# OPERATIONAL ASPECTS OF CRAB CAVITIES AT THE ELETTRA 2.0 STORAGE RING LIGHT SOURCE

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## *Abstract*

We investigate the upgrade of the Elettra 2.0 diffraction-limited storage ring light source with radiofrequency transverse deflecting cavities generating picosecond-long X-ray pulses of moderate intensity and high repetition rate. Based on a preliminary RF design, operational aspects, challenges and solutions to make the crab cavity scheme simultaneous to the standard operation of the facility, are presented and discussed, also in view of the users' community wish list.

## INTRODUCTION

Elettra 2.0 is a cutting-edge upgrade of the existing Elettra synchrotron light source facility positioned to be one of the most advanced research infrastructures worldwide and devoted to supporting a wide range of scientific fields [1]. From advanced materials science to biology and medical applications, the new facility will provide researchers with access to vastly enhanced high-resolution imaging and spectroscopic capabilities. This project aims to significantly enhance the scientific output of the facility by upgrading the accelerator and beamline systems to the production of X-ray pulses of picosecond-scale duration, at MHz repetition rate, and simultaneous to the standard multi-bunch operation of the light source, to meet the growing demands of scientific and industrial users.

## WORKING PRINCIPLE

Three superconducting (SC) RF cavities, a.k.a. crab cavities (CC), connected in series, resonant respectively at a 6-fold (3 GHz for the two outer cavities) and 6.5-fold frequency (3.25 GHz for the single inner cavity) of the main RF, determine a steady-state configuration of vertically tilted bunches, with varying inclination along the ring circumference [2]. The charge distribution reaches the equilibrium in the 6-dimensional phase space [3,4]. The photon beam emitted by tilted bunches exhibits a longitudinal-vertical correlation (t,y). A vertical slit at some distance from the ID samples the central portion of the stretched photon pulse, thus selecting a short portion in time, though at some reduced flux. The vertical plane of deflection is chosen because the ratio of radiation flux over pulse duration is maximized by a smaller electron beam emittance. Indeed, Elettra 2.0 adopts a flat-beam configuration, with the vertical emittance controlled to be less than 5% of the horizontal one. The CC are installed in a non-dispersive straight section to avoid synchro-betatron coupling and beam instability [5]. The short pulse performance is tightly related to the design of the front-end and optical elements of the photon beamlines. Indeed, the short light pulse can be produced either through physical cut of the emitted radiation in the front-end area (drift mode) or, after a gentle angular selection in the front-end, at the location of light beam's waist, for example generated by vertical pre-focusing optics at the entrance of a monochromator (hybrid mode).

## DISTRIBUTIONS AT EQULIBRIUM

The reach of equilibrium duration by three bunch modes is shown in Fig.1. The different longitudinal emittances reflect the different focusing to which the three bunches are subject in the longitudinal plane. The horizontal emittance at equilibrium is the same, which confirms a linearized motion of the vertically-tilted particles and weak coupling. The vertical emittance of the tilted bunch is dominated by the correlation in the vertical phase space. The vertical emittance of the standard bunch is approximately doubled by the residual (unbalanced) kick from the CC (not shown).

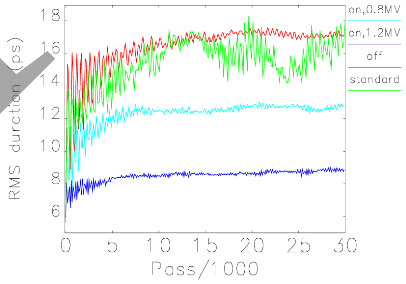

Figure 1: RMS bunch duration from zero-current parameters to the equilibrium in the presence of 3HC, for the tilted bunch ("on", blue and light blue), the same camshaft bunch with CC turned off ("off", red), and for the standard bunch in the middle of the train with CC turned on ("standard", green). The tilted bunch's duration is shown for two maximum deflecting voltages of 0.8 MV and 1.2 MV at 3 GHz (respectively, 1.5 and 2.3 MV total voltages).

