Detector for Laser Wire and Beam-in-Gap Diagnostics Systems

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Introduction

For both the laser wire beam profile monitor and the laser beam-in-gap (BIG) beam current monitor, the laser-neutralized H^0 beam is converted to protons and detected with a proton detector. The yield of protons ranges from perhaps 20,000 protons (BIG) to perhaps $1x10^8$ protons (laser wire) during a 12-ns Q-switched laser pulse.

The choices for a proton detector include a Cerenkov radiator, a scintillator detector, or secondary emission (SEM) plates. This Note reviews the signal characteristics for each of these detectors.

Other detectors, including an ion chamber and a NaI(Tl) sodium iodide crystal , are not considered, because the risetime is too long, and therefore discrimination against background is poor. Another reason for having a good temporal response is to look at the edges of the chopper gap, where there are likely to be partially chopped microbunches.

Proton Yield

In both laser wire and beam-in-gap, the laser neutralization point will be located just upstream of a dipole in the SNS Linac-to-Ring Beam Transport (LRBT). The dipole magnets are each 5.3 meters long, and have a bend angle of 11.25 degrees. The dipoles are C magnets, with the flux return yoke on the inside of the arc, so the neutralized H^0 are easily extracted from the primary beam. At the downstream end of the dipole, the neutralized H^0 beam is separated from the H^- beam by about 52 cm. After exiting from the magnet, a thin foil will convert the H^0 to protons.

At the preferred point of neutralization (upstream of dipole DD7), the horizontal and vertical b functions are 0.5 and 2.0 m respectively. Using a normalized emittance of 0.5 mm-mrad at 1 GeV, the proton beam is of the order of 10 mm diameter (100% width) at the exit of a 5.3-m long dipole magnet. The dispersion at the neutralization point is about 1.5 m, adding about 1.5 mm for a 0.1% dp/p. Uncertainty in the exact centerline of this neutralized beam requires that the detector be at least 50 mm diameter.

For calculating the proton yield, we use the program LaserY4.exe[1]. We use as input

Peak beam current	56 mA
Beam in gap	6 μA (10^{-4} of peak current)
Beam energy	1000 MeV
H^- beam size	2 mm, rms
Laser	Nd:YAG, 1.06 microns
Laser pulse	200 mJ, 12 ns long
Laser beam angle	90 degrees, single pass
Laser beam size	1 mm rms (beam in gap application)
	0.5 mm rms (laser wire application)

The yield of protons is, from LaserY4.exe

Laser wire	6×10^8 protons (15% yield)
Beam in gap	7×10^4 protons (16% yield)

Secondary Emission Detector

The secondary emission (SEM) detector would be a sandwich array of thin cathode foils, each about 1 mil thick, sandwiched with high voltage anode foils of equal thickness in high vacuum. The nominal SEM signal yield per surface is 1%, so a sandwich of 50 two-sided cathode foils separated by 51 anode foils would have a total signal yield of about 100% of the incident proton beam.

Application	electron yield	peak current	peak voltage across 50 ohms
Laser wire	6×10^8 electrons	8 mA	400 mV
Beam in gap	7×10^4 electrons	0.9 μA	45 μV

Thermal noise is about 0.5 nV/vHz, or 5 μV for 100 MHz BW. If 6 dB is added for electronics front-end noise figures, these numbers become 1 nV and 10 μV. Thus the signal amplitude is adequate for the laser wire applications, but very marginal for the beam in gap application.

This SEM assembly would be about 50 cm long, assuming a 5-mm cathode to anode spacing. The capacitance for a single surface (50 mm dia, 5 mm spacing) is about 3.5 pF. Thus 100 surfaces represents about 350 pF of shunt capacitance. Combining this shunt capacitance with a 50-ohm output impedance yields a risetime of 17 ns, which is marginally too long for good temporal discrimination against background.

Cerenkov Radiator

The Cerenkov light yield is [1]

$$Y = \frac{1}{137}\left[1 - \frac{1}{n^2 b^2}\right]\frac{2p \cdot df}{c} \quad \text{photons per unit length}$$

where f=c/λ, c is the speed of light, b is the proton velocity, and n is the index of refraction of the radiator.

