Moving Solid Metallic Targets for Pion Production in the Muon Collider / Neutrino Factory Project

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BNL

FIGURES

A full version of the paper was published as MUC-NOTE-TARGET-234

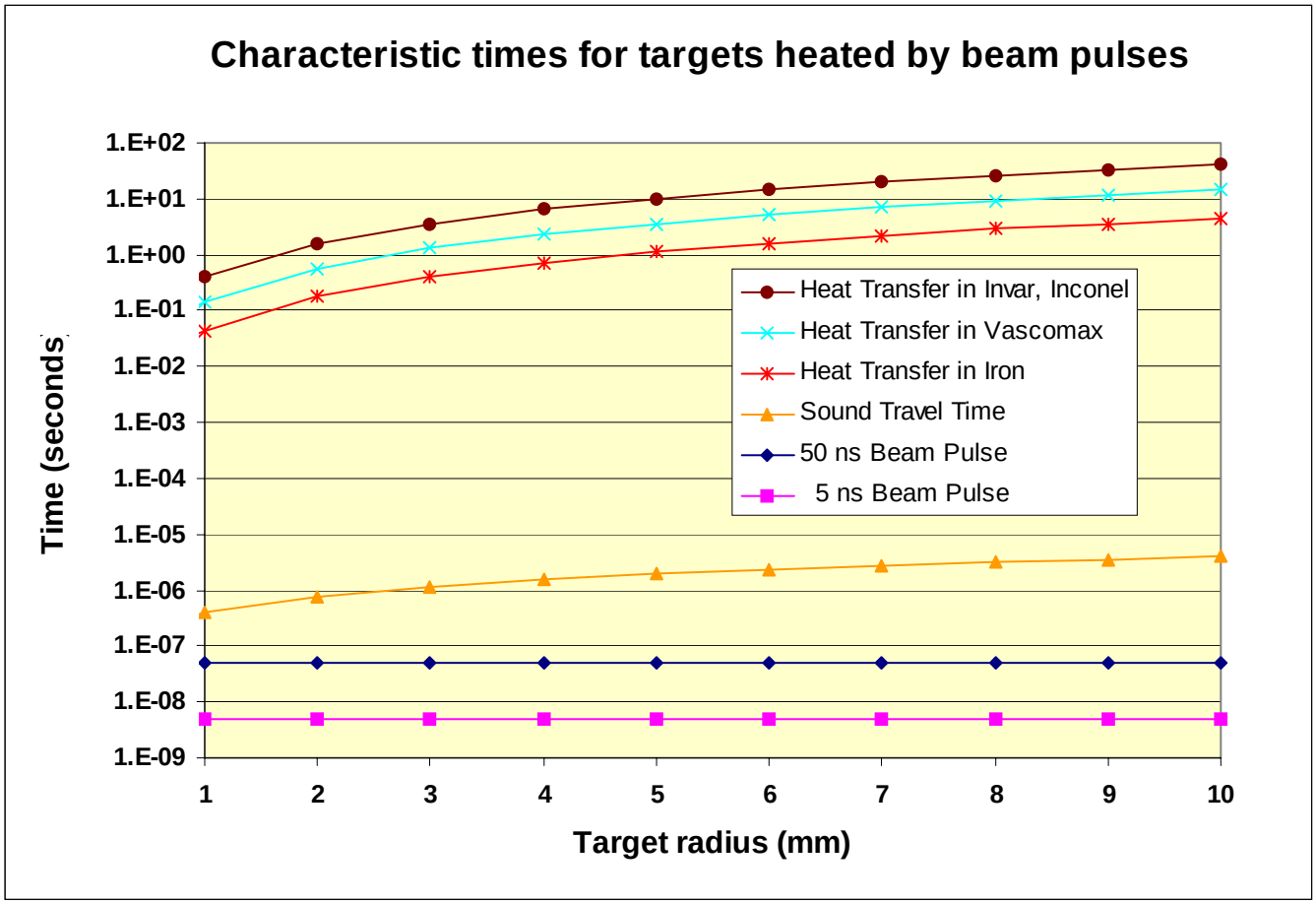

Characteristic times for targets heated by beam pulses
Time (seconds)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1
2
3
4
5
6
7
8
9
10
Target radius (mm)
Heat Transfer in Invar, Inconel
Heat Transfer in Vascomax
Heat Transfer in Iron
Sound Travel Time
50 ns Beam Pulse
5 ns Beam Pulse

Fig. 1

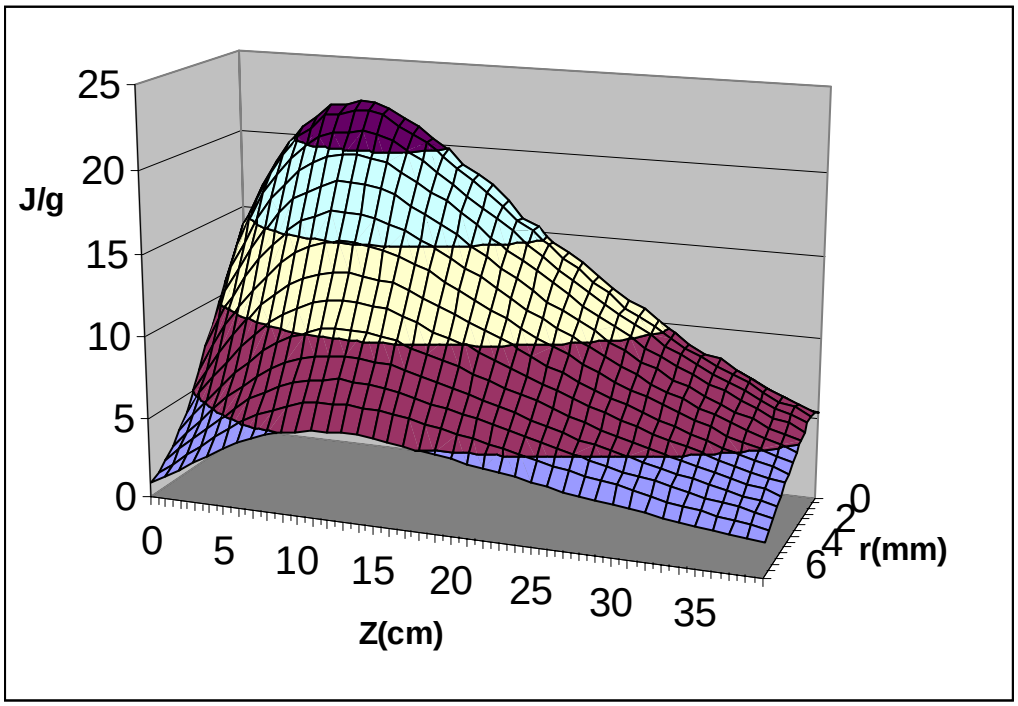


Fig. 2 Three-dimensional view of energy deposition MARS data for a 3 mm rms radius 16TP beam on a 7.5 mm radius iron target.

Table 1. Maximum energy density deposited by a 16TP, 24 GeV beam in an iron target.

Beam width [rms mm]	.5	1	1.5	2	2.5	3	3.5
Target radius [mm]	1.25	2.5	3.75	5	6.25	7.5	8.75
Maximum energy density [J/g]	305	105	55.6	36.0	26.5	22.1	16.5

Table 2. Mechanical an thermal characteristics of the materials

	Density	Linear Exp. Coeff.	Young Modulus	Bulk Modu-lus	Poisson Ratio	Specific Heat @ constant pressure	Thermal Conducti-vity	Yield Stren-gth	Fatigue Endu-rance Limit
Symbol	ρ	α	Y	B	μ	c_p	λ	$\sigma_{0.2}$	σ_{-1}
Unit	g/cm^3	$10^{-6} / {}^0K$	G Pa	G Pa		$J/(g\ {}^0K)$	$W/(m\ {}^0K)$	M Pa	M Pa
Iron	7.87	12.5	205	171	0.30	0.478	80	170	~85
Inconel 718	8.19	13.1	200	158	0.29	0.435	11.2	1034	586
VascoMax C-350	8.08	15.0	200	167	0.30	0.450	25.2	2242	758
Super Invar	8.15	0.63	144	88.9	0.23	0.515	10.5	276	~138

Table 3. Typical Chemical Compositions (%).

Element	C	Al	Si	S	Ti	Cr	Mn	Fe	Co	Ni	Cu	Nb	Mo
Atomic Number	6	13	14	16	22	24	25	26	27	28	29	41	42
Inconel 718		0.5			1	19		19		52.5		5	3
Vasco Max C-350	.02	0.1	.05	.005	1.4		.05	63	12	18.5			4.8
Super Invar	.05	.07	.09	.01		.03	.4	62	5.4	31.8	.08		

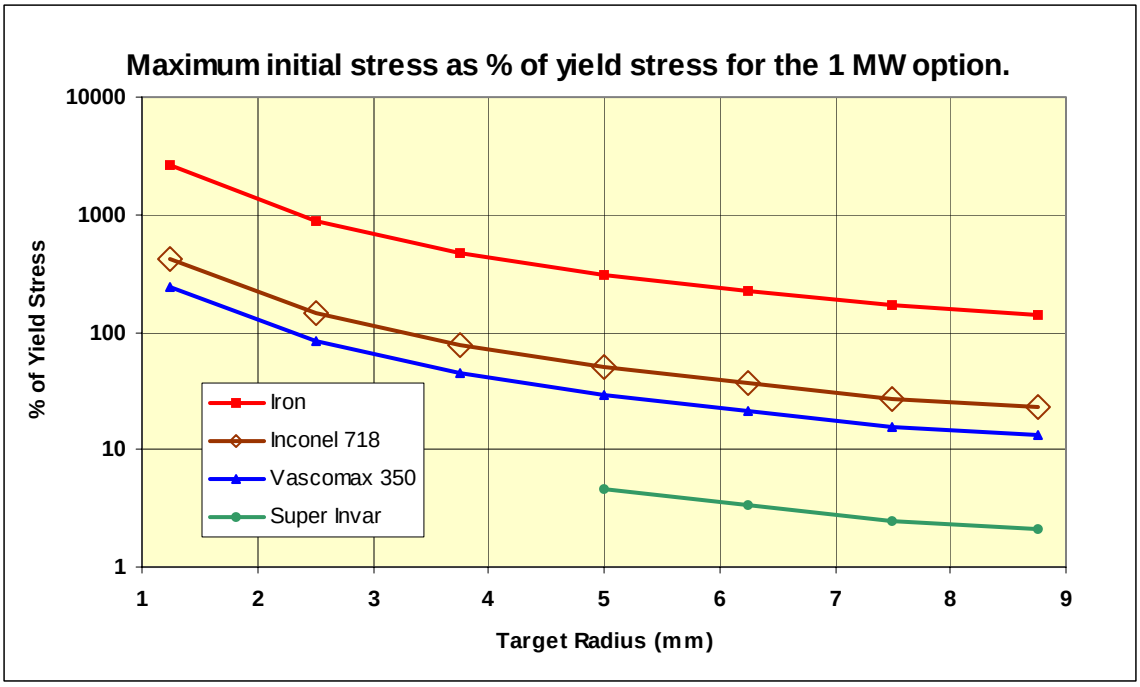

Maximum initial stress as % of yield stress for the 1 MW option.
% of Yield Stress
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 3

