A NEW DIAGNOSTIC SYSTEM FOR STUDYING THE INJECTOR AND INJECTION AT THE ZERO GRADIENT SYNCHROTRON (ZGS)*

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Introduction

A series of four segmented Faraday cups (SFC) have been installed in the ZGS for the purpose of making quantitative measurements of injection parameters. The location of these SFC's is shown in Fig. 1. The beam position and distribution can be measured in the horizontal and vertical planes immediately after the inflector (L-1 section), in the vertical plane 90° from the inflector (L-2 section), and in the horizontal plane 180° from the inflector (L-3 section). This information allows the direct determination of relative energy, energy spread, emittance of the injector beam and injection angle, injection and capture efficiency as a function of betatron amplitudes, first harmonic orbit warps at injection, and the injection radial tune.

The SFC's are constructed of electrically isolated bars which are arranged in horizontal or vertical arrays. Each bar is switched between a calibrated capacitor and ground by a single-pole, double-throw FET switch. In normal use, the individual segments are switched from ground to the calibrated capacitors for a selected 10 μs interval of the injected pulse. An electronic commutator system samples the charge which was collected on each capacitor. The information is directed into a CDC-924A computer which provides a CRT display of the distribution and some elementary information about position, injected charge, and shape of the charge distribution.

The SFC system was originally conceived as part of the program to retune the ZGS after the titanium vacuum chamber installation.[1] It was felt that knowledge on typical injector parameters for good capture and acceleration was essential to a successful retuning program. The equipment developed for this purpose allowed gathering this information on a pulse-to-pulse basis with typical beam loading on the preaccelerator and linac. Considerable data on the characteristics of the ZGS injector beam and understanding on the control of the characteristics were obtained with the SFC system.[2]

Mechanical Construction

L-3 Straight Section SFC

This SFC is intended for radial measurement of the beam over the 30 in width of the ZGS vacuum chamber. Forty-three vertically mounted 3/8 in wide pickup segments are spaced at 3/4 in intervals in a fiberglass insulating frame (see Fig. 2). These segments, which are 1/2 in deep, capture essentially 100% of the impinging protons. This spacing, which gives a first-turn capture efficiency of 50%, yields adequate spatial resolution and a SNR of 40 dB for 10 μs increments of the injected beam. Each of the segments is connected to the vacuum chamber interface connectors by about 4 ft of Kapton insulated No. 22 gauge wire. Buffer segments are installed between each pickup segment in order to minimize crosstalk between pickup segments due to secondary particles. The buffer segments are tied to a common insulated bus. The original intent was to run these buffers with some deflecting potential, but subsequent measurement showed that merely grounding these buffers was adequate.

The buffer strips also capture protons so that the transmission efficiency of the cup assembly is only 38%. Only 19% of the initial beam is captured for display on the second pass through the SFC and about 7% on the third pass. Each of the buffer segments is coated with a phosphor so that a TV view complements the computer display.

L-2 Straight Section SFC

This SFC is intended for vertical size measurements over 14 in of the outer radius of the vacuum chamber. There are 36 horizontally mounted signal segments which are made of 0.064 in wide aluminum. They are mounted on 0.164 in centers. Aluminum buffer segments, 0.020 in wide, are mounted midway between the signal segments. The capture efficiency of this cup assembly is 39%. The vertical span of this cup is slightly greater than the new 5 in high ZGS vacuum chamber. Two columns of glass spacers, 0.04 in x 0.5 in x 0.5 in, are used to maintain the vertical spacing of the metal segments. The whole unit is held together by pressure supplied by the insulating frame. The wiring details are similar to L-3.

