PERFORMANCE AND PERSPECTIVE OF MODERN SYNCHROTRON LIGHT SOURCES

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Abstract

The first synchrotron radiation was used in a so called parasitic mode from high energy machines (1st generation). At the end of the 1970s and the beginning of 1980s accelerators dedicated to the production of synchrotron radiation were built (2nd generations). With the investigation and developments of insertion devices in the middle of 1980, the 3rd generation synchrotron radiation sources were built and emittances down to some nmrad could be reached. At present around 50 Synchrotron Radiation sources are existing around the world. All of these sources reached there the specification (energy, current, emittance, beam stability, etc.) very soon after the commissioning. With the 4th generation, emittances of down to around 100 pmrad should be reached. This is still a factor of 10 away from the requirement of a diffraction limited light source. According to the expertise in designing and operating of synchrotron radiation sources this should be reachable in the future, but only with circumferences of some kilometers like Petra III or PEP-X. Overall the performances and perspective of synchrotron light source are remarkable.

INTRODUCTION

The layout of the European Synchrotron Radiation Facility (ESRF) [1] (see Fig.1) is an example of a modern Synchrotron Light Source. It starts with an electron Linac with an energy of 200 MeV, which will be injected via a transfer line into the booster synchrotron and accelerated up to 6 GeV. From the booster synchrotron the beam goes over another transfer line into the storage ring. With a repetition frequency of 10 Hz the beam will be accumulated in the storage ring until reaching its final value of 200 mA (for the ESRF).

The ESRF exist of 32 achromat's with the magnet sections and the straights for the installation of the ID's.The characteristics of the Linac, Booster and Storage-ring are changing for the different light sources. At the Swiss Light Source, ALBA and TPS [2-4] the booster is located in the storage ring tunnel in order to reduce the emittance. For these facilities the emittance of the beam is smaller as 10 nmrad. Details of all Light Sources can be found under "www.lightsources.org" within the rubric "Light sources of the world". Overall there are 47 Light Sources in the world.

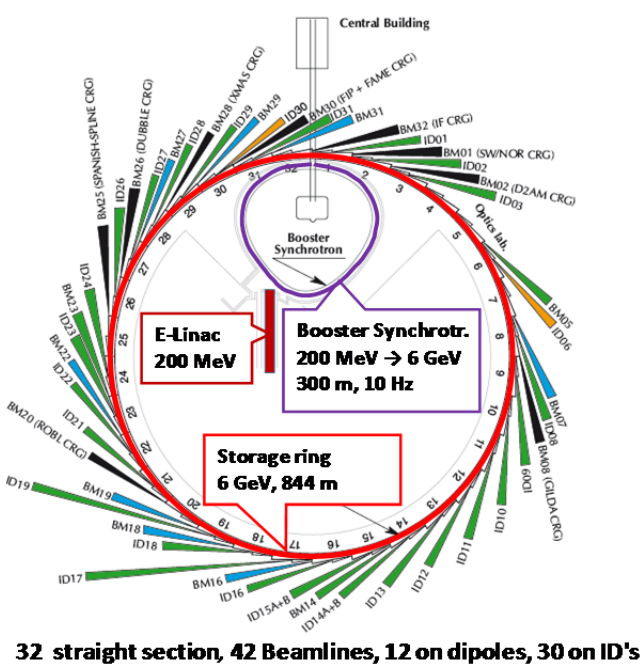

Figure1: General layout of a synchrotron light source with the Linac, Booster Synchrotron, Storage-Ring and the beam lines around the storage ring.

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The brilliance (Br) of the synchrotron radiation (Eq.1) is the most important factor for the users, it is given by the emitted photon flux (Fl) per second and 0.1% resolution divided by the cross sections ($\sum_x$, $\sum_y$) and divergences ($\sum'_x$, $\sum'_y$) of the beam (see Eq.1). The emitted photon flux is proportional to the stored beam current and the characteristics of the source (bendings or insertion devices). The cross sections and the divergences of the beam are given by the emittance ε_x and ε_y as well the machine functions β_x, α_x and γ_x, η_x and η'_x are the horizontal dispersion and its derivate. The horizontal emittance of a lattice is given by the Eq. (2) [5],[6],[7]

$$\boldsymbol{B_r = \frac{Fl}{4\pi^2 \sum_x \sum'_x \sum_y \sum'_y}} \qquad (1)$$