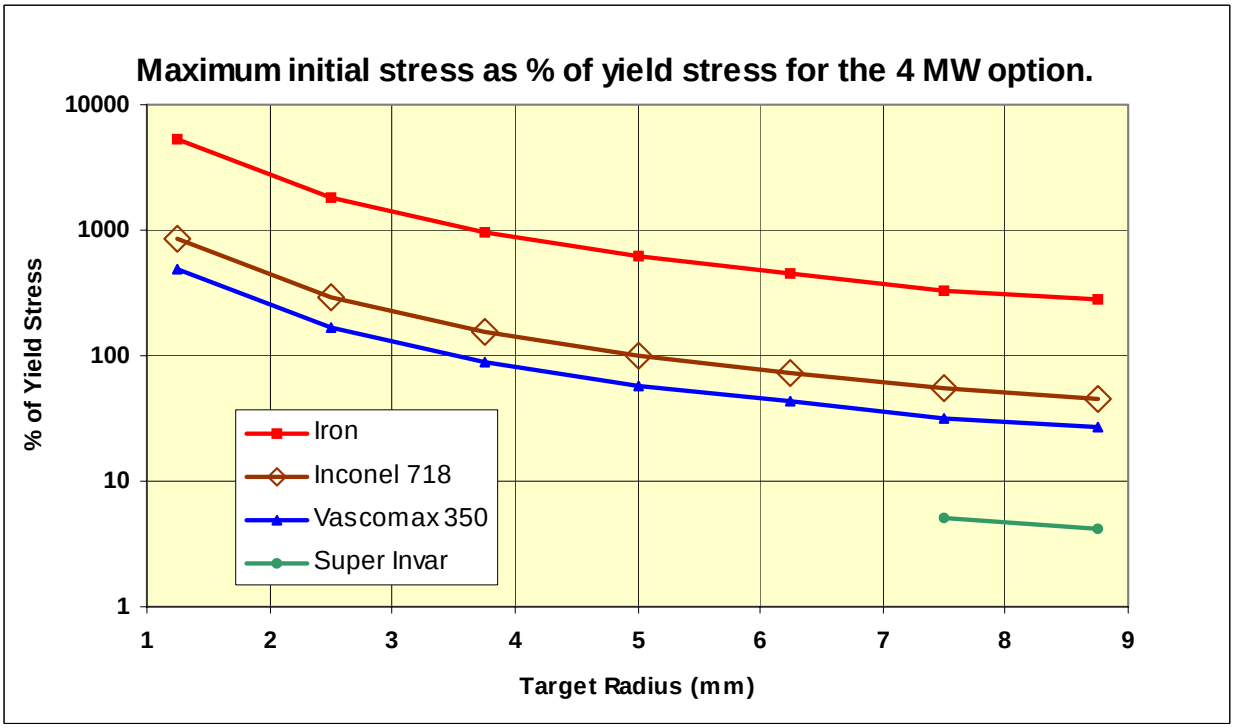

Maximum initial stress as % of yield stress for the 4 MW option.
% of Yield Stress
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 4

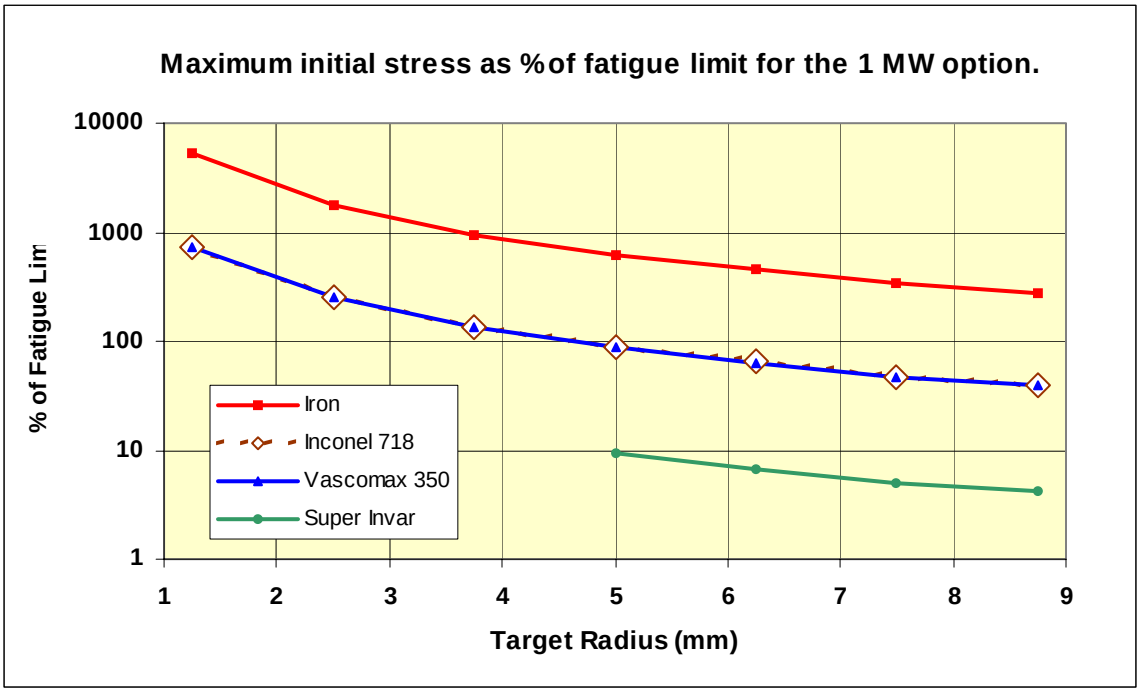

Maximum initial stress as %of fatigue limit for the 1 MW option.
% of Fatigue Lim
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 5

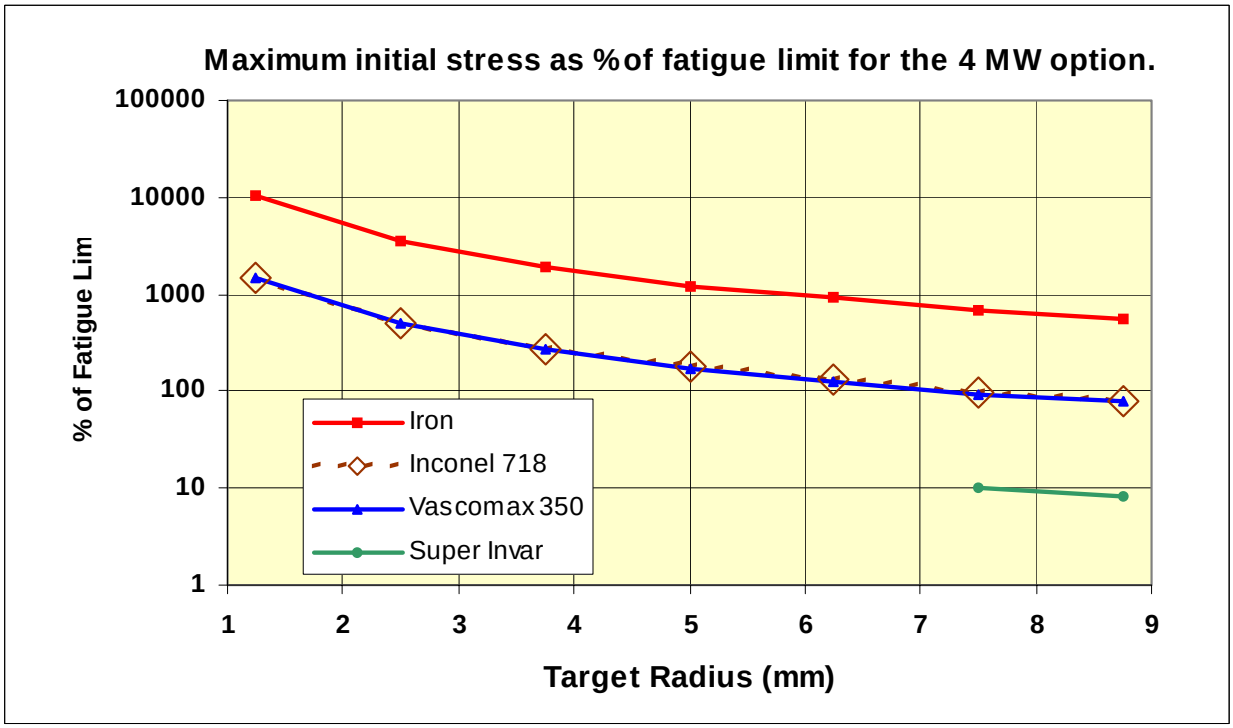

Maximum initial stress as %of fatigue limit for the 4 MW option.
% of Fatigue Lim
100000
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 6

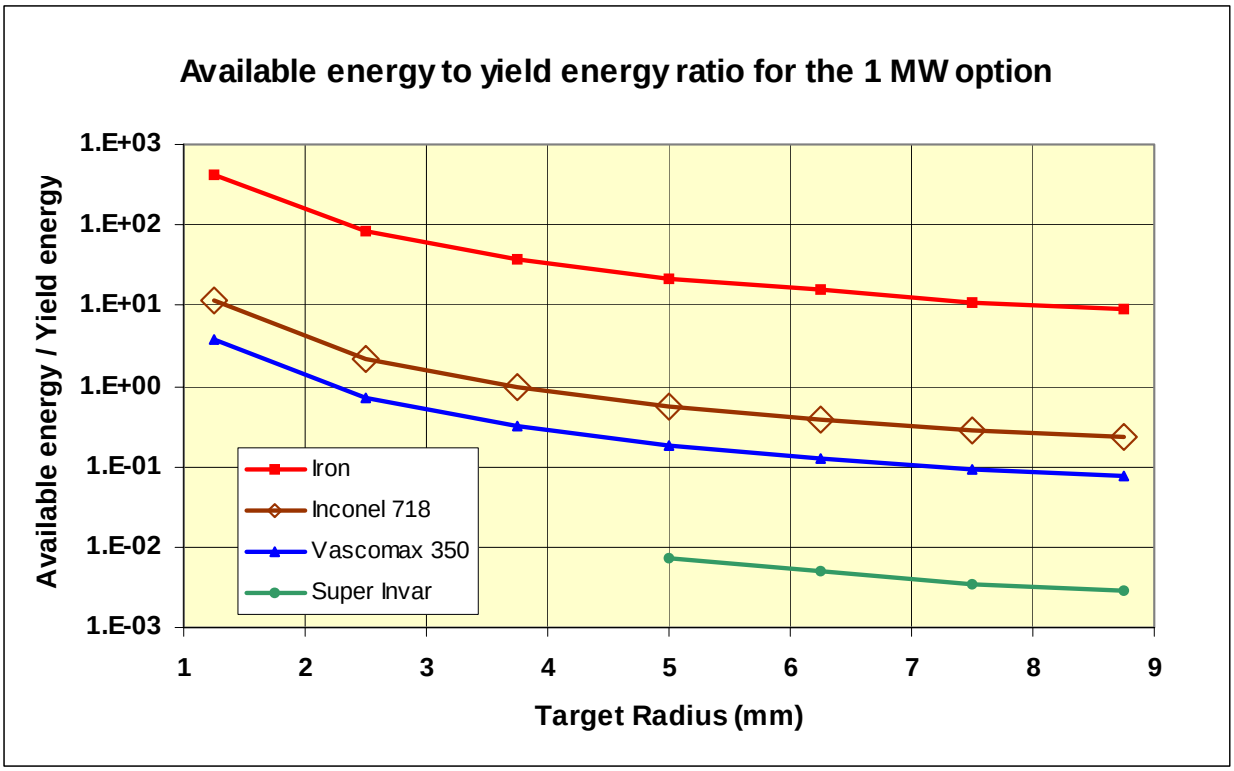

Available energy to yield energy ratio for the 1 MW option
Available energy / Yield energy
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 7

