CANDLE PROJECT OVERVIEW*

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Abstract

CANDLE – Center for the Advancement of Natural Discoveries using Light Emission – is a 3 GeV energy synchrotron light facility project in the Republic of Armenia. The main design features of the new facility are given. The results of the beam physics study in the future facility is overviewed including the machine impedance, single and multi-bunch instabilities, ion trapping and beam lifetime. The preliminary list of first group beamlines is discussed.

INTRODUCTION

The research highlights, based on the usage of synchrotron radiation in biology, medicine, chemistry, material and environmental sciences, the broadband application field for the results in pharmacy, electronics and nano-technology, promoted the design and construction of a number of third generation light sources worldwide at the intermediate energies 2.5-3.5 GeV [1].

Since 1967 the 6 GeV electron synchrotron in Yerevan Physics Institute (Armenia) was in operation. Number of unique results obtained on this facility includes the study of pion photoproduction, eta-meson generation, transition and channelling radiations. Nevertheless, even in 80's it was well understood that the next accelerator facility in Armenia should be a life and material sciences oriented project [2].

The new synchrotron light source project named CANDLE is a 3 GeV nominal energy electron facility, the spectrum of synchrotron radiation from bends, wigglers and undulators of which covers the most essential region of photons energy 0.01- 50 keV suitable for investigations at the cell, virus, protein, molecule and atomic levels. The conceptual design of the new facility [3] has been completed in 2002 and received a favourable recommendation by the Review Panel [4].

The basic approaches that underlie the project are:

- CANDLE will be a brand new facility with the infrastructure corresponding to state-of-the-art in accelerator and experimental techniques.
- The facility will operate as an international laboratory, open for all the qualified specialists.
- The facility is designed to be a world-class machine with the competitive spectral flux and brightness, the stable and reproducible photon beam, the high rate of the control with user-friendly environment.

DESIGN OVERVIEW

The CANDLE general design is based on a 3 GeV electron energy storage ring, full energy booster synchrotron and 100 MeV S-Band injector linac (Fig.1).

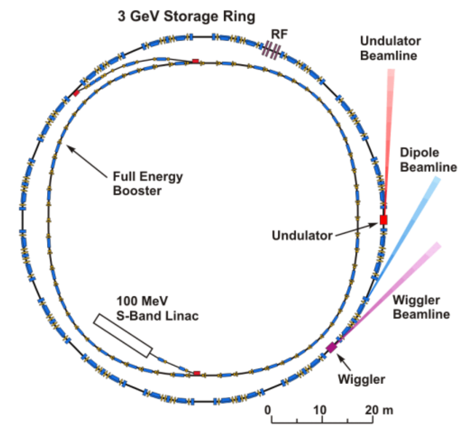

Figure 1: The general layout of CANDLE facility.

The full energy booster synchrotron operating with the repetition rate of 2 Hz and the nominal pulse current of 10 mA provides the storage of 350 mA current in less than 1 min. The storage ring of 216m in circumference has 16 DBA type periods. The harmonic number of the ring is h=360 for the accelerating mode frequency 499.654 MHz. The main parameters of the facility are given in Table 1.

Table 1: The facility main parameters.

Energy E (GeV)	3
Circumference (m)	216
Current I (mA)	350
Number of lattice periods	16
Betatron tunes	13.2 /5.26
Horiz. emittance (nm-rad)	8.4
Beam lifetime (hours)	18.4

In total 13 straight sections of 4.8 m in length are available for insertion devices (ID). The photon beams from the dipoles and the conventional ID's are covering the energy range of 0.01-50 keV with high spectral flux and brightness. Fig. 2 presents the CANDLE spectral brightness for the dipole (1.35 T), undulator (0.3 T) and wiggler (1.3 T, 2 T) sources.

