# RESONANT COHERENT DIFFRACTION RADIATION SYSTEM AT ERL TEST ACCELERATOR IN KEK*

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*Abstract*

Coherent radiation from a short bunched electron beam has been expected to be a high power source in THz regime. Especially the feature of the modern energy recovery linac is suitable for a high averaged power source. We propose to test an advanced scheme of resonantly exciting coherent diffraction radiation in an optical cavity. By stimulating the radiation in a multi-bunch beam, highly enhanced radiation power can be extracted. This system can excite all the cavity longitudinal modes at the same time, it can be a broadband source. We are preparing an experimental setup to test the resonant radiation in the cERL at KEK.

## INTRODUCTION

A test accelerator of energy recovery linac, cERL [1], has been operating in KEK. It can produce a low emittance and short bunched beam at a high repetition rate. The feature is suitable for testing a THz coherent radiation source.

We have been preparing a test experiment [2] for an advanced scheme based on CDR (Coherent Diffraction Radiation) arranged to be a cavity which matches the bunch repetition. Figure 1 shows the scheme of the system. The optical cavity is placed on the beam axis in the straight section. The cavity mirrors have a small hole in the center so that the beam can pass through. If the bunch length is short enough to emit a coherent radiation, resonant modes of the cavity are excited by the beam. Since the electromagnetic wave excited by the preceding bunches stimulates the radiation of the following bunches, the beam power can be efficiently converted to the radiation if the bunch repetition matches the fundamental frequency of the cavity.

When the cavity is well designed to be resonantly excited by the beam repetition, a broad bandwidth of longitudinal modes are excited at the same time. This situation realizes a unique feature that can be understood as a mode-locked laser or a broadband FEL.

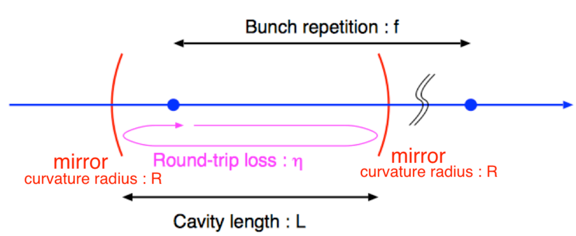


Figure 1: Scheme of the experiment.

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This type of experiments were carried out with a configuration of CTR or CSR, where the beam hits the mirrors [3] [4]. The CDR configuration without destroying the beam is the key for the next stage to operate in a higher beam power. The configuration becomes possible with recent low emittance linacs. An experiment at the milli-meter wavelength regime with a small number of bunches has been reported [5]. Our experiment aims to show a possibility for realizing a high averaged power and broad bandwidth THz source at a modern ERL accelerator.

## PRINCIPLE

### *Excitation of a Cavity Mode*

The cavity modes couple the beam via the electric field along the beam trajectory. Since the fundamental transverse mode does not have a longitudinal electric field, it can not be excited by this layout. On the other hand, the electric field of the higher order transverse mode, $TM_{10}$ (or $TM_{01}$ by exchanging $x$ with $y$) mode, is written as follows,

$$E_{10}^{x} = \frac{A}{w(z)}\frac{x}{w(z)}\exp\left(-\frac{x^2+y^2}{w^2(z)}\right)\cdot\exp[i(\omega t - kz + \phi(z)] \quad (1)$$

$$w(z) = w_0\sqrt{1+\frac{z^2}{z_0^2}}, \quad z_0 = \frac{\pi w_0^2}{\lambda} \quad (2)$$

$$\phi(z) = 2\tan^{-1}(\frac{z}{z_0}) \quad (3)$$

where $\lambda$ is the wavelength, $k = 2\pi/\lambda$, $\omega/k = c$. $A$ is a scale factor. The radiation propagates in the $z$-direction. $w_0$ is the size at the waist. $\phi(z)$ is known as Gouy phase. $z_0$ is Rayleigh length.

The longitudinal field can be calculated by the following simple equation

$$ikE^z = \frac{\partial E^x}{\partial x} \quad . \quad (4)$$

The beam of speed $c$ on the center axis feels the longitudinal field of

$$E_{10}^{z}(x, y = 0) = -\frac{A}{kw^2(z)}\exp[i\phi(z)] \quad . \quad (5)$$

Integration of $E^z$ along the beam trajectory gives the excited power of the mode. We can understand that the beam excites the cavity mode via the Gouy phase. Excitation of $TM_{10}$ and $TM_{01}$ at the same time results in the radially polarized donuts distribution, the well known characteristics of CDR/CTR.


