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Advanced Studies for the Dynamics of High Brightness Electron Beams with the Code MILES

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Abstract. High brightness electron beams enable a wide spectrum of applications ranging from short wavelength radiation sources to high gradient wakefield acceleration. The rich dynamics that are intrinsic in charged particles accelerated in complex systems require a careful description in the analysis and design of a given machine, particularly regarding its stability. Numerous computer codes are in use by the accelerator community for such purposes. In particular, MILES is a simple tracking code we have developed that allows fast evaluations of collective effects in RF linacs. In this paper we extend the simple models previously developed to describe specific, diverse applications that can benefit from the fast simulation tools developed in MILES. Examples of this kind include particle driven acceleration schemes in a plasma where driver and witness beams propagate in the "comb" pulse-train configuration. Specifically, we investigate the self-induced fields excited within the X-band rf-linac stage of EuPRAXIA@SPARC_LAB. Further, we discuss additional advanced topics such as resistive wall wakefield effects in planar FEL undulators and their impact on the radiation emitted.

1. Introduction

A wide panorama of applications including advanced light sources [1, 2], lepton colliders [3] and particle radiotherapy [4], rely on high brightness electron linacs. It is thus crucial to ensure high quality beams which demands thorough studies of their dynamics in turn. Such motivations have led us to the development of MILES, a custom tracking code based on semi-analytical models describing space charge and wakefield effects in high brightness e^- linacs [5, 6, 7]. The advantage of such models is to reduce the computational times without severe losses in the accuracy which motivates the inclusion of additional features to our code. Indeed, so far MILES was mainly adopted to describe the dynamics in RF linacs however, the goal of this paper is to usher in a larger class of problems that we can investigate by using similar models. The examples discussed throughout the paper examine different aspects of EuPRAXIA@SPARC_LAB, an X-ray FEL user facility under development at Frascati National Laboratories (INFN-LNF) [8].

Such a facility combines radio-frequency (RF) linacs with particle driven wakefield acceleration (PWFA) stages where "laser comb" beams, *i.e.* drivers plus witness, are utilized. The RF linac consists of an S-band (2.856 GHz) injector stage followed by an X-band (11.9942 GHz) booster where the electrons are accelerated up to $\sim 130\,\mathrm{MeV}$ and $\sim 500\,\mathrm{MeV}$, respectively. The plasma stage increases the energy of the witness beam up to $\sim 1\,\mathrm{GeV}$ after which an undulator system induces the lasing process.

2. SRWF in comb beams

Plasma wakefield acceleration schemes constitute an attractive technique to achieve very high accelerating gradients, in the GV/m scale [9, 10]. Particle driven acceleration is obtained by using the intense wakefields excited in the plasma by a high charge *driver* beam in order to accelerate a low charge *witness* beam properly delayed. Such a technique can also exploit multiple driver, charge modulated beams to optimize the acceleration of the witness which is known as *laser comb* configuration [11, 12, 13]. In the following we will use MILES to investigate the dynamics of single driver comb beams in the X-band linac stage for EuPRAXIA@SPARC_LAB. As the beam-plasma interaction is a complex process, to find simplified models describing such a problem is beyond our scopes. However, the evaluation of short-range wakefield (SRWF) effects induced by rf linacs and responsible for mutual coupling in comb beams is still a subject of interest.

Table 1 summarizes the main parameters characterizing the driver and the witness beam at the output of the S-band injector stage which precedes the X-band linac. The X-band linac for EuPRAXIA consists of two stages with eighth $\sim 0.9\,\mathrm{m}$ long sections each which accelerate the electrons coming from the S-band injector at $\sim 125\,\mathrm{MeV}$ up to an energy of approximately $530\,\mathrm{MeV}$.

Table 1. Beam parameters at the exit of the S-band injector.

