CON 96-05
March 10, 1996

CESR SEXTUPOLE UPGRADE

A. Mikhailichenko

CESR's sextupole described in [1,2]. Sextupole with a field dependence $B_y \equiv S\cdot(x^2-y^2)$, $B_x \equiv 2Sxy$ used here for compensation of chromaticity, induced by regular quadrupoles and also for compensation the chromaticity, induced by strong lenses around IP (local and unlocal compensation).

At the time of proposal, the operational energy supposed to be up to 10 *GeV* and, of cause, no pretzels. That defined the profile, represented on Fig. 1. This profile yields maximal possible sextupole strength with acceptable level of higher order harmonics. The length of the iron package is 127 *mm* (5 *in*). This

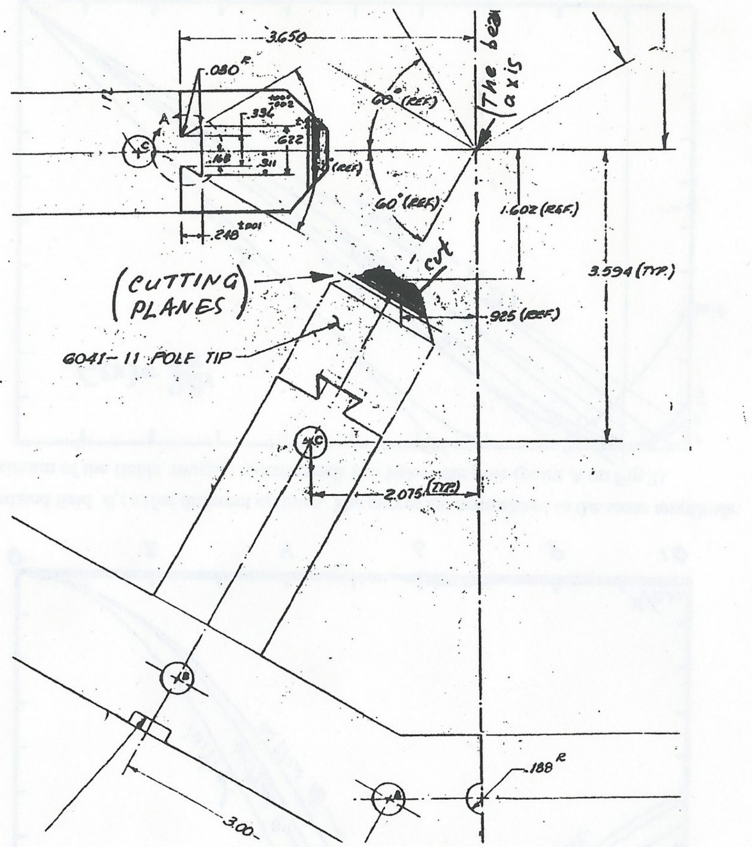

Fig.1. The drawing of the sextupole. There are shown two poles of six. Upgrade is nothing else but cutting the poles along longitudinal direction. These cutting planes for different values of cuttings are shown also.

package assembled with 1.5 *mm* laminations. The pole made as a separate element and it is 248 *mm* long (9.75 *in*). We specially notice here that the pole length is about two times longer, than the package. Namely this circumstance yields a saturation of the lens rather, than one can expect from 2D cross section in the regular part. The pole placed in the yoke with dovetail lock and is fixed in place with help of two spacers. The pole can be removed from the lens by sliding in longitudinal direction after unscrew at least one of two bolts. The bore diameter is 94 *mm*. Number of turns per pole, according to drawing is 160. Two additional coils, having 270 turns each, use the sextupole hardware for horizontal field production, giving vertical steering to the beam.

At present time the energy is fixed practically at the level about 5.3 *GeV*, and the beam has displacement in the vacuum chamber due to the pretzel operation mode. This two circumstances give a move to search for some possible improvements of the field quality. The basis of proposal made, is an attempt to improve the harmonics content on expense of sextupole field strength. We considered from the very beginning the *simplest* manipulation with the profile. As a result we choose the pole cuttings, parallel to it's longitudinal axis, Fig. 1. The strategy used, occur to be in line with improvement of steering field *also*.