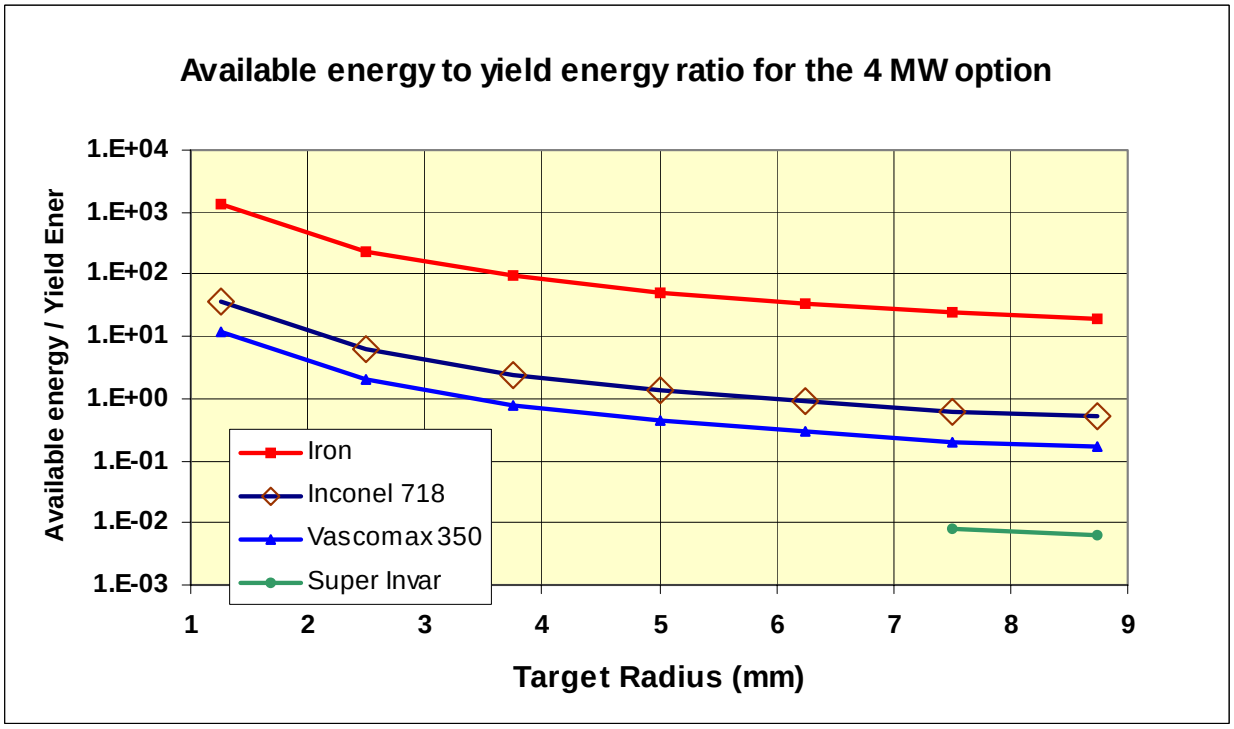

Available energy to yield energy ratio for the 4 MW option
Available energy / Yield Ener
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig 8

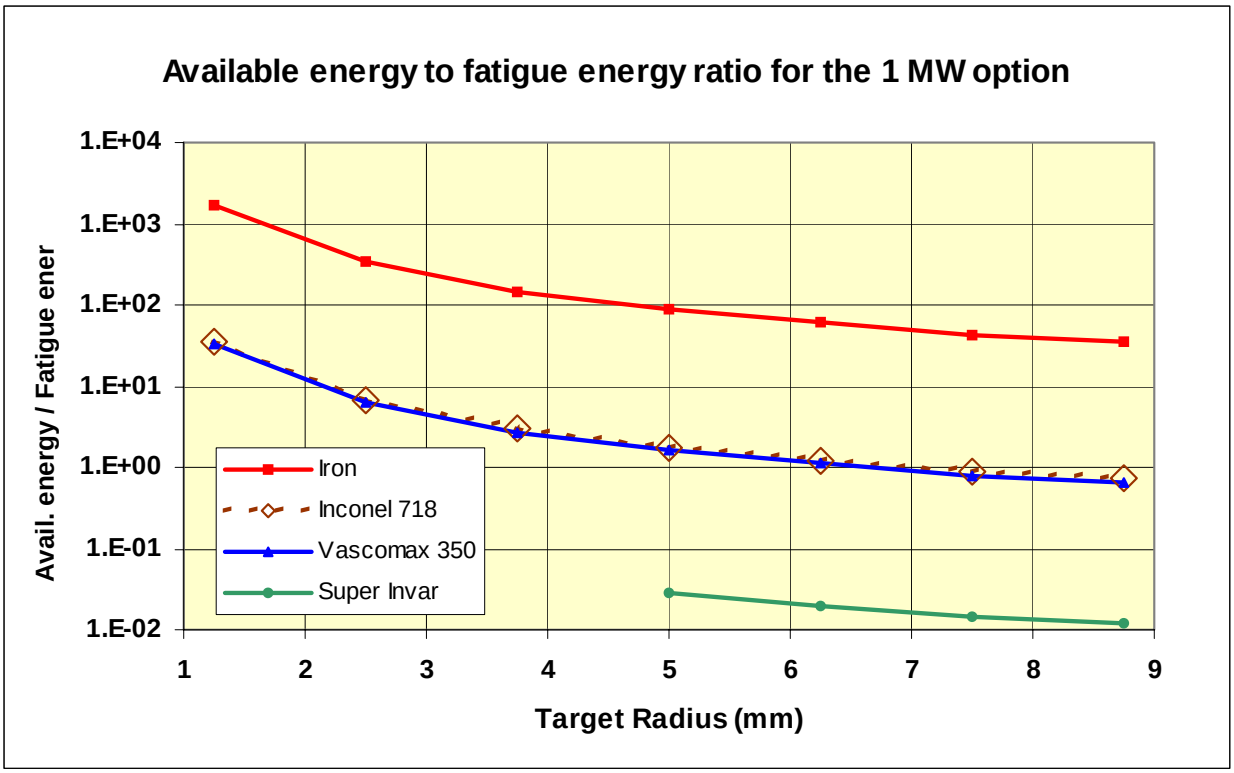

Available energy to fatigue energy ratio for the 1 MW option
Avail. energy / Fatigue ener
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 9

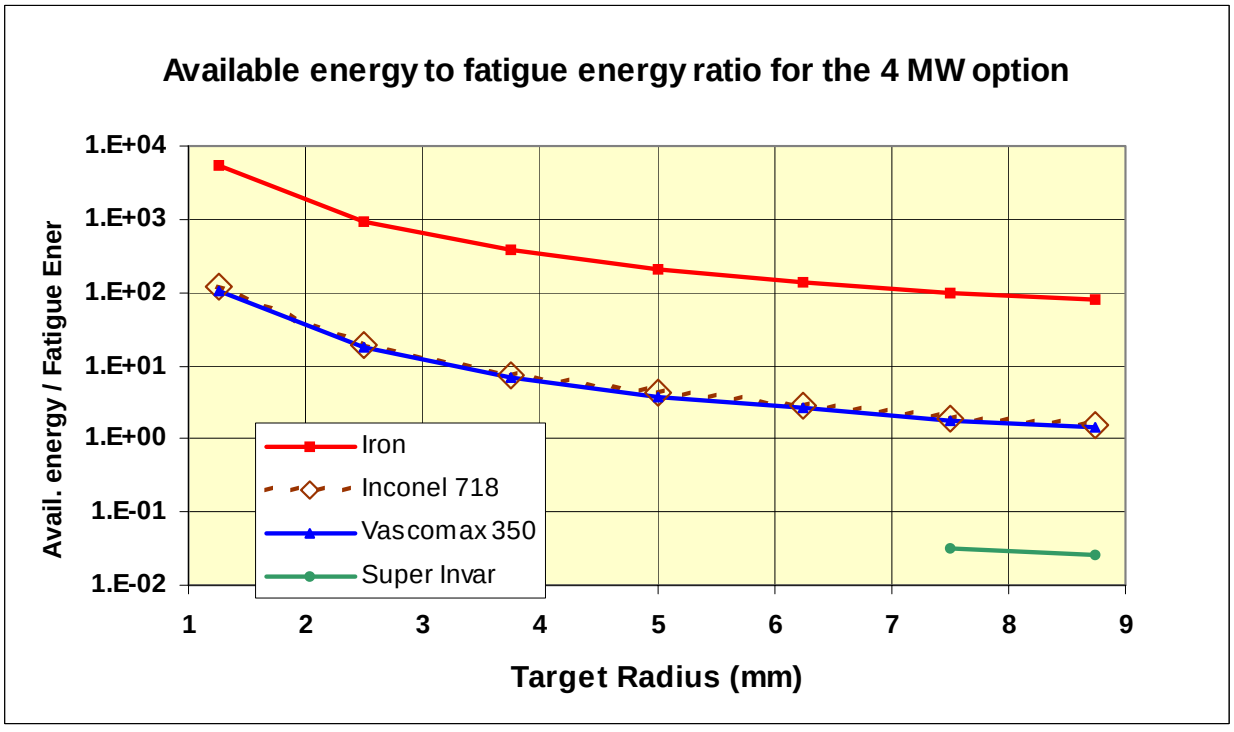

Available energy to fatigue energy ratio for the 4 MW option
Avail. energy / Fatigue Ener
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1
2
3
4
5
6
7
8
9
Target Radius (mm)
Iron
Inconel 718
Vascomax 350
Super Invar

Fig. 10

Table 4 1 MW-option results for a 7.5 mm radius target

	Iron	Inconel 718	Vascomax C- 350	Super Invar
Maximum Stress/ Yield Stress	1.7	0.27	0.16	0.025
Maximum Stress/ Fatigue Limit	3.3	0.48	0.47	0.050
Available Energy/ Yield Energy	10.9	0.28	0.09	0.004
Available Energy/ Fatigue Energy	43.6	0.87	0.81	0.014

Table 5 4 MW-option results for a 7.5 mm radius target

	Iron	Inconel 718	Vascomax C-350	Super Invar
Maximum Stress/ Yield Stress	3.4	0.54	0.32	0.05
Maximum Stress/ Fatigue Limit	6.7	0.95	0.94	0.10
Available Energy/ Yield Energy	24.2	0.61	0.21	0.008
Available Energy/ Fatigue Energy	96.8	1.93	1.79	0.03

