IAEA FEC 2016

26th IAEA Fusion Energy Conference

26th IAEA Fusion Energy Conference
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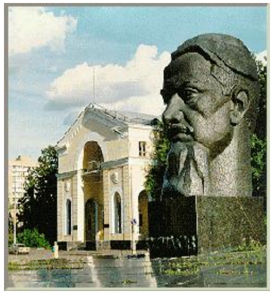
17-22 October 2016

FNS/1-1



NATIONAL RESEARCH CENTER
KURCHATOV INSTITUTE

НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ
ЦЕНТР «КУРЧАТОВСКИЙ ИНСТИТУТ»

STATUS OF DEMO-FNS DEVELOPMENT

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DEMO-FNS Team

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Outline

- **Introduction**
- Three-dimensional modeling of neutron flux in DEMO-FNS
- First wall material damage
- Scenario for new DEMO-FNS configuration
- Passive MHD stabilization
- Upgrade of enabling systems

  Superconducting magnet system

  Vacuum vessel

  Divertor cassettes

  Blanket

  Tritium fuel cycle
- **Conclusions**

Introduction

MISSION of DEMO-FNS:

- **Fusion-fission hybrid facility based on superconducting tokamak DEMO-FNS is developed in Russia for integrated commissioning steady-state and nuclear fusion technologies at the power level up to 40 MW for fusion and 400 MW for fission.**
- **Facility is considered in RF as the main source of technological and nuclear science information that complement the ITER research results in the fields of burning plasma physics and control.**

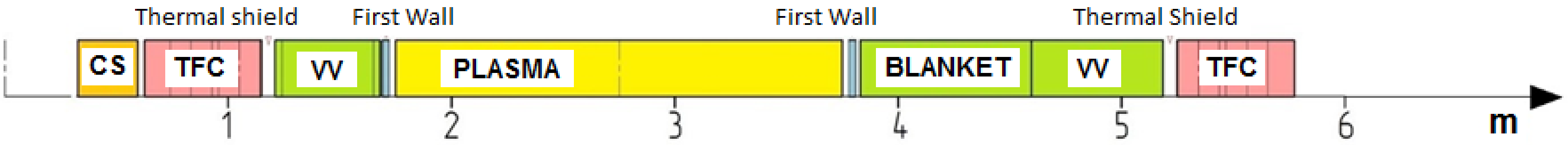
Design challenges for Q~1 tokamak in hybrid system

- **SSO**
- **Neutron environment (heating, insulation, testing, etc.)**
- **Remote handling**
- **Integration (tokamak – hybrid blanket; blanket & nuclear fuel cycle)**
- **Economics & Legislation**

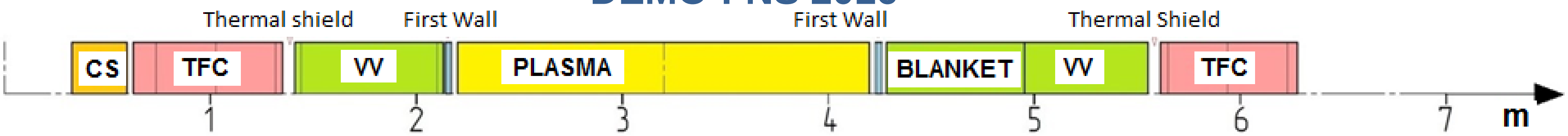
Changes of DEMO-FNS 2016 vs 2015

Development of Design
NF 55 2015 (073035)

DEMO-FNS 2015

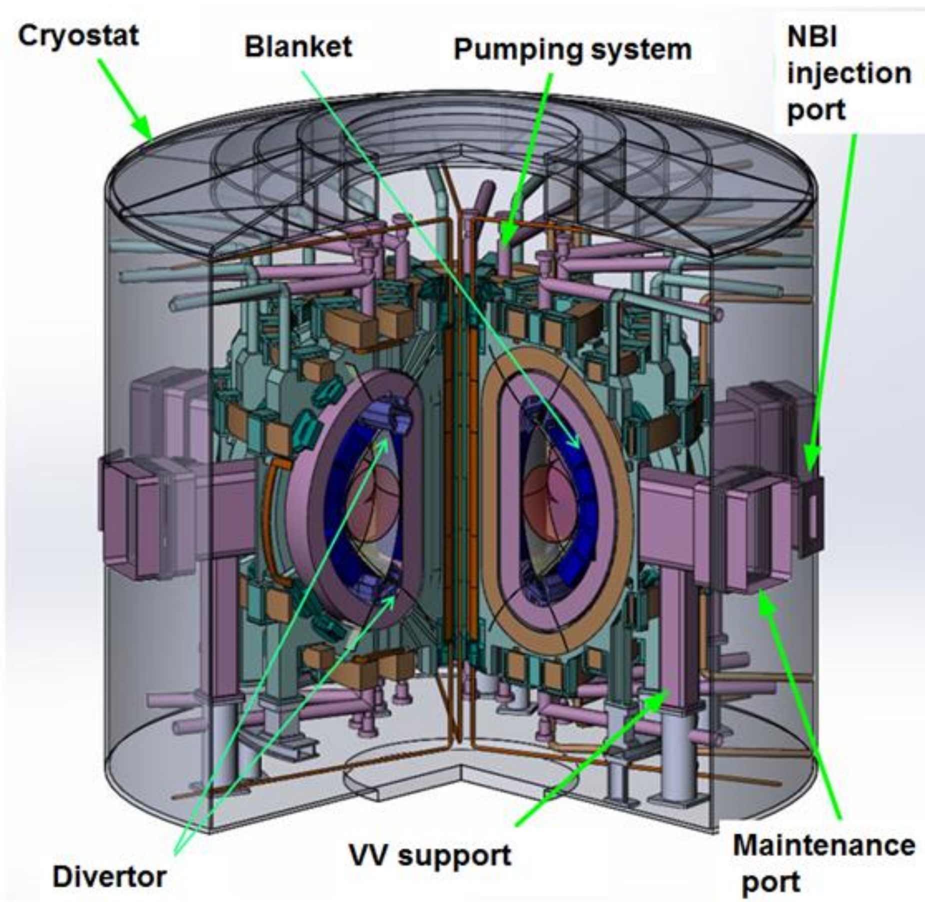


DEMO-FNS 2016



Parameters	2015	2016
Nuclear heating limit, mW/cm^3	1	0,05
Current density $\langle j_{TFi} \rangle$, MA/m^2	24	18
Toroidal coils width, m	0.525	0.725
Shielding thickness, m	0.470	0.720
Major radius R, m	2.75	3.2
Plasma elongation, k_X/k_{95}	2.1/2.0	2.0/1.9
Toroidal field max B_c ,T	12	12
Magnetic Ripples d_{ripple}, %	0.15	0.28

