DAΦNE TECHNICAL NOTE

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DAΦNE MAIN RINGS SYNCHROTRON RADIATION MONITORS DESIGN CRITERIA

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Introduction

The synchrotron radiation monitors design for the DAΦNE Main Rings is presented. The first part of the note includes the analysis of the parameters which are relevant in optimizing the features of the source inside a dipole magnet and the description of the routine Synch1_2 specially developed to facilitate the monitor design. In the second part, the solutions adopted for DAΦNE are illustrated. The description of the machine measurements that will be performed is also included.

1. Source Definition

1.1 Characteristics of Synchrotron Light

The power spectrum of the synchrotron radiation emitted by a single electron, with energy E, moving along a circular trajectory of radius R is given by [1] (SI units):

$$\frac{\partial P}{\partial\psi\,\partial\lambda} = \frac{27}{32\,\pi^3}\frac{e^2 c}{4\pi\varepsilon_0}\frac{\gamma^8}{R^3}\left(\frac{\lambda_c}{\lambda}\right)^4\left(1+\gamma^2\psi^2\right)^2\left[K^2_{2/3}(\zeta)+\frac{\gamma^2\psi^2}{1+\gamma^2\psi^2}K^2_{1/3}(\zeta)\right] \qquad (1)$$

with

$$\zeta = \frac{\lambda_c}{2\lambda}\left(1+\gamma^2\psi^2\right)^{3/2}$$

and where ψ is the angle between the electron orbit plane and the trajectory of the emitted photon, λ is the photon wavelength, e is the electron charge, c is the speed of light, ε_0 is the permittivity of free space, $\gamma = E/m_0c^2$, $K_{2/3}$ and $K_{1/3}$ are modified Bessel functions and λ_c is the *critical wavelength* defined as:

$$\lambda_c = \frac{4}{3}\pi R\gamma^{-3} \qquad (2)$$

The synchrotron radiation is elliptically polarized. In (1) the term with $K_{2/3}$ represents the electromagnetic component with the electrical field vector in the plane of the orbit (σ-mode), while the one with $K_{1/3}$ describes the component which has perpendicular electrical vector (π-mode).

The typical opening angle is given, if $\lambda \gg \lambda_c$, by [1]:

$$\psi_{typ} \approx \frac{1}{\gamma}\left(\frac{\lambda}{\lambda_c}\right)^{1/3} \tag{3}$$

To obtain the power spectrum of the synchrotron radiation emitted in the bending magnets in a real ring of length L, we have to multiply (1) by the factor F_r :

$$F_r = \frac{2\pi R}{L} \tag{4}$$

1.2 Measurement Resolution

1.2.1 Horizontal Resolution & Source Length

In the hypothesis of gaussian beams, the horizontal resolution Δx can be calculated by the quadratic sum of three different errors:

$$\Delta x = \left(\Delta x_C^{\,2} + \Delta x_D^{\,2} + \Delta x_{DF}^{\,2}\right)^{1/2} \tag{5}$$

where

$$\Delta x_C = \text{curvature error}$$

$$\Delta x_D = \text{diffraction limit error}$$

$$\Delta x_{DF} = \text{depth of field error}$$

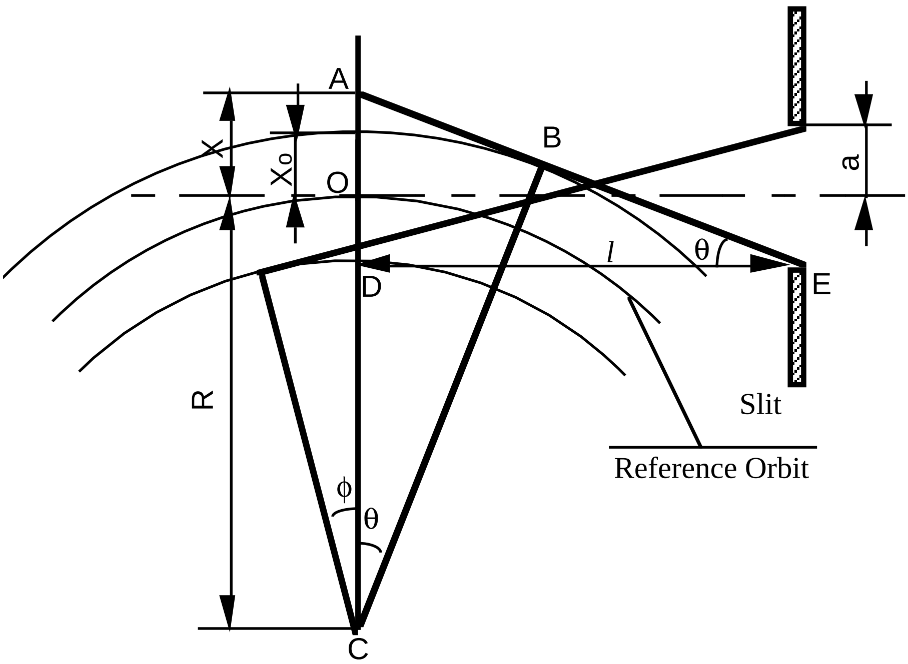

Figure 1. Typical Source Area Top View.

The source, as it will be shown later, has a finite size. The curvature of the particles trajectory, within this length, causes the curvature error. Figure 1 shows the essential geometry of a light source in a constant magnetic field area (dipole magnet case). The half horizontal size (envelope) of the electron beam is indicated with x_o . If the angles θ and ϕ are small enough (l » a, x_o) then x_o can be considered constant over the interested trajectory part.

In this approximation:

$$\begin{aligned} R + x_0 &= (R + x)\cos\theta \\ x + a &= l\tan\theta \end{aligned} \tag{6}$$

but

$$\tan\theta = \left(\frac{1}{\cos^2\theta} - 1\right)^{1/2}$$

which, used with the two previous expressions, gives the equation in the variable x :

$$\left[(R + x_0)^2 - l^2\right]x^2 + 2\left[a(R + x_0)^2 - l^2 R\right]x + a^2(R + x_0)^2 + l^2 x_0(x_0 + 2R) = 0$$

that has the physical solution:

$$x = \frac{l^2 R - a(R + x_0)^2 - \sqrt{l^2 (R + x_0)^2\left(a^2 - 2aR - x_0^2 - 2Rx_0 + l^2\right)}}{(R + x_0)^2 - l^2} \tag{7}$$

The value of x given by (7) is the beam horizontal size measured by the optical system (this can be seen in figure 1), then the curvature error in the measurement is given by:

$$\Delta x_C = x - x_0 \tag{8}$$

The same approach can be used for the angle ϕ (see figure 1). Anyway in real source geometries, this angle is very close to θ and it is generally a good approximation to use θ and the expressions (7) and (8) for the error estimate.

To calculate the longitudinal extension δz (length) of the source, or in other words the length of the part of the trajectory where the photons emitted by beam are collected by the optical system, one can write (see figure 1):

$$\delta z = (\phi + \theta) R \cong 2\theta R \tag{9}$$

where the approximated relation holds again for small angles. Once calculated x, θ can be derived using, for example, the second expression in (6).

The diffraction limit error can be evaluated using [2]:

$$\Delta x_D = \frac{\lambda}{2\,\upsilon} \tag{10}$$

where υ is the half aperture angle of the system source+slit and λ is the wavelength at which the measurement is done.

From figure 1:

$$\upsilon = arctan\,\frac{a}{l} \approx \frac{a}{l}$$

Finally the depth of field error can be expressed, with a good approximation, by:

$$\Delta x_{DF} \approx \frac{\delta z}{2}\,\upsilon \qquad (11)$$

where δz is calculated using (9).

1.2.2 Vertical Resolution

The vertical resolution of the measurement can be determined by the expression [3]:

$$\Delta y = \left(\Delta y_D^2 + \Delta y_{DF}^2\right)^{1/2} \qquad (12)$$

where

Δy_D = *diffraction limit error*

Δy_{DF} = *depth of field error*

In the same way of the horizontal case, we can write:

$$\Delta y_D = \lambda \,/\, (\,2\vartheta\,) \qquad (13)$$

and

$$\Delta y_{DF} = \delta z\ \vartheta \,/\, 2 \qquad (14)$$

where δz is given by (9), λ is the measurement wavelength and ϑ is the *total angular half-aperture of the photon beam* .

This angle comes from the photon beam intrinsic divergence, given by (3), and from the electron beam divergence which can be expressed by:

$$\psi_{beam} = (\gamma_y\,\varepsilon_y)^{1/2} = \left(\frac{1 + \alpha_y^2}{\beta_y}\,\varepsilon_y\right)^{1/2} \qquad (15)$$

where β_y , α_y , γ_y are the vertical Twiss parameters at the source point and ε_y is the beam vertical emittance (zero vertical dispersion has been assumed).

Considering that these two divergences are uncorrelated quantities, we can write (Gaussian distributions are assumed):

$$\vartheta = \left(\psi_{beam}^2 + \psi_{typ}^2\right)^{1/2} \qquad (16)$$

At this point it is evident that a proper choice of the system parameters (λ, l, a) has to be done in order to achieve the needed measurement accuracy.

