OPTICAL TECHNIQUES IN BEAM DIAGNOSTICS

M. Ferianis, Sincrotrone Trieste, Trieste, Italy

Abstract

Optical Techniques are widely used in beam diagnostic instruments giving more and more detailed information on different beam aspects. In recent years, the strong development of opto/electronic components and the thorough exploitation of physical phenomena, in the field of particle-to-photon converters, have greatly contributed to the diffusion of optical based Diagnostic tools. In this paper an overview on optical techniques in beam diagnostics is given with a detailed analysis of optical sources like Synchrotron Radiation, Transition Radiation and Diffraction Radiation. A first broad classification is possible based on the wavelength of the observed radiation: x-ray, visible, IR and mm-wave radiation based instruments are dealt with in this paper. Optical techniques which routinely measure beam profiles are presented and examples of state of art methods given.

1 INTRODUCTION

In recent years extensive developments have been made in optical techniques in beam diagnostics to fulfil the instrumentation requirements from new machines (e.g. 4th generation Light Sources [1], FEL [2]). Producing smaller and smaller beams, in 6D phase space, puts more and more stringent requirements on the performance of diagnostics. This intense activity is confirmed by the fact that optical techniques are though to be used for new measurements, like Optical Beam Position Monitors [3] based on Diffraction Radiation [4].

An optical technique extracts beam information from optical radiation, embedded between high energy X-rays and the Microwaves [5]. The frequencies extend from 3×10^{12} to 3×10^{18} Hz and the photon energies from 0.012 eV to 12.408 keV. The performance relies on the selected optical source, i.e. the physical process generating the radiation. Also the opto-electronic detector and the whole acquisition system contribute to the achievement of optimum performances. Three optical sources are dealt with in this paper:

- Synchrotron Radiation (SR)
- Transition Radiation (TR)
- Diffraction Radiation (DR)

2 OPTICAL RADIATION SOURCES

The electric field of a randomly moving charged particle may present two terms, depending on $d\beta/dt$ [6]:

$$\mathbf{E} = \mathbf{E}_C + \mathbf{E}_R \qquad (1)$$

$\mathbf{E}_C$ is the Coulomb field, also called near-field, and it is proportional to $1/r^2$: it is predominant close to the charge.

$\mathbf{E}_R$ is the Radiation field, also called far-field, and it scales as $1/r$. $\mathbf{E}_R$ reaches large distances from the source and it is proportional to both the velocity (β) and acceleration ($d\beta/dt$) of the charge. Many properties of $\mathbf{E}_R$ (radiated power, spatial distribution etc.) improve with γ (Lorentz Factor). Electrons start generating optical radiation at much lower total energies than protons.

3 SR BASED DIAGNOSTICS

3.1 Synchrotron Radiation

Both longitudinal and transverse (γ^2 factor more radiation), w.r.t. the charge motion, accelerations generate $\mathbf{E}_R$ [7]. The radiation produced by transverse acceleration due to a perpendicular magnetic field **B** is called Synchrotron Radiation (SR).

SR characteristics [6,7] relevant to diagnostics are:

- small vertical opening angle: diffraction effects

$$\alpha_c \cong 1/\gamma\, (\lambda/\lambda_c)^{1/3} \quad \text{for } \lambda \ll \lambda_c \qquad (2)$$

where $\lambda_c = 4\pi\rho/3\gamma^3$, strongly collimation in the forward direction

- finite emission zone length: depth of field effects
- polarization: $E=E_\sigma+E_\pi$, with $E_\pi=0$ in the orbit plane
- broad spectrum: $\omega_{max}=2\pi/\Delta t=3\pi c\gamma^3/2\rho$, being

$$\Delta t = t_f - t_0 = 4\rho/3c\gamma^3 \qquad (3)$$

- high power density: critical extraction mirror

The number of emitted photons by a single electron in one revolution is: n/rev. = 0.0662γ [6].

3.2 Transverse profile measurements

3.2.1 Imaging

A recent review of SR based techniques can be found in [8]. The theory of SR imaging can be found in [9]. Due to the small vertical beam emittance and to the finite length of the emitting source, diffraction and depth of field (dof) limit the resolution of SR imaging. Considering the geometry of SR imaging (paraxial approx.), diffraction is generally treated in the Fraunhofer approximation. The field, E_σ and E_π, components on the image plane are computed from the source field distribution, considered as 2D Gaussian.