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	$>10^{19}$
Consumed/generated electric power,	MW	up to 200
Discharge time,	h	up to 5000
Capacity factor		0.3
Life time,	years	30

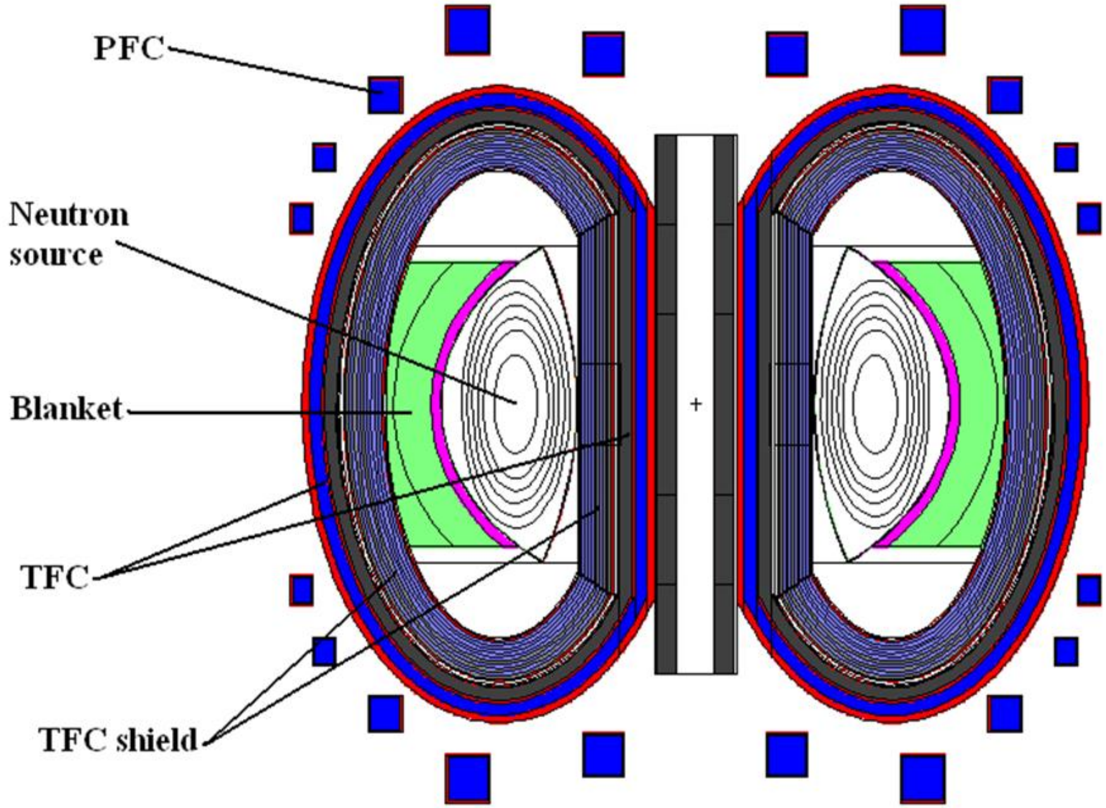
Cutaway view of DEMO- FNS tokamak

Three-dimensional modeling of neutron flux

Materials of concern
- Superconductors
- Insulation
- Structural materials
- Plasma facing components