Remark. It has been demonstrated [4] that the diffraction limit error (13) can be reduced using only the σ-mode polarized part of the synchrotron light. The reduction amount has to be evaluated by simulating and analyzing the diffraction pattern of this mode, using the parameters of the system under study.

1.3 Synch Routine

In order to facilitate the design and optimization of the DAΦNE synchrotron light source, the routine Synch1_2 has been developed. It is a FORTRAN code, which applies the previously described theory. The routine input quantities are the ring and beam parameters, the geometry of the light source, according to the nomenclature given in [3], and the wavelength interval one wants to use. The most relevant output parameters are:

Cut off Lambda : or critical wavelength (2).

Single e^- emitted power : obtained from the integration of (1), corrected with (4), over all the meaningful azimuth values and over the selected wavelength interval.

Normal/parallel power ratio : the ratio of the power emitted in the π - mode and that in the σ - mode. This quantity may be useful if one decides, as mentioned before, to use only the σ - mode to reduce the diffraction limit error.

Single bunch radiated power and total radiated power : They are respectively the power radiated by a single bunch and that radiated by the total beam current in the multibunch mode.

Source length : The value is calculated using (9).

Single bunch accepted power and total accepted power : These are the part of the emitted power which is accepted by the source system, for the single bunch and for all the beam respectively. These values are important in designing the optical line and in choosing the sensitivity of the detectors to be used in the measurements.

Single bunch peak power : It is the peak power of the accepted photon bunch (assuming gaussian beams). The knowledge of this quantity becomes useful if very fast detectors are used.

# of accepted photons/bunch : If the accepted power becomes very small and detectors like photomultipliers have to be used, then it is preferable to work in terms of number of photons. The output value is calculated using the average wavelength over the selected interval.

x measurement errors : The absolute and relative errors in the x (horizontal) beam dimension measurement, calculated from (5).

x curvature error : The value is calculated using (8).

x diffraction error : The value is calculated using (10).

x depth of field error : The value is calculated using (11).

y measurement errors : The absolute and relative errors in the y (vertical) beam dimension measurement, calculated from (12).

Diffract./depth of field error ratio : The ratio between the errors (13) and (14), which affect the vertical measurement.

Photon beam divergence. The value is calculated from (3).

2. DAΦNE Main Rings Synchrotron Radiation Monitor

2.1 Monitor Parts Description

2.1.1 Light Source

Table 1 shows the relevant DAΦNE parameters and Table 2 the optical characteristics at the selected source point[5]:

Table 1. DAΦNE General Parameters.

Energy	510 MeV
Ring Length	97.69 m
Dipole Bending Radius	1.4 m
Natural Emittance	10^{-6} m rad
Natural Relative Energy Spread	3.97×10^{-4}
Particles/Bunch	9×10^{10}
Max Number of Bunches	120
r.ms. Natural Bunch Length	8.1×10^{-3} m
r.m.s. Anomalous Bunch Length	3.0×10^{-2} m

Table 2. Characteristics at Source Point (1% Coupling)

β_x	6.46 m
β_y	7.87 m
α_x	0.468
α_y	0.165
Dispersion	~ 0 m
Horizontal Beam Size (rms)	2.5×10^{-3} m
Vertical Beam Size (rms)	2.8×10^{-4} m

Figure 2 shows the source region lay-out. The source points, one per beam, are 18.5 deg inside a parallel face dipole magnet in the DAΦNE ring half section (see also Figure 4). A 35 mm diameter aluminum mirror, 0.8 m downstream the source point, will vertically deflect the photon beam, through a vacuum window, onto a slit 1.065 m far away from the source point. A window on the photon beam axis, upstream the source point, allows the alignment of the optical line and the calibration of the transverse dimension measurement using a laser in behalf of the beam.

The average power on the mirror is 185 W, with 120 bunches at nominal current, the peak value is ≈ 2 kW (values calculated by Synch1_2). The power density is ~ 2.6 W/mm^2 for the average value and ~ 28 W/mm^2 (max) for the peak one. These numbers indicate that the mirror has to be water cooled and that an accurate design has to be done in order to avoid thermal deformations.

