EMITTANCE MEASUREMENT AT AMPS AND DELTA USING LASER COMPTON SCATTERING

G. Luijckx, R. Maas, R. Tamoschat
NIKHEF, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands
N. Marquardt
DELTA, University of Dortmund, Emil-Figge Str. 74b, 44221 Dortmund, Germany

Abstract

A non-destructive method for determining the electron beam transverse emittance at the Amsterdam Pulse Stretcher (AmPS) ring and the Dortmund Electron Test Accelerator (DELTA) is described. The emittance is calculated by measuring the beta functions and the electron beam transverse profiles. Monitoring of the horizontal and vertical tune shifts by wobbeling one of the machine quadrupoles provides the beta functions. The beam profile is obtained by scanning the electron beam with a laser beam and measuring the Compton scattered photons downstream from the interaction point. The goal is to measure the emittance with an accuracy of better than 20%. This method has been chosen because of the comparatively small beam sizes at DELTA and the wide range in beam size of an order of magnitude needed to be covered. At present estimated beam sizes at AmPS are of the order of a fraction of 1mm. In the near future vertical beam sizes below 100μm are expected for both AmPS and DELTA.

1 INTRODUCTION

To measure transverse emittance is important, because

- the luminosity of the interaction at facilities designed for collision experiments
- the brightness of the photon beam generated at synchrotron radiation sources
- the free electron laser (FEL) gain

are all directly related to emittance.

The AmPS-ring [1] at the National Institute for Nuclear and High Energy Physics in Amsterdam is a combined stretcher and storage ring in operation for nuclear physics since 1992. The lattice has been designed for stretcher operation. The nominal parameters are 200mA of stored beam current, 900MeV energy, and a natural emittance of $160\mathrm{nm.rad}$. A new lattice configuration [2] has become operational recently in order to reduce the emittance by a factor of 3.

DELTA [3] is a 1.5GeV storage ring, located at the University of Dortmund, designed for FEL operation, general accelerator research and the generation of synchrotron radiation. The maximum current is 500mA. Natural emittances in the range $11 - 130\mathrm{nm.rad}$ are expected for different lattice configurations.

The emittance ϵ_u, $u = x, y$, in the two transverse directions will be deduced from measurements of the β-functions and the electron beam profiles σ_u according to the relation

$$\epsilon_u = \frac{\sigma_u^2}{\beta_u} \qquad (1)$$

at a location where the dispersion function is zero. Measurements of electron beam profiles by laser Compton scattering have been performed in the past under various beam conditions [4], [5].

2 BEAM PROFILE MEASUREMENT

2.1 *Principle set up*

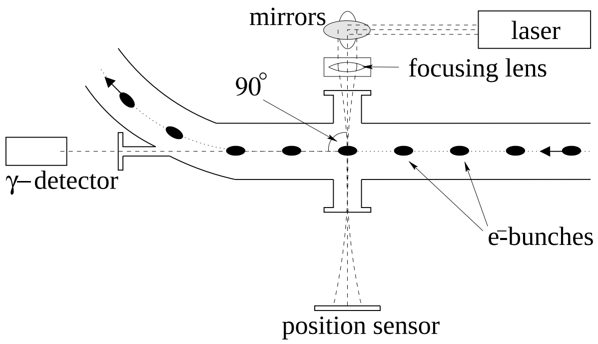

Figure 1: Top view of the profile measurement set up by laser Compton scattering.

A top view of the beam profile measurement set up by Compton scattering is presented in figure 1. A high-power, well-focused laser beam is interacting with the moving electron beam. The Compton scattered photons enter a detector located after the next bending magnet, downstream from the interaction point (IP). By translation of the focusing lens the electron beam is scanned by the laser beam. From the dependence of the detector signal on the vertical position of the laser beam the electron beam profile is deduced.

2.2 *Compton scattering*

The kinematic of Compton scattering is illustrated in figure 2. An incoming electron of energy E_0 interacts with a laser photon of energy k_0. The *energy* k of the outgoing photon is measured, the scattered electron is left undetected. The unpolarized differential cross section is given elsewhere [6].

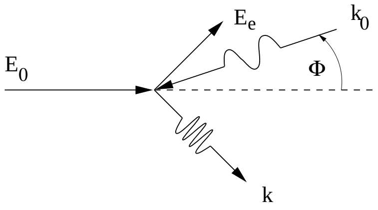

Figure 2: Kinematic of the Compton process.

