**Superharp - A Wire Scanner
with Absolute Position Readout
for Beam Energy Measurement at CEBAF**

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Figure 2: The conjunction part between stepper motor and shaft encoder

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	$\pm 1.526 \times 10^{-5}$
Angle data output	Parallel binary, 18 bit resolution, TTL compatible
Inhibit/enable	Active low input
Converter busy	Positive pulse, 0.5 to 1.5 μ s duration
Analog output	± 10 V DC at maximum tracking rate

Table 2: Parameters of superharp motion with 16 bit encoder readout

Pitch of lead screw	2.54 mm
Distance between two limit switches	~ 3 inch
Microsteps per revolution	51200
Microsteps per 16 bit count	25
Position resolution (per 16 bit count)	$1.240234 \mu\text{m}$

Figure 3: Block diagram of tracking multi-turn shaft resolver

nal equal to the sine and cosine of the fine and coarse resolvers of the transducer. These signals are then converted to digital by the converters which are fed into the digital combiner which removes the amplitudes and gearing errors.

The Table 1 gives major performance of HTMDS90-64-DB18-1P tracking multi-turn encoder.

To match capability of PC computer, the intermediate 16 bit of 18 bit of the tracking encoder is used to transfer position data and the highest and the lowest bits are eliminated. The basic parameters of superharp moving mechanism are shown in table 2.

16 bit position accuracy is equal to a $1.24 \mu\text{m}$ resolving power of translation motion of shaft encoder, it is good enough for required position measurement precision (better than $10 \mu\text{m}$). To avoid from wrap around of 16 bit encoder readout in a 18 bit motion range, the offset (the readout range of 16 bit, which corresponds to the distance between two position limit switches plus harp deacceleration distance after position limit switch is hit) of each encoder has been pre-adjusted to ensure that the reading is between 256 - 65800. Encoder tracking unit uses positive logic, the input register uses negative logic. A logic level conversion should be made by software when data signals from encoder tracking unit (positive logic) are transmitted into 60A input register (negative logic) to keep a complementary output which indicates the realistic motion.

Because the translation of the wire is generated by the rotation of stepping motor through a rotary axes, the backlash of the transmission screw makes the major contribu-

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tion to the error of the position readout. This will be discussed in error analysis.

2.2 Improvement of electronics

The configuration of original preamplifier is based on the isolation amplifier which is used to isolate electrode input and the output for better noise rejection. There is still a severe noise problem caused by switching frequency of stepper motor current driver whenever the harp is moving or stopped and high frequency noise generated by wire electrode antenna as common mode rejection rate is pretty poor. Sometimes, the profile output is entirely modulated by the noise interference. Even though a fast Fourier transformation can be used to separate beam profile from noise background in a time domain [7], but the basic solution should be put on electronics itself.

Low frequency noise is straight forward contributed by switching frequency of the current driver of stepper motor through direct ground coupling between pre-amplifier and stepper motor. Following Nylon insulation couplings are used to connect motor with transmission screw, also motor with encoder. The motor case, the encoder case are separately grounded through a common point.

An AD549 electrometer amplifier with extra high input impedance, extra low offset current is used to replace the isolation amplifier of original CEBAF harp preamplifier. The differential inputs amplifier has very high CMRR (common mode rejection rate) which effectively reduces the high frequency noise picked up by electrode wire through the input ends.

Figure 4 shows a comparison of the noise level between the original isolation amplifier and the new differential input preamplifier during harp when a sine signal is fed to the input of amplifiers. The result noise count is greatly reduced from 363 counts to 20-50 counts by the procedure mentioned above.

The output of harp preamplifier is then sent to DSP Model 1008 eight channel programmable signal conditioner, which contains eight individual instrumentation amplifiers in a fully programmable CAMAC single width package. The differential input amplifiers with gains up to 1024 are well suited to transmit signal through long cable in a very noisy environments because of good common mode rejection rate up to 100 dB, low noise less than $2 \mu V$ V_{pp} .

2.3 Study on Vibration Sources

In order to study wire vibration caused by different sources, microscope video camera is temporarily mounted on the moving plate of superharp as shown in Figure 5. The object lens of camera microscope traces the motion of the wire and the instant wire image is displayed at a fixed position on TV screen. The wire size is used as the reference scale of vibration amplitude. During the wire travels towards and backwards in the whole range, no vibration can be observed, therefore, the moving mechanism (stepper motor, lead screw, and Thomson rods) does not

Figure 4: Comparison of noise level of electrometer differential input preamplifier (upper) and the original isolation amplifier (lower)

Table 3: Vertical and horizontal components of ground motion at CEBAF

Location	Subject	$v_v (\mu m/s)$	$v_h (\mu m/s)$
EEL 122	10'x4' steel optical bench	3.5	7
EEL 126	6'x4' granite table with full load	10.0	14
EEL Hall	8'x4' granite table without load	11	7
Injector	QD0L09 girder with running water	14	17.8

cause wire vibration. The wire vibration with amplitude larger than $10 \mu m$ is generated by ground motion and adjacent mechanical noise sources (for example, the cooling water running through the pipe, vibration of mechanical pumps).

