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THE MAIN PROBLEMS AND ITS SOLUTIONS IN MODERN SR SOURCES

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Abstract

This report is an attempt to consider the basic accelerator problems arising in connection with the requirements of the SR experiment in modern synchrotron radiation sources based on electron storage rings, and the technological solutions available today.

INTRODUCTION

Half a century has passed since the targeted use of synchrotron radiation in experiments in the various areas of knowledge. During this period of time SR sources were turned into factories of photons with high intensity and brightness.

Development of accelerator technologies over the past twenty years has also led to many important results. Successfully tested new magnets designs and fabrication technologies, the innovative vacuum technology, new RF generators for solid state amplifiers, a revolution in digital beam monitoring systems and in feedback systems for orbit correction.

These new technologies will ultimately determine the possible outstanding options for future new accelerator complexes and boundaries moved in experiments.

EVOLUTION OF SR SOURCES

Brightness and Coherence

The pursuit of high stability and high brightness, the desire to increase the coherent radiation fraction has defined crucially perfection of dedicated synchrotron radiation sources based on the electron storage rings.

The average and pick values of the spectral brightness - photon density in 6D phase volume depend on SR intensity and phase spaces of electron beam and radiation phase space of separate electron - are given by the formulae (eq.1).

$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{\Sigma_x(\lambda)\cdot\Sigma_y(\lambda)(s\cdot\%BW)},\ B_{pk}(\lambda) \propto \frac{N_{ph}(\lambda)}{\Sigma_x(\lambda)\cdot\Sigma_y(\lambda)(\sigma_t\cdot\%BW)} \quad (1)$$

The coherence plays an important role in experiments. Uniform phase wave front of transversely coherent X-rays permits to make coherent imaging, holography, speckle, etc.; the possibility to be focused to smallest spot size – nano-focus; the availability of high flux (~ 10^{14}-10^{15} photon/sec) in small spot – slits may not be required, etc; round beams mean symmetric optics, circular zone plates, flexibility in optics.

According with definition the radiation coherent fraction at a given wavelength equals to the relation of the phase volume of the diffraction - limited source to the phase volume of the real source (eq. 2).

$$f_{cog}(\lambda) = \frac{\lambda/4\pi}{\Sigma_x(\lambda)}\cdot\frac{\lambda/4\pi}{\Sigma_y(\lambda)} \quad (2)$$

Here: $\Sigma_{x,y}(\lambda) = \sqrt{\sigma_r^2(\lambda)+\sigma_{x,y}^2}\cdot\sqrt{\sigma'^2_r(\lambda)+\sigma'^2_{x,y}}$,

σ_τ – bunch length, $\varepsilon_r(\lambda) = \lambda/4\pi$ – the diffraction limited emittance for coherent Gaussian photon distribution (laser beam) and $\varepsilon_r(\lambda) \approx \frac{\lambda}{2\pi}$ - the diffraction limited emittance for undulator radiation from single electron filament, $\varepsilon_{x,y}$ are the horizontal and vertical emittances of the electron beam, $\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\cdot\beta_{x,y}}$, $\sigma'_{x,y} = \sqrt{\varepsilon_{x,y}/\beta_{x,y}}$ -standard horizontal and vertical sizes and the angles of electron bunch, $\sigma_r = \frac{\sqrt{2\lambda L}}{2\pi}$ and $\sigma'_r = \sqrt{\frac{\lambda}{2L}}$ – the size and the angle of photon beam from single electron filament in a undulator with length of L.

We note the absolute value of the coherent part of the total flux is important too. Optimize trade-off between low of emittance vs stored electron current value is necessary.

SR sources Optical Structures Evolution

Electron SR sources that worked with large emittances in spurious mode are considered as SR sources of the 1st generation. The 2-nd generation - 10-100 nm-rad specialized SR sources working mainly on radiation from bending magnets.

The 3-rd generation, 10-1 nm rad specialized SR sources operating on radiation from Insertion Devices. First - 1994: ESRF (France); ALS (USA); Elettra (Italy); next decades: ALBA (Spain), APS (USA), Bessy II (Germany), DIAMOND (UK), MAX III (Sveden), PETRA II (Germany), PLS (South Korea), SLS (Swiss), SOLEIL (France), SPRING-8 (Japan), TLS (Тайвань) and others).

