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Engineering Design of the MYRRHA. Part III

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MYRRHA – Draft 2
Sub-critical Core Neutronics Design Calculations

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On behalf of MYRRHA team and MYRRHA support

http://www.sckcen.be/myrrha

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STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

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7. Reactivity effects and Operational sub-criticality margins
8. Concluding remarks
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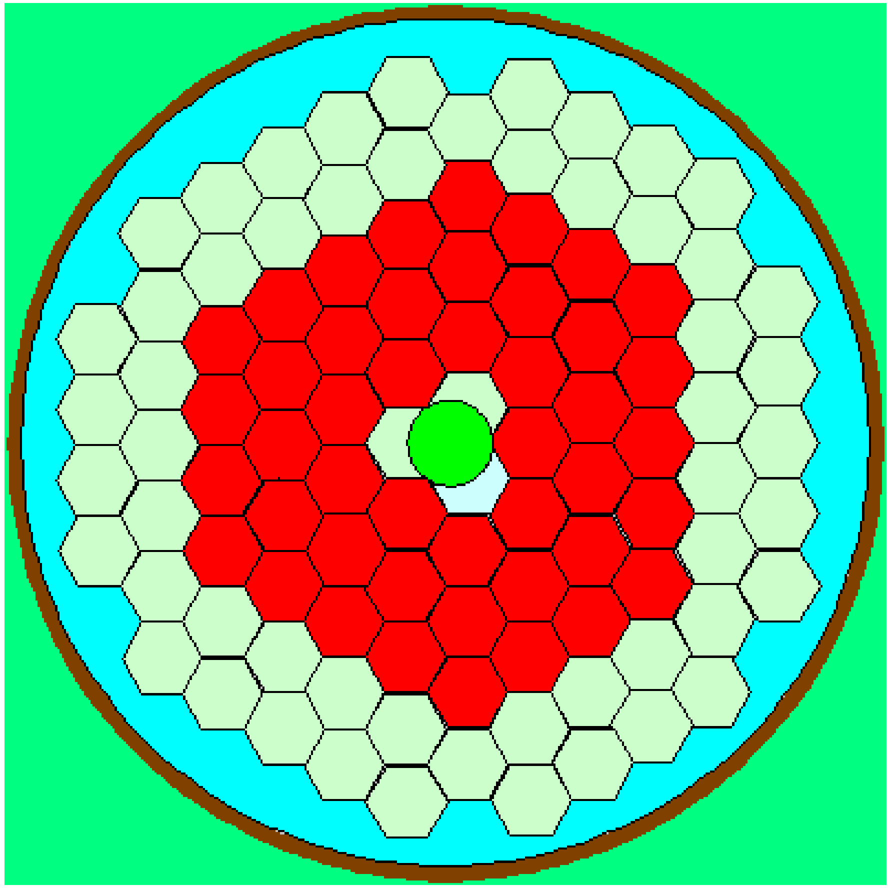
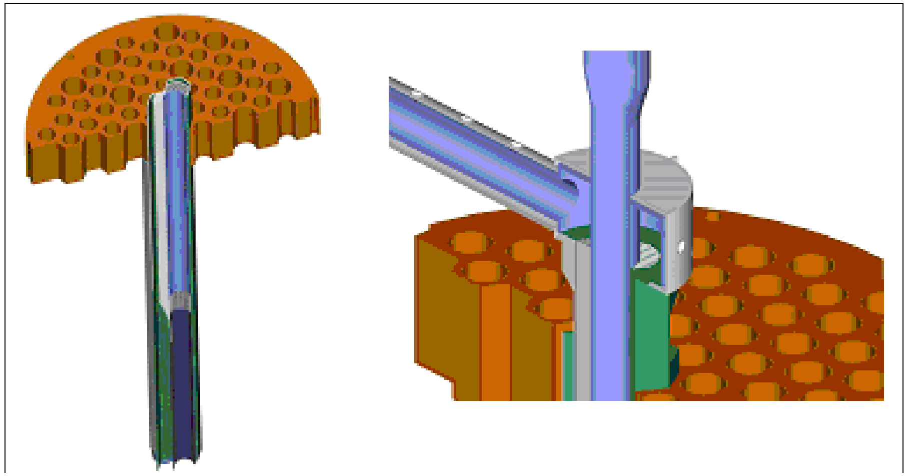
Sub-critical core design requirements and constraints

- Proton Beam:
  - 350 MeV-5 mA
  - Spot size (FWHM)=15 mm (gaussian spatial shape assumed)
- The initial $k_{eff} \sim 0.95$
- Nominal power ~*50 MWth*
- Fast neutron flux: ~ 10^{15} n/cm²s
- Thermal neutron flux (inside IPS-like loop): $1.0 - 2.0\ 10^{15}$ n/cm²s

MYRRHA ADS: Typical Core Configuration





- 102 channels
- Target-block hole fitted out within the 3 central channels
- Surrounding active zone loaded with 45 fuel SA (30wt% Pu/HM; 91 pins/SA)
- Outer reflector zone composed of 54 “reflector” assemblies

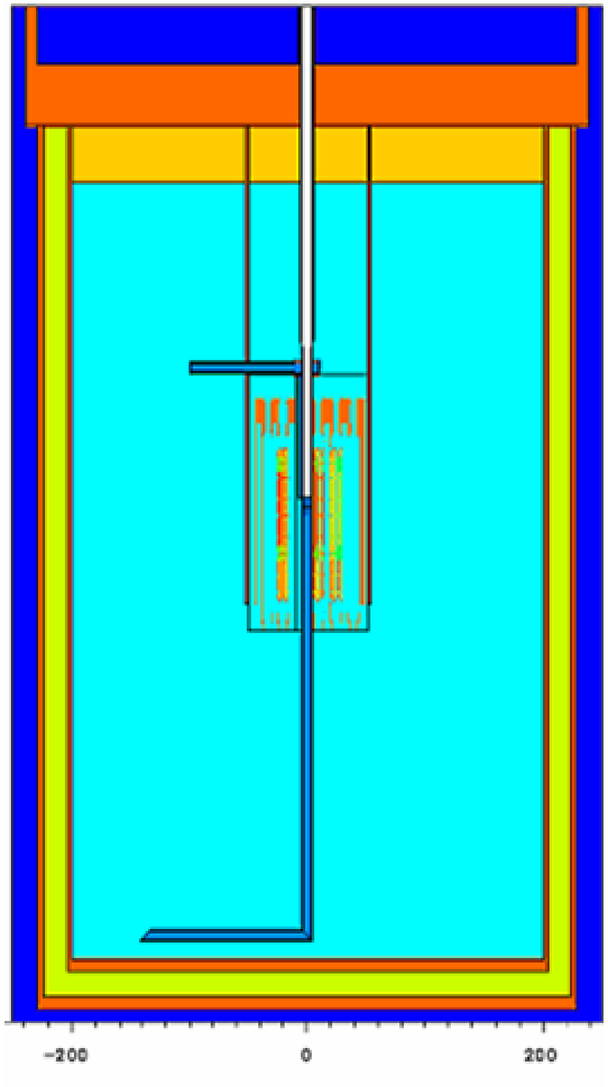
Core Analysis tools

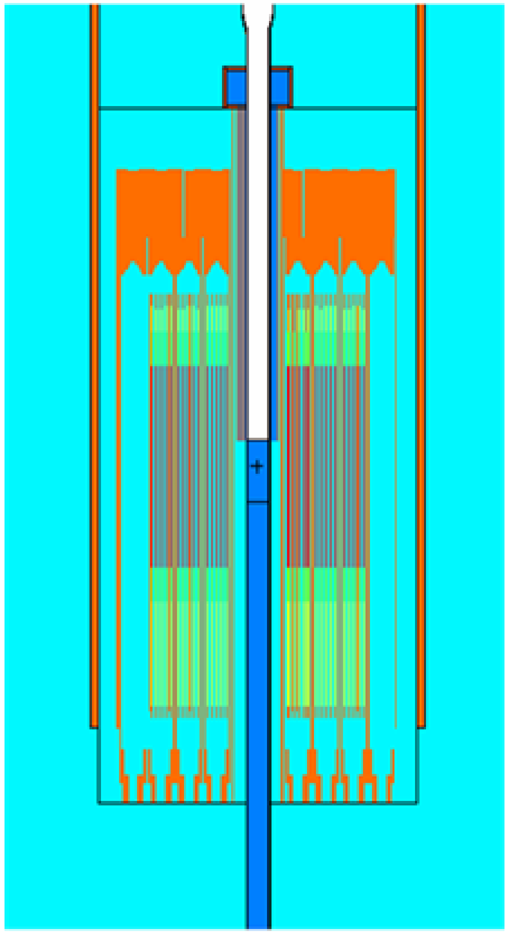
- Nuclear data (within table range; INC-model beyond):
  - Neutrons: JEF2.2 (MCB-package) combined to LA150n(Pb, Bi and steel elements);
  - LA150h or physical models for protons.
- MCNPX 2.5.e beta version used:
  - Enables one to "mix-and-match" data tables having different upper energy boundaries and table data with INC models
- ALEPH (home-made)code, coupling MCNPX and ORIGEN2.2 in a more efficient way, to carry out core burn-up calculations
  - Nuclear data: JEF2.2 processed using NJOY99.90

Geometrical model

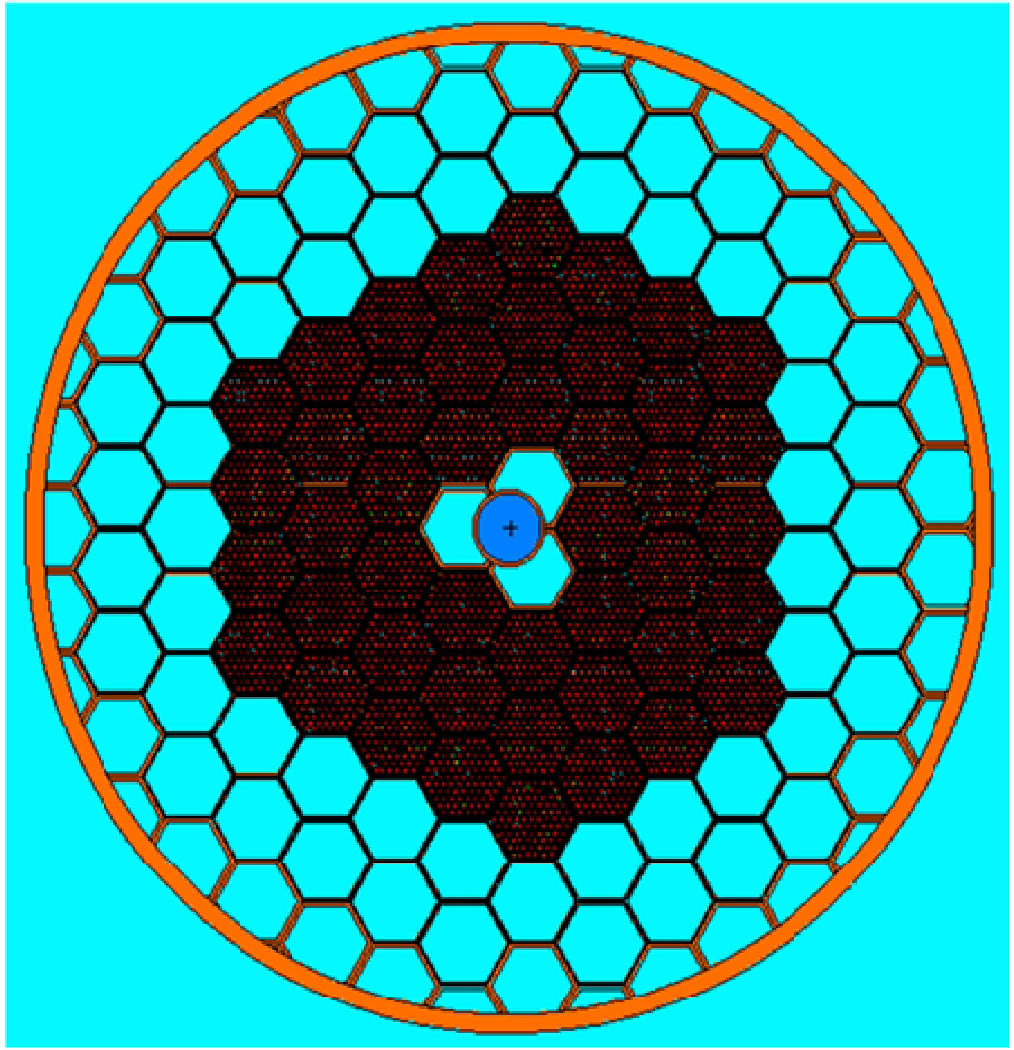
- Updated and Completed
  - Fuel pin and assembly design revised
  - Assembly extension parts from the inlet nozzle through the outlet nozzle
  - Assembly and fuel-pin bundle grids
  - Core barrel and core suspension tube
  - Top lid and radial shielding concrete
  - Top (pool) gas plenum
  - Spallation target loop (inner part)

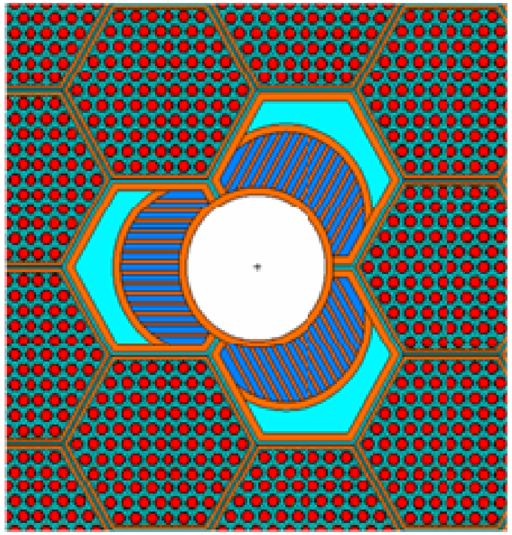
MYRRHA MODEL for MCNPX calculations

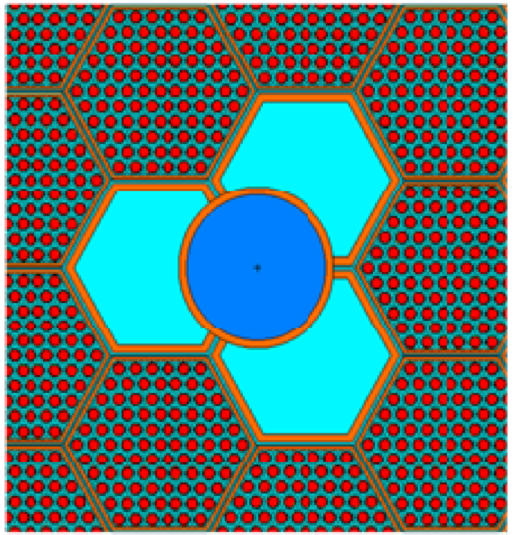




MYRRHA MODEL for MCNPX calculations (cont'd)







