SCHEMES OF SUPERRADIANT EMISSION FROM ELECTRON BEAMS AND "SPIN-FLIP EMISSION OF RADIATION"

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Abstract

A unified analysis for Superradiant emission from bunched electron beams in various kinds of radiation scheme is presented. Radiation schemes that can be described by the formulation include Pre-bunched FEL (PB-FEL), Coherent Synchrotron Radiation (CSR), Smith-Purcell Radiation, Cerenkov-Radiation, Transition-Radiation and more. The theory is based on mode excitation formulation – either discrete or continuous (the latter - in open structures). The discrete mode formulation permits simple evaluation of the spatially coherent power and spectral power of the source. These figures of merit of the radiation source are useful for characterizing and comparing the performance of different radiation schemes. When the bunched electron beam emits superradiantly, these parameters scale like the square of the number of electrons, orders of magnitude more than spontaneous emission. The formulation applies to emission from single electron bunches, periodically bunched beams, or emission from a finite number of bunches in a macro-pulse.

We have recently employed the formulation to calculate a new kind of coherent radiation from electron beam: enhanced Electron Spin Resonance Emission from a polarized electron beam. Estimates of the characteristics and possible applications of this effect are presented.

SUPERRADIANT EMISSION FROM AN E-BEAM BUNCH

Expanding the radiation field in terms of a complete set of eigenmodes (in free space or in a waveguide, the governing equations describing the radiative emission from a free electron beam are [1]:

$$\mathbf{E}(\mathbf{r},\omega)=\sum_{\pm q} C_q(z,\omega)\tilde{\mathbf{E}}_q(\mathbf{r}) \tag{1}$$

$$\mathbf{H}(\mathbf{r},\omega)=\sum_{\pm q} C_q(z,\omega)\tilde{\mathbf{H}}_q(\mathbf{r}) \tag{2}$$

$$C_q^{out}(\omega)-C_q^{in}(\omega)=\sum_{j=1}^{N}\Delta C_{qj}=-\frac{1}{4P_q}\sum_{j=1}^{N}\Delta W_{qj} \tag{3}$$

$$\Delta W_{qj}=-e\int_{-\infty}^{\infty}\mathbf{v}_j(t)\cdot\tilde{\mathbf{E}}_q^{\,*}(r_j(t))e^{i\omega t}dt+\int_{-\infty}^{\infty}\boldsymbol{\mu}_j(t)\cdot\tilde{\mathbf{H}}_q^{*}(\underline{r}_j(t))e^{i\omega t}dt \tag{4}$$

$$\frac{dW_q}{d\omega}=\frac{2}{\pi}P_q\left|C_q^{out}(\omega)\right|^2 \tag{5}$$

Here we added in Eq. 4 the second (magnetic emission) term in order to be able to take into account radiation from the spin of the electron.

Substituting (3) in (4), one obtains for the spectral radiative energy per mode:

$$\begin{aligned}\frac{dW_q}{d\omega}=\frac{2}{\pi}P_q\Bigg\{&\left|C_q^{in}(\omega)\right|^2+\\+&\left|\Delta C_{qe}^{(0)}(\omega)\cdot\sum_{j=1}^{N}e^{i\omega t_{oj}}\right|^2+\\+&\left[C_q^{in*}(\omega)\cdot\Delta C_{qe}^{(0)}(\omega)\cdot\sum_{j=1}^{N}e^{i\omega t_{oj}}+c.c.\right]+\\+&\left[C_q^{in*}(\omega)\cdot\sum_{j=1}^{N}\Delta C_{qj}^{st}(\omega)+c.c.\right]\Bigg\}\equiv\\\equiv&\left(\frac{dW_q}{d\omega}\right)_{in}+\left(\frac{dW_q}{d\omega}\right)_{sp/SR}+\left(\frac{dW_q}{d\omega}\right)_{ST-SR}+\left(\frac{dW_q}{d\omega}\right)_{st}\end{aligned} \tag{6}$$

The term of interest in eq. (6) is the second term. It describes spontaneous emission (shot noise) if the electrons entrance phase ωt_{0j} are random and describes "superradiance" if the phases are correlated. In particular, if $\left\langle (t_{0j}-t_0)^2\right\rangle^{1/2} \langle\langle 2\pi/\omega$ (a single ultra-short bunch) the emission is superradiant (energy proportional to N^2) and coherent. For bunch duration t_b < 1pSec this provides a wide range radiation source in a wide frequency range up to the THz regime.