According to the formulae (3), connecting main optics and structure parameters with natural emittance ε,

$$\varepsilon \propto E_0^2\frac{\langle\mathcal{H}/\rho^3\rangle}{\langle 1/\rho^2\rangle},\quad \varepsilon = F(\nu_x, lattice)\cdot\frac{E_0^2}{J_x\cdot N_d^3} \quad (3)$$

to decrease the natural emittance, we can: a) to reduce the energy E_0, b) to increase the bending radius ρ - this leads to larger circumference; c) to decrease so called dispersion invariant $\mathcal{H}=\gamma\eta^2+2\alpha\eta\eta'+\beta\eta'^2$ and, as the consequence, we have to have stronger and more frequent focusing; d) to increase damping - J_x, that is additional damping wigglers to be installed.

Almost all possible kinds of magneto-optical structures were investigated: from structures of type DBA (Double-Bend Achromat or Chasman-Green Achromat) and TBA (Triple-Bend Achromat) to so-called

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theoretically minimum emittance-TME. It is clear from (1), that to achieve ultralow emittance needs to use a structure with Multiple Bend Achromats (MBA), that is, to maximize the inverse cubic dependence of emittance on the number N_d of bending magnets.

Structure of MBA

Figure 1 demonstrates the passage from DBA to MBA. Here the dispersion (and $\mathcal{H}$) is limited to very small values.

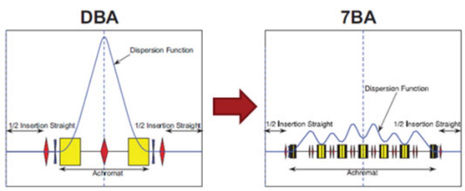

Figure 1: The passage from DBA to MBA.

Table 1 shows the coefficients, which demonstrate proportional decrease of natural beam emittance depending on the structure of the cell.

Table 1: Lattice Style Factors

$\varepsilon_0 = F \cdot C_q \cdot \gamma^2 \cdot \theta^3$		
Lattice style	***F***	
90^0 FODO	$2\sqrt{2}$	= 2.83
137^0 FODO	1.2	= 1.20
DBA	$1/4\sqrt{15}$	= 0.085
TBA	$1/6\sqrt{15}$	=0.057
MBA, if M=7	$(1/12\sqrt{15})(M+1)/(M-1)$	= 0.029
TME	$(1/12\sqrt{15}$	= 0.022

Structure of MBA with 7-magnets on the cell was first applied on the SR source MAX-4 in 2016 [1]. Thanks to the much lower dispersion, the MBA structure allows to use narrow vacuum chambers, small BMs pole gaps, and, consequently, compact magnets (reducing a power consumption and the current price), to shorter cell of magnetic structure. Thus, the number of single cells for a given circumference can be increased. This, in turn, allows further reduction of a single cell bend angle, which leads to even lower emittances (and, moreover, reduces the vacuum chamber heat load due to weaker SR radiation). Thus, the use of MBA closes positive feedback.

To decrease the electron beam emittances to values comparable and smaller than the phase volume of the diffraction-limited source in the needed spectral range became the main goal in the creation of 4-th generation SR sources.

4th generation, 0.1-0.01 nm-rad specialized SR sources using ERL, XFEL, USR and their combinations [2].

Conceptual Design of 3+-4th Generation SR Sources Based on MBA - Structures

As the examples we consider upgradable ESRF-EBS structure (commissioning phase – 2019), and the newly proposed structure (2017) in the project of modernization of the SLS-SLS-2. It should be noted that the draft ESRF-EBS maximally used the experience of creating the Swedish SR source MAX-IV. And in the original project of SLS-SLS-2 modernization the experience of these last two projects was fully used.

The new 7-BA lattice allow the ESRF storage ring to operate with a decrease in horizontal emittance by a factor of about 30 and a consequent increase in brilliance and coherence of the photon beam. The increase will be substantially higher than 30 at X-ray energies larger than 50 keV [3]. EBS will be installed instead of the existing 6 GeV basic ring ESRF with keeping the perimeter 844 m, periodicity (32 cells) and coordinates of the beam channels. EBS is based on achromatic cell c 7 bending magnets (7BA). Old and new cell structure of the ESRF-EBS is shown in Fig. 1. The location of the magnetic elements EBS on cell is shown in Fig. 2.