$$\boldsymbol{\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint \frac{H(s)}{\rho^3}(s)ds}{\oint 1/\rho^2(s)ds}} \qquad (2)$$

where Cq = 3.84*10-13 m, the integrals are taken along the ring circumference, J_x is the horizontal partition number, ρ is the reference orbit radius, γ is the normalized energy ($\gamma = E/m_0c^2$), H is the dispersion invariant (see Eq. 3)

$$\boldsymbol{H = \gamma_x^2 \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x^2 \eta'^2_x} \qquad (3)$$

$$\boldsymbol{\alpha_x = -\frac{1}{2}\beta'_x \ , \qquad \gamma_x = \frac{1+\alpha_x^2}{\beta_x}} \qquad (4)$$

DESIGN OF LOW EMITTANCE STORAGE RINGS

Low emittance lattices were initially developed for the 3rd generation light sources on the basis of the Double Bend Achromat (DBA) [8] and Triple Bend Achromat (TBA) [9]. A general solution for a so called isomagnetic ring, a ring in which all the magnets are identical, is given by Eq. 5.

$$\boldsymbol{\varepsilon_x = C_q * \frac{\gamma_0^2}{J_x} * \frac{1}{3*4\sqrt{15}} * F * \varphi^3 =}$$
$$\boldsymbol{A * \frac{F}{J_x} * \frac{E^2 * \varphi^3}{GeV^2 * rad^3}} \qquad (5)$$

where F is a lattice factor and φ is the deflection angle of the bending magnets, the constant A = 31.64 nmrad. According to Eq. 5 the emittance depends upon the deflection angle of the 3rd power or is proportional to the inverse of the number of magnets to the 3rd power ($\varepsilon_x \approx 1/\mathrm{Nmagnets}^3$). For the DBA –the theoretical minimum emittance is given ([10], [11], [12]) with a F-value = 3 and for the TME-lattice it is F=1

The emittance can be decreased too, by increasing the horizontal partition number Jx, (see Eq.2) which is given by the Eq. (6):

$$\boldsymbol{J_x = 1 - D, \quad D = \frac{1}{2\pi}\int \eta(s)\left[\frac{1}{\rho^2} - 2\frac{G}{\rho * B}\right] ds} \qquad (6)$$

$$\boldsymbol{\varepsilon_{Wi} = \varepsilon_0 * \frac{U_0}{U_0 + U_{Wi}}} \qquad (7)$$

where B is the magnetic field and G is the gradient.. The change of the emittance with damping wigglers is given by Eq. 7. Where ε_o is the emittance without damping wigglers, Uo is the emitted radiation power without wigglers and U_{Wi} is the radiation power of the damping wigglers.

LATTICES OF MODERN LIGHT SOURCES

To achieve low emittance the following points should be considered:

►The number of magnets has to be large.

►For a TBA – or MBA-Lattice, the outer bending magnets must be shorter by roughly a factor 2

►The bending magnets should be combined-function with vertical focusing to increase Jx. Combined-function bending magnets have also the advantage of leading to a compact machine.

► Damping wigglers can be installed to increase the horizontal partition number J_x

► Longitudinal gradient bending magnets have the potential to decrease the emittance further.

