Fusion Reactor Technology II
(459.761, 3 Credits)

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Contents

ITER TBM

- TBM의 개발은 ITER 산하의 TBWG(Test Blanket Working Group)를 통하여 각 참여국의 TBM 시험계획을 검토하고, 각 계획 간의 조정을 협의하면서 진행되고 있음.
- TBWG는 ITER 참여국들이 ITER 장치의 3개 equatorial port(#16,18,2)에 설치될 TBM의 종류 및 시험 계획을 마련하는 것이 핵심 목표임.
  (3개의 Port를 6개 참가국이 공유)
- 공간적 제한으로 인하여 참여국들이 국제협력을 통한 TBM 개발 및 시험을 수행함으로써 TBM 숫자를 6개로 줄이는데 동의하였으며, 현재 TBM 숫자 감소 및 포트 분담방안에 대한 협의가 이루어지고 있음.
- TBWG는 블랑켓의 특성에 따라 5개의 종류로 분류하여 5개의 Working Subgroup을 두고 있음.
  - WSG1 : He-Cooled Ceramic Breeder
  - WSG2 : Lithium Lead
  - WSG3 : Water-Cooled Ceramic Breeder
  - WSG4 : Liquid Lithium
  - WSG5 : Molten Salt

Merits and demerits of models

- WSG1 : He-Cooled Ceramic Breeder
- WSG2 : Lithium Lead
- WSG3 : Water-Cooled Ceramic Breeder
- WSG4 : Liquid Lithium
- WSG5 : Molten Salt

	고체형 블랑켓		액체형 블랑켓		
	WSG1	WSG3	WSG2	WSG4	WSG5
기술적 성숙도	높음	보통	조금 낮음	낮음	매우낮음
삼중수소 회수	쉬움	쉬움	보통	어려움	보통
삼중수소 침투	보통	보통	많음	적음	매우 심각
삼중수소 증식비율	낮음	낮음	높음	높음	높음
증배재	많이 필요	많이 필요	필요없음	소량 혹은 필요없음	TBD
증식재 농축	30-90%	30-90%	90%	90%	고농축 TBD
중성자 조사에 따른 증식재 피해	많음	많음	적음	적음	적음
증식재 재활용	어려움	어려움	N/A	N/A	N/A
방사성 폐기물	많음	많음	보통	적음	적음

Merits and demerits of models

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- WSG5 : Molten Salt

	고체형 블랑켓		액체형 블랑켓		
	WSG1	WSG3	WSG2	WSG4	WSG5
사용주기	3-4년	3-4년	연장가능	연장가능	연장가능
구조재 부식	적음	보통	많음	많음	매우 심각
MHD에 의한 압력강하	N/A	N/A	많음	보통	적음
액체 증식재 회로 유지보수	N/A	N/A	어려움	어려움	어려움
액체 증식재 활성	N/A	N/A	낮음	높음	낮음
열교환기 설계			증식재를 냉각재로 사용할 경우 열교환기 설계가 복잡함		
최고온도	리튬세라믹 허용온도 (900 ℃)	리튬세라믹 허용온도 (900 ℃)	구조재 허용온도	구조재 허용온도	구조재 허용온도
열효율	낮음	낮음	고 열효율 가능	고 열효율 가능	고 열효율 가능

TBM concepts of ITER parties

- 다음과 같이 모든 참가국이 2개 이상의 블랑켓을 검증하기 위한 계획을 가지고 있음.

국 가	TBM 개념		구조재	증식재
중 국	Solid	Helium Cooled Solid Breeder	CLAM	Li4SiO4
	Liquid	Dual Cooled Lithium Lead or Quasi-Static Lithium Lead	CLAM	PbLi
EU	Solid	Helium Cooled Pebble Bed	EUROFER	Li4SiO4(Li2TiO3)
	Liquid	Helium Cooled Lithium Lead	EUROFER	Pb-17Li
일 본	Solid	Water Cooled Solid Breeder Helium Cooled Solid Breeder	F82H	Li2TiO3
	Liquid	Li Self Cooled w/o Be * Dual Cooled Lithium Lead * Flibe Self Cooled *		

* 협력을 통한 참여

** Day-1에는 submodule 참여, 향후 전체 TBM 검증

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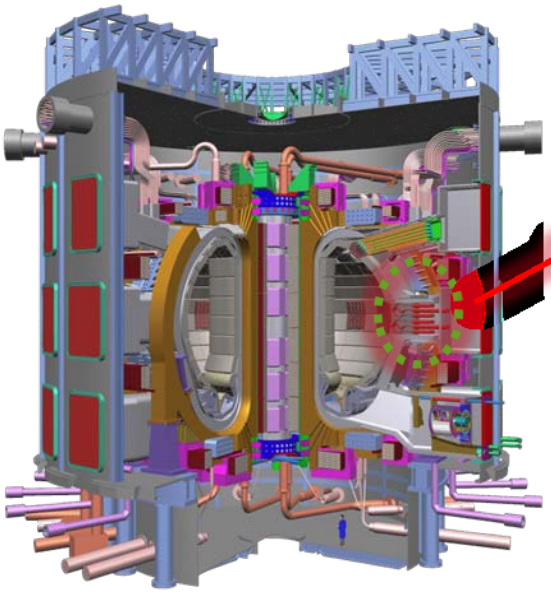
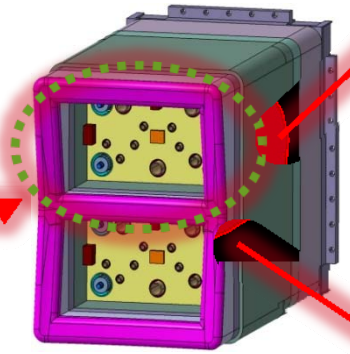
국 가	TBM 개념		구조재	증식재
러 시 아	Solid	Ceramic Helium Cooled	FS 9CrMoVNb	Li4SiO4
	Liquid	Lithium Self Cooled	V-Cr-Ti	Li
미 국	Solid	Helium Cooled Ceramic Breeder *	F82H	Li4SiO4(Li2TiO3)
	Liquid	Dual Cooled Lithium Lead	F82H	Pb-17Li
인 도	Solid	Helium Cooled Ceramic Breeder	LAFM	Li4SiO4(Li2TiO3)
	Liquid		LAFM (Li-V)	Pb-17Li
한 국	Solid	Helium Cooled Solid Breeder **	LAFM	Li4SiO4
	Liquid	Helium Cooled Molten Lithium	LAFM	Li

