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FERRO-ELECTRIC FAST REACTIVE TUNER APPLICATIONS FOR SRF CAVITIES

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Abstract

A Ferro-Electric fast Reactive Tuner (FE-FRT) is a novel type of RF cavity tuner containing a low loss ferroelectric material. FE-FRTs have no moving parts and allow cavity frequencies to be changed extremely quickly (on the timescale of 100 s of ns or less). They are of particular interest for SRF cavities as they can be placed outside the liquid helium environment and without an FE-FRT it's typically very difficult to tune SRF cavities quickly.

FE-FRTs can be used for a wide variety of use cases including microphonics suppression, RF switching, and transient beam loading compensation. This promises entirely new operational capabilities, increased performance and cost savings for a variety of existing and proposed accelerators. An overview of the theory and potential applications will be discussed in detail.

INTRODUCTION

RF cavities are designed to operate at a specific frequency but there exist an abundance of pervasive phenomena which cause their actual frequency to differ from the design value. Some of these phenomena cause static or slowly varying errors in frequency such as: imprecisions in cavity fabrication; mechanical deformations during assembly and installation; or slowly changing environmental conditions such as temperature. Other phenomena cause frequency errors which vary rapidly with time, including: microphonic vibrations, Lorentz force detuning and transient beam loading.

Slowly varying frequency perturbations can be well corrected with mechanical tuners. However, whilst impressive results have been achieved by various groups using fast piezo tuners both for Lorentz force detuning control [1] and microphonics suppression [2, 3], correcting fast frequency variations with mechanical systems is inherently difficult; for the fastest variations such as transient beam loading, it is essentially impossible. As a result the most common way to overcome fast frequency shifts is by a combination of overcoupling the fundamental power coupler in order to broaden the resonance and using extra RF power. This technique is effective but wastes large amounts of RF power.

In this paper we address a novel tuner type called the Ferro-Electric Fast Reactive Tuner or FE-FRT. This tuning method could offer frequency tuning orders of magnitude faster than what is currently available, with low losses, no moving parts, large tuning range and wide applicability across SRF.

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PRINCIPLE OF OPERATION

Fundamentally FE-FRTs work by passing RF power through a transmission line containing ferroelectric material and reflecting it back to the cavity. The permittivity of the ferroelectric is controlled via application of a high voltage across the ferroelectric altering the RF path length. This causes the phase of the RF fields and therefore the reactance of the tuner as seen by the cavity to change, altering the frequency of the cavity.

An FE-FRT connected to a cavity via an antenna and transmission line can be modelled by the equivalent circuit shown in Fig. 1. The cavity is modelled by a conductance G, capacitance C and inductance L connected in parallel. The tuner admittance as seen by the cavity (after transformation along the transmission line and through the antenna) is:

$$Y_F = G_F + iB_F, \tag{1}$$

and is also connected in parallel.

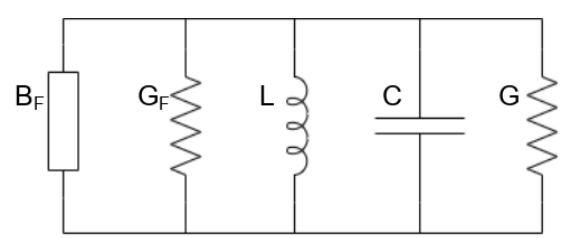

Figure 1: Equivalent Circuit Model of FE-FRT coupled to cavity.

The theory of FE-FRTs has already been presented in [4], the most important results are summarised in Table 1.

The Figure of Merit

The best way to specify the performance of an FE-FRT is with the Figure of Merit (FoM). The FoM is independent of cavity or antenna geometry and of transformation along a lossless transmission line (although it can be significantly reduced by a long lossy line). There are many equivalent ways to write the FoM; we state below the ones we later use in this paper. A quantity with a subscript 1 or 2 is to be understood as the value of that quantity when the

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Table 1: Review of Theoretical Results

Description	Symbol	Equation
Tuning range	$\Delta\omega_F$	$\frac{-\omega_0 \Delta B_F \sqrt{L/C}}{2}$
Dissipated Power	P_F	$U\frac{G_F}{C}$
Reactive Power	$\mathscr{P}_F$	$U\frac{B_F}{C}$
Increase in Bandwidth	σ	$\frac{G_F}{C}$

FE-FRT is in one of its extreme states i.e. with the minimum or maximum voltage applied across the ferroelectric.

