Passive cooling of s.c. magnetic systems for the protection from ionizing radiation of habitats in space.

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Motivation

Long duration manned mission

↓

Large volume habitats for astronauts

↓

Substantial mitigation of GCR flux inside the habitats

↓ (Passive systems inadequate)

Huge s.c. magnetic systems needed

↓

Main problem: **how to maintain them cool**

LT s.c. (NbTi, NbSn):
active cooling needed

What about
MgB_2 and HT s.c. ??

In first approximation the equilibrium temperature of the system can be obtained by matching the absorbed heat with the heat released to space; considering only the Sun(*):

$$S*\alpha* A_a = \sigma*\varepsilon* A_e*(T_{eq}^4-4^4)$$

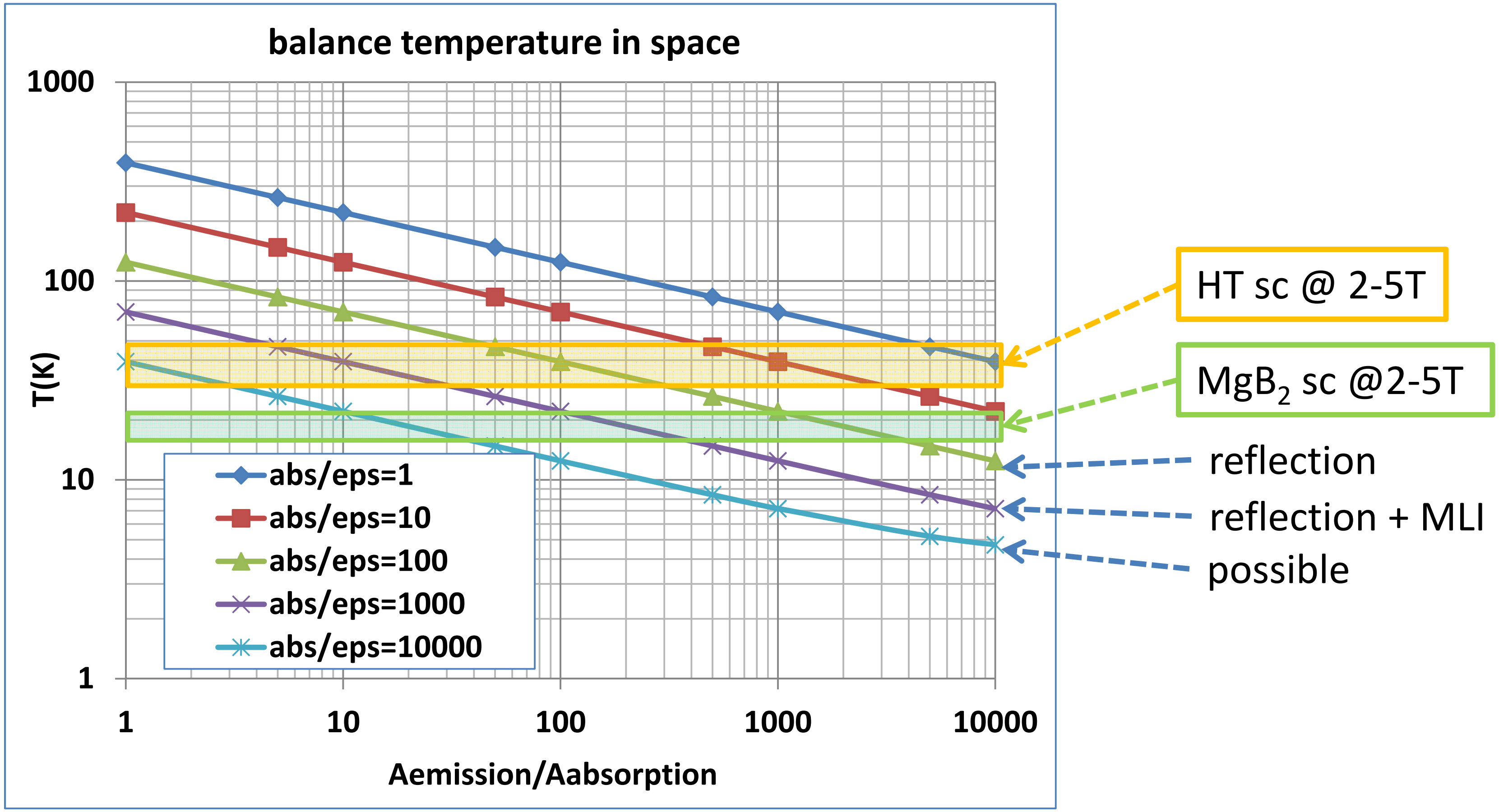
$$[\approx \sigma*\varepsilon* A_e*T_{eq}^4 \quad (\text{forT>10K})]$$

$$T_{eq}^4 = (S/\sigma)*(\alpha/\varepsilon)*(A_a /A_e) = (S/\sigma)*R_{\alpha\varepsilon}*R_A$$

@ 1AU : $(S/\sigma) = 0.135\ W/cm^2/5.67*10^{-12}\ W/cm^2K^4 = 0.02381*10^{12}$

$$T_{eq} = 393K * {}^4\sqrt{R_{\alpha\varepsilon}} * {}^4\sqrt{R_A}$$

(*) Hadley Cocks,DHTSC (Deployable High Temperature Superconducting Coil), Journal of The British Interplanetary Science, 44 (1991) 99-102


balance temperature in space
1000
100
10
1
T(K)
1
10
100
1000
10000
Aemission/Aabsorption
abs/eps=1
abs/eps=10
abs/eps=100
abs/eps=1000
abs/eps=10000
HT sc @ 2-5T
MgB$_2$ sc @2-5T
reflection
reflection + MLI
possible

$R_{\alpha\varepsilon}=0.01$ (just reflection) $\sqrt[4]{R_{\alpha\varepsilon}} = 0.316$

$T_{eq} = 124.2K * \sqrt[4]{R_A}$

$R_{\alpha\varepsilon}=0.001$ (easy, reflection + MLI) $\sqrt[4]{R_{\alpha\varepsilon}} = 0.178$

$T_{eq} = 69.9K * \sqrt[4]{R_A}$

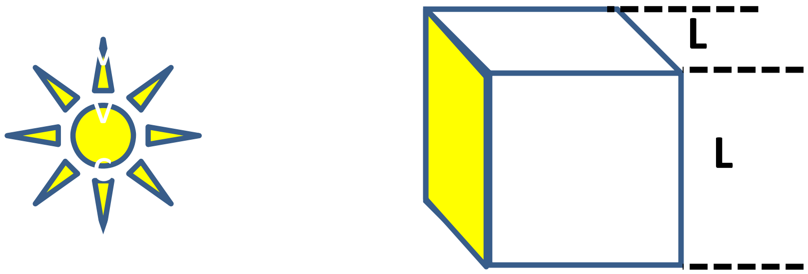
$R_{\alpha\varepsilon}=0.0001$ (possible) $\sqrt[4]{R_{\alpha\varepsilon}} = 0.100$

