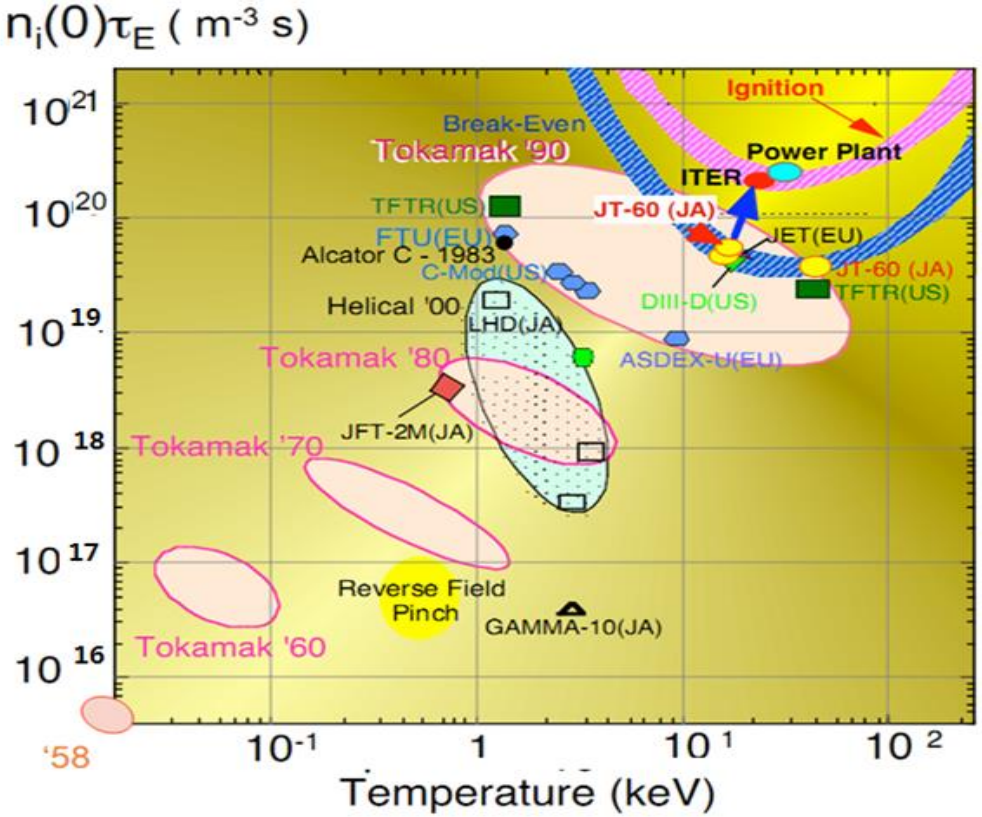
Alternative concepts: Stellarator

Steady-state, but ?

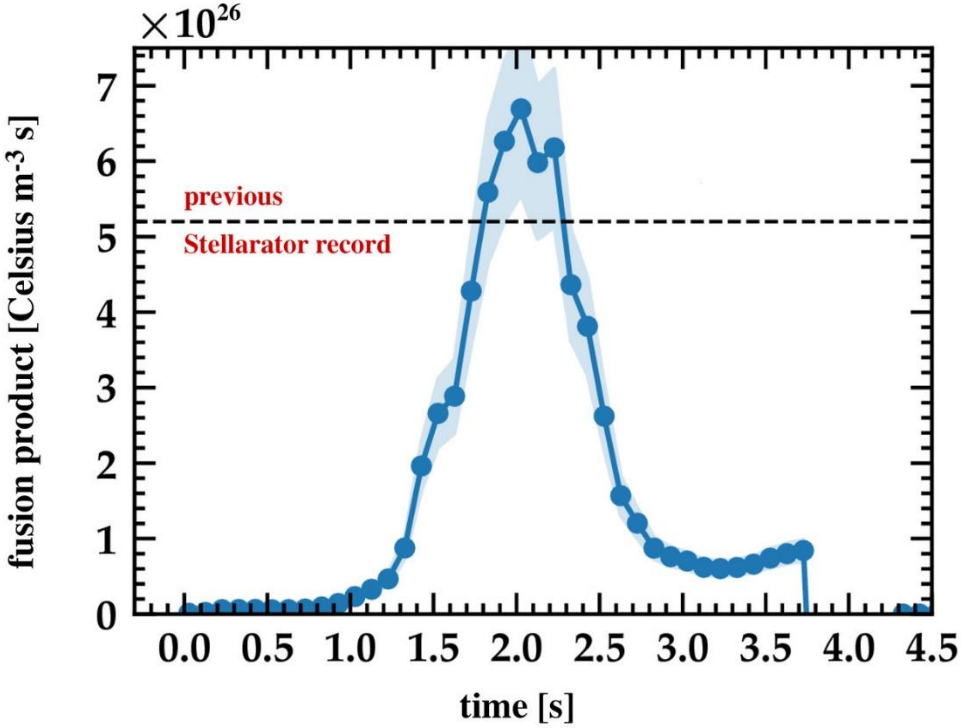
Magnetic Fusion led by Tokamak

JET: 17MW fusion power/24MW heating (1997), Q~0.7
Ion temperature > 10 keV
Fusion triple product ~ 10^{21} keV s /m^3



Stellarator (W-7X, 2018)

Pulse length ~ 100 s
Ion temperature < 3 keV
Fusion triple product < 5x10^{19} keV s /m^3



Andreas Dinklage et al.,
"Magnetic configuration effects on the Wendelstein 7-X stellarator", Nature Physics, 21 May 2018

Alternative concepts: Inertial Confinement Fusion

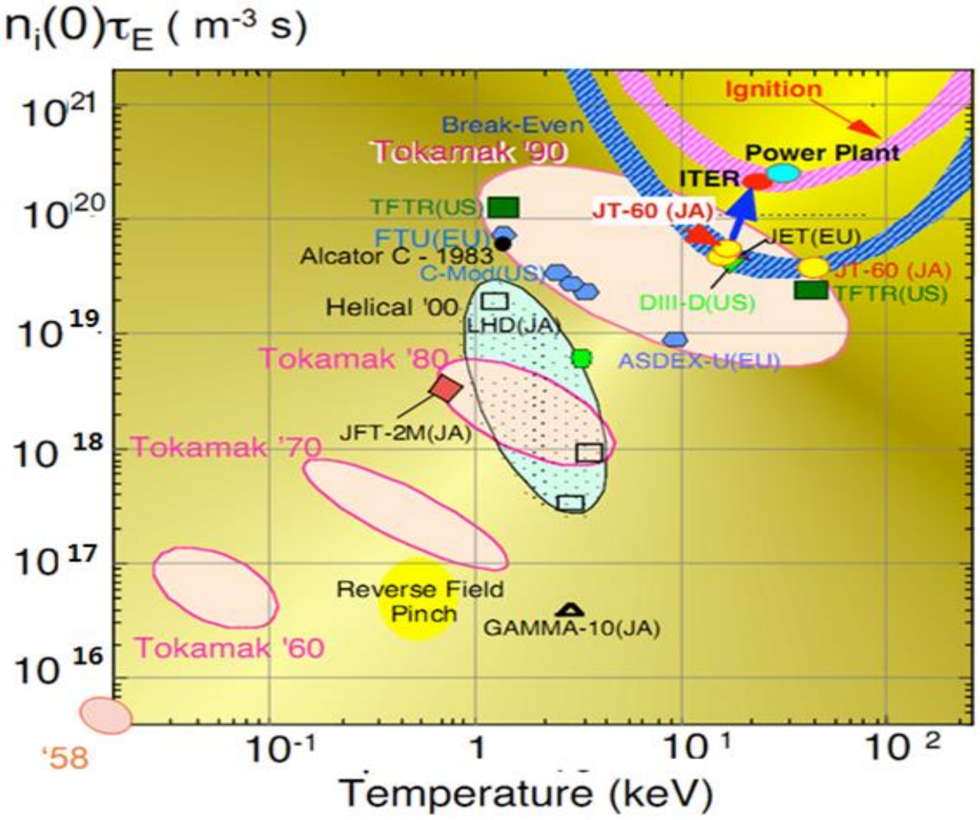
Simpler reactor design, but ?