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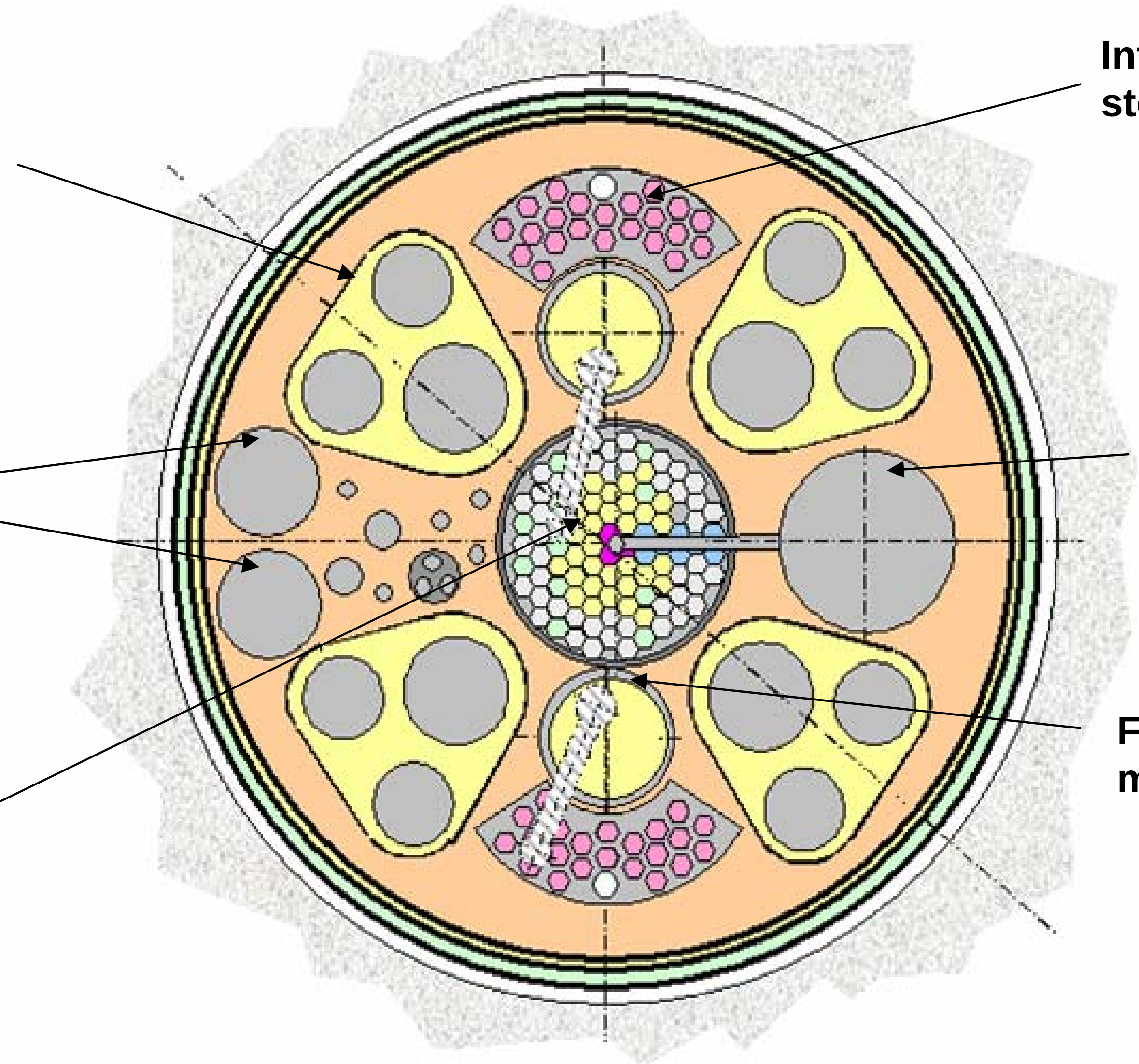
MYRRHA: general sketch



Results

- Comprehensive and reliable set of results provided:
  - Reactivity effects
  - Nuclear data sensitivity analysis
  - Operational sub-criticality margins
  - Consistent Power and Flux maps
  - Irradiation-induced damage parameters (DPA, gas-production)
  - MA and LLFP transmutation performances
- Improved quality of document

Overview of the MYRRHA core characteristics (BOL)

Neutronics Parameters	Units	MYRRHA ADS values
Proton beam energy	MeV	350
Accelerator current	mA	5
Proton beam heating	MW	1.43
Spallation neutron yield		6.03
neutron source Intensity	10^{17} n/s	1.88
Initial fuel mixture	MOX	$(U\text{-}Pu)O_2$
Initial (HM) fuel mass (m_{fuel})	Kg	514
Initial Pu-enrichment (Pu/U+Pu)	wt%	30
Initial Pu isotopic vector $^{238}Pu/^{239}Pu/2^{40}Pu/^{241}Pu/^{242}Pu$	wt%	1.27/61.88/23.50/8.95/4.40
K_{eff}		0.9552
K_s		0.9601
MF = 1 / (1 - K_s)		25.04
Source importance: φ*		1.127
Thermal Power (*) (P_{th})	MW	51.75
Av. Fuel power density (P_{th}/V_{fuel})	W/cm³	937
Specific power	kW/kgHM	101
Peak linear Power (hottest pin)	W/cm	352
Av. Linear Power (hottest pin)	W/cm	272
Max Φ_{total} in the fast core (near the hottest pin)		4.1
Max $\Phi_{>1\ MeV}$ in fast core (near the hottest pin)	10^{15} n/cm²s	0.8
Max $\Phi_{>0.75\ MeV}$ in fast core (near the hottest pin)		1.0
(*) E_f = 210 MeV/fission		

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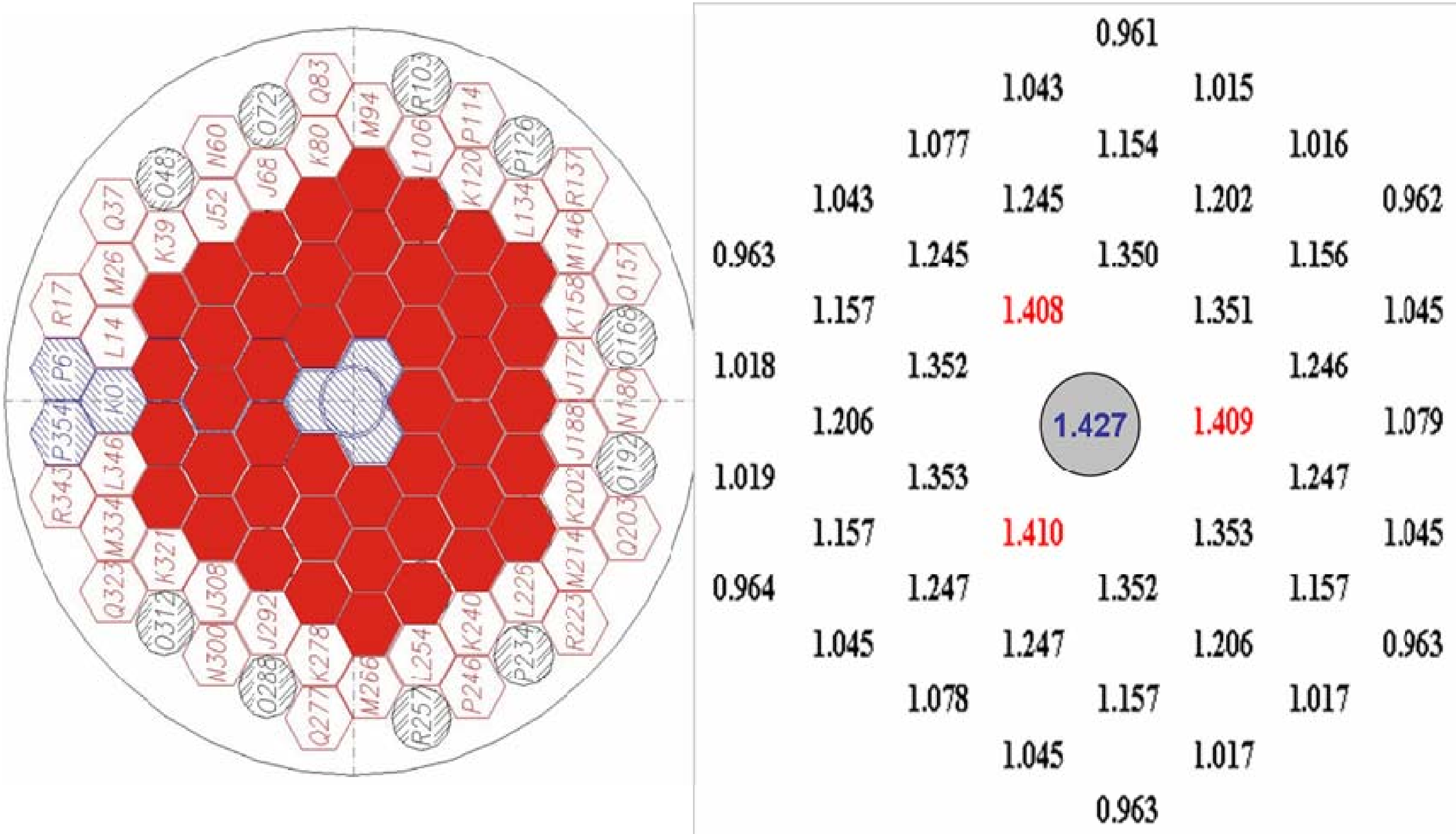
Sub-critical Core:
Assembly Power map

MYRRHA



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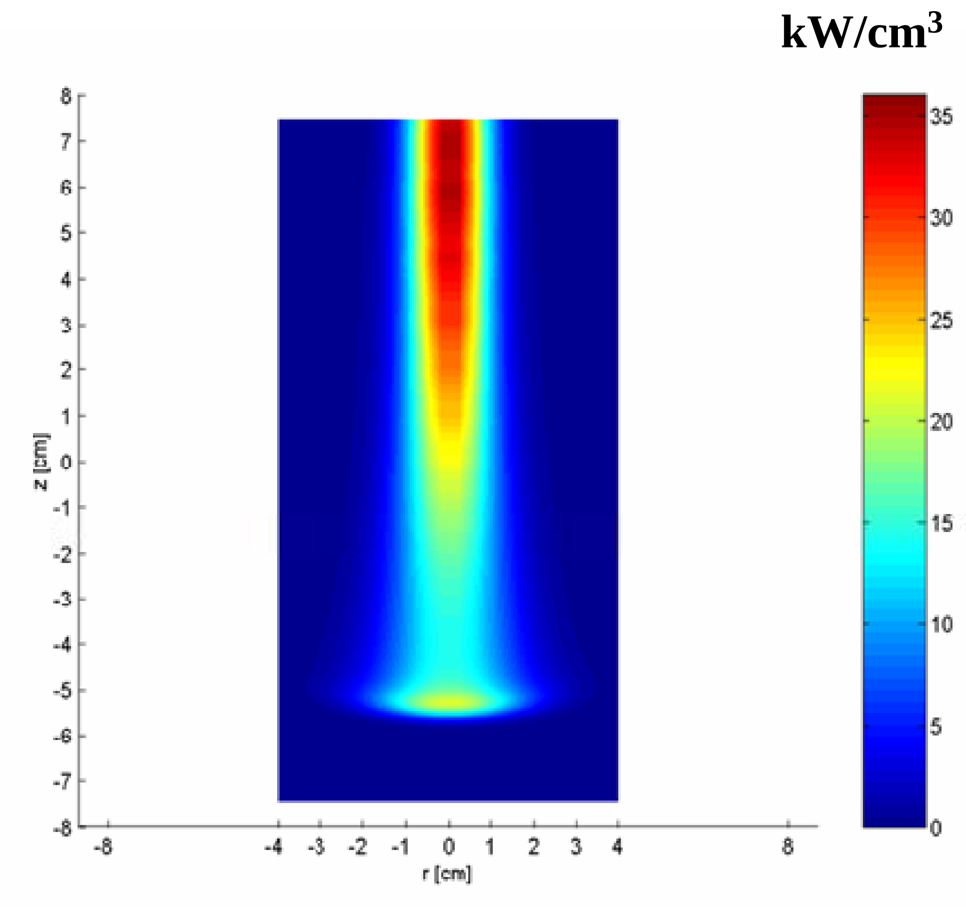
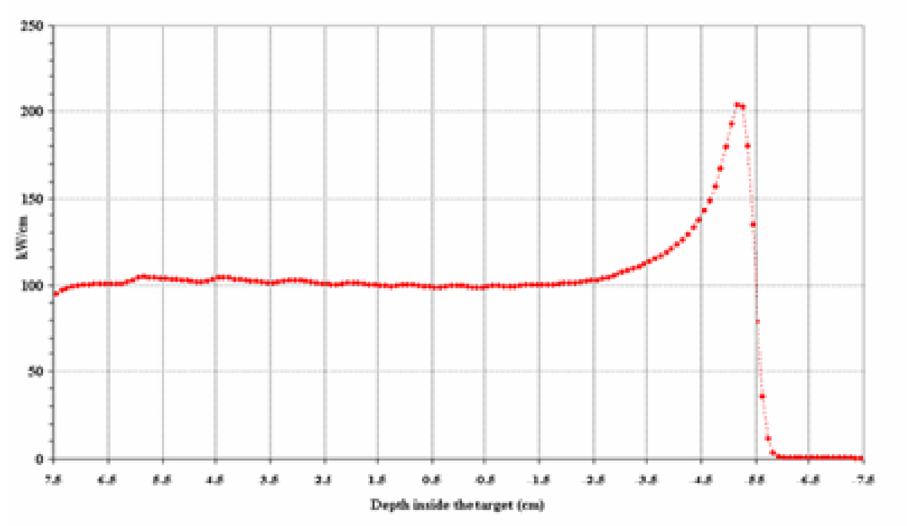
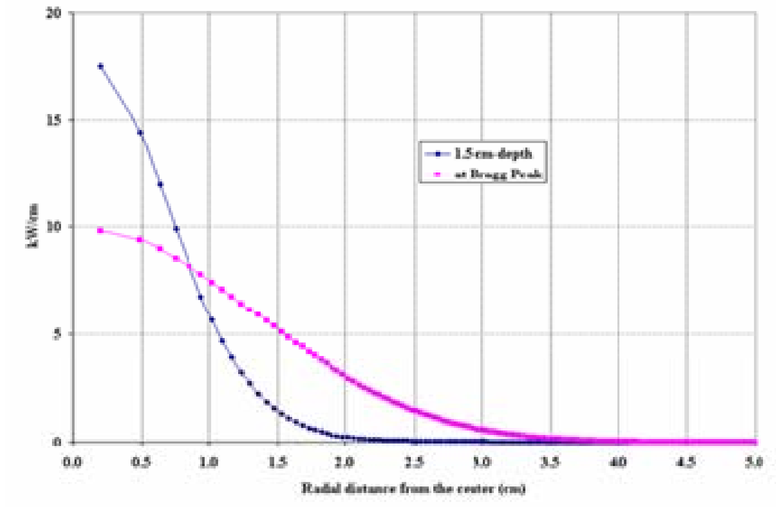
Spallation target Heating