Zones of concern
- Central pole
- Ports for NBI

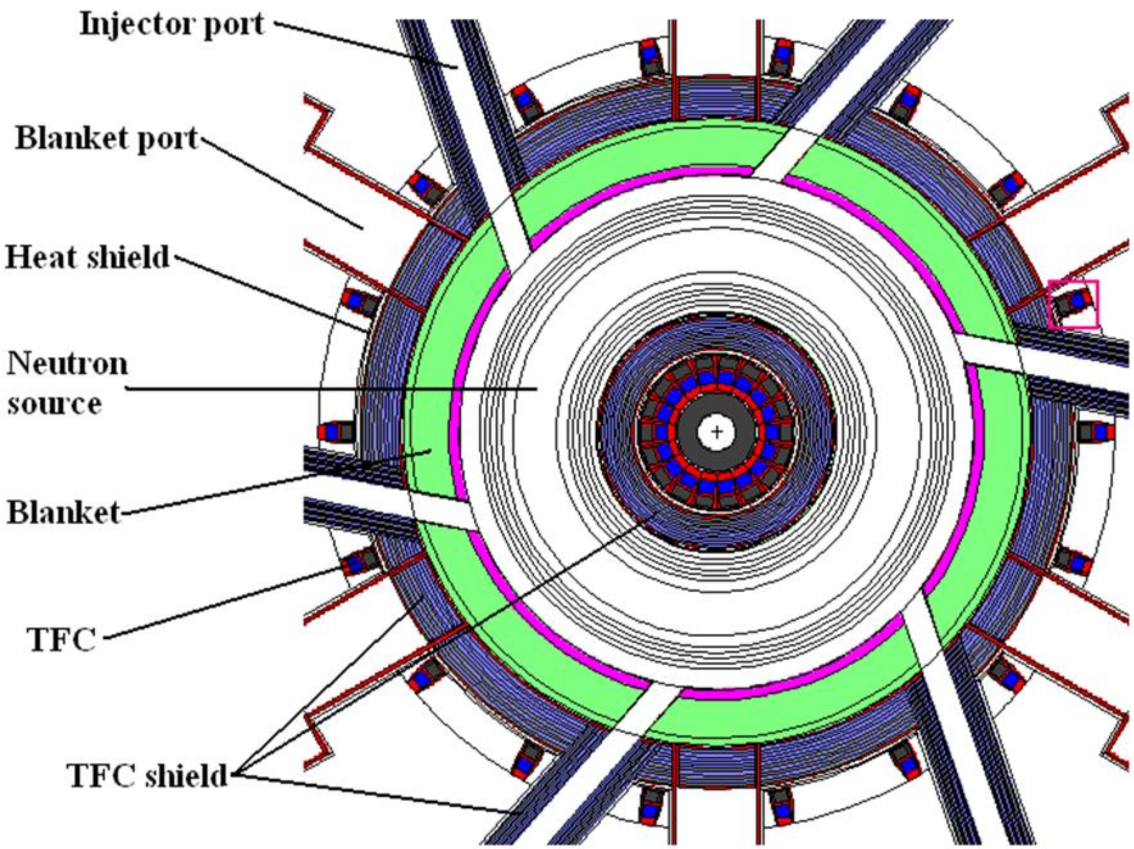
A.V. Zhirkin et al.
FEC-26 FNS/P5-11



Vertical cross-section of DEMO-FNS neutronics model

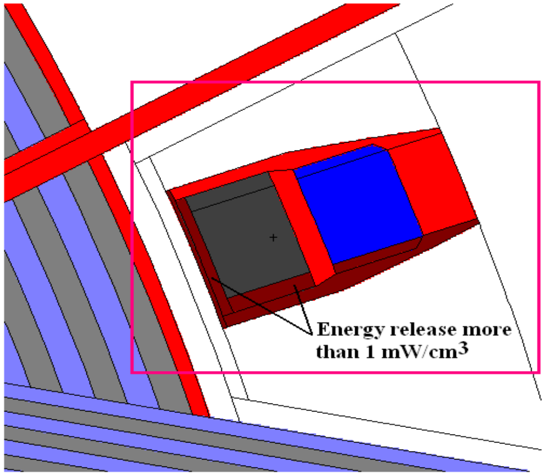
Requirements on calculation accuracy and benchmark experiment precision were addressed

Three-dimensional modeling of neutron flux



Horizontal cross-section of DEMO-FNS model

Zone with highest heat flux



- WC has high shielding effect
- SS/H_2O shielding is chosen as simplest and cheapest option

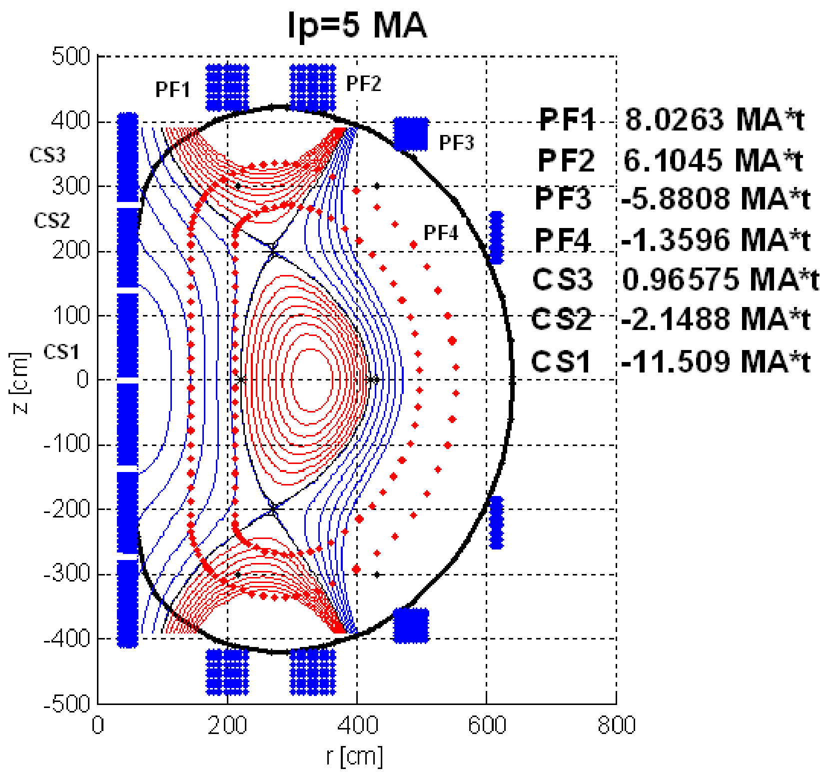
First wall material damage

- Neutronic performance and inventory analyses were carried out
- The D-T-neutron wall loading for DEMO-FNS is ~ 0.2 MW/m^2

FW component	Material	dpa per fpy	He, appm per fpy	T, appm per fpy	H, appm per fpy	Heat, W/cm^3
PFC (armour)	CFC	3.2	230	0.03	0.2	4.1
	Be	2.6	670	28	29	4.9
	W	0.90	~40	0.005	~900	~100
Heat sink	CuCrZr	3.2	22	0.2	150	25
Coolant	H_2O	0	25	~0.001	-20	5.7
Structure	SS	3.1	130	0.05	140	20
	Eurofer	3.0	130	0.02	90	22
	EK-164	3.2	160	~0.01	~160	21
	V-4Cr-4Ti	3.8	12	0.01	550	~20

- FW radiation damage for Hybrid System with k_{eff} 0.95 is ~2 times higher than that for pure fusion system under the same 14 MeV neutron FW loading

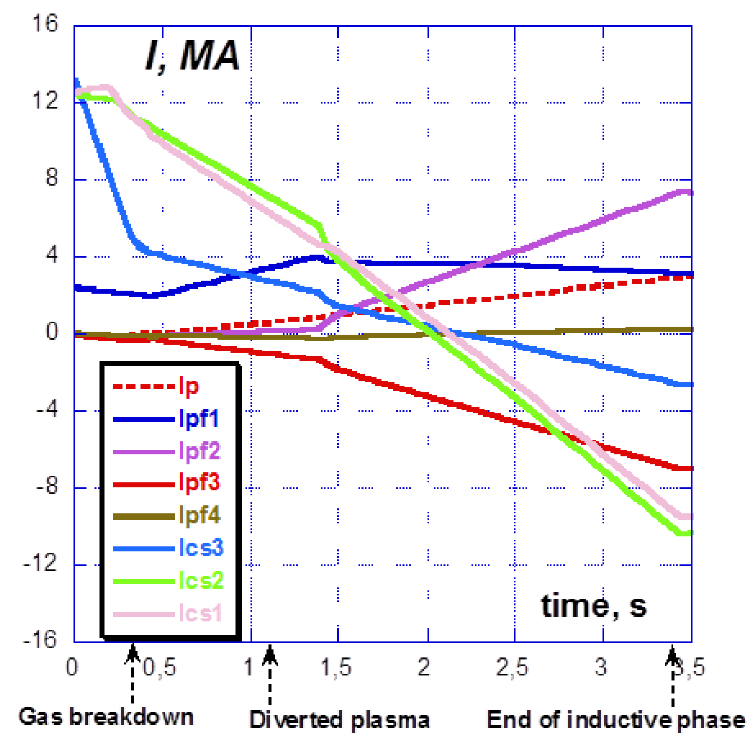
Magnetic configuration and scenarios for new DEMO-FNS design



