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Superharp – A wire scanner with absolute position readout for beam energy measurement at CEBAF

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Abstract

The CEBAF superharp is an upgraded beam wire scanner which provides absolute beam position readout using a shaft encoder. Superharps allow for high precision measurements of the beam's profile and position ($\Delta x \sim 10\ \mu m$). The Hall C endstation at CEBAF will use three pairs of superharps to perform beam energy measurements with 10^{-3} accuracy. The three pairs are installed at the beginning, the mid-point and the end of the Hall C arc beamline. Using superharps in conjunction with a dual sensor system: the direct current pick-up and the bremsstrahlung detectors, beam profile measurements can be obtained over a wide beam current range of $1 \sim 200\ \mu A$.

1. Introduction

The Hall C arc beamline will be used as a spectrometer for absolute beam energy determination proposed in Refs. [1-4]. The following formula is used to determine the beam momentum:

$$p = \frac{e}{\Theta}\int B\, dl ,$$

where $\int B\, dl$ is the magnetic field integral over the path of the electron beam and Θ is the bending angle through which the electron beam is deflected. Taking e as a constant, this leads to the uncertainty relation:

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta \int B\, dl}{\int B\, dl}\right)^2 + \left(\frac{\Delta\Theta}{\Theta}\right)^2} .$$

$\int B\, dl$ is determined by mapping bending magnets absolutely using a combination of NMR and Hall probes. The bending angle θ is determined by the relative orientation between two vectors; the incoming beam and the outgoing beam. The power supply current to the arc dipole magnets is varied such that the beam is centered at the end of the arc. All non-dipole magnets (quadrupoles, sextupoles and beam correctors) are set to zero field integral.

The positions and the directions of the beam at the beginning, the mid-point and the end of the arc spectrometer are measured by three pairs of superharps. For each superharp scan, the resulting histogram peak centroids are computed using the equation: $x_{centroid} = \Sigma n_i x_i / \Sigma n_i$.

2. Modification of CEBAF harp

The mechanism and test results of the superharp prototype are described in Ref. [5]. The superharp system differs from the original CEBAF harp in the following way: absolute position readout electronics, dual beam profile detection system (current pick-up and bremsstrahlung detection) and a vibration-free support system.

2.1. Position transducer

The superharp's absolute position is determined using a rotary encoder. The linear movement of the superharp wire is translated into rotary motion via a screw thread rod. The measured value is derived directly from the pattern of the graduated disk, and each position is assigned a permanent, non-volatile value. An electromagnetic rotary encoder is able to operate in high radiation environments.

The MR-90 multi-turn shaft resolver (a product of Computer Conversion Corporation) was selected. The specification of the MR-90 shaft encoder is listed in Table 1. The shaft of the MR-90 encoder is mechanically connected to the shaft of the driving stepper motor (SLO-SYN M063-LF-401).

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Table 1
Parameters of HTMDS90 encoder

Input	64 turn NEMA 12 transducer
Turns for full counts	64
Counts per turn	2^{12} (65536)
Repeatability	± 1 LSB
Accuracy	$\pm 1.526 \times 10^{-5}$ ± 1 part in 65 536
Angle data output	Parallel binary, 18 bit resolution, TTL compatible
Inhibit/enable	Active low input
Converter busy	Positive pulse, 0.5–1.5 μs duration
Analog output	± 10V dc at maximum tracking rate

A tracking multi-turn encoder system consists of a multi-turn transducer (two geared resolvers), a reference generator, a fine and coarse converter, a digital combiner and interfacing circuitry. The reference generator produces a precision ac voltage signal which is used as a reference of the transducer. The transducers (resolvers) give a line to line voltage signal equal to the sine and cosine of the fine and coarse resolvers of the transducer. These signals are then digitized and fed into the digital combiner which removes the amplitudes and gearing errors.

To match the capability of a 16-bit PC computer, the intermediate 16 bit of 18 bit encoder output is used to transfer position data (the most significant and least significant bits are discarded). The basic parameters of the superharp moving mechanism are shown in Table 2. The 16 bit accuracy translates to a linear resolution of 1.24 μm.

To avoid wrap around of the 16 bit encoder output, the mechanical linkage between the encoder and the stepper motor drive shaft is configured such that the linear motion of the harp (defined by limit switches at each end) translates to an encoder readout in the range of 256–65800.

