Preliminary considerations on the longitudinal polarization at SuperKEKB

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Introduction.

Here we present our proposal for SuperKEKB geometrical and lattice modifications, needed to achieve the longitudinal polarization of the electron beam at the HER/LER intersection point [1, 2, 3].

The key point is that we shall find the geometrical solution for placement of two 90^0 spin-rotators at the required bending angles relative to the beam axis at IP.

Let's remind that the HER beam energy is E=7 GeV and the corresponding spin tune is ν_0=15.886. This means that the wanted bending angle between each spin rotator and IP is $\theta = \pm \pi/(2\nu_0) \approx \pm 0.099$. Below we present a solution with θ= - 0.0948 for the orientation of the left spin-rotator axis relative to the beam axis at IP, and θ=+0.0948 for the right spin-rotator. Small difference between the optimal and the proposed θ is not significant - spin projection on the longitudinal axis will be reduced only by a factor: $\sin(\nu_0\theta) = 0.9979$. New HER layout with embedded spin-rotators is shown at the Fig.1.

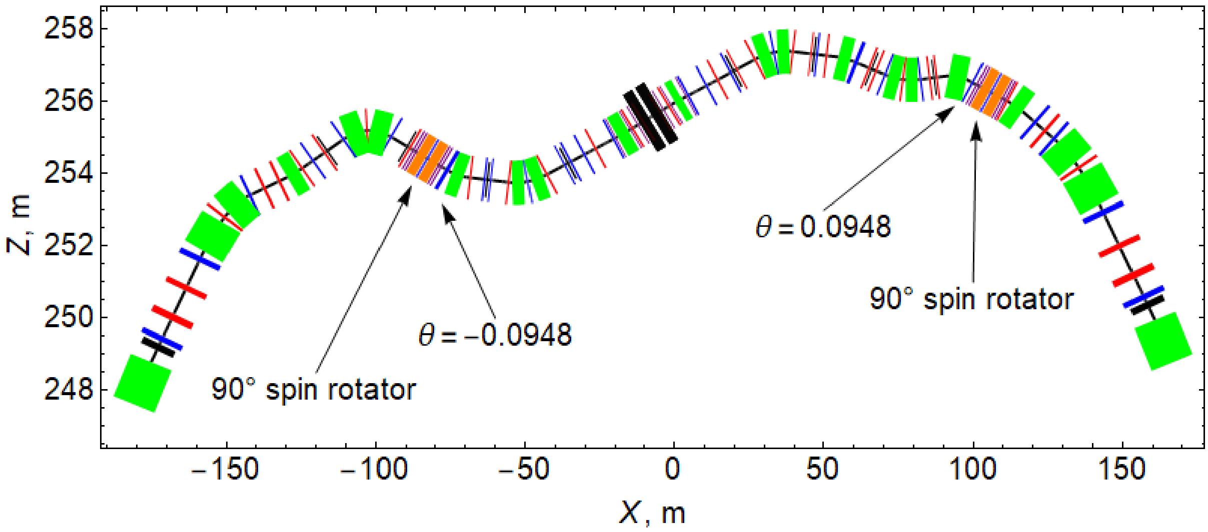

Figure 1. Modified HER long FF straight-section. By brown color are shown solenoids and quads of two 90^0 spin-rotators. Their axis are oriented under θ=+-0.0948 rad relative to the beam axis at IP. Few bends at both sides from IP are changed to achieve these specified angles. Optically both spin rotators and modified bends and quads are matched to nearby unperturbed sectors of the total long FF straight section.

