Overview of an Accelerator-based Neutron Source for Breeding Blanket Components Test

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2023 KNS Spring Meeting

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Backgrounds

Fusion Energy at a Turning Point

Administration

MARCH 15, 2022

Fact Sheet: Developing a Bold Vision for Commercial Fusion Energy

OSTP › BRIEFING ROOM › PRESS RELEASES

Fusion Science and Technology are at a Turning Point

A fusion reaction in which more energy is produced than is consumed always seemed to be decades in the future. Recent advances, building on 70 years of groundbreaking fusion science and technology by DOE National Laboratories and other agencies, universities, and industry, demonstrate that we are closer than ever to a viable reaction. **Just in the past year, there have been many technical achievements reported in the media. For example:**

- a privately-funded U.S. fusion company demonstrated its prototype 20-tesla high-temperature-superconducting magnet, opening up an exciting new high-field, compact approach to commercial fusion energy,

ITER ($6.1B initially) (cf, ~$6.7B for LHC)

> 75% construction (finally $45B - $65B)

12.01.2021

Commonwealth Fusion Systems Raises $1.8 Billion in Funding to Commercialize Fusion Energy

CFS

Commonwealth Fusion Systems (CFS) announced it has closed on more than $1.8 billion in Series B funding to commercialize fusion energy. This includes capital to construct, commission, and operate SPARC, the world's first commercially relevant net energy fusion machine. In addition, it will enable the company to begin work on ARC, the first commercial fusion power plant, which includes developing support technologies, advancing the design, identifying the site, and assembling the partners and customers for the future of fusion power.

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nature

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nature › articles › article

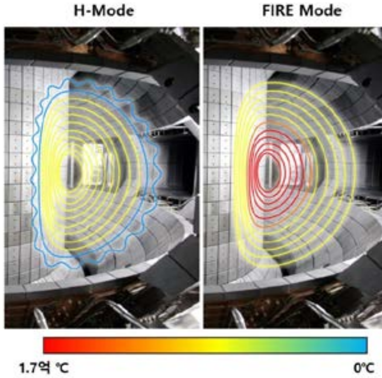
Article | Published: 07 September 2022

A sustained high-temperature fusion plasma regime facilitated by fast ions

H. Han, S. J. Park, C. Sung, J. Kang, Y. H. Lee, J. Chung, T. S. Hahm, B. Kim, J.-K. Park, J. G. Bak, M. S. Cha, G. J. Choi, M. J. Choi, J. Gwak, S. H. Hahn, J. Jang, K. C. Lee, J. H. Kim, S. K. Kim, W. C. Kim, J. Ko, W. H. Ko, C. Y. Lee, J. H. Lee, ... Y.-S. Na + Show authors

Nature 609, 269–275 (2022) | Cite this article

4701 Accesses | 490 Altmetric | Metrics



Not only Tokamak but also other Concepts

Department of Energy

DOE National Laboratory Makes History by Achieving Fusion Ignition

DECEMBER 13, 2022

Energy.gov » DOE National Laboratory Makes History by Achieving Fusion Ignition

For First Time, Researchers Produce More Energy from Fusion Than Was Used to Drive It, Promising Further Discovery in Clean Power and Nuclear Weapons Stewardship

The U.S. Department of Energy (DOE) and DOE's National Nuclear Security Administration (NNSA) today announced the achievement of fusion ignition at Lawrence Livermore National Laboratory (LLNL)—a major scientific breakthrough decades in the making that will pave the way for advancements in national defense and the future of clean power.

US Department of Energy

nature

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nature › news explainer › article

NEWS EXPLAINER | 13 December 2022

Nuclear-fusion lab achieves 'ignition': what does it mean?

Researchers at the US National Ignition Facility created a reaction that made more energy than they put in.

