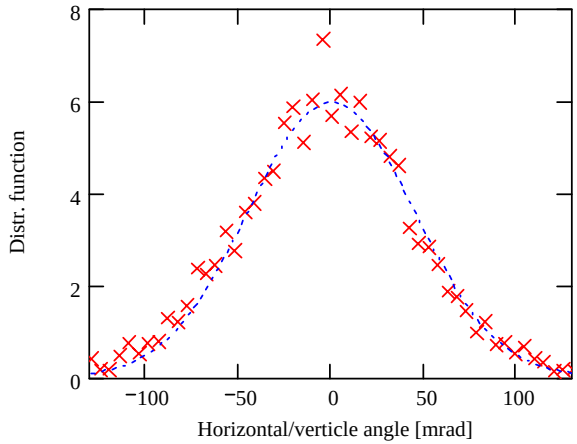
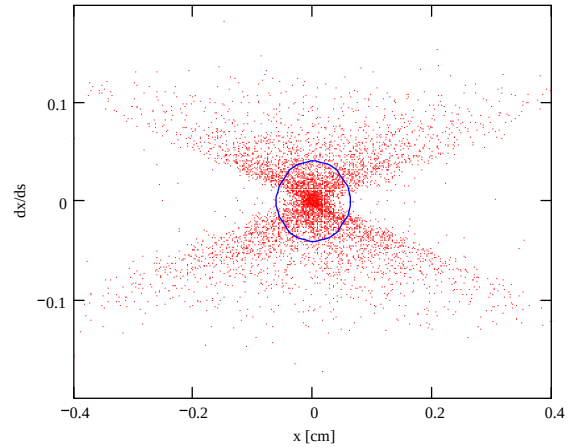


Angular distribution function of 8 GeV antiprotons coming out of 8 cm nickel target

$$f(\theta) \propto \exp\left(-\frac{\theta^2}{2\sigma_\theta^{\,2}}\right) \quad ,$$

$$\sigma_\theta \approx \frac{1.1}{\gamma}\sqrt{\frac{m_\pi}{m_p}} \quad ,$$

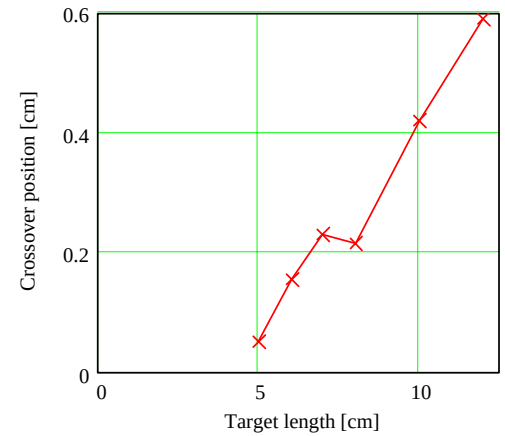


Coordinates of antiprotons in x - x' phase space simulated with MARS

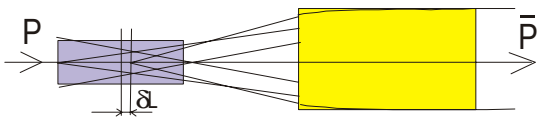
$$\frac{d^2 f}{da_x da_y} \propto const$$

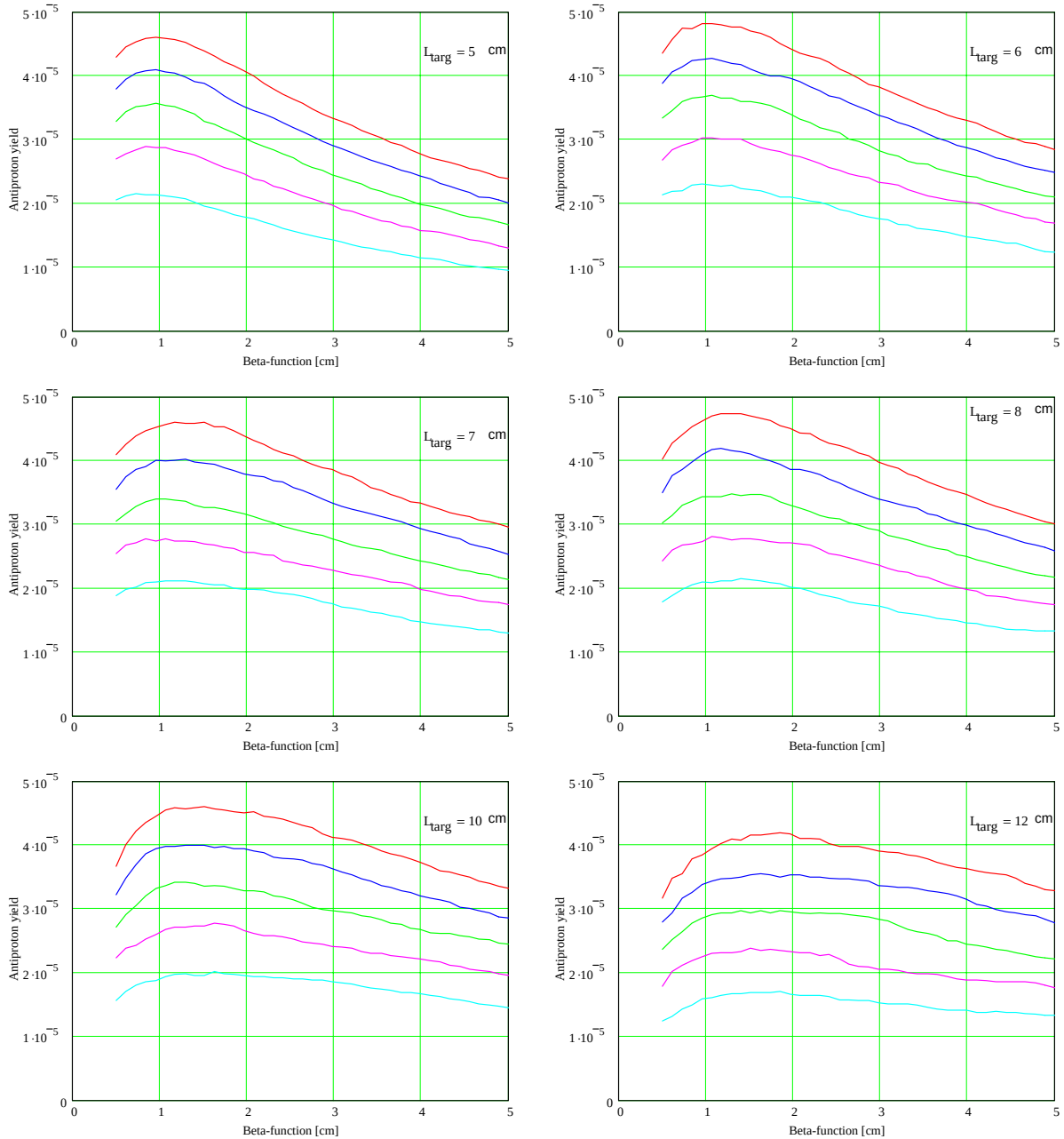
for $$\frac{a_x^{\,2} + a_y^{\,2}}{L_{t\arg}\sigma_\theta^{\,2}} << 1$$

