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Megawatt Range Fusion Neutron Source for Technology and Research

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Abstract

Advances in fundamental science and many of the modern special and innovative technologies are associated with the use of high-output sources of neutrons. At the present time the most powerful neutron sources are constructed on the basis of fission reactors and charged particle accelerators. However, due to the high cost and engineering problems fission reactor and accelerator sources can hardly be expected to appreciably surpass the level of 10^{18} neutrons per second either in the near-term or in the long-term perspective. Controlled nuclear fusion reactions in tokamaks offer a possibility to create stationary neutron sources with strengths of 10^{16}-10^{20} n/s. Up to date tokamaks have already demonstrated the generation of 5×10^{18} neutrons per second with neutron energy 14.1 MeV in D+T reaction and 5×10^{16} neutrons per second with neutron energy 2.5 MeV in D+D reaction. So far, tokamaks have not been considered to serve as research-oriented neutron sources. Our analysis shows that the achieved level of tokamak technologies is feasible to create a unique and world's most powerful 14.1 MeV neutron source with 10 MW power using D+T reaction or 2.5 MeV neutron source with 0.1 MW power using D+D reaction. These possibilities rely upon the realization of fusion reactions in a two-component (beam-plasma) spherical tokamak where a significant contribution to the fusion power occurs from the interaction between fast suprathermal beam deuterons and bulk plasma nuclei. In this scheme optimal plasma parameters (density and energy confinement time) are lower than those necessary to maintain the same fusion rate in a Maxwellian plasma. If 14.1 MeV neutron breeding is used on Beryllium or Uranium, the source strength may be increased by a factor of 2 or 5 respectively. The spherical tokamak approach may be recommended for research neutron sources and fusion-fission hybrid demonstration experiments.

1. Applications of powerful neutron sources

Neutron Technology and Fusion = Femtotechnology

Two devices useful for potential applications of neutrons

I Hybrid reactors

- **external neutron source**
- **sub-critical active core**
- **coupling of NS and active core**
- **fuel cycle**

(Main topic of this Workshop)

see also B.V Kuteev and V.I. Khripunov (VANT, Fusion, No. 1, 2009, in Russian)

II Neutron sources for technology and research

- **general physics**
- **nano- and biotechnology**
- **material science**

In this presentation we talk about research neutron sources and hybrids based on tokamak concept

Neutron applications

Numerous applications of fusion neutrons had been considered earlier by DOE-FESAC, ARIES etc.

- Hydrogen fuels
- Transmutation
- Electric power
- Process heat
- Detection
- Radioisotopes
- Desalination
- Radiotherapy
- Activation analysis
- Radiography
- Tritium production
- Fission fuel breeding

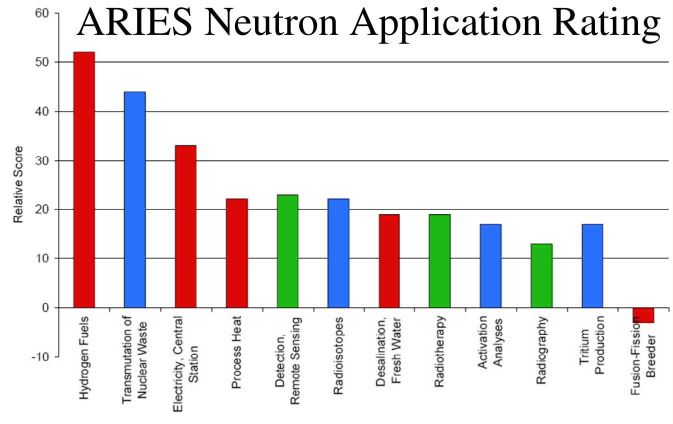
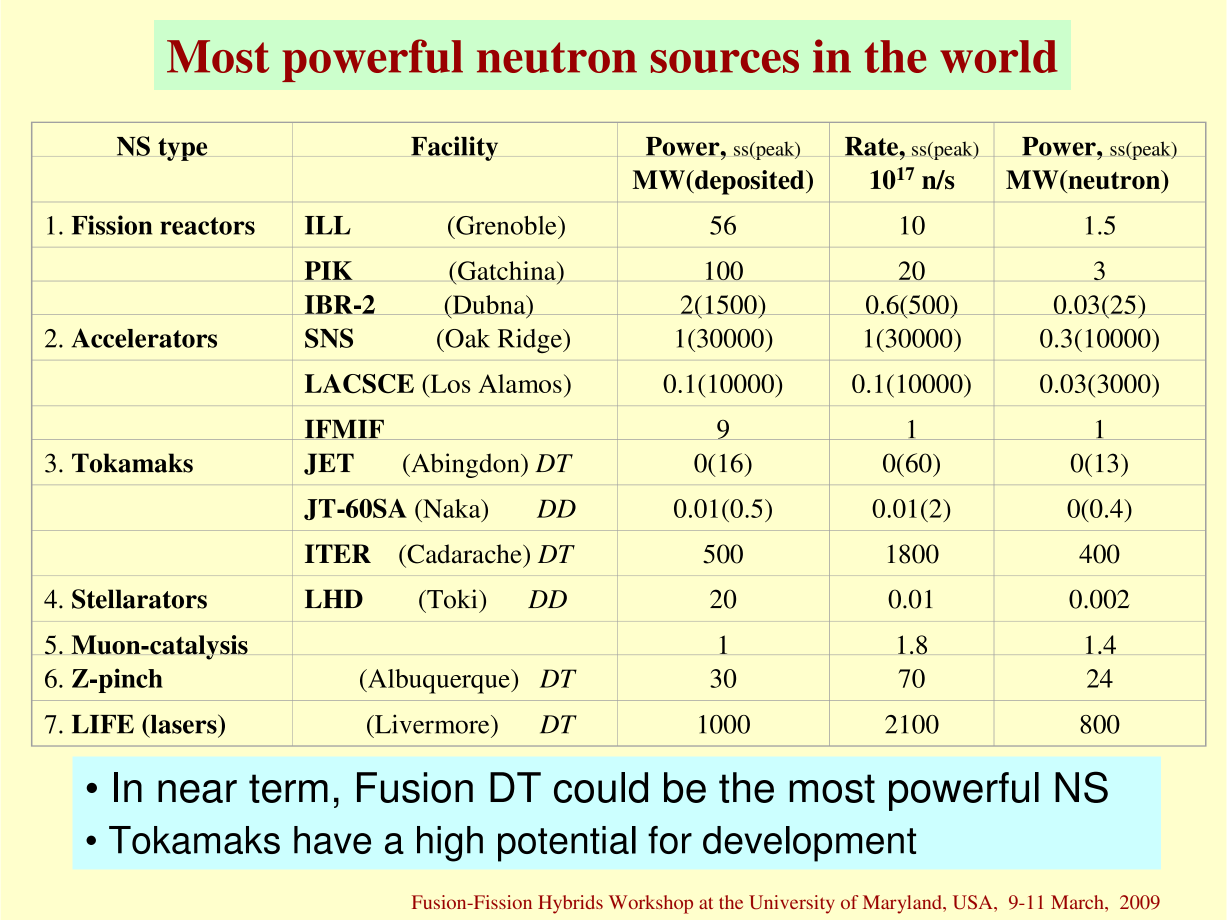