'챗GPT의 아버지', 이번엔 핵융합.. MS에 전기 만들어 판다

파이낸셜뉴스 입력 2023.05.11 07:29 수정 2023.05.11 07:29

샘 올트먼, 5년 내 '핵융합 상용화' 약속
"전세계에 값싼 전기 공급하겠다" 자신

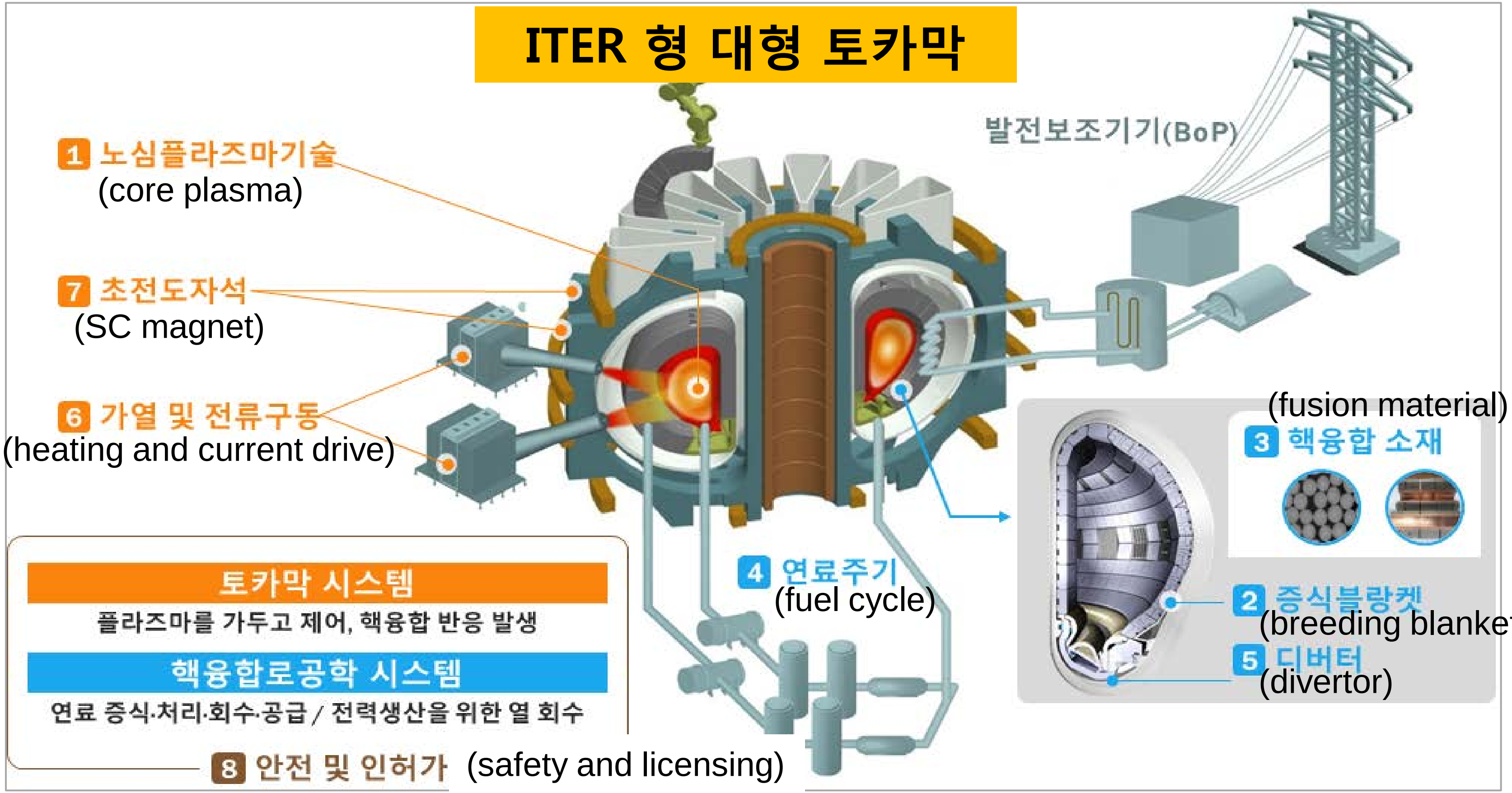
샘 올트먼 오픈 AI 최고경영자(CEO). 사진=연합뉴스

HELION · Fusion energy · Our technology · Who we are · Careers

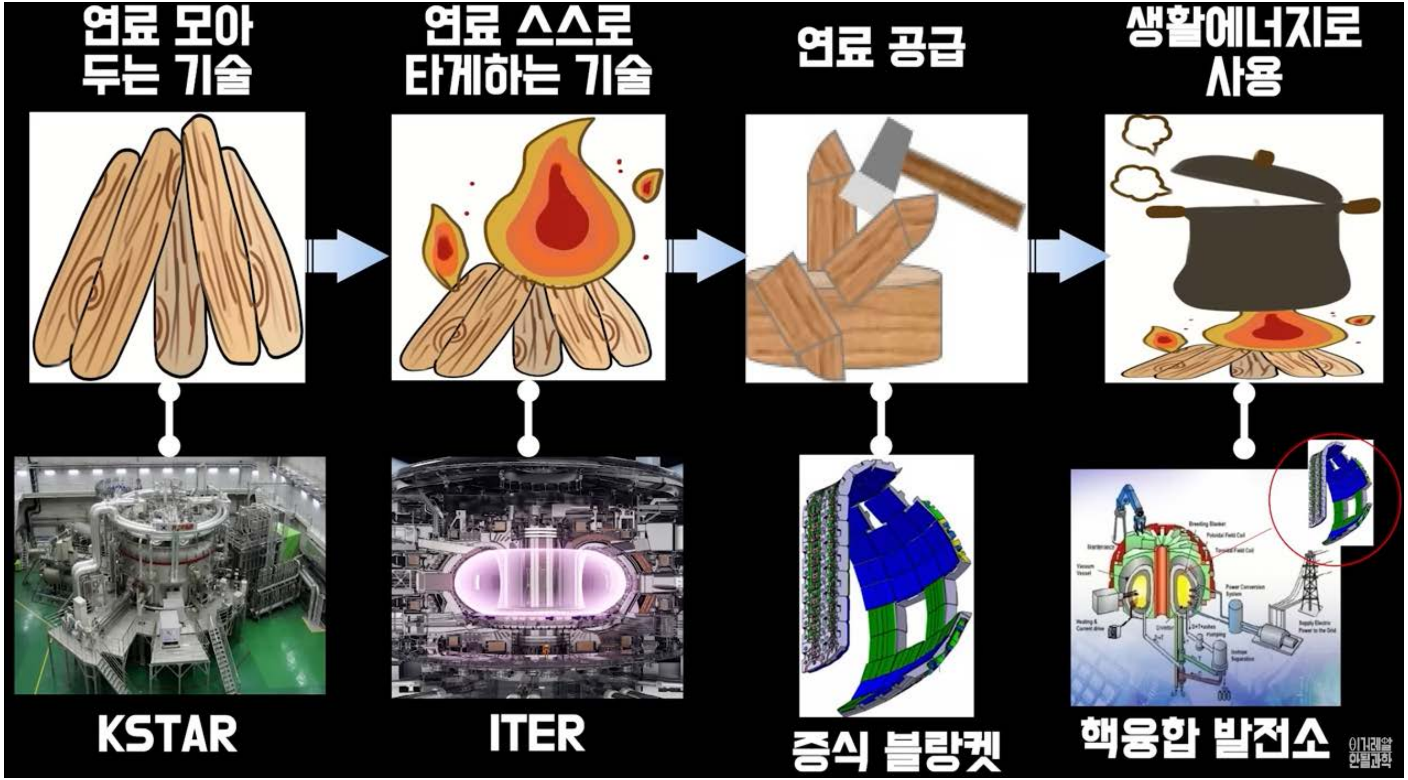
field-reversed configuration (FRC): aneutronic fusion

Helion's plasma accelerator raises fusion fuel to 100 million degrees Celsius and directly extracts electricity with a high-efficiency pulsed approach.

8 Core Technologies for Fusion Reactor

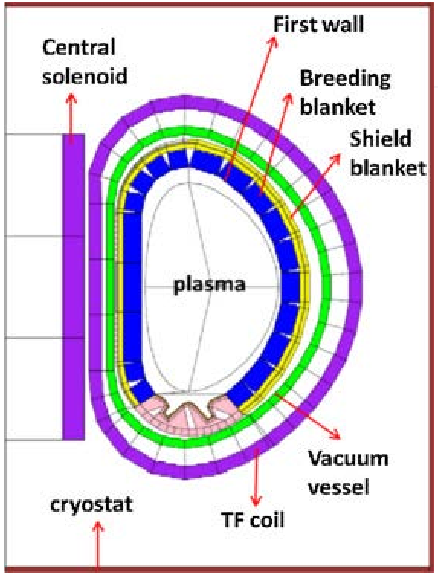


Roadmap by KFE



→ lithium containing ceramics, with a focus on lithium titanate and lithium orthosilicate, mostly in a pebble form

Why Breeding Blanket?



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Breeding blanket

3 languages

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From Wikipedia, the free encyclopedia

The tritium **breeding blanket** (also known as a **fusion blanket**, **lithium blanket** or simply **blanket**), is a key part of many proposed fusion reactor designs. It serves several purposes; one is to act as a cooling mechanism, absorbing the energy from the neutrons produced within the plasma by the nuclear fusion reaction between deuterium and tritium (D-T), another is to "breed" further tritium fuel, that would otherwise be difficult to obtain in sufficient quantities, through the reaction of neutrons with lithium in the blanket.[1] The breeder blanket further serves as shielding, preventing the high-energy neutrons from escaping to the area outside the reactor and protecting the more radiation-susceptible portions, such as ohmic or superconducting magnets, from damage.

Of these three duties, it is only the breeding portion that cannot be replaced by other means. For instance, a large quantity of water makes an excellent cooling system and neutron shield, as in the case of a conventional nuclear reactor. However, tritium is difficult to obtain in sufficient quantity to run a reactor through other means, so if commercial fusion using the D-T cycle is to be achieved, successful breeding of the tritium in commercial quantities is a requirement.

Breeding blanket designs are mostly based on lithium containing ceramics, with a focus on lithium titanate and lithium orthosilicate.[2] These materials, mostly in a pebble form, are used to produce and extract tritium and helium; must withstand high mechanical and thermal loads; and, should not become excessively radioactive upon completion of their useful service life.

To date, no large-scale breeding system has been attempted, and it is an open question whether such a system is possible to create.

ITER runs a major effort in blanket design and will test a number of potential solutions.[3] Concepts for the breeder blanket include helium-cooled lithium lead (HCLL), helium-cooled pebble bed (HCPB), and water-cooled lithium lead (WCLL) methods.[4] Six different tritium breeding systems, known as Test Blanket Modules (TBM) will be tested in ITER.[5]

Why Breeding Blanket?

CH What is breeding blanket?

A breeding blanket is a component of a nuclear fusion reactor that surrounds the plasma core and serves several important functions. In a fusion reactor, the aim is to generate energy by fusing atomic nuclei together, typically isotopes of hydrogen, such as deuterium and tritium. These reactions release a tremendous amount of energy but require extremely high temperatures and pressures.

One of the challenges in a fusion reactor is to sustain the fusion reactions by providing a sufficient supply of fuel and maintaining the appropriate conditions. This is where the breeding blanket comes into play. The breeding blanket primarily has two functions:

1. Fuel Production: The breeding blanket is responsible for generating additional fuel for the fusion reactions. It contains a material, often lithium or lithium compounds, which interacts with the high-energy neutrons released during fusion. The neutrons transfer energy to the lithium atoms, causing them to undergo nuclear reactions and produce tritium, which is an essential fuel for fusion. This process is known as tritium breeding.
2. Shielding and Heat Extraction: The breeding blanket also acts as a radiation shield, protecting the reactor's structural components and external environment from the intense neutron flux produced during fusion. Additionally, the breeding blanket absorbs some of the fusion-generated heat and transfers it to a coolant, typically a liquid metal or helium, which then circulates and transfers the heat to a power cycle for electricity generation.