To achieve a high accuracy of beam position measurement, wire vibration must be suppressed not only by optimizing the harp configuration but also effectively damping all possible vibrations. One major reason that causes wire vibration is mechanical motion of ground by local traffic and night coal train.

A pair of accelerometers (L-10, horizontal sensor and vertical sensor, Martin products) are used to find out local ground motion amplitude at different locations. The calibrated voltage output of accelerometers is $0.7V/(inch/second)$ on a 75Ω terminator. Table 3 gives the measuring results.

Figure 7: The wire orientation on balsa fork is checked on the optical comparator

Figure 8: Two superharps are installed on granite table

Figure 9: Superharp prototype is installed at the edge of the girder OL09. The beam loss monitor is located above the x-y beam steering magnets on the girder

3 EXPERIMENTAL TEST OF SUPERHARP PROTOTYPE

The purpose of the first experimental test is to: a) verify normal operation of superharp prototype with absolute position encoder as the position sensor; b) improve current sensitivity and broaden current dynamic range from $1 \mu\text{A}$ to $100 \mu\text{A}$; c) improve signal/noise ratio. In order to study b) and c), two analog signal pick-up channels - direct current measurement by wire electrode and bremsstrahlung detection are independently used to determine beam profile (current profile and radiation profile).

3.1 Experimental Apparatus

The superharp prototype was located on the girder OL09 at CEBAF injector section as shown in Figure 9.

Three parallel tungsten wires with different diameters ($10\mu\text{m}$, $22\mu\text{m}$, and $50\mu\text{m}$) were mounted on the balsa fork for observation of vertical beam profiles with different current sensitivity. A beam loss monitor was installed 1 meter downstream the superharp for radiation profile measurement. A beam viewer was installed on the girder OL08, 20 ft upstream from superharp and a regular CEBAF harp was settled on girder OL10, 20 ft downstream.

The PC based superharp prototype data requisition system was located in north linac service building. A block diagram of electronics used in the tests is shown in Figure 10.

The beam energy at CEBAF injector is 45 MeV, duty factor 7.5×10^{-3} , the pulse width is $125 \mu\text{s}$, and frequency is 60 Hz. During the experiment peak beam current was tuned from $1 \mu\text{A}$ to $115 \mu\text{A}$.

Figure 10: Block diagram of superharp prototype electronics

Table 4: Major specification of Hamamatsu 931B side-on photomultiplier

Spectrum range	300-660 nm
Cathode luminosity response	40 μ A per lm
Current gain	6×10^6
Rise time	1.8 ns
Transit time	18 ns
Number of dynodes	9

3.2 Radiation Profile Pick-Up

The radiation level near the sensor wire which is moving across the electron beam will be entirely dominated by the bremsstrahlung X or gamma rays produced in the target wire. This local dose rate will be a function of emission angle and also be dependent on wire diameter and the presence of surrounding material. The dose rate at BLM location (1 m from sensor wire with 30° emission angle) for per kW beam power loss can be estimated by the formula [9]:

$$D = 2700\sqrt{E}\theta^{-1.5}Gyh^{-1}kW^{-1}$$

where E is the electron energy in MeV and θ the emission angle in degree. When 45 MeV 1μ A electron beam is scanned by the sensor wire, the beam power loss in the wire is about 1.08μ W [6] and corresponding dose rate is approximately 112μ rad per hour that is the dose detected by the BLM channel of superharp system when the wire is crossing the beam.

The radiation detector is a Hamamatsu 931B side-on photomultiplier with general specification listed in Table 4.

No scintillator is required for Hamamatsu 931B photomultiplier. The side-on glass envelope generates

Figure 11: Current profile (upper) and Bremsstrahlung profile (lower) for 45 MeV 1μ A beam

scintillation and Cherenkov radiation under a certain Bremsstrahlung radiation environment when energetic electron beam bombarding the wire. When electron beam interacts with wire, the primary radiation - Bremsstrahlung x-ray is produced. With increasing the energy of electrons the following secondary emissions take into place: electron-positron pair (electromagnetic shower); photonuclear interaction - photo-neutrons; neutron-proton pair; photo pion; and muon pair. When CEBAF electron beam energy increases from 45 MeV to 4 GeV, the dose rate will increase by factor 3 with stronger forward angle emission. This is why one beam loss monitor can be used to observe radiation beam profiles from two cascade superharps on each granite table while those two harps are operated independently.