## LIGHT PULSES

Figure 2 shows the theoretical minimum pulse duration at each beamline in the limit of diffraction and electron-light matching condition. The impact of the energy spread is evaluated (solid lines) and compared to the case of a monochromatic electron beam (dotted lines). As expected, the elongation of the pulse duration due to the electron

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beam energy spread is more evident at higher photon energies, and especially for those obtained with higher harmonic numbers.

Figure 3 shows the ratio $\frac{\varepsilon_r}{2\varepsilon_0} := \frac{\sigma_r \sigma_{r'}}{2\sigma_{r,0}\sigma_{r',0}} = 2\pi\sigma_r\sigma_{r'}/\lambda$, evaluated from photon beam dimensions simulated directly at the *source point* (i.e., ID location) for CC turned off, and 1:1-imaged from the slit back to the source point for CC turned on. The ratio is the amplification factor of the intrinsic *photon* beam emittance due to non-zero *electron* beam transverse emittance and energy spread. The ratio equals 0.5 when the electron beam transverse emittance is well below the diffraction limit condition, or $\varepsilon^e_{x,y} \ll \varepsilon_0$. It is 1 for a monochromatic electron beam right at the diffraction limit and matched to the intrinsic photon size. In both cases, and say for a ratio up to 2, a large degree of transverse coherence of the light through the beamline is expected. On the opposite, the ratio is much larger than 1 for an electron beam far from the diffraction limit, and radiation is poorly or not at all coherent. In short, the ratio allows us to identify which of the considered beamlines will be able to exploit transverse coherence in the spectral range of interest, either in standard or short pulse mode.

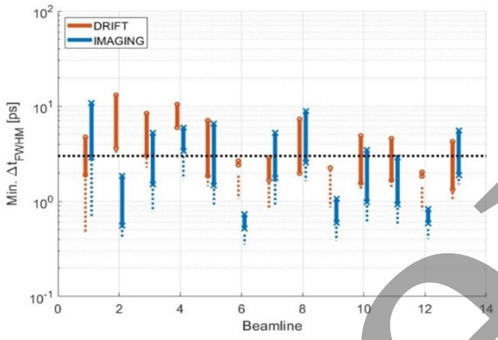

Figure 2: Theoretical minimum FWHM pulse duration at the Elettra 2.0 beamlines, calculated for drift (red) and hybrid optics (blue), across the beamline's full spectral range and for beam RMS energy spread of 0.1%. Dashed vertical lines are for the ideal case of a monochromatic electron beam. An arbitrary threshold at 3 ps duration is shown to guide the eye (horizontal black dotted line).

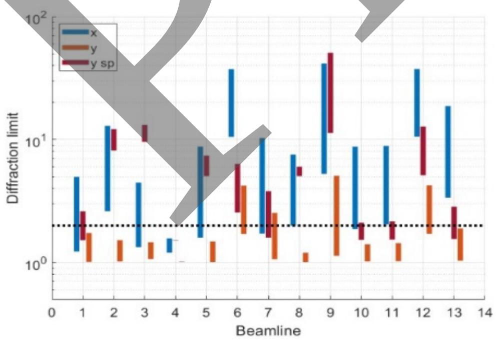

Figure 3: Colored bars below the horizontal dotted line identify a large degree of transverse coherence, respectively in the horizontal plane (blue), in the vertical plane with CC turned off (orange) and CC turned on (red, short pulse mode or "sp" in the legend).

## RF JITTERS

A summary of the contributions to the static (=systematic) and dynamic (=effective) turn-averaged vertical emittance growth of tilted and standard bunches is reported in Tables 1, 2. The total relative emittance growth (per bunch type) is estimated as the quadratic sum of the individual contributions.