Accelerators for Fusion-like Neutrons

Fusion-like Neutron Source

→ No proper facility to test and study blanket/devertor under fusion-like environment

- Neutron energy: 14.1 MeV
- Neutron wall loading: 1 MW/m^2 (100 W/cm^2)

➡ Neutron flux at first wall: 4.5x10^{13} n/cm^2/s

➡ Material damage: ~10 dpa/yr

- ITER: 0.75 MW/m^2
- K-DEMO: 3 MW/m^2

1 dpa/yr (Fe) = 4.8x10^{12} n/cm^2/s

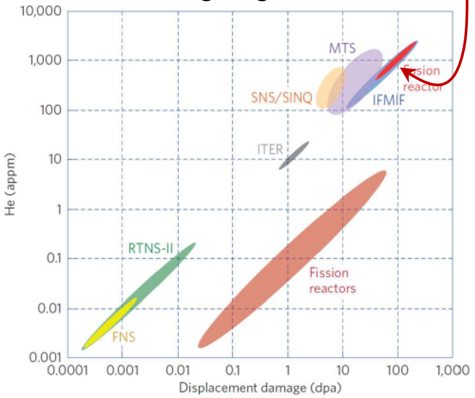
- Neutron spectrum에 대한 고려 필요

➡ He production: ~10 appm/dpa

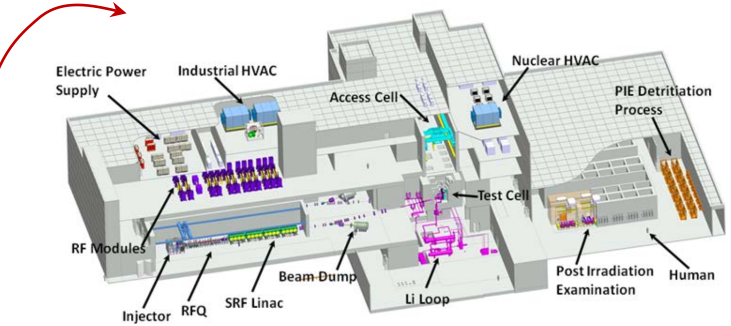
Transmuted (gaseous)

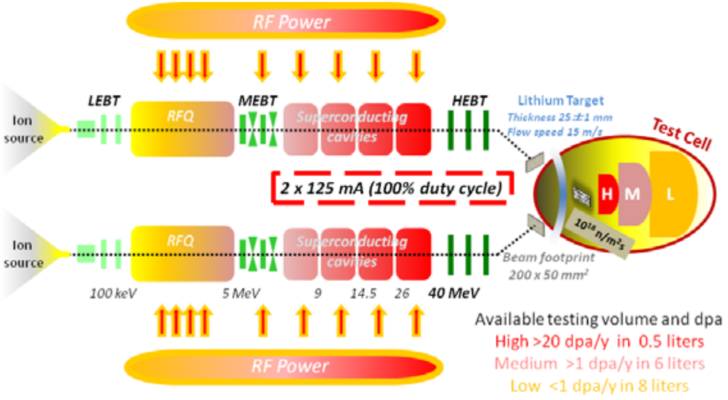
- He production: significant impact on mechanical properties
  - ^{56}Fe(n,α)^{53}Cr (threshold energy = 3.7 MeV)
  - 12 appm/dpa (fusion reactors)
  - 0.3 appm/dpa (fission reactors)
  - 70 appm/dpa (spallation sources)

Log-Log scale



Nature Physics 12 (2016) 424





Neutron flux: ~10^{14} n/cm^2/s
Total dose > 100 dpa

[K. J. Jeong (SNU)]

History of Accelerators for Fusion Materials

AN INTENSE Li(d,n) NEUTRON RADIATION TEST FACILITY FOR CONTROLLED THERMONUCLEAR REACTOR MATERIALS TESTING

P. GRAND, K. BATCHELOR, J. P. BLEWETT, A. GOLAND, D. GURINSKY, J. KUKKONEN, and C. L. SNEAD, Jr.
Brookhaven National Laboratory, Upton, New York 11973

Received November 16, 1975
Accepted for Publication January 16, 1976

1975~

INTRODUCTION

The needs of the Controlled Thermonuclear Reactor (CTR) program related to radiation damage in fusion reactor materials are becoming critical to the development of the planned Experimental Power Reactor. The 14-MeV neutron sources with high enough fluxes [$>10^{14}$ n/(cm^2 sec)] in large volumes (~1 liter) do not exist. Neutron sources being constructed or pro-

NUCLEAR TECHNOLOGY VOL. 29 JUNE 1976

The design of this Li(d,n) intense neutron source is based on the acceleration of a 100-mA deuteron beam to 30 MeV followed by stripping in a liquid-lithium target.[3] The resulting neutron intensity, whose energy spectrum is centered at ~14 MeV, will be $>2 \times 10^{16}$ n/sec produced in the forward direction, highly peaked, on the deuteron beam axis. The production process enables us, therefore, to obtain neutron fluxes $>10^{14}$ n/(cm^2 sec) in a volume adequate for experiments (>600 cm^3).

Note that these parameters can be met utilizing state-of-the-art, proven technology in the accelerator field, and liquid-metal handling area to achieve a viable and reliable neutron radiation test facility, and that this facility could be made operational as early as 1981.

*To meet the average beam current on the order of 100 mA, CW is advisable (but, not as critical as in ADS)

	Ion source					RFQ					Project
Prototype	Species	Type	Current energy	Gas fraction	Emittance	Type fabrication choice cavity approach	Frequency Length Length in λ	Current energy	P_{beam} P_{RF}	Peak field	Objective current a energy accelerating principle
FMIT (1980s)	H_2^+	Cusp-field	240 mA 75 keV	$<40\%$	0.3π mm · mrad	4 vanes Adjustable vanes and C-seals No segmentation	80 MHz 4 m 1	100 mA 2 MeV	193 kW 407 kW	1 Kp	*Fusion materials research* 100 mA CW @ 35 MeV DTL
LEDA (1990s)	H^+	ECR ion source	110 mA 75 keV	$>90\%$	0.2π mm·mrad	4 vanes 8 brazed modules flanged 4 segments coupled	350 MHz 8 m 9.3	100 mA 6.7 MeV	670 kW 1450 kW	1.8 Kp	up to 2000 *Tritium production* 100 mA CW @ >1 GeV CCDTL & Elliptical cavities up to 2004 *Fusion materials research* 125 mA @ 40 MeV CCDTL initially, SC cavities from 2002
LIPAc (2010s)	H^+/D^+	ECR ion source	140 mA 100 keV	$>90\%$	0.3π mm·mrad	4 vanes 18 brazed modules flanged No segmentation	175 MHz 9.7 m 5.7	125 mA 5 MeV	625 kW 1300 kW	1.8 Kp	*Fusion materials research* 125 mA CW @ 40 MeV DTL initially, HWR from 2008

IFMIF(EU-JP BA): similar cost as SNS ($1.4B) or ESS (€1.8B)

