THE ACCELERATOR COMPLEX OF CESLAB

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1. Introduction

In this text we report on the layout and description of the accelerator complex of CESLAB. This includes the electron source, linear accelerator, booster, and the storage ring, as well as the background facility. Several tables and figures concerning the accelerator parameters are given. An exhaustive and detailed study of the complex will be presented in the Conceptual Design Study of CESLAB, the first release of which is currently in the final stage of preparation.

The CESLAB synchrotron is a third generation synchrotron radiation facility that has been designed with several objectives in mind:

- The usable range of photon energies should extend to at least 40 keV.
- The photon beam should have high stability and a lifetime longer than 10 hours.
- The accelerator should incorporate many straight sections for a variety of insertion devices.
- The dimension of the source at the extraction points should be, at most, 0.25 mm.
- The light source should have a vertical collimation comparable to that of the natural SL emission.
- The accelerator design should have the potential for future upgrades.
- The temporal structure of the light source should allow some use of the single bunch mode for dynamic studies.

In addition, we have imposed the criteria that the accelerator design should be simple enough to guarantee its feasibility and, also, that its cost should be comparable to that of other currently planned synchrotron light sources in Europe.

The above considerations have led us to an accelerator energy of 3 GeV and a magnetic lattice that is essentially an Expanded Double Band Achromat.

Table 1. Energies produced through Linac structure.

	P [kW]	E[MeV]
Buncher	5	15
Act. Section I	20	55
Act. Section II	20	55
at Exit	25 MW KL1	125 MeV

2. Linac

A linear accelerator (Linac) is a device for accelerating charged particles. The CESLAB Linac is designed to be able to operate in single and multibunch mode. It is made up of a 90 kV thermo-ionic gun, a 500 MHz sub-harmonic prebuncher, a 3 GHz prebuncher, a 3 GHz/22-cells standing wave buncher and two travelling wave accelerating sections with constant gradient (Fig. 1). Two pulsed klystrons feed the accelerating sections and the 3 GHz buncher, while the sub-harmonic prebuncher and the buncher are fed from an independent RF amplifier. Beam focusing is ensured by solenoids up to the bunching section and by a triplet of quadrupoles in between the two accelerating sections. This device should deliver 125 MeV output energies with 80% transmission efficiency from gun to exit.

Table 2. Basic parameters at the Linac Exit.

	Single-bunch mode	Multi-bunch mode
Working frequency	3 GHz	3 GHz
Number of pulses	1 8	modulation 500 MHz
Bunch length	< 1 ns (FWHM)	0.3-1 s (112 ns)
Charge	2 nC	4 nC
Energy	MeV	MeV
Repetition rate	3 5 Hz	3 5 Hz

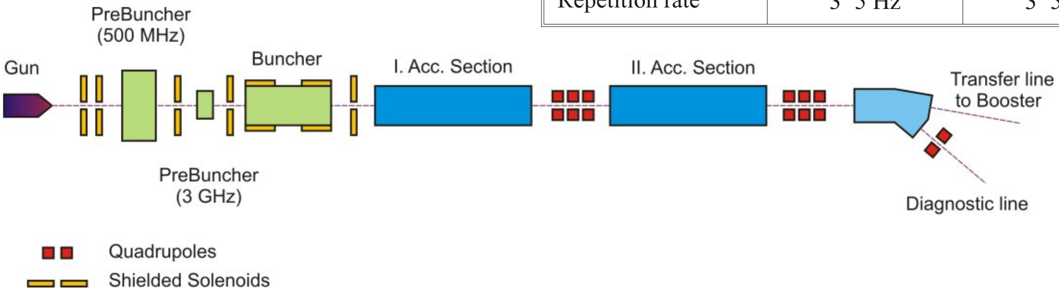

Figure 1. The Linac structure.