$$a_x \equiv \sqrt{\varepsilon_x}\ ,\ a_y \equiv \sqrt{\varepsilon_y}$$

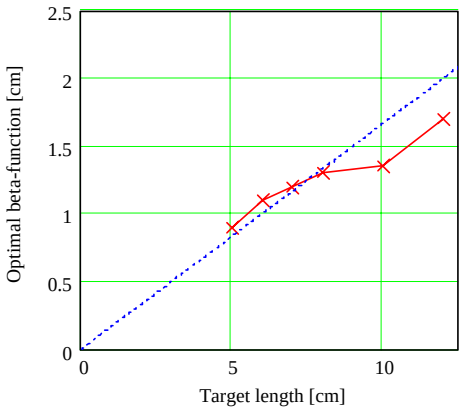


Dependence of the waist position on the target length





Dependence of antiproton yield into ±2.25% momentum spread on the beta-function at the target for the beam acceptances of 15, 20, 25, 30 and 35 mm mrad, and target lengths from 5 to 12 cm. Waist positions have been optimized and their values are shown in Figure 3.4. The proton beam energy is 120 GeV, and the rms beam size at the target is 100 μm. The kinetic energy of antiprotons is 8 GeV.



Dependence of the optimal beta-function on the target length

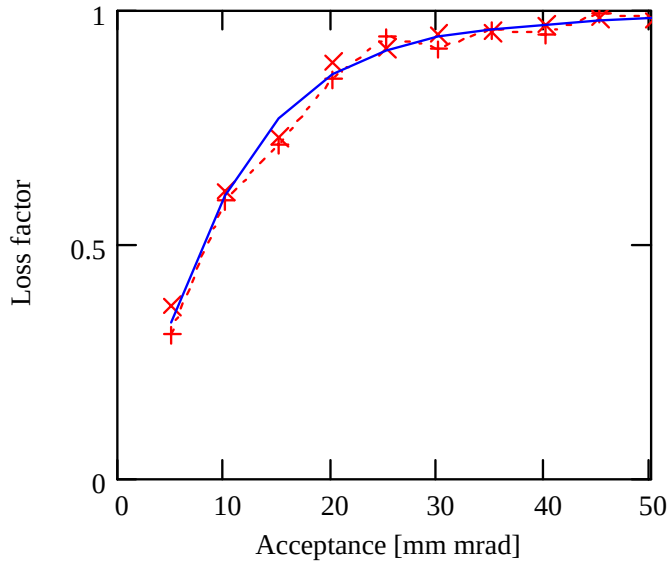
Passage through lithium lens

1. **Nuclear absorption** $\kappa_{lens} = \exp\left(-\frac{L_{Li}}{L_{Abs_{Li}}} - \frac{L_{Be}}{L_{Abs_{Be}}}\right) \approx 0.82$

