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LASER-HEATER UNDULATOR MAGNET PHYSICS REQUIREMENTS

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Brief Summary:

This specification summarizes physics requirements for the laser-heater undulator magnet, including magnet parameters, and construction/installation tolerances such as field quality, maximum dimensions, alignment, etc.

Change History Log:

Rev Number	Revision Date	Sections Affected	Description of Change
000	Sep. 7, 2006	All	Initial Version
001	Feb. 5, 2008	All	Update parameters to 758 nm laser

Laser-Heater Undulator Magnet Physics Requirements

Introduction

The laser-heater system is located in the injector area and is used to add a small level of 'slice' energy spread to the electron beam in order to provide Landau damping of the micro-bunching instability in the linac. A fraction of the IR drive laser beam at a wavelength of 758 nm co-propagates with the electron beam through the laser-heater undulator, producing a 758-nm energy modulation on the electron bunch. The undulator is located at the center of the laser-heater chicane. The chicane effectively time-smears the energy modulation, leaving a completely uncorrelated energy spread (~45 keV rms nominally). The physics requirements of the laser-heater system are described in PRD 1.2-004. This document lists the physics requirements for the laser-heater *undulator* magnet, including parameters, and construction and installation tolerances.

Parameters

The laser-heater undulator is a permanent-magnet, planar-type wiggler with the wiggle direction in the horizontal plane (vertical field orientation). The gap must be adjustable in a continuum to accommodate various electron beam energies, and slightly variable laser wavelength (±5 nm), as listed in Table 1. The gap must also be able to open far enough to effectively 'switch off' the undulator (25-100 mm). At all gap settings the first and second field integrals must be within the tolerances listed below. In addition, the terminations at each end of the undulator must be designed to produce a wiggle with an average position of zero, rather than a one-sided trajectory wiggle.

Table 1. Laser-heater undulator parameters at minimum, maximum, and nominal electron energy.

parameter	symbol	120 MeV	135 MeV	180 MeV	unit
Maximum physical length of undulator	L_u	-	550	-	mm
Undulator period	λ_u	-	54	-	mm
Number of full undulator periods*	N_p	-	9	-	-
Undulator gap†	g	39.0	34.0	26.5	mm
Undulator parameter (at λ_{laser} = 758 nm)	K	1.047	1.385	2.229	-

* not including terminations

† gap adjustment range should be from 25 mm to about 100 mm

Tolerances

The undulator tolerances are listed in Table 2. The various tolerances listed in the table are described in the sections to follow, including the method used to define and calculate the tolerances.

Table 2. Laser-heater undulator tolerances.

parameter	symbol	value	unit
Horizontal alignment tolerance	$\|\Delta x\|$	1	mm
Vertical alignment tolerance	$\|\Delta y\|$	1	mm
Longitudinal alignment tolerance	$\|\Delta z\|$	5	mm
Roll angle tolerance (of entire undulator)	$\|\Delta \varphi\|$	40	mrad
Pitch angle tolerance (of entire undulator)	$\|\Delta \theta_y\|$	3	mrad
Yaw angle tolerance (of entire undulator)	$\|\Delta \theta_x\|$	10	mrad
Max. first field integrals at end of undulator (x and y)[1]	$\|\int B_{x,y} dz\|$	0.040	G-m
Max. second field integral *anywhere* along undulator (x and y)[1]	$\|\iint B_{x,y} dz' dz\|$	0.20	G-m^2
Max. pole field errors (rms, correlated[2])	$(\Delta B/B)_{rms}$	1	%
Max. pole gap taper error (linear gap variation over und. length)	Δg	0.3	mm
Max. accumulated phase error over full undulator	$\|\Delta \psi\|$	15	deg
Max. sextupole field at r = 10 mm (with largest gap, 100 MeV)	$\|b_2/b_0\|$	10	%
Min. full-width beam stay-clear hor. aperture in the undulator[3]	w	65	mm
Min. full-height beam stay-clear ver. aperture in the undulator	h	18	mm
Repeatability of gap setting (rms, assuming nom. gap of 34 mm)	σ_g	0.05	mm
Estimated min. pole width required	x_w	50	mm

1. The 1st and 2nd field integral tolerances must be met at all possible gap settings, including the full-open gap used to effectively 'switch off' the undulator (~100 mm).
2. "Correlated" here means that this level of field error is allowed as long as the 1st and 2nd field integral tolerances are also met.
3. This stay-clear width includes the vacuum chamber size necessary to allow switching on or off the laser heater chicane, which introduces a 35-mm horizontal offset of the beam.