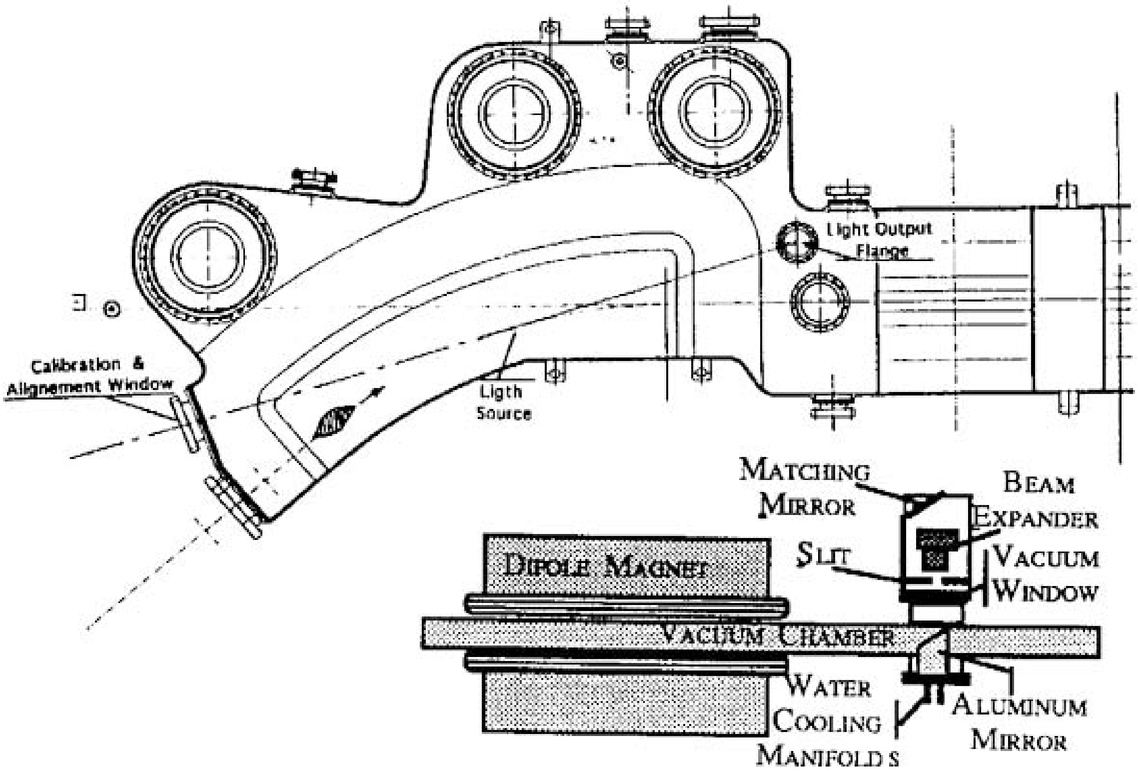

Figure 2. Light Source Lay-out.

A very important choice, in designing a synchrotron light monitor, is the range of wavelengths to use. From the measurements resolution point of view, the shorter is the wavelength the better is the resolution. On the other hand the optical line becomes difficult to set up and expensive for small wavelengths. As a reasonable trade-off, it has been decided to work within the visible range (~ 400 ÷ 700 nm; the necessary filtering is obtained by properly choosing the metallic mirror and the vacuum window). In this way two major advantages are obtained: a wide variety of commercial optical components (mirrors, splitters, etc.) can be used and the optical channel, which connects the light source to the instrumentation hall (see Figure 4), can be completely in air. Concerning the resolution, the situation is critical in the vertical transverse size measurement, because of the small beam height.

The Synch1_2 output file in Figure 3 shows that, with a maximum wavelength of 600 nm and a slit half aperture of 1 mm, the relative error on the vertical measurement is less than 4 %. Decreasing the wavelength value would decrease the error (Diffraction/Depth of Field Ratio = 2.949; Figure 3), but at the expenses of the power available for the measurement. The cut at 600 nm is provided by an optical filter, placed in the transverse size measurement set-up (see § 2.2.1).