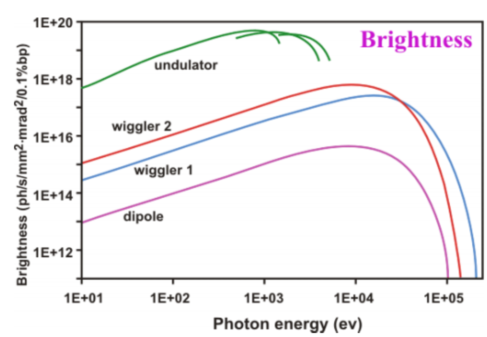

Figure 2: CANDLE spectral brightness.

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The design of the machine is based on conventional technology operating at normal conducting conditions. The 6 ELETTRA type cavities provide the total gap RF voltage of 3.3 MV thus ensuring the Touschek lifetime of about 40 hours. With 1 nTorr vacuum pressure the total beam lifetime is at the level of 18.4 hours. The vacuum chamber of the ring is based on the stainless steel antechamber geometry design.

The facility design implies the operation in the single, multi-bunch and top-up modes thus providing the broadband application of the experimental techniques.

OPTICS AND DYNAMIC APERTURE

The CANDLE design has 16 identical Chasman-Green type cells with non-zero horizontal dispersion in the middle of the long straight section $\eta_x = 0.18m$ that provides 8.4 nm-rad horizontal emittance of the beam. The emittance by factor of about 2 is smaller with respect to achromatic lattice ($\eta_x = 0$) that provides 18 nm-rad of horizontal emittance.

The spectral brightness of the photon beam from undulators in synchrotron light sources is one of the main figures of merits that define the advance of the facility design to utilize the whole capacity of the insertion devices. The optimisation of the optical parameters of the lattice to obtain a high spectral brightness of the photon beams from insertion devices keeping large the dynamical aperture of the ring was an important issue of the R&D study [4]. The results of the study for CANDLE show that for a real electron beam the brightness in short wavelength range is high for the lattice with large beta value in the straight section. In longer wavelength range, the high brightness implies the small beta lattice.

Fig.3 shows the dependence of the normalized brightness on the emitted photon energy for different horizontal beta values at the source point. Dashed line corresponds to the optimal beta values associated with each photon energy. The improvement of the brightness with small horizontal beta is visible only for the photon energies below 0.1 keV. Starting from 0.5 keV the brightness increases with larger betatron fuction, and in the energy range of higher than 5 keV the brightness actually reaches its maximum for the 8 m of beta value.

In vertical plane the beam emittance is given by the coupling of the horizontal and vertical oscillations. Fig.4 shows the normalized brightness versus of the vertical beta function for CANDLE nominal lattice and 1% coupling. The small vertical emittance of the beam shifts the characteristic regions of the brightness behaviour to harder X-ray region. The increasing of the spectral brightness with low beta is now visible in the photons energy range of 0.5-8 keV and starting from about 10 keV the brightness increases for high beta function. Due to the small vertical emittance of the electron beam, the achievement of the high brightness in whole spectrum range of emitted photon implyes the low vertical beta design. The comparatevely low vertical beta function in undulators is improving the machine performance as well by means of reducing the linear and non-linear effects of insertion devices. Taking into account the requirement to have sufficient dynamical aperture of the CANDLE storage ring, the horizontal and vertical betatron functions in the middle of the straigth sections are optimized to $\beta_x = 8.1m, \beta_y = 4.85m$.

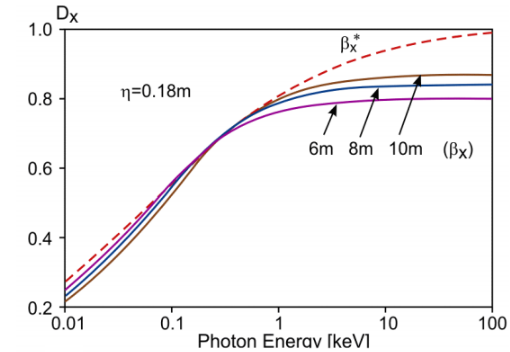

Figure 3: The normalized CANDLE brightness versus photon energy for various horizontal beta.