The luminosity for the interaction of the electron and laser beam moving in directions z_e and z_λ respectively is

$$\mathcal{L}_{\mathrm{comp}} = 2c\cos^2(\Phi/2)\int n_e(\vec{x}_e,t)\,n_\lambda(\vec{x}_\lambda,t)\,dx\,dy\,dz\,dt \tag{2}$$

where n_e, n_λ are the electron and laser photon densities respectively and c is the speed of light. Luminosities for different configurations have been calculated. The results, given in sections 2.3 and 2.5, depend on

- the interaction angle Φ
- three different principles of laser operation: continuous wave (cw), Q-switched, and modelocked
- the longitudinal position in the ring

2.3 Choice of the geometry and position

Signal rates and accuracies have been calculated for two different geometries, in particular for an interaction angle $\Phi = 0^\circ$ (Compton backscattering) and $\Phi = 90^\circ$.

1. Compton backscattering: signal rates are sufficient for all types of lasers considered, but a large systematic error in the profile measurement of 43% for a Q-switched or cw-laser and 13% in case of a modelocked laser was calculated. The error is due to averaging the transverse electron beam size in the longitudinal direction.
2. 90° interaction: beam sizes are measured at one fixed longitudinal position. As will be shown in section 2.5 sufficient signal to noise ratio can be obtained with a Q-switched laser.

Based on these results the 90° interaction as sketched in figure 1 is chosen. At AmPS the position at the end of a 32.5m long straight section is chosen as IP, because of zero dispersion, despite the larger background due to bremsstrahlung. A suitable interaction chamber is under construction.

2.4 Background

The strongest component of the background is due to bremsstrahlung from interaction of the electrons with the residual gas. The differential cross section for this process depends to good approximation quadratically on the atomic number Z of the rest gas [7]. The luminosity for bremsstrahlung increases linearly with the gas pressure $P[\mathrm{Pa}]$, the average electron beam current $I[\mathrm{mA}]$ and the interaction length $l_{\mathrm{int}}[\mathrm{m}]$

$$\mathcal{L}_{\mathrm{brems}} = 4.521\times 10^{10}\frac{P\cdot I\cdot l_{\mathrm{int}}}{T}(\mathrm{s}^{-1}\mathrm{b}^{-1}) \tag{3}$$

For reasons given in sections 2.5 and 2.6 energy rate rather than count rate is being measured. For bremsstrahlung the energy rate dE_{brems}/dt is given by

$$\frac{dE_{\mathrm{brems}}}{dt} = \mathcal{L}_{\mathrm{brems}}\cdot\int_0^{E_0}\frac{d\sigma_{\mathrm{brems}}}{dk}k\,dk \propto E_0 \tag{4}$$

The expected values for dE_{brems}/dt of bremsstrahlung photons with energies above 0.1MeV for 100mA average e$^-$-beam current is presented in table 1.

Table 1: Expected background for typical AmPS and DELTA machine parameters and given interaction length.

	AmPS	DELTA
e$^-$-beam energy E_0 [GeV]	0.9	1.5
atomic number Z	5	5
vacuum pressure P [Pa]	6.7×10^{-7}	1.3×10^{-8}
interaction length l_{int} [m]	32.5	6.5
dE_{brems}/dt [MeV/s]	8.1×10^{7}	5.4×10^{5}

Background from synchrotron radiation is completely negligible, since the critical energy at AmPS and DELTA is 0.49keV and 2.26keV respectively at nominal beam energy. One has to compare these values with multiples of the mean energy of the Compton scattered photons of 7.1MeV for AmPS and 19.6MeV in the case of DELTA.
Charged particles will be vetoed by a plastic scintillator placed in front of the photon detector.

2.5 Choice of the laser

For a 100mA electron beam of nominal energy and electron beam parameters as given in [1], [3] signal to noise ratios have been calculated for three types of laser. An average laser power of 1W, 532nm wavelength and a focus spot size of $\sigma_{x_\lambda}\times\sigma_{y_\lambda} = 20\mu\mathrm{m}\times 20\mu\mathrm{m}$ have been assumed. Particle density distributions for both beams were assumed to be Gaussian. Electron beam envelope and Gaussian propagation of the laser beam have been taken into account. The results for AmPS are presented in table 2. For DELTA the signal is a factor 2.8 larger for the cw or Q-switched laser, and a factor 3.7 in case of the modelocked laser. Since background is a factor 150 smaller compared to AmPS an excellent signal to noise ratio is expected for DELTA.
For the cw and the modelocked laser signal and background are continuous with respect to the time scale given by the energy measurement. For the Q-switched laser all the Compton photons are produced within a time in the order of the laser pulse width. By gating the detector the signal to noise ratio can be drastically improved . Based on these results a Q-switched laser has been chosen.