This formulation can be applied to any kind of free electron radiation scheme, including:

- Coherent Smith-Purcell,
- Cerenkov Radiation
- Transition Radiation,
- Cyclotron Resonant Emission (CRE).

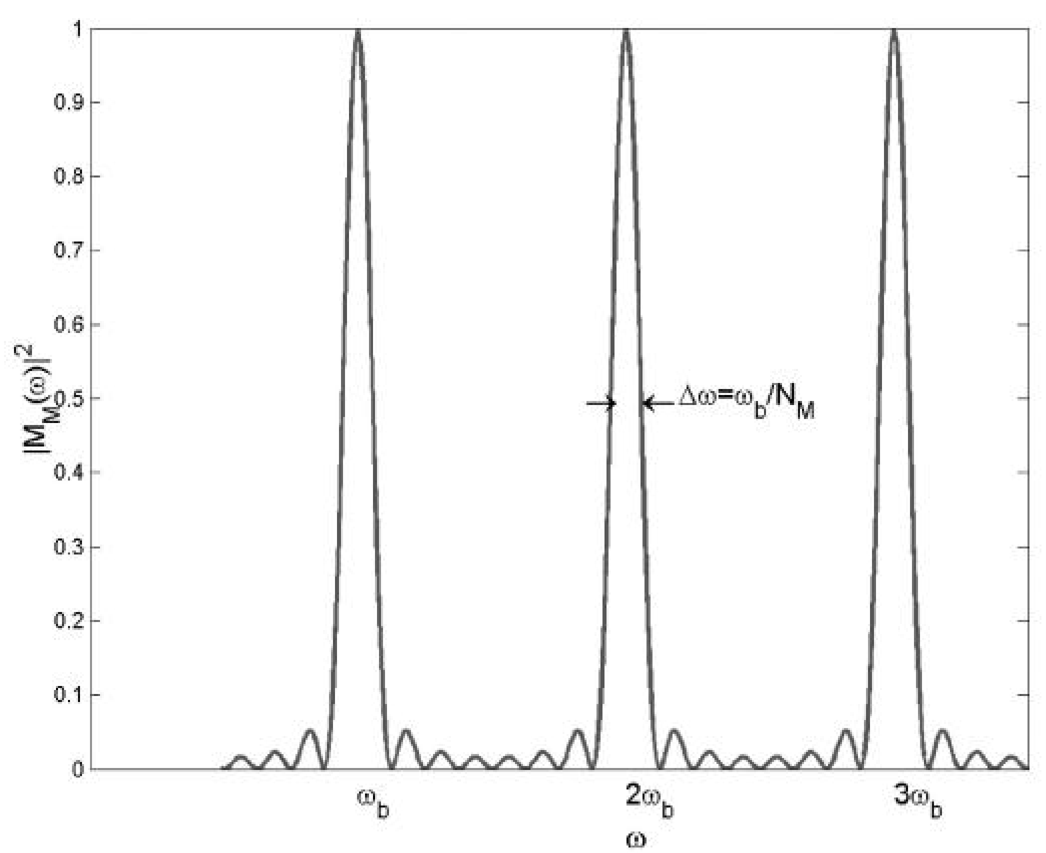

Figure 1: The Superradiance lineshape function of a macropulse composed of NM bunches emitting at harmonics n=1,2,3.

Of special interest is the common case of multiple bunches in a long macropulse. In this case we predict that the emission from the different bunches interfere coherently and a very narrow band superradiant emission field will be measured at the detection site at all harmonics n of the bunching frequency ω_b. The emission line (Fig. 1) is given by:

$$M_M(\omega)=\frac{\sin\left(N_M\pi\omega/\omega_b\right)}{N_M\sin\left(\pi\omega/\omega_b\right)} \tag{7}$$

and the emission linewidth is:

$$\frac{\Delta\omega}{n\omega_b}=\frac{1}{nN_M} \tag{8}$$

where N_M is the number or bunches in the macropulse.