2.2. Improvement of electronics

The original preamplifier used by the harp system is based on an isolation amplifier which decouples the input electrode from the output for better noise rejection. There is still a severe noise problem caused by the switching of the stepper motor's drive frequency whenever the harp is moving. Sometimes the interference is so great that it completely masks out the beam profile during a harp scan. Even though a fast Fourier transformation can be used to separate beam profile from noise background in a time domain [6], a preferred solution is to reduce the noise using harp electronics.

Table 2
Parameters of superharp motion with 16 bit encoder readout

Pitch of lead screw	2.54 mm
Distance between two limit switches	~3 in.
Microsteps per revolution	51 200
Microsteps per 16 bit count	25
Position resolution (per 16 bit count)	1.240234 μm

The superharp system has replaced the isolation amplifier with an AD549 electrometer amplifier with extra high input impedance and extra low offset current characteristics. The amplifier with differential inputs has very high CMRR (common mode rejection rate) which effectively reduces the high frequency noise picked up by electrode wire.

The superharp preamplifier output is sent to a DSP Model 1008 eight channel programmable signal conditioner, which is packaged in a single width CAMAC module. The differential input amplifiers in this unit provide gains from 1 to 1024. The DSP 1008 is well suited to the transmission of the signal through a long length of cable in a very noisy environment, because of its good common mode rejection rate up to 100 dB with noise values of less than 2 μV V_{p-p}.

2.3. Study on vibration sources

In order to study wire vibration caused by different sources, a microscope video camera was temporarily mounted on the superharp fork carriage. The camera viewed the superharp wires and displayed the wire image on a closed circuit monitor. The wire size itself was used as the reference scale when measuring the vibration amplitude.

When the superharp fork was moved into and out of the beam pipe over its full operating range of three inches no vibration was observed. Therefore the superharp moving mechanism (stepper motor, lead screw, and Thomson rods) do not cause wire vibration.

Wire vibrations with amplitudes larger than 10 μm are generated by ground motion (local traffic and nearby railroad activity) and adjacent mechanical noise sources (for example, cooling water flow, vibration of mechanical pumps). To achieve accuracy of beam position measurements, wire vibration must be suppressed by not only optimizing the harp configuration, but also effectively damping all possible external vibrations.

A pair of accelerometers (L-10A, horizontal sensor and vertical sensor, Martin products, Ltd.) were used to measure the local ground motion amplitude at different locations within CEBAF. The calibrated voltage output of the accelerometers is 0.79 V/(inch/second) on a 75 Ω terminal resistor. Table 3 gives the

Table 3
Vertical and horizontal components of velocity of ground motion in site measured by accelerometer

Location	Subject	v_v (μm/s)	v_h (μm/s)
EEL 122	10′ × 4′ steel optical bench	3.5	7
EEL 126	6′ × 4′ granite table with full load	10.0	14
EEL Hall	8′ × 4′ granite table without load	11	7
Injector	QD0L09 girder with running water	14	17.8

measurement results (the output amplitude has been converted into μm/s).

2.4. Improvement of support mechanism

In order to dampen vibrations from external sources, a heavy granite table is used to support the superharps instead of the standard aluminum beam line girder. The installation of granite tables in the Hall C beam line was found to reduce the vibration amplitude by a factor of five. The superharps on the granite table are vibrationally decoupled from the other beam line elements with bellows.

2.5. Mechanical configuration of the fork

A further improvement was made on the fork's mechanical configuration. A balsa wood fork is used instead of the original aluminum because its resonance frequency is much higher. The weight of the balsa fork is 1.7 g, less than the corresponding aluminum fork. The balsa fork is also more rigid because of its anisotropic fiber structure.

During wire assembly the balsa fork is clamped in an aluminum fixture. Dowel pins are secured to the fork, and the superharp wire is strung between them. The wire is tensioned by hanging a weight to it while it is glued into place with TorrSeal. Correct tensioning of the wire is critical to prevent wire sagging during beam scans when the wire is significantly heated by the beam.

Balsa forks are pre-conditioned in a vacuum bell jar evacuated with a pump. After the sensor wire is mounted, the fork is kept in the bell jar to avoid environmental humidity. No outgassing problems were found using thoroughly dried, carefully stored superharp forks during prototype beam testing experiments in December 1993 and Hall C beam line operations in July 1994. During a beam line surveying process, the forks stayed in the air for two weeks, and no distortions of the balsa forks were found.