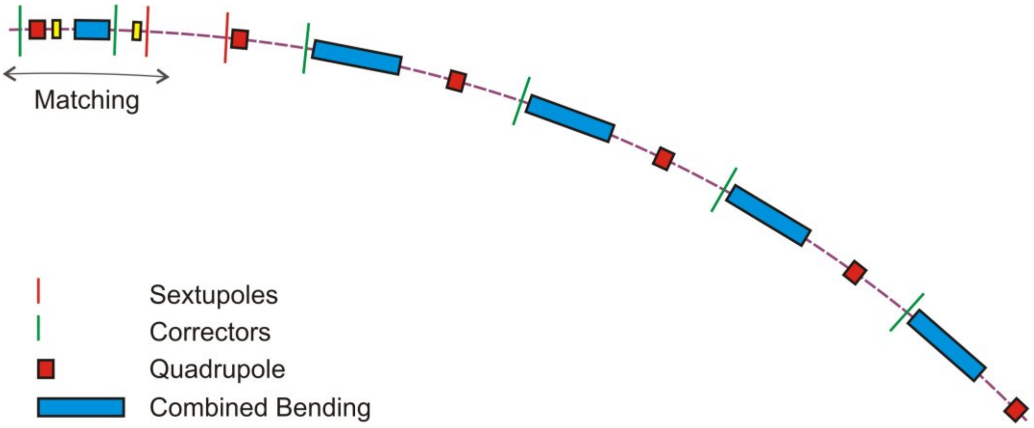

Figure 2. A part of the Booster. The lattice is modified FODO type structure with 4-fold symmetry. One quarter consists of 8 regular FODO cells and 2 matching cells.

3. Booster

The electrons at the Linac output have energy about 125 MeV and they need to be further accelerated by a Booster to energy 3 GeV. The Booster lattice is modified FODO type structure (a combined function bending magnet and a quadrupole) with four-fold symmetry and its inner perimeter is 249.6 meter. Each quadrant has 10 cells, 8 regular FODO cells and 2 matching cells (Fig. 2). The quadrants are connected by four 2.46 m long straight sections. These will be used for injection and extraction, for RF system installation and for diagnostic components. The Booster has all together 40 bending magnets providing also the vertical focusing, 60 quadrupoles (the horizontal focusing), 16 sextupoles and 72 steering magnets. The Booster RF system is based on a 5-cell Petra type cavity, fed with 43 kW to deliver 1 MV at 5 mA (500 MHz). These 43 kW are provided by an 80 kW Inductive Output Tube (IOT). Identical IOTs are used also in the Storage ring. It ensures huge spare power. The Booster lattice delivers an emittance of cca. 9 nm·rad. This is sufficiently small to ensure high enough injection efficiency for top-up operation. Accelerated 3 GeV electrons are kicked to a Storage Ring via a transfer line.

4. Storage Ring

The Storage Ring will have an outer circumference of 268.8 m and it will share its shielded tunnel with the full energy Booster synchrotron. The inner circumference of the Booster will be 249.6 m, which makes the spacing between the two rings roughly 3 meters. The 100 MeV Linac preinjector will have its own bunker neighbouring with the inner wall of the shielded tunnel.

The Storage Ring lattice will be of an expanded Double Bend Achromat type with 4 super-periods (corresponding to 4 quadrants of the Storage Ring). An important advantage of the EDBA lattice is its flexibility for choosing working points (betatron tunes) without affecting the performance of the storage ring. For example, the horizontal