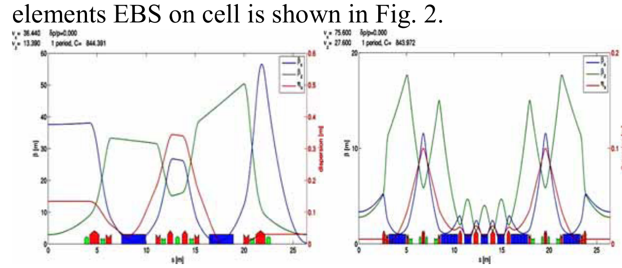

Figure 2: Old and new cell structure of the ESRF-EBS.

The basic EBS structure provides the same optics on all straights, horizontal β-function 3.4 m, i.e. removed interleaving of channels with high β (38 m) and low β (0.35 m). It is a hybrid configuration which combines the advantages of a large number of bending magnets with small dispersion, and azimuths with the presence of a large dispersion (for effective correction of chromaticity, as in DBA). Short dipoles with strong transversal field gradients have also been introduced in EBS cell - DQ1: 1.028 m, 0.57 T, 37.1 T/m; DQ2: 0.800 m, 0.39 T, 31.4 T/m.

Thanks to the stronger focus (H/V tunes are 76.21/27.34) and weaker bending magnets with a longitudinal gradient magnetic field (agreed with low value of the local dispersion invariant $\mathcal{H}$), horizontal beam emittance of EBS obtained is about 160 (133) pm-rad (4nm-rad today).

The chromatic aberrations correction is achieved by two sextupole families, whose gradients constitute about 1,9 kT/m2. Geometrical aberrations caused by the sextupoles are minimized by proper selecting their locations on the ring and with the introduction of the octupoles in the lattice structure. This nonlinear optics can be accurately tuned to accept large momentum deviations (till 4%) and a relatively large (8-10 mm) dynamic aperture (DA), providing a long Touschek`s lifetime and high injection efficiency, despite a very small emittance [4] (Leemann et al. 2009, Leemann & Streun, 2011) .

The work of EBS is planned in constant emittance mode. To stabilize energy losses, a specialized wiggler can be used and, consequently, the horizontal emittance can be reduced to 160 • (1-0.5 / 3.0) = 133 pm-rad.

Coming back to the coherence, it must be said that the degree of coherence of existing SR sources of third-

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generation, despite the high brightness of the radiation, is still very low. Thus, for ESRF-EBS with an electron energy of 6 GeV in order to reach f_{cog} = 0.5 at a wavelength of 1 Angstrom, a SR source with emittance of about 5 pm-rad is required. In EBS with a calculated minimal emittance of 60-80 pm - rad (for a round beam), the degree of coherence at f_{cog} = 0.5 is reached for wavelengths of 6-10 Angstroms only.

- SLS-2. SLS-2 parameters are presented in Table 2. Optical structure of SLS-2 differs significantly from that of ESRF-EBS, see Fig. 3.

Table 2: SLS-2 Parameters

Energy	2.4 GeV	Hor. damping partition J_x	1.71
Circumference	290.4 m	Energy loss	554 keV/turn
Tunes, $\nu_{x,y}$	37.20/15.30	Nat.Emittance	102-126 pm
Chromaticities, $\xi_{x,y}$	-95.0/-35.2	En. spread, 10^{-3}	1.03-1.07
Momentum compaction, α	$-1.33 \cdot 10^{-4}$	Damp. time, $t_{x,y,E}$	4.9/8.4/6.5 ms

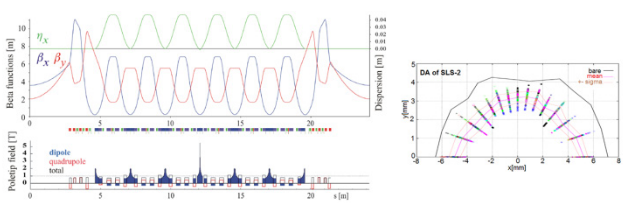

Figure 3: New elementary cell of SLS-2 (blue: dipole red: quadrupole; green: sextupole; orange: octupole) and DA.

First of all, the relatively small circumference of the main ring is 290 meters compared to 844 meters. However, according to the project, the modernized Swiss light source will have a natural emittance of about 260 pm -rad at 2.4 GeV. The SLS-2 project allows, within small limits, a change in the coordinates of the emission points and spectral properties for most existing beam lines.

