MICRON SIZE LASER-WIRE SYSTEM AT THE ATF EXTRACTION LINE, RECENT RESULTS AND ATF-II UPGRADE

Blair, G A (John Adams Institute at RHUL) *et al*

01 December 2009

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579.

This work is part of EuCARD Work Package **9: Technology for normal conducting higher energy linear accelerators**.

MICRON SIZE LASER-WIRE SYSTEM AT THE ATF EXTRACTION LINE, RECENT RESULTS AND ATF-II UPGRADE[*].

G. A. Blair, S. T. Boogert, G. Boorman, A. Bosco, L. Deacon, P. Karataev
(John Adams Institute at RHUL, London, UK), D. Howell, L. J. Nevay, L. Corner, N. Delerue,
B. Foster, F. Gannaway, M. Newman, R. Senanayake, R. Walczak (John Adams Institute at Oxford, UK),
H. Hayano, A. Aryshev[†], N. Terunuma, J. Urakawa (KEK, ATF, Japan)

Abstract

The KEK Accelerator test facility (ATF) [1] extraction line laser-wire system has been upgraded last year allowing the measurement of micron scale transverse size electron beams. The most recent measurements using the upgraded system are presented. The ATF-II extraction line design [2] call for the major upgrade of the existing laser-wire system. We report on the hardware upgrades, including the major hardware upgrades to the laser transport, the laser beam diagnostics line, and the mechanical control systems.

INTRODUCTION

The recent measurements at the KEK, ATF extraction line were performed to account for contributions to σ_y, the size of the convolution between the electron beam and laser beam, as measured during an electron beam measurement using a laser-wire scan. The smallest convoluted beam size, σ_y, was measured after $x-y$ coupling correction as 3.65 ± 0.09 μm (Fig. 1). Using various measurements and models [3] the laser beam size was estimated to be $\sigma_{lw} = 2.2 \pm 0.2$ μm. Therefore the minimum measured electron beam size was 2.91 ± 0.15 μm. After measuring the dispersion a contribution to the vertical electron beam size due to $x-y$ coupling was found to be 3.03 ± 0.66 μm.

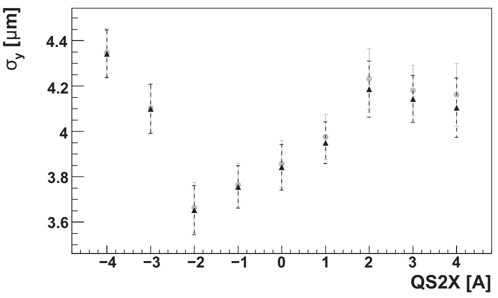

Figure 1: $QS2X$ skew quad scan 23/05/08. $QD4X$ set to 74 A. The grey filled circles are the Gaussian plus 0^{th} order polynomial fits. The black triangles are the Gaussian plus 1st order polynomial fits.

Using all the above information the electron beam emittance in the ATF extraction line was measured as 232^{+11}_{-33} pm as by the laser wire. The vertical emittance design value of the ATF damping ring is 20 pm, and this increases in the extraction line to 3 times this value, but a value of 206 pm was measured in April 2008 using a wire scanner, confirming the laser wire measurement. Therefore a lower emittance electron beam would be necessary to test the ultimate performance of the current laser-wire system. Also, a more precise knowledge of the laser beam size, σ_{lw}, is needed to measure the vertical electron beam size at each quad setting and therefore calculate the emittance.

Additional factors contributing to the laser beam size include the input beam size on the lens, lens aberrations, and the M^2 laser propagation factor. Simulations and measurements [3] indicate that the lens introduces spherical aberration above a certain input beam size and these affect the quality of the laser. Therefore in order to achieve $\sigma_{lw} < 1$ μm a reduction of the input beam size at the final focus lens (Fig. 3) is needed [4, 5, 6, 7, 8].

LASER-WIRE SYSTEM ATF-II UPGRADE

The ATF-II extraction line design calls for a major upgrade of the existing laser-wire system. This upgrade includes: interaction chamber relocation, detector relocation/upgrade, laser transport line (LTL) simulation & design, laser diagnostics upgrade, DAQ upgrade, laser relocation and upgrade with a laser mode quality improvement aiming to achieve 1 μm resolution. In this paper we present the laser diagnostics upgrade and discuss DAQ upgrade.

