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Shintake Monitor

Nanometer Beam Size Measurement and Beam Tuning

Jacqueline Yan[a]*, Masahiro Oroku[a], Youhei Yamaguchi[a], Takashi Yamanaka[a], Yoshio Kamiya[b], Taikan Suehara[b], Sachio Komamiya[a], Toshiyuki Okugi[c], Nobuhiro Terunuma[c], Toshiaki Tauchi[d], Sakae Araki[c], Junji Urakawa[d]

a Department of Physics, The University of Tokyo, 7-3-1, Bunkyo District, Tokyo,113-0033, Japan
b ICEPP, The University of Tokyo
c Accelerator Laboratory, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
d Institute of Particle and Nuclear Studies, KEK

a

Abstract

A novel final focus system design featuring the Local Chromaticity Correction scheme has been proposed for ILC. This is to be verified at ATF2, a test facility for ILC, through focusing an e- beam down to the design vertical beam size (“σ_y”) of 37 nm. Shintake Beam Size Monitor (“IPBSM”), installed at the virtual interaction point of ATF2, is the only existing device capable of measuring σ_y below 100 nm, making it indispensable for achieving the goals of ATF2 and a strong candidate for R&D at future linear colliders. This is attributed to its ingenious technique of scanning the phase of laser interference fringes relative to the e- beam. Beam sizes are derived from the resulting Compton signal modulation measured by a downstream detector. Having been upgraded in a variety of ways since its first debut at FFTB, Shintake Monitor is capable of measuring a wide range of σ_y from 25 nm to 6 μm with better than 10% resolution. This paper describes the system’s design, role in beam tuning, and various hardware upgrades to further improve its performance.

Keywords: ILC; electron linear collider; beam size; luminosity; laser interference, accelerator;

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[a] *Email: jackie@icepp.s.u-tokyo.ac.jp*

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1. Introduction

The ILC (International Linear Collider) holds great potential for detection and detailed analysis of new physics beyond the Standard Model. Clean e-e` collisions enable precise observations of the most fundamental processes free of synchrotron radiation loss. However, with only one chance for acceleration, a linear collider faces stringent power challenges and demands in luminosity, which is expressed as :

$$L = \frac{n_b N^2 f_{rep}}{4\pi\ \sigma_x^* \sigma_y^*} H_D \qquad \left(n_b : \text{no. of bunches},\ \text{N: bunch population},\ f_{rep} : \text{rep. rate},\ H_D : \text{disruption parameter} \right) \qquad (1)$$

The Gaussian beam cross section in the denominator signifies the importance of beam focusing. The design horizontal and vertical beam sizes at ILC's interaction point (IP) are $\sigma^*_x = 640$ nm and $\sigma^*_y = 5.7$ nm , respectively[1,2]. This is energy-scaled to $\sigma^*_y = 37$ nm, and $\sigma^*_x = 2.2$ μm at ILC's final focus test facility Accelerator Test Facility 2 (ATF2). ATF2 has two primary goals: to verify the "Local Chromaticity Correction" scheme by demonstrating focusing of σ^*_y down to its design value, and to stabilize beam trajectory with nm precision under this small σ^*_y. Shintake Monitor, installed at ATF2`s virtual IP, is the only existing device capable of measuring beam sizes below 100 nm. Its outcomes are indispensible to achieving ATF2's 1st goal, and thus is crucial in realization of ILC.

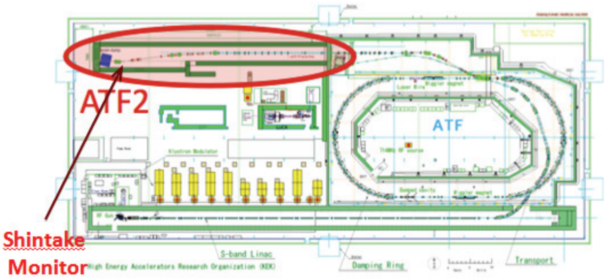

Fig. 1. Location of Shintake monitor in the ATF(2) beamline [3,7]

1. Measurement Scheme of Shintake Monitor

1.1. Beam size measurement method

Fig 2 (left) shows the schematic layout of the Shintake Monitor. The laser, introduced to IP in pulses synchronized with e- beam pulses is split into two paths by a half mirror, then cross to form interference fringes. The phase between the laser paths, controlled by a piezoelectric stage, is scanned relative to the e-beam as it traverses the fringes perpendicularly at IP. A downstream gamma detector measures the modulation depth ("M") of the resulting Compton scattered photon signal. Signal intensity measured at each phase point make up the spectrum for M, which is large for well focused beams, and small for dispersed beams (see Fig. 2 (right)).