Figure 2-2. Ranked Weighted Values Of Fusion Products

Both research sources and hybrids are needed

2. Neutron Sources - State of the Art



Most powerful neutron sources in the world

NS type	Facility	Power, ss(peak)	Rate, ss(peak)	Power, ss(peak)
		MW(deposited)	10^{17} n/s	MW(neutron)
1. **Fission reactors**	**ILL** (Grenoble)	56	10	1.5
	PIK (Gatchina)	100	20	3
	IBR-2 (Dubna)	2(1500)	0.6(500)	0.03(25)
2. **Accelerators**	**SNS** (Oak Ridge)	1(30000)	1(30000)	0.3(10000)
	LACSCE (Los Alamos)	0.1(10000)	0.1(10000)	0.03(3000)
	IFMIF	9	1	1
3. **Tokamaks**	**JET** (Abingdon) *DT*	0(16)	0(60)	0(13)
	JT-60SA (Naka) *DD*	0.01(0.5)	0.01(2)	0(0.4)
	ITER (Cadarache) *DT*	500	1800	400
4. **Stellarators**	**LHD** (Toki) *DD*	20	0.01	0.002
5. **Muon-catalysis**		1	1.8	1.4
6. **Z-pinch**	(Albuquerque) *DT*	30	70	24
7. **LIFE (lasers)**	(Livermore) *DT*	1000	2100	800

- In near term, Fusion DT could be the most powerful NS
- Tokamaks have a high potential for development

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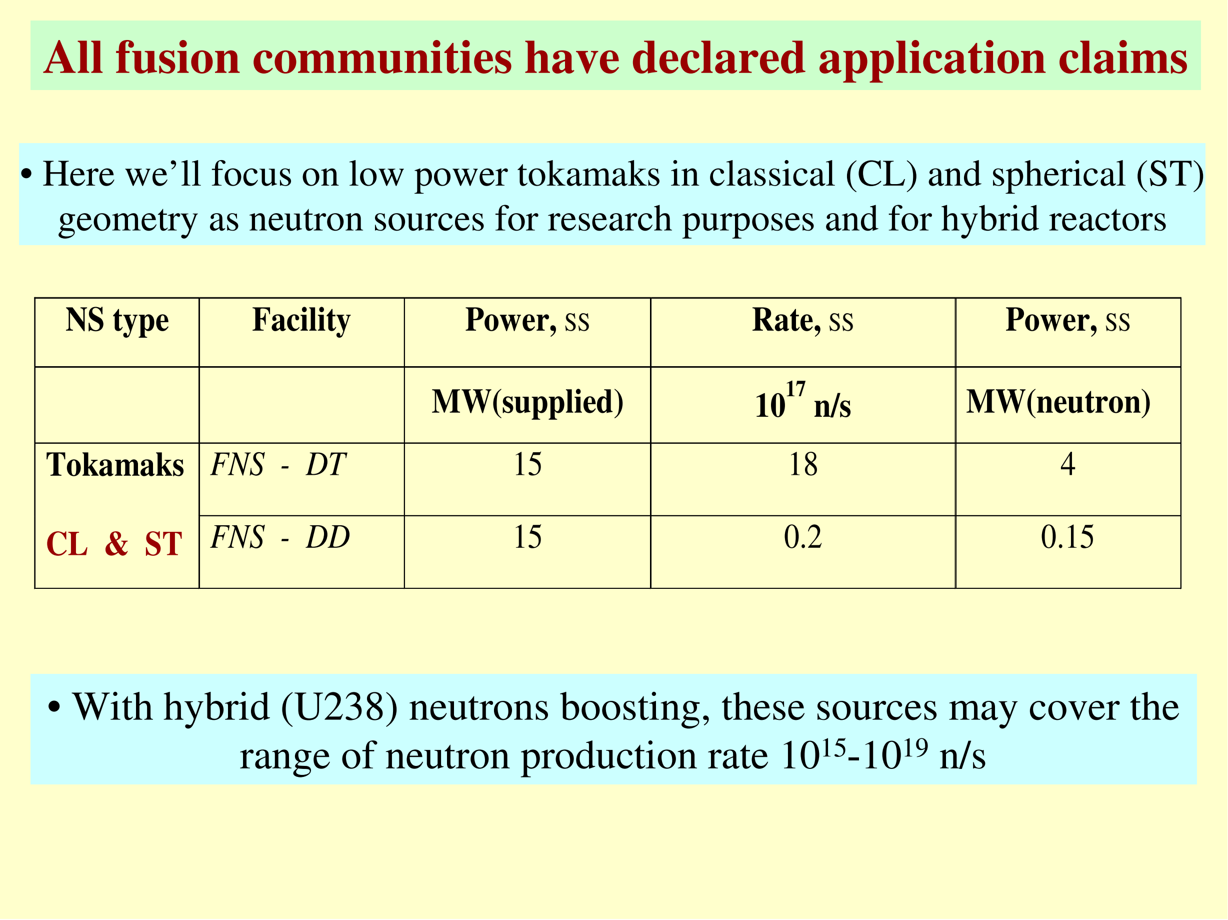


All fusion communities have declared application claims

- Here we'll focus on low power tokamaks in classical (CL) and spherical (ST) geometry as neutron sources for research purposes and for hybrid reactors

NS type	Facility	Power, ss	Rate, ss	Power, ss
		MW(supplied)	10^{17} n/s	MW(neutron)
Tokamaks	*FNS - DT*	15	18	4
CL & ST	*FNS - DD*	15	0.2	0.15

- With hybrid (U238) neutrons boosting, these sources may cover the range of neutron production rate 10^{15}-10^{19} n/s

3. Demands and reachable neutron source parameters

“Commercially produced turn-key neutron sources are readily available with source strengths up to 10^{13} n/s (e.g., AccSys Technology, Inc. model PL-11).

Low-power neutron sources, with source strengths up to 10^{14} n/s, such as the Low Energy Neutron Source (LENS) facility, now under construction at Indiana University, USA, require a local capability in accelerator technology and engineering, and a capital investment in the range of \$10M to \$30M, with operating costs that are 10 to 15% of the capital cost.