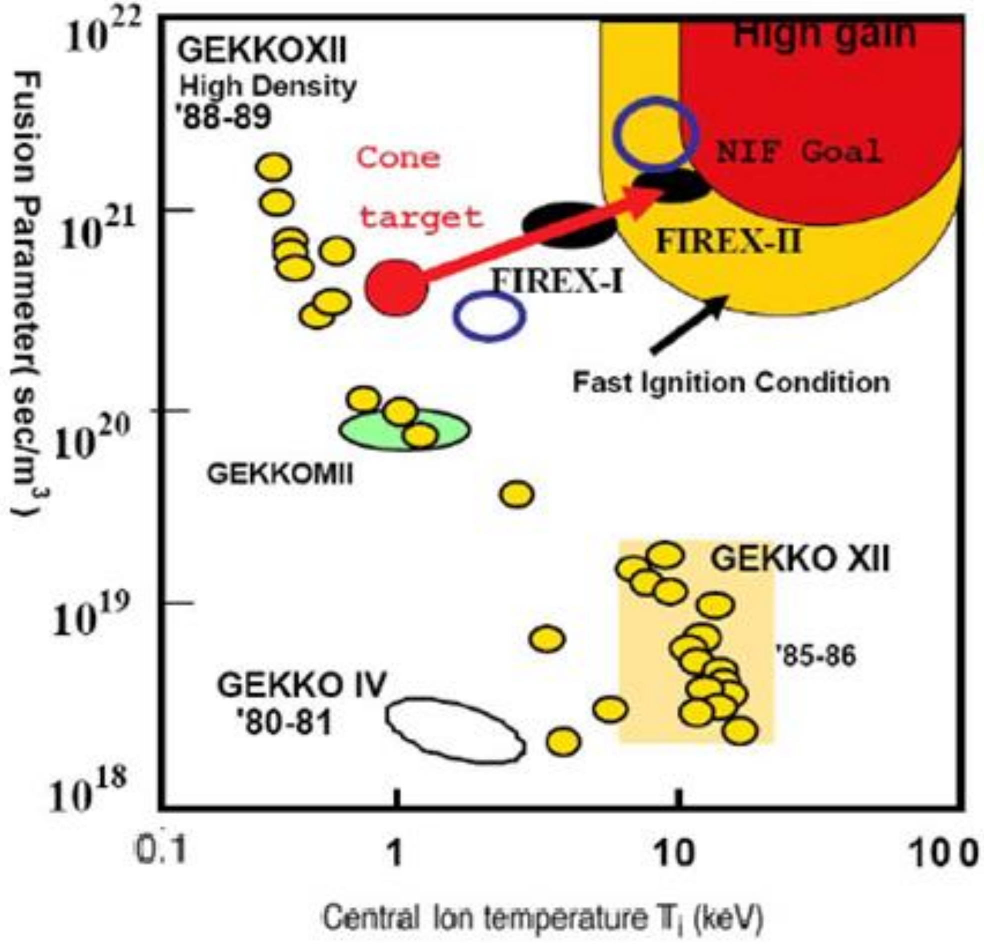
Q=output power/input power

Magnetic Fusion Q~0.7

Inertial Fusion Q~0.015

JET: 17MW fusion power/24MW heating (1997)
ITER: 500MW fusion power/50MW heating (2035) Q~10

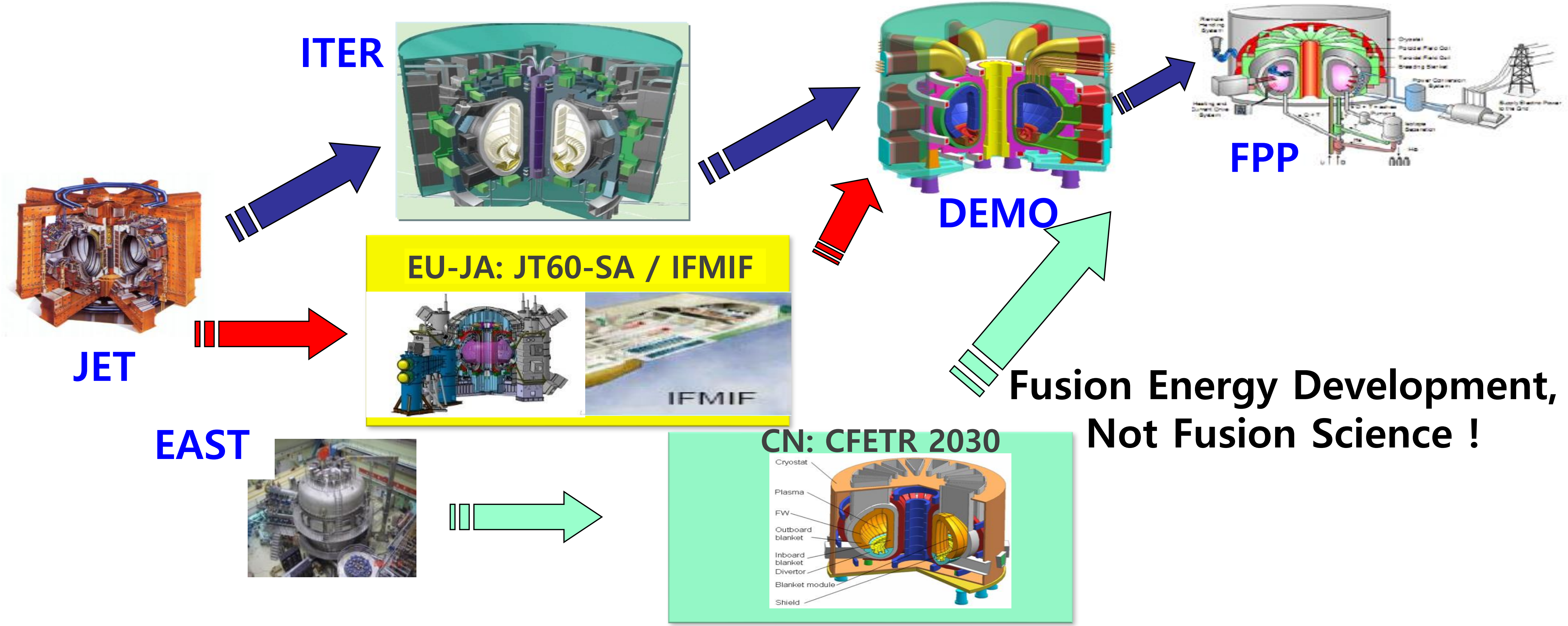




National Ignition Facility (NIF): (Goal)20MJ fusion energy/1.8MJ heating Q~10
(Nature 2/12/2014)17kJ fusion energy/~10kJ delivered/1.8MJ laser (2013)

World Fusion Energy Development Roadmap (with Tokamak)

EU: 2012 DEMO Roadmap, updated for fusion electricity by mid 2050
Japan: 2014 Report on technology bases for DEMO



JET

ITER

EU-JA: JT60-SA / IFMIF

EAST

CN: CFETR 2030

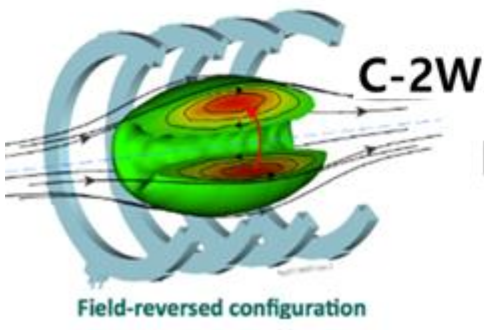
DEMO

FPP

Fusion Energy Development,
Not Fusion Science !

World Fusion Energy Development Roadmap: New Fast Track?

Fusion Startups



SPARC (CFS)
C-2W(TAE technology)
Lockheed Martin
Tokamak Energy
General Fusion

CFETR, China
STEP, UK
....

UK: STEP

The Spherical Tokamak for Energy Production

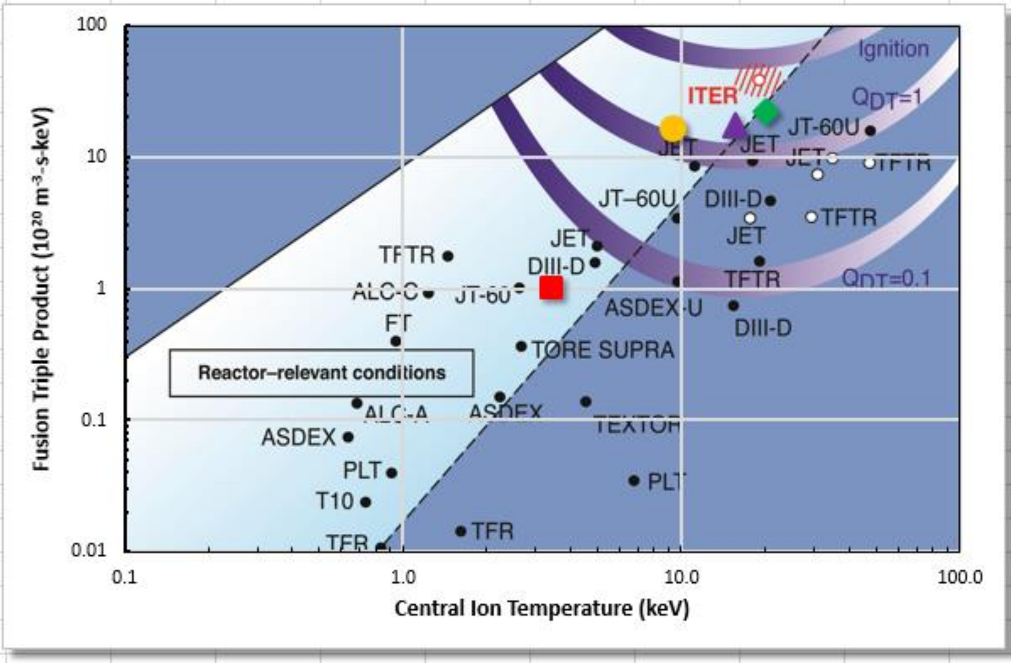
£220M investment over the next four years to develop the conceptual design of a fusion power plant by 2024 offering the prospect of constructing a fusion power station to provide **energy to the grid by 2040.**