$T_{eq} = 39.3K * \sqrt[4]{R_A}$

$T_{eq} = 39.3K * \sqrt[4]{R_A}$

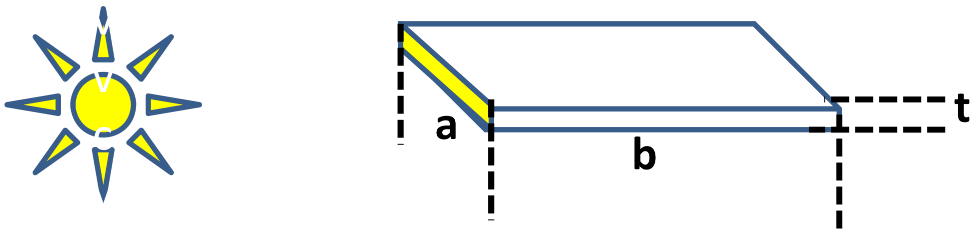
$R_A = 2\pi R^2/4\pi R^2 = 0.5$

$\sqrt[4]{R_A} = 0.841$



$R_A = L^2/6L^2 = 0.133$

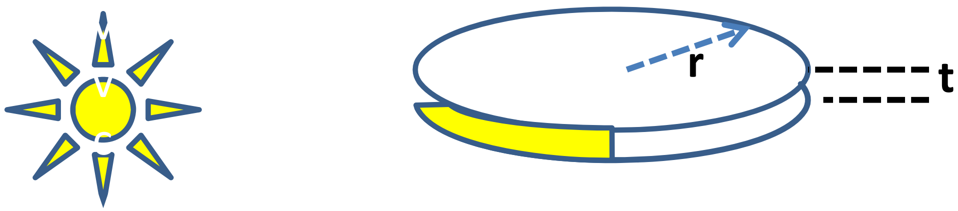
$\sqrt[4]{R_A} = 0.604$



$R_A = at/(2ab+2a+2b)$

for $t=0.1a$, $a=b \rightarrow R_A = 1/24$

$\sqrt[4]{R_A} = 0.452$



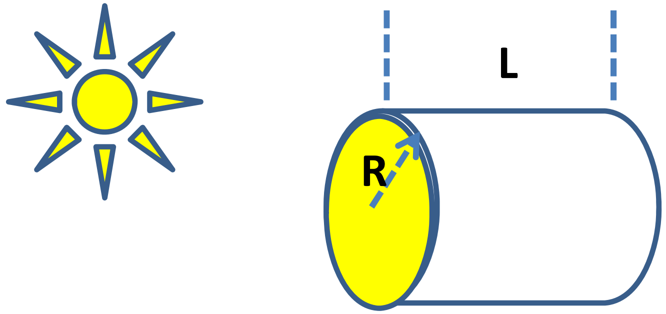
$R_A = rt/(2\pi r2+2\pi rt)$

for $t=0.1r \rightarrow R_A = 1/34.5$

$\sqrt[4]{R_A} = 0.412$

$T_{eq} = 39.3K * \sqrt[4]{R_A}$

Wire



$R_A = 1/(2+2L/R)$

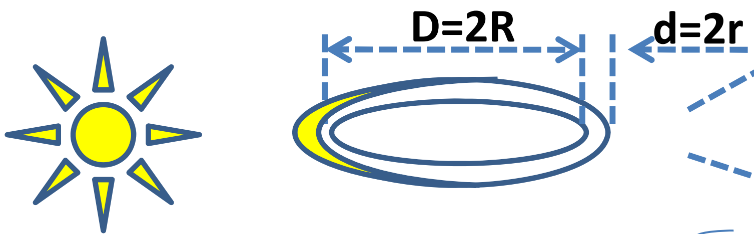
for L=2R → $R_A = 1/6$ $\sqrt[4]{R_A} = 0.639$