IFMIF-DONES(EU), A-FNS(JP), CMIF(CN), FPNS(US) etc.: half of IFMIF

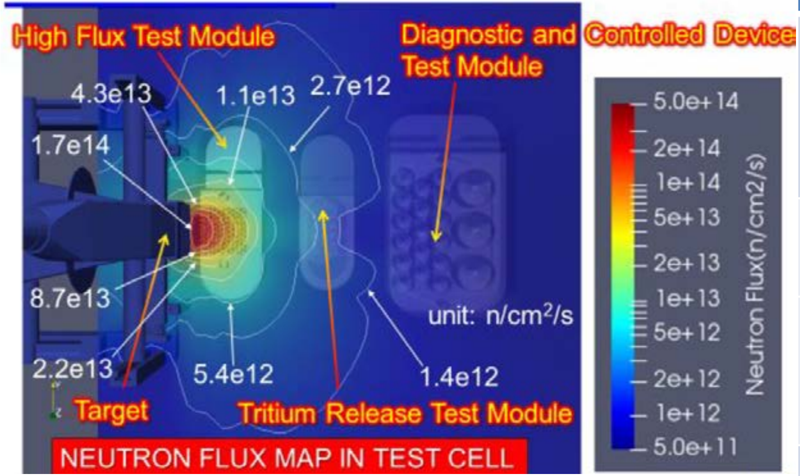
Recent Trends Worldwide

→ The requirements for the early phase of the neutron source are significantly reduced, opening the possibility of a staged approach to IFMIF in which its construction can be developed in phases, with the first one focused only on DEMO needs (max ~20 dpa initially, followed by max 50 dpa in a second phase).

Facility	Beam	Beam energy	Beam current	Beam Power	Target	Beam spot at target	Neutron flux	Remark
GANIL-SPIRAL2 (France)	H^+, D^+, Heavy ion CW or Pulse	40 MeV	5 mA	200 kW	Solid Li (thin) Be/Carbon (thick)	$\sim 10\ cm^2$	$\sim 10^{15}$ n/s	Neutron For Science (TOF, possible fusion-relevant exp.), Super Separator Spectrometer
SARAF-PHASE2 (Israel)	H^+, D^+ CW or Pulse	40 MeV	5 mA	200 kW	LiLiT	$\sim 2\ cm^2$	$\sim 10^{15}$ n/s	Nuclear physics, High energy neutron induced experiments
IFMIF-DONES (EU) **A-FNS (Japan)**	D^+ CW	40 MeV	125 mA	5 MW	LiLiT	5 cm × 10 cm 5 cm × 20 cm	$> 10^{18}\ n/m^2 \cdot s$ 20~50 dpa	Neutron irradiation tests on the DEMO reactor materials (blanket/divertor)
CMIF (China)	D^+ CW	50 MeV	10 mA	500 kW	Granular flow Be	5 mm × 15 mm (smaller spot)	$\sim 10^{18}\ n/m^2 \cdot s$ 20~50 dpa/y	For ADS and fusion materials (not much recent progress)
MYRRHA-Phase1 (Belgium)	H^+ CW	100 MeV	4 mA	400 kW	Water cooled spallation target (W, Ta)	400 cm^2 (either direct proton irradiation or neutron converter)	$10^{13}\ n/cm^2/s$ 0.4 dpa/200 days	ISOL system (low power) and Fusion material research (full power)

Example of A-FNS (Japan)

Neutron flux field in Test Cell of A-FNS



List of Neutron Irradiation Plan in A-FNS.

Region	Test Module	Materials
High Flux	Blanket Structural Material	RAFM (F82H)
	Divertor Functional Material	RAFM, W, Cu
	Blanket Functional Material	$Be_{12}V$, $Be_{13}Zr$, $Be_{12}Ti$, etc Li_2O, Li_2TiO_3, etc.
Middle Flux	Tritium Release Test Module	BS+BFM for tritium recovery
	Creep Fatigue Test Module	RAFM (F82H)
Low Flux	Diagnostic Controlled Device	MI, Mo, W, etc
	Blanket Nuclear Property	BS+BFM for neutronics
	Neutron Flux Measurement	Activation foils, etc
(Others)	Medical RI production*	Mo for Mo-99

More Recent Activity

→ US is planning a Fusion Prototypic Neutron Source (FPNS), which could be constructed in the near term at moderate cost with accelerator parameters similar to IFMIF-DONES. More detailed cost estimates by ORNL.

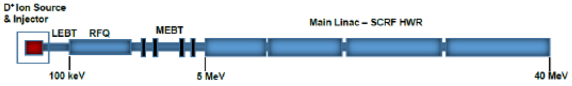


Figure 3 – Option 1 schematic layout.

Table 7 – Option 1 accelerator specifications.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.3
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ (LEDA Based)	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	5.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.61
Structure Power (MW)	0.56
Total RF Power (MW)	1.17
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.30
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	9.6
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	5
Bunchers	2, 5-gap IH cavities
MEBT Length (m)	2
Main Accelerator	
Structure Type	SC 2-gap HWR
RF Frequency (MHz)	175
Output Energy (MeV)	40.0
No. Structure Segments	4 Cryomodules
Cavity Design β	β=0.094, β=0.094, β=0.164, β=0.164
No. Cavities per Cryomodule	Cryomodules 1,2 = 6 Cryomodules 3,4 = 4
Cryomodule output energy (MeV)	9.0, 14.5, 26.0, 40.0
Output Beam Current (mA)	125
Beam Power (MW)	4.4
Structure Power (MW)	0.2
Total RF Power (MW)	4.6
Transverse Focusing Type	SC EM Solenoids
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.3
Structure Length (m)	22.7
Total RF Power – RFQ + SCRF Linac (MW)	5.8

SC　　　　NC

Option 1		Option 2	
Subsystem	**Cost ($M 2019)**	**Subsystem**	**Cost ($M 2019)**
RFQ (175 MHz)	11.28	RFQ (175 MHz)	11.28
SCRF HWR (175 MHz)	34.05	NC DTL (175 MHz)	32.82
RF Power	19.94	RF Power	26.15
Cryoplant	8.50		
Total	**73.76**	**Total**	**70.25**

Inherent complexity　　　　No operating CW DTL

TRL 7 > TRL 6

Figure 5 – Option 2 schematic layout.

Table 10 – Option 2 accelerator specifications.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.3
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ (LEDA Based)	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	5.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.61
Structure Power (MW)	0.56
Total RF Power (MW)	1.17
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.30
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	9.6
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	4
Bunchers	2, 175-MHz, 2-gap cavities
MEBT Length (m)	2
Main Accelerator	
Structure Type	NC DTL
RF Frequency (MHz)	175
Output Energy (MeV)	40.0
No. Structure Segments	TBD
Output Beam Current (mA)	125
Beam Power (MW)	4.4
Structure Power (MW)	2.0
Total RF Power (MW)	6.4
Transverse Focusing Type	Permanent-Magnet Quadrupoles
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.3
Structure Length (m)	23
Total RF Power – RFQ + SCRF Linac (MW)	7.6

More Recent Activity

The High Brilliance Neutron Source (HBS), currently under development at Forschungszentrum Jülich, a room temperature solution has been chosen because of the much simpler technology avoiding a cryogenic plant, the development of cryo-modules and suitable power couplers [H. Podlech et al, IPAC 2019].

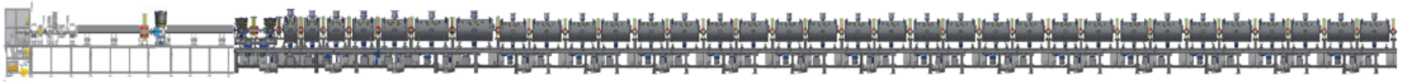


Figure 3: Conceptual layout of the HBS-Linac. It consists of an ECR-source, LEBT, RFQ, MEBT and the CH-DTL.

Table 1: HBS Top-Level Requirements

Parameter	Specifications
Particle type	Protons
Accelerator type	RF Linac
Peak beam current	100 mA
Final energy	70 MeV
Beam duty factor	6%
RF duty factor	11%
Pulse length	52/208/833 μs
Repetition rate	384/96/26 Hz
Peak beam power	7 MW
Average beam power	420 kW

Similar beam power as other SC-based machines, but the beam is pulsed with much higher current.

