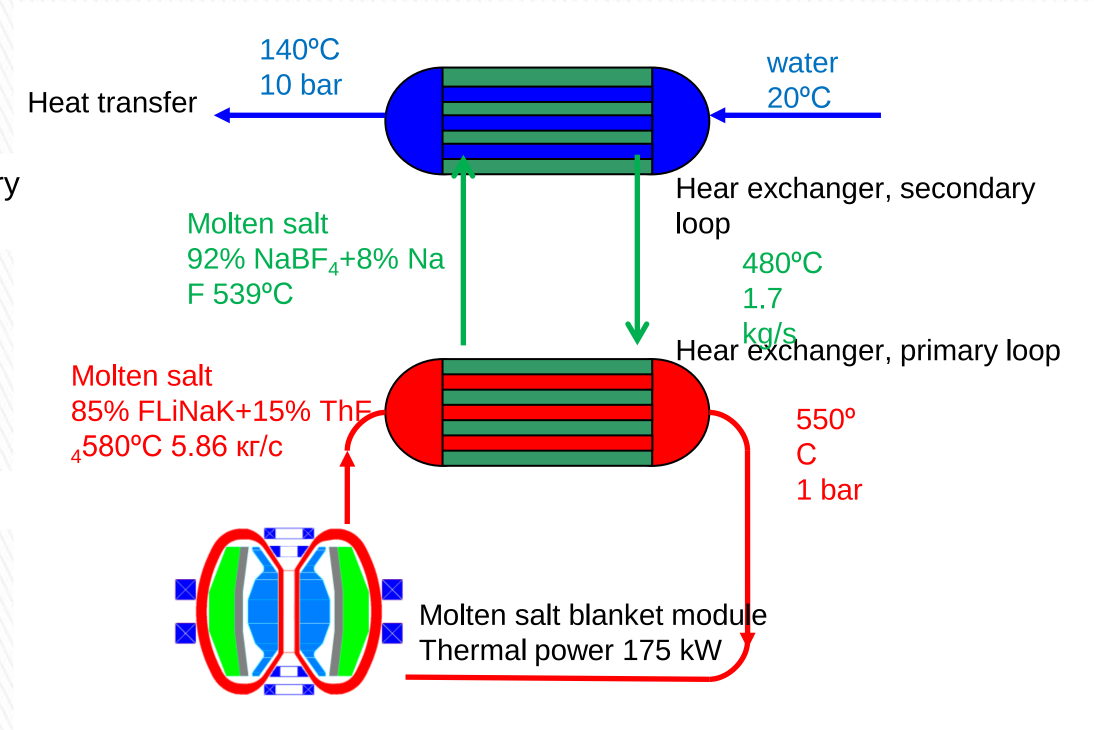
# Model used for FNS-ST neutronics




- Source strength $10^{18}$ n/s (3 MW) provides thermal neutron flux 5 $10^{14}$ n/cm$^2$s
- Be central post allows to reach ~$10^{15}$ n/cm$^2$s

# Two nuclear fuel cycles are considered




**U-Pu**

**1Pu+1T per 1n(DT)**

**Th-U**

**0.6U+1T per 1n(DT)**

# Conclusions

- Development of “Fusion for neutrons” paradigm gives copper coil compact tokamak a chance to become a feasible **prototype** for commercial applications
- Demonstration FNS prototype urgently needs SSO technologies
- MW range FNS is sufficient to demonstrate new neutron and hybrid technologies
- FNS needs further research on specific issues of anisotropy plasma physics and advanced fusion technologies and materials
- More concepts of neutron applications are needed to advance fusion development

