2.8 STORAGE RING DIAGNOSTICS

2.8.1 Introduction

This section is intended to be a comprehensive summary about the SLS storage ring beam instrumentation. The design concepts presented here are based on the present status of the respective diagnostics systems. They still might change during the design phase, if more appropriate solutions regarding performance, resource allocation or schedule are found. These issues will be resolved on a case by case basis and are out of the scope of this document. The resource and schedule estimates for each instrument are given in an additional, also updated *SLS Electron Beam Instrumentation* paper. Chapter 2.8.2 gives a short overview of the SLS storage ring measurements, which will be nescessary to set up and commission the storage ring, to measure the machine and beam parameters and to maintain the design performance during routine operation. The following sections go more into detail and provide more or less elaborated design concepts for each instrument.

2.8.2 SLS Storage Ring Measurements

Measurement	**Comments**	**Instrument**
Current and injection efficiency	Pickup (toroid) shall be magnetically shielded and temp. stabilized	Parametric Current Transformer (Bergoz)
Position - destructive	Essential device during the commissioning, useful later	OTR and FS
Position - nondestructive first turn	Same concept as turn by turn	Digital Beam Position Monitor System in first turn mode
Position - nondestructive closed orbit	Mechanical movements of pickups will be measured and compensated.	Digital Beam Position Monitor System in closed orbit mode
Position - nondestructive fast global feedback	SVD algorithm will be applied, therefore only communication between neighboring sectors has to be realized.	Digital Beam Position Monitor System in feedback mode
Position - nondestructive turn by turn	Better understanding of the machine. Tune measurement.	Digital Beam Position Monitor System in turn by turn mode
Transverse profile	A bending magnet beamline for diagnostics purposes will be installed.	SR beamline
Tune	Slow, with high resolution	Storage Ring Tune Monitor
Longitudinal profile	A bending magnet beamline for diagnostics purposes will be installed.	SR beamline Streak Camera
Emmittance	A bending magnet beamline for diagnostics purposes will be installed.	SR Beamline
Lifetime	A method with a scraper can be used.	PCT Scraper

Aperture, halo		Scraper
Radiation	PIN-diodes distributed around the ring and placed at „hot spots“.	Beam Loss Monitor
Longitudinal instabilities		Ring Electrode + Spectrum Analyzer, Streak Camera
Transversal instabilities		Stripline Electrode + Spectrum Analyzer
Energy and energy spread	A bending magnet beamline for diagnostics purposes will be installed.	SR beamline

2.8.3 Design Concepts for SLS Storage Ring Instrumentation

This part of the document provides the specifications and device descriptions for beam instrumentation at the SLS storage ring. For some (low priority) devices, this will presently be a rough assessment. For other, high priority devices like the BPM system and the tune measurement more detailed design concepts and specification lists are already given in this document.

2.8.3.1 Optical Transition Radiation (OTR) Screens - Flourescent Screens

During commissioning of the storage ring (partly) destructive devices like OTR-screens will be used for monitoring the electron beam position and profile [1,2]. Like in the booster synchrotron two OTR-ports will be placed along the injection line of the storage ring in order to assure proper matching of the electron beam during injection. Moreover two additional OTR-screens will be installed for supporting commissioning and for trouble shooting in case of a machine failure.

The impedance contribution of the OTR viewports to the total impedance budget of the storage ring has to be minimized. Since the same requirements are valid for the booster viewscreens it should be possible to adopt an only slightly modified booster design.

For linearity and resolution reasons, OTR is preferred over the use of flourescent screens. Still every profile monitor port will be equipped with two selectable stations for an OTR screen and an optically transperant, but highly sensitive quarz screen. The latter will be used in the low current top up mode of the SLS.

As a special option for advanced control and optimization of the injection process into the storage ring, we are presently investigating the use of very thin (500 nm) Si_3N_4 wafers as OTR-foils. In combination with gateable CCD cameras (< 1 µs gating time), this will allow to observe the position and the matching of the electron beam into the storage ring over serveral (consecutive) turns.

2.8.3.2 Parametric Current Transformer (PCT)

A PCT [3] is usually used for measuring the average beam current in accelerators. Since it has a large dynamic range (> 10^7), a relatively high bandwidth (DC to 100 kHz) and a high resolution (0.5 µA at 1 s integration time), it is the ideal instrument to measure the beam life time and the injection efficiency into the storage ring [4]. The PCT is an off the shelf instrument, which is delivered by the *Bergoz* company. It consists of a sensor head, a matching front end electronics and an output electronics chassis. Special, radiation resistive and RF shielded cables (up to a length of 200 m) can also be delivered by the *Bergoz* company. The working principle is similar to the MPCT, which is described in the booster synchrotron diagnostics section (chapter 3.2.6). Like in the booster some effort has to be put into the development of a shielding against stray magnetic fields and in a temperature stabilization [5].

2.8.3.3 Horizontal and Vertical Scrapers (HS and VS)

There will be two horizontal and one vertical scrapers in the storage ring. One of the HS will be placed in a dispersive section of the ring, where it is possible to acquire information about the energy distribution of the electron beam. An additional HS and a VS will be both placed at a non-dispersive section of the ring, in order to get information about the transverse beam distribution, to eliminate possible beam halos and to establish an alternative method for measuring beam life time in the storage ring. The scrapers will be electrically isolated and watercooled. The mechanical supports have to be very stable in order to guarantee a sub-micrometer resolution of the scraper position.

2.8.3.4 Digital Beam Position Monitor (BPM) System

The SLS digital BPM electronics represents a departure from conventional BPM system design approaches. Multiplexing of pick-up signals to a common processing chain is a preferred technique to obtain high stability and resolution. Wide-bandwidth systems on the other hand implement log-ratio, AM/PM, simultaneous 4 channel processing or some other processing scheme.

The SLS BPM system is required to provide both features: high stability of position readings on one side and turn-by-turn capability on the other. A way to build such system is to combine low bandwidth multiplexed electronics with high bandwidth electronics which provides turn-by-turn capability. However, there are two problems associated with this scheme. The first one is routing of four pick-up signals from a single BPM to two types of electronics. The second one is the data acquisition part, which again has to accommodate two different types of electronics.

During our concept development process we searched in the following directions:

1. Commercial off-the shelf modules
2. Solutions from other labs
3. New technologies
4. New ideas

The electronics we decided to develop for the SLS is a four-channel system. The design implements two schemes to overcome disadvantages associated with standard four-channel systems. The first one is the use of a pilot signal to keep the gain of the four channels matched within the dynamic range. The second one is direct intermediate frequency (IF) sampling and digital demodulation which offers excellent linearity and stability over time and temperature. The solution is also cost advantageous. It offers the required sub-micron resolution and programmable bandwidth, including turn-by-turn capability at a cost that would be the cost of two seperate electronic systems to perform the same function.

2.8.3.4.1. SLS BPM System Architecture

There will be a total of 72 BPMs in the SLS storage ring, subdivided in 12 sectors with 6 BPM stations at a time. Every sector encloses a straight section with three BPM stations on each side. This layout was mainly driven by the data collection and communication requirements of the SVD correction algorithm [6], which will be applied for global orbit stabilisation in feedback operation mode. Figure 1 shows the SLS BPM system architecture and figure 2 shows the foreseen BPM electronics rack layout.