For SR from a bend, the contributions of diffraction and depth of field are [10]:

- $\sigma_{(\sigma+\pi)diff} = 0.279\, (\lambda^2/\rho)^{1/3}$ (4)
- $\sigma_{(\sigma)diff} = 0.206\, (\lambda^2/\rho)^{1/3}$ (4')
- $\sigma_{(\pi)diff} = 0.429\, (\lambda^2/\rho)^{1/3}$ (4'')
- $\sigma_{dof} = 0.34\, (\lambda^2/\rho)^{1/3}$ (5)

By using the E_σ component, only, and imaging at shorter λ, diffraction effects are minimised. Though, on

MAX-II, a σ_y= 15 μm has been measured using the E_π component of SR [11].

To evaluate the emittance from $\sigma_{x,y}$ or $\sigma'_{x,y}$, the lattice functions (α, β, γ, η) at the source point have to be known. The following relation is used [7]:

$$\sigma_{X,Ytot} = \sqrt{\varepsilon_{X,Y} \cdot \beta_{X,Y}(s) + \eta^2(s) \cdot \sigma^2{}_\delta} \tag{6}$$

The limited knowledge of the lattice functions also limit the accuracy of the emittance measurements.

At DAΦNE [12], the image acquisition and analysis of the profile monitor rely on a Laser Beam Diagnostics system [13].

3.2.2 X-ray imaging

X-ray imaging improves the resolution due to reduced diffraction effects. The x-ray image from a pinhole (d=diam.), placed at a distance L_o from the source, is acquired by a CCD camera via a converter screen, placed at L_i from the pinhole. If the electron beam divergence is smaller than the SR natural opening angle, than only beam size measurement allows the determination of beam emittance. The contributions to the measured image due, respectively, to pinhole non-zero dimensions ($S_{pinho.}$), diffraction from the pinhole [15], S_{diff}≅$0.52\lambda L_i/d$, and screen plus acquisition system (CCD, lens) resolution (S_{screen}) have to be carefully evaluated for a pinhole systems [14,15,16]. S_{diff} can be a few μm [14].

Beam size computation from the acquired image requires the deconvolution of the pinhole diffraction pattern and video camera resolution from the measured image. Also for pinhole systems, limited knowledge of machine parameters ($\alpha,\beta,\eta,\eta',\sigma_e$) affects the final result.

3.3 Longitudinal profile measurements

3.3.1 Time-domain techniques

The duration of the single electron SR light pulse (3) is negligible (≈10^{-15} s) if compared to typical bunch lengths (10^{-10} to 10^{-12} s). Therefore, the intensity profile vs. time of the SR pulse represents the charge distribution along the orbit. Time-domain techniques allow the measurement of the longitudinal profile down to ≈1ps ("Picosecond Diagnostics" [18]). Single-Shot techniques allow also a dynamic observation of the bunch [19,20], even on a turn-by-turn basis. The Streak Camera (SC) is the ideal instrument to perform Single-Shot measurements with ps resolution. With additional optical arrangements, 3D (long. and trans.) beam imaging has been performed on LEP [21]. At CERN, the autocorrelation function of the SR pulse from LEP has been measured in single-shot with a few ps resolution, by means electro-optic devices (fast CdTe photoconductor [22]). Sampling techniques measure the average (on successive turns) profile: a very stable beam and trigger are required. The Optical Sampling Scope [23] acquires repetitive signals up to 30 GHz.

At ELETTRA, both techniques have been tested [24]: the SC data (σ vs. I_b) almost overlay with the ones taken with a fast Photodiode [25] which was directly connected to a 50 GHz sampling scope head [26].

At ELETTRA, a new SC [27] system will be installed, October this year. With a Synchroscan frequency of 250 MHz, the acquisition of consecutive bunches, 2 ns apart, will be possible. The Control System integration of the SC [28] is implemented on a VXI-PC [29], running LabView® [30]. This solution provides the VXI hardware environment [EMI/EMC features, ease of integrating custom timing (jitter < 2 ps) and interlock boards, power supplies] with the LabView®/CVI®/ Windows®OS software environment. As a confirmation, the VME Image Processing Board [31] has been rapidly linked to the VXI-PC, via a LabView® dedicated driver.

