Energy-Recovery Option for a Future X-ray Free-Electron Laser

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Abstract

A superconducting electron linac together with an energy-recovery system, which has been demonstrated as a useful driver for high-power IR-FELs, seems to be an attractive device for a future X-ray FEL facility as well, because the energy-recovery enable one to reduce the RF generator power required for the operation and also reduce the radiation from the beam dump. Automatic cancellation of beam loading by energy-recovery makes bunch-train structure flexible, which is preferable for experimental users. We summarize critical issues in energy-recovery option for a future X-ray Free-Electron Laser.

1 FUTURE XFEL AS A USERS FACILITY

Since a free-electron laser (FEL) has, in principle, no limitation in its lasing wavelength, extensive efforts have been devoted to develop FELs in the region of wavelength in which other coherent sources are not available. As a result of recent progress of high-brightness photo-cathode injectors and demonstration of SASE-FEL in visible and UV, construction of X-ray FELs becomes a realistic target for coming decade.

A proof-of-principle experiment of XFEL, SLAC/LCLS, has been proposed and will be constructed soon [1]. An XFEL facility for experimental users will be considered, after the demonstration of XFEL at SLAC/LCLS. Another XFEL device DESY/TESLA-FEL is designed as a users facility, where four beam-lines of SASE-FEL and six beam-lines of spontaneous radiation are installed and XFEL radiation with flexible pulse trains, from a single-shot to 10MHz repetition, is available [2]. Such flexible pulse trains with high-duty operation is intrinsic for various scientific applications, but it is only achievable by superconducting linac. A future XFEL users facility, therefore, will be based on a superconducting linac.

2 ENERGY-RECOVERY LINACS

An energy-recovery superconducting linac has been developed as a driver of high-power IR-FEL at TJNAF [3], in which beam average current can be increased four times with keeping RF generator power. In JAERI, a similor system is under construction as a high-power FEL driver [4]. A synchrotron light source and a linac-on-proton collider using energy-recovery superconducting linacs are also proposed [5][6].

The principle of the energy-recovery is the conversion of electron energy into RF power by reinjecting the high-energy electron beam into superconducting RF cells at decelerating phase. The advantage of the energy-recovery is, primarily, to reduce the required RF power to run the accelerator. We see, in the next section, how much RF power can be saved by energy-recovery. The energy-recovery also decreases the electron energy at the beam dump as small as the injection energy. Since heat load and radiation at the beam dump are greatly reduced by small dump energy, the design of radiation shield around the beam dump can be simplified. Thus, the capital cost and running cost of the facility can be saved by energy-recovery. Automatic cancellation of beam-loading by accelerating and decelerating beams also promises flexible operation of the bunch trains. This is a great benefit for experimental users at a future XFEL facility.

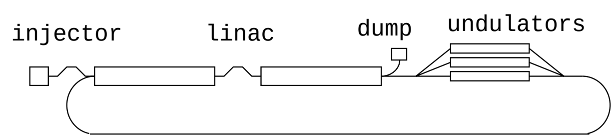

Figure 1: Energy-recovery XFEL.

3 MINIMUM RF GENERATOR POWER

Since the primary advantage of the energy-recovery is saving RF generator power to drive the accelerator, we start with a quantitative discussion on the RF power.

The optimal coupling coefficient between an RF cavity and an external RF source, which makes the generator power minimum is found to be [7]

$$\beta_{opt} = \sqrt{(1+b)^2 + \left[\frac{2\delta f}{\Delta f_0} + b \tan\phi_b\right]^2} \;, \qquad (1)$$

where $b = P_b/P_c$ is the ratio between the beam power and the power dissipated in the cavity, $\Delta f_0 = f_0/Q_0$ is the intrinsic bandwidth of the cavity and δf is the cavity detuning, ϕ_b is electron bunch phase with respect to the RF crest. Note that the detuning is the sum of the static detuning δf_0 and the microphonics δf_m : $\delta f = \delta f_0 + \delta f_m$.

When the microphonics can be neglected, the optimal coupling coefficient to minimize the RF generator power is

$$\beta_{opt} = 1 + b = 1 + \frac{P_b}{P_c} \;, \qquad (2)$$

and the generator power becomes

$$P_g = \beta_{opt} P_c = P_b + P_c \;, \qquad (3)$$

which is the well-known condition for “no reflecting power.”

