MULTI-STAGE WAKEFIELD ACCELERATORS

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ABSTRACT

Large field-gradients for ultra-high energy accelerators can be achieved in structures excited by intense, short particle bunches. In order to extract the energy from the driver at the fastest possible rate, it should be sent through a high-impedance aperture, just as the beam to be accelerated. It then has to be replaced periodically in short stages, which also minimizes the reduction of gradients due to blow-up or particle loss occuring in a driver interacting with the structure over a long distance.

1. INTRODUCTION

Acceleration by wakefield transformers, first proposed in 1981[1)], is based on the idea that high accelerating gradients can be obtained in an aperture of a structure if it is excited by a beam passing through a different aperture which has lower impedance than the one used for acceleration. In this manner, the energy loss (per particle) in the strong "driving" beam can be kept small, while the energy gain (per particle) in a weaker accelerated beam may be larger by the impedance ratio of the two beams.

At present, it appears that the largest impedance ratios can be obtained in a concentric device : the driver passes through an annular slot with large radius and the accelerated beam along the axis of a small central hole of a disk-loaded waveguide with rotational symmetry. Impedance ratios of 10, 20 or more can be obtained in this manner. An experimental verification of this scheme is presently being prepared at DESY[2)].

Unfortunately, the practical realization of such a device meets with some difficulties. The generation of very short annular rings with high charge is already not easy, but is rendered more complicated by the requirement that the rings should not rotate when they pass through the annular slot because of the supports necessary to hold the inner disks in place. Actually, these supports destroy the rotational symmetry of the device and will make slots in the driving beam which will thus become more vulnerable to transverse instabilities. This lack of rotational symmetry also makes field computations and simulation of particle motion very difficult, and only results neglecting this effect have so far been published.

Because of the very short accelerating structure ($\sim$40 cm), these considerations are only of limited impact on the experiment which is presently being assembled at DESY. However, they could become quite restrictive in a full-length structure where the beams have to be accelerated over several kilometers in order to reach TeV energies. Due to the concentric geometry, staging (i.e. accelerating in short sections) does not appear very attractive, as it requires disposing of the spent annular driver and introducing a new one without disturbing the accelerated beam. Re-acceleration of the decelerated driver has been proposed[4], but will probably not restore the beam once it has been blown-up by instabilities.

Also the alternative of replacing the annular driver by a number cylindrical beamlets disposed symmetricaly around the slot has been discussed. Again there are problems of transverse stability of the driver, and in addition exact synchronism is required in order to avoid reducing the acceleration and to minimize transverse deflection of the accelerated beam.

Other embodiments of the wakefield transformer have ