APPLICATIONS OF FLAT TO ROUND BEAM TRANSFORMATION FOR RADIATION SOURCES

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Abstract

A transformation between a flat beam (large ratio of horizontal to vertical emittance) and a round beam (equal emittances) can be generated by means of a skew quad and solenoid insertion. It is discussed how this could improve the properties of synchrotron radiation from a helical undulator (with superimposed solenoid field) in storage ring light sources. The possibility of enhancing the gain in FELs is also considered.

1 INTRODUCTION

A beam optics insertion, which transforms a flat ($\varepsilon_y \ll \varepsilon_x$) beam into a round ($\varepsilon_y = \varepsilon_x$) one inside a solenoid, was originally proposed by Derbenev [1] in an electron cooling scheme for hadron beams. It was later shown that the inverse transformation can be used with a low emittance photocathode rf gun to generate a flat beam for e+e- linear colliders [2]. The experimental demonstration of such a flat beam electron source was first performed at the A0 test facility at FNAL [3, 4]. In this paper, I would like to communicate a few considerations of possible further applications of the flat-to-round transformation in the context of incoherent and coherent synchrotron radiation sources.

Helical superconducting undulators are apparently attractive radiator devices because of the possibility of relatively high magnetic field at small period length. A discussion of the (challenging) technical design aspects is beyond the scope of this note. However, the geometric layout of such a device, presumably using a bifilar superconducting coil with opposite current, seems to be well suited to combine it with a superimposed strong solenoidal field generated by a second layer of superconducting coil. The presence of the longitudinal field B_z makes it possible to have a round beam inside the device, matched to a flat beam outside. The asymmetry in the two emittances ($\varepsilon_y \ll \varepsilon_x$) is obvious for a storage ring, but it can also be desirable to transport a flat beam instead of a round one in single pass beam lines (SASE FELs, recirculating or energy recovery linac radiation sources). In such beam lines, the symmetry between the x and y-plane is broken by the presence of bunch compressors and arcs, which are usually oriented in one (the horizontal) plane.

2 BEAM OPTICS ADAPTER

The adapter between a round beam inside a solenoid and a flat beam outside is realised as a combination of a skew block transformation together with the end field of the solenoid. The properties of the adapter are briefly summarised here, a more detailed discussion can be found in [5,6].

Consider a perfectly flat ($\varepsilon_y=0$) beam (momentum p_0), which is passed through the following 4×4 skew block transformation:

$$C = \frac{1}{2}\begin{bmatrix} N+M & N-M \\ N-M & N+M \end{bmatrix}$$

The 2×2 matrices N, M have the form

$$M = \begin{bmatrix} \cos\mu & \beta\sin\mu \\ -\frac{1}{\beta}\sin\mu & \cos\mu \end{bmatrix}, \quad N = M(\mu + \pi/2)$$

The phase μ is a free parameter, the essential point is the 90 deg. phase *difference*. A simple practical realisation of the matrix C is done with a symmetric skew quadrupole triplet [7].

This transformation turns the beam into a vortex distribution (x'-y and y'-x correlation). The successive passage through the solenoid endfield removes this correlation and the beam is paraxial in the solenoid body field. The parameter β is equal to the Larmor beta-function in the solenoid,

$$\beta = 2p_0/eB_z$$

With a small but non-vanishing vertical emittance, the beam in the solenoid is not paraxial, instead the vertical phase space is transformed into Larmor motion. For $\varepsilon_y \ll \varepsilon_x$ the Larmor radius is small compared to the beam radius. The horizontal and vertical emittances of the round beam are equal, $\varepsilon_{x,r}=\varepsilon_{y,r}=:\varepsilon_r$ and the 4-D phase space volume is conserved: $\varepsilon_r=(\varepsilon_x\cdot\varepsilon_y)^{1/2}$. Proper matching to the skew block requires $\beta_{x,y}=\beta$ and $\alpha_{x,y}=0$ for the flat beam. The round beam is characterised by an approximately constant size over the length of the solenoid, $\sigma_{x,y}=(\varepsilon_x\cdot\beta/2)^{1/2}$, and angular spread $\sigma'_{x,y}=(2\varepsilon_y/\beta)^{1/2}$. The effective beta-function is $\beta_{eff} = \sigma/\sigma' = \beta\cdot(\varepsilon_x/\varepsilon_y)^{1/2}/2$.

3 INSERTION DEVICE FOR STORAGE RINGS

Modern synchrotron radiation storage rings have, as a result of good orbit and betatron coupling correction, achieved emittance ratios $\varepsilon_y/\varepsilon_x$ well below 1%. Using a helical undulator with solenoid focusing as an insertion device would allow to reduce the horizontal emittance in the undulator by about one order of magnitude and in a certain wavelength regime the radiation can be diffraction limited simultaneously in both planes. For example, a 2GeV beam with horizontal emittance of $2\cdot10^{-9}$ m, emittance ratio 0.25%, would operate at the diffraction limit at about 1nm wavelength. The radiation could be generated by a λ_u=1cm period length undulator with B_u=0.8T field strength. A superimposed solenoid field of 6.6T requires a matching condition $\beta_{x,y}$=2m. The effective beta-function is in this case β_{eff}=20m, which seems adequate for a long insertion device. The flat-to-round transformation also helps to provide a reasonable acceptance for horizontal injection oscillations: assuming a 3mm aperture radius of the undulator, the acceptance for this parameter example is A_x=9mm·mrad.