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If we take the microphonics into account, the optimal coupling coefficient becomes

$$\beta_{opt} = \sqrt{(1+b)^2 + \left[\frac{2\delta f_m}{\Delta f_0}\right]^2} \ , \tag{4}$$

and the RF generator power is

$$P_g = \frac{1}{2}\left[(b+1) + \sqrt{(b+1)^2 + \left(\frac{2\delta f_m}{\Delta f_0}\right)^2}\ \right] P_c \ . \tag{5}$$

In usual superconducting accelerators without energy-recovery, we see $(P_b/P_c) \gg (\delta f_m/\Delta f_0)$ and $P_b \gg P_c$, then eq.(4) can be reduced into eq.(2) and the optimum coupling coefficient and the generator power are basically determined by beam power. Superconducting accelerators with energy-recovery, however, the RF generator power is dominated by the microphonics and we find in the limit of full energy-recovery $b \to 0$:

$$P_g \simeq \frac{\delta f_m}{\Delta f_0}\ P_c = \frac{V_c^2 \delta f_m}{(R/Q) f_0} \ . \tag{6}$$

It shows that the required generator power is proportional to the amount of cavity detuning due to the microphonics δf_m.

If we use parameters similar to the TESLA cavity, $f_0 = 1.3GHz$, $V_c = 25MV/m$, $(R/Q) = 998\Omega/m$, $Q_0 = 1 \times 10^{10}$ and the amount of microphonics measured at TTF $\delta f_m = \pm 10Hz$ [8], the generator power can be reduced as small as $P_g = 4.8kW/m$ with $Q_L = 6 \times 10^7$ by energy-recovery. It means that an XFEL driver of 15GeV and 10mA, whose beam power is 150MW, is operated with total RF generator power of 3MW as theoretical limit.

In practical design of RF systems, we must take controllability and stability of the system into account. In the operation of energy-recovery linacs, small coupling, which means large loaded Q, makes external compensation of RF instability difficult, in general[9]. The coupling coefficient, therefore, should be optimized to make RF power minimum with keeping control margin for stable operation. Typical values of loaded Q in superconducting electron linacs are, $Q_L = 2 \times 10^6$ in TESLA, $Q_L = 4 \times 10^6$ in TJNAF/IR-demo. We need, at least, 10 times larger loaded Q to participate in the benefit of energy-recovery. Operation with rather high loaded Q, $Q_L = 2 \times 10^7$ is under consideration in CEBAF upgrade for 12GeV[10].

4 CRITICAL ISSUES IN ER-XFELS

Critical issues in the design of energy-recovery XFEL (ER-XFEL) can be divided into three categories : general issues for energy-recovery linac (ERL), general issues for XFEL and specific issues for ER-XFEL.

4.1 ERL general issues

In the construction of ERLs at TJNAF/IR-demo and JAERI-FEL, several design requirements have been pointed out, which are isochronous arcs, injection and dump chicanes, consideration of RF stability, average current limitation by BBU. For ERL with higher energy, transverse focusing of two beams having different energy in a long linac should be considered. This focusing is optimized by graded-gradient focusing, in which a FODO lattice parameters is matched to the lower energy beam and the betatron function for each beam becomes maximum near the highest energy. It is shown that moderate focusing with $\beta \leq 100m$ is available in a 1000m linac by graded-gradient focusing[11].

4.2 XFEL general issues

Generation of low emittance electron beam by photocathode RF gun, acceleration and compression of the bunch without emittance dilution are common requirements for XFELs. Recent studies show that collective phenomena such as surface roughness of an undulator duct can be relaxed by low-charge option, in which electron bunch of lower charge is used with keeping charge density in the phase space. The low-charge option is also helpful to suppress CSR in return arcs of ERL-XFELs.

4.3 ER-XFEL specific issues

Dynamic perturbation on decelerating beam energy arising from FEL interaction is a trigger of RF instability in ERLs for high-power FEL oscillators. The conversion efficiency of SASE-XFEL, however, is small as 10^{-4}, and energy perturbation due to the FEL is less critical in ER-XFELs, unless R_{56} in the return arc is large.

An XFEL for hard x-ray requires electron energy higher than 10GeV, which corresponds to a 600m linac with assuming 25MV/m gradient and 0.7 filling factor of RF cells in the accelerating structure. Transverse focusing must be applied with graded-gradient method.

Interruption of linac structure by bunch compressors and coherent synchrotron radiation (CSR) in return arcs are discussed in the following.

5 RETURN ARC CONFIGURATION

Reinjection of electron beam into the accelerator for energy-recovery can be made by two type of return arcs. One is recirculating beam transport used in TJNAF/IR-demo and JAERI-FEL, in which decelerating beam is reinjected from the injector side. The other is folding beam transport, in which decelerating beam is reinjected as antiparallel to the accelerating beam. It is used in Reflextron, energy-doubled linacs for medical application [12].