-> Conceptual design stage of FNS-ST in 2011-2012

# Demand for E&N from Fusion

**F4Energy** **ITER -> DEMO -> PROTO** pure fusion

**Q = 5 -> ~30 -> >30**

**F4Neutrons** **FNS-P -> FNS-D -> FNS-C -> FNS-T -> FNS-F** hybrids

plasma demo control transmutation fuel

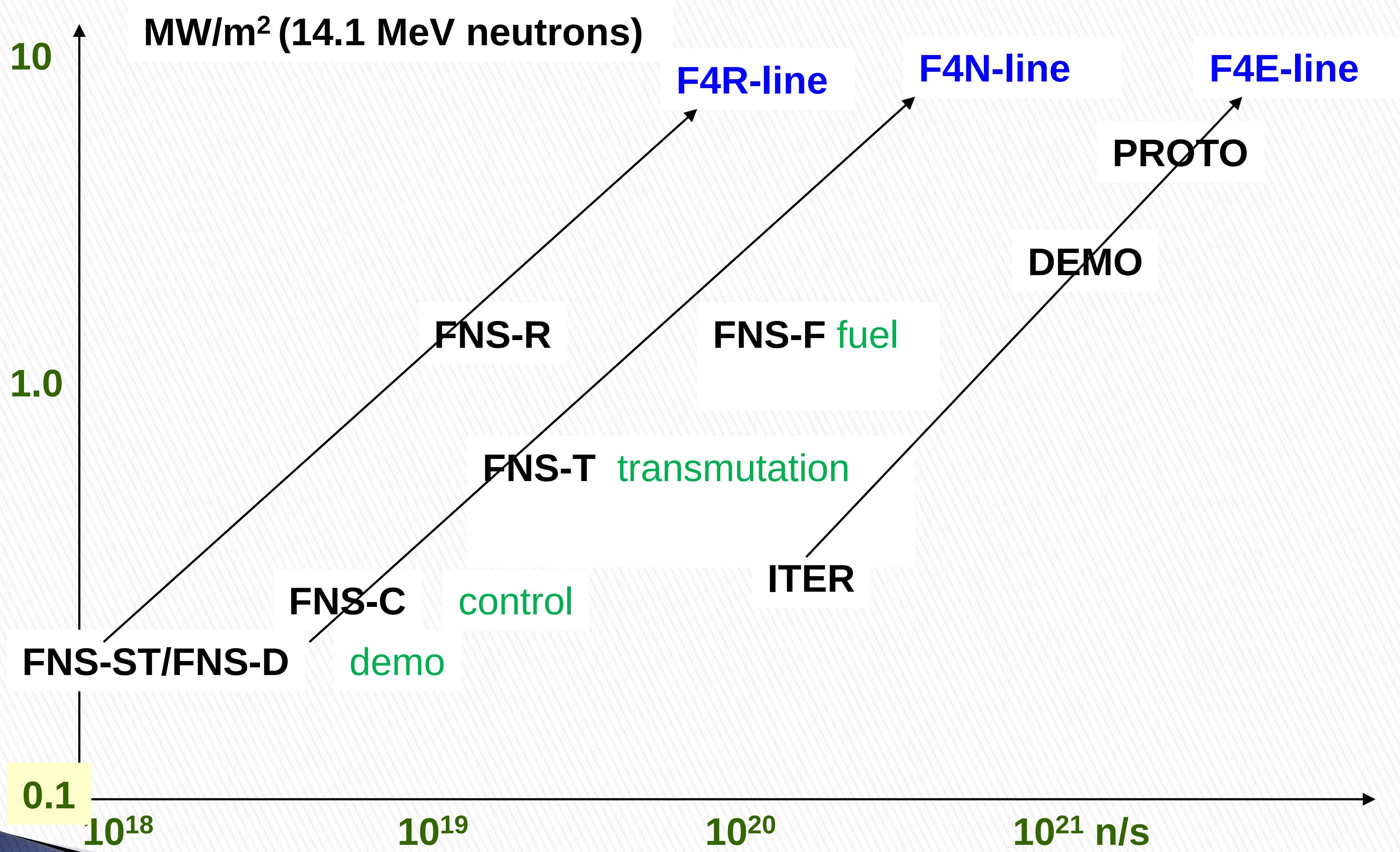
**N-Rate = 0 -> ~$10^{18}$ -> $10^{19}$ -> > $10^{20}$ n/s**

**F4Research** **FNS-ST -> FNS-R** pure and hybrids

**N- thermal flux = ~$10^{15}$ -> $10^{16}$ n/cm$^2$s -> $10^{17}$ n/cm$^2$s**

Ignitor

# Neutron loading and production rate




**FNS-P: SSO plasma in neutron design is needed**