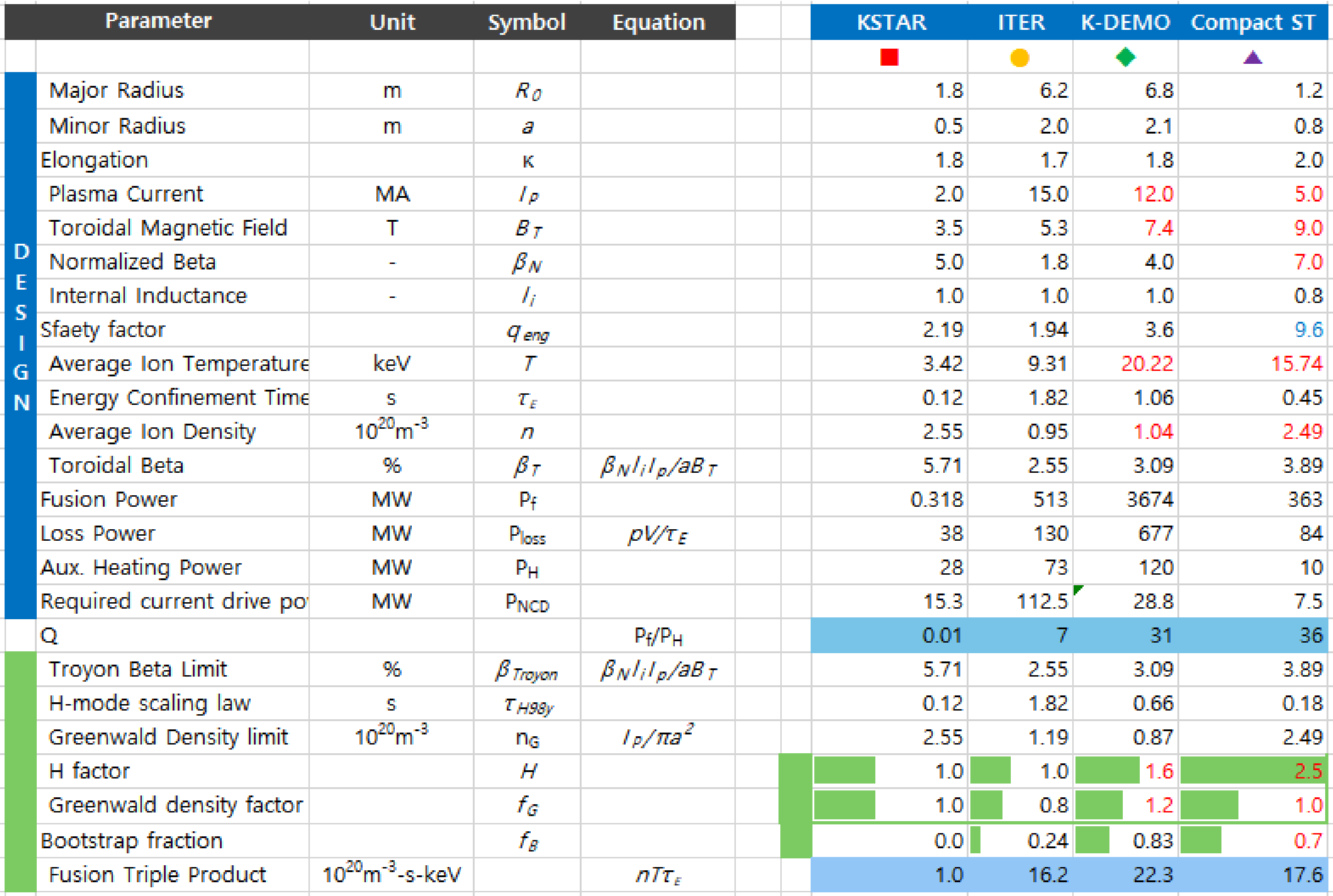
- Deliver predictable net electricity > 100MW
- Innovate to exploit fusion energy beyond electricity production
- Ensure tritium self-sufficiency
- Materials and components qualification under appropriate fusion conditions
- Viable path to affordable lifecycle costs

Let’s design our own fusion reactor system (beginning of this class)

Setting goal: Compact ST fusion power plant (fusion version of SMART)

- Power from SMART: 330 MW_{th}, 100MW_{e}
- Size of reactor from SMART: H=2m, D=1.83m → R=1.2m, a=0.8m, κ=2.0



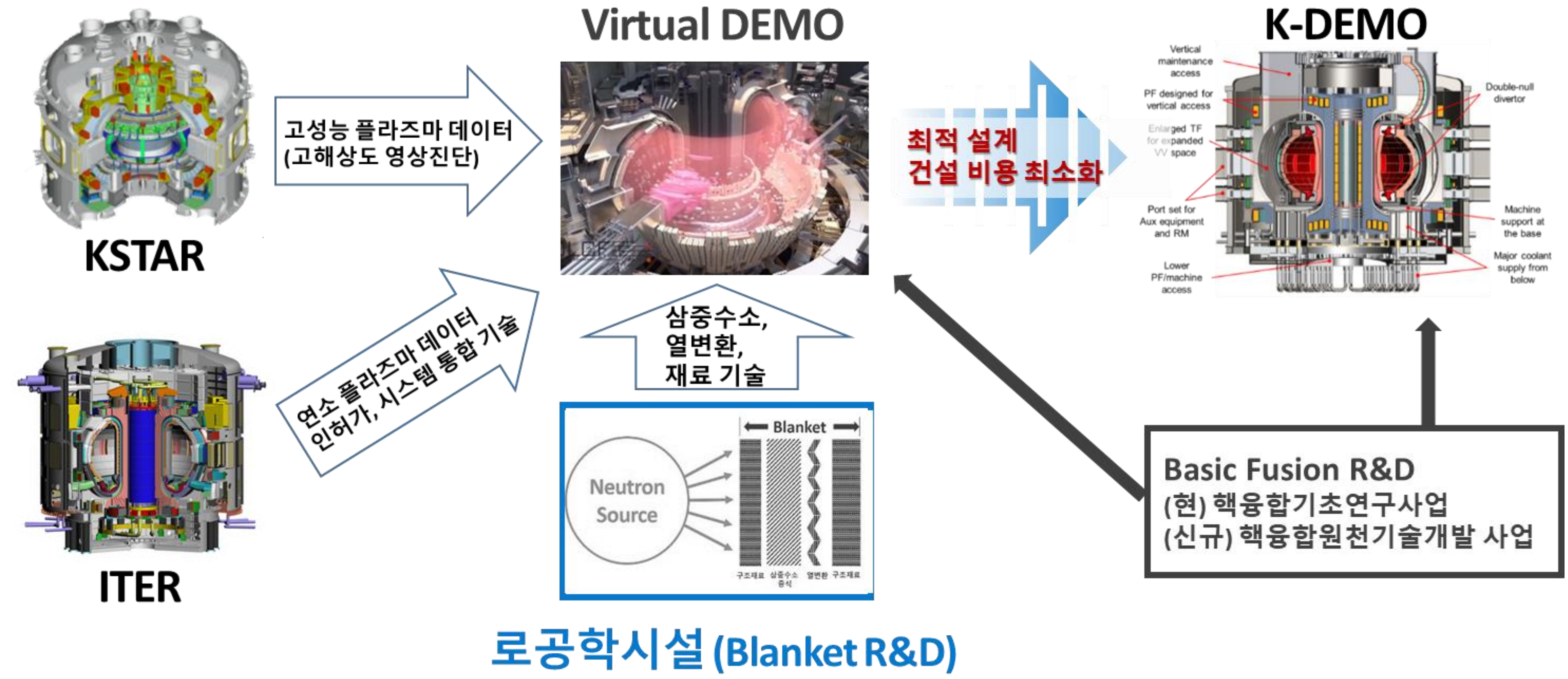


	Parameter	Unit	Symbol	Equation	KSTAR	ITER	K-DEMO	Compact ST
					🟥	●	◆	▲
DESIGN	Major Radius	m	R_0		1.8	6.2	6.8	1.2
	Minor Radius	m	a		0.5	2.0	2.1	0.8
	Elongation		κ		1.8	1.7	1.8	2.0
	Plasma Current	MA	I_p		2.0	15.0	12.0	5.0
	Toroidal Magnetic Field	T	B_T		3.5	5.3	7.4	9.0
	Normalized Beta	-	β_N		5.0	1.8	4.0	7.0
	Internal Inductance	-	l_i		1.0	1.0	1.0	0.8
	Sfaety factor		q_{eng}		2.19	1.94	3.6	9.6
	Average Ion Temperature	keV	T		3.42	9.31	20.22	15.74
	Energy Confinement Time	s	τ_E		0.12	1.82	1.06	0.45
	Average Ion Density	$10^{20}m^{-3}$	n		2.55	0.95	1.04	2.49
	Toroidal Beta	%	β_T	$\beta_N l_i I_p/aB_T$	5.71	2.55	3.09	3.89
	Fusion Power	MW	P_f		0.318	513	3674	363
	Loss Power	MW	P_{loss}	pV/τ_E	38	130	677	84
	Aux. Heating Power	MW	P_H		28	73	120	10
	Required current drive po	MW	P_{NCD}		15.3	112.5	28.8	7.5
	Q			P_f/P_H	0.01	7	31	36
	Troyon Beta Limit	%	β_{Troyon}	$\beta_N l_i I_p/aB_T$	5.71	2.55	3.09	3.89
	H-mode scaling law	s	τ_{H98y}		0.12	1.82	0.66	0.18
	Greenwald Density limit	$10^{20}m^{-3}$	n_G	$I_p/\pi a^2$	2.55	1.19	0.87	2.49
	H factor		H		1.0	1.0	1.6	2.5
	Greenwald density factor		f_G		1.0	0.8	1.2	1.0
	Bootstrap fraction		f_B		0.0	0.24	0.83	0.7
	Fusion Triple Product	$10^{20}m^{-3}$-s-keV		$nT\tau_E$	1.0	16.2	22.3	17.6