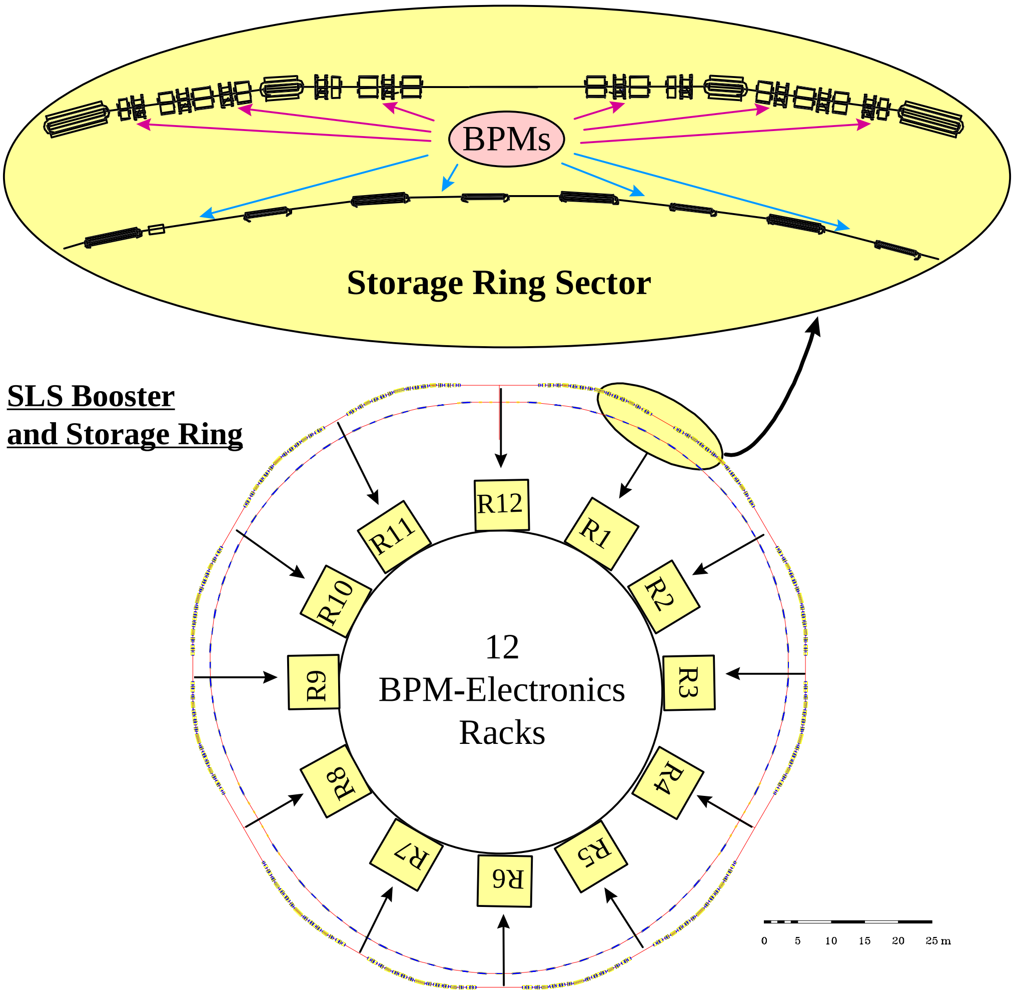

Figure 1: SLS BPM system architecture

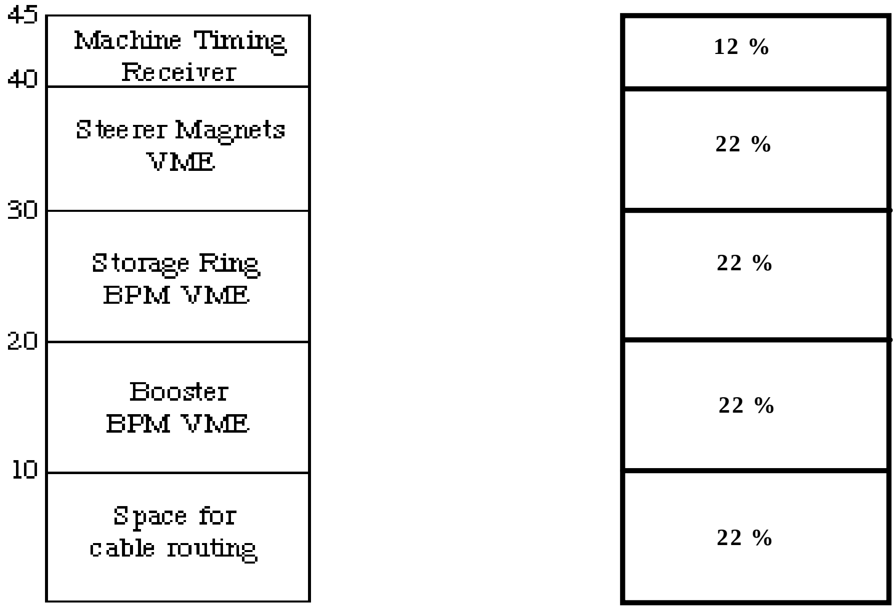

Figure 2: BPM electronics rack layout

2.8.3.4.2. Storage Ring BPM Stations

The SLS storage ring BPMs will be button type monitors with four diagonal buttons. The expected output power for 1 mA average current at 500 MHz will be -53 dBm into 50 Ω. The sensitivities (ΔV/ΣV) in the horizontal and vertical direction will be 0.06 mm^{-1} and 0.07 mm^{-1} respectively. The loss factor referred to single bunch operation will be 5.4 mV/pC per BPM station and the total $|Z|/n$ for all 72 BPM stations in the storage ring will sum up to 14 mΩ. Figure 4 shows a MAFIA plot of the upper half of the SLS storage ring BPM chamber with button electrodes and a representation of the equipotential lines of the field distribution in the chamber. It can be seen that we are expecting very linear behaviour in an area of ± 2.5 mm around the center.

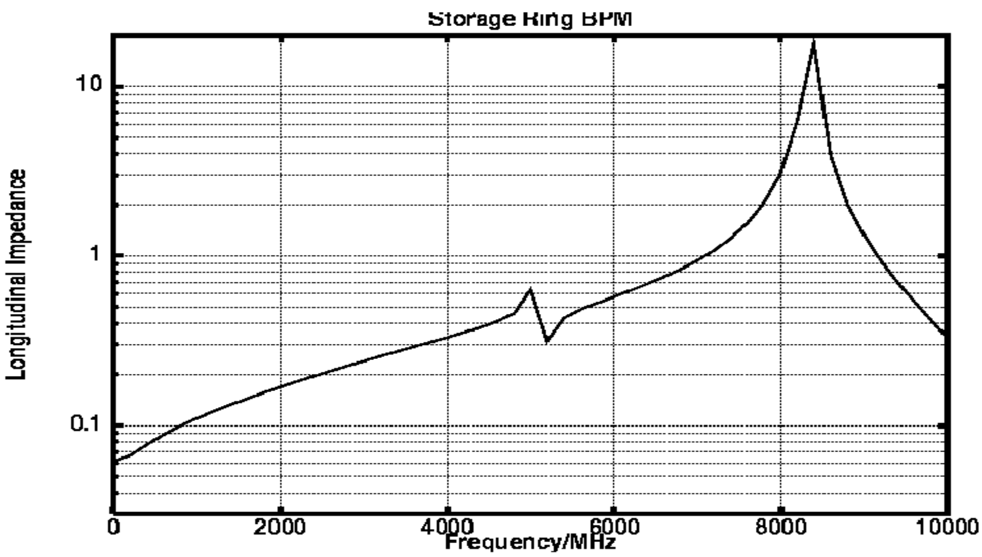

Figure 3: Beam impedance plot of BPM station

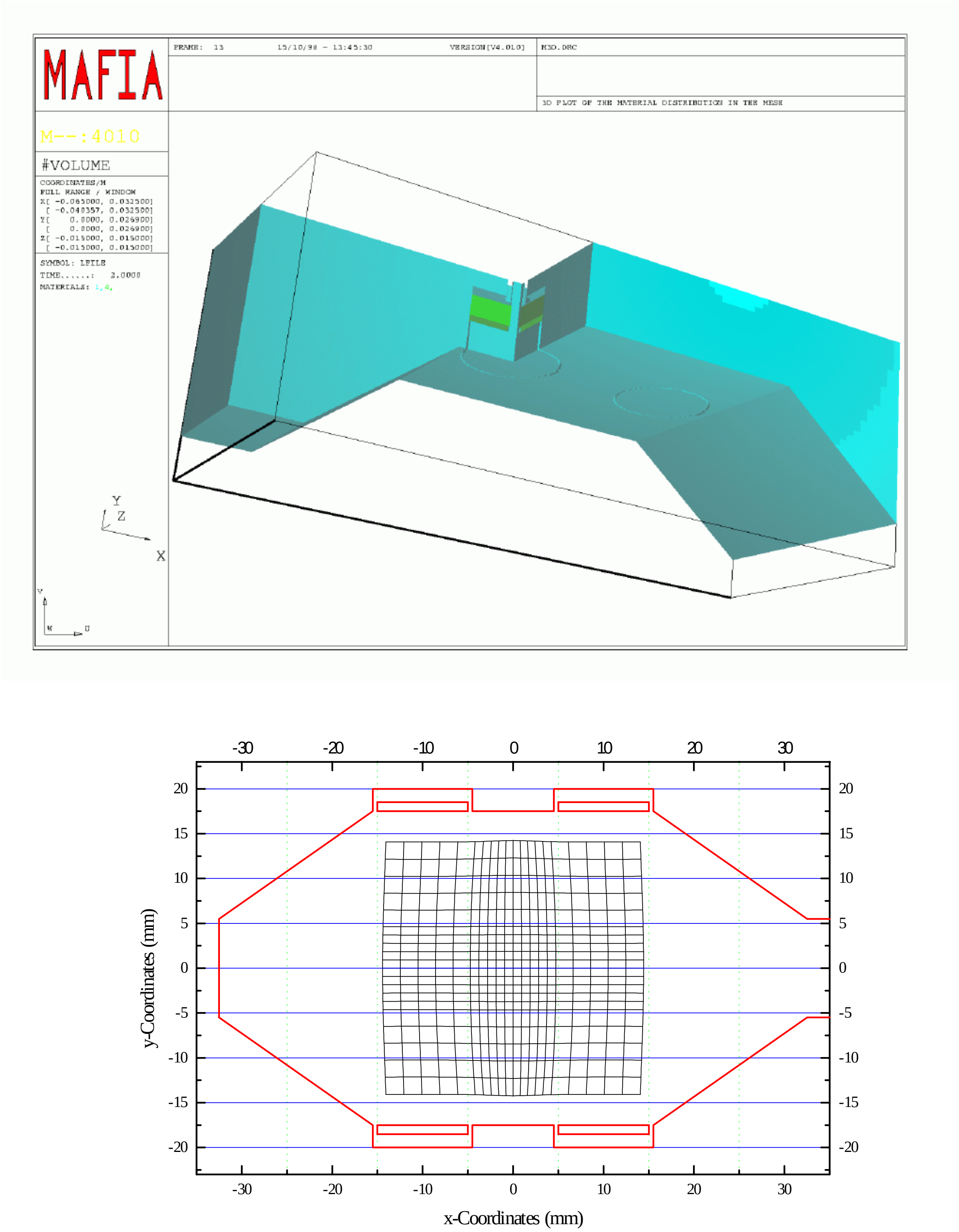

Figure 4: MAFIA plot of the upper half of the SLS storage ring BPM chamber with button electrodes (above). Field distribution of SLS storage ring BPM chamber (below).