Inflector SFC's (L-1)

Two more SFC's are mounted in L-1 so that they can be placed directly after the inflector. One unit senses radial distribution and the other vertical. Each has an active area 2.25 in x 2.25 in. This area is filled with 48 aluminum segments 0.032 in wide and 1/2 in deep. They are separated by 0.005 in thick H-film insulation. All 48 segments are brought through the vacuum interface isolated from each other. The original intent was to use 24 as buffer strips, if required. The H-film proved to be an adequate buffer so that all 48 segments were used as active elements. This yields good resolution for a typical 0.6 in diam beam. The capture efficiency is 86%.

The 50 MeV proton current delivers an average power of about 100 W to the L-1 SFC. This is concentrated into an area of about 0.4 in^2 with primary heat

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transfer by radiation. Measurements indicate a stable operating temperature of 675°F is reached after 20 min of operation. The insulation is rated for about 850°F. Examination of this SFC after use indicated that the adhesives on the H-film had boiled out, but the H-film itself was unharmed. Since the structure is held together by a metal frame, the adhesive is important only to simplify initial assembly.

Sampling, Scanning, and Display System

General

Each SFC is fed through the vacuum chamber interface in two 24-pin hermetic connectors. Bundles of RG 174/U coaxial cables of identical length carry the signal some 100 ft to the sampling and scanning electronics. The electronics are located in an area of relatively low radiation. These electronics consist of two separate sets of 48-channel simultaneous sample and holds and two sets of synchronized 48-channel time sequential multiplexers. The dual nature of the electronics allows them to handle two separate SFC inputs.

The scanning multiplexer connects "held" channels sequentially to a high impedance buffer amplifier. The scanning multiplexer can operate automatically either from its own 100 μs clock or it can wait after sampling to be scanned by external commands. In the typical operating mode, the buffer amplifier output is linked to an analog-to-digital (A/D) converter which is controlled and synchronized by the ZGS central control computer. The central computer interrogates the SFC scanning multiplexer in synchronism with the A/D conversion and transmission such that the analog signal on each cup segment is separately stored in the computer memory. The computer then scales, normalizes, and displays the data, as shown in Fig. 3. Computation of total current, full width half max, and beam center are made and included in the display. Hard copy of the CRT display is available, as is a printout from a line printer which includes both graphic and tabular data presentation.

Electronic Operating Sequence.

Figure 4 is a simplified schematic of the sampling and scanning electronics. The uniqueness of the system lies in its sampling capability. Sample times of 10 μs duration allow us to separate dB/dt effects from energy effects.

The typical sequence of operation is as follows: The rest state of the line #1 FET's, line #2 FET's, and FET #6 is on (conducting); while FET's #3, #4, and #5 are off. Thus, the storage capacitor, C_s; the cable capacitance, C_c; and the amplifier capacitance are held discharged, and captured proton current is conducted to ground through the line #1 FET's. At some selected time, t_o, in the injected beam pulse, the line #1 FET's are turned off for about 10 μs. Also at t_o, FET #6 is turned off for 60 ms. At the end of the 10 μs, the line #2 FET's are turned off and the line #1 FET's are again turned on. Thus, charge has been stored on all C_s's for 10 μs. Some 2 ms later, the central control computer begins its interrogation scan. It reads cup n-1 at t-1 for 300 μs by turning on FET #5, then cup n is read at t by turning off FET #5 and turning on FET #4, etc. The scan is completed some 15 ms later. Sixty milliseconds after t_o, the line #2 FET's and FET #6 are again turned on and all capacitors are cleared to await the next t_o.

Electronics--General Comments

The sampling transistors are n-channel junction FET's chosen primarily for their low "drain on" resistance of 30 Ω. They are protected against voltages higher than ± 5 V by biased clamping diodes (not shown). The scanning transistors are part of a commercial integrated circuit package of eight FET's with built-in FET to diode transistor logic interfacing and three-line binary diode transistor logic decoding. These lines scan within the package while a fourth line overrides these three and allows shifting to another integrated circuit package. The time sequencing logic is generated by a straight binary countdown with appropriate decoding. The buffer amplifier is a Fairchild 741 operated as a voltage follower. The frequency characteristics of the 741 give adequate channel-to-channel stepping while suppressing the switching spikes from the scanning FET's.