Nonetheless, the fusion community prefers CW beam (from Y. J. Lee of ORNL)
→ Less peak power, more similar situation as fusion plant

Acvitivities in Korea

Activities in Korea (selected)

The First Workshop on IFMIF-EVEDA/IFERC and Beyond
Pohang Accelerator Laboratory
29-31 July 2013

29th July, Monday

14:00 – 14:30	Registration	
14:30 – 14:40	Welcoming Remark	M. H. Cho
14:40 – 15:00	Introductory Remarks	P. Barabaschi and M. Mori
15:00 – 15:40	K-DEMO Design, R&D and International Collaboration	G. S. Lee
15:40	Coffee Break	
16:00 – 17:00	Overview of IFMIF-EVEDA Project (w. Discussion)	J. Knaster
17:00 – 18:00	Overview of IFERC Project (w. Discussion)	N. Nakajima
18:00	Close	
18:30	Banquet/Dinner at POSCO International Centre	

30th July, Tuesday

8:30 – 10:30	Plan beyond the IFERC and IFMIF-EVEDA	K. Ushigusa
	IFMIF/ENS Options	R. Heidinger, A. Ibarra, A. Moeslang
10:30 – 10:45	Coffee Break	
10:45 – 12:30	Discussions	
12:30 – 14:00	Lunch	
14:00 – 15:30	Korean Accelerator Program Overview and PAL Tour	W. Namkung
15:45 – 16:30	Move from PAL to KOMAC	
16:30 – 18:00	KOMAC Overview and Facility Tour	Y. S. Cho
18:30	Dinner at Gyeongju	

31st July, Wednesday

8:30 – 12:00	Discussions and other talks	
12:00	Lunch	
13:00	Adjourn	

* **Technical Seminar** (for anyone stay longer + PAL and NFRI Members):

14:00 – 15:00	Superconducting Accelerators for Hadrons and Test Facilities	S. H. Kim

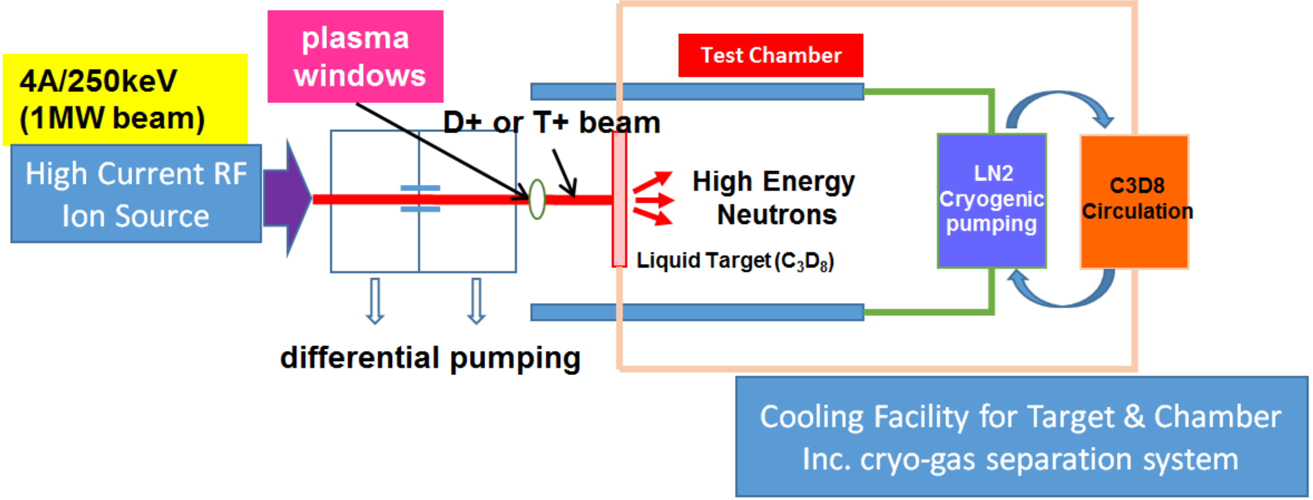
Activities in Korea (selected)

~2016

Busan International Fusion Neutron Source (BIFNS)

Busan Natl' Univ., Dongeui Univ., Seoul Natl' Univ.
NFRI, KAERI, KIMS, City of Busan, BISTEP

Beam energy	reaction	N yield [n/s]
300keV/10A (3MW)	DD	1.6×10^{14}
	DT	6.2×10^{15}
250keV/4A (1MW)	DD	0.4×10^{14}
	DT	2.1×10^{15}



Activities in Korea (selected)

Case studies by KFE

중성자원 종류	주요 사양	특기사항	검토사항
d + ^{6}Li stripping (LINAC) IFMIF	- 40 MeV /125 mA (5 MW) - 열부하(20x20㎝): ~100 MW/m^2 - 중성자 : 1E^{17} n/s (forward) (> 10 MeV) - 중성자속 : 5E^{14} n/cm^2·s - 조사 영역 : 0.1 L (10~20 dpa/y)	- IFMIF EVEDA 기술 존재 - Liquid Li Target(50x100 mm^2) 기술(유속15m/sec) - 125 mA 연속운전 기술 필요 - 구축 공간 : 100 x 50 m - EU(IFMIF-DONES), 일(A-FNS)	- 가속기 건설(투자 (약 1조원) 대비 효율 낮음) - 투자 측면을 제외할 경우, 기술 측면에서 가장 매력적임 - 고강도 중성자원으로 구조재 연구 가능
D+T (이온 Beam)	- 0.2 MeV /40 A (4 MW) - 열부하 : ~100 MW/m^2 - 2E^{15} n/s (핵융합중성자 : 14.1 MeV) - 중성자속 : 1E^{13} n/cm^2·s - 조사 영역 : 10x20 ㎝ (~1 dpa/y)	- 많은 R&D 필요(회전 표적, T 증착 등) - Solid Target(TiT_2) 가능 (회전rpm:~1,000) - CW 가능 연구 필요 - 이탈리아(ENEA), 중국(INEST, HINEG-II) 설계/연구만 진행 중	- 외부로부터 반입되는 삼중수소 이슈 - 추가 Target 관련 R&D 필요 - (약 3,000억원+기술리스크)
d + ^{7}Li (RFQ 가속기)	- 3 MeV /100 mA (0.3 MW) - 열부하 : ~10 MW/m^2 - 4.4E^{14} n/s (10 Mev 이상 ~30%)	- 3 MeV/20 mA 경험(100 mA 기술 개발 필요) - Solid Target 가능 여부 - CW 가능 추가 연구 필요	- 소규모 가속기 타입 (투자 대비 효율 저) - CW 100mA 기술 확인 필요 - 고속중성자 비율 30% 정도
d + ^{7}Li (이온 Beam)	- 1 MeV /5 A (5 MW) - 열부하 : ~100 MW/m^2 - 1.2E^{15} n/s (10 Mev 이상 ~30%)	- 1 MeV 개발 경험 없음 - Liquid Li Target 기술 필요 - CW 어려움	- 가열기술 연계 개발 가능(투자 효율 저) - 기술 성숙도 가장 낮음 - 고속중성자 비율 30% 정도 - 핵융합 가열장치 개발과 연계가 있는 장점
p + ^{9}Be (Cyclotron)	- 70 MeV /1 mA (0.07 MW) - 열부하 : ~2 MW/m^2 - 6E^{14} n/s(70%, <30° forward) (고속중성자 10 Mev 이상)	- 1 mA 가능 여부 - CW 가능 여부 - Solid Target 가능	- 사이클로트론 핵융합 중성자원 시설 구축 - 고에너지(70 MeV), 고전류(1 mA) 연속 운전가능 R&D 필요 - 기술 성숙도 가장 높음 (기성품 있음) - 투입비용 대비 효율 높음