The mechanical alignment will follow the same concept as the alignment of the magnets on the girders. Instead of being rigidly attached to the adjacent (quadrupole) magnets (like at ELETTRA and ESRF), the BPMs will be mounted on a precisely machined support, which is fitting on the alignment rail of the SLS girders. Since this mechanical alignment concept indicates an initial accuracy of the BPM readings within 0.5 mm relative to the adjacent quadrupole axes (here all possible offsets and errors in the electronic chain of the BPM system are already taken into account), commissioning of the storage ring will be possible without time consuming alignment procedures of the BPM chambers. The final calibration of the BPMs (definition of their „zero“-position) will then be accomplished with the method of *B*eam *B*ased *A*lignment [7]. Since BBA is an „end to end“ method, it will give the BPM position relative to the adjacent quadrupole with the resolution of the BPM electronics. Therefore each quadrupole will be equipped with it’s own power supply, which will be capable to perform a ≤ 5% sweep with a 3 Hz frequency for dynamic BBA.

The long term stability of the calibrated mechanical positions of the BPM chambers becomes more and more important issue [8] especially after shut down periods and when running different filling patterns in the storage ring. In these cases not only the linearity of the electronics but also mechanical drifts of the BPM chambers due to thermal effects like e.g. changes in the ambient temperature of the storage ring tunnel and different thermal loads on the vacuum chambers have to be considered. An effective movement of the BPM chambers overrides the alignment and calibration of the chamber’s position and leads to false readings and corrections of the electron beam position.

At the SLs it is planned to supervise such effects by the implimentation of a mechanical *PO*sition *M*onitoring *S*ystem (POMS) which improves the reliability of the BPM readings and eases storage ring operation. The center pieces of this system will be 144 highly precise optical sensing devices, which serve as dial gauges for measuring the relative positions (and position changes) of the BPM chambers to the adjacent quadrupole magnets. We will use the so called „smart photosensors“ by the Baumer Electric company [9], which give absolute position measurements of sub-µm resolution for rather low prices (≤ 500 SFr. per sensor including electronics). With two sensors per BPM station the horizontal and vertical positions of the BPM chambers will be constantly read out and updated in the final position processing of the BPM electronics (by the DSP).

2.8.3.4.3. Digital BPM (DBPM) Electronics

In the following sections the electronics of the digital BPM system for SLS is described. It consists of three parts, which will be implemented in VME modules: the RF-front end, the digital receiver and the DSP controller.

2.8.3.4.3.1. Specifications

Parameter	Specification
Dynamic Range Multibunch Mode (average current) Single Bunch Mode (average current) Pulsed and First Turn Mode (peak current)	 1 - 400 mA 1 - 20 mA 1 - 10 mA
Position Measuring Radius [1]	5 mm
Pin-max, 400 mA, beam 5 mm off center	-8 dBm
Pin-min, 1 mA, Centered Beam	-65 dBm
Resolution (100 kHz bandwidth) 10 - 400 mA 1 - 10 mA	 ≤ 1 µm ≤ 10 µm
Beam Current Dependence [2] 1 - 400 mA	 ≤ 100 µm

Relative 1 to 5 Range [2]	≤ 5 µm
Maximum Data Acquisition Rate	$f_{revolution}$
Closed Orbit Operator Display Rate	2 orbits/s
Feedback Mode Throughput	4000 x&y meas./s
Modes of Operation	Pulsed Booster Turn-by-turn Tune Closed Orbit Feedback

[1]The position measuring radius defines an area, within which the specification for resolution, and beam current dependence are met. This is for any beam current between 1 and 400 mA. The system can provide position measurements outside the specified boundary or down to 0.01 mA with a lower accuracy.

[2.] Let us assume we are measuring beam position of a beam which is stable in its position somewhere within the position measuring radius. Beam current dependence is defined as a peak-to-peak deviation of the measured position if the beam current changes as specified. The “relative 1 to 5” range means that the 5 µm specification holds whenever the beam current changes by not more than factor 5. As an example: 80-400 mA, 1-5 mA, 4-20 mA, ...

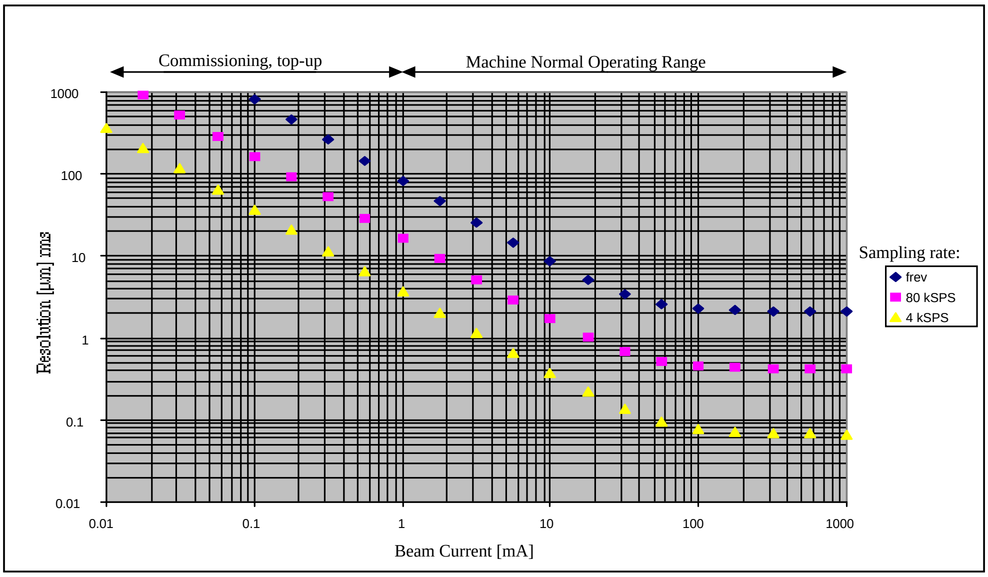

Figure 5: Expected DBPM system resolution for different beam currents and sampling rates.

2.8.3.4.3.2. Block Diagram and Theory of Operation

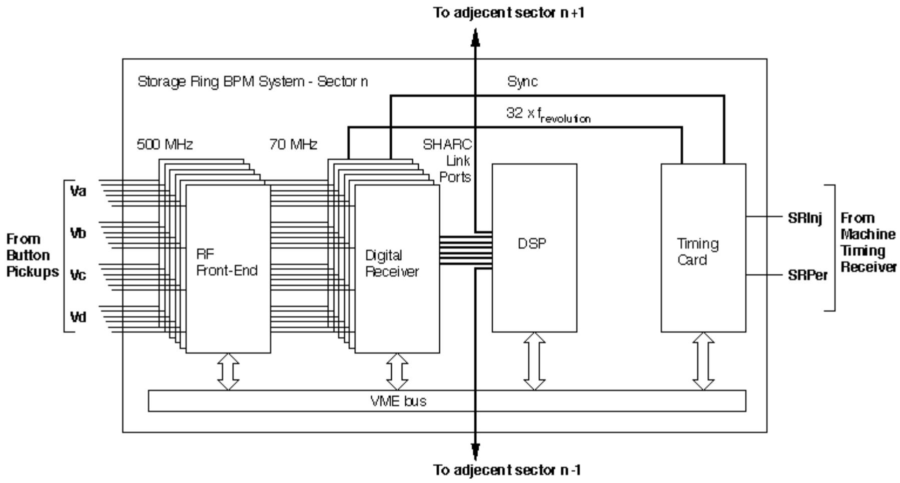

Figure 6: Storage ring BPM electronics block diagram.

The four **RF front-end** channels tune to 500 MHz, the first harmonic of the machine, and outputs four 70 MHz band-limited signals. A gain control loop keeps the sum of the output voltages constant whatever the input signals are. The relative gain deviation between the four channels is less than 0.1 dB over the 1 to 400 mA dynamic range. To equalize the gain of the four channels, we use a pilot signal of a different frequency than the carrier signal from the buttons.

The **digital receiver** module conceptualy consists of two building blocks., an analog to digital converter (ADC) and a digital receiver (DR). The 70 MHz band-limited signal is sampled with a wide-band 12 bit analog-to-digital converter. The sampling of the 70 MHz band-limited signal occurs at a rate of 32 times the revolution frequency; 33.3 MS/s and 35.56 MS/s for storage ring and booster respectively. We decided for under-sampling to eliminate the need for a second downconversion stage (see also discussion about undersampling in paragraph 2.8.3.4.2.4.). The data stream from the ADCs is sent to four digital receivers. The ADCs and DR are available from Analog Devices, Harris and Graychip.

The decimated data streams from digital receivers are formated, serialized and sent to a **DSP module** which performs multiple functions. It scales the input samples and applies corrections, calculates position and current, filters, formats data for desired application, adjusts pilot signal amplitude or calculates fast Fourier transformation. In storage ring two DSPs equip 6 BPM electronics per sector. More processing power is needed to implement the global orbit feedback algorithm.

The electronics is integrated into EPICS control system. Users will be able to select among different operating modes of the system depending on location or desired application. We have foreseen the following modes of operation:

1. **Pulsed**

One sample taken for each sync signal. Intended for injector and transfer line BPM measurements. Assuming 3 Hz injection, one sample will be taken every 333 ms.

2. **Booster**

Each BPM will provide position measurements through-out the acceleration cycle. Two orthogonal display modes are envisioned. First, user displays a single BPM measurement or group of them in time domain. This would allow tracking of position as the beam is accelerated. Second, user displays booster closed orbit at different time intervals.