Injector exit parameters	Witness	Driver
Charge (pC)	30	200
Rms spot size (μm)	118	127
Rms length (fs)	17	207
Emittance (μm)	0.55	1.5
Mean energy (MeV)	124	126
Energy spread (%)	0.18	0.55
Bunch separation (ps)	0.5	- -

2.1. Benchmark with ELEGANT

As a preliminary step, we start by establishing the validity of our models by a benchmark with previous simulations performed with ELEGANT [14, 15]. Figure 1 shows a comparison of the rms transverse envelope within the first X-band linac stage ($\lesssim 350\,\mathrm{MeV}$). In this simple example, the beam propagates on axis and is not subjected to wakefield effects. The transverse optics system consists of alternating gradient quadrupoles located in the drift spaces among consecutive sections. It can be noticed that, due to the high charge ratio, the dynamics are mainly dominated by the driver beam and that the agreement with ELEGANT is excellent.

2.2. Short-range wakes in RF linacs

Short-range wakefields in periodic accelerating structures have been studied extensively by use of diffraction theory [16, 17, 18] and well known formulas for the wake-function of short bunches

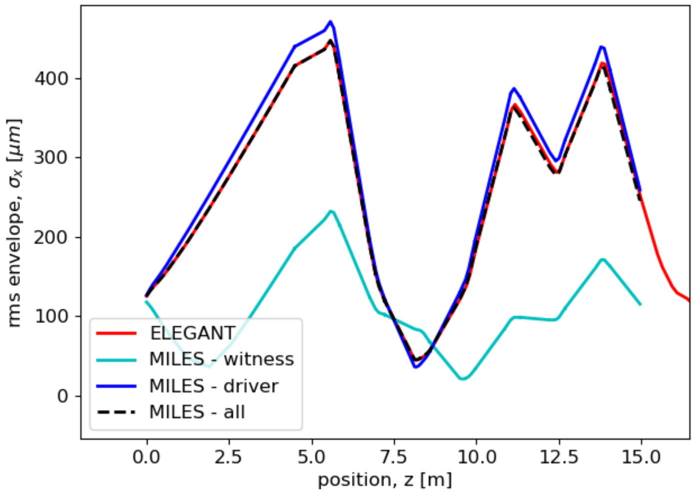

Figure 1. Rms envelope of a comb beam in the X-band linac: witness (cyan), driver (blue) and overall beam (black, red).

can be found in [19]. Such models show that small cell irises induce intense wakefields whose effect is particularly relevant for high frequency linacs such as those in the X-band stage. The main concern is represented by the transverse dipole wakes since their strength scales as a^{-3} (a being the iris radius) and they cause emittance dilution due to the correlation between the planes [20]. Here we use MILES to investigate the emittance growth in presence of alignment errors. In Fig. 2 we consider the 8 accelerating sections in the first stage of the X-band linac at EuPRAXIA and we assume that they are affected by $\pm 50\,\mu$m offsets with alternate sign. It can be noticed that, as the beam travels off-axis exciting dipole wakefields, the overall emittance grows. However, the witness is only slightly affected by this process ($\sim -9\%$ variation) because, due to the short dimensions, the intra-beam correlation effect remains moderate.

3. Resistive wall induced energy spread in undulators

In this section we adopt MILES to evaluate the energy spread induced by the resistive wall (RW) wakefields in a magnetic undulator and its effect on the FEL radiation. Narrow energy spectra are indeed crucial for FEL performance. A commonly used criterion for efficient lasing requires that $\sigma_\gamma/\langle\gamma\rangle \lesssim \rho$ where ρ is the “Pierce parameter” typically in the order of $\sim 10^{-3}$ [21]. Here we investigate possible dilution effects due to the interaction with the beam pipe in the EuPRAXIA@SPARC_LAB undulator. The first part of the section introduces the models taking into account the RW effects whereas the second part discusses the impact on the FEL performance.

3.1. AC resistive wall Impedance

Beams propagating in vacuum chambers with a finite conductivity experience self-induced fields that are described by the resistive wall impedance model. In particular, the monopole longitudinal impedance for a circular pipe of radius a assumes the form [22, 23, 24]

$$Z(k) = \frac{Z_0}{2\pi a}\left(\frac{\lambda(k)}{k} - \frac{ika}{2}\right)^{-1} \tag{1}$$