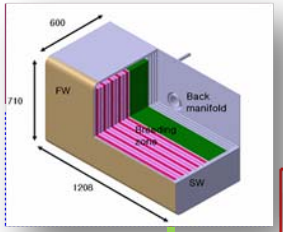
* 협력을 통한 참여

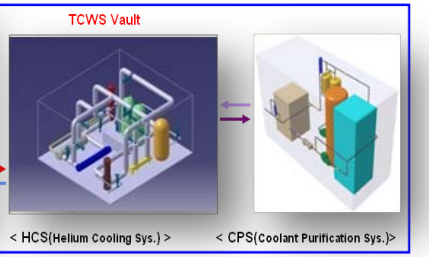
** Day-1에는 submodule 참여, 향후 전체 TBM 검증

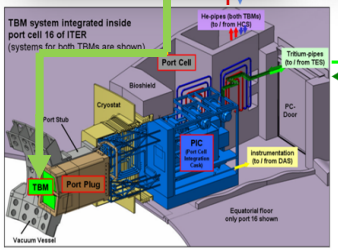
TBM concepts of Korea

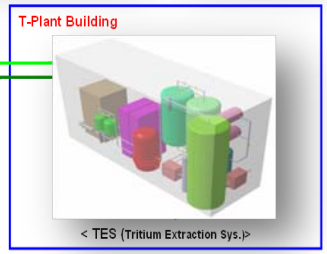




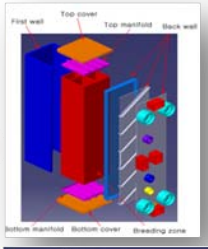


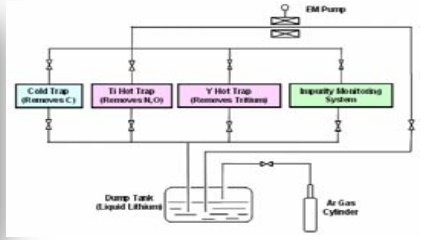


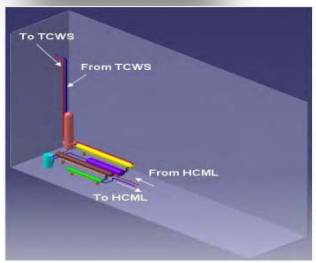


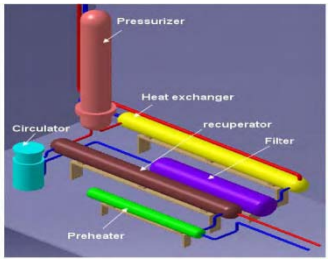


NFRI 국가핵융합연구소 National Fusion Research Institute



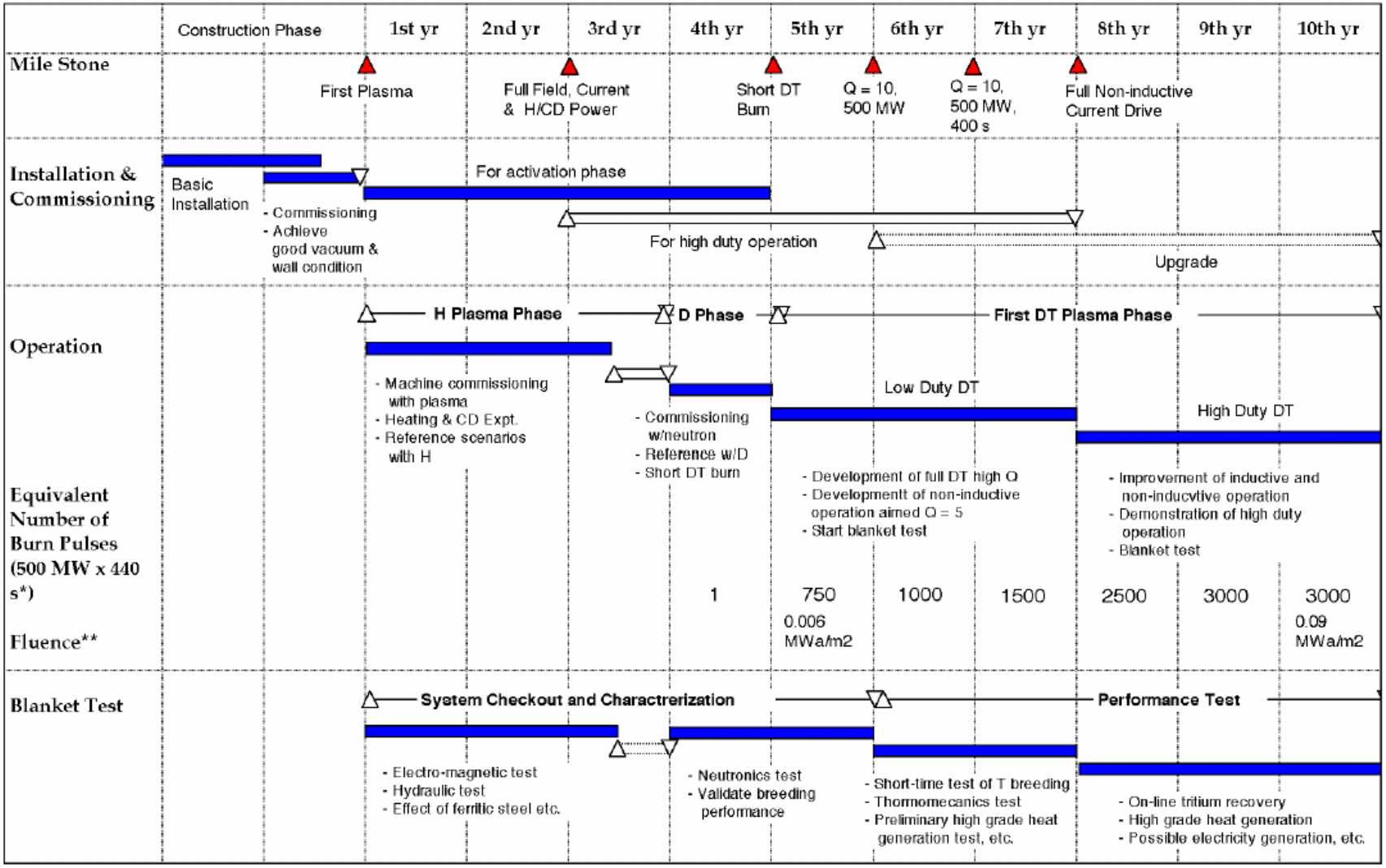






KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

ITER operation plan for first 10 years



TBM 단계별 검증 계획

- 1단계 운영기간 10년 동안 4개의 플라즈마 Phase에 대하여 4가지 타입의 TBM을 아래와 같이 단계적으로 검증할 계획임.

