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J. Bosser, L. Burnod, R. Coisson, G. Ferioli, J. Mann, et al.. Characteristics of the radiation emitted by protons and antiprotons in an undulator. *Journal de Physique Lettres*, 1984, 45 (7), pp.343-351. 10.1051/jphyslet:01984004507034300 . jpa-00232353

HAL Id: jpa-00232353

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Submitted on 4 Feb 2008

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Classification
Physics Abstracts
41.70

Characteristics of the radiation emitted by protons and antiprotons in an undulator

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(Reçu le 1^{er} septembre 1983, accepté le 15 février 1984)

Résumé. — Les distributions angulaires et spectrales du rayonnement visible émis par un faisceau de protons de haute énergie dans un onduleur ont été mesurées pour la première fois. Le même dispositif a également permis l'observation visuelle directe d'un faisceau d'antiprotons. Les interférences entre les rayonnements dus aux bords des aimants de courbure et ceux propres à l'onduleur ont été observées par l'analyse de la distribution angulaire.

Abstract. — Spectral and angular distribution of visible radiation emitted by a high energy proton beam in an undulator have been measured for the first time. The same device has also allowed the direct visual observation of a beam of antiprotons. Interference in the radiation from two magnet edges and that between the edges and the undulator has also been seen in the angular distribution.

1. Introduction

Undulators, i.e. transverse periodic magnetic fields, in which electrons emit narrow-band synchrotron radiation (SR), or « undulator radiation » [1], have been studied theoretically [2] and experimentally [3] and have been used to produce X-rays of high spectral brilliance. Even in modern high-energy accelerators, SR from protons has a critical frequency in the far infrared, however by using the « edge effect » [4] it was possible to observe SR from protons produced by the SPS (400 GeV super proton synchrotron) in CERN [5] and to use this light as a transverse beam profile monitor [6]. To increase the visible light intensity as well as to allow imaging of low current proton and antiproton beams at the storage energy (270 GeV, $\gamma = 288$), an undulator was installed [7], following an idea proposed a few years ago [8]; the measurements showed a power increase by a factor of 70.

In this paper we describe the measurements made at energies up to 400 GeV to check the characteristics of the light emitted by protons in an undulator, and the observation of interference effects in the light emitted from the two bending magnet edges, and from undulator and edges. We also report the visual observation of an antiproton beam.

The radiation emitted by protons in a magnetic field, although not different in principle from that emitted by an electron (same spectrum for equivalent γ and equivalent trajectory), can be quite different in practical situations. This has been shown clearly in the properties of the « edge

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effect » [5], which had not been observed before with electrons. This difference was also apparent in the present experiment as the narrow-band spectrum appeared at frequencies much higher than the critical one (either corresponding to the undulator peak field, or in the bending magnet).

2. Analytical expression.

For the theory, we refer to some review papers [9-11]; we remind hereafter the main features verified by this experiment.

If the field $B(z)$ (Fig. 1) is the sum of an undulator (with peak field B_0 , period $\lambda_0 = 2\pi/k_0$ and length $L = n\lambda_0$) and edges of bending magnets (let $M(Z)$ be the magnetic field at each of the two edges, at a distance Λ from each other, and $\text{rect } x = 1$ for $-1/2 < x < 1/2$ and 0 elsewhere) :

$$B(z) = -\sin k_0 z \text{ rect } z/L + M(z - a + \Lambda/2) + M(-z - a - \Lambda/2) \quad (1)$$

the spectral brightness in a direction defined by the angle θ from the direction of motion of the particle and angle ϕ of rotation from the orbit plane, for a current I at energy γmc^2 ($\gamma^2 \gg 1$) is proportional to the Fourier transform of the magnetic field [11, 12] :

$$\frac{d^2W}{d\Omega d\omega} = \frac{e^3 I}{8\pi^3 \epsilon_0 m^2 c} \gamma^2 F^2(\theta, \phi) |\tilde{B}(k)|^2 \quad (2)$$

with

$$k = \frac{1 + \gamma^2 \theta^2}{2\gamma^2 c} \omega.$$

F^2 describes the angular distribution of intensity :

$$F^2(\theta, \phi) = (1 + \gamma^2 \theta^2)^{-4} [(1 - \gamma^2 \theta^2 + 2\gamma^2 \theta^2 \sin^2 \phi)^2 + 4\gamma^4 \theta^4 \sin^2 \phi \cos^2 \phi] \quad (3)$$

