FRONT END CONCEPT FOR A WAKE FIELD MONITOR

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Abstract

Wake field monitors (WFMs) are used to directly measure the alignment between beam and RF accelerating structure via the transverse higher mode spectrum. As a sub task of the EuCARD^2 project, we are developing a front end for the monitors of the multipurpose X band structure installed at the SwissFEL Injector Test facility (SITF) at PSI. We plan to use electro optical technology offering strong advantages in the robustness to interference and radiation, and in the ease of signal transport. We present the concept of the device, discuss the theoretical performance in terms of noise. For a proof of principle, we built a basic system, which we tested together with the existing monitors with beam at SITF.

INTRODUCTION

Inside RF accelerating structures, the level of transverse wake fields responsible for emittance dilution is determined by the alignment between structure and beam. Wake field monitors (WFMs) are devices for the direct measurement of this effect by coupling to the transverse higher order modes (HOM) excited by the offset beam. This is specially of interest for X band structures used in low to medium energy accelerators like free electron lasers, where the beam degradation due to transverse single bunch wake fields is a much bigger concern.

For structure with HOM damping like those developed for the CLIC project, suitable signals can be extracted from the HOM couplers. More classical structures, like the multipurpose X band structures [1,2] developed in a collaboration between PSI, CERN and Sincrotrone Trieste, use special pickup geometries to couple to the internal wake fields inside the structure.

As part of the EuCARD^2 project [3]), we are in the process of developing front ends for these class of devices, to be used for the existing wake field monitors installed in SITF at PSI [4] and FERMI at Sincrotrone Trieste. Given the relatively high frequency and large bandwidth and the need to operate the front end in a radiation environment, we decided not to use a classical RF front end, but to use an electro-optical approach, which promises the following advantages:

- Technology already used in space communications, so there is considerable experience concerning the radiation hardness of the device.
- Use of optical fibers vs. hollow wave guides in classical RF, which are cheaper, more flexible to put, have much larger bandwidths, are ideal to carry signal over long distances and have virtually no problem with electromagnetic interference.
- Only minor amount of hardware exposed to the radiation in the tunnel, essentially only an optical modulator and a microwave limiter near the structure.
- Off the shelf components available for bandwidths up to 40 GHz (practically tested even up to 1.5 THz)
- Possible secondary applications for break down monitors, wide band wall current pickups etc.

Measurement Principle

Wake field monitors are not isolated devices, but integrated parts of RF acceleration structures, whose transverse wake fields they are measuring. Fig. 1 shows the inner volume of such a structure, which we are using as a signal source for the front end.

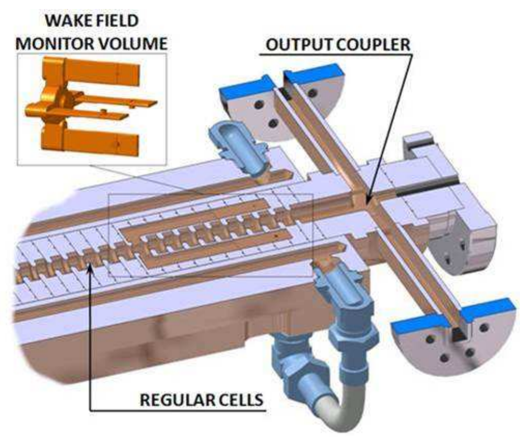

Figure 1: Wake field monitor inside a cutoff accelerating structure.

It is a 72 cell traveling wave structure working at the European X Band frequency of 11.9985 GHz. Its design employs a large iris, $5\pi/6$ phase advance geometry, which minimizes transverse wake field effects while still retaining a good efficiency. Its function in the FEL projects at PSI and Sincrotrone Trieste is actually not to accelerate the beam, but to compensate nonlinearities in the longitudinal phase space of the beam caused by prior acceleration stages [5].

One of the characteristics of its constant gradient structure design is the smooth variation of the cell dimensions along the structure, which compensates for internal losses and keeps the gradient of the fundamental mode constant. This leads to a spread of the synchronous frequency of the position dependent dipole modes over the 15-16 GHz region. Upstream, an offset beam will excite lower dipole mode frequencies than downstream. Also, the modes will not extend throughout the structure, but will be confined. To capture as much information as possible, two sets of monitors are used, one in the middle coupling to dipole modes in the upstream half of the structure and a second towards the downstream end for the other part. The fundamental limit for the monitor resolution is given by the precision of the internal alignment between individual cells [1]. We expect values below 10 μm.