Alignment Tolerances

The natural vertical undulator focusing is described by the inverse focal length [Nuhn, 2006]

$$\frac{1}{f_0} = -\frac{k_u^2 K^2 L_u}{2\gamma^2}\cos(k_x x)\cosh\left(\sqrt{k_u^2 + k_x^2}\, y\right), \tag{1}$$

where $k_u = 2\pi/\lambda_u$, K is the undulator parameter, L_u is the undulator length, γ is the electron energy in rest mass units, x and y are the transverse misalignments, and

$$k_x = \frac{1}{r}\sqrt{2\left|\frac{b_2}{b_0}\right|}, \tag{2}$$

with r as the reference radius at which the sextupole relative field roll-off, b_2/b_0, is evaluated (Fig. 1).

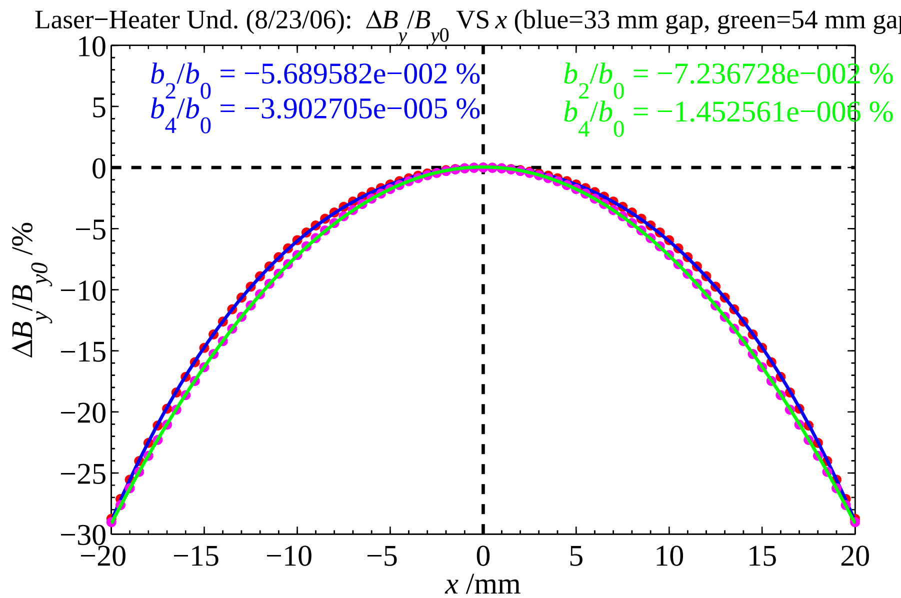

Figure 1. Modeled undulator relative field variation at longitudinal pole center vs. horizontal position, x, for a gap of 33-mm (blue curve) and 54-mm gaps (green curve) and with a 50-mm pole width. The sextupole field at $x = \pm 10$ mm is −5.7% and −7.2%, for the two gaps respectively.

At $x = y = 0$, the nominal vertical focusing of the undulator is compensated by nearby matching quadrupole magnets. If the undulator is misaligned, however, the focusing will change with beta-mismatch amplitude of

$$\Delta\zeta = \frac{\beta^2}{2}\left(\Delta\frac{1}{f}\right)^2, \tag{3}$$

where $\Delta 1/f$ is the change in inverse focal length, with respect to Eq. (1), due to a transverse misalignment (x or y).

$$\Delta\frac{1}{f} = -\frac{k_u^2 K^2 L_u}{2\gamma^2}\left\{1 - \cos(k_x x)\cosh\left(\sqrt{k_u^2 + k_x^2}\, y\right)\right\}, \tag{4}$$

At the nominal 135-MeV beam energy, a horizontal and vertical beta function of $\beta_{x,y} \approx 10$ m, and using the parameters of Table 1, with a sextupole field roll-off of $|b_2/b_0| = 10\%$ at $r = 10$ mm, a horizontal misalignment of $x = 3$ mm or a vertical misalignment of $y = 1$ mm, causes a tolerable mismatch amplitude of 0.1%. To be safe, we choose a 1-mm tolerance for both planes. The sextupole field roll-off does not alter the vertical focusing for an aligned system, and it does not add horizontal focusing.