Calculations made with help of code MERMAID [4], used Newton/Conjugate Gradients iterative method. The field lines for the profile cut are represented on Fig. 2.

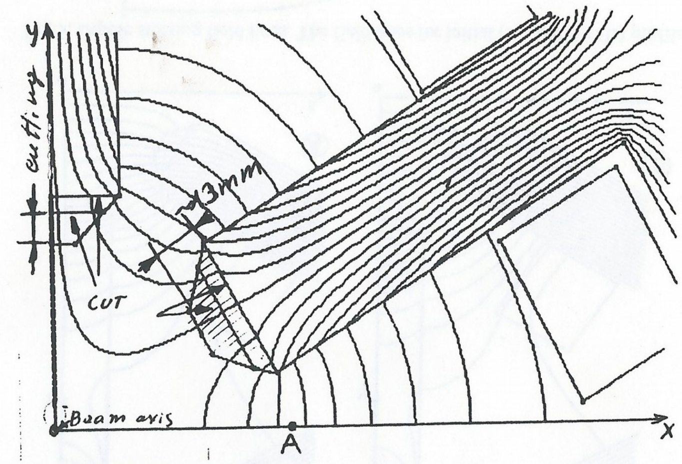

Fig.2. The profile cut. The cutting represented is about 13 mm (full cutting). The cutting measured from the top of the pole surface. Represented also the initial and intermediate profiles. For this output the region inside these last two profiles is air. In the region around point A, the gradient expected to be close to zero.

On Fig.3 and Fig.4 there are represented the calculated curves for magnetic field and gradient for different cuttings. The field maximum occurs below the pole edge. The gradient curves are more informative for estimation the quality factor. For sextupole the allowed harmonics are $V_m \cong r^{3(2m+1)-1} Sin(3(2m+1))$,

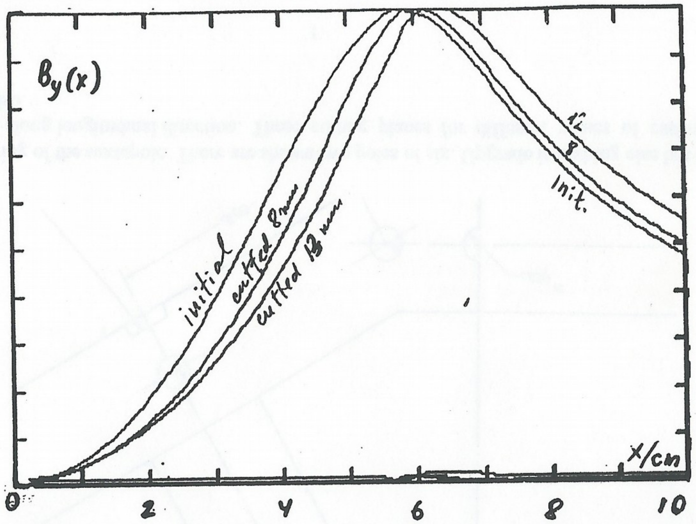

Fig. 3. Calculated field $B_y(x)$ for different cuttings. The curves are normalized to the same amplitude. Maximum of the fields roughly corresponds to x below the pole (point A on Fig.2).