for L=20•R → $R_A = 1/42$ $\sqrt[4]{R_A} = 0.393$

for L=100•R → $R_A = 1/202$ $\sqrt[4]{R_A} = 0.265$

for L=1000•R → $R_A = 1/2002$ $\sqrt[4]{R_A} = 0.150$

Coil



no membrane

$R_A = (2R \bullet 2r)/(2\pi R \bullet 2\pi r) = 1/\pi = 0.318$

$\sqrt[4]{R_A} = 0.751$

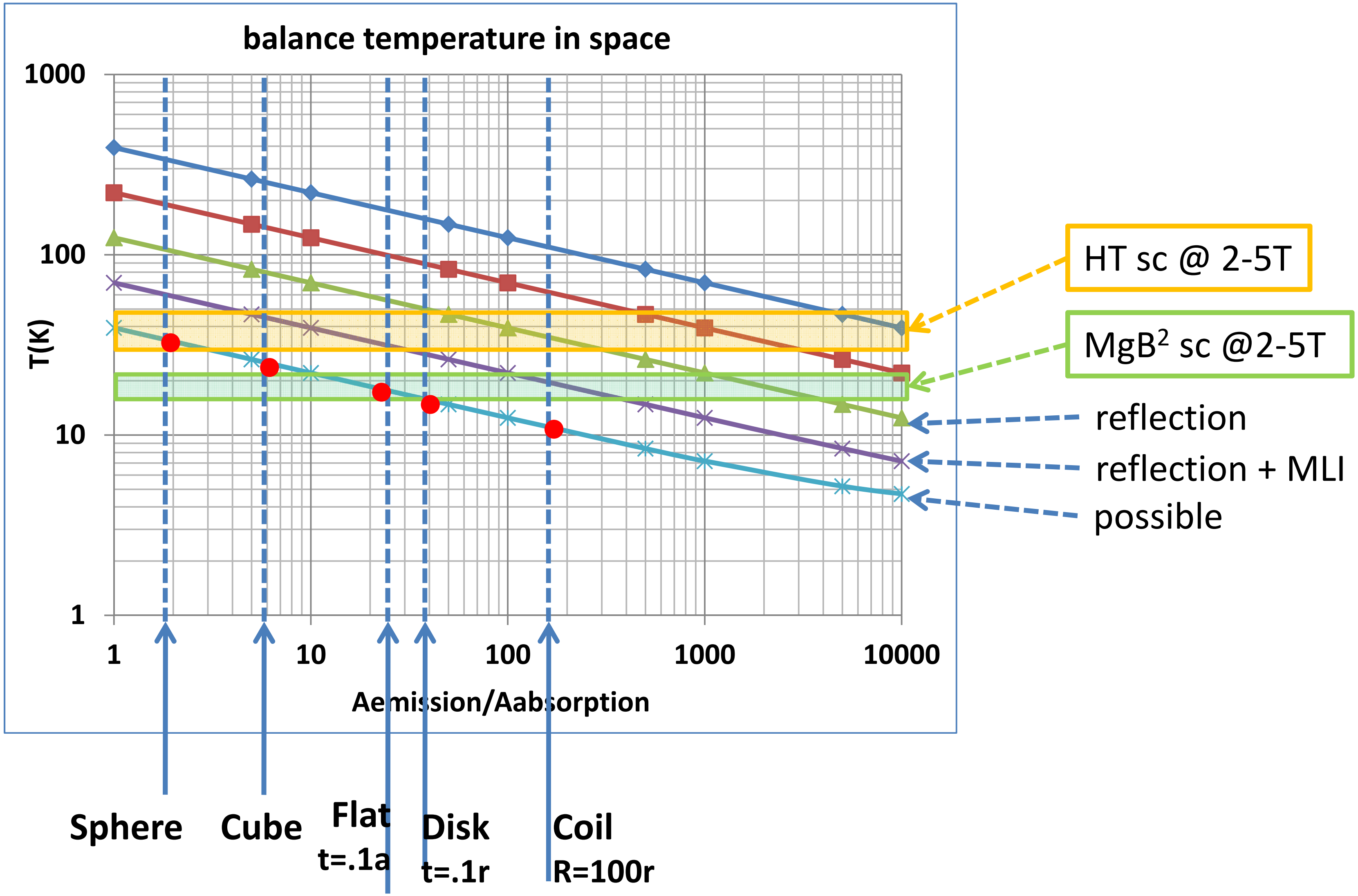
with membrane

$R_A = (2R \bullet 2r)/(2\pi R \bullet 2\pi r + 2\pi R^2)$

for R=100•r → $R_A = 0.00631$ $\sqrt[4]{R_A} = 0.282$

for R=1000•r → $R_A = 0.000636$ $\sqrt[4]{R_A} = 0.159$

for R=100•r → $R_A = 0.0000637$ $\sqrt[4]{R_A} = 0.089$



balance temperature in space
1000
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T(K)
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1000
10000
Aemission/Aabsorption
HT sc @ 2-5T
MgB2 sc @2-5T
reflection
reflection + MLI
possible
Sphere
Cube
Flat
t=.1a
Disk
t=.1r
Coil
R=100r

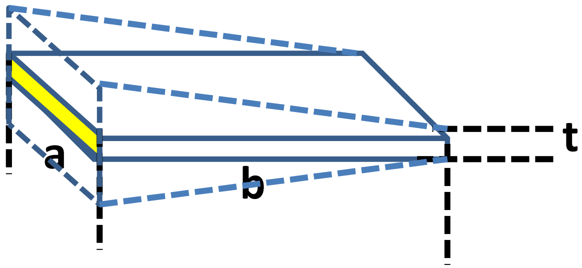
Geometry	$R_A = A_{in}/A_{out}$		$R_{\alpha\varepsilon} = 10^{-4}$
			T_{eq}(K)
Sphere	0.5		33.1
Cube	0.133		23.7
Flat table	0.0417		17.8
Disk	0.0290		16.2
Wire: L/R = 20	0.0239		15.4
L/R = 100	0.00495		10.4*
Coil: R/r = 100	0.00631		11.2*
R/r = 1000	0.000636		7.0*
R/r = 10000	0.0000637		4.3*

Not possible due to finite angular dimension of Sun

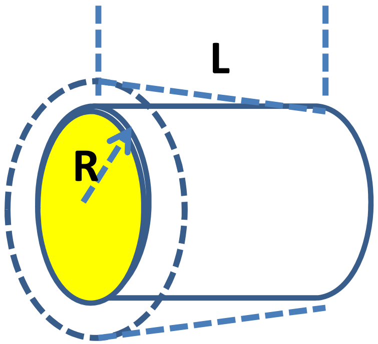
* Corrected for the CMB

But the source is not a point:

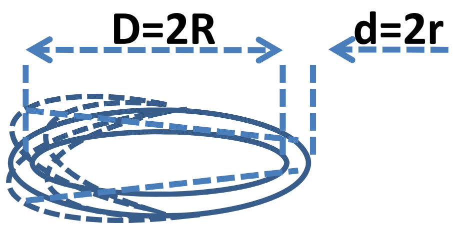
SUN: α = 9.3mrad @ 1AU



$b \leq 100t$



$L \leq 100R$

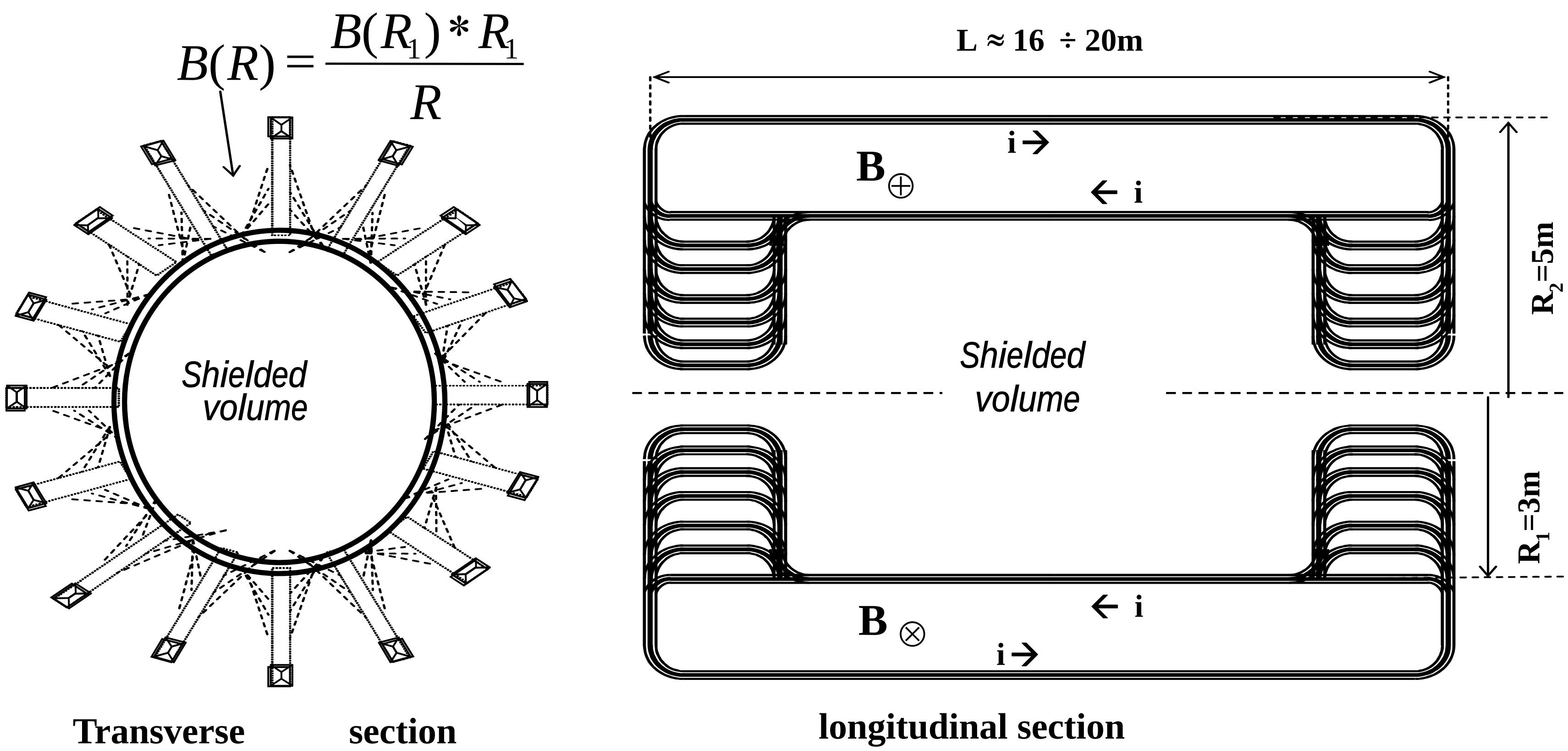


$R \leq 100r$

Let’s apply to the design of ‘habitats’ for deep space

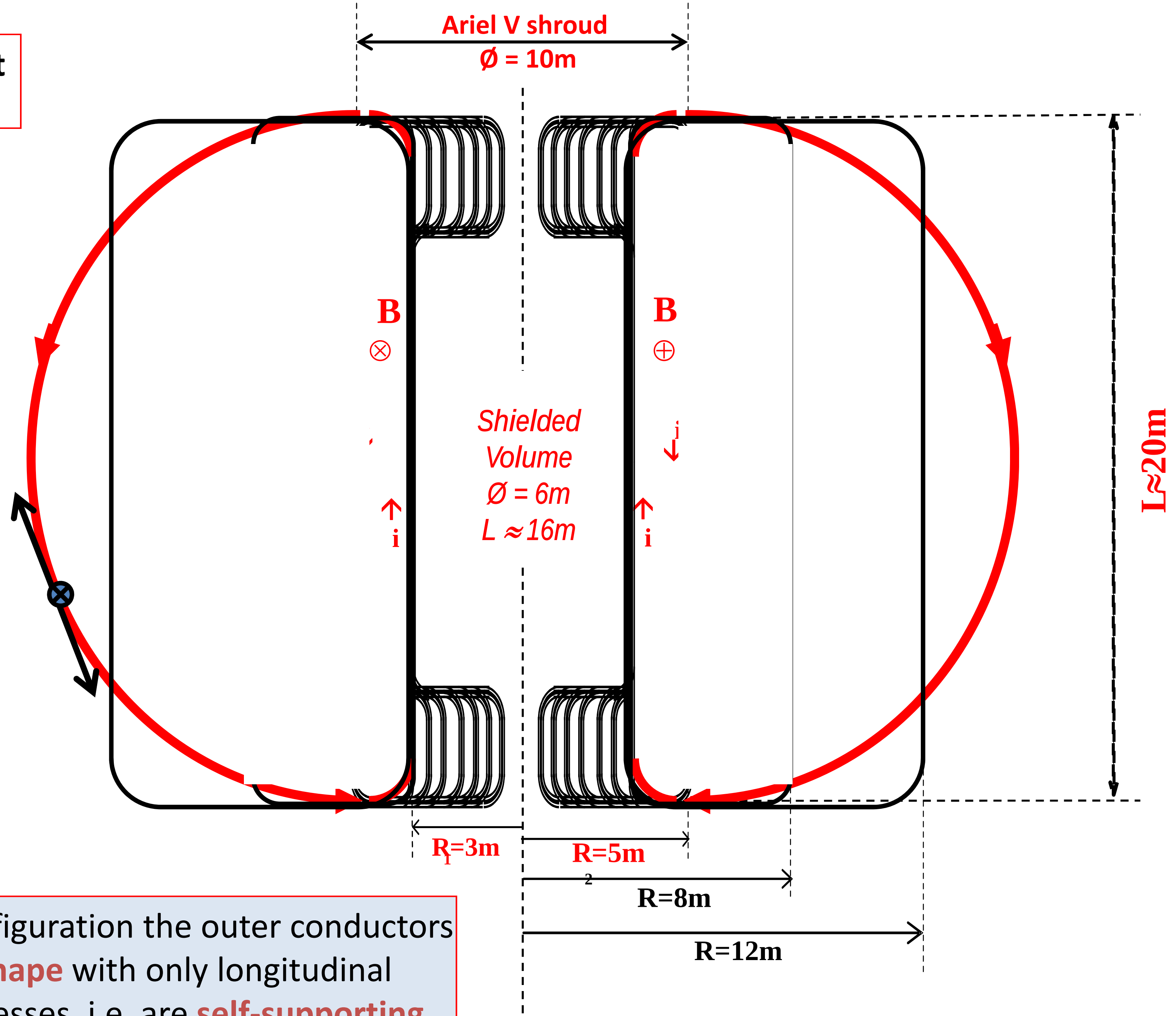
Case (a) – Magnetic system for reducing by 4-5 times the GCR flux
inside a **500m^3 habitat**

Case (b) – Magnetic system for reducing by 4-5 times the GCR flux
inside a **1000m^3 habitat**

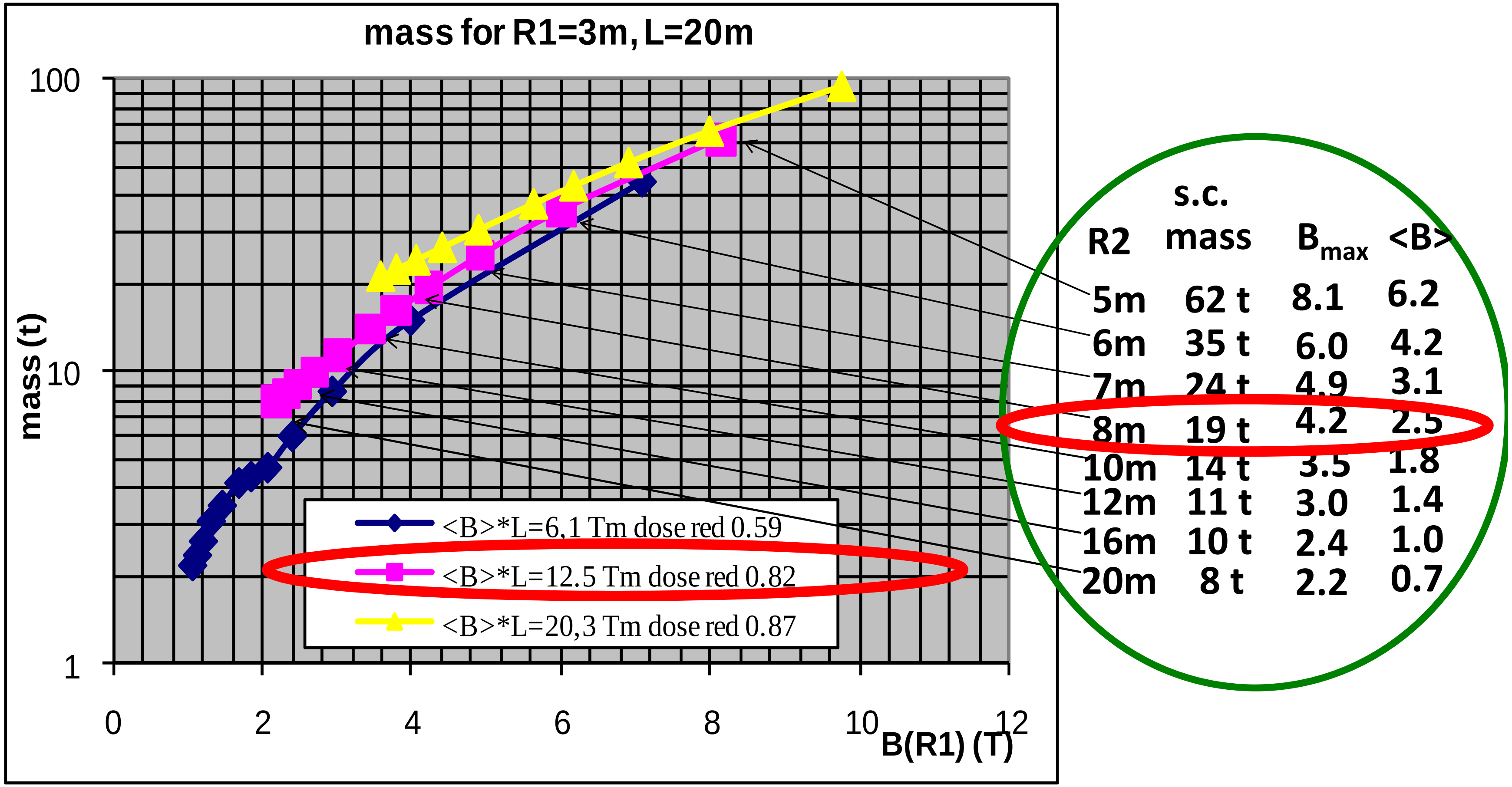


Configuration assumed to evaluate the protection of a ***6m diameter cylindrical habitat****.*

