



Science & Technology
Facilities Council

Progress on Solid Target Studies

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Outline

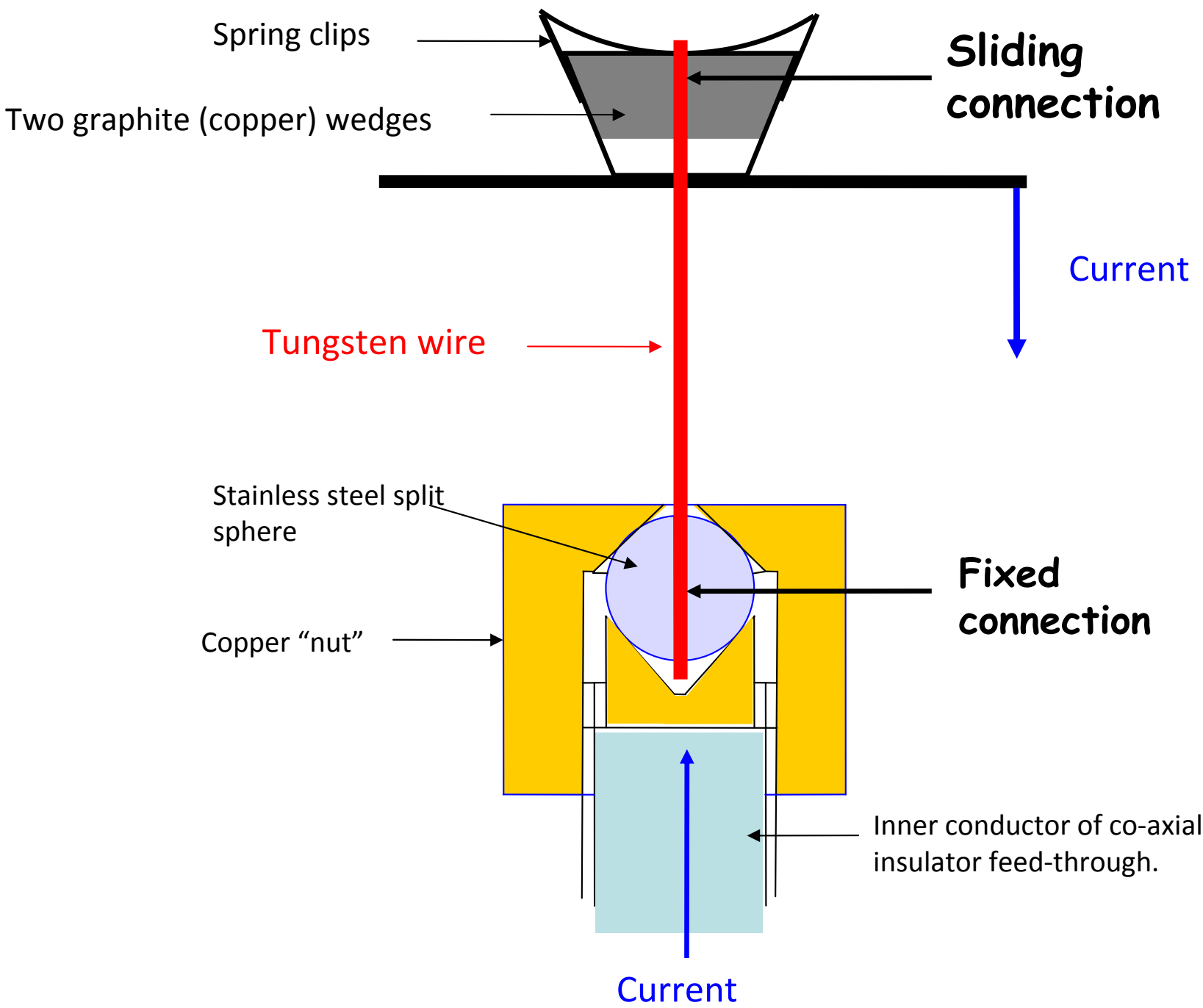
1. Reminder of the Solid Target Design and Studies.
2. Progress on measuring target lifetime.
3. Progress on measuring shock motion using the VISAR.
4. Future work.

Solid Target Studies

1. The original idea was to have a **tantalum toroid** rotate through the beam and threading the pion collection/focussing solenoid. The toroid operated at ~ 1600 K and **radiated the heat** to the surrounding water cooled walls.
2. The main problem was considered to be **thermal shock** generated by the ns long proton pulses (10 GeV, 4 MW beam).
3. Thermal Shock Studies: **A) Lifetime Test.**
A high current pulse was passed through a 0.5 mm diameter tantalum wire, simulating the stress expected in a full size target. The number of pulses was counted before failure of the wire. Tantalum quickly proved to be too weak and was replaced by tungsten. Great care was needed to align the wire in the support structure to minimise the very large Lorenz magnetic forces. Most failures were probably due to this and to the wire sticking in the sliding free-end support /electrical connection.

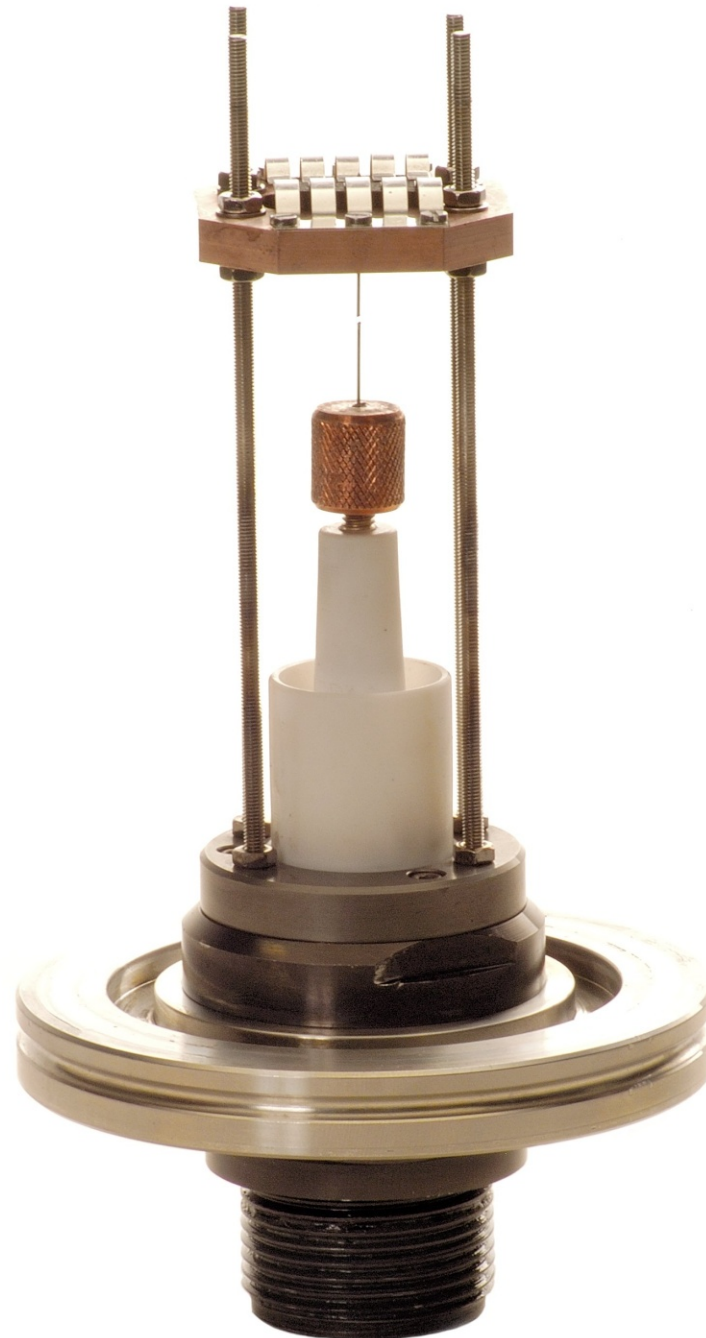
It soon became evident in the wire shock tests that thermal shock was not the problem. The wire was not failing from a single or a few shock pulses, but could survive millions of pulses. The problem is not thermal shock but fatigue and creep. Fatigue and creep are not amenable to analysis. It is not possible to predict the number of cycles to failure with any accuracy.

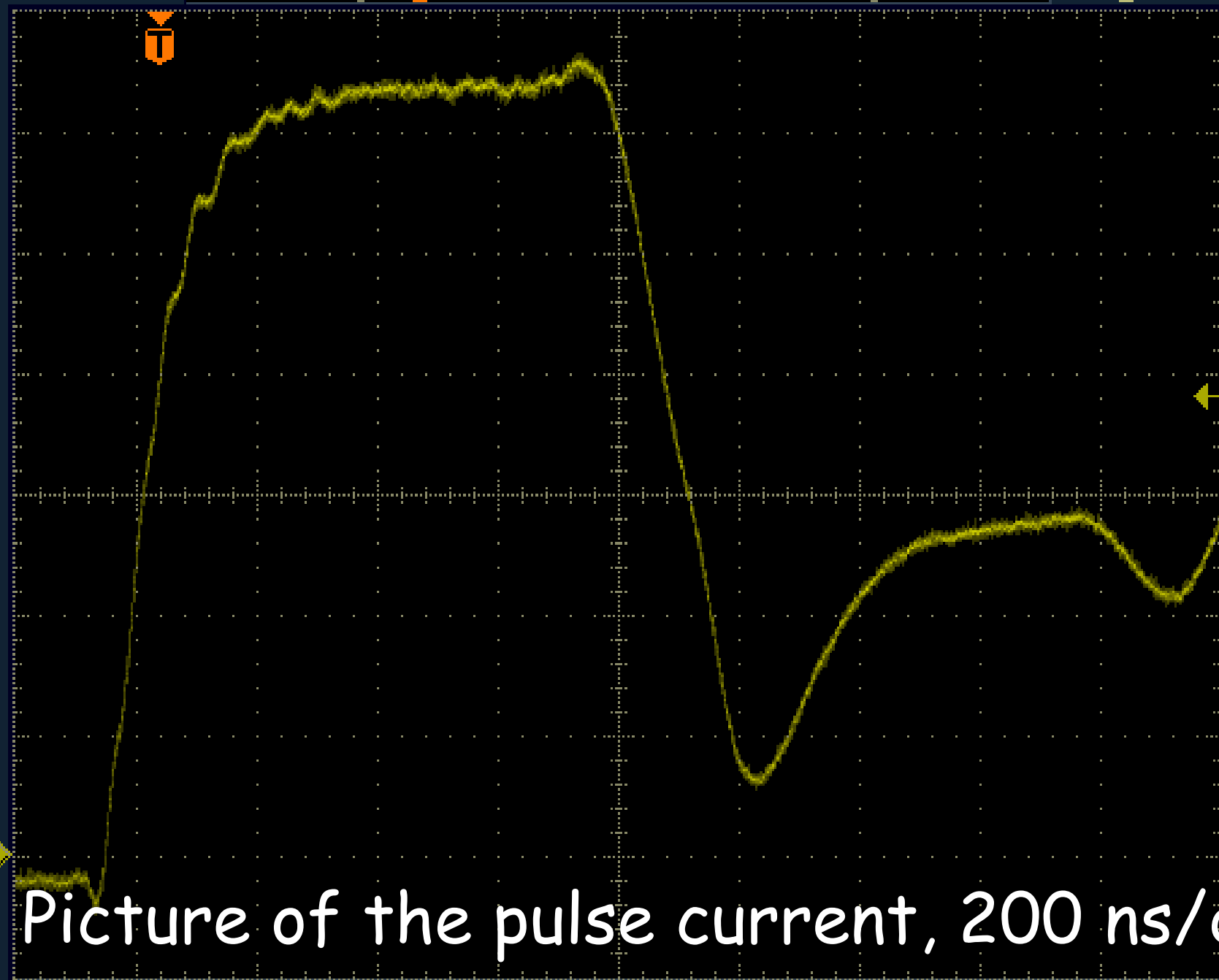
Vertical Section through the Wire Test Apparatus



W26

Tungsten
Wire
Assembly





Picture of the pulse current, 200 ns/division

Ch1 1.00 V B_w M 200ns A Ch1 f 3.80 V

12.00 %

Some Results: 0.5 mm diameter Tungsten Wires

Target Number	Pulse Current A	Temp Jump K	Peak Temp K	Number of Pulses to Failure	Comments	Equivalent Power, MW, in Target Diameter	
						2 cm	3 cm
W03	4900 7200	90 200	2000 2200	$>3.4 \times 10^6$ 16,500	Broke	2.3	4.8
W08	6400	150	1900	$>1.6 \times 10^6$	Wire stuck to top connection (cu blocks)	3.9	8.4
W09	5560 5840	120 130	1900 2050	4.2×10^6 9×10^6	Top connector failed	3 3.3	6.4 7.0
W15	6400	180	1950	1.3×10^6	Wire stuck to top connection (cu blocks)	3.9	8.4
W26	6200 7520- 8000	140 ~230	2000 ~1800	10×10^6 3×10^6	Broke	3.6 ~6	7.8 ~12
W28	6560	180	1900	26.4×10^6	Crack appeared	4.1	8.8
W30	4720	93	1870	54.5×10^6	Broke	2.1	4.7
W36	6480	150	600	113.2×10^6	Not Broken	4.0	8.6

"Equivalent Target": This shows the equivalent beam power (MW) and target radius (cm) in a real target for the same stress in the test wire. Assumes a parabolic beam distribution and 3 micro-pulses per macro-pulse of 20 micro-s.

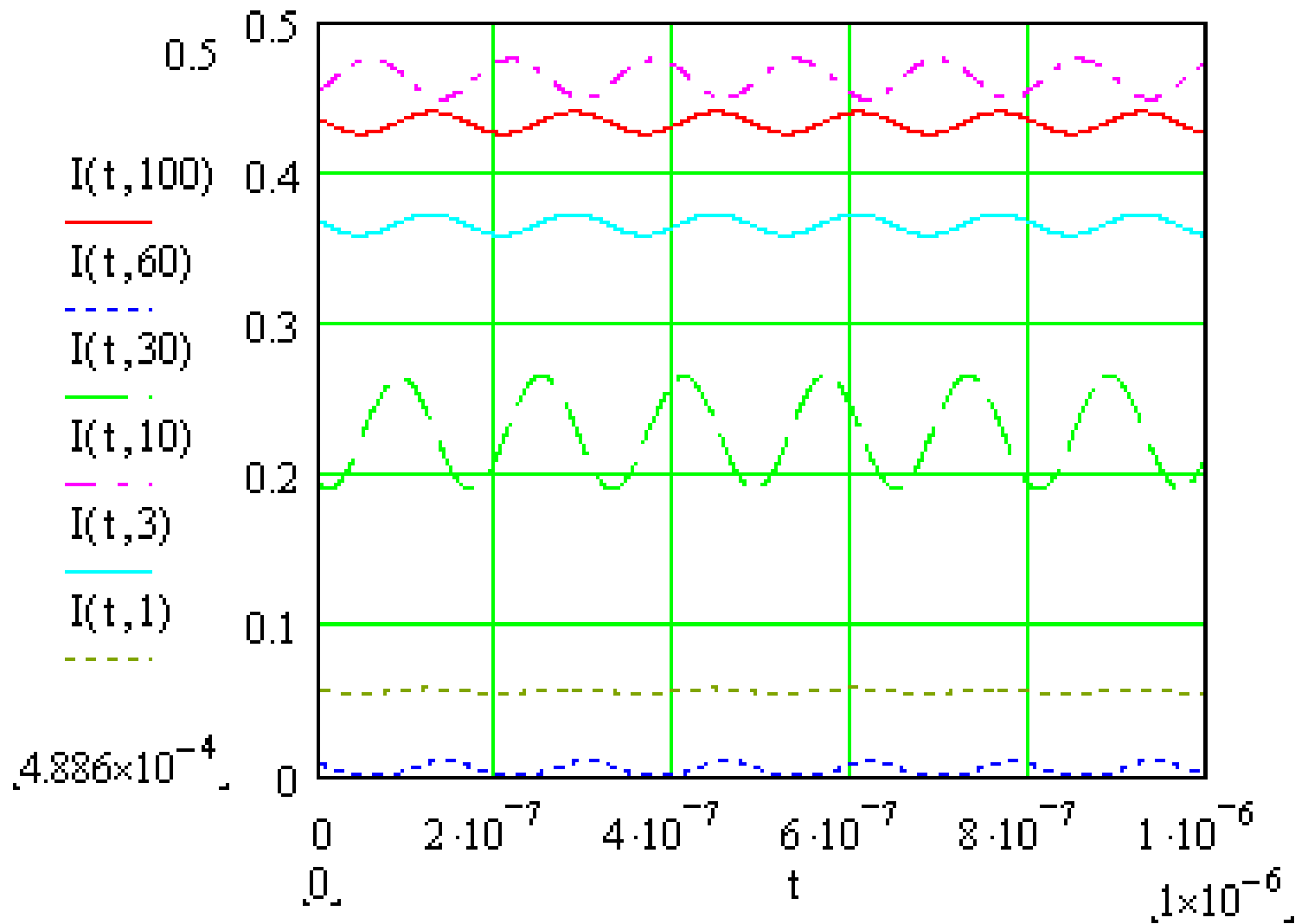
Conclusions

I believe that the viability of solid tungsten targets at high-temperature for a long life (~10 years) has been demonstrated with respect to thermal shock and fatigue and will not suffer undue radiation damage.

3. Thermal Shock Studies: B) Measure Surface Motion and deduce the constitutive equations of state at high temperature under shock conditions.