The wire orientation was verified and adjusted using an optical comparator (Jones and Lawson, Coordinate Measuring Machine). On the optical comparator the fork image was enlarged by a magnification factor of 10 and displayed on the goniometric optical screen. The angular accuracy of wire orientation was determined to be within ±0.1° at 45° tilt angle.

2.6. Survey on superharps

Using surveying equipment, the center of the beam pipe was determined. While sighting along the pipe's central axis, the superharp was moved until the wire was centered with respect to the beam pipe. The encoder value was read and recorded as the 'zero' position. The 'zero' position is then used as an absolute reference coordinate and the beam centroid positions at different locations along the arc spectrometer are measured in this coordinate system. After surveying individual superharps, the superharps were mounted in pairs on their granite tables as shown in Fig. 1. The alignment was then performed between superharp pairs.

The individual superharp fiducialization error is estimated to be 50 μm (95% confidence level, $\sim 4\sigma$). The superharp to superharp survey error is 100 μm [7]. There is a slight difference between survey errors in air and under vacuum, because the backlash of the transmission screw vanishes in vacuum under the single direction force generated by the outside air pressure.

3. Experimental test of superharp prototype

The first superharp prototype was tested at the CEBAF accelerator injector with a low energy electron beam. The purpose of this experiment was to: (a) verify normal operation of the superharp prototype using absolute position encoder as the position sensor; (b) improve the current sensitivity and broaden the current dynamic range from 1 μA to 100 μA; (c) improve the signal to noise ratio. Two analog signal pick-up channels—the direct current pick-up by wire electrode and the bremsstrahlung detection—are independently used to determine beam profile.

3.1. Experimental apparatus

The superharp prototype was located on the girder OL09 in the CEBAF accelerator injector section. Two parallel tungsten wired with different diameters (10 and 22 μm) were mounted on the balsa fork for observation of vertical beam profiles with different current sensitivity. A beam loss monitor was installed 1 m downstream of the superharp for radiation profile measurement.