MYRRHA







Pin-by-pin power map (hot assembly) and linear power density curve (hot pin)

15.72 15.58 15.50 15.30 15.15 14.98

15.84 15.74 15.58 15.47 15.31 15.11 14.97

15.97 15.83 15.72 15.61 15.47 15.30 15.11 14.93

16.09 15.97 15.82 15.70 15.56 15.41 15.27 15.10 14.85

16.18 16.06 15.93 15.79 15.67 15.52 15.37 15.19 14.98 14.76

16.30 16.11 16.00 15.85 15.75 15.62 15.42 15.28 15.03 14.85 14.68

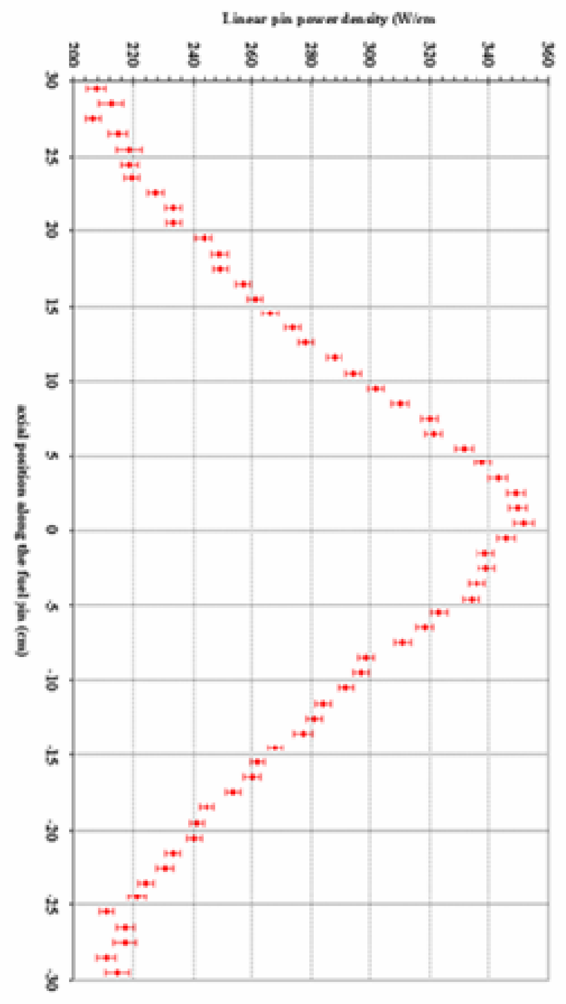
16.16 16.05 15.91 15.80 15.62 15.44 15.32 15.16 14.93 14.78

16.11 15.97 15.84 15.71 15.59 15.38 15.21 15.04 14.84

15.99 15.84 15.73 15.59 15.45 15.29 15.08 14.91

15.83 15.75 15.61 15.47 15.33 15.11 14.94

15.68 15.60 15.46 15.33 15.11 14.96



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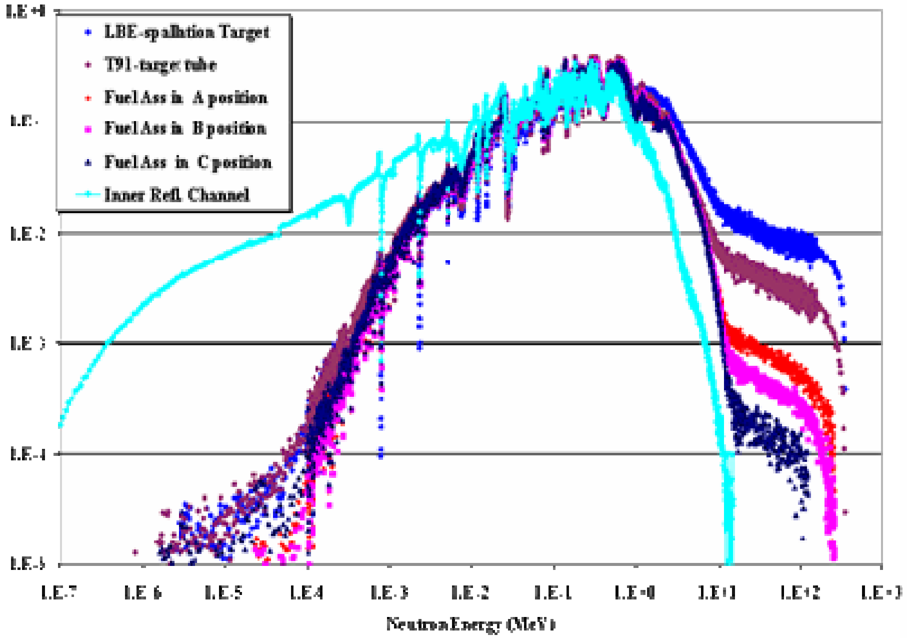
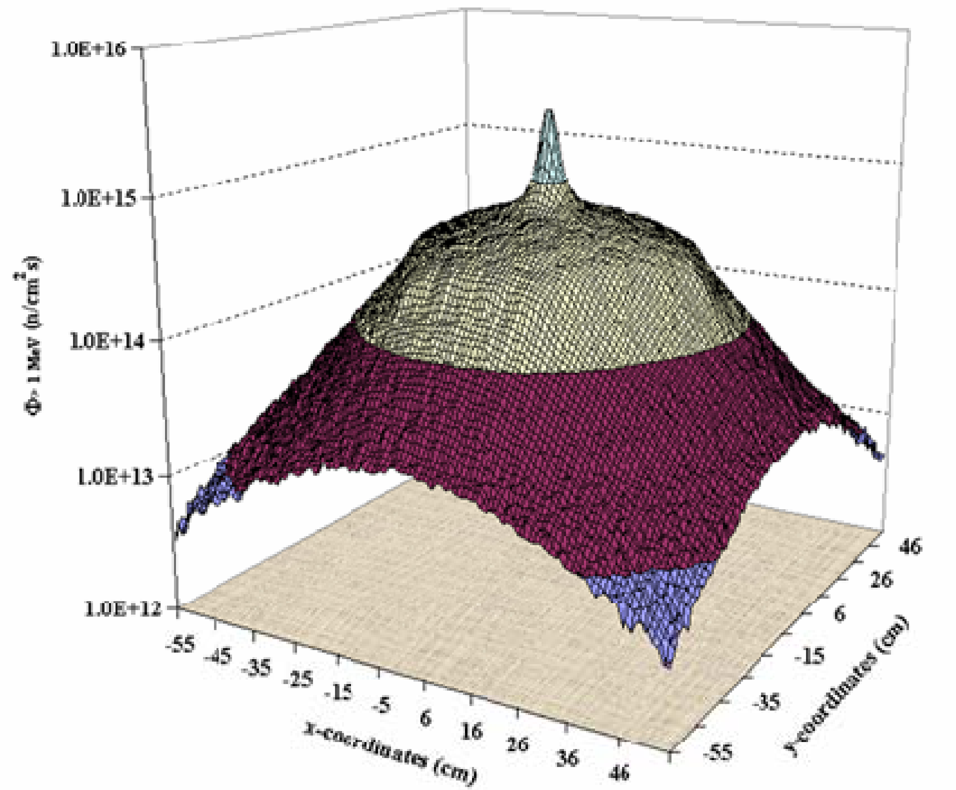
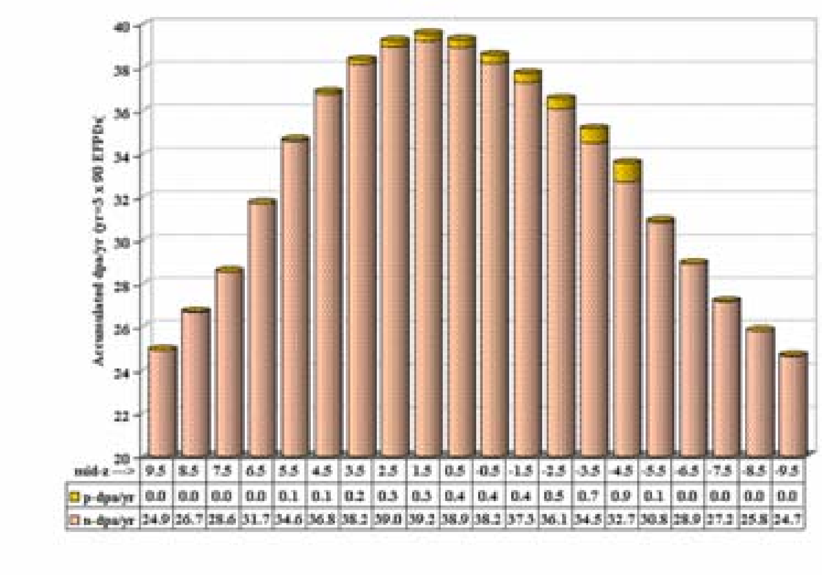
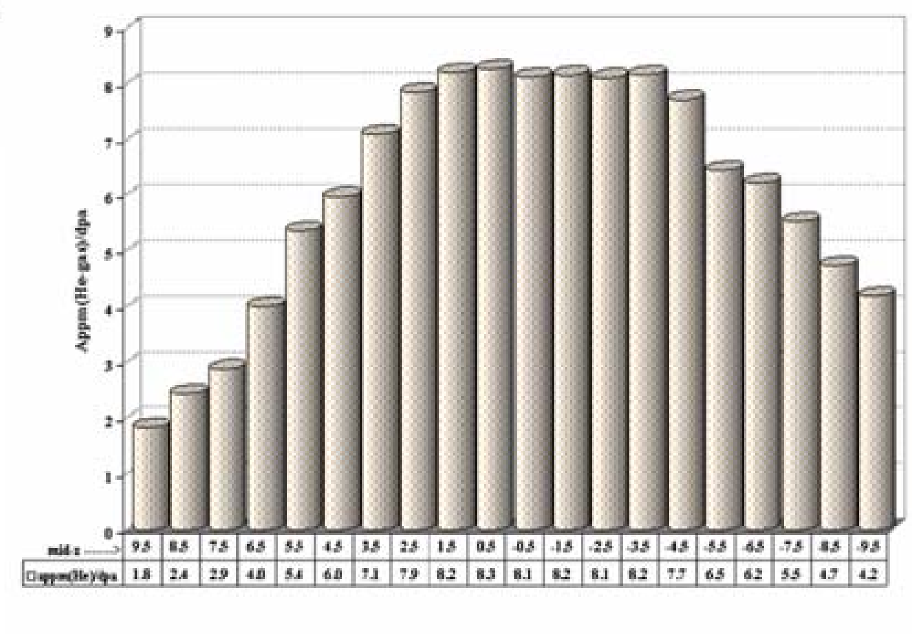
Spectra and Flux



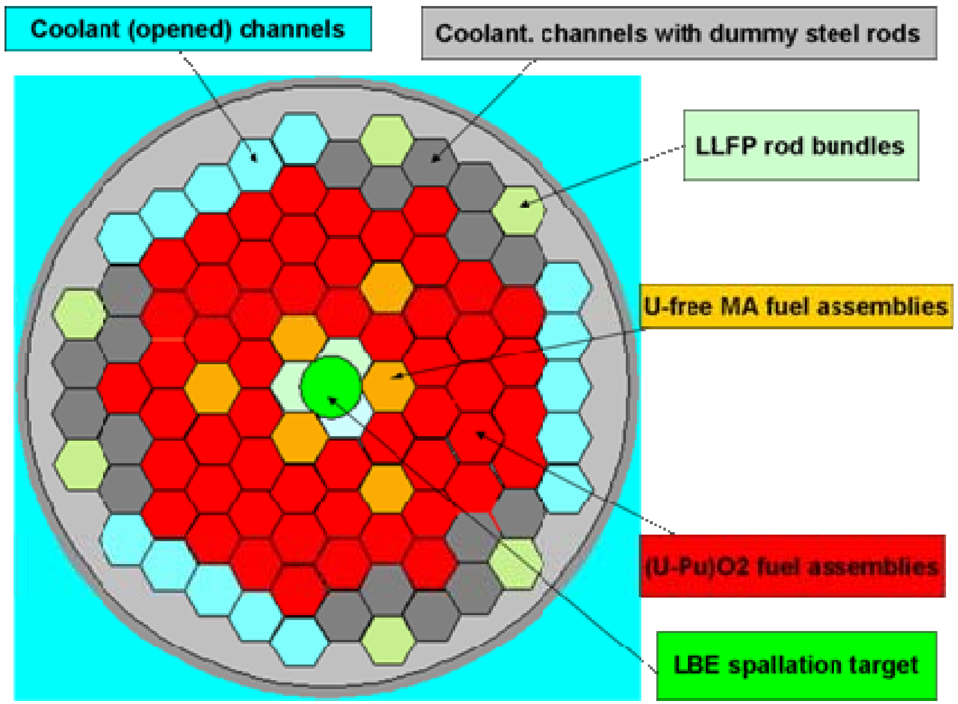


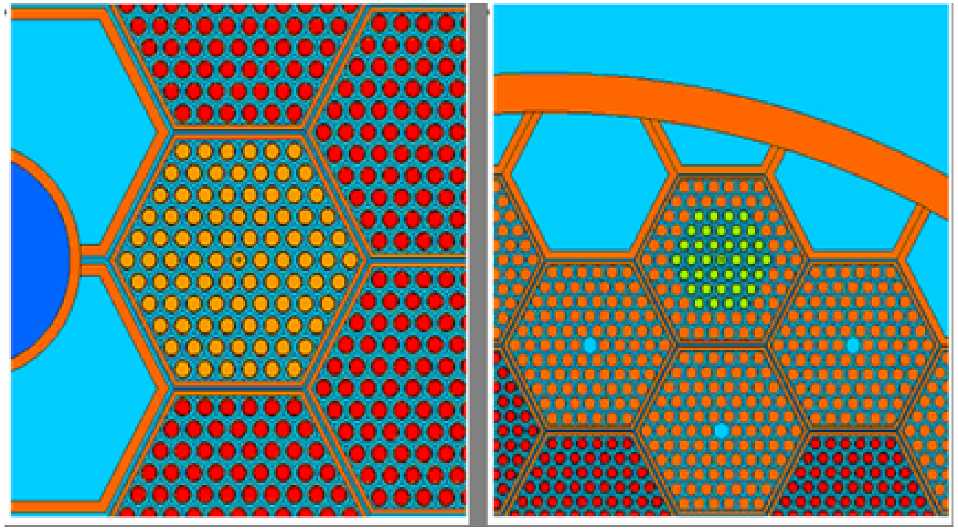
DPA-damage and Helium-gas production in T-91steel pipe