For a wavelength range from 4000 to 7500 Angstroms, the yield is then approximately

$$Y = \left[1 - \frac{1}{n^2 b^2}\right] \bullet 230 \quad \text{photons per cm}$$

We consider a 20-cm long glass Cerenkov radiator, with density r = 4.5 grams per cm^3 and index of refraction n = 1.76 (Schott Glass SF-1). The total energy loss for a 1-GeV incident proton (b = 0.875) in the glass is about 160 MeV (to 840 MeV, b = 0.85), and the total photon yield is about 3500 photons per proton in the 4000 to 5500 Angstrom range. The spectral sensitivity of the photon detector and the photon absorption in the glass will modify this result.

The light is radiated forward in a cone of half angle $\cos^{-1}(1/nb) = 47$ degrees, which is totally internally reflected in the glass. Thus a photon detector at the downstream end should collect most of the light. Assuming a 20% efficiency for converting the photons to electrons, the signals are then (assuming a planar photodiode detector)

Application	electron yield	peak current	peak voltage across 50 ohms
Laser wire	4×10^{11} electrons	5 A	250 V
Beam in gap	5×10^{7} electrons	0.7 mA	30 mV

Thus the signals are about 600 times larger than from the secondary emission detector. A good planar photodiode, such as the ITT FW series, could easily handle this range of peak current, with leakage current and shot noise in the 10^{-10} amp range. The ITT photodiodes, with a solid cathode and a wire-grid anode, are linear up to about 10 amps peak. Because both the Cerenkov signal and the photodiode response are in the 100 ps range, very good temporal resolution of the beam microstructure (2.5 ns period) is possible. Using the same thermal noise estimates as calculated earlier, the S/N ratio is acceptable for the beam in gap application, provided electrical interference noise (RFI) from other sources can be adequately shielded.

Background signals from stray radiation should not be a problem. Cerenkov radiators are insensitive to neutrons, but are sensitive to high-energy gammas (primarily those that create electron positron pairs). A few cm of lead shielding should be adequate to shield a Cerenkov detector in the SNS tunnel.

Scintillator Detectors.

There are two basic types of scintillators; inorganic scintillators, such as NaI(Tl), and organic (such as NE102). The inorganic scintillators have a very high effective Z, high density, and good light yield (say 3 photons per 1 keV of dE/dx), but a very long decay time constant (about 250 ns for NaI(Tl)). On the other hand, organic scintillators have a low Z, low density, and short time constant (a few ns). Because we are detecting charged particles rather than gammas, the organic scintillator is the better choice.

Because the light output is proportional to dE/dx, the incident protons should first be degraded to about 150 MeV from 1 GeV. This raises the proton dE/dx from about 2.3 MeV-cm^2/gm to 5.8 MeV-cm^2/gm. Thus the proton energy loss in a 20-cm-long cylinder of scintillator is about 100 MeV. Using a conversion efficiency of 1 photon radiated into 4π per keV of energy loss (Bicron BC-400) yields 100,000 photons per incident proton, about 30 x higher than a Cerenkov radiator. It has a decay time of about 2.4 ns. Unlike the Cerenkov detector, much of the light is not internally reflected, so the scintillator must be covered with a good reflecting surface (e.g., aluminum foil).

Unlike a Cerenkov radiator, organic scintillator is very sensitive to both neutrons (proton recoil) and low energy gammas. So the shielding requirements are more severe. To degrade 1-GeV protons to 150 MeV, about 290 gm/cm^2 (25 cm) of Pb is required. Thus the scintillator is well shielded in front. Pb is not a good shield for neutrons, however, so perhaps a lower Z material is better. The scintillator should be shielded on the sides as well.

Detector location

With the laser located just upstream of dipole #7, the ideal location for the detector is just downstream of quadrupole QH18, between dipoles #7 and #8. This location is on the wall (not aisle) side of the beamline, and there appears to be adequate space. The H^0 beam is about 55 cm from the H^- beam at this point. These locations are shown in the attached drawing. The dipole magnets are C magnets, with the flux return bar on the inside of the arc, and open on the outside. The vacuum chamber would be identical to the chamber in dipole #1, where the H^- beam is extracted to the linac beam dump.

Conclusion

A Cerenkov detector appears to be the best choice for the protons in beam-in-gap measurement. It is also suitable for laser-wire profile measurements. Because of its good temporal response, a Cerenkov-based detector could also be used for looking at the beam microstructure. Because of uncertainties in exactly where the H^- beam may be in the LRBT aperture, the detector should be about 100-mm diameter.