Synch 1.2 400 - 600 nm ; PARALLEL FACE DIPOLE ; 0.01 coupling

LINE	
l0 (m)	: 0.5653
d (m)	: 0.2656
Slit Half Aperture (m)	: 0.1000E-02
RING PARAMETERS:	
Energy (MeV)	: 510.0
Relative Energy Spread	: 0.3970E-03
Natural Emittance (m rad)	: 0.1000E-05
Coupling	: 0.1000E-01
Bending Radius (m)	: 1.400
Revolution Frequency (Hz)	: 0.3068E+07
Number of Bunches	: 120.0
Charge/Bunch (C)	: 0.1442E-07
Bunch Length (sigma) (m)	: 0.3000E-01
BEAM OPTICAL FUNCTIONS @ SOURCE:	
Beta x (horizontal) (m)	: 6.457
Alpha x (horizontal)	: 0.4679
Eta x (horizontal) (m)	: 0.0000E+00
Deta x (horizontal)	: 0.0000E+00
Beta y (vertical) (m)	: 7.872
Alpha y (vertical)	: 0.1648
INTEGRATION PARAMETERS:	
Lambda Start (nm)	: 400.1
Lambda Stop (nm)	: 600.0
Lambda Number Int. Steps	: 2000
Ksi Number Int. Steps	: 50
CALCULATION RESULTS:	
Total Average Current	: 5.309 (A)
Cut Off Lambda	: 5.881 (nm)
Source Magnet Edge Angle	: 0.3230 (rad)
l: Source-Slit Distance	: 1.065 (m)
Single e- Emitted Power	: 0.3030E-11 (watt)
Normal/Parallel Power Ratio	: 0.3142
Single Bunch Radiated Power	: 0.2727 (watt)
Total Radiated Power	: 32.73 (watt)
Source Length	: 0.9299E-02 (m)
Single Bunch Accepted Power	: 0.2883E-03 (watt)
Total Accepted Power	: 0.3460E-01 (watt)
One Turn One Bunch Ac. Ener.	: 0.9397E-10 (joule)
Single Bunch Peak Power	: 0.3746 (watt)
# of Accepted Photons/bunch	: 0.2365E+09
Photon Average Lambda	: 500.0 (nm)
Electron Beam x dim (sigma) (m)	: 0.2529E-02
x Measurement Error (sigma) (m)	: 0.3196E-03
x Measurement Relative Error	: 0.7955E-02
x Curvature Error (m)	: 0.7735E-05
x Depth of Field Error (m)	: 0.4367E-05
REMARK: In the following part the larger lambda has been used	
x Diffraction Limit Error (m)	: 0.3194E-03
Electron Beam y dim (sigma) (m)	: 0.2792E-03
y Measurement Error (sigma) (m)	: 0.6773E-04
y Measurement Relative Error	: 0.2901E-01
Diffract./Depth of Field Error Ratio	: 2.949
Photon Beam Divergence (rad)	: 0.4677E-02

Figure 3. Synch 1_2 Output File: DAΦNE Light Source.

2.1.2 Optical Channel and Instrumentation Hall

Figure 4 shows the top and side view of the optical channels.