(the first term is the parallel component, the second is the perpendicular component) and $\tilde{B}(k)$ is the Fourier transform of $B(z)$:

$$|\tilde{B}(k)|^2 = B_0^2 n^2 \left[\frac{\sin(k - k_0)L/2}{(k - k_0)L/2} \right]^2 + 2|\tilde{M}(k)|^2 \sin^2 k\Lambda/2 + 4|M(k)| \frac{\sin(k - k_0)L/2}{(k - k_0)L/2} \sin k\Lambda/2 \sin ka. \quad (4)$$

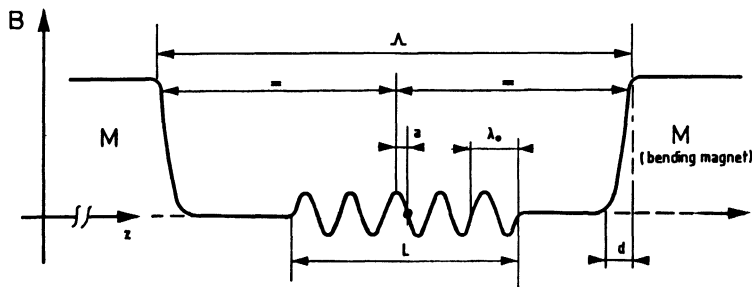


Fig. 1. — Magnetic field of the whole structure (undulator plus edges of bending magnets) as a function of coordinate z along proton trajectory. a is the distance between centre of undulator and mid-point between edges.

The undulator term (the first) describes a narrow band of relative bandwidth $\Delta\omega/\omega \simeq 1/n$, around an angle-dependent central frequency :

$$\omega_1 = \frac{2\pi c}{\lambda_0} \frac{2\gamma^2}{1 + \gamma^2 \theta^2} = \frac{2\gamma^2 c k_0}{1 + \gamma^2 \theta^2} \quad (5)$$

with total power

$$W = \frac{e^3 I}{12 \pi \epsilon_0 m^2 c^2} \gamma^2 B_0^2 L. \quad (6)$$

The edge term $|\tilde{M}|^2 \sin^2 kA/2$ describes a series of rings, analogous to Newton's rings, due to interference at fields emitted at each bending magnet edge. With a filter at wavelength λ , the edge contribution has (ideally) zeroes for energies and angles satisfying the relation :

$$\frac{A}{2\gamma^2 \lambda} (1 + \gamma^2 \theta^2) = \text{positive integer} \quad (7)$$

and a cut-off at wavelengths $\sim d/2\gamma^2$: if d is the distance over which the field rises (see Fig. 1),

$$2\gamma^2 \frac{d}{c}$$

is the risetime of the electromagnetic pulse emitted by a particle as seen by the detector (« edge effect », Ref. [4]).

The last term indicates interferences between undulator and edges.

By integrating equation (2) over all angles to obtain $dW/d\omega$ the result is only a function of $(\omega/2\omega_0 \gamma^2)$ where $\omega_0 = k_0 c$.

This means that the same information on $dW/d\omega$ can be obtained by varying ω for a given γ or by fixing ω and plotting $dW/d\omega$ as a function of $1/\gamma^2$.

3. Experimental set-up and results.

The experimental apparatus has been set up for beam image observation at 270 GeV, with anti-proton currents as low as a few μA ; the undulator period was chosen to match the fixed beam energy in colliding beam mode to the peak of the detector response, around 550 nm, and its length determined so that the limited depth of field of the image formation introduces a blur not greater than that due to diffraction.

The SR produced by p and \bar{p} in the undulator is measured by two oppositely located telescopes, as seen in figure 2. All the equipment has to be remotely controlled.