Medium-power pulsed neutron sources (e.g., ISIS in the UK, and the Lujan Center in the USA), with source strengths up to 10^{16} n/s, require substantial infrastructure to design and construct. Costs associated with a medium-power facility are an order of magnitude more than that of a low power facility.” IAEA-TECDOC-1439

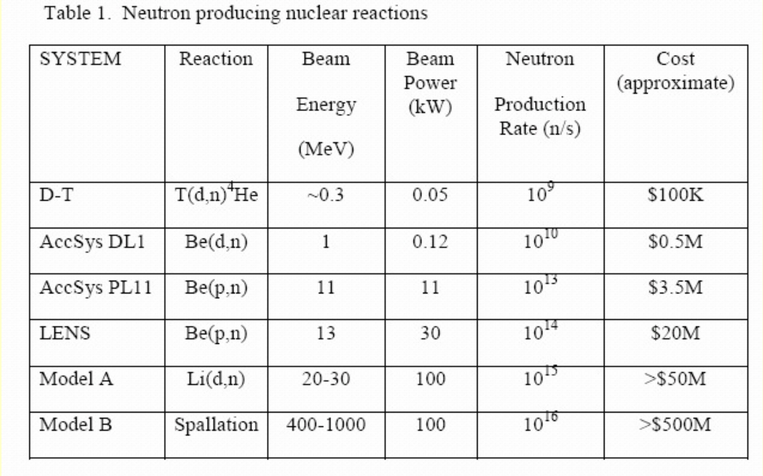
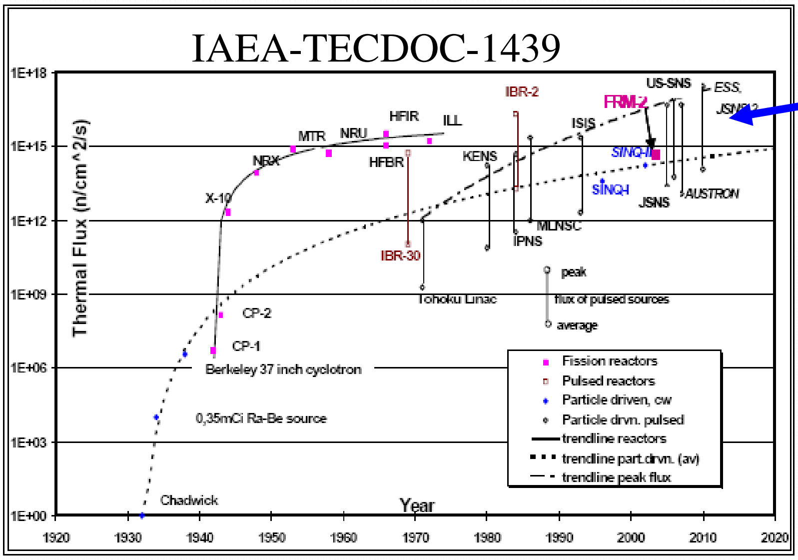


Table 1. Neutron producing nuclear reactions

SYSTEM	Reaction	Beam Energy (MeV)	Beam Power (kW)	Neutron Production Rate (n/s)	Cost (approximate)
D-T	T(d,n)^{4}He	~0.3	0.05	10^9	\$100K
AccSys DL1	Be(d,n)	1	0.12	10^{10}	\$0.5M
AccSys PL11	Be(p,n)	11	11	10^{13}	\$3.5M
LENS	Be(p,n)	13	30	10^{14}	\$20M
Model A	Li(d,n)	20-30	100	10^{15}	>\$50M
Model B	Spallation	400-1000	100	10^{16}	>\$500M

- Free neutron is a very expensive product!
- Tokamak FNS makes neutrons cheaper



Tokamak FNS (10^{19} n/s)

- May become the leader among steady state NS in near future

Figure 1. Thermal neutron flux available at various neutron sources as a function of time since Chadwick’s discovery of the neutron. For pulsed sources, the vertical bar indicates the range spanned from the average flux to the peak flux available. Depending on the experiment being considered, the relevant parameter for comparison to a steady-state source could be on either extreme of these bars (or indeed somewhere in the middle). Italics indicate proposed projects.

A Comparison of Reactors & Short Pulse Spallation Sources (R.Pynn, 2006) +Tokamaks

Short Pulse Spallation Source	Reactor	Tokamak FNS
Energy deposited per useful neutron is ~20 MeV	Energy deposited per useful neutron is ~ 180 MeV	~40 MeV (1 fus. → 5 fiss.)
Neutron spectrum is "slowing down" spectrum – preserves short pulses	Neutron spectrum is Maxwellian	14 MeV
Constant, small $\delta\lambda/\lambda$ at large neutron energy => excellent resolution especially at large Q and E	Resolution can be more easily tailored to experimental requirements	Like both
Copious "hot" neutrons=> very good for measurements at large Q and E	Large flux of cold neutrons => very good for measuring large objects and slow dynamics	Deceleration spectrum
Low background between pulses => good signal to noise	Pulse rate for TOF can be optimized independently for different spectrometers	Like reactor
Single pulse experiments possible	Neutron polarization has been easier	Like reactor

Q – wave vector difference, E – energy of neutron

Tokamak FNS has similar or better features for many applications

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M. Matsukawa et al. FT/P7-5 FEC2006

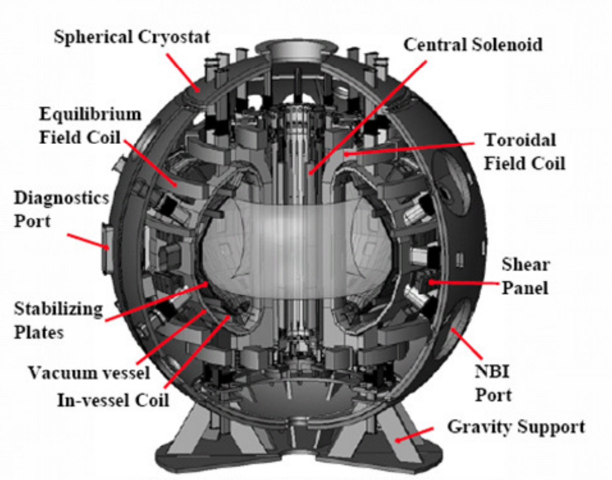


Fig. 1. Cut-set view of JT-60SA.

TABLE I: BASIC PARAMETERS OF JT-60SA.

Parameter	Large Plasma (DN)	ITER Similar (SN)
Plasma Current Ip (MA)	5.5	3.5
Toroidal Field Bt (T)	2.72	2.59
Major Radius (m)	3.01	3.16
Minor Radius (m)	1.14	1.02
Elongation, κ_{95}	1. 83	1.7
Triangularity, δ_{95}	0. 57	0.33
Aspect Ratio, A	2.64	3.10
Shape Parameter, S	6.7	4.0
Safety Factor q_{95}	3.77	3.0
Flattop Duration	100 s (8 hours)	
Heating & CD power	41 MW x 100 s	
N-NBI	34 MW	
ECRH	7 MW	
PFC wall load	10 MW/m^2	
Neutron (year)	4 x 10^{21}	

Tokamak JT-60SA, year 2014, 2x10^{17} n/s DD-fusion source

Options for fusion-fission demonstration experiment with 100 MW total FF-power

- **Auxiliary heating and magnetic systems set the cost of a demonstration experiment**

Constrains: Heating power < 15 MW
Dissipation in TF magnet < 10 MW

- **Superconducting coils are possible for classical tokamaks A > 2.5 providing high magnetic fields ~6 T**