Design studies by KAERI

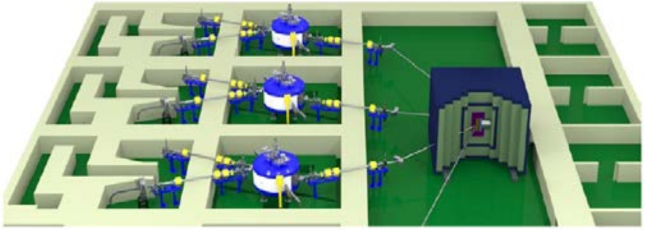
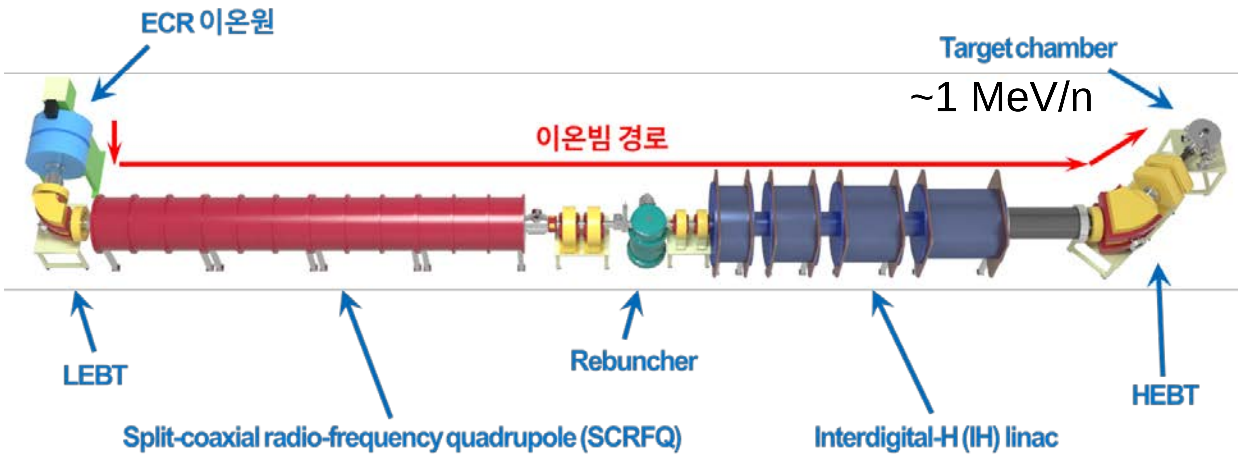


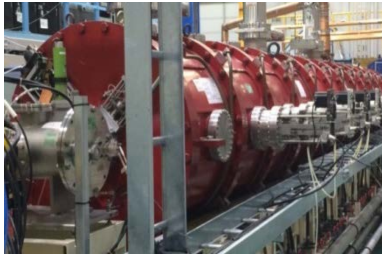
FIG.4. Example of CANS application for fusion material and blanket.

For both the 20 MeV and 30 MeV proton beam (0.1 mA) with the selected targets (Be), neutron yields of 8.8×10^12 n/s and 1.9×10^13 n/s, respectively, are expected.

Activities in Korea (selected)

KAHIF (KAERI Heavy Ion Irradiation Facility ← TRIAC/KEK)   [S. H. Noh (PKNU)]




방사선발생장치사용허가증

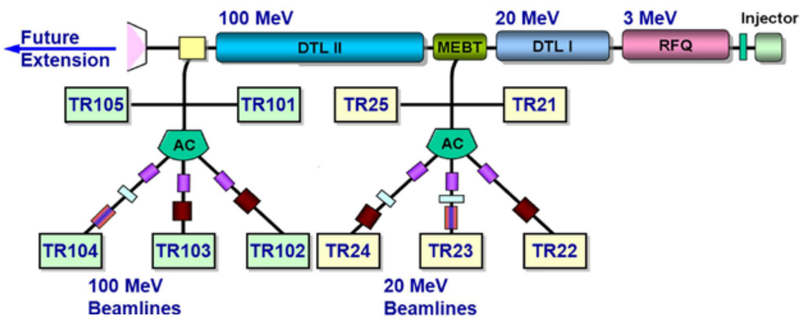
2017년 8월 18일

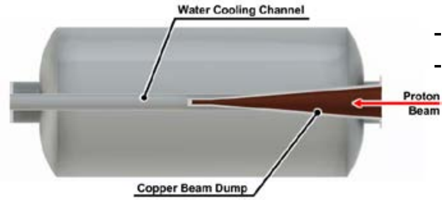
원 자 력 안 전 위 원 회

- Simulation of “fusion neutrons” by ion beams
- Temperature controlled target chamber (< 1500 °C)
- Successful commissioing with He^{+} (7.8 euA peak), Ar^{10+} (0.8 euA peak) at duty cycle 28.8%
- Upgrade planned to inject metal ions (ex, Fe)

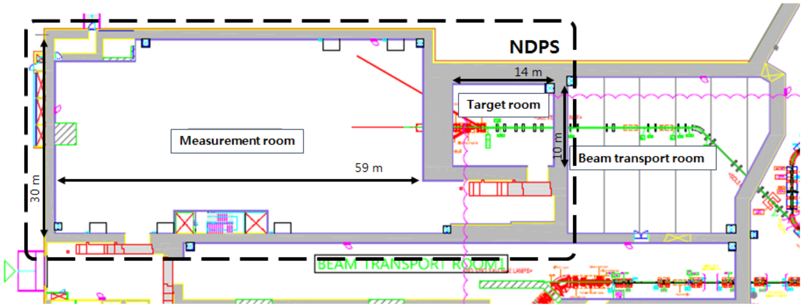
[More recent updates by D. W. Lee (KAERI)]

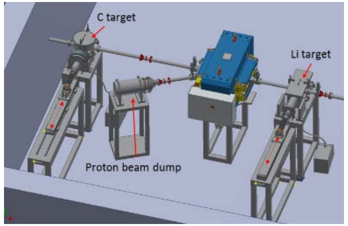
What about KOMAC or RAON?





- Pulsed white neutron source: 100 MeV p
- Beam dump as a neutron converter





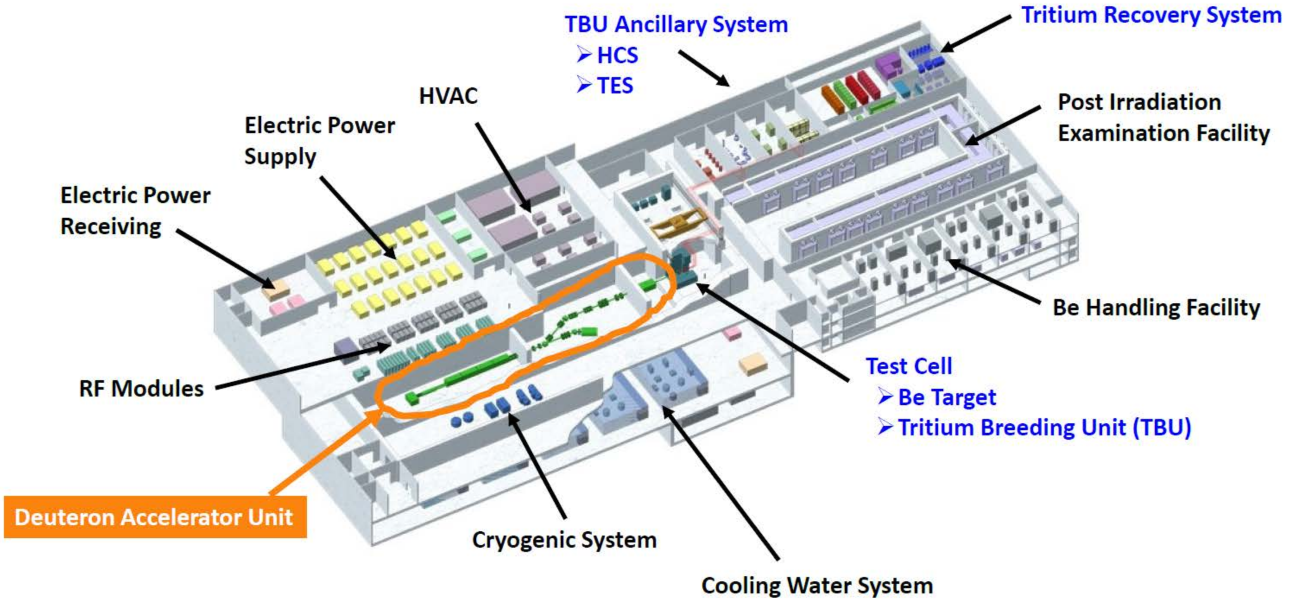
- White neutrons: C(d,n): 98 MeV D+
- Mono-energy neutrons: Li(p,n): 83 MeV p