A beam viewer was installed on girder OL08, 20 ft

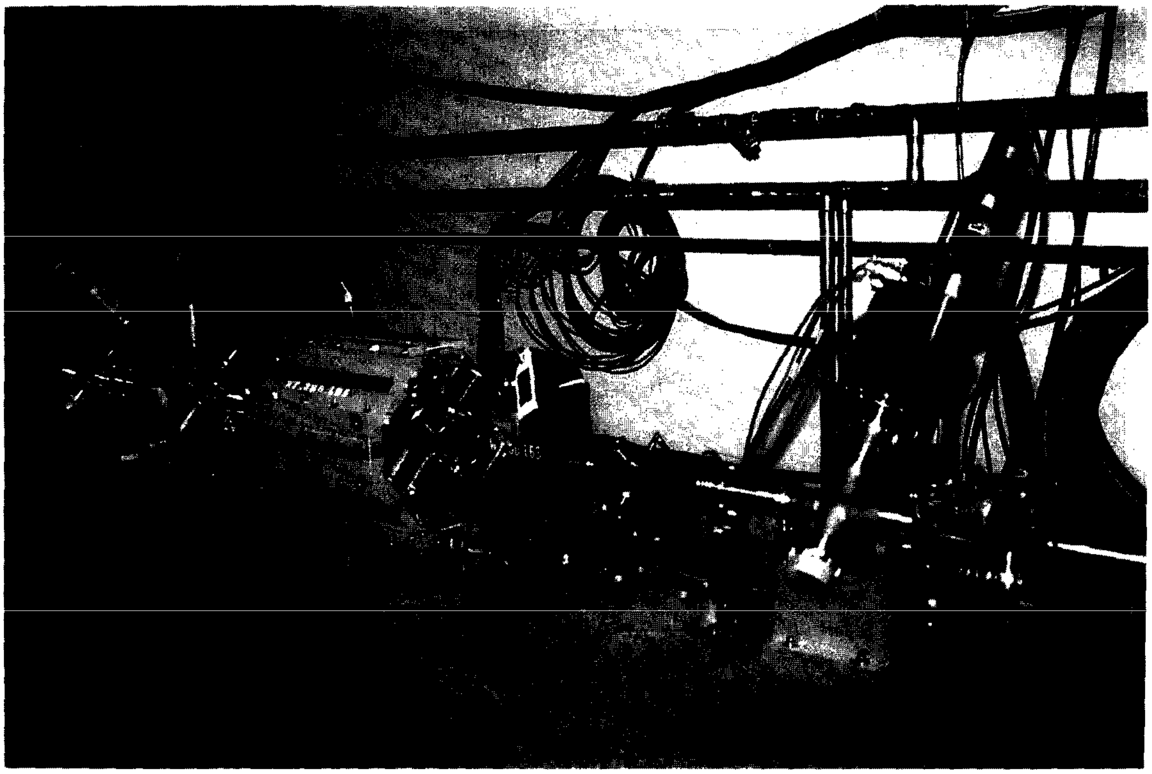

Fig. 1. The 5th and 6th superharps were permanently installed on the third granite table at the end of the Hall C arc beam line. The distance between them is 188 cm. The other two paris of superharps were installed on similar granite tables at the beginning and the mid-point of the arc line.

upstream from the superharp and a regular CEBAF harp was positioned on girder OL10, 20 ft downstream. A block diagram of the electronics used in tests is shown in Fig. 2. The beam energy at the CEBAF injector was 45 MeV, the duty factor was 7.5×10^{-3}, the pulse width was 125 μs, and the pulse beam frequency was 60 Hz. During the experiment, the peak beam current was tuned from 1 μA to 115 μA.

3.2. Radiation profile pick-up

The radiation in the vicinity of a superharp wire as it is scanned through an electron beam is entirely dominated by bremsstrahlung X- or gamma-rays produced in the target wire. The local dose rate is a function of the emission angle, wire diameter and the presence of surrounding material. The dose rate at any radiation detector located 1 m downstream from a superharp and at a 30° emission angle is given by the formula [8]:

$$D = 2700\sqrt{E}\theta^{-1.5}\ \mathrm{Gy\,h^{-1}\,kW^{-1}},$$

where E is the electron energy in MeV, θ is the emission angle in degree and Gy = 100 Rad. When a 45 MeV 1 μA electron beam is scanned by the superharp, the beam power loss in the wire is about 1.08 μW [9] which corresponds to a radiation dosage of approximately 112 μrad per hour at the superharp's beam loss monitor.

The standard CEBAF beam loss monitor (Hamamatsu 931B side-on photomultiplier with plastic enclosure) is used as the bremsstrahlung radiation detector. No external scintillator is required for the beam loss monitor since the photomultiplier's glass envelope generates sufficient scintillation and Čherenkov radiation to produce a radiation signal.

When an electron beam collides with a metal wire, the primary radiation, the Bremsstrahlung X-ray is produced. With increasing electron energy the following secondary emissions take place: electron–positron pair (electromagnetic shower) and photonuclear interaction (photo-neutrons, neutron–proton pair, photo pion, muon pair). When the CEBAF electron beam energy increases from 45 MeV to 4 GeV, the dose rate increases by a factor of three, with strong forward angle emissions. Therefore, one beam loss monitor positioned downstream can be shared between two superharps operating independently.

The beam loss monitor signal processing is per-

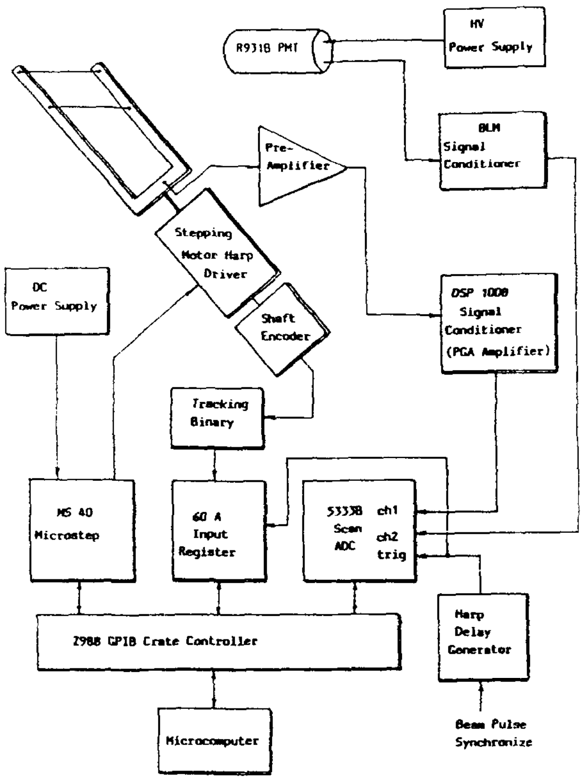

Fig. 2. The block diagram of the superharp prototype electronics.

formed by a separate card located in the BLM controller module. Signal processing can operate in one of two modes; linear or logarithmic. For superharp radiation signals, the logarithmic mode was chosen, because it covers a wide dynamic range (eleven decades). The logarithmic mode is also especially useful for extracting low amplitude signals from the noisy background. For both modes the input signal produces an output analog voltage in the range 0-5 V which is passed onto the data acquisition system's ADC.