3. **Turn-by-turn**

User can select N (1024, …, 8192) successive measurements to be taken per each sync cycle. Display modes will depend on application. In general users would be able to select between time domain and frequency domain data formats.

4. **Closed orbit**

In this mode of operation measurements are taken continuously. Data is used for closed orbit display in control room.

5. **Feedback**

Measurements are taken in the same way as in the closd orbit mode and are processed continuously to provide position information to global feedback.

6. **Tune**

From data acquisition point of view this mode of operation is the same as in the turn-by-turn mode. However, a software algorithm on DSP will calculate Fast Fourier Transform and extract tune data from the results. One dedicated BPM for booster and storage ring respectively will constantly operate under this mode of operation.

The following timing diagrams show sync signal and digital receiver (DR) output data stream for different modes of operation.

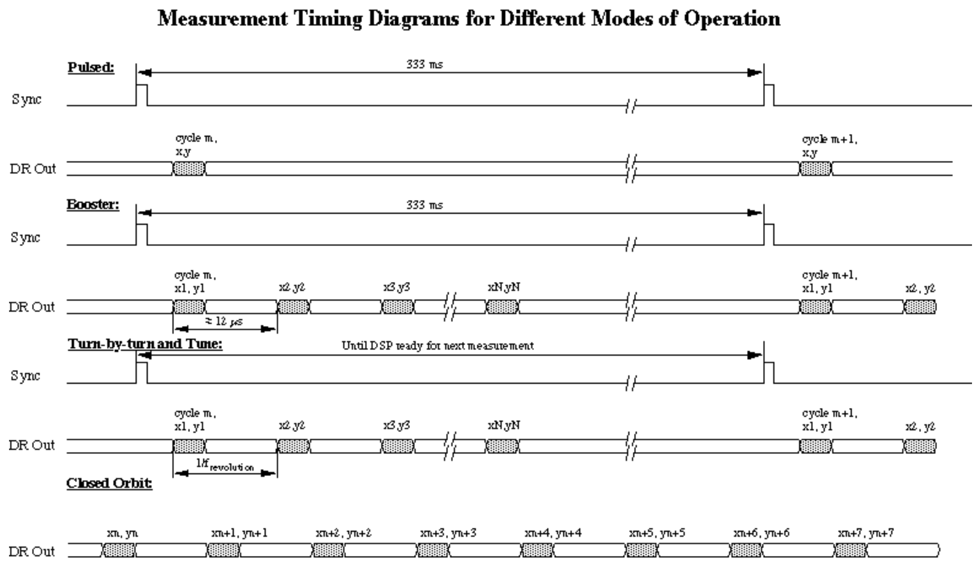

Figure 7: Timing diagrams for different modes of operation.

2.8.3.4.3.3. RF-Front End

The RF front-end for Beam Position Monitoring System consists of four equal channels tuned to the 500 MHz spectral component of the incoming signal which is down converted to an intermediate frequency of 70 MHz. Critical aspects of proposed RF front-end are:

1. gain tracking of the four channels over full dynamic range
2. input impedance matching over full dynamic range
3. linearity of the system
4. long-term stability of each individual stage

Parameter	**Specification**
Input RF Frequency - f_c	500 MHz
$P_{in, max}$	-8 dBm
$P_{in, min}$	-65 dBm
P_{out} (IF outputs a, b, c and d)	-2 dBm (0.5V_{p-p}@50 ½)
Intermediate Frequecy (IF)	70 MHz
Noise Figure @ $P_{in,}$= -65 dBm @ $P_{in,}$= -33 dBm @ $P_{in,}$= -8 dBm	 ≤ 7 dB ≤ 8 dB ≤ 30 dB
Bandwidth @ 3dB	3 MHz
Ambient Temperature Range	22 ^{o}C - 28 ^{o}C
Input Return Loss @ f_c ±5 MHz	≤ 26 dB
Conversion gain variation of any channel with respect to any other channel within the whole dynamic range	≤ 0.1 dB
Intrinsic conversion gain variation of any channel with respect to any other channel	≤ 0.5 dB
IF output level tollerance	≤ ±1 dB
Local Oscillator Frequency	430.5 MHz
Pilot Signal Frequency	501.5 MHz
Frequency stability of the LO and pilot signal	≤ 10 ppm

The RF front end will conform to VME form factor and will be 8 HP wide. The following figures present the block diagram of the RF front-end prototype that is currently under design by Micro Giga company. The prototype implements some features that will not be found on the final RF front-end. It offers a second downconversion and four additional IF outputs (2.5 MHz) to facilitate some specific measurements we plan to perform on the prototype.

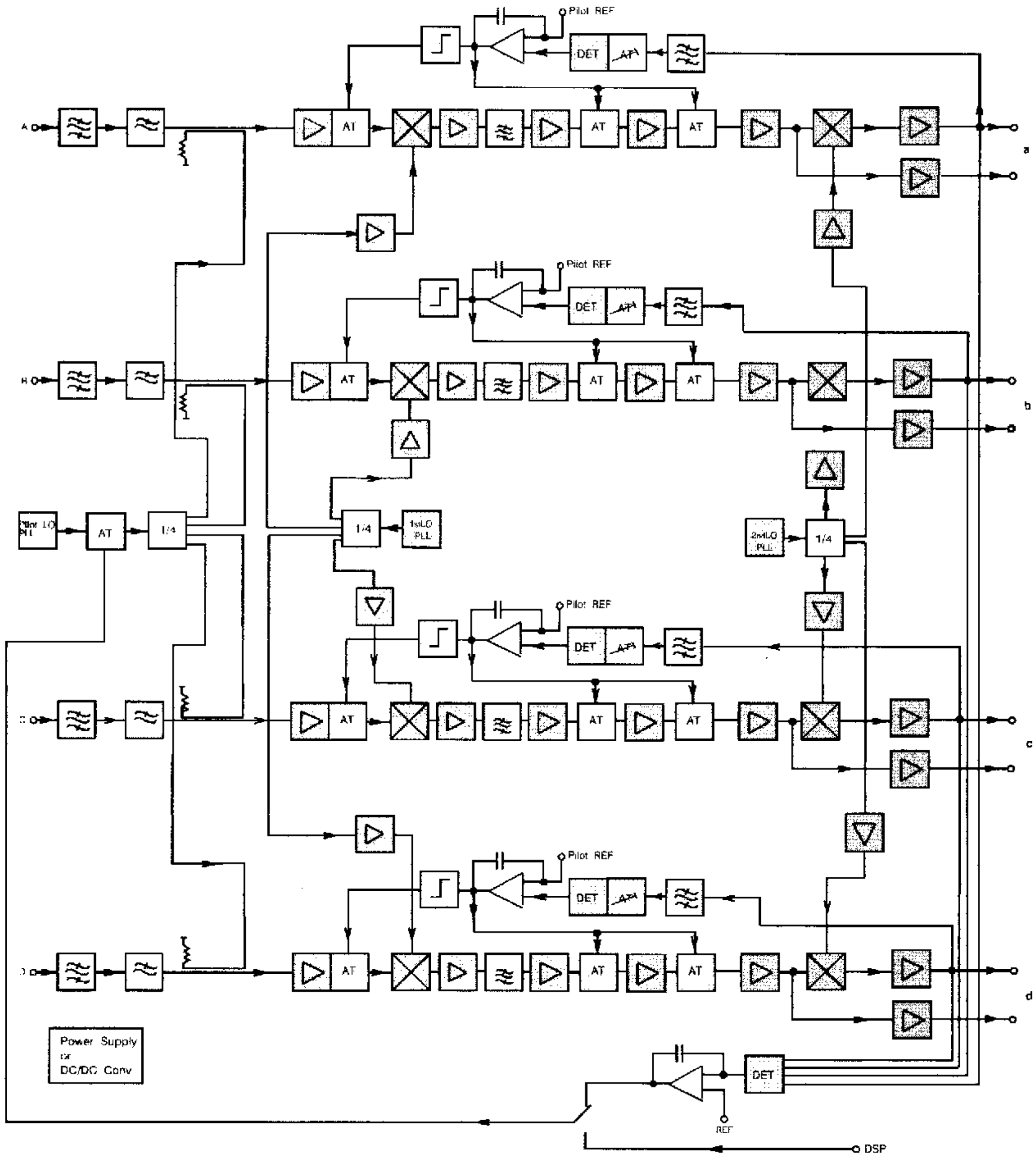

Figure 8: RF front-end prototype block diagram. The prototype includes also a second downcoversion stage that will not be present on the final RF module. The reason for the second RF stage is for prototyping purposes only, to verify digital receiver performance under different operating conditions.