Laser diagnostics upgrade

ATF-II laser-wire laser diagnostics is being improved towards an automated M^2 [1] and laser divergence measurements. The rest of the laser monitoring (i.e. output power, temperature and other) will remain the same [3] and will not be discussed further.

A remotely controlled power selector will be incorporated in the high power laser path to choose between a few modes of laser-wire operation. The first mode is the primary scanning mode when the full laser power will be sent to the LTL and interaction point (IP). In the second

---

[*] Work supported in part by the STFC LC-ABD Collaboration, the Royal Society, the Daiwa Foundation, and by the Commission of European Communities under the 6th Framework Programme Structuring the European Research Area, contract number RIDS-011899 and in part by a Grant-in-Aid for Scientific Research [17GS0210], Quantum Beam Technology Program by JST.

[†] alar@post.kek.jp

[1] The factor M^2 is a parameter that describes the laser beam quality, it characterizes how close to diffraction limit it is possible to focus a laser.

mode the laser beam will path through the sampling beamsplitters resulting in 1% laser power transmission to the LTL. This mode will be used for the laser diagnostics purposes. In the third mode the only CW alignment laser beam will be sent down to LTL. In order to perform either M^2 or laser divergence measurements right after the power selector the second mirror selector will be installed .

In case of the M^2 measurements the laser beam will be focused by 1 m plano-convex lens toward a special laser-profiling CCD-camera that could be translated along the laser beam propagation direction to measure the beam size at each point [3].

In case of the laser divergence measurements the laser beam will be sent to the LTL which consist of a two compact diagnostics stations ($Station\#1$ and $Station\#2$). Each station supports two modes of operation: ‘primary’ - high power laser transmission and ‘secondary’ - low power alignment/diagnostics mode, and consists of a remotely controlled insertion mirror (to choose between operation modes), short-focus lens and CCD camera (to focus the low power laser beam avoiding overfill the CCD and to measure the beam size/position offset respectively). Figure 2 shows simplified model of the ATF-II laser-wire LTL.

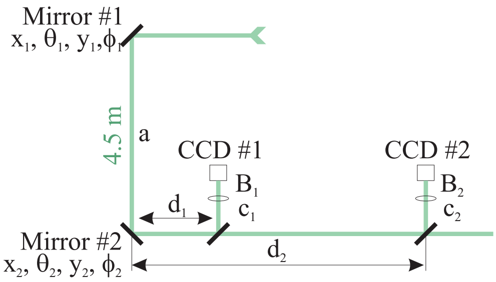

Figure 2: Simplified model of the ATF-II Laser-wire LTL, B_1 and B_2 are the distances between lenses and the $CCD\#1$ and $CCD\#2$ respectively.

All LTL estimation were based on the well known ray tracing technique considering two reference planes, called the *input* and *output* planes, each perpendicular to the optical axis of the system. A light ray enters the system when the ray crosses the input plane at a distance x_1 from the optical axis while traveling in a direction that makes an angle θ_1 with the optical axis. Some distance further along, the ray crosses the output plane, this time at a distance x_2 from the optical axis and making an angle θ_2.

The angle θ_1 could be considered as a laser divergence and the distance x_1 as an initial laser spot radius[2] (see Fig. 3). At the same time θ_1 could be an angle between laser propagation direction and the optical axis caused by mirror’s misalignment. To resolve this ambiguity it was proposed to use two diagnostics stations ($Station\#1$ and $Station\#2$) for the laser alignment and diagnostics purposes. Because only in this case it is possible to accurately measure laser divergence and calculate correction angle for motorized mirrors[3].

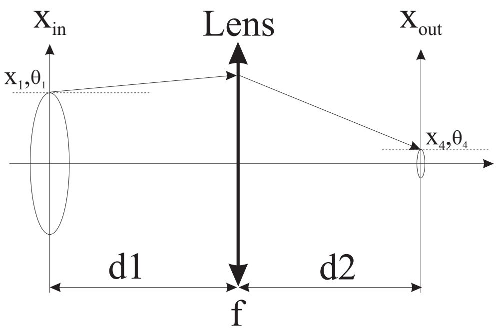

Figure 3: General geometry of one diagnostic Station of ATF-II Laser-wire LTL.