The magnetic configuration was optimized for new design requirements to minimize currents in poloidal field coils

•*Unique feature – X-points are far from PFC*
→much higher currents needed (like in ITER)

➢ Discharge scenarios were simulated using DINA code



Evolution of currents at ramp-up stage

The current ramp-up scenario in DEMO-FNS

Time, s	0.1	3	300 (DD)	1000 (DT)
Ipl, MA	0.1	3	4.25	5.05
R, m	2.45	3.2	3.2	3.2
a, m	0.25	1	1	1
k	1	2	2	2
δ	0	0.5	0.5	0.5
β_{pol}	2.6	0.31	1	0.88
li	0.82	0.72	0.7	0.8
ψ_{res}, V*s	0	-1.43	-0.23	0.77
ψ_{tot}, V*s	8	0.1	0.12	0.12
ECRH, MW	1	3.5	6	6
NBI, MW	0	0	30	30
P_{α}, MW				12
<n>, $10^{19}m^{-3}$	2.5	8	8	8
H-factor	1	1	1.3	1.3
Neutrons, s^{-1}	-	-	$3x10^{17}$ (DD)	$2.3x10^{19}$ (DT)

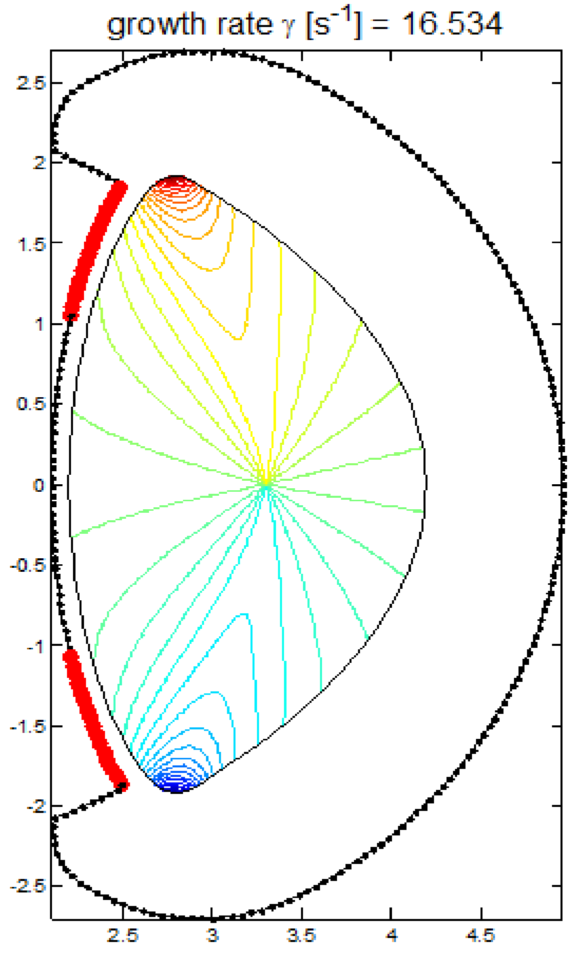
ASTRA code

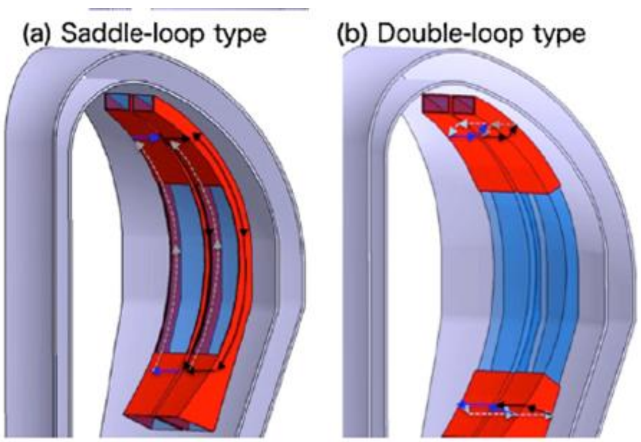
Scenario stages:

- **Breakdown period with current 0.1 MA during 0.1 s.**
- **Inductive current ramp-up to 3 MA in 3 seconds by a solenoid.**
- **A further current rise due to the generation of current on the beam, and the bootstrap current.**

Passive MHD stabilization

- ➢ **needed for vertical stability and control during current rump-up and SSO**





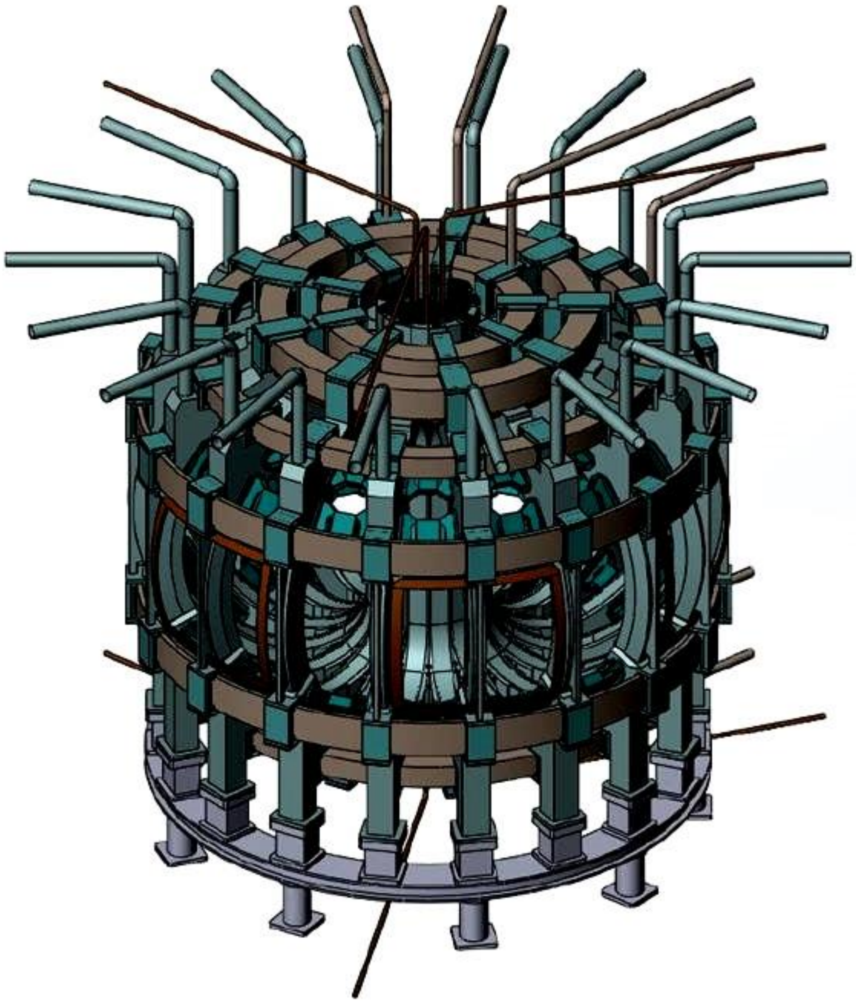
Hiroyasu Utoh et al. Fusion Engineering and Design 103 (2016) 93–97
← Sadakov (1992)