The folding configuration, which is also called time-reversal beam transport, is preferable for better transverse focusing of both accelerating and decelerating beams, because the beams have same energy at arbitrary position in the accelerator. However, the folding configuration causes bunch collision which introduce tune shift and emittance growth in the beams. Coherent tune shift due to the two beam collision is estimated as [13]

$$\Delta\nu_x \simeq 1.2\xi_x \ , \quad \xi_x^{(1)} = \frac{N^{(2)} r_e \beta_x^{(1)}}{\gamma^{(1)} 2\pi\sigma_x^{(2)}(\sigma_x^{(2)} + \sigma_y^{(2)})} \ , \quad (7)$$

where (1) and (2) mean two beams respectively. Substituting typical parameters for ER-XFEL : the number of electrons per bunch $N = 3 \times 10^9$ and normalized emittance $\varepsilon_n = 1$mm-mrad, and assuming the beams have same energy and transverse size at the collision point, we find the coherent tune shift $\Delta\nu \simeq 0.8$. Successive collisions of two beams with such a large tune shift results in large instability, and the folding configuration is excluded from ER-XFELs.

6 INTERPOSITION OF BUNCH COMPRESSORS

A magnetic chicane for bunch compression is installed in an accelerator for an XFEL to produce electron bunches of very high peak current. The parameters for the bunch compressor, electron energy at the buncher, momentum compaction, are determined by total design of longitudinal phase space management. The energy-recovery option introduces additional constraint : the accelerating and decelerating beams must keep their RF phase after the magnetic chicane. To satisfy this constrain, momentum compaction R_{56} becomes as large as the RF wavelength, which introduces large amount of higher-order nonlinearity in the longitudinal phase space rotation. Though this problem can be cleared by installing the compressor where two beams have the same energy, design of longitudinal phase management is largely restricted.

7 CSR PROBLEMS

Emittance dilution caused by coherent synchrotron radiation (CSR) in a curvature path is a sever problem to design bunch compressors for XFELs. The CSR problem is also a major concern in return arcs of ER-XFELs, because the emittance dilution during the return arcs increases the transverse size of decelerating beam and may bring unstable phenomena such as BBU. In this section, we estimate energy dissipation and emittance growth in return arcs based on the first-order approximation.

Unshielded CSR power emitted by an electron is obtained by

$$\frac{dW}{d(ct)} = \frac{C\ q}{R^{2/3}\sigma_s^{4/3}} \ , \quad (8)$$

where q is bunch charge, R is radius of curvature orbit, σ_s is bunch length, and coefficient C for Gaussian bunch is $C \sim 7.9$[eV · m / nC]. If we choose parameters, $q = 0.5$nC, $\sigma_s = 30\mu$m, $R = 50$m as an example of ER-XFEL return arc, each electron in the bunch loses its energy by $dW/d(ct) = 300 keV/m$, which results in 0.3% energy dissipation for 15GeV beam after a 180 degree arc. Total energy dissipation including SR and CSR becomes about 1% in this example. Although it is non-negligible energy dissipation to consider energy balance in ER-XFELs, these dissipation is constant as far as the bunches have the same temporal profile, and the compensation of the SR and CSR loss is less critical than dynamic beam energy dissipation by SASE-FEL, which is in the order of 10^{-4}.

Emittance growth due to the CSR in return arcs is also a severe problem in ER-XFELs. If the above return arc consists of 30 bending magnets and average beam size in the bending is $\sigma \sim 10\mu m$, the CSR introduces emittance growth $\varepsilon_n \sim 3$mm-mrad in each bendings, using approximation

$$\Delta\varepsilon_n \sim \gamma\sigma\Delta\alpha \ , \quad (9)$$

where $\Delta\alpha$ is bending angle error caused by CSR energy loss. When the phase of horizontal betatron and the phase of dispersion function have same values at all the bendings, total emittance growth after the return arc becomes maximum as $\varepsilon_n \sim 90$mm-mrad. It has been shown that this emittance growth can be partially suppressed by choosing appropriate betatron phase advance in each isochronous cell[14].

8 SUMMARY

We presented issues of concern to discuss a future XFEL users facility based on an energy-recovery superconducting linac. Although it requires big efforts to solve the listed issues, some of which are common challenge to XFELs or energy-recovery machines already proposed. Therefore, progress towards providing those required technology is expected.

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