Table 2: Compton signal dependent on vertical electron beam size σ_{y_e}. Effective signal to noise ratio for a cw, Q-switched and modelocked laser at AmPS.

	cw	Q-sw.	model.
peak power	1 W	10 MW	14 W
repetition rate		10 Hz	476 MHz
FWHM pulse width		10 ns	150 ps
$\frac{dE_{\mathrm{comp}}}{dt}$ [MeV/s]			
($\sigma_{y_e} = 500\mu$m)	$2.1 \cdot 10^3$		$1.7 \cdot 10^4$
($\sigma_{y_e} = 100\mu$m)	$1.0 \cdot 10^4$		$8.3 \cdot 10^4$
($\sigma_{y_e} = 50\mu$m)	$1.9 \cdot 10^4$		$1.6 \cdot 10^5$
gating time $[\frac{\mathrm{ns}}{\mathrm{pulse}}]$		100	
signal/noise			
($\sigma_{y_e} = 100\mu$m)	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^2$	$1.0 \cdot 10^{-3}$

A 10Hz Nd:YAG laser [1] with FWHM pulse width of 8ns is the laser of choice. The second harmonic ($\lambda = 532$nm) with an output energy of 200mJ/pulse is used.

2.6 Detector and expected results

In order to improve the pulsed signal with respect to the continuous background, the detector signal should be integrated over a time comparable to the full length of the laser pulse (~ 20ns), thus a fast photon detector is required. The use of undoped cesium iodide or barium fluoride as suitable material is considered. Energy resolution of calorimetric detectors improves with deposited energy E as $1/\sqrt{E}$. The energy deposited by Compton photons per laser pulse for a 100mA beam current is expected to be in the order of several 100MeV. Therefore it is estimated that an energy resolution of better than 10% is achievable. Since energy resolution improves with increasing integration time a compromise between resolution and signal to noise ratio needs to be found.

Finally the beam parameters and expected signal to noise ratios $(S/N)_{x,y}$ calculated for the IP and the laser of choice are presented in table 3. Gating time of the photon detector is 100ns and 1μs for AmPS and DELTA respectively.

Table 3: Natural horizontal emittances, vertical emittances for 50% coupling, transverse beam sizes at the IP and signal to noise ratios (S/N) as expected for standard and reduced/low emittance lattices at AmPS and DELTA.

	AmPS		DELTA	
	std. ϵ	red. ϵ	std. ϵ	low ϵ
ϵ_x [nm.rad]	160	52	43	11
ϵ_y [nm.rad]	32	10	9	2
σ_x [μm]	1140	660	620	310
σ_y [μm]	270	240	290	140
$(S/N)_x$	$2.2 \cdot 10^1$	$3.9 \cdot 10^1$	$1.7 \cdot 10^3$	$3.3 \cdot 10^3$
$(S/N)_y$	$9.6 \cdot 10^1$	$1.1 \cdot 10^2$	$3.7 \cdot 10^3$	$7.2 \cdot 10^3$

3 MEASUREMENT OF β-FUNCTIONS

At AmPS and DELTA the β-functions are obtained by changing the quadrupole focusing strength K by a few percent and observing the induced tune shift $\Delta\nu$

$$\Delta\nu = \frac{1}{4\pi} \oint \Delta K(s)\beta(s)ds \simeq \frac{1}{4\pi}\Delta K_{\mathrm{q}}\beta_{\mathrm{q}}l_{\mathrm{q}} \quad (5)$$

where l_{q} denotes the effective length of the chosen quadrupole, and the β-function at this position β_{q} is assumed to be constant within the quadrupole. The tune can be measured by Fourier-analyzing the signal of a beam position monitor.

At AmPS this method has been applied in the past and given reliable results in good agreement with theoretical predictions. At present the absolute accuracy in the tune measurement is about 0.002 and the error in changing the K-value is 5%. The future goal is to achieve an error in the β-function measurement of better than 2%.

At DELTA work on the ring is still in progress. β-functions have not been measured yet, since first beam has been produced very recently (May 1996).

4 DISCUSSION

A sufficient signal to noise ratio can be obtained by $90°$ Compton scattering using a Q-switched 200mJ/pulse laser at AmPS and DELTA. Since electron beam size increases linear with beam energy the values for beam sizes given in table 3 are upper limits.

Gating of the detector is necessary to reduce bremsstrahlung background. The error of the profile measurement is mainly determined by the error of the energy measurement. It is expected that the required accuracy in the profile measurement of better than 10% can be achieved.

5 REFERENCES

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