Tuning range and bandwidth definition: The originaly published definition of the FoM[4] is:

$$\mathrm{FoM} = \frac{\Delta\omega_F}{\sqrt{\sigma_1\sigma_2}}, \tag{2}$$

where $\Delta\omega_F$ is the tuning range and σ_1 and σ_2 are the increases in bandwidth of the cavity due to the FE-FRT at zero and maximum applied bias field respectively.

Reactive and dissipated power definition: The FoM can also be written in terms of the change in reactive power and the dissipated power as follows:

$$\mathrm{FoM} = \frac{\Delta\mathscr{P}}{2\sqrt{P_1P_2}}, \tag{3}$$

where $\Delta\mathscr{P}$ is the maximum change in reactive power and P_1 and P_2 are the dissipated powers of the two extreme states.

Q^{FRT} definition: The final definition of the FoM equation we show here is written in terms of Q^{FRT} as:

$$\mathrm{FoM} = \frac{\Delta\omega_F}{\omega_0}\sqrt{Q_1^{FRT}Q_2^{FRT}}, \tag{4}$$

where ω_0 is the resonant frequency of the cavity without an FE-FRT attached in rad/s and $Q_i^{FRT} = \frac{\omega_i U}{P_i}$ where ω_i is the resonant frequency of the cavity with the FE-FRT in state i, U is the cavity stored energy and P_i is the power dissipated in the FE-FRT when it is in state i.

PROOF OF PRINCIPLE FE-FRT

A proof of principle (PoP) FE-FRT was designed by S. Kazakov and V. Yakovlev, built by Euclid and successfully tested on an SRF cavity at CERN. A photograph and 3D rendering are shown in Fig. 2. It connects to the cavity on the left via a co-axial cable and to a high voltage source on the right. Details of the test and a full description of the PoP FE-FRT are detailed in [4].

Unfortunately, the PoP FE-FRT suffers from losses which are too great to make it a practically useful tuning device. The principle cause of this is that the surface of the ferroelectric material was brazed to ensure good thermal and electrical contact with the inner and outer conductor. It has since been discovered that this results in a surface with a very low conductivity.

Studies are underway to develop a brazeless FE-FRT with an improved RF design. Based on the material parameters in Table 2 we believe FE-FRTs can be constructed with more than an order of magnitude less percentage power loss [5].

FERROELECTRIC MATERIAL

For best performance the ferroelectric material used in an FE-FRT should in general have a low permittivity, a high tunability (defined as the permimttivity with zero applied field divided by the permittivity with maximum applied field) and a low loss tangent.

The material used in the PoP FE-FRT tuner [6, 7] is a BST(M) material ($BaTiO_3$ - $SrTiO_3$ solid solution with Mg based additives)[1]. Counter-intuitively the introduction of linear (non-tunable) Mg-based ceramic additives increases the tunability whilst keeping the loss tangent low [8, 9]. The response time of the material to applied electric fields is also extremely fast; a similar bulk ferroelectric material has been measured to respond in < 30 ns [10].

The BST(M) material is insensitive to radiation, is easily machinable and has low gas permeability. Together the properties explained above mean this is a very interesting material for FE-FRT development. Some of the most relevant properties of this material are given in Table 2.

Table 2: Ferroelectric Material Parameters

Parameter	Value
Loss Tangent/Frequency[2]	$1 - 4 \times 10^{-6}\,\mathrm{MHz}^{-1}$ [11]
Relative Permittivity at 0 field	159.9 ± 0.6 [11]
Tunability at 8 V/µm	1.4 [12]
Breakdown Strength	20 V/µm [12]
Estimated temp. rise limit	50 K
Thermal conductivity	$7.02\,\mathrm{Wm^{-1}K^{-1}}$

FREQUENCY SHIFT AND RESPONSE TIME MEASUREMENTS

Voltages of 1 kV and 4.5 kV were alternately applied to the PoP FE-FRT whilst an RF amplifier sending constant power to the cavity was swept over a frequency range around the resonant frequency. The observed transmitted power and difference in phase between the forward and transmitted signals, as shown in Fig. 3, offer a clear visualisation of the functional aspects of an FE-FRT. In particular, we see a clear shift in resonant frequency between the two voltages but also, a significant increase in bandwidth with increased bias voltage, causing reduced peak transmitted power at 4.5 kV.