The undulator is an electromagnet with the following parameters [7] : $n = 5$, $\lambda_0 = 8.8$ cm, maximum peak field (vertical) $B \simeq 0.32$ T [deflection parameter $b = B_0 \lambda_0 / 2\pi m_0 c \simeq 10^{-3} \ll 1$] corresponding to 2 000 A in the windings (dissipation 180 kW). The field is slightly non linear as a function of the current, because of saturation of iron at higher fields. The fixed magnet gap is 4.6 cm. The proton beam energy is up to 400 GeV in fixed target mode with up to 1.5×10^{13} protons. The energy is 270 GeV in proton-antiproton storage ring operation with up to 5×10^{11} protons (corresponding to ~ 3 mA current) and 5×10^9 antiprotons stored. The other data given in figure 1 are : $A = 1\,070$ mm, $a = 55$ mm, $d \sim 5$ cm.

The television detector (microchannel image intensifier associated with an intensified silicon target) received a total light power up to ~ 2 nW (for a current of 10 mA), and could work with ~ 1 pW of light, corresponding to a current of ~ 3 μA .

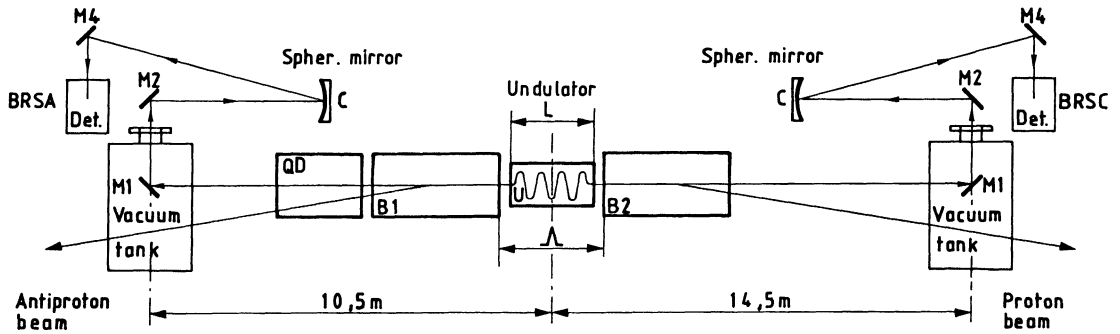


Fig. 2. — Experimental apparatus : the light emitted in the undulator U by protons (right) and by antiprotons (left) is deflected by surface mirrors M outside a quartz window and towards concave mirrors C which form an image of the undulator on the image detectors (silicon intensified targets [6]). Narrow-band filters or lenses can be placed in front of the detector. A 3×3 mm square image on the detectors (collected in 40 ms) is memorized in digital form.

For the present investigation, only minor modifications could be made to this apparatus, such as placing lenses and narrow-band filters in front of the image detector.

The light power was verified to be proportional to the proton or antiproton current over the whole range of beam currents (using attenuators) and this justifies the use of this instrument distribution.

The light power was also proportional to the square of the undulator magnetic field, as shown in figure 3 for a fixed proton current (10 mA) and energy (270 GeV).

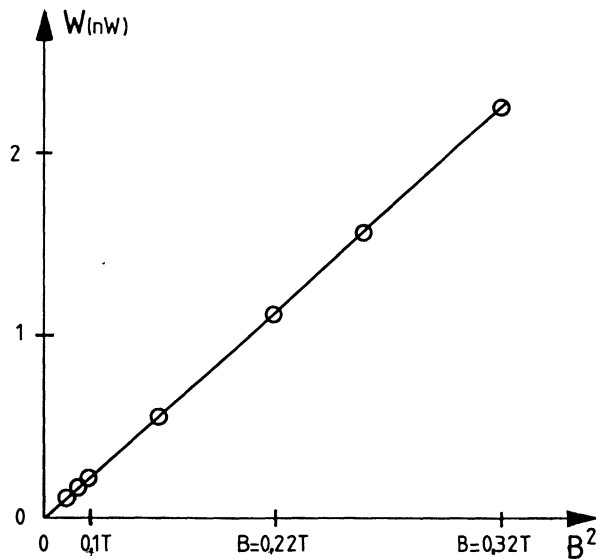


Fig. 3. — Light power from undulator at fixed energy (270 GeV) and proton current, vs. square of undulator field B .

For a beam-off centre, it varied with the vertical displacement as $B_0(y)$ (in our case $\partial^2 B_0/\partial y^2 = 16.4 \text{ G mm}^{-2}$).