Type	Plasma Phase	Test Objectives
EM TBM (Electro-Magnetic)	H-H	- EM force & momentum에 대한 구조 강건성 - 일차벽 열, 구조 강건성 - 냉각시스템 및 원격장치 시험 - 계장 장치 시험 및 요구조건 확인 - MHD 관련 열수력 코드 검증 - 전기절연 코팅 검증
NT TBM (Neutron-Tritium)	D-D early D-T	- neutron flux, gamma flux, 삼중수소 생성율 및 분포, volumetric heat deposition 측정 - neutronics 코드 검증 - 핵 data 평가 - 삼중수소 증식/추출 시험 - 삼중수소 제어 검증 (회수, 침투, 침투 방어 코팅 등) - 노외 시험 결과 검증

TBM 단계별 검증 계획

- 1단계 운영기간 10년 동안 4개의 플라즈마 Phase에 대하여 4가지 타입의 TBM을 아래와 같이 단계적으로 검증할 계획임.

Type	Plasma Phase	Test Objectives
TM TBM (Thermo-Mechanic) TT TBM (Thermo-mechanic & Tritium control)	low duty D-T	- 열구조 거동 분석 - 열수력 및 구조 코드 검증 - 증식재 재료의 최대 허용온도 측정 및 안전계수 결정 - 삼중수소 제어 검증 (회수, 침투, 침투 방어 코팅 등) - 계장 장치의 검증 - 방사능 레벨 확인 및 방사능 차폐 능력 검증
PI TBM (Plant Integration) IN TBM (INtegral)	high duty D-T	- 다양한 운전 시나리오에 대한 열, 삼중수소 추출 능력 평가 - 선행 시험들의 신뢰도 확인 - 종합적인 성능 평가

TBM 단계별 검증 계획

- 2단계 운영단계에서도 추가적인 시험이 예상됨.
- 우리나라를 제외한 타 참여국의 경우 TBM 개념설계는 모두 완성되어 TBWG에 DDD(Design Description Document)를 이미 제출한 상태이며, 공학설계를 통하여 DDD를 수정할 계획임.
- 우리나라는 현재 헬륨냉각 고체형 (NFRI 주도) 및 헬륨냉각 액체형 (KAERI 주도)에 대한 연구가 2006년부터 본격으로 시작되었음.

Solid type: common principles

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Breeding Zone (BZ) configuration	Breeder Out Tube (BOT) with Cells	BOT with BUs	BOT with parallel beds	BOT with parallel beds	BIT (Breeder In Tube)	BOT	BOT with parallel beds
TBM dimension W x H x D (mm)	664×890×~630 1/4 port	1270x740x~700	1290x760x~600	530x1740x~600	510x840x750 1/4 port	402x710x600	910x1490x495 (version with 100mm frame)
Power deposition	760 kW	950 kW	1162 kW	1088 kW	446 kW	330 kW	1455 kW
Tritium production (peak) (μg/s)	1.18	1.16	1.08 (TM module)	0.98 (TM module)	0.92		2.93
BZ(CB+BE+Refl) thickness	29 cm	40 cm	8.1 cm (total)	6.4 cm (total)	50	40 cm	9(2/3/4) cm
He pressure drop in TBM (MPa)	~0.29	~0.3	~0.1	~0.1	0.008/0.0014 (FW/BZ)	~0.1	To Be Determined (TBD)

(a) The data refer to the EU PI-TBM.
(b) Basic technology is established. now under irradiation test

Solid type: structural material

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Material	EUROFER	EUROFER	F82H	F82H	Ferritic steel 9CrMoVNb	RAFS	LAFM
Operational temp.	300-550°C	300-550°C	280-550°C	280-550°C	300-550ºC	300-550°C	300-550ºC

Solid type: coolant

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Coolant medium	He	He	He	P. Water	He	He	He
Pressure	8 MPa	8 MPa	8 MPa	15 MPa	8 MPa	8 MPa	8 MPa
Operational temp.	300-500°C	300-500°C	300-500°C	280-325°C	300-500°C	300-500°C	300-500°C
He velocity in FW/BZ (m/s)	69/18	85/35	35/14		19/7	TBD	29/10
Chemical composition	TBD	10-100 Pa H20 100-500 Pa H2 other < TBD	TBD, base condition is H_2O: Dew point -70°C O_2: 0.1vpm H_2: 10vpm N_2: 0.5vpm CO_2 etc: 10vpm	pH= 6 8 Conductivity < 0.1 microS/cm Dis. H_2 = 25 35 cc/kg dis. O_2 < 0.1 ppm Cl < 0.001 ppm Mineral < 0.005 ppm	TBD	TBD	TBD

Solid type: ceramic breeder

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Ceramic Breeder	Li_4SiO_4	Li4SiO4 (Li_2TiO_3)	Li_2TiO_3	Li_2TiO_3	Li_4SiO_4	Li_4SiO_4/Li_2TiO_3	Li4SiO4
Li-6 enrichment (%)	80	40-90	~90	~90	30-90	40-70	40
Typology	Single Size Pebble Bed (SS PB)	SS PB	SS PB	SS PB	PB ?	SS PB	SS PB
Operational temp.	400-950°C	450-920°C	280-900°C	280-900°C	400-1000°C	450-920°C	450-900 °C

Solid type: neutron multiplier

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Material	Be	Be	Be/BeTi	Be/BeTi	Be	Be	Be
Typology	BN PB	SS PB	SS PB	SS PB or BN (Binary) PB (TBD)	Porous body	SS PB	SS PB
Operational temp.	400-620°C	450-600°C	280-600°C	280-600°C (BeTi= 280-900°C)	400-550°C	450-600°C	570-680°C