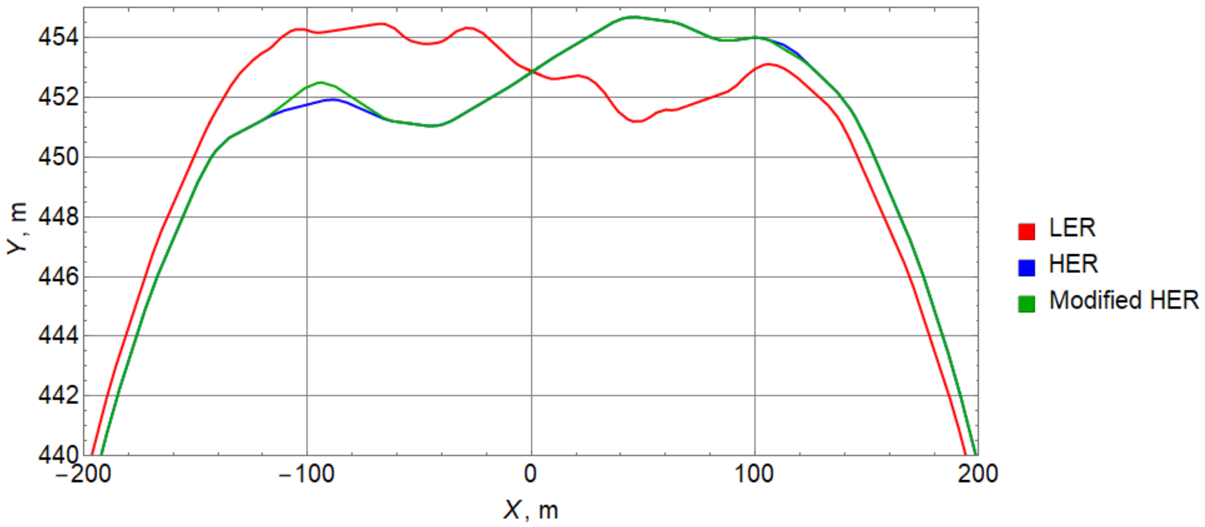

Figure 2. HER and LER orbit separation scheme. The difference between the original and the proposed beam trajectories in HER is shown by blue and green colors, respectively.

Spin rotator lattice design.

To rotate the electron spin by 90^0, the needed longitudinal magnetic field integral is defined by the ratio:

$$Bl = \frac{\pi}{2(1+a_e)} BR$$

Where BR is a beam rigidity and a_e≈$1.16·10^{-3}$ is an electron anomalous magnetic moment.

In our calculations we took *E*=7 GeV, $BR = 23.3495$ T·m, $Bl = 36.635032$ T·m.

We choose the following parameters of each of two solenoids: the field induction $B = 6.54197$ T and the length $l = 2.8$ m. These parameters, in our opinion, look technically realizable, while any shorter version will became too difficult to wind a coil and to handle the solenoid's body against excessive mechanical stresses.

Among variety of different coupling compensation schemes considered in [4], most compact and economic in quads powers is a version with a single normal oriented quad in between two solenoids, plus two skewed doublets of quads at the ends of the insertion, see Fig.3. Such a scheme was realized as the Superconducting Siberian Snake, be constructed by our BINP team and installed at AmPS stretcher ring, NIKHEF, Amsterdam [5].

Doublets at the ends of the insertion are rotated around the beam axis in opposite directions by the angles:

$$\varphi = \pm\frac{Bl}{4BR} = \pm 22.474^0$$

Coupling compensation appears when 2x2 transport matrices of the total insertion satisfy to the condition: $T_y = -T_x$. Moreover, we specify $T_{x,y}$ to be equivalent to the matrix of a drift they occupy. Then 4x4 transport matrix of the total spin rotator insertion looks like:

$$T = \begin{pmatrix} 1 & L & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & -L \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

As one can see, the additional phase advance $\Delta\Psi_y = \pi$ is accumulated by the vertical motion along each spin rotator. This resulted in additional betatron tune shift $\Delta\nu_y = 1$ at the full FF-insertion.

Table 1. Spin rotator lattice parameters for beam rigidity $BR = 23.3495$ T·m, L=9.89112 m.

Element type	Length, m	Field/Gradient, T, T/m
Quadrupole 1	0.46227	-23.2503
Drift 1	0.436	
Quadrupole 2	0.46227	24.081
Drift 2	0.25	
Solenoid	2.8	6.54197
Drift 3	0.25	
Quadrupole 3	0.57004	-29.1537

