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General-Purpose Synchrotron Radiation Sources

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Abstract

General-purpose sources of synchrotron radiation are proposed to satisfy those future needs of basic, applied, and industrial research as well as of industrial production which cannot be covered adequately by the existing machine types. Their spectrum extends into the hard X-ray range. They feature a mixed lattice composed of superconducting and normal conducting bending magnets, and dispersion-free straight sections to accommodate insertion devices. The mixed lattice offers an additional way of minimizing the emittance by optimizing the distribution of bending angle among the different types of bending magnets. At an energy of 1.5 GeV the emittance in a six-period Triple Bend Achromat lattice can be brought into the 10^{-7} - 10^{-8} m·rad range.

Allzweck-Synchrotronstrahlungsquellen

Zusammenfassung

Allzweck-Synchrotronstrahlungsquellen werden vorgeschlagen, um in der Grundlagen-, der angewandten und der Industrieforschung sowie in der industriellen Fertigung den zukünftigen Bedarf zu decken, der durch existierende Maschinentypen nicht in angemessener Weise befriedigt werden kann. Ihr Spektrum erstreckt sich bis in den harten Röntgenbereich. Sie sind gekennzeichnet durch eine aus supraleitenden und normalleitenden Ablenkmagneten aufgebaute gemischte Magnetstruktur sowie durch dispersionsfreie Driftstrecken zur Aufnahme von Wigglern und Undulatoren. Die gemischte Magnetstruktur bietet eine zusätzliche Möglichkeit, die Emittanz durch geeignete Verteilung des Ablenkwinkels pro Magnet auf die verschiedenen Magnettypen zu minimieren. Bei einer Elektronenenergie von 1.5 GeV kann die Emittanz in einem Ring mit 6 aus drei Ablenkmagneten bestehenden Achromat-Zellen in den Bereich von 10^{-7} - 10^{-8} m·rad gebracht werden.

(Invited paper 11th International Conference on the Application of Accelerators in Research and Industry, Denton, Texas, Nov. 5-8, 1990).

1. Introduction

The landscape of synchrotron radiation sources has many features. Various sources [1] are in operation, under construction, or planned. They include the parasitically used or dedicated facilities of the 1^{st} and 2^{nd} generation, respectively, the sources of the 3^{rd} generation which are characterized by an extensive use of insertion devices and which are mostly under construction or design, the family of the four 6-10 GeV sources under construction or design in Europe, the United States, Japan, and the Soviet Union, and a variety of sources, such as the compact, and partly superconducting rings, designed for specific purposes like X-ray lithography.

The development of the 3^{rd} generation sources and the 6-10 GeV machines serves preferentially research which seeks to extend the state-of-the-art of synchrotron radiation experiments. Besides the growing use in basic research a significant increase can be expected in the fields of applied and industrial research and development and of industrial production, applications which depend on the easy access to and availability of synchrotron radiation. This foreseeable need is the reason to propose a general-purpose (gp) source which aims at combining a hard radiation spectrum with a low emittance and high brilliance at moderate size and cost.

In the following, we first discuss the main features of gp sources and work out the conditions for minimum emittance under special consideration of the new aspect of bend angle optimization. Then, two specific examples are given, namely an asymmetric Chasman-Green and a Triple Bend Achromat lattice. Finally, a preliminary layout of a gp source is shown.

2. Main features of gp sources

The gp source as envisaged here will have both, superconducting and normal conducting bending magnets, and the available radiation spectra will extend into the hard X-ray range. It will further have long dispersion-free straight sections to accommodate insertion devices such as wigglers, undulators, and microundulators. Six superperiods might be sufficient to bring the emittance in the 10^{-7} - 10^{-8} m·rad range for an electron energy of 1.5 GeV. How close the theoretical minimum emittance can be approached will depend on the same design criteria which are applied on 3^{rd} generation sources, e.g., chromaticity, momentum acceptance and dynamic aperture.

