CAVITY-BASED BEAM DIAGNOSTICS AT ELSA*

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Abstract

Online monitoring of the intensity and position of an electron beam of a few hundred pA in the experiment beamlines at the ELSA facility is enabled by a system of resonant cavities. The position signal extracted from the resonators amounts to about 10^{-19} W for 0.1 mm displacement at a beam current of 400 pA. It is separated from noise by phase-sensitive detection in a lock-in amplifier. The beam's position is obtained with a precision of one tenth of a millimeter, the signal strength being normalized by a beam current measurement with an uncertainty of a few pA. Via frequency mixing, the cavity signal of 1.5 GHz is converted down to a frequency below 100 kHz in order to be accepted by the amplifier, requiring a local oscillator stabilized by a feedback loop to 10^{-6} precision. Details of the measurement system are presented.

MOTIVATION

The hadron physics fixed-target experiments at the accelerator facility ELSA depicted in Fig. 1 rely on an electron beam with a current in the sub-nA regime, extracted from the 3.5 GeV storage ring by resonance extraction.

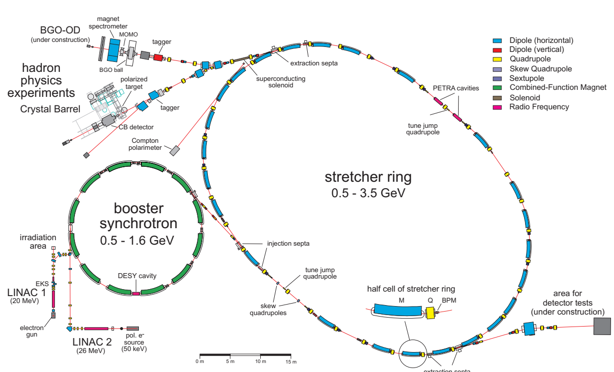

Figure 1: The electron stretcher accelerator ELSA.

In the standard mode of operation, the stretcher ring is filled by several injections delivered by the booster synchrotron, the beam energy then is raised up to the desired end energy and an extraction phase of a few seconds ensues. The magnets are then ramped down and the next cycle begins with a new injection.

The experiments at the facility rely on photoconversion, the electron beam is focused on an interchangeable radiator target leading to the emission of photons via bremsstrahlung processes. When gathering experimental data during beam time, permanent control of the beams' properties like intensity and position is critical to ensure stable conditions at the radiator. It was decided to design and install a set of resonant cavities, each optimized with regard to its diagnostical purpose, into the external beamlines, this approach fulfilling the essential requirement on an online diagnosis technique to be non-destructive.

A COMBINED SYSTEM OF INTENSITY AND POSITION DIAGNOSIS

In a resonant cavity, an infinite number of well defined electro-magnetic field distributions or eigenmodes oscillating with the corresponding resonance frequency are fulfilling the boundary conditions set by the metal walls. For diagnostical purposes, electrical field components being aligned with the particle beam are required. The particles of a bunched beam entering the cavity are slightly decelerated, the energy lost is stored in the cavity fields and can be partly extracted by a coupling device.

Due to the ease of manufacturing, cavities of cylindrical shape are considered here. Depending on the eigenmode excited by design, the voltage of the extracted RF signal is proportional to some of the quantities to be measured:

TM_{010} mode: beam current I
TM_{110} mode: beam current $I \times$ displacement Δu.

Δu will be used in the following as a placeholder for the displacement in either transversal direction. A full setup includes at least one cavity whose TM_{010} mode is tuned to an integer harmonic of the accelerator RF frequency. The beam current value deduced from its signal allows to account for the intensity dependance of the position signal.

Since the longitudinal electric fields of the TM_{110} or dipole mode only rise from zero when leaving the center of the cavity's transversal plane in one particular direction, two TM_{110} cavities are necessary to gain a complete position measurement. The orientation of the eigenmode fields in a cylindrical cavity is, by nature of its symmetry, degenerated in the polar angle, thus the correct field setup in each resonator has to be ensured by mode separators detuning the resonance frequency of any non-desired mode orientation.