The signal conditioner of BLM is a separate card within the BLM controller module. Either linear or logarithmic signal conditioning mode can be used for different functions. In the case of superharp, BLM conditioner is switched to logarithmic mode which covers very wide dynamic range (11 decade). The logarithmic mode is specially used to extract low level signals from noise background. For either two conditioning mode, the input signal range is converted to a 0-5 volt voltage range for the data acquisition network.

3.3 Experimental Beam Profiles

A series of beam profiles were obtained during the superharp prototype on beam testing at different beam current from 1μ A to 125μ A. Each profile plot consists of current profile and Bremsstrahlung profile in the same position coordinate. Two peaks, corresponding to 10μ m and 22μ m wire respectively, are displayed in beam profile plot and the third 50μ m wire is out of motion range.

Figure 11 shows the worse beam profile with a beam

Figure 12: Current profile (upper) and Bremsstrahlung profile (lower) for 45 MeV 5 μ A beam

Figure 14: Current profile (upper) and Bremsstrahlung profile (lower) for 45 MeV 25 μ A beam

Figure 13: Current profile (upper) and Bremsstrahlung profile (lower) for 45 MeV 10 μ A beam

Figure 15: Current profile (upper) and Bremsstrahlung profile (lower) for 45 MeV 50 μ A beam

Figure 16: Current profile (upper) and Bremsstrahlung profile (lower) for 45 MeV 100 μ A beam

Table 5: Comparison between current profile and Bremsstrahlung profile at 1 μ A beam current

	Current	Bremsstrahlung
Average noise (V)	0.034	0.05
Peak noise	0.27	0.14
10 μ m wire peak	0.28	0.44
S/N ratio (10 μ m)	1.04	3.14
22 μ m wire peak	0.39	0.92
S/N ratio (22 μ m)	1.44	6.57

current of 1 μ A. In upper current profile the average S/N ratio is about 1.04 at 10 μ m wire, 1.44 at 22 μ m wire, and this was greatly improved by Bremsstrahlung logarithmic system. A N/S ratio comparison between current profile and radiation profile at 1 μ A current (motor speed: 2000 steps/second, the gain of programmable amplifier: 64) is shown in Table 5.

From experimental data mentioned above, several technical highlights could be summarized as the following:

- Bremsstrahlung beam profile has higher sensitivity than current pick-up at low current, specially below 5 μ A (45 MeV).
- One beam loss monitor can be used as common Bremsstrahlung profile pick-up sensor for two cascade superharps when beam energy increases to GeV because the enhanced forward angle radiation
- To prevent saturation effect of beam loss monitor, the distance between BLM location and superharp can be increased to 200 - 300 cm, also the emission angle could be set beyond 30 degree at higher beam energy because dose yield is increased.

Figure 17: x-y current profiles for 600 MeV 25 μ A pulsed beam

- The linear current channel provides a non-distorted beam profile, which has higher accuracy to determine the center of mass of beam profile as "beam position". The adequate range is from 5 μ A to 100 μ A.
- 22 μ m diameter tungsten wire was selected as sensor wire because of its good balance between sensitivity and position resolution.

4 SUPERHARPS INSTALLATION

Based on the successful experiment result of superharp prototype beam testing in December 1993, eight superharps were installed on Hall C beam line in July 1994. Six of them were installed in BSY arc section for beam energy measurement in nearly future, the final two were installed in chicane section just in front of target as regular beam profile monitors. The first 600 MeV CEBAF electron beam profile was obtained during this run as shown in Figure 17.

Two 22 μ m wires which are perpendicular each other were installed on the fork. When the harp scans with 45° tilt angle, the beam horizontal profile and the vertical one are displayed successively. The profile on the left side is vertical and the horizontal one is on the right side.

A 17-th bit cable was added on the 16 bit cable between encoder interface (tracking unit) and the Jordan input register in order to keep data effective in any case.

Some special noise problems occurred during the installation of eight superharps on Hall C beam line and they were greatly suppressed by systematic study on the local electric connection and grounding path.

The cross talk between preamplifier and reference frequency generator of the encoder was entirely suppressed by firmly connecting encoder enclosure and preamplifier box.

Table 6: Error Sources

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 fork	4
Subtotal (Repeatability)	13
Survey error:	
Harp fiducialization error	50

Figure 18: The video microscope camera system installed on optical bench looking at the wire position before and after scan to determine wire motion repeatability

The 60 Hz spike type noise with few volt amplitude comes from different grounding level between beam line and superharp system and improper grounding of superharp electronic system. Reconnecting common ground cable of beam line to preamplifier box made spike noise disappeared.

