Neutronics Analysis on a Compact Tokamak Fusion Reactor CREST

Q. HUANG[1,2], S. ZHENG[2], L. Lu[2], R. HIWATARI[3],
Y. ASAOKA[3], K. OKANO[3], Y. OGAWA[1]

[1] High Temperature Plasma Center, the University of Tokyo, JAPAN
[2] Institute of Plasma Physics, Chinese Academy of Sciences, CHINA
[3] Nuclear Technology Research Laboratory, Central Research Institute of Electric Power Industry (CRIEPI), Tokyo, JAPAN

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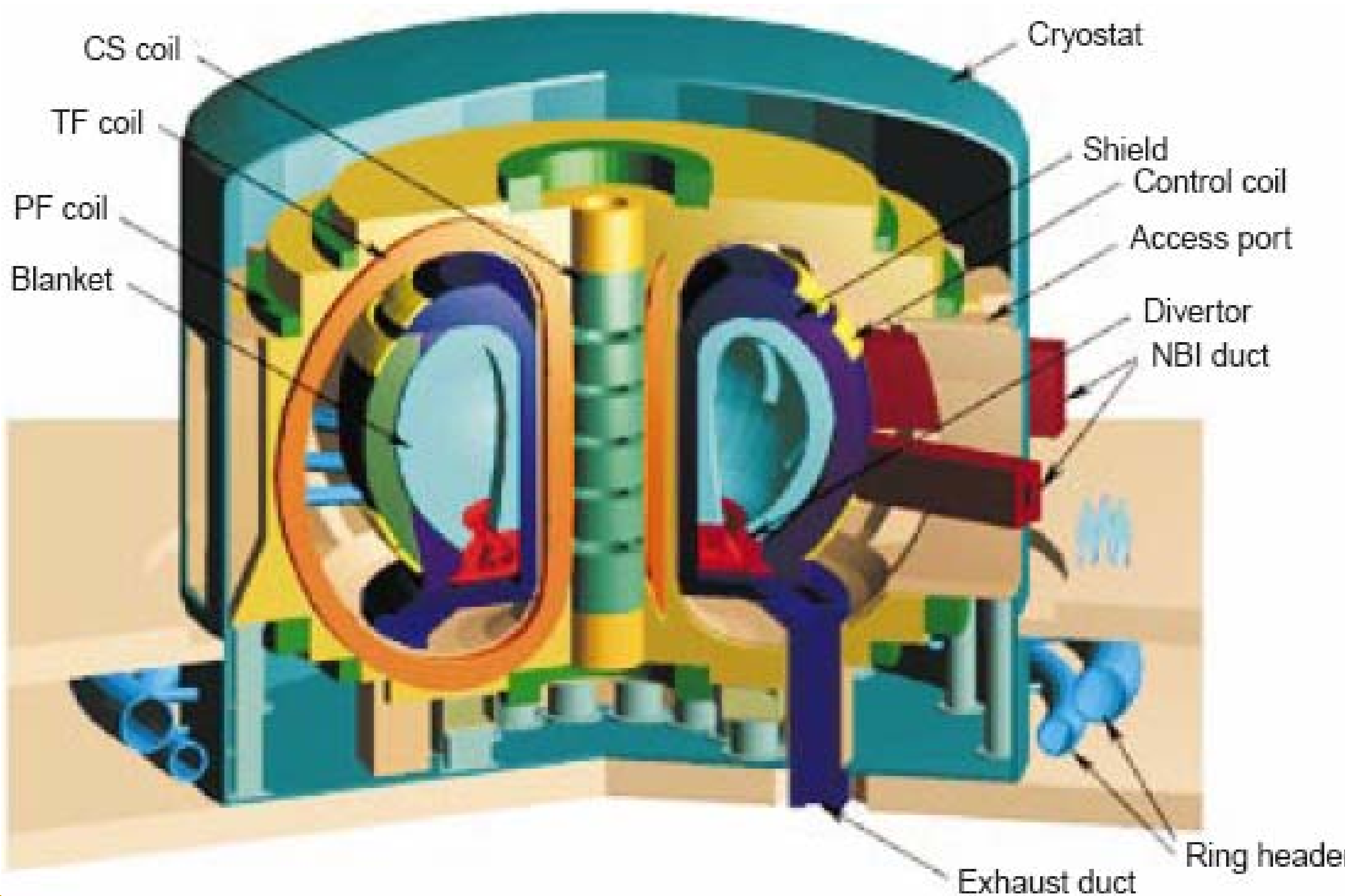
Introduction of CREST

CREST: Compact REversed Shear Tokamak



Bird's-eye view of the CREST

Basic characteristics of CREST

- high β plasma
- high thermal efficiency with water/steam cooled system
  (ODS-ferritic steel F82H, 350~900K)
- easy maintenance for high availability
  full sector removal
  large TF coils and large horizontal ports (14 in total)
- tritium self-sufficient
  (Li_2ZrO_3 + Be pepple bed blanket)
- moderate aspect ratio and elongation
  (similar to ITER advanced mode plasma)
- competitive cost
- Zr shell

In the high β reversed shear plasma configuration,
the conducting wall near the plasma is required
to avoid ideal MHD instabilities

Main parameters of CREST

R(m)	5.4
a(m)	1.59
κ	2.0
δ	0.5
β_N	5.5
B_{max}(T)	12.5
P_{fu}(GW)	2.97
P_{net}(GW)	1.16
$P_{w,aver}$(MW/m^2)	4.17
$P_{w,max}$(MW/m^2)	6.30
Heat flux(MW/m^2)	1.2
η_{th}	41%

Inboard + Outboard blanket (122 zones)

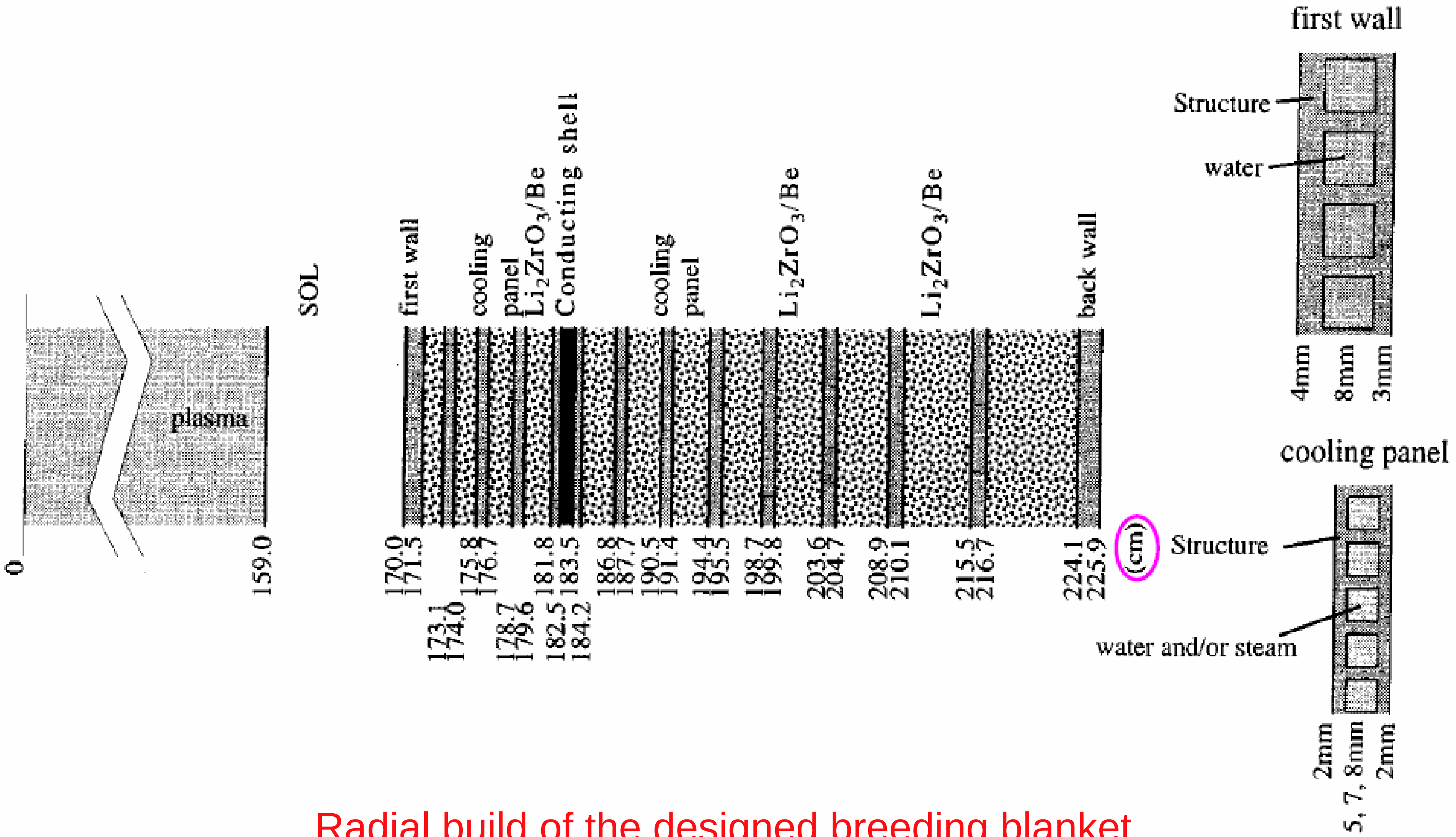
	CREST						
No	Zone	Inbord Side			Outbord Side		
		distance	thickness	material	distance	thickness	material
1	Plasma	381	159	void	699	159	void
2	SOL	370	11	void	710	11	void
3	Structure	369.6	0.4	100%F82H	710.4	0.4	100%F82H
4	Water Channel	368.8	0.8	30%F82H+70%H2O	711.2	0.8	30%F82H+70%H2O
5	Structure	368.5	0.3	100%F82H	711.5	0.3	100%F82H
6	Mixed Breeding Zone	366.9	1.6	13.6%LiZrO3+57.6%9Be	713.1	1.6	13.6%LiZrO3+57.6%9Be
7	Structure	366.7	0.2	100%F82H	713.3	0.2	100%F82H
8	Steam Channel	366.2	0.5	30%F82H+20%H2O	713.8	0.5	30%F82H+20%H2O
9	Structure	366	0.2	100%F82H	714	0.2	100%F82H
10	Mixed Breeding Zone	364.2	1.8	13.6%LiZrO3+57.6%9Be	715.8	1.8	13.6%LiZrO3+57.6%9Be
11	Structure	364	0.2	100%F82H	716	0.2	100%F82H
12	Steam Channel	363.5	0.5	30%F82H+20%H2O	716.5	0.5	30%F82H+20%H2O
13	Structure	363.3	0.2	100%F82H	716.7	0.2	100%F82H
14	Mixed Breeding Zone	361.3	2	13.6%LiZrO3+57.6%9Be	718.7	2	13.6%LiZrO3+57.6%9Be
15	Structure	361.1	0.2	100%F82H	718.9	0.2	100%F82H
16	Steam Channel	360.6	0.5	30%F82H+20%H2O	719.4	0.5	30%F82H+20%H2O
17	Structure	360.4	0.2	100%F82H	719.6	0.2	100%F82H
18	Mixed Breeding Zone	358.2	2.2	13.6%LiZrO3+57.6%9Be	721.8	2.2	13.6%LiZrO3+57.6%9Be
19	Structure	358	0.2	100%F82H	722	0.2	100%F82H
20	Steam Channel	357.5	0.5	30%F82H+20%H2O	722.5	0.5	30%F82H+20%H2O