Accuracy and Calibration

The quality of the information depends totally on matching the gain of each channel. The gain of each channel depends primarily on the matching of all storage and cable capacitance. The storage capacitors are 0.005 μF dipped mylar type with a 1% value tolerance. The cable capacitance is controlled by using matched lengths of coaxial cables. Adequate SNR required the selection of the small capacitors. With such small capacitors, differential leakage is often a problem. However, since the signal is held < 60 ms, an SNR in excess of 40 dB is achieved.

The cable capacitance, C_c, may be as large as 0.003 μF, so it must be a part of any current readout calibration. In the calibration procedure, C_s, is considered a standard; and a known fixed current, I, is injected only into C_s for some unknown time, Δt (~10 μs). ΔV is measured at the scanner buffer amplifier output and the exact value $\Delta t = C_s \Delta V/I$ is calculated. The cable and cup are now connected and I is injected into C_c and C_s in parallel. C_c is then calculated by $C_c = (I\Delta t/\Delta V) - C_s$. For the computer calculation of proton current, the SFC capture efficiency η must be included to give current per segment, I_s, as a function of voltage per segment, V_s. The resulting equation is:

$$I_s = \frac{(C_s + C_s)\, V_s}{\eta} .$$

Analytical Concepts

As stated above, these SFC's allow a determination of the relative energy, energy spread, emittance of injector beam and injector angle, injection and capture efficiency as a function of betatron amplitude, first harmonic orbit warps at injection, and the injection radial tunes. This is accomplished in the following way.

Relative Energy, Energy Spread, and Radial Tune

Relative changes in the energy and magnetic field will cause the peak of the injected beam to move radially in L-3 according to the following relationship:

$$\frac{\nu_x^2}{1 - \cos \nu_x \pi} \left(\frac{dR}{R}\right) = \frac{dT}{2T} - \frac{dB}{B} \qquad (1)$$

where

ν_x = radial betatron tune,

R = effective machine radius, $2\pi R$ = sum of magnet + straight sections' length,

T = kinetic energy of injected beam,

B = magnetic field at injection.

If $d\nu/dR = 0$ and dB/dt is known, dT/dt can be determined with the L-3 SFC by progressively delaying the 10 μs sample window through the injector pulse. Likewise, if the sample time is held fixed relative to the beam pulse, and the beam pulse is moved relative in time, one has a measure of dR/dB. If dR/dB is not constant, $d\nu_x/dR \neq 0$, an injection tune problem is indicated, since $d\nu_x/dR$ for the ZGS should be zero at injection.

The beam width in L-3, corrected for the beam emittance and small field change during the sample time (0.175 G), gives the energy spread of the injector beam. Typically, the beam at the inflector is between 0.4 and 1.0 in wide and has a divergence between 0.5 and 2.0 mrad. A monochromatic beam with this emittance would have a radial spread between 0.8 and 1.8 in at L-3. The appropriate value for dR in Eq. (1) should be 1.3 in less than the measured beam spread. The dB/dt correction amounts to 1.04 in. In addition to the ± 0.5 in uncertainty as a result of emittance, spatial resolution introduces another ± 0.375 in. Thus, the accuracy of the energy spread measurement is on the order of ± 22 keV.

Injector Beam Emittance

The vertical emittance of the injected beam is measured with the L-1 and L-2 SFC's. The measurement on the L-1 SFC is made just after the inflector, and so is an accurate measure of vertical width and position of the injected beam. The L-2 SFC is 90° around the ring, which is between 63 and 70° in vertical betatron phase. This amount of rotation in phase space translates divergence at the inflector into vertical beam spread at L-2, or

$$\pm y'_m = \frac{\nu_y dy}{2R \cos\left[(1-\nu_y)\pi/2\right]} \qquad (2)$$

where

y'_m = maximum vertical divergence of injected beam,

ν_y = normalized vertical betatron frequency,

dy = measured beam spread on L-2 SFC.

