M. Ries, Nonlinear momentum compaction and coherent synchrotron
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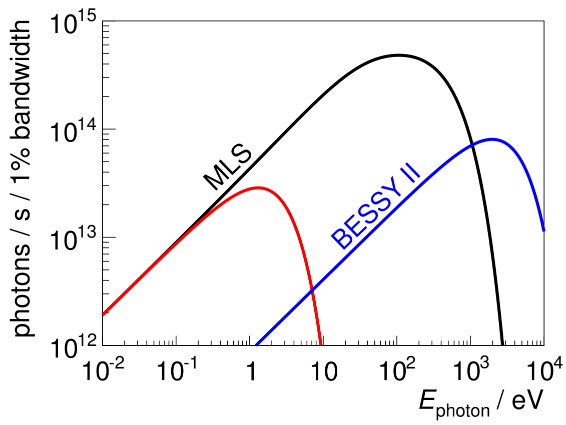
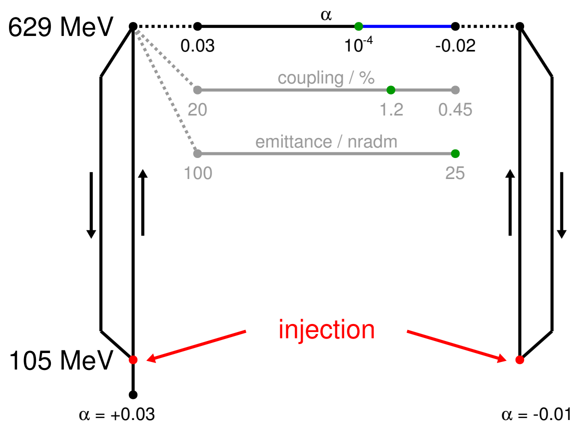
## 1.2 Metrology Light Source

The Metrology Light Source (MLS) is an electron storage ring based synchrotron light source in Berlin (Germany) owned by the PTB. It was designed, built and is now operated by the Helmholtz-Zentrum Berlin (HZB) [18]. The main purpose of the MLS is to serve as a reference source in the Extreme Ultraviolet (EUV) regime for metrology applications [17, 19]. The MLS is used in a spectral range covering FIR, Mid-Infrared (MIR), Near-Infrared (NIR), Vacuum Ultraviolet (VUV) to EUV. The black line in Fig. 1.1(a) shows a calculation of the spectrally




(a) MLS: spectral range




(b) MLS: operation principle

Figure 1.1: Spectrally resolved photon flux for the EUV-beamline at the MLS (a). The black line corresponds to operation at 629 MeV, whereas the spectrum at the injection energy 105 MeV is shown in red. For comparison, the spectrally resolved photon flux of the EUV beamline of the PTB at BESSY II is shown (blue). Operation scheme of the MLS - a ramped synchrotron (b).

resolved photon flux at the EUV beamline of the MLS for a stored beam current of 200 mA. The critical photon energy of the spectrum is about 360 eV. The blue line corresponds to the EUV beamline of the PTB currently in operation at BESSY II. The EUV beamline at the MLS will supplies more than one order of magnitude higher flux mainly due to optimized geometric beam line parameters.

The MLS is a ramped synchrotron operated in storage ring mode during user shifts. A racetrack microtron is used to accelerate electrons to the injection energy of 105 MeV [20]. Electrons are accumulated from the microtron to the storage ring up to 200 mA, which is the upper limit imposed by radiation protection policies. Subsequently, there is an energy ramp to 629 MeV, which takes about three minutes. As the MLS is a “low” electron energy machine as well as very flexible in operation, it is designed to be automatized to a high degree. For this purpose the concept of a state machine was applied. An automated master control program was implemented, that knows all available machine states as well as all transitions between states. Figure 1.1(b) shows a sketch of the operational concept [21]. Energy ramps exist for positive and negative momentum compaction (see chapter 3) indicated by the vertical plane. Beam parameters are relaxed during the energy ramp to maximize reliability as well as beam current conservation. Upon reaching the target electron energy the dipole magnet excitation is kept constant – storage ring mode. Afterwards, beam parameters like momentum compaction factor, beam size or beam emittance are adjusted by "optic ramps" to fit user demands using elements such as quadrupole and sextupole magnets.

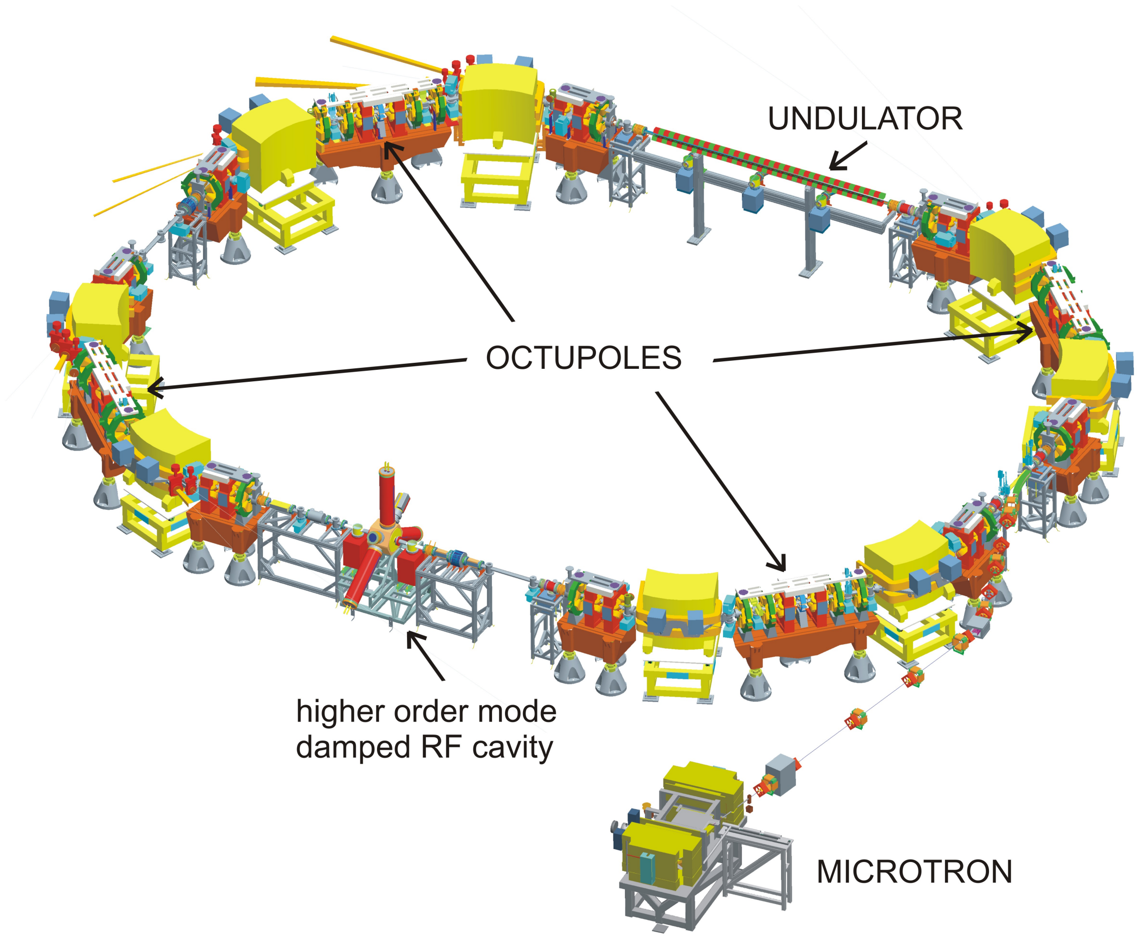



Figure 1.2: Scheme of the MLS.

A sketch of the MLS hardware is shown in Fig. 1.2. There are four double bend achromat cells with a slight break in symmetry in the connecting short (2.5 m) and long (6 m) straight sections. The lattice is characterized by a small bending radius $\rho = 1.528$ m inside the dipole magnets in combination with a large bending angle per dipole of $\pi/4$. The large bending angle per dipole leads to a high value of the dispersion function in the center of the achromat. There are 24 quadrupoles powered by individual power supplies providing a high degree of freedom in the scope of linear beam optics [22]. In addition, the MLS holds three families of sextupole magnets to be able to control the chromaticity in all three planes. Finally, there is one octupole magnet per cell placed in the center of the achromat, where the dispersion is at its maximum. Therefore the octupole has maximized impact for longitudinal beam dynamics. The purpose of the third sextupole magnet family and the octupole magnet is to control higher orders of the momentum compaction factor. This plays an important role when operating the MLS in the short bunch mode – "low-$\alpha$". In this way, the MLS is the first electron storage ring optimized by design for higher order momentum compaction control as well as the generation of coherent synchrotron radiation [18, 23].

A single, normal conducting, higher order mode damped RF cavity is used to accelerate the electrons and to resupply the energy lost due to synchrotron radiation [24]. It is able to supply 500 kV of effective acceleration voltage with a prospective upgrade to 700 kV. Table 1.1 gives a review of MLS machine parameters that will be relevant throughout this work.

The "standard user mode" is characterized by a horizontal emittance of about 120 nm rad. Transverse $\beta$-functions as well as the dispersion function $D$ for this mode are shown in Fig. 1.3. The data was obtained by fitting the orbit response of the corrector magnets to a model of the storage ring (see section 4.1). Beam optics of standard user operation at the MLS are deviating from the classical achromat setup. The value of the dispersion function at the septum magnet (at $s = 0$ m) was set to zero to increase the momentum acceptance and hence the beam lifetime [25].

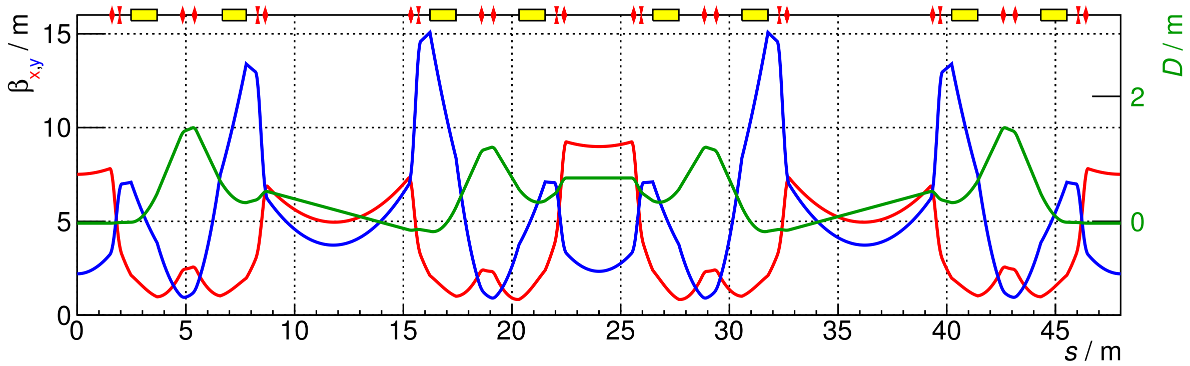



Figure 1.3: MLS magnet optics for standard user operation: Horizontal (red) and vertical (blue) $\beta$-functions $\beta_{x,y}$ as well as horizontal dispersion $D$ (green) were measured by fitting a model to the orbit response matrix (LOCO [26]). The top axis indicates the position of dipole (yellow) and quadrupole (red) magnets.

Due to the compact design of the MLS, the circumference is too short to allow operation with a significant gap in the filling pattern. Clearing gaps are commonly used at storage rings with a length in the order of 100 ns to fight trapping of ions by the attractive potential generated by the electron beam. Alternative countermeasures are in action such as clearing electrodes, a NEG-coated vacuum chamber section as well as electron beam shaking. The impact of ions on the dynamics of stored electrons is enhanced by a comparatively low electron energy. This is particularly inconvenient at injection energy, where the injection is severely hampered imposing current limitations.

Of special interest for the presented work is the momentum compaction factor. At the MLS the momentum compaction factor can be varied over a wide range covering about three orders of magnitude as well as operation with positive or negative values. This flexibility is intended by design to enable short bunch operation, which will be discussed in detail in section 3.

| **parameter** | **standard user** | **low alpha** | **tuning range** |
|---|---|---|---|
| electron energy | 629 MeV | | 50 MeV ... 629 MeV |
| $\gamma$ | 1231 | | 98 ... 1231 |
| current | 200 mA | 200 mA (bursting)<br>0.3 mA (stable) | 1 pA ... 200 mA |
| bunch current | 2.5 mA | 2.5 mA (bursting)<br>4 µA (stable) | 1 pA ... 10 mA |
| bunch charge | 400 pC | 400 pC (bursting)<br>0.6 pC (stable) | $e$ ... 1.6 nC |
| typical lifetime<br>(at 629 MeV, 195 mA) | 4.5 h | 10 h | $<$ 30 h |
| RF cavity voltage | 500 kV | 500 kV | $<$ 500 kV |
| mom. comp. factor<br>$\alpha_0$<br>$\alpha_1$<br>$\alpha_2$ | <br>0.03<br>$-0.4$<br>$\approx 1$ | <br>$1.3 \times 10^{-4}$<br>$< 0.01$<br>$\approx 3$ | <br>$-0.03 \dots 0.07$<br><br>$-200 \dots 200$ |
| tunes<br>horizontal tune<br>vertical tune<br>longitudinal tune | <br>3.178<br>2.232<br>0.017 | <br><br><br>0.0011 | <br><br><br>$< 0.07$ |
| natural chromaticity | $\xi_x = -3.4$<br>$\xi_y = -5.6$ | $\xi_x = -4.2$<br>$\xi_y = -6.0$ | |
| damping partition numbers * | $J_x = 1.05$ , $J_y = 1.0$ , $J_s = 1.95$ | | |
| damping times *<br>$\tau_x$<br>$\tau_y$<br>$\tau_s$ | <br>21.1 ms<br>22.2 ms<br>11.4 ms | | <br>21.1 ms... 42 s<br>22.2 ms... 44 s<br>11.4 ms... 23 s |
| zero current bunch length (rms) * | 19 ps | 1.3 ps | sub-ps ... 100 ps |
| horizontal emittance | 120 nm rad | 200 nm rad | $>$ 25 nm rad |
| emittance coupling $\varepsilon_y/\varepsilon_x$ | 0.5% | 20% | |
| circumference | 48 m | | |
| RF frequency | 499.654 MHz | | |
| revolution frequency | 6.2457 MHz | | |
| harmonic number | 80 | | |
| max. dispersion | 1.5 m | 1.9 m | $>$ 0.9 m |
| dipole bending radius | 1.515 m | | |
| magnetic induction (bend) | 1.384 T | | $\leq$ 1.384 T |
| energy loss per turn * | 9140 eV | | 0.4 eV ... 9140 eV |
| crit. photon energy * | 360 eV | | 0.2 eV ... 360 eV |
| fill pattern | homogeneous | | arbitrary |
| full chamber height | 42 mm | | |
| full chamber width | 70 mm | | |
| smallest hor. aperture | 20 mm (septum magnet) | | |

Table 1.1: Selected beam and machine parameters of the MLS. Values marked with * are calculated.