Using this simple geometry (Fig. 3) one can obtain transfer matrix from *input* to *output* planes by multiplying 3 transfer matrices: for the drift from X_{in} to Lens, transfer matrix of a thin Lens and the drift from Lens to X_{out}.

$$\begin{pmatrix} x_4 \\ \theta_4 \end{pmatrix} = \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix}$$

, where x_1, θ_1 and x_4, θ_4 are the input and output laser spot radii and angles respectively, d_1 and d_2 are the distances from the input plane to the lens and from the lens to the output plane respectively, f is the focal length of the lens.

By multiplying transfer matrices it is possible to show that:

$$\begin{aligned} x_4 &= \left(1 - \frac{d_2}{f}\right) \cdot x_1 + \left[\left(1 - \frac{d_2}{f}\right) \cdot d_1 + d_2\right] \cdot \theta_1 \\ \theta_4 &= \frac{-1}{f} \cdot x_1 + \left(\frac{-1}{f} \cdot d_1 + 1\right) \cdot \theta_1 \end{aligned} \tag{1}$$

One can see that the change of the initial laser spot radius x_1 changes only observed image radius x_4 but not shifts the laser spot image on CCD. And the change in the laser propagation direction (θ_1) shifts the images position only. In order to correct the laser propagation angle and measure the laser divergence angle one should measure the laser image position shift and the radius (diameter) change at a two well separated diagnostics stations. The $Mirror\#1$ or $Mirror\#2$ can be used for the angular corrections. In the first case: $A_1 = a + d_1 + c_1 = 4.8$ m, $A_2 = a + d_2 + c_2 = 16$ m and in the second: $A_1 = d_1 + c_1 = 0.3$ m, $A_2 = d_2 + c_2 = 11.6$ m, where A_1 and

---

[2] It is important to notice that all considerations were made in assumption of a good alignment of entire LTL, especially the necessary and sufficient conditions were that the full laser images can be seen at CCD’s and all optical components are well aligned.

[3] Further, the only one plane of optical system will be considered because the only difference between horizontal and vertical planes is that the change in inclination angle of the mirror in horizontal plane corresponds to the double angle change of the outgoing ray.

A_2 are the distances between adjusting $Mirror$ to be used and $Lens\#1$ and $Lens\#2$ respectively.

Rewriting Eq. 1 for $Station\#1$ and $Station\#2$ separately and collecting equations with x_{st_i} (because in a reality we are able to measure only position shift x_{st_i}, but to correct it we should change the mirror angle θ_1) one can find:

$$\begin{aligned} x_{st\_1} &= \left(1-\frac{B_1}{f}\right)\cdot x_1 + \left[\left(1-\frac{B_1}{f}\right)\cdot A_1 + B_1\right]\cdot\theta_1 \\ x_{st\_2} &= \left(1-\frac{B_2}{f}\right)\cdot x_1 + \left[\left(1-\frac{B_2}{f}\right)\cdot A_2 + B_2\right]\cdot\theta_1 . \end{aligned}$$

Solving this system of equations we have:

$$\begin{aligned} x_1 &= \frac{X4\cdot x_{st\_1} - X2\cdot x_{st\_2}}{X1\cdot X4 - X3\cdot X2} \\ \theta_1 &= \frac{X1\cdot x_{st\_2} - X3\cdot x_{st\_1}}{X1\cdot X4 - X3\cdot X2} \end{aligned} \tag{2}$$

, where $X1 = \left(1-\frac{B_1}{f}\right)$, $X2 = \left[\left(1-\frac{B_1}{f}\right)\cdot A_1 + B_1\right]$, $X3 = \left(1-\frac{B_2}{f}\right)$, $X4 = \left[\left(1-\frac{B_2}{f}\right)\cdot A_2 + B_2\right]$.

