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# Alternative lattice options for energy recovery in high-average-power high-efficiency free-electron lasers

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**Abstract.** High-average-power free-electron lasers often rely on energy-recovering linacs. In a high-efficiency free electron laser, the main limitation to high average power stems from the fractional energy spread induced by the free-electron laser process. Managing beams with large fractional energy spread while simultaneously avoiding beam losses is extremely challenging and relies on intricate longitudinal phase space manipulations. In this paper we discuss a possible alternative technique that makes use of an emittance exchange between one of the transverse and the longitudinal phase spaces.

**Keywords:** high-power beams, free-electron lasers, energy recovery, phase space manipulation, beam dynamics
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## MOTIVATION

High-average-power free-electron lasers (FELs) often relies on energy-recovering linear accelerators (linac) [1, 2]. In such energy-recovering linacs (ERLs) the beam is accelerated and manipulated to match the FEL requirements. After participating to the FEL interaction the “spent" beam is decelerated and disposed. The FEL-induced fractional energy spread $\sigma_{\delta,FEL}$ results in a significant longitudinal emittance dilution approximately given by

$$\varepsilon_{z,F} \simeq \varepsilon_{z,0}\frac{\gamma_F}{\gamma_0}\left[1+\frac{\sigma_{\delta,FEL}}{\sigma_{\delta,0}}\right], \tag{1}$$

where $\varepsilon_{z,0}$ is the longitudinal emittance at injection in the linear accelerator, $\gamma_0$ and $\gamma_F$ are respectively the energies at injection and downstream of the FEL insertion device. The origin of fractional momentum spread dilution during the beam-FEL interaction process was investigated in several papers [3, 4] and approximately scales as $\sigma_{\delta,FEL} \simeq 8\eta_{FEL}$ with $\eta_{FEL}$ being the FEL efficiency [5].

In a conventional ERL lattice, the wiggler-to-linac transport is setup to perform a 90 deg rotation of the longitudinal phase space: the large energy spread of the exhaust beam it reduced at the expense of the bunch length [6, 7, 8, 9, 10]. Although the method has proven successful in existing high-power FELs, its extension to higher-efficiency FELs is not straightforward [11, 12]. In this paper we present another class of manipulations

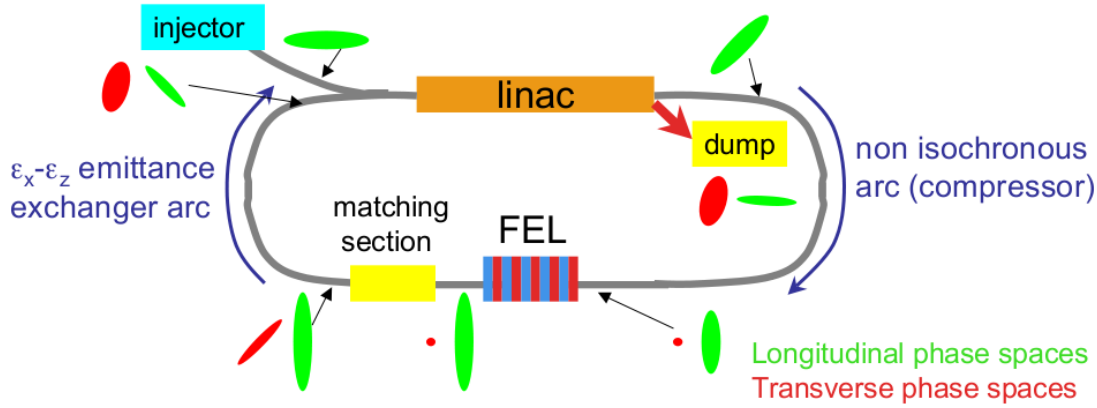


**FIGURE 1.** Overview of the ERL concept based on transverse-to-longitudinal emittance exchange.

that could find applications in ERL-driven high-power and high-efficiency FELs. The scheme, pictorially described in Fig. 1, consists in exchanging the transverse horizontal and longitudinal emittances associated to the beam downstream of the FEL. The large longitudinal emittance is exchanged with a smaller horizontal emittance thereby reducing significantly the final fractional energy spread and bunch length. The technique, pending extensive numerical studies, could be eventually implemented in, e.g., the 10 kW Jefferson Lab's FEL where the initial emittance partition $(\varepsilon_x, \varepsilon_z) \sim (5, 40)$ [$\mu$m] becomes $(\varepsilon_x, \varepsilon_z) \sim (5, 150)$ [$\mu$m] downstream of the FEL [13].