The horizontal emittance is measured with the L-1 and L-3 SFC's. The horizontal size is measured with the L-1 SFC. The horizontal divergence is measured by looking at the size of the beam on the second turn (recall that the L-3 transmits ~38% of the beam). On the second turn, L-3 is almost exactly 450° away from the inflector in betatron space so that the beam width $x = (2R/\nu)\, x'_o$ + correction. A correction of 0.5 in is required due to the field ramp of 17.8 kG/s and a correction due to energy spread of about 0.6 in.

First Harmonic Orbit Warps and Injection Angle

Because of the transparency of the L-3 SFC, the profile for the first three turns can be seen. With the beam position on three successive turns, ν_x, and dB/dT, it is possible to determine the injection angle and the L-1 to L-3 relative warp in the equilibrium orbit by solving the three simultaneous equations

$$-(B-x_i) = (13.5-A) \cos (i\pi \nu_x) + \frac{x'_o R}{\nu_x} \sin (i\pi\nu_x) , \qquad (3)$$

where

B = equilibrium orbit position in L-3 measured relative to the vacuum tank center,

A = equilibrium orbit position in L-1,

x_i = beam position of the i^{th} turn in L-3,

x'_o = injection angle,

R = machine radius.

B-A is, of course, the first harmonic orbit warp. Debunched beam is used in this measurement in order to better define beam center on each turn.

Injection and Capture Efficiencies

Injection and capture efficiencies can be measured as a function of betatron amplitude by injecting chopped beam (~ 10 μs beam pulse), adjusting the injection time to produce the proper betatron amplitude (determined using the L-3 SFC), and measuring the beam that survives injection by collecting it on an inside radius Faraday cup in the case of injection efficiency or accelerating it and measuring captured Q.

Utilization and Results

One of the primary uses of the SFC system is to minimize the turnon period after long shutdowns. The injection parameters and linac operating conditions can be adjusted in an hour or two. This procedure generally guarantees reasonably intense beams when the SFC's are withdrawn from the beam. The SFC system is also used when periods of beam instability arise and it is desirable to separate problems between the accelerator and the linac. Tests are periodically performed with the SFC's to identify potential problems before they produce serious beam instability.

Typically, when the ZGS is accelerating beams over 3×10^{12} protons/pulse, the injector beam increases in energy on the order of 2.5 to 2.75 keV/µs. An energy ramp of 3.7 keV/µs would maintain a constant equilibrium radius with the ZGS injection magnet ramp of 17,800 G/s; and so with a 2.5 keV/µs energy ramp, the equilibrium orbit moves radially inward about 2 to 3 in during the injection period. The energy spread of the injector beam is around ± 250 keV. Figure 5 shows typical capture and acceleration efficiency during the injection pulse. The injection window is on the order of 100 to 120 µs wide. Amplitudes of radial betatron oscillations are between 1.5 and 2.5 in. Injected beam with somewhat larger or smaller amplitudes does not get captured.

The total energy spread during injection is the sum of the energy spread of the injector beam, 85% of which is within ± 120 kV; and the energy ramp, which is 2.7 keV/µs for about 100 µs or 270 keV. This beam is injected into a nonaccelerating RF bucket which has an energy acceptance of 475 keV. After injection, the RF voltage is ramped from 3.5 kV to 24 kV. The energy spread with the normal accelerating potential is 900 keV, with corresponds to 16 in of radial width. Apparently, the optimum injection scheme fills radial width of the chamber with 16 in of synchrotron motion and 5 in of betatron motion. Several inches of radial aperture is apparently consumed by errors in the RF frequency, nonlinearities in the equilibrium orbit, and fluctuations in equilibrium radius due to a finite number of breakpoints in the function generator of the master oscillator.