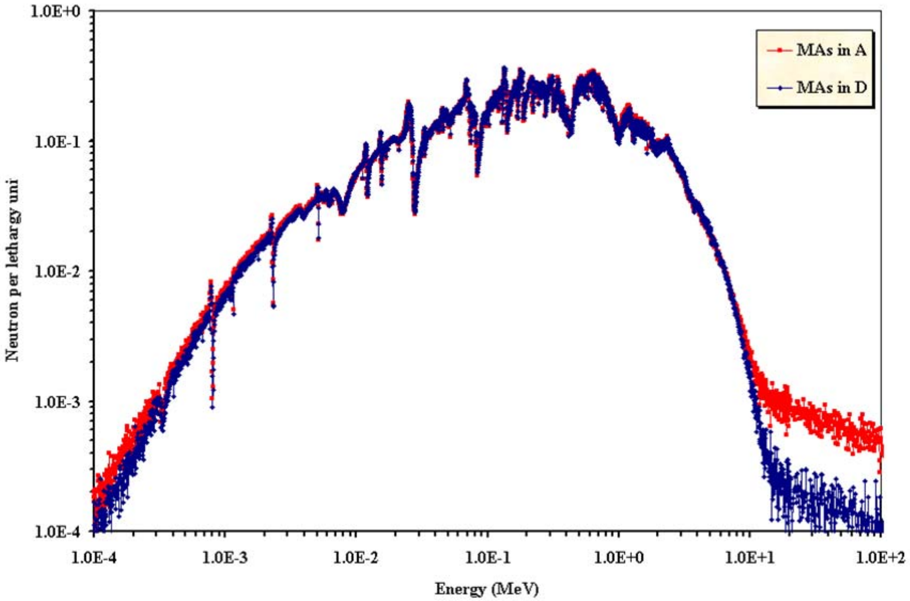
MA and LLFP transmutation: Core loading

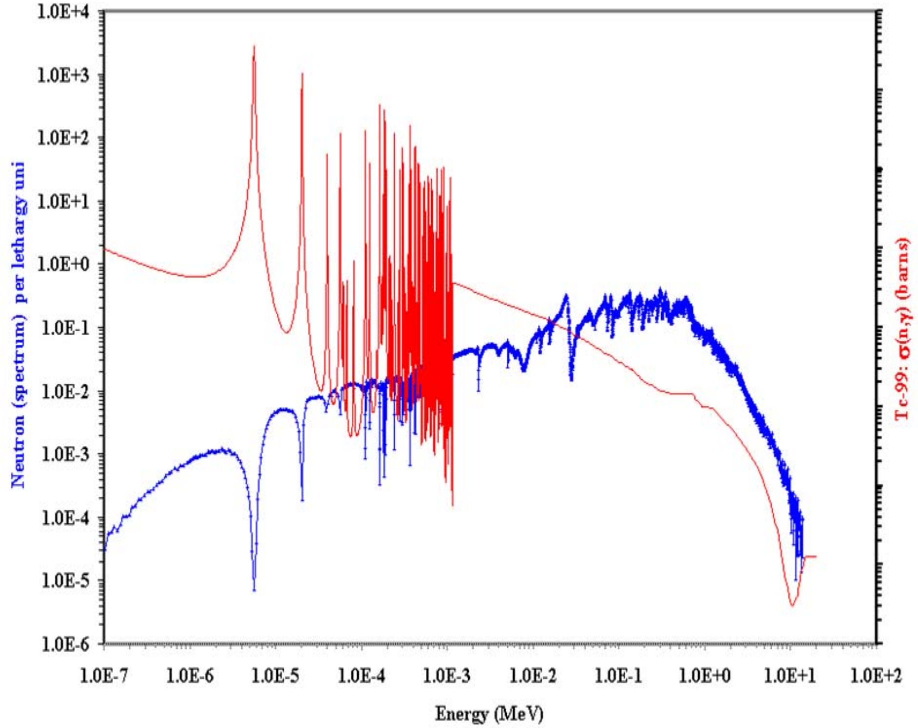




MA pellet vector	wt% fraction
Pu/Am/Cm/Mg/O	23.25/30.32/6.06/19.18/20.19
^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu	5.06/37.91/30.31/13.21/13.51
^{241}Am/^{243}Am	66.67/33.33
^{244}Cm/^{245}Cm	90/10

Neutron spectra in MA and LLFP samples





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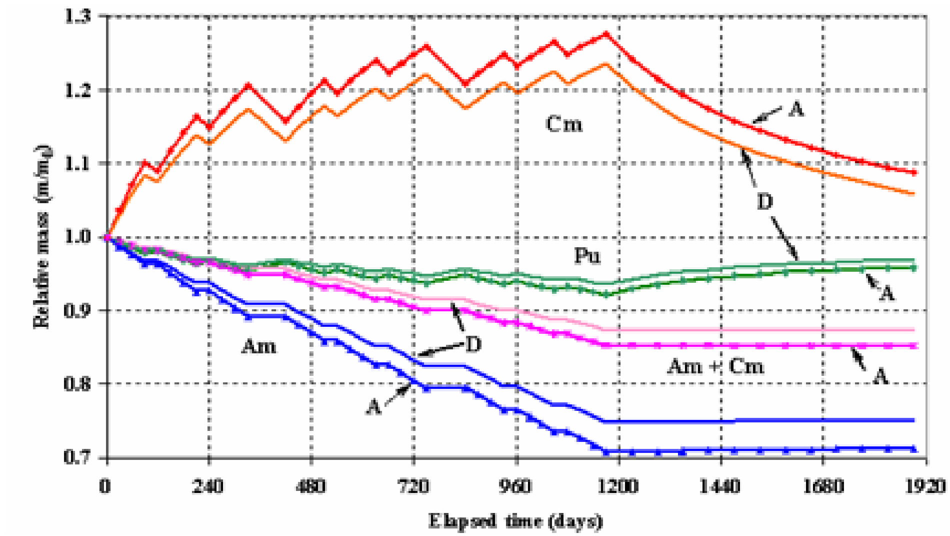
MA and LLFP (amounts in gram)

	A or D	A	D	A	D
Pu-238	183	326	294		
Pu-239	1372	-493	-434		
Pu-240	1097	-15	3		
Pu-241	478	-179	-167		
Pu-242	489	79	72		
Pu	3619	-282	-232	-7.8%	-6.4%
Am-241	3015	-1025	-892		
Am-242		124	115		
Am-243	1507	-419	-366		
Am	4522	-1319	-1143	-29.2%	-25.3%
Cm-242	0	107	97		
Cm-243	0	6	5		
Cm-244	813	104	84		
Cm-245	90	26	22		
Cm-246	0	5.8	4.9		
Cm	903	249	212	27.5%	23.4%
All (Z>88) Actinides	9044	-1333	-1143	-14.7%	-12.6%
ℵtot (n/cm^2s)		$3.15\ 10^{15}$	$2.71\ 10^{15}$		



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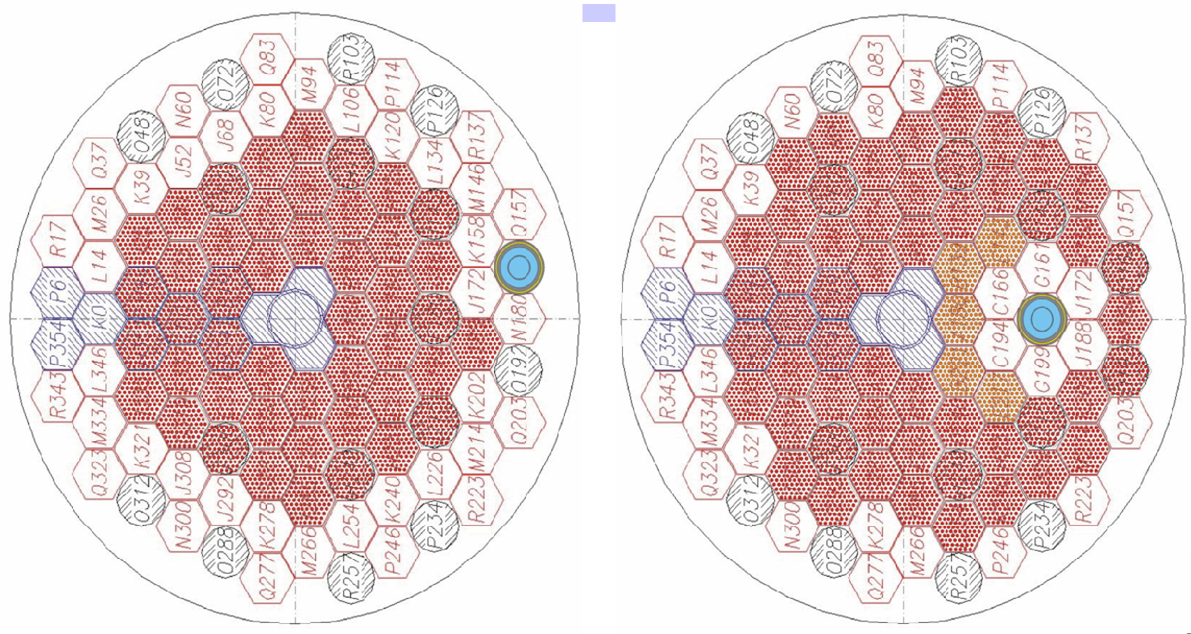
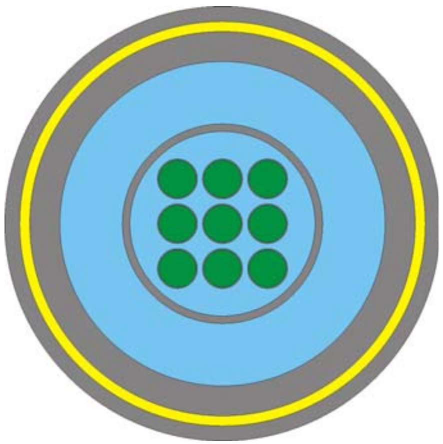
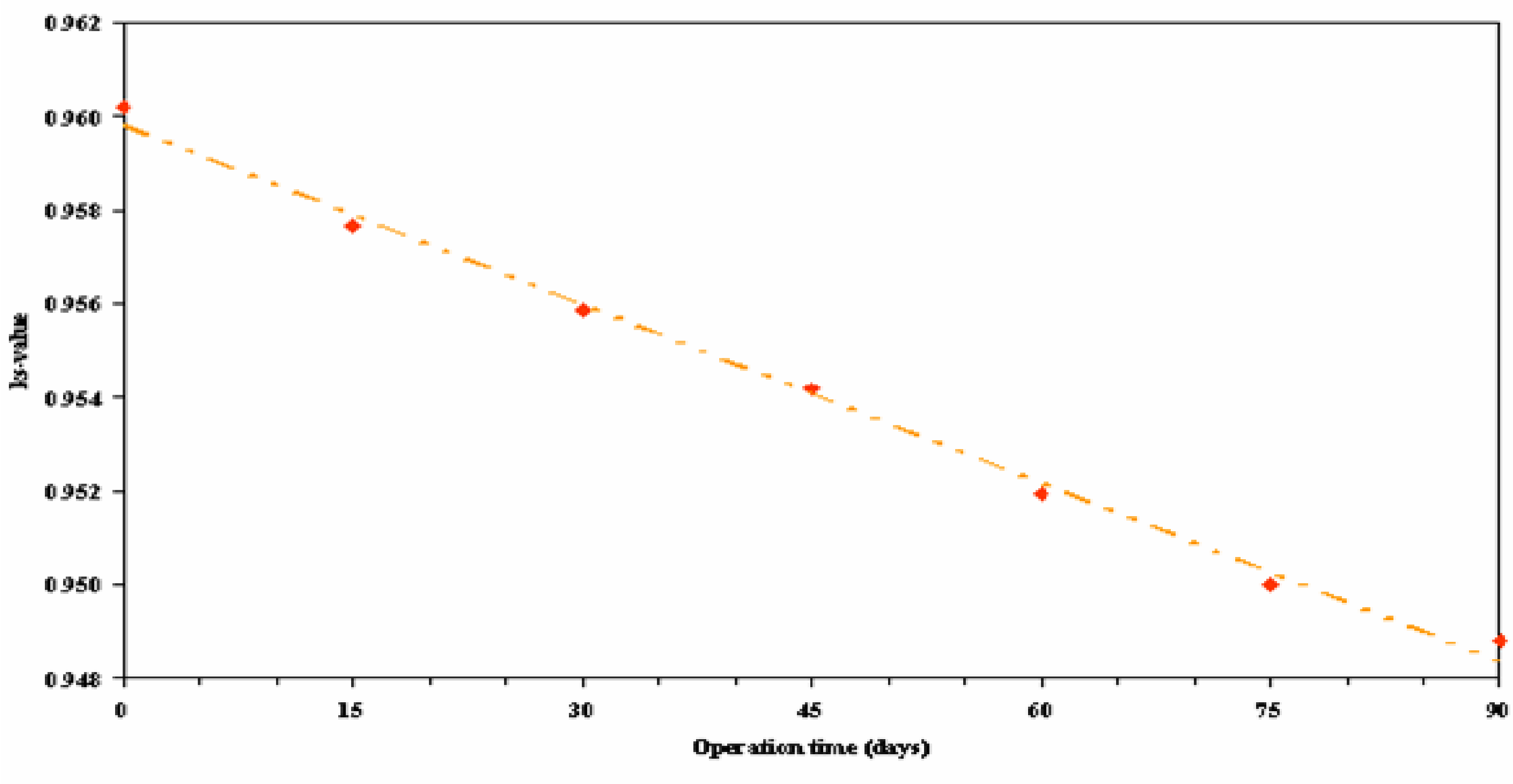
Core configuration with IPS-like water-moderated loop





	inner position	outer position
ks	0.959	0.957
Ptot (MW)	50	48
Peak linear Power (W/cm)	327	311
Total flux (10^{15} n/cm^{2}s)	2.5	1.7
¬<0.5 eV (10^{15} n/cm^{2}s)	1.1	0.8

K_s swing



- Δρ=-1667 pcm pcm/cycle (1cycle=90 EFPDs) (i.e., -19 pcm/EFPD).