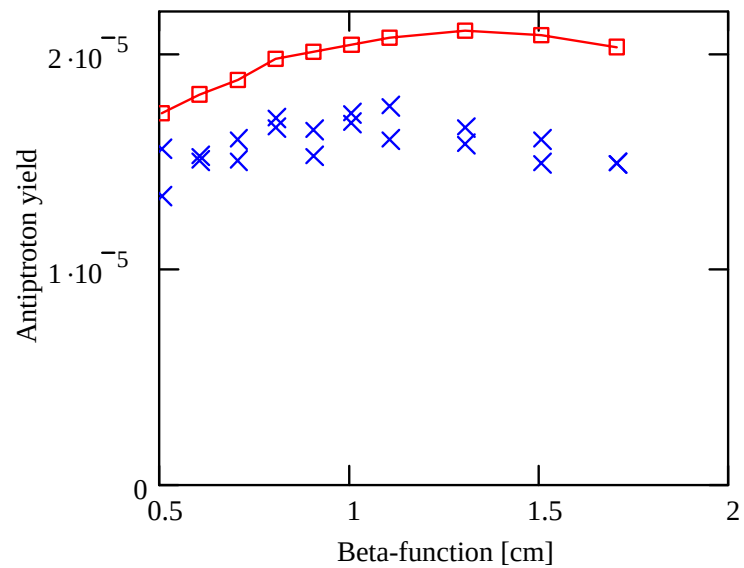
2. **Multiple scattering** $\sqrt{\overline{\theta^2}} = \frac{13.6\,\text{MeV}}{\beta P c}\sqrt{\frac{L_{Li}}{X_{Li}} + \frac{L_{Be}}{X_{Be}}} = 0.635\,\text{mrad}$,

   For the lens with radius of 1 cm that yields $\Delta\varepsilon$ = 6.3 mm mrad

3. **Non-linearity**



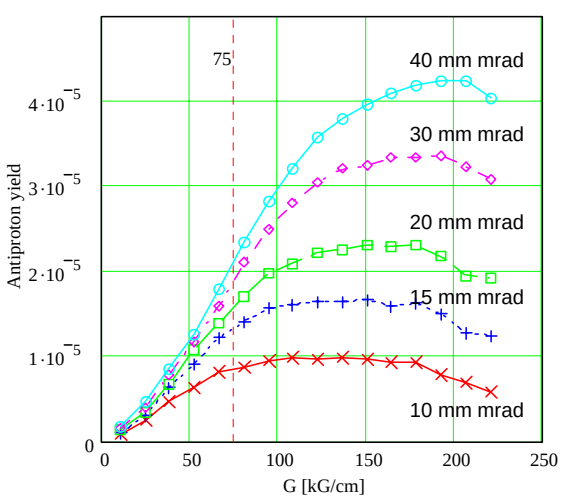
Loss of antiproton yield due to multiple scattering as function of machine acceptance for currently used lithium lens and beta-function at the target of 1.5 cm



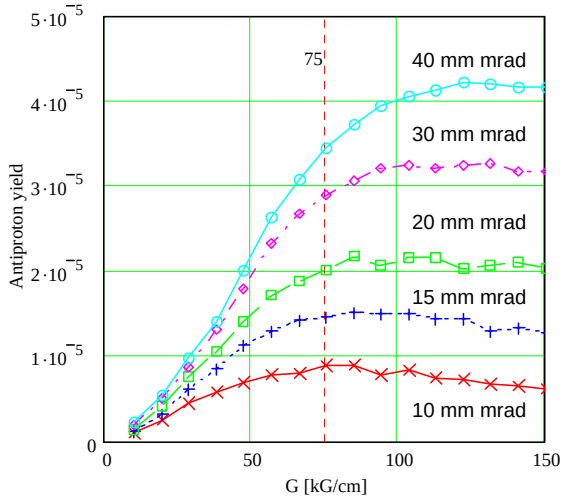
Dependence of antiproton yield on the beta-function at the target for acceptance of 15 mm mrad. Solid line – no scattering and absorption in the lens, × – only multiple scattering is taken into account.

Antiproton yield as function of lens gradient for different target lengths and radii