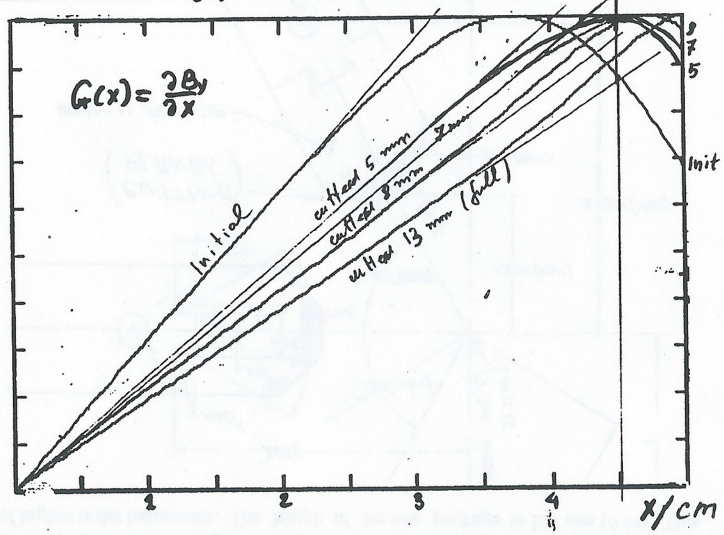

Fig. 4. Calculated gradient curves for different cuttings. The curves are normalized to the same maximal value of the gradient. Ideal sextupole must generate a *linear* dependence in all aperture.

m=0,1,2,3,... . That are $\cong x^2, x^8, x^{14}, x^{20}, \ldots$ (for the transverse field dependence). In our case we obliged to consider first three harmonics as minimum (because of the improved profile gives harmonic for $B_y \approx b \cdot x^8 \propto 0$, see lower). In the region below the pole tip, the gradient changes it's sign. At the point of the field maximum (point A on Fig.2), the gradient is equal to zero. When the cutting is 7 *mm*, the gradient line is *below* the straight line, corresponding to the ideal gradient. One can see that for the cutting 8 *mm*, indeed, the gradient line lies *above* the ideal line at some distance around 3-4.5 *cm*. That is the game of the lowest harmonics x^8, x^{14}: together they must give decrease of gradient curve at the higher transverse displacements. We tried to keep minimal deviation of the real gradient line from the ideal at the transverse distance x=4.5 *cm* . Generally one can agree, that *any* cutting (even up to 13 *mm*) will improve the quality of the gradient behavior.

The dipole steering requirements move the choice to the 8 *mm*, see lower. So the final cutting must be somewhere between 7 and 8 *mm*. On Fig. 5 there are represented lines map for initial and cutted profiles. On Fig. 6 there are represented the curves, corresponding to initial and cutted profiles for the total current in the steering coil, equal to 1 *kA turns*.

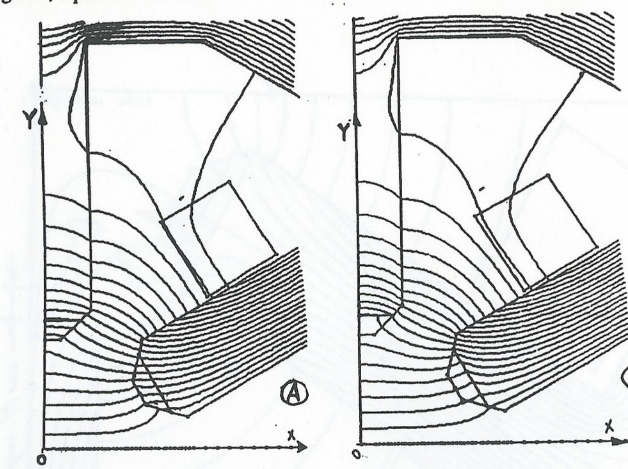

Fig.5. Dipole steering field lines. The field lines for initial (A) and cut (B) profiles.

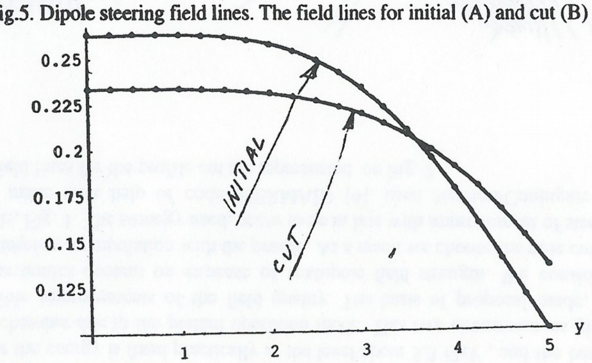

Fig. 6. $B_x(y, x=0)$ dependence for initial and cut profiles. The total current is $1 kA \cdot turns$.

As the harmonic $B_y \approx b \cdot x^8 \propto 0$, all expansions are very sensitive to the numeric noise. On the Fig. 7 below there is represented the calculated gradient behavior for initial and cut poles.