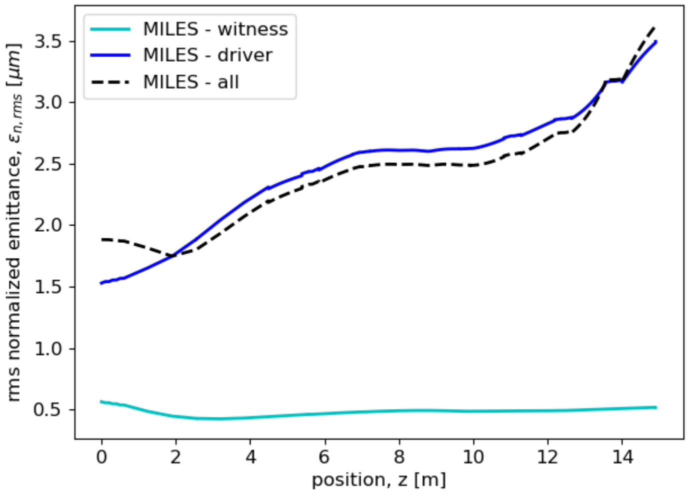

Figure 2. Rms normalized emittance growth in the X-band linac for EuPRAXIA in presence of misaligned sections.

where $\lambda(k) = \sqrt{Z_0\sigma|k|/2}(i + \text{sign}(k))$ and $Z_0 \approx 377\,\Omega$ is the free-space impedance. At low frequencies, the electrical conductivity σ is a real quantity and Eq. (1) provides the DC impedance. Conversely, at high frequency the AC impedance is obtained by including a complex conductivity $\tilde{\sigma} = \sigma/(1 - ikc\tau)$ which takes into account the effect of a finite relaxation time τ [25]. Although a closed form for the inverse Fourier transform of Eq. (1) does not exist in the AC case, an approximate representation can be found in terms of a damped resonant mode (*see* [23]). Thus, the short-range longitudinal wake-function per unit length has the form

$$w_{\parallel}(s) = \frac{Z_0 c}{\pi a^2} e^{-s/4c\tau} \cos\left(\sqrt{\frac{2k_p}{a}} s\right), s \geq 0 \tag{2}$$

where $k_p = \sqrt{Z_0\sigma/c\tau}$ is the plasma wavenumber.

In addition, the wake-function can also be evaluated numerically with dedicated electromagnetic (EM) codes. In particular, IW2D (Impedance Wake 2D) allows to calculate the RW impedance per unit length of pipes with uniform but arbitrary cross section [26]. In Fig. 3 we show the wake-function per unit length for a hollow circular beam pipe made of copper ($\sigma = 5.8\,10^7$S/m and $c\tau = 8.1\,\mu$m) with a 2 mm radius. The solid red curve represents the analytical approximation in Eq. (2) whereas the dashed blue curve is obtained with IW2D. Notice that the EM simulation requires finite values of γ which results in nonzero contributions for $s < 0$ that is, ahead of the source particle.

3.2. FEL radiation performance

The reference case that we consider in the following takes into account the EuPRAXIA@SPARC_LAB undulator for the production of 4 nm photon beams [27]. The undulator section consists of ten 2 m long modules with a period of 18 mm. Ultra-relativistic beams at ~ 1 GeV and ~ 1.8 kA peak current propagate within a circular copper vacuum chamber co-axial with the undulator. Longitudinal wakefields are excited according to Eq. (1) and (2) and, thus, we use the wake-function calculated by IW2D in Fig. 3 for the evaluation of the energy spread

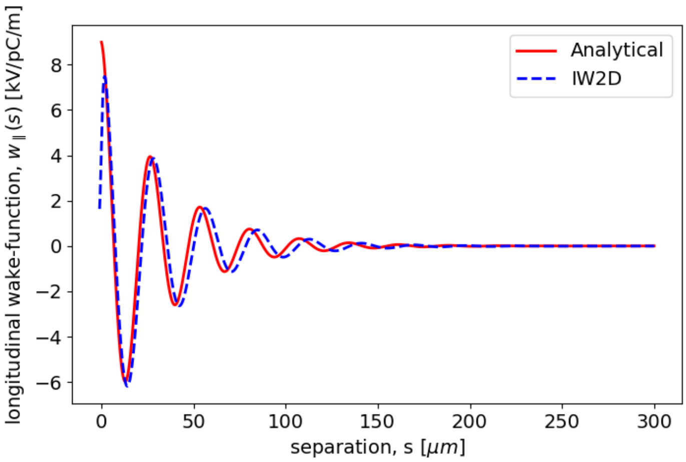

Figure 3. AC resistive wall wake-function per unit length for a Cu circular pipe of 2 mm radius.