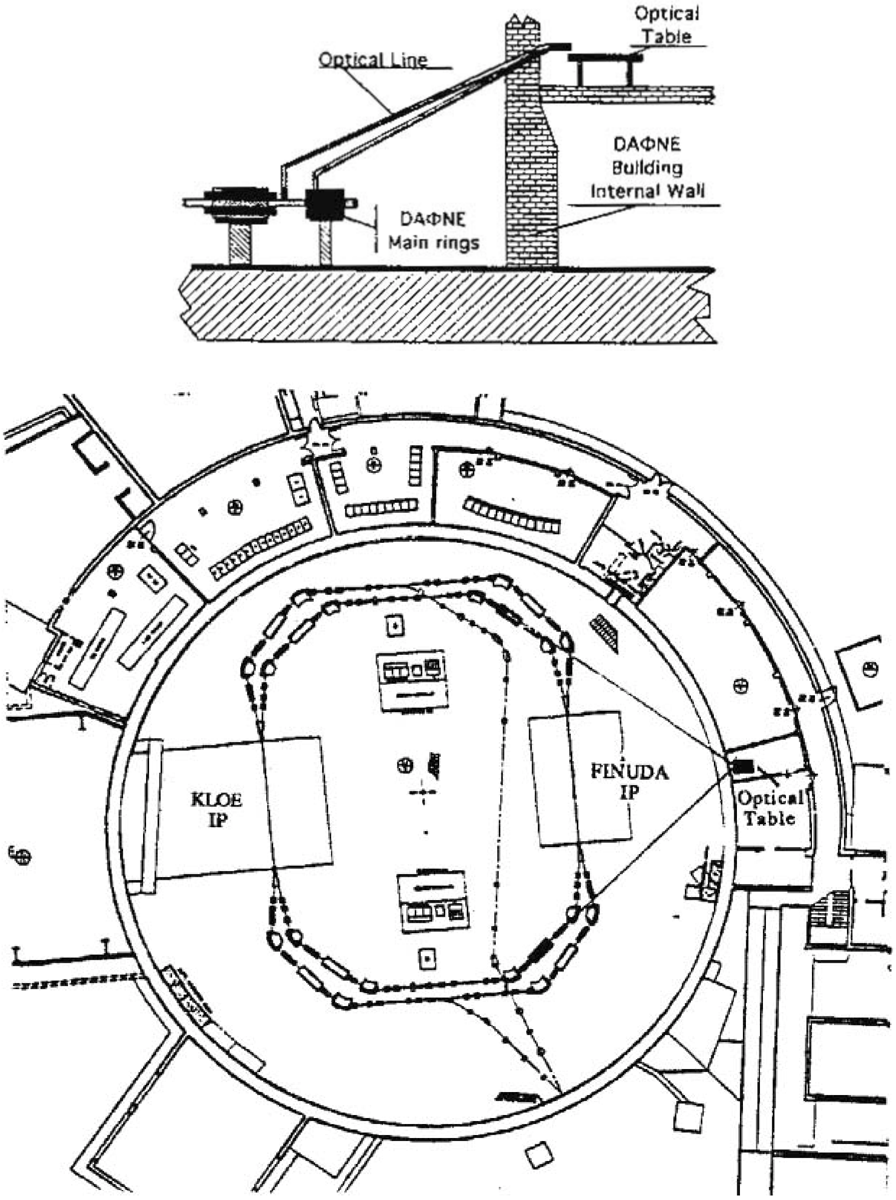

Figure 4. Optical Channels Lay-out. Side and Top View.

By observing the figure, some design criteria can be noted:

- The light source points are in the dipole magnet DHRPS201 of the positron ring and DHRES201 of the electron ring. They are optically equivalent. The choice of a zero dispersion region will allow the measurement of the beam emittances, as it will described in § 2.2.1.

- The optical lines, connecting the sources to the Instrumentation Hall, have mirror symmetry with respect to each other. This feature simplifies the design of the lines, makes the calibration of the measurements easier and allows interchangeability of the components between the lines.

- The Instrumentation Hall is outside the concrete wall of main rings hall, in a room at an higher level with respect to the machine plane. From the radiation hazard point of view, this feature makes the hall a safe area, where it is possible to stay when the beams are stored. The operations of setting-up and calibrating the measurement systems will result extremely simplified. It is worth remarking that the described capability allows to avoid the necessity of remotely controlled parts.

Each of the two optical channel starts from a beam expander downstream the slit, see figure 2. This is an achromatic system of lenses with focus in the source point. In this configuration, the divergent photon beam from the source is transformed in such a way that the photon trajectories become parallel to the optical line axis.

The distance between the source point and the slit is much larger than the distance between the slit and the beam expander (~ 10 times). This configuration makes the system able to tolerate relatively large transverse movements of the beam center of mass (coherent betatron oscillations, off-axis orbits).

A set of three mirrors transports the light from the source area to the optical table in the Instrumentation Hall. These mirrors must be mounted on kinematic optical mounts. No remote control is required because the setting operation will be performed using the photon beam of an HeNe laser through the calibration window. The first of this matching mirrors is visible in Figure 2; the other two will be placed on the instrumentation hall. The last optical component is another beam expander with focus in the detector of the transverse dimension measurement system (see § 2.2.1). The focus distance of this expander defines the overall optical system magnification. The described line, which is ~ 20 m long, must be surrounded by an opaque black pipe to prevent distortions due to thermal effects in air and to avoid noise caused by environmental stray lights.

Figure 5 shows the optical table lay-out. It is evident that also the configuration of this table (1.2×1.8 m^2) has mirror symmetry, with all the advantages already described.

The routine measurements (§ 2.2) will be independently and simultaneously available for both the beams. This feature will be obtained by properly splitting the light between the different measurement systems according to their detectors sensitivity.