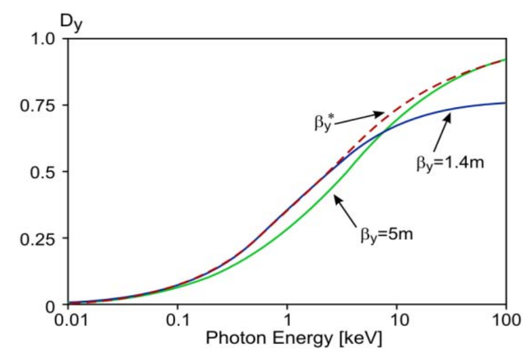

Figure 4: The normalized CANDLE brightness versus photon energy for various vertical beta.

The compratevely high beta values in middle of straight section are significantly improving the dynamical aperture of the ring. Fig.5 shows the CANDLE storage ring dynamic aperture with 3% energy spread which is sufficient for facility stable operation.

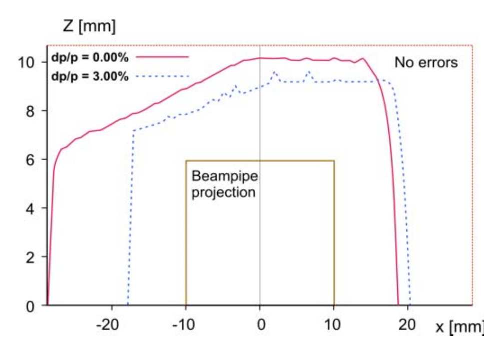

Figure 5: The storage ring dynamic aperture (ID).

The reduction of the dynamics aperture due to magnets fringe field effects has been carefully analysed [6]. The corresponding technique has been developed to adjust the quadrupole strengths around the ring.

BROADBAND IMPEDANCE

To prevent the single bunch instabilities in the ring, the impedance caused by the walls resistivity and roughness, BPM's and transitions has been carefully analysed. Fig. 6 presents the longitudinal and transverse impedances of the storage ring for various distributed impedance sources.

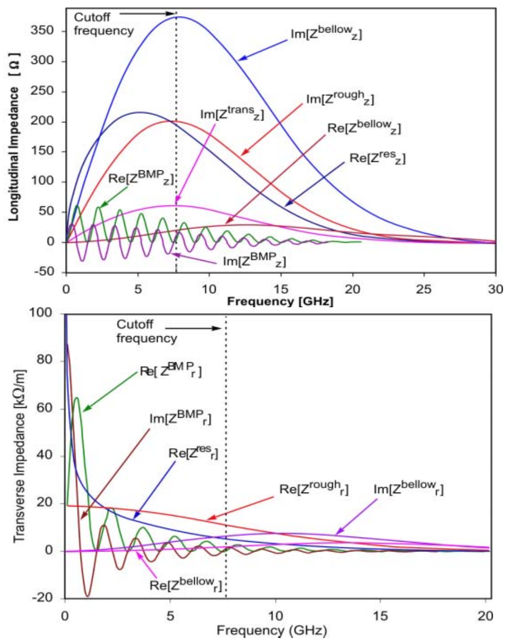

Figure 6: Longitudinal and transverse impedances of the ring caused by the walls resistivity, roughness, BPM's and transitions.

The normalized longitudinal broadband impedance for the CANDLE storage ring without ID's is at the level of 0.35 Ω. The corresponding single bunch threshold current is 8.9 mA. The transverse impedance of the ring without ID's is 12.6 kΩ/m that defines the threshold current of 113 mA for the transverse single bunch instability. The CANDLE nominal operation current of 350mA implies the single bunch current of 1.24 mA that is far below of the threshold currents.