Virtual DEMO를 통한 핵융합 실증로 개발 전략 (NFRI)

◆ 현재(KSTAR, ITER)와 미래(K-DEMO)를 이어주는 징검다리 Virtual DEMO 추진

◆**핵융합로공학 시험 시설** 확보 여부가 성패를 좌우할 것으로 예상 !



KSTAR

ITER

Virtual DEMO

K-DEMO

고성능 플라즈마 데이터
(고해상도 영상진단)

연소 플라즈마 데이터
인허가, 시스템 통합 기술

삼중수소,
열변환,
재료 기술

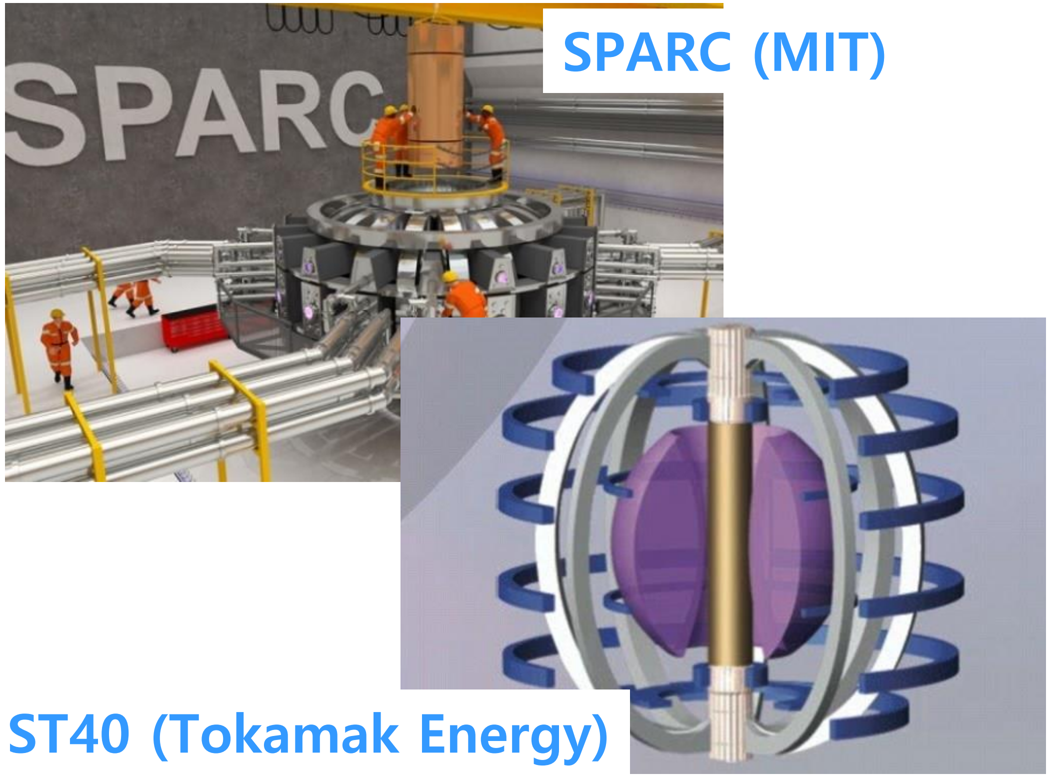
최적 설계
건설 비용 최소화

Basic Fusion R&D
(현) 핵융합기초연구사업
(신규) 핵융합원천기술개발 사업

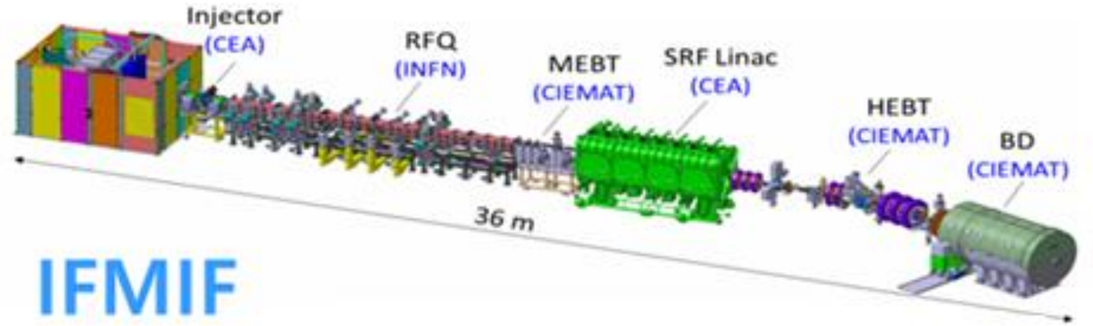
로공학시설 (Blanket R&D)

핵융합로공학 시험 시설 구축

핵융합 재료 조사시험장치인 강력한 중성자 발생장치가 핵심



고온초전도 자석 기반 핵융합 중성자 발생 장치



가속기 기반 중성자 발생 장치

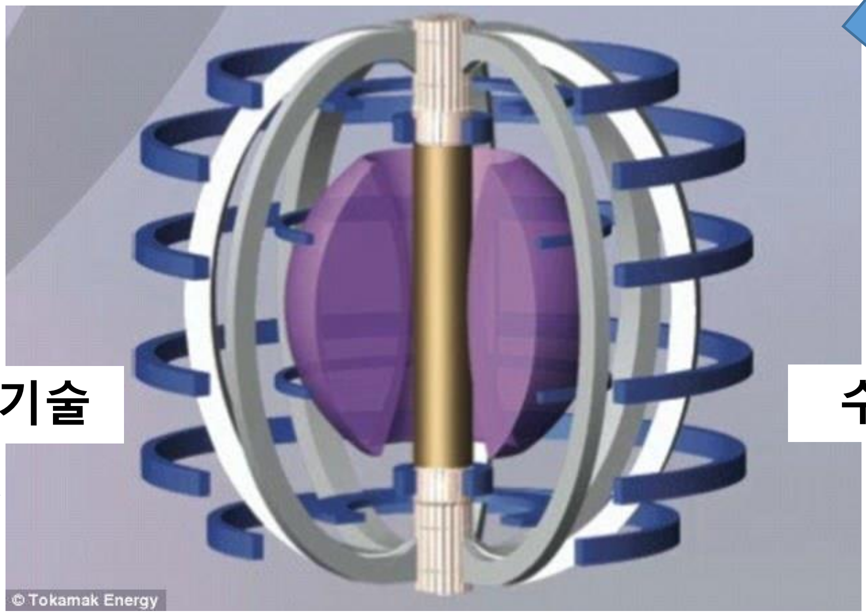
Intense Neutron Source

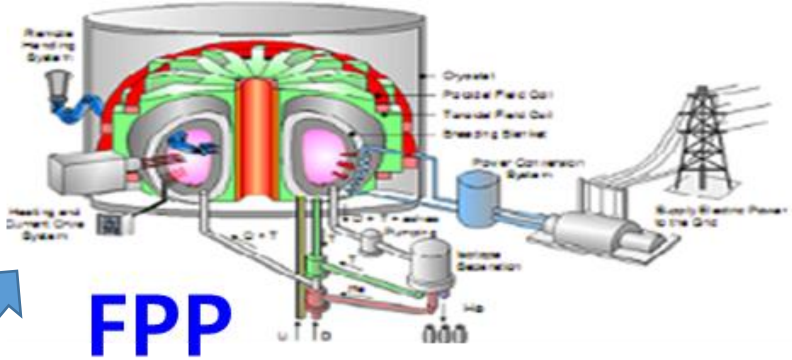
- High field tokamak fusion neutron source or accelerator-based spallation source
- High intensity **fusion neutron sources** for fusion material test and other applications

수소 핵융합 미래 에너지 복합 연구 단지?