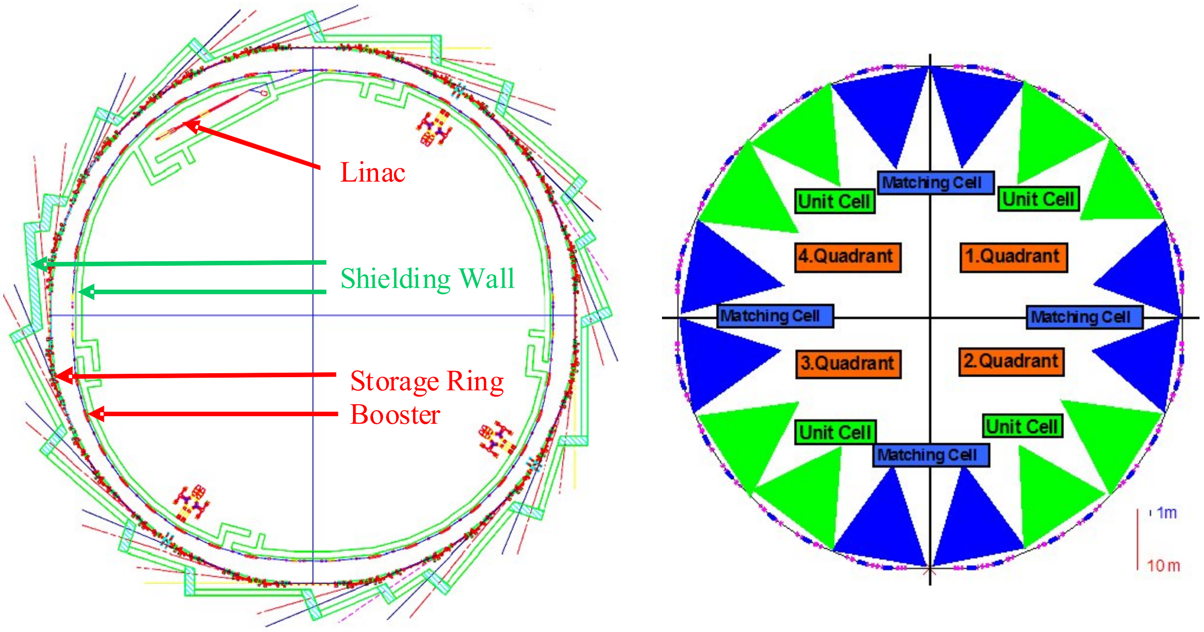

Figure 3. Layout of the accelerator complex and layout of the cells along the ring.

tune can vary in the range $18 < Q_x < 19$ and the vertical tune in the range $8 < Q_y < 8.7$ whilst the emittance and chromaticity change by less than 5%.

Each of the four super-periods in the lattice will consist of 4 cells (see Fig. 3). There will be 3 *medium* straight sections (4.2 m long) and 2 *short* straight sections (2.6 m long) in each super-period. Neighbouring super-periods (quadrants) will be separated by a *long* straight section of 8 m length. Altogether 38% of the circumference will be devoted to the straight sections. Some of them, however, will be used for RF plants, diagnostics and injection, so not all of them will be usable for the installation of synchrotron light generating insertion devices (Tab. 3).

The magnets in the Storage Ring are of three types: bending magnets (1.42 T dipolar magnetic field which provides bending of the beam along its trajectory), quadrupoles (focusing of the divergent beam) and sextupoles (correction of chromatic aberration from its natural negative value to a small positive one). The bending magnets will be constructed so as to have a slight quadrupolar component. This will provide some of the vertical focusing, thereby reducing the need for some quadrupoles and saving space.

The natural emittance of the Storage Ring will be $_{x0}$ = 4.3 nm·rad. A small-emittance lattice like ours can be operated in the top-up mode where the storage ring is kept full by frequent injections of beam. Top-up operation has the advantage for light source users that the photon intensity produced is essentially stable. This is in contrast to the decay mode where the stored beam decays to some level before refilling occurs.

The dispersion in the straight sections will have a non-zero value (Tab. 4) so that the dimensions of the source are reduced, thus increasing the potential flux density at the sample. This will occur at the expense of an acceptable increase in divergence.

Because of space restrictions, there will be used doublets instead of triplets of quadrupoles which will result in high values of betatron function in all straight sections (Tab. 4). Nevertheless, if low values were needed (for example, in the event of wishing to use narrow gap insertion devices), the option remains open for the future inclusion of symmetrically placed pairs of a third family of quadrupoles. This should allow for a further reduction of the beta function in some straight sections.

As to instabilities, longitudinal ones are not expected. Transversal instabilities however will occur at currents well below the designed level, so transverse feedback system will be necessary. The orbit control will be on a sub-micron level.

As the electron beam will lose around 1.3 MeV of energy with each turn (including losses in IDs), there will be three RF stations along the Storage Ring supplying the lost energy. In each station there will basically be two sets of

Table 3. Basic parameters of the Storage Ring lattice.