Solid type: neutron reflector

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Material	N/A	N/A	N/A	N/A	N/A	N/A	Graphite
Typology	N/A	N/A	N/A	N/A	N/A	N/A	TBD
Operational temp.	N/A	N/A	N/A	N/A	N/A	N/A	530-750°C

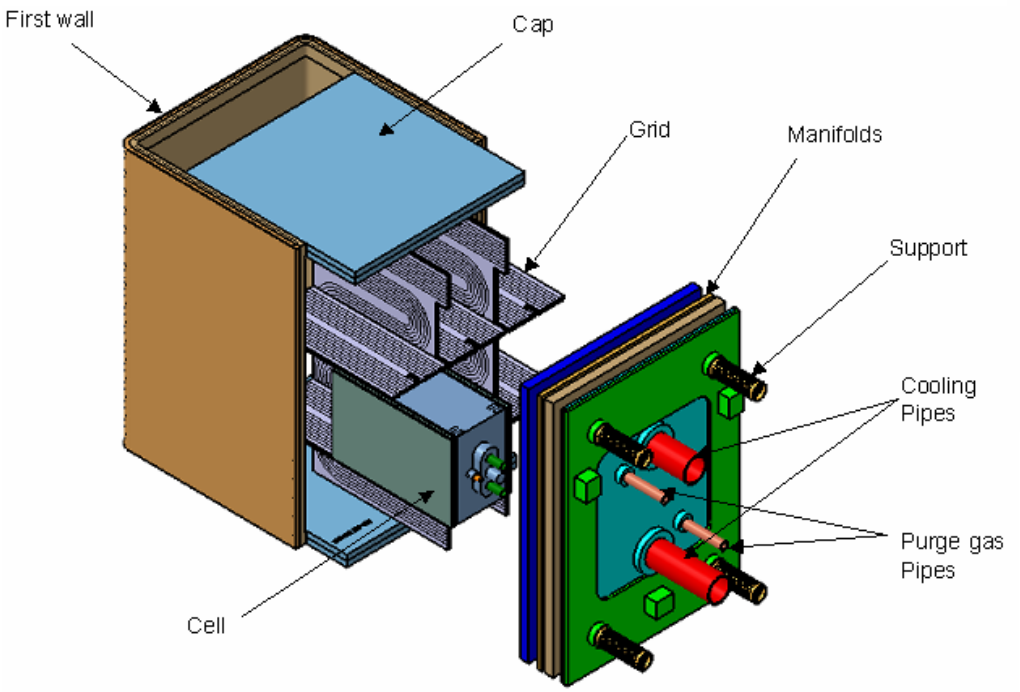
Solid type: purge flow

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	**HCSB**	**HCPB (a)**	**HCSB**	**WCSB**	**CHC**	**HCCB***	**HCSB**
Fluid	He	He	He	He	He (Ne)	He	He
Pressure (MPa)	0.12	0.11	0.11	0.11	0.12-0.15	0.1	TBD
Mass flow He / tritium generation	0.6 g/s He/ 0.1g/day T				TBD		TBD
Max. velocity	25 cm/s	20 cm/s	0.5-2 cm/s	0.5-2 cm/s	TBD	10 cm/s (TBD)	TBD
Chemical composition	$He:H_2$= 1000:1 others<TBD	0-200 Pa H2 Others<TBD	H_2:0-100 Pa others: TBD (parameter)	H_2:0-100 Pa others: TBD (parameter)	TBD	1000 ppm H_2	TBD

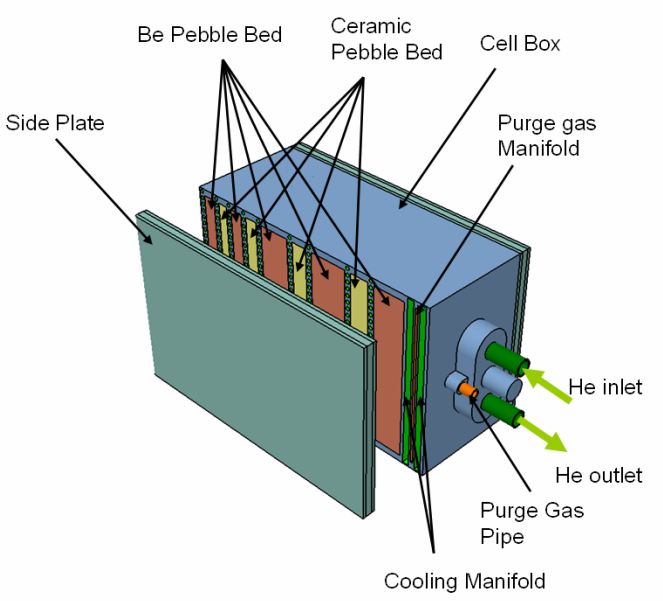
Solid type: tritium barriers

TBM Parameters	CH	EU	JA	JA	RF	US	KO
Label	HCSB	HCPB (a)	HCSB	WCSB	CHC	HCCB*	HCSB
Composition	Al_2O_3 layer and TiC or TiN coating	none	Alumina with primer on purge gas side (b)	Alumina with primer on purge gas side (b)	TBD		