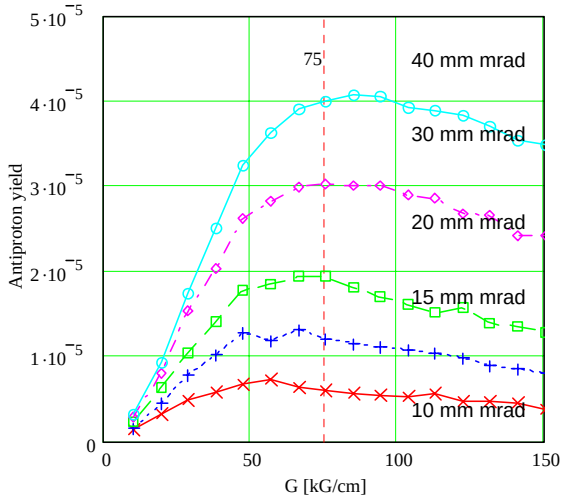
L=15 cm



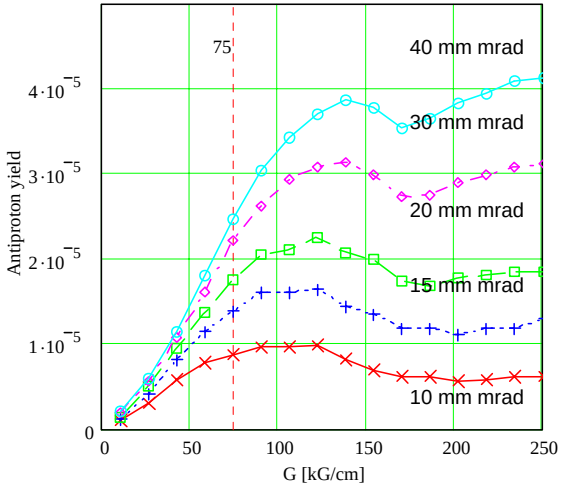
R=0.66 cm

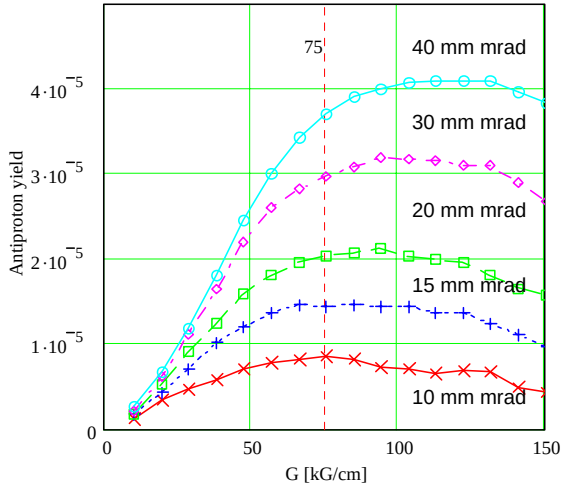


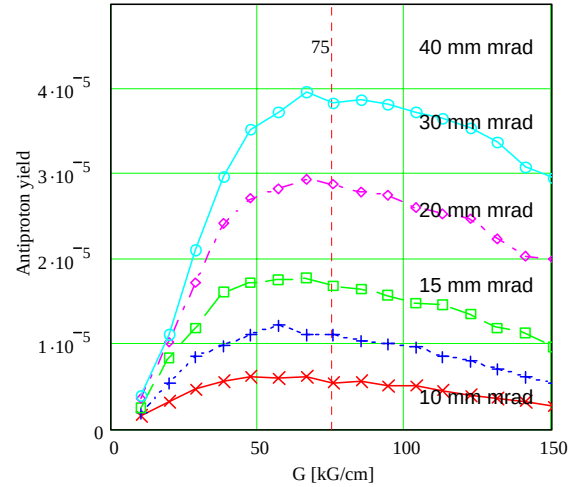
R=1 cm



R=1.5 cm

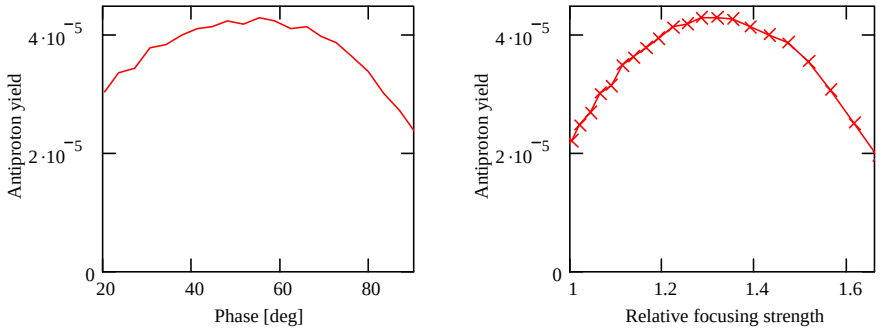




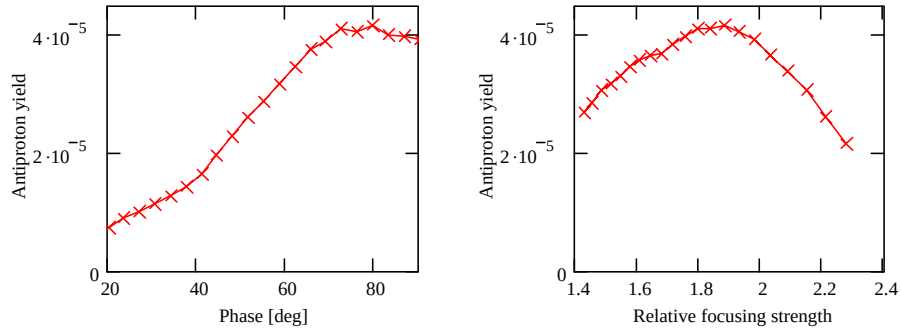


L=18 cm

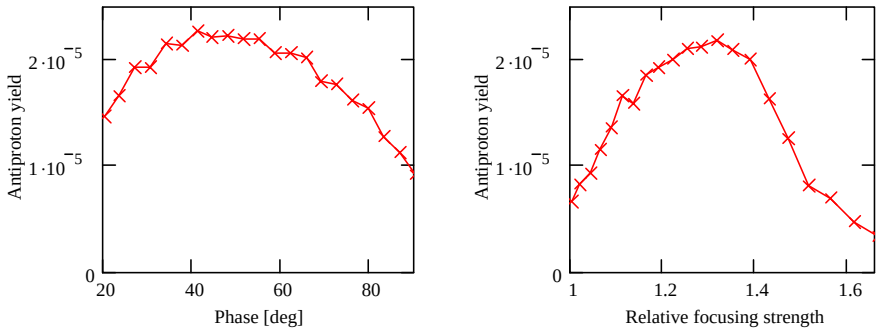
Antiproton yield as function of lens current and phase