Table 1: *Shot-to-shot*, i.e. random ($\sigma_x$), and time-averaged, i.e. *systematic* ($\Delta\sigma_x/\sigma_x$) variation of X-ray pulse and standard bunch parameters at equilibrium, in the presence of high frequency (> 100 kHz) CC RF peak voltage and phase jitter. The total peak deflecting voltage is 2.3 MV. The photon energy range is 0.1–10 keV. Legend is: F = X-ray pulse flux, $\Delta t$ = X-ray pulse duration, $\sigma_y$ = vertical size of the standard bunch at IDs

| | | $\boldsymbol{\Delta V/V = 0.01\%}$ | $\boldsymbol{\Delta\varphi = 0.01}$ **deg** |
|---|---|---|---|
| X-ray pulse | $\boldsymbol{\sigma_F}$ | < 1% | 1% |
| | $\boldsymbol{\sigma_{\Delta t}}$ | < 0.1% | < 0.1% |
| | $\boldsymbol{\Delta\sigma_t/\sigma_t}$ | 10% – 40% | |
| Standard bunch | $\boldsymbol{\Delta\sigma_y/\sigma_y}$ | ~70% | |

Table 2: *Systematic* vertical emittance dilution of *standard* bunches with CC turned on at 2.3 MV total peak voltage

| **Source** | $\boldsymbol{\varepsilon_y}$ **dilution factor** |
|---|---|
| Momentum compaction | << 1 |
| Chromaticity | << 1 |
| Quantum diffusion | 1.3 |
| Transient beam loading | 2.0 |
| **Total** | 2.4 |
| **After CC tuning** | ~1.1 |

## NONLINEAR DYNAMICS

The CC can be designed such that the peak value of higher order coefficients, which are time-dependent, are small enough to be either neglected or easily compensated by tweaking existing multipole magnets in the accelerator. The CC system we are taking into consideration is the RF SC Quasi-waveguide Multi-cell Resonator (QMiR) proposed in [6]. The original design was considered for SPEAR3 but, also because of the excessive multipolar field components [7], an elliptical cavity design was eventually chosen as a reference for that project. We carried out an optimization of the original QMiR design [8] as for gap and geometry of the protrusions, which promises multipole coefficients small enough to meet the Elettra 2.0 specifications, and still with margin of optimization.

To evaluate its impact on the dynamics of the stored beam, the dynamic aperture and the momentum acceptance were simulated in the pessimistic scenario of a skew sextupolar integrated field systematically synchronized with the bunch's arrival time. We assume a total maximum normalized integrated gradient of $k_2 l = 1.2\ m^{-2}$ (288 kV/cm$^2$). This is approximately equal to 1% of the largest integrated sextupole strength in Elettra 2.0 and consistent with values in the literature [3,9]. A preliminary optimization of the e.m. design of the QMiR shows a skew sextupole component smaller than 100 kV/cm$^2$ per cavity, for the total peak deflecting voltage of 2.3 MV on axis, see Fig.4-left. Figure 4-right shows the on- and off-momentum dynamic aperture (left) at the injection point, and the momentum acceptance evaluated at the sextupole magnets (right), as a result of particle tracking in the presence of a skew sextupole component at the location of the CC. We conclude that, even in the absence of any compensation, the stability of the stored beam is not affected.

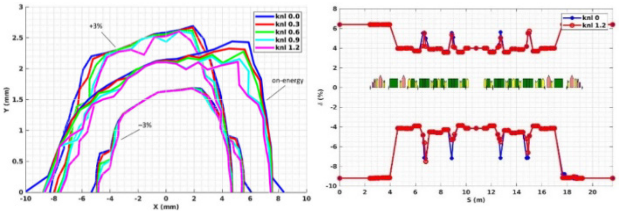

Figure 4: On- and off-momentum dynamics aperture (left) and momentum acceptance (right) as function of the skew sextupole normalized integrated gradient at the CC location, assumed to be systematically synchronized with the bunch's arrival time. Tracking was performed for 3 damping times.

## RF DESIGN AND IMPEDANCE BUDGET

A conceptual design of superconducting QMiR cavities for Elettra 2.0 has been provided by Fermilab in [8]. Since then, an optimization of that design has been carried out internally to Elettra 2.0, and is illustrated in Fig.5 [10], and Table 3. It allows the installation of the 3-cavity system in 2 m overall (including the cryostat), with a transverse size of approximately 1.6 m side-by-side. The CC are planned to be installed upstream of a pre-existing 1.8 m-long ID in a long straight section of Elettra 2.0, which will be serving a photon beamline since the first run of Elettra 2.0.