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Fuel burn up after 90 EFPDs in MWd/kgHM)

MYRRHA

				6.57			
			7.13		7.19		
		7.36		7.88		7.19	
	7.13		8.48		8.20		6.57
6.57		8.48		9.18		7.88	
	7.88		9.56		9.18		7.13
7.19		9.18				8.48	
	8.20				9.56		7.36
7.19		9.18				8.48	
	7.88		9.56		9.18		7.13
6.57		8.48		9.18		7.88	
	7.13		8.48		8.20		6.57
		7.36		7.88		7.19	
			7.13		7.19		
				6.57			

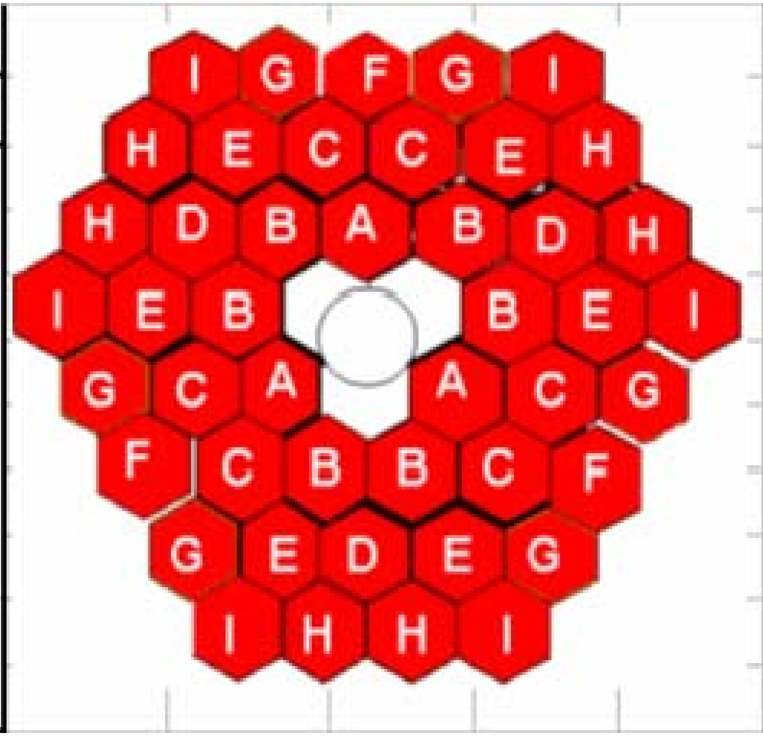
Assembly relative power at BOC and at EOC

				0.84			
			0.91	0.83	0.89		
		0.94	0.91		0.89	0.89	
	0.91	0.94		1.01		0.89	0.84
0.84	0.91		1.08	1.01	1.05		0.83
0.83		1.08	1.08		1.05	1.01	
	1.01	1.08		1.17		1.01	0.91
0.89	1.01		1.21	1.18	1.17		0.91
0.89		1.17	1.23		1.18	1.08	
	1.05	1.18				1.08	0.94
0.89	1.05				1.21		0.94
0.89		1.17			1.23	1.08	
	1.01	1.18				1.08	0.91
0.84	1.01		1.21		1.17		0.91
0.83		1.08	1.23	1.17	1.18	1.01	
	0.91	1.08		1.18		1.01	0.84
	0.91		1.08		1.05		0.83
		0.94	1.08	1.01	1.05	0.89	
		0.94		1.01		0.89	
			0.91		0.89		
			0.91	0.84	0.89		
				0.83			

FA mean power:
BOC: 1.167 MW
EOC: 0.815 MW

Fuel Assembly reactivity worth map

FA position	$\Delta\rho$ (pcm) BOC	$\Delta\rho$ (pcm) EOC	$\Delta\rho_s$ (pcm) BOC	$\Delta\rho_s$ (pcm) EOC
A	1406	1403	1260	1239
B	1320	1368	1237	1330
C	1195	1227	1048	1126
D	1128	1215	948	976
E	1030	1104	896	927
F	827	878	694	796
G	756	807	708	675
H	754	742	632	675
I	612	677	568	516



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Fuel Temperature (Doppler) effect Doppler constant (K_D = Tdk/dT)

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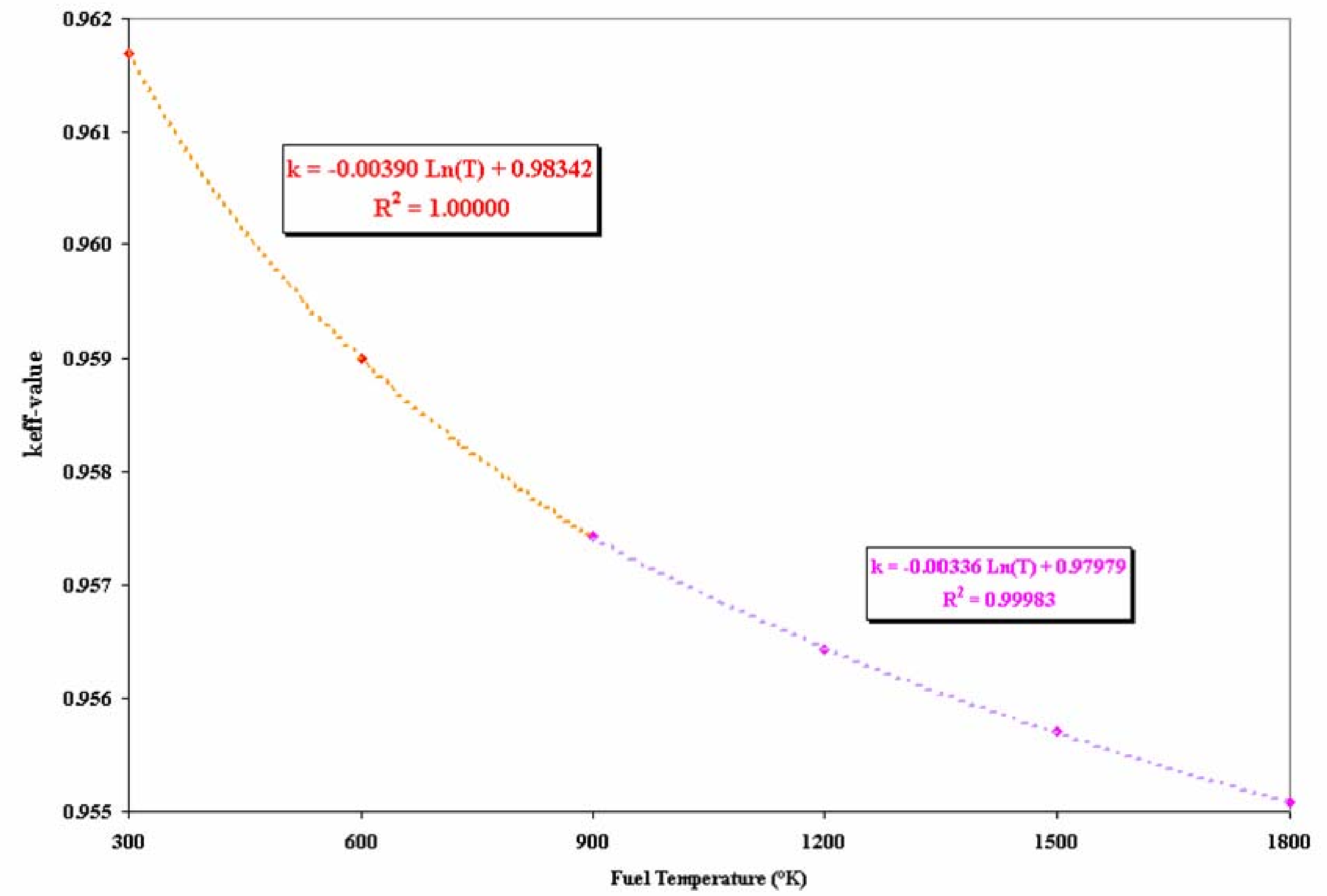
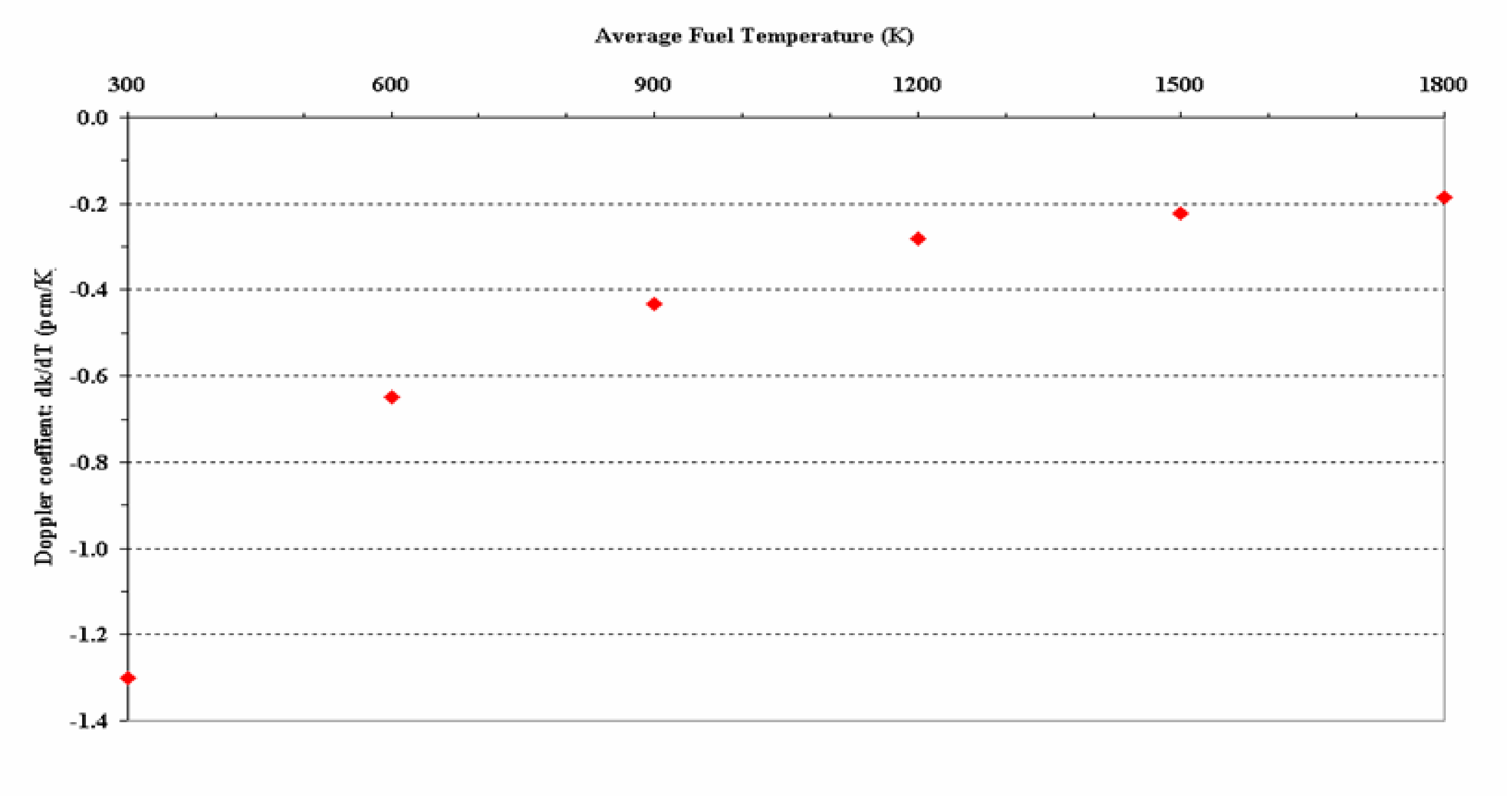
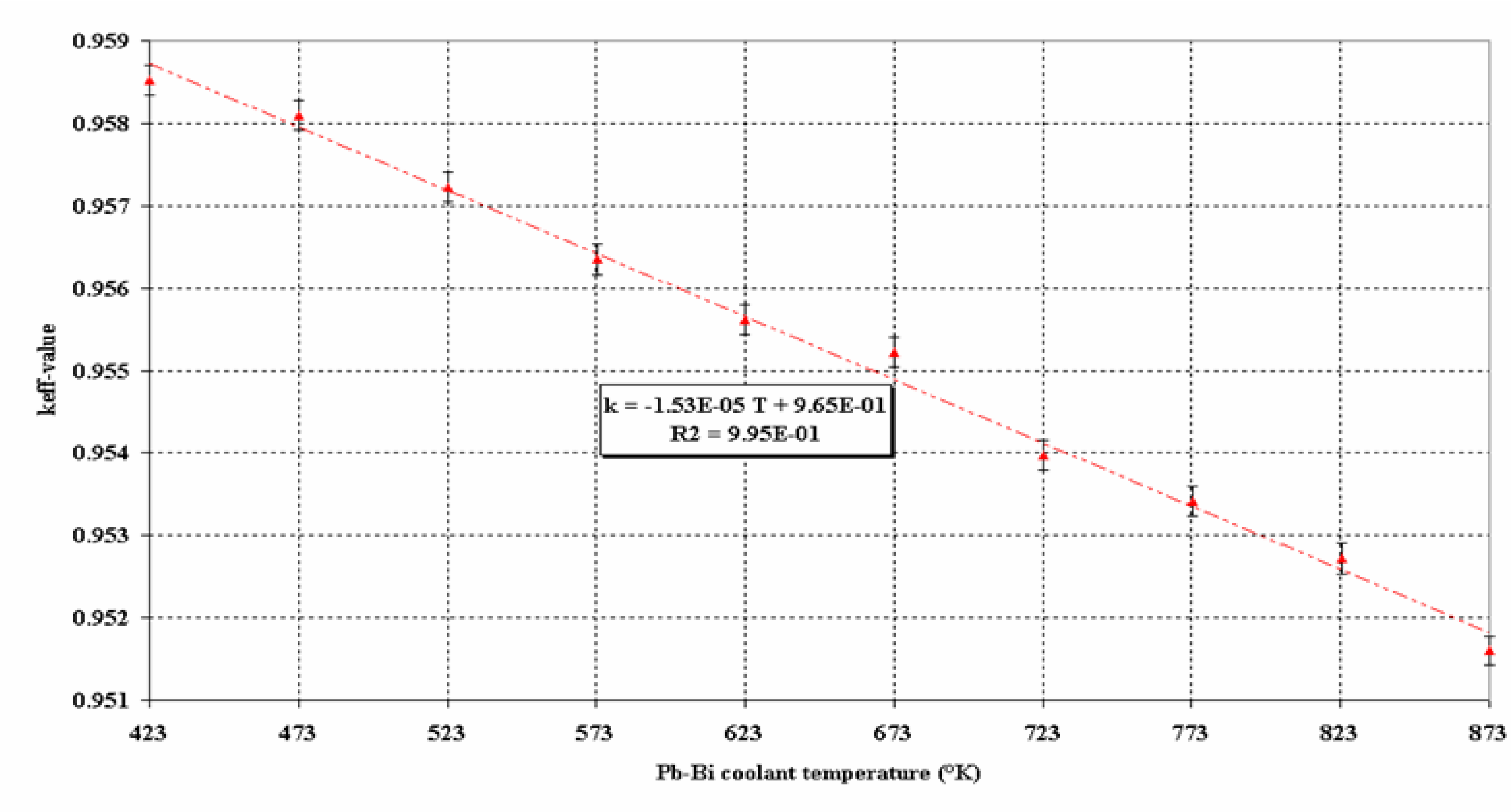