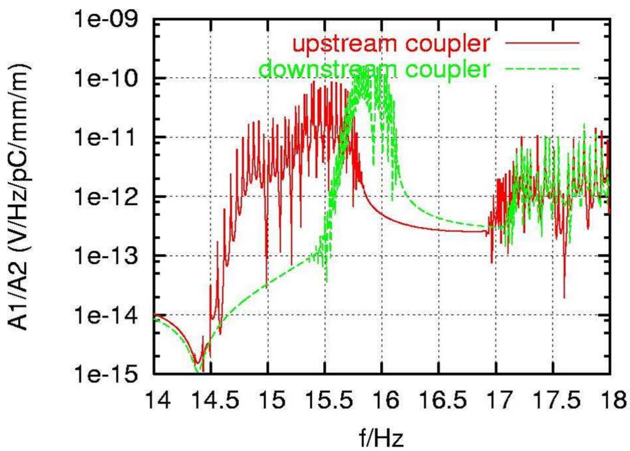

Figure 2: Theoretical WFM signal spectrum.

As the signals of interests are in the sub-milliwatt range, while the fundamental mode is powered with tens of megawatts, an important criterion in the design of the WFM is to eliminate any coupling of the fundamental mode into the monitor output. Furthermore we would like to see a purely position dependent signal, meaning that there should be no trace of higher order longitudinal modes. This was achieved by the coupling geometry shown in Fig. 1. A hollow waveguide is coupled to the coupling cavity so, that it rejects any longitudinal modes by symmetry. The chosen cutoff frequency further attenuates any trace of the fundamental 12 GHz before transitioning into a coaxial feed-through. The calculated spectra of the upstream and downstream WFMs are shown in Fig. 2.

For the signal levels, we measured peak amplitudes of 10 V/nC/mm [6], which, taking into account signal distortions and reflection in the measurement setup, correspond relatively well with the value of 6 V/nC/mm of the equivalent circuit model (which omits high order dipole bands) and 4 V/nC/mm obtained with a full model calculation using CST Microwave Studio [7].

A WFM is comparable to a classical cavity BPM in that respect, that we have position dependent signals, but there is an important difference. The WFM signal is directly proportional to the wakes and so to the degradation of the beam. The golden orbit with respect to the structure is given by minimizing the WFM readings, whereas a BPM needs a secondary procedure like e.g. beam based alignment to get a reference position. The WFM acts also as a self diagnostic tool for the accelerating structure: if amplitudes stay elevated at the minimum, problems with the internal alignment (bends, kinks and randomly displaced resonators) are probably the reason.

FRONT END CONCEPT

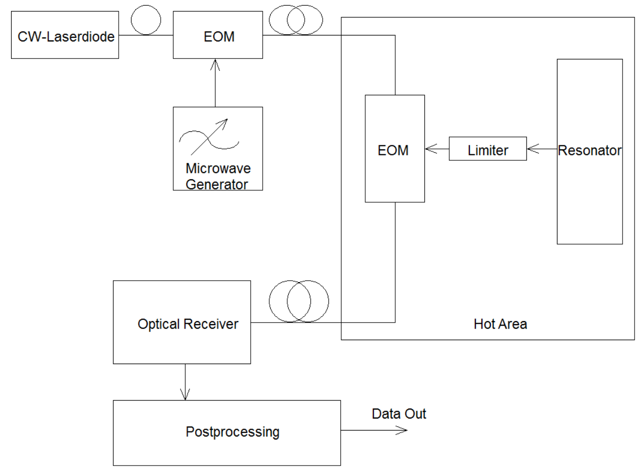

Figure 3: Layout of electro optical front end.

Basically, the front end is a down converter based on optical components as shown in Fig. 3. We have an optical source consisting of a very low noise laser diode, whose output is intensity modulated with a CW local oscillator signal of 12-15 GHz using a first electro-optical modulator (EOM). This is followed by a second modulator fed with the WFM signal. The resultant optical signal is converted back to an electronic output by a photo diode, where only the down converted part of the spectrum is used for further post processing.

