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SINGLE BUNCH PROFILE MEASUREMENT USING SYNCHROTRON LIGHT FROM AN UNDULATOR

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Introduction

For protons with energies up to 400 GeV classical theory shows that the critical energy of the synchrotron radiation due to the constant field of the bending magnets is in the far infrared with a negligible part in the visible light spectrum. However it was shown that the magnetic field discontinuity at the edges of the bending magnets shifts the spectrum to the visible region where the normal light detectors can be used[1)]. This "edge effect" allowed the detection of visible synchrotron radiation emitted by high energy protons in the CERN Super Proton Synchrotron (SPS)[2)]. The first application of this effect was to measure by a non-interceptive method the transverse proton density distribution for an energy above 270 GeV and intensity greater than 1×10^{12} protons[3)].

For the use of the SPS as a proton-antiproton collider at 270 GeV with p bunches having 10^{10} to 10^{11} particles and $\bar{p}$ bunches having 10^9 to 10^{10} particles, it was necessary to enhance the synchrotron light by an undulator[4)] and to develop a more sensitive and gated detector to get p and $\bar{p}$ single bunch profiles.

The Undulator

In a periodic magnetic structure, called an undulator, particles undergo a sequence of alternating transverse deflections which are a source of radiation. For a given wave frequency defined by the particle energy ($\gamma m_o c^2$) and the magnetic period (λ_u) interference occurs enhancing the emitted radiation.

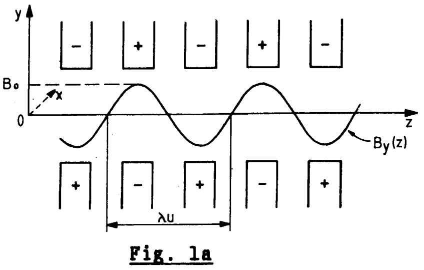

Fig. 1a

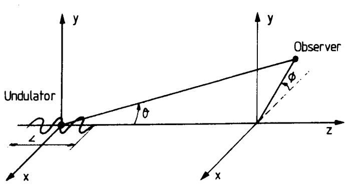

Fig. 1b

The theory of the undulator is well developed[5)]. For a transverse magnetic field (Fig. 1a)

$$B_y = B_o \sin(2\pi z/\lambda_u),$$

the radiation emitted by relativistic particles is concentrated in a narrow cone of half aperture $\sim 1/\gamma$ (Fig. 1b) and the wavelength emitted at an angle Θ from the direction of motion is given by

$$\lambda_o = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{k^2}{2} + \gamma^2\theta^2\right)$$

where $k = \frac{e B_o \lambda_u}{2\pi m_o c}$ is of the order of 10^{-3} in our present application. At $\Theta = 0$ we have $\lambda_o = \frac{\lambda_u}{2\gamma^2}$

The power emitted per unit solid angle is

$$\frac{dP}{d\Omega} = \frac{r_o\ e^2\ c^3\ B_o^2\ \gamma^4}{\pi m_o\ c\ \left(1+\frac{k^2}{2}\right)}\ \frac{\left(1+2\gamma^2\theta^2(1-2\cos^2\theta)+\gamma^4\theta^4\right)}{(1+\gamma^2\theta^2)^5}$$

with $r_o = \frac{1}{4\pi\varepsilon_o}\frac{e^2}{m_o c^2}$

Integrating over Ω and neglecting k the total radiation power is

$$P_o = \frac{r_o\ e^2 c^3 B_o \gamma^2}{3 m_o\ c^2}$$

which is the power of ordinary synchrotron radiation, but concentrated on λ_o.

with $\nu_o = \frac{2c\gamma^2}{\lambda_u}$ and $x = \frac{\nu}{\nu_o} = \frac{\lambda_o}{\lambda}$

$$\frac{dP/P_o}{d\nu/\nu_o} = 3x\,(1 - 2x + 2x^2)$$

The choice of operating with visible light (λ_o = 530 nm) implies that

$$\lambda_u = 2\gamma^2\lambda_o = 88\ \text{mm}.$$

The particles present in a bunch have a statistical longitudinal distribution much larger than the wavelength of light. Therefore their radiation is not coherent and can be added, giving for a beam current I_b and an undulator length L

$$P_{OI} = \frac{r_o\ e\ c^2\ I_b\ L\ B_o^2\ \gamma^2}{3\ m_o\ c^2}$$

The larger the number N of magnetic periods, the greater the radiation power concentrated at the wavelength λ_o. Two magnets are displaced to insert the undulator, which causes a closed orbit kick that is compensated by transverse displacements of the two adjacent quadrupoles. Keeping this compensation small enough inside the range of the possible SPS betatronic working points gives a pratical limit for the undulator length corresponding to N = 5 (Fig. 2).