The mixed lattice, composed of normal and superconducting bending magnets is favourable because

a) the spectrum of synchrotron radiation can be harder at a given value of the emittance ε when using superconducting magnets since, for a given lattice, the characteristic wavelength λ_c scales as $\lambda_c \sim 1/(\varepsilon B)$, where B is the magnetic field,

b) the bending angles can be used to further minimize the emittance,

c) radiation from wigglers and undulators can be kept from going through the superconducting magnets, thereby relaxing the requirements on the aperture of the radiation slot and the related heat load,

d) the number of superconducting magnets and thus their influence on the dynamic aperture is reduced, and

e) there might be experiments which benefit from the softer spectrum provided by the normal conducting bending magnets.

3. Minimum emittance with angle optimization

In the following, two lattices, Chasman-Green (CG) and Triple Bend Achromat (TBA), both including superconducting and normal conducting bending magnets, are discussed in terms of their emittance (Fig. 1). It should be noted that the number of straight sections is fixed to six in order to bring the emittance into the desired range, but still keeping the machine as small as possible. Consequently, the bending angle per magnet before optimization is 30^o in the CG case and 20^o for TBA.

Following Helm et al. [2] the emittance is given by

$$\varepsilon = c_q \gamma_e^2 I_5/(I_2 - I_4)$$

with $c_q = 3.84 \cdot 10^{-13}$ m, γ_e the ratio of the particle energy to its rest energy, and the synchrotron radiation integrals

$$I_2 = \sum_i l_i/\rho_i^2 ,$$

$$I_4 = \sum_i l_i \langle\eta\rangle_i/\rho_i^3 ,$$

$$I_5 = \sum_i l_i \langle H\rangle_i/|\rho_i|^3$$

$< >_i$ indicate mean values over the bending magnet whose length and bending radius are l_i and ρ_i, respectively. H is the function

$$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

with the usual Twiss functions α, β, γ, and the dispersion function η. Then, for a separated function lattice and using $\varphi_i = l_i/\rho_i$ we find $I = I_5/(I_2 - I_4)$ as

$$I = (\varphi_1\langle H\rangle_1/\rho_1^2 + \varphi_2\langle H\rangle_2/\rho_2^2)/((\varphi_1/\rho_1)(1-\langle\eta\rangle_1/\rho_1) + (\varphi_2/\rho_2)(1-\langle\eta\rangle_2/\rho_2))$$

Here, $\langle H\rangle_i$ is the average value of the function H calculated with $\eta_i = \eta_i' = 0$ at the magnet edges outside the achromat for the CG case, and $\eta_1 = \eta_1' = \alpha_2 = \eta_2' = 0$ for the TBA case (see fig. 1) .

The usual procedure to find the minimum emittance for identical magnets is now to set the derivatives of I with respect to α_i and β_i (CG case) or α_1, β_1, η_2, and β_2 (TBA case) to zero and solve the four equations for the respective quantities. When the magnets are not identical, there is a further variable to minimize I, namely φ_1 at fixed bending angle per cell. As we shall see below, the angle optimization applies not only to the case of magnets with different bending radii ($\rho_1 \neq \rho_2$), but in the case of a TBA lattice also to magnets with identical radii ($\rho_1 = \rho_2$).

The emittance becomes minimum with respect to the α_i and β_i for the following values (i = 1, 2):

CG case:

$$\alpha_{i,min} = \left[(4F_1(\varphi_i) - F_2(\varphi_i))F_2(\varphi_i)/F_3(\varphi_i)^2 - 1\right]^{-1/2}$$

$$\beta_{i,min} = \rho_i(4F_1(\varphi_i) - F_2(\varphi_i))/[F_2(\varphi_i)(4F_1(\varphi_i) - F_2(\varphi_i)) - F_3(\varphi_i)^2]^{1/2}$$