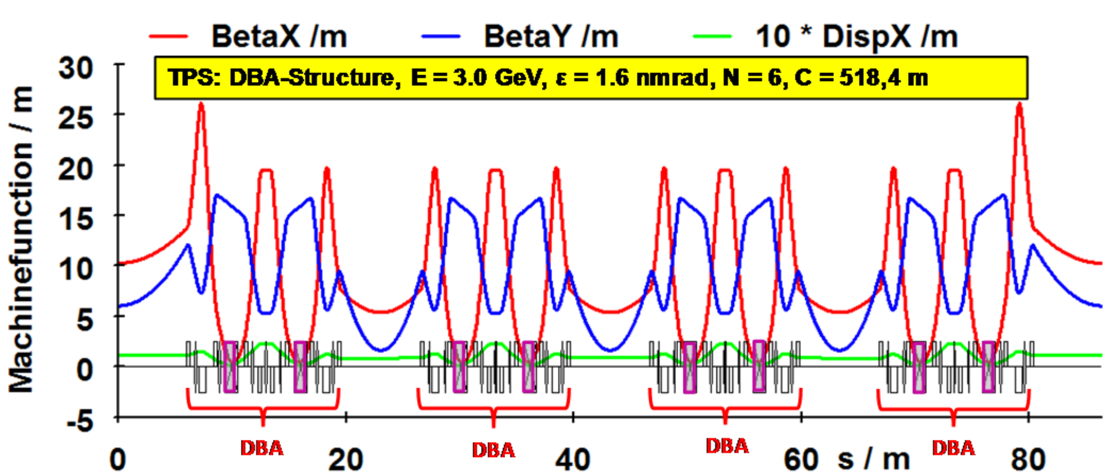

Figure 2: The lattice of the Taiwan Photon Source (TPS).

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In Fig.2 is given as an example for the layout of a modern Synchrotron Light Source that one of the Taiwan Photon Source (TPS) [13]. It has a DBA structure with a TME-settings in the bendings and different lengths of the straight sections (6*12 m and 18*7m). NSLS II is reducing the emittance from 2 nmrad to 0.5 nmrad by introducing damping wigglers

A summary of the characteristics of the modern light sources is presented in Table 1. The white boxes are sources with a DBA structure, the green boxes with a TBA and the yellow ones with a TME-lattice. A good way to compare the different light sources is to look for the available space for the installation of insertion devices as well the so called normalized emittance or K-value given by Eq. 8

$$K = 0.0316 * \frac{\varepsilon_x \; GeV^2 * rad^3}{E^2 * \varphi^3} \quad (8)$$

Table 1: The main parameters of modern light sources (3rd generation)

Source	Lattice	Energy (GeV)	Emitt. nmrad	Jx	Ins. Length (m)	Current (mA)	Angle (rad)	Circumf. (m)	Percent. (%)	K-Value
ALS	TBA	1.9	5.6	1.4	81	500	0.1745	196.8	41.2	9.249
BESSY II	DBA	1.9	6.4	1	89	250	0.1963	240	37.1	7.425
ELETTRA	DBA	2	7	1.32	74.78	300	0.2618	258	29.0	3.090
SLS	TBA	2.4	5	1	80.28	400	0.1745	288	27.9	5.175
SESAME	TME	2.5	25.7	1.68	54.56	200	0.3927	133.1	41.0	2.151
NSLS-xray	DBA	2.5	44.5	1	18	500	0.3927	170.08	10.6	3.725
SOLEIL	TME	2.75	3.72	1	159.6	500	0.1963	354	45.1	2.060
CLS	DBA	2.9	18.2	1.6	62.4	200	0.2618	170.4	36.6	3.821
SPEAR III	DBA	3	18.2	1.2	67	500	0.16535	234.13	28.6	14.171
ASP	TME	3	7.13	1.36	75.55	200	0.2244	216	35.0	2.221
DIAMOND	DBA	3	2.84	1	218.2	300	0.1309	561.6	38.9	4.457
ALBA	TME	3	4.29	1.3	103.44	400	0.1963	268.8	38.5	1.996
TPS	TME	3	1.6	1	210	400	0.1309	518.4	40.5	2.511
PAL-II	TME	3	5.6	1.33	118.92	400	0.2618	281.82	42.2	1.099
SSRF	TME	3	2.6	1	152	300	0.1571	432	35.2	2.360
ESRF	DBA	6	3.94	1	237.8	200	0.09817	844	28.2	3.665
APS	DBA	7	2.514	1	268.8	100	0.0785	1104	24.3	3.360
SPRING 8	TME	8	2.4	1	329	100	0.0714	1440	22.8	3.264

The K-value gives an indication of how much the emittance converges to the theoretical minimum one. The minimum K value for the TME structure is 1 and for the DBA structure is 3. These value will be reached by ELETTRA [14] and PAL II [15]. ELETTRA reaches the minimum value for the DBA-structure because the phase advance between the 2 bending magnets is π.

In order to reduce the emittance, as in the case of SESAME [16], ASP[17], ALBA[18] as well PAL II, and build a compact machine there should be a gradient in the bending magnets, leading to a partition number J_x above 1.3. According to table 1 and Eq.(6), PAL II, with a K-factor of 1.1 is the most advanced design of a synchrotron light source. Also under the aspect that 42.2 % of the circumference are dedicated to straight sections. A synchrotron light source should have a high brilliance, but also a lot of long straight sections for the installation of the insertion devices. In table 1, there are given the length of the straight section as percentage of the circumference. SOLEIL[19] has with 45.1 the largest percentage. Most of the recent build light sources have numbers around 40 %. The ESRF and APS are coming up only with 20 to 30 %.