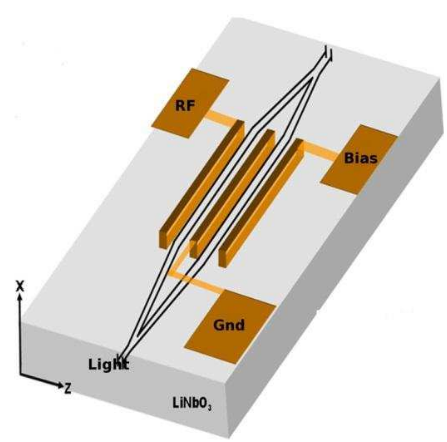

Figure 4: Electro optical modulator.

Fig. 4 shows the schematic layout of such an EOM. Essentially, it is a Mach Zehnder Interferometer: The incoming polarized light is split in two paths going through a Lithium Niobate crystal. Applied electrical fields change the phase delay of the light going through the signal, one path is modulated by the signal, the other by a DC bias and the recombination of both paths at the end of the modulator result in a phase to amplitude conversion of the signal. By a suitable choice of the DC bias, we can change the characteristics of the EOM from classical amplitude modulation to quadrature type [8].

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In practice, only the second modulator needs to be in the tunnel and be exposed to radiation. The supporting circuitry consists of an input filter, eliminating unwanted spectral information and a microwave limiter to protect the modulator from overload. The bias is supplied externally via a heavily shielded cable. All the other parts, laser diode, LO, photo diode and post processing electronics can be placed suitably outside the tunnel. The signal attenuation in an optical fiber is very small, so distances of several hundred meters pose no problem.

System Considerations

Comparing the efficiency of analog fiber optical transmission systems with the direct transmission of Rf via TEM-lines or waveguides, the noise behavior of optical transmission systems is one of the main distinctive features.

Main contributors to the overall noise in a optical system are the shot noise due to the detectable quantum nature of light and the relative intensity noise (RIN) of the laser source commonly used in these systems. Additionally, thermal noise has to be added like in direct transmission systems.

The effect of thermal noise, relatively minor here and not shown, usually is much stronger in RF based systems, since the transmission losses are very high also over comparably short distances affecting the signal to noise ratio (SNR).

A noise calculation for an analog optical transmission system with amplitude modulation including the effects of all the kinds of noise described above can be performed using [9–11], resulting in a SNR mainly depending on the optical power level.

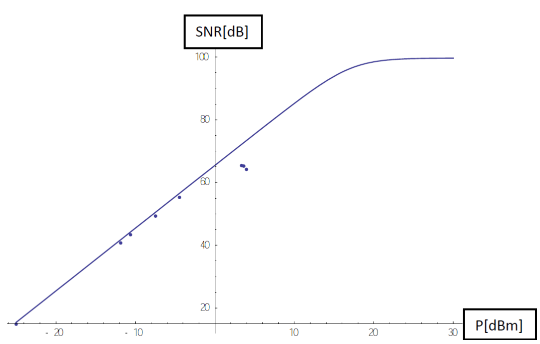

Figure 5: SNR versus optical drive power (modulation index 9.63%, bandwidth 20 kHz).

Calculated and measured SNR are shown in relation to the optical power level in the photo diode in Fig. 5. The measurements have been performed with a single modulator, the modulation index has been controlled by a measurement with an optical spectrum analyzer (m=0.0963). It was done using a R&S FSEK30 spectrum analyzer at a resolution bandwidth of 20kHz and a single mode fiber pigtailed photo diode. For a double modulation, as used in the front end, the effective modulation index, which is the product of the pre-modulation factor (with the LO) and the signal modulation, needs to be used.

For the photo diode used, saturation starts to degrade the SNR optical power levels in excess of 3 dBm. With the components presently in use, there is no sense in boosting the optical power at the diode to level higher than around -5dBm. Fig. 6 shows the relation between SNR and bandwidth.

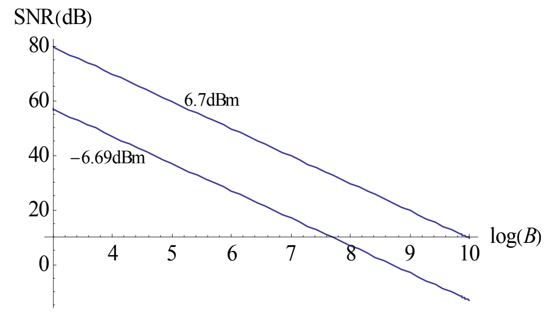

Figure 6: Theoretical S/N ratio versus bandwidth for two different optical drive powers.