Pitch and yaw tolerances are set by several factors, including an effective period error with yaw angle, θ_x, scaling as $\cos(\theta_x)$, a focusing error due to an off-axis, angled transport through the undulator, especially the pitch angle, θ_y, through the $\cosh(2\pi y/\lambda_u)$ sextupole-like vertical field variation, and the final factor is steering correction capability. The focusing error due to pitch angle suggests a 3-mrad tolerance (tracking studies with $B_y = B_0\cosh(2\pi y/\lambda_u)$), while the yaw angle tolerance is based on steering correction range, estimated at ±2.5 mm ($|\theta_x| <$ (2.5 mm)/(0.25 m) = 10 mrad). The effective period error with yaw angle is not an issue: $|\theta_x| < \cos^{-1}(1 - |\Delta\lambda/\lambda|) \approx$ 140 mrad, with $|\Delta\lambda/\lambda| \approx 1\%$.

The roll angle of the full undulator magnet as a whole is not a sensitive error, except that it generates some small anomalous focusing in the horizontal plane. Evaluating Eq. (1) with $x = y = 0$, but multiplying by the roll error, $\Delta\varphi$, estimates the horizontal focusing error. At $|\Delta\varphi|$ = 40 mrad, the mismatch amplitude is 0.1% (using Eq. (3) with β_x = 10 m).

Geometric Aberrations

Tracking has been done for sextupole field roll-off of $|b_2/b_0|$ = 10% at r = 10 mm causing no significant emittance growth in either plane. This is due to the fact the poles reverse field polarities and therefore the sextupole aberration cancels locally, for both effects: $B_y \sim x^2$ and $B_y \sim y^2$.

Field Integrals

The laser and electron beam must co-propagate through the undulator with adequate transverse spatial overlap in both planes (less than one rms beam size). This overlap requirement sets the tolerance on the second field integral (beam position) evaluated everywhere along the undulator. The beam position at any location, z, along the undulator is related to the second field integral tolerance as:

$$x(z) = \frac{1}{(B\rho)}\int_0^z\int_0^{z'} B_y\,dz''dz'\,. \tag{5}$$

With the nominal 200-μm rms beam size in both planes, we can accept a 50-μm maximum overlap error, $x(z)$ or $y(z)$, and with the most sensitive beam energy of 120 MeV, the second field integral tolerance is 0.20 G-m^2, which is the maximum value allowed at any point, z, along the undulator. This tolerance applies equally to <u>both</u> planes (x and y) and also needs to be achieved at all gap settings, including the full open position.

Similarly, the first field integral (beam angle) after the full undulator length must be small enough not to kick the beam more than about 200 μm in the linac. With $\beta_x = \beta_y$ = 10 m in the undulator, and a typical value of $\beta_{x,y}$ in the linac of 50 m, the maximum allowable kick angle is:

$$\theta \approx \frac{200\ \mu\text{m}}{\sqrt{(10\ \text{m})(50\ \text{m})}} \approx 10\ \mu\text{rad}\,. \tag{6}$$

The final kick angle is related to the first field integral over the full undulator length as:

$$\theta = \frac{1}{(B\rho)} \int_0^{L_u} B_y dz' , \tag{7}$$

meaning that the first field integral tolerance (taken at 120 MeV) is 0.040 G-m. This tolerance applies equally to both planes (*x* and *y*) and also needs to be achieved at all gap settings, including the full open position.

The laser-heater undulator is located at the center of a four-dipole chicane, which can be switched off. This shifts the horizontal electron beam position by 35 mm in the undulator as shown in Fig. 2.

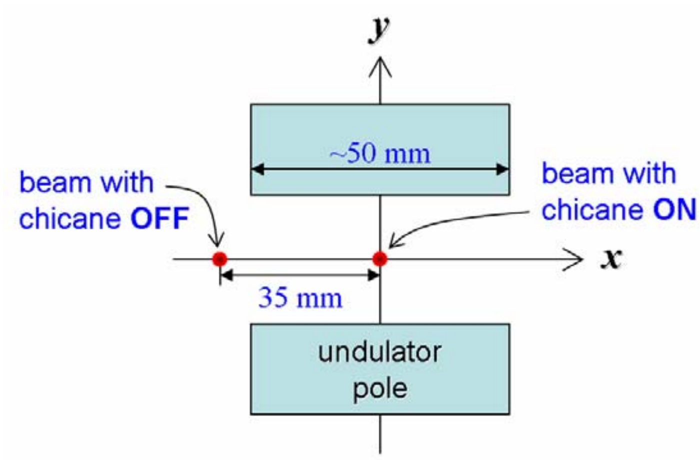

Figure 2. Beam position with respect to undulator poles (beam out of paper) with chicane ON (center red dot) and chicane OFF (left red dot). The field integrals at chicane-OFF position must also meet the same tolerances as those for chicane ON.