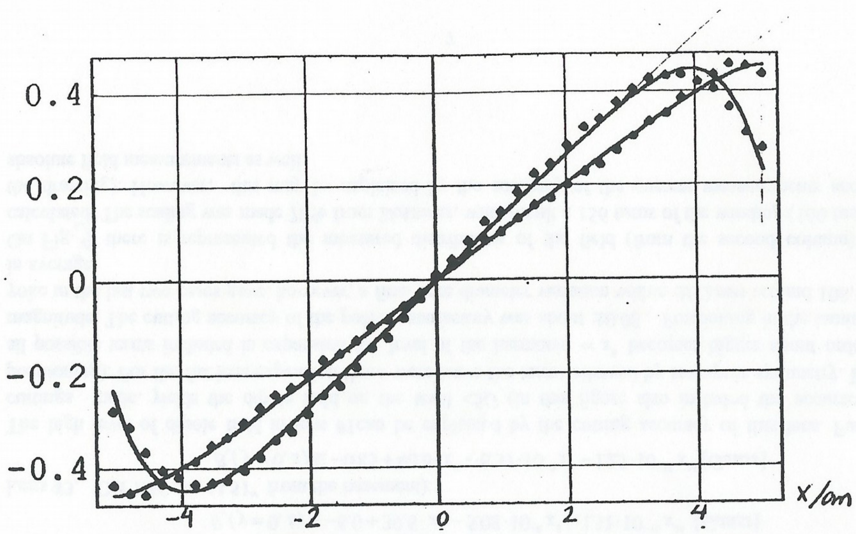

Fig. 7. The gradient behavior for cutting 8*mm*. The spline is made with two harmonics.

From the fitting of the *gradient* curves representation can be made for the *field* behavior as the following.
Current: 2*kA*, $x \le 5cm$.
Initial:
Two harmonics: $B_y(x) \cong 0.067 \cdot x^2 - 6.5 \cdot 10^{-7} x^8$.
Three harmonics: $B_y(x) \cong 0.07 \cdot x^2 - 1.1 \cdot 10^{-6} x^8 + 1.6 \cdot 10^{-11} x^{14}$
Cut 8*mm*:
Two harmonics: $B_y(x) \cong 0.049 \cdot x^2 - 8.9 \cdot 10^{-8} x^8$.
Three harmonics: $B_y(x) \cong 0.0494 \cdot x^2 - 1.4 \cdot 10^{-7} x^8 - 8 \cdot 10^{-12} x^{14}$
The *field* variation due to the presence of harmonics is 8% and 1.5% for initial and cut poles correspondly. The most important, however, is variation of the *gradient* at the aperture 4.5*cm*. It is about 50% and 10% correspondly.
To improve the accuracy of the fittings (made with Mathematica), the output points were symmetrizied for the region $x \rightarrow -x$, i.e. the same value of the field, calculated with the code, was substituted for *x* and *-x*. The results represented on the Fig. 8 below. The analytical behavior can be represented as the following (the current 2 *kAturns*)

$$B_y(x) \cong 0.0689 \cdot x^2 - 1.066 \cdot 10^{-6} x^8 + 1.685 \cdot 10^{-11} x^{14} \text{ - initial}$$

$$B_y(x) \cong 0.0485 \cdot x^2 + 1.060 \cdot 10^{-7} x^8 - 5.883 \cdot 10^{-12} x^{14} \text{ -cut 8 } mm.$$

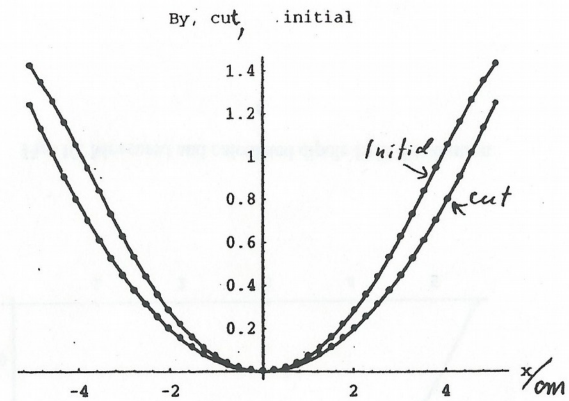

Fig 8. The field behavior for initial and cut poles. 2*kAturs*. The curves were symmetrizied around *x*=0.