SLS-2 uses the 7BA structure. 5 bending magnets in the central part of the mirror-symmetrical cell are made with a longitudinal gradient, the maximum field B = 2.2.T is achieved in the short central part of the magnets, after which the field decreases to both edges of the sections with a homogeneous field. Such a matching makes it possible to further reduce the emittance in regions with non-zero dispersion. We note that in four cells the field of the central magnets reaches 5.5T - these are four so-called super bends, providing bright sources in the hard X-ray range.

Besides, between magnets with longitudinal gradients two bending magnets with the opposite magnetic field and vertical focusing, so-called antibends, are installed. Except increasing in radiation dumping (and, therefore, reduction of an emittance), these antibends bring a redistribution of decrements in Jx+Jy=3 sum in favor of horizontal direction Jx≈1.7, in addition reducing a natural emittance. Thus, in the SLS-2 project all imaginable opportunities of reduction of a natural emittance are used, apparently.

PROBLEMS AND SOLUTIONS IN MODERN SR SOURCES

- *Small vacuum chambers vertical apertures.* The stronger fields excite the electron beam due to closer location of "geometric" vacuum chamber inhomogeneities (transitions, bellows, SR absorbers) and wake-fields due to resistive walls. The result is the emergence of strong single bunch instabilities, such as: transversal modes coupling instability (TMCI, sometimes called the "fast head-tail instability"); microwave instability; a stronger multi-bunch instability due to resistive wall.

- *Extreme optical structures parameters (Ultimate Storage Rings, M. Borland, Nov.2010).* With the increasing number of bending magnets N_{dp} inside the MBA structures, reduced dispersion $\langle\eta\rangle \sim 1/N_{dip}$ in MBA shall entail the reduction momentum compaction factor $\alpha \sim 1/N_{dip}^2$. That, in turn, leads to a shortening of the bunch $\sigma_z \sim N_{dip}^{0.5}$, to the reducing of the synchrotron oscillation frequency $\nu_s \sim 1/N_{dip}^1$. *Smaller values of* $\boldsymbol{\nu_s}$ *and* $\boldsymbol{\alpha}$ *aggravate* and cause TMCI and a microwave instability at lower threshold currents. Relationship of threshold current in one bunch with the number of dipole magnets is expressed as follows:

for TMCI: $I_{thres}^{TMCI} \sim \frac{E}{\langle\beta\rangle N_{dip}^{1.5}}$;

for microwave instability: $I_{thres}^{MW} \sim \frac{E^{3.3}}{N_{dip}^{5.5}}$.

- *"Extremal Beam parameters".* High particles density in the bunches results in: reducing the life time due to multiple intra beam scattering (IBS) $\frac{1}{\tau_{IBS}} \sim \frac{N_b N_{dip}^{5.5}}{E^{8.1}}$ and increasing both energy and transverse emittances; leads to small life time (small 6-dimension beam emittance) due to Touschek's single scattering acts $\frac{1}{\tau_{TUS}} \sim \frac{N_b N_{dip}^{1.8}}{E^{4.1}}$. On the other hand, small betatron functions provide the reduced excitations depending on transverse vacuum chamber impedance.

Methods to Suppress (to Reduce) TMCI

- *Ensuring "smoothness" of the vacuum chamber* for minimizing a coupling impedance between a bunch and the walls. The differences between the vertical sizes of the adjoining cameras are at the level of technologically possible - 0.03 mm with the angle of transition (2-3) degrees, and the counted longitudinal broadband impedance of Z/n ~ 0.67 Ohms is admissible in EBS. A microwave instability threshold is about 1.4 mA per bunch. That is, work in a multi-bunch mode does not present a problem till 200 mA of electron current, but a single-bunch regime with a large current is impossible.

- *Choice of metal for VC.* To reduce the transverse impedance of resistive wall the replacement stainless vacuum chamber at azimuths with low vertical beta-

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function on the aluminum vacuum chamber on the azimuths with a large vertical beta function (azimuth injection, for example) is also possible.

- *The elimination of the strong chromatic effect* arising due to the orbit lengthening for particles with a deflected energy (small α1 and large α2). The families of sextuples are planed to work with rather high positive chromatic optics rings (+4 - +10 for the new ESRF).
- *Setting up transverse and longitudinal feedbacks* to suppress coherent instabilities is obligatory. Standard requirements: the excitation amplitudes do not exceed 0.1 of the standard size of the bunch in any direction.
- *HOM suppression* - the installation of RF cavities with suppression of their own higher modes (HOM);
- *RF cavities with a multiple harmonics* added to the main RF to control the longitudinal sizes of bunches and, then, the partial suppression of microwave instabilities.