21	Shell	356.5	1	100%Zr(4.31E-02)	723.5	1	100%Zr(4.31E-02)
22	Steam Channel	356	0.5	30%F82H+20%H2O	724	0.5	30%F82H+20%H2O
23	Structure	355.8	0.2	100%F82H	724.2	0.2	100%F82H
24	Mixed Breeding Zone	353.2	2.6	13.6%LiZrO3+57.6%9Be	726.8	2.6	13.6%LiZrO3+57.6%9Be
25	Structure	353	0.2	100%F82H	727	0.2	100%F82H
26	Steam Channel	352.5	0.5	30%F82H+20%H2O	727.5	0.5	30%F82H+20%H2O
27	Structure	352.3	0.2	100%F82H	727.7	0.2	100%F82H
28	Mixed Breeding Zone	349.5	2.8	13.6%LiZrO3+57.6%9Be	730.5	2.8	13.6%LiZrO3+57.6%9Be
29	Structure	349.3	0.2	100%F82H	730.7	0.2	100%F82H
30	Steam Channel	348.8	0.5	30%F82H+20%H2O	731.2	0.5	30%F82H+20%H2O
31	Structure	348.6	0.2	100%F82H	731.4	0.2	100%F82H
32	Mixed Breeding Zone	345.6	3	13.6%LiZrO3+57.6%9Be	734.4	3	13.6%LiZrO3+57.6%9Be
33	Structure	345.4	0.2	100%F82H	734.6	0.2	100%F82H
34	Steam Channel	344.7	0.7	30%F82H+20%H2O	735.3	0.7	30%F82H+20%H2O
35	Structure	344.5	0.2	100%F82H	735.5	0.2	100%F82H
36	Mixed Breeding Zone	341.3	3.2	13.6%LiZrO3+57.6%9Be	738.7	3.2	13.6%LiZrO3+57.6%9Be
37	Structure	341.1	0.2	100%F82H	738.9	0.2	100%F82H
38	Steam Channel	340.4	0.7	30%F82H+20%H2O	739.6	0.7	30%F82H+20%H2O
39	Structure	340.2	0.2	100%F82H	739.8	0.2	100%F82H
40	Mixed Breeding Zone	336.4	3.8	13.6%LiZrO3+57.6%9Be	743.6	3.8	13.6%LiZrO3+57.6%9Be
41	Structure	336.2	0.2	100%F82H	743.8	0.2	100%F82H
42	Steam Channel	335.5	0.7	30%F82H+20%H2O	744.5	0.7	30%F82H+20%H2O
43	Structure	335.3	0.2	100%F82H	744.7	0.2	100%F82H
44	Mixed Breeding Zone	331.1	4.2	13.6%LiZrO3+57.6%9Be	748.9	4.2	13.6%LiZrO3+57.6%9Be

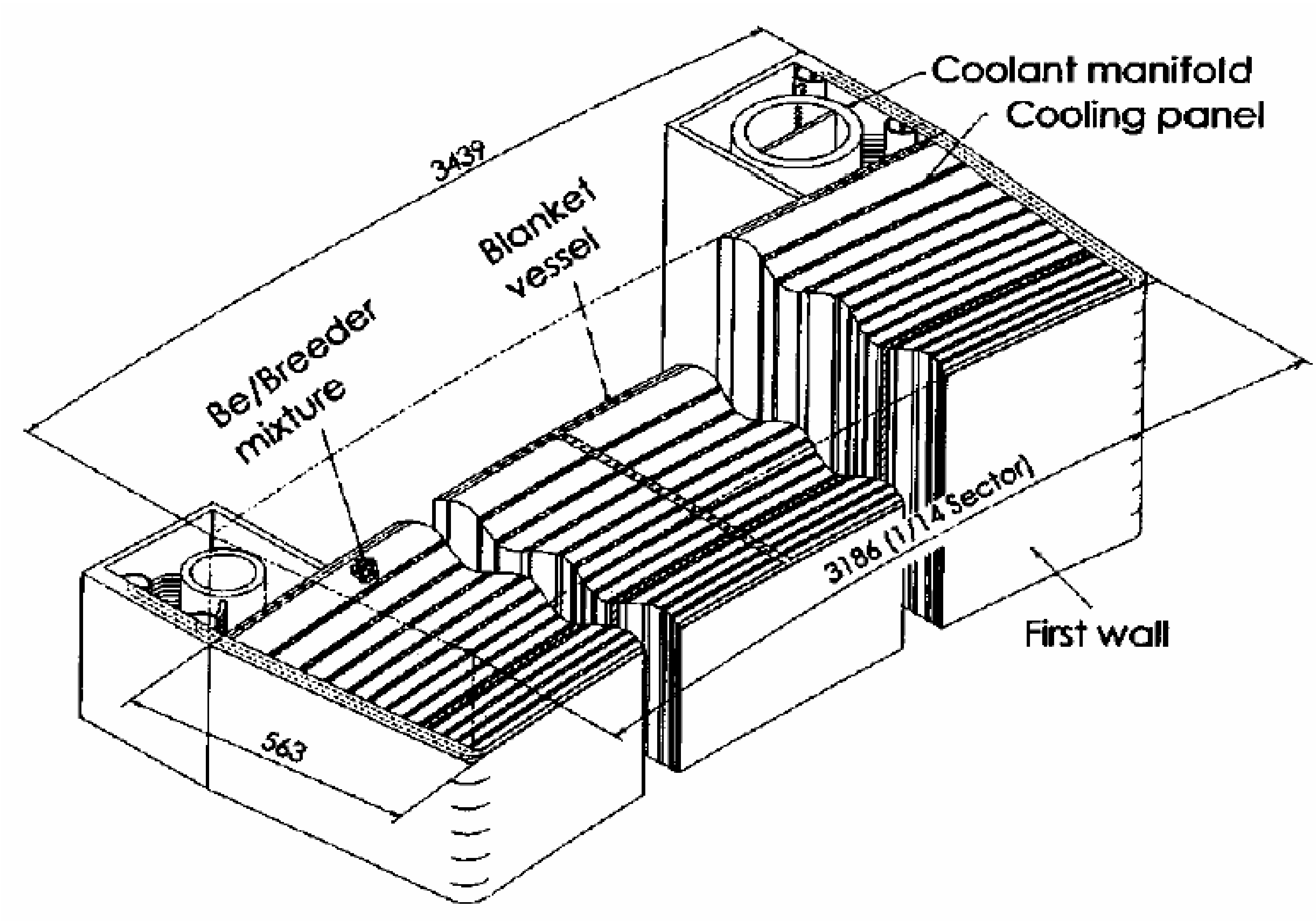
45	Structure	330.9	0.2	100%F82H	749.1	0.2	100%F82H
46	Steam Channel	330.1	0.8	30%F82H+20%H2O	749.9	0.8	30%F82H+20%H2O
47	Structure	329.9	0.2	100%F82H	750.1	0.2	100%F82H
48	Mixed Breeding Zone	324.5	5.4	13.6%LiZrO3+57.6%9Be	755.5	5.4	13.6%LiZrO3+57.6%9Be
49	Structure	324.3	0.2	100%F82H	755.7	0.2	100%F82H
50	Steam Channel	323.5	0.8	30%F82H+20%H2O	756.5	0.8	30%F82H+20%H2O
51	Structure	323.3	0.2	100%F82H	756.7	0.2	100%F82H
52	Mixed Breeding Zone	315.9	7.4	13.6%LiZrO3+57.6%9Be	764.1	7.4	13.6%LiZrO3+57.6%9Be
53	Structure	315.7	0.2	100%F82H	764.3	0.2	100%F82H
54	Steam Channel	314.9	0.8	30%F82H+20%H2O	765.1	0.8	30%F82H+20%H2O
55	Structure	314.1	0.8	100%F82H	765.9	0.8	100%F82H
56	void	310.1	4	void	789.9	24	void
57	Shield	254.1	56	75%F82H+25%H2O	859.9	70	75%F82H+25%H2O
58	void	250.1	4	void	1059.9	200	void
59	Helium Can	240.1	10	SS (Mo: 1.26e-3; Cr: 1.58e-2; Ni: 9.85e-3; Fe: 5.91e-2)	1069.9	10	SS (Mo: 1.26e-3; Cr: 1.58e-2; Ni: 9.85e-3; Fe: 5.91e-2)
60	SCM	160.1	80	55.2%SS+5.8%NbCd+11.8%Cu+ 6.3% Mo+5.4% Ti+1.9%B4C+ 13.6%4He	1149.9	80	55.2%SS+5.8%NbCd+11.8%Cu+ 6.3% Mo+5.4% Ti+1.9%B4C+ 13.6%4He
61	Helium Can	150.1	10	SS (Mo: 1.26e-3; Cr: 1.58e-2; Ni: 9.85e-3; Fe: 5.91e-2)	1159.9	10	SS (Mo: 1.26e-3; Cr: 1.58e-2; Ni: 9.85e-3; Fe: 5.91e-2)

Thickness of the FW: 1.5cm
Thickness of the blanket: 54.4cm
Thickness of the inboard shield: 56cm
Thickness of the outboard shield: 70cm

There are 12 TB zones for i/b and o/b blankets respectively, between them are the steam channels and structures.



Radial build of the designed breeding blanket



Cross-section of the CREST outboard blanket

Codes & data library

- MCNP/4C
- FENDL/2

- MCAM

  developed by FDS team in ASIPP, China

  - to transfer 3D solid geometry into cell cards and surface cards for MCNP input file automatically
  - to show 3D geometry automatically by inputting the cell cards and surface cards, M cards and/or transforming cards from a input file of MCNP
  - windows interface

Models

Geometry:

- 2D model

  to consider the effect of the details in the blanket and FW

  details of the blanket are included as shown in above table

- 3D models (1/14, 1/7)

  to analyze the effect of the openings on TBR, TF coils etc

  FW

  Blanket (uniformed blanket, no detail regions as 2D calculations)

  Shield (different thickness for inboard & outboard)

  TF coil (cross-section: trapezia shape)

  PF & CS coils

  NBI port (in option, one of the openings,

  to consider its effect to neutronics issues)

  (no detail design of the divertor, not included in the model)

Neutron source:

- 2D models

  uniformed volume source

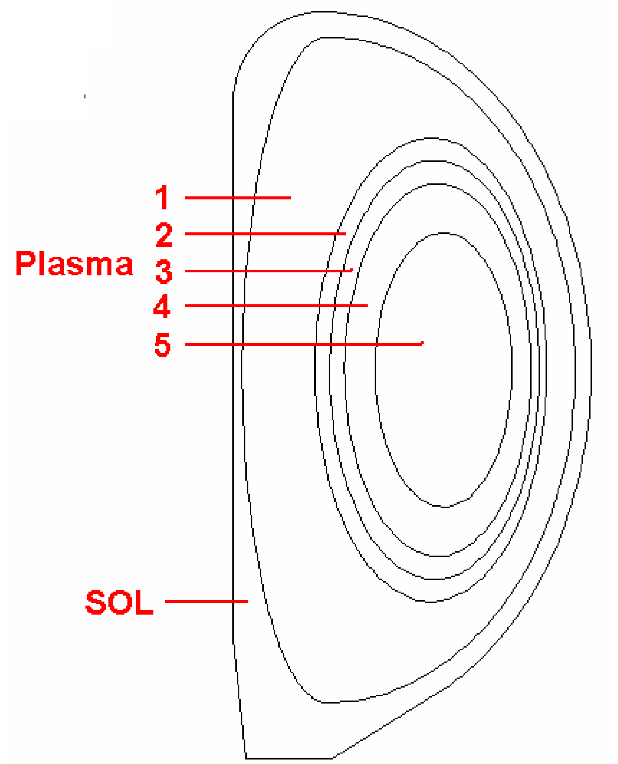
- 3D models

  5 layers in source description

  Probability in the 5 cells:

  - 0.038 (cell 1)
  - 0.070 (cell 2)
  - 0.104 (cell 3)
  - 0.296 (cell 4)
  - 0.492 (cell 5)

  1.000



Materials:

- 2D models

  details of the blanket are included as shown in above table

- 3D models (1/14, 1/7)

FW 63%F82H + 37%H_2O

(uniformed, there are 3 layers in 2D model)

Blanket (50%^{6}Li)

14.28%F82H; 10.02%Li_2ZrO_3; 42.45%^{9}Be; 2.92%H_2O; 1.8%Zr

(uniformed blanket)

Shield 75%F82H + 25%H_2O

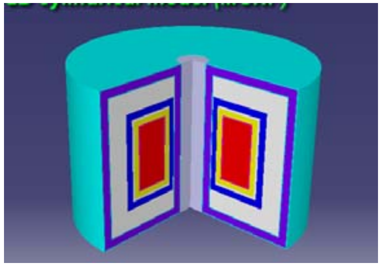
He-can SS (Mo:1.26e-3; Cr:1.58e-2; Ni:9.85e-3; Fe:5.91e-2)

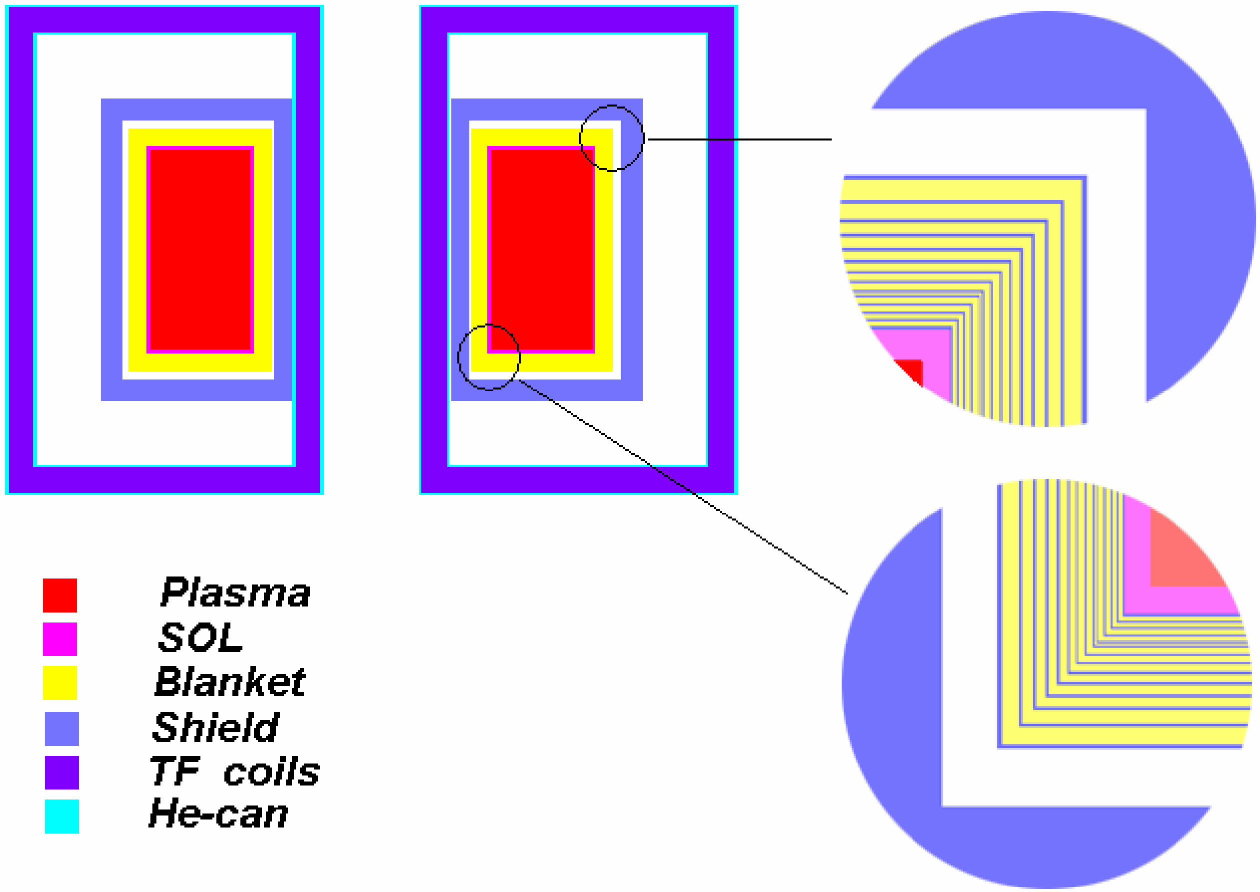
SCM SC material (55.2%SS; 5.8%Nb_3Sn; 11.8%Cu; 6.3%Mo;

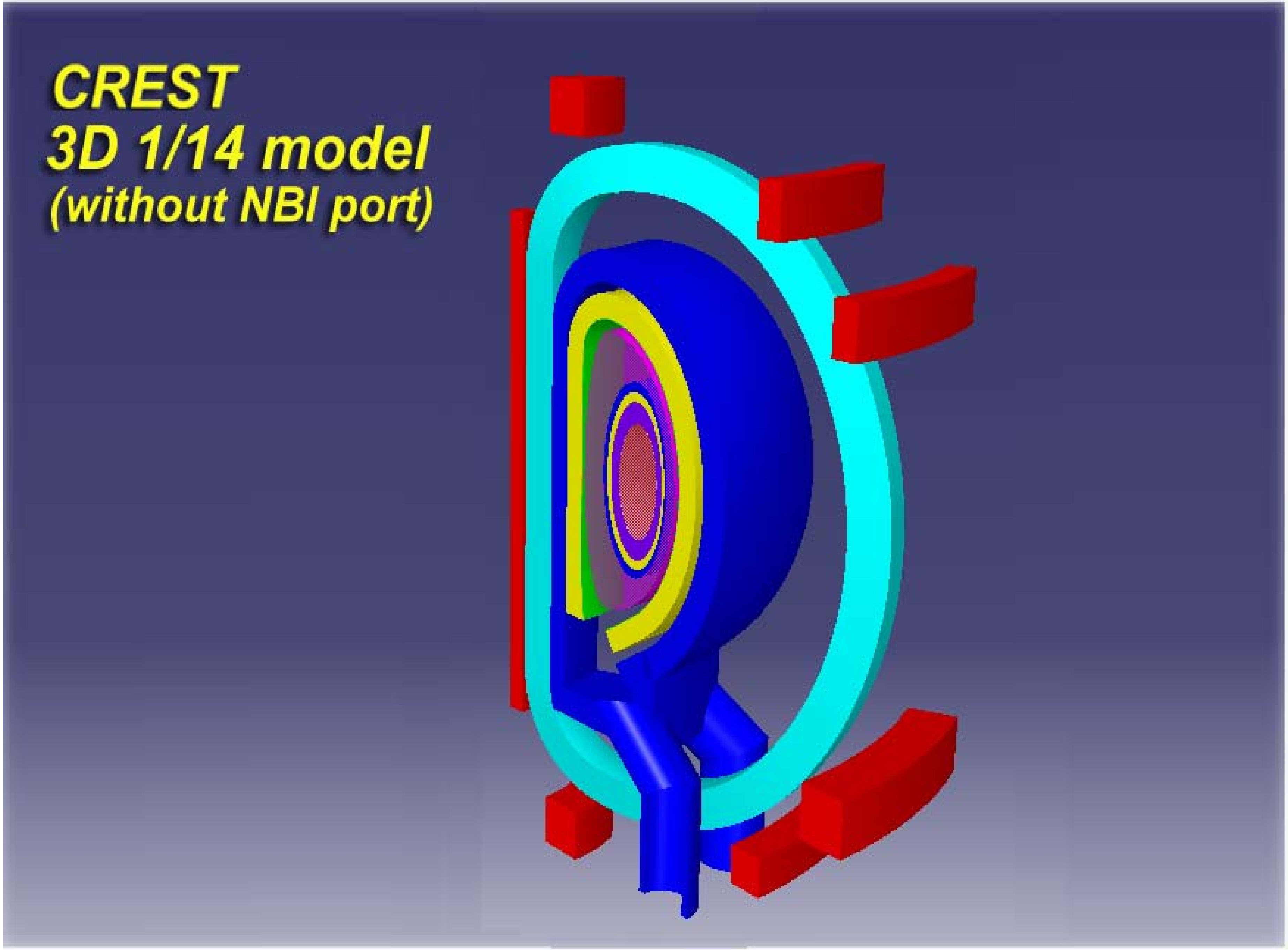
5.4%Ti; 1.9%B_4C; 13.6%^{4}He)