KINX level lines of the normal plasma displacement for n=0 vertical instability with the growth rate γ=17 s^{-1}.

Plasma controllable

Wall parts marked red assumed 10 times higher conducting than chamber walls (e.g. 0.75 cm of copper vs 3 cm steel)

Electromagnetic system of DEMO-FNS



General view of EMS

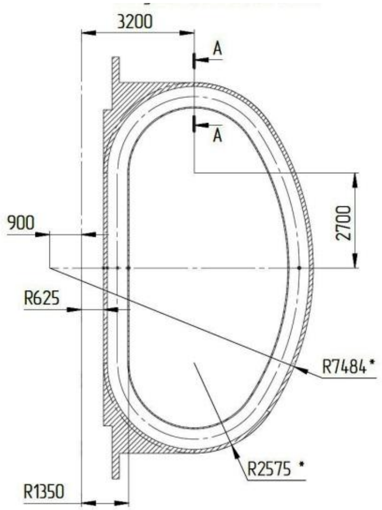
Superconducting electromagnetic system (EMS) of DEMO-FNS includes:

- **Toroidal field coils (TFC) -18 units**
- **Central solenoid (CS) sectioned**
- **Poloidal field coils (PFC) 4 pairs**
- **Correction coils (CC) 3 groups, 18 units**
- **Vertical control coils – 2 units**
- **HTS current leads**

materials:

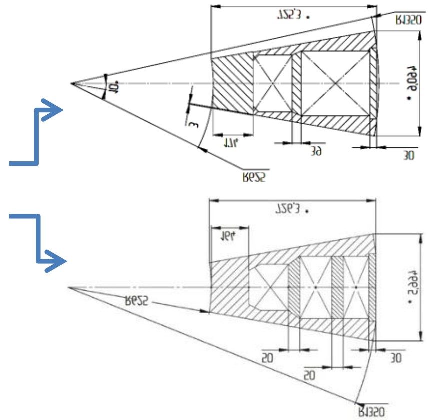
Nb_3Sn, NbTi, HTS,
SS, Cu-alloys
Polyimide insulator
He-coolant