deployement concept

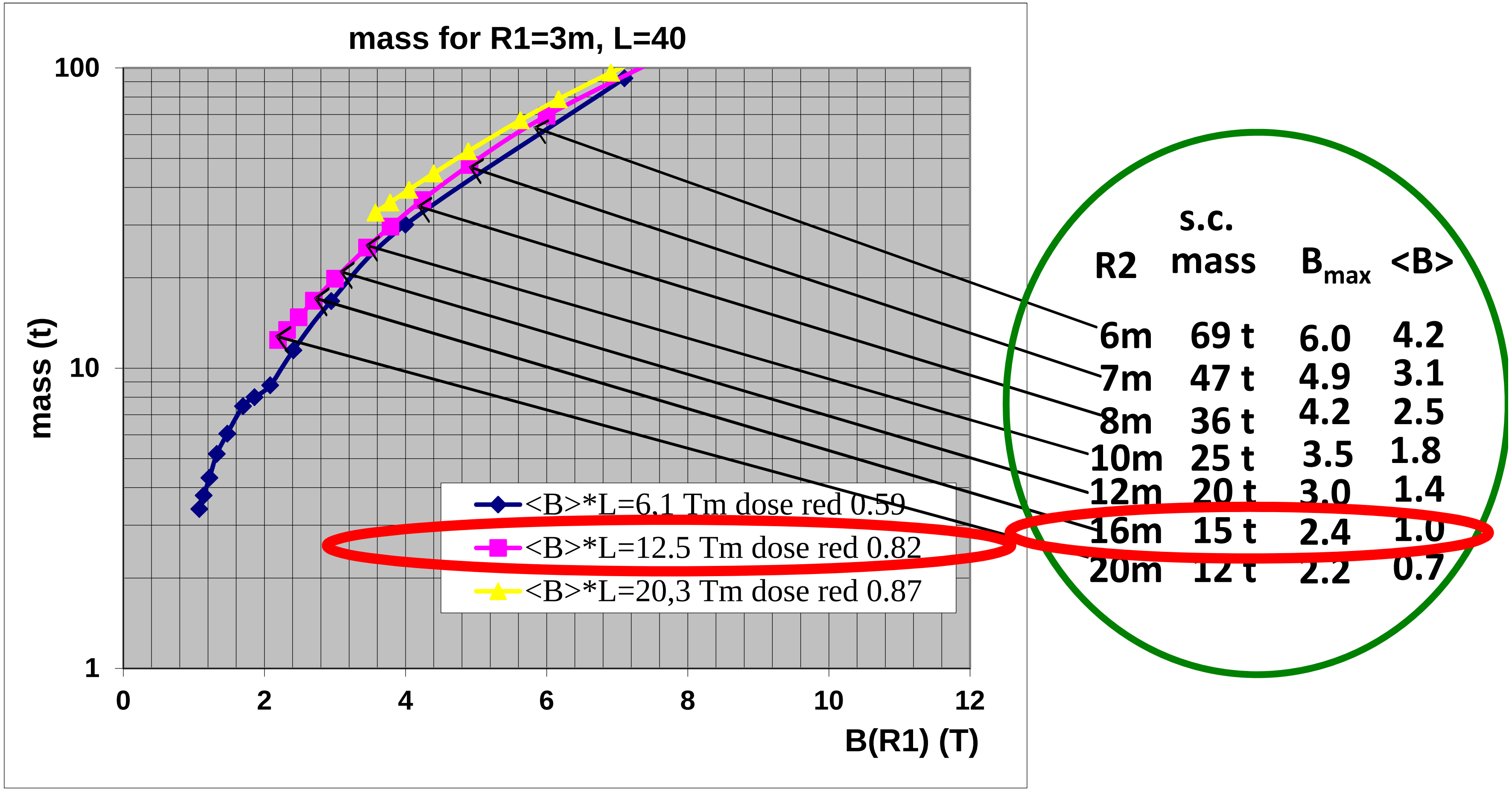


In toroidal configuration the outer conductors assume a **'D' shape** with only longitudinal mechanical stresses, i.e. are **self-supporting**.



Current density in MgB_2 cable 1kA/mm^2@ B(R_1)=2T, 1kA/mm2 x2/B(R_1) @ B(R_1)>2T

s.c. mass of the system realized by MgB_2 sc cable, for the values 6.1, 12.5, 20.3 Tm of the bending power <B>(R_2-R_1) (corresponding to 0.59, 0.82, 0.87 reduction of the GCR dose) and several values of the outer diameter as a function of the maximum magnetic field intensity.*



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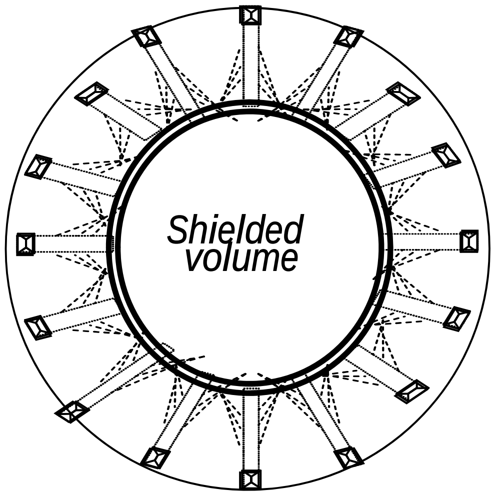
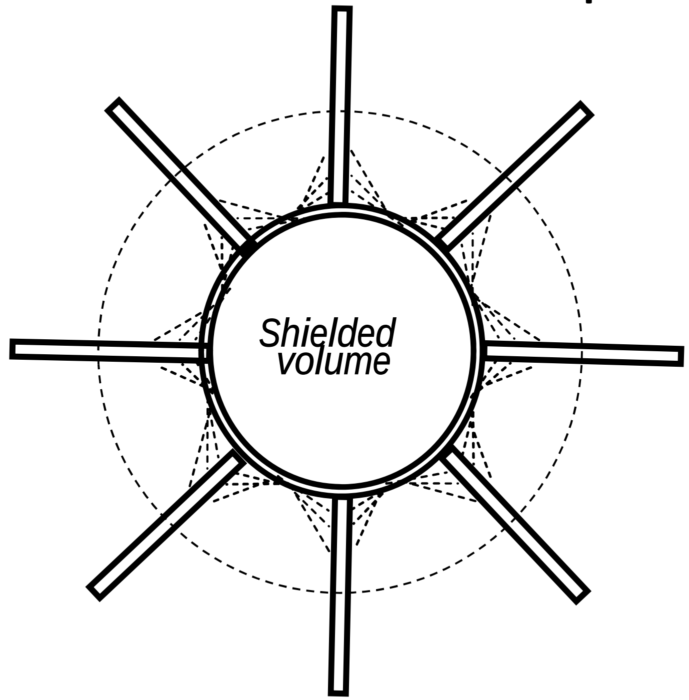
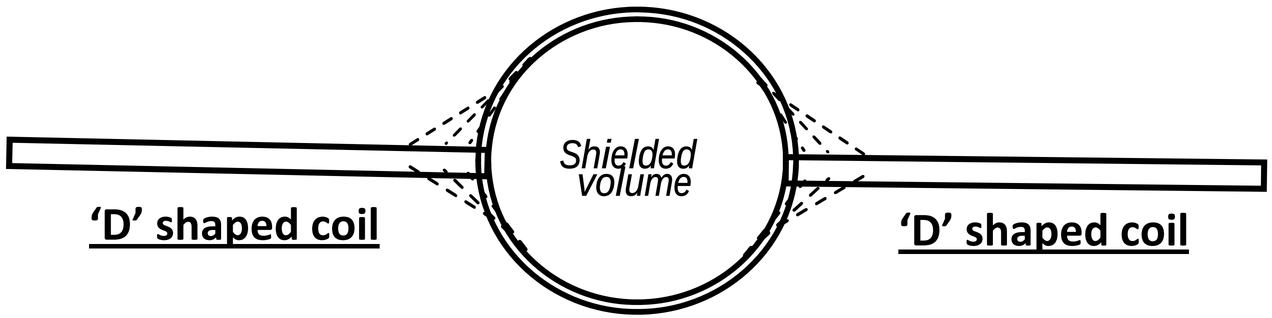
small R2
→ outer conductor ≈ continuous