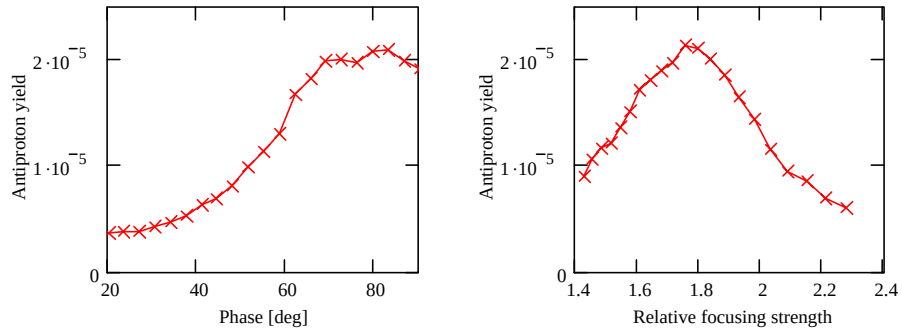
T_{pulse} = 360 µs, ε = 40 mm mrad



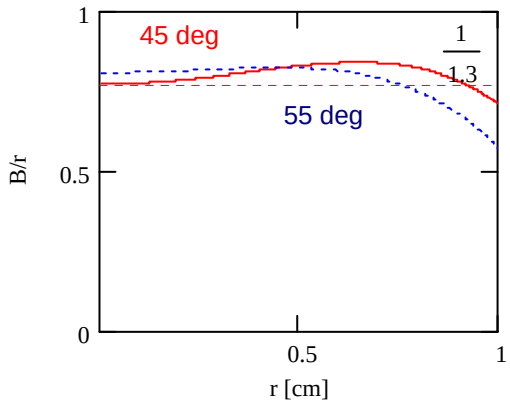
T_{pulse} = 200 µs, ε = 40 mm mrad



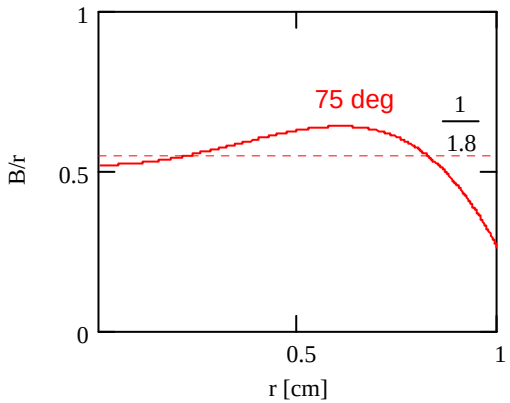
T_{pulse} = 360 µs, ε = 20 mm mrad



T_{pulse} = 200 µs, ε = 20 mm mrad



P ∝ 1.3^2*360=608



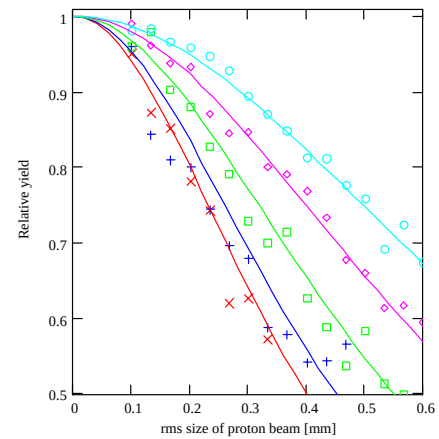
P ∝ 1.8^2*200=648

Where we presently lose and how much?

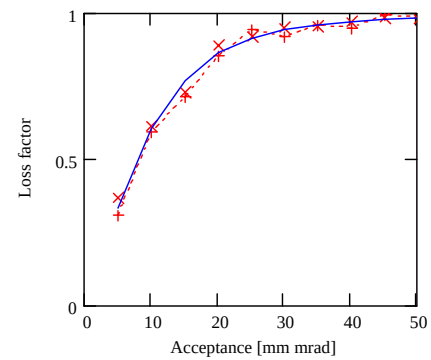
	Total loss for ε mm mrad		Can gain back for ε mm mrad	
	20	40	20	40
Lack of focusing strength	10%	20%	0*?	8%*?
Proton beam size	10%	5%	7	3
Absorption in the lens**	18%	18%	-	-
Multiple scattering in the lens	10%	3%		
Lithium lens non-linearity	0	0	0	0

* - length lengthening by 3 cm

** - 1% per 1 cm of lithium



Proton beam size effect



Multiple scattering effect

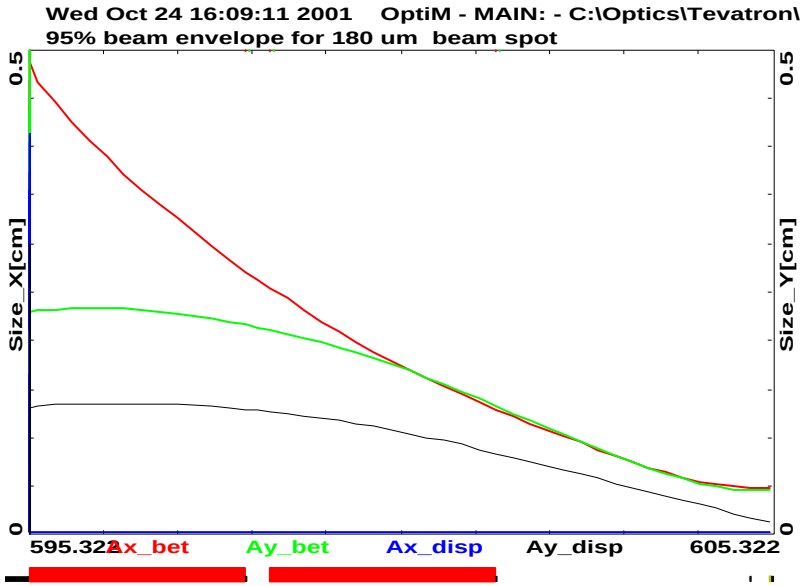
Lens pulse of 360 μs looks well optimized