TBA case:

$$\alpha_{1,\,min} = \left[(4F_1(\varphi_1) - F_2(\varphi_1))F_2(\varphi_1)/F_3(\varphi_1)^2 - 1\right]^{-1/2}$$

$$\beta_{1,\,min} = \rho_1(4F_1(\varphi_1) - F_2(\varphi_1))/[F_2(\varphi_1)(4F_1(\varphi_1) - F_2(\varphi_1)) - F_3(\varphi_1)^2]^{1/2}$$

$$\beta_{2,min} = \rho_2[F_1(\varphi_2)(F_2(\varphi_2) - 2)/F_2(\varphi_2)]^{1/2}$$

$$\eta_{2,min} = -p/2 - (p^2/4 - q)^{1/2}$$

with

$$p = -2\rho_2^2(\sin\varphi_1/(\rho_1\sin\varphi_2) + 1/\rho_2)$$

and

$$q = -\rho_2F_1(\varphi_2)p - (\rho_2^2\beta_2/\varphi_2)\Big[\varphi_1[(4F_1(\varphi_1) - F_2(\varphi_1))/(2\beta_{1,min}) -$$

$$\alpha_{1,min}F_3(\varphi_1)/\rho_1 + \beta_{1,min}F_2(\varphi_1)/(2\rho_1^2)] +$$

$$\varphi_2[(4F_1(\varphi_2) - F_2(\varphi_2))/(2\beta_{2,min}) + \beta_{2,min}F_2(\varphi_2)/(2\rho_2^2)]\Big].$$

Here, we use the functions

$$F_1(\varphi) = 1 - \sin\varphi/\varphi,\ F_2(\varphi) = 1 - \sin\varphi\cdot\cos\varphi/\varphi,\ F_3(\varphi) = (1 - \cos\varphi)^2/\varphi.$$

The equation for φ_1 resulting from the derivative of I with respect to φ_1, keeping $\varphi_1 + \varphi_2$ constant, turns out to be so elaborate that no attempt is made to solve it explicitly. Instead, the emittances can be plotted versus φ_1 to find the minimum graphically, taking into account the values $\alpha_{i,\ min}$ and $\beta_{i,min}$ (CG) and $\alpha_{1,min}$, $\beta_{1,min}$, $\beta_{2,min}$, and $\eta_{2,min}$ (TBA), as given above.

4. Specific examples

Fig. 2 shows the emittance ε versus the bending angle of the first, normal conducting, magnet φ_1. The bending radii are chosen as ρ_1 = 4.16 m and ρ_2 = 1.25 m corresponding to 1.2 and 4 T, respectively. The electron energy is 1.5 GeV equivalent to γ_e = 2935.

It can be seen that, in the CG case, the optimized angles of the normal conducting and the superconducting magnets are 34.5^0 and 25.5^0, respectively. The corresponding Twiss values at the magnet edges are α_1 = 3.715 , β_1 = 3.788 m , α_2 = -3.786 , β_2 = 0.851 m . If the bending radii are equal, the minimum occurs at 30^0 for each magnet, as we would expect for symmetry reasons. However, its value is 15 % larger.

In the TBA case, the optimized angles are 19.4^0 for the normal conducting and 10.6^0 for half of the superconducting magnet which happens to be only a small deviation from the usual case of identical angles. The corresponding Twiss values at the edge of the first and in the middle of the central magnet are α_1 = 3.823 , β_1 = 2.166 m , η_2 = $7.27\cdot10^{-3}$ m, β_2 = $5.97\cdot10^{-2}$ m. It is interesting to see, however, that for equal bending radii the minimum occurs at 17.6^0 for the first magnet and 12.4^0 for half of the central one. It is 14 % larger than in the mixed lattice case, but 15 % smaller than in the usual TBA case with identical magnets. This feature might be useful to optimize conventional TBA lattices.

The emittance values calculated so far should be considered as lower bound. As with the usual sources of the 3^{rd} generation, consideration of chromaticity and dynamic aperture might lead to higher values in practice. This optimization of lattices for the cases considered here is not complete yet.