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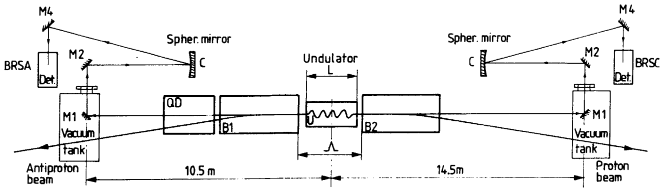

Fig. 2

An undulator was built [6,7] taking into account the following constraints:

To avoid perturbation of the SPS vacuum, the undulator magnets are installed outside of the vacuum chamber with a gap height H = 46 mm, leading to a magnetic field on the axis B_0 which is about 0.7 times the field at the pole surface B_p.

Having at our disposal a 2000A, 90V power supply, instead of a permanent magnet, an electromagnet configuration was designed. This also allows to change the emitted light power according to the beam intensity. The maximum field B_0 is 0.32 T on the z axis for I = 2000A in the magnet.

The magnetic structure being of finite length the theoretical power spectrum given by eq. 1 has to be convolved with the Fourier transform of a square wave (sin x/x function). It becomes larger and fits with the photo cathode response of the image detector. Taking into account the finite length of the undulator and the proximity of the two adjacent magnets, spectral and angular distributions of the radiation were calculated and experimentally verified[8]. The combined influence of the undulator and the edge effect are in good agreement with the predicted values.

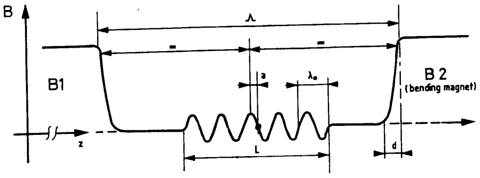

Fig. 3

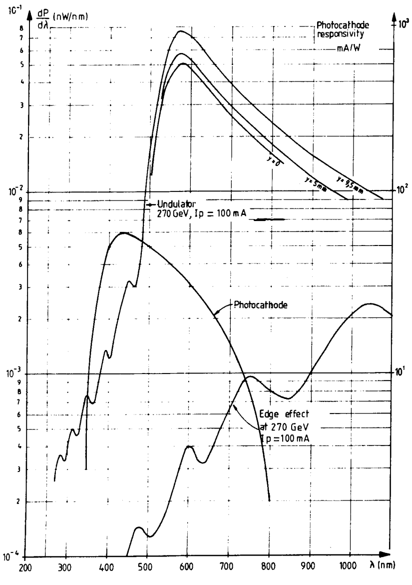

Fig. 4

At 270 GeV the power in the visible light reaching the detector was measured and found to be equal to 70 times the power given by the edge effect, as expected by integrating the theoretical spectrum shown in Fig. 4.

The Detector

The experimental set-up (Fig.2) takes advantage of the light emitted by both proton and antiproton beams. On each side at a distance where light and particle beams are well separated the mirror M1 extracts the light out of the vacuum chamber through a glass window. An optical system made from a Herschel type telescope focuses the image onto a camera. Since the light emitted at the undulator level is proportional to the number of particles, the image at the input of the camera corresponds to that of the p or $\bar{p}$ transversal density multiplied by the magnification factor (1/4).

Errors due to diffraction and depth of field have been analysed and found to be less than .2 mm for both[9].

The image detectors consist of a micro-channel image intensifier followed by very sensitive Vidicon of Silicon Intensified Target type (SIT) for p and of Intensified Silicon Target type (ISIT) for $\bar{p}$.

The special associated electronics has two fundamental purposes: the bunch selection, by gating the micro-channel intensifier to take the light emitted by only one bunch at each revolution, and the record of the individual bunch profiles in the vertical and horizontal planes. To do so, the vidicon target is analysed over the surface of interest (90 lines, 90 columns) with a resolution of (32x32) μm^2. Each diode charge is scanned at a rate of 40 ms, amplified, converted into digital form and stored into a memory. All the memories (90 x 90) can be accessed by computer. To reduce the data transfer to the computer, when only the horizontal and vertical profiles are requested, a summation line-by-line and column-by-column is made by hardware.

Experimental results

Having gained two orders of magnitude in sensitivity with the undulator and detector, beam profiles with an antiproton bunch intensity as low as 10^9 particles were recorded at 270 GeV.

Being a non interceptive device, the horizontal and vertical profiles of the p and $\bar{p}$ beams are continuously displayed by hardware in the control room giving an on-line diagnostic in case of large and rapid variations either in beam position or dimensions.

To record the beam profile behaviour during a $p\bar{p}$ coast, digital acquisition and processing are made on request. The beam sizes are defined by the standard deviations σ of the distribution converted in mm at the source location (undulator).

Fig. 5 shows a typical print-out of the 3 p and the 3 $\bar{p}$ bunch profiles in the vertical plane. From the whole memory a 3 dimension antiproton single bunch profile can be displayed (Fig. 6).

At low intensity special care must be taken to eliminate the vidicon dark current by calibration with a shutter in front of the camera.

Usually the beams are gaussian, which is checked by an on-line gaussian fit of the distribution. But at low intensity (< 3 x 10^9 particle/bunch) some noise could remain in which case the gaussian fit gives a better approximation than the raw σ.