One can see, that for this level of cutting, the sign of the harmonics reversed (like one can expect from the figure 4). The values of harmonics dropped about order of magnitude. So in further optimizations the cuttings were considered around 7.5 *mm*.
Measurements carried out with the help of Hole probe meter[1], what gives a moderate accuracy, acceptable in our case. That was about 10^{-3} on the field level $10^3 G$. An absolute calibration made with magnetic field standard, made with permanent magnets. The Hole probe moved in horizontal plane with help of standard optical table having linear bearings with estimated accuracy of positioning about 0.1*mm*. Position of the Hole probe, corresponding to *x*=0 was determined by the place, where the field has a minimum. Three lenses were measured totally, showing practically the same behavior. There was found, that there exist a sensitivity to the magnetic history of the lens. So the lenses required normalization with the current up to saturation. The resistance of each of six coils is $R \cong 0.241^{+0.001}_{-0.000}\, Ohm$, giving about 1.448 *Ohm* totally.

[1] Gaussmeter MG-40, WALKER Scientific INC.

For sextupole field the measured field dependence can be represented as following (x in *cm*, B in *kGauss*) .

Transverse distance, x *cm*	*B(x)*, Initial, *kGs*	CUT *B(x)*, Lens #1, *kGs*	CUT *B(x)*, Lens #2, *kGs*	CUT *B(x)*, Lens #3, *kGs*
0.0	-0.007	-0.0244	0.001	0.006
0.5	0.004	-0.014	0.009	0.015
1.0	0.041	0.0153	0.036	0.044
1.5	0.105	0.064	0.084	0.092
2.0	0.196	0.132	0.150	0.159
2.5	0.312	0.220	0.237	0.247
3.0	0.453	0.326	0.343	0.354
3.5	0.611	0.453	0.467	0.485
4.0	0.778	0.602	0.615	0.636
4.5	0.933	0.775	0.788	0.812
5.0	1.070	0.971	0.970	0.997
5.5	1.162	1.146	1.131	1.157
6.0	1.197	1.235	1.214	1.239
6.5	1.155	1.190	1.193	1.214

One can see, that the maximal value of the field is not differs much for cut and for initial lens.
The current in one turn is 10*A*.

The points, represented in this table were fitted and expanded. All expansions for the x value are valid for $x \le 6.5 cm$.

Lens #1. Initial:

$$B_y(y=0,x) \cong -5.3 + 50.4 \cdot x^2 - 4.84 \cdot 10^{-7} x^8 + 2.39 \cdot 10^{-12} x^{14} \; [Gauss]$$

Cut $\cong 7.42 \pm 0.23 mm$:

$$B_y(y=0,x) \cong -27.6 + 39.9 \cdot x^2 - 5.24 \cdot 10^{-9} x^8 - 1.89 \cdot 10^{-12} x^{14} \; [Gauss]$$

Lens #2. Cut 7.62 *mm* (1.5″ from the basement, see Fig.11):

$$B_y(y=0,x) \cong -6.0 + 39.6 \cdot x^2 - 5.08 \cdot 10^{-8} x^8 - 1.31 \cdot 10^{-12} x^{14} \; [Gauss]$$

Lens #3. Cut 7.36 *mm* (1.51″ from the basement):

$$B_y(y=0,x) \cong -0.85 + 40.6 \cdot x^2 - 6.37 \cdot 10^{-8} x^8 - 1.25 \cdot 10^{-12} x^{14} \; [Gauss]$$

The high level of dipole field in lens #1can be explained by the cutting accuracy of this lens. Further cuttings made, yields the dipole field on the level <5*G* (in this figure also included the accuracy of positioning). For the fist lens expansion there were leave the terms allowed by sextupole symmetry. If the all possible terms included in expansion the level of the harmonic $\propto x^8$ becomes bigger about order of magnitude. The cutting accuracy of the poles manufactory was about ±0.08. Positioning in the laminated yoke in the last two cases gave, however, a final bore diameter variation within ±0.2 *mm* around 108.7*mm* in average.
On Fig. 9 there is represented the measured distribution of the field (from the second column) and calculated. The scaling was made 78% from 2*kAturns*, what result a 156 turns of the winding (160 turns in the drawing). However, this may be explained by the accuracy of the current measurements and the absolute field measurements as well.