Fig. 3 shows the preliminary layout of a ring based on an angle-optimized TBA lattice with 5.4 m long dispersion-free straight sections. Five ID's can be accommodated in this lattice, the 6^{th} straight being used for RF and injection. At 1.5 GeV electron energy the bending magnets (1.2 T and 4 T) produce spectra with λ_c= 0.7 nm and 0.2 nm. Emittance is less than 10^{-7} m·rad. Circumference is 111.6 m.

5. Conclusion

General-purpose sources can be more brilliant than conventional ones because they work at lower energy due to the superconducting magnets and benefit from angle optimization. The latter aspect does not only apply to mixed lattices like in general-purpose sources, but also to conventional TBA lattices. With six superperiods emittance values in the 10^{-7} - 10^{-8} m·rad range should be achievable at 1.5 GeV electron energy.

Acknowledgment

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References

[1] For an overview, see any recent accelerator conference proceedings, e.g., Proc. 1989 IEEE Particle Accelerator Conf., March 20-23, 1989, Chicago, Illinois, 89CH2669-0.

[2] R.H. Helm, M.J. Lee, P.L. Morton, M. Sands, IEEE Trans. Nucl. Sci. NS-20(1973)900.

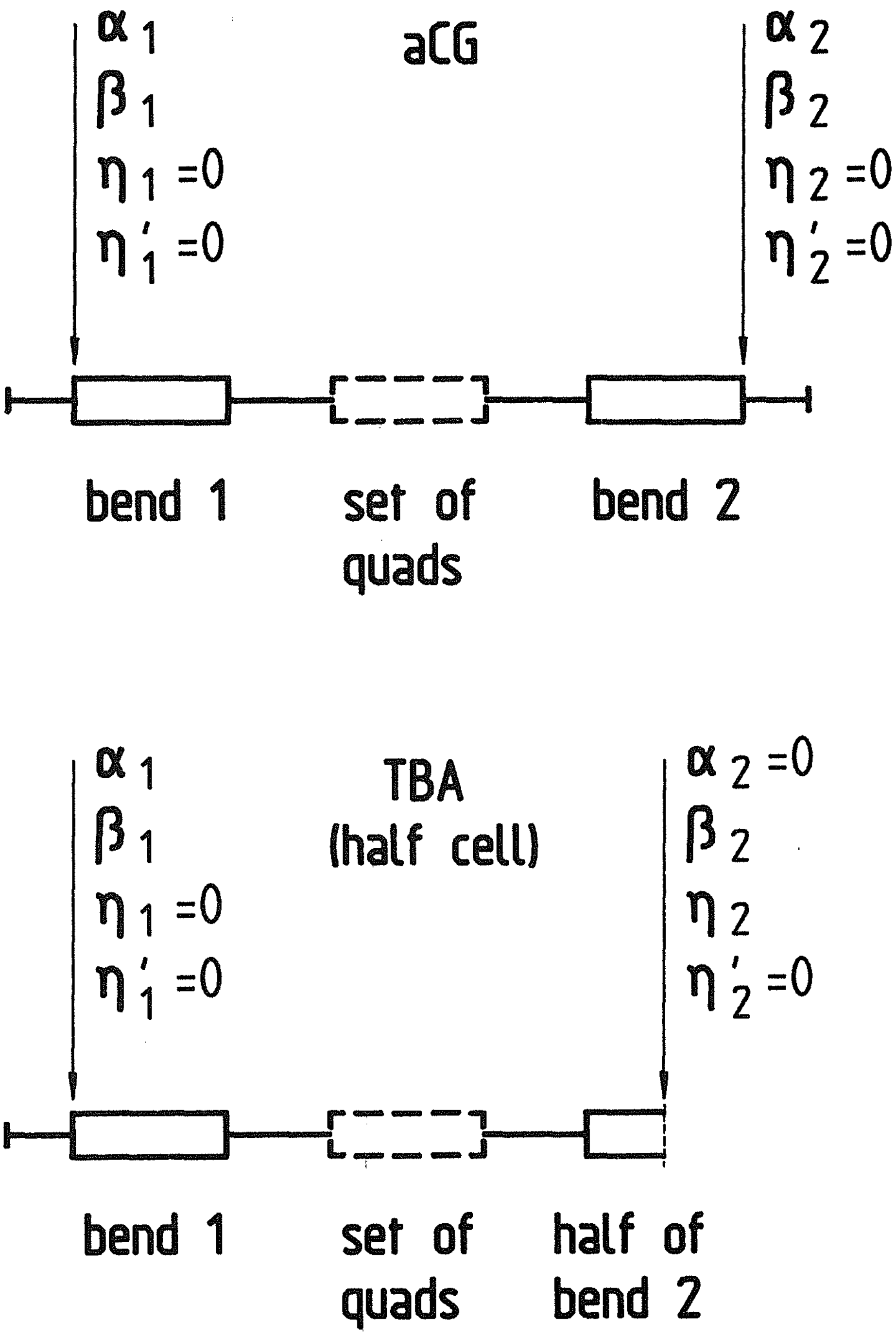

Fig. 1: Schematic of the two lattice types discussed: aCG asymmetric Chasman-Green, TBA Triple Bend Achromat.

