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SIMULATION STUDIES OF BBU SUPPRESSION METHODS AND ACCEPTABLE TOLERANCES IN DIELECTRIC WAKEFIELD ACCELERATORS*

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Abstract

The advantage of dielectric wakefield accelerators (DWAs) is the ability to achieve accelerating gradients well above the limits of conventional accelerators. However DWAs will also produce high transverse wakefields if the beam propagates off-center, which grow even faster than the accelerating gradient when the width of the beam channel is decreased. It is highly important to suppress single beam breakup (BBU) instability in order for the beam to propagate long enough so that a reasonable amount of energy (e.g., 80%) from the drive bunch is extracted. In addition bending of the dielectric channel has a similar effect to off-center steering of the beam with the required tolerances on the channel straightness typically in a few micron range. For both rectangular and circular dielectric lined waveguides we use a FODO lattice with a tapered strength for suppression of BBU. We impose initial energy chirp on the drive beam to make use of the BNS damping. We change rectangular waveguide orientation by 90 degrees with a small step to make use of the quadrupole wakefield focusing. These and other techniques and tolerance requirements are discussed and simulation results are presented in this paper.

INTRODUCTION

Accelerating gradients as high as several GV/m have been demonstrated in short dielectric tubes fed by electron beams [1]. However, when it comes to staging, a problem of high transverse wakefields arises. Narrowing of the dielectric tube results in higher accelerating gradient which is generally in inverse proportion to the tube radius squared. However the transverse wakefields grow even faster in inverse proportion to the tube radius cubed [2]. Consequently smaller tube size causes premature BBU that will lower the accelerator efficiency and the maximum achievable energy due to the beam loss. More efficient use of the drive bunch can be obtained if the BBU instability is effectively suppressed.

SIMULATIONS IN ELEGANT

DWA modelling was performed in Elegant to study ideas and configurations for their effectiveness in fighting BBU [3]. Even though Elegant [4] is considered as a primarily transfer matrix type of an accelerator code, it has all the necessary capabilities to fully account for different particle energies in beamline elements (including quadrupole magnets) with momentum kicks. This is especially important as the drive and the witness bunches in the DWA may have different particle energies by as much as several orders. We implemented both longitudinal and transverse wakefields (dipole and quadrupole) in Elegant by supplying their Green's functions as a table of time dependent values in a separate input file.

BUNCH SHAPES FOR HIGH TRANSFORMER RATIO

To achieve high efficiency in a DWA a drive bunch with a ramped current which creates a high transformer ratio wakefield (HTRW) has to be used [5]. The wake of a ramped bunch has a uniform decelerating field acting on the whole drive bunch except only for a small part of it at the beginning, where the field is lower. It was suggested to use a specific double triangular (DT) current to excite the HTRW [6, 7]. Any HTRW is also associated with near linear growth of the transverse deflection force towards the tail of the drive bunch, which in turn linearly increases with the beam offset from the tube's axis. It makes the tail of the drive bunch most susceptible to the BBU. The main longitudinal and dipole wakefield modes have close frequencies, but their Green's functions are 90° out of phase with the longitudinal gradient reaching the peak value right behind the drive charge and the transverse gradient reaching its peak value a quarter wavelength downstream.

BBU SUPPRESSION

The well-established way to confine the charged particle beam is to use a FODO lattice consisting of magnetic quadrupoles of alternating polarity. The period of the FODO lattice has to be much smaller than the typical length of instability's growth. At the same time, smaller periods require higher magnetic gradient to provide adequate focusing. If quadrupoles are too strong, there is an overfocusing. So the quadrupoles need to be strong enough to have pronounced focusing effect, but not too strong to cause instability. As the drive beam loses energy the magnetic strength of the FODO lattice needs to be tapered to keep it optimal for the particles in the tail of the drive bunch which are most susceptible to the BBU (Fig. 1).

The FODO suppression of the BBU instability is not very efficiency as is. The reason for that is that once the beam has an off-center shift, it will oscillate in the FODO

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lattice, so that all parts of it contribute to the transverse wakefield almost in phase. To randomize the particles' transverse coordinates an energy chirp can be used: particles with different energies then have different oscillation times in the FODO lattice that results in growth of the differential oscillation phase in between them. It is more beneficial to have a negative chirp as it ensures that the chirp will not decrease due to the head particles having lower deceleration and that the tail particles will oscillate faster. Such suppression method is also called BNS damping after Ref. [8].