An additional contribution to the ring impedance will be dominated by the small gap undulator vacuum chamber installed in the straight section of the ring.

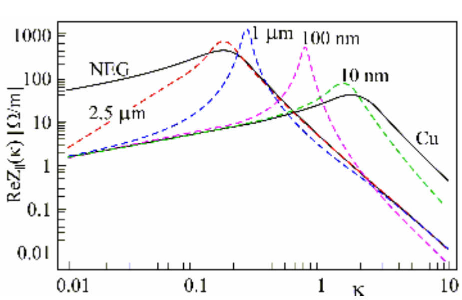

Figure 7: Real part of copper-NEG tube longitudinal impedance for various cover thickness.

To reduce the resistive impedance of the chamber the laminated walls are usually used, i.e the copper chamber covered by the NEG (Non-Evaporated Getter). Fig. 7 presents the real part of the point charge longitudinal impedance [7] for the cooper-NEG, 5 mm aperture vacuum chamber. The evaluation of the transverse impedance of laminated vacuum chamber is given in [8]. The results of this study will be used to evaluate the single bunch instabilities with the real broadband impedance of the ring equipped with the wigglers and undulators in the straight sections.

COUPLED BUNCH INSTABILITIES

The narrow band impedance of the storage ring, basically the longitudinal and transverse High Order Modes (HOM) excited by beam in the RF cavities, determine the longitudinal and transverse multi-bunch instabilities.

The longitudinal and transverse coupled bunch instabilities for the CANDLE storage ring have been studied for the original ELETTRA cavity option. Fig. 8 presents the growing rate of longitudinal and transverse coupled bunch instabilities versus the relative mode index n for the 282 beam oscillation modes.

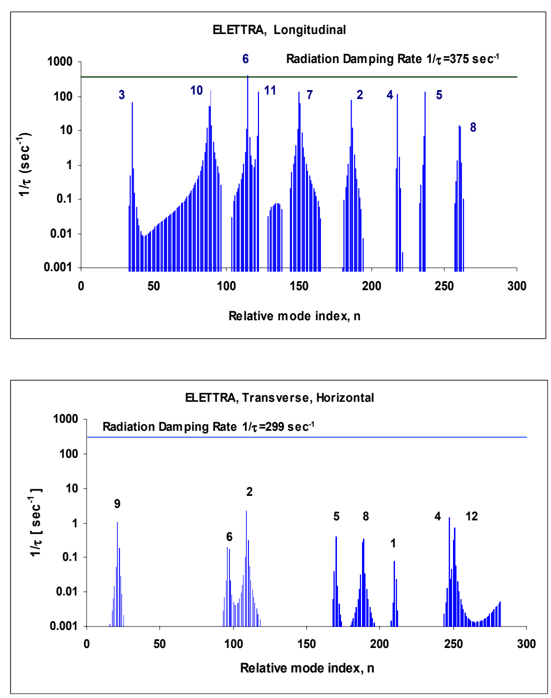

Figure 8: The longitudinal and transverse coupled bunch instabilities growing rate versus beam oscillation modes.

The growing rates of instabilities are mostly below the synchrotron radiation damping coefficients, except for L6 longitudinal mode that excites the instability at relative oscillation mode of n=115. After the cavities RF measurements, the instability cures will be developed to ensure the stable operation of the facility.

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ION TRAPPING

To prevent the reduction of the beam lifetime due to ion trapping, the stability of the transverse motion of the ions has been checked along the regular lattice of the storage ring. The results are presented in Fig. 9.

Figure 9: Number of unstable ions versus number of bunches in the ring.

The effect of the ion trapping is observed when the number of bunches in the ring exceeds 90. The optimal value of the number of bunches for the CANDLE storage ring has been defined 282 which provides an ion-cleaning gap of 78 RF buckets not filled with the electrons. With such a cleaning gap, only 6 ions number are trapped. An additional criterion for the optimisation of the number of bunches in multi-bunch operation mode is an analysis and comparison of the list of trapped ions with the mass numbers of real residual gas species. Fig. 10 presents the trapped ion masses versus filled RF buckets.