Completely different is the layout of PETRA III [20]. It worked as a collider and has been converted into a synchrotron light sources. The layout of PETRA III is presented in Fig.3, it is a 6 GeV machine with circumference of 2304 m and a stored current of 100 mA. In one of the octant (NE to E) a DBA structure has been introduced and in the other octants from E to NE the original FODO structure is in use. The machine functions of the FODO as well the DBA-structure are given in Fig.3.

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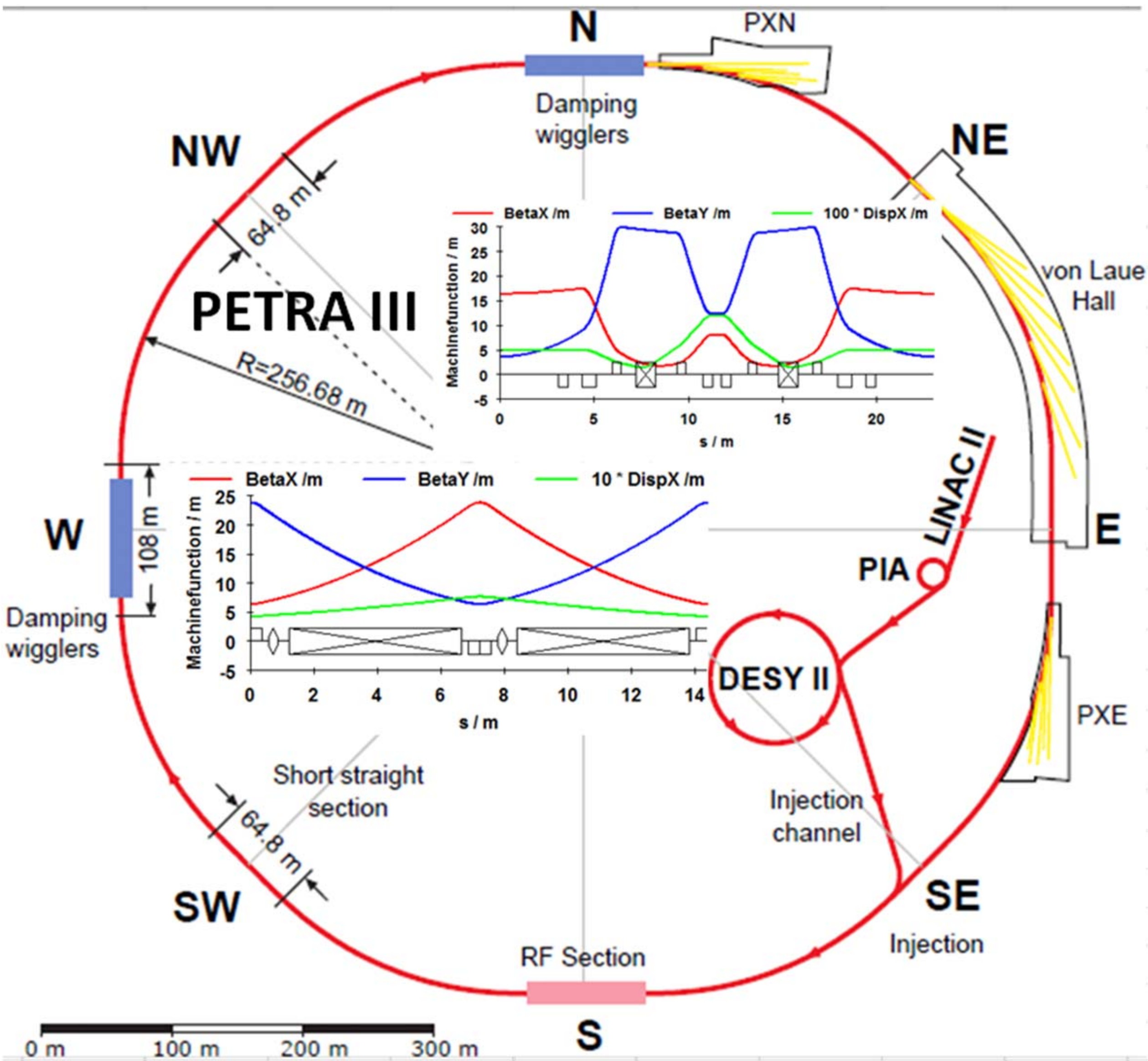

Figure 3: The layout of the Synchrotron radiation Source PETRA III.