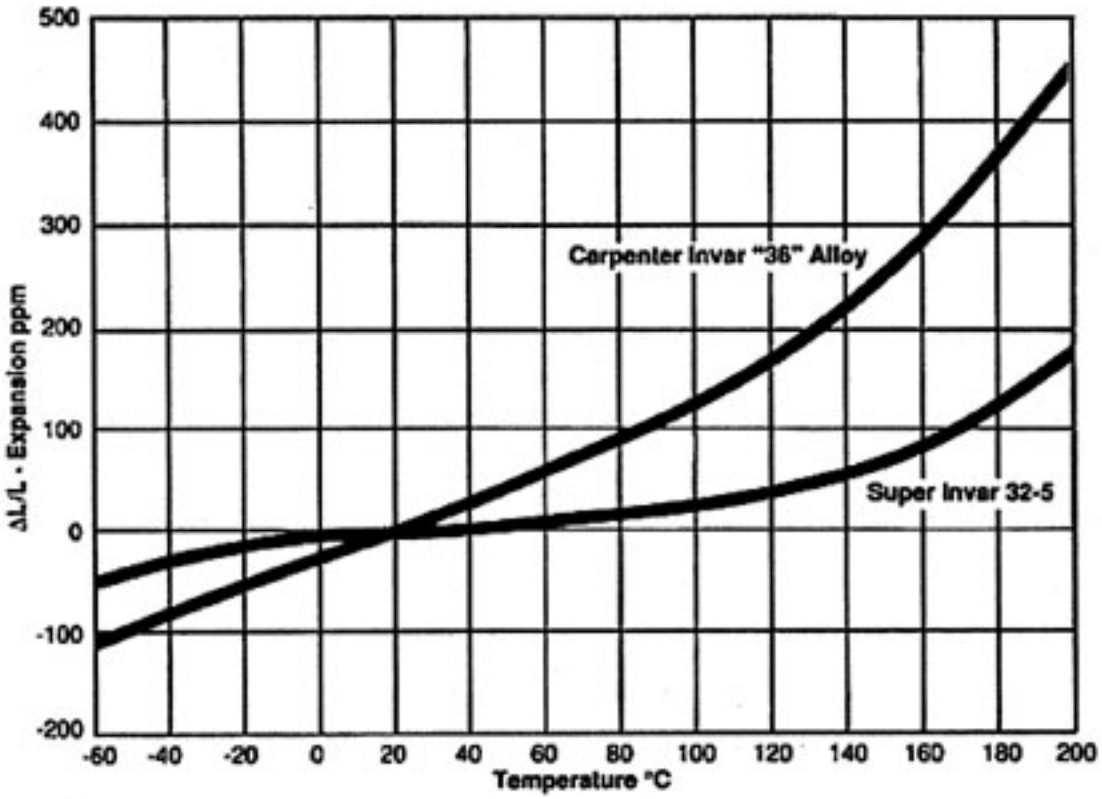
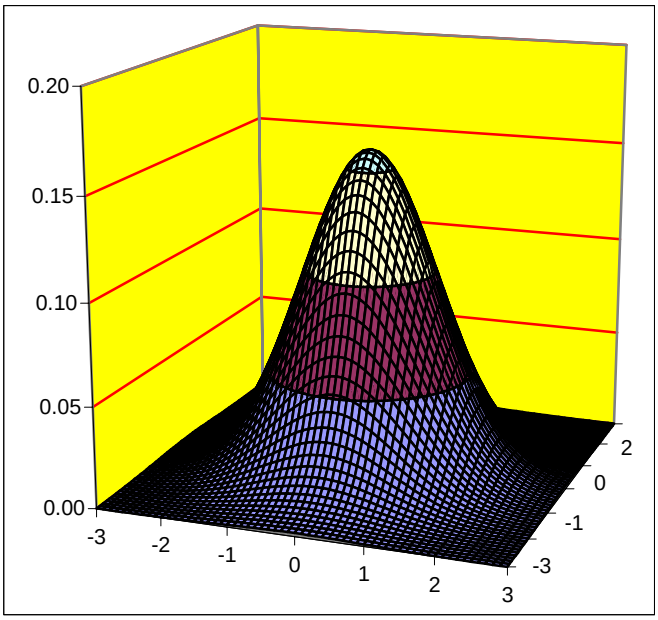


Fig. 11 Linear expansion as a function of temperature for Invar and Supper Invar alloys.



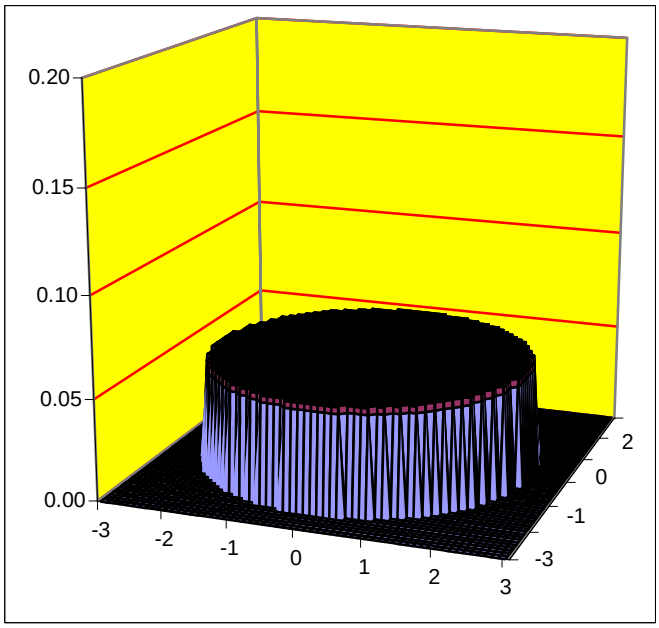


Fig 12a **Fig. 12b**

Comparison of a doubly Gaussian beam profile (a) with an ideal flat profile (b) containing the same number of particles.

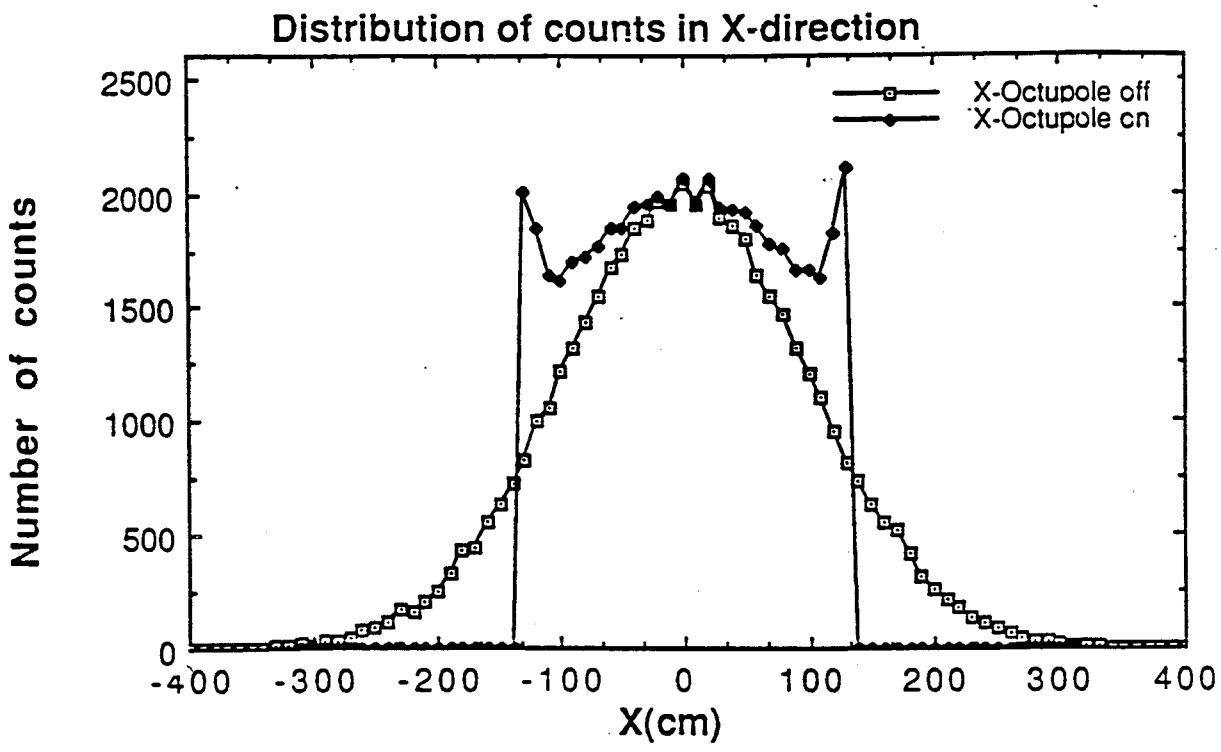


Fig. 13 Octupole-lens generated beam profile compared to a Gaussian profile with the octupole turned off.

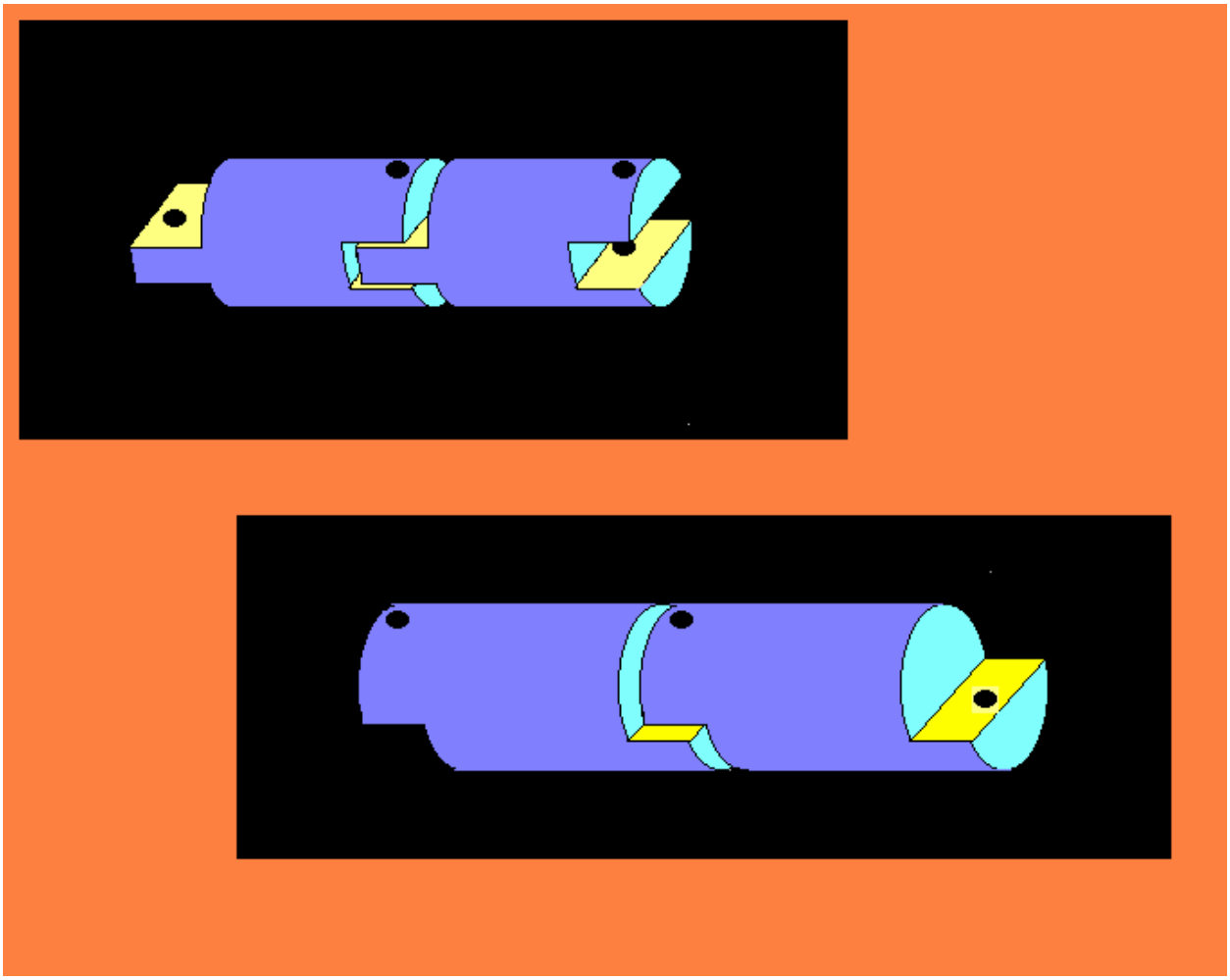


Fig. 14 Schematic examples of metallic chain links showing rather compact designs with large metal to gap volume rtatios.