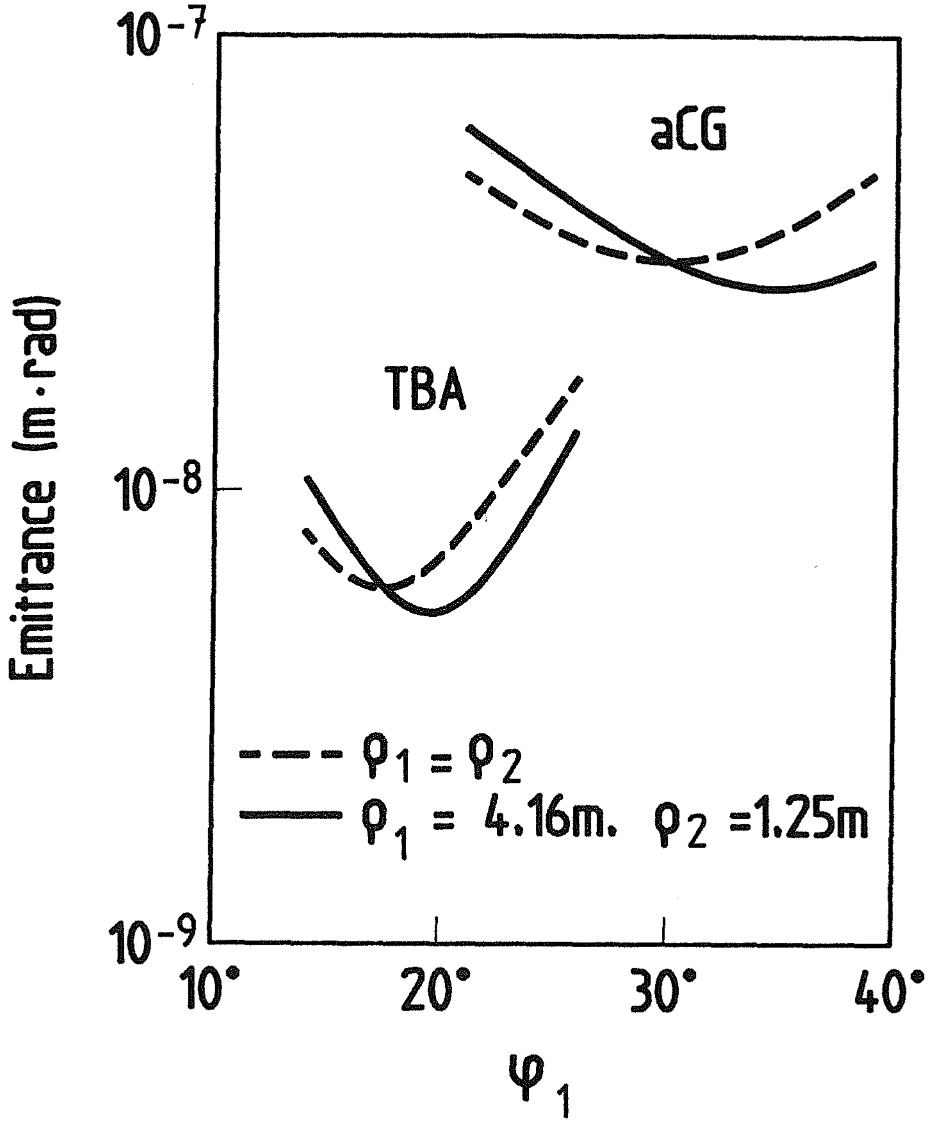

Fig. 2: Minimum emittance ε versus bending angle of the first, normal conducting, bending magnet. The total bending angle per cell is fixed to 60^0. Note that the nominal bending angle per magnet is 30^0 for the CG