Solid type TBM

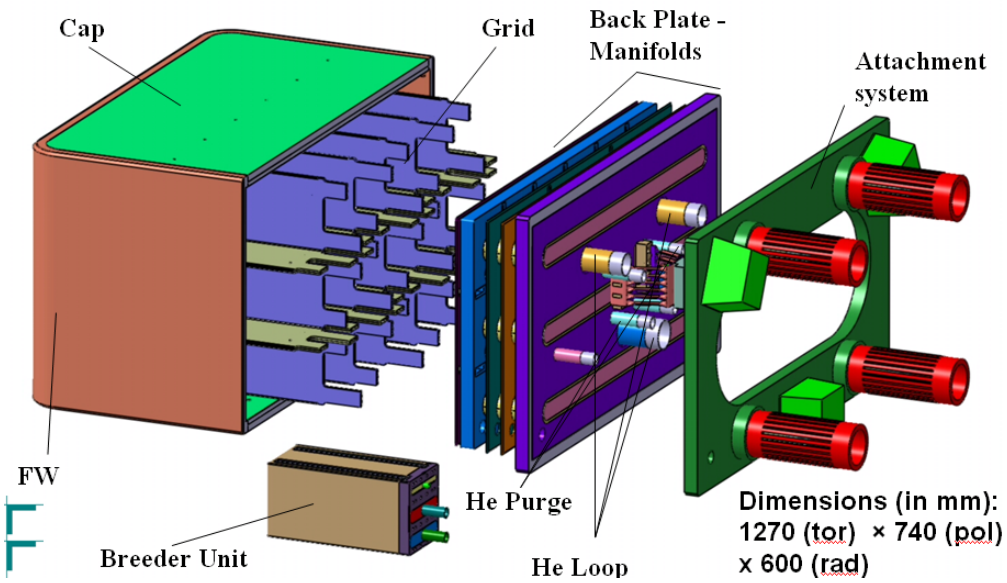


Exploded 3D View of CH HCSB

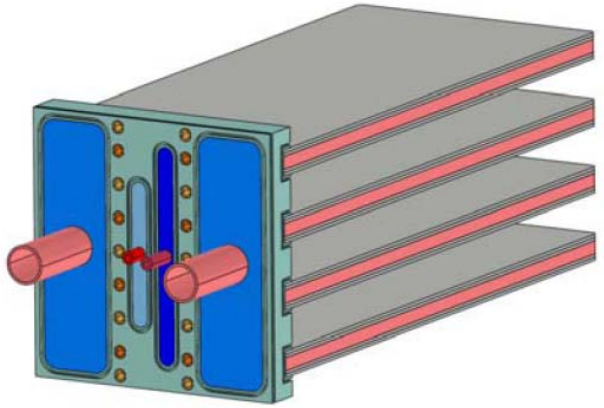


Schematic View of CH HCSB Sub-module

Solid type TBM

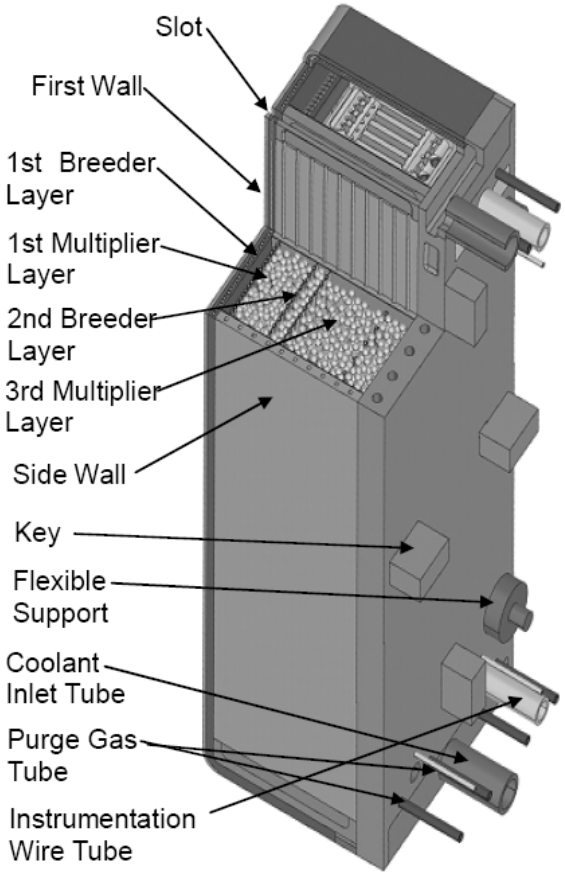


Exploded 3D View of EU HCPB TBM

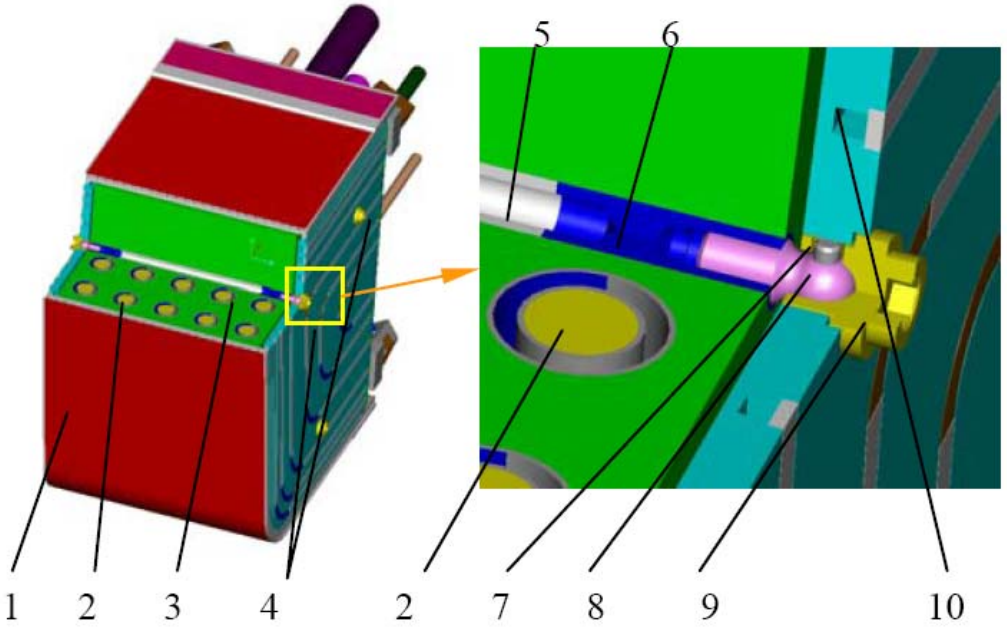


Schematic View of
EU HCPB Breeder Unit

Solid type TBM



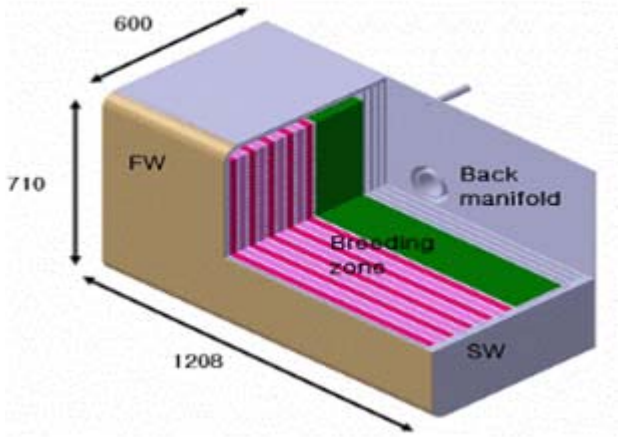
3D View of JA WCSB TBM



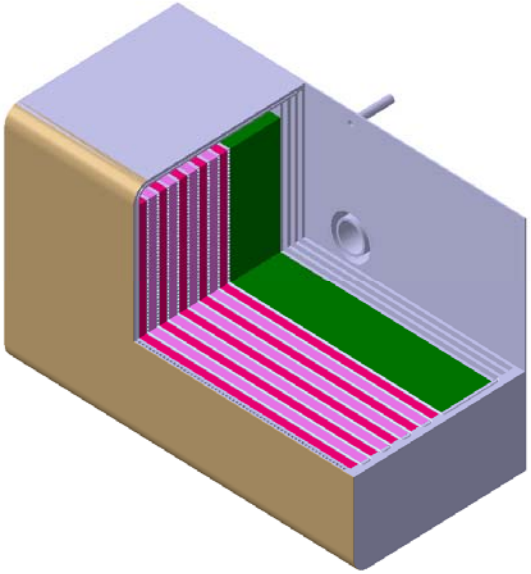
1-casing; 2-breeder; 3-multiplier; 4-attachment elements for TBZ; 5-rod; 6-threaded bush; 7-pin; 8-spherical hinge; 9-bushing with hexagon socket head; 10-cooling channel of casing

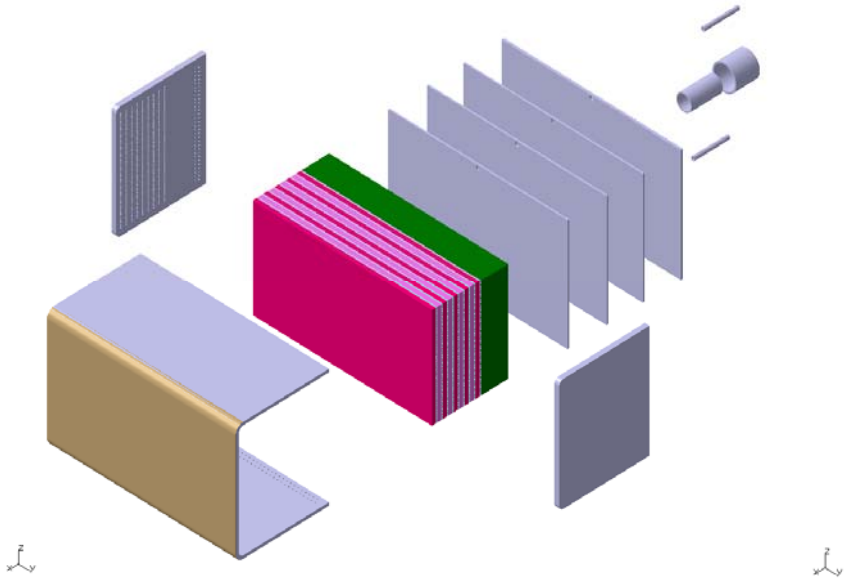
3D View of RF CHC TBM

Solid type TBM



KO HCSB TBM Concept





Liquid type

	CH	CH	EU	US	RF	KOR
Label	**DLL**	**SLL**	**HCLL**	**DCLL**	**Li self-cooled**	**HCML**
Structural material	CLAM	CLAM	EUROFER	F82H	V-Cr-Ti	RAFM
Breeder	PbLi	PbLi	Pb-17Li	Pb-17Li	Li	Li
Module dimension W x H x D (m)	0.626x1.832 x0.476	0.626x1.832 x0.476	0.626x1.838 x0.626	0.645x1.864 x0.413	0.514x1.72 x0.015	0.514x1.72 x0.443