- Average beam current is limited to 1.6 mA
- User facility
- No space or infrastructure for fusion material irradiation or tritium breeding module test

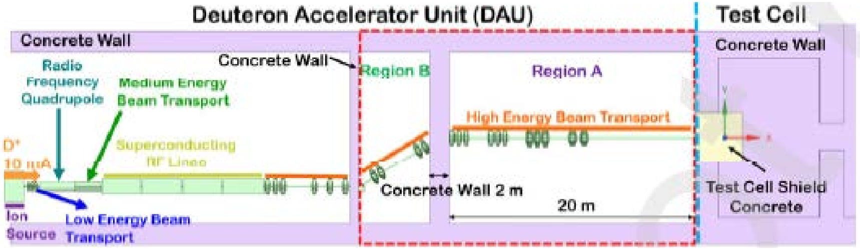
- Average beam current is limited to 1 mA or less
- User facility
- No space or infrastructure for fusion material irradiation or tritium breeding module test

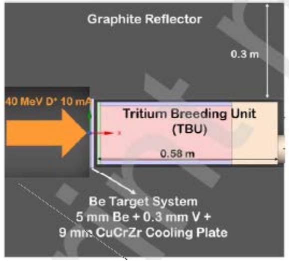
Integrated Breeding Test Facility (IBTF) by KFE

[From iFPC 2022]



D+
40 MeV
(20 MeV/u)
Max 10 mA
CW





6.68E+15 n/sec

[S. H. Hong et al. (KFE)]

Layout of Deuteron Accelerator Unit (DAU)

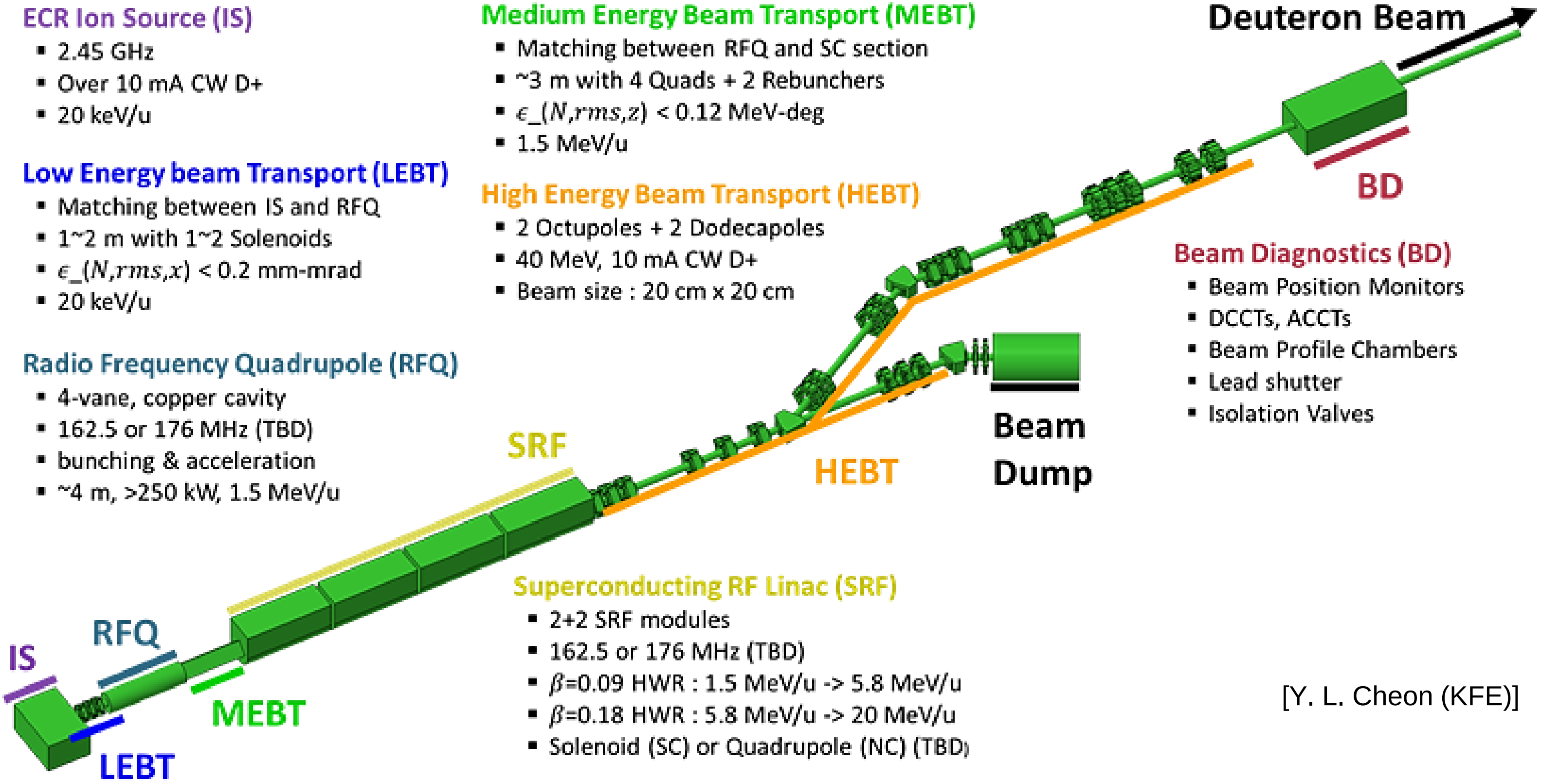
ECR Ion Source (IS)
- 2.45 GHz
- Over 10 mA CW D+
- 20 keV/u

Low Energy beam Transport (LEBT)
- Matching between IS and RFQ
- 1~2 m with 1~2 Solenoids
- $\epsilon\_(N,rms,x)$ < 0.2 mm-mrad
- 20 keV/u

Radio Frequency Quadrupole (RFQ)
- 4-vane, copper cavity
- 162.5 or 176 MHz (TBD)
- bunching & acceleration
- ~4 m, >250 kW, 1.5 MeV/u

Medium Energy Beam Transport (MEBT)
- Matching between RFQ and SC section
- ~3 m with 4 Quads + 2 Rebunchers
- $\epsilon\_(N,rms,z)$ < 0.12 MeV-deg
- 1.5 MeV/u

High Energy Beam Transport (HEBT)
- 2 Octupoles + 2 Dodecapoles
- 40 MeV, 10 mA CW D+
- Beam size : 20 cm x 20 cm



Beam Diagnostics (BD)
- Beam Position Monitors
- DCCTs, ACCTs
- Beam Profile Chambers
- Lead shutter
- Isolation Valves