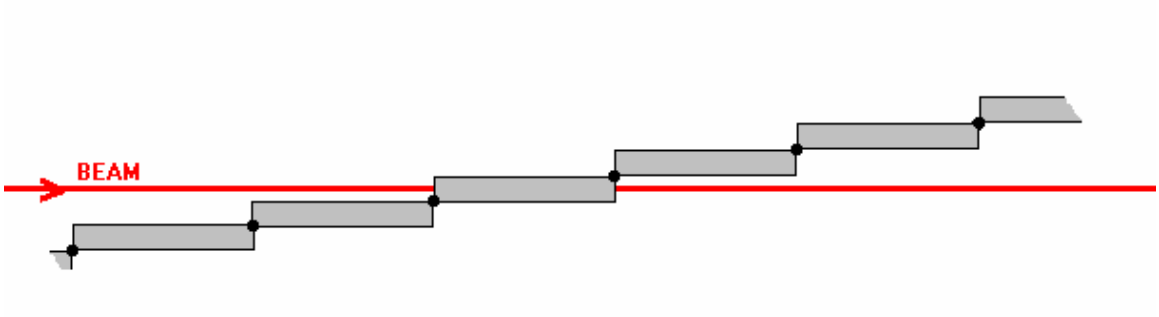
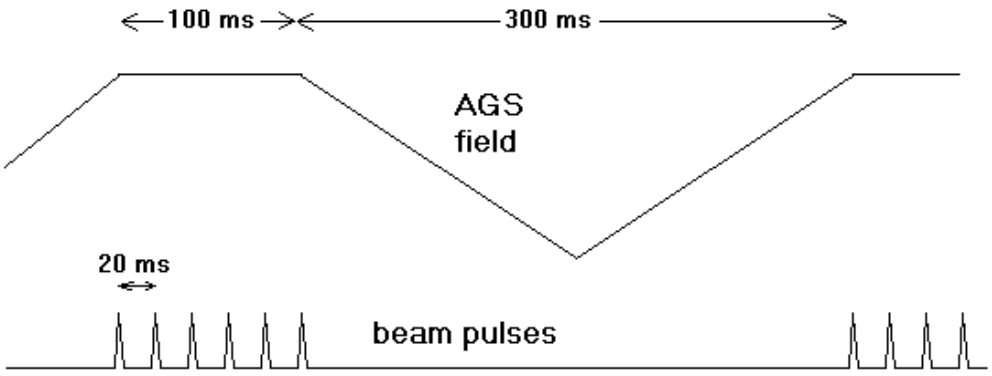


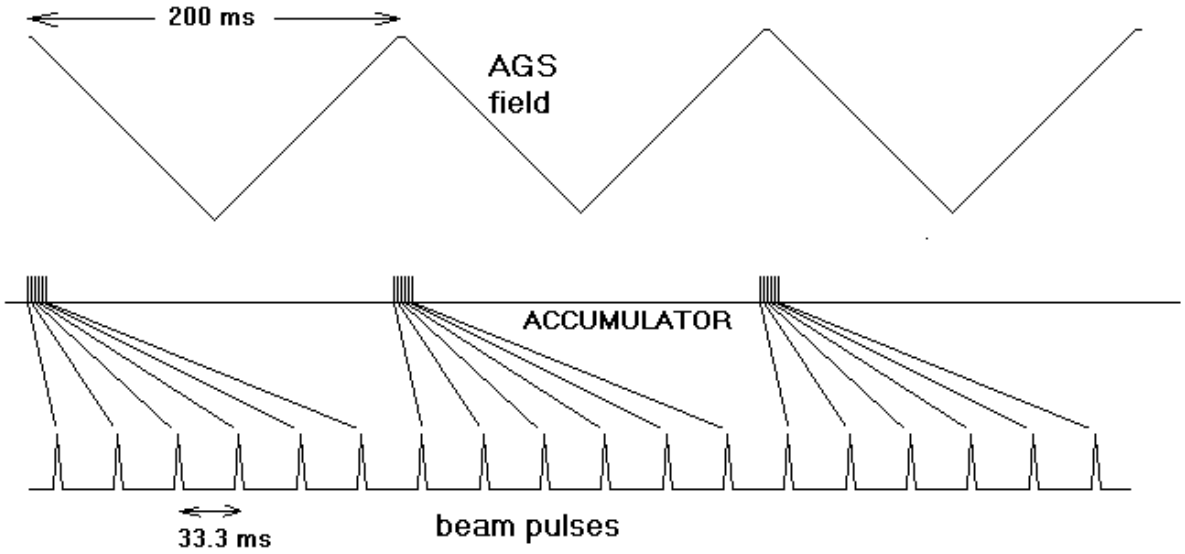
Fig.15 Schematic example of a chain with long links that would allow the beam to be coaxial with the target.

1 MW OPTION



15 pulses per second
66.7 kJ per pulse
17.3 TP per pulse

4 MW OPTION



30 pulses per second
133 kJ per pulse
34.7 TP per pulse

Fig. 16 Proton beam pulse sequences for the proposed 1 MW and 4 MW options.

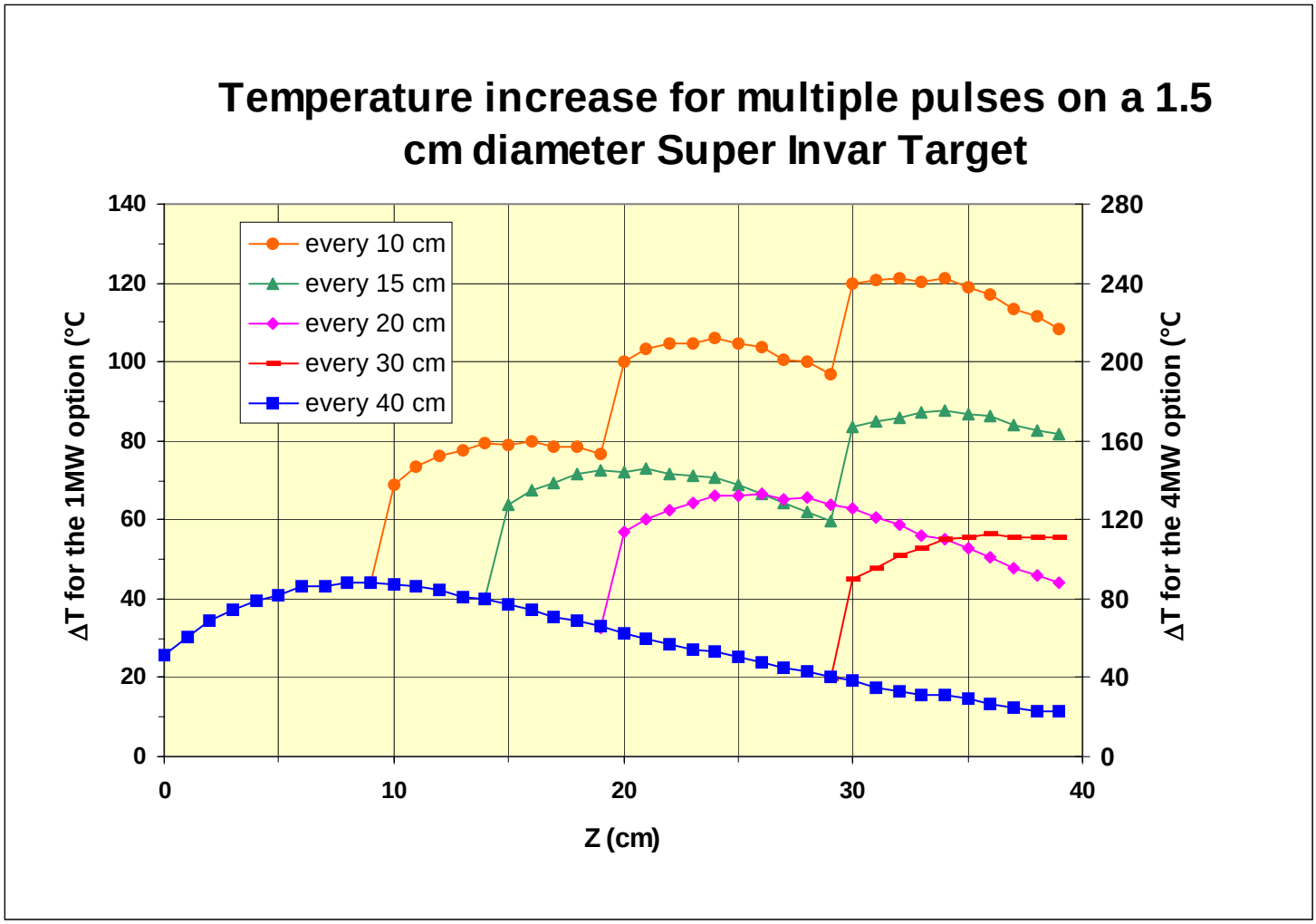

Temperature increase for multiple pulses on a 1.5 cm diameter Super Invar Target
every 10 cm
every 15 cm
every 20 cm
every 30 cm
every 40 cm
ΔT for the 1MW option (°C
ΔT for the 4MW option (°C
Z (cm)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
0
10
20
30
40

Fig. 17

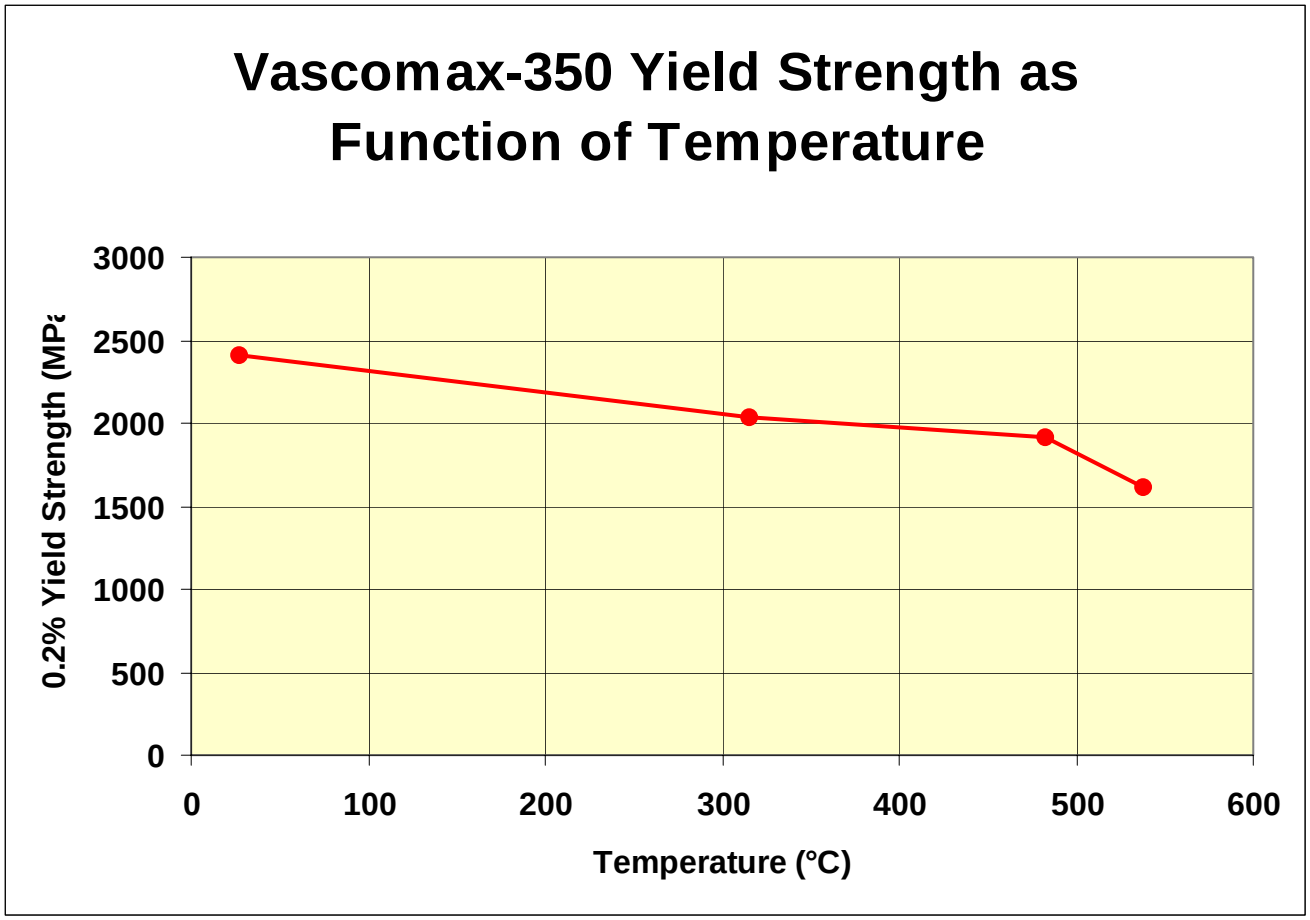

Vascomax-350 Yield Strength as Function of Temperature
0.2% Yield Strength (MPa
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
Temperature (°C)