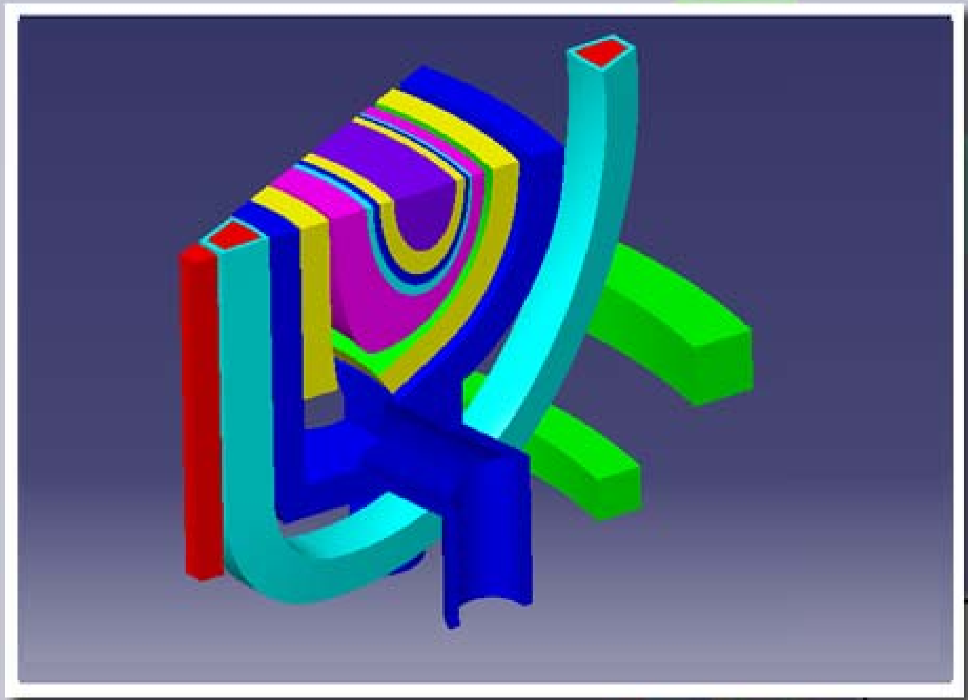
NBI port wall 75%F82H + 25%H_2O

Detail 2D cylindrical model

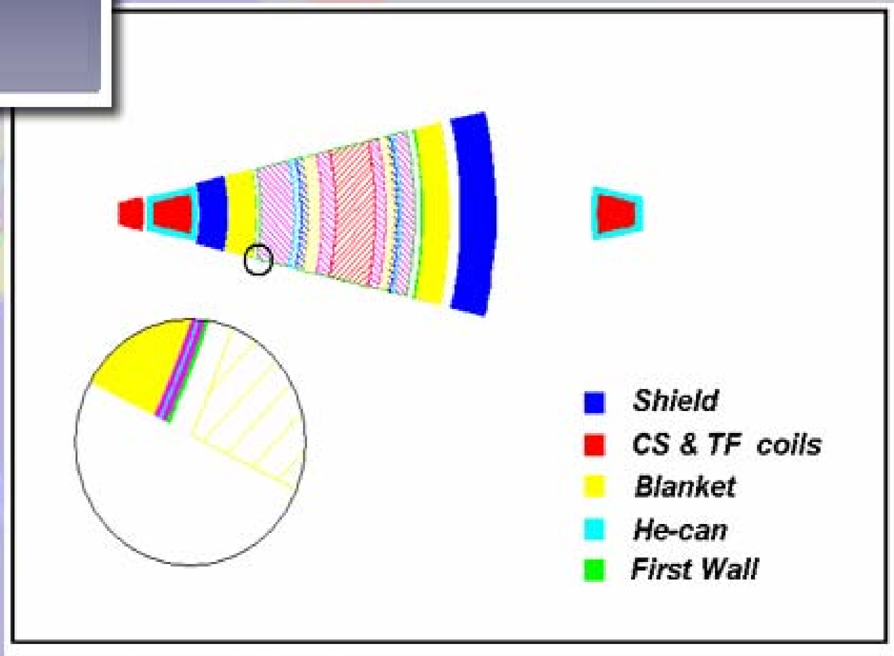


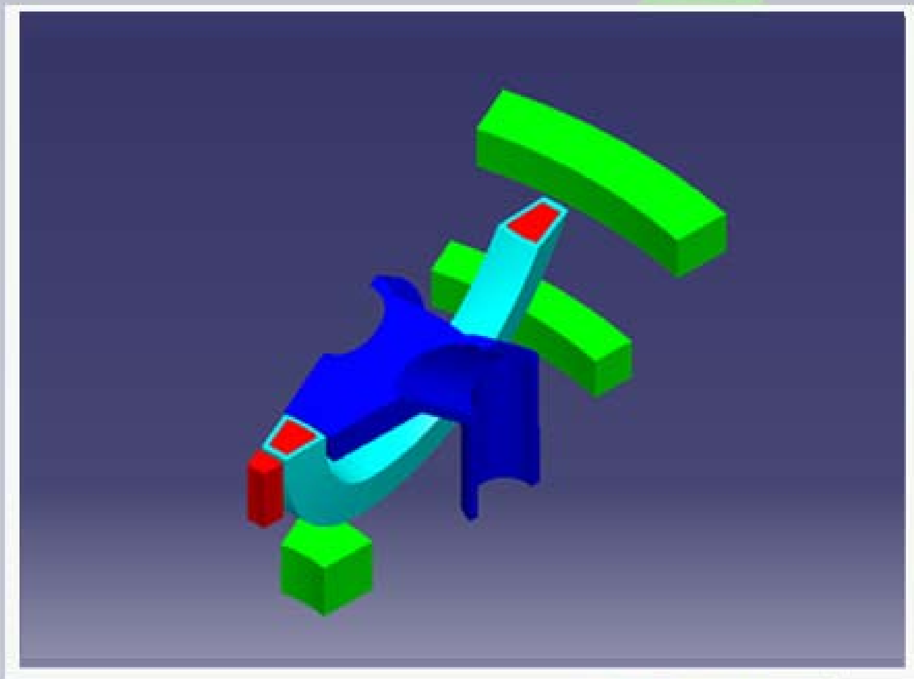



CREST
3D 1/14 model
(without NBI port)