Laser fringe intensity is expressed using intensity of magnetic field (***B***), averaged over time as:

$$\overline{B_x^2 + B_y^2} = B^2(1 + \cos\theta \cos 2k_y y) \qquad (2)$$

Here, x and y are coordinates perpendicular to e- beam, θ is laser crossing angle, k = 2π/λ (λ : laser wavelength) is wave number, while $k_y = k\sin(\theta/2)$ is its component normal to the fringe. Assuming Gaussian distribution, N, the number of Compton signal photons, is related to beam centre y_0 and σ_y as[2].

$$N \propto \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(\frac{-(y-y_0)^2}{2\sigma_y^2}\right)\left(B_x^2+B_y^2\right)dy \Rightarrow N = \frac{N_0}{2}[1+\cos(2k_y y_0)\cos(\theta)\exp(-2(k_y\sigma_y)^2)] \qquad (3)$$

M = amplitude / average, is calculated in eq (4) from N_+ and N_- , max. and min., respectively, of signal intensity. The measurable range for σ_y as in eq (5), is determined by the laser fringe pitch "d" corresponding to a particular θ (Table 1). Fig 3 (left) relates M and σ_y for each θ mode[4].

$$\mathrm{M} = \frac{N_+ - N_-}{N_+ + N_-} = |\cos(\theta)|\exp\left(-2(k_y\sigma_y)^2\right) \qquad (4)$$

$$\Rightarrow \sigma_y = \frac{d}{2\pi}\sqrt{2\ln\left(\frac{|\cos(\theta)|}{M}\right)} \qquad d = \frac{\pi}{k_y} = \frac{\lambda}{2\sin(\theta/2)} \qquad (\lambda = 532 \text{ nm for ATF2}) \qquad (5)$$

Table 1. Observable beam sizes vary with fringe pitch, which is determined by laser wavelength and crossing angle

Crossing angle θ	174 deg	30 deg	8 deg	2 deg
Fringe pitch d	266 nm	1.028 μm	3.81μm	15.2μm
Measurable σ_y	25 ~ 110 nm	80 ~ 400 nm	360 nm ~ 1.4 μm	1.2 ~ 6 μm

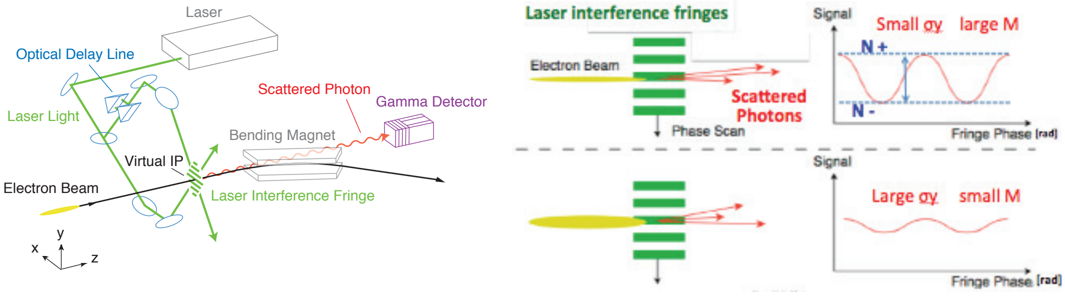

Fig 2. (left) Schematic layout of Shintake Monitor[4] (right) Relationship between beam size and modulation depth