case and 20^0 for TBA. The large difference between the two cases stems, thus, from the φ^3-dependence of the emittance.

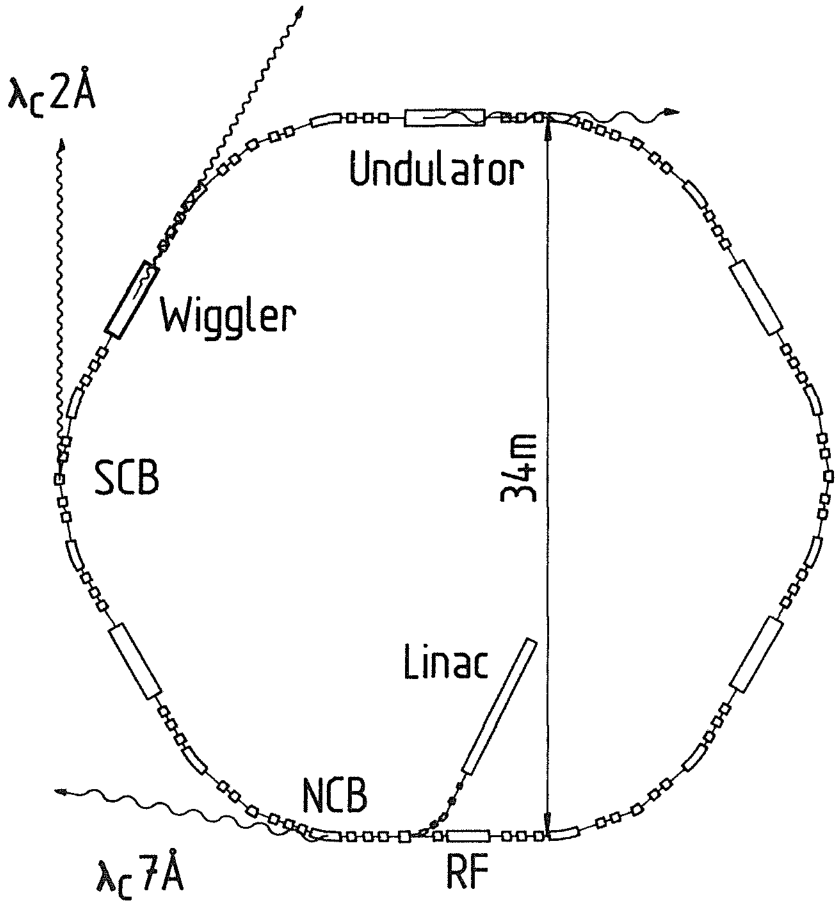

Fig. 3: Preliminary layout of a general-purpose source based on a Triple Bend Achromat lattice.