신재생 에너지 기술

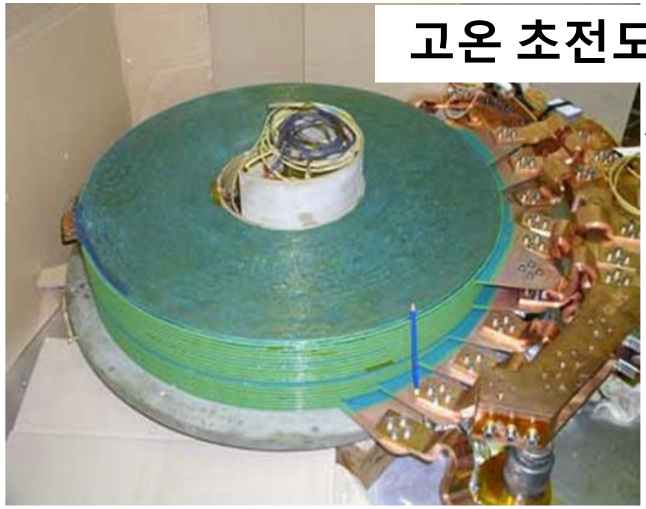
고온초전도 자석 기반
핵융합 공학 실증 장치
수소 생산 Pilot 장치


© Tokamak Energy



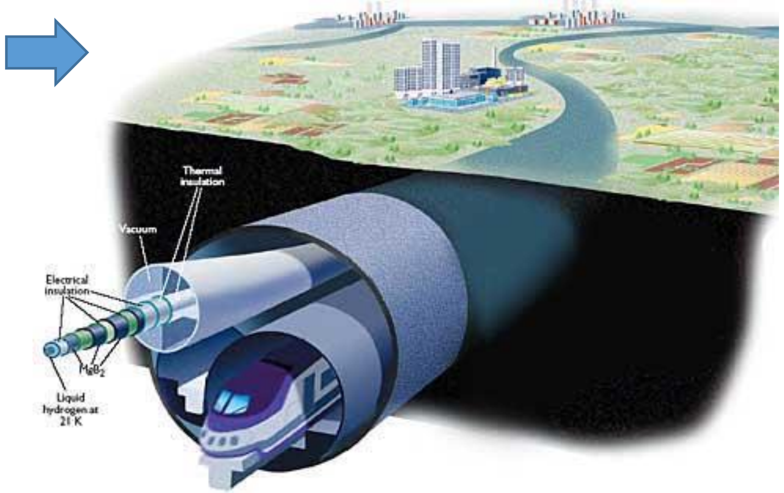
FPP

핵융합 재료기술
블랭킷 기술
중성자 활용 기술


고온 초전도 자석기술

초전도에너지저장 장치(SMES)

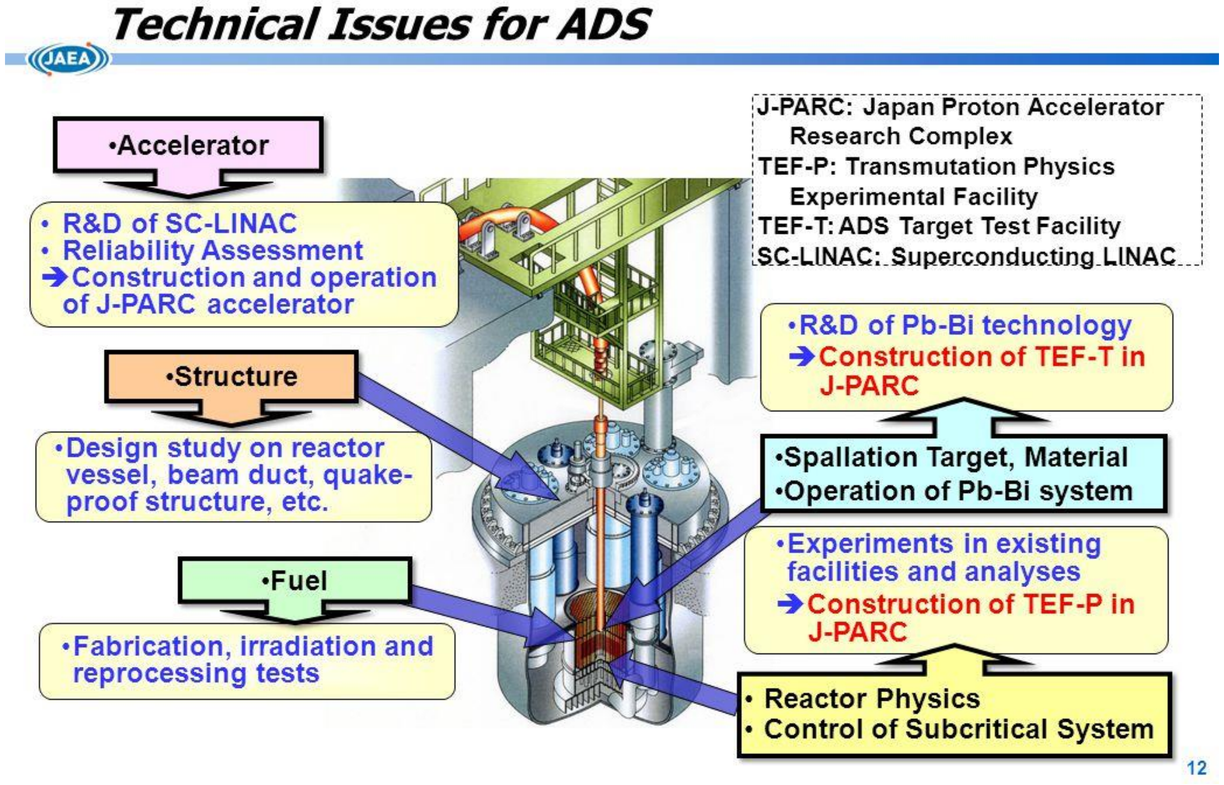
수소 생산 기술



Fusion-Fission Hybrid Reactor

- Sub-critical fission reactor for safety
- Long lead-time for fusion reactor

ADS(accelerator driven system)



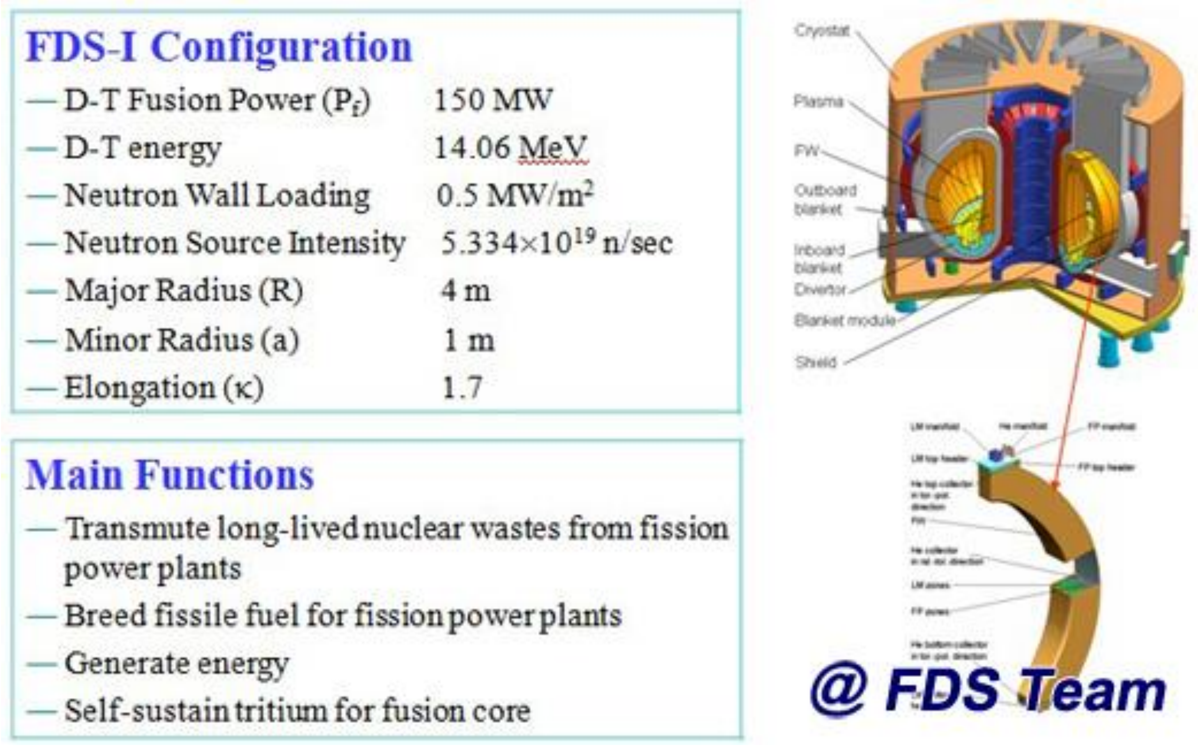
Technical Issues for ADS

J-PARC: Japan Proton Accelerator Research Complex
TEF-P: Transmutation Physics Experimental Facility
TEF-T: ADS Target Test Facility
SC-LINAC: Superconducting LINAC