A typical result of measurement made through a narrow-band filter with varying proton energy is reported in figure 4. The continuous line is the integral of equation (2) over angles (as a function of γ for a fixed ω): the peak is due to the undulator and has a maximum at an energy slightly higher than $(\lambda_0/2 \lambda)^{1/2}$ because of the effect of the convolution with the $\sin k/k$ function, and a tail at higher γ due to the contribution of larger angles θ , while the increase from 350 to 400 GeV is due to the « edge effect », slightly modulated by the effect of interference between edges. The reason for the difference between experimental data and expected results was accounted for by the limited angular acceptance, as was understood in the angular distribution measurements (see below) where one sees the approximately square solid angle accepted by the system of three rectangular mirrors used to direct the light onto the detector. Due to decrease of frequency with angle, a diaphragm cutting large angles decreases the low-frequency (here high energy) tail of the undulator spectrum; numerical integration of equation (2) over the actual square solid angle agrees with experimental data.

For the same reason the degree of polarization was greater than 7/8 (7/8 would be the value for the whole radiation). The light was mainly polarized in the horizontal plane, which was the plane of the trajectory in the undulator. The energy γ_m corresponding to maximum power with various filters was in agreement with the integral of equation (2) over the angles; the maximum power corresponding to different filters (taking of course into account the different detector response) was proportional to $1/\lambda^2$, as for all filters $\Delta\lambda \simeq 50 \text{ nm}$ (then $\Delta\omega$ was proportional to $1/\lambda^2$).

4. Angular distribution.

A second set of measurements was made (again with filters, with $B_0 \simeq 0.25 \text{ T}$) by incorporating a lens of 150 mm focal distance in front of the detector, then imaging the back focal plane of the concave mirror onto the detector such that the intensity distribution on the second detector was proportional to the angular distribution of the emitted light. This data was recorded for various values of γ : a qualitative picture (photograph of TV display) is shown in figure 6 for two values of λ . The angular opening for different values of λ and γ is described by equation (5) (see also Fig. 5).

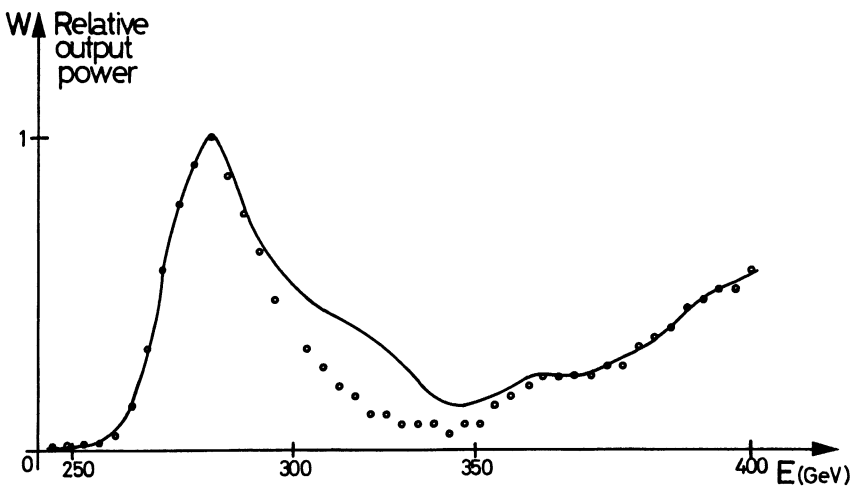


Fig. 4. — Power through a narrow-band filter ($\lambda = 0.55 \mu\text{m}$, $\Delta\lambda = 50 \text{ nm}$) as a function of γ . The continuous line indicates the ideal power collected over all angles, the circles are the experimental data collected over a limited solid angle (a square $\sim 1/\gamma$ times $1/\gamma$).