FREE ELECTRON SPIN FLIP EMISSION OF RADIATION

The magnetic interaction term in Eq. 4 can be used for calculating the emission from a particles carrying a magnetic moment $\underline{\mu}_j$ (for electrons $\left|\underline{\mu}_j\right| = g\frac{1}{2}\mu_B$ where μ_B is the Bohr magenton):

$$\Delta W_{qj}^{m}=\frac{i\omega_s}{2}\int_{t_{0j}}^{t_{0j}+L/v_z}\tilde{\boldsymbol{\mu}}_j\cdot\mathbf{H}_q^*\left(\mathbf{r}_j\right)e^{-i\omega_s\left(t-t_{0j}\right)-ik_{zq}z_j(t)+i\omega t}dt \tag{9}$$

$$\left(\frac{dW_q}{d\omega}\right)_{sp}=\frac{N}{32P_q}\left(\frac{\omega'_{s0}\,L}{v_z\gamma}\right)^2\left|\tilde{\ }_j\cdot\tilde{\mathbf{H}}_q^*\right|^2\operatorname{sinc}^2\left(\theta L/2\right) \tag{10}$$

$$\theta=\frac{\omega-\omega_s}{v_z}-k_{zq} \tag{11}$$

has the emission from the different bunches interfere coherently and a very narrow band superradiant emission field will be measured at the detection site at all harmonics n of the bunching frequency ω_b. The emission line (Fig. 1) is given by:

The radiation pattern described by the $\operatorname{sinc}^2\left(\bar{\theta}/2\right)$ function is the same as in CRM emission. Indeed the FESFER emission is almost at the same frequency as the CRM emission:

$$\frac{\delta\omega}{\omega_0}=\frac{\omega_s-\omega_c}{\omega_0}=\frac{g-2}{2}=1.16\times10^{-3} \tag{12}$$

and the ratio between them is given by:

$$\frac{dW_q^m / d\omega}{dW_q^c / d\omega} = \alpha^2 \frac{\left\langle \left| \sum_{j=1}^{N} e^{i\omega_{s0} t_{0j} + i\varphi_{s0j}} \sin\Psi_j \right|^2 \right\rangle_{\perp s}}{\left\langle \left| \sum_{j=1}^{N} e^{i\omega_{c0} t_{0j} + i\varphi_{c0j}} \beta_{\perp j} \right|^2 \right\rangle_{\perp c}} \quad ; (13)$$

where

$$\alpha = \frac{\hbar\omega'_{c0}}{2\gamma mc^2} \langle\langle 1$$

This ratio is very small when the spin precession phases are random (spontaneous emission) but it can be enhanced by a big factor N=q/e (q is the charge per bunch) if the e-beam is polarized (in the transeverse dimension) and emits superradiantly, and if the CRM electron gyration phases are random and emit spontaneous emission [1].

An alternative way to enhance the detection of FESFER is to operate in a mode where also the CRM emission is superradiant, and measure the beat-wave signal between the FESFER and CRM frequnecies:

$$\left|\mathbf{E}(\mathbf{r}_\perp, L, t)\right|^2 \propto DC + \alpha\beta_{\perp 0}(P_\uparrow - P_\downarrow)\sin[\delta\omega(t - t_0 - L/v) + \varphi_{c0} - \varphi_{s0}] \quad (14)$$

CONCLUSIONS

- Superradiant emission from *sub-pS*ec e-beam bunches is a promising high power thz radiation scheme.
- Formulation for coherent spectral power of any kind of radiation scheme and bunching wave-form was derived.
- New schemes of Free Electron Spin-Flip emission of radiation (FESFER) and Spin-State modulation (FESMER) are proposed. They may be useful for controlling and monitoring the spin-state of polarized electron beams.
- Detection of FESFER may be enhanced by operating at superradiance emission conditions and by Heterodyne detection.

REFERENCES

[1] A. Gover, “Superradiant and stimulated superradiant emission in prebunched electron-beam radiators – part I: Formulation”, Physical Review Special Topics – Accelerators and Beams Vol. 8, issue 3 (030701) (March 2, 2005).