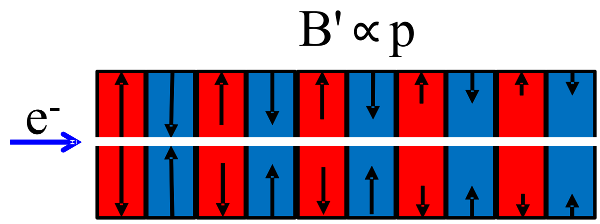

Figure 1: FODO lattice with the magnet strength linearly decreasing towards higher propagation distances.

In reality high energy chirps are hard to produce and the beams with big chirps are hard to transport. This leads to the idea of increasing beam chirp inside the DWA with a help of wakefields by means of a special parabolic addition to the double triangular beam current which produces a linear growth of the decelerating field towards the tail of the drive bunch.

Table 1: A Sample DWA Setup

Initial electron energy in the bunches	400 MeV
Main accelerating mode frequency	300 GHz
Maximum magnets' strength	1300 T/m
Quadrupoles' length/space between	4 / 0 cm
DT bunch charge/length	8 nC / 1 mm
Main bunch charge/rms length	50 pC / 10 μm
Circular dielectric tube ID/OD	2 / 2.123 mm
Dielectric constant	3.75

Table 2: The Distance Traveled by the Beam before BBU

Configuration number	Configuration description	Propagation length
I	No FODO	0.72 m
II	FODO with no chirp	4.5 m
III	FODO with 15% chirp	20 m
IV	FODO with reduced chirp (7%) & parabolic current content	19.68 m

We simulated DWA with parameters from Table 1. The FODO lattice strength was optimized to follow the energy loss by the particles in the drive bunch tail. The beginning part of the FODO lattice had constant magnetic strength because realistically the strength of a quadrupole magnet is not likely to exceed 1300 T/m limit. Table 2 lists the length of stable propagation. In the best case III the main bunch accelerates from 400 MeV to 2.03 GeV in 20 m, and the drive bunch contributes 80% of its initial energy to the wakefield.

BEAMLINE'S TOLERANCES

The use of strong magnetic quadrupoles for beam's confinement has its own drawbacks. One of the biggest concerns is that due to the high magnetic strength, even small misalignments of quadrupoles may result in a severe change of the beam's trajectory. A not perfectly aligned FODO structure can cause beam breakup. To estimate the allowable tolerances, simulations were done where quadrupoles had random offsets in X and Y transverse directions characterized by the RMS value and truncated at 2.5 RMS. We studied configuration III from Table 2 and two sets of offsets. For 0.1 μm RMS X and Y offsets no particle loss happened before 20 m. However for 1 μm RMS X and Y offsets the particle loss started already at 5 m, reaching 50% at 20 m. The 1 μm tolerance is beyond the usual FODO fabrication capabilities. To realize such a high tolerance a tuning mechanism will be required. Yet, the adequate tuning procedure is difficult.

Another reason for early BBU may be a not perfectly straight dielectric tube. Depending on the manufacturing technique it will have its center oscillating around straight line with a specific period. According to simulations performed for different initial phases and different periods of the tube's center deviation from the otherwise axially symmetric system, the period is quite an important factor determining the likelihood of BBU. Figure 2 gives the idea of BBU behaviour versus bending period. The same parameters from the above Tables 1 and 2 (case III) were employed and the tube's center oscillation amplitude from the axis of 10 μm was used. As it follows from the simulation data, bending periods close to 50 cm are the most dangerous.

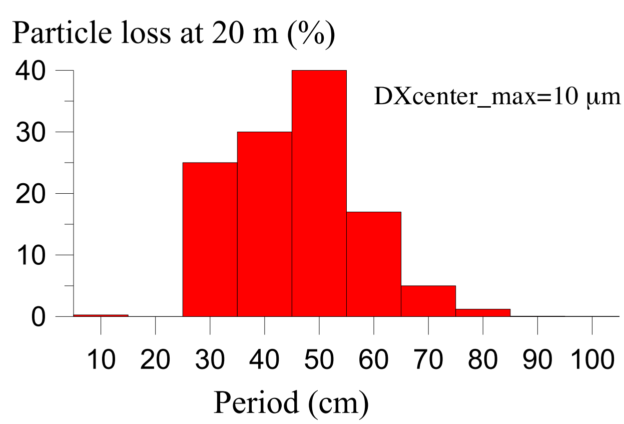

Figure 2: Simulated particle loss for different bending periods which are whole numbers of decimeters.