Liquid breeder volume in TBM (m^3)	0.244	0.285	0.292	0.28	0.022	<0.028
Compare to DEMO configuration	Similar	Similar	Nearly identical	Similar	Similar	Unknown
Power deposition (MW)	0.92	0.89	0.93	1.34	0.65	0.793
Neutron multiplier	N/A	N/A	N/A	N/A	Be	N/A
Neutron reflector/ shielding material	N/A	N/A	N/A	N/A	WC	Graphite

*without reactor auxiliary heating system
** 12% divertor area excluded, average in steady state regime

Liquid type

	CH	CH	EU	US	RF	KOR
Label	**DLL**	**SLL**	**HCLL**	**DCLL**	**Li self-cooled**	**HCML**
Flow channel insert	SiC_f/SiC	N/A	N/A	Metallic FCI or SiC_f/SiC	N/A	N/A
MHD insulation	N/A	N/A	N/A	N/A	CaO, AlN, Er_2O_3,Y_2O_3, multi-layers	N/A
Tritium barrier	Al_2O_3	Al_2O_3	Natural oxide/Al_2O_3	Natural oxide	N/A	N/A
Key power conversion loops						
Primary helium	X	X	X	X	N/A	X
Liquid breeder	X	N/A	N/A	X	X	N/A
Intermediate loop	Helium	N/A	N/A	Helium	Organic	N/A
Water/steam	X	X	X	X	X	X
FW heat flux, ave/peak (MW/m^2)	0.3/0.5	0.3/0.5	0.25/0.5	0.3/0.5	0.27/0.5	0.3/0.5
Neutron wall loading (MW/m^2)	0.78 peak	0.78 peak	0.78 peak	0.78 peak	0.78 peak	0.78 peak

