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OPTICAL BEAM DIAGNOSTICS ON PEP*

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Introduction

In designing the PEP optical diagnostics we have been able to build on the experience gained with SPEAR.[1] Most of the problems at SPEAR could be traced to the optical diagnostic system being inside the tunnel. nel. A machine shutdown is required for any maintenance or modification. This implies that in order to make such an instrument successful, a large engineering effort must be mounted to ensure 100% operation at startup. The functions that do not work at startup may never be made to work; this has happened at several machines. Experimental setups are likewise risky and time consuming.

A point which has been borne out in both SPEAR and PEP is that the mechanical part of the instrument, the special vacuum chamber, the optical mounts, the alignment and adjustments, require approximately 60% of the effort and cost of the optical diagnostics. It is far better to economize on detectors and electronics than on mechanical and optical essentials.

Vacuum Chamber[2]

The two PEP primary mirrors, one each for e^+ and e^-, are of pure Be, flat and optically polished, clamped to water-cooled mounts on the chamber wall. The mirrors share one chamber at one arc symmetry point. A slot 5 mm high cuts through both at the beam median plane to allow the powerful small angle x-ray flux to pass through without heating the mirrors, for good closed orbits. The design of the mirrors is thus conservative: Be mirrors can withstand the radiation from a maximum beam without permanent deformation,[1] but under normal operating conditions they see very little thermal load.

Alignment of mirrors is done in the vacuum laboratory during final assembly. Since the (Be) mirrors are closely (optically) followed by adjustable mirrors, the alignment tolerance is 10^{-2} radian on two axes. The mirrors have no adjustments outside the chamber.

The exit ports are synthetic fused quartz† discs, 13 mm thick, 15 cm diameter, sealed to flanges through glass grades. System aperture at this point is determined by the Be mirrors, whose elliptical surface defines a 6.4 cm diameter circle. The excess diameter of the ports allows for optical distortion at the edges due to the sealing process. To improve the RF impedance of the chamber, a fine BeCu screen shields the exit port.

Vibration is a serious concern in this system since the source, the beam, is 6 m from the first optical element, the Be mirror. A tolerance of 50 μm for vibration-induced image degradation gives an angular vibration limit of 10^{-5} radian. Detailed studies[2] showed the major source of vibration to be the mirror water cooling. The chamber design is heavy and solid to minimize vibration: 500 Kg of sand in the chamber support stand also serves as a damping mass.

Two chambers on each side of the mirror chamber need special design to allow horizontal (7×10^{-3}) and vertical (3×10^{-3}) aperture for the visible synchrotron light. This is in contrast with SPEAR in which only mirror chambers were required. The difference lies in the ratio of beam stay-clear diameters to magnet bending radii in the two rings.

Optics§

The vertical opening angle for visible (600 nm) synchrotron light is 2.4×10^{-3} radian FWHM in PEP at all energies. The ultimate resolution limit (Table 1)

Table 1. Parameters List, E = 15 GeV

Vertical opening angle of light, λ = 600 nm	2.4×10^{-3} radian FWHM
Instrument angular aperture	3×10^{-3} radian vertical 7×10^{-3} radian horizontal
Visible light power 400 nm to 800 nm	5.3×10^{-6} watts/mA (beam) × m radian (horizontal angle)
Vertical resolution limit,[a] diffraction limited, at 600 nm full width ½ maximum	220 μm
Angle between line of sight & line of emission points[b]	arc tan 21.5
Distance from beam point to first (Be) mirror	6.17 m
Lattice function values at optical monitor	β_x = 19.2 m β_y = 17.70 m η_x = 1.13 m
Bending radius at beam point	165.5 m

[a] details to be published in a future PEP note.
[b] see references 1 and 3.

of a visible light optical monitor is set by this opening angle. The resolution is degraded by geometric effects[1,3] involving the beam size, the horizontal aperture of the instrument and orbit shifts.

The ultimate resolution at 600 nm is 220 μm FWHM. The horizontal beam size (5 mm) increases this to 230 μm and using the full horizontal aperture of the instrument (7×10^{-3} radian) increases it to 600 μm. Orbit shifts not greater than ±3 mm do not require focus correction, although this capability exists in the instrument. The horizontal field must be stopped down to $.5 \times 10^{-3}$ radian to utilize the full resolution of the system.

The criterion that all the optical elements possible are to be accessible during beam operation puts the first focussing element 23 m from the light source. To achieve an overall magnification ≃1 in a limited space, we use a Newtonian reflecting telescope with an "eye-piece" magnifier (Fig. 1). The specified field of view of the telescope is 40 mm diameter circle at 20 m, an angular field of 2×10^{-3} radian, but the field within which high resolution is needed is 1×10^{-4} radian. This is well within the "good" field of a spherical reflector,[4] even when the prime image is magnified. Careful collimation of the spherical reflectors is, of course, required.

At the bottom of the 10 m long 61 cm diameter vertical shaft leading up to the optics building, 1.5 m from the exit port on the vacuum chamber, is a 15 cm diameter circular plane mirror on a 2-axis, remote-controlled, angular-variable mount. This adjustment brings the synchrotron light straight up the long shaft and constitutes the prime alignment of the system.