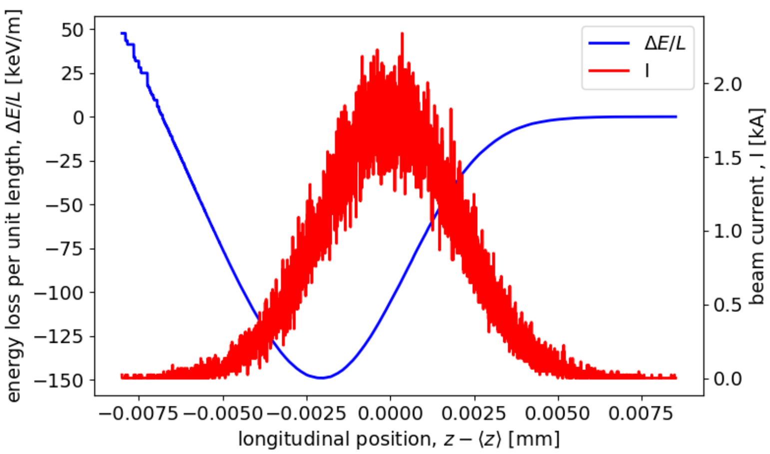

Figure 4. Slice energy loss per unit length (blue) and beam current (red).

induced within the chamber. As an example, Fig. 4 shows the energy loss per unit length by each slice of a 30 pC, 2 μm rms Gaussian beam in a copper pipe with 2 mm radius.

The emission of radiation from the FEL process is simulated with the code `GENESIS1.3` [28]. The information shown in Fig. 4 is accounted for including the additional energy spread induced by the chamber resistive wall. Figure 5 shows the power of the radiation produced by each slice at the exit of the undulator section, in presence of wakefields excited in cylindrical pipes with 2 and 3 mm radii. As a result, the FEL emission process is slightly perturbed because of the moderate energy loss induced by the RW wakes which is also shown in the upper left corner of the figure.

4. CONCLUSION

In this paper we introduced new aspects of the beam dynamics in MILES that go beyond the case of single bunches in RF linacs. The examples presented here show the potential of progressively extending a custom code in order to include additional useful features. It is anticipated that we will extend such a framework to perform studies on multi-drive, charge-modulated comb beams

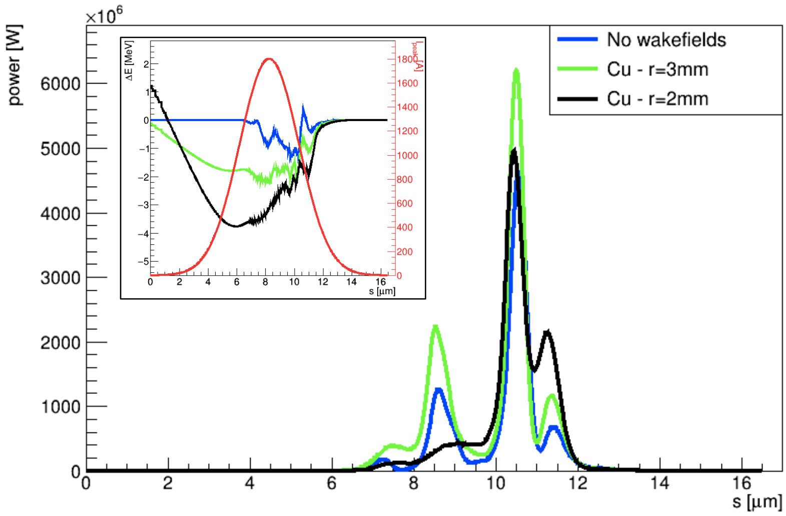

Figure 5. FEL radiation power from each beam slice at the exit of the undulator. The slice energy loss is also shown in the upper left corner together with the current profile (red).

as well as new wakefield problems ranging from plasma capillaries to the emission of coherent synchrotron radiation (CSR).

Acknowledgements

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