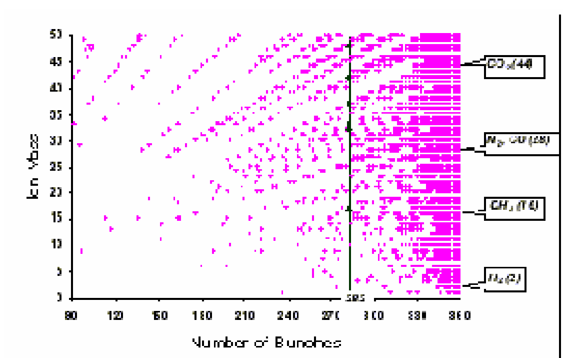

Figure 10: The trapped ion masses versus number of the filled RF buckets.

The trapped ion mass numbers in CANDLE storage ring are given in Table 2; the number of bunches is 282. The comparison with species of the ions in the residual gas that can occur in the chamber shows that for the given number of bunches 282 no components of residual gas will lead to trapped ions in the ring. The chosen number of bunches in the storage ring, 282 bunches from available 360 RF buckets, provides practically trapped ions-free operation of the machine at almost 80% filling.

Table 2: Trapped ion masses and residual gas species.

Trapped ion masses	Residual gas species
-	2, H_2
-	16, CH_4
17	-
-	28, N_2,CO
32	-
33	-
37	-
42	-
-	44, CO_2
48	-

BEAM LIFETIME

Beam lifetime in the storage ring is dominated by three beam loss-processes: the quantum excitation, intra-beam scattering (Touschek effect), and scattering off of residual gas molecules (elastic and inelastic). The Touschek lifetime is the most critical one. Fig.11 shows the Touschek lifetime evolution along the lattice for various energy acceptances. For a circulating current of I = 350 mA, the charge per bunch is 0.9 nC assuming 282 RF buckets of the total 360 are filled. For an energy of 3 GeV and RF energy acceptance of 2.38%, the average Touschek lifetime over the ring is then about 39 hours.

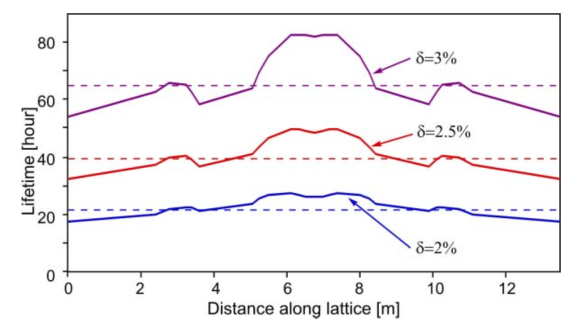

Figure 11: Touschek lifetime evolution along the lattice for various energy acceptances (solid lines).

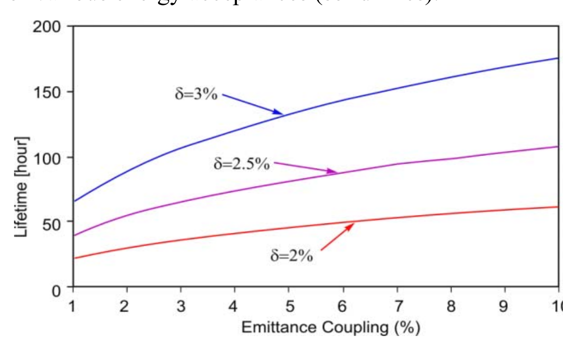

Figure 12: Averaged Touschek lifetime vs emittance coupling and energy acceptance.

Fig. 12 shows the Touschek lifetime dependence on the coupling coefficients for different energy acceptance. In particular, for a coupling of 2% and energy acceptance of 2.4% the Touscheck lifetime is at level of 54 hours.