Fig. 18

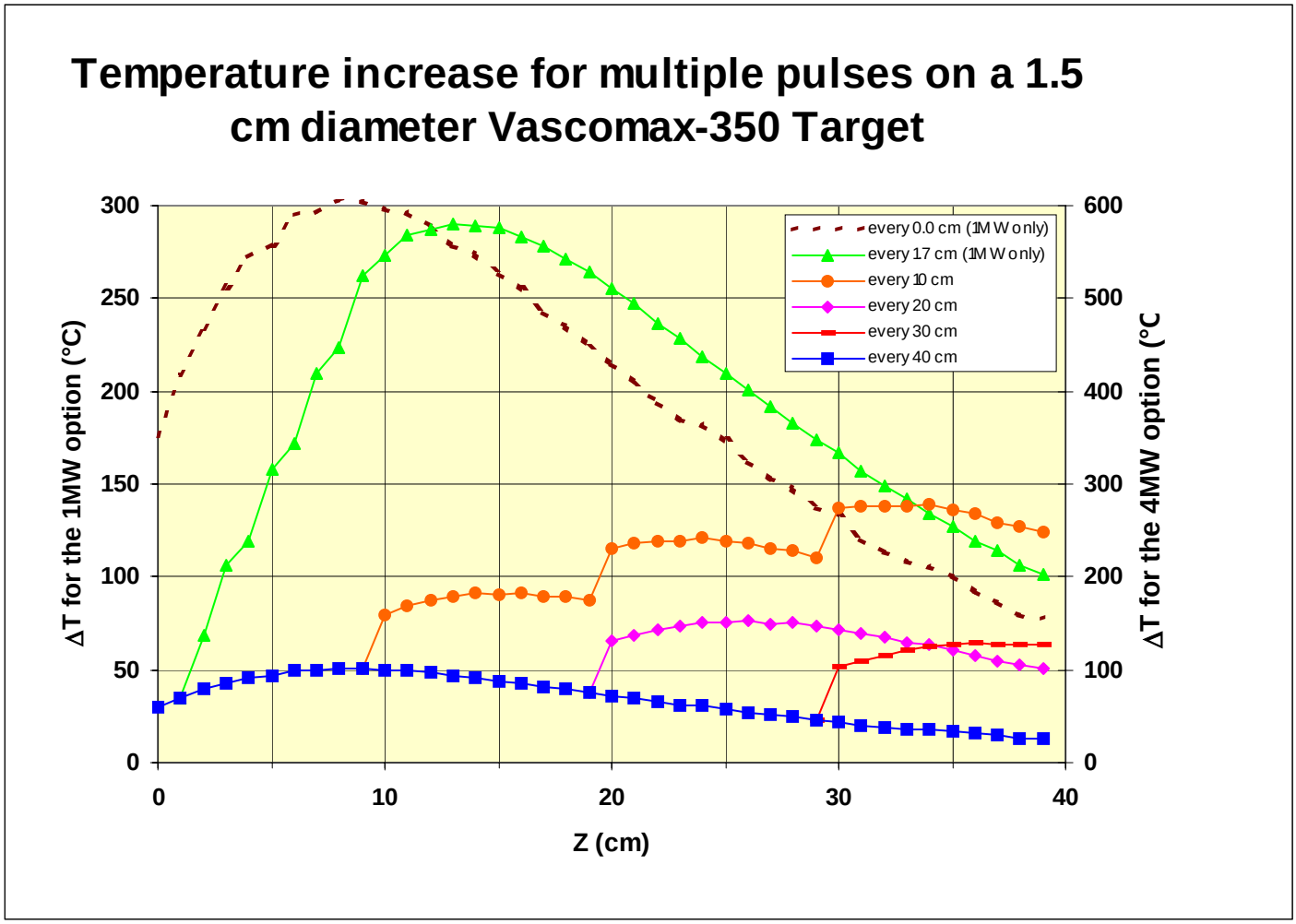

Temperature increase for multiple pulses on a 1.5 cm diameter Vascomax-350 Target
ΔT for the 1MW option (°C)
ΔT for the 4MW option (°C
Z (cm)
every 0.0 cm (1MW only)
every 17 cm (1MW only)
every 10 cm
every 20 cm
every 30 cm
every 40 cm
0
50
100
150
200
250
300
0
100
200
300
400
500
600
0
10
20
30
40

Fig. 19

Table 6. Examples of target velocities and lengths according to assumptions explained in the text.

	Velocity (continuous motion)	Minimum length (continuous motion)	Average Velocity (intermittent motion)	Minimum length (intermittent motion)
	m/s	m	m/s	m
Super Invar - 1 MW Option	7.5	175		
Vascomax C-350 - 1 MW Option	0.85	16.8	1.0	18
Super Invar - 4 MW Option	12.0	274		
Vascomax C-350 - 4 MW Option	3.0	34		

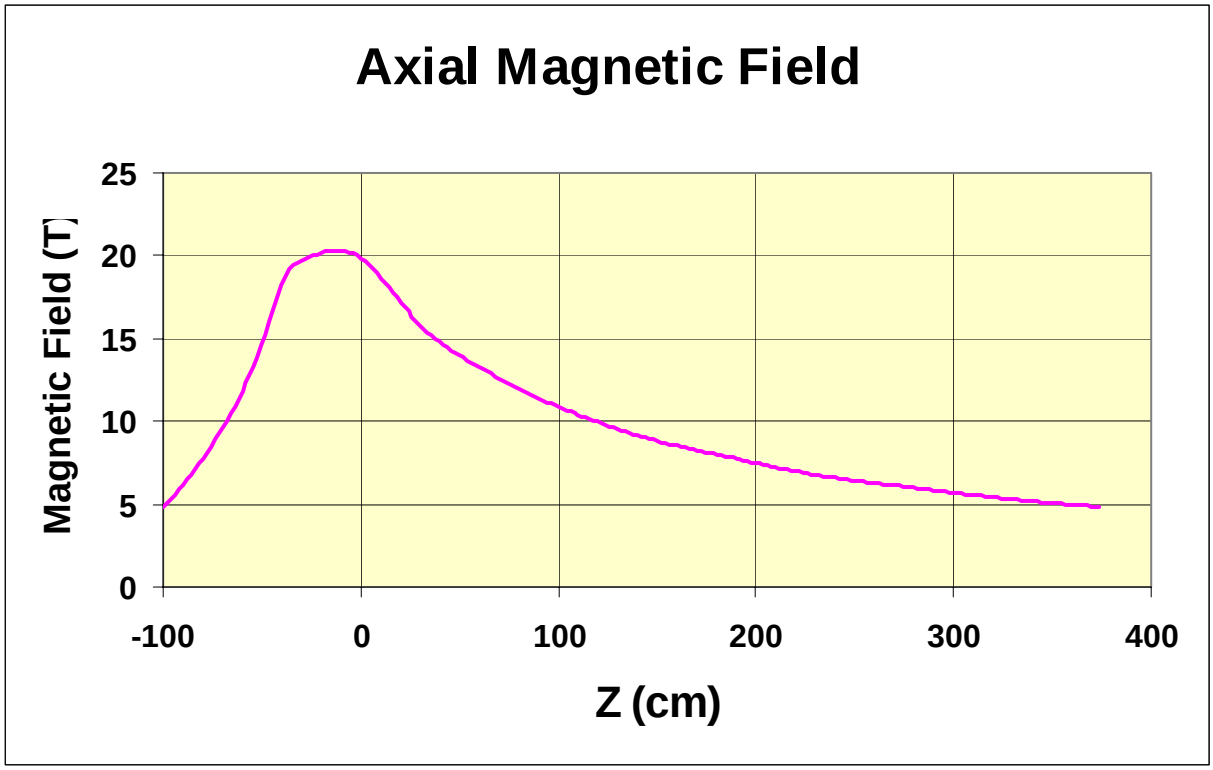


Fig. 20 Axial magnetic field calculated for the 20T solenoid arrangement described in the Feasibility Study[1)].

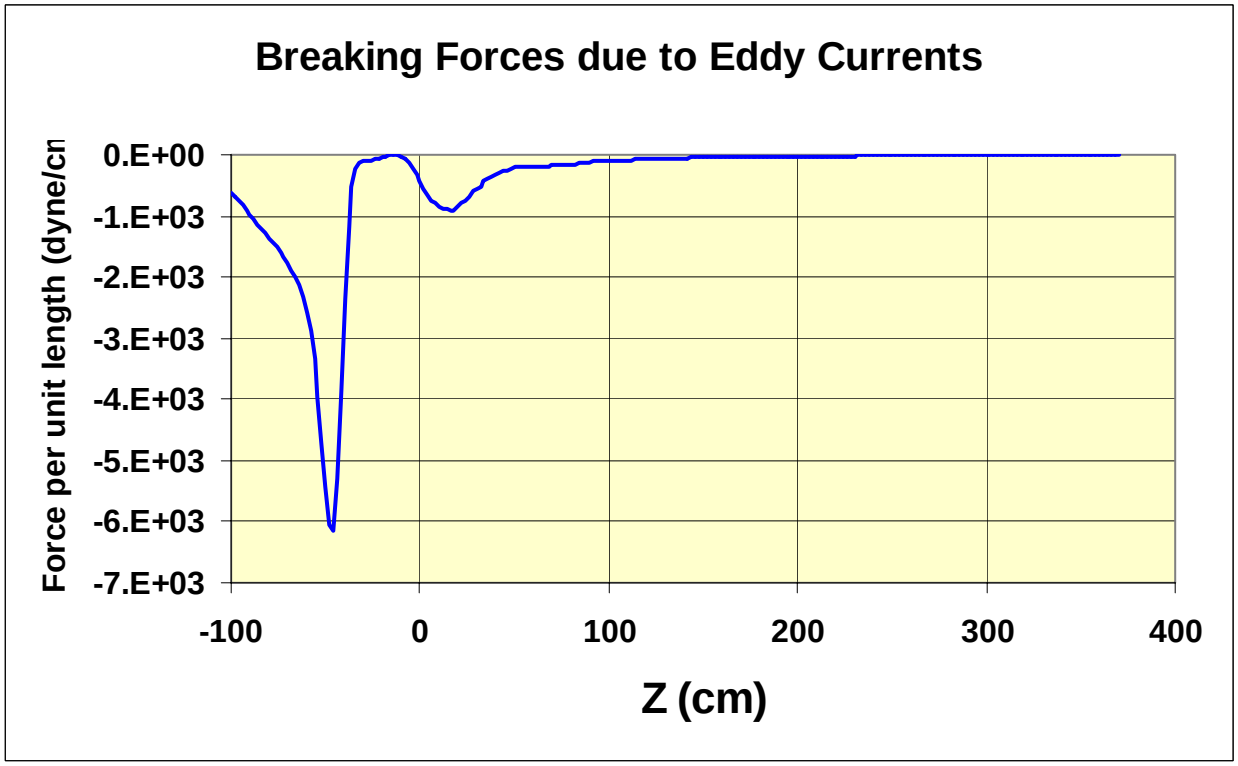


Fig. 21 Breaking forces per unit target length due to Eddy currents in a 1.5 cm diameter Vascomax C-target