The bare lattice of PETRA III is leading to an emittance of 8.2 nmrad (7.1 from the FODO-arcs and 1.1 from the DBA-arc) the corresponding radiation losses per turn are 521 keV from the FODO arcs and 48.7 from the DBA-arc. With the introduction of 20 damping wigglers (B=1.52 T and L=4 m) the radiation loss per turn will be increased by 4.2 MeV; this reduces the emittance by a factor 8.37 down to 1 nmrad.

For the accelerators it is of interest, in order to cross check the accuracy of the different programs, to look for the difference of the actual settings to the design ones. This can be given by the β – beating, which is the difference of the real and the designed β – values. The corresponding values for some light sources are given in [21]. According to these numbers the accuracy of the design should be better as 1 %; SOLEIL and Diamond reached 0.3 to 0.4 %. The theoretical vertical emittance should be zero, because there isn't any deflection in the vertical direction. The tolerances of the alignment procedure gives some offset to the position of the magnets which leads to some extend to a deflection in the vertical direction. The emittance in the vertical direction gives some ideas about the correct positioning of the magnets, as well the correction procedure for the offset by correctors. Values of the vertical emittance down to 1 pmrad could be reached at the SLS and ASP [22]. A lot of rings aren't operating at the minimum vertical emittance because of the reduced lifetime which are not in favour of the users.

MODERN LIGHT SOURCES A SUMMARY

The situation of the modern light sources can be summarized as the following:

► Most of the present light sources (3rd generation) used the DBA structure.

► All the light sources reached the user requirement, that the stability of the beam should be better as 1/10 of the

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beam cross section. For most of the Light Sources the beam stability is in the sub-µm region.

► In order to minimize the emittance some machines have a dispersion in the straights and use the TME-setting

► Damping wigglers have been introduced for reducing the emittance.

► Most of the light sources use the "topping up" injection mode.

► All machines have been commissioning and reached there specification in a short time.

►The vertical emittance in the range of pmrad have been reached.

► All the light sources are using closed orbit and bunch by bunch feedback systems.

► The user time goes up to over 95% of the operation time, in some case up to 99

All of this shows that the synchrotron light sources are very reliable and we can go for the next generation of synchrotron light sources, the 4th generation.

THE NEXT GENERATIONS (4TH) OF SYNCHROTRON LIGHT SOURCES

Synchrotron light sources with a factor of 10 to 20 smaller as the 3rd generation are called the 4th generation. Eq.(5) clearly favours the lattice with many bending magnets in an achromat and indeed the most challenging design make use of the so-called multiple bend achromat's (MBA) lattices. MBA's were first proposed by Einfeld [23] and later selected for the baseline design of MAX IV [24], based on a 7BA which delivers an emittance of 330 pmrad. The machine functions of MAX IV and the corresponding layout are shown in Fig.3. The layout of MAX IV is very well described in [25]