The summary of the electron beam lifetimes in CANDLE storage ring for 1% coupling and N_2 equivalent gas pressure of 1 nTorr is given in Table 3. An integrated beam lifetime in storage ring is at the level of 18.4 hours.

Table 3: Storage ring electron beam lifetimes.

Gap Voltage MV	3.3
Energy Acceptance %	2.376
RMS bunch length (mm)	6.5
Average beta hor./vert. (m)	5.2/10.5
Beam lifetimes	
Elastic scattering (hours)	91.4
Inelastic scattering (hours)	55.4
Touschek lifetime (hours)	39.5
Quantum lifetime (hours)	$>10^{38}$
Total lifetime (hours)	18.4

FIRST GROUP BEAMLINES

The increasing demand of synchrotron radiation usage worldwide drives the scenario for the first stage beamlines that are an integrated part of the facility construction. Based on the existing synchrotron radiation usage statistics, the following beamlines have been preliminary selected to build at the first phase of CANDLE construction [9]: LIGA (dipole), General Diffraction and Scattering Beamline (dipole), X-ray Absorption Spectroscopy Beamline (dipole), Soft X-ray Spectroscopy Beamline (undulator), Imaging and Small Angle X-ray Scattering Beamlines (Wiggler). The technical design of the beamlines is based on the reasonable freedom in optical elements to meet user demand.

LIGA beamlines. The LIGA beamlines will cover the experiments with three photon energy regions: 1-4 keV for fabrication of X-ray masks and thin microstructures up to 100 µm height, 3-8 keV for standard LIGA microstructures fabrication with resists height up to 500 µm and 4-35 keV for deep lithography.

General Diffraction and Scattering *Beamline.* The beamline is based on the dipole source and will produce a moderate flux of hard (5-30keV) focused or unfocused tuneable monochromatic X-rays sequentially serving two experimental stations: EH1 for roentgenography routine or time resolved experiments, low or high temperature studies of polycrystalline materials, for reflectivity investigations of thin films and multi-layers; EH2 for single crystal structure determination, the charge density studies and anomalous dispersion experiments.

XAS Beamline. The XAS beamline will cover a photon energy range up to about 35 keV. Using a differential pumping system this beamline can be operated with no window before the monochromator and will produce sufficient intensity in soft X-ray region of the spectrum. This region covers the K edges of elements such as Si, S, P and Cl, which are of high technical interest. Using double crystal monochromator and gold coated total reflection mirror, the beamline will be able to operate in hard X-ray region allowing users to measure EXAFS of all elements either at K or L3 edges.

Imaging Beamline. Using the radiation from 3 T permanent wiggler this beamline will provide a high flux "white" or tuneable monochromatic coherent radiation in 6-120 keV photon energy range at about 150m from the source. The experimental program will include: phase contrast and diffraction-enhanced imaging; hard x-ray microscopy; holographic imaging and tomography; micro-focusing; X-ray topography, diffractometry; micro-fluorescence and high resolution inelastic scattering.

SAXS Beamline. The beamline will be based on the advanced Bonse-Hart camera. The scientific applications include small and ultra small angle X-ray scattering and nuclear resonance. The primary optical elements of the beamline include the high resolution and high heat load monochromators.

Soft X-ray Spectroscopy Beamline. This beamline has unique capabilities to address complex problems in materials, environmental and biological sciences. The high brightness photon beam from the undulator will support this beamline. Two types of microscopes are proposed: a zone plate based scanning transmission X-ray microscope and a photoelectron emission microscope.

SUMMARY

The progress of the new facility project after completion of facility design report is summarized in the CANDLE laboratory activity reports. The next stage of the project development implies an extensive prototyping program, the RF, magnet and vacuum test stands establishment, number of machine and user international workshops. The international collaboration is highly appreciated and we express our deep gratitude to all colleagues for their interest, support and cooperation.

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