Currently a VISAR* is being used to measure the surface accelerations/velocities. We started by trying to measure the radial vibrations of the wire but once I understood how the VISAR worked it was clear that the expected signal would be in the noise. I am now setting up to measure the vibrations of the "free" end of the wire. This gives larger signals and should enable us to get results - when the power supply has been refurbished.

*Velocity Interferometer System for Any Reflector



VISAR signals from the radial motion of a 0.5 mm diameter tungsten wire. (Calculated for simple sinusoidal oscillation of surface.) **Signals in the noise.**

Looking at the end of the wire will have other advantages:

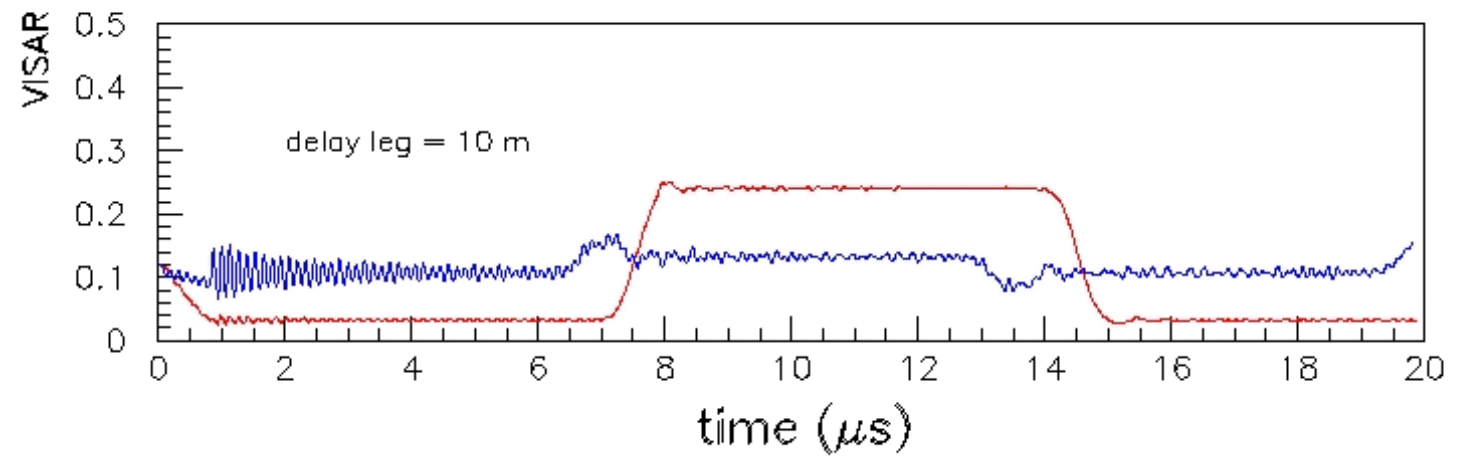
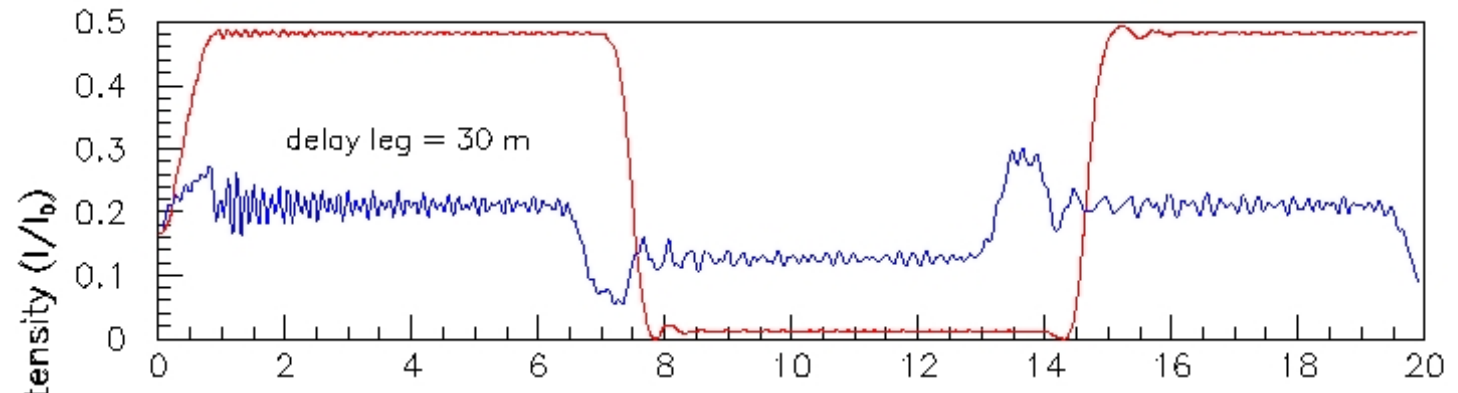
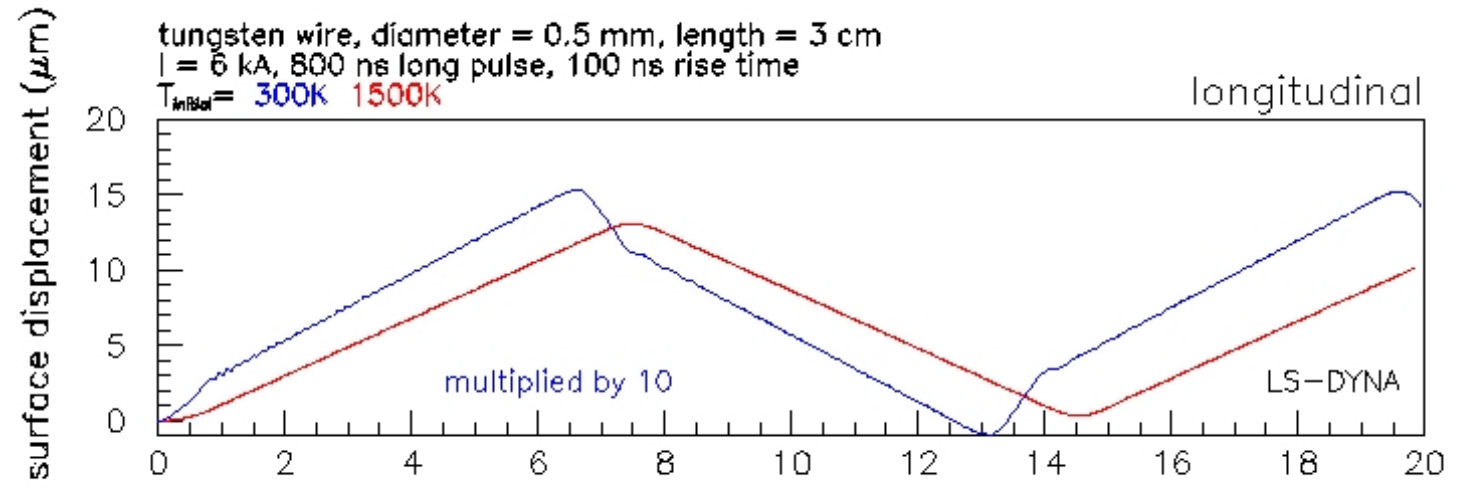
a) Measuring the radial motions with the VISAR, it was not possible to have successive current pulses close together and hence to have the wire hot (~ 1800 K) because the wire bent and the laser (VISAR) was no longer aligned on the wire. Hence we could only carry out measurements at \sim room temperature.

b) Measuring the axial motion, the "free end of the wire is well located (except axially) so heating the wire with successive pulses should not be a problem. Hence, we can make VISAR measurements from room temperature to (~ 1800 K).

Goran Skoro

Measuring the free end of a 0.5 mm diameter tungsten wire. 6000 A pulse.

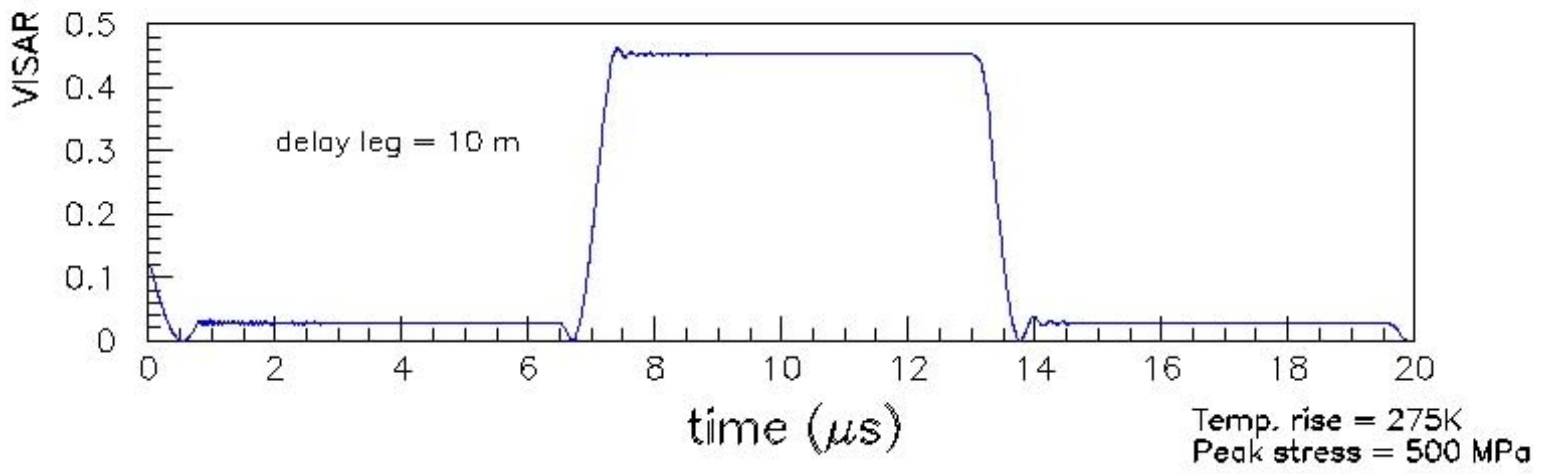
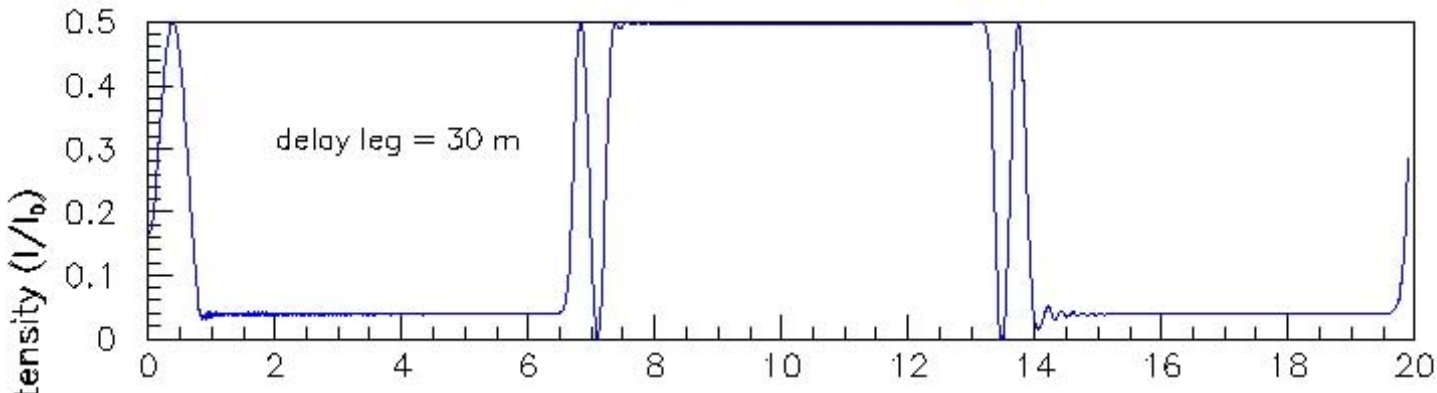
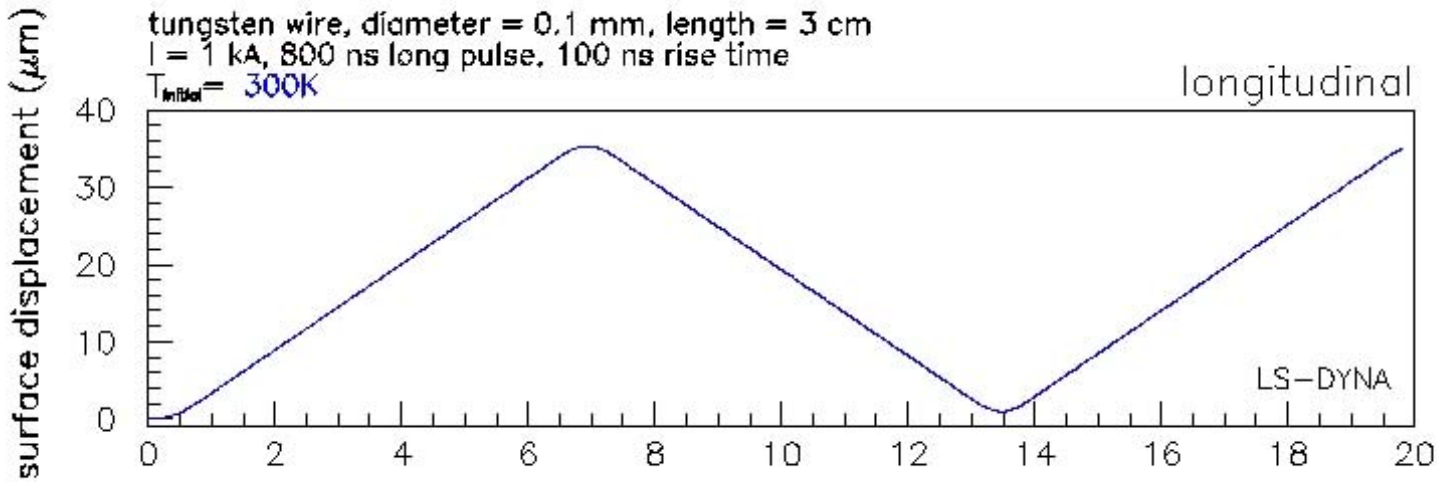
300 K
1500 K



Goran Skoro

Measuring the free end of a 0.1 mm diameter tungsten wire. 1000 A pulse. 300 K

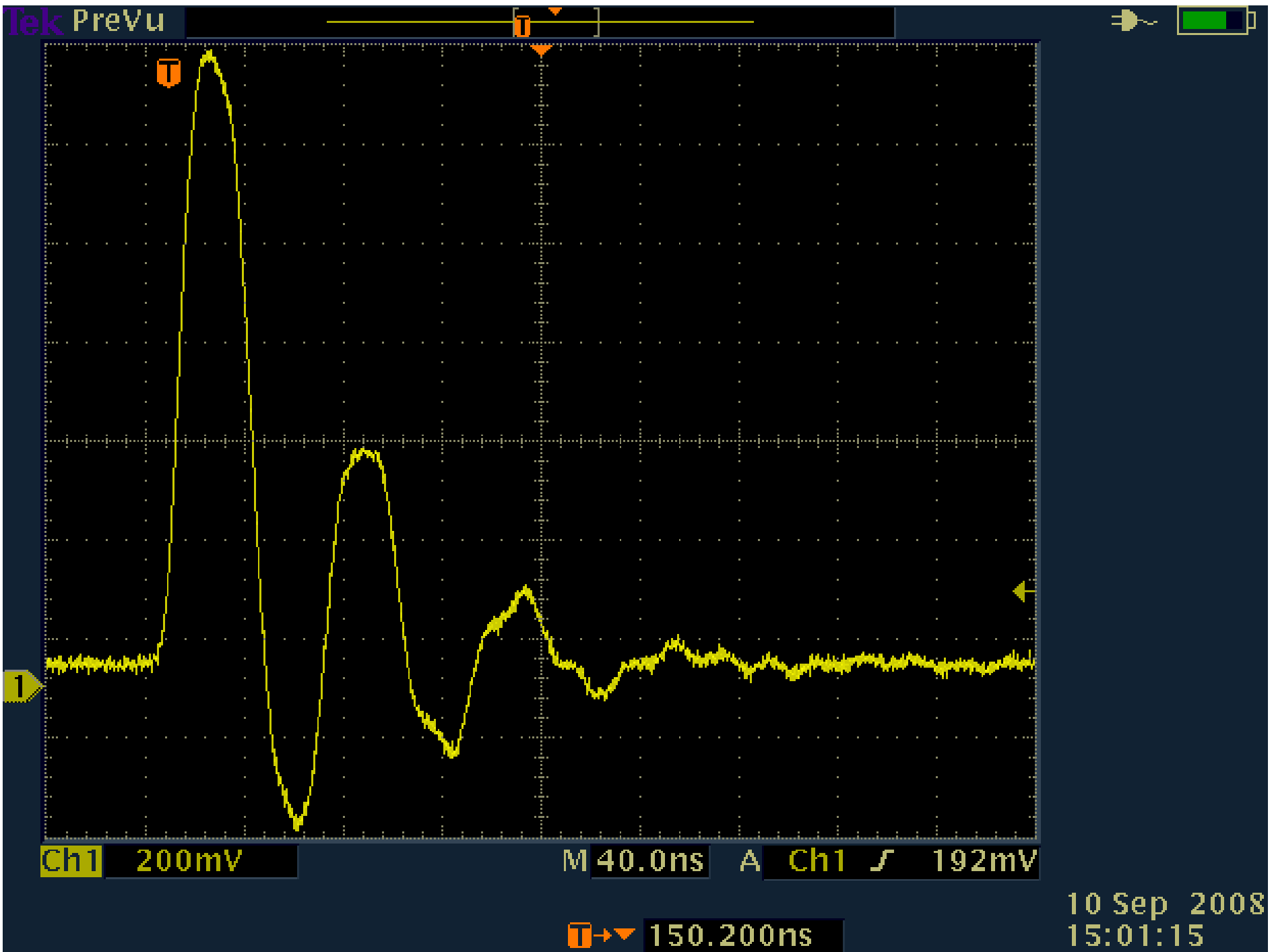
Excessive Stress
 $\sigma = 500 \text{ Mpa}$,
 $\Delta T = 500 \text{ K}$



The present power supply has a 100 ns rise time and 800 ns flat top. Ideally we would like a faster shorter pulse to generate the shock. **A prototype capacitor/spark gap power supply** has been built and tested to give shorter pulses - 20-30 ns rise and 30-40 ns fall, no flat top, peak current 20-40 kA.