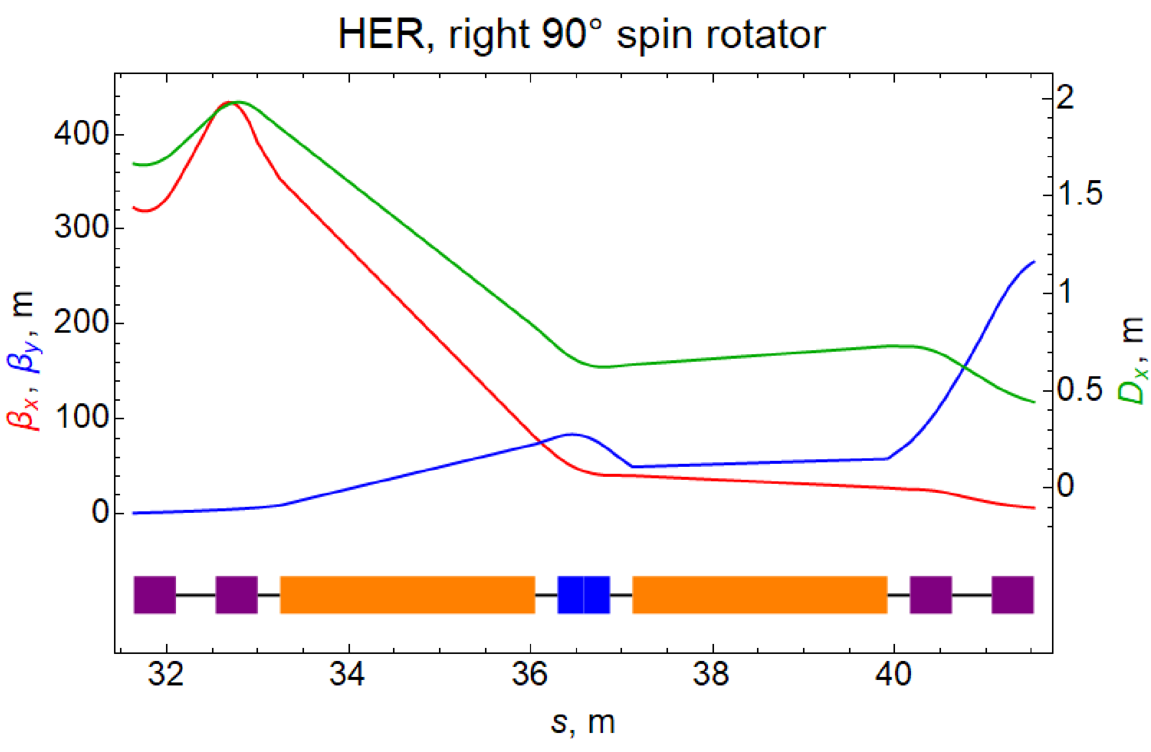

Figure 3. Lattice functions for the right-side spin rotator. Solenoids are painted by yellow, the central quad is normal, while doublets are rolled anti-symmetrically by $\varphi = \pm 22.474^0$.

By switching off solenoids and quads we will simply return to the unperturbed optics with the same matrices as a drift with a length L=9.89112 m, except of that the global vertical tune will jump down by $\Delta\nu_y = -1$ from the value when solenoids are switched on.

Geometry modification.

To accommodate spin rotators at the wanted orientation relative to the beam axis at IP we were forced to change few bending angles at both sides from the IP. So, the dipole BLA4RE was weakened – its bending angle was reduced from θ=.0480687 to θ=.02715394 and its length was changed from 5.9022 m to 3.96143 m. Instead of, a dipole BLA2RE was made stronger – its bending angle was increased from θ=.0348280 to θ=.05574273 and a length was increased from 3.96143 m to 5.9022 m. Effectively, the parameters of these two magnets were almost interchanged!