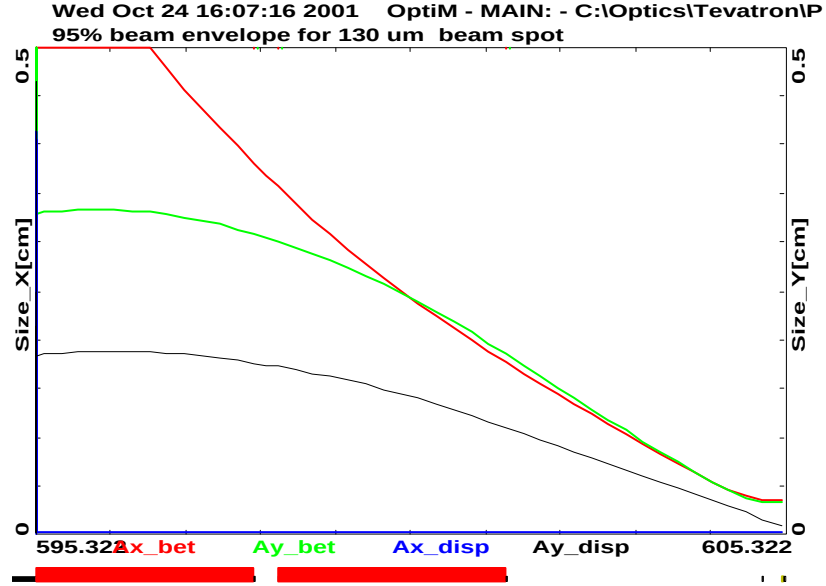
Power deposition in the target

$$E_D \approx 890[\mathrm{J/g}]\left(\frac{200\,\mu\mathrm{m}}{\sigma_{pb}}\right)^2 \frac{N_p}{5\cdot 10^{12}}$$ -

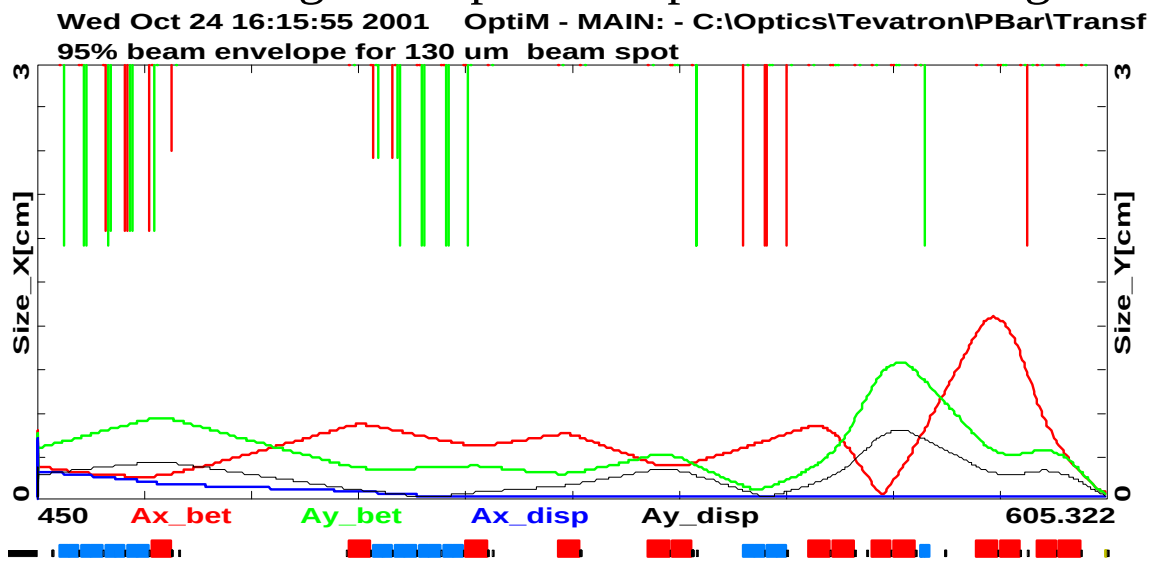
1. Power deposition at the target prevents achieving a smaller beam size (currently ~180 μm) !!!
2. Slip stacking requires swiping on the target (r=0.3 mm has to be sufficient for σ=100 μm and 10^{13} protons)