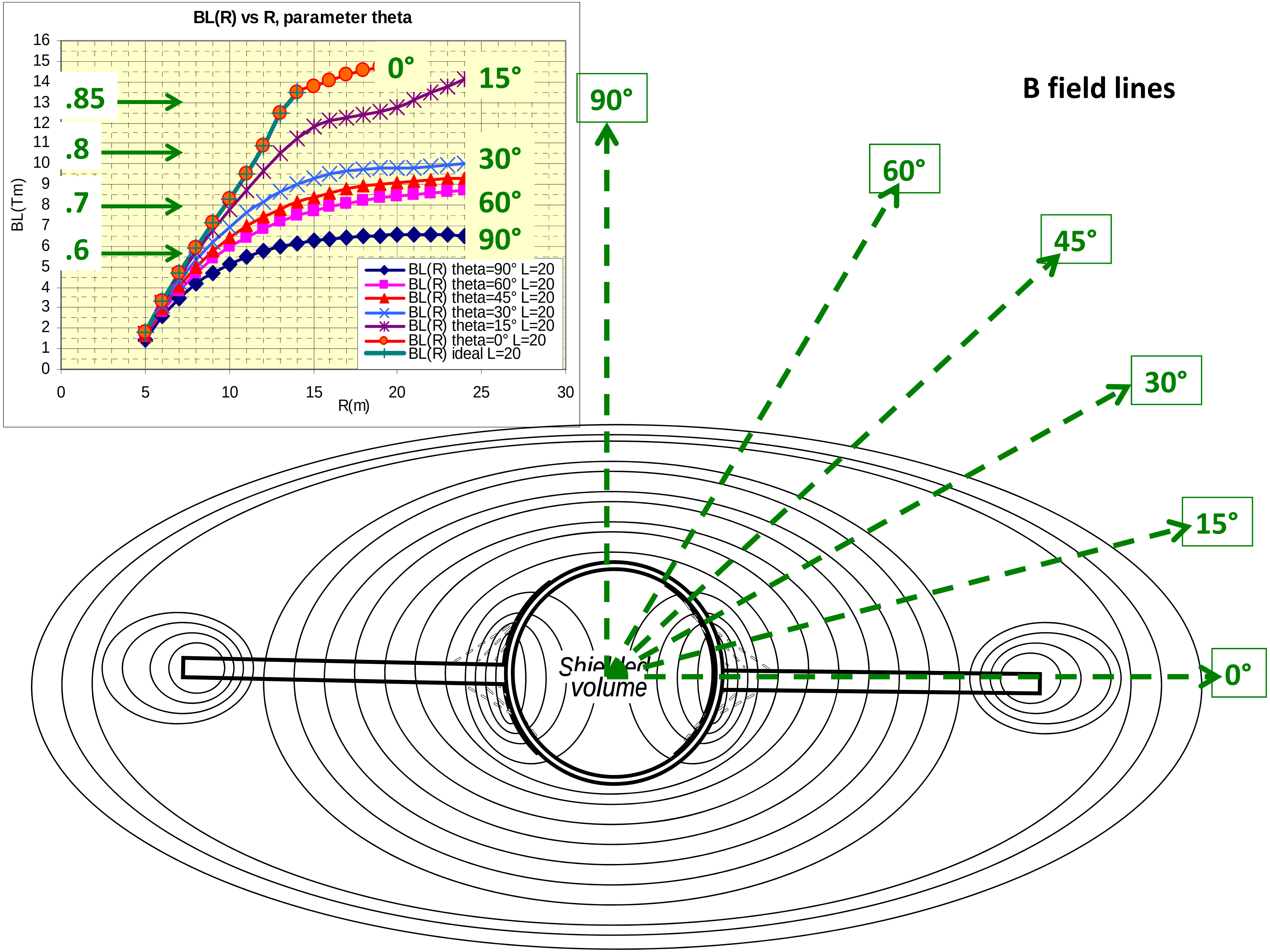


large R2
→ outer conductor can be lumped



For very large R2
→outer conductors
can be very few

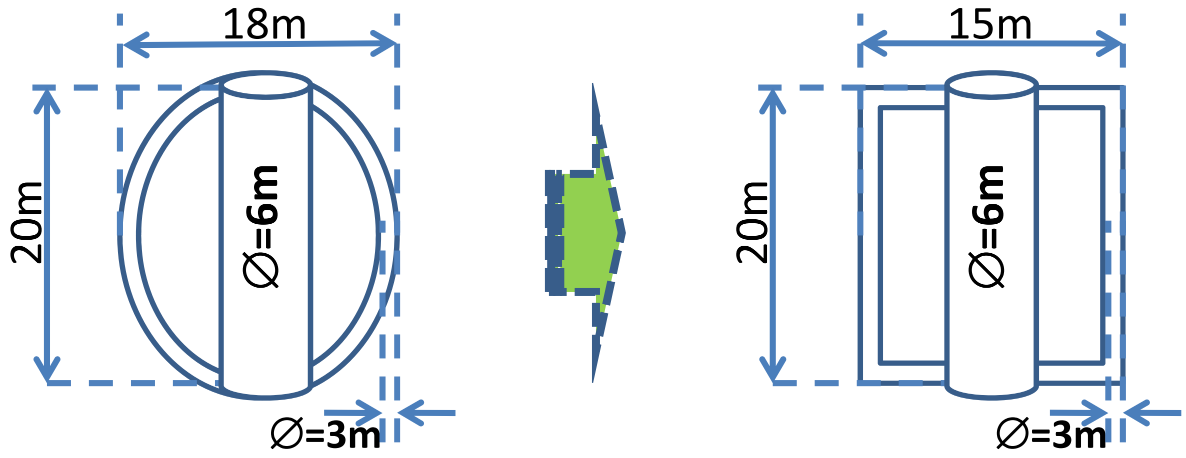




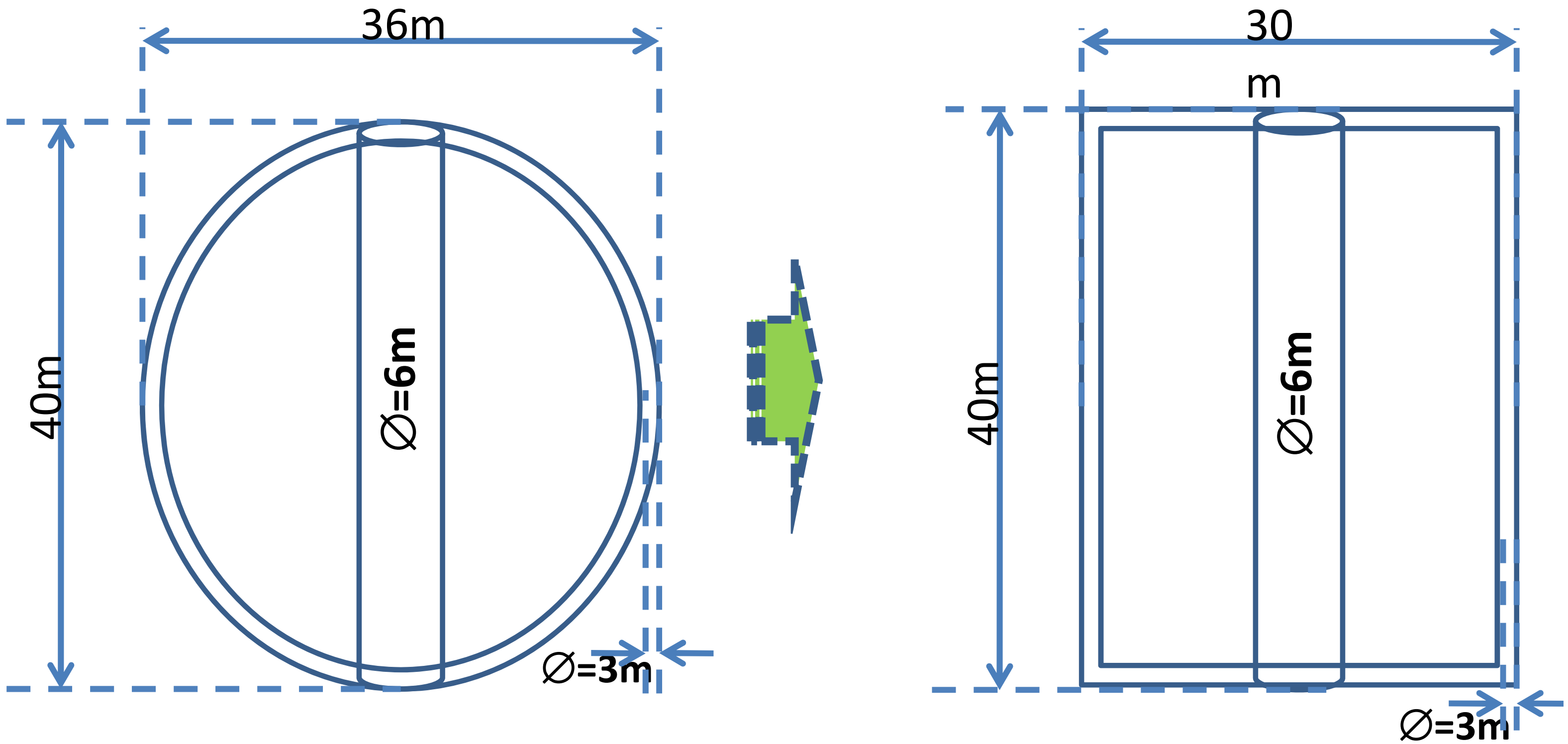
BL(R) vs R, parameter theta
BL(Tm)
R(m)
.85
.8
.7
.6
0°
15°
30°
60°
90°
BL(R) theta=90° L=20
BL(R) theta=60° L=20
BL(R) theta=45° L=20
BL(R) theta=30° L=20
BL(R) theta=15° L=20
BL(R) theta=0° L=20