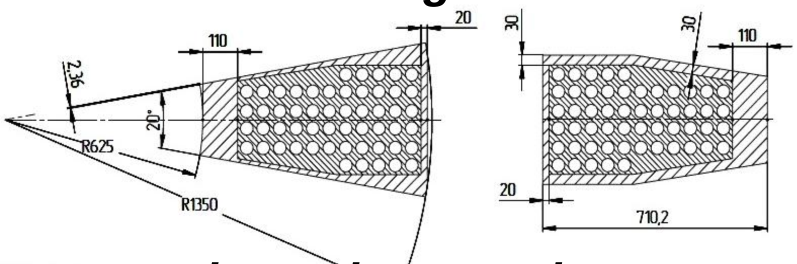
Torioidal field coils



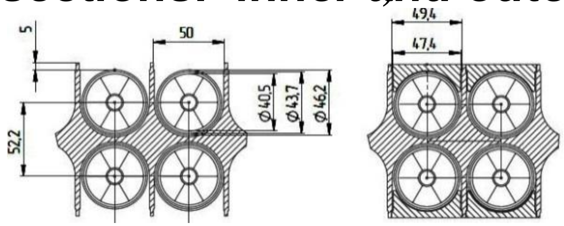
Coil unit of TFC in casing

Options

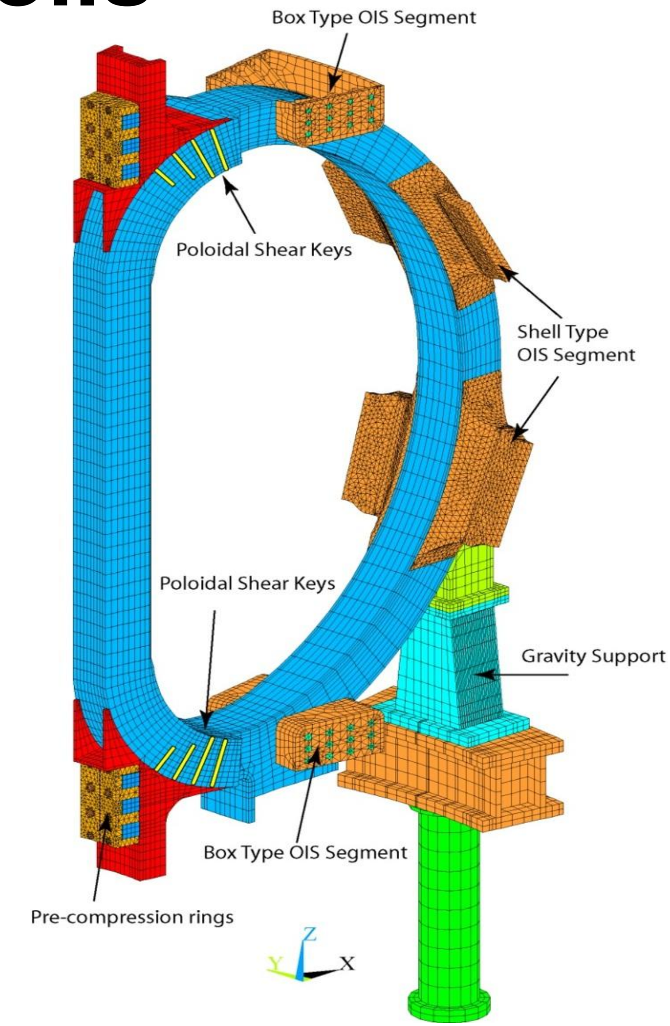




cross-sections: inner and outer



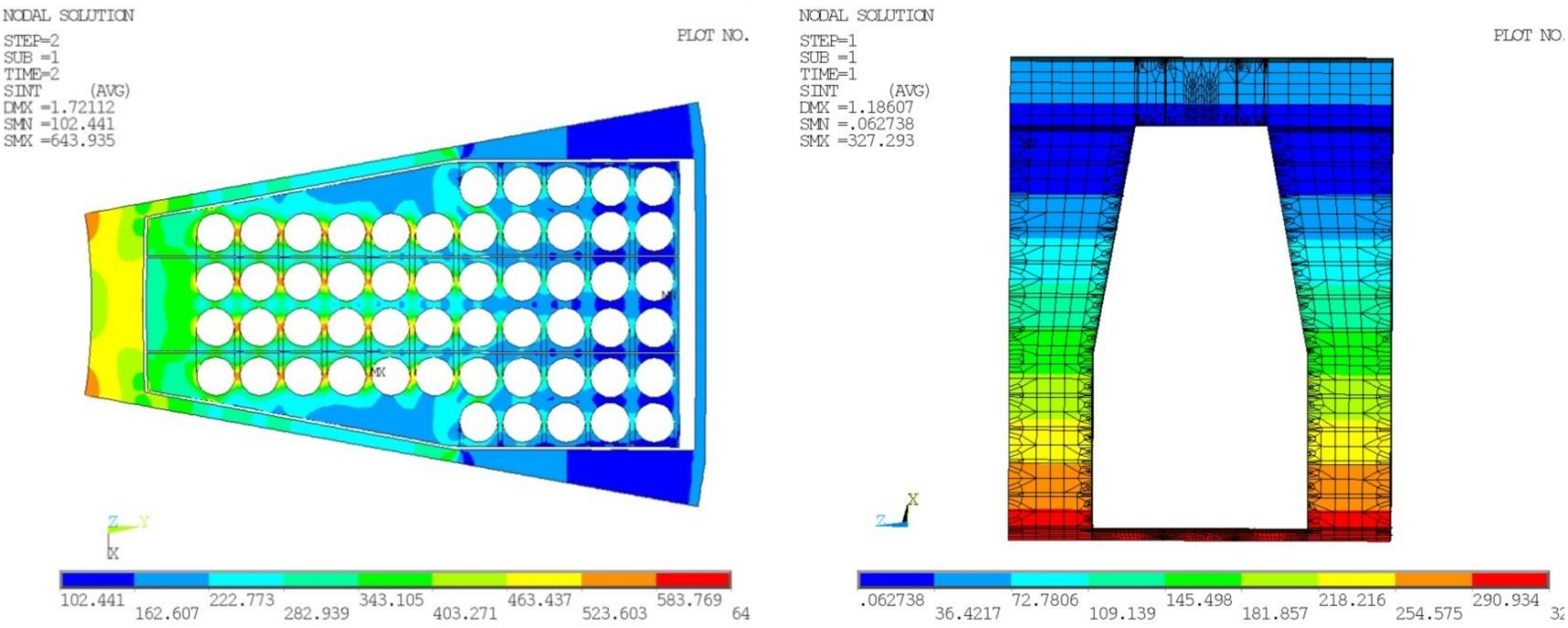
conductors in radial plate



ITER like design was chosen after multi-option analysis

Toroidal field coils

Results of stress analyses

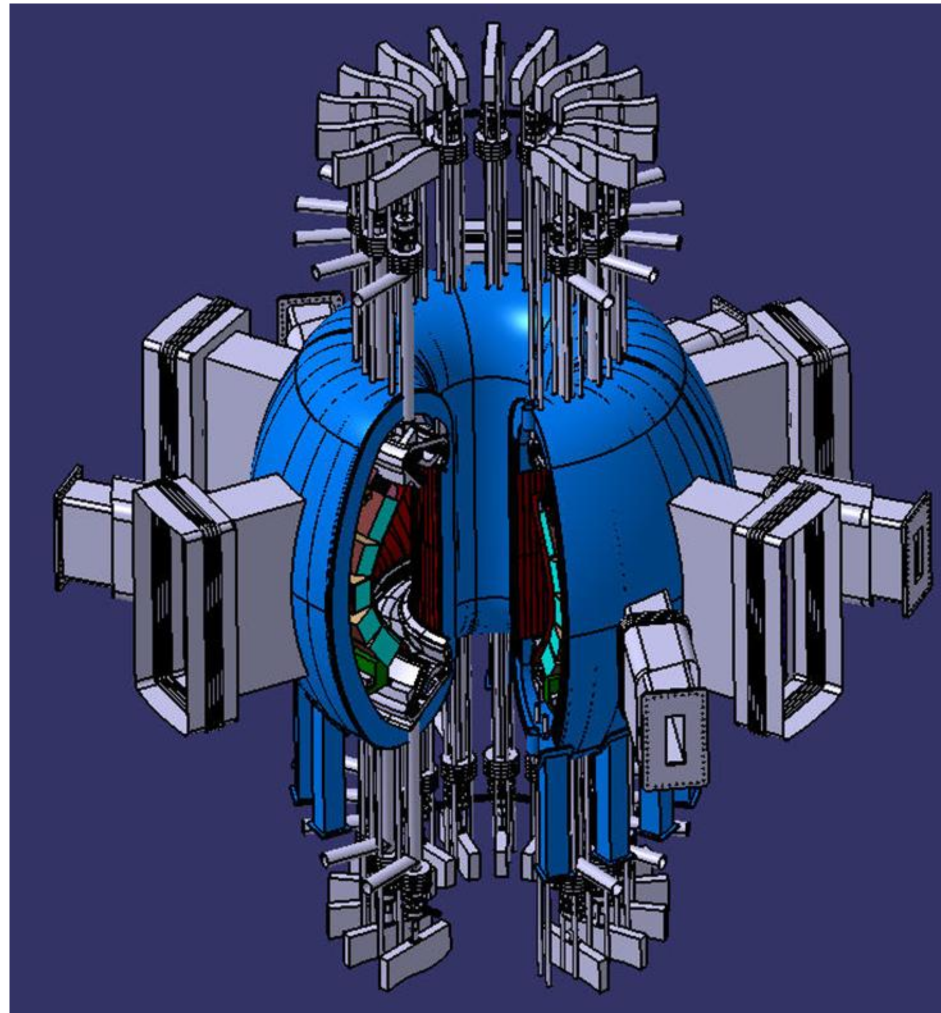


The design meets the criteria for static strength

Vacuum vessel

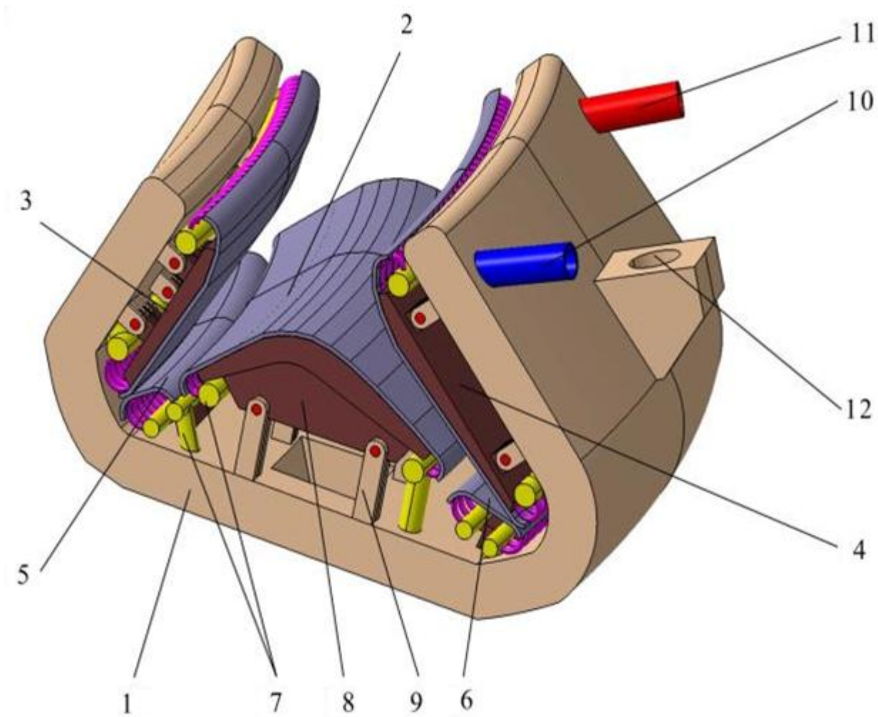
Composition of Vacuum vessel:

- **6 sectors**
- **Body with shielding**
- **Maintenance and injection ports**
- **Pumping ports**
- **VV supports**
- **Bearing units for in-vessel components**
- **Feedthroughs of the VV water cooling system and in-vessel components**



- **Material - SS 316L**
  2 MWa/m^2 – n-damage <20 dpa
- **VV height - 6.8 m**
- **Outer diameter - 11.1 m**