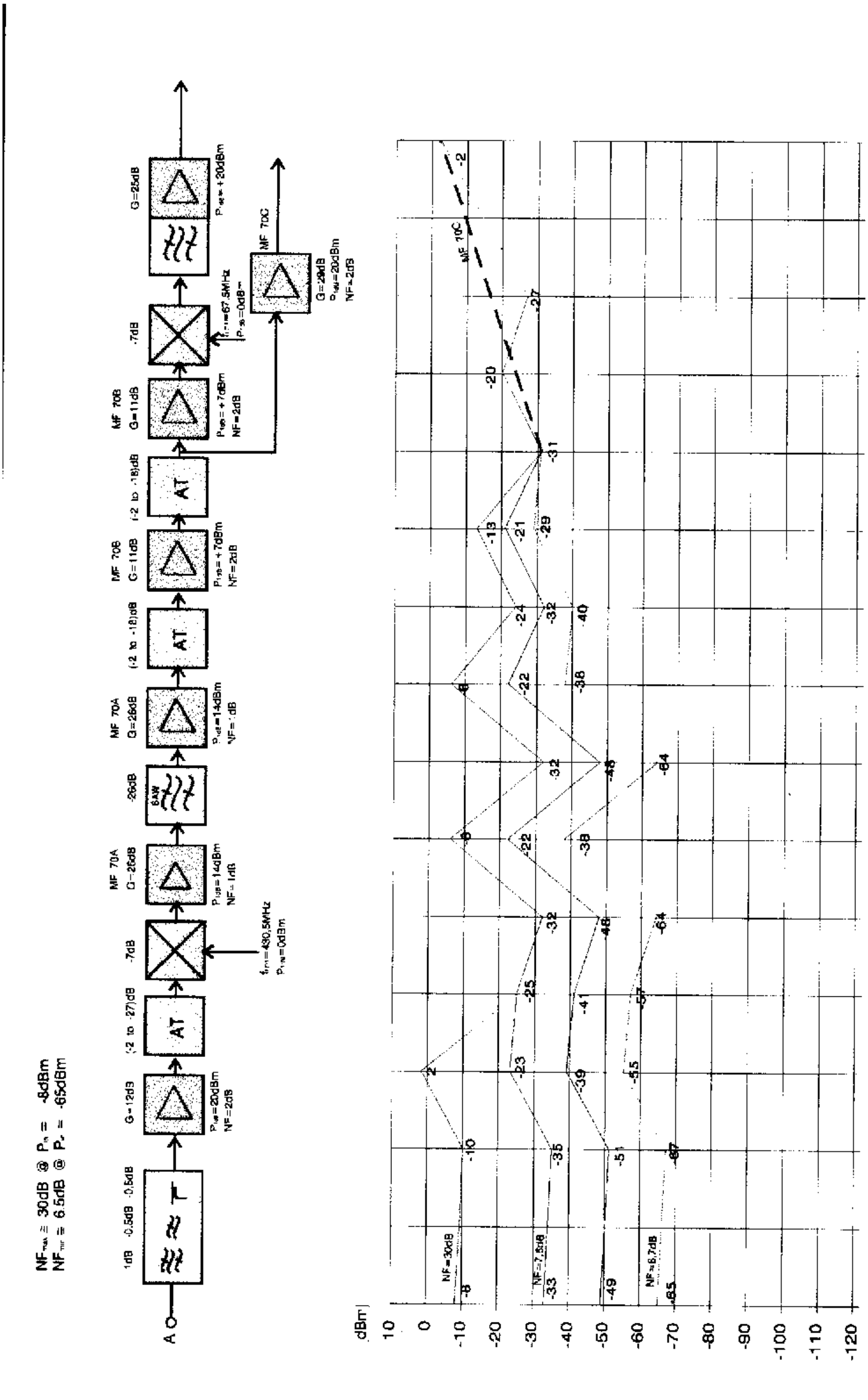

Figure 9: Signal level along each channel.

The constant conversion gain and the gain tracking of the four channels over the full dynamic range are achieved by introducing a pilot signal into the system. The pilot signal is used as a reference and is inserted as a signal with the frequency inside the bandwidth of the IF filters.

Its frequency is 1.5MHz higher than the signal of interest. It enables regulation of each channel gain separately. It is generated by a local oscillator and split into four equal signals. Each one is inserted in one of four channels. The level of each pilot signal is approximately 10 dB bellow the mean level of all input signals:

$$P_{pilot,inp} = (P_A+P_B+P_C+P_D)/40 \qquad \text{Eqn. 1}$$

By assuming constant frequency response of all components, the total gain of each channel is set according to the detected output level of the pilot signal at the end of each channel. The most non-linear components are detectors but they all operate under the same conditions (at the same level of the detecting signal). Applying second AGC loop sets adequate level of input pilot signal. Detected mean level of the sum of all four output signals is compared by the reference signal. The level of the pilot signal is then adjusted according to their integrated difference, so the required level of the output signals is always achieved. Consequently the level of the input pilot signal is adapted to the level of all four inputs according to the Eqn. 1. Required linearity of the system is obtained by operating all the active components in the chain (amplifiers, mixers) significantly bellow the 1 dB compression point (20 dB and more). The level of the pilot signal is approximately 10 dB lower than the input signals to avoid additional degradation of the system linearity and to keep the radiation of the pilot signal back to the accelerator at an insignificant level. One of the critical component is the IF filter. A good long-term stability, temperature stability as well as high selectivity are achieved by using SAW filters. As the insertion loss of the SAW filter is high, a special care should be given to the required system linearity and high dynamic range. A good input impedance match at the pick-up electrodes, its' long-term stability and independence of the input signals' level, is achieved by using combination of ceramic band-pass filter, microstrip low-pass filter and balanced low-noise amplifier at the input of each channel. Low-noise amplifier should have good noise figure, high linearity and high isolation to reduce the influence of the variation of attenuators' input impedance to the receiver input impedance. Required system gain variation is provided by three voltage controlled attenuators. By increasing the input signal level, the last two attenuators are starting to increase their attenuation first. After that, the first attenuator is starting to attenuate in order to ensure better system linearity and good S/N ratio. The signal level along each channel is shown in Figure 7. The first IF frequency of 70 MHz is chosen to maximize the possibility of using standard commercially available components (i.e. IF filters) and to enable good image frequency rejection.

According to the requested bandwidth and choice of the pilot signal frequency (501.5 MHz), the intermediate filter is realized by a SAW filter. The 3 dB bandwidth of the IF filter is 3 MHz and 1 dB bandwidth is 2.5 MHz. The frequency of the 1^{st} local oscillator is 430.5 MHz. The local oscillator is synthesized by PLL loops to quartz reference. A special attention during circuit design should be given to the mutual coupling between different channels. A proper layout design and metal shielding are required to decrease it to less than 60dB.

2.8.3.4.3.4. Digital Receiver Module

The digital receiver VME module is the second signal-processing module in the system. Four fast ADCs sample band limited (3 MHz) IF signal that contains 69.5 MHz downconverted button signal and 71.0 MHz pilot signal. They are followed by four digital downconverters. Downconverters output decimated data streams in a form of interleaved I (In-phase) and Q (Quadrature) data. The purpose of the formatter is to convert the I and Q information to amplitude and phase, reducing the workload on DSP. The module will have two different options to deliver data: Analog Devices SHARC link port or Texas Instruments 'C40 comm port. Two different mezzanine modules will be developed for this purpose. Digital receiver parameters are set via VME bus.

Parameter	Specification
Input Signal	
Carrier Frequency	69.5 MHz
Pilot Frequency	71.0 MHz
Input Impedance	50 ½
Input Signal Level	
Mean (Va, Vb, Vc, Vd)	-2 dBm (0.5 V_{p-p})
Maximum	+4 dBm (1.0 V_{p-p})
Sampling Frequency (32 x $f_{revolution}$)	
Booster	35.56 MS/s
Storage Ring	33.33 MS/s
Bandwidth @ 3dB	3 MHz
Data Output Port (mezzanine board)	TI 'C40 Comm Port or AD Sharc Link Port
Digital Receiver Parameters Control	via VME bus
ADC resolution	12 bit
Gain tempco	-50 ppm/°C

There are many reasons for sampling at such high rate. The main one is that it allows to under-sample 70 MHz signal (see undersampling concept later in this section) and eliminates a need for a second downconversion stage. The other reason is processing gain. It is the improvement in signal-to-noise ratio gained through fast sampling and digital filtering and rate reduction. A term decimation is used to indicate the ratio of input data rate (delivered from AD converter) to output data rate (output from digital receivers). Large processing gains may be achieved in the decimation and filtering process. The narrowband filtering is actually the source of the processing gain associated with digital receivers and is simply the ratio of the passband to whole band expressed in dB.

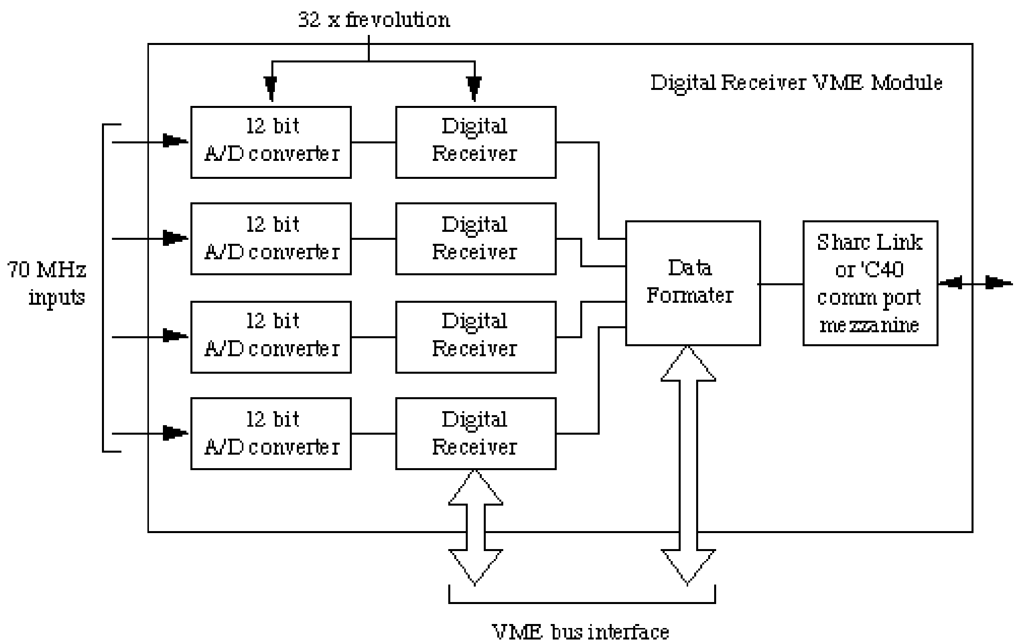

Figure 10: Digital receiver VME module block diagram.