3.3. Experimental beam profiles

A series of beam profiles were obtained during the beam testing at different beam currents from 1 to 125 μA. Each profile plot consists of a current profile (upper) and a Bremsstrahlung profile (lower) both with the same beam position coordinate. Two peaks, corresponding to 10 and 22 μm wires are displayed in the beam profile plots.

Fig. 3 shows a dual beam profile for a beam current of 1 μA. In the upper plot, the current profile has an average signal to noise (S/N) ratio of about 1.04 for the 10 μm wire, and 1.44 for the 22 μm wire. This was greatly improved by the Bremsstrahlung radiation profile, as can be seen in the lower plot. Here the S/N

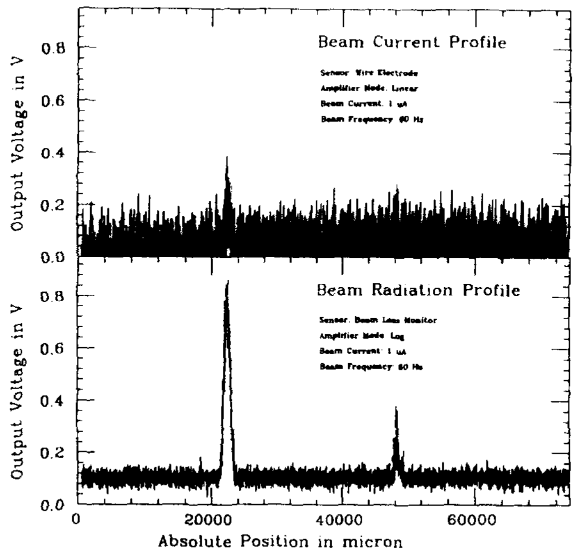

Fig. 3. The current profile (upper) and the Bremsstrahlung profile (lower) produced by the superharp prototype for a 45 MeV 1 μA electron beam.

ratio is 3.14 for the 10 μm wire, 6.57 for the 22 μm wire.

The dual profile for the 25 μA beam is shown in Fig. 4. The current profile keeps a linear response, while the top of the Bremsstrahlung peak shows distortion due to the logarithmic signal processing.

From the experimental results, several technical points can be summarized:

(1) The Bremsstrahlung beam profile has a higher

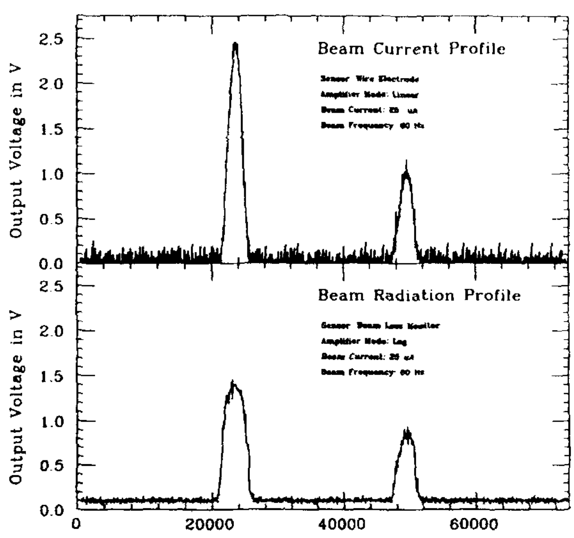

Fig. 4. The current profile (upper) and the Bremsstraglung profile (lower produced by the superharp prototype for a 45 MeV 25 μA electron beam.

sensitivity compared with the current pick-up at low beam current, specially below 5 μA (beam energy 45 MeV).

(2) One beam loss monitor can be used as a common Bremsstrahlung profile pick-up sensor for two upstream superharps when the beam energy is in the GeV range, because of the enhanced forward angle radiation.

(3) To prevent saturation effect of the beam loss monitor, the distance between the BLM and its superharps should be increased to 200–300 cm. In addition, the emission angle can be set greater than 30° at higher beam energies to offset higher radiation levels. The bias of the Hamamatzu photomultiplier may also be remotely adjusted to give the optimum response.