[1] This material was developed by Euclid Techlabs in collaboration with E. Nenasheva.
[2] The loss tangent scales approximately with frequency over a wide range.

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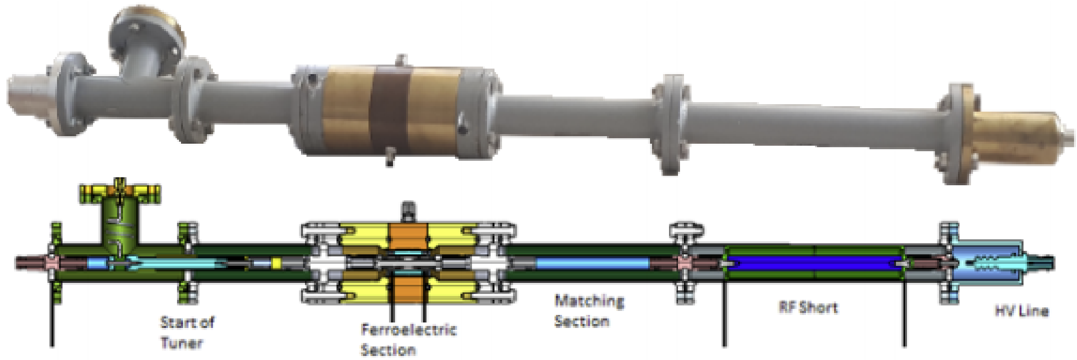

Figure 2: A photograph and cut away 3D rendering of the PoP FE-FRT.

The Q_0 of the cavity was measured to be $\approx$ 4.66.10^8, and a Breit-Wigner distribution was fitted to the transmitted power data in Fig. 3 by which it was possible to calculate the increase in bandwidths due to the FE-FRT at 1 kV and 4.5 kV as 237 Hz, 444 Hz respectively. Together with the measured change in resonant frequency of $\approx$ 480 Hz it was possible to estimate the FoM of the PoP FE-FRT to be 1.49, which is too low to be practically useful. This low FoM was caused both by larger than ideal RF losses in the FE-FRT combined with vertical cryostat constraints of a long transmission line connecting the FE-FRT to the cavity. By comparison, brazing-less FE-FRT designs utilising a shorter connecting transmission line are predicted to obtain FoMs in excess of $\approx$ 20 for this frequency. This is a conservative estimate applicable for applications requiring a large change in reactive power. For low reactive power applications such as microphonics control, even higher FoMs could be obtained.

The speed an FE-FRT can change a cavity's frequency is one of it's most exciting properties. To measure it we apply a HV pulse with the circuit shown in Fig. 4 where a 40 nF capacitor is charged before closing a relay to send the HV pulse down a 50 Ohm coaxial cable to the FE-FRT.

Previous results found a measurement limited upper bound for the frequency response of 50 µs [4]. This measurement was hampered by weak signals and small frequency shifts due to non-optimally designed fundamental power coupler, pick-up and FE-FRT antennas.

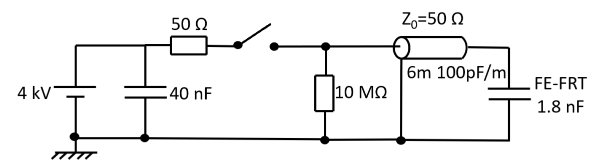

Figure 4: External circuit used to apply high voltage to FE-FRT.

In the latest test these problems were overcome and frequency jumps of several kHz were measured with improved signal strength as shown in Fig. 5. The noise on the frequency is large as, to keep the highest possible time resolution of 200 ns, no signal averaging was used. The time difference between the last measured point below 10% and the first above 90% of the transition between the average frequencies measured before and after the transition is 600 ns. The same criteria applied to the voltage rise gives a time of 800 ns. This discrepancy is explained by the limited time resolution, by the noise on the frequency measurement and also as the ferroelectric does not respond strongly below $\approx$ 1 kV. It appears likely that the frequency response is limited by the external circuit and that the intrinsic response time is even faster than the 600 ns measured.