Angular correction for the motorized mirror can be calculated as:

$$\Delta\theta = \frac{X1\cdot\Delta x_{st\_2} - X3\cdot\Delta x_{st\_1}}{X1\cdot X4 - X3\cdot X2} \tag{3}$$

, where Δx_{st_1} and Δx_{st_2} are the laser image position offsets at $CCD\#1$ and $CCD\#2$ respectively. Alternatively the angular correction can be calculated as follows:

$$\Delta\theta = \frac{\Delta x_{st\_i} - \left(1-\frac{B_i}{f}\right)\cdot x_1}{\left[\left(1-\frac{B_i}{f}\right)\cdot A_i + B_i\right]} \tag{4}$$

, where x_1 is the initial transverse laser beam radius received from Eq. 2.

The proposed algorithm for defining laser parameters then includes: measurement of the laser beam transverse sizes (x_{st_1}, x_{st_2}) and the centroid offsets (Δx_{st_1}, Δx_{st_2}) at the two locations ($Station\#1$ and $Station\#2$) along the laser beam path. The laser angular divergence can be then derived using Eq. 2. Using Eq. 3 or Eq. 4 the angular correction for the $Mirror\#1$ or $\#2$ and the input beam size on the final focus (FF) lens can then be calculated.

To estimate maximum deflection angles of 2$''$ motorized mirrors (equipped with ThorLabs DC-servers) which could be applied at the LTL (assuming that only commercially available optical components are used) lets consider the uttermost $Station\#2$ only. The focal lengths f of the lens is 150 mm ($CVI\ PLCX - 50.8 - 77.3 - C$), initial laser spot radius $x_1 = 8$ mm, distances from CCD ('Firstsight Vision'-$CM - 040GE$) to Lens $B_i = 140$ mm (in order to have $x_{st\_i} = 0.5$ mm, laser image spot radius on CCD), the CCD active area size 6.49 (h) x 4.83 (v) mm. The maximum deflection angles for LTL are calculated using Eq. 4 where: $\Delta x_{st\_i}\_hor = 2.74$ mm and $\Delta x_{st\_i}\_ver = 1.91$ mm and summarized in Table 1.

Table 1: Calculated maximum deflection angles

Correction mirror	**Plane**	**Inclination angle**	**DC-server move**
$Mirror\#1$	H	±0.97 mrad	±62 μm
$A_i = 16$ m	V	±1.23 mrad	±78 μm
$Mirror\#2$	H	±1.29 mrad	±81 μm
$A_i = 16$ m	V	±1.62 mrad	±102 μm

DAQ upgrade

The data acquisition system for the ATF laser-wire was based upon multiple small executable programs written either in C++ or Labview, running either on Linux or Windows operating systems. A central data acquisition system communicates to each program via a short messaging protocol based on TCP/IP. The present upgrade of the DAQ system will keep all the advantages of a modular acquisition system using 'Experimental Physics and Industrial Control System' (EPICS) [9]. This enables the varied components of such a system (accelerator, optical devices, digital to analogue converter) to communicate and distribute data more effectively.

UPGRADE STATUS

The LTL and FF installation begins at March 2009 with $Station\#1$ and $Station\#2$ table supports and Interaction Chamber installation. We are planning to relocate the laser during the summer 2009. And general time table is as follows: electron beam optics & background study - beginning of ATF-II operation at November 2009, establishing of a stable electron beam transverse size measurements to the end of 2009.

REFERENCES

[1] ATF: Accelerator Test Facility Study Report JFY 1996-1999, H. Hayano et al. KEK-INTERNAL-2000-6.

[2] The ATF2 collaboration, ATF2 (Accelerator Test Facility) proposal, 2006, `http://lcdev.kek.jp/ILC-AsiaWG//WG4notes/atf2/proposal/`

[3] S.T. Boogert, et al., in preparation

[4] S.T. Boogert, et al., EPAC'06, June 2006, Edinburgh, UK, p. 738.

[5] L. Deacon, et al., PAC'07, June 2007, Albuquerque, US, p. 2636.

[6] A. Aryshev, et al., EPAC'08, June 2008, Genoa, Italy, p. 1065.

[7] L. Deacon, Ph.D. thesis submitted to the University of London, 2009

[8] A. Aryshev, et al., TIPP'09, March 2009, Tsukuba, Japan, to be published in NIMA

[9] EPICS web site: `http://www.aps.anl.gov/epics/`