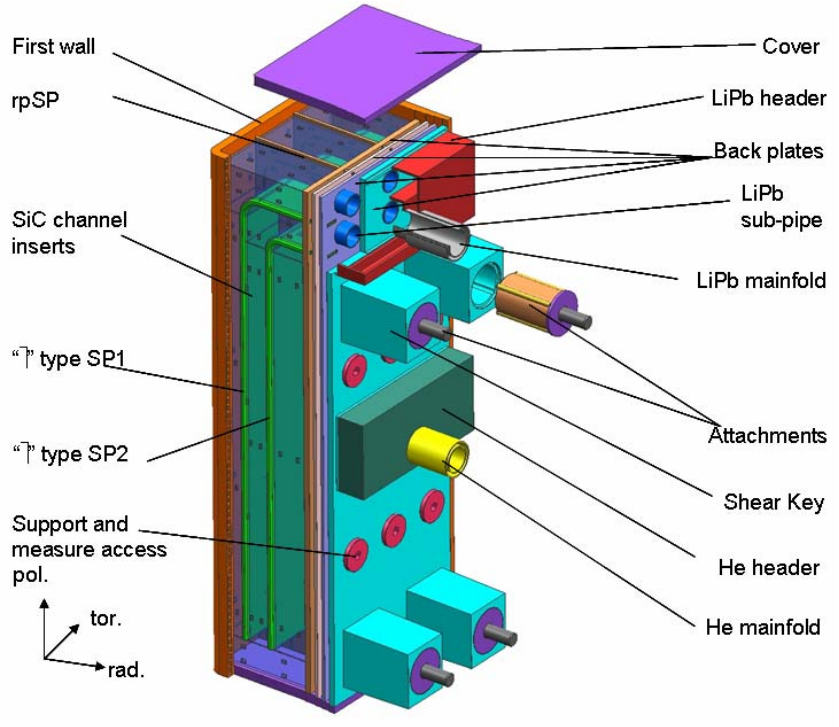
Liquid type

	CH	CH	EU	US	RF	KOR
Label	**DLL**	**SLL**	**HCLL**	**DCLL**	**Li self-cooled**	**HCML**
Primary coolant parameters						
He inlet/outlet (°C)	340/420 (He)	340/420 (He)	300/410	360/419 (He)	250-450/ 350-550 Li @<0.5 MPa	300/338 (He)
He coolant operating pressure (MPa)	8	8	8	8	N/A	8
He velocity in FW/SP/CP (m/s)	53/49	67/62		50.8	N/A	45
Tmax, FW @ 0.5 MW/m^2 (°C)	546	547	550	549	~675	508.7 @ 0.3 MW/m^2
Tmax, multiplier (°C)	N/A	N/A	N/A	N/A	=560	N/A
Tmax, reflector/primary shield (°C)	N/A	N/A	N/A	N/A	650	<900
He pressure drop in module (MPa)	0.88	1.07	0.29	0.81	N/A	TBD
Pumping power (kW)	331	508	83	~342	3.5 kWe	TBD

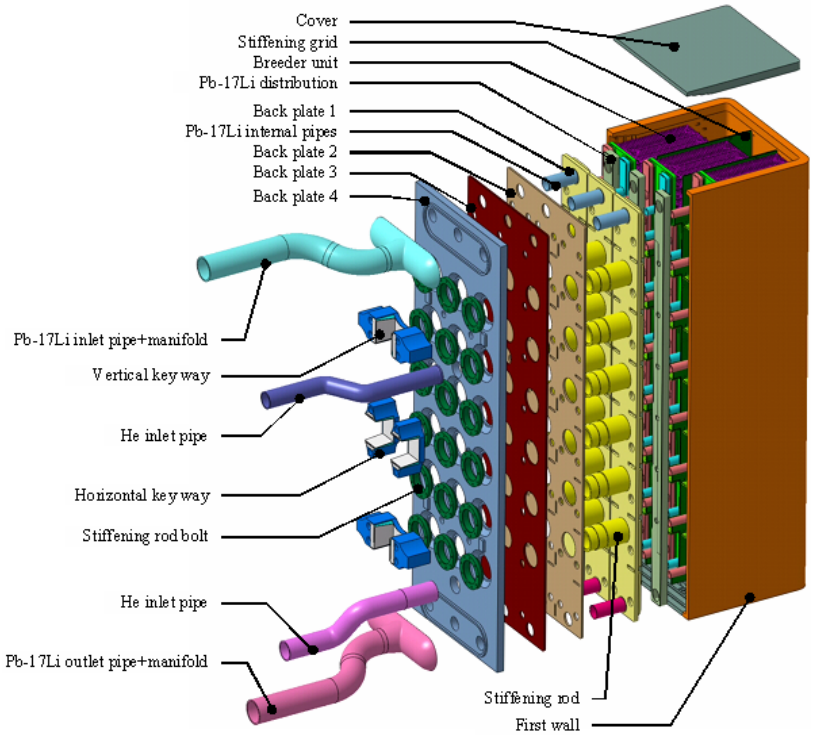
Liquid type

	CH	CH	EU	US	RF	KOR
Label	**DLL**	**SLL**	**HCLL**	**DCLL**	**Li self-cooled**	**HCML**
Breeder inlet/outlet (°C)	480/700	~/450	300/480	360/470*	250-450/ 350-550	338/393
Breeder pressure (MPa)	1	-	<1	2	0.5	TBD
Breeder Tmax (°C)	700	480	543	500	550	TBD
Breeder/structural material interface Tmax (°C)	434	478	520	<470	590	<500
Mass flow rate (kg/s)	5.2	0.1~1	0.33	~1.6	1.07	TBD
Breeder flow max velocity (m/s)	0.162	0.03	0.08 in BU	0.0975	0.5	<.001-.002
Breeder coolant pressure drop (MPa)	0.1	?	<0.8	0.302	<0.5	TBD
TBR	0.44	0.46	0.43	0.741	?	0.79
Li-6 enrichment (%)	90	90	90	90	90	TBD
Disruption impact	?	?	?	?	?	?