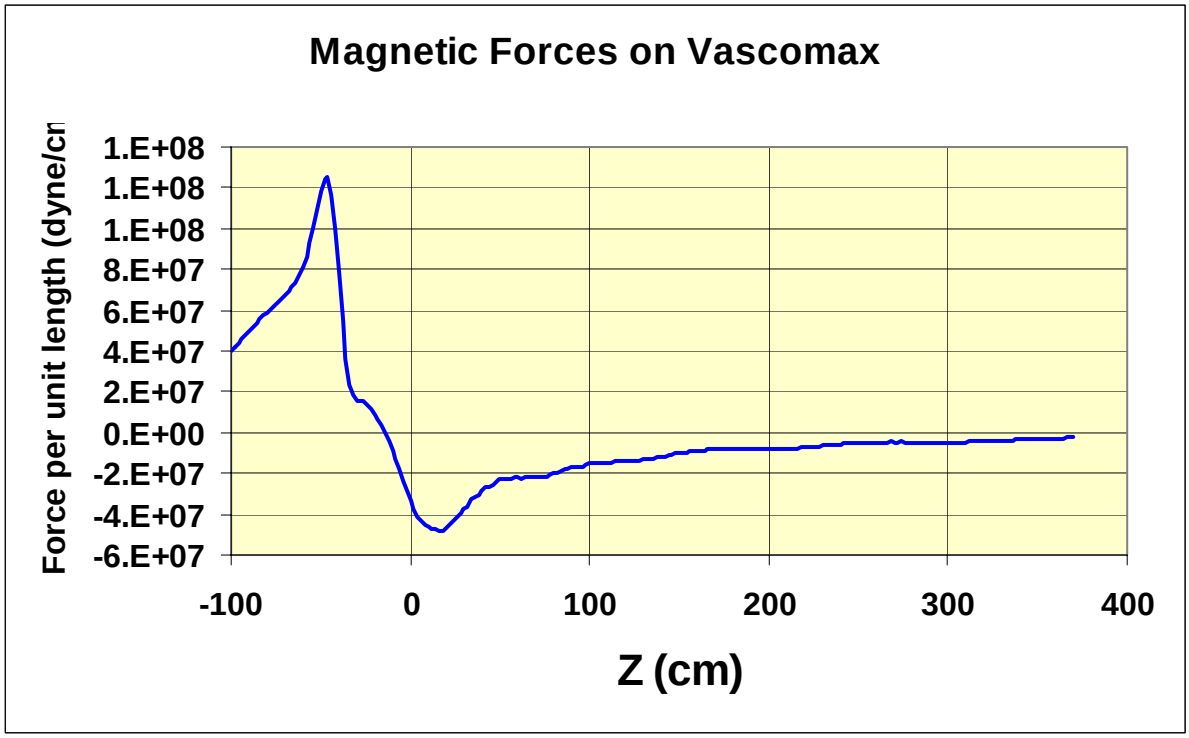


Fig. 22 Magnetic forces on a 1.5 cm diameter Vascomax C-350 target placed in the field shown in fig. 20.

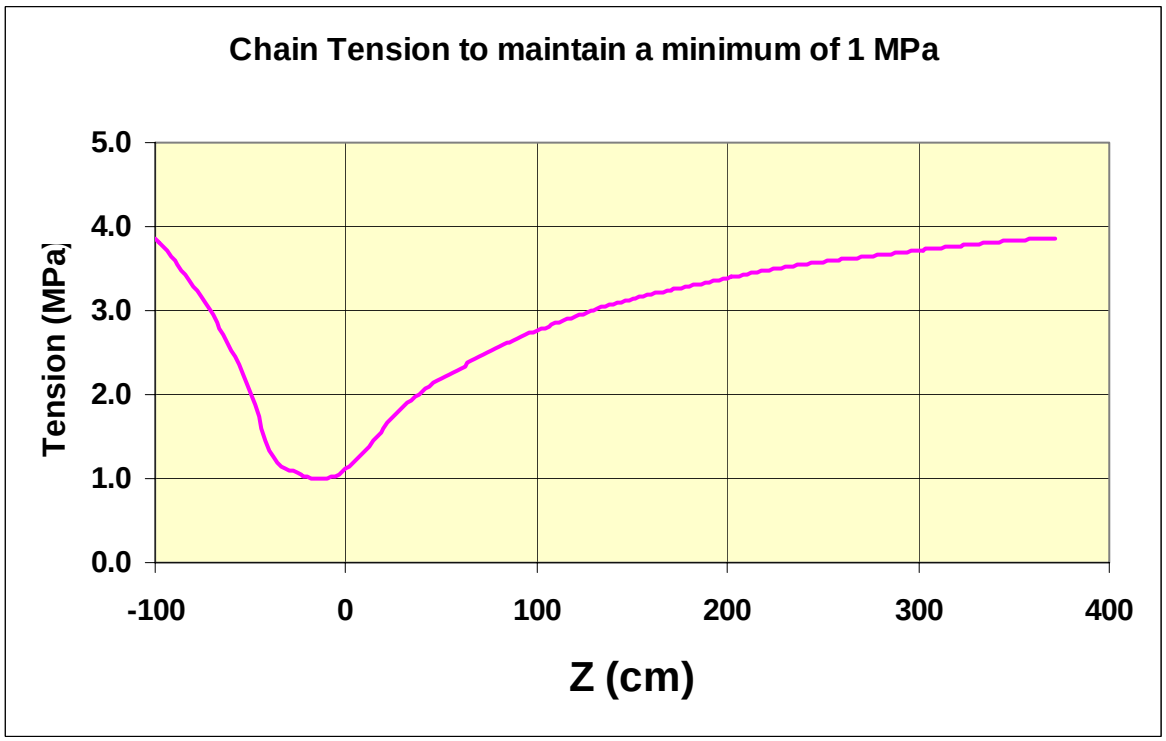


Fig. 23 Tension as a function of position for a 1.5 cm diameter Vascomax C-350 target placed in the field

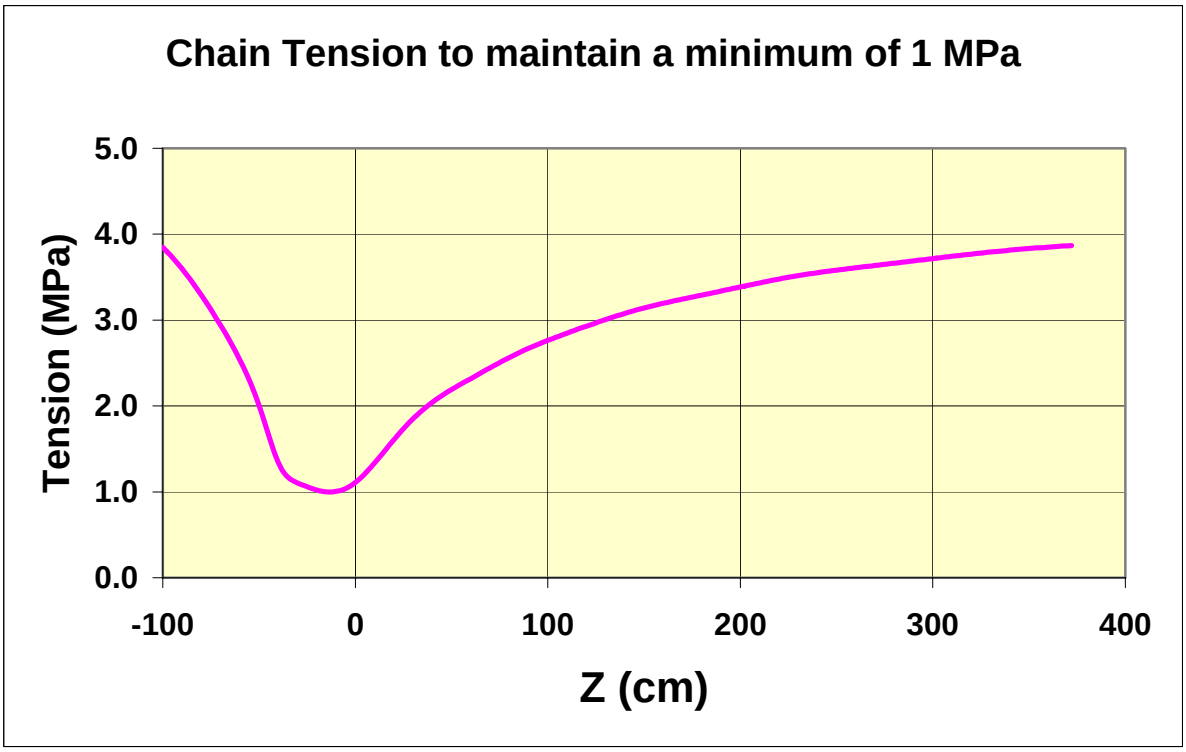


Fig. 23 Tension as a function of position for a 1.5 cm diameter Vascomax C-350 target placed in the field shown in fig.20. In this example, an external tension is applied to achieve a minimum tension of 1 MPa.

