Beam transport to the SXLS ring

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Abstract

Design of a transport line with highly restrictive space and beam size requirements and with flexibility in the orientation of the injector is presented. An analytic method, based on symbolic algebra is used to find optimal regions of the design parameters. The fine tuning of the parameters were then performed with a standard matrix program. Special interest was paid to the question of dispersion vector matching large angle bend with very small bending radius using non-iron bending magnets with very small gap area.

1. Introduction

The SXLS ring [1] is a superconducting compact synchrotron/storage ring of 8.5 m circumference, runing at 696 MeV and providing $\lambda_{critical}$=10 A for x-ray lithography. It is a two superperiod machine consisting of two superconducting combined function bending magnets, four warm quadrupoles and four warm sextupoles. Injector is a 200 Mev LINAC [2]. Injection takes places at one of the straight sections immediatelly before the ring quadrupole (see Fig. 1). It has to fit into the small space left by the beam line, the cryostat and other elements of the densely packed compact ring. On the other hand, the presence of iron close to the superconducting ring dipoles has to be avoided.

The transport line consists of a triplett, followed by an achromatic bend (29°) with horizontal/vertical waist in the middle to allow matching of 1% momentum spread from the LINAC to the 0.1% momentum spread in the ring. This is followed by a quintuplett, which basically serves to match the phase space ellipses into the ring, and finally a total of 151° bend. This last bend consists of two combined function bending magnets with small radius of curvature (B≥2 T) and a septum. There is also a quadrupole between the two bending magnets, separated by drift spaces from them. This last 151° bend will bring the beam parallell with the stored beam as well as match the dispersion and its derivative into the ring. The high field bending magnets and quadrupole will be pulsed non-iron magnets. The design, as shown on Fig. 1, is such, that by reversing the direction of a 29° achromatic bend in the transport line, the LINAC can be lined up either with the long axis of the ring or with the closest beam line, thus making future installation flexible.

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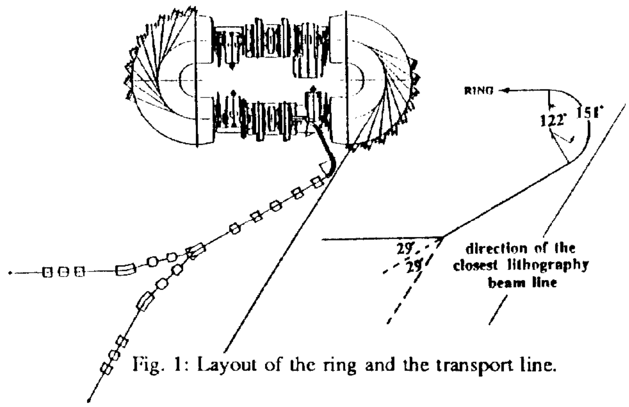


Fig. 1: Layout of the ring and the transport line.

2. Geometry considerations

The septum magnet is in one of the straight sections immediatelly before the ring quadrupole. From the values of the machine parameters at that point of the ring, the matching conditions can be obtained.

It is desirable to limit the presence of iron in the proximity of the superconducting coils of the 180° ring dipole. The only element, where iron is needed (to confine the flux) is the pulsing septum. The maximum achievable bending field in the septum is 1.1 - 1.3 T, and this dictates a minimum bend of 9° to clear the vacuum pipe.

To establish the geometry of the injection into the ring let us imagine to proceed in the reverse direction, from the septum towards the linac, bending the beam to the right, away from the ring. After the septum (in the reverse direction), the *minimum bending field, in order to clear elements in the ring as well as the cryostat itself, is 2.5 - 2.0 T,* the lower field corresponding to the higher operating field in the septum. The larger the bending field is, the more compact the final injection can be made and the easier it is to clear all ring elements as well as the lithography beam lines. From purely geometrical considerations, *to keep as far as possible from the lithography lines, B = 3 T would be preferable to 2 T.* Calculations in the following sections will be shown for both, B = 2 and 3 T.

The minimum total bend (including the septum) is 122°, dictated by the closest lithography beamline. Instead, we chose this bend to be 151° for the following two reasons. Since the SXLS machine is a prototype, it will be more flexible if the design allows future installations at the customer's site with two different linac orientation. This can be achieved if the magnitude of the total final bend (θ_{tot}), and the momentum spread matching achromatic bend (θ_{achr}), are chosen such that: θ_{tot} ±

θ_{achr}=180° or 122°. These conditions yield θ_{tot} = 151° and θ_{achr} = 29°. The second reason is that, as it will be discussed later, the larger the total bend is, the easier is to match the dispersion vector into the ring.