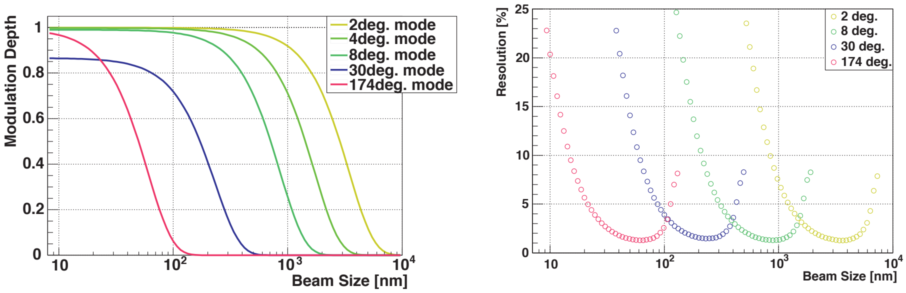

Fig. 3 . For each θ mode[4] : (left) Relationship between beam size and modulation depth (right) Measurement resolution vs σ_y^*

1.2 Comparison with Shintake Monitor at FFTB

Table 2 shows upgrade of Shintake Monitor at ATF2 from FFTB (Final Focus Test Beam) at SLAC, where it had first succeeded in measuring a $\sigma^*_y \sim 70$ nm with 10% resolution, whereas the design size was 60 nm[1,2,3].

- Laser wavelength was halved by SHG from 1064 nm to 532 nm to accommodate smaller σ_y at ATF2
- The range of measurable beam sizes has been widened owing to newly designed laser optics. Continuously adjustable θ modes are added to encompass σ^*_y as large as several μm.
- Instead of shifting the e- beam using steering magnets, at ATF2 M is produced by scanning laser fringe phase relative to a fixed beam, using piezoelectric stages (see Sec 1.1) . This contributes to higher degrees of freedom in beam tuning .
- A newly designed gamma detector features a multi-layer CsI(Tl) design arranged that optimizes separation of signal from BG by taking advantage of their difference in energy spectrum .

Table 2 . Electron beam and Shintake Monitor parameters: ATF2 vs FFTB. [7]

	FFTB	ATF2
Beam energy	46.6 GeV	1.28 GeV
1 photon energy	8.6 GeV	15 MeV
rep. rate	30 Hz	1.56 Hz (3 Hz)
e- / bunch	1 x 10^{10}	0.5 -1 x 10^{10}
Bunch length	3 ps	16 ps
Design IP beam size	(σ_x,σ_y) = (900 nm, **60 nm**)	(σ_x,σ_y) = (2.2 μm, **37nm**)
Laser wavelength	1064 nm	532 nm (SHG)
Detector Layout	Single layer	**Multi-layer**
Scan method	Shifts beam	**scan laser fringe phase, fix beam**
Measurable range	40 – 720 nm	**25 nm – 6μm** + laserwire mode for σ_x (< 30μm)

1.3. Overall Layout and Structure

Shintake Monitor is made up of a laser optics consisting of a laser table linked by a transport line to a main “vertical table “at IP, a gamma detector, and DAQ electronics (see Fig 3[4]).

On the **laser table** in a laser hut, the Nd:YAG Q-switched laser is created in 8 ns (FWHM) pulses with peak power 164 MW, sufficient for generating Compton photons. Diagnostic devices monitor various properties e.g. timing, intensity, profile, polarization. Then laser is delivered to IP via a 20 m transport including intermediate mirrors and beam expanders / reducers to adjust laser spot size and divergence.

After emerging onto the **vertical table**, the laser first passes through a 95% reflection mirror. The reflected 95% energy beam is divided by a 50% beam splitter into upper and lower paths which are focused to a waist by final lenses and cross at IP to form interference fringes. The e- beam, also focused to a waist at IP, is collided against these fringes, then disposed safely by a bending dipole into a dump. Meanwhile Compton signal photons proceed straight into the gamma detector through collimator apertures. Depending on the targeted beam size, “mode switching” between θ = 174° , 30°, and 2° - 8° (continuously adjustable by prism stages) is carried out by remote control of rotating stages carrying mirror actuators. Meanwhile, the transmitted 5% energy laser is admitted to a diagnostic section, where alignment, phase, and timing are monitored real-time by position sensitive detectors and photodiodes.

Shintake Monitor`s **gamma detector** is made of CsI(Tl) scintillators divided up into 4 front 40 mm layers and a large 290 mm back “bulk” layer. Energy deposit from shower development triggered by incident photons is transformed into scintillation light, which enters PMTs coupled to each layer. This multi-layer design separates signal and BG by taking advantage of their distinct in energy spectrums (15 MeV for signal vs 53 MeV for BG) at ATF. Collimators are installed in front of the detector to cut BG.