The undulator/solenoid insertion creates vertical emittance from quantum fluctuations, since transverse kicks inside the undulator are transformed into the vertical phase space outside. The equilibrium emittance due to the undulator alone (i.e. disregarding radiation in other bending magnets of the ring) can be calculated as:

$$\varepsilon_{y,u} = 5\cdot10^{-14} m \cdot \left(\frac{B_u}{T}\right)^3 \left(\frac{\lambda_u}{cm}\right)^2 \frac{1}{E/GeV} \frac{\beta}{m} \frac{L_u}{m}$$

This does not appear to cause a serious emittance degradation, unless one considers undulators of very high field or with long period.

For a practical layout with an insertion device of the type described here, one also has to take into account effects on the beam optics from the weak focusing of the undulator field and from the non-zero integrated longitudinal undulator field component along the helical orbit. Both effects require a slight re-matching of the adapter. Furthermore, the chromaticity of the insertion as well as the alignment tolerances need to be carefully analysed.

As a more speculative application, one may also consider the possibility to use the insertion device for a storage ring-based FEL. The better overlap of a round electron beam with the photon beam and the reduced dilution of micro-bunching, which for a flat beam is dominated by the large horizontal emittance, can improve the single pass FEL gain. It is conceivable that thus a high FEL output power can be achieved even in a wavelength regime where only mirrors of rather low reflectivity are available.

4 SINGLE PASS RADIATION SOURCES

Unlike storage rings, in linac (or recirculating linac) driven radiation facilities there is no obvious asymmetry between the horizontal and vertical beam emittance since the beam properties are mainly determined by the source instead of reflecting the equilibrium between radiation damping and quantum excitation. However, the presence of bunch compressors and, for recirculation schemes, arc sections can cause emittance growth which is much larger in the horizontal bending plane than in the vertical plane. Especially for short bunches, coherent synchrotron radiation (CSR) can be a substantial source for emittance dilution. It can therefore still be advantageous to transport a flat beam (generated in a source similar to the one proposed in ref. [2]) through the compressor and arc sections before returning it to a round shape in the undulator device. For example, if CSR causes a 200% growth of the emittance in the horizontal plane for a round beam with 1mm·mrad normalised emittance, then transporting instead a flat beam with ratio $\varepsilon_x/\varepsilon_y$=10mm·mrad/0.1mm·mrad would reduce the relative emittance growth to a more acceptable 20%. This argument is, of course, only correct to the extend to which the emittance growth in the vertical plane remains negligible. In a practical approach, the optimum emittance ratio for the flat beam will therefore have to be determined by also taking into account dilution effects in the vertical plane. While the scheme considered here aims at reducing CSR emittance growth from very short bunches, a different approach was recently proposed [8], which also uses a flat beam, but applies compression to the photon pulse instead of the electron bunch.

The superconducting helical undulator with superimposed solenoid focusing can be a suitable device for a SASE FEL in the (soft) X-ray regime. This is demonstrated by the following example of an 8nm FEL driven by a 1.5GeV electron beam. All relevant parameters are listed in Table 1. The simulation of the FEL process with the code GENESIS [9] shows a gain length below 1m and saturation of the photon beam power at about 15m of undulator length (see Fig. 1).

Table 1: Parameters for the SASE FEL example.

Beam energy	1.5 GeV
Bunch charge	1 nC
Peak current	2.5 kA
Undulator parameter K_u	2.427
Period length λ_u	2 cm
Photon wavelength	8 nm
Solenoid field B_z	6.6 T
Flat beam norm. emittances $\gamma\cdot\varepsilon_{x,y}$	10^{-5} m/ 10^{-7} m
Beta functions $\beta_{x,y}=\beta$	1.5 m
Round beam size $\sigma_{x,y}$	50 μm
Norm. emittance $\gamma\cdot\varepsilon_r$	10^{-6} m
Effective beta function β_{eff}	7.5 m
Gain length	≈ 0.9 m

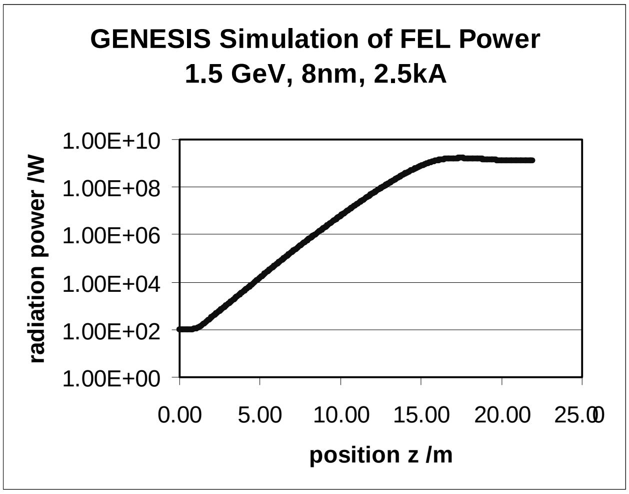

Fig. 1: Genesis simulation of the FEL gain with the parameter example shown in Table 1.

5 CONCLUSIONS

The examples discussed above show that a helical undulator with solenoid focusing can be a useful device in context with the flat-to-round beam transformation. Whether or not this approach is the preferable solution for a radiation facility depends on the particular layout and design parameters. In addition, a number of technical issues have to be addressed regarding the design of the superconducting undulator. Tight requirements for field homogeneity must be fulfilled and an alignment within a fraction of the beam size must be achieved, which requires beam-based procedures. Beam diagnostics and correction equipment has to be integrated. For the likely case that a long device would be built in sections, the mismatch due to the gaps in the solenoid field must be compensated.

Finally, I would like to mention an advantageous synergy effect regarding the technical development of superconducting helical undulators: these devices are very useful for radiation sources as well as polarised positron sources for linear colliders. In a project like TESLA [10], which combines a High Energy Physics and an FEL user facility, such a synergy effect would be highly welcome.

6 REFERENCES

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