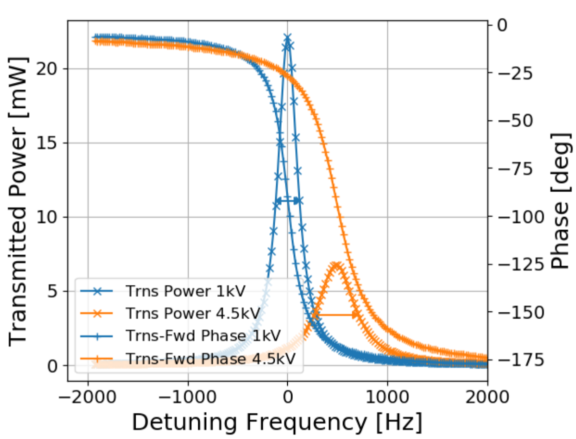

Figure 3: Power and phase resonance curve data obtained in generator driven mode for ferroelectric high-voltage bias fields of 1 kV (blue) and 4.5 kV orange.

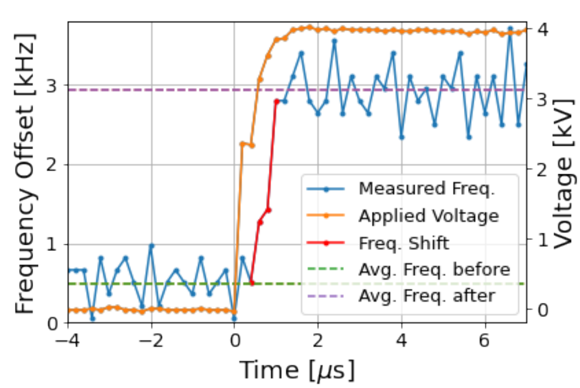

Figure 5: Measured frequency response (blue) of a cavity to a 4 kV high voltage pulse (orange) applied to the connected FE-FRT.

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APPLICATIONS

The unique abilities of FE-FRTs enable many new possibilities some of which we consider in more detail below.

Frequency Switching

In some situations cavities must switch between different frequencies. For example the proton synchrotron (PS) accelerator at CERN is equipped with three 80 MHz normal conducting accelerating cavities, the properties of which are shown in Table 3. Two cavities are required to operate at $\approx$ 80.11 MHz to accelerate protons and one cavity to operate at 79.96 MHz or 79.88 MHz to accelerate Argon or Lead ions respectively. Each cavity is equipped with two mechanical tuners both having a range of $\approx$ 360 kHz, however should one of the cavities fail the mechanical tuners are too slow to allow parallel proton and ion operation.

Table 3: 80 MHz PS Cavity Parameters

Parameter	Value
Design Q_0	22600 [13]
Measured Q_0	17000 [14]
$R/_{Q}$	56 Ω [13]
Nominal Voltage	300 kV [13]
Nominal stored energy	3.2 J

Because of this, it is foreseen to install a fast tuner on one or more cavities able to change the frequency by 230 kHz on a timescale of 100s of milliseconds. The required specifications for such a tuner are shown in Table 4.

Table 4: Received Specifications

Parameter	Value
Tuning Range	230 kHz
Q_{0+FRT}	> 10000
FoM	> 70

The large tuning range and relatively large stored energy require a large change in reactive power of $\approx$ 9.2 MVar in the tuner which is easily calculated using:

$$\Delta\mathscr{P}_F = 2U\Delta\omega_F. \quad (5)$$

The required timescale is achievable by many types of tuner and significant progress has already been made in developing a ferrite reactive tuner [14]. The very low loss tangent of the ferroelectric material FE-FRTs can however be expected to achieve a higher FoM and therefore a higher Q which would require less RF power.

The design and performance of an FE-FRT meeting the specifications is the subject of [5] which predicts a FoM of $\approx$ 100. From this FoM the FE-FRTs dissipated power can be estimated, using Eq. (3), as $\approx$ 46 kW. For comparison the cavity walls dissipate $\approx$ 96 kW at nominal voltage.