3.3.2 Frequency-domain techniques

Frequency-domain techniques cover fsec bunch lengths [32]. Independent of the physical process (SR, TR, Cherenkov Rad. [33], Diffraction Rad., Smith-Purcell Rad. [34]) generating the observed radiation, the Power spectrum is defined as [35,7]:

$$P(\lambda) = P_0(\lambda)N + P_0(\lambda)N(N-1)f(\lambda) \tag{7}$$

where N is the number of particle in the bunch, $P_0(\lambda)$ is the single particle Power spectrum and f(λ) is the form factor (equal to the squared Fourier transform of the longitudinal distribution function S(z) of the bunch):

$$f(\lambda) = \left| \int S(z) \cdot e^{2\pi i z/\lambda} dz \right|^2 \tag{8}$$

The form factor for a gaussian bunch profile is [36]:

$$f(\lambda)=\exp(-4\pi^2\sigma^2/\lambda^2) \tag{9}$$

with $L_b=\sqrt{(2\,\pi)}\sigma$, or for a rectangular profile:

$$f(\lambda)=(\sin x/x)^2, \tag{10}$$

where $x=\pi L_b/\lambda$, L_b is the bunch length.

The two terms in (7) represent the incoherent and coherent emission. The form factor can be estimated only from coherent emission. Coherent emission requires the form factor to extend up to the frequencies where $P_0(\lambda)$ is non-zero. Only ultra-short bunches emitt coherently [37]. Very recently, techniques using also incoherent radiation have been proposed [38, 39].

A technique, based on a Coherent SR (CSR) Power detector, has been developed [40] at CEBAF to measure ultra-short electron bunches (L_b=0.5 mm). The CSR Power detector uses a GaAs Shottky diode (500 GHz - 3 THz) which measures the power of CSR for λ=0.05÷1mm. A very good resolution has been obtained (few fsec for gaussian bunches) as the CSR Power signal varies from 2.8 V (σ_{RMS}=450 fsec) to 13.5 V (σ_{RMS}=91 fsec).

3.4 Technological issues

Extraction mirror configurations coping with the SR heat loads (P_{tot}>1kW) are under study at multi-GeV Storage Rings. On ESRF Storage Ring [41], a temperature sensor moves the mirror vertically off the central part of the SR beam. At PEP-II, on HER [42], a grazing incidence slotted mirror is used; an adaptive optics mirror (325 independent 0.5x0.5 mm reflecting elements [43]) is under test. At the APS Storage Ring [44], a slotted cooled vacuum mirror is used with a tube absorber in front of it being now under test.

4 TR BASED DIAGNOSTICS

4.1 Transition Radiation

Transition Radiation (TR) is produced when a uniformly moving charged particle crosses the separation surface between two media with different dielectric constants. TR has been theoretically predicted in 1946 [45] but only in the mid 70's proposed [46] as a Beam Diagnostics technique. TR is widely used both on Linear and Circular machines. The main features are: directionality, promptness, linearity, angular distribution dependence on γ and ε. As the TR emission originates on a surface, very thin foils can be used making it almost non-destructive to the beam [47] and suitable for high-power (100 MW/mm^2 [52]), high-intensity (kA) beams [48]. The spectral intensity emitted (per unit solid angle) by a ultra-relativistic charge crossing a metal (ε>>1) foil in vacuum is [49] (transition metal to vacuum):

$$\frac{d^2W(\omega,\theta)}{d\omega \cdot d\theta} = \frac{q^2}{4\pi^2 c} \cdot \frac{\sin^2\theta}{\left(1-\beta\cos\theta\right)^2} \tag{11}$$

where β is the particle velocity and θ is the angle of emission with respect to the axis of the particle beam. The total angular field of the optical system has to be >4/γ as TR presents significant tails. The photon yield is γ dependent and it is adequate for γ>20 (≈1 ph./1000 e^- from Al foil in visible). The Formation Length:

$$L_V = \frac{\gamma^2\lambda}{2\pi} \tag{12}$$

also named Coherence Length, is defined as the distance measured along the electron path over which the Coulomb and Radiation fields are in phase (≤ 1 rad).