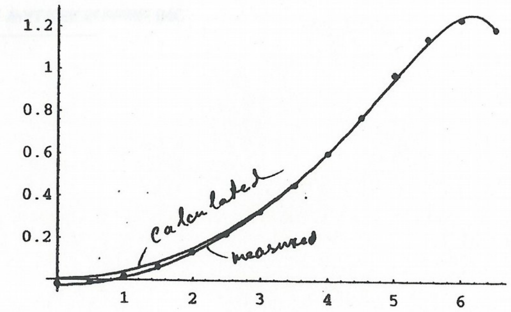

Fig.9. The field distribution; calculated and measured.

For steering dipole field the picture of field lines is represented on Fig. 5A,B. The calculated values of $B_y(x)$ is represented on Fig.6. On Fig. 10 there is represented comparison between calculation and the measurements after the cut made. The measurements made with current 3*A*, the calculated field adjusted for 817.44 *Aturns*.

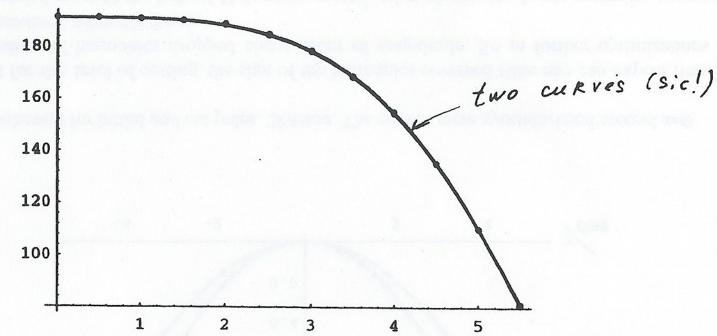

Fig. 10. Measured and calculated dipole field distribution.

The curves on Fig. 10 are

$$B_x(y, x=0) \cong 191.1 + 0.081\cdot y^2 - 0.19\cdot y^4 + 0.0043\cdot y^6 - 0.00013\cdot y^8$$ -- measured

$$B_x(y, x=0) \cong 191.1 + 0.021\cdot y^2 - 0.185\cdot y^4 + 0.0043\cdot y^6 - 0.00013\cdot y^8$$ -- calculated

According to calculations for total current of $1 kA\cdot turns$, initial horizontal field dependence as a function of vertical coordinate can be expressed as following (y in cm).
Initial:

$$B_x(y, x=0) \cong 263. + 0.495\cdot y^2 - 0.52\cdot y^4 + 9.64\cdot 10^{-3} y^6 \,[Gauss].$$

For the same current final horizontal field dependence (after cutting) can be expressed as

$$B_x(y, x=0) \cong 234. - 0.16\cdot y^2 - 0.19\cdot y^4 + 1.53\cdot 10^{-3} y^6 \,[Gauss].$$

One can see, that second term changed it's sign. In principle one can fined the cutting level, what eliminates the second term in the field dependence. We didn't specify this. This harmonic decreased about 3 times.

On Fig. 11 there is represented the saturation curve. The normalization made to initial curve by changing the level of sextupole with respect to initial according to the measurements (and calculations).

Longitudinal distribution of the field is represented on Fig. 12. The field as a function of longitudinal distance was measured at transverse position of the probe x=4cm . Two lines correspond to the margins of accuracy in definition of the edge with the Hole probe, what is ± 0.5 *mm*. Line at coordinate 4.7 *cm* correspond to effective edge of the lens at this transverse displacement. From this curve one can conclude, that the effective edge is at the distance about 1.5 *cm* apart from geometrical edge of the poles. This corresponds to 248+30=278 ± 1 *mm* of effective length, what is now about 5*mm* longer, than initial (272 *mm* according [2]).