The Intensity Cavity

When designing a position measurement system, a previously built cavity designed for current measurements could be relied upon [1]. Since the radius of a resonant cavity essentially scales with the inverse of the resonant frequency,

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the latter had been chosen, due to space and cost considerations, to be 1.5 GHz, the third harmonic of the accelerator RF frequency. The cavity made of copper is located in the external beam line of the stretcher ring at roughly one meter distance of the point of extraction. The resonators' main characteristics are summarized in table 1.

Table 1: Parameters of the Intensity Cavity

Parameter	Value
Mode	TM_{010}
Inner Diameter	129 mm
Inner Length	82 mm
Opening Diameter	34 mm
Resonant Frequency ν_0	1.499010 GHz
Shunt Impedance R_S	2.1 MΩ
Unloaded Quality Factor Q_0	11900
Coupling Factor κ	3.5

The signal extracted from the intensity cavity passes several stages of bandpass filtering and pre-amplification, undergoing a frequency downconversion in the process. It finally is demodulated by means of a logarithmic amplifier.

Calibration of the current measurement has been done by comparison with a calibrated Faraday cup located inside the beam dump the electron beam is led to after having passed the radiator target.

Since the RF circuitry processing the cavity output has proven to be not entirely reliable over time, a new setup is about to be installed in order to extend the reliability and sensitivity of the current measurement. Due to extensive similarities, it will be discussed in parallel to the position measurement system.

The Position Cavities

When designing the position cavities, space restrictions in the external beam line led to the choice of the third harmonic of the accelerator RF as resonance frequency [2]. Due to the TM_{110} not being the fundamental mode, the inner diameter amounts to roughly 24 cm, the cavities thus being even bulkier than the TM_{010} one. The costs for copper proving prohibitive, an aluminum alloy featuring long-term stability by being 3D forged was settled upon as a material.

Both cavities have been carved out of the end faces of a solid cylinder, the opening drilled into the center of their common wall serving as a short section of beam pipe designed to be long enough to prevent energy flow between the resonators. Circular metal covers screwed to both ends of the cylinder complete the setup. In order to ensure the desired properties, the following features of the chosen cavity design had to be investigated by means of computer simulations with the MAFIA code [3]:

Tuning plunger: Metallic cylinder designed to raise the cavity's resonance frequency when driven into it.

Pair of capacity cylinders: Located symmetrically to the beam opening on the cavities' common wall, they further the signal strength by concentrating the field lines in the region of the coupling antenna mounted directly opposite to one of them in the lid.

Pair of mode separating cylinders: Mounted symmetrically close to the barrel on the common wall of the resonators and almost equalling their inner length, they detune the frequency of any undesired TM_{110} mode orientation featuring non-vanishing fields in their proximity.

In addition, the cavity construction plans feature ducts allowing for water cooling. The water temperature is stabilized to $< 0.5\,°C$, thus frequency shifts of about 35 kHz per °C are effectively reduced. Energy is extracted by means of one coupling antenna installed on each resonator's screw mounted cover, respectively. Its position coincides with one of the two field maxima of the TM_{110} mode whose distance from the center is essentially given by the maximum of the J_1 Bessel function compared to its first root located at the cavity's boundary. The characteristics of the position cavities are detailed in table 2.

Table 2: Parameters of the Position Cavities

Parameter	Value
Mode	TM_{110}
Inner Diameter	242 mm
Inner Length	52 mm
Opening Diameter	34 mm
Resonant Frequency ν_0	1.499010 GHz
Shunt Impedance R_S / Δu^2 (CST)	820 Ω / mm^2
Unloaded Quality Factor Q_0	11900
Coupling Factor κ	1.05

DETECTING THE CAVITY SIGNALS

The power of the extracted RF signal can be calculated according to

$$P = R_S I^2 B^2 \frac{\kappa}{(1+\kappa)^2 + 4Q_0^2 \left(\frac{\Delta\nu}{\nu_0}\right)^2} \quad , \qquad (1)$$

the cavity parameters can be taken from table 1 and table 2, respectively. In the position case, the shunt impedance $R_S(\Delta u)$ inherently depends on the square of the displacement of the beam. The quantity B denotes the influence of the harmonic of the resonator frequency and the bunch length, whereas $\Delta\nu$ stands for the detuning of the cavity when compared to the design frequency ν_0.