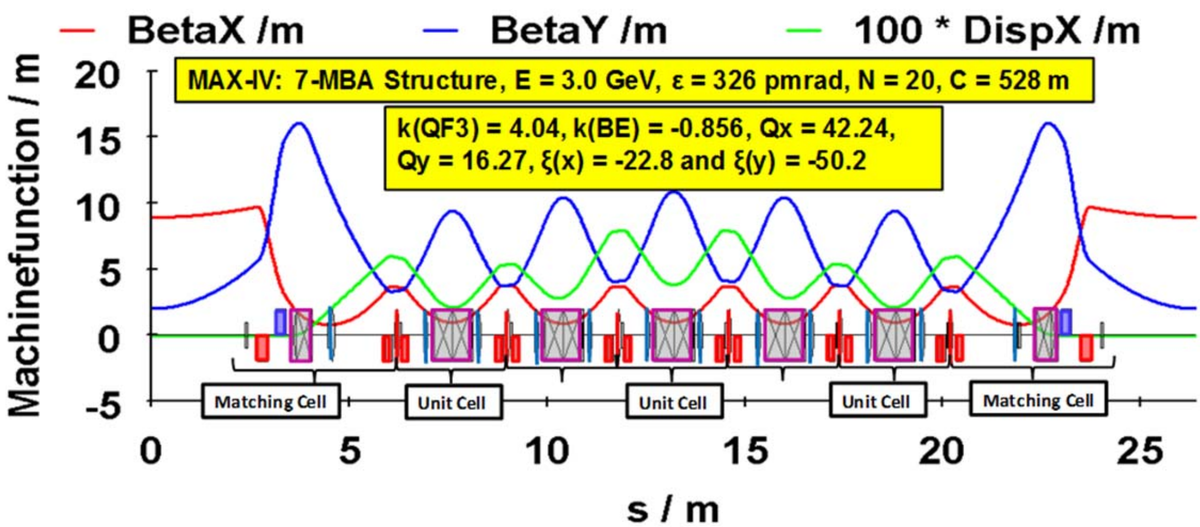

Figure 3: MBA-lattice of MAX IV with 7 bending magnets

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Completely different to MAX IV is the layout of the ESRF-Upgrade project ESRF-EBS [26] with the so called "Hybrid Multi Bend Achromat" (HMBA) (see Fig.4). The project started in spring 2012.

The layout is given by 2 DBA – structures at the beginning and the end of the achromat in order to have a large dispersion function for chromaticity corrections. These 2 sections are connected with 3 combined function magnets with a gradient of 38 T/m (see Fig.4) and 4 high gradient quadrupoles with gradients of 90 T/m (see Fig. 4). The ESRF-EBS design is very compact in order to replace the existing one in the same tunnel and leading to an emittance of 132 pmrad. For first time, the bending magnets will be build up with permanent magnets and will have a longitudinal gradient to reduce the emittance by roughly 15%. For the update of the APS [27] also a HMBA lattice will be used.

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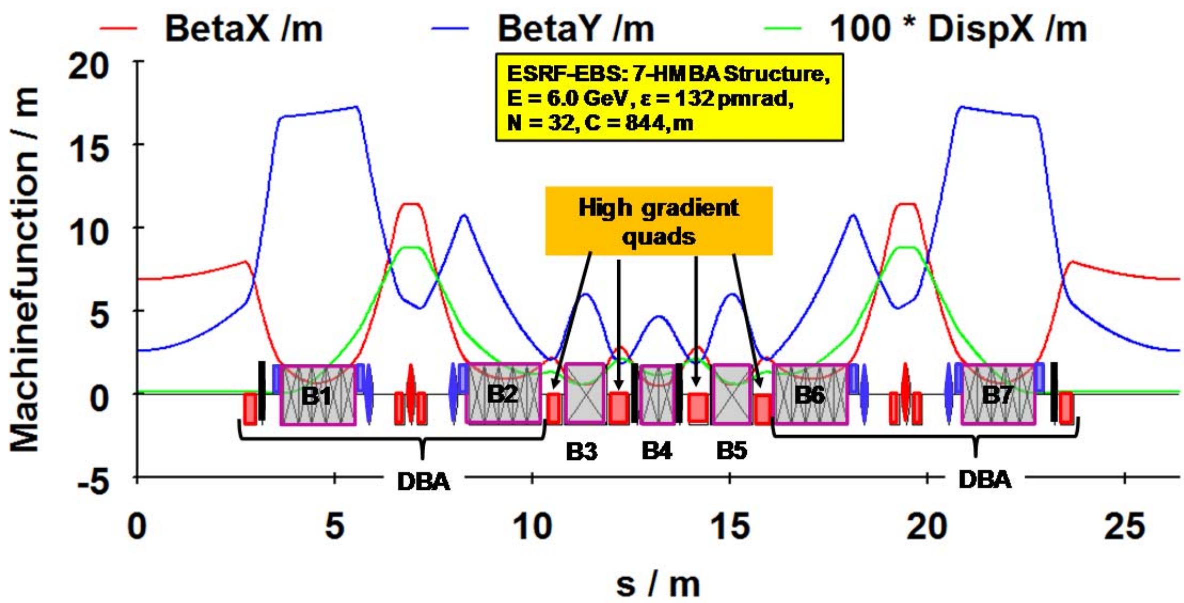

Figure 4: The lattice of the 7HMBA of the ESRF-EBS upgrade.