Transverse behavior of vertical field as a function of longitudinal coordinate is represented on Fig. 13. The figures on the graphs corresponds to the distance from the edge. So, -8, for example, corresponds to transverse distribution at the 8 *cm* inside the lens. The current level in this set was 10*A*. On the basis of 3D measurement there were no found an influence of the edge field to the quality of the field. Probably this is a game of the type of the profile: for correction of the fringe field effects, the pole need to be have less magnetic material in the region, closest to the axis, what is naturally present in the profile.

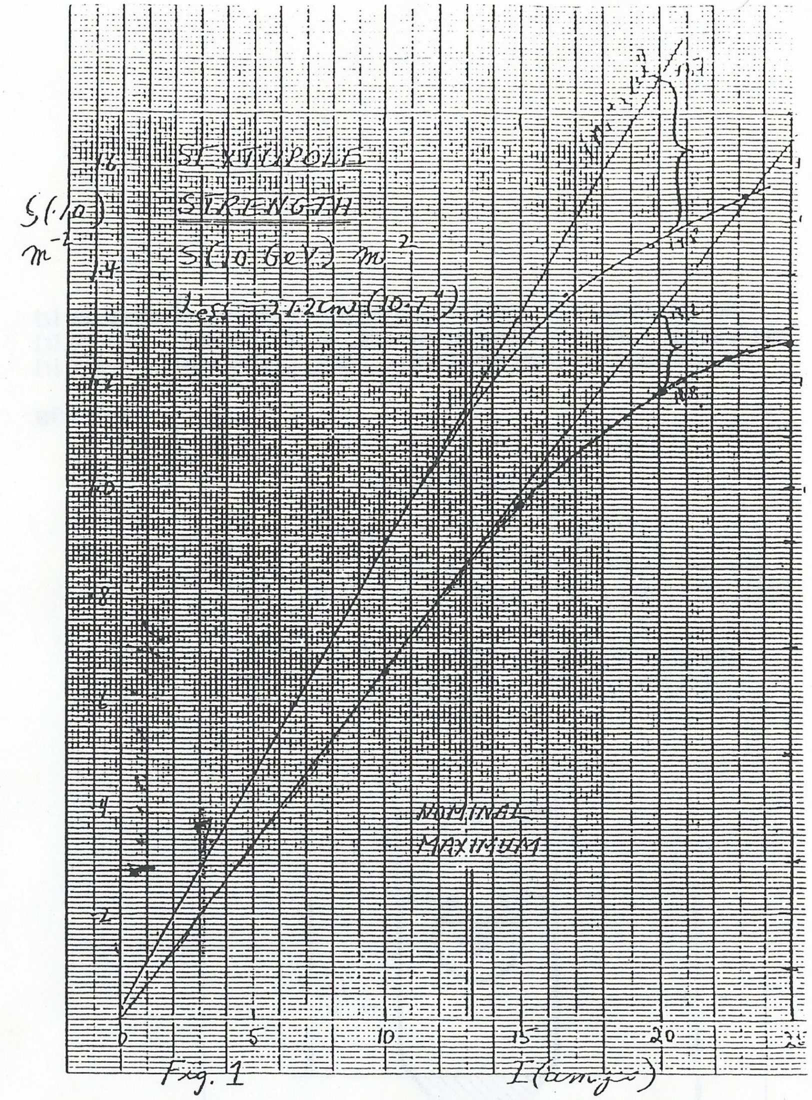

Fig. 11. The saturation curve for initial and cutted profile. The original curve taken from [2].