Components

An important feature of the proposed front end architecture is the robustness to radiation damage, which means essentially the robustness of the electro optical modulator to this effect.

In standard semiconductors, the main effect consists in a slow destruction of the PN junction in the doped semiconductor by the radiation leading to an ever larger leakage current crossing the barrier. In an electro optical modulator, we donâĂŹt have any transition of this type. Exposing the Lithium Niobate in the EOM to radiation will lead to an ever larger number of defects in the crystal structure of the material. The optical beam carrying the signal will get scattered at these defects and become attenuated. The modulator gets blind and its optical return loss worsens.

For our system, we chose the Photline modulator type MX-LN-2, which, in order to validate its suitability for space application, was tested by the manufacturer among other things for its radiation hardness [12]. The modulators were exposed to 60 MeV protons with a dose density of $10^{11} p/cm^{\hat{A}}$š and γ rays from Co^{60} source with a dose rate of 36 rad/h, the total integrated dose was 10 krad. The samples were successfully tested at various temperatures with respect to their optical return loss, which was supposed to stay above 38 dB.

For the CW laser source, we use the 1772 high power laser diode provided by Emcore. Its special feature is a very low relative intensity noise (RIN) of -163dB/Hz at a output power level of 17dBm.

As a photo receiver a photo diode from Albis Optoelectronics of the type PQW18A with a responsitivity of 0.87A/W was used. It is pigtailed with a single mode optical fiber. We used a version, where the RF signal output is shunted with 50 Ohms. The bias is supplied via a RC-low pass circuit.

Electronic Post-processing

At the output of the photo diode, we plan to have three different signals paths to allow specialized measurements:

As an operator signal, we need to measure the power of the complete signal. Required is a high sensitivity for low signal levels giving a high precision for the structure alignment in combination with a large dynamic range. A logarithmic detector offers the right approach to this problem. To that end, we are currently evaluating the type HMC602LP from Hittite, which seems to be a suitable choice with a bandwidth of 8 GHz, a RF threshold level (detection limit) of -65 dBm and a dynamic range of 72 dB. One of the beam tests shown later was performed using this device.

The measurement of internal misalignments of the structure needs a detector with a high sensitivity, while not requiring such a high dynamic range, since the structure itself should be well aligned for this type of measurement. We plan to look at scan the spectrum (corresponding to the scan for local offsets inside the structure), by having a varying LO frequency in combination with a fixed band pass filter after the photo diode. Their level and envelope will be measured by tunnel diode detectors. We are planning to use a component with built-in low noise preamplifier from Herotek (DTA1-1880A), which offers a detection threshold of -80 dBm with a high sensitivity of 1V/μW. Devices for test and evaluation are now in house and under evaluation.

At last, there is still need for an expert type signal, basically the raw output signal of the photo diode with some minimum filtering and amplification.

BEAM TESTS

A validation of the raw WFM signals was already done and is described in [6]. We built a proof of principle system containing the electro-optical system as shown in Fig. 3, which allows to measure one WFM channel. After testing it in the lab with sinusoidal signals, we connected it to the WFM pickup of the X band structure installed in SITF. The LO frequency used was 15 GHz. The accelerating structure containing the wake field monitors sits on movers, which allow to shift and tilt the structure with respect to the beam. All measurements were done with a LeCroy SDA816zi digital scope, featuring 18 GHz bandwidth and 40 GS/s sample rate, which allowed also to record the raw signals from the structure.

Fig. 7 compares the output of the raw RF signals from the WFM with the signal of the electro-optical front end, where the signals were scaled to the same sensitivity. Both measurements are strongly dominated by the digitization noise of the scope. Nonetheless the EOM signal (out of the photo diode) shows a more pronounced minimum, corresponding to a resolution of 20 μm at the measured bunch charge of 140 pC to be compared to a value of 37 μm for the raw signal.