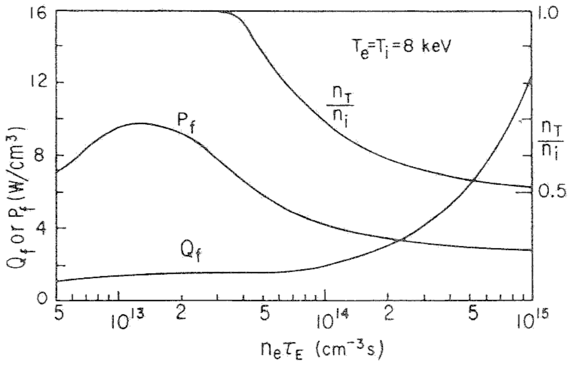
- **Copper coils with water cooling are simpler for spherical tokamaks**

Power dissipation constrains limit TF in ST to 1.5 T

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 is maximum at lower $n\tau_E$ ~10^{13} cm^{-3} s



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

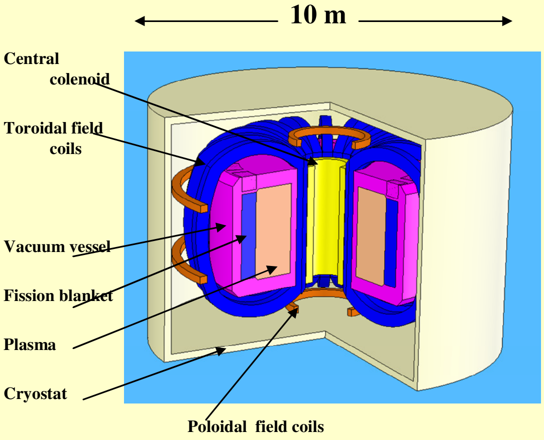
Dependence of P_f and Q_f on $n_e\tau_E$ for an 8-keV D-T plasma heated by 200-keV D beams. Maximum Q_f is attained for the plasma composition given by n_T/n_i, where n_i is the bulk-ion density. $p = 0.655$ J/cm^3. Radiation loss is included in τ_E. Alpha-particle effects are neglected.

4. Classical and spherical tokamaks as fusion neutron sources

Classical tokamak FNS (W.M. Stacey-like, fast spectrum core)

Basic plasma parameters

Fusion power D+T	5	MW
Fission power U238, Th232	145	MW
Fuel production (Pu, U)	85	kg/y
Tritium consumption	275	g/y
Electric power	<50	MW
Neutron energy	14,06	MeV
Neutron load (14 MeV)	0,1	MW/m^2
Neutron production rate	1,8 10^{18}	1/s
Major radius	2,34	m
Minor radius	0,75	m
Elongation	2	



Technologies to be demonstrated:

- Fusion-fission energy production
- Fission fuel production
- Transmutation
- Tritium production

Milestones

Conceptual design	2009
Engineering design	2010
Prototype	2015
Demonstration	2025

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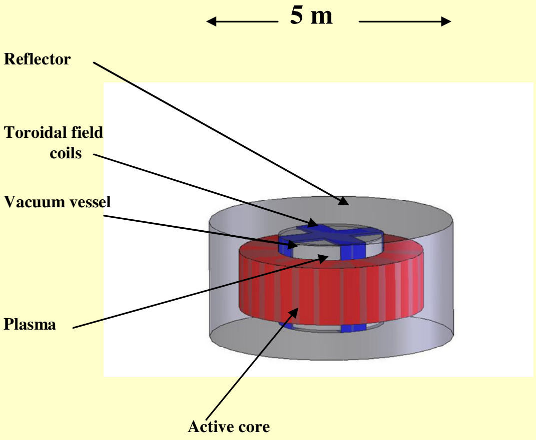
Spherical tokamak FNS with fast spectrum core

Basic plasma parameters

Fusion power D+T	1	MW
Fission Power U238, Th232	100	MW
Fuel production (Pu, U)	60	kg/y
Tritium consumption	55	g/y
Electric power	<30	MW
Neutron energy	14,06	MeV
Neutron load (14 MeV)	0,1	MW/m^2
Neutron production rate	3,8 10^{17}	1/s
Major radius	0,47	m
Minor radius	0,27	m
Elongation	3	



Technologies to be demonstrated:

- Technology and research source
  - Fission fuel production
  - Fusion-fission energy production
  - Transmutations
  - Tritium production

Milestones

Conceptual design	2009
Engineering design	2010
Prototype	2013

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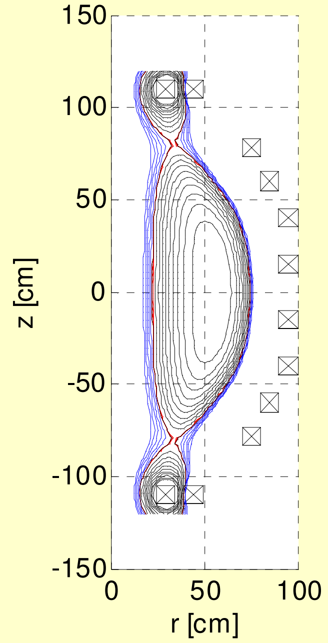
Basic parameters FNS-SC, FNS-ST and ITER

	FNS-SC superconductor	ITER	FNS-ST Copper coils
Volumes	Cubic meters		
Plasma chamber	52.57	1100	2
Shield	133.61	1227	0
Active core/blanket	38.65	316.8	5.93 (ring 0.74-1.34, 1.5)
Toroidal coils	31.2 (Nb_3Sn)	402(Nb_3Sn)	3 (Copper)
Magnetic field (center)	6.8 T	5.3 T	1.35 T
Surface	Square meters		
First wall	100	~1000	11
Power	MW		
Total thermal power	150	500	100
Neutron source	5	400	1
Cryogenics/Resistive	3	18	1 / 5.1
Additional heating	15	52	15
Neutron load (14 MeV)	MW/m^2		
Average	0.05	0.56	0.1
Cost	B$		
	0.8	10	< 0.2

Basic parameters FNS-SC, FNS-ST and ITER (contd.)