4.2 TR Transverse measurements

On line beam emittance measurements are possible [48]. By focusing the beam to an x(y) waist on a backward reflecting OTR foil, the x(y) beam spatial distribution, and beam divergence, can be measured using parallel, and perpendicular, polarised components: $\varepsilon_{rms}=\beta\gamma\theta_{rms}r_{rms}$,

where: θ_{rms} is the x(y) beam divergence, r_{rms} is the x(y) beam radius:

$$r_{rms} = \sqrt{\frac{\int x^2 I_x(x,y)dxdy}{\int I_x(x,y)dxdy}}$$

where $I_x(x,y)$ is the spatial intensity distribution of the image of the beam at an x waist. Beam sizes have been measured [51,52,71] below the so-called $\gamma\lambda$ limit. It may have been defined [53] after a miss-interpretation of OTR spatial distribution (which is actually much wider than ±1/γ). Studies on OTR resolution are under way [54,55]. OTR transverse phase space measurements have been carried out at European laboratories, as TTF [49] and ELETTRA [56]. Also beam position and profile evolution (in 1 μs steps) along the TTF macro pulse has been nicely measured [49,57].

Beam divergence can be estimated either with TR from a single foil or with a two-foil [48,58,59] interferometer (OTR Interferometer invented by Wartski [60]). Divergent beams cause the fringes to blur. L, ≥L_v, is the distance between the two foils. OTRI fringe position is related to γ as:

$$\theta_M = \sqrt{\frac{2\lambda}{L} \cdot \left(p - \frac{L}{2\lambda}\right)\gamma^{-2}} \tag{13}$$

θ_M is the maxima separation angle, p=k+0.5,k integer.

4.3 Bunch Length from Coherent TR (CTR)

CTR is very well suited for frequency-domain measurements as $P_0(\lambda)$ is flat with ω. Measuring sub-picosecond bunches with CTR has been proposed since 1991 [61]. By means of interferometric techniques (Michelson interferometry), the Interferogram (average time-domain plot) is obtained which represents the auto-correlation ($c_{ff}(t)=\int f(t)\bullet f(t-\tau)d\tau$) of the bunch distribution f(t). According to the Wiener-Khintchine relation [66]:

$$\left|F\{f(t)\}\right|^2 = F\left\{c_{ff}\right\} \tag{14}$$

where F\{f(t)\} indicates the Fourier transform of f(t), by Fourier transforming the Interferogram, P(λ) is obtained which is related to f(t) through the form factor f(λ). Interferometers are used as Spectrometers in Infra-Red Fourier Transform Spectrscopy (FT-IR) [62]. At Stanford (SUNSHINE) prof. Wiedemann's group has successfully applied this technique to the measurements of ultra-short bunches [63,64]. The following effects have been recently analysed [65]:

- beam splitter thickness (BS_{th}) interference effects ($BS_{th} \geq L_b$ / 3 reduces such effects).
- dispersion effects (rather than H_2O vapor absorption) due to the air propagation. The interferogram obtained in air was some 24 % wider than the vacuum one.
- reflections at the bolometer crystal, front and back, surfaces. Such reflections cause satellites on the interferogram which lead to a distorted spectrum.
- particle distribution evaluation from the computed spectra. The analysis, considering both a gaussian or rectangular particle distribution, concludes that the real shape is, probably, a gaussian core (L_b=84 μm) with a gaussian tail (150 μm). The critical determination of the bunch distribution is the main limitation of this method [32].

Longer (few ps) bunches have been measured with frequency-domain techniques also in European labs. At Darmstadt [68], the measured interferogram (Michelson type) has been corrected due to non-flat efficiency of the

Mylar beam splitter ($k=10\div100cm^{-1}$). A Streak Camera, measuring the FEL spontaneous emission harmonics, provided the information on the bunch profile, not available from the interferogram. At TTF, after a direct frequency measuremens by means of a Filter Spectrometer [67], a Martin-Puplett interferometer has been used. Thanks to wire grid polarises and reflectors it presents a flat efficiency [66].