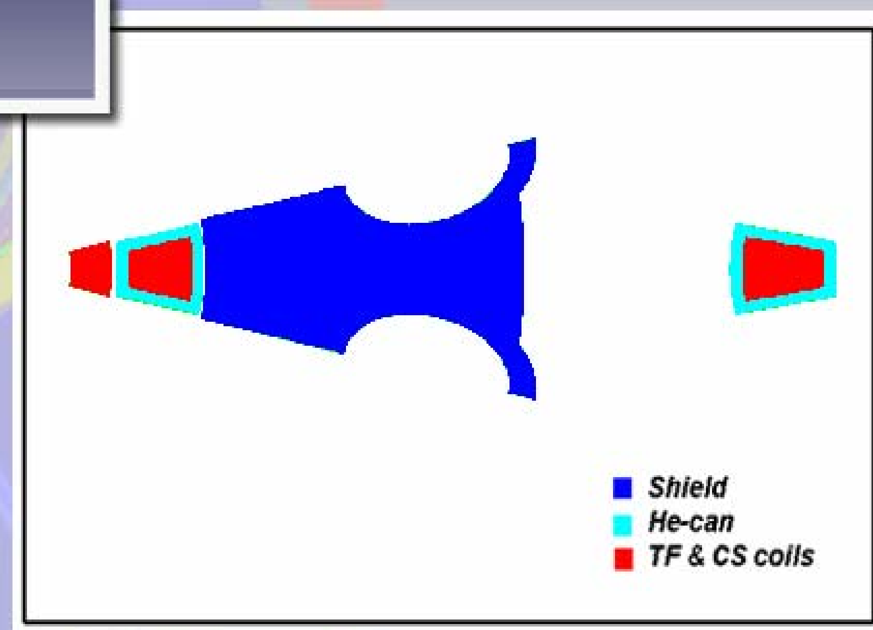


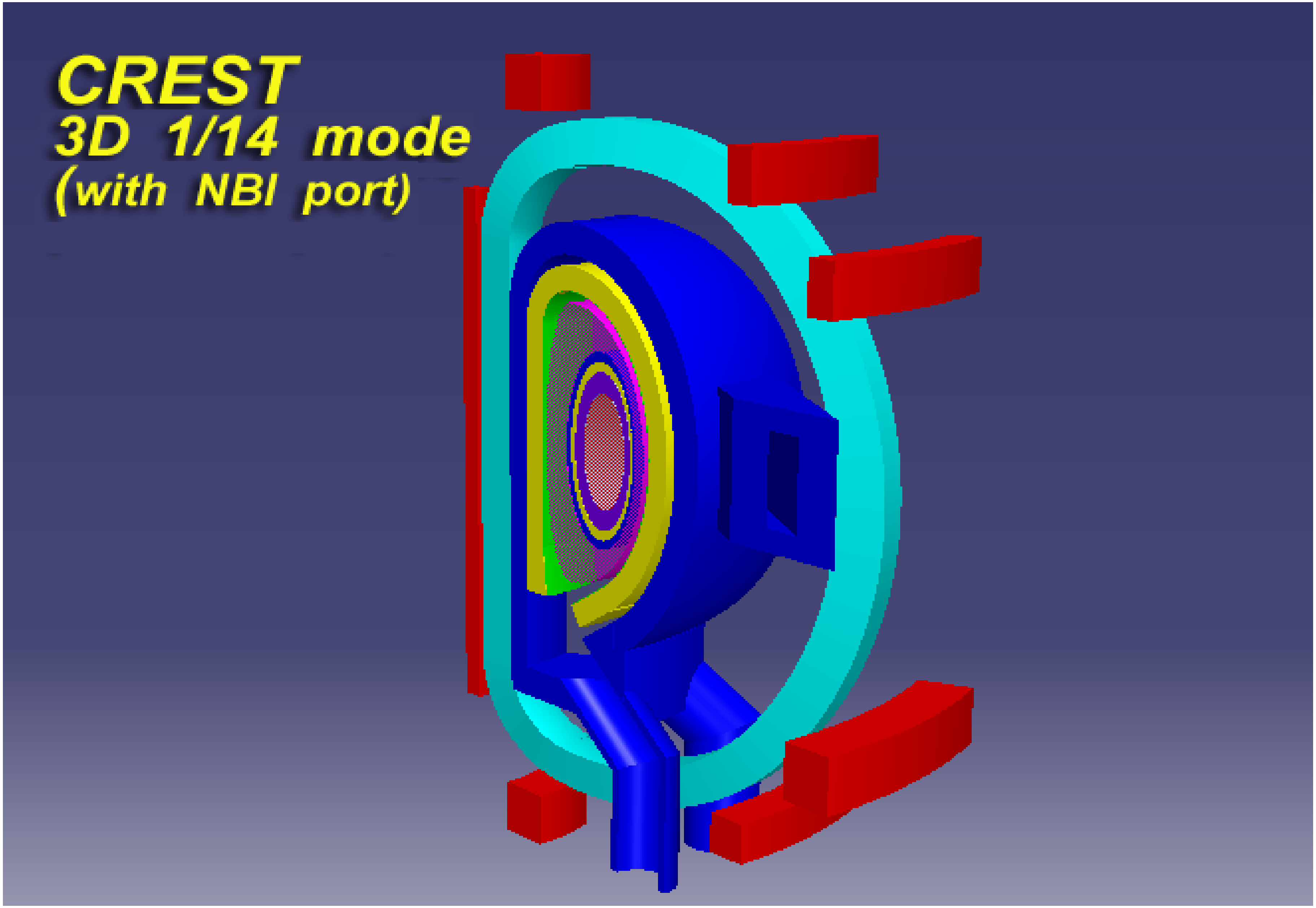
Section A

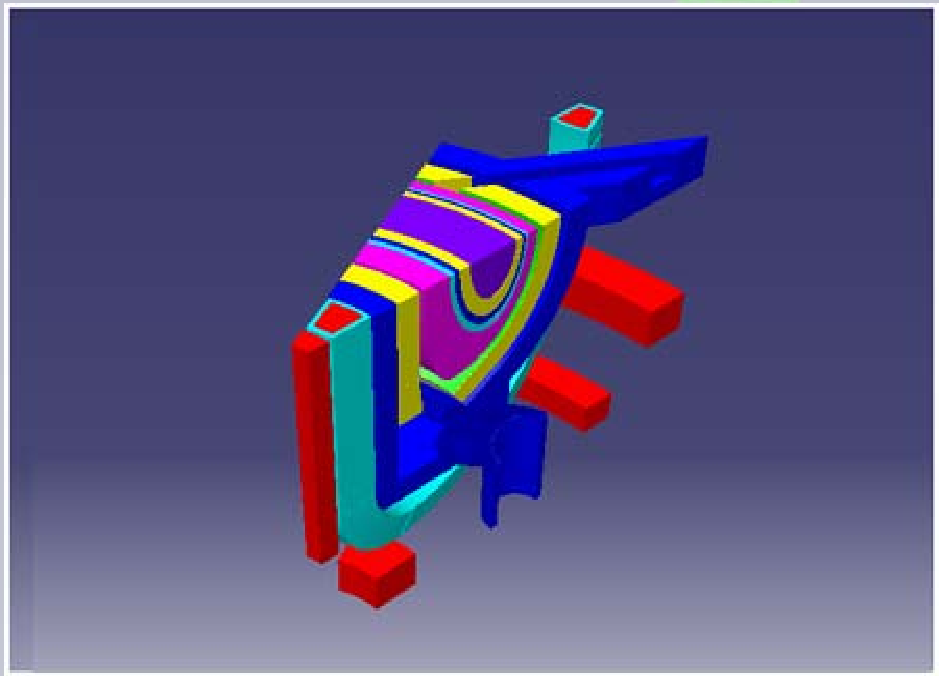




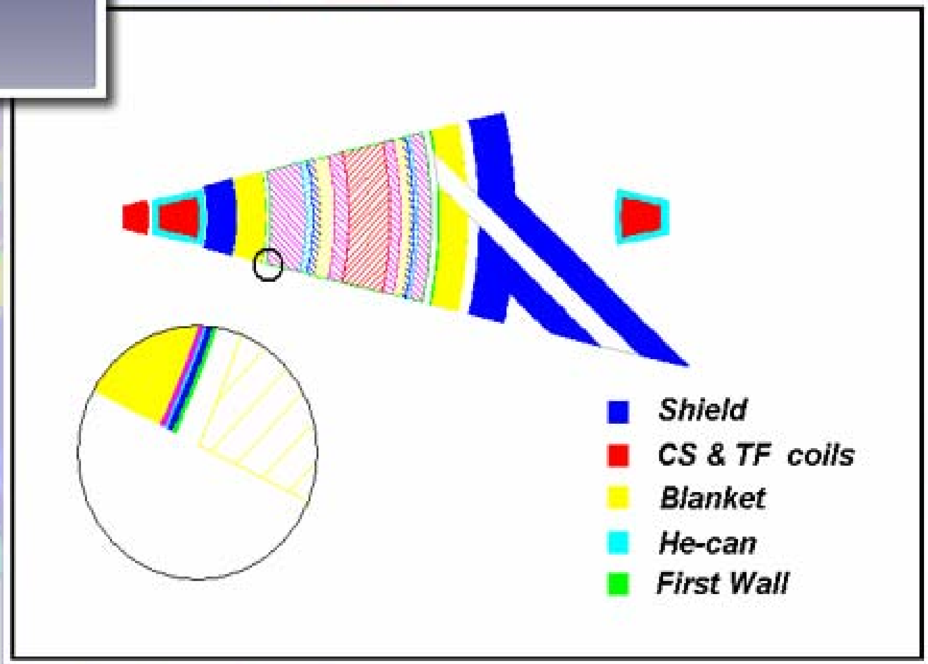
Section B

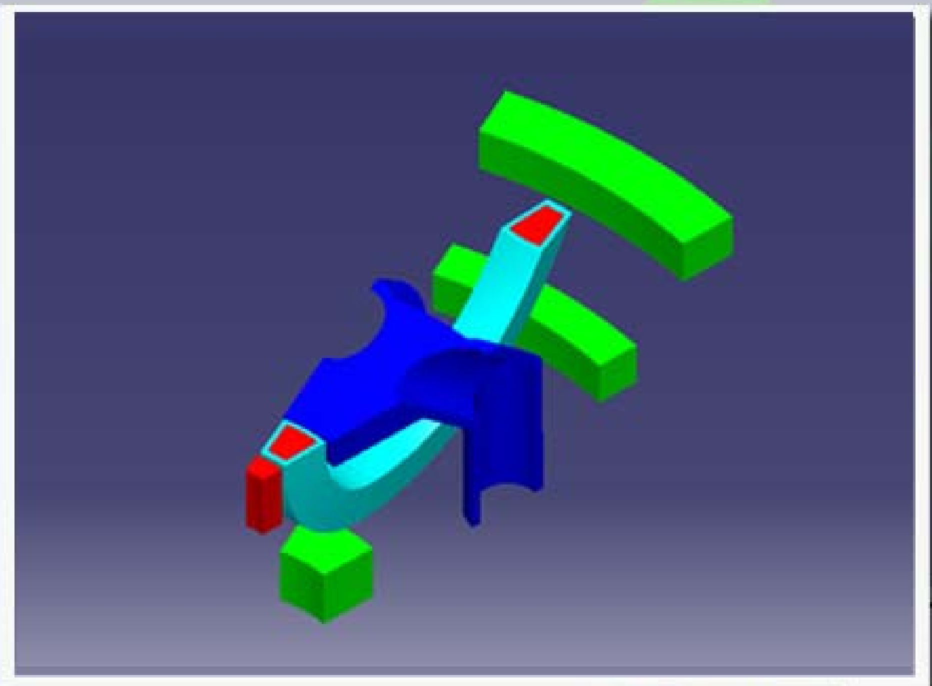



CREST
3D 1/14 mode
(with NBI port)