- **Inner diameter - 2.82 m**
- **Inner surface of VV body - 286 m^2**
- **VV Volume - 270 m^3**
- **Weight of the VV body - 630 ton**
- **VV temperature - 200 ^{0}C**

Upgrade of divertor cassettes



1 - cassette case,
2 – heat removal panel,
3 - internal panel
4 - external panel
5 - internal reflector,
6 - external reflector
7 - collectors,
8 – Dome,
9 - supporting device with hinge
10 - standpipe with coolant,
11 - drain pipe with a coolant,
12 - gripper arm

Divertor is double null and consists of 36 independent cassettes
Trend – “closed configuration”

In new device configuration distance from the poloidal magnetic field coils to divertor X-point sufficiently increased (above 45 cm), which required upgrading the divertor cassette

Reduction of the outer leg length more than 2 times, from 1.3 m to 0.6 m

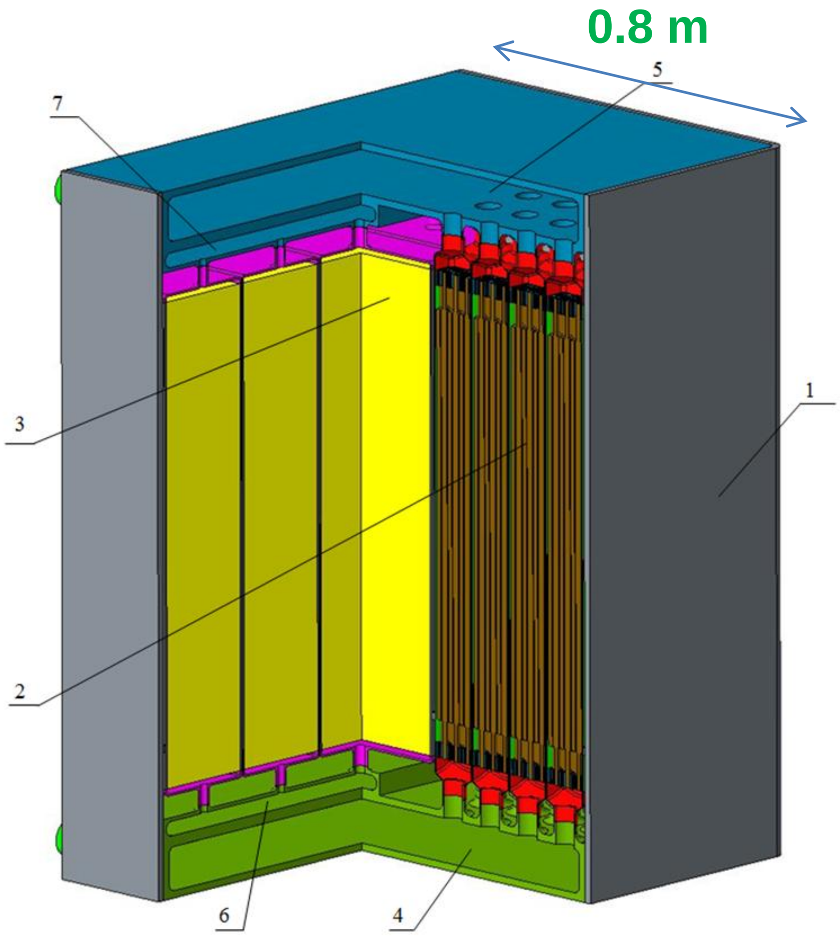
Size of the area for placing the divertor cassettes was dropped by 2 times