BL(R) ideal L=20
B field lines
90°
60°
45°
30°
15°
0°
Shielded volume

Let's apply to the design of 'habitats' for deep space

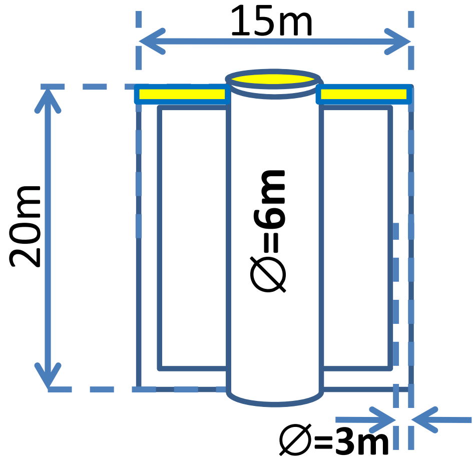
Habitat 500 (500 m³)



Habitat 1000 (1000 m³)



Habitat 500
(500 m³)

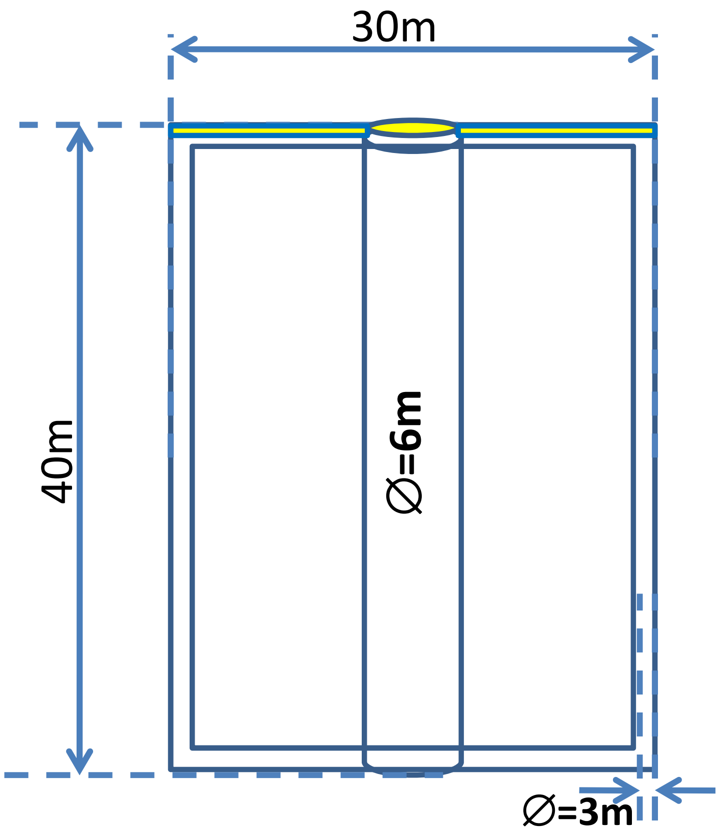


Mass(MgB_2)=20t

$R_A = 55m^2/947m^2 = 0.0581$

$T_{eq} = 39.3 \bullet \sqrt[4]{0.0581} =$ **19.3K**

Habitat 1000
(1000 m³)