As an **analog to digital converter**, we choose AD9042 from analog devices. It offers the best performance among 12 bit high-speed analog to digital converters at a low price. Some performance relevant to the DBPM system are listed below:

Parameter	**Specification**
Resolution	12 bit
Sampling rate	41 MSPS/s
Differential nonlinearity	±0.3 LSB
Integral nonlinearity	±0.75 LSB
Gain tempco	-50 ppm/^{o}C
On chip sample and hold	

Each **digital receiver** consists of three elements: a local oscillator, a complex mixer and one or more decimating low pass filters.

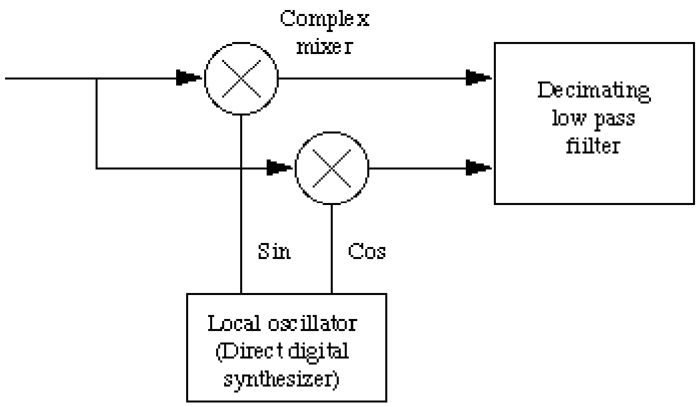

Figure 11: Digital receiver simplified block diagram.

By setting the local oscillator phase advance per clock cycle we can select to tune to the button signal frequency (69.5 MHz) or to the pilot signal frequency (71.0 MHz).

To understand the function of the digital receiver, think of it as a hardware pre-processor for the DSP. It pre-selects only the signals we are interested in and removes all others. This provides an optimum bandwidth and minimum sampling rate into the DSP. The number of DSPs is directly proportional to the sampling rate of the input data. By reducing the sampling rate in decimating filters we dramatically reduce the cost and complexity of the DSP system which follows. Digital receivers are available from Analog Devices, Harris and Graychip.

Finally we should also briefly descibe the **undersampling concept**. Let us consider the case of a signal that occupies a bandwidth of 1MHz and lies between 6 and 7MHz as shown in below.

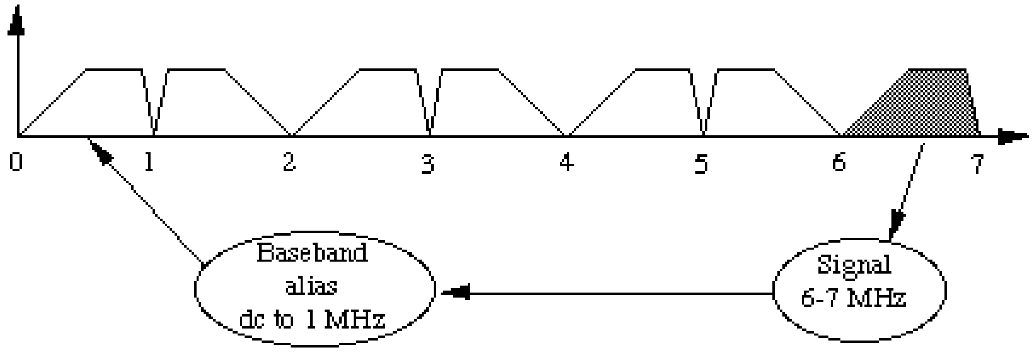

Figure 12: Aliasing of a 6-7 MHz signal to baseband.

Shannon's theorem states that the signal (bandwidth = 1MHz) must be sampled at least at 2MSPS in order to retain all the information (avoid overlapping aliased components). Assuming that the ADC sampling rate, fs is 2MSPS, additional sampling frequencies are generated at all integer multiples of fs : 4MHz, 6MHz, 8MHz, etc. The actual signal between 6 and 7MHz is aliased around each of these sampling frequency harmonics, f s , 2f s , 3f s ,4f s , ..., hence the term harmonic sampling. Notice that any one of the aliased components is an accurate representation of the original signal (the frequency inversion, which occurs for one-half of the aliased components, can be removed in software). In particular, the component lying in the baseband region between dc and 1MHz is the one calculated using a Fast Fourier Transform, and is also an accurate representation of the original signal, assuming no ADC conversion errors. The FFT output tells us all the characteristics of the signal except for its original position in the frequency spectrum, which was apriori knowledge.

2.8.3.4.3.5. Digital Signal Processing (DSP) Module

As a last stage in the common signal processing chain the down converted and digitized button signals from the BPMs are transferred to a fast processor (digital signal processor, DSP). It applies corrections to the data, calculates the x and y positions, does filtering and provides them to the SLS control system, to the operator display and to the global orbit feedback system. For SLS there will be two similar digital beam position monitoring systems for the booster and for the storage ring. The only difference is that in the storage ring the BPM system is part of a global orbit feedback system which results in some additional requirements. The same operation modes like shown in section 2.8.3.4.3.2. are available on the DSP module. From the digital signal processing point of view several of these modes are nearly similar. The different requirements to the digital signal processor are listed in the following.

a) **turn-by-turn mode / pulsed mode / tune mode**

In turn-by-turn mode the beam position of a bunch in the booster and in the storage ring has to be monitored turn-by-turn. The revolution frequency is 1.111 MHz in the booster and 1.042 MHz in the storage ring. Therefore the digitized data from the digital down converter (DDC) to the DSP (4 x 16 bit from the button signals) have to be transferred within a 900 ns or 960 ns periode, respectively. This corresponds to a transfer rate of 8.89 and 8.34 MBytes/s. The high transfer rates don't allow on-line calculation of the beam positions. Therefore the measured data are stored in memory and analysed off-line for further machine studies. The raw data of at least 10,000 turns are stored in the DSP memory. The required memory per BPM is therefore 80 kByte (4 x 16 bit x 10,000 turns). Because data are taken turn-by-turn they can also be used for tune measurements. The digital signal processor has to apply Fast Fourier Transformation in order to extract tune data from the BPM signals. In pulsed mode a sample is taken every injection cycle (3 Hz). Since the datarate is much lower than in turn-by-turn mode the x and y position can be calculated on-line and stored in memory. Beside to that, it is equal to the turn-by-turn mode.

b) **closed orbit mode / feedback mode**

Since the digital beam position monitoring system is part of a global orbit feedback it has to provide the x and y positions with the required sampling frequency. This sampling frequency is determined by the control theoretical point of view. It also has to provide the beam position to the operator in the control room with a data rate of 2 orbits/s.

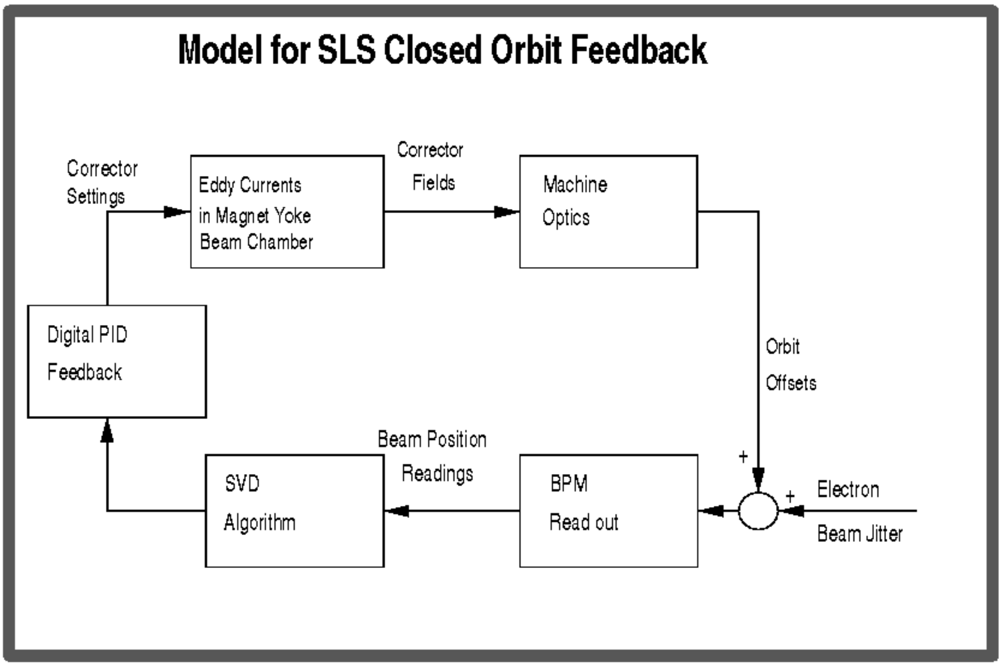

Figure 13: Model for closed orbit feedback

The design goal of the feedback system is to suppress beam displacements in the frequency range up to 50 Hz sufficently in order to keep them below 1 μm.Studies with the feedback loop model shown in Figure 13 have been carried out. The transfer functions of the corrector magnets including the effect of eddy current in the vacuum chamber are based on calculations on the design magnet while the transfer function of the power supply has been assumed to be a low pass filter first order with a -3 dB bandwidth of 500 Hz. For the mapping from the BPM readings to the corrector settings the SVD algorithm is used . In order to guarantee the required noise suppression up to 50 Hz a sampling frequency of 4 kSamples/s is necessary. The magnitude of the simulated closed orbit feedback gain is shown in Figure 14.