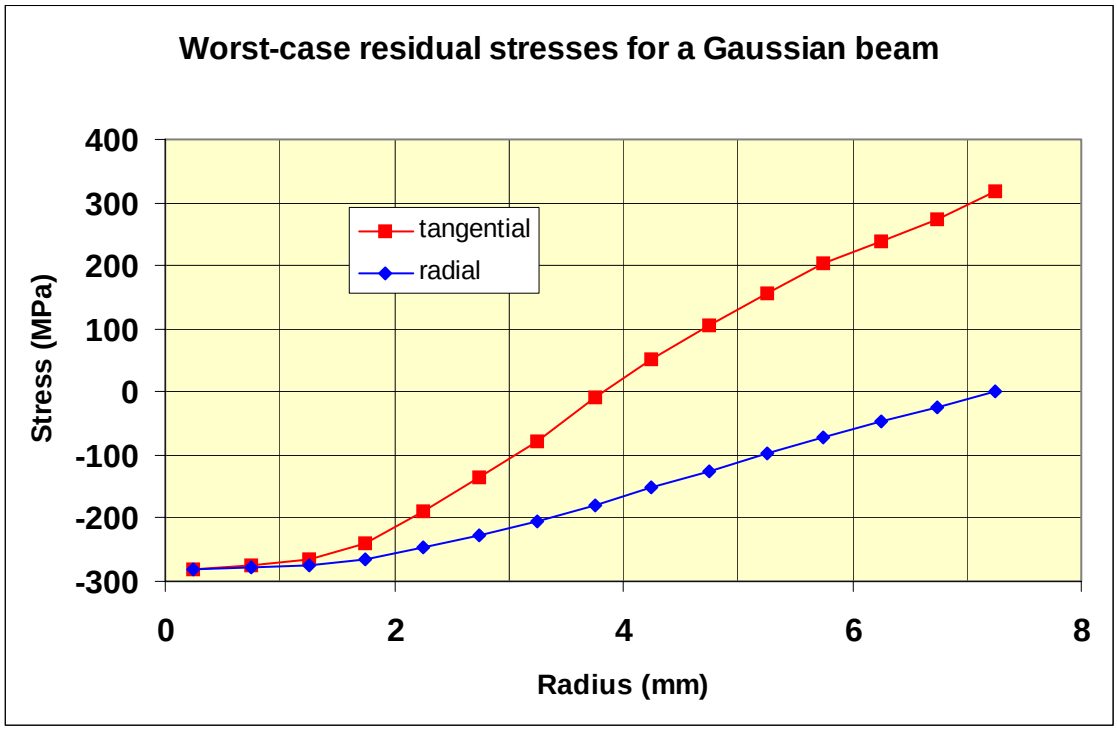

Worst-case residual stresses for a Gaussian beam
Stress (MPa)
400
300
200
100
0
-100
-200
-300
0
2
4
6
8
Radius (mm)
tangential
radial

Fig. 24

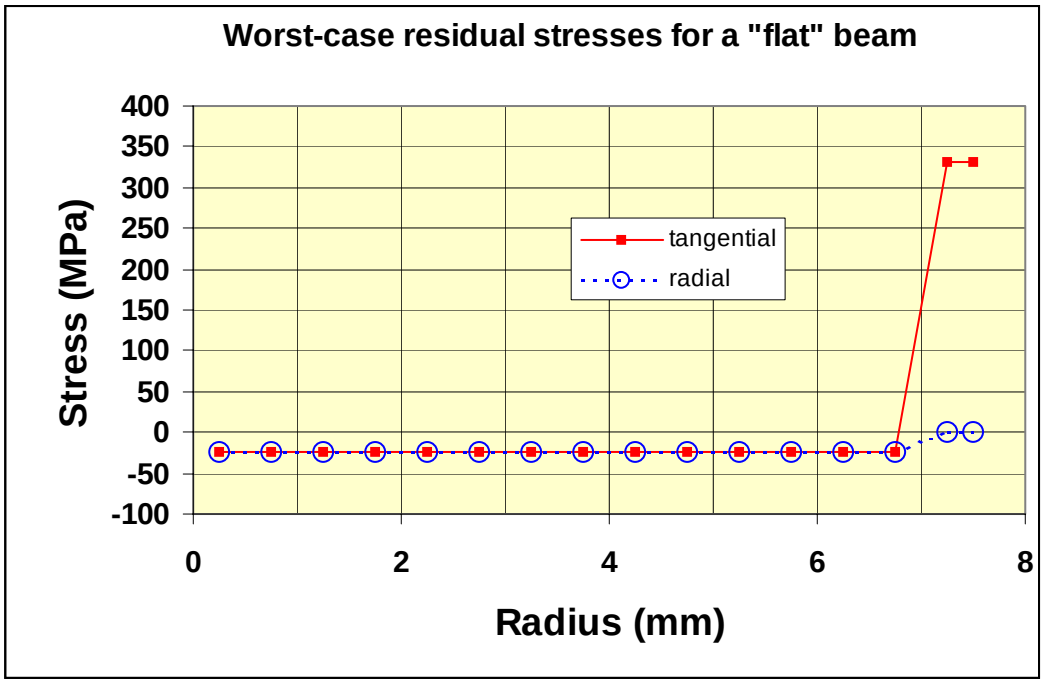

Worst-case residual stresses for a "flat" beam
Stress (MPa)
400
350
300
250
200
150
100
50
0
-50
-100
0
2
4
6
8
Radius (mm)
tangential
radial

Fig 25

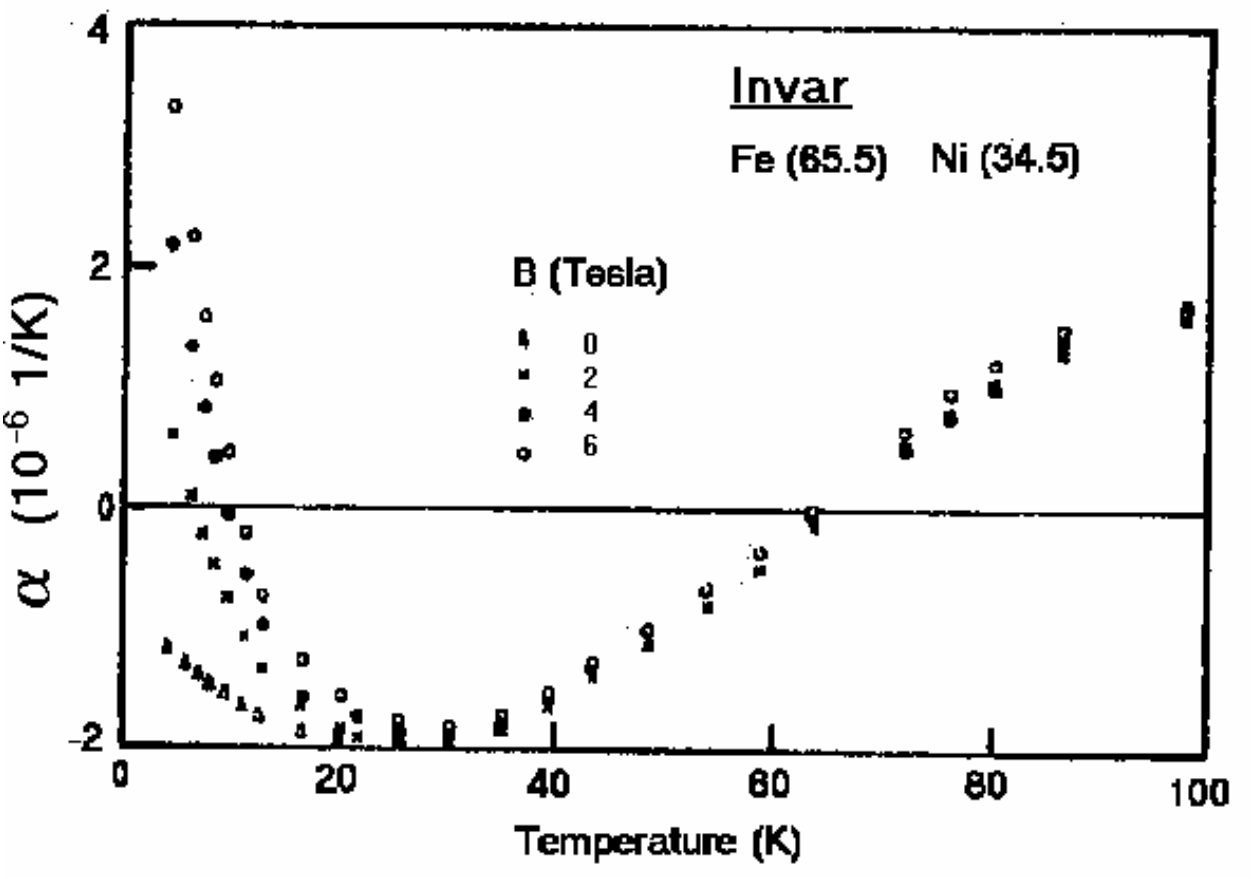


Fig. 26 Invar linear expansion coefficient as a function of temperature and magnetic field [19].

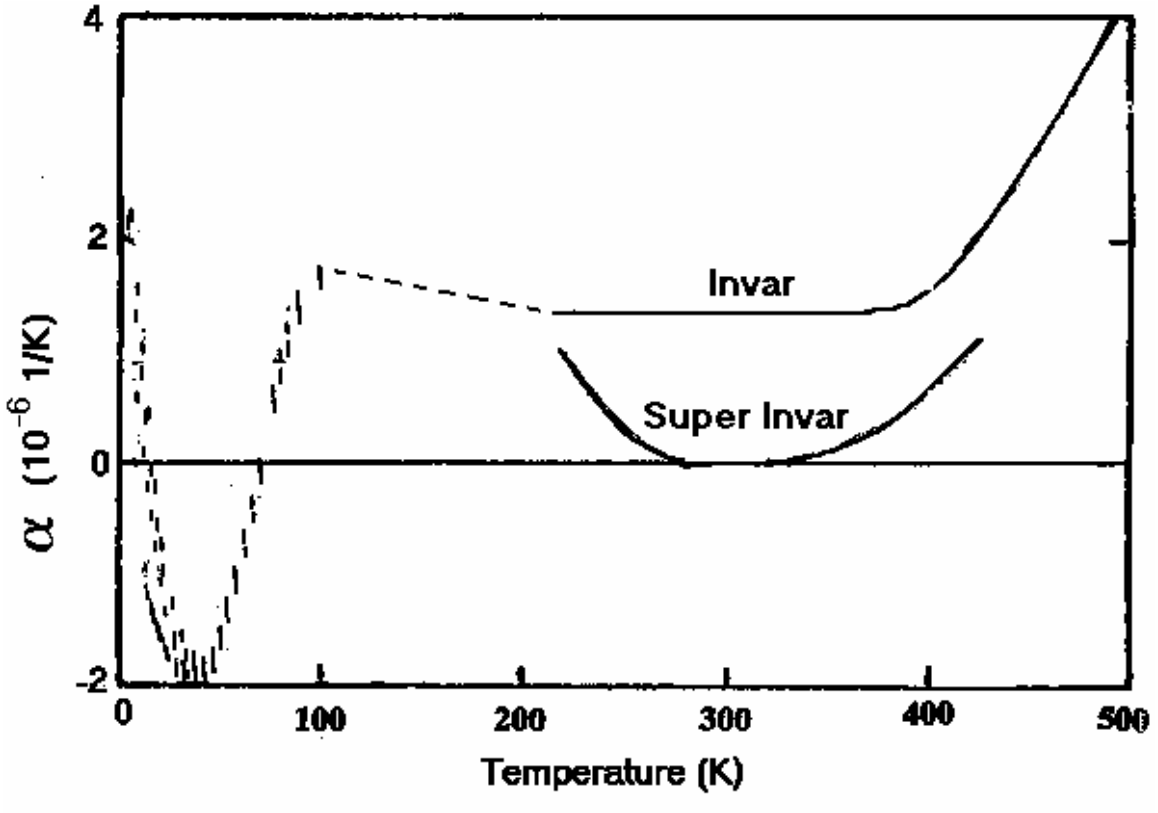


Fig. 27 Low temperature data[20] from Fig. 26 combined with known expansion coefficients at higher temperatures.

Table 8. Comparison of advantages and disadvantages the three alloys considered in this paper.

MATERIAL	ADVANTAGES	DISADVANTAGES
Super Invar	Largest margin for thermal shock tolerance. Absence of large magnetic forces.	Narrow temperature range and low heat conductivity leading to the need for long chains or cables. The largest uncertainty regarding deleterious effects of radiation damage.
Vascomax C-350	Largest tensile strength. Good heat conductivity allowing the use of relatively short chains or cables.	The material is ferromagnetic and will be subject to large magnetic forces
Inconel 718	Good fatigue endurance limit similar to Vascomax C-350. Absence of large magnetic forces.	Poor heat conductivity (similar to Super Invar) requiring long chains of cables, but not as long as for Super Invar since the temperature range is not as small.