Microphonics Suppression

Superconducting cavities in low or zero beam loading machines such as ERLs and heavy ion accelerators typically suffer from microphonic induced frequency variations much larger than the intrinsic cavity bandwidth. In order to power the cavity and maintain stable field levels such machines typically use massivley overcoupled fundamental power couplers to artificially increase the cavity bandwidth. This causes the vast majority of RF power sent to the cavity to be reflected, dissipated in a load and wasted.

The RF power required to maintain the cavity voltage in the presence of a peak microphonics detuning of $\Delta\omega_\mu$ is [15]:

$$P_{RF} = \frac{V_c^2}{4 R/_{Q} Q_L}\frac{\beta+1}{\beta}\left[1+\left(2Q_L\frac{\Delta\omega_\mu}{\omega_0}\right)^2\right]. \quad (6)$$

By compensating microphonics with an FE-FRT it is shown in [16] that the RF power required is given by:

$$P_{RF}^F \approx \frac{2U\Delta\omega_\mu}{\mathrm{FoM}}, \quad (7)$$

and the peak and average forward power are therefore reduced by a factor of $\frac{FoM}{2}$ and $\frac{FoM}{4}$ respectively. For certain projects this can lead to huge power savings. For example, assuming a relatively conservative FoM of 30, it was shown that the total electrical power for RF for the LHeC would be reduced from 22.2 MW to 2.96 MW.

Transient Detuning

For the first time FE-FRTs provide a tuner that is likely fast enough to alter the cavity detuning $\Delta\omega_D$ during gaps in bunch trains. Which would allow significant reduction of RF power whilst also maintaining a constant cavity phase in the presence of transient beam loading. We call this newly proposed RF powering scheme ”Transient detuning”, and a full theoretical derivation and an example accelerator use case is detailed elsewhere [17, 18].

Here we illustrate, without a rigorous proof, the basic principle by considering an idealised special case where particle bunches all transit a cavity at the falling zero-crossing of the cavity voltage and the cavity and RF beam current phase and frequency are not permitted to move with respect to the generator drive current. Under these simplifications, the RF power P_{RF} required to maintain a voltage V in the cavity in the presence of beam loading is[19, 20]:

$$P_{RF} = \frac{V^2 Q_e}{8 R/_{Q} Q_L^2} + \frac{R/_{Q} Q_e}{2}\left[\frac{V\Delta\omega_D}{\omega_0 R/_{Q}} + \frac{I_b(t)}{2}\right]^2, \quad (8)$$

where $R/_{Q}$ is the cavity shape constant, Q_L is the loaded quality factor, Q_e is the external Q-factor of the power coupler, ω_0 is the cavity resonant frequency, $I_b(t)$ is the magnitude of the RF beam current, and $\Delta\omega_D$ is the cavity detuning defined as the difference between the cavities resonant frequency and the RF generator frequency and not to be confused with $\Delta\omega_F$ the FE-FRTs tuning range.

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For comparison we first consider the "half-detuning" scheme[21] which does not utilise an FE-FRT and where $\Delta\omega_D$ is set to a fixed value of:

$$\Delta\omega_D = \frac{-\bar{I}_b \omega_0 {}^R\!/_Q}{4V}, \tag{9}$$

where $\bar{I}_b$ is the average RF beam current during the filled portion of the beam (i.e. excluding the gaps in the beam). In this scheme the generator power in the beam and non-beam segments is equal and minimised when the external Q is:

$$Q_e^H = \frac{2V_c}{{}^R\!/_Q \bar{I}_b}, \tag{10}$$

where we have assumed $Q_e^H << Q_0$ and hence $Q_L \approx Q_e^H$. In this case the generator power is given as:

$$P_{RF}^H = \frac{V\bar{I}_b}{8}. \tag{11}$$

Transient detuning would use an FE-FRT to quickly change ω_0 to switch $\Delta\omega_D$ from 0 in beam gaps to $-\frac{\omega_0 {}^R\!/_Q \bar{I}_b}{2V}$ during beam segments. In this way the second term of Eq. (8) is always 0 and the generator power is minimised. The tuning range required of the FE-FRT to achieve this is simply:

$$\Delta\omega_F = \frac{\omega_0 {}^R\!/_Q \bar{I}_b}{2V}. \tag{12}$$

We can now approximate the FE-FRT's contribution to the cavity's loaded Q by substituting Eq. (12) into Eq. (4) as:

$$Q_F = \frac{2V\mathrm{FoM}}{\bar{I}_b {}^R\!/_Q}, \tag{13}$$

where we have assumed $Q_F \approx Q_{F1} \approx Q_{F2}$. It is now straight forward to calculate the RF power in the transient detuning case, P_{RF}^F, as:

$$P_{RF}^F = \frac{V^2(Q_e + Q_F)^2}{8 {}^R\!/_Q Q_e Q_F^2}. \tag{14}$$

Equation (14) is minimised when $Q_e = Q_F$ in which case we obtain upon substitution of Eq. (13):

$$P_{RF}^F = \frac{V\bar{I}_b}{4\mathrm{FoM}}. \tag{15}$$

By comparing Eq. (11) with Eq. (15) we see that transient detuning could in principle reduce average RF power consumption by a factor of $\approx \frac{\mathrm{FoM}}{2}$ compared to half-detuning.

Exotic Next Generation Cavities and Cryomodules

Frequency pertubations such as microphonics and Lorentz force detuning reduce performance and can dramatically increase the required RF power. Because these pertubations degrade performance and increase RF power requirements and as active control of these perturbations is challenging, huge efforts are often made in cavity [22] and cryomodule design [23] to passively suppress cavity vibrations and reduce coupling to external vibration sources. The ability of FE-FRTs to effectively counteract such perturbations could dramatically ease this design effort. This could enable reduced costs, increased feasibility of new and innovative ideas, and improved performance for instance by allowing reduced wall thickness increasing cooling of the inner cavity surface.

Another area where FE-FRTs could act as an enabling technology is for Nb_3Sn coated cavities. Nb_3Sn has a significantly higher critical temperature than Niobium, can achieve higher Q_0 values and could in theory allow accelerating gradients up to 96 MV/m [24]. However Nb_3Sn is brittle and one problem facing its use for cavities is that mechanical tuning has been demonstrated to significantly reduce both the Q_0 and accelerating gradient that can be achieved [25]. FE-FRTs can help overcome this limitation by providing a way to tune cavities without mechanically deforming them.

CONCLUSION

FE-FRTs can manipulate cavity frequencies on the timescale of 100s of nanoseconds or less, with tuning ranges applicable to SRF cavity operation. This tuning is achieved by controlling the reactive power flow in the combined cavity-tuner system, thereby adjusting the resonance condition without mechanical deformation of the cavity. Such attributes permit applications across a variety of different use cases.

In particular, microphonics suppression for low or zero beam loading machines and transient detuning for high beam loading machines are of particular interest, where the average RF power consumption could be reduced by a factor of approximately $\frac{\mathrm{FoM}}{4}$ and $\frac{\mathrm{FoM}}{2}$ respectively. Also, with estimates based on the material parameters indicating practically achievable FoMs in the range of 20 to more than 100 (depending on the specific application and frequency of operation), very significant power savings are possible.

Improved compensation of frequency perturbations would relax design requirements for cavities and cryomodules leading to cost savings as well as increased feasibility of envelope pushing designs. In addition as no mechanical deformation is needed, FE-FRTs could permit tuning of Nb_3Sn coated cavities without degradation in performance by avoiding inducing strain in, or potentially cracking, the Nb_3Sn layer.

In order to realise these grand ambitions it will be necessary to demonstrate that FE-FRTs can be constructed which exhibit minimal RF losses and can handle significant reactive power flows. Management of dissipative losses and thermal heating of the ferroelectric material have to be carefully considered, and as learnt from the proof of principle FE-FRT, brazing-less integration of the ferroelectric material is advised. Finally, a practical FE-FRT, besides having a high FoM and power handling capability, must produce a large enough change in phase to enable the required tuning range to be achieved without an unrealistically strong coupling.

Detailed design of a much improved FE-FRT tuner is already underway, with manufacturing envisioned this year.

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