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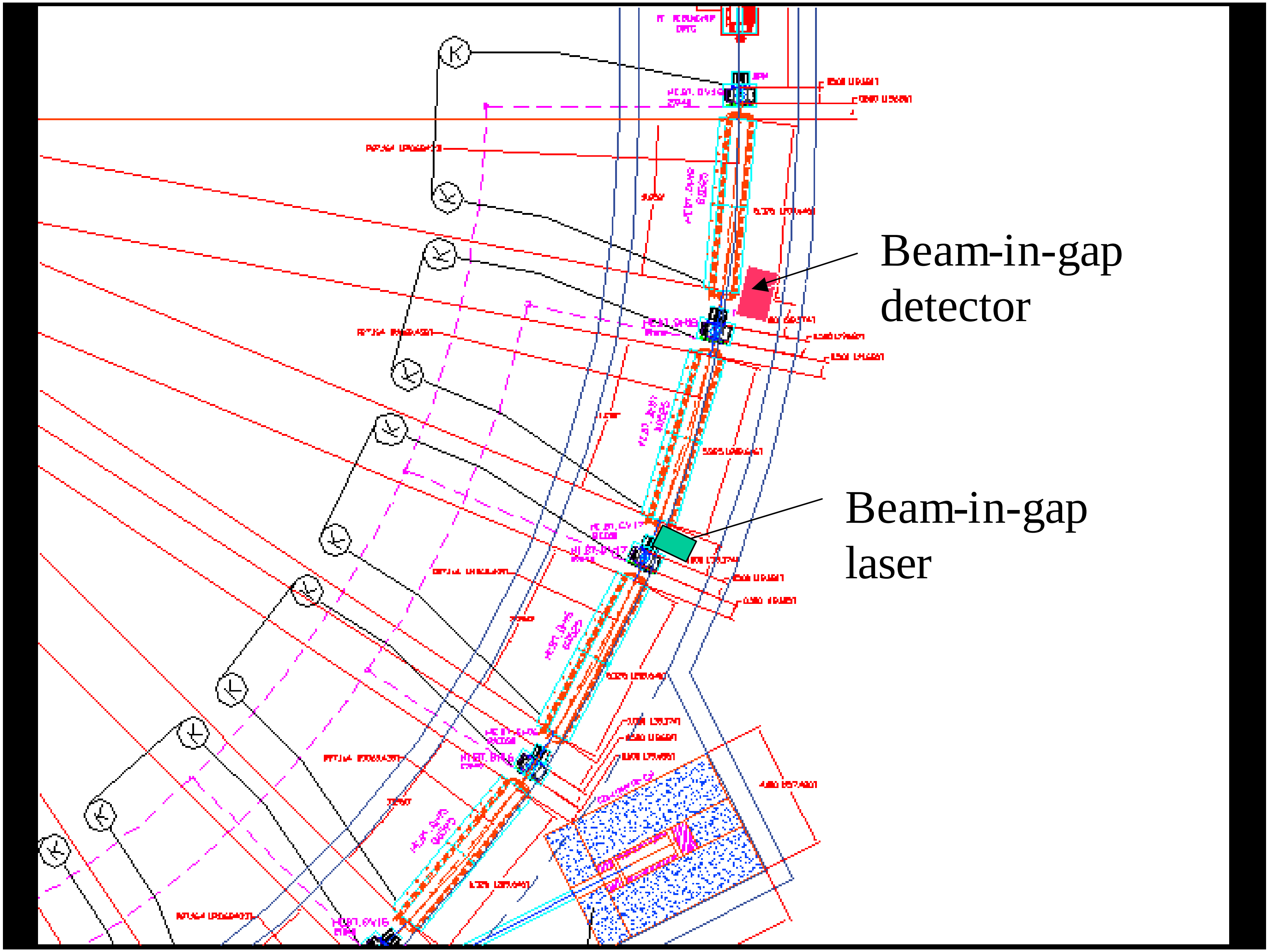
[1] LaserY4.exe; application program for Windows, R. Shafer 12/99. This program calculates the laser neutralization H^0 yield, including the Lorentz-transformation into the H^0 rest frame, the energy dependence of the neutralization cross section, and saturation effects.

[2] L. I. Schiff, “Quantum Mechanics”, McGraw Hill (1955), second edition, Eq 37.14 (page 271).


Beam-in-gap
detector
Beam-in-gap
laser