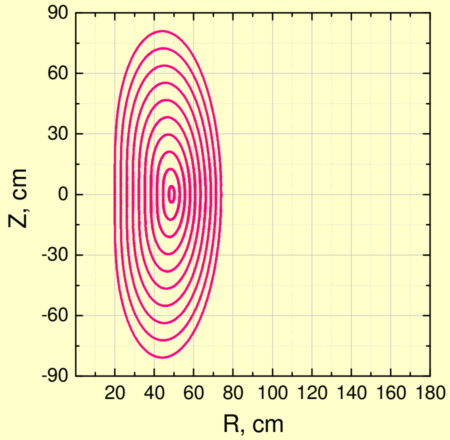
	FNS-SC superconductor	ITER	FNS-ST Copper coils
Current, MA	4	15	3
Density, 10**20 m-3	0.5	1.1	2
Temperature, keV	10	16	7
Elongation	1.7	1.7	3
Triangularity	0.5	0.4	0.5
q95	4.8	3	3.53
Confinement time IPB98, s	0.47	3.4	0.04
Beta toroidal	0.009	0.03	0.6
Beta poloidal	0.69	0.7	1.14
Beta normalized	1.1	2-2.9	7.4
Current drive, up to MA	4.0	4.27	3.9
Bootstrap current, MA	0.67	3.5	2
Greenwald density, 10^{20} m^{-3}	2.2	1.3	13



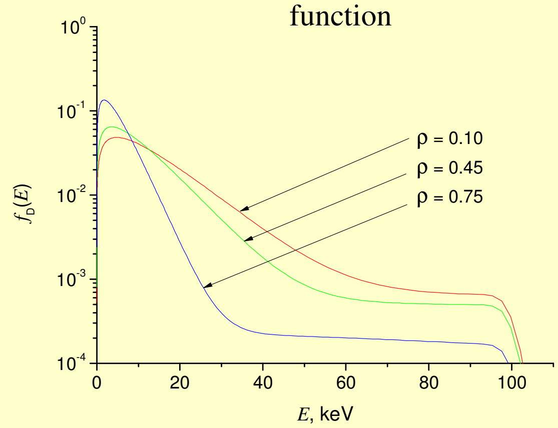
I_p, MA	3.0
q_{95}	3.53
B_t, T	1.35
β_t	0.61
β_N	7.25
$l_i(3)$	0.18
K_{sep}	3.10
a, cm	26.3
Δ_{up}	0.6
Δ_{dw}	0.6
R_{mag}, cm	54.6
R_{sep}, cm	33.0
Z_{sep}, cm	80.5

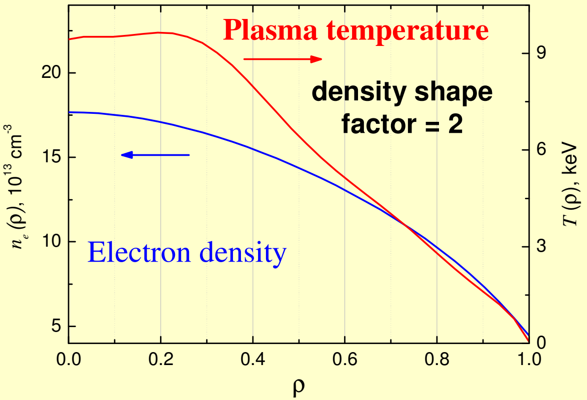
Plasma equilibrium in FNT-ST is reached in DINA simulations

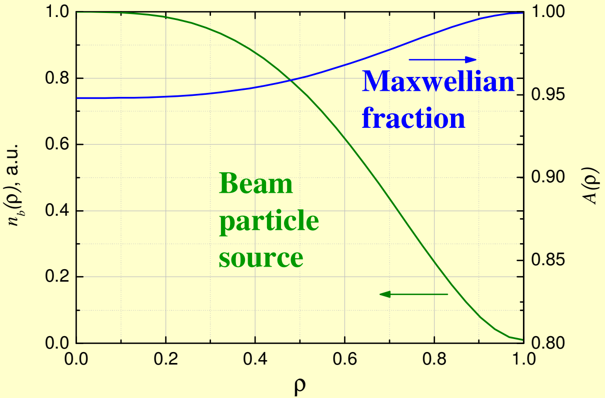
FNS-ST cross section



Deuteron distribution function



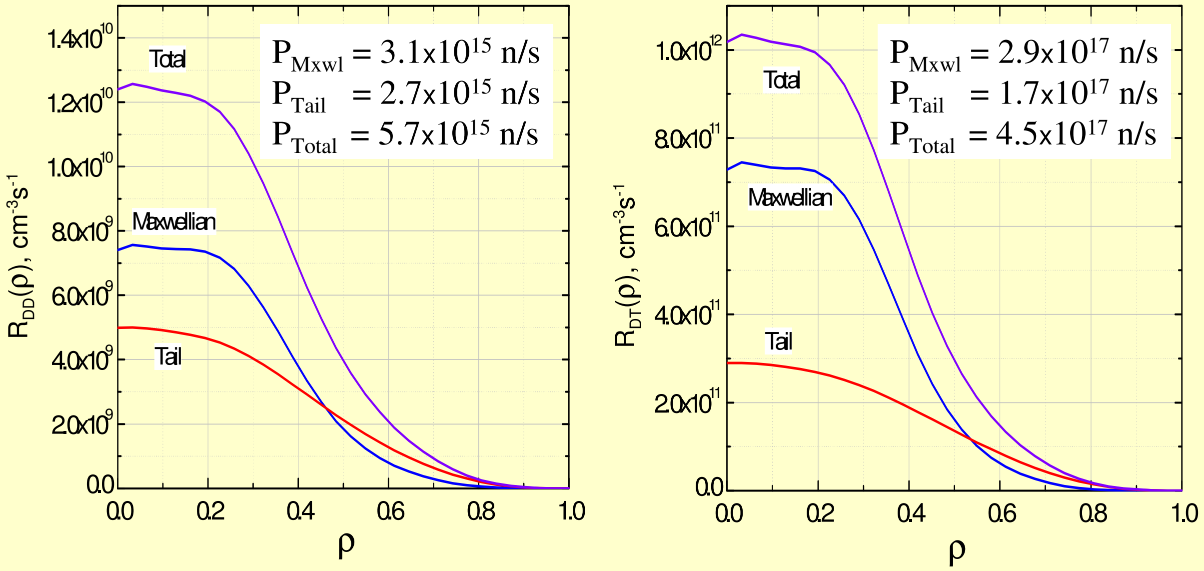




Neutron production rate in FNS-ST, shape factor = 2

Fusion rate DD

Fusion rate D:T =1:1



- Benchmarking on JET and TFTR experiments gives 50% accuracy

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Neutron production rate in FNS accounting for the beam plasma interaction (no beam ion orbit losses)

D beam 100 keV	**FNS-SC aV/D=0.5**	**FNS-SC aV/D=2**	**FNS-ST aV/D=0.5**	**FNS-ST aV/D=2**
100% D **(no T)**	9.04x10^{15} s^{-1}	9.25x10^{15} s^{-1}	5.10x10^{15} s^{-1}	5.73x10^{15} s^{-1}
50% D 50% T	6.54x10^{17} s^{-1}	6.73x10^{17} s^{-1}	3.77x10^{17} s^{-1}	4.51x10^{17} s^{-1}
100% T	2.03x10^{18} s^{-1}	1.63x10^{18} s^{-1}	8.40x10^{17} s^{-1}	6.32x10^{17} s^{-1}

- Source strength is higher than 5x10^{15} n/s (DD) and 3x10^{17} n/s (DT)

Shape factor aV/D = 0.5 corresponds to a broader density profile

How the simplest FNS should look like?