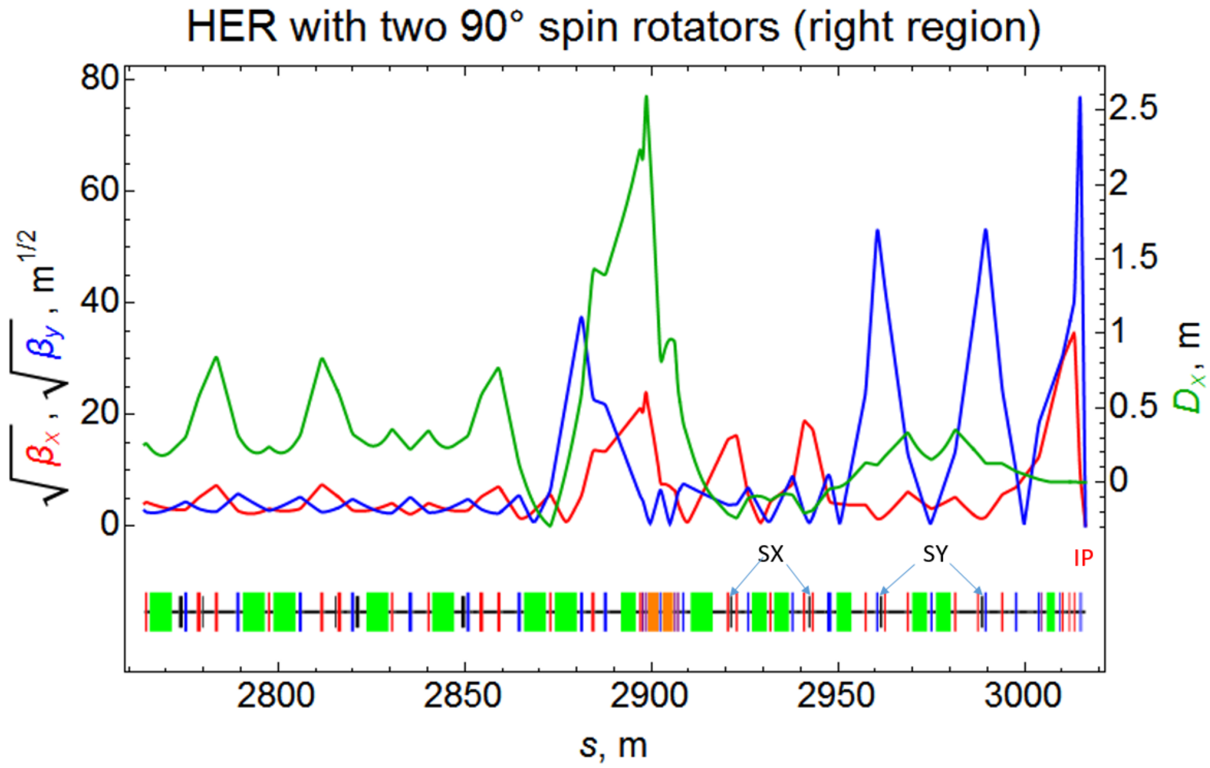

Figure 4. A spin rotator begins and ends by the purple skew-quads and is replacing the drift LTR087 between the quads QLA4RE and BLA2RE. Non-interleaved pairs of sextupoles SX and SY are shown by black color, solenoids by brown color.

Besides, many other drifts are modified, especially the drift LTR087 was increased in length roughly by 5.55 m to provide the required empty space 9.89112 m for placement there of the spin rotator. Some drifts are decreased in length to compensate the geometrical shift of the insertion's end-points.

The **left-side spin rotator** was inserted in between the dipoles BLB1LE and BLX2LE.1, more precisely, in between the quads QLB3LE and QLB4LE. It is increased the length of the drift LTL059 from 5.0503674 m to the required 9.89112 m. Spin rotator will replace this drift.