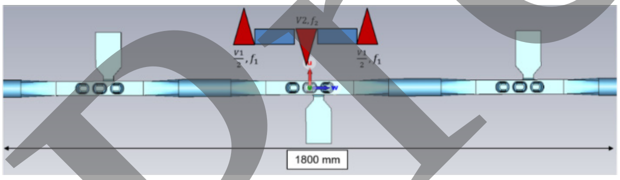

Figure 5: E.m. design of a single module of QMiR tuned at 3 GHz: a) geometric model with input coupler, b) intensity distribution of the vertical electric field (top) and of the horizontal magnetic field (bottom), c) three optimization steps (from left to right) of the central stub flatness, d) longitudinal profile of the vertical electric field (brown), horizontal magnetic field (green), and longitudinal electric field (light blue), in arbitrary units

The SC option of the CC system is integrable in the existing cryogenic infrastructure of Elettra, which is already supplying liquid He at 4.3 K to a SC wiggler and to the passive SC 3HC; moreover, at least one super-bend will be installed in Elettra 2.0. An alternative layout with a dedicated He-liquefier for working temperature in the range 2–3 K is under study, in view of potential reduction of the BCS resistance and minimization of the required RF power to supply the cavities [11].

Table 3: Specifications of SOM and HOM impedance budget below cutoff, loss and kick factor of the *total* CC system, in comparison to Elettra 2.0 impedance budget without CC, and corresponding average current instability thresholds computed from simulations. An RMS bunch duration of 15 ps, and linear chromaticity of +2 in both transverse planes were assumed. The "CC design" values for the S/HOMs refer to the mode with highest impedance and $Q_{ext} > 50$

| | **E2.0 budget** | **CC specs.** | **CC design** |
|---|---|---|---|
| $R_{z,H}$ [MΩ] | 1 | 1 | 0.3 |
| $R_{z,H} f_H$ [MΩ GHz] | 1 | 5 | 1.5 |
| $R_{x,H} k_H$ [MΩ/m] | 11 | 4.5 | 3.5 |
| $R_{x,H} f_H^2$ [MΩ GHz$^2$] | 0.6 | 1.5 | 0.8 |
| $R_{y,H} k_H$ [MΩ/m] | 11 | 1.5 | 0.2 |
| $R_{y,H} f_H^2$ [MΩ GHz$^2$] | 0.6 | 0.5 | 0.1 |
| $\lvert Z_{th,L}/n \rvert_{bb}$ [Ω] | 0.85 | 0.1 | <0.06 |
| $R_{z,bb}$ [kΩ] | 4.8 | 0.5 | 0.26 |
| $R_{x,bb}$ [MΩ/m] | ~0.2 | 0.1 | <0.01 |
| $R_{y,bb}$ [MΩ/m] | 0.56 | 0.1 | <0.01 |
| Loss factor [V/pC] | 20 | 1.4 | 2.5 |
| Horiz. kick factor [V/pC/mm] | ~3 | 0.6 | 0.5 |
| Vert. kick factor [V/pC/mm] | 4.8 | 1.0 | 0.8 |

## CONCLUSION

The feasibility study of CC for the production of picosecond-long photon pulses at Elettra 2.0 is ongoing. The CC system, including the cryostat, can be hosted in a length of 2 m in a dispersion-free straight section to install three SC RF QMiR-type cavities in a cryostat. The study was conducted with the purpose of evaluating the short pulse performance in the presence of all boundary conditions established by the Elettra 2.0 project infrastructure and accelerator design. In other words, the CC are envisioned as an upgrade to Elettra 2.0 after its first users' operation phase will be completed. The ultimate performance of the scheme depends, among several other parameters, on the bunch length at equilibrium. We verified that this can be manipulated in a hybrid filling pattern with a suitable tuning of the RF harmonic cavity and in the presence of transient beam loading.

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