Measuring the end motion of the wire and using this capacitor power supply and the original psu will enable us to obtain good VISAR signals for wire temperatures from 300 to 1800 K and simulate the stresses to be found in the target.

Calculations using LS-DYNA by Goran Skoro to simulate the shock stress and motions in the target and wire. Also simulating the VISAR signals.



Current pulse from prototype Capacitor/Spark Gap PSU

Current and Future Work

1. Complete VISAR measurements (longitudinal motions of the test wire). Build (probably) capacitor psu?
2. Continue life tests on wires.
3. Life and radiation tests of better materials - WReHfC?
4. In-beam few pulse test of a W bar on ISIS.
5. Continue to study pion yield and capture and the solenoid field requirements.
6. **Mechanical design of the target bar moving mechanism and the solenoid.** Once we have a really nice solution to moving the bars in and out of the beam the target problem is solved since we have shown that the lifetime is >10 yrs (- but should have in-beam test).
7. Target station design and costing.
8. Optimisation of the target geometry and density.



Optimisation of the Target Geometry and Density for Maximum Pion Yield

-

The Importance of Pion Absorption

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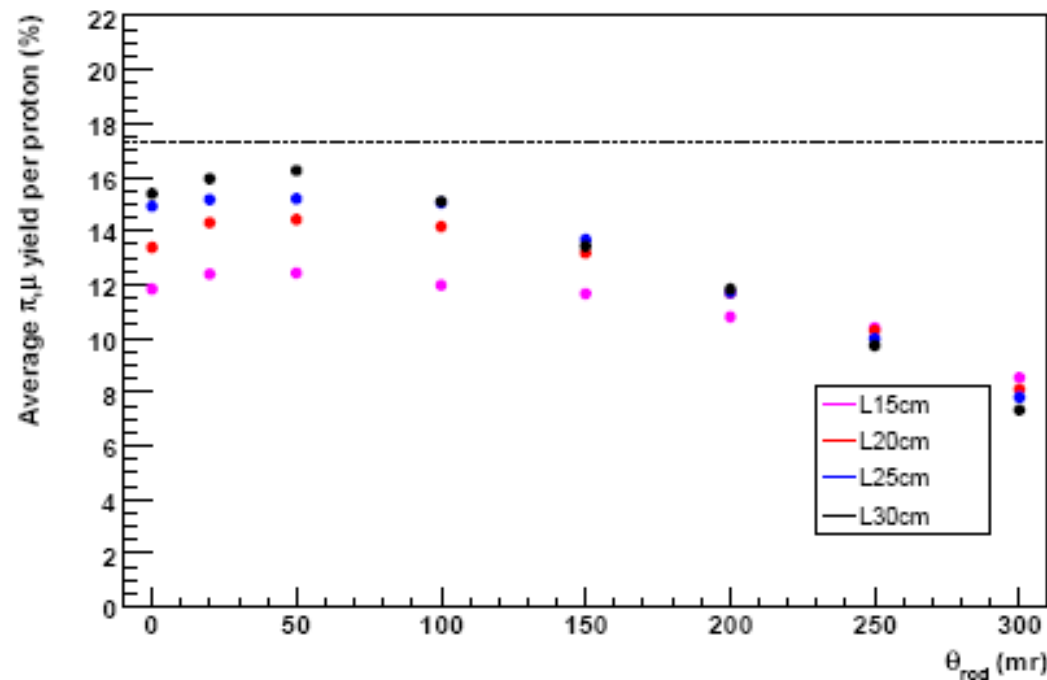
**With thanks to
John Back and Stephen Brooks
for computer calculations and discussions**

John Back calculated the yield from a 50% density tungsten powder target. Presented at Oxford-Princeton Workshop, May 2008. In fact John had done a similar calculation in May 2007 and the significance of the result had eluded me at the time.

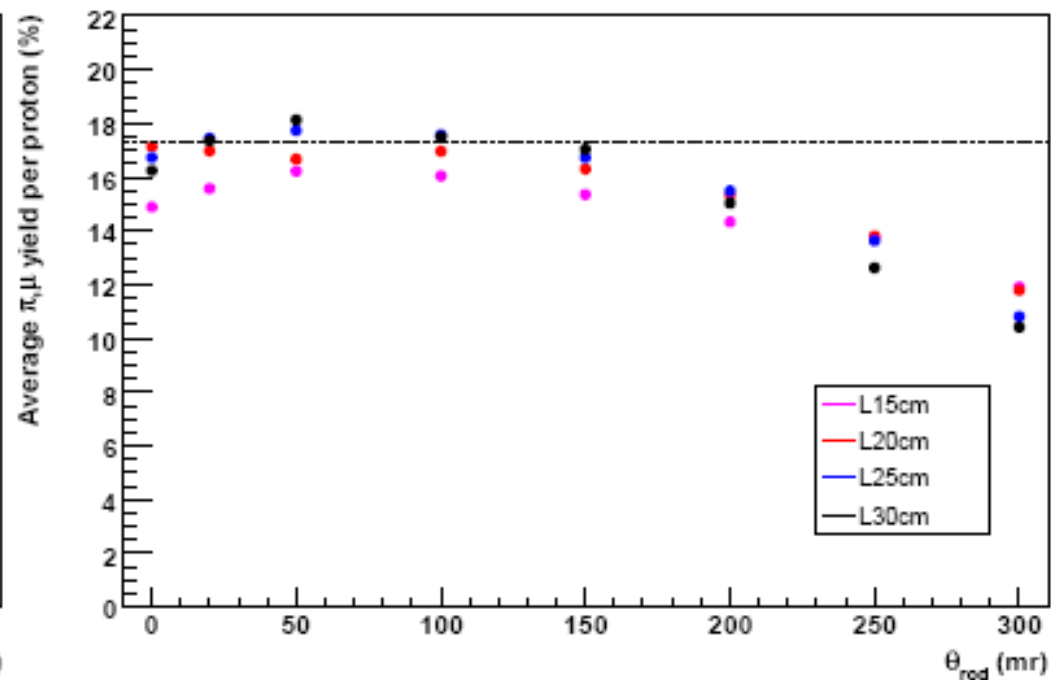
Powder jet target yields

- Following plots show the yield for a W powder particle jet:
 - Jet simulated as a simple cylinder, with $\rho = 0.5\rho_W$
 - Jet parameters: useable length, radius and tilt
 - Assuming $r_{\text{beam}} = r_{\text{jet}}$, $\theta_{\text{beam}} = \theta_{\text{jet}}$, unlike Hg jet case
- Use Study 2 geometry for the powdered jet (not Helmholtz arrangement)
- Comparing yields against those from the solid W target Helmholtz arrangement
- Also comparing the yields from the powdered jet with the yield from the optimal Hg jet case.

Charge averaged π, μ yield per proton at $z = 6$ m for $r_{\text{beam}} = 0.25$ cm



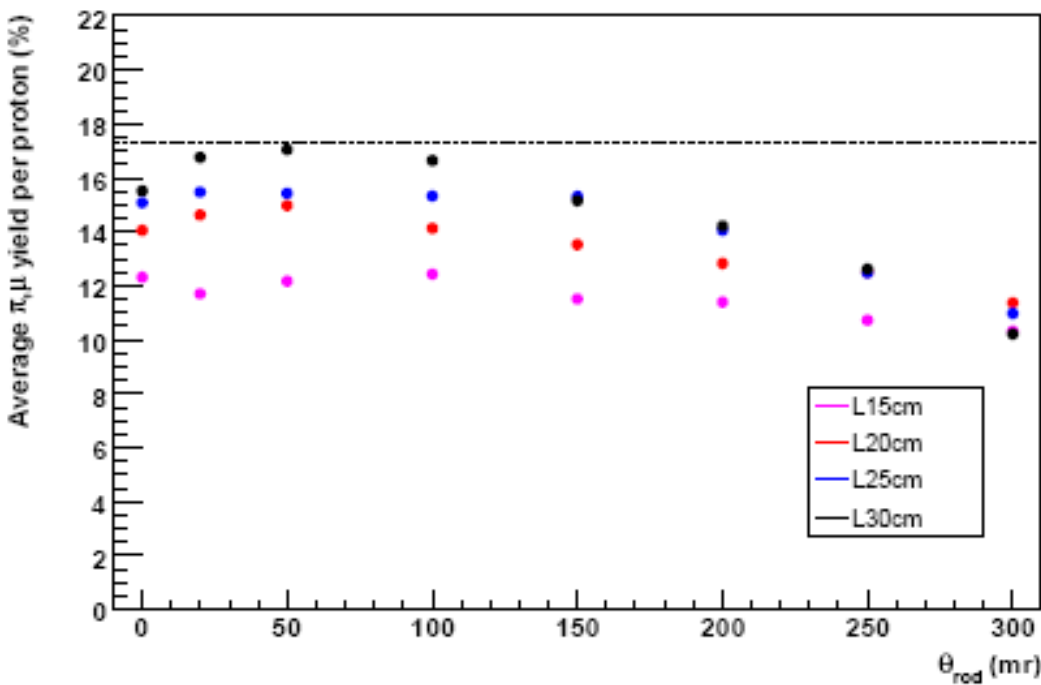
Powdered jet



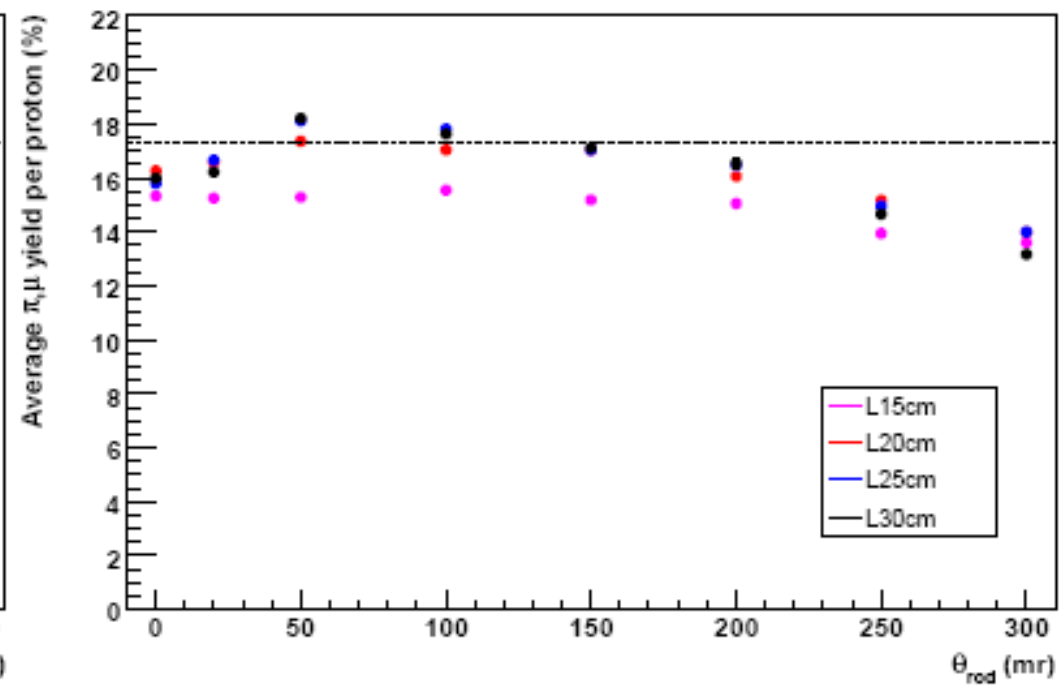
Solid (Helmholtz)

Dotted line is Hg jet yield for 10 GeV beam (using StudyII optimal tilt, radii)

Charge averaged π, μ yield per proton at $z = 6$ m for $r_{\text{beam}} = 0.50$ cm



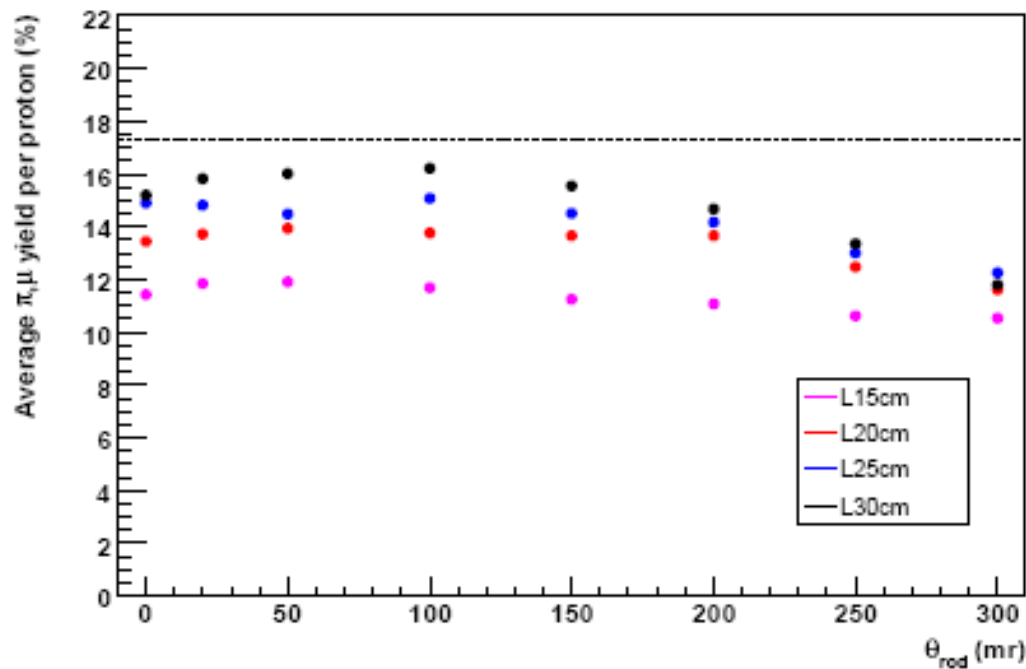
Powdered jet



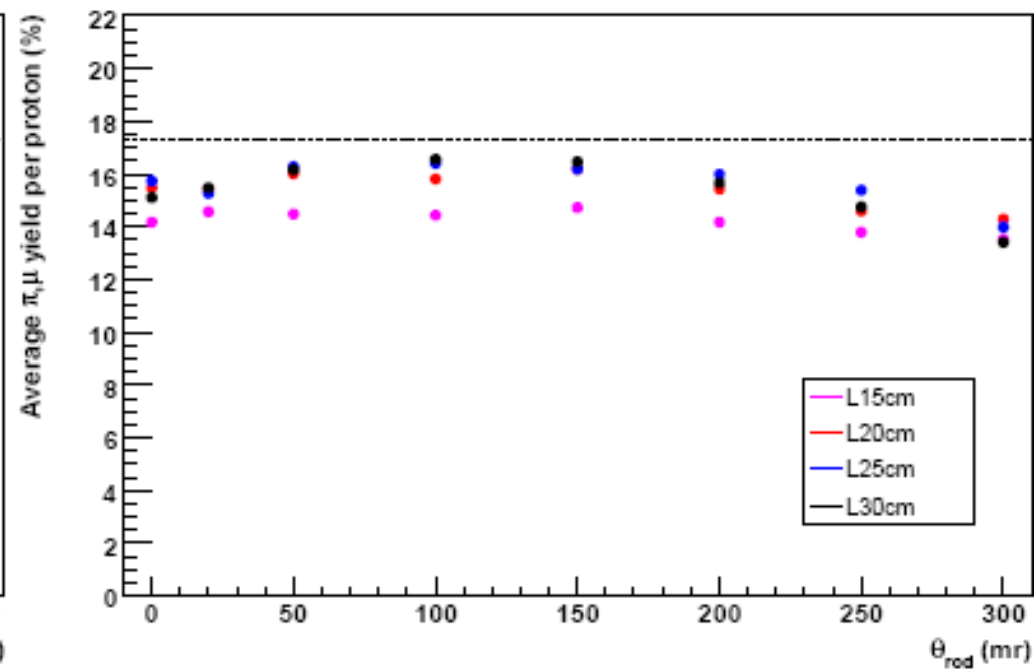
Solid (Helmholtz)

Dotted line is Hg jet yield for 10 GeV beam (using StudyII optimal tilt, radii)

Charge averaged π, μ yield per proton at $z = 6$ m for $r_{\text{beam}} = 0.75$ cm