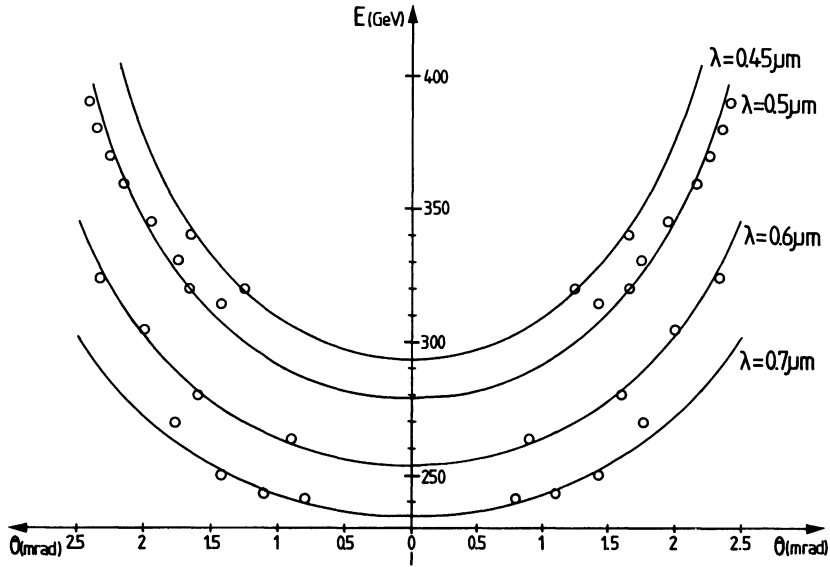


Fig. 5. — Aperture of the radiation cone as a function of energy, for various wavelengths (at $\theta < 1$ mrad there is not a ring, but a large spot, then experimental data are at larger angles).

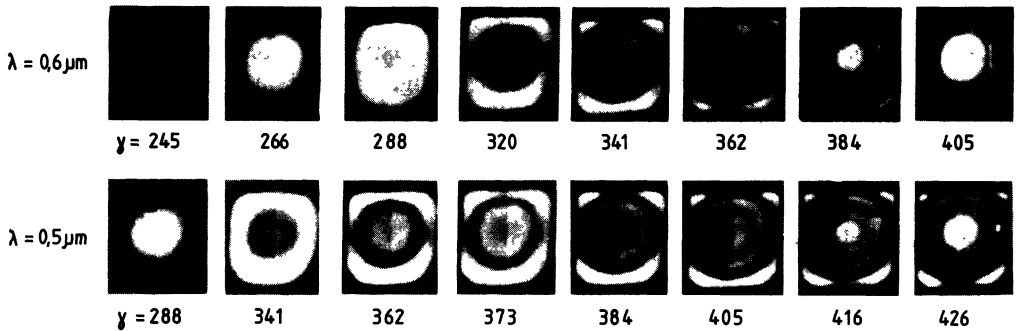


Fig. 6. — Photographs of TV displays of angular distribution of light for two wavelengths, for several values of γ , within the limits of angular acceptance. At low energy only the undulator appears, then the spot becomes a ring of increasing radius; at higher energies, rings due to interference between edges appear and move outwards.

A plot of the intensity on a section ($\phi = \pm \pi/2$) of the angular distribution of the interference between edges [13], taking one line of the TV scan, is given in figure 7. The minima of these curves correspond to the zeroes indicated by equation (7), but slightly displaced to larger angles because of convolution with the finite filter bandwidth.

Eventually, observation of angular distribution with various filters was repeated with the current in the undulator reversed. Figure 8 is an example of how the interference between undulator and edges modifies the angular distribution: at angles where the amplitudes of light from the two sources are non-zero, there can be enhancement or suppression depending on the relative phase.