Fuel Temperature (Doppler effect) Doppler coefficient (dk/dT)



Coolant Temperature (density) reactivity effect (dk/dT)



Sensitivity to neutron cross-section libraries

Code	Nuclear data	err	errmax	errint	Ptable	ks	keff	Δρ	φ*
MCB	**JEF 2.2**	0.002	0.04	5.0E-7	yes	0.95961	0.95506	**496**	**1.12**
MCB	**JEF 2.2**	0.002	0.04	5.0E-7	no	0.95979	0.95578	**437**	**1.10**
MCB	**ENDF 6.8**	0.002	0.04	5.0E-7	yes	0.96881	0.95895	**1061**	**1.33**
SCK•CEN	**JEF 2.2**	0.001	**Optimal accuracy**		yes	0.96470	0.95479	**1076**	**1.29**
SCK•CEN	**JEF 2.2**	0.001	0.01	5.0E-8	yes	0.96423	0.95435	**1074**	**1.29**
SCK•CEN	**JEF 2.2**	0.001	0.01	5.0E-8	no	0.96457	0.95568	**964**	**1.26**
SCK•CEN	**JEF 2.2**	0.002	0.02	1.0E-7	yes	0.96437	0.95509	**1008**	**1.27**
SCK•CEN	**JEF 2.2**	0.002	0.04	5.0E-7	yes	0.96464	0.95480	**1068**	**1.29**
SCK•CEN	**ENDF 6.8**	0.001	0.01	5.0E-8	yes	0.96898	0.95971	**997**	**1.31**
SCK•CEN	**JEFF 3.0**	0.001	0.01	5.0E-8	yes	0.96511	0.95533	**1061**	**1.29**

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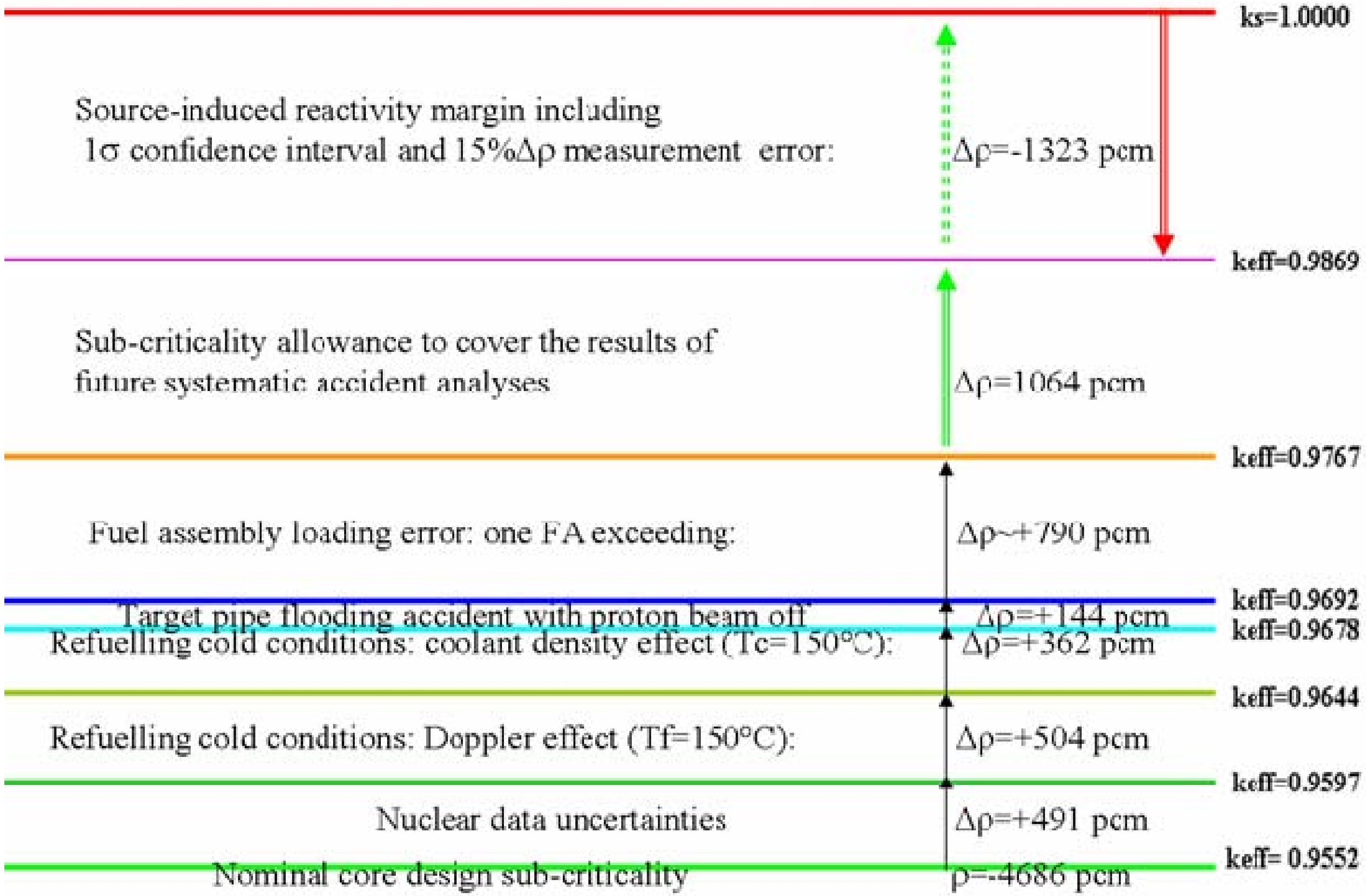
Estimated operational sub-criticality margins

MYRRHA



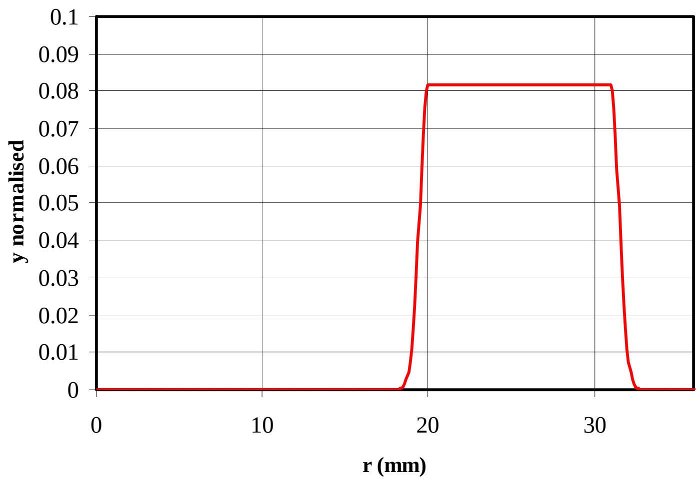
Concluding remarks

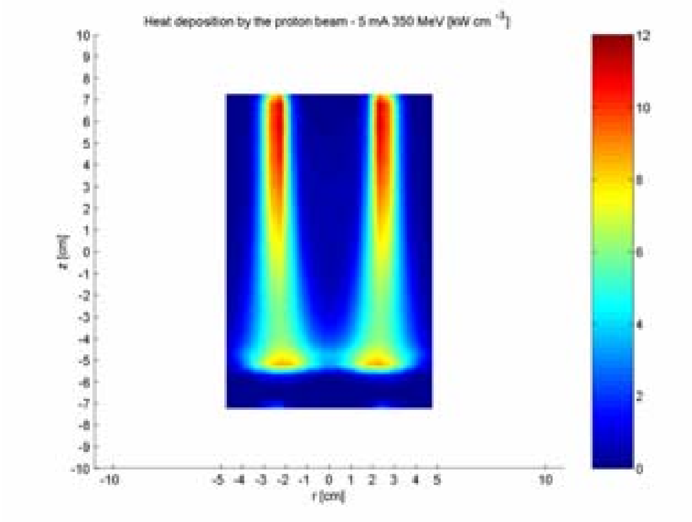
- The sub-critical core achieves a primary source neutron multiplication factor, ks, of 0.9600 (the keff-eigenvalue being 0.9552). The adopted sub-criticality level, -4686 pcm, is larger enough to keep the MYRRHA core far away from criticality.
- The reactivity swing induced by core burn-up amounts to about -19 pcm/EFPD starting from a fresh core
- At 5 mA beam intensity, the sub-critical core delivers a thermal power of 51.75 MW. An additional 1.43 MW is deposited by the proton beam mainly inside the liquid metal spallation target.
- The average linear power density over the hottest pin is 272 W/cm with the peak power limited to 352 W/cm.

Concluding remarks

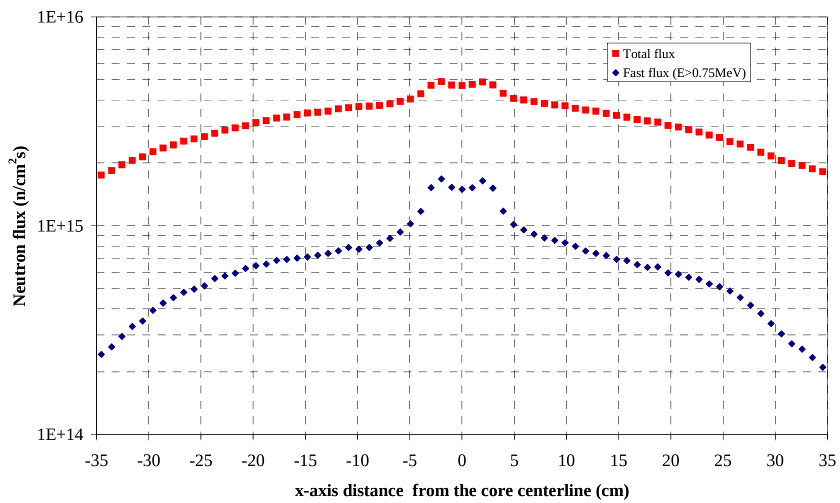
- The targeted order of magnitude in fast flux, viz. 10^{15} n/cm^{2}s, is achieved in the near of the hottest fuel pin.
- An accumulated dpa-damage dose up to 39 dpa over a 3x90 EFPDs irradiation period may be expected along the spallation target pipe with appm(He)-to-dpa ratios up to 8.
- MA transmutation has been investigated by considering six IMF-target assemblies, containing 7.24 kg of low graded plutonium, 9.04 kg of americium and 1.81 kg of curium, irradiated in fast spectrum channels during a 3-years campaign (810 EFPDs in total). The calculations yield a net decrease of 2.48 kg in the actinide mass, mainly due to the removal of americium (-2.46 kg). There is net mass increase of 0.46 kg for curium. The burned-out mass of plutonium is 0.51 kg

Effect of proton beam spatial shape





	Gaussian spatial beam profile	Real Beam Profile
k_S	0.9601	0.9597
M	25.04	24.82
n/p	6	6
P (MW)	51.75	50.9



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Proton beam option: 350 MeV-5 mA Vs. 600 MeV-2 mA

Neutronics Parameters	Units	MYRRHA 350 MeV Vs 600 MeV	
Proton beam energy	MeV	350	600
Accelerator current	mA	5	2
Proton beam energy	MW	1.75	1.20
Proton beam heating		1.43	0.74
Deposited fraction of beam energy	%	81.5	61.4
In-depth p-beam penetration (~Bragg peak)	mm	126	290
Free surface z-position	mm	+75	+150
Source neutron yield per incident proton	n/p	6.0	15.6
neutron source Intensity	10^{17} n/s	1.9	1.9
Initial fuel mixture	MOX	$(U\text{-}Pu)O_2$	$(U\text{-}Pu)O_2$
Initial (HM) fuel mass (m_{fuel})	Kg	514	514
Initial Pu-enrichment (Pu/HM)	wt%	30	30
K_{eff}		0.95521	0.95522
K_s		0.96007	0.95847
$MF = 1 / (1 - K_s)$		25.04	24.08
Source importance: φ^*		1.127	1.082
Thermal Power (†) (P_{th})	MW	51.75	51.27
Specific power	kW/kgHM	101	100
Peak linear Power (hottest pin)	W/cm	352	324
Av. Linear Power (hottest pin)		272	268
Φ_{total} (at the hottest pin position)	10^{15} n/cm^{2}s	4.04	3.86
$\Phi_{>1\ MeV}$ (at the hottest pin position)		0.74	0.64
$\Phi_{>0.75\ MeV}$ (at the hottest pin position)		0.98	0.85