Optics issues for AP1 line



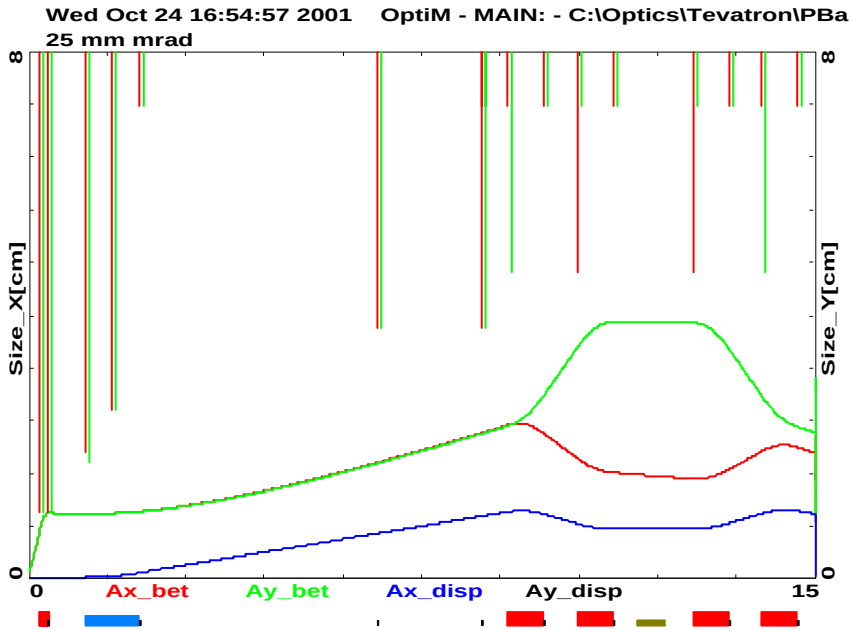


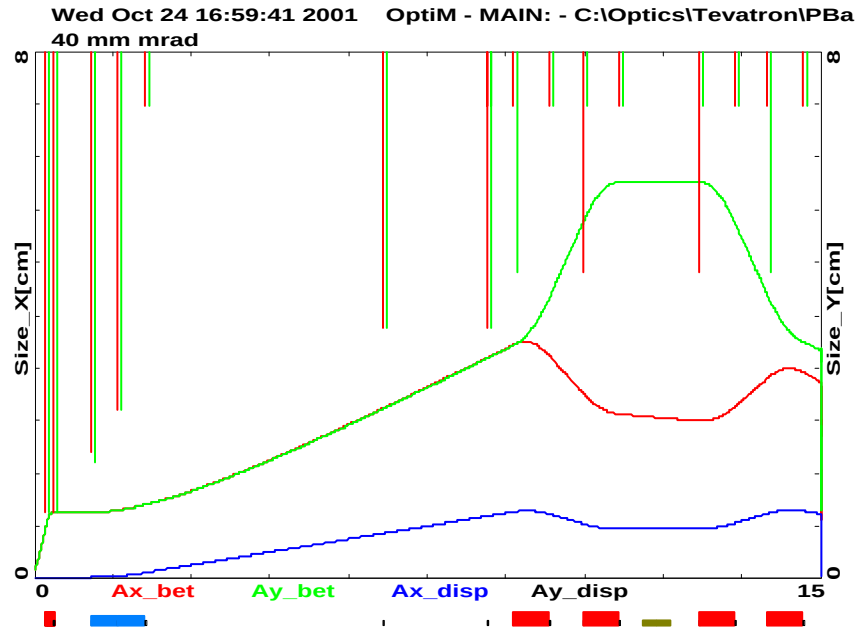
1. Smaller beam size on the target less power deposited in the target window