3. Dispersion matching bend

The final 151° bend has to provide dispersion vector matching into the ring besides bending the injected beam parallell with the stored beam. As a consequence, the bend after the septum (still in reverse direction) is broken into two bending magnets with a horizontally focusing quadrupole between them. The strength (k_q) and location (i.e. the θ_3, θ_4 split of the total Θ=θ_{tot}-θ_{septum}=142° bend) of the quadrupole is chosen to match the $\eta_T = \eta_T' = 0$ in the transport line with η_R = -1.2, η_R' = -.6 in the ring. One would like to make the bend as compact as possible (no or very short drift spaces and short quadrupole) in order to clear the closest lithography beam line. It turns out, however, that *it is impossible to match the dispersion vector without drift space* with either B = 3 T or with B = 2 T.

Consider a horizontal composite bend (vertical can be treated similarly), consisting of two bending magnets with bending fields B_3 and B_4, bending angles θ_3 and θ_4 ($\theta_3+\theta_4=\Theta$) and field indices of n_3 and n_4 with a horizontally focusing quadrupole between them. The quadrupole is separated from the dipoles by L_3 and L_4 drift spaces. The length and the strength of the quadrupole is l_q and k_q (=B'/Bρ). Calculating the standard second order transport matrix of the bend as:

$$M=M^{B_2}\,M^{L_1}\,M^{Q}\,M^{L_2}\,M^{B_1},$$

the resulting η and η' will be:

$$\eta = \eta_a + q_{12}b_{11}\eta'_b + q_{21}(L_1\eta'_b + \eta_b)(b_{11}L_2 + b_{12}) + q_{11}[b_{11}\eta_b + (b_{11}(L_1 + L_2) + b_{12})\eta'_b] \quad (1a)$$

$$\eta' = \eta_a + q_{12}b_{21}\eta'_b + q_{21}(L_1\eta'_b + \eta_b)(b_{21}L_2 + b_{22}) + q_{11}[b_{21}\eta_b + (b_{21}(L_1 + L_2) + b_{22})\eta'_b]\,. \quad (1b)$$

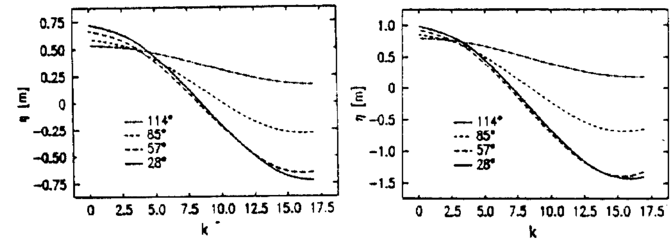
In eqs.(1) q_{ij} are the quadrupole matrix elements and a_{ij}, η_a and η'_a are the matrix elements representing the B_1 dipole. The b index refers to the B_4 dipole.

Eqs.(1) can be written in a simple format if $L_1=L_2=0$, $\rho_3=\rho_4$, $n_3=n_4$ and if the thin lens approximation for the quadrupole is valid ($q_{11}=q_{22}=1$, $q_{12}=0$ and $q_{21}=-\delta=-1/f_x$):

$$\eta=\frac{\rho}{h^2}\left\{1 - \delta\,\frac{\rho}{h}[1 - C(h\theta_3)]S(h\theta_4) - C(h\Theta)\right\} \quad (2a)$$

$$\eta'=\frac{1}{h}\left\{-\delta\,\frac{1}{h}[1 - C(h\Theta)]S(h\theta_4) + 1 - C(h\Theta)\right\} \quad (2b)$$

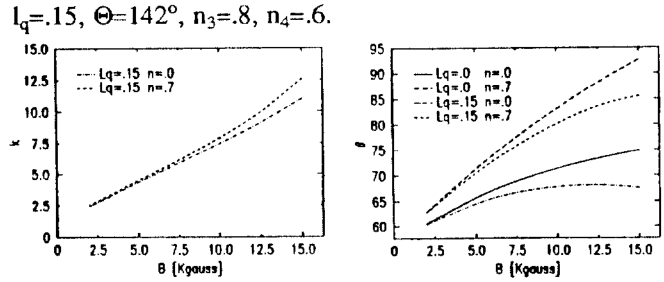
η was calculated from eq.(1a) at $B_3=B_4$=3 and 2T, and is plotted on Figs.2 as a function of k_q for $L_1=L_2=0$, $n_3=n_4$=.5, Θ=142°, l_q=.15m and different values of θ_4.