Lattice type	EDBA (Expanded double-bend achromat)
Energy	E = 3 GeV
Number of cells	N = 16
Circumference	C = 268.8 m
Circulating current	I = 400 mA
Straight sections available for IDs	L = 3 8 m, 12 4.2 m, 2 2.6 m
Number of dipoles/ quadrupoles/ sextupoles	32 / 112 / 120
Dipolar magnetic field in bending magnets	B = 1.42 T
Critical energy	E_c = 8.5 keV
Natural emittance	$_{x0}$ = 4.3 nm·rad
Emittance ratio (coupling)	$_y/\ _x < 1\%$, typically 3
Energy spread	
Betatron tunes	$Q_x = 18.18$, $Q_y = 8.37$
Natural chromaticities	$C_x = -39$, $C_y = -27$
Lifetime	t > 10 h
RF frequency	f_{RF} = 500 MHz
Harmonic number	h = 448
Momentum compaction factor	$_c = 8.8\quad 10^{-4}$

Table 4. Overview of some important parameters of the beam at possible light extraction points.

Light Extraction Point	Betatron function		Dispersion	Electron beam size		El. beam divergence	
	$_x$ [m]	$_y$ [m]	D_x [cm]	$_x$ [m]	$_y$ [m]	$_x$ [m]	$_y$ [m]
Long Straight Section	10.2	5.2	14.6	263	15	21	3
Medium Straight Section	2.0	1.2	9	133	7	47	6
Short Straight Section	8.6	5.8	23	310	16	23	3
Bending Magnet Center	0.4	23.9	2	44	32	116	2

the following: a Higher Order Mode Damped Cavity (a nose cones cavity with ferrite loaded dampers) and a Cavity Combiner combining two 80 kW Inductive Output Tube transmitters. The RF frequency and voltage will be 500 MHz and 600 kV, respectively.

The vacuum chamber will be made of stainless steel. The main part of the chamber profile will have an octagonal shape with height and width of 28 × 68 mm. This part of the profile will be connected via a communicating slot (15 mm high, 22 mm long) to an antechamber where all the connections to pumping system etc will be located. This will be so as not to disturb the smooth shape of the chamber, as this would contribute to RF resonances that would destabilize the beam. Inside bending magnets the profile of the vacuum chamber will be similar but slightly narrowed (with an angle of 8 degrees) towards the inside of the curved trajectory.

During standard operation, the facility will consume about 9 MW of electrical power. In order to deal with peaks of consumption and future expansions a total of 12 MW will be needed. From the 9 MW of consumed power, about 4 MW will feed the accelerator and beamlines, 4 MW will be devoted to cooling and high voltage and the remaining 1MW to offices, workshops and laboratories.

5. Insertion Devices

Insertion devices (ID) serve to produce synchrotron light of special characteristics that is led to beamlines and used in experimental hutches. As each beamline calls for different wavelength ranges and different properties of the light (such as polarization), there will be necessary various types of insertion devices. As for now, the beamline proposals are not ready yet, so let us deal with this topic only in general.

If electrons travel on a curved trajectory due to the presence of a magnetic field (therefore experiencing centripetal acceleration), they emit electromagnetic radiation called synchrotron radiation. In the case of electrons travelling nearly at a speed of light, the radiation is emitted (due to Lorentz transformation) tangentially to their direction of travel in a narrow cone with the angle of 1/ radians. (Here is the ratio of particle's energy and its rest energy, for electrons expressed handily as = 1957 *E* [GeV])

Naturally, in a bending magnet this radiation occurs too. This is why there are specially designed cooled radiation absorbers in the antechambers of the bending magnet vacuum chambers whenever this radiation is not intended as a source of light for a beamline. The synchrotron radiation in a bending magnet is a broadband one (Fig. 4a),