The energy dependence and energy spread of the injector are dependent on the RF level of the linac, preaccelerator HV, and the linac-debuncher relative phase. Details are provided in Reference 2.

The horizontal emittance of the injector beam is normally 0.6 ± 0.1 π mrad-in and the vertical emittance is 0.6 ± 0.1 π mrad-in. The horizontal waist at the inflector is usually about 0.9 in and is located with the gaussian tail clipped by the inner radius edge of the inflector. The vertical waist at the inflector is normally about 1.2 in and the vertical divergence is about ± 1 mrad. As a result, the vertical beam fills about 3 in of height at injection.

Injection timing is adjusted so that the start of the injector pulse is observed at the largest radial position, normally about 11 or 12 in from center of the vacuum chamber.

Summary

The SFC system provides detailed information about the injector beam and the capture and early acceleration cycle of the ZGS more rapidly and accurately than was previously possible. The system was an important part of the retuning program after the titanium vacuum chamber installation. The SFC's are frequently employed in maintaining stable ZGS operation with intense beams.

Acknowledgments

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References

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[2] E. F. Parker, Argonne National Laboratory, Recent Measurement of the ZGS Injector Beam Characteristics, 1972 Proton Linear Accelerator Conference, Los Alamos, New Mexico, October 10-13, 1972, LA-5115 (November 1972), pp. 63-66.