Figs. 2: η as a function of the quadrupole strengths for different values of θ_4 at (a) B=3T and (b) B=2T.

One can see, that there is a minimum value of the $\eta(k_q)$ function which can be reached with a given set of parameters. *The minimum and the location of the minimum (k_q) sligthly depends on the gradient in the bending magnet but strongly depends on the bending field, on the θ_3, θ_4 split of the total bending angle and on the quadrupole lengths:* It can be shown, that (a) lower bending field or larger field index help in lowering η_{min} and k_q, (b) longer quadrupole results in weeker quadrupole, but increases η_{min}, (c) smaller θ_4 results in strongly lower η_{min}, and slightly weeker quadrupole, and (d) η (and η') has a minimum as a function of **Θ**, and this minimum is reached at 180°.

Let us now consider the conditions of dispersion vector matching. The eqs.(1) nonlinear equations have to be solved for the strength (k_q) and location (θ_4) of the quadrupole with a given set of the remaining eight parameters; Θ, ρ_3, ρ_4, n_3, n_4, l_q, L_1 and L_2. First, we will explore the most compact geometry, when $L_1=L_2=0$. The solutions can be seen on Figs.3, where k_q and θ_4 are plotted as a function of the B bending field with n=.0 and .7 field indices and l_q=.15m quadrupole length. One can see, that already at B=1.5T strong quadrupole (k_q >10) is needed. For higher bending fields, drift spaces have to be allowed. On Figs. 4, k_q and θ_4 are plotted as a function of the L_1 drift space with L_2 as parameter and with B=3T, l_q=.15, Θ=142°, n_3=.8, n_4=.6.



Figs.3: Location (θ_4) and strengths (k_q) of the matching quad is shown as a function of the B bending field for Θ=142°, l_q=.15m. and n=.0, .7

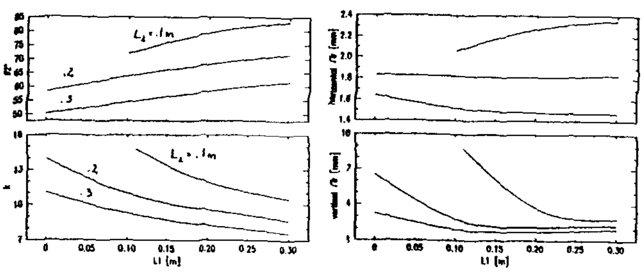
In addition to matching the beam into the ring, the beam size have to fit within the very small aperture (≈1.0-1.5cm²) of the pulsing bending magnets. The beam size, divergence and orientation of the phase space ellipse are given by the matrix elements as:

$$x=\sqrt{\Sigma_{x,11}},\quad x'=\sqrt{\Sigma_{x,22}},\quad \alpha=\frac{r}{\sqrt{(1-r^2)}},\quad \text{where}\quad r=\frac{\Sigma_{x,12}}{\sqrt{\Sigma_{x,11}\Sigma_{x,22}}}$$

and similar expressions for the vertical case. The Σ matrix transforms as

$$\Sigma = M\, \Sigma^0\, M^T.$$

Proceeding in the reverse direction, that is starting with the desired horizontal and vertical phase space ellipses at injection, the Σ matrix was calculated before *the B_3 bending magnet using the previously obtained* solutions for the strengths and location of the dispersion matching quadrupole. The calculated H and V beam sizes are also plotted on Figs. 4 as a function of L_1 with L_2 as parameter for Θ=142°, B=3T, l_q=.15m and n_1=n_2=.6. One can see, that only solutions with $L_2 \geq$.2m and $L_1 \geq$.1m yield reasonably small horizontal and vertical beam sizes at the same time.



Figs. 4: θ_4, k_q, and the horizontal/vertical beam sizes, calculated to match the dispersion vector are shown as a function of L_1, while L_2 is used as parameter. Θ=142° n_3=.8, n_4=.6, and l_q=.15 m.