Section A





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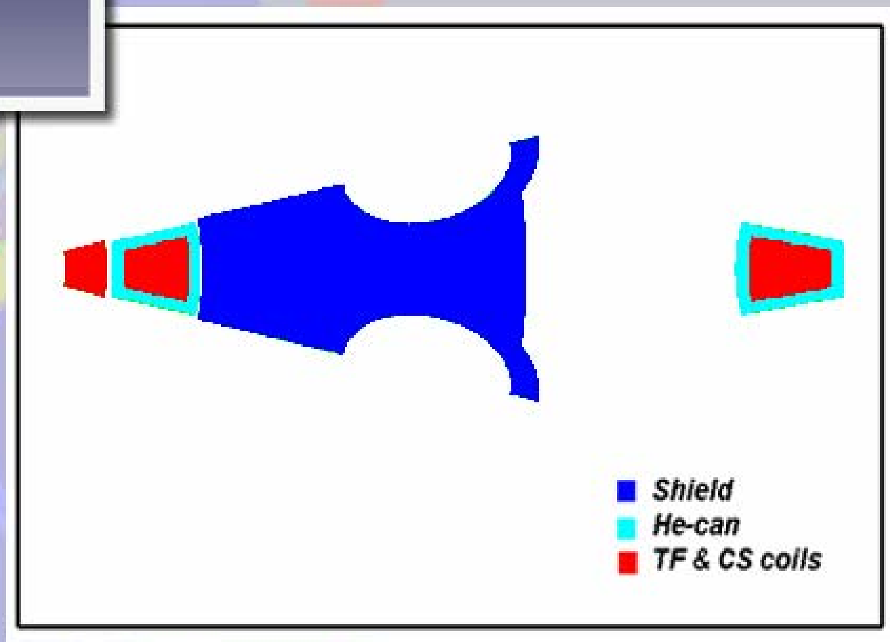
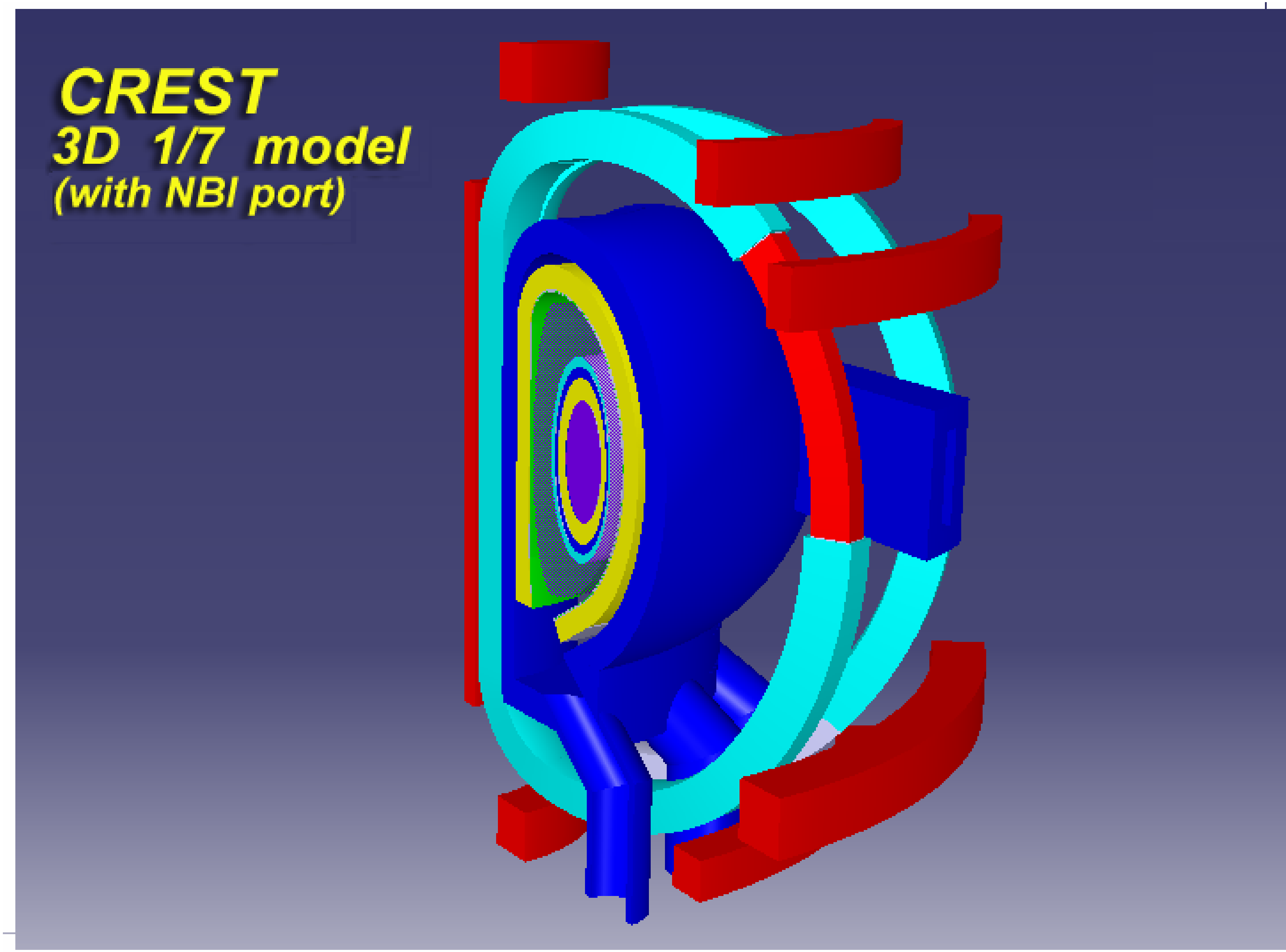
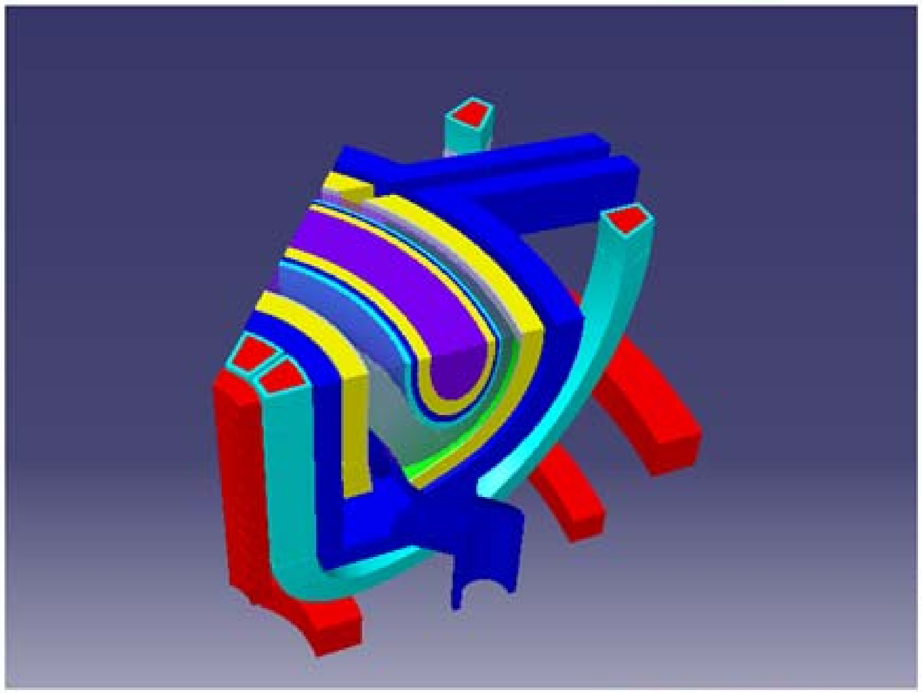
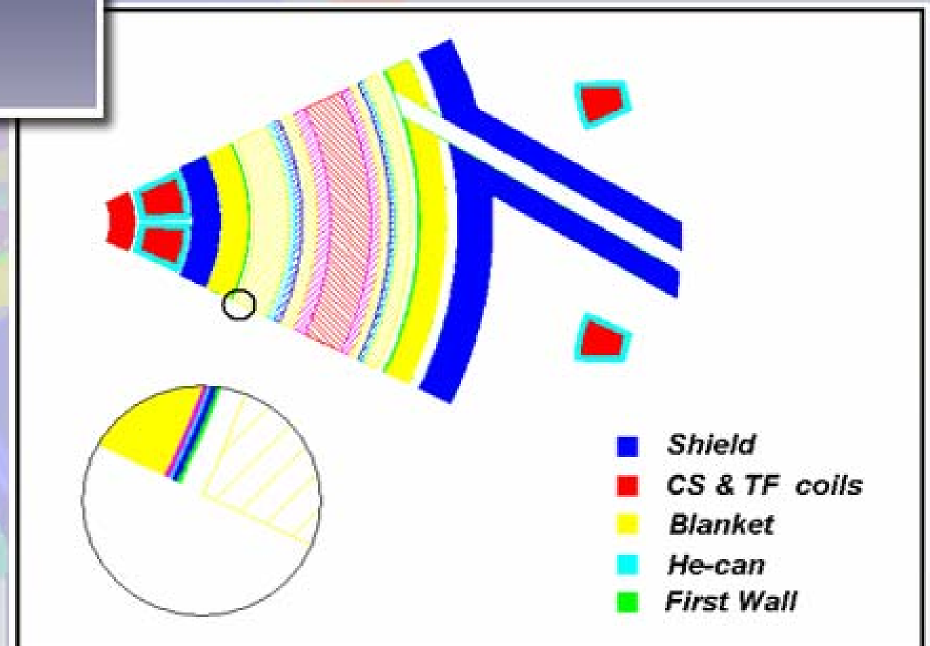
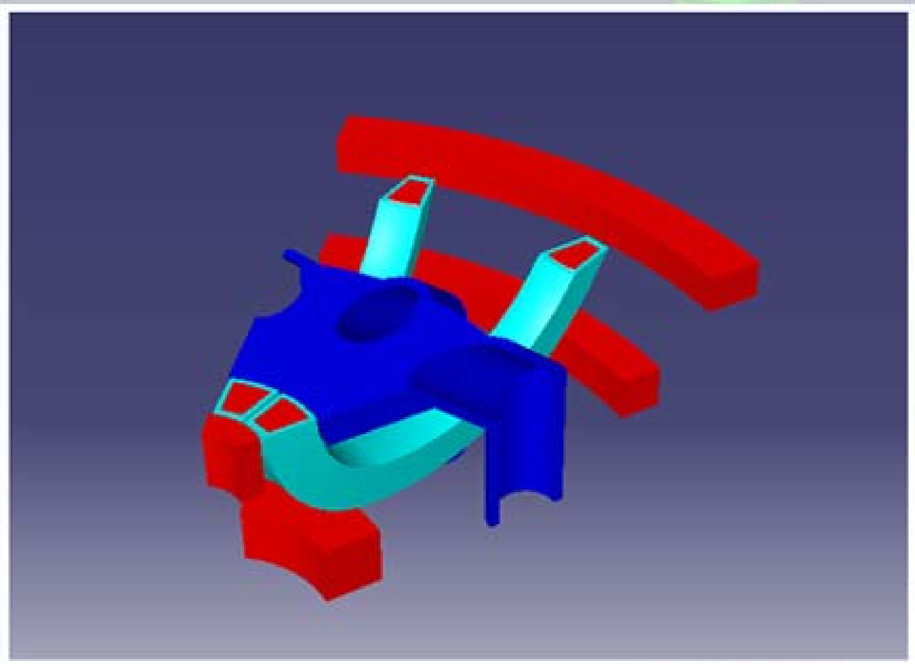



CREST
3D 1/7 model
(with NBI port)



Section A





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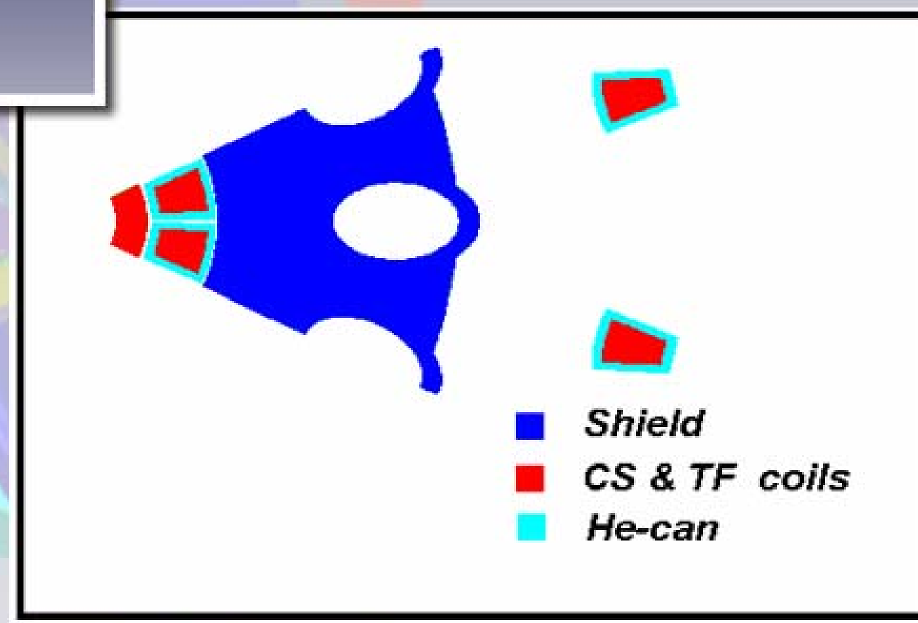


Results

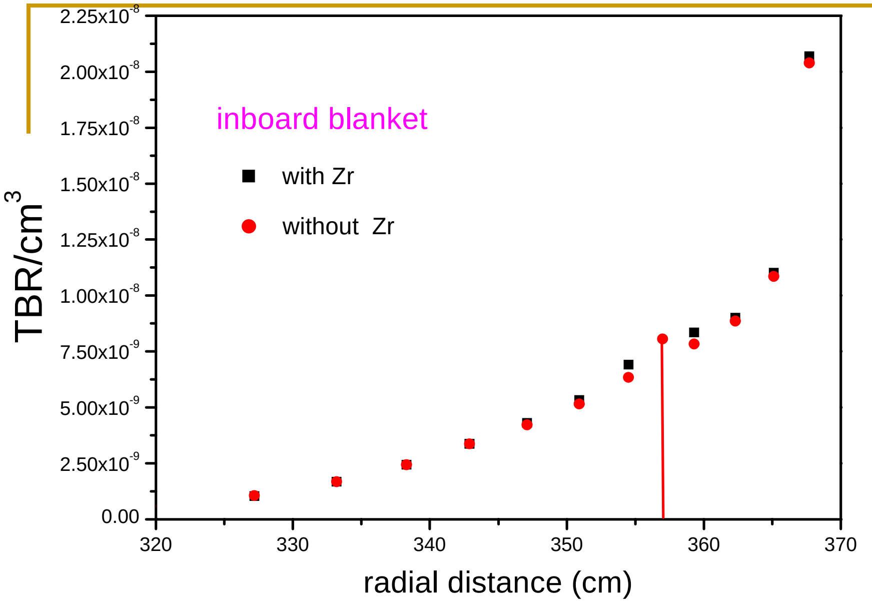
TBR:

replaced with tritium breeding material

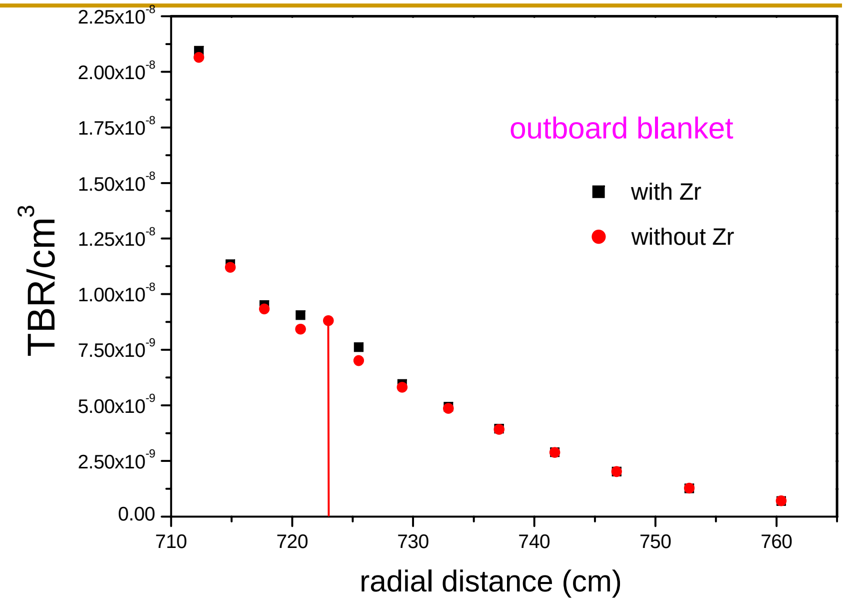
2D-cylinder model

	Detailed blanket with Zr shell		Detailed blanket without Zr shell	
Contribution	TBR	%	TBR	%
Inboard blanket	0.276	20.7	0.282	20.7
Outboard blanket	1.055	79.3	1.078	79.3
^{6}Li	1.321	99.3	1.349	99.2
^{7}Li	0.010	0.7	0.011	0.8
Total TBR	**1.33**		**1.36**	