Standing waveform "Ring" noise is caused by mechanical vibration at partial travel of the harp scan (mostly near one end of moving range) while a misalignment of Thomson rods exists. Realignment of Thomson rods should be done until getting vibration vanished.

5 POSITION ERROR ANALYSIS

In order to test the repeatability of the motion of the superharp, a microscope video camera is mounted on a fixed stands on the granite table as shown in Figure 18. By looking at encoder readout, the harp is driven through entire motion range (3 inch) and then back to the original position. The position repeatability includes position error caused by backlash of driving screw, the error of encoder readout, and position uncertainty of wire size. The repeatability of wire motion is experimentally found to be better than $10 \mu\text{m}$. In survey process, under observation by the instrumentation telescope, the wire motion repeatability is about $20 \mu\text{m}$. The two different data comes from either different precision of measuring systems (Microscope and telescope) or different accuracy of transmission screws adjustment on a certain harp.

For beam energy measurement the absolute beam position is obtained from beam profile data by superharp system. The harp absolute position accuracy is required to be better than $50 \mu\text{m}$, which is equivalent to 3×10^{-5} contribution to the energy error. There are several factors which influent wire position accuracy beside survey error.

The smaller the wire size, the better the position resolution in the sense of differential current measurement during a complete scan. In fact, wire size is determined by

both beam size and the requirement of minimum current sensitivity. For $100 \mu\text{m}$ beam size the wire size contribution to position uncertainty is not sensitive and $22 \mu\text{m}$ wire is chosen for superharp.

Backlash of transmission screw is a major contribution to position error. The backlash is estimated not larger than $10 \mu\text{m}$ for 2.54 mm pitch lead screw. In vacuum the nut plate experiences a constant force only in one direction and the backlash entirely vanishes.

The sensor wire becomes loose when there is certain deformation of balsa fork. All balsa material and forks were pre-vacuumed and stored in a bell jar. After calibration and installation no fork deformation can be observed. Due to there is a pre-tension as the wire is installed on the fork, the wire deformation within a long term is restrivted less than $5 \mu\text{m}$.

Classified error sources are listed on Table 6

6 EVALUATION ON PRESENT SYSTEM

- The basic performance of present superharp system meets the requirement of 10^{-3} beam energy measurement.
- Stepper motor driving system can be simplified by using various translation driving mechanism because the instant position readout is only determined by encoder.
- To avoid from coupling problem and to reduce position error, the best way to measure transverse displacement of the wire of scanner is to use linear encoder firmly connected with the moving part of the harp. The common used optical linear encoder could reach the order of submicron within 1000 mm range (Heidenhain). With linear encoders featuring distance-coded reference marks, the absolute position value can be re-established by crossing over two consecutive reference marks (after a traverse of 20 mm).

The major elements of incremental linear encoder are high density optical grating and the photoelectric readout system. Careful study on local radiation level in BSY arc beam line is necessary.

- Beam loss monitor is suitable for the use of the only analog sensor on superharp and current pick up channel can be eliminated because the BLM conditioner can be operating in either logarithmic mode or linear mode and Hamamatsu 931B tube can also be replaced by 12 dynodes 30 mm diameter FEU-115M PM. It will have higher sensitivity and wider dynamic range.
- The wire holding system and wire survey procedure has to be simplified to meet the requirement of fast wire replacement in a 1-2 year period. (from SLC experience, about 90% of the 40 μ m diameter wires have broken during routing use.) A technique to realize highly reproducible wire-fork installation is to be developed.
- To meet the procedure of beam energy measurement, EPICS based software needs a further development to provide dual beam profile measurement and display, high precision beam centroid algebra, and automatic control for sequential scan of 6 superharps in arc spectrometer.

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Activity	Persons involved
Project initiation	C. Yan
Coordinator	R. Carlini, J. Denard
Mechanical design	E. Feldl
Bench testing of superharp prototype	C. Yan, H. Feng
Mechanical assembly	P. Adderley, E. Feldl
PC based control system	P. Adderley
Balsa harp mechanism	R. Wojcik
Preamplifier	B. Kross, J. Van Dyke
Prototype beam testing	K. Jordan
Design of granite table and beam line support	R. Wojcik, C. Yan
Installation on beam line	J. Van Dyke, H. Fanning
Survey and calibration	S. Williams, B. Kross
Beam line electronics installation	J. Dahlberg
System verification	K. Capek, A. Silva
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	D. Barker, S. Wood
	J. Van Dyke, B. Kross
	C. Yan
Documentation	C. Yan

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