The signal strength of the intensity cavity amounts to some 10^{-13} W for a typical current of 400 pA, the position cavities will feature some 10^{-19} W for said current at a beam displacement of 0.1 mm.

Phase Sensitive Detection

In order to resolve these signals being overlaid with noise, a detection scheme featuring a narrow enough bandwidth is required. Since the cavity signals are linked by a stable phase relation to the accelerator's RF master generator, the method of phase sensitive detection can be relied upon.

In a digital lock-in amplifier (LIA) of type SR830, each cavity's signal is multiplied in a DSP with a synthesized digital sine wave gained from a reference signal derived from the master generator. The product contains among others a DC component proportional to both signals' amplitudes, as well as to the cosine of their relative phase. The influence of the latter can be compensated for by performing a second multiplication with the reference digitally phase-shifted by 90°, thus completing the information of the voltage vector.

By some adjustable multi-stage lowpass filtering effected still within DSP, the oscillating components in the signal product can be attenuated and the cavity signal amplitude can be determined. Typical signal strengths lie in the µV range. The phase information gained allows to discriminate in the case of the position measurement which cavity half the beam has passed through. A detuning of the position cavities by a $\Delta\nu$ of about 30 kHz has proven useful to prevent temperature fluctuations to have the actual cavity resonance frequency drift across the third harmonic of the accelerator RF. In that case, 180° are added to the phase offset between cavity and accelerator RF signal, thus confounding the sign of the position value.

Frequency Mixing

Since available lock-in amplifiers do not cover frequencies in the cavity signal's range, frequency mixing is required in order to convert both the reference and the cavity signal down to the operating range of the LIA in use which is limited to 102 kHz. The above mentioned phase relationship between cavity and master generator is critical, therefore the signal of the latter has to be tripled in frequency in order to be able to use the same local oscillator for both the cavity and the reference signals.

The setup is quite sensitive to temperature dependent shifts in the local oscillator's (LO) operating frequency set close to $\nu_0 = 1.499010$ GHz. As a consequence, it has to be stabilized down to a few kHz. Hence, a voltage controlled oscillator has been chosen, its parameters can be derived from table 3. The frequency stabilization is taken care of in the software of the measurement system. A 12 bit D/A converter is installed in the control PC, the tuning voltage to be applied is derived from the reference frequency reading provided by the LIA.

Determining the Beam Position

In order to determine the beam's position, a linux-based PC system takes on the readout of three LIAs connected via GPIB, two of which are in use for the position measurement, the third being foreseen for a future high-sensitivity current measurement setup. During the extraction phase of one accelerator cycle, the voltage readings of the LIAs fed with the cavity signals are retrieved by the diagnosis programme with a maximum sample rate of up to 8 Hz (limited by the LIA's query processing speed).

The measured voltages then are divided by the actual current reading of the intensity cavity and then scaled by a calibration factor composed of the parameters entering Eq. 1. This factor has been determined empirically by wire-scans performed at the radiator position close to the location of the position cavity and is in accordance with the calculated value within 20 %.

The remaining discrepancy is still being investigated, main sources of error on the theoretical side are deemed to be the shunt impedance derived from simulations, on the experimental side, the current measurement is supposed to be not entirely accurate. In the present state, relative position deviations of about 100 microns can be detected.

Table 3: Parameters of the LO Used for Frequency Mixing

Parameter	**Value**
Manufacturer	EMF Systems
Target frequency range	1.498910–1.499110 GHz
Temperature stability	30 kHz / °C
Tuning range	±9 MHz
Tuning slope	1.8 kHz/mV

CONCLUSION

In the experimental beamlines at the electron stretcher accelerator ELSA, a system of resonant cavities allows online monitoring of both beam current and beam position, relying on signals well below the fW range. The accuracy and longtime stability of the current measurement will be improved by the installation of new RF circuitry analoguous to the position measurement setup, thus furthering the reliability of the entire system. The increased sensibility of a current measurement relying on phase sensitive detection will prove useful in the near future when low intensity runs based on single bunch operation in the stretcher ring will be performed.

REFERENCES

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[3] CST Computer Simulation Technology AG