## PROPOSED SCHEME

In the proposed concept the linac-to-wiggler transport is identical to a standard high-power FEL driver ERL: the beam is longitudinally compressed at the wiggler location and the longitudinal phase space downstream of the FEL interaction is an up-right ellipse characterized by the rms bunch length $\sigma_{z,F}$ and fractional energy spread $\sigma_{\delta,F}$.

The wiggler-to-linac transport incorporates an emittance exchanger beamline capable of swapping the horizontal and longitudinal trace space emittances. Methods to exchange one of the transverse and the longitudinal have been first discussed in Reference [14] and more recently investigated in the context of high-gain FELs [15, 16]. A possible emittance exchange beamline, proposed in Reference [17], is based on a deflecting cavity flanked by two dogleg sections. Here, in an attempt to minimize the number of dipole magnets used (to possibly mitigate collective effect such as coherent synchrotron radiation), we seek to implement an emittance-exchanging beamline that also bends the beam's trajectory by 180 deg as needed in a collinear energy-recovering linac. Considering the general problem of a deflecting cavity sandwiched between two dispersive sections and imposing the symplectic condition yields a constraint on the dispersion vectors $\vec{\eta} \equiv (\eta, \eta' \equiv d\eta/ds)$ generated by the downstream $\vec{\eta}_d$ and upstream

$\vec{\eta}_u$ dispersive beamlines. These vectors are related via [18]

$$\vec{\eta}_d = \begin{pmatrix} R_{11,d} & R_{12,d} \\ R_{21,d} & R_{22,d} \end{pmatrix} \vec{\eta}_u, \tag{2}$$

where $R_{ij,d}$ are the elements of the $2 \times 2$ horizontal transfer matrix associated to the downstream beamline. The deflecting cavity strength ($\kappa \equiv \partial x'/\partial z$) was taken to be $\kappa = -1/\eta_d$. In this preliminary study we also forced the upstream and downstream sections to be similar in design and found a possible solution consisting of two 90-deg bending sections separated by the deflecting cavity. Each 90-deg section is composed of two dipoles and three quadrupoles; see Fig. 2. In this particular example the quadrupoles in the upstream bending section are tuned to generate a total dispersion $\vec{\eta}_u = (0.5, 0)$ while the ones located in the downstream section are set to fulfill Eq. 2. The evolutions of the dispersion function and its slope along the two beamlines are shown in Fig. 3.

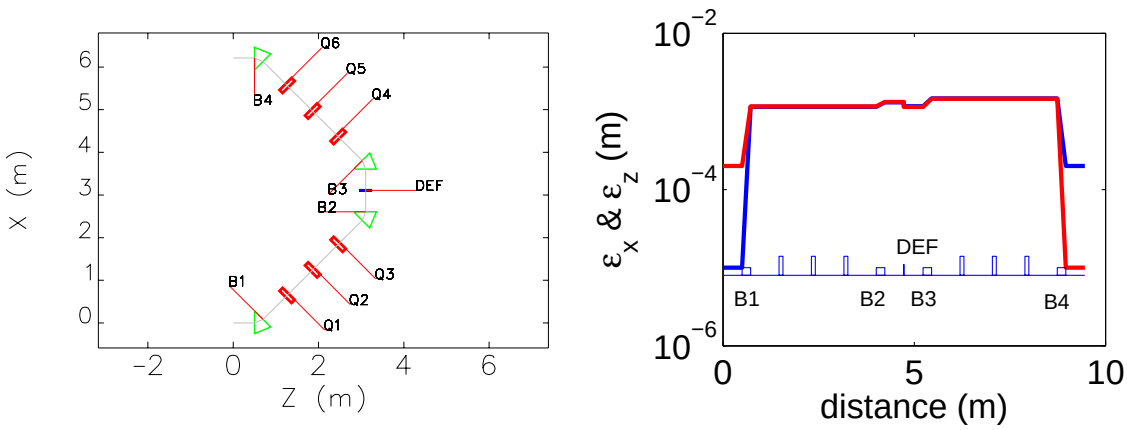


**FIGURE 2.** Example of a 180-deg arc designed to exchange the horizontal and longitudinal emittances (left). Evolution of transverse (red) and longitudinal (blue) emittances along the 180-deg arc (right). The legend for the left plot is: "Q1"..."Q6" correspond to quadrupole, "B1"..."B4" to dipoles and "DEF" indicates the location of the deflecting cavity. The quadrupoles Q1-Q3 and Q4-Q6 are setup to generate the dispersion functions shown in Fig. 3. These first order single-particle dynamics simulations were performed with ELEGANT [19].