(†) E_f = 210 MeV/fission

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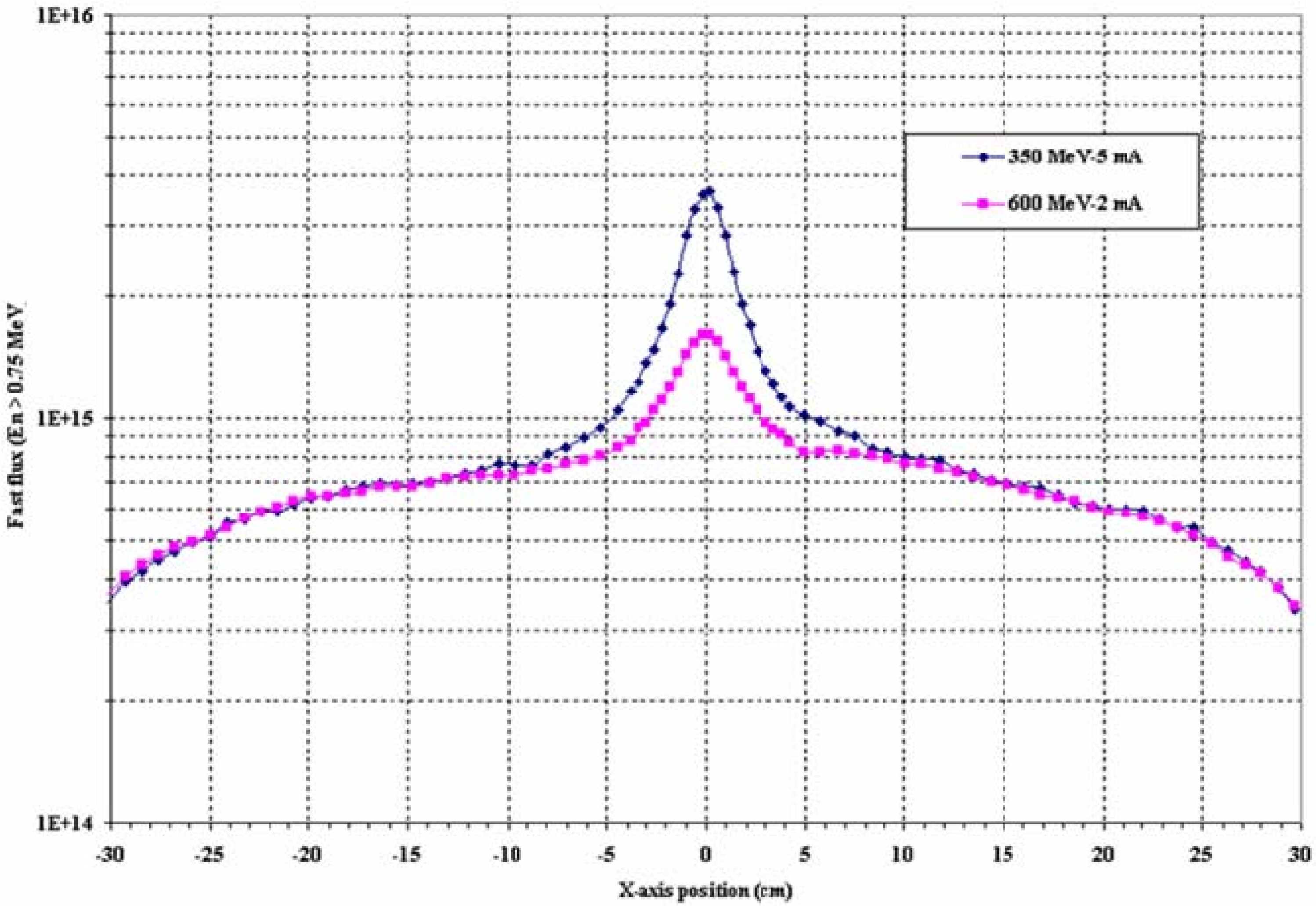
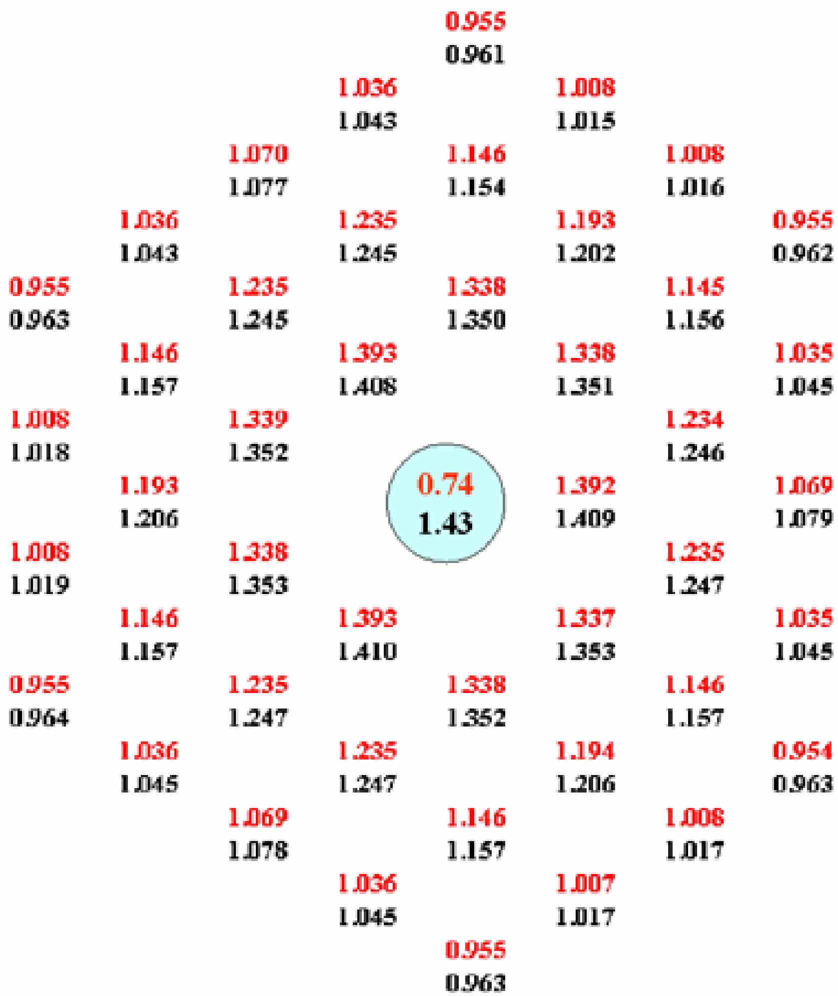
350 MeV-5 mA Vs. 600 MeV-2 mA: Fast flux

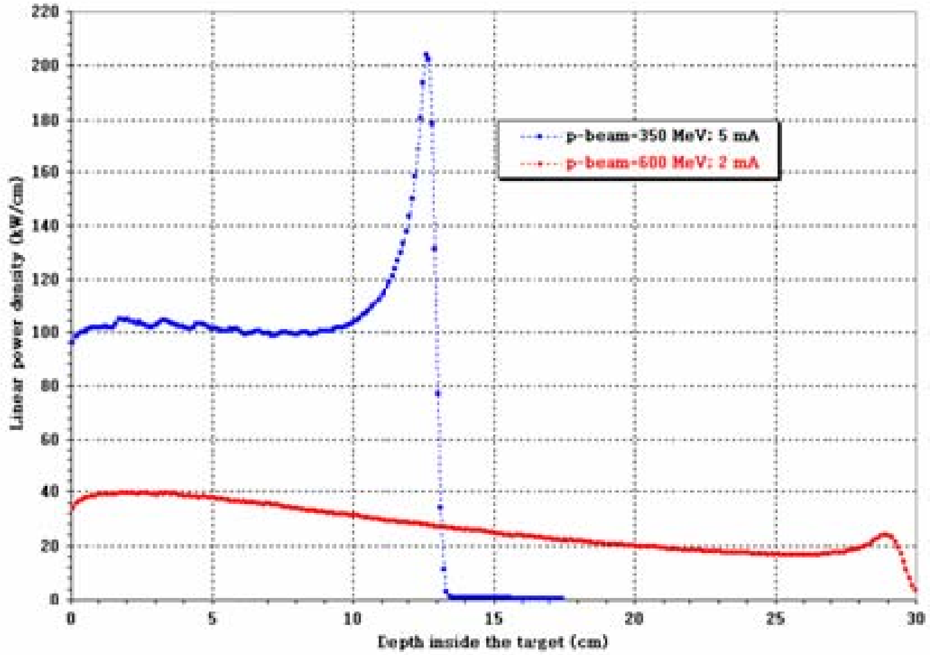
MYRRHA



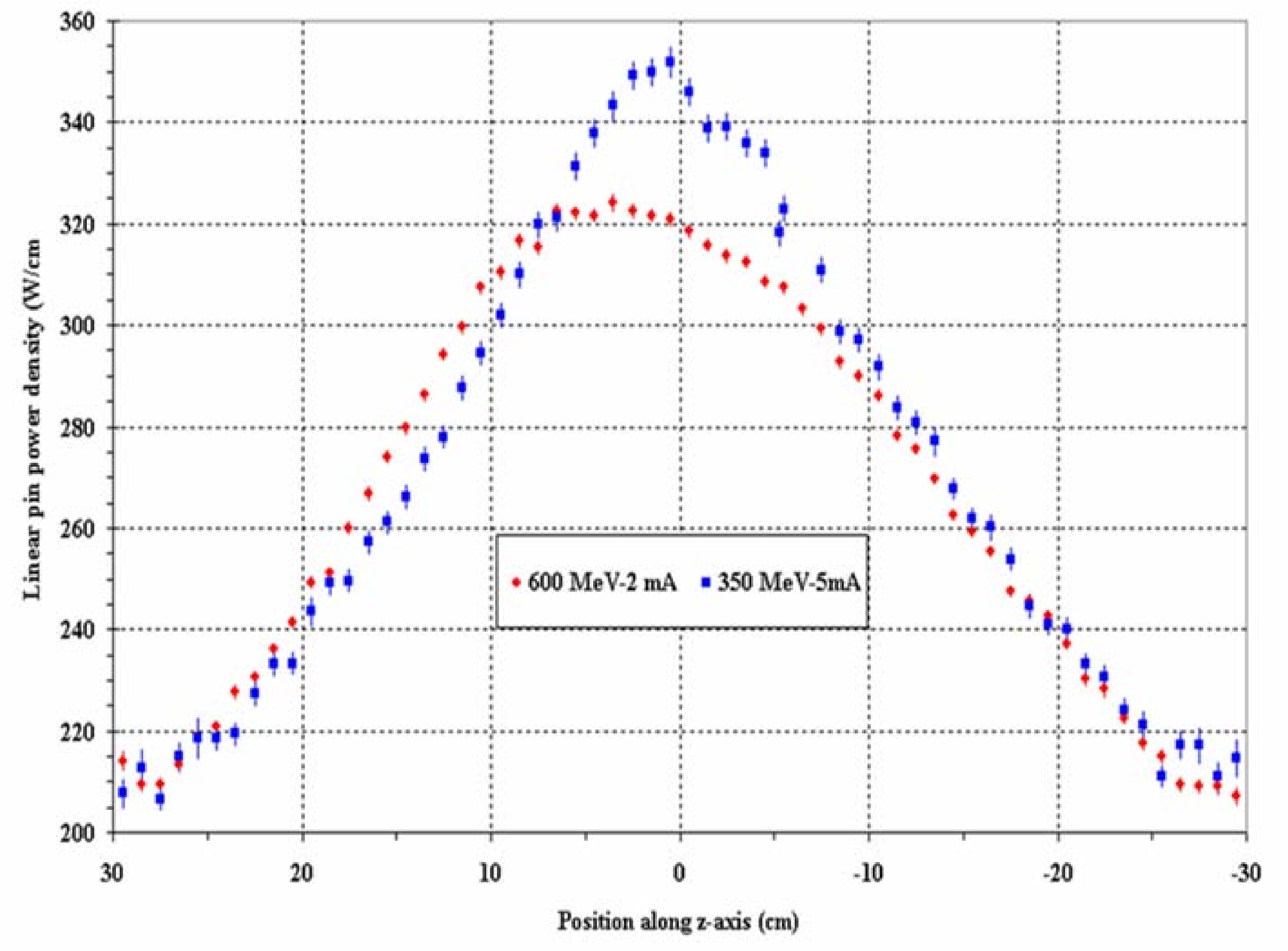
350 MeV-5 mA Vs. 600 MeV-2 mA: Fast flux