- Accelerator
  - R&D of SC-LINAC
  - Reliability Assessment
  - → Construction and operation of J-PARC accelerator
- Structure
  - Design study on reactor vessel, beam duct, quake-proof structure, etc.
- Fuel
  - Fabrication, irradiation and reprocessing tests
- R&D of Pb-Bi technology
  - → Construction of TEF-T in J-PARC
- Spallation Target, Material
- Operation of Pb-Bi system
- Experiments in existing facilities and analyses
  - → Construction of TEF-P in J-PARC
- Reactor Physics
- Control of Subcritical System

12

FDS(Fusion driven system)



FDS-I Configuration

— D-T Fusion Power (P_f)	150 MW
— D-T energy	14.06 MeV
— Neutron Wall Loading	0.5 MW/m^2
— Neutron Source Intensity	5.334×10^{19} n/sec
— Major Radius (R)	4 m
— Minor Radius (a)	1 m
— Elongation (κ)	1.7

Main Functions

- Transmute long-lived nuclear wastes from fission power plants
- Breed fissile fuel for fission power plants
- Generate energy
- Self-sustain tritium for fusion core

@ FDS Team

Tritium breeding? Molten salt hybrid reactor

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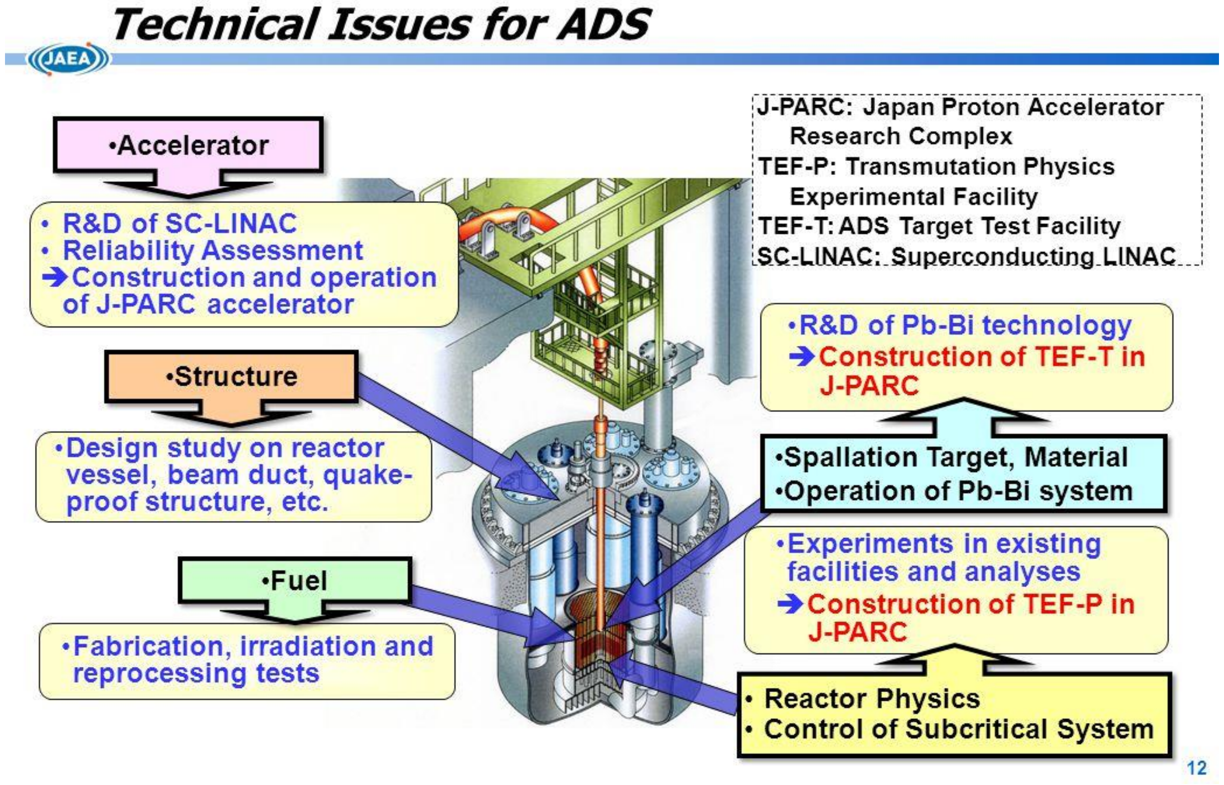
- Long lead-time for fusion reactor

ADS(accelerator driven system)



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- R&D of SC-LINAC
- Reliability Assessment

→Construction and operation of J-PARC accelerator

•Structure

•Design study on reactor vessel, beam duct, quake-proof structure, etc.

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•Fabrication, irradiation and reprocessing tests

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•Spallation Target, Material
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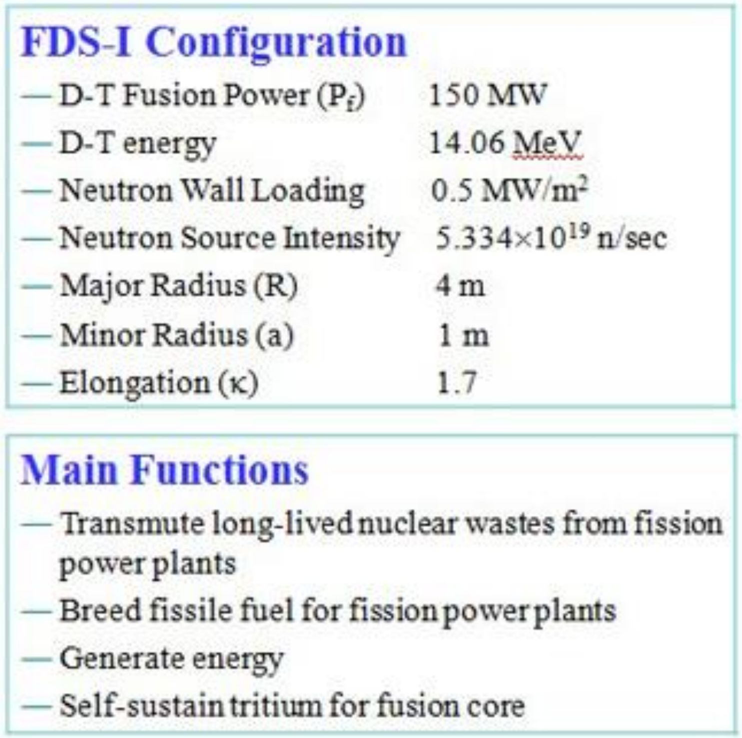
- Control of Subcritical System

FDS(Fusion driven system)



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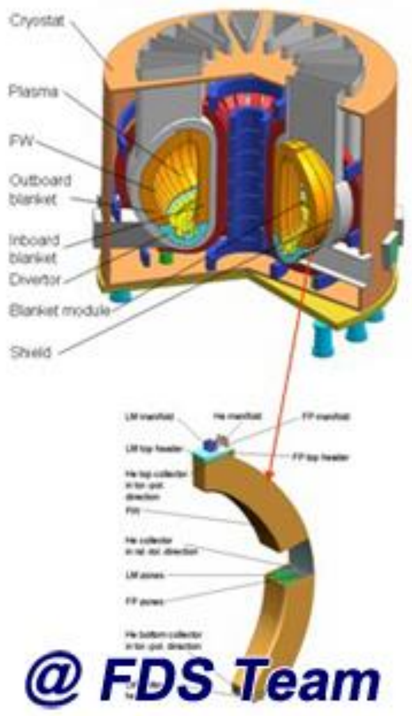
- Breed fissile fuel for fission power plants
- Generate energy
- Self-sustain tritium for fusion core