In parallel to the design of the ESRF-update is the design of the new 3 GeV Light source SIRIUS in Brazil with a 5 MBA [28]. In this case the 2 DBA - structure are combined with only one bending magnet. There seems to be an advantage of the HMBA against the MBA; SIRIUS with 5 bends has a smaller emittance as MAX IV with 7 bends (280 /330). Diamond is proposing an upgrade with a double DBA-structure (DDBA). This upgrade should lead to a smaller emittance as well a larger number of straight sections. This is only possible by going over from the DBA to the double DBA structure (DDBA) [29]. The introduction of one DDBA-cell has successfully already been done.

A different approach will be used for the upgrade of the Swiss Light Source (SLS). The SLS is using the idea of decreasing the emittance by introducing a longitudinal gradient in the bending magnet [30] [31]. The layout of the real unit cell is given in Fig. 5. Within the unit cell there are 5 bending magnets, in the middle one (B3) with a longitudinal gradient, followed by B2 with a horizontal gradient and B1 with a reversed field and a horizontal gradient too. The The layout of the achromat with 5 unit cells and the matching section is given in Fig. 6, leading to an emittance of 134 pmrad [32]. Which means the upgrade will provide a decrease of the emittance by a factor of 37.

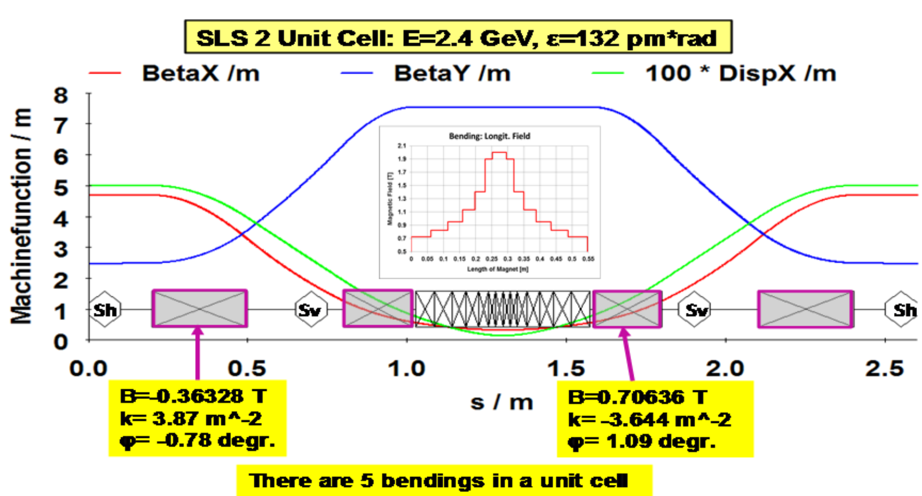

Figure 5: The unit cell for the upgrade of the SLS.

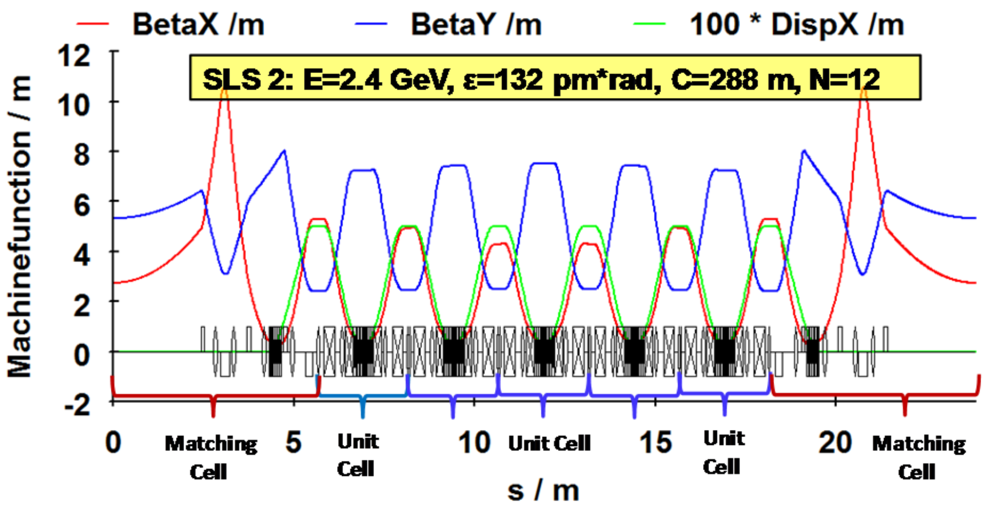

Figure 6: The layout of an achromat for the upgrade of the SLS.