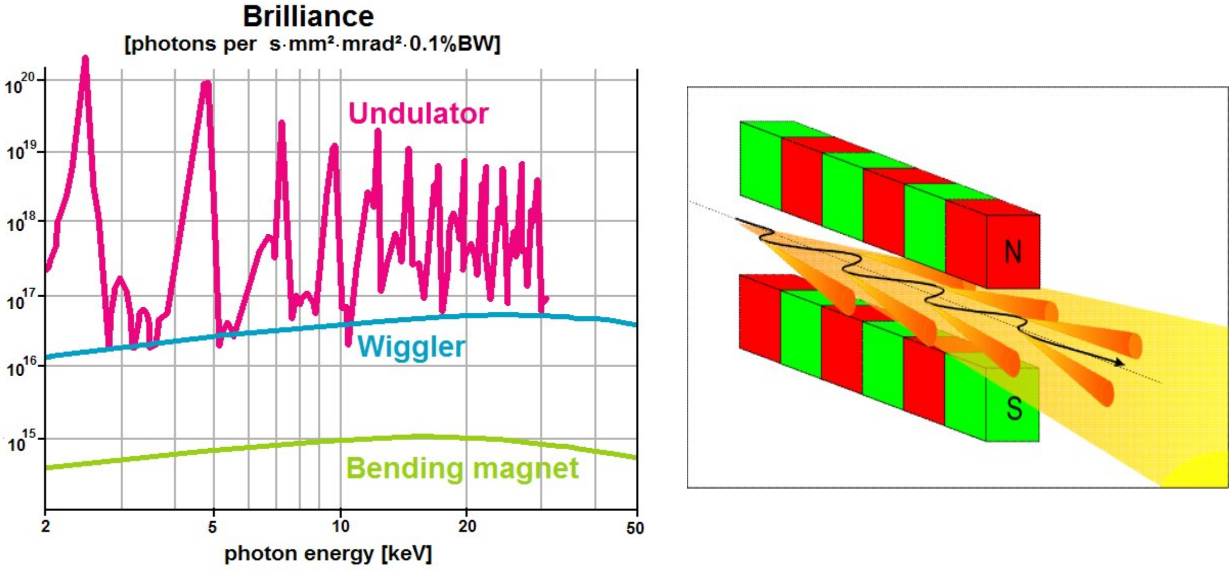

Figure 4. a – comparison of the radiation from a bending magnet, a wiggler and an undulator, b – schematic layout of a wiggler.

peaking near the critical energy (which denotes the median of the radiated power)

$$E_{\mathrm{crit}}\ [\mathrm{keV}] = 0.665\ B\cdot E^2\ \ [\mathrm{T;\ GeV}].$$

With our bending magnets where B = 1.42 T and E = 3 GeV, this energy will be 8 keV. Above the critical energy, the number of radiated photons falls exponentially. The highest energy where the bending magnet synchrotron radiation still has acceptable intensity is usually taken as 5 times E_{crit}, so in our case 40 keV.

Wigglers and undulators are called insertion devices because they are inserted in the straight sections of the storage ring. They are basically arrays of strong magnets of alternating polarity that repetitively bend the beam to and from as shown in Fig. 4b. An insertion device magnet array is situated close to the electron beam so as to generate the highest possible field, but extra care is taken so as not the limit the aperture for the circulating electron beam too much, as this would reduce the beam lifetime.

In the case of wigglers, the beam deflections are large compared to the natural emission angle of synchrotron radiation 1/ . Wigglers produce a fan shaped beam of photons the characteristics of which is similar to that of a bending magnet. It is also a broadband one, but the intensity is multiplied by the number of dipoles in the array, so here the highest usable energy is up to seven times the wiggler's critical energy.

The magnet array of undulators is devised so that the beam deflections are very small, comparable to the angle 1/ . The radiation emitted from the individual poles of the magnet array interferes coherently, and the beam is a narrow, pencil-shaped one. Due to the interference the spectrum exhibits many narrow energy bands at the harmonics of the fundamental energy (which depends on beam energy, on-axis magnetic field and on array period length). Also, the radiation per solid angle goes up with the square of the number of magnet dipoles which makes the undulator a very bright source at its peak energies.

Superconducting insertion devices offer the possibility of using very high magnetic fields unattainable by classical means. Long-period, few-pole superconducting wigglers with fields around 5 T can produce broadband radiation around a high critical energy. Superconducting microundulators can be used for free electron lasers where they are able to cover the entire infra-red range even with a very-low-energy beam.

Circularly polarized radiation can be achieved using planar helical undulators which produce 100% circular polarization. Circular or arbitrarily elliptical polarization can be achieved by elliptical undulators/wigglers. These are two planar devices, one acting in horizontal, the other in vertical plane, where the direction of the beam deflection is being rotated by 90° every array period.