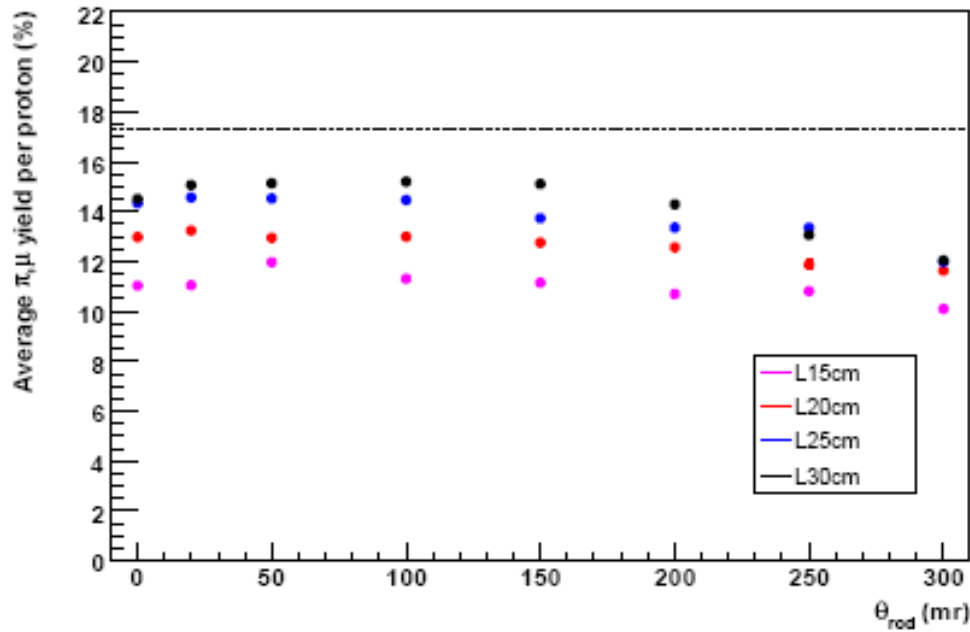
Powdered jet



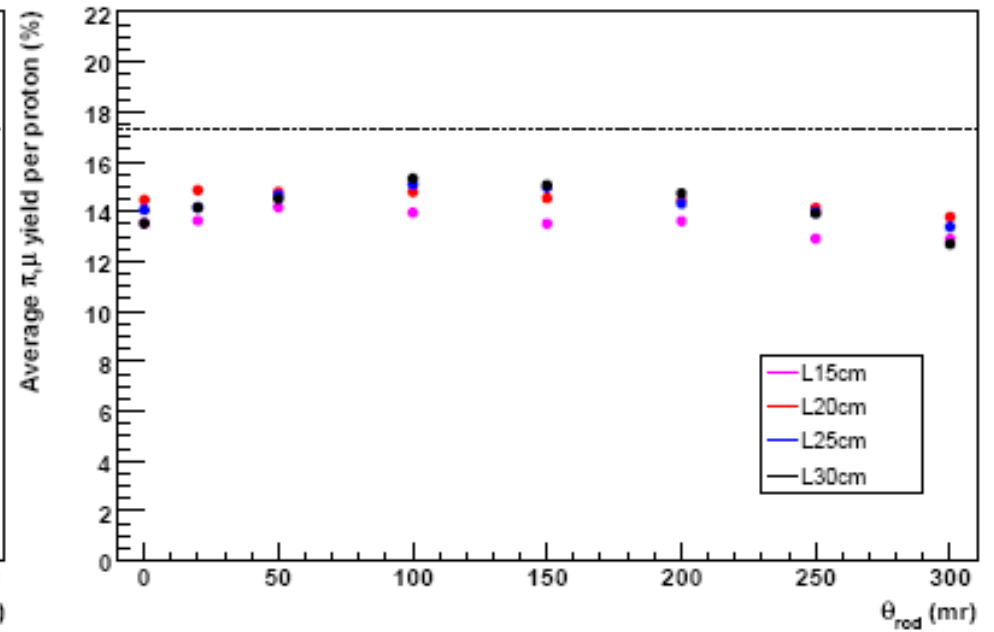
Solid (Helmholtz)

Dotted line is Hg jet yield for 10 GeV beam (using StudyII optimal tilt, radii)

Charge averaged π, μ yield per proton at $z = 6$ m for $r_{\text{beam}} = 1$ cm



Powdered jet



Solid (Helmholtz)

Dotted line is Hg jet yield for 10 GeV beam (using StudyII optimal tilt, radii)

Surprising Result:-

- ✓ The tungsten powder jet has a good yield - slightly smaller than the solid target.
- ✓ Getting larger as the target and beam radius increases. Almost equal at $r = 1$ cm.

Why Surprising?

I expected the yield to vary as the target density and I had assumed that the pion absorption was not large.

A Simple Model for Pion Yield from the Target

Assume that the number of pions produced per proton hitting the target is p and that the fraction of pions absorbed in the target is a . Then, the yield of pions for a solid target is,

$$Y = p(1-a)$$

and for a target of the same geometry and material but density f , is,

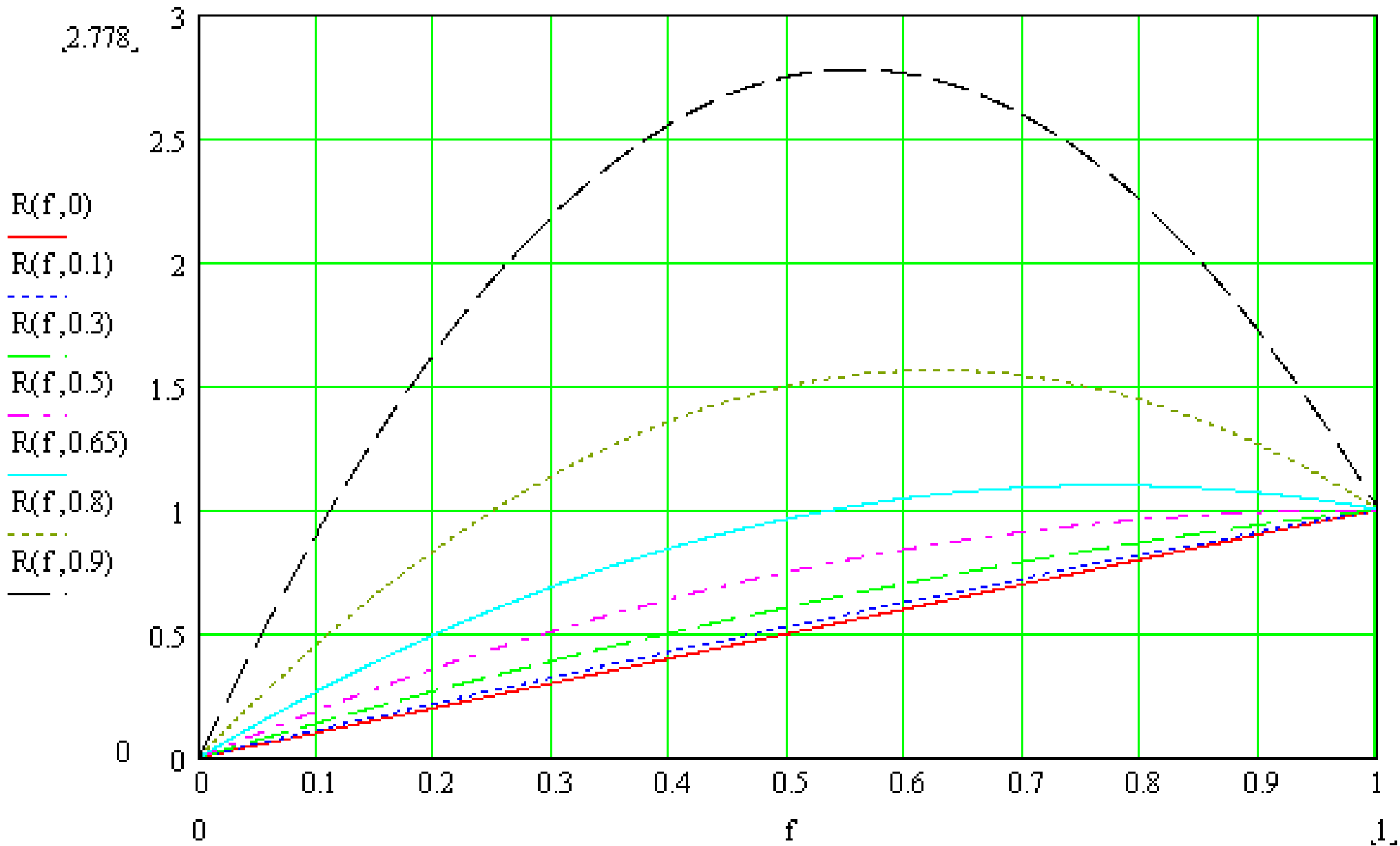
$$Y_f = fp(1-fa)$$

The ratio,

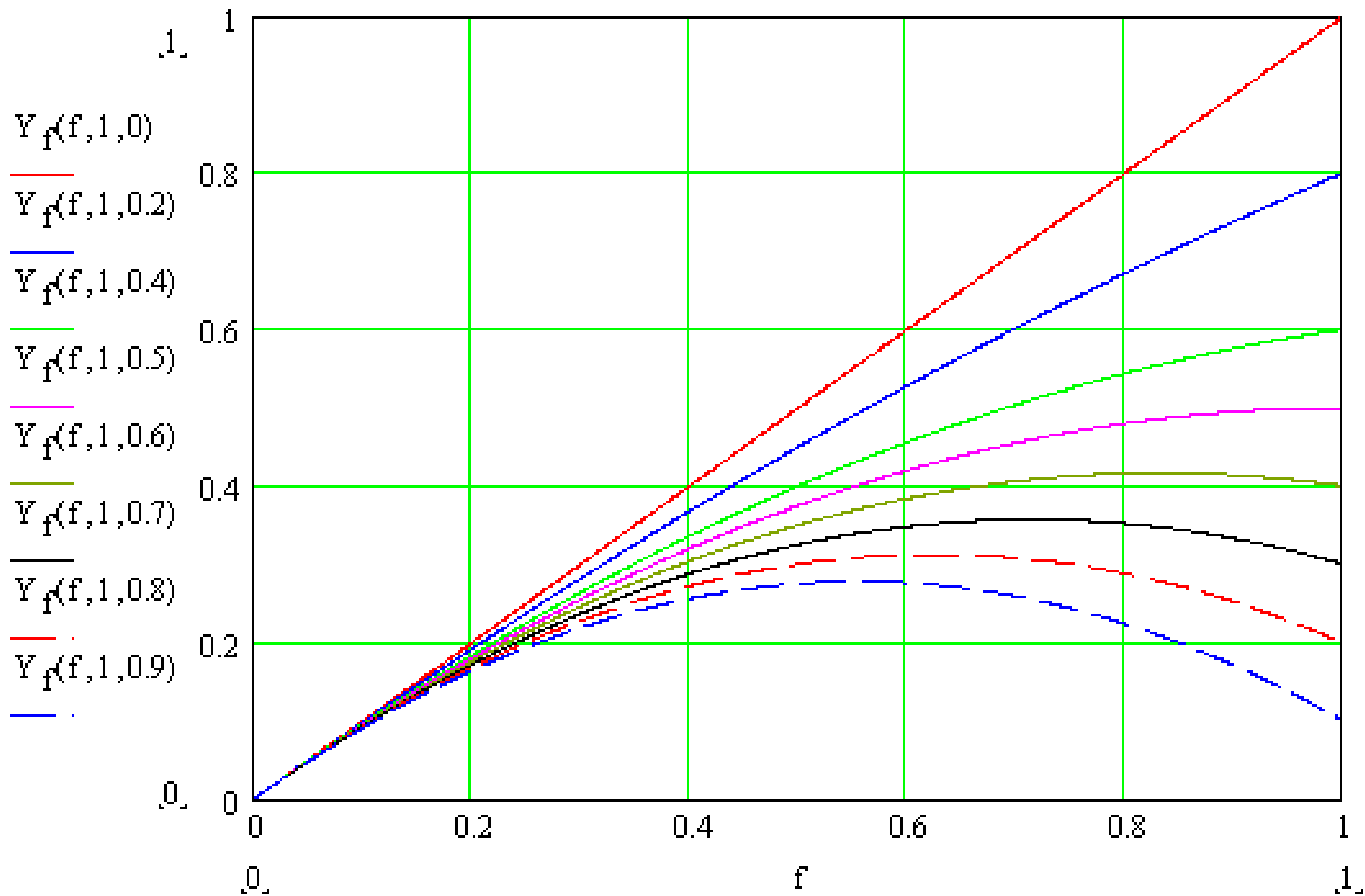
$$R = Y_f / Y = f(1-fa) / (1-a)$$

is shown in the next slide as f varies.

N.B. No magnetic field. Acceptance not included.



Graph of the yield ratios, $R = Y_f/Y$ for various target densities, f , and absorptions, a . Absorption of $a = 0.5-0.65$ would seem to fit John Back's calculations.



Yield as a function of target density, f , for different absorptions, a .

Now calculate the yields using
MARS (*Goran Skoro*).

The next slide shows the MARS calculation superimposed on my simple model.

N.B.

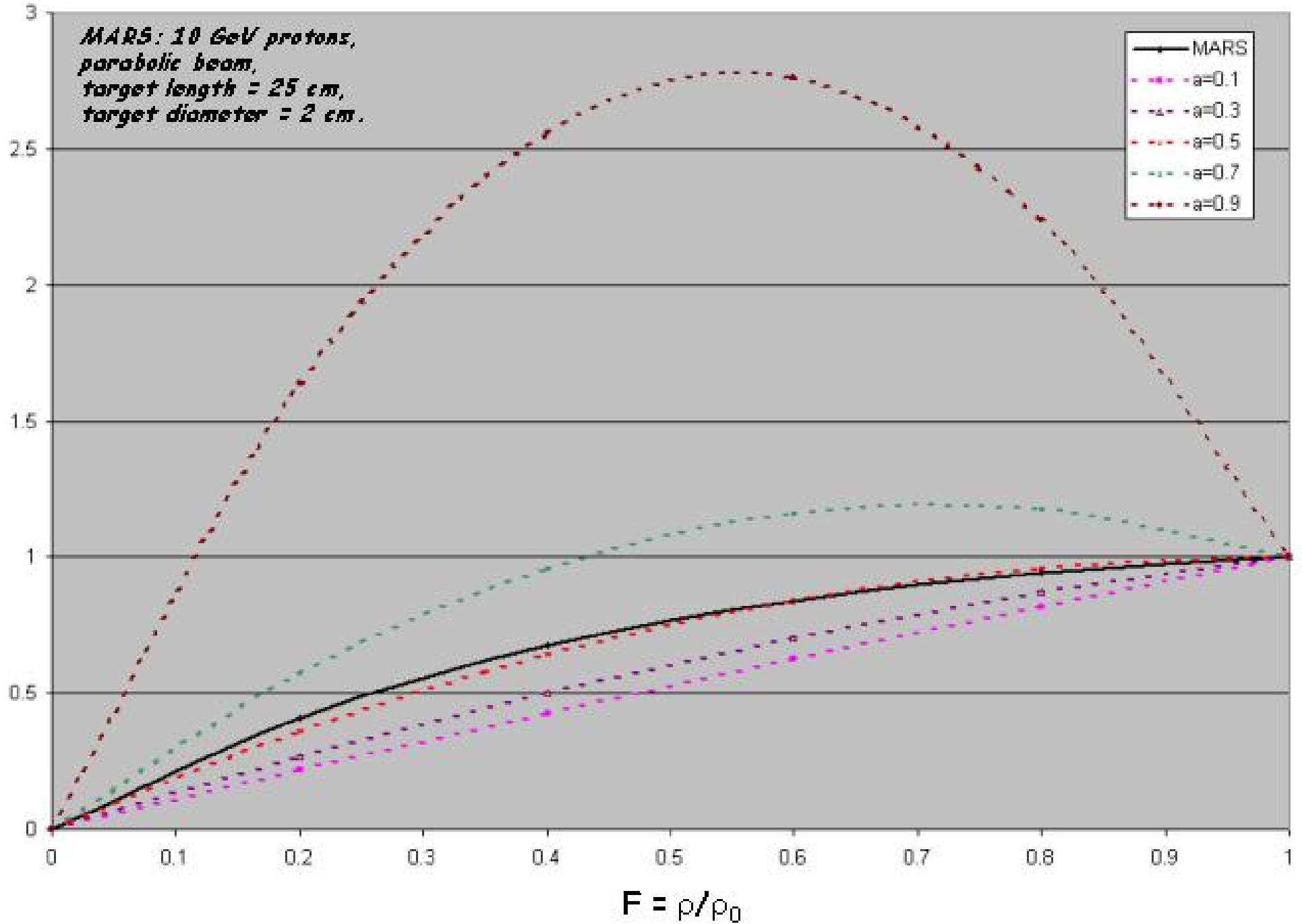
No magnetic field.

Yields are from the target surface, not downstream.