2. Shintake Monitor and Beam Tuning

Measurement by Shintake Monitor commences after σ^*_y has been tuned below 3.5 μm, within range confirmable by wire scanners. Multi-knob tuning[5] of beam trajectory and intensity affect signal photon paths. Energy loss from striking collimators or abruptly changed BG sources alter shower energy deposit, thus degrading detector resolution. We start out by confirming that gamma rays are not deviated from the 10 mmϕ center of a collimator, and if necessary adjust beam orbit or rearrange collimator blocks.

Laser Q-switch timing is adjusted to beam timing with precise digital modules. The e- beam pulse of 16 ps is much shorter than the laser pulse width of 8 ns (FWHM). Collision would be hindered by a sudden timing jump of a few ns. Stable operation generally requires timing jitter to be suppressed below 500 ps.

Laser position must be maintained under precise alignment for M detection and accurate fringe scans. First, laser spots are overlapped with the beam within O(10 μm) on a screen monitor at IP. Following this is finer "laserwire scan[4]", where laser is scanned transverse to e- beam using mirror actuators to locate the Compton signal peak. This also serves to measure laser spot size at IP, nominally 10-15 μm. Finally "z-scan[4]" resolves longitudinal offset to achieve the sharpest fringe contrast i.e. deepest modulation.

After completing all spatial and temporal alignments, we are ready to measure beam sizes. The results are fed back to the beam tuning and focusing process.

3. Performance

3.1. Expectations

Shintake Monitor is capable of measuring σ_y* of 25 nm - 6 μm in 90 bunches with resolution < 10% (Fig. 3 right). This comes from simulation under S/N = 3.5 and 50 % bunch-by-bunch BG fluctuation. The expected accuracy for measuring the design beam size is :

$$37 \pm 1.4\,(\boldsymbol{stat.})^{+0}_{-2}\,(\boldsymbol{sys.})\ \mathbf{nm} \tag{6}$$

Although our system functions at very near design expectations, the measured M is still impacted by statistical and systematic errors (see 3.2, 3.3 for details). Statistical errors are related to detector resolution and fluctuations in beam trajectory, beam current, and laser power. Large signal jitters would cause small signal modulation to be either unobservable, or severely degraded in precision. Systematic errors degrad fringe contrast and cause under-evaluation of M, thus determining the lower measurable limit for σ_y*.

3.2 Statistical Errors

Statistical errors is evaluated to be ~ 10% for 90 bunch measurements of 25 nm - 6 μm, under S/N ~ 5. However this expectation may not be met as σ_y* is focused down smaller, since more stringent S/N is to be encountered, and measurement precision of a smaller σ_y* would be degraded more significantly by the primary sources in Compton signal intensity as described below[4,8].

- **Detector Resolution:** Because the detector separates signal from BG by taking advantage of their distinct difference in shower development, its resolution is degraded by energy spectrum becoming altered by the following factors: (1) Change over time in gain or light collectivity (2) Suddenly altered BG levels and sources (3) Gamma rays losing extra energy to collision with collimators (4) Beam size or trajectory fluctuations.
- **Laser Timing and Intensity Instability** :Because e- beam pulses of 16 ps interacts with much shorter laser pulses of 8 ns (FWHM) width, even a few ns change in laser timing during beam passage will impact operation with onsets of Compton signal jitters due to pulse-to-pulse inconsistency in the laser power "felt" by the beam. Laser power is monitored through measurements by a photodiode and TDC.

This method has been crosschecked using an energy meter to have a precision better than 1 % . Typical fluctuation in either timing or intensity is measured to be 1 - 2%.

- **ICT Monitor Resolution:** Signal energy is normalized by beam current measured by an "integrated current transformer (ICT) monitor". This suppresses statistical errors due to beam current jitter down to the ICT monitor resolution, measured to be about 2.5 - 5%.