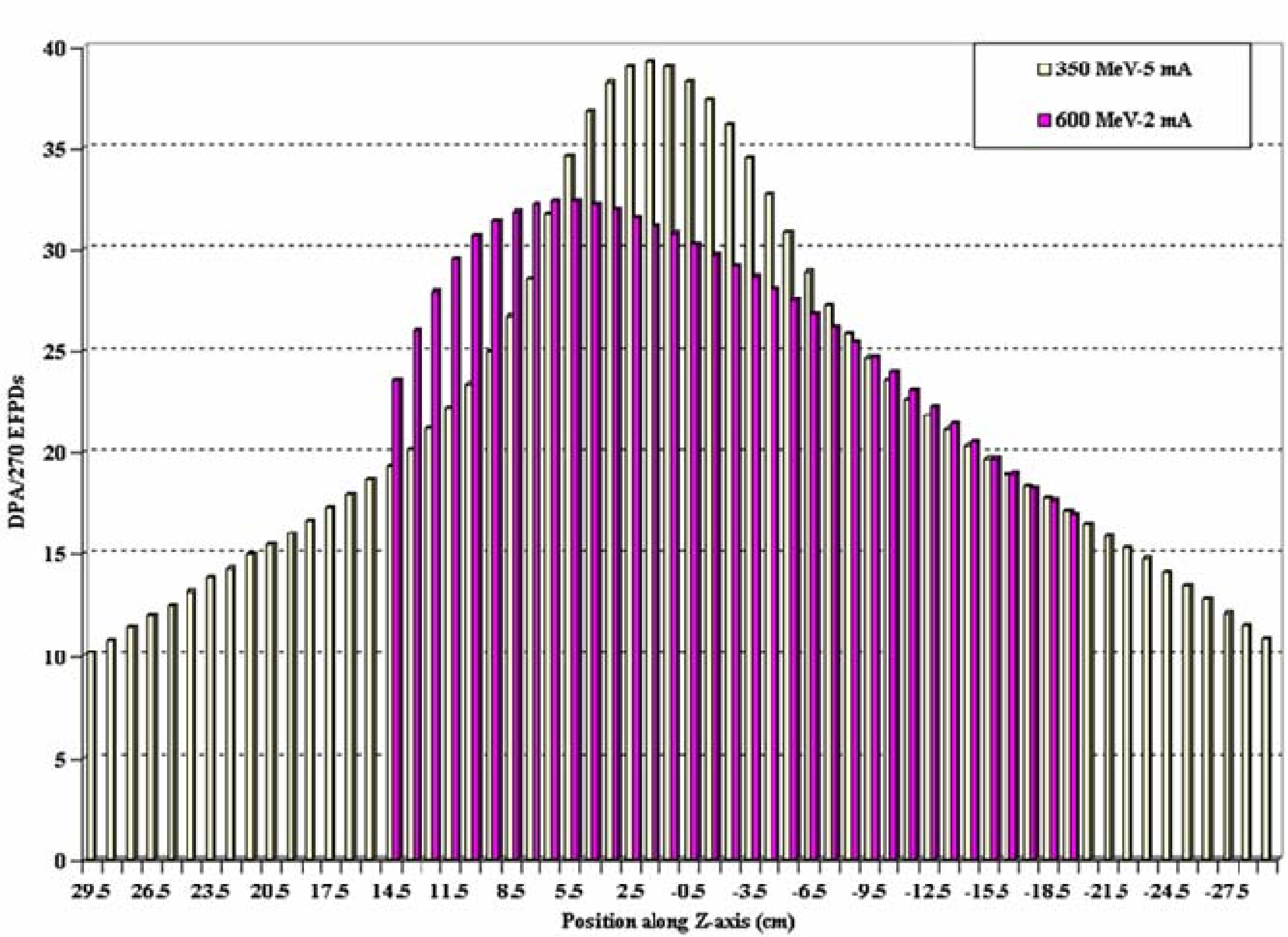
Ep= 600 MeV; Ip=2 mA; P=51.27 MW
Ep= 350 MeV; Ip=5mA; P=51.75 MW



350 MeV-5 mA Vs. 600 MeV-2 mA: Linear power density along the hottest pin



350 MeV-5 mA Vs. 600 MeV-2 mA: DPA/270EFPDs along the target duct



350 MeV-5 mA Vs. 600 MeV-2 mA: DPA/270EFPDs along the hottest pin clad

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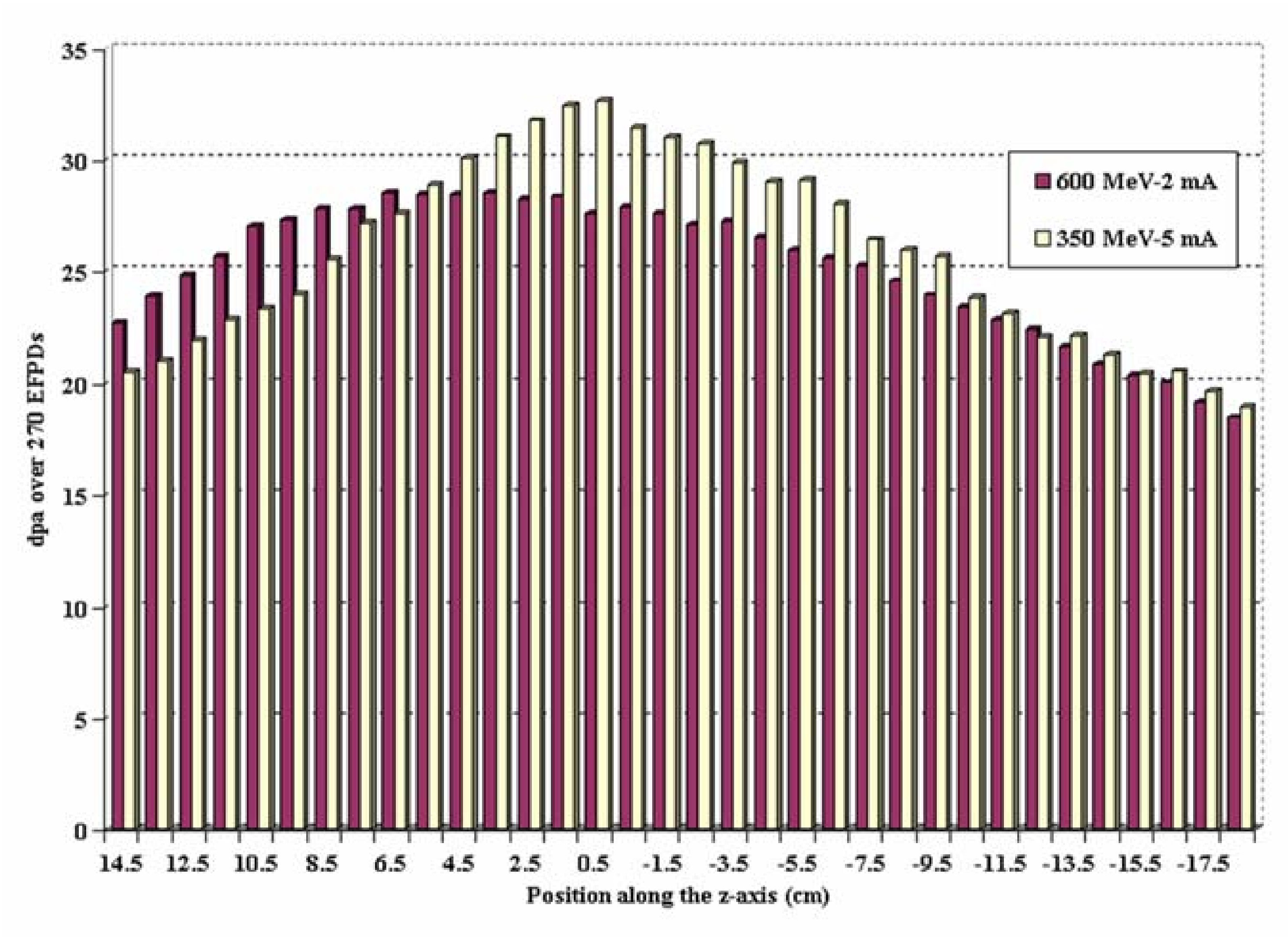
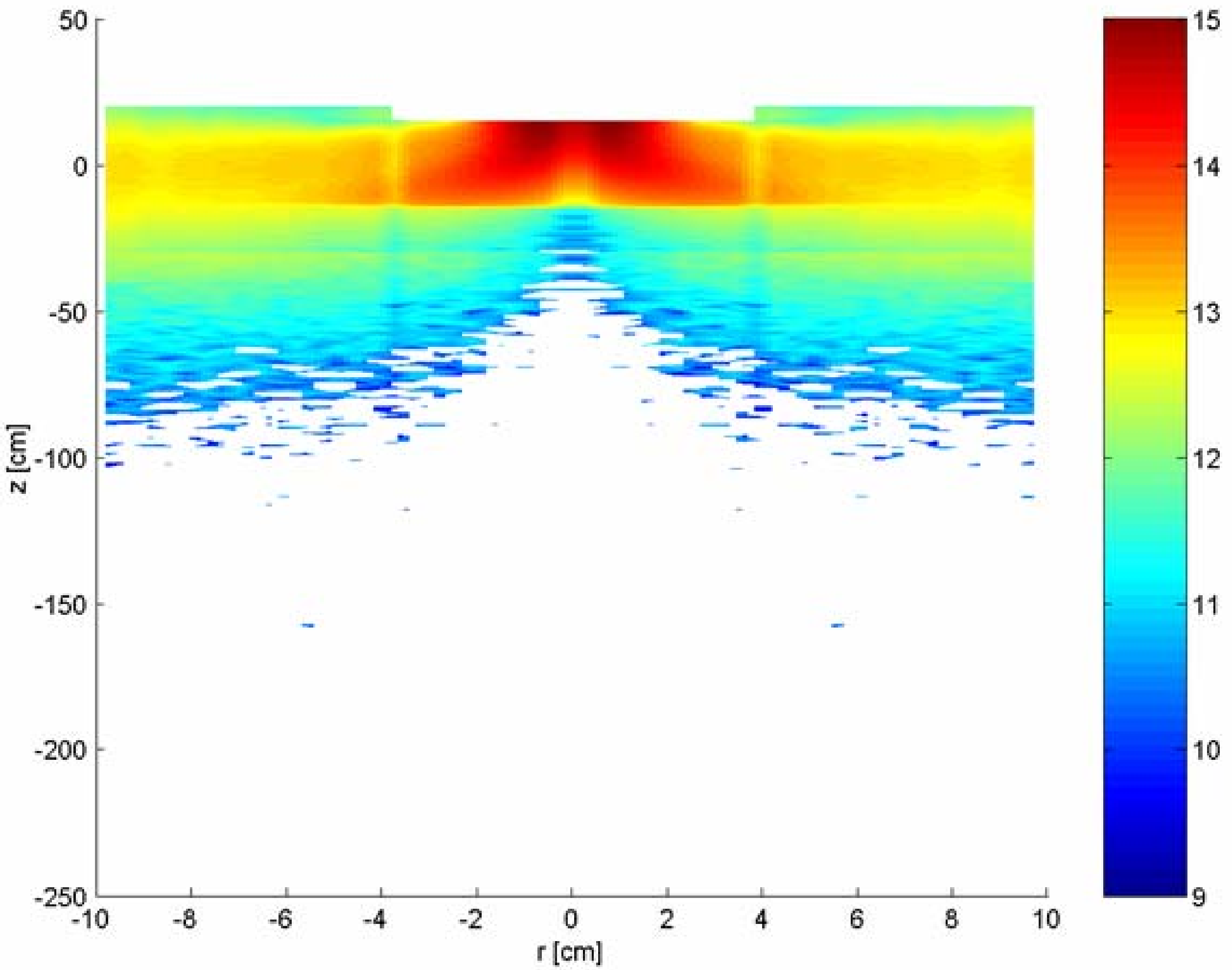
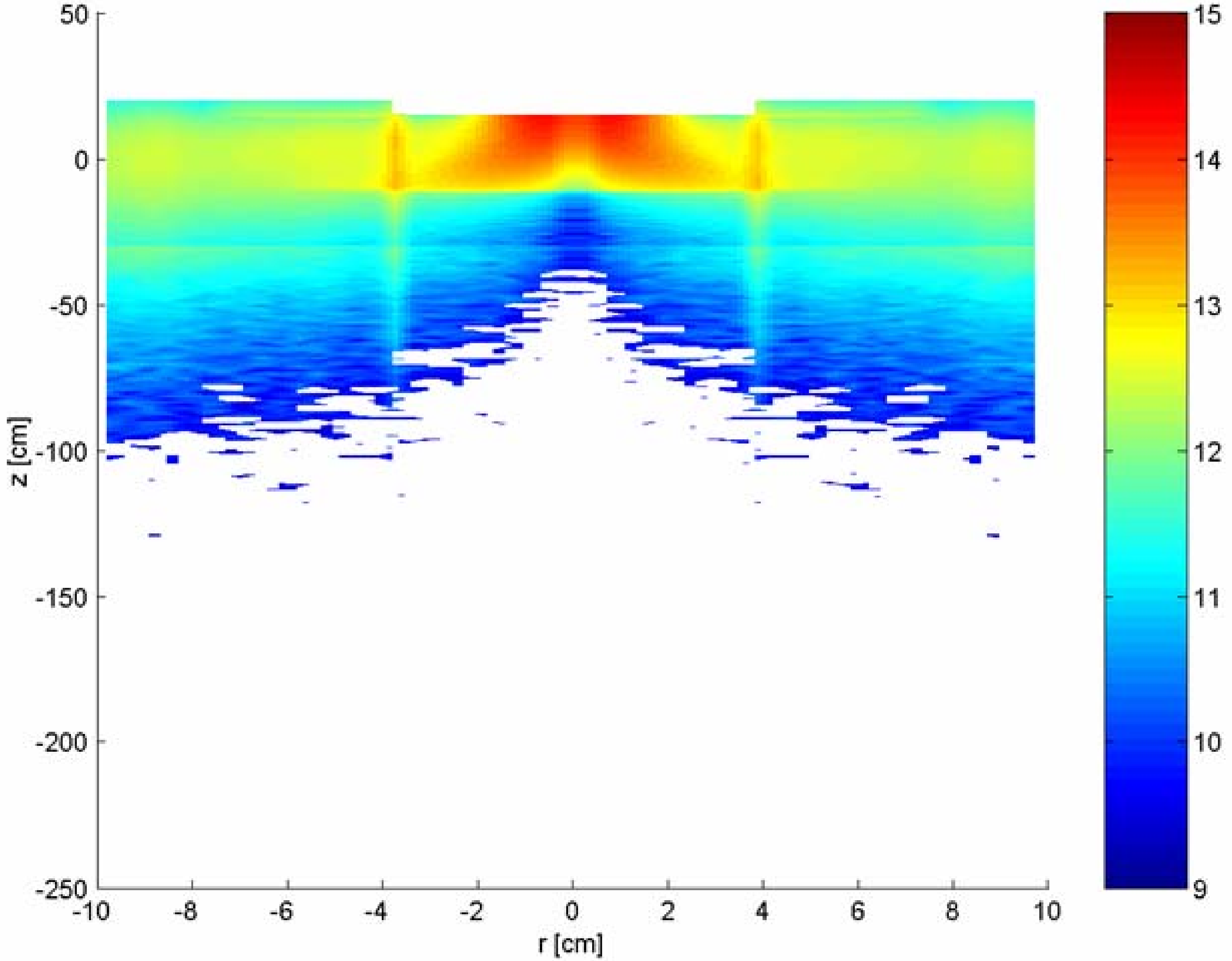
MYRRHA



Non-fission (external) neutron source distribution



Proton particle distribution



Concluding remarks

- A 600 MeV-2 mA driving proton beam is shown to yield similar core characteristics as a 350 MeV-5mA proton beam
- In the case of 600 MeV the flux and hottest fuel pin power are less peaked and the peak dpa-damage is also lower.
- Moreover the target heating rate inside the liquid-metal spallation target is lower by a factor of two.
- Calculations show that neither neutrons nor protons will reach the bottom of the tank. No specific shielding is therefore required.