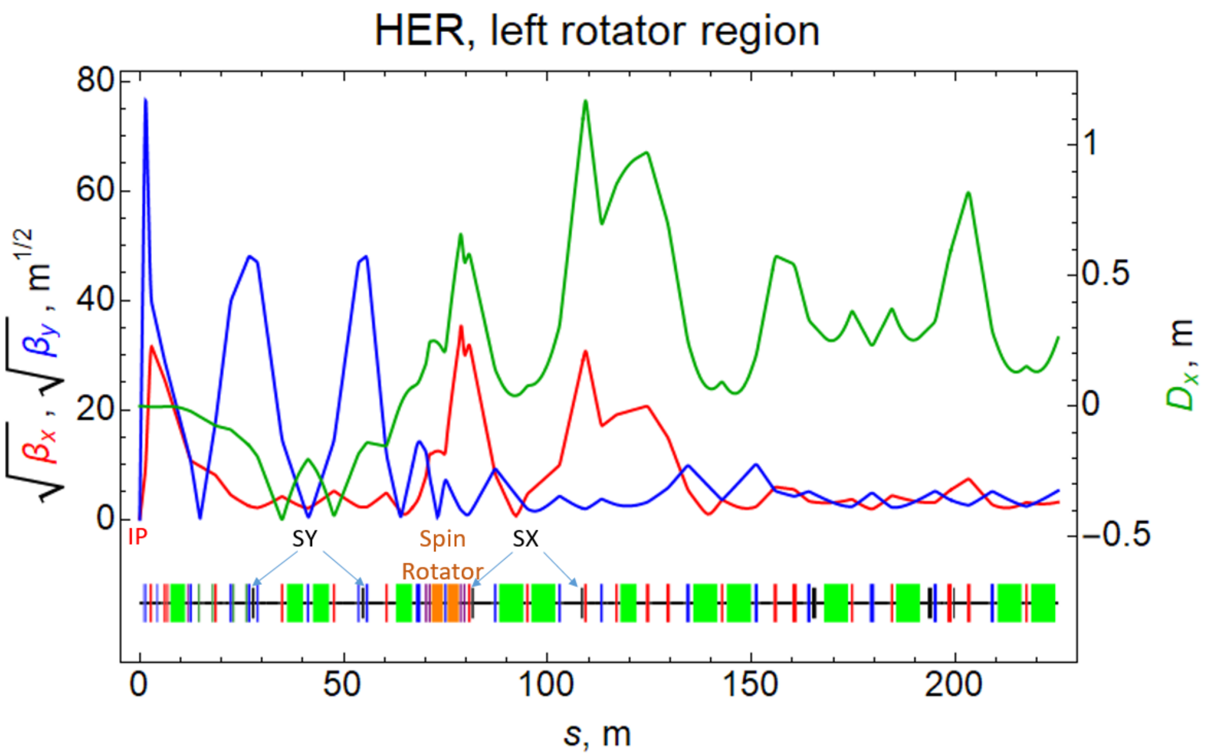

Figure 5. Matched to nearby structure the left-side spin rotator. By brown color are shown solenoids. Here spin rotators is inserted between sections with non-interleaved sextupoles.

The strength of the BLB1LE dipole was significantly increased. Its bending angle was changed from the initial θ= -.0229996 to θ= -0.03878348. A block of two dipoles, BLX2LE.1 and BLX2LE.2, with the bending angle θ=.0259281 and L=3.96143 m each, was replaced by longer dipoles with θ= 0.03571471 and a length L=5.9022 m for each dipole.

These dipoles, together with the quads QLX1LE.1, QLX1LE.2 and QLX2LE, constitute a structure with minus-unity diagonal elements of the x,y-coordinate transformation matrix, in between the non-interleaved sextupoles SLXTLE.1 and SLXTLE.2. We kept this property unchanged!

We also have reversed polarity of the BLA2LE dipole field. Its bending angle was changed from θ= +.0206421 to θ= -0.01814187.

Many drifts were shortened to compensate the lengthening of the drift LTR087 – the future place for the spin rotator.

Geometrically and optically the modified left-side insertion, as well as the right-side one, is matched to the neighbour sections. Still this insertion is somewhat longer compared to the original structure it replaces. The total difference is 40.2 mm. Therefore, we shall find some ways of how to make the circumferences of HER and LER rings equal. Probably it will become easier to increase the length of the LER orbit, instead of decreasing the length of the HER circumference.

Spin relaxation time.

The Sokolov-Ternov radiative self-polarization process is characterized by the polarization time $\tau_{ST} = 31650$ s and *P*=0.924 asymptotic polarization degree. But, with the installed in HER the proposed above spin rotators the spin relaxation time will drop down to a level of about $\tau_{LP} = 3000 - 5000$ s, depending on the exact energy value and some other factors. Correspondingly, the equilibrium self-polarization degree will drop down also, roughly in same proportion. But, in fact, we are not too much interesting in these numbers, because of almost fully polarized beam from a source will be top-up injected into HER and will be renewed with a characteristic time of about 600 s. Therefore, the longitudinal polarization degree is expected to be very high for any of the chosen helicity.

After successful adaptation of the SAD version of the Super-KEKB linear lattice to our needs, we got the equivalent its description in terms of the MADX code, including all geometrical and lattice changes made for accommodation of two 90^0 spin rotators. Then we, with much less efforts, have worked out the input file for the code ASPIRRIN [6, 7]. After this, we got many outputs by running this code. Some results are presented in Fig. 6-9.