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### *Broadband Excitation*

The cavity has longitudinal modes spaced with equal distance in the frequency domain. The frequency of the $n$-th longitudinal mode $\nu^{(n)}$ can be written as

$$\nu^{(n)} = \frac{c}{2L}\left(n - \frac{4}{\pi}\tan^{-1}(\sqrt{\frac{L}{2R-L}})\right) \quad , \qquad (6)$$

where $L$ is the cavity length (distance of the two mirrors), $R$ is the radius of curvature of the mirrors (We assume a symmetrical 2-mirror cavity). The frequency difference in the nearest modes is $c/2L$, called FSR (Free Spectral Range). The frequency of the first mode $\nu_1$ is called CEO (Carrier Envelope Offset). The CEO depends on the design of the cavity, namely the ratio of $R/L$.

Here, we consider $n$-th longitudinal mode. Compared with the single bunch case, the power enhancement after infinite numbers of bunch passage can be written as

$$p^{(n)} = \frac{1}{2-\eta-2\sqrt{1-\eta}\cos\theta^{(n)}} \quad , \qquad (7)$$

where $\eta$ is the round-trip power loss ratio. $\theta^{(n)}$ is the phase shift between bunches. It can be written as

$$\theta^{(n)} = 2\pi\frac{\nu^{(n)}}{f} \quad . \qquad (8)$$

$f$ is the bunch repetition frequency. When $\theta^{(n)}$ is an integer multiple of $2\pi$, the excitation of multiple bunches constructively add up, we call it resonance. The power enhancement reaches $\sim 4/\eta^2$ at the equilibrium where cavity loss balances the excitation.

Since the resonance condition depends on $n$ as can be seen in Eq.6, each longitudinal mode resonates at a little different $f$. In other words, if the bunch repetition $f$ is fixed, each longitudinal mode resonates at a different cavity length $L$. So, ideal broadband excitation is not realized in general. But in the special case of $R = L$, the CEO becomes zero. And the resonance condition does not depend on $n$ if $f$ coincides with the FSR (perfect synchronization). This situation is shown in Fig.2. The power enhancement is shown as colors on a map of the cavity length $L$ and the longitudinal mode number $n$. In the special design of CEO=0, all the longitudinal modes resonates at the cavity length that matches bunch repetition (A). But in general cases of CEO≠0, there is no such a special condition (B).

If we detect the radiation power with a wide-band detector, we observe sum of all the longitudinal modes $\sum_n p^{(n)}$. Figure 3 shows a calculation example of excited power as a function of the cavity length. If the cavity is designed to be CEO=0, a strong excitation due to contribution of all the modes is realized at the perfect synchronization.

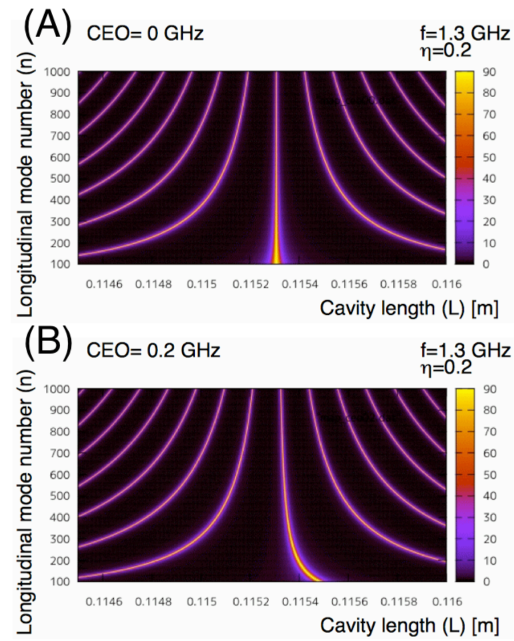


Figure 2: Resonance map.

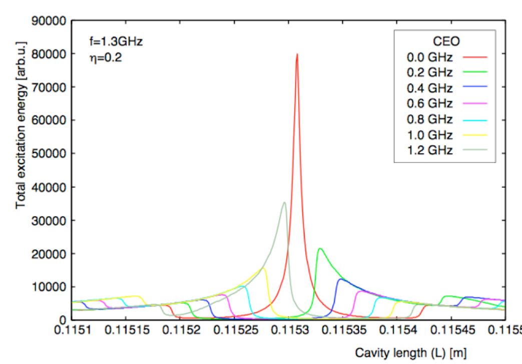


Figure 3: Power in cavity length scan.