Using the logarithmic detectors described above improves the situation still more, since we do a detection of the signal envelope giving an output signal with a strongly reduced

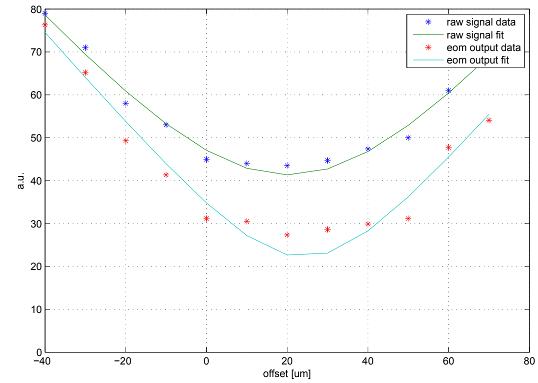

Figure 7: Comparison of raw signal output versus photo diode signal as a function of beam offset inside structure.

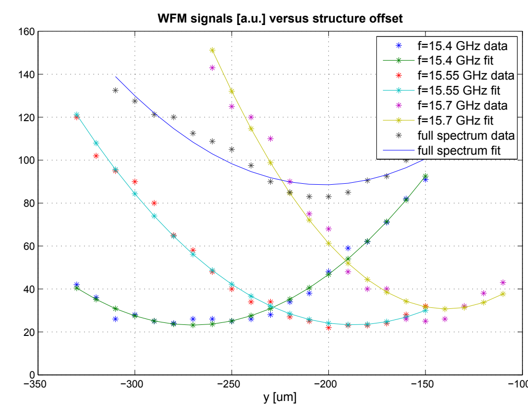

Figure 8: Spectral scan showing structure tilt, the curve with the full spectrum gives the average offset, while the filtered data shows the offset of different segment (15.4 GHz upstream end, 15.55 GHz near cell 18, 15.7 GHz in the middle of the structure.

bandwidth of 10 MHz. These were used for a rather interesting experiment, whose results are shown in Fig. 8. Here the structure was tilted with respect to the beam. For the upstream monitor, which receives wake field signals from the first half of the structure, it means, that regardless of the offset, while the structure may be centered e.g. in the middle, there are always parts of the structure at an offset generating wake field signals. This means for the full signal, that we see a relatively flat minimum as we move the beam versus the structure.

But now, the frequencies of the excited spectrum are correlated with the position along the structure (described in more detail e.g. in [1]. If we filter out parts of the spectrum, we should be able to see the offsets of individual segments inside the structure. This was done here, a band pass with 100 MHz bandwidth was inserted between photo diode and logarithmic detector. We measured at three frequencies, 15.4 GHz (corresponding to the upstream end), 15.55 GHz (moving in by a quarter) and 15.7 GHz (roughly in the middle of the structure). The corresponding curves show minima

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at offsets of -270, -190 and -140 μm, which is a perfect illustration of this effect.

The filter bandwidth used here is still relatively wide. We are in the process of ordering narrow band filters with a bandwidth of 10 MHz (corresponding to the bandwidth excited by an individual resonator inside the structure). In combination with the high sensitivity tunnel diode detectors described above, we hope to obtain a far better resolution of this type of measurement, possibly enabling us to see the internal cell to cell alignment of the accelerating structure.

SUMMARY AND OUTLOOK

Wake field monitors couple directly to the transverse wake field inside RF accelerating structures and are excellent device to measure structure alignment to the beam. We describe a concept for the front end for their wide bandwidth signals in the 15 GHz range.

For the architecture, we follow an electro-optical approach, where signal down conversion and transport is done in the optical domain. This offers significant advantages in terms of radiation hardness of the required components. Also, the signal transport happens over relatively cheap optical fibers with minimum attenuation and signal distortion even over longer distances. When looking at the signal to noise behavior, the most important criterion is to have a sufficient optical drive power to stay out of the region, where photon shot noise becomes visible.

For a proof of principle, we built a simplified system for one signal channel, which was subsequently tested with beam. Using just the internal scope functionality, we obtained already a resolution of 20μm at a bunch charge of 140pC. Scaling this to the nominal SwissFEL bunch charge of 200 pC, this gives us already 14 μm. We did also first tests using a wide band logarithmic detector to post process the electronic output from the photo diode. With this setup, we were able to do first tests of advanced measurement options – we were able to clearly distinguish offsets of individual segments inside the accelerating structure.

Next steps are the evaluation of high sensitivity tunnel diode detectors, which we plan to use to measure internal structure misalignment. Also, we have equipment on order for the digital control and readout, which we need to make the scans for frequencies and offset really functional.

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