Superconducting RF Linac (SRF)
- 2+2 SRF modules
- 162.5 or 176 MHz (TBD)
- β=0.09 HWR : 1.5 MeV/u -> 5.8 MeV/u
- β=0.18 HWR : 5.8 MeV/u -> 20 MeV/u
- Solenoid (SC) or Quadrupole (NC) (TBD)

[Y. L. Cheon (KFE)]

Layout of Deuteron Accelerator Unit (DAU)

[Y. L. Cheon (KFE) and E. Cosgun (UNIST)]

Bore diameter: 36 / 40 mm

$\sim$50 m

Ion source	LEBT	RFQ	MEBT	SC Linac		HEBT	
ECR IS (NC) 2.45 GHz	Matching between IS and RFQ	4-vane 176 MHz –bunching & acceleration	Matching between RFQ and SC section ❖ Space charge	HWR (SC) 176 MHz (2 cryomodules) $\beta = 0.091$	HWR (SC) 176 MHz (2 cryomodules) $\beta = 0.181$	2 Octupoles (For making rectangular shape of beam) 30° Dipoles 2 (Achromatic) Beam diagnostics ($\sim$4 m)	Target Cell (Solid Be 20 cm x 20 cm) Expected neutron yield : $\sim 10^{17}$ $n/m^2/s$
D^+ CW Max 10 mA 20 keV/u	2 Solenoids 20 keV/u	171 kW 5.24 m 1.5 MeV/u	4 Quads + 2 Rebunchers Beam diagnostics 1.5 MeV/u	1.5 MeV/u -> 6 MeV/u	6 MeV/u -> 20 MeV/u		• Beam Dump (Dose rate simulation study)
				Solenoid (SC) L = 250 mm			

Extraction current $\sim$12 mA ➢ L = 20 cm	Solenoids L = 400 mm ➢ L = 2 m	• Total power : 171 kW • Inter vane V : 70 kV ➢ L = 5.24 m	Beam diagnostics • BPM (position monitor) • ACCT • BPC (profile chamber) ➢ L = 2.3 m	# cryo : 2 ($\sim$3.7 m) # cavities/cryo : 6,7 # cavities : 13 Cavity L : 155 mm # solenoids/cryo : 6 # solenoids : 12	# cryo : 2 ($\sim$4 m) # cavities/cryo : 7 # cavities : 14 Cavity L : 308 mm # solenoids/cryo : 4 # solenoids : 8	Beam diagnostics • BPM (position monitor) • BCT (ACCT, DCCT) • BPC (profile chamber) ➢ L = $\sim$20 m	• Lead shutter • Cu • Water cooling
				➢ L = 17.34 m ($\sim$20 m)			
Target beam : Average 5 mA • Max 10 mA	• Chopper (Low duty cycle beam measurement for commissioning test)	• ACCT • Vacuum $< 10^{-7}$ $mbar$	• Scrapers • Vacuum $< 10^{-7}$ $mbar$	• Solenoid B max : 6.7 T • RF Power : > 400 kW • Vacuum : $< 10^{-8}$ $mbar$ • 4.5 K • BPM(position monitor), BPC (profile chamber)		Remote + Hands-on • Vacuum $< 10^{-7}$ $mbar$	• Scraper (at the end of HEBT) • Vacuum $< 10^{-5}$ $mbar$

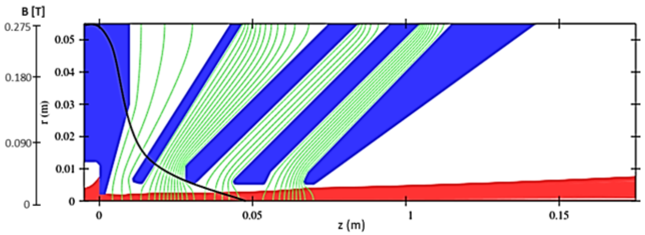
SS316L → Aluminium

Start-to-End Simulation of DAU

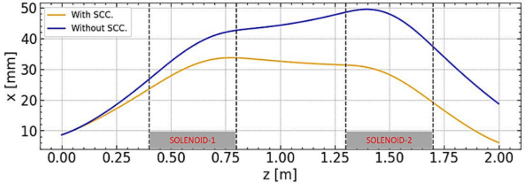
[Y. L. Cheon (KFE) and E. Cosgun (UNIST)]

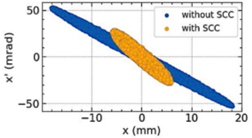
ECR Ion source → **LEBT** → **RFQ**

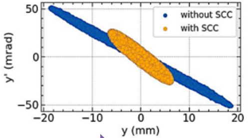
IBSimu code

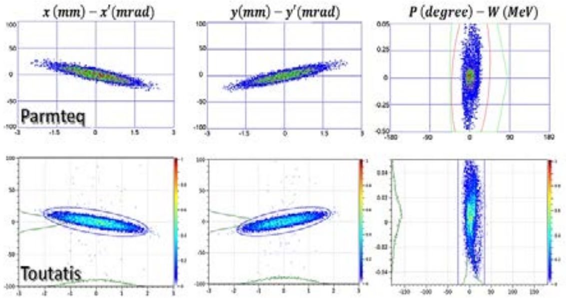


Warp code



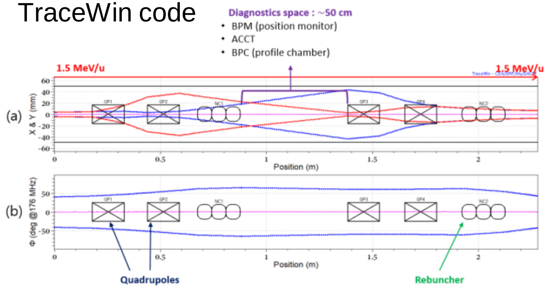


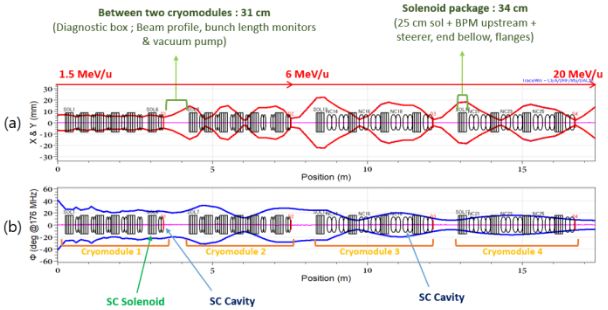




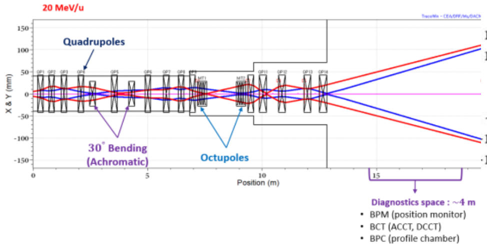
MEBT → **SRF LINAC** → **HEBT** → **Target**

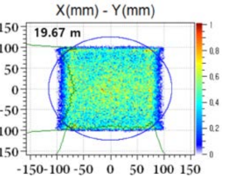
TraceWin code





Or rastering magnets





→ No showstoppers in beam dynamics point of view → Technology Readiness / Cost / Schedule would matter

Possible Collaborators

CEA (France)

VITZRO (Korea)

Summary and Conclusion

- For Blanket Structural Material, Divertor Functional Material, Tritium Release Module of DEMO, neutron irradiation experiments with relatively low energy (~40 MeV), high average current D+ accelerators are being pursed worldwide.

- Korean fusion and accelerator communities should look into best options for domestic fusion engineering program [e.g., dedicated tritium breeding unit tests with a moderate-intensity D+ accelerator via Niche marketing (틈새시장전략) or Mid-entry Strategy (중간진입전략)].

- Accelerator technology seems rather matured, whereas target design and neutronics are getting more challenging.

Thank you
for your attention !