- Spherical two-component tokamak with water cooled copper coils
  R = 0.5 m, a = 0.3 m, k = 2-3, elongation = 0.5-0.6
  magnetic field B > 1.35 T, plasma current < 3 MA

- Steady state NBI 100-150 keV, < 15 MBт

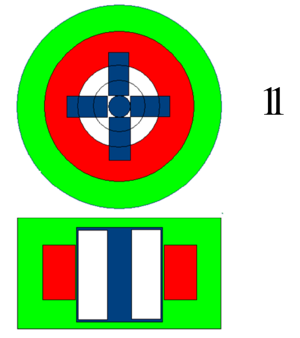
- Beam-plasma fusion Q_b = 0.5-0.8 (Jassby optimized)

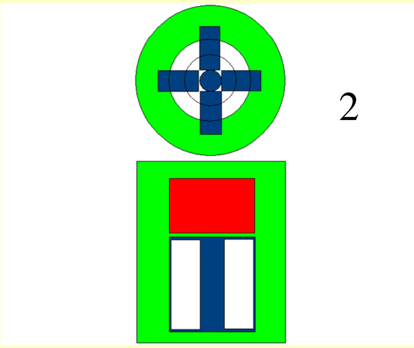
- Fusion power D+T < 7.5 MW; D+D < 0.1 MW

• Neutron production rate	up to 2×10^{18} n/s
• Total power consumption	< 30 MW
• Cost	< $ 0.2B
• Operation life	> 30 years

5. Coupling of a fusion neutron source and an active core in hybrid reactors

Options for NS and active core coupling





The first one is similar to M.Kotschenreuther (2009)

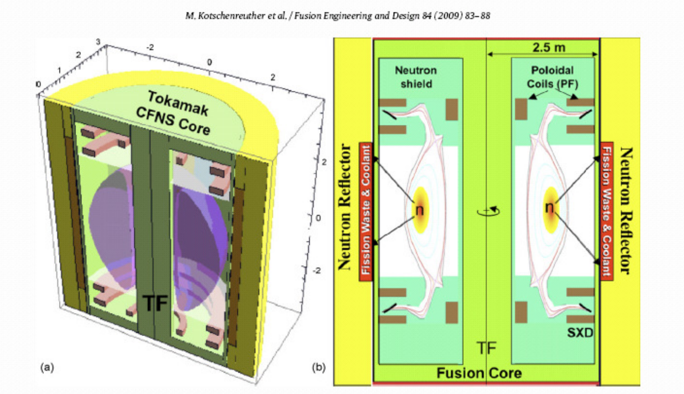
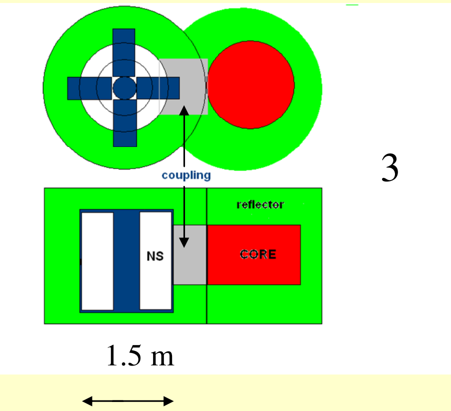

M. Kotschenreuther et al. / Fusion Engineering and Design 84 (2009) 83–88

Fig. 1. (a) 3D and (b) 2D schematics of a CFNS-based Fusion–Fission Hybrid shown with actual dimensions used in MCNPX [27] calculations.



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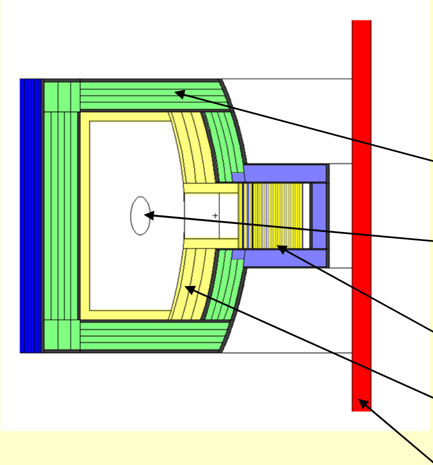
First evaluations of the neutronics for classical tokamak are optimistic



Coils

Plasma – source of primary neutrons

Active core

Be reflector-multiplier

Lead reflector

- **The active core $k_{eff} = 0.95$ is placed outside magnetic field**
- **Fission power is 91 MW at 5 MW source**
- **Changing the active core by natural Uranium blanket (0.7% ^{235}U) reduces the power by a factor of 10**
- **Depleted Uranium fuel (0.35% ^{235}U) reduces the power by a factor of 25**

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1. Applications of powerful neutron sources

It is natural to qualify nuclear reactions and the processes of neutron production as femtotechnology keeping in mind the characteristic 1-15 fm size of the interacting objects. The basic requirements are similar to NS for hybrids and research NS. A research source without fission may be simpler than a hybrid. A small difference exists between options I and II if a fission area exists in NS for neutron multiplication. Such NS is specified as a Neutron Factory. A high power neutron source is the key control element of hybrid fusion-fission reactors and the useful neutron producer for research purposes. Note that the rating of neutron applications may be volatile and politically sensitive. For some countries (China, Russia) the fission fuel production may be of high priority due to delays foreseen with mass implementation of fast reactor technologies.

2. Neutron Sources - State of the Art

For powerful neutron sources the typical neutron production rate is evaluated to be 10^{17} n/s. Fission reactors have reached 10-20 in these units for steady state (SS) and 500 for pulse mode (peak). Accelerator spallation sources have 1 and tend to 5 in SS regime, while they have up to 10000 in short nano- or microsecond pulses. Tokamaks have second pulse achievements up to 60 today (JET), however ITER operation will shift them to SS champion level of 1800. DD in JT-60SA will make tokamaks comparable with spallation NS. Stellarators have poor experience even in DD operation regimes. Muon catalysis intensities are close to those of spallation sources. For Inertial Fusion systems (both for Z-pinch and lasers) a production of up to 10^{19} neutrons per single shot may be reached in a few years. All fusion communities have declared application claims. This means that a strong competition between different approaches for a simple, reliable and cheap neutron source is likely to occur. Both DT and DD reactions are considered.

3. Demands and reachable neutron source parameters

Tokamak fusion neutron source (FNS) features are similar or better than those of reactors and accelerators for many applications. Since 1970 reactor sources are close to saturation of the flux reached. Spallation sources have overcome reactors in 1990s, however flux growth is rather slow. Tokamak FNS reaching 10^{19} n/s may become the leader.

We have analyzed opportunities of a low-cost fusion-fission experiment with emphasized application-oriented goals. We have come to a conclusion that 1-10 MW FNS is capable to provide neutrons for the low cost hybrid demonstration experiment with fission power of 100 MW grade. We used constrains for Heating power and Power used for magnetic field production. Classical tokamak option was considered with superconducting coils. Spherical tokamak was considered with copper coils. We should note that even MW fission power hybrid reactor based on DD fusion source is an interesting step to implementing the fusion and hybrid technologies. Due the low power and internal tritium poduction such experiments may become available and numerous. At the initial stage of hybrid technology development the MW power level seems to be sufficient and similar to fission reactor development history.