3.2. Systematic error

Various types of systematic errors are interpreted using *"modulation reduction factors"* C_i (i = 1, 2, ...), which reduce the measured M from its theoretical value as $M_{meas} = C_\alpha C_\beta ......M_{ideal.}$ These smear laser fringe contrast and lead to a beam size over-evaluation from $\sigma^2_{y.meas}$ to $\sigma^2_{y.meas} + |\Sigma \ln C_i|/2k_y^2$. Table 3 summarizes M reduction factors evaluated specifically for ATF2[2,4]. Some are laser related e.g. misalignment, polarization, and intensity, while others are beam related e.g. beam position jitter.

- **Laser position and profile at IP:** To prevent bias due to offset of laser intersection from beam center i.e. IP, we use mirror actuators with resolution < 50 nm to adjustment laser position within 1/10 of laser spot size (σ_{laser}) in both transverse and longitudinal. Fine readjustment is conducted typically once an hour against pointing instability or drift. On the other hand, misalignment in focal point of the final lens cause imbalanced profile i.e.σ_{laser} between the two laser paths, and thus local bias on fringe intensity interacting with e- beam. This can be resolved by adjusting lens set-up.
- **Relative position jitter:** Fluctuation in relative position between beam and fringe phase would smear the M curve and cause σ_y*over-evaluation. Beam position jitter, which arise from magnet vibrations or unstable extraction from damping ring, are anticipated to be monitored by nm resolution IPBPMs by the time we of measure σ_y*~ 37 nm at the sensitive 174 deg mode. Meanwhile, long-term laser path stabilization will be reinforced by a feedback system composed of actuators and PSDs.
- **Fringe tilt effects:** The 174 deg mode would be significantly biased by a tilt between the plane upon which interference fringes with respect to e- beam, due to laser path misalignment. For this, the measured σ_y* will corrected using tilt measured by a specially configured PSDs[4].
- **Spherical Wavefront Effects:** If collision point with e- beam is offset from laser waist, the finite curvature of Gaussian laser spherical wavefronts cause the beam to feel "distorted" fringes. A scanning system consisting of lens on a moving stage has been attached to the final lens, and is expected to align laser focal point to IP within 100 µm precision when measuring the smallest σ_y* at 174 deg[4].
- **Change of Beam Size within Fringe:** Because e- beam waist is tuned to the exact IP, an offset in collision point would cause the measured σ_y* to fluctuate within the finite longitudinal length of the laser fringes. We must reinforce alignment precision for the heaviest impacted 174 deg mode[4].

Table 3 : (upper limits of) modulation reduction factors C_i for each systematic error type for design size 37 nm with 174 deg mode and 300 nm size with 8 deg mode. Some bias factors affect only the sensitive 174 deg mode [4]

Modulation reduction factor	**300 nm at 8 deg**	**37 nm at 174 deg**
Total power	97.8 ±1.8 %	99.8 ±0.1%
Alignment (z: longitudinal)	> 99.1%	> 99.1%
Alignment (t: transverse)	> 99.6%	> 99.6%
Spatial coherence	> 99.9%	> 99.9%
Fringe phase / beam position jitter	> 98.0%	> 98.0%
Fringe tilt (longitudinal)	> 98.2%	[99.3% : 99.6%]
Fringe tilt (transverse)	> 99.9%	> 99.9%
Spherical wavefronts	100%	> 99.7%
Beam size growth within fringe	100%	99.7%
Total : Πi Ci	> 91.1%	[95.1% : 95.4%]

4. Status of Shintake Monitor

Fig. 4 left and right shows the M plots for the smallest σ_y* measured by Shintake Monitor during continuous beam runs in 2010, for May and Dec, respectively.

Due to tentative tuning issues, a special “10 x β_y*“ beam optics had been implemented in spring of 2010[5], resulting in an exceptionally high S/N >10. The theoretically feasible σ_y* under this optics was ~ about 100 nm, whereas multi-knob tuning achieved σ_y* ~ 300 nm.