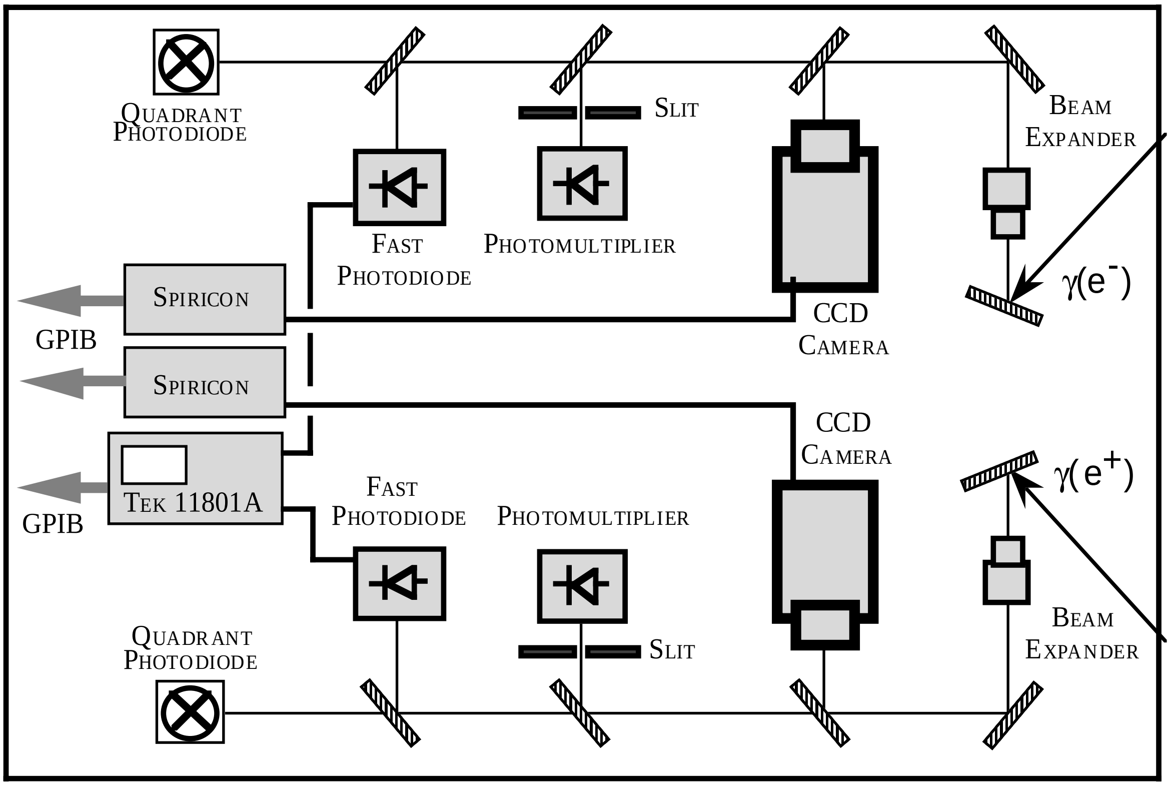

Figure 5. Optical Table Lay-out.

2.2 Routine Measurements

2.2.1 Transverse Beam Sizes

In order to measure the beam transverse distributions, a CCD camera and an image analyzer are used. The camera, a PULNIX TM 6 has the CCIR standard, 752 × 582 video matrix, CCD area 6.5 × 4.8 mm^2 with a pixel dimension of 8.6 × 8.3 μm^2. The best matching between the beam image size and the CCD area is obtained with a magnification of ~ 0.5. Anyway, a zoom objective in front of the camera permits to vary the overall magnification. This feature is helpful in improving the resolution in the vertical measurement.

The image analyzer is the SPIRICON LBA 100A which permits to capture, display and analyze the camera image. This device allows to present views of the beam transverse shape simultaneously to several calculations (horizontal and vertical beam dimensions, beam location, gaussian fits, etc.) with repetition rate up to 15 Hz. The SPIRICON is a stand alone instrument with a maximum repetition rate of the profile display on a color monitor of 15 Hz; the high speed GPIB data transfer permits the integration with the control system.

It is worthwhile mentioning, although obvious, that from the transverse size measurement, some important beam parameters can be derived:

- *beam emittances*., whose evaluation implies the knowledge of the ring optical functions at the source point.

- *beam transverse size variation* due to beam instabilities.

2.2.2 Bunch Length Measurement

The bunch length is measured by a fast detector+high bandwidth oscilloscope system. The New Focus 143-4 photodiode ensures DC-25 GHz bandwidth and 17 psec rise time. The conversion gain is 5 V/W and the maximum input power for linear response is 25 mW.

The coupling between radiation and the photodetector active area (25 μm diameter) is provided by a single mode fiber optic in which the light is collected by a GRIN lens collimator. The latter aperture is 3 mm diameter and the central accepted wavelength range is 633±15 nm. A variable optical attenuator is needed in front of the collimator to avoid saturation at high current.

The detector output is directly connected to the digital oscilloscope TEKTRONIX 11801A (50 GHz bandwidth and 200 KHz sampling rate). The integration with the control system is performed via IEEE488.

With these devices the bunch duration, assumed as gaussian with σ=100 psec, is measured with a negligible error: ~ 0.3%.

The oscilloscope sampling rate and record length imply that about 8000 turns are needed to sample the whole beam pulse. Therefore the bunch shape must be stable during the measurement (~ 2.7 ms).

The system sensitivity makes the measurement possible with stored currents as low as 2 mA. This feature should permit the study of the turbulent bunch lengthening in the case of DAΦNE.

2.2.3 Beam Incoherent Response Measurement.

Figure 5 also shows a slit+photomultiplier system for the beam transverse density measurement, whose set-up is showed in Figure 6.

The beam is transversely excited by a sweeping oscillator+kicker system. The slit, horizontal for the vertical measurement and viceversa, selects the photons around the light distribution maximum performing a measurement of the density around this position.

The effect of incoherent oscillations on the beam is to decrease this density [6]. In this way the existence of non-linear phenomena (read beam-beam interaction, lattice non-linearities, ion trapping, etc), that generates incoherent oscillations, can be detected and measured [7].