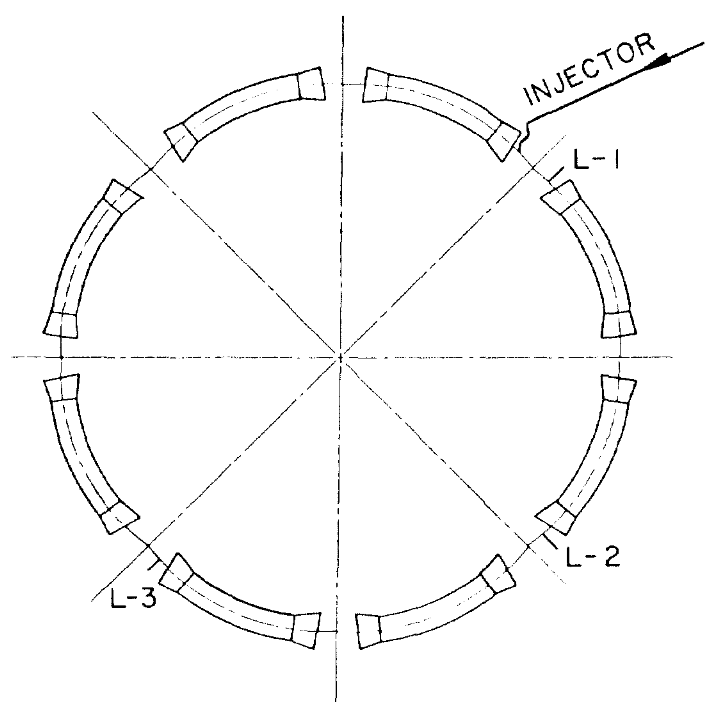

Fig. 1 SFC Locations in ZGS Ring

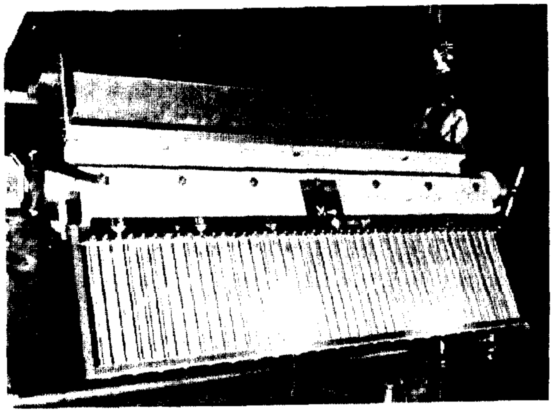

Fig. 2 Photograph of L-3 SFC

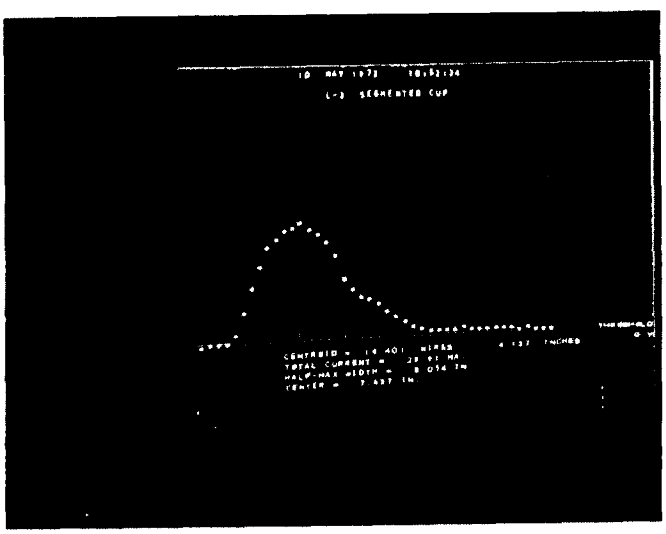

Fig. 3 Typical CRT Display of Beam Distribution on L-3 SFC

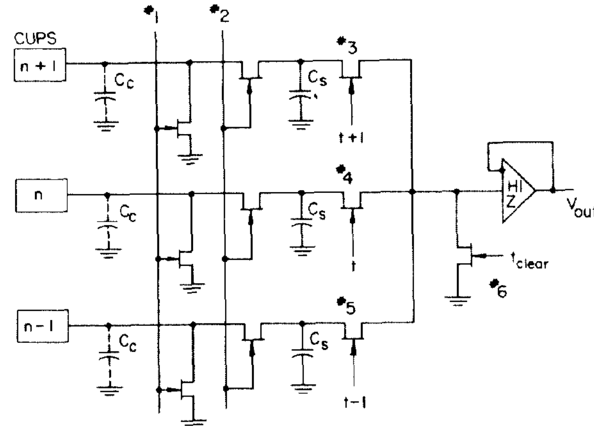

Fig. 4 Simplified Schematic of the Sampling and Scanning Electronics

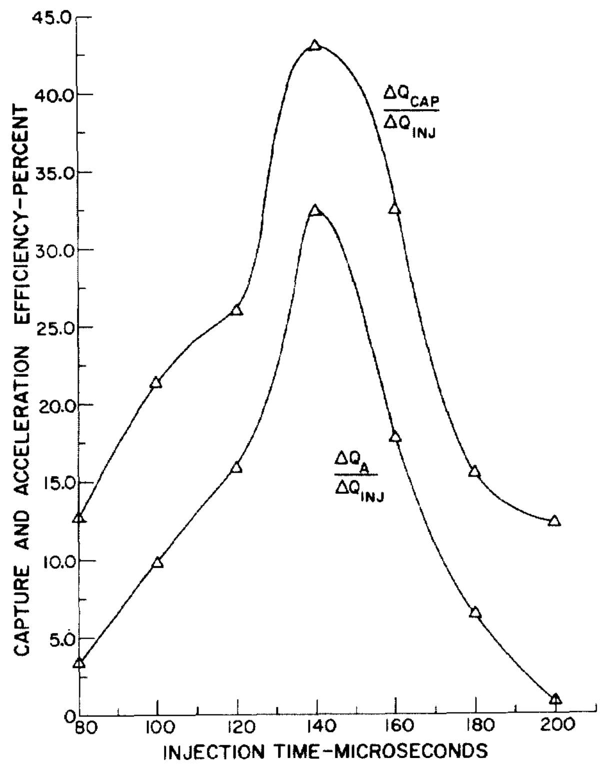

Fig. 5 Capture and Acceleration Efficiency During Injection Pulse