The quadratic dependence on N (particle in the bunch) of the CTR Power spectrum has been confirmed by observations in many labs. [67, 69].

5 DR BASED DIAGNOSTICS

Diffraction Radiation (DR) occurs when a charged particle in uniform motion passes a conducting structure such as a circular aperture in a metallic foil. Accelerator physicists consider DR as a consequence of the energy loss experienced by electrons when they pass by any vacuum chamber discontinuity. Although DR has been studied since the early 60's, only in the very recent years it has been investigated as a diagnostic tool [4]. The name DR originates from the fact that it is produced by the diffraction of the field associated with the beam. DR has many features similar to TR, like spatial distribution and energy dependence; the main difference is that DR is non-destructive to the beam. The intensity of forward emitted DR from electrons moving at relativistic velocity can be expressed as [69]:

$$P(D,\lambda,\theta) = I_0(\lambda,\theta)\,[E(D,\lambda,\theta)]^2, \qquad (15)$$

where:

$$E(D,\lambda,\theta) = J_0\left(\pi D \sin\frac{\theta}{\lambda}\right)\cdot\frac{\pi D}{\beta\lambda\gamma}\cdot K_1\left(\frac{\pi D}{\beta\lambda\gamma}\right) \qquad (16)$$

and $I_0(\lambda,\theta)$ is the TR emitted from an electron passing a metallic foil in vacuum, D is the aperture diameter, β the particle velocity referred to c, γ the Lorentz factor, λ the wavelength of the radiation, θ the observation angle, J_0 and K_1 are the Bessel function of order zero and modified 1st order, respectively. Backward DR is described by the same formula by letting $\theta=\pi-\theta$. As:

$$|E(D,\lambda,\theta)| < 1$$

$$\lim_{\frac{D}{\lambda}\to 0} E(D,\lambda,\theta) = 1$$

when D tends to zero, DR tends to TR and it is always less intense than TR. In [69] a complete characterisation of DR is presented: both forward and backward DR have been observed, at the λ=0.9, 1.3 and 2.4 mm, from three circular apertures of different diameters (10, 15 and 20 mm). The investigated DR properties are:

- angular distribution
- intensity vs. beam current dependence
- spectrum

The observation of DR in not simple due to the geometrical measurement set-up. Forward DR from the aperture has been observed with simultaneous backward TR from the mirror and backward DR from the aperture has been observed with a partially reflected forward TR from the mirror. The angular distribution presents two peaks as TR; both peak separation and intensity decrease with D. Calculations confirm the measurements qualitatively (some discrepancies on peak separation).

The effects of different aperture (inner, a and outer, b) diameters have been used by Barry [70] to explain the frequency band-pass behaviour which appears in the DR field formula which he derived by applying Fraunhofer diffraction theory and which is valid for $a<\gamma\lambda/2\pi<b$, where:

$$\rho_e=\gamma\lambda/2\pi \qquad (18)$$

is the incident field effective radius. For given aperture size (*a*, *b*), the emitted DR decreases both at the longer λ, where $\rho_e>b$, and at the shorter λ, where $a>\rho_e$. When $b<\gamma\lambda/2\pi$ very little low-frequency energy is scattered by the foil; when $a>\gamma\lambda/2\pi$, again very little high-frequency energy is scattered.

The spectrum has been investigated [69] and the enhancement factor, due to Coherent DR (CDR), measured to be equal to $1.5\mathrm{x}10^8$ ($N=1.8\mathrm{x}10^8$e/bunch). From the measured spectrum the bunch length, L_b, has been determined by inverse Fourier transform of the $f(\lambda)^{1/2}$. The value of L_b=0.2mm, obtained by means of CDR, was found in agreement with data taken with other techniques: L_b=0.25 mm (CSR) and L_b=0.28 mm (CTR).