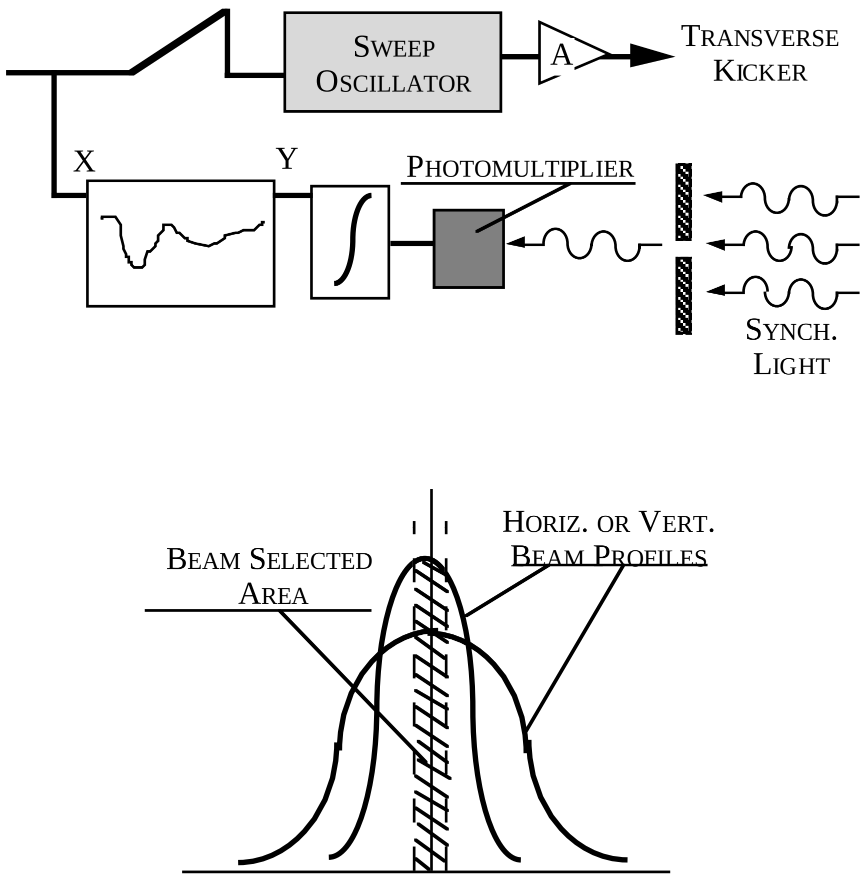

Figure 6. Density Measurement Set-up.

2.2.4 Tune Measurements

A method for measuring the machine tunes using synchrotron radiation is shown in Figure 7.

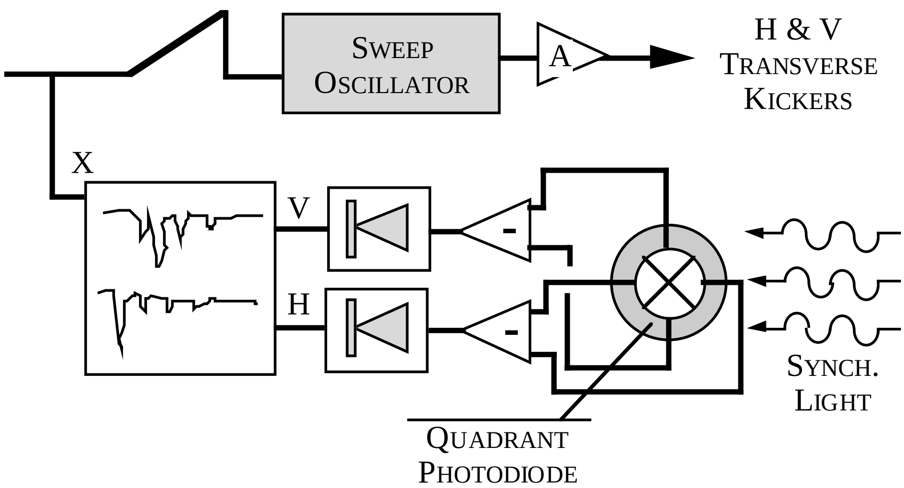

Figure 7. Tune Measurement Set-up.

The measurement uses almost the same set-up of the previously described density measurement, but the detecting device is now a quadrant photodiode which, in the shown configuration, is sensitive to the photon beam center of mass position (it is the optical equivalent of an electromagnetic beam position monitor). Exciting the beam in both the transverse planes, a simultaneous tune measurement can be performed.

Apart from the tune measurement, the quadrant photodiode is used for the alignment of the line on the optical table (see Figure 5).

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