Pion yields from the tungsten targets with different densities

*MARS: 10 GeV protons,
parabolic beam,
target length = 25 cm,
target diameter = 2 cm.*

Ratio of the yields, $R = Y(\rho)/Y(\rho_0)$



So it looks like a good fit to the model, with absorption,

$$a = \sim 0.5.$$

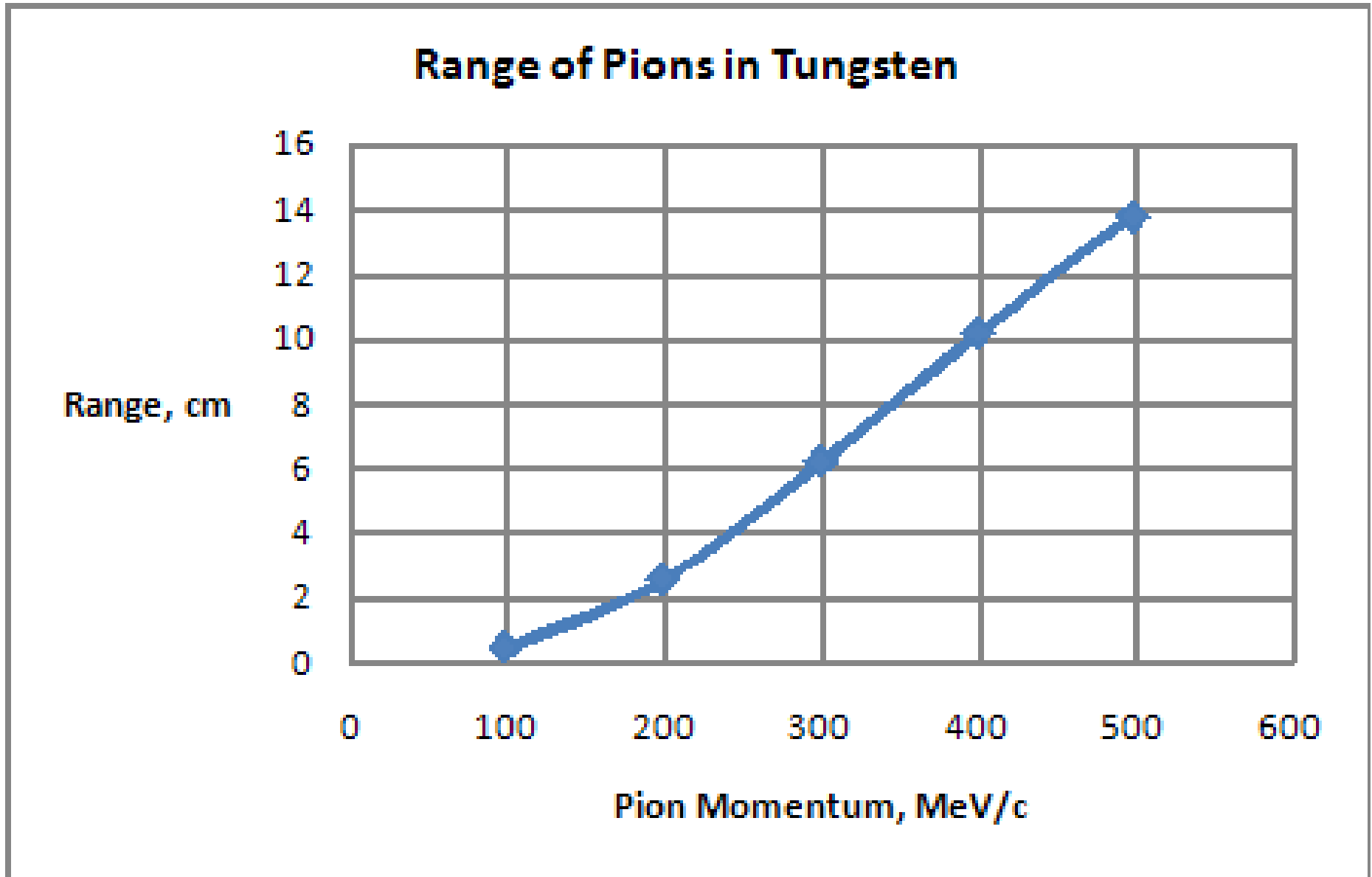
Again Large Absorption!!

So it looks like absorption is around 0.5 from both John and Goran's results.

NOTE:

Stephen Brooks has made a better approximation of the absorption and fits the MARS result very well.

The range of pions in tungsten in the momentum range 100-500 MeV/c is shown below.



The pions of low momentum will only get out of the target if they have a short path length within the target. So absorptions of 0.5 are realistic.

So, I ask:- What is the origin of the usefully accepted pions:

1. From where do the pions originate?
2. With what momenta?
3. With what angles?

Perhaps knowing the answers will enable us to optimise the target density and geometry for maximum useful yield.

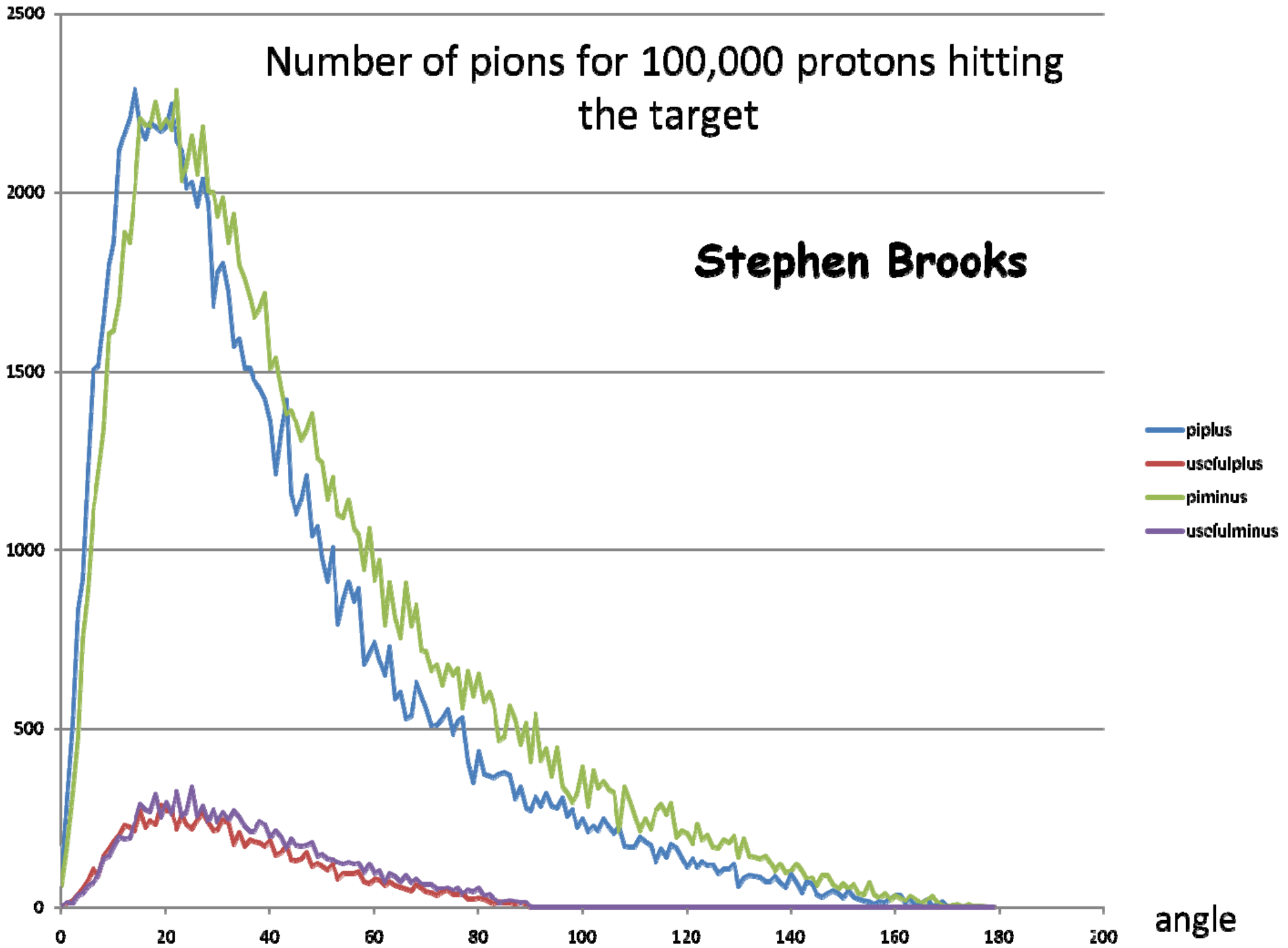
Stephen Brooks has made some plots of:

1. Number of pions emerging from the target surface versus the angle.
2. Number of pions emerging from 1 cm long bins along the axis of the surface of the target. Also included at $z = 20$ cm are the pions emerging from the end of the target cylinder. In terms of pion density at the surface, the pion density is twice as high from the end of the target as the best density from the cylindrical part of the target.
3. Number of pions emerging from the target as a function of angle within 1 cm long axial bins.
4. Number of pions emerging from the target as a function of momentum versus 1 cm long axial bins.

N.B. In all cases there are 100,000 protons hitting the target. The number emerging from the target and the number accepted into the cooling channel (*the useful pions*) are shown.

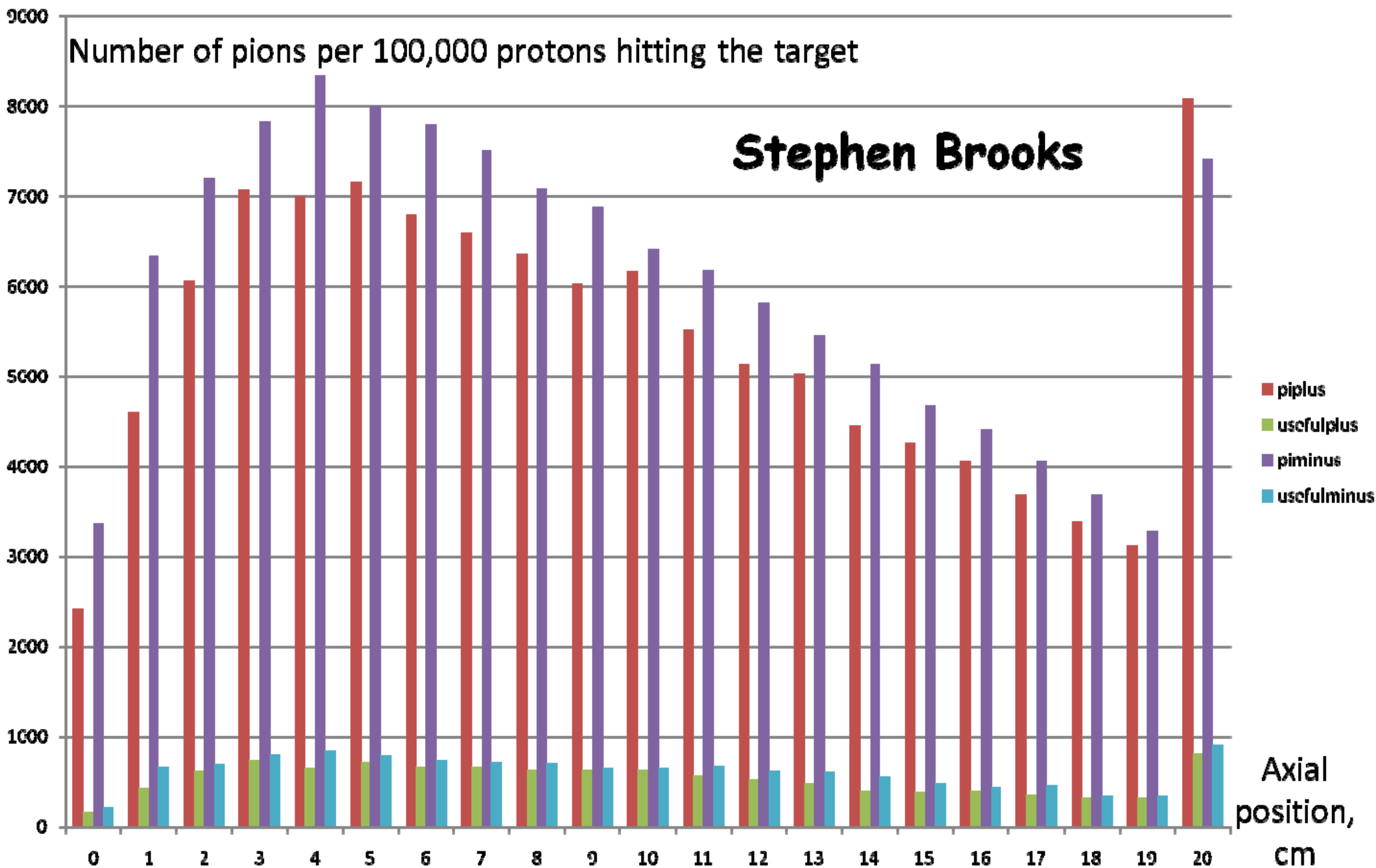
Number of pions for 100,000 protons hitting the target