Diagnostic specific topics are covered in [4]:

- definition of a geometric set-up for DR observation without loosing the non-interceptive nature of DR.
- extension of TR based techniques to DR in order to be able to measure beam divergence, spatial distribution around the aperture, beam emittance and bunch length
- investigation of interferometric techniques with two foils, being L the distance between them.
- exploitation of CDR where the N^2 factor can make single shot measurements possible

A table, reported in [4], lists both for electrons and protons at different γ's the relevant quantities involved in a DR measurement as:

- $\lambda_{th\text{-}inc}=2\pi a/\gamma$: threshold wavelength for incoherent DR
- L_V, maximum coherence length (as in 12)
- $a_{max}(L_b)\cong\gamma\lambda/2\pi$: maximum aperture radius for coherent bunch length measurements for two different bunch length values. As for OTRI, the distance L between the two foils has to be in the range of L_v.

6 CONCLUSIONS

By using an appropriate combination of the optical techniques presented in this paper - based on Synchrotron, Transition and Diffraction Radiation - a complete analysis of relativistic beams is possible with the resolution (6D) required by new generation machines.

7 ACKNOWLEDGEMENTS

The author thanks the colleagues, from American and European laboratories, who shared the results of their works. Special thanks to A. Andersson, as SR advisor, H. Wiedemann for his support on Coherent TR, M. Castellano, J. C. Denard, D. Rule and A. Variola for their help in deepening TR techniques, R.P. Walker and C. J. Bocchetta for their patience in reading the manuscript.