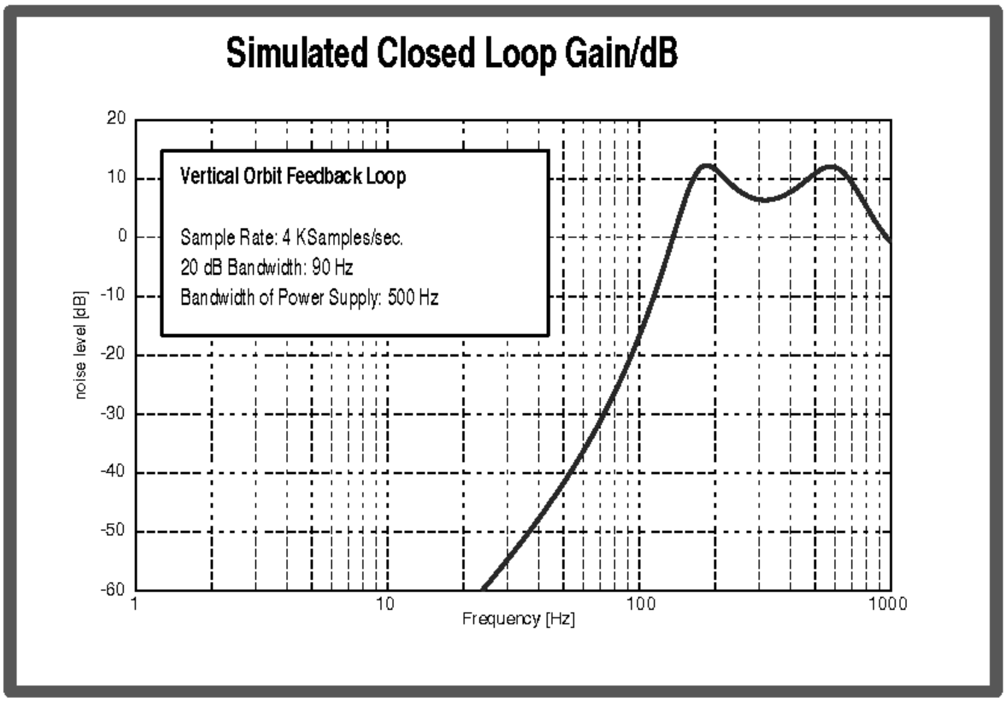

Figure 14: Simulated closed orbit feedback gain.

In this model noise can be suppressed up to 90 Hz with 20 dB (= factor 10) if the parameters in the PID controller are optimized. Here a processing delay of 250 μs has been assumed which corresponds to one sampling periode. It has to be mentioned that these calculations are partially based on theoretical assumptions (e.g. the power supply including controller). The 4 kHz sampling rate was a result of this feedback model with a safty margin to guarantee the required noise suppression in the real storage ring. Other laboratories (like APS) came to similar sampling rates in their orbit feedback loop.

c) **booster mode**

During acceleration in the booster the BPM system provides the beam position through-out the acceleration cycle with the same data rate (4 KSamples/s) as it is foreseen in the feedback mode of the storage ring.

The requirements of the different operation modes can be fulfilled with state of the art DSPs. In total, 72 BPMs and 72 corrector magnets will be installed in the storage ring while the booster will contain 52 BPMs and equal numberof corrector magnets. Each of the 12 sectors contains 6 BPMs and 6 corrector magnets in the storage ring and 4 to 5 BPMs and corrector magnets in the

booster as shown in figure 2. Studies on commercially available DSP boards turned out that even a single processor can handle the data from 6 BPMs. Because of the layout of BPMs and corrector magnets and the use of the SVD algorithm, the necessary information of the global orbit feedback can be reduced to few BPM readings per corrector magnet. The matrix given by the SVD algorithm relates the settings of a corrector magnet only with the readings of the three adjacent BPMs. Therefore it is obvious to decentralize the global orbit feedback and distribute the required computing power to the different sectors. With feasible expense a second digital signal processor can calculate the new corrector magnet settings and perform the control algorithm.

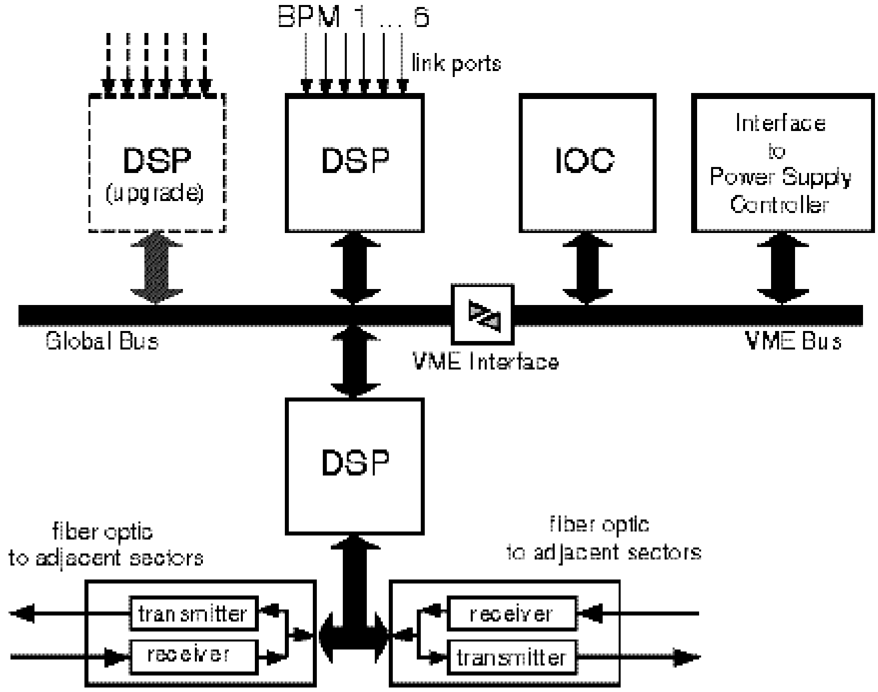

Figure 15: DSP topology for SLS storage ring.

The required digital signal processor topology consist of two processors per sector with the ability to communicate to the DSPs in the adjacent sectors. The presently most suitable digital signal processor on the market seems to be the SHARC ADSP2106x from Analog Devices. Two of those processors will be hosted on a single VME board per sector. The VME bus is the interface to the standard input output controller (IOC) which will be located in each crate. This IOC is part of the overall EPICS control system. The interface between the DSP and the digital down converter has been chosen to be the fast link ports of the DSP which are capable to transfer data as a point-to-point link with 40 MByte/s. In turn-by-turn mode the raw data (down converted four button signals) are stored in the DSP memory. Due to the fast link port and the sufficient memory a FIFO (fast input fast output) buffer is dispensable on the digital down converter board. The dual port DSP memory provides the information directly to the IOC and therefore to the EPICS control system or for off-line analysis. In feedback mode the raw data from the DDC will be processed on-line. The calculated x/y positions of the BPMs at the boundary of a sector will be passed to the adjacent sectors by an optical fiber link port with a transfer rate of 40 MBytes/s. The overall DSP topology is therefore a ring of processors. The new corrector magnet settings are passed to the power supply controllers through the VME bus. A 4 kHz timing signal from the timing system triggers the DDC to pass the data to the DSP. The DSP itself is fully data driven. The fast link ports and signal processors minimize the delay in the processing chain which is an important parameter in the feedback loop. For stability reasons, it has to be kept smaller than 250 us.

The DSPs are able to switch between the different modes of operation within a few microseconds after receiving the request. Additionally, the modularity of the DSP system provides easy upgrade possibilities. Each VME-DSP board is capable to host multiple digital signal processors sharing a global bus. Thus, more sophisticated algorithms and calculations can be implemented in future. Even additional BPMs could be added to the ring topology. The booster BPM system is identical to the one of the storage ring apart from the fiber optic links to adjacent sectors since no global orbit feedback will be installed. The hardware layout for the storage ring BPM system for one sector is shown in Figure 15.

2.8.3.5. Tune Measurements

We plan to have dedicated tune measurement systems in both the booster and storage ring. The general layout consists of an Arbitrary Waveform Generator (AWG) exciting the beam via a kicker and a dedicated button BPM station for the measurement of the betatron tune oscillation. In order to process the BPM sgnals, the standard BPM electronics is used. The bandwidth of the digital downconverter (DDC) has to be adjusted to include the sidebands generated by the tune. The fractional tune is obtained via an FFT of the resulting signal done by the DSP board.

The actual system layout for the storage ring is the following. The position measurement is done by a separate BPM in sector 5, which is not part of the closed orbit feedback system. The BPM electronics as well as the arbitrary waveform generator is housed in a separate tune measurement rack containing also the BPM electronics and the AWG for the booster tune measurement. Since it is planned to install a fast bunch by bunch feedback system in the storage ring including fast kickers as well as power amplifiers, we are going to use these to excite the beam motion (In order to allow a betatron oscillation, the bunch by bunch feedback has to be switched off anyway, since it would suppress any transverse movements.). As for the moment, the decision on power amplifiers and kickers is still open.