(4) The linear current beam profile channel provides a non-distorted beam profile, which has higher accuracy when used to determine the center of mass of beam profile peaks. The center of mass values provides a measurement of the beam position.

(5) 22 μm diameter tungsten wire was selected as the sensor wire because of its good balance between sensitivity and position resolution.

4. Superharps installation

Following the successful commissioning of the superharp prototype in December 1993, eight superharps were installed in the Hall C beam line in July 1994. Six were installed in the beam switchyard arc section for the purpose of beam energy measurements which are to start late in 1995. The other two were installed immediately in front of the Hall C target chamber to allow beam incident angle and beam emittance measurements on the target.

All eight superharps are monitored and controlled by the Experimental Physics and Industrial Control System (EPICS) instead of prototype PC-based data aquisition system. The entire superharp system was successfully tested during July, October and December runs in 1994. At the time of writing, the system is completely calibrated and ready for beam energy measurements.

5. Position error analysis

To test the repeatability of the motion of the superharp, a microscope video camera was securely mounted onto a granite superharp table such that it was possible to view the superharp wires. The superharp was then repeatedly driven through its entire motion range (three inches), and the encoder reading at the camera position was recorded. Possible errors which may effect position repeatability include: backlash by the driving screw, error in the encoder readout and position uncertainty due to variation in wire size. The repeatability of wire motion is experimentally found to be better than 10 μm.

Table 4
Position error sources analysis

Classified error source	Figures (μm)
Mechanical error:	
Uncertainty due to wire size	2
Backlash of transmission screw	10
Encoder resolution	1.24
Wire vibration	2
Body deformation (long term)	5
Wire deformation (long term)	5
Angular misalignment of wire	4
Total (Repeatability)	13
Survey error:	
Harp fiducialization error	50

For beam energy measurements the absolute beam position is derived from superharp profile scans. The absolute beam position accuracy from an individual superharp profile measurement is required to be better than 50 μm, which is equivalent to a 3×10^{-5} contribution to the absolute energy error.

Wire position accuracy is determined by several factors: survey error, the finite sensor wire size, transmission backlash and the sensor wire looseness.

For a 100 μm electron beam size and a 22 μm diameter wire, the wire size error is not significant. Backlash of the transmission screw is a major contribution to position error. The backlash is estimated to be no larger than 10 μm for a 2.54 mm pitch lead screw. In vacuum the nut plate experiences a force in a single direction and the backlash entirely vanishes.

The sensor wire becomes loose if there is a deformation of the balsa fork. All balsa materials and forks were pre-vacuum treated and stored under vacuum. After calibration and installation no fork deformation was observed. The sensor wire is constantly under tension, and the wire deformation is less than 5 μm.

A complete list of error sources is shown in Table 4.

6. Evaluation of the present superharp system

The performance of the CEBAF superharp system meets the requirements for a 10^{-3} beam energy measurement. The position accuracy is better than 20 μm.

The existing stepper motor driving system may be replaced with simpler systems such as air cylinders or linear motors, because the instantaneous position readout is only determined by the encoder and is independent of the driving mechanism.

To avoid any possible slippage in the mechanical coupling between the stepper motor drive shaft and the encoder it may be necessary to replace the rotary encoder by a linear encoder which is attached to the superharp drive plate. An optical linear encoder can provide submicron accuracy over an operational range of 1000 mm.

The beam loss monitor may be used as the only beam profile detection sensor, eliminating the need for a current pick-up sensor from the scanning wire. This is possible, because the BLM conditioner can be operated in both logarithmic and linear modes. The Hamamatsu 931B photomultiplier tube may be replaced with another model, providing higher sensitivity and wide dynamic range (for example the 12 dynodes 30 mm diameter head-on FEU-115M). BLMs may also be optimized by adjusting the distance to the superharp wire, their applied bias and the gain of their signal conditioners.

The wire holding system and wire survey procedure need to be simplified to meet the requirement of fast wire replacement over a one to two year period. Experience from SLC indicates that about 90% of their 40 μm diameter wires have broken during routing use.

Acknowledgements

We take this opportunity to thank the engineering and technical staffs of CEBAF for their hard work in the design and construction of the superharp system. We also appreciate the importance of the skill and the efforts of the operations crews of the CEBAF machine control group to the successes of the superharp experiment.

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