8 REFERENCES

[1] H. Winick "4th Generation Light Sources", PAC'97.
[2] M. Cornacchia, SLAC Pub 7433 March 1997.
[3] J. C. Denard, private communication, May 98
[4] D. Rule et al. "Noninterceptive Beam Diagnostics Based on Diffraction Radiation", BIW '96, Argonne.
[5] E. Wagner et al."Optical Sensors", vol.6 part of "Sensors, a comprehensive survey". 1992, VCH .
[6] A. Hofmann, CAS 1989 on FEL - CERN 90-03.
[7] H. Wiedemann, "Particle Accelerator Physics", vol. II, Springer Verlag 1993.
[8] A. Andersson "Doctoral Thesis, University of Lund", 1997.
[9] A. Hofmann and F. Meot, NIM A203 (1982) 483.
[10] A. Hofmann "Beam Diagnostics and Applications", tutorial at BIW '98, Stanford.
[11] A. Andersson and O. Chubar "Beam Profile measurements with visible Synchrotron Light on MAX II", EPAC '96, Barcelona.
[12] C. Biscari et al. "DAΦNE Beam Instrumentation", BIW '98, Stanford.
[13] Spiricon(inc., Laser Beam Diagnostics LBA-100A.
[14] P. Elleaume et al., J. Synch. Radiation (1995) 2, 209.
[15] Z. Cai et al., Rev. Sci. Instrum. 67 (9) Sept. 1996.
[16] J.Safranek and P. Stefan "Emittance measurement at the NSLS X-ray Ring",
[17] J. Byrd "Beam measuremnts with synchrotron radiation", CAS on Beam Meas. May '98 Montreux.
[18] E. Rossa, Opt. Engineering (Aug. 95) 34 2353.
[19] K. Scheidt "Dual Streak Camera at the ESRF", EPAC '96, Barcelona
[20] A. Fisher et al. "Streak-Camera Measurements of the PEP-II High-Energy Ring", BIW '98, Stanford.
[21] E.Rossa et al. "Real Time Single Shot 3D measurement of Picosecond photon bunches", BIW '94, Vancouver.
[22] Developed in collaboration with LETI,Grenoble (F).
[23] Sampling Optical Oscilloscope, OOS-01,Hamamatsu.
[24] M. Ferianis et al. "Bunch Length Measurements at Elettra", DIPAC '95 Frascati
[25] NEW FOCUS Inc. Santa Clara (CA) USA
[26] Tektronix 11801A sampling scope - 50 Ghz head .
[27] Optoscope, Photonetics (D).
[28] S. Bassanese, "Tesi di Laurea, Univ. di Trieste",under preparation.
[29] VXI-PC 745, National Instruments.
[30] LabView and CVI, National Instruments.
[31] IC-40 VME Image Processing board, Eltec (D).
[32] G. Krafft "Diagnostics for ultra-short bunches", DIPAC '97, Frascati.
[33] Oyamada et al. "Coherent Radiation at Submillimeter and Millim. Wavelengths", PAC'93.
[34] K. Woods et al.,Phy. Rev. Lett.,74(19),p.3808,1995.
[35] Nodvick and D. Saxon, Phy. Rev. 96, 180 (1954)
[36] C. Settakorn et al. "Coherent far-infrared radiation from electron bunches", APAC '98, KEK.
[37] C. Hirschmugl et al., Phy.Rev.A 44, 1316, 1991.
[38] M. Zolotorev et al., SLAC-PUB-7132 March 1996
[39] J. Krzywinski et al., p.207, DIPAC `97, Frascati.
[40] D. X. Wang et al., App.Phys.Lett. 70(4) 529, Jan 97.
[41] K. Scheidt "UV and Visible Light Diagnostics for the ESRF Storage Ring", EPAC '96, Barcelona.
[42] A. Fisher "Instrumentation and Diagnostics for PEP-II", BIW '98, Stanford.
[43] MEMS Optical Inc., Huntsville, Alabama, USA.
[44] B. Yang and A. Lumpkin "Particle-Beam Profiling Techniques on the APS Storage Ring", BIW '96, Argonne.
[45] I. Frank and V.Ginzburg, J.Phys.USSR 9(1945) 363.
[46] L. Wartski "Doctoral Thesis, Universite de Paris Sud, Centre d'Orsay" (1976)
[47] J. C. Denard et al. "Experimental Diagnostics Using Optical Transition Radiation at CEBAF", BIW '94.
[48] R. B. Fiorito and D. W. Rule "Optical Transition Radiation Beam emittance Diagnostics", BIW '93.
[49] A. Variola "Doctoral Thesis, Universite de Paris Sud, Centre d'Orsay" (1998) - LAL 98-01.
[50] D. Rule and R. Fiorito "Imaging micron-sized beams with Optical transition Radiation", BIW '90 Batavia.
[51] X. Artru"Experimental investigations on geometrical resolution of electron beam profiles given by OTR in the GeV energy range", EPAC '96, Barcelona.
[52] J.C.Denard et al. "High Power beam Profile Monitor with Optical transition Radiation", PAC '97.
[53] K. McDonald and D. Russell, US-CERN School on "Observation ... in Particle Beams", Capri 1988.
[54] M. Castellano and V. Verzilov, LNF-98/017 (P), 1998. Submitted to Phy.Rev. ST Acc. Beams.
[55] X. Artru "Resolution power of Optical Transition Radiation: theoretical considerations", submitted to NIM B.
[56] M. Ferianis et al. "The OTR based Diagnostic system for the Elettra Linac: first results and future upgrades", DIPAC '97 Frascati.
[57] M. Castellano et al. "OTR Measurements for the TTF Commissioning", DIPAC '97, Frascati.
[58] X. K. Maruyama at al., NIM B79 p.788 (1993).
[59] A. Lumpkin et al., NIM A296 p. 150 (1990).
[60] L. Wartski et al. J. Appl. Phys 46 (1975) 3644
[61] W. Barry in "Workshop on Advanced Beam Instrumentation", KEK Proceedings 92-1, June 91.
[62] Application Note, Nicolet Instrument Corporation.
[63] P. Kung et al., Phy. Rev. Lett. Vol. 73 (1994) 967.
[64] H. Lihn et al., Phy. Rev. E Vol. 53 (1996) p. 6413.
[65] C. Settakorn et al. "Femtosecond electron bunches", APAC '98, KEK.
[66] K. Hanke "Doctoral Thesis, Universitat Hamburg, (1997) - Nov. 1997, TESLA 97-19.
[67] K. Hanke "Electron Bunch Length Monitors for the Tesla Test Facility", DIPAC '97, Frascati.
[68] V. Schlott et al., Part. Acc. Vol. 52, N. 1 (1996).
[69] Y. Shibata at al., Phys. Rev. E, 52 (1995) 6787.
[70] W. Barry "Measurement of Subpicosecond Bunch Profiles using Coherent TR",BIW '96, Argonne.
[71] P. Piot et al. "High Current CW Beam Profile Monitors using Transition Radiation at CEBAF", BIW '96, Argonne.