At the top of the shaft a plane mirror brings the light into a horizontal (normal to gravity) plane, and

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† Dynasil 1000. This material has excellent resistance to radiation darkening.

§ One system only is discussed. All of the description applies to both except where noted.

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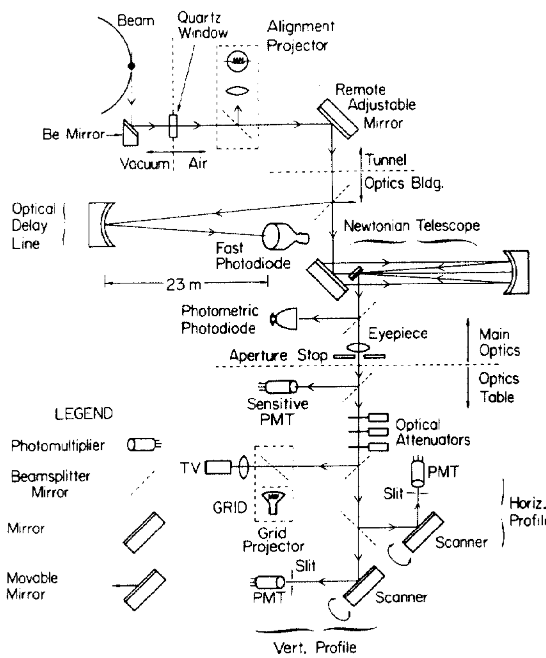

Fig. 1. Schematic of one side, e^-, of optical monitors. Bunch length measurement exists only on the e^- side.

into the Newtonian telescope. The aerial, M = 1, image is formed in the same plane over the surface of a 1.5 × 2.4 m laboratory optical table.* All the optical components comprising the detector system are bolted to the table's flat surface in the style of optical research set-ups.

An aperture stop is used in the horizontal plane only. Two independently adjustable blades define the horizontal aperture at the eyepiece lens of the telescope.

The optics building is 10 × 10 m, and contains the telescopes, detector electronics, the optical table, work and storage space. The optical system from the vacuum chamber to the telescope eyepiece is sealed and airtight. The optical table has a dustproof light-tight enclosure.

Detectors

Injection Photomultiplier

A 14-stage photomultiplier sees the entire field of view of the telescope through a 10% pellicle† beam-splitter. The direct signals, stretched electronically and viewed directly on an oscilloscope, are very useful during first injection into a newly set-up ring.

Photometric Beam Current Measurement[1]

The light from the whole field, via a 10% beam-splitter, is brought onto the surface of a 25 mm diameter Si photodiode, operated in the photovoltaic mode to eliminate dark current. The current is amplified, filtered and read by a digital voltmeter into the CAMAC system. A CAMAC-controlled shutter in front of the diode is used to set zero. A CRT display showing current as a function of time, lifetime and fill rate is a primary diagnostic.

Bunch-by-Bunch Photometric Measurement

As above, but a fast, biased Si photodiode is used, followed by fast amplifiers and single-pass A/D conversion. This allows measurement of the current in the three separate bunches per beam.

Television

A 10% beamsplitter leads to an arrangement of lenses, grid projector and TV camera which produces a head-on image of the beam mixed with a dimension grid (Fig. 1). The camera used is a commercial vidicon type. Attenuating filters controlled from the machine console in a 1, 3, 10 sequence are upstream of the TV camera. The center of the dimension grid is used operationally as the reference center for the beam in the entire instrument.

Quantitative Profile Measurement

The stored beams have two-fold symmetry about perpendicular axes. Two slit or line scans completely define the beam density distribution. Out of a variety of scanning methods possible, the PEP monitors use mechanical scanning of the images across slits followed by photomultiplier intensity detectors.

The slits and photomultipliers are stationary, the images being angle-scanned by servo-corrected electromechanical scanners.§ The sweep width, rate and center position can be adjusted, since the scanners have a linear response in angle of .3 radian full width with a frequency response starting at DC and rolling off above 100 Hz. The scanners can be stopped so that a chosen position on the beam image is fixed over the slit, and the photodetector signal studied via an oscilloscope, spectrum analyzer, etc.

PEP's three bunches per beam are separated by 2.5 μs, the time resolution of the scanner PMT's is 2 ns. The pulse train coming out of a scanner detector contains three time multiplexed profiles, which are demultiplexed and stretched with gated sample-and-hold circuits. Either one of the three bunch profiles is selected and displayed, or all three are summed for display.

To avoid detector saturation, attenuating filters are put upstream of the scanner devices. These are the same filters which level the light for the television cameras. The vertical profile slit can be tilted in angle under remote control to compensate for beam tilt.

Bunch Length Measurement

The synchrotron light is modulated with the electron bunch length information.[5] The fast photodiode used is the same one used at SPEAR.[6] A major technical problem is the stable triggering of the sampling oscilloscope which looks at the photodiode signal. At PETRA[7] this has been solved with a precise electronic countdown of the ring radio frequency.