The transfer matrix of the emittance exchanger beamline has the form

$$M = \begin{pmatrix} 0 & A(R_{ij,u}, R_{56,u}, \vec{\eta}_u) \\ B(R_{ij,d}, R_{56,d}, \vec{\eta}_u) & 0 \end{pmatrix}, \tag{3}$$

where $i, j = 1, 2$. The final $2 \times 2$ covariance matrix associated to the longitudinal phase space downstream of the exchanger beamline is

$$\Sigma_z = \varepsilon_{x,F}^2 A \begin{pmatrix} \beta_{x,M} & -\alpha_{x,M} \\ -\alpha_{x,M} & \frac{1-\alpha_{x,M}^2}{\beta_{x,M}} \end{pmatrix} \widetilde{A} \tag{4}$$

where $\widetilde{A}$ denotes the transpose of $A$ and $\alpha_{x,M}$ and $\beta_{x,M}$ are the Courant-Snyder parameters downstream of the matching section shown in Fig. 1. The latter equation has two

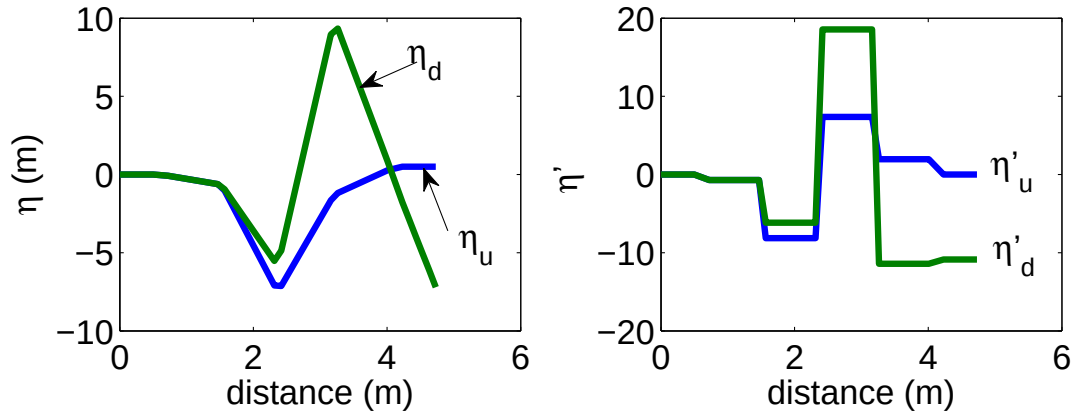


**FIGURE 3.** Horizontal dispersion (left) and dispersion slope (right) evolutions in the B1-B2 (blue) and B3-B4 (green) sections shown in Fig. 2; see text for details.

important implications. Firstly, the transverse matching section can be used to tune the transverse Courant-Synder parameters to tailor the longitudinal trace space ellipse downstream of the emittance-exchanging beamline. In particular the correlated energy spread and bunch length can be chosen to eventually yield the lowest possible fractional energy spread after deceleration. Secondly the final longitudinal emittance is smaller that the one obtained during the standard longitudinal phase space gymnastic implemented in conventional ERL lattices. This reduction of longitudinal phase space area is done at the expense of the transverse horizontal trace space which is generally easier to control.

## DISCUSSION & SUMMARY

A possible main advantage of the technique introduced in this paper over the conventional longitudinal phase space gymnastic implemented in ERLs is its independence on the FEL-induced energy spread. We therefore suggest that designing an ERL lattice that incorporates the discussed transverse-to-longitudinal emittance exchange may provide a viable path for operating MW-class high-efficiency FELs.

The method might also have additional benefits since it inherently results in a $2 \times 2$ block anti-diagonal transport matrix for the total recirculation loop (i.e. linac exit to linac entrance) in the $(x, x', z, \delta)$ trace space. Such properties might be useful for mitigating and possibly suppressing the beam break-up instability similarly to the proposed coupling schemes in the transverse trace space $(x, x', y, y')$ [20, 21]. The latter type of methods increases the beam break-up threshold current but cannot suppress the instability since it is in practice difficult to precisely align the polarization of the harmful dipole higher order mode(s) [HOM(s)] along one of the transverse directions. On the other hand the scheme introduced in this paper couples the HOM-induced transverse perturbations due to, e.g. dipole modes, to longitudinal perturbations and vice-versa.

In summary we presented an alternative scheme for managing the large fractional energy spread induced in efficient high-power FELs. A linear and “primitive" analysis of the suggested technique seems promising but further work needs to be done in order to fully demonstrate the viability of the method. In particular nonlinear and thick-lens effects should be analyzed and the impact of the deflecting cavity on the multibunch beam dynamics need to be assessed.

## ACKNOWLEDGMENTS

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