➔ Ability to operate in "detached" mode requires new simulations using the two-dimensional code SOLPS (in progress)

Blanket of DEMO-FNS

Functions: transmutation of minor actinides (MA) and self-sufficient tritium breeding

Coolants: NaK, H_2O, He – choice is steel needed



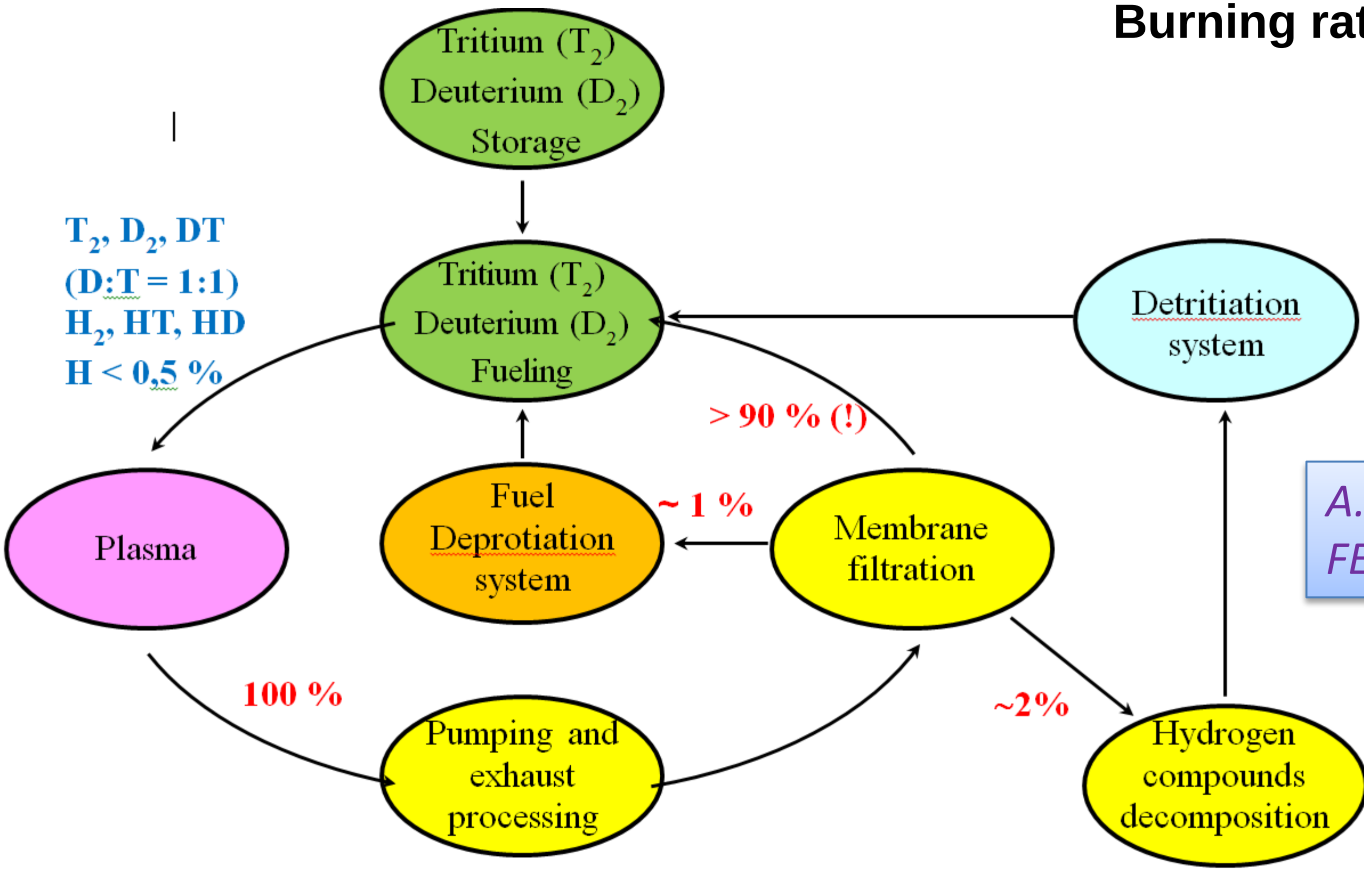
1 - module case;
2 – subrcitical active core;
3 – T-breeding zone (ceramic breeder) Li_4SiO_4;
4 - coolant inlet collector;
5 - coolant outlet collector;
6 – inlet He-gas collector;
7 – outlet He-gas collector

Initial composition of the MA mixture (total weight ~ 40 ton)

Nuclide	Mass fraction, %
Np237	44.5
Am241	48.6
Am242m	0.04
Am243	6.1
Cm243	0.02
Cm244	0.74

Tritium fuel cycle of DEMO-FNS

Burning rate ~ 2kg T per year



A.V. Spitsyn et al.
FEC-26 MPT/P5-38

Diagram of Tritium fuel cycle

Tritium fuel cycle of DEMO-FNS

Design assumes:

- No separation of D / T mixture and use of an 50:50% of D and T
- A small fraction of the fuel (<2%) delivered to the hydrogen isotopes separation system, only for deprotiation
- Separate deuterium loop (without T) used for a Neutral beam injection system

Tritium storage at the site required for operation of tokamak fueling system:

0.65 kg for D:T = 1:0 better current drive

1.0 kg for D:T = 1:1

excluding tritium in long-term storage systems and tritium retention in the structural and functional materials

Conclusions

- Safety and operation requirements initiated important changes of DEMO-FNS design in 2016
- Major radius increased from 2.75 to 3.2 m
- Enabling systems were upgraded including
  - Vacuum vessel
  - Radiation shield
  - Divertor
  - Blanket
  - Fueling cycle

- Design activity was supported by R&D in
  - Neutronics
  - Discharge scenario
  - Vertical stability
  - Optimization of the device layout
  - Subsystems including EMS, VV, divertor, blanket and T-fuel cycle

- Issues of integrating the hybrid facility in the nuclear fuel cycle of Russian nuclear power engineering are currently under consideration

THANK YOU FOR YOUR ATTENTION