2. Aperture limitations can be a problem if we will go to 130 μm beam size (~ 1 km horizontal beta-function)

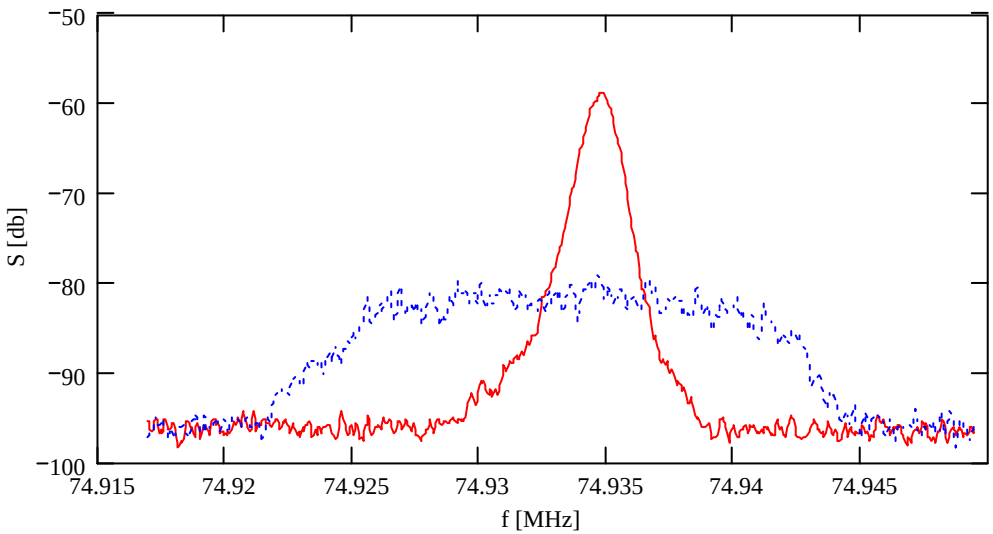
Optics issues for AP2 line

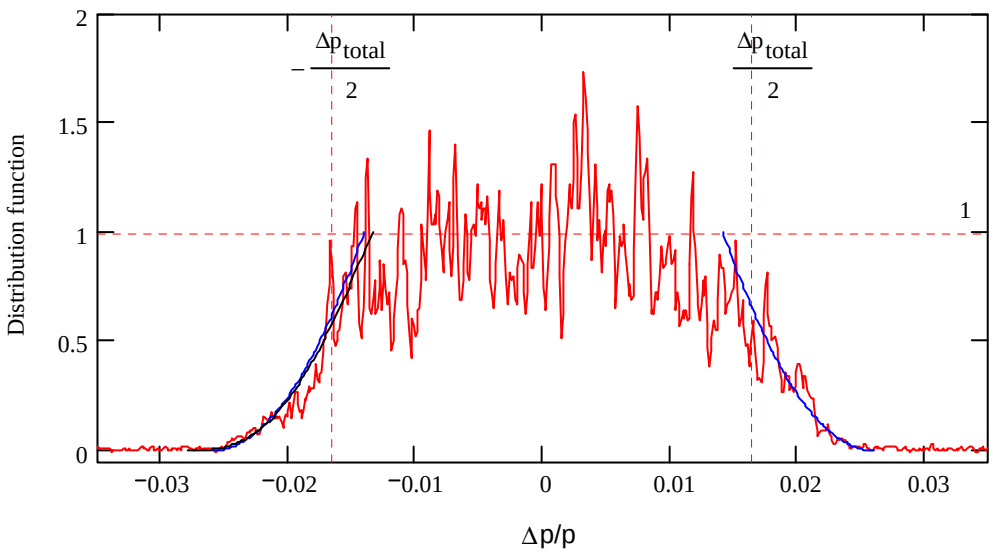


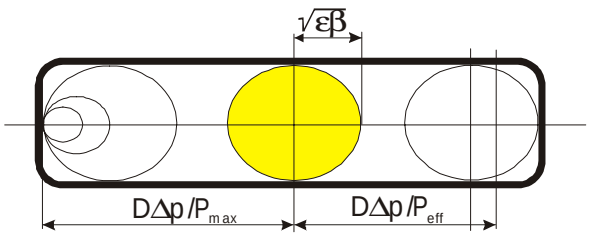


1. Choise of the optimum lens radius
   a. We have sufficiently large aperture in the first triplet and we are OK with 1 cm lens
   b. Lens of larger size will bring increased effect of multiple scattering and is not expected to be better
   c. Smaller lens is not compatible with 40 mm mrad acceptance

Debuncher aperture







$\Delta p/p_{max}=\pm 2.6\%$,
$\Delta p/p_{eff}=\pm 1.65\%$,

$$\varepsilon_x \approx \frac{D^2 \delta p^2}{\beta_x}$$

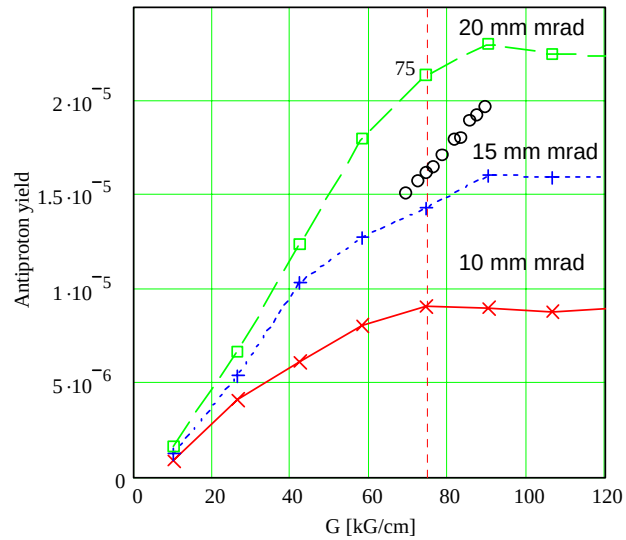
D = 2.08 m
β_ξ = 15.3 m

$$\Rightarrow \varepsilon_x \approx 40\ \mathrm{mm}\cdot\mathrm{mrad}$$???

Where are we, and where were we?

1. Debuncher and AP2 line apertures are the most probable reasons of today's low performance.
2. Discrepancy between predictions and observations can be related to
   a. Not very well optimized optics or steering in the course of measurements
   b. Incorrect calibration of lens gradient due to incorrect current measurements or incorrect calculations of current distribution in the lens

$$G \approx \frac{2I_0}{cr_0^{\,2}} \frac{\rho_{Ti}}{\rho_{Ti} + 2\rho_{Li}\dfrac{d_{Ti}}{r_0}} 0.78 \approx \frac{2I_0}{cr_0^{\,2}} 0.74$$



Simulations are done for Δp/p=±2%

The plan of improvements

1. Lens (10 – 15% increase of the yield is expected)
    a. Stay with the same radius
    b. If we will not figure out how we could reliably increase the lens current (20 to 40% are desirable) we have to increase its length by 20-25%.
    c. Can we achieve the required repetition time of 1.5 s with the solid lens
2. Beam swiping on the target (5 – 7% increase of the yield and possibility to double the proton beam intensity is expected).
    a. Clearing apertures in AP1 line because it implies a smaller beam on the target and larger beam in the triplet
    b. Optimization of coil positions
    c. Fixing hardware
3. Opening apertures, fixing optics and steering in AP2 and Debuncher with the aim to achieve 35-40 mm mrad acceptance should bring the antiproton yield to $30\text{-}40 \cdot 10^{-6}$ (1.5-2 times better than the historical best)

Questions to answer

1. What needs to be modified in the target station? Should it be just the lithium lens or something else?
2. Do we see any necessity to use the liquid lithium lens for Run IIb?
3. If we modify the solid lens what needs to be changed? - the radius, the length, the current pulse or something else.
4. Why current lens breaks? How it could be modified to avoid this?
5. Do we need any additional instrumentation for target station?