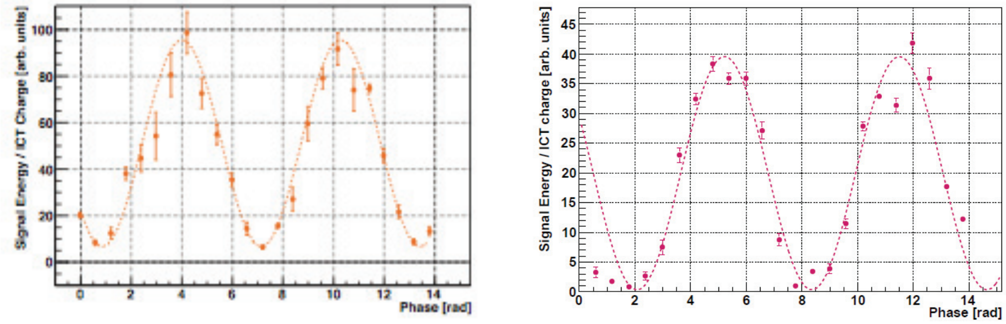

Fig. 4: Interference scans for the smallest σ_{meas}* in 2010. (left) May, 8 deg: σ_y*= 300 ± 30 (stat.) $^{+0}_{-30}$ (syst.) nm (right) Dec, 6 deg: σ_y*= 280 ± 90 (stat.) nm [4,7]

After β_y* had been restored to the nominal 0.1 mm in autumn 2010, BG levels rose significantly from May, typically as high as 100-120 GeV, and S/N was only 0.2-0.5. The smallest σ_y* measured by Shintake Monitor during this run averaged at 280 ± 90 nm (stat.) at 5.96 deg. Immediately after this laser optics was switched on to 30 deg in pursuit of smaller sizes. However, signal jitters far larger than simulated prevented M-reconstruction. A series of investigation resulted in the following beam and laser instability factors as being dominantly responsible[9]:

- High BG levels (low S/N), which degrades detector precision in signal-BG separation
- Fluctuations in beam trajectory and/or laser path, leading to fringe phase errors.
- Degraded laser profile, which signifies deteriorated laser quality over time.

Our efforts to resolve these were interrupted by the immense Great Eastern Japan Earthquake on March 11, and eventually we were unable to commission the 30 deg mode. Despite clear goals had aimed at achieving σ_y* ~ 37 nm by 2011 spring, it took a long time to assess and repair the damage ATF suffered, alongside electricity deficit. While eagerly awaiting beam time to resume in 2011 autumn, we are upgrading hardware and devising more accurate measurement schemes, especially for the challenging 37 nm. These will contribute to smooth commissioning of higher operation modes to measure the design σ_y* before the end of fiscal year 2011.

5. Future Goals

5.1 Measuring the 37 nm beam size

Shintake Monitor is on its way to measure ATF2’s design vertical beam size while serving as a vital beam tuning tool. This demands favorable conditions for both beam and laser optics.

At present the system meets standards in measuring σ_y* > 300 nm. Specialized hardware upgrades (see Sec 3.3) are needed for suppressing below 10% systematic errors intrinsic to the 174 deg mode[4,8], such as the focal scanner for spherical laser wavefronts, and the tilt monitor for fringe tilt. Feedback correction of beam position jitters are anticipated of the nm precision IP-BPMs.

5.2 Prospects for application at ILC

After achieving ATF's goals, the next step is to upgrade Shintake Monitor in aim of utilizing it as the nm resolution beam size monitor necessary for initial commissioning of the ILC beamline[3,4].

An intense UV laser of $\lambda < 200$ nm is required for producing the narrow fringe pitches for measuring $\sigma_y^* = 5.7$ nm at ILC. Potential challenges lie in laser focusing and stable operation under extremely high intensity.

With ILC's higher beam energy, signal energy will approach beam energy, thus BG energy as well. This removes the merit of the current multilayer detector, and calls for the development of a new detector.

High energy also reduces total Compton scattering cross section at ILC to 1/3 of ATF``'s (assuming 250 GeV for ILC and 1.28 GeV for ATF). High laser intensity is required for maintaining adequate number of signal photons.

Shintake Monitor has met demands for 3 Hz test operation at ATF in Dec 2010. Further upgrades are ongoing to adapt to ILC's multi-bunch operation, which enables speedier measurement than the present single bunch mode.

Although ATF2 is a scaled down version of ILC, the technologies verified there are directly applicable to ILC. Shintake Monitor's R&D and contributions to the upcoming success in achieving ATF(2) 's goals are indeed valuable for realization of ILC–like future Tev scale linear colliders.

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