Stephen Brooks

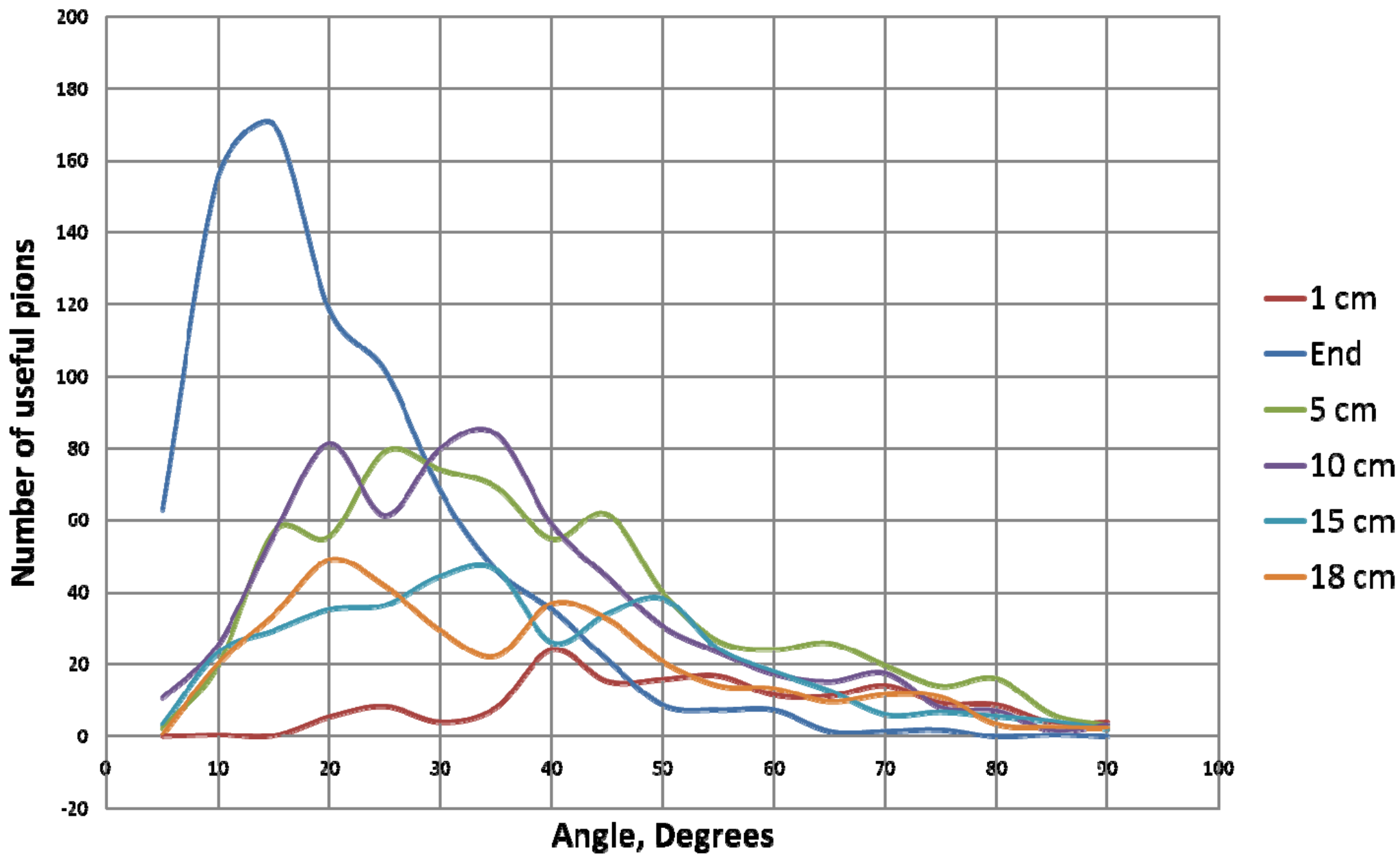


Number of pions per 100,000 protons hitting the target

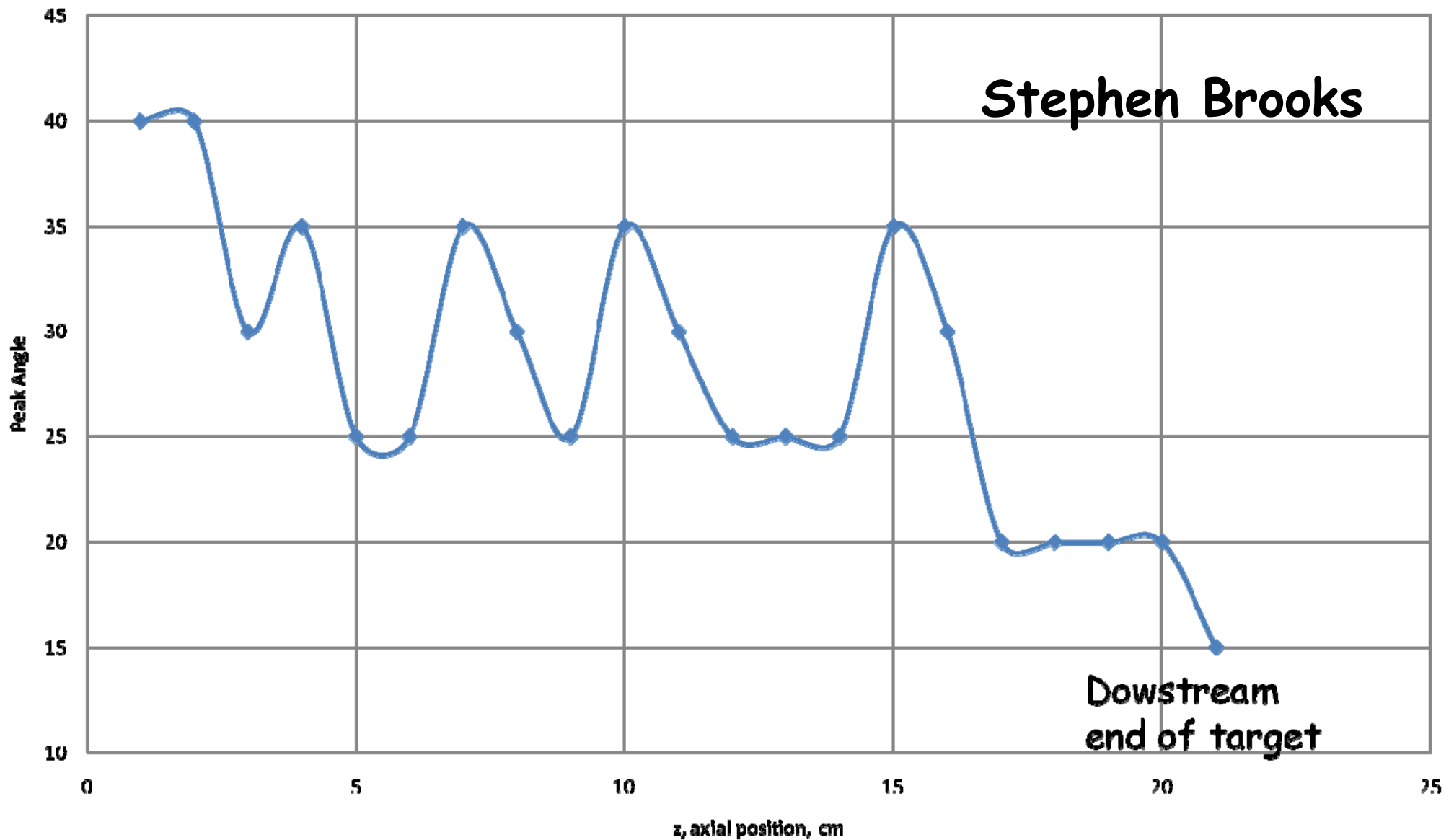
Stephen Brooks



Number of useful pions v angle of emergence at different axial positions



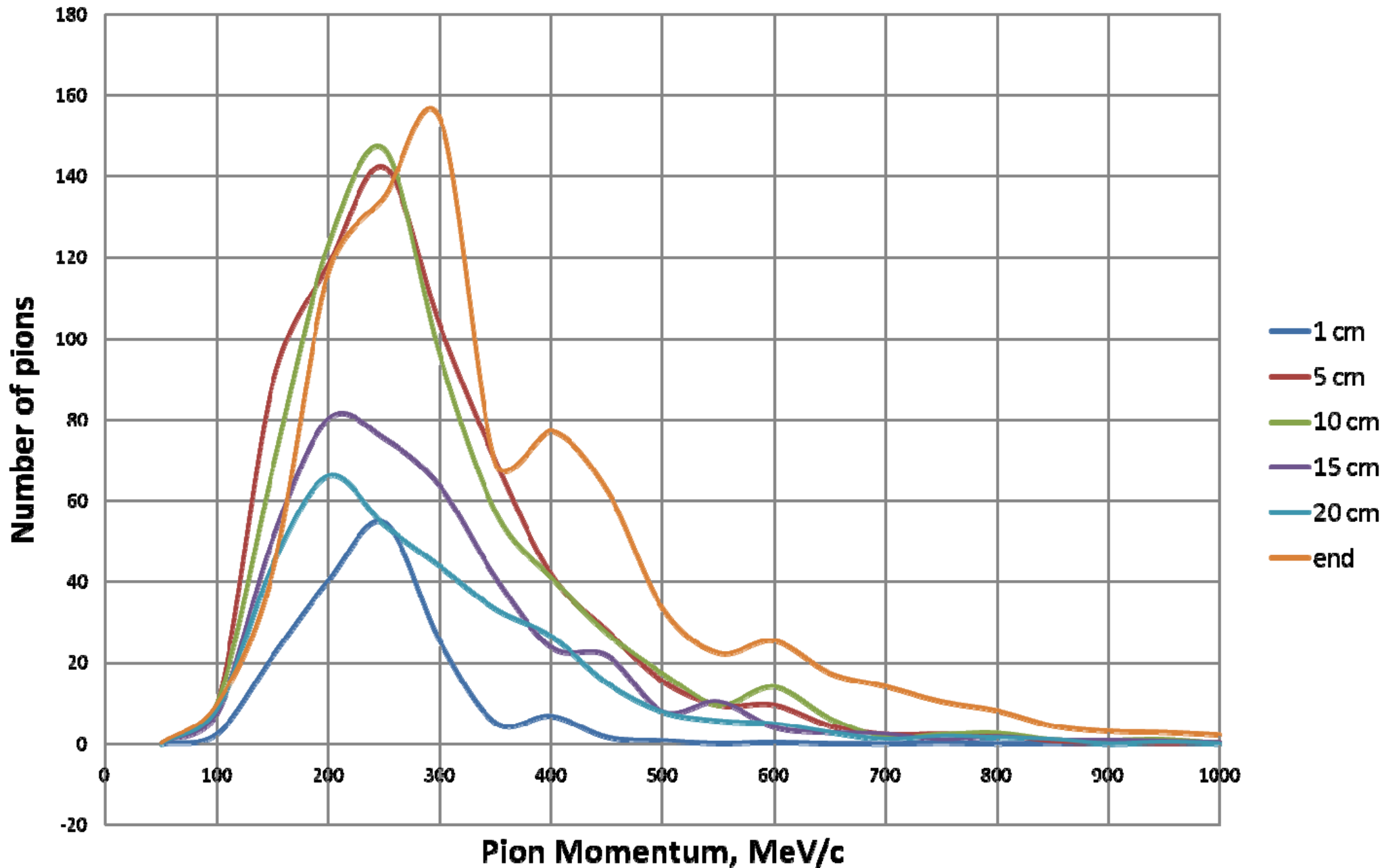
Peak angle versus axial position



Graph of the peak angle of the angular distribution of useful pions versus axial position, z (1 cm bins).

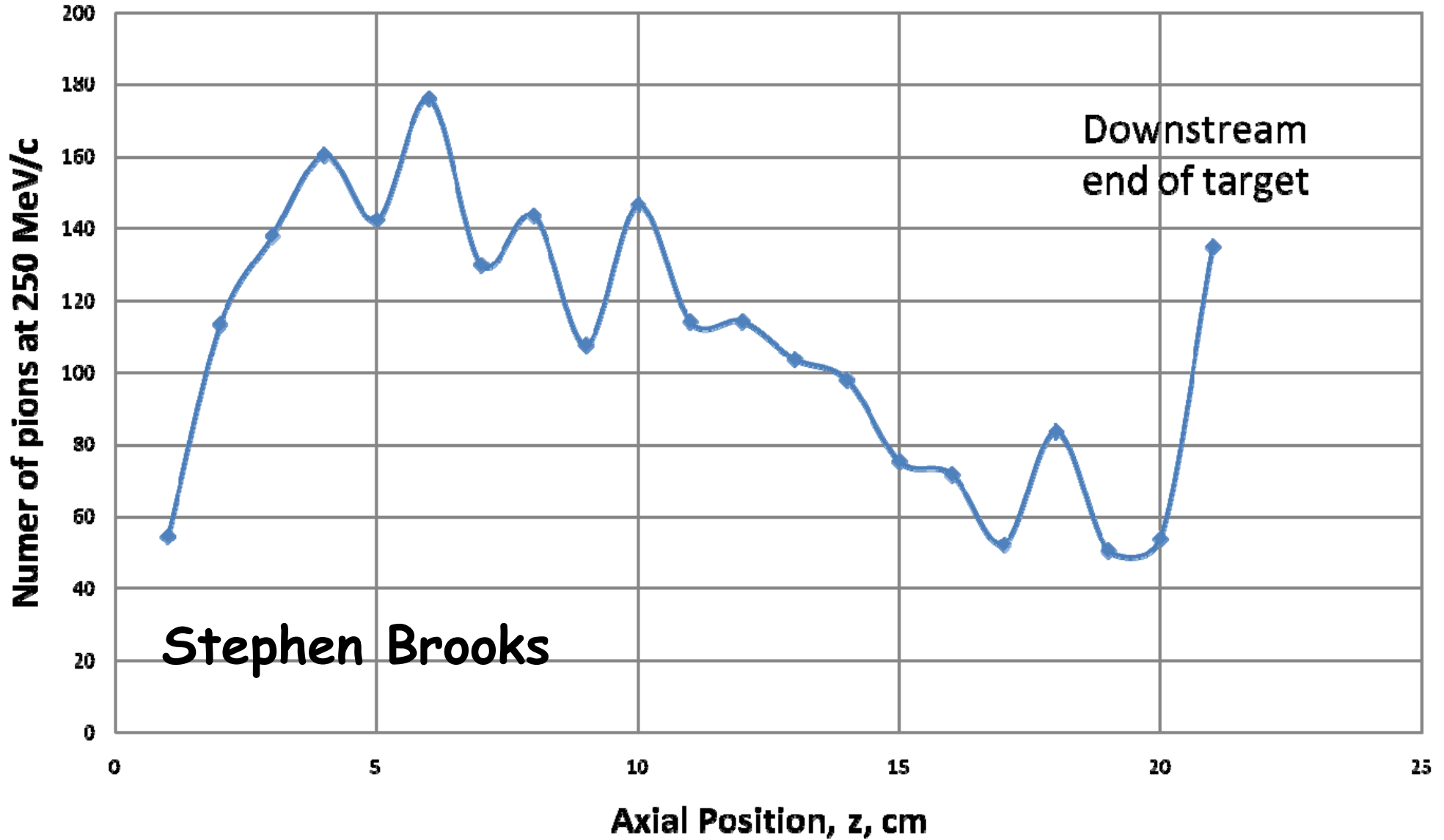
The peak no. of pions is approximately constant with z , but at the end is 3 times higher.

Useful Number of Pions versus Momentum from different target axial bins



The number of useful pions produced per 100,000 protons at different axial positions along the target versus their momenta, MeV/c.

No of Useful Pions at 250 MeV/c versus Axial Position



The peak of the useful pion distribution is at an momentum of ~ 250 MeV/c for all values of axial positions, z.

Goran Skoro is now computing the yield from targets with different shapes and densities. Here are some of the results so far. The calculations use MARS and include the magnetic field. Then a cut is made on the likely acceptance of the pions into the machine several meters downstream. The target length is kept at 20 cm and the target and beam are not tilted with respect to the magnetic axis.

NuFact target shape

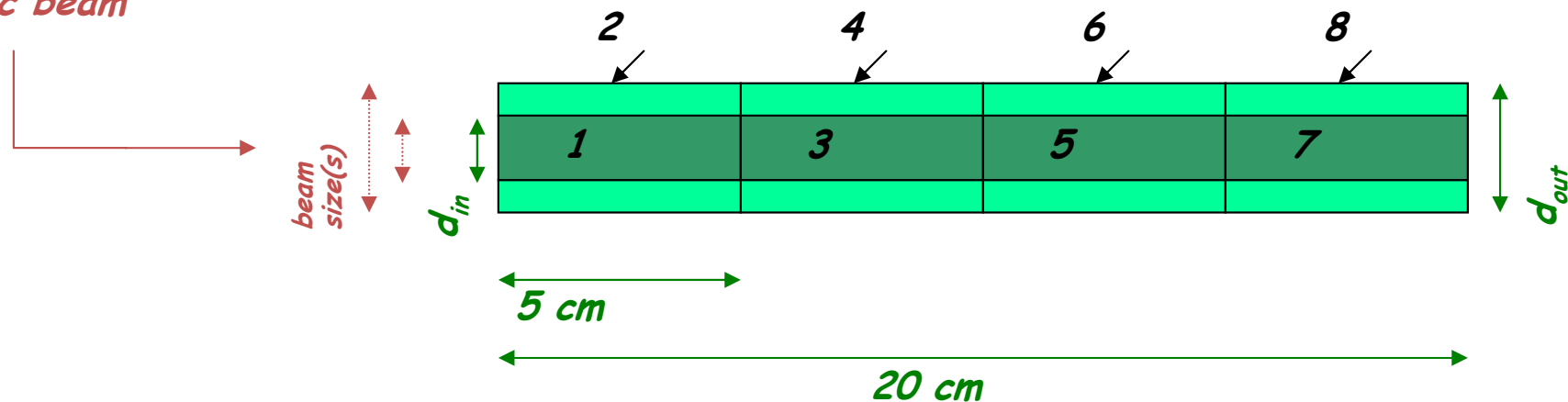
Goran Skoro

08 December 2008

Reminder: Optimisation of the tungsten target shape*

Idea

*10 GeV protons
parabolic beam*



8 segments (inner and outer cylinder; 4 divisions along the length)

each segment -> 2 possible density values (50(10)% and 100% of tungsten density)

number of different configurations = $2^8 = 256$

It means 256 MARS simulations (100.000 incoming protons per job)

*Let MARS decide what is the optimal configuration of the target
(on the basis of the pions yield)*

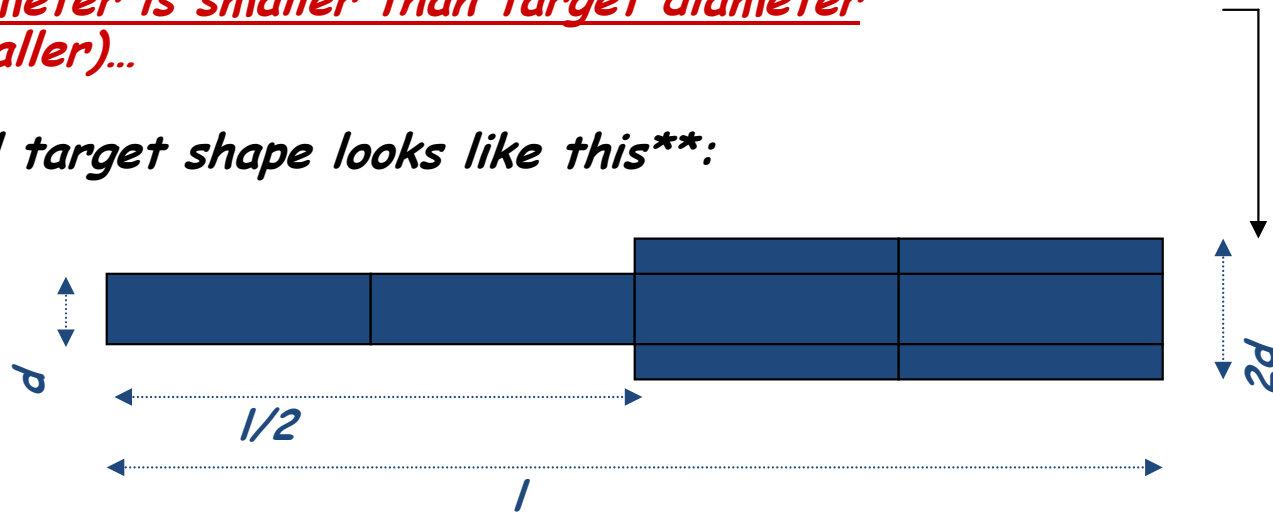
Reminder: Optimisation of the tungsten target shape*

Results

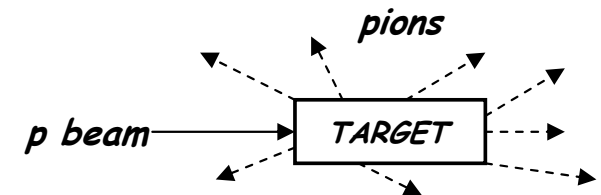
If beam radius = target radius The best option is to have full 100% density target

If beam diameter is smaller than target diameter
(here 2x smaller)...

...the optimal target shape looks like this**:



This is the result if we count all pions (no magnetic field)



What is the result for the target in a Neutrino Factory?