It should be emphasized that neutron production conditions (P_f) are different from those for energy production (with highest Q_f). Beam plasma interaction gives reasonable neutron production even at low $n\tau$. Q beam-plasma slowly decays with $n\tau$ and stays at 0.5-0.8 level in a wide range if the electron temperature is higher than 4 keV.The regime with optimal neutron production should be the essential design requirement.

4. Classical and spherical tokamaks as fusion neutron sources

A classical tokamak with 5 MW power may have the design similar to that considered by W.M. Stacey (2006) but 100 times smaller in power. This machine has small tritium consumption and plasma loads in the range studied by JET, TFTR. The technologies to be demonstrated are listed in the figure. Possible design and construction schedule may be within a decade. Power amplification factor about 30 allows using keff <0.95.

A spherical tokamak demonstration experiment was considered for fusion power 1 MW and higher fission-fusion amplification ~100. The major radius is ~ 0.5 m and the minor radius ~0.3 m. Such dimensions make the design to be compatible with research source requirements. The time schedule may be shorter ~ 5 years.

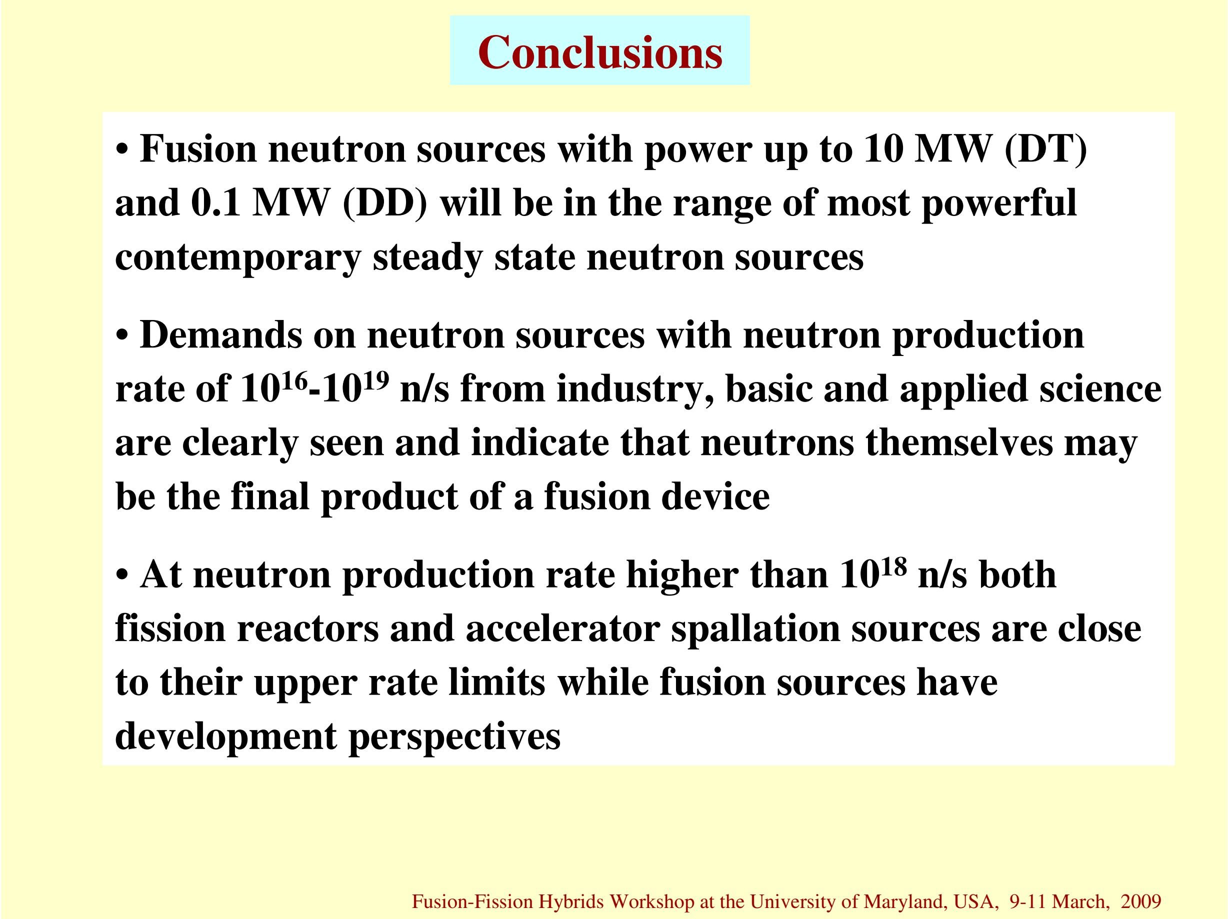
Basic parameters of SC (superconducting) and ST (spherical tokamak) versions are compared in the table with those of ITER. Volume of ST is only 2 cubic meters. No shielding is required for long-term operation of ST at <0.1 MW/m2. The cost of classical tokamak source will be lower than $1B. The cost of ST < $0.2B. Parameters of Classical tokamak are in the tested area so the confidence of reaching them is high. The ST parameters are close to the stability and heat load limits at 15 MW additional heating. However, 3-5 MW fusion power may be sufficient to reach 1 MW in neutrons.

Two-D neutron production rate was estimated for plasma parameters obtained in one-D simulations. The beam plasma ratio and ion distribution functions were also simulated one-D. In ST the beam (tail) and bulk plasma (Maxwell) fusion/neutron rates are comparable. In classical tokamak the beam input is higher. A wide range of neutron production rate from 10^{15} up to 2×10^{18} n/s is reachable varying D:T ratio and power. We have still not taken into account the orbit losses of the beam ions. This means that the simulation results may overestimate the production rate. We are working on this critical problem.