Although a signal derived from a pickup electrode provides a very stable trigger, approximately coincident with the first arrival of the synchrotron light pulse, a sampling oscilloscope requires a ≃ 100 ns pretrigger. We delay the light pulse by deflecting it into a 23 m in length section of 60 cm steel pipe buried in the earth adjacent to the optics building, reflecting it back into the photodetector. A remote controlled optical delay of 300 ps can be inserted for time calibration.

The trigger is put in coincidence with machine triggers to select one of three bunches. The bunch signal is stable and reproducible.

Test, Alignment and Calibration

The Be mirror and the quartz windows were tested by standard optical methods. The windows, which gave less than λ/4 distortion before being fused into the glass grades, were distorted as much as 2λ in the worst case.

The optical system was tested *in situ* in the ring. The mirror vacuum chamber was installed and aligned with chambers removed through the first adjacent bend

* By Newport Research Corporation.
† Thin plastic film stretched over a lapped frame.[1]

§ Manufactured by General Scanning Corporation.

magnet. Temporary windows on the ends of the vacuum chamber kept it clean through the optical tests. Using sources and targets positioned at the emission point in the bend magnets, the plane reflecting mirrors and focussing elements were aligned. The system magnification and resolution were defined with white and filtered white light. The results showed system resolution much smaller than the synchrotron light diffraction limit.

Startup, Operation and Modifications

In the first days of PEP operation, the full aperture photomultipliers provided one of the chief clues to the progress of beam storage. They have served the function of first-used machine diagnostic since and their function is so necessary that we intend to move them into the tunnel, where they will be unaffected by any possible misalignment problem.

As soon as beam was stored, the television cameras came into use. The effective field of view on screen, based on predicted orbit corrections, was 15 mm × 15 mm. From day-to-day, the beam spot was completely off the TV camera. We finally realized that this was due to very large local orbit distortions, and remote control alignment of the system to keep the image centered has been added.

Beam current measurement is essential in studying injection rates and beam lifetime. The photometric system exhibited extreme sensitivity to orbit changes, this being traced to its position on the optical table downstream of numerous apertures. A move upstream to a point within the telescope near the prime focus has greatly improved the stability of current measurement, especially for the case of topping up a stored beam, a situation in which the photomultiplier is not usable. The short term stability of current measurement has reached 1×10^{-3} with a filtering time constant of 1 s.

When the optical system is out of focus, two beam images appear. This is due to the slot in the primary (Be) mirror. This effect is useful for focussing the image in the same manner as a split-image range finder on a camera. If the telescope is seriously miscollimated, the two images can appear quite different, even having different tilts. The slot passes enough visible synchrotron light power to cause errors in the photometric beam-current measurement system due to vertical orbit shifts.

The smallest vertical profile yet observed is 750 μm FWHM, much larger than the theoretical minimum of 230 μm. Systematic work remains to be done to separate the contributions to the measured profile size from optical and beam effects.

The long lever arms and the large number of adjustable components make the alignment of the system critical and easy to upset. An internal alignment system has been added which projects the image of a reticle through the whole system, for both e^+ and e^-, into all detectors. This lets us adjust and modify the system during beam-off times without having to fear a misaligned instrument at startup.

The air column in the 10-m vertical shaft connecting the tunnel with the optics building can be unstable, although there is no through motion of air. The image of the beam has been observed to scintillate as much as 100 μm after the air seal has been broken and the air in the shaft is not in equilibrium. This is generally not a serious problem, but corrective measures are under study, including a slow, laminar motion of air through the shaft.

Control and Interface

Most critical functions, e.g., attenuating filters, scanned beam profile, are hard-wired to PEP control, approximately 200 m from the optics building. Photometric beam current readings are taken at the building, feeding to a CAMAC branch connected to the PEP central computer.[8]

The profile scanners, controlled by an input voltage, are computer-driven via a CAMAC D/A channel. The voltage levels corresponding to light intensity on the profile are similarly read back to the computer. The selection of separate bunches can be computer-controlled, as can various shutters to set baselines. Centering the beams on the scan is simple, since a beam centered on the television camera crosshairs is centered on the scan.

The sampling oscilloscope used for bunch length measurement is in the optics building, physically close to the fast photodiode. The low-frequency horizontal and vertical output signals from the oscilloscope are sent over analog channels to PEP control for routine display.

Conclusions

Building the diagnostic system out of the tunnel has been worth the effort. Modifications have been made on almost all systems, and a completely new system, the bunch-by-bunch current measurement, has been developed during physics running on PEP. New detectors, CCD-scanned photodiode arrays, have been tested and installed by others on the optical table, and machine physics experimenters have used the optics building as a laboratory.

The ultimate vertical resolution of the instrument is just at the limit of being useful for overall machine coupling studies. For higher resolution on a machine of the same size, one must use ultraviolet optics or x-ray devices[9] such as the one now installed on PEP. For machines with larger radii of curvature, such systems are absolutely necessary.

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