IBS and Microwave Instability

In principle, the decrease in the Tuschek's effect is achieved when the RF system of the SR source is operated in the GHz range with an increased number of bunches (and a decrease in the peak current in a single bunch). And for this there are already (available) GHz generators and cavities (superconducting - niobium, multicellular, super high Q-factor).

However, as a consequence of the high frequency, the threshold current of the microwave instability decreases, at all other things being equal (total electron current, electron energy, energy spread, the momentum compaction factor, voltage on the cavities). So the operation of the SR source in the single bunch mode is impossible, since it is impossible to minimize microwave instability impact by substantially increasing the length of the bunch without loss of emittance.

Therefore, at present, a preference is given to RF systems operating at relatively low frequencies (320 MHz ESRF, 100 MHz - MAX4) with the setting of harmonic cavities (distortion of the potential well in synchrotron motion) and 8-10 times the elongation of the bunches in comparison with the longitudinal sizes with respect to quantum fluctuations. In this case Touschek`s lifetime for the multi-bunch mode is 21 hrs (EBS).

NEW TECHNOLOGIES FOR SR SOURCES

The huge number of magnetic and vacuum elements with small geometrical cross-sections and super dense arrangement of them on a ring are the most characteristic properties of SR sources of new generation (MAX4, ESRF-EBS, etc.). As a result the demands on mechanical production accuracy have increased with emerging the modern higher technological capabilities.

We give some examples of the production accuracy which was reached at last light sources:

Coincidence of magnetic and mechanical axes within a circle with a radius of 10-15 microns in the absence of side motions of lenses on a girder - PSI;

Exhibition of elements on girder according to the external geodesy signs "tied" to magnetic axes by means of cross motions with an accuracy of 0.01 mm - DIAMOND, ESRF– EBS, MAX4 ;

Flatness of the directing surfaces of girder in ESRF-EBS – scope of a deviation in the vertical direction from average situation - 40 microns on length of 4-5 m.

MBA cells of EBS requires focusing with quadrupoles and sextupoles with very high gradients: 100T/m and 1,9kT/m^2. But, in connection with reduction DA, the quadrupoles bore radius decreases up to 13 mm, and in sextupoles - up to 19.2 mm. *But the tolerances of absolute errors in bore radii have decreased and became admissible within* ± 0.04 *mm.*

Magnetic System Technology

Working the light source on the nominal non-tunable and precisely specified electron energy allows using the assemblies made of permanent magnets (PMs) from rare-earth materials and in hybrid combinations instead of electromagnets!

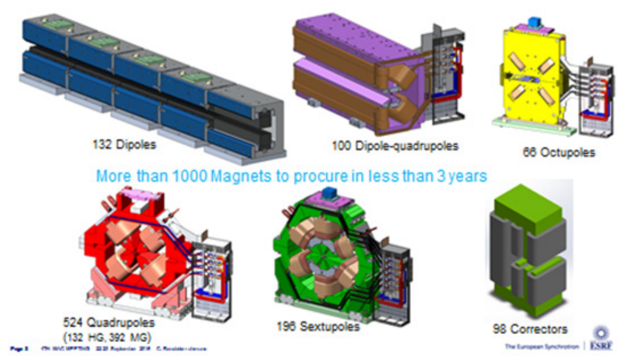

Figure 4: Magnetic elements of EBS.

So, in the project ESRF - EBS there are 132- long dipole magnets (1788 mm) (see Fig.4) with a longitudinal gradient field of two types: DL1 with B = 0.67-0.17 T and DL2 with B = 0.54-0.17 T. Yokes and poles of these magnets produce magnetic field plots as 5 steps. They are made in the form of rectangular blocks of magnetic iron.

Between the iron poles and the c-shaped iron yoke, from three sides, permanent magnet blocs from rare earth material Sm2Co17 are located. Thus, iron poles concentrate the magnetic field generated by permanent magnets. The pole gaps are of 25.5-30.5 mm. In addition, the temperature compensation based on passive nickel-iron inserts (magnetic shunts with low temperature Curie) is introduced in the magnetic circuit. As a result, the temperature compensation is dB/B/dT < 40ppm/C for all DLs at 23^0 C.

Dipoles on permanent magnets (PM) are equipped with the system of control of the field of small range on

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the basis of the coil with current. The key moments of such designs are minimization of amount of magnetic material, development of systems of control and a possibility of "shimming" of magnetic field.