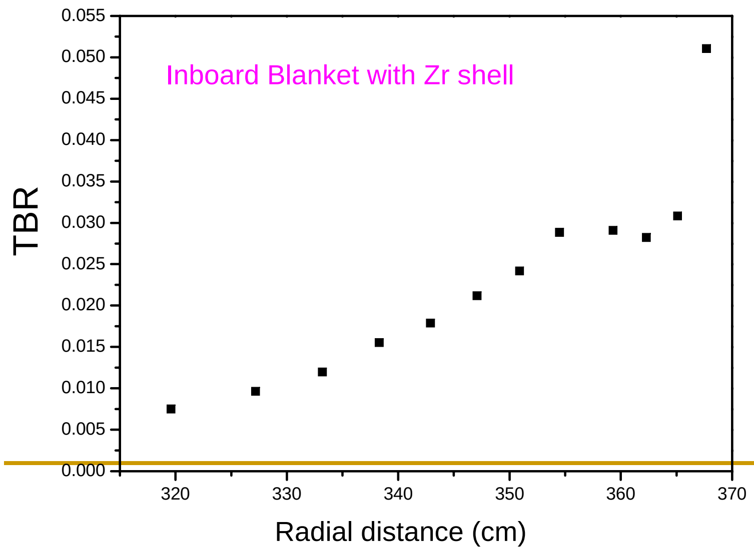
- total TBR = 1.33 for 2D model
- Contribution of ^{6}Li and ^{7}Li: ~99%; ~1%
- Contribution of the i/b and o/b blankets: ~20%; 80%
- The effect of Zr shell to TBR is 0.03.



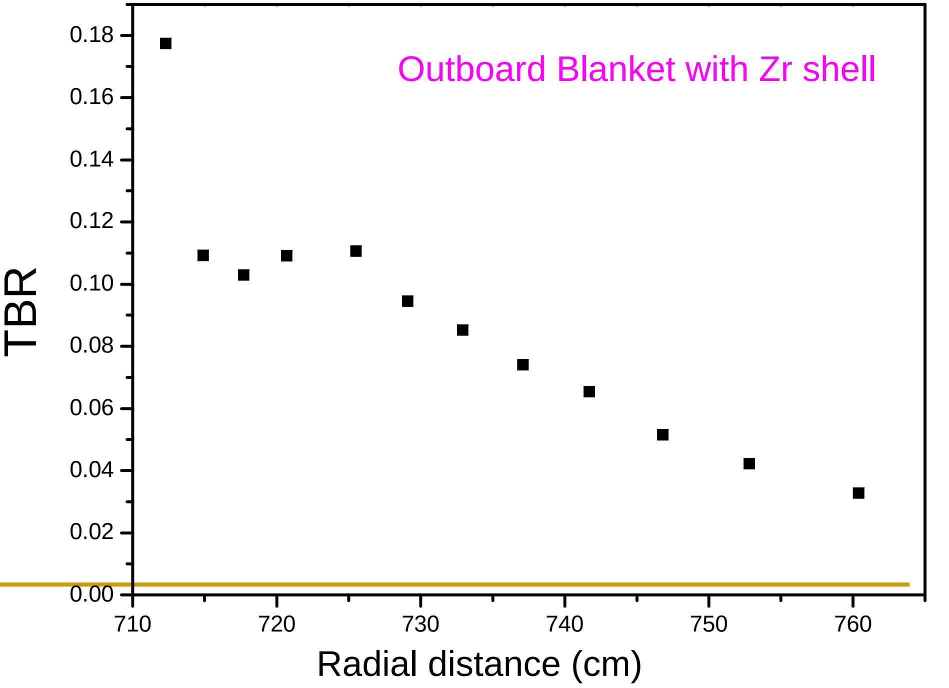
inboard blanket
with Zr
without Zr
TBR/cm^3
radial distance (cm)



outboard blanket
with Zr
without Zr
TBR/cm^3
radial distance (cm)



Inboard Blanket with Zr shell
TBR
Radial distance (cm)



Outboard Blanket with Zr shell
TBR
Radial distance (cm)

3D model

1/14 model	Uniformed blanket (with NBI)		Uniformed blanket (without NBI)	
Contribution	TBR	%	TBR	%
inboard	0.333	26.3	0.339	26.0
outboard	0.934	73.7	0.965	74.0
^{6}Li	1.256	99.2	1.293	99.2
^{7}Li	0.010	0.8	0.010	0.8
Total TBR	**1.27**		**1.30**	

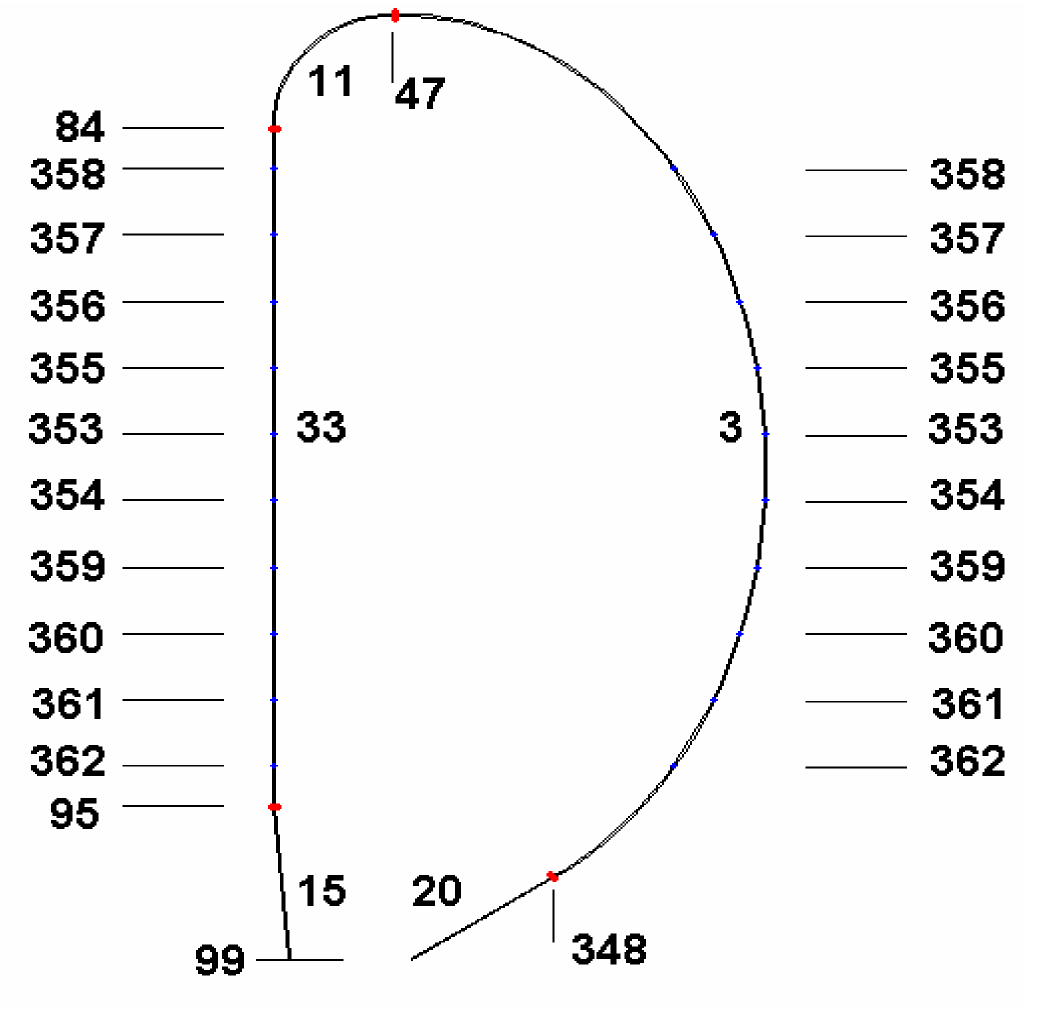
1/7 model	Uniformed blanket (with NBI)	
Contribution	TBR	%
inboard	0.336	26.3
outboard	0.942	73.7
^{6}Li	1.268	99.2
^{7}Li	0.010	0.8
Total TBR	**1.28**	

- TBR = 1.28, 1.27 for 1/14 model, 1/7 model respectively (with NBI)
- Reduction of TBR due to the NBI port is 0.03
  (in the two models, the reduction of blanket volume due to opening of the NBI port are the same,
  percentage of the port volume in blanket are 2.8%, 1.4%)

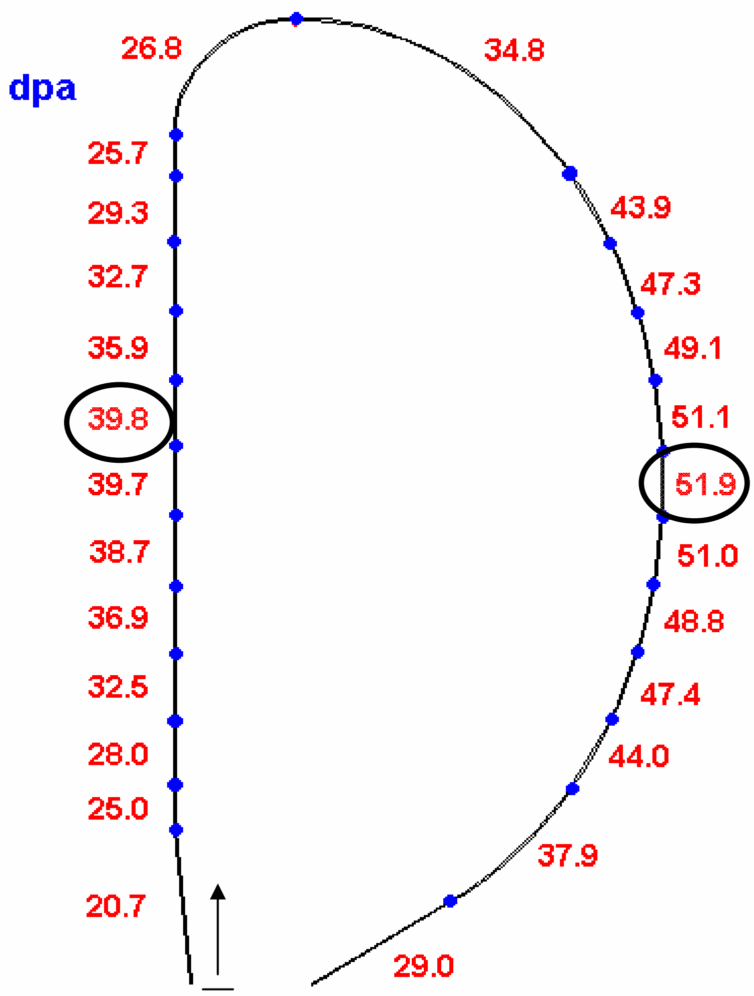
Comparing with 2D model:

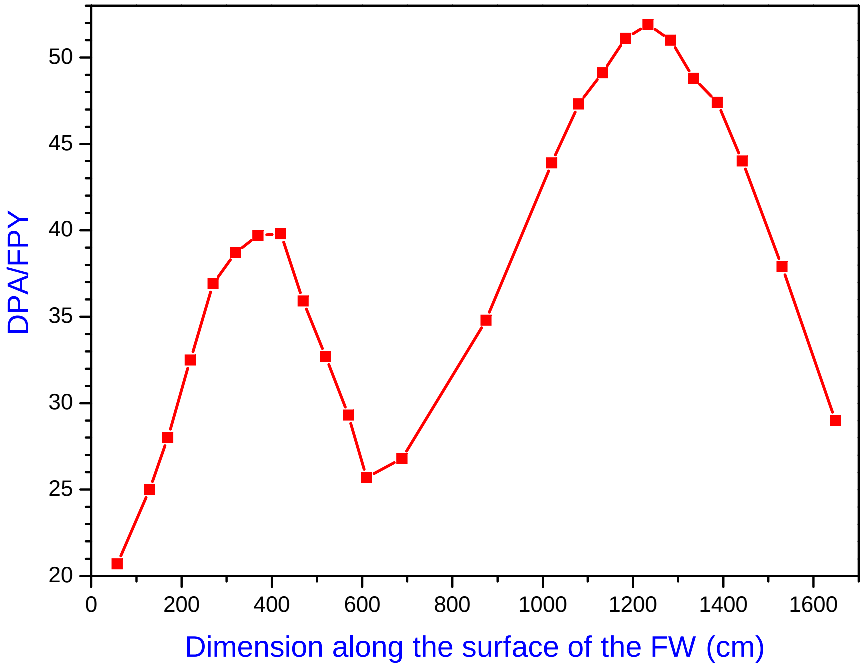
- Contribution of ^{6}Li and ^{7}Li: ~99%; ~1%
- Contribution of the i/b and o/b blankets: ~25%; 75%
  (the same as 2D result)
- reduction of TBR is ~0.05 (3D(1/7) model to 2D model) opening; uniformed/detail blk

DPA & wall loading at the FW



DPA/FPY at the FW



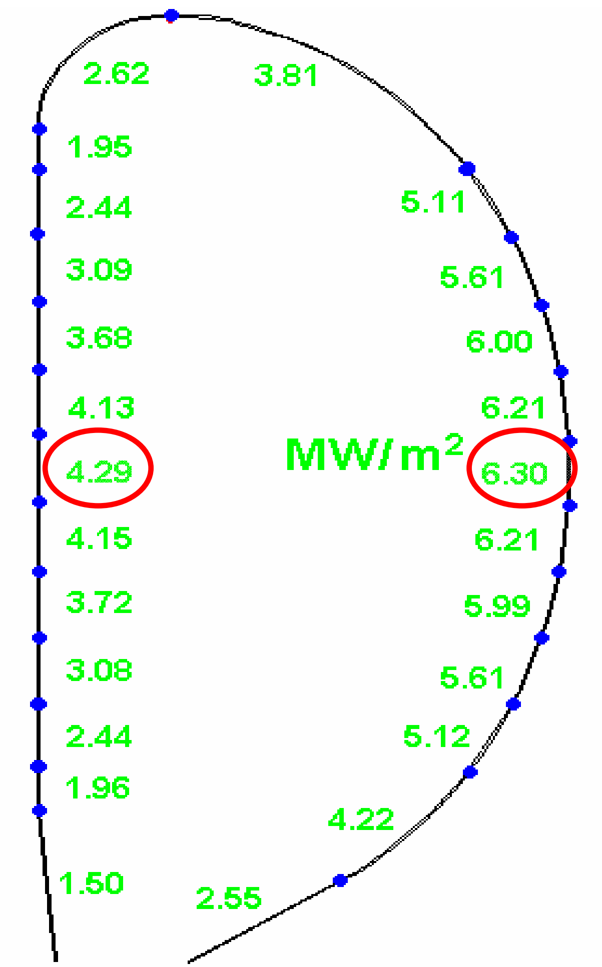


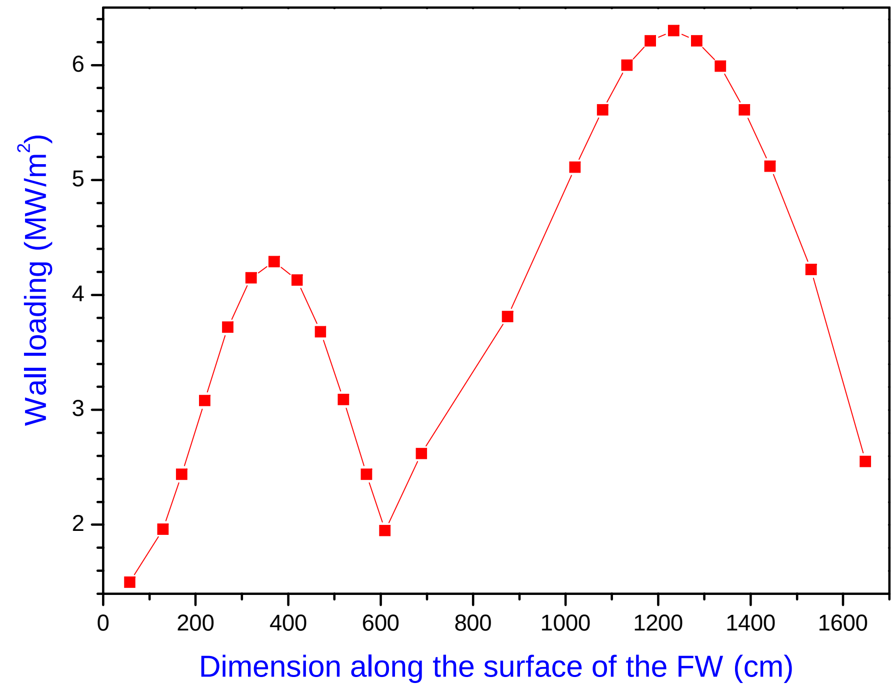
max DPA/FPY at the mid-plane of the FW:

Inboard FW	39.8
Outboard FW	51.9
Life time	~3yr

average DPA/FPY: 38.1

Wall loading





max wall loading(MW/m^2) at the mid-plane:

Inboard FW	4.29
Outboard FW	6.30

average Pw: 4.17MW/m^2

Nuclear Heat

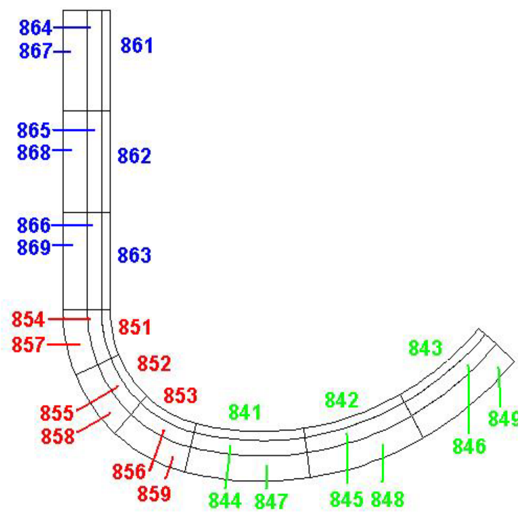
P_{fusion}=2.97GW M=1.38

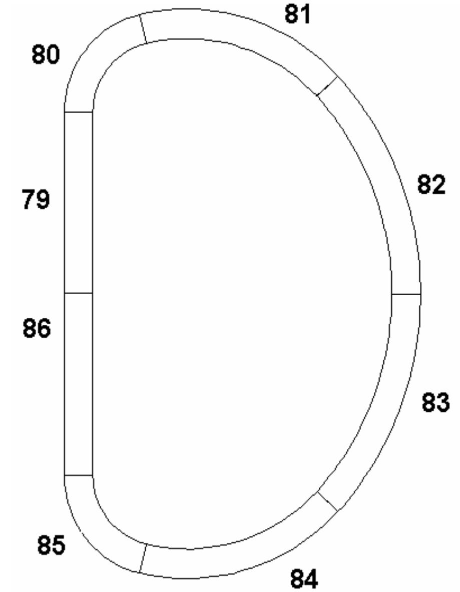
Component	W/cm^3 (average)	MW	%	error
FW	36.64	305.02	**9.31**	0.4%
Blanket	8.58	2752.06	**84.04**	0.3%
Shield	0.35	216.44	**6.61**	6.2%
Exhaust duct	1.10E-02	1.19	0.04	7.3%
PF coils	6.56E-06	2.09E-03	6.38E-05	8.3%
CS coils	3.97E-06	1.66E-04	5.07E-06	9.3%
TF coils	2.59E-05	**7.10E-03**	2.17E-04	5.1%
He-can of TF coils	1.02E-04	1.86E-02	5.68E-04	3.4%
Total		**3274.74**		

Nuclear heat in TF coils for ITER is limited to <17KW.

the shield gives good protection to TF coils from this point of view.

Nuclear Heat in TF coil





Cell no. / mW/cm^3 / error	Layer						
	1st layer (15cm)	851 / 1.80 / 0.09	852 / 3.07 / 0.05	853 / **4.69** / 0.04	841 / 3.17 / 0.02	842 / 0.67 / 0.03	843 / 0.06 / 0.17
	2nd layer (25cm)	854 / 0.65 / 0.08	855 / 1.06 / 0.05	856 / 1.54 / 0.04	844 / 0.99 / 0.02	845 / 0.23 / 0.04	846 / 0.004 / 0.18
	3rd layer (40cm)	857 / 0.24 / 0.14	858 / 0.27 / 0.31	859 / 0.67 / 0.11	847 / 0.39 / 0.03	848 / 0.10 / 0.08	849 / 0.001 / 0.19

- max nuclear heat density in TF coil: 4.7mW/cm3
- Results in cell 86 (mid-plane cell) are in calculation in order to get the max nuclear heat density at the mid-plane for the TF coil.

- Dose rate to insulator
- Peak fast neutron fluence

Conclusion

- necessary calculation on analysis on neutronics issues for CREST in 3D model are done

max. wall loading(MW/m^{2}) 4.29(i/b); 6.30(o/b);

4.17(aver.)

max DPA/FPY 51.9 (i/b); 39.8(o/b);

38.1(aver.)

~3yr

tritium self-surficient (Total TBR >1)

energy multiplication M ~1.4

Nuclear heat to TF coils is < ITER's criteria

max nuclear heat density in TF coil: 4.7mW/cm^3

TBR:

- Contribution of ^{6}Li and ^{7}Li: ~99%; ~1%
- Contribution of the i/b and o/b blankets: ~25%; 75%
  (the same for 2D and 3D results)

- Reduction of TBR due to the NBI port is 0.03

- TBR = 1.27 for 3D 1/7 model
- reducing of TBR is ~0.05
  (comparing the result of 3D(1/7) model with that of 2D model)

- The effect of Zr shell to TBR is 0.03 in 2D model.

- results are reasonable
- consistent with some of 1D ANISN results done before

- analysis on damage to TF coil due to openings such as NBI port etc are underway