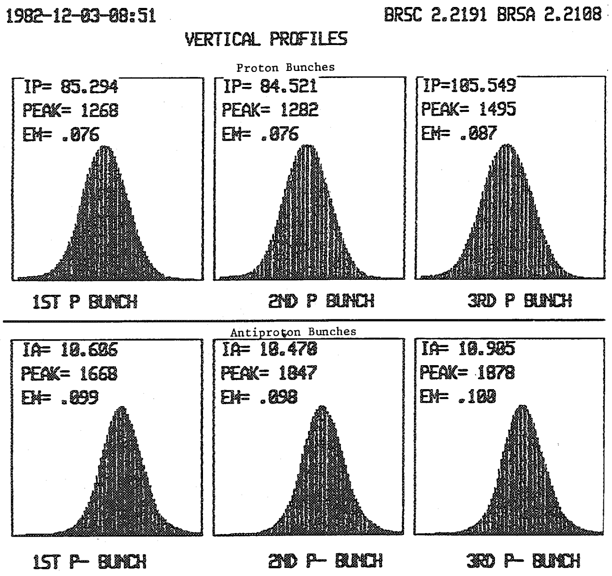

Fig. 5

IP = Proton bunch intensity in 10^9 unit	IA = Antiproton bunch intensity in 10^9 unit

EM = Bunch emittance in πmm.mrad unit

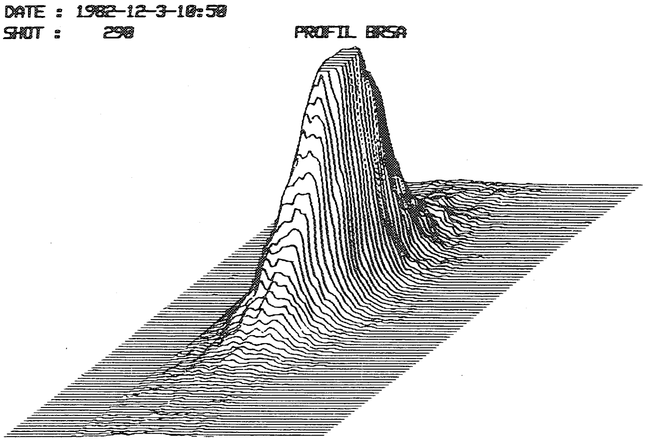

Fig. 6

Knowing at the source location the betatronic amplitudes (β_V, β_H), the momentum compaction factor (α_p), and assuming a dispersion in momentum ($\Delta p/p$), the emittances at 2σ are computed in both planes by

$$\varepsilon_V = 4\ \sigma_V^2\ /\beta_V$$

$$\varepsilon_H = \{4\ \sigma^2{}_H - (\alpha_p\ \ \Delta p/p)^2\}\ /\beta_H$$

Cross calibrations with a wire scanner monitor have shown a good agreement between the two methods.

The emittance recording during a coast was sometimes useful for detecting the blow-up of one beam or even of one individual bunch.

A very useful application was to deduce the luminosity L at the intersection point from the single bunch emittance and intensity mesurements, using the relation

$$L = f_o\ (n/A_{eff})\ (N_p/n_p)\ (N_{\bar{p}}/n_{\bar{p}})$$

(Np/np) = number of protons per bunch
$(N\bar{p}/n\bar{p})$ = number of antiprotons per bunch

f_o = revolution frequency

$n = \mathrm{Inf}\ (np, n\bar{p})$

$$A_{eff} = \frac{\pi}{2}\sqrt{(\beta_H^*\ \ \beta_V^*}\ \sqrt{(\varepsilon_{Hp} + \varepsilon_{H\bar{p}})\ (\varepsilon_{Vp} + \varepsilon_{V\bar{p}})}$$

$\beta^*{}_H$, $\beta^*{}_V$ = betatronic amplitudes at the interaction point

An independent luminosity measurement is provided by the physicists by counting the number of $p\bar{p}$ events in two telescopes. A calibration of this method was deduced from the measurement of the total $p\bar{p}$ cross section[10].

The luminosity evolution during a coast (Fig. 7) shows good agreement between the synchrotron light and the telescope methods.

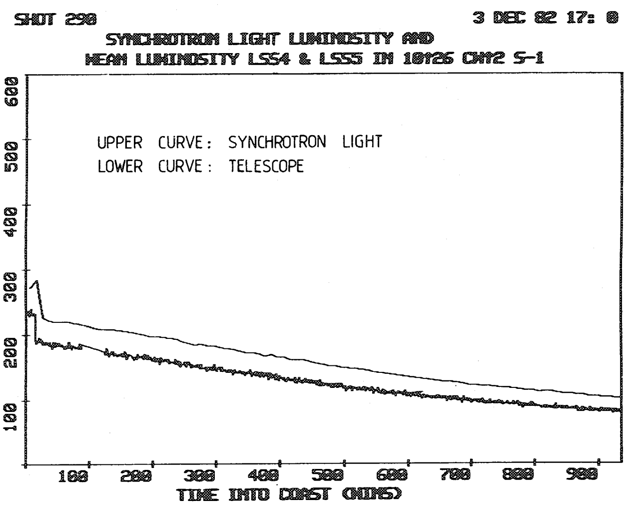

Fig. 7

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