One can see from the above analysis, that *at B=3T either the beam size can be kept small (≈1cm²) or all beam lines can be cleared, but it is difficult to satisfy both criteria at the same time*. The solutions which clear the beam lines require stronger quadrupoles (therefore the resulting beam size is larger). By increasing the length of the quadrupole the strengths is decreasing, (but of course, at the same time the length of the bend is also increasing). By lowering the bending field to B=2T, weeker ($\delta \approx 1/\rho$) quadrupole is needed to match the dispersion vector, and therefore the horizontal focusing/vertical defocusing will be less. However, this is more then compensated for by the increase in the length ($l \approx \rho$) of the bending magnet. As a net result, the $\sigma_{x,y}$ beam size will even slightly increase. However, the gap area of the non-iron dipoles can be increased by the same ratio as the bending field is decreased.

In Table-1, three cases of the 142° bend are presented. The first case cuts one beam line, the second barely and the third safely avoids all of them.

Table-1

Parameters of different dispersion matching bends with Θ = 142°.

$L_{1,2}$ m	$B_{3,4}$ T	θ_4	$n_{3,4}$	B' T/	l_Q m	σ_x cm	σ_y cm	$(3\sigma)^2$ cm²
.10-.3	3	48	.8-.60	29	.25	.28	.43	1.08
.15-.2	3	58	.8-.60	51	.15	.34	.38	1.16
.10-.2	2-3	62	.8-.55	54	.15	.42	.45	1.70

4. Achromatic bend / Momentum dispersion matching

The 29° achromatic bend serves to match the original 1% momentum dispersion to that of .1% in the ring. It consists of two 14.5° bending magnets operating at .582 T bending field *(l=.29 m, ρ=1.146 m) and two 15 cm* long quadrupoles separated from each other by 30 cm to accomodate the aperture (on which the beam is focused). The quadrupoles are separated from the dipoles by 25 cm drift spaces.

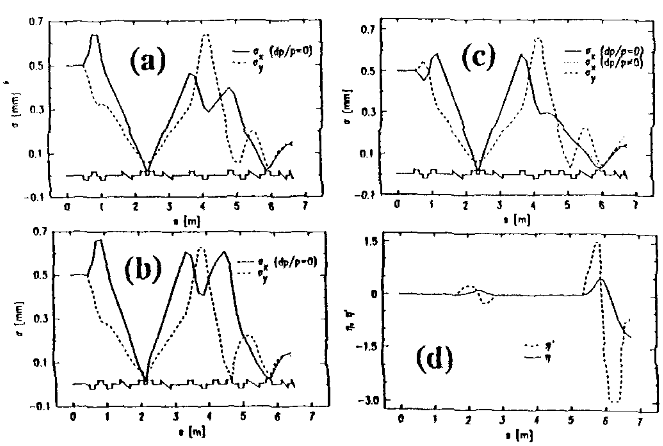
The beam is focused at the middle of the achromatic bend with the help of the $Q_{1,2,3}$ quadrupole triplett after the linac.

5. Phase space ellipse matching

After the achromatic bend, a quadrupole quintuplett *is used to match the horizontal and vertical phase space* ellipses from the slit through the second half of the achromat and through the 151° dispersion matching bend into the ring.

6. Beam envelope and accuracy of matching

The location and the strengths of the quadrupoles as well as the beam envelope through the whole transport line for the three cases presented in Table-1 are shown on Figs. 5. The quadrupole strengths are somewhat different for the three cases, but the quadrupole locations were kept the same. *In all three cases the match of the disper*sion vector and the phase space ellipses into the ring are good to the third decimal place The dotted line on Fig. 5b shows the effect of $\delta p/p$=1% in the 29° achromatic bend and the effect of the $\delta p/p$=.1% in the 151° final bend. The dispersion and its derivative is shown of Fig. 5d. The effect of $\delta p/p \neq 0$ and the behaviour of η and η' are very similar for all cases.



Figs.5: Horizontal and vertical beam envelopes through the whole transport line, for cases presented in Table-1.

7. References

[1] J.Murphy et all.,"Comissioning of the SXLS ring at Brookhaven", *These Proceedings*.

[2] P.Letellier et all., "Comissioning of the 200 MeV Injector Linac", *Proc. IEEE Conf. on Accelerator Physics, 1989.*