Liquid type TBM

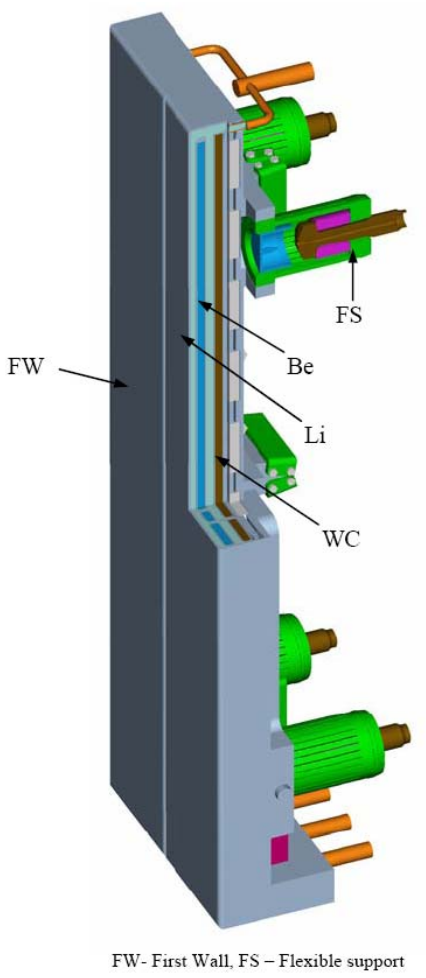


3D View of CH DLL TBM



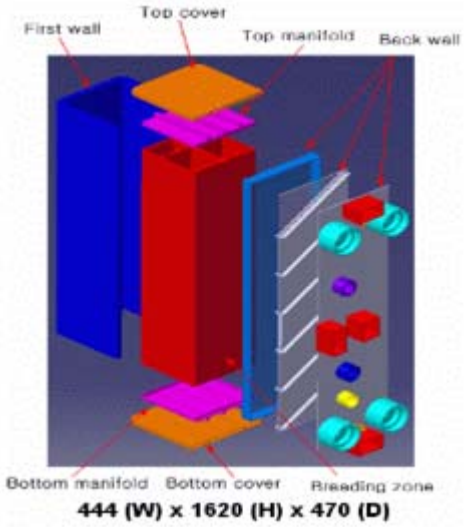
Exploded View of EU HCLL TBM

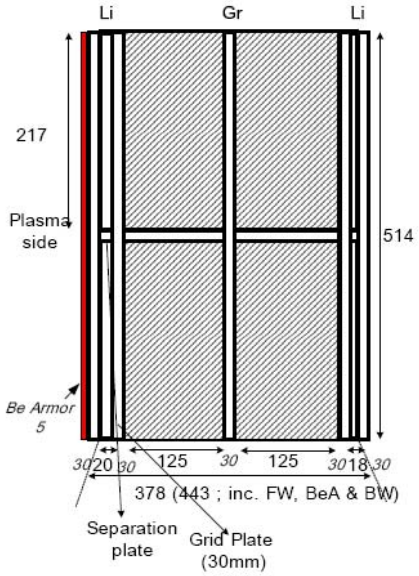
Liquid type TBM

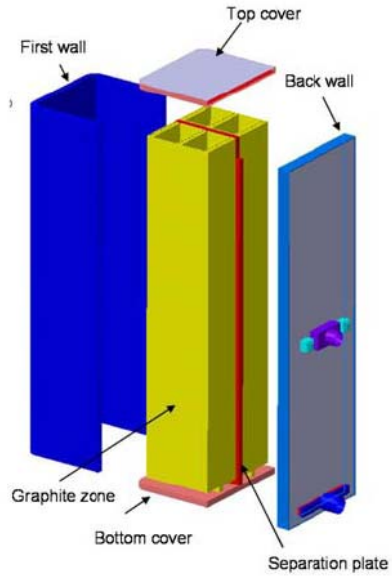


FW- First Wall, FS – Flexible support

3D View of RF LSC TBM

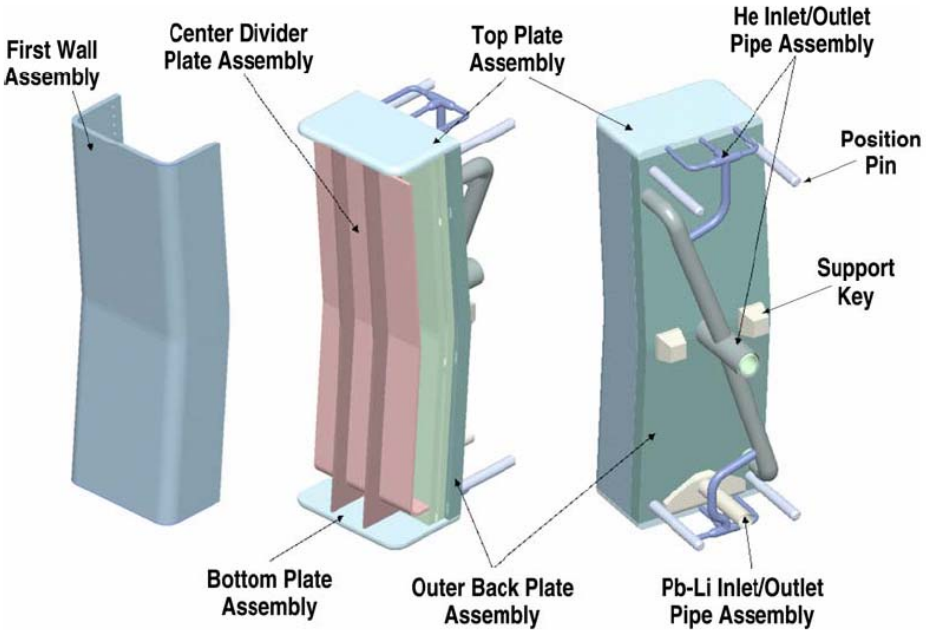




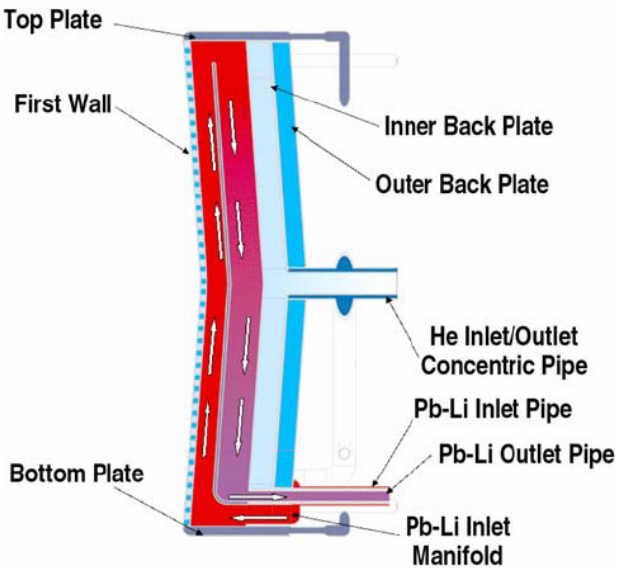


Concept of KO HCML TBM

Liquid type TBM



US DCLL TBM Sub-assemblies



2D Schematics of Pb-17Li Circuit in the US DCLL TBM