BBU IN RECTANGULAR WAVEGUIDE

One of the differences between electromagnetic properties of circular and rectangular dielectric-lined waveguides is that due to the lack of rotational symmetry in the rectangular geometry the wakefield additionally

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gets a quadrupole component (Fig. 3). As opposed to the dipole component, the quadrupole component can be excited by the on-axis beam and the force from it acting on the witness particle is proportional to the off-axis shift of the witness particle itself. The quadrupole force is focusing in one transverse direction and defocusing in the other one with its sign depending on the phase of the electromagnetic wave. To implement the complex wakefield of the rectangular waveguides into the Elegant model we used the Rectangular Waveguide code [9] to compute the Green's functions.

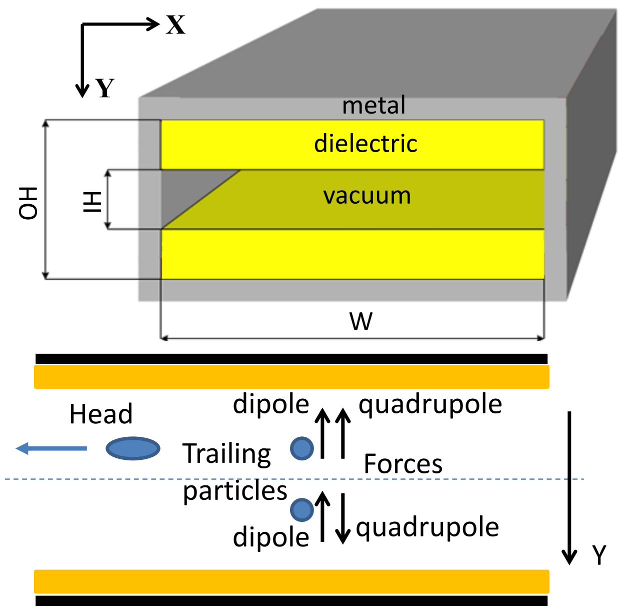

Figure 3: DWA based on a rectangular dielectric-lined waveguide (top). Deflecting forces acting on trailing particles in the rectangular DWA (bottom).

If the strength and the main period of the longitudinal Green's function of the rectangular DWA are made close to the one in the circular DWA case, the transverse wake forces become of similar strength too. We did not notice considerable improvement in terms of suppressing the BBU by switching to the rectangular geometry.

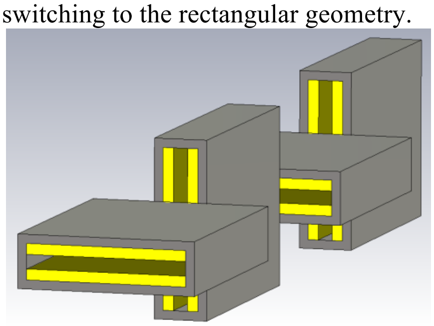

Figure 4: Configuration with an alternating quadrupole field.

Similar to the case of magnetic FODO lattice, quadrupole wakefield can be made to have an alternating sign. Figure 4 shows a possible configuration: the waveguide orientation changes 90 degrees every half a period. Simulations show that the quadrupole wakefield is more likely to contribute to the BBU than to suppress it except for the following case. When the magnetic FODO lattice is weak the quadrupole wake can be used to aid in confining particles in the beam tail. It is achieved by using the same period and a proper phase in between the quadrupole fields acting on the particles in the beam tail.

CONCLUSION

A complete beamline model was developed in Elegant which allowed us to simulate BBU in DWAs with account for FODO and other BBU stabilization measures. Some analytical approaches together with BBU simulations in Elegant were used for FODO lattice and beam chirp optimization. Some realistic DWA configurations were simulated where drive bunch contributed up to 80% of its energy into the wakefield.

The BBU sensitivity to different beamline tolerances was studied in simulations. It turned out that very high alignment tolerances are required especially for the FODO quadrupoles, which might not be achievable in the experiment.

The analyses of DWAs of rectangular section showed that rectangular DWAs have quadrupole wakefields which can be used to lower requirements on the FODO lattice strength if properly phase-synchronized, but otherwise they are harmful.

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