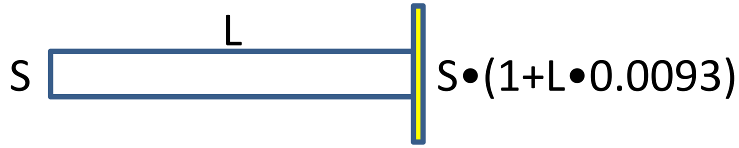


Mass(MgB_2)=16t

$R_A = 100m^2/3094m^2 = 0.0323$

$T_{eq} = 39.3 \bullet \sqrt[4]{0.0323} =$ **16.7K**

Angular dimensions of the Sun @ 1AU = 0.0093 rad



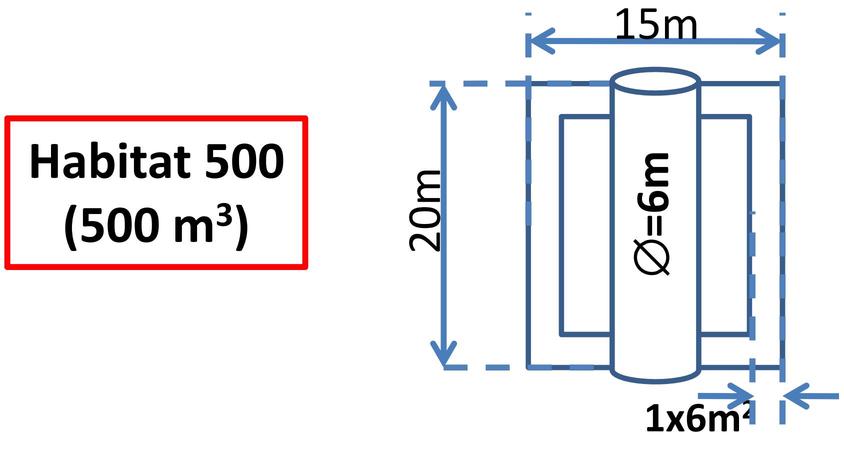
Habitat 500 (500 m³)

$T_{eq}=39.3\bullet\sqrt[4]{0.0612}=\mathbf{19.6\ K}$ [19.3+0.3]

Habitat 1000 (1000 m³)

$T_{eq}=39.3\bullet\sqrt[4]{0.0362}=\mathbf{17.1\ K}$ [16.7+0.4]

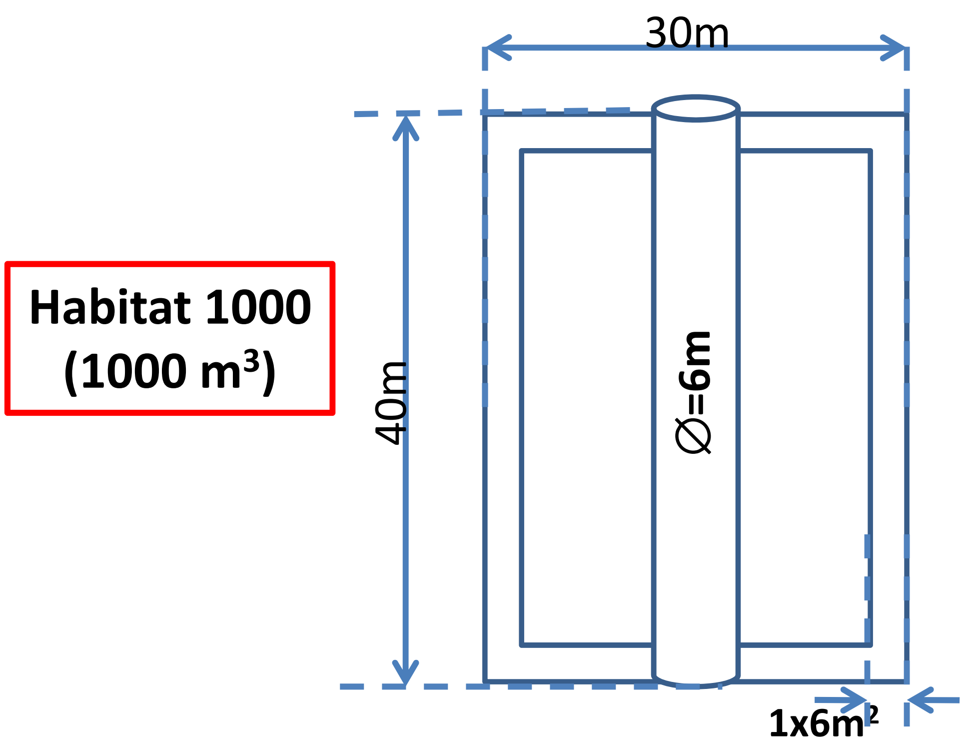
Modifying return current cross section from ∅**=3m** to **1x6m²** (MgB_2 masses do not change):



R_A=37m²/850m²=0.0435

T_{eq}=39.3•⁴√0.0435=**18.0 K**

(19.3)



R_A=52m²/2480m²=0.0210

T_{eq}=39.3•⁴√0.0210=**15.0 K**

(16.7)

‘minimum’ heat produced by **1 astronaut**:
about 2500 Kcal/day = 10450 J/day = 12.35 W

Effect on the T_{eq}:

Habitat 500 (500 m³)

For $A_{\alpha\varepsilon}=10^{-4}$, input from Sun: 58•1350W•10^{-4}=7.43W

T_{eq}’= T_{eq}•$^4\sqrt{19.8/7.43}$ = 19.6•1.28= **25.0 K** (1 astronaut)

T_{eq}’= T_{eq}•$^4\sqrt{107.4/7.43}$ = 19.6•1,95 = **38.2 K** (100 W)

T_{eq}’= T_{eq}•$^4\sqrt{130.9/7.43}$ = 19.6•2.05 = **40.2 K** (10 astronauts)

Habitat 1000 (1000 m³)

For $A_{\alpha\varepsilon}=10^{-4}$, input from Sun: 112x1350Wx10^{-4}=15.1W

T_{eq}’= T_{eq}•$^4\sqrt{27.5/15.1}$ = 17.1•1.16 = **19.8 K** (1 astronaut)

T_{eq}’= T_{eq}•$^4\sqrt{115.1/15.1}$ = 17.1•1.66 = **28.4 K** (100 W)

T_{eq}’= T_{eq}•$^4\sqrt{138,6/15.1}$ = 17.1•1.74 = **29.8 K** (10 astronau

Summarizing

	Point Sun	Extended Sun	return current: shaped cross section	+ 100 W inside (8 men equivalent)
Habitat 500	19.3 K	19.6 K	18.3 K	38.2 K
Habitat 1000	16.7 K	17.1 K	15.4 K	28.4 k

Conclusions

The HT sc and the MgB_2 materials allow designing sc magnetic systems to be operated in space without cryocoolers

Habitats of huge dimensions (500 to 1000 m^3) can be operated in deep space without having recourse to active cooling by finalizing their design and handling their attitude in space

Work in progress

Complete simulation (design, total mass, cooling) of the protection of a large habitat in deep space

Cooling of habitats in LEO:

- Sun-pointing attitude more difficult to be realized
- the Sun contribution is halved, but
- the Earth albedo is difficult to be treated.

Astronaut’s activities and electronics devices must be considered and schematized

Did you resist until the end?

Thank you!