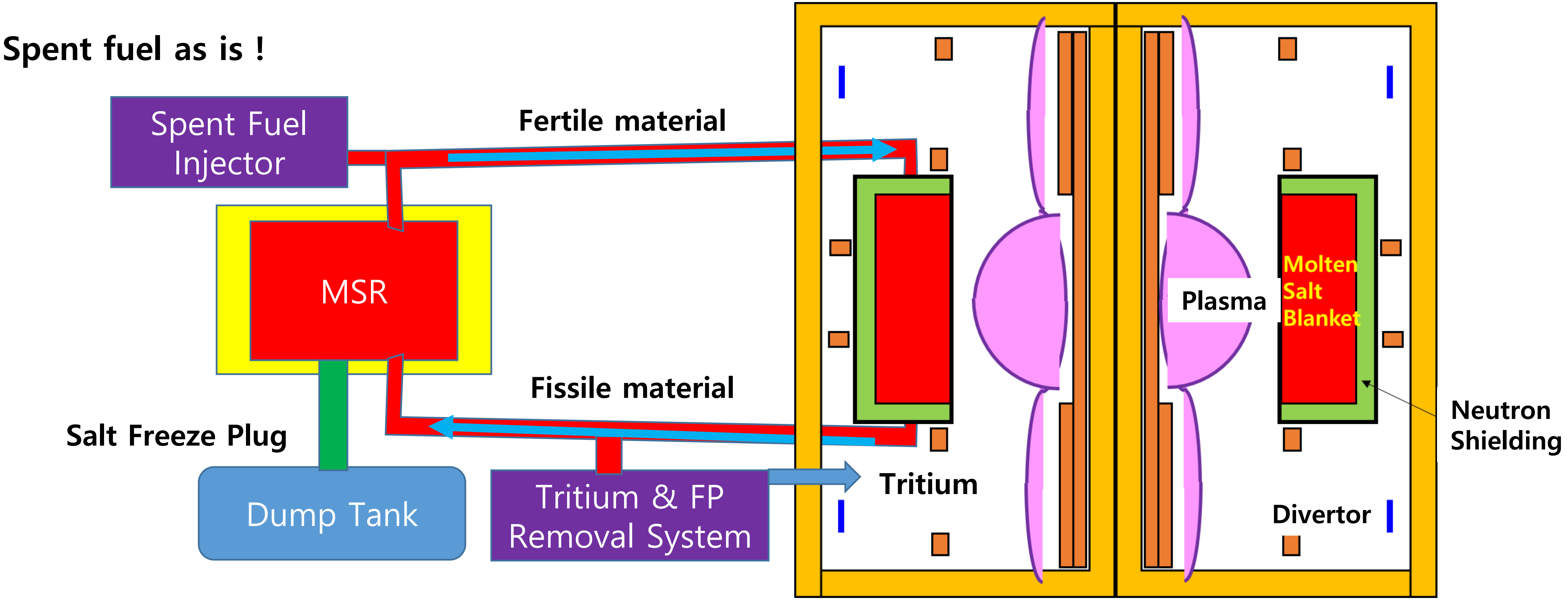


@ FDS Team

Tritium breeding? Molten salt hybrid reactor

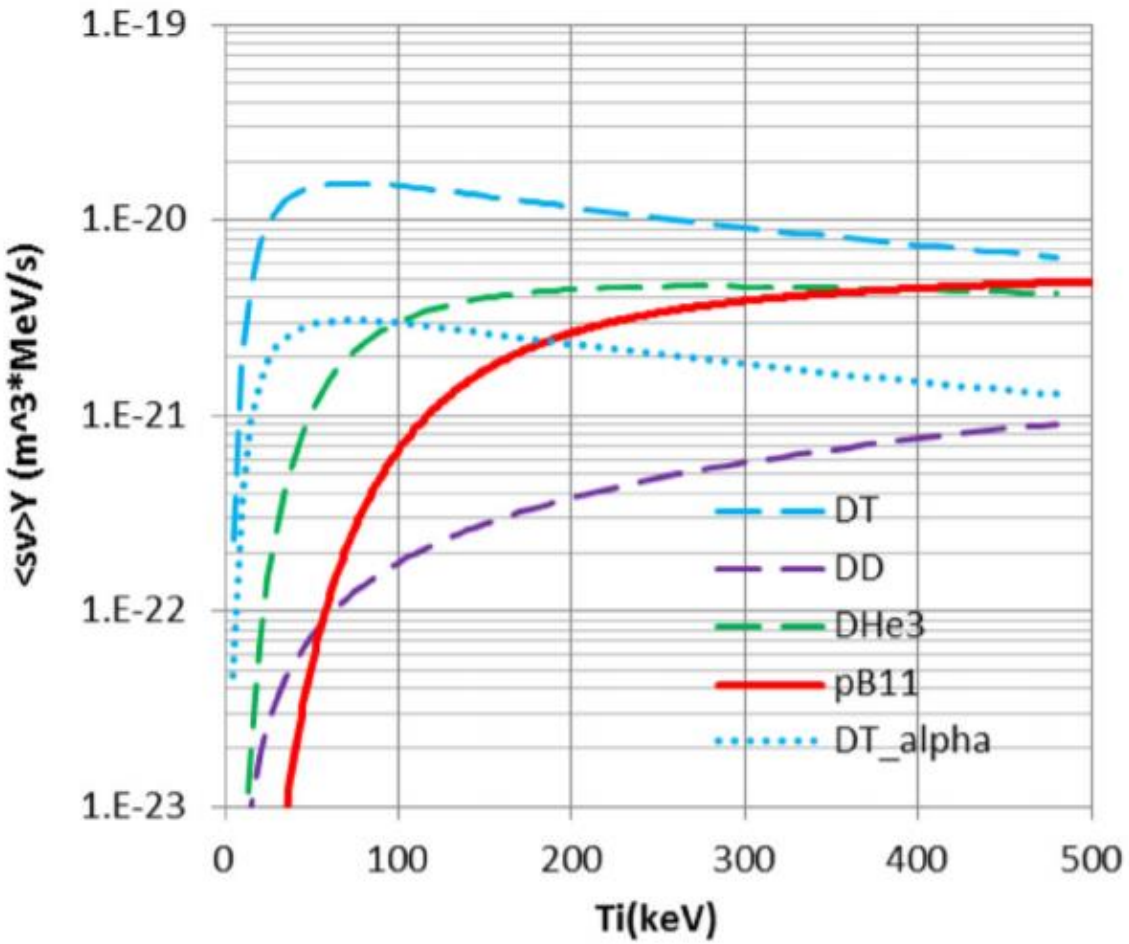
Molten Salt Hybrid Reactor

- **Molten Salt Hybrid Reactor (MSHR) with Spherical Torus as a 14MeV DT neutron source**

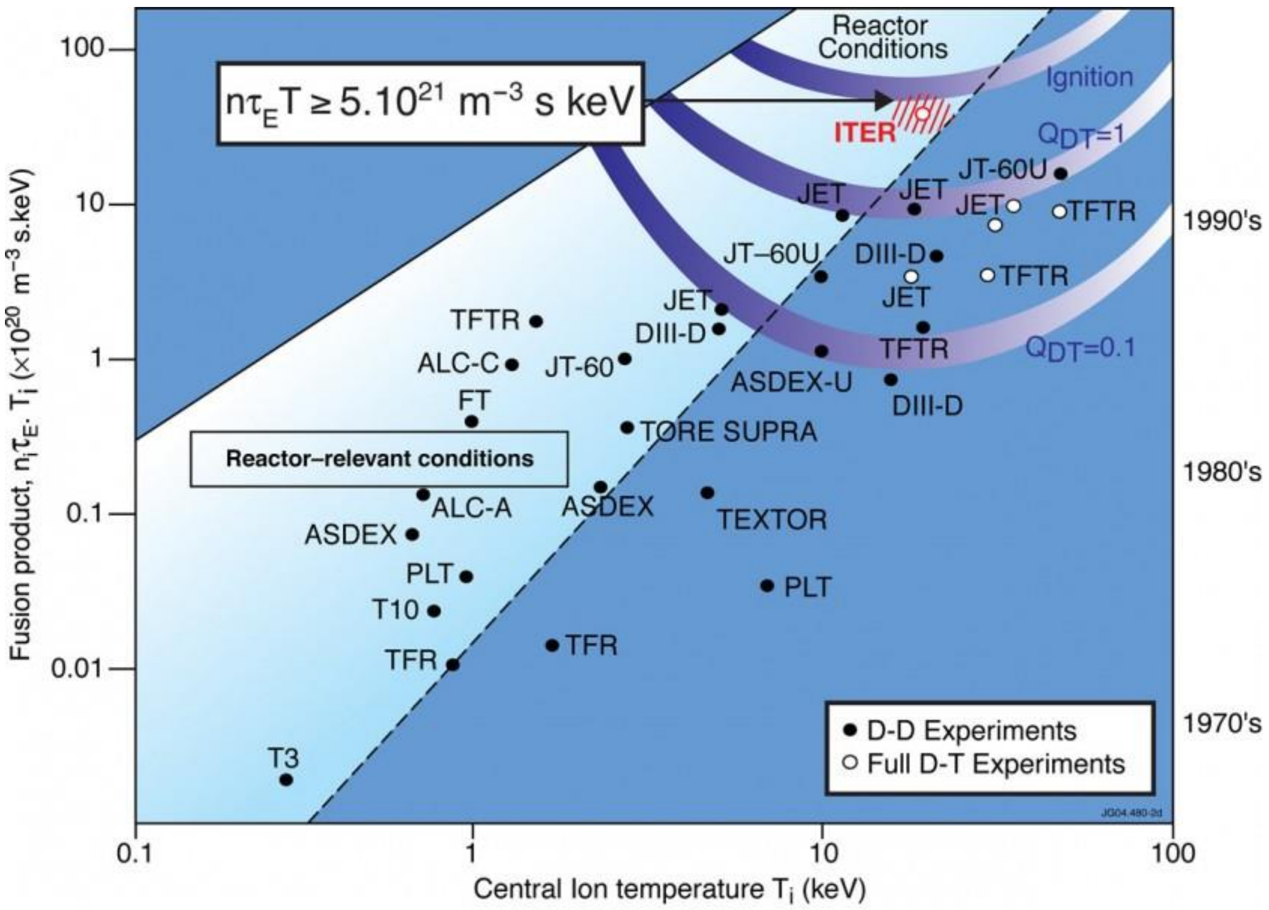


Fusion without Neutron and Tritium

$p + {}^{11}B \rightarrow 3\ {}^{4}He + 8.68\ \text{MeV}$



Magnetic Fusion (Tokamak) Performance



Putvinski et. als., Nucl. Fusion 59 (2019) 076018

D-T: $\langle\sigma v\rangle/k^2T^2 = 1.24\times10^{-24}\ m^3/s/keV^2$ at kT=13.6keV