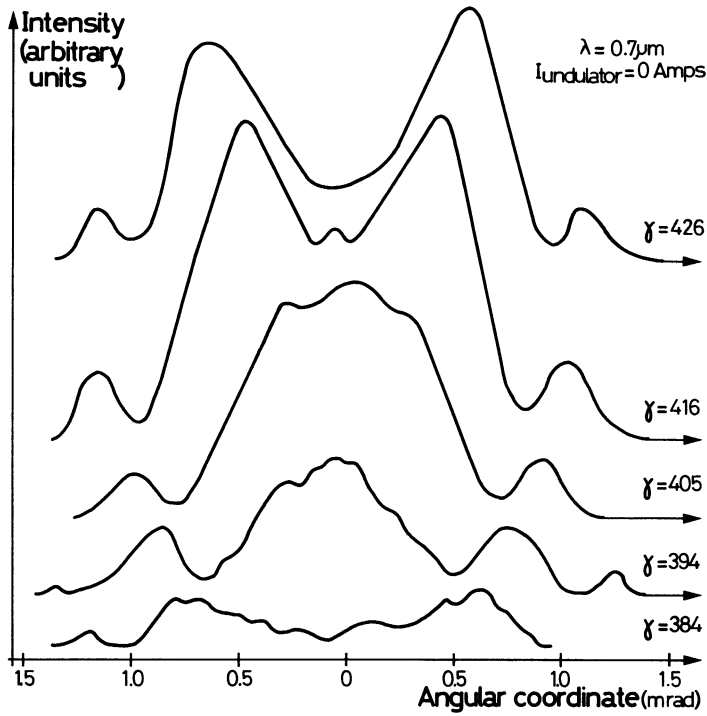


Fig. 7. — Angular intensity distribution ($\phi = \pm \pi/2$) of light through a $\lambda = 0.7 \mu\text{m}$ filter. This shows the evolution of the rings due to interference of edges (the undulator is turned off).

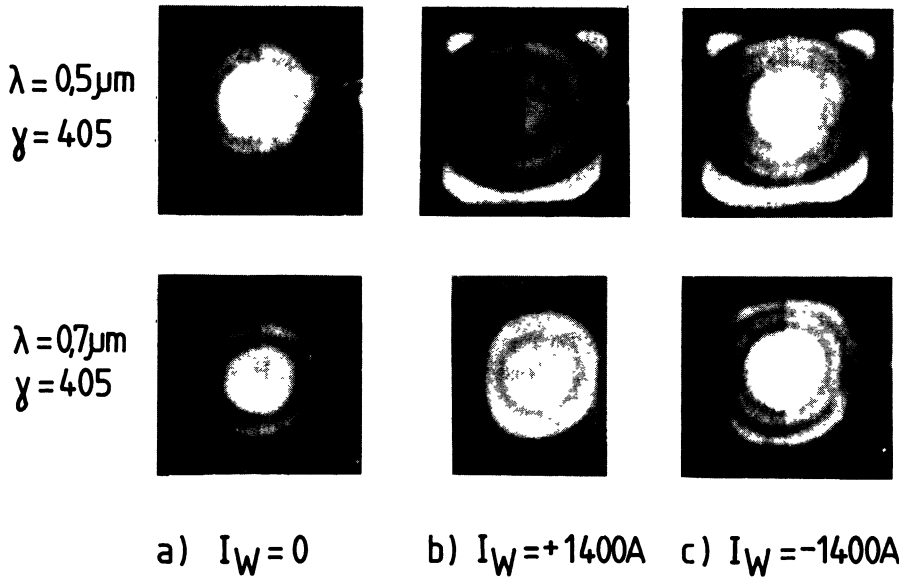


Fig. 8. — Angular distribution ($\gamma = 405$): a) without undulator (edges only), b) with undulator, c) with undulator with reversed current (then magnetic field changed in sign). The change in intermediate rings is due to interference of undulator radiation and « edge effect ».

Here the effect is small because the two sources have different angular distribution at the same λ , and interference occurs between an inner sidelobe of the $\sin^2[(k - k_0) L/2]/[(k - k_0) L/2]^2$ undulator spectrum and an outer ring of the edges, therefore only a qualitative observation has been possible.

5. Conclusion.

The present observations were not only of academic interest, extending to the case of protons and antiprotons the experimental studies that have been developed up to now only with electrons, and showing peculiarities which are connected with the unusual value of the parameters (undulator peak at frequency higher than critical frequency in bending magnets, interference between edges), but was also necessary to assess the possibilities and limitations of the apparatus for beam current density imaging.

Besides the verifications of linearity with current, with B^2 , etc., which in practice served rather to show that there were no other disturbing spurious effects (except noise), the study of the angular distribution (including the limited angular acceptance) was necessary to estimate the effect of light diffraction and the limited depth of field of the image formation, as analysed in reference [14], and therefore the resolution obtainable as a beam imaging device, which turns out to be of the order of 0.2 mm.

The $p\bar{p}$ beam imaging apparatus, which has the property of being completely non-destructive for the beam, and non-disturbing to other nearby instruments, is being used for continuous follow-up of the beam sizes and form for each individual circulating bunch (Ref. [15]).

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