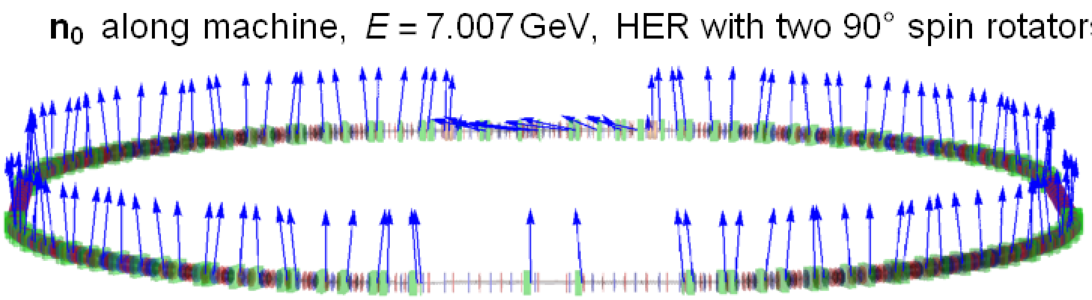

Fig.6 The equilibrium spin direction along the machine at E=7.007 GeV. Everywhere spin aligned vertically except of the FF region where spin lies in the horizontal plane.

The presence of integer $\nu_0 = 16$ and resonances with the betatron frequences $\nu_0 \approx 15.5$ or $\nu_0 \approx 16.5$ makes a life difficult in their vicinity, with many deeps in the depolarization time behavior, see Fig.7. This is the consequence of resonance dependence of $\gamma\, \partial\vec{n}/\partial\gamma$ on the spin frequency detuning from those resonance values. At optimal values of the spin tune, the module of $\gamma\, \partial\vec{n}/\partial\gamma$ is relatively small, in the order of 2.5 in average over the circumference, see Fig8. But at E=7.007 GeV it increases up to 30.

There is a great sense to make much better choice of HER energy, if possible. One can see that the optimal energies are E=6.715 GeV and E=7.15 GeV with τ=10000 s and τ=6000 s correspondingly. Some compromise could be found at E=6.9 GeV, where τ=2000 s.