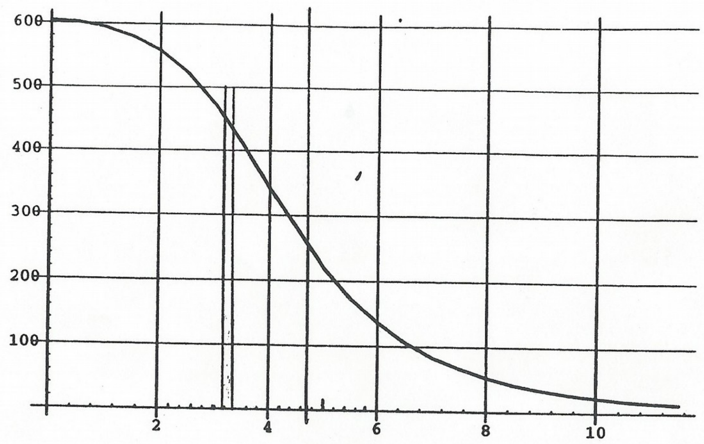

Fig.12 Longitudinal distribution of the field, measured on transverse displacement ***x=4cm*** **. Two lines correspond to the margins of definition of the edge. Line at coordinate 4.7** ***cm*** **correspond to effective edge of the lens at this transverse displacement.**

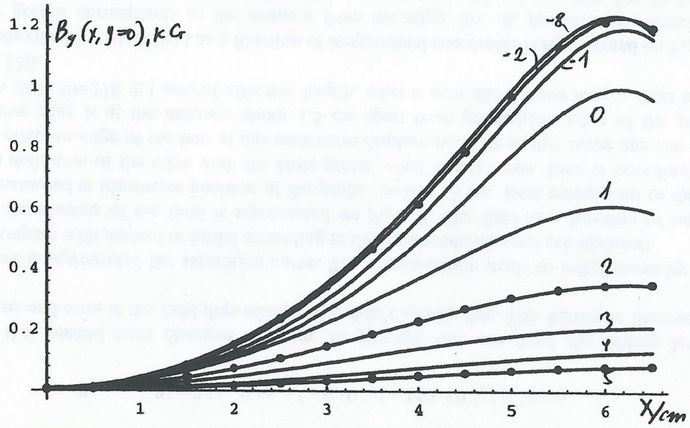

Fig.13. Transverse behavior of the field as a function of longitudinal position. "0" on the graph corresponds to the geometrical edge of the lens. "-8" corresponds 8*cm* inside the lens.

Conclusion. The final drawing represented on the Fig. 12. So, the final cutting chosen is about 7.36 *mm*. This will reduce the harmonic $\approx x^8$ at least 7 times. Variation of the gradient (deflection from the linear behavior) will be few percent only instead of 40-50% at the boundary of aperture. The sextupole strength will drop only to 80% of initial value (for fixer current). The cutting also improve the properties of the vertical steering field. This field reduced on 80%, the same as the sextupole field.

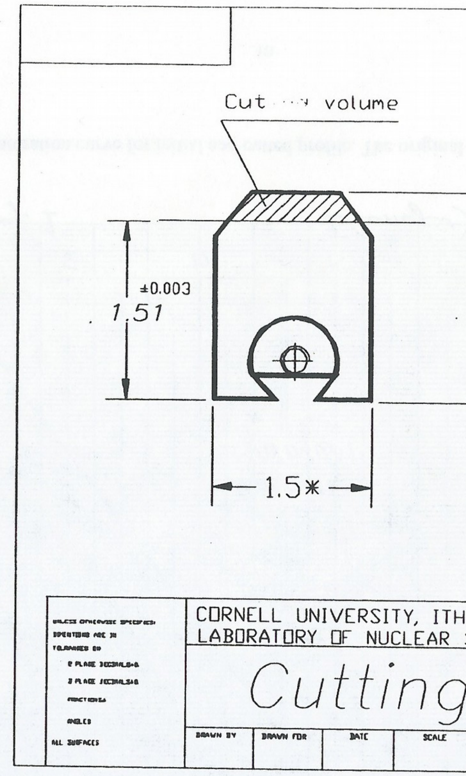

Fig. 14 .The final cutting.

References

[1] "CESR. A design report for Cornell Electron Storage Ring", CLNS 360, April 1977.
[2] D. Larson, L. Roberts, R.Talman, "Sextupole Magnet Measurements", CBN 78-1, 1978.
[3] A.N. Dubrovin, E.A. Simonov, MERMAID user's guide, BINP, Novosibirsk, 1990.