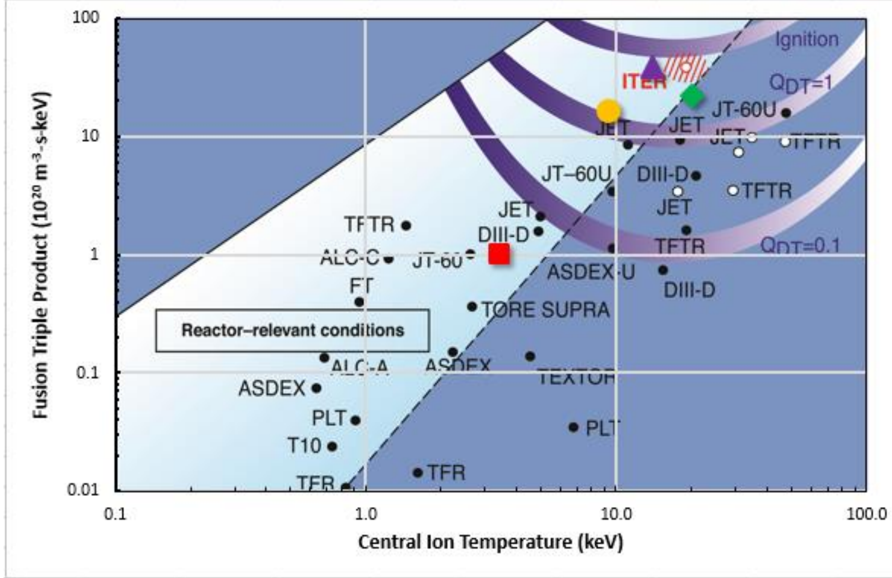
P-B: $\langle\sigma v\rangle/k^2T^2 = 3.1\times10^{-27}\ m^3/s/keV^2$ at kT=123keV

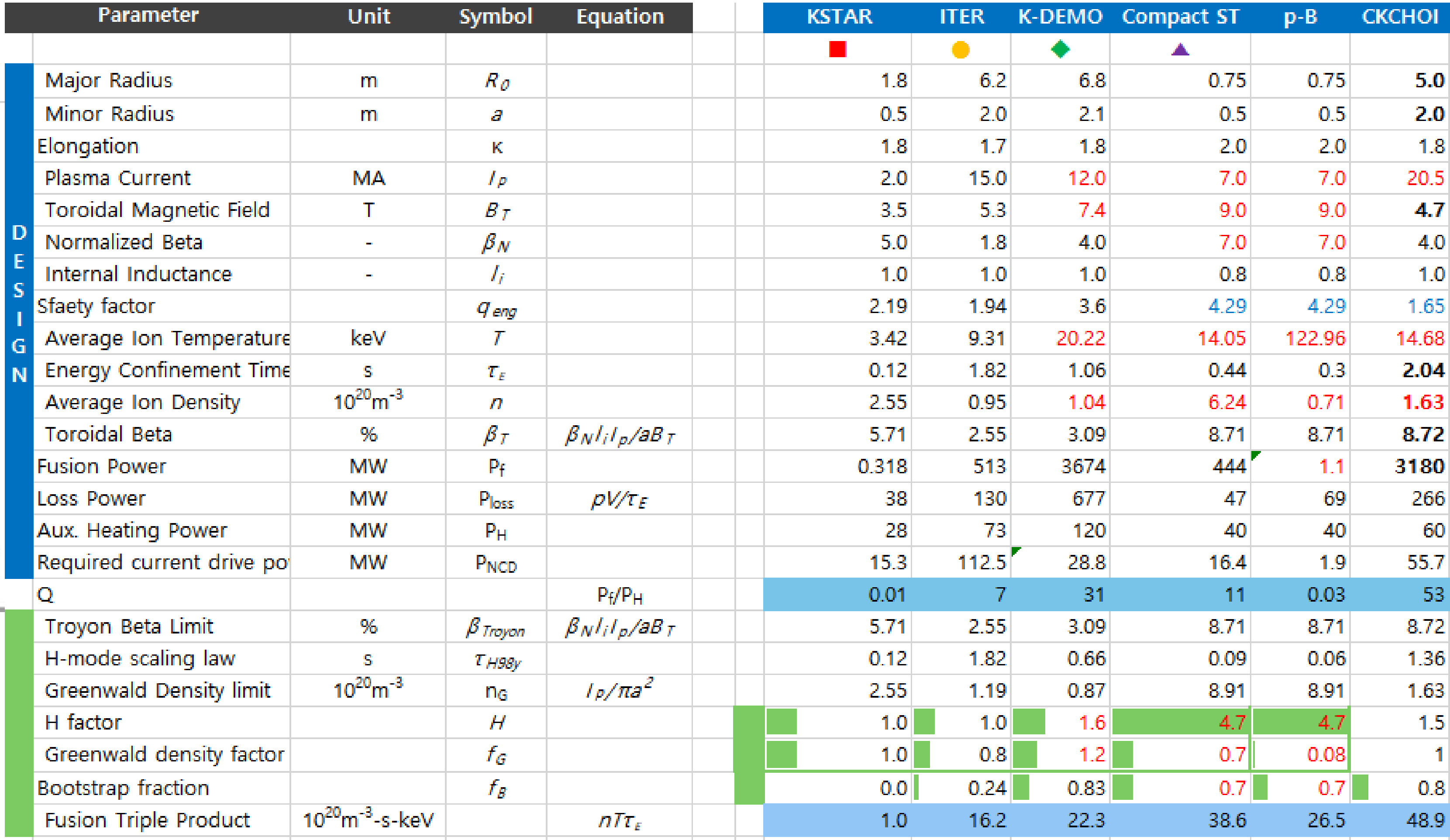
Temperature beyond 100keV ? Feasible?

Let’s design our own fusion reactor system (end of this class)

Setting goal: Compact ST fusion power plant (fusion version of SMART)

- Power from SMART: 330 MW_{th}, 100MW_e
- Size of reactor from SMART: H=2m, D=1.83m → R=0.75m, a=0.5m, κ=2.0





	Parameter	Unit	Symbol	Equation	KSTAR	ITER	K-DEMO	Compact ST	p-B	CKCHOI
					🟥	●	◆	▲		
DESIGN	Major Radius	m	R_0		1.8	6.2	6.8	0.75	0.75	**5.0**
	Minor Radius	m	a		0.5	2.0	2.1	0.5	0.5	**2.0**
	Elongation		κ		1.8	1.7	1.8	2.0	2.0	1.8
	Plasma Current	MA	I_p		2.0	15.0	12.0	7.0	7.0	20.5
	Toroidal Magnetic Field	T	B_T		3.5	5.3	7.4	9.0	9.0	**4.7**
	Normalized Beta	-	β_N		5.0	1.8	4.0	7.0	7.0	4.0
	Internal Inductance	-	l_i		1.0	1.0	1.0	0.8	0.8	1.0
	Sfaety factor		q_{eng}		2.19	1.94	3.6	4.29	4.29	1.65
	Average Ion Temperature	keV	T		3.42	9.31	20.22	14.05	122.96	14.68
	Energy Confinement Time	s	τ_E		0.12	1.82	1.06	0.44	0.3	**2.04**
	Average Ion Density	$10^{20}m^{-3}$	n		2.55	0.95	1.04	6.24	0.71	**1.63**
	Toroidal Beta	%	β_T	$\beta_N l_i I_p/aB_T$	5.71	2.55	3.09	8.71	8.71	**8.72**
	Fusion Power	MW	P_f		0.318	513	3674	444	1.1	**3180**
	Loss Power	MW	P_{loss}	pV/τ_E	38	130	677	47	69	266
	Aux. Heating Power	MW	P_H		28	73	120	40	40	60
	Required current drive po	MW	P_{NCD}		15.3	112.5	28.8	16.4	1.9	55.7
	Q			P_f/P_H	0.01	7	31	11	0.03	53
	Troyon Beta Limit	%	β_{Troyon}	$\beta_N l_i I_p/aB_T$	5.71	2.55	3.09	8.71	8.71	8.72
	H-mode scaling law	s	τ_{H98y}		0.12	1.82	0.66	0.09	0.06	1.36
	Greenwald Density limit	$10^{20}m^{-3}$	n_G	$I_p/\pi a^2$	2.55	1.19	0.87	8.91	8.91	1.63
	H factor		H		1.0	1.0	1.6	4.7	4.7	1.5
	Greenwald density factor		f_G		1.0	0.8	1.2	0.7	0.08	1
	Bootstrap fraction		f_B		0.0	0.24	0.83	0.7	0.7	0.8
	Fusion Triple Product	$10^{20}m^{-3}$-s-keV		$nT\tau_E$	1.0	16.2	22.3	38.6	26.5	48.9