*http://hepunx.rl.ac.uk/uknf/wp3/shocksims/mars_dyna/Tungsten/Target_Shape.ppt

**Using a better (finer) segmentation we would obviously have some kind of paraboloid shape

NuFact target

20 T magnetic field

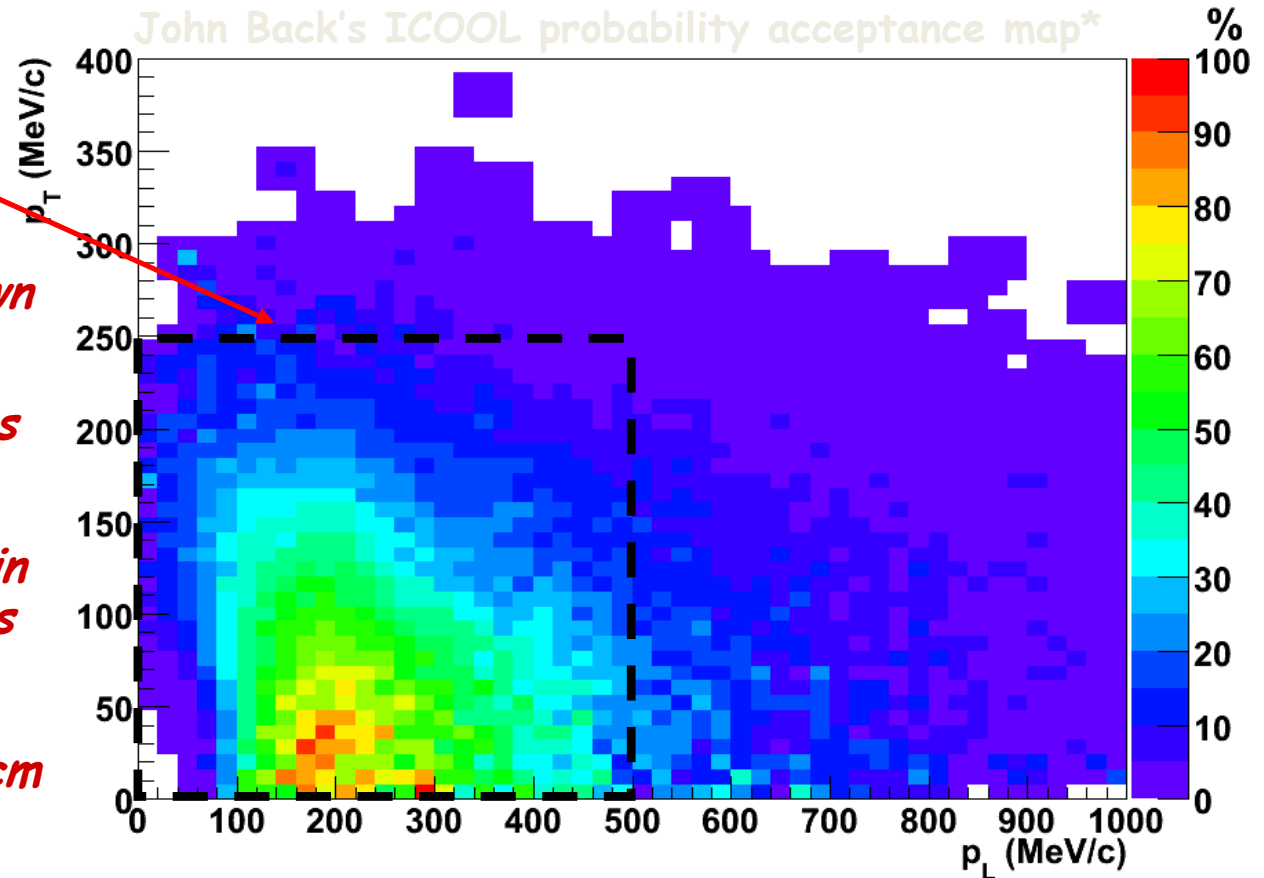
Cuts on pions p_T and p_L

*Pions counted a few meters down
within estimated aperture*

*Beam is parabolic (as in previous
analysis)*

*2⁸ different configurations (as in
previous analysis) -> calculations
take much more time now*

*Target length is constant = 20cm
(as in previous analysis)*



*http://hepunix.rl.ac.uk/uknf/wp3/pimuyields/pimuYield_12Jun08.pdf

In fact, we have 2 'different' studies here:

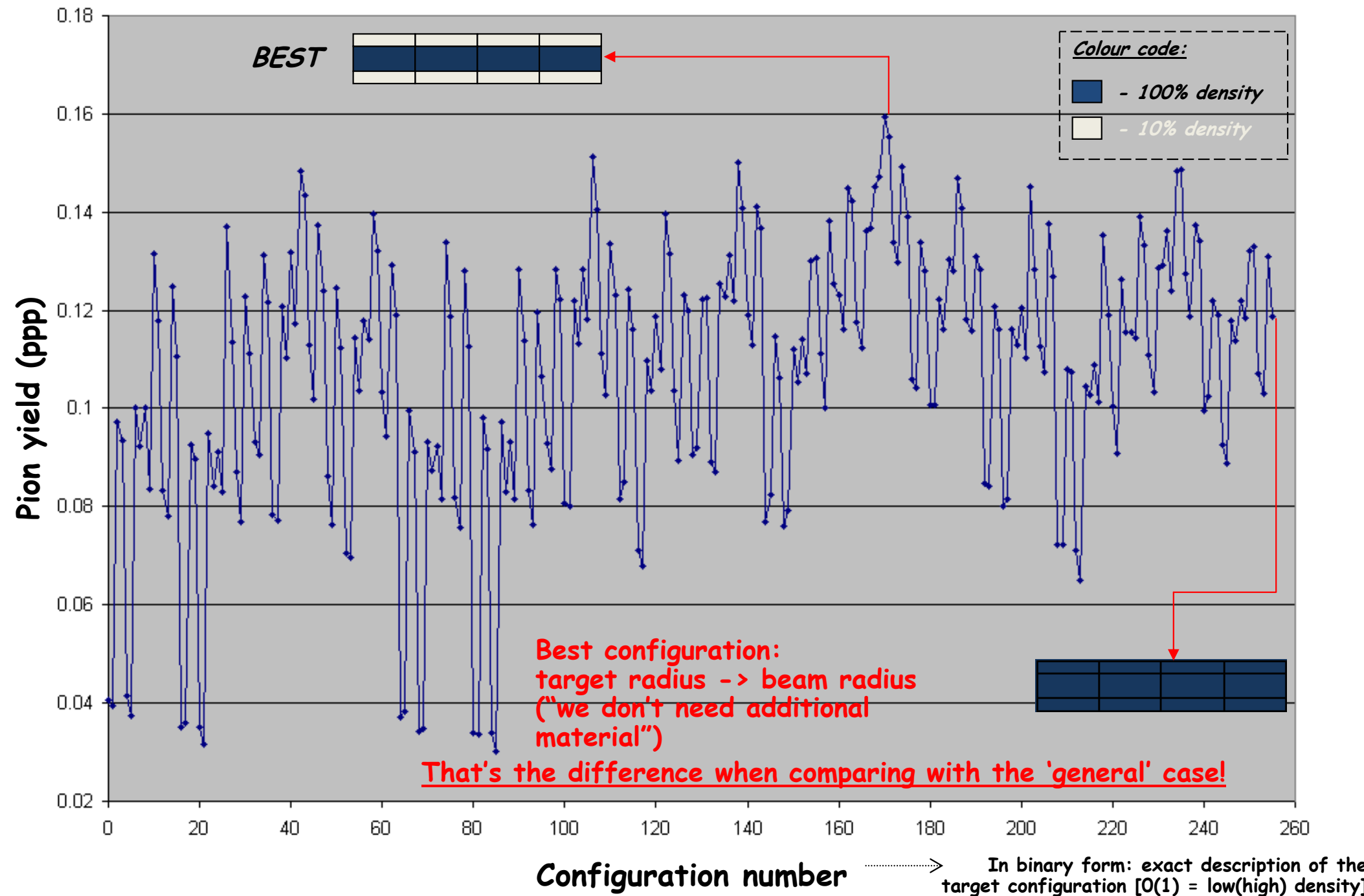
Optimisation of the target density - 100% and 50% density combinations

Optimisation of the target shape - 100% and 10(1)% density combinations

Optimisation of the NF tungsten target shape

Beam radius 0.5 cm; target radius = 1 cm

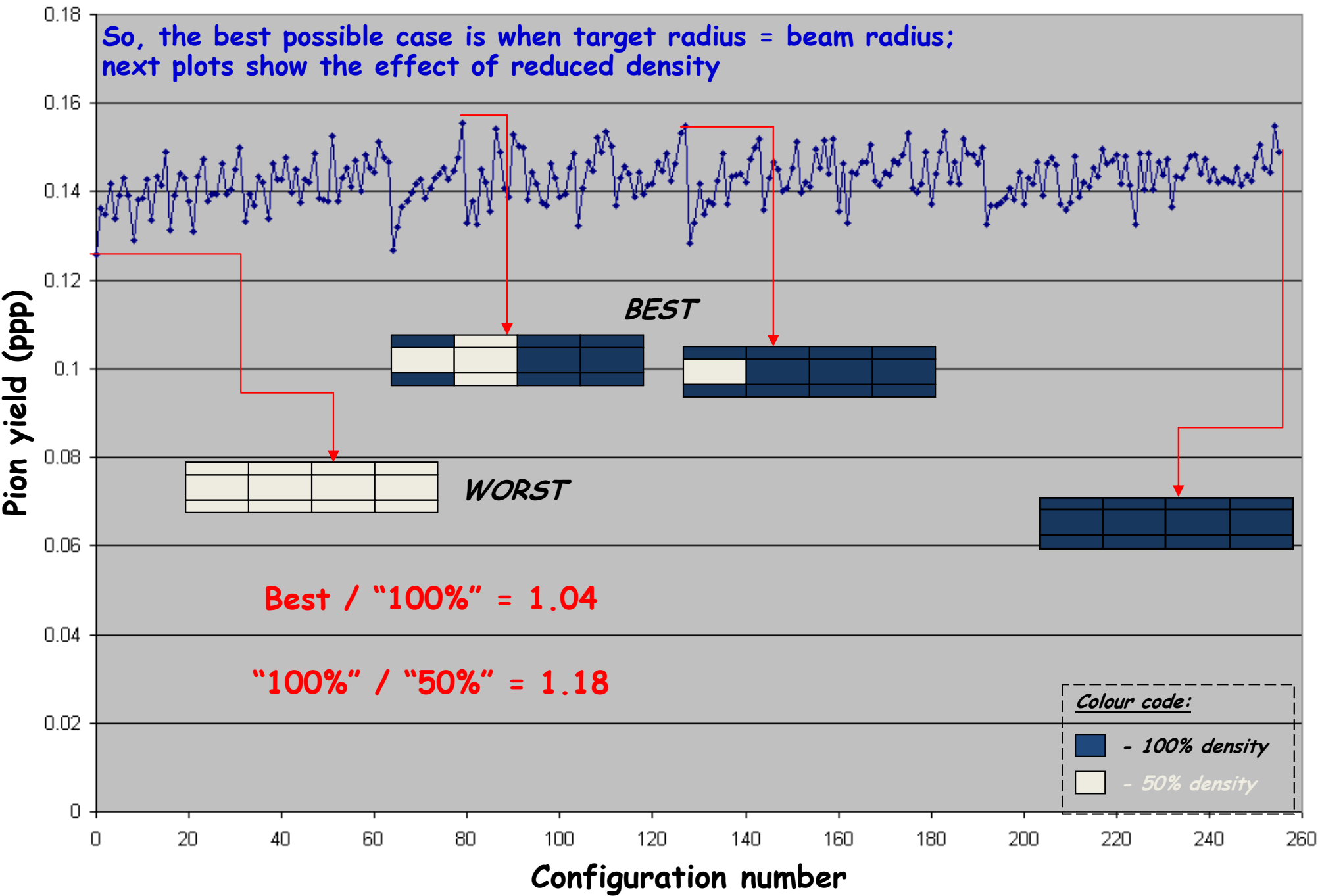
Results: pions yield shown as well as a few characteristic target configurations (best and worst ones included)



Optimisation of the NF tungsten target density

Beam radius = target radius = 0.5 cm

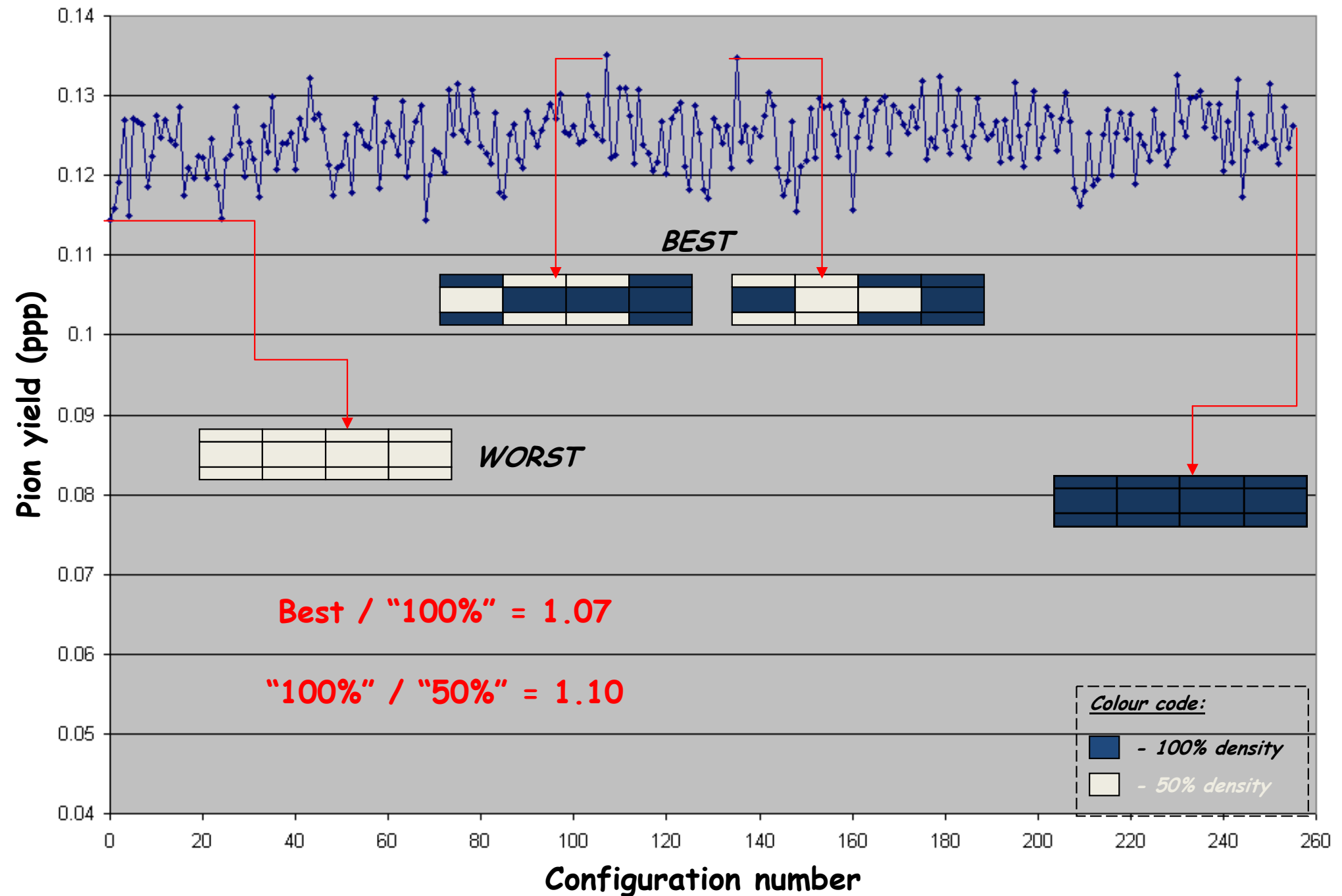
Results: pions yield shown as well as a few characteristic target configurations (best and worst ones included)



Optimisation of the NF tungsten target density

Beam radius = target radius = 1 cm

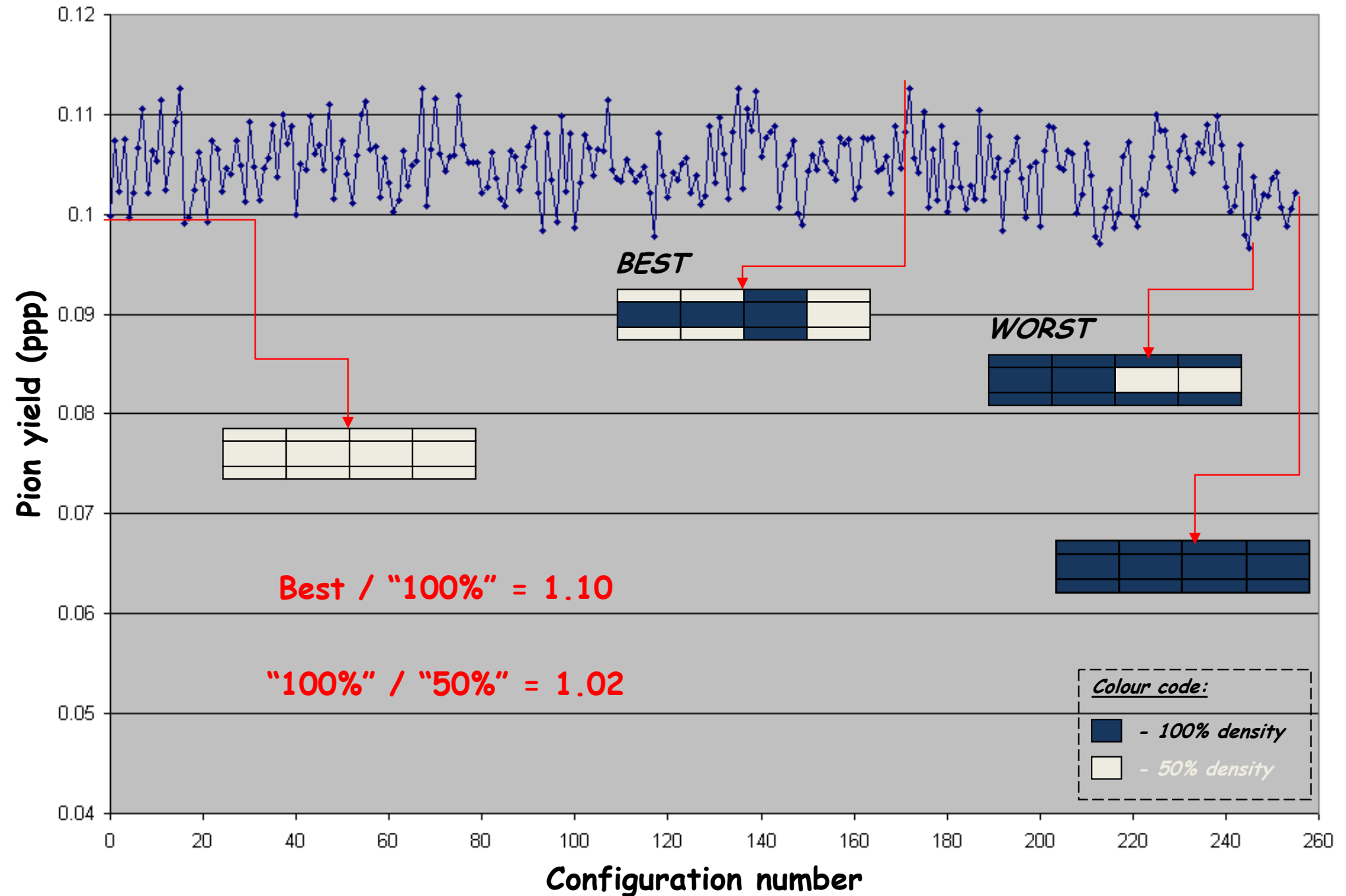
Results: pions yield shown as well as a few characteristic target configurations (best and worst ones included)