## DESIGN OF THE EXPERIMENTAL SETUP

### *Setup of the Cavity*

Table 1 summarizes the beam parameters we assumed and the design parameter of the cavity. Assuming the nominal repetition of 1.3 GHz at cERL, we designed 115 mm cavity. Figure 4 shows the cavity assembly. The mirror holders have adjustment systems for performing mechanical pre-alignment before the installation. One of the mirror is attached on a piezo stage for scanning the cavity length.

There is a trade-off between the size of the beam holes and the power loss of the cavity. Since the higher order mode has donut distribution, it is possible to have a reasonable beam hole keeping the loss small.

The radiation excited in the cavity is extracted from one of the beam hole. We designed to put another mirror to reflect

Table 1: Beam and Cavity Parameters

| Parameter | | value |
|---|---|---|
| Bunch repetition | $f$ | 1.3 GHz |
| Beam energy | $E$ | 20 MeV |
| Bunch charge | $q$ | 1 pC |
| Normalized emittance | $\epsilon_n$ | 1 $\mu$m |
| Bunch length | $\sigma_t$ | 150 fs |
| Cavity length | $L$ | 115 mm |
| Mirror curvature radius | $R$ | 115 mm |
| Mirror hole diameter | $d$ | 3 mm |
| Mirror diameter | $D$ | 50 mm |
| Cavity loss | $\eta$ | 0.05 |
| Extraction efficiency | $T$ | 0.025 |
| Target frequency | $\nu$ | 0.5 THz |

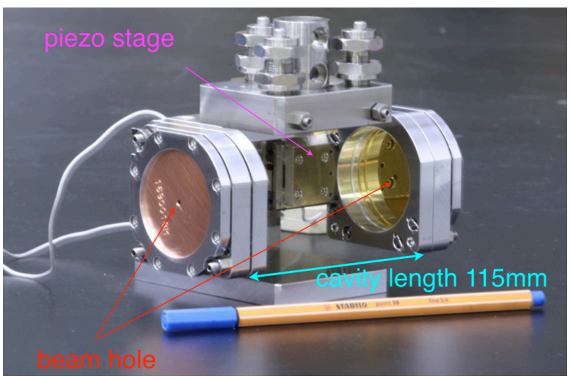


Figure 4: Cavity assembly.

the extracted radiation in the perpendicular direction. The chamber layout is shown in Fig.5.

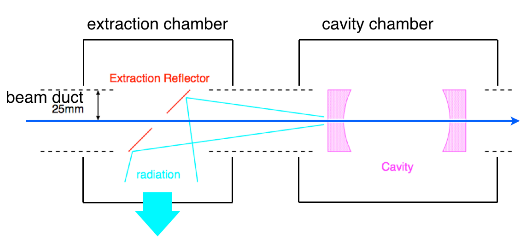


Figure 5: Chamber layout.

### *Installation in the cERL*

We are preparing to install the CDR cavity system in the cERL. The layout is shown in Fig.6. In the bunch compression operational mode of the cERL, the acceleration rf phase at the main linac is set to be off-crest for introducing an energy chirp in the bunch. Then, by adjusting the longitudinal dispersion in the arc section, a short bunch beam can be realized in the straight section. There is a bunch length monitor based on an interferometer system measuring CTR from an inserted target. The planned location of the installation is next to the monitor.

Prior to the installation, we have been testing beam tuning of the bunch compression operation. We confirmed that the rms bunch length of 250 fs can be realized reproducibly. We also measured beam emittance by the quadrupole-scan method and confirmed that the normalized emittance of 2 $\mu$m·rad can be realized in the bunch compression mode at bunch charge of 2 pC.

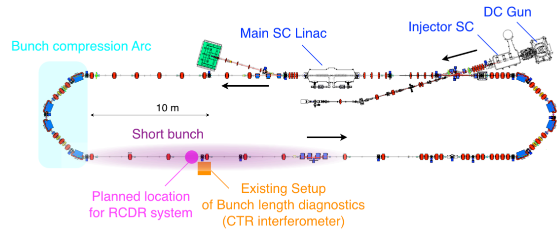


Figure 6: Installation in the cERL.

## SUMMARY

The first thing to prove in the beam experiment will be the resonance signal. By scanning the cavity length, resonance peak shown in Fig.3 will be measured. From the peak width and hight, we will be able to discuss the characteristics of the cavity such as power loss.

In order to realize this scheme to be a high power cw source, the most important and unknown thing is the beam loss. The key of this system is transmitting the beam in the small beam holes. A similar situation has been tested in an ERL machine [6].

The system installation is planned in the summer of 2017. Although the next operational schedule of the cERL is not determined yet, we are preparing the setup assuming beam operation in early 2018.

## ACKNOWLEDGMENT

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