The measurement part in the booster ring corresponds to that of the storge ring. A separate pickup is used with the BPM electronic installed in the tune measurement rack. For the beam excitation, a stripline kicker with only two electrodes is used. By placing the electrodes diagonally, the beam gets excited simultaneously in both, horizontal and vertical, planes. The diagnostics kicker is under construction at the moment, the same type of arbitrary wave form generator as for the storage ring will be used. A decision on the power amplifier used to drive the kicker has yet to be made.

2.8.3.6. Synchrotron Radiation (SR) Beamline

A SR port will allow to perform transverse and longitudinal profile measurements as well as emmittance and energy distribution measurements of the electron beam in the storage ring. Therefore a bending magnet beamline will be donated to electron beam diagnostics purposes, where it is planned to perform beam monitoring using x-ray optical components.

2.8.3.6.1. Transverse Profile

The most direct way to obtain information about the source size is to produce a direct image. In principle, this can be done with radiation in the visible region using standard optical set-ups. However, very brilliant sources like the SLS are diffraction-limited in the visible region, i.e. the source size and divergence angles are much bigger than in the x-ray region. In order to avoid this limitation, the source should be imaged at x-ray wavelengths. As shown in x-ray microscopy, the most efficient lenses for imaging in the soft x-ray region ($E \approx 1$ keV) are Fresnel zone plates. Two possible set-ups can be used for beam monitoring:

1. A zone plate generates a (demagnified) image of the source (see figure below). In the image plane, a small pinhole is mechanically scanned and the transmitted radiation is

detected to give the image signal. As zone plates are highly chromatic, the x-ray wavelength can be selected by changing the distance between the zone plate and the pinhole. A central stop on the zone plate blocks out zero-order radiation.

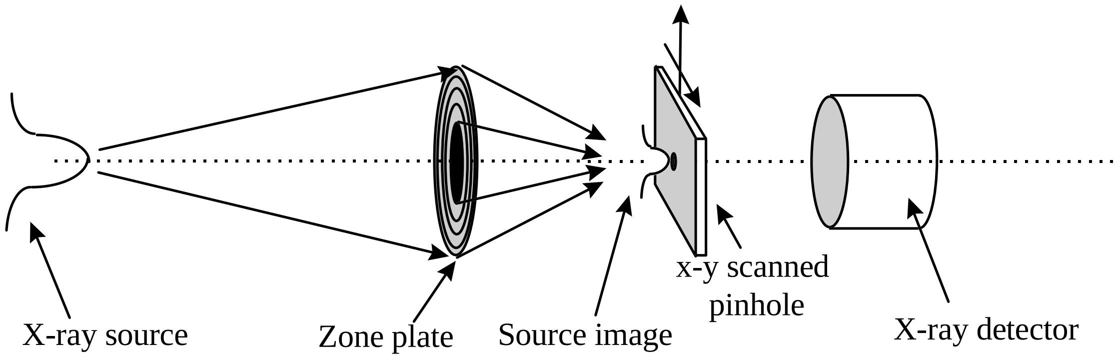

Figure 16: "Scanning type" beam monitor based on zone plate optics

2. The source image generated by a zone plate is imaged with high magnification by a second zone plate onto a imaging detector (e.g. a CCD camera). Again, the distance between the first zone plate and the pinhole selects the x-ray wavelength. The two beam monitor set-ups are in a sense analogue to the two principal set-ups used in x-ray microscopy. For beam monitoring purposes, the scanning type set-up should be preferred due to the smaller number of optical components.

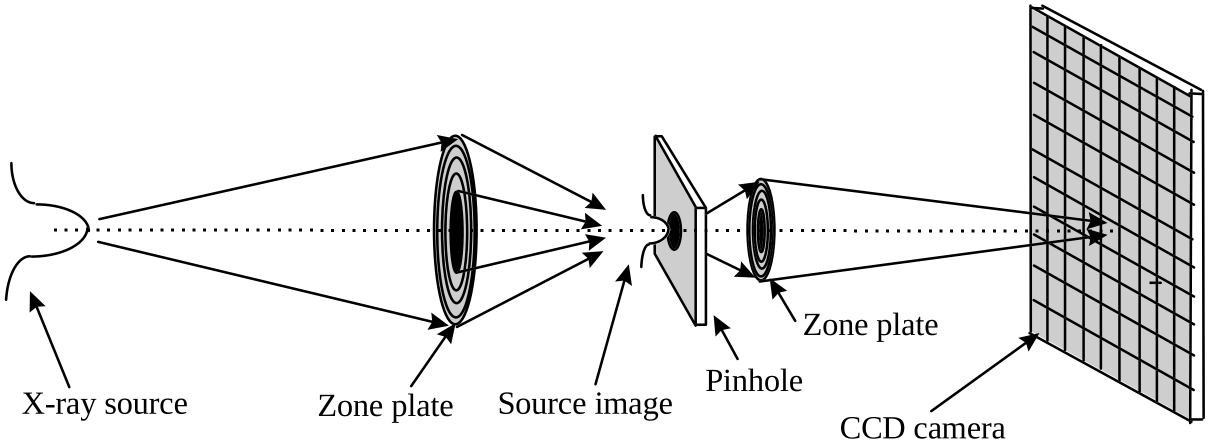

Figure 17: "Imaging type" beam monitor

The relevant technologies and know-how for the generation of the x-ray optical components are available at the Micro- and Nanostructures Lab (LMN) of PSI. This includes the manufacture of support membranes, e-beam writing of diffractive optical elements (zone plates), reactive ion etching, electroplating as well as the building of scanning probe microscopes.

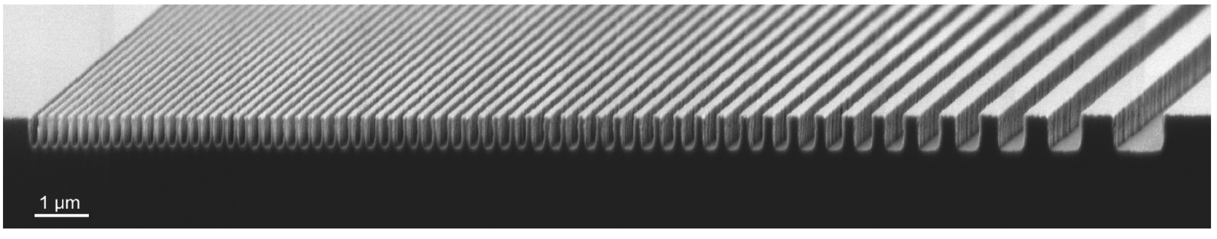

Figure 15: Silicon zone plate structures manufactured at the LMN using e-beam lithography and reactive ion etching.

2.8.3.6.2. Longitudinal Profile and Beam Instabilities

The knowledge and control of the longitudinal beam profile and its dependency on different machine parameters and settings (current, energy etc.) might be important in case of time resolved experiments. Moreover the tracking down and control of bunch to bunch instabilities is an important issue for the optimization and over all stability of the storage ring. Both longitudinal profile and bunch to bunch instabilities of the electron beam in the storage ring can be measured with visible radiation from a dedicated SR diagnostic beamline. In the SLS case of electron bunch lengths in the order of 10 ps the time resolution of photodiodes is not sufficient anymore and a streak camera system will be the appropriate device. In order to deploy the time resolution of such a streak system a proper and jitter free (sub ps) synchronization with the electron beam is essential. Therefore quite some effort has to be put in the distribution of the RF bunch clock to the optical diagnostics lab.

2.8.3.7. Beam Loss Monitors (BLM)

During commissioning of the booster synchrotron and the storage ring the monitoring of electron beam losses will be very helpful in order to determine possible machine failures and critical (hot) spots of the machine. They will also be helpful to monitor beam losses when introducing new elements and devices (like undulators etc.) in an already operational storage ring. Since the locations of beam losses cannot be foreseen and will constantly change when introducing new devices, a highly flexible system will be preferred. The Bergoz company are newly offering very compact BLMs [10], which can easily located around the storage ring. The working principle is based on two PIN-photodiodes, which are mounted face to face and coincidentally count charged particles. The coincidence measurement principle makes them insensitive to synchrotron radiation, so that the spurious counting rate is less than one count in ten seconds. The counting rates is up to 10 MHz and the dynamic range is in the order of 10^8. The output is TTL compatible and the radiation resistance is tested up to 10^8 rads.

2.8.4 References

[1] P. Piot, J.-C. Denard, P. Adderley, K. Capek and E. Feldl, *High-current cw beam profile monitors using transition radiation at CEBAF*, Proc. of the 7th workshop on beam instrumentation, Argonne 1996.

[2] C. Bovet, CERN, private communication.

[3] Bergoz Precision Beam Instrumentation, Technical Note.

[4] K.B. Unser, *Measuring bunch intensity, beam loss and bunch lifetime in LEP*, CERN/SL/90-27 (BI).

[5] J. Bergoz, private communication.

[6] See chapter about beam dynmacis in this handbook.

[7] P. Röjsel, Proc. EPAC ´94 (1994) 1557

[8] L. Farvaque, 5th Annual Workshop on European Synchrotron Light Sources (1997)

[9] Optischer Messgeber, Patentanmeldung Nr. 00562/94-0, Baumer Electric AG.

[10] Bergoz Precision Beam Instrumentation, Technical Note.