DIFFRACTION LIMITED LIGHT SOURCES

The 4th Generation Light Sources with emittances around 200 pmrad are diffraction limited for photon energies up to 0.5 keV. Most of the users are interested in the range of up to 10 keV with a required emittance of 10 pmrad. The project which can meet this requirement is PEP-X. PEP-X is the idea by converting PEP II with a hexagonal tunnel into a dedicated [33] .

Synchrotron Light Source (see Fig. 34) with a circular geometry. The length of the tunnel will be 2.2 km, with 6 times 243 m for arcs and 6 times 123 m for straights. Each arc with the length of 243 m includes 8 * 7 MBA achromat's with a length of 30.4 m. The layout of the 7MBA achromat's are similar to that one of MAX IV and is given in the middle of Fig.7. With overall 48*7MBA arcs, an energy of 4.5 GeV an emittance of roughly 20 pmrad can be reached. By matching the coupling factor and introducing damping wigglers an emittance of 5 pmrad can be reached. Because of the high current per bunch the emittance will be increased by the intra-beam-scattering to 10 pmrad [34].

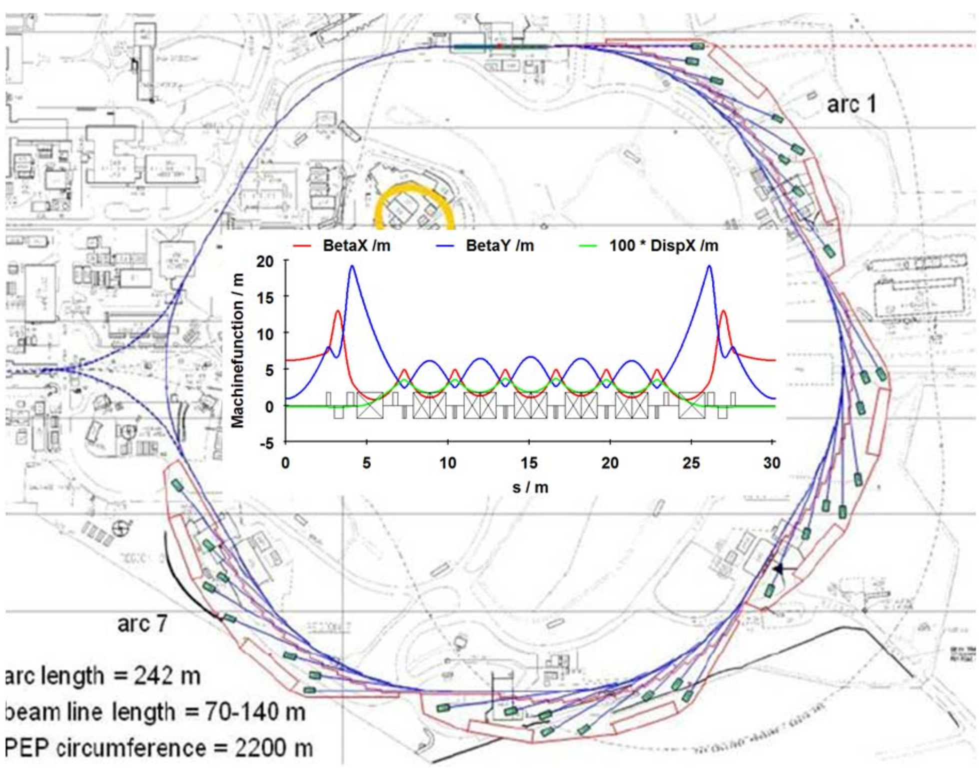

Figure 7: The layout of PEP – X with 72 7BA cells and 5m long straight.

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CONCLUSION

All the synchrotron Light Sources reached there specification in a sometime and the user time goes up to 95 - 99%. All of this shows us this the performance of the Light Sources is very high. There is a good agreement with the actual and the design values, which shows that the codes for the design of the different components and for the beam dynamics are very accurate. The first 4th Generation Light Source MAX IV reached already at 200 mA all the specifications and this will happen also for the upgrade of all the other projects. All of which makes us very confident to design a storage ring which meets the requirement of a "Diffraction Limited Light Source".

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