Optimisation of the NF tungsten target density

Beam radius = target radius = 1.5 cm

Results: pions yield shown as well as a few characteristic target configurations (best and worst ones included)



A few words about results (part I)

- In general case*, if beam radius is smaller than target radius the optimal target shape is:



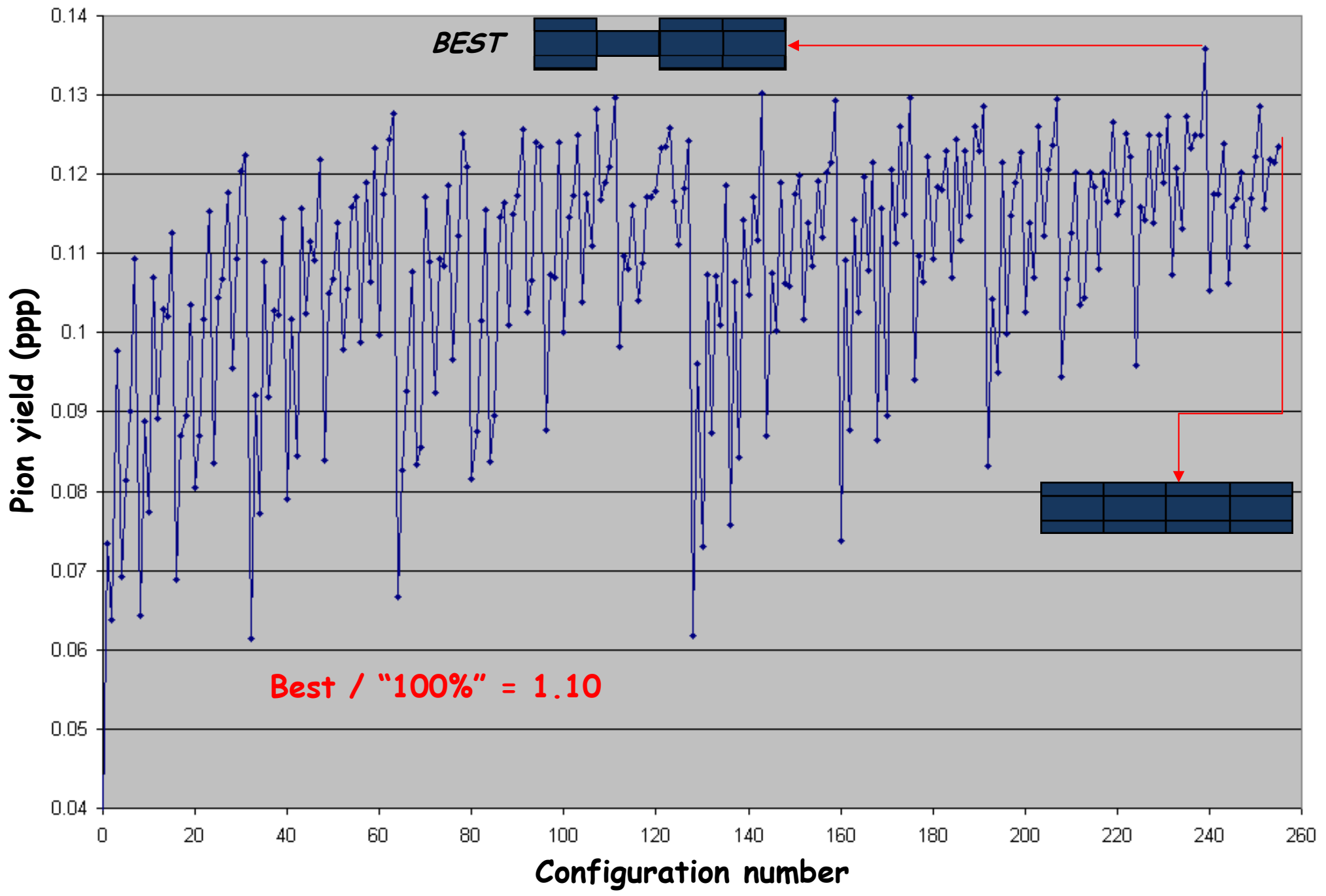
- For particular conditions at Neutrino Factory it is much better when the beam radius is equal to the target radius
- In general case*, if beam radius = target radius then the best option is to have full 100% density target
- For particular conditions at Neutrino Factory we have different situation: some configurations with reduced density have higher yields (this effect increases with increasing beam(target) radius)
- Ratio of yields for 100% and 50% density target is practically equal to 1 for 1.5 cm beam(target) radius (this ratio increases with decreasing beam(target) radius)

So, it seems that for particular conditions at Neutrino Factory we should have 'reduced' amount of material in front of the beam - this probably means different optimal shape of the target...

Optimisation of the NF tungsten target shape

Beam radius = target radius = 1 cm

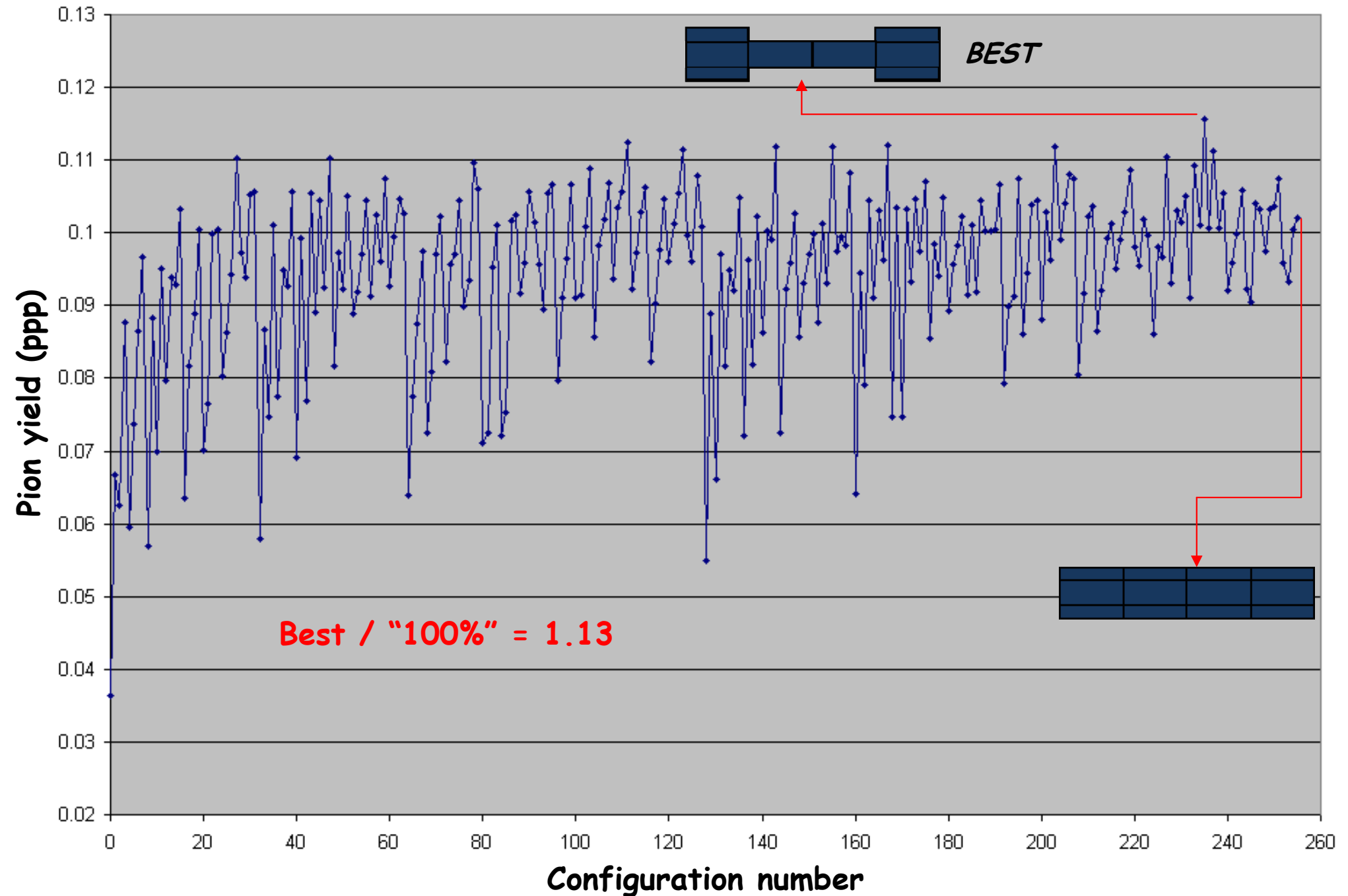
Results: pions yield shown as well as a few characteristic target configurations (best and worst ones included)



Optimisation of the NF tungsten target shape

Beam radius = target radius = 1.5 cm

Results: pions yield shown as well as a few characteristic target configurations (best and worst ones included)



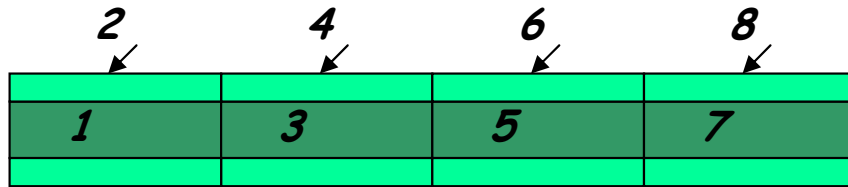
A few words about results (part II)

- In general case*, if beam radius = target radius then the best option is to have full 100% density target
- For particular conditions at Neutrino Factory these shapes



'produce' 10 to 15% more pions than full cylinder.

Appendix: Configuration Number

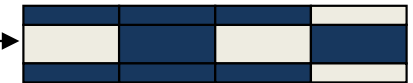


Target has 8 segments (inner and outer cylinder; 4 divisions along the length). Segment numbers shown on the left.

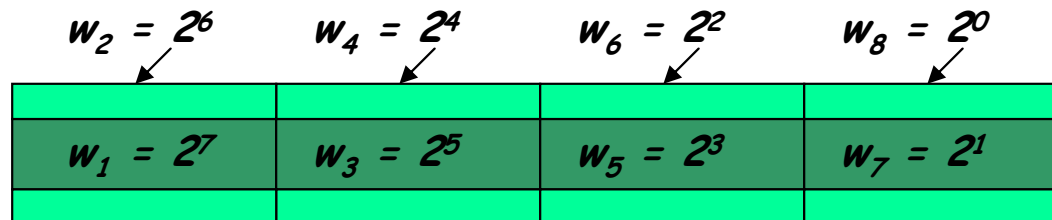
'Density coefficient' of segment i is a_i .

$a_i=1$ for 100% density; $a_i=0$ for low density (50% or 10%).

Each target configuration can be described by a set of density coefficients: $a_1a_2a_3a_4a_5a_6a_7a_8$ (for example - 01110110).



If we define 'Binary weight' of segment i to be w_i (the values shown below)...



... then we can calculate the configuration number (x-axis on the previous slides):

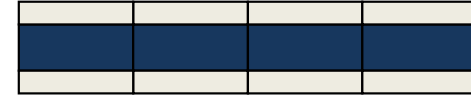
$$\begin{aligned} \text{Configuration Number} &= \sum_{i=1}^8 a_i w_i = a_1 2^7 + a_2 2^6 + a_3 2^5 + a_4 2^4 + a_5 2^3 + a_6 2^2 + a_7 2^1 + a_8 2^0 = \\ &= a_1 \cdot 128 + a_2 \cdot 64 + a_3 \cdot 32 + a_4 \cdot 16 + a_5 \cdot 8 + a_6 \cdot 4 + a_7 \cdot 2 + a_8 \cdot 1 \end{aligned}$$

For example, 01110110 = $0 \cdot 128 + 1 \cdot 64 + 1 \cdot 32 + 1 \cdot 16 + 0 \cdot 8 + 1 \cdot 4 + 1 \cdot 2 + 0 \cdot 1 = 118$

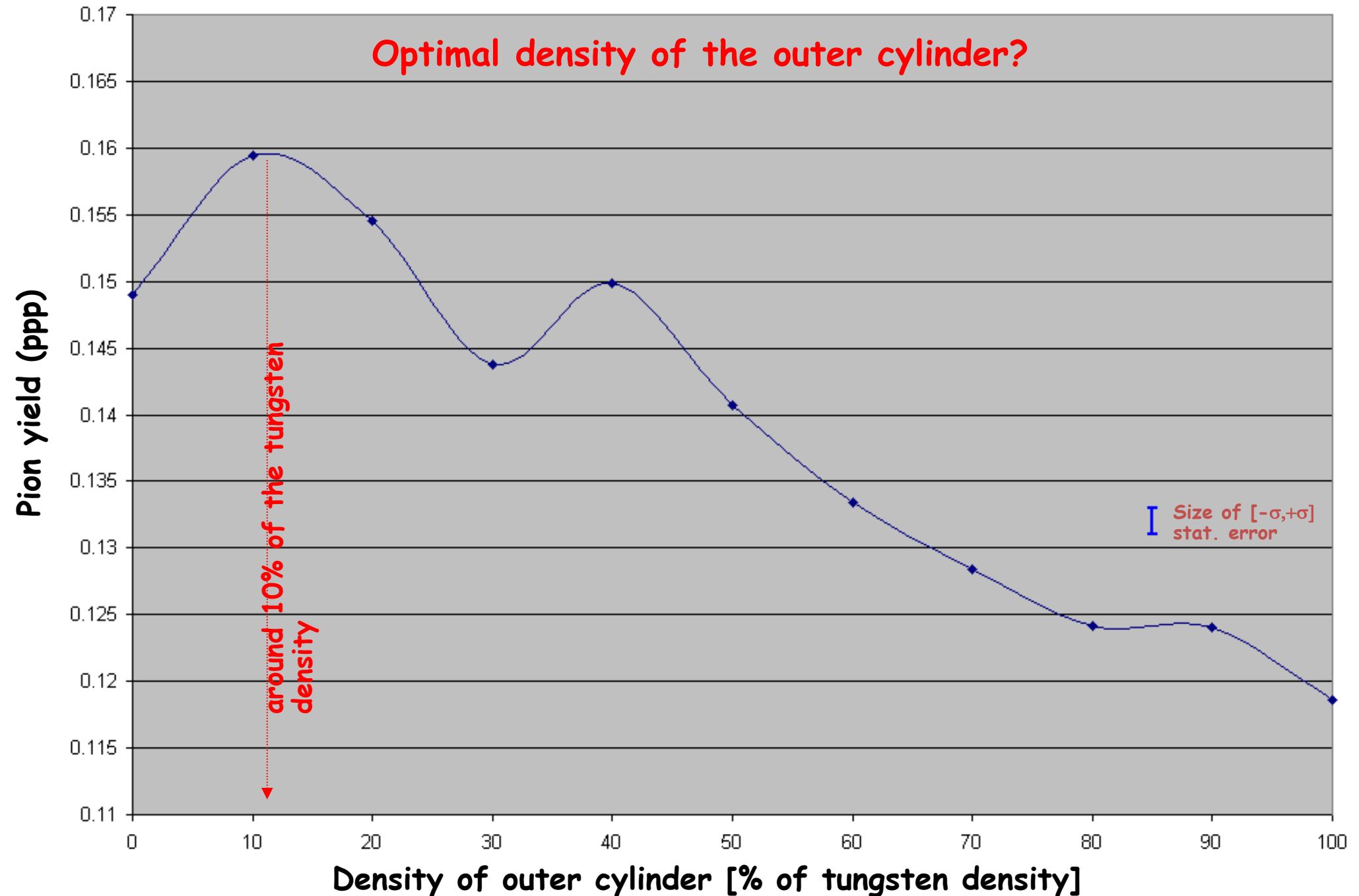
Update I

11 December 2008

When beam radius = 0.5 cm and target radius = 1 cm then the best scenario (see Slide 5) is to have 100% density core (0.5 cm radius) and less dense outer cylinder



Optimal density of the outer cylinder?



Summary

1. Pion Absorption is significant in the target. About half the pions are absorbed.
2. Reduced Density Targets can have high yields ~equal to the solid.
3. It is possible to tailor the target geometry to maximise the pion yield.
4. There are advantages in having a lower density target:
 - a. The energy dissipated is reduced, lowering the stress, the temperature and lengthening life.
 - b. It will be possible to reduce the target diameter (because the power is reduced and less surface area is required for radiation cooling) thereby decreasing the absorption in the radial direction and increasing the yield.

b. (continued)

However, if a is less than 0.5 then it is always an advantage to have the maximum density. There is an optimum which is being investigated using MARS etc. - including varying the diameter, density and radius over the target geometry.

c. It will be possible to make a target from thin tungsten foil discs, enhancing the thermal emissivity and further reducing the temperature of radiation cooled targets and/or reducing the target diameter.

Alternatively the target could be made from foamed metal - but the thermal conductivity is not so good as discs in the radial direction!