5. Coupling of a fusion neutron source and an active core in hybrid reactors

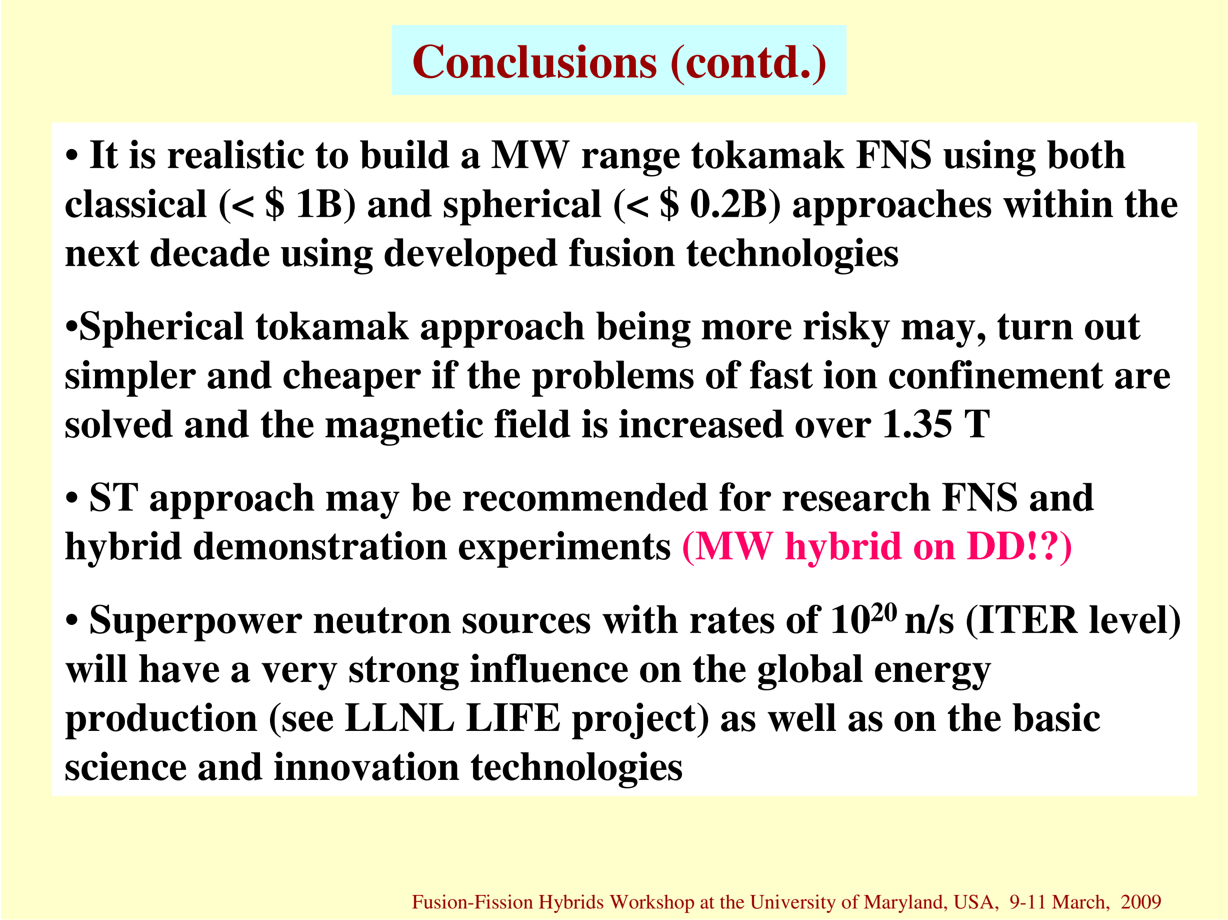
ST tokamak is more compatible for coupling with an active core in hybrids than the classical one. Several options have been considered. The coaxial placement (1) is similar to that considered by M. Kotschenreuther (2009). The axial geometrical arrangement (2) may be better for smaller active core sizes. The neighbor geometrical arrangement of the FNS and active core (3) may give design advantages as well. For classical tokamak we have considered geometrical arrangement of the active core outside the magnetic field, which allows using metal coolants. The simulation results are optimistic.

6. Conclusions



Conclusions

- Fusion neutron sources with power up to 10 MW (DT) and 0.1 MW (DD) will be in the range of most powerful contemporary steady state neutron sources
- Demands on neutron sources with neutron production rate of 10^{16}-10^{19} n/s from industry, basic and applied science are clearly seen and indicate that neutrons themselves may be the final product of a fusion device
- At neutron production rate higher than 10^{18} n/s both fission reactors and accelerator spallation sources are close to their upper rate limits while fusion sources have development perspectives



Conclusions (contd.)

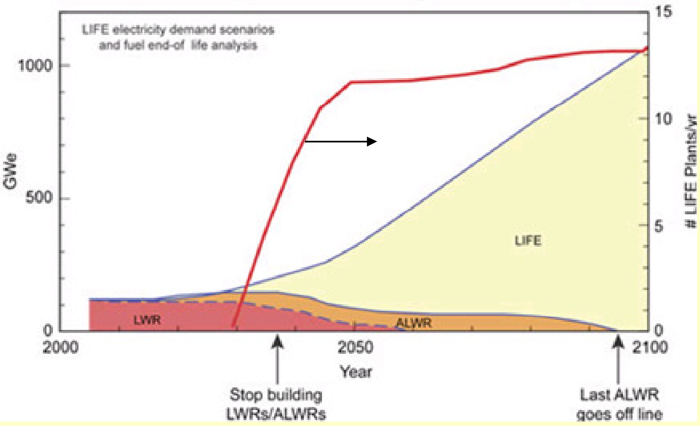
- It is realistic to build a MW range tokamak FNS using both classical (< $ 1B) and spherical (< $ 0.2B) approaches within the next decade using developed fusion technologies
- Spherical tokamak approach being more risky may, turn out simpler and cheaper if the problems of fast ion confinement are solved and the magnetic field is increased over 1.35 T
- ST approach may be recommended for research FNS and hybrid demonstration experiments (MW hybrid on DD!?)
- Superpower neutron sources with rates of 10^{20} n/s (ITER level) will have a very strong influence on the global energy production (see LLNL LIFE project) as well as on the basic science and innovation technologies

“LIFE could meet U.S. electricity needs from two nuclear waste streams: spent nuclear fuel (SNF) and depleted uranium (DU). The nation currently has about 53,000 metric tons (MT) of SNF and about 550,000 MT of DU. In the LIFE base scenario, the waste generated by LWRs and and ALWRs grows to about 120,000 MT of SNF and 1 million MT of DU by about 2030.” (https://www.llnl.gov/)

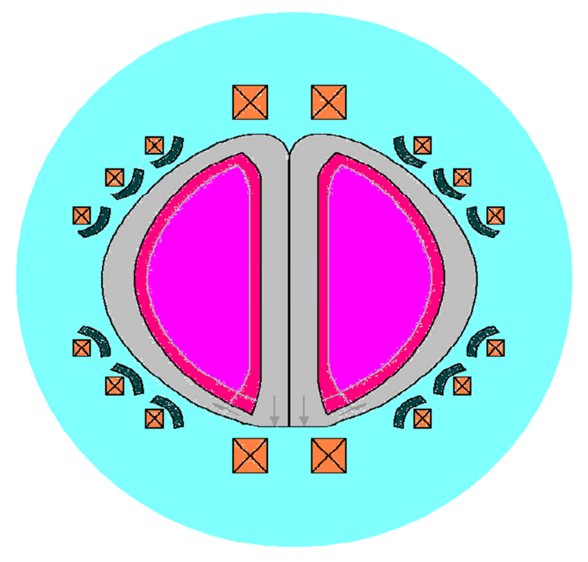
LLNL forecast assuming appearance of

10^{20} n/s neutron source

predicts total changing the existing power engineering



MW power tokamak FNS is a necessary step towards the future



Let us make 10^{23} fusion neutrons per year working for Kurchatov’s challenge to get “one gram per day”!