The design of the magnetic poles of quadrupole lenses operating close to the saturation limit uses high-quality grades electrical steel. Individual laminae of magnetic yoke are obtained after stamping with a deviation from the specified profile of 20 microns.

The quadrupole and the sextupole lenses yokes allow to pass X - ray beams. The bore radius of lenses is manufactured with high mechanical accuracy (<40 μm) and the lenses have the excellent coincidence of the measured magnetic characteristics with the calculated values.

We note a presence of *high magnetic field gradients* in quadrupoles, creating the *high storage ring chromaticity*, and in sextupoles, serving to control the chromaticity level, leads to both *a nonlinear motion* and a very small dynamic aperture (DA). Transition of ESRF to structure 7BA demanded a production more than 1000 magnets within 3 years: 132 PM dipoles, 100 dipole-quadrupoles, 524 quadrupoles (132 HG and 392 MG), 196 sextupoles, 66 octupoles and 98 orbit correctors. The feeding of each of about 1500 magnetic elements (EBS) is produced by separate power supply. The replacement of the failed power supply has to be made so fast that it didn't lead even to small losses of electrons of a bunch.

Vacuum System

In modern SR sources, vacuum chambers with small cross sections and low vacuum conductivity predominate. These permit *to decrease* the total amount of pure metals - *electrical steels, copper*, etc., and *to reduce* sharply *the electricity consumption.*

The basic EBS vacuum chamber profiles are manufactured from extruded aluminum alloy. More sophisticated chambers, requiring connection of vacuum pumps, sensors and residual gas analyzers, are made of stainless steel.

Where necessary, the transition to stainless steel through intermediate flanges using explosion welding is ensured. Special attention is paid to the accurate connection of individual vacuum chamber parts in order to eliminate large differences in sizes and large angles when connecting the neighbor sections, seeking in each case, the minimum contribution to the impedance at frequency bandwidth up to more than 20 GHz.

Vacuum pumping is ensured by not evaporating getter (NEG) coating through all circumferences (MAX-4, EBS, SLS-2 [5]). Not absorbed gases will be collected by the pumps with a spray of titanium ions. It is possible to use embedded lumped pumps combining small ion sputtering and NEG cartridges.

Radiation from dipole magnets is absorbed, mainly by lumped absorbers of radiation. The design of the anti-chamber in the main vacuum chambers ensures the passage of a photon beam into the SR beam lines. The inner surface of an anti-chamber with a large area is covered with NEG, which provides a high speed of distributed pumping. The EBS vacuum chamber on the super-period includes several pressure gauges, a gas analyzer, ion pumps and NEG cartridges, BPMs, etc...

Radiofrequency System

RF system solved two problems mainly**:** A minimization of the IBS impact leading to emittance and energy spread growing; a small 6-D emittance and small lifetime due to Touschek`s single scattering.

As was shown in section “IBS and Microwave Instability” that RF system operating GHz range with an increase in the number of bunches, closes the possibility to work in the single bunch mode.

Bunch lengthening by the additional passive or active RF cavities at the multiple harmonics (as rule 3-d harmonics) leaves the possibility of working in the one bunch mode with a "large" current (at ESRF with 320 MHz Touschek`s effective bunch length is increased from 2.9 mm to 17.3 mm).

Finally, a low main frequency (100 MHz) is chosen for the MAX-IV RF system yielding long bunches, which are further elongated by passively operated third-harmonic Landau cavities, thus alleviating collective effects, both coherent (*e.g.* resistive wall instabilities) and incoherent (intrabeam scattering).

The next relatively new trend relates to the transfer of RF systems from klystron transmitters to solid-state amplifiers (SSA), based on IJBT transistors. The advantages of the SSA are: modularity of execution; high peak power on the accelerating cavity, high reliability of the RF source due to the redundancy of the SSA in the event of a malfunction in the operation of one or two SSAs per one summation cavity.

CONCLUSION

Thus, the powerful and successful advance of accelerator physics in the study of particle dynamics in complex nonlinear optical structures with small dynamic apertures, supported by new accurate technologies in the creation of magnets, vacuum chambers, RF equipment, provides opportunities to pass from the calculated stage for the creation of bright diffraction limited sources with emittances of about 1 pm-rad, providing a high degree of coherence at a wavelength of about 1 Angstrom.

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