Field Errors

The bandwidth of the system is related to the inverse of the number of poles, $1/N_p$, as shown in Fig. 3. Random pole field errors are tolerable at the level of 1% rms, but only if the 1^{st} and 2^{nd} field integrals tolerances are also met.

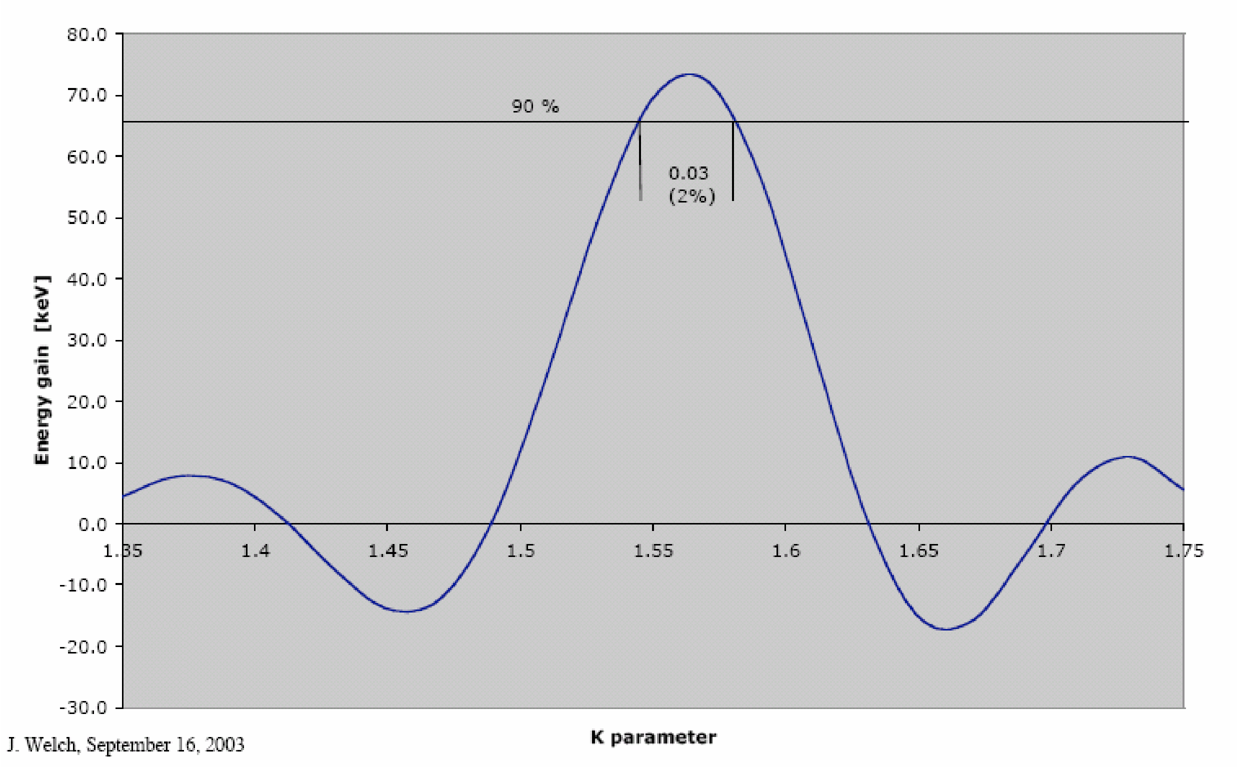

Figure 3. The bandwidth of the laser-heater undulator, where a 1% change in *K* results in a 10% drop in energy gain (drawn for an older value of *K* with 10 periods, but still representative).

Phase Errors

Similar to the random field error tolerances, a 1% field variation over 9 periods will produce a total phase error of 9×360°×1% ≈ 30°, which we cut in half here for safety (15°).

Repeatability of Gap Setting

With a 1% *K* error producing a 10% gain reduction, as shown in Fig. 3, and assuming a 34-mm nominal gap, the mean gap of the entire undulator must be set to a precision of (34 mm)×0.45%/3 = 50 μm rms, where a 0.45% gap error produces only a 2% gain reduction and a factor of three has been included to allow for a 3-sigma worst case on this rms gap repeatability tolerance.