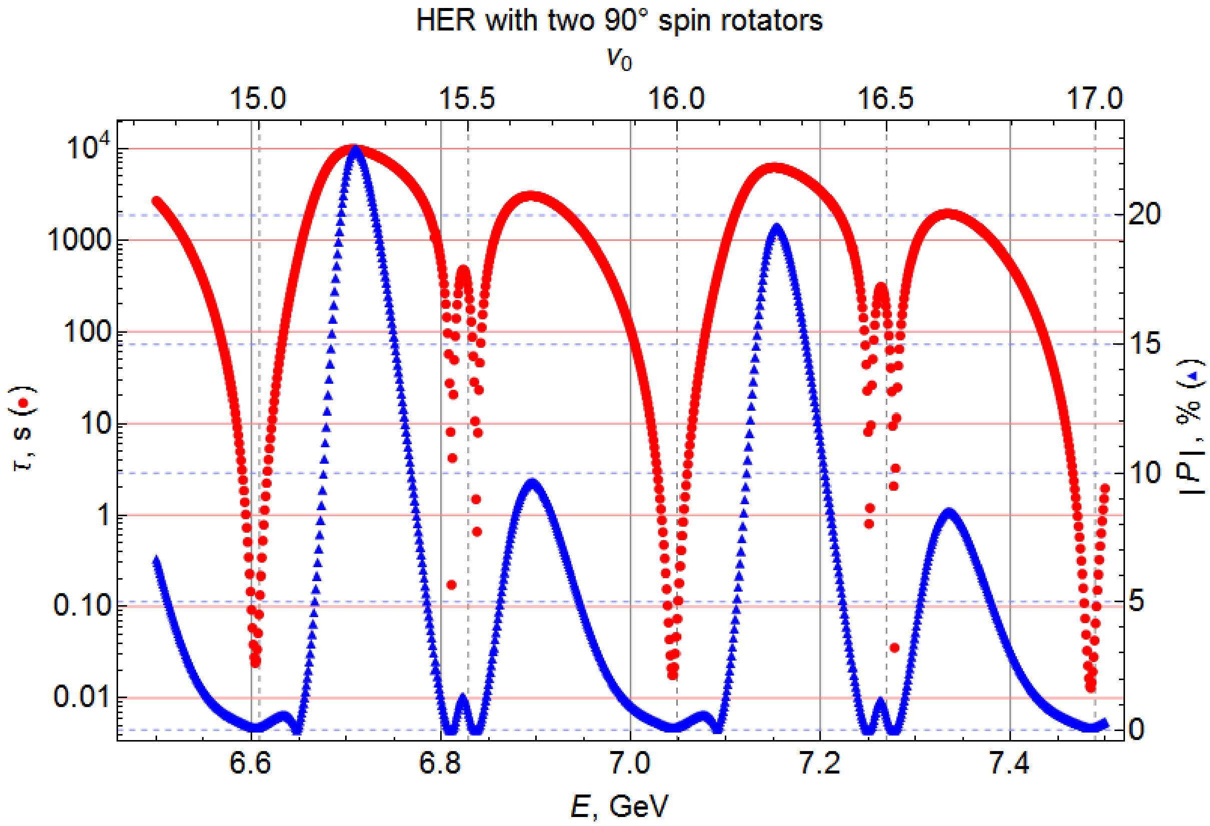

Fig.7 Spin relaxation time (red points) and the equilibrium radiative self-polarization degree. Optimal for LP energy points are E=6.715 GeV and E=7.15 GeV.

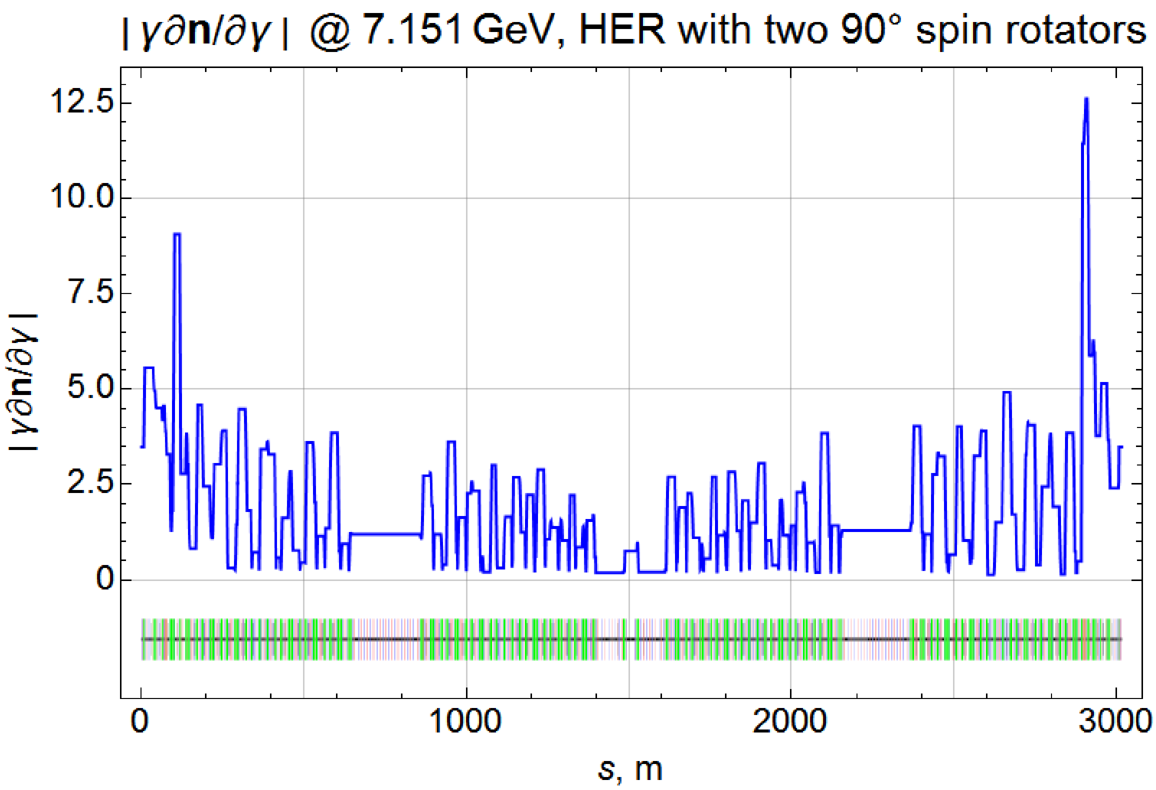

Fig.8 Spin-orbit coupling vector distribution along the machine at E=7.151 GeV.

Conclusion.

The presented above draft of HER lattice modifications proposed for realization of the longitudinal polarization can be considered as very preliminary training in redesigning of the FF scheme. Hope it gives some feeling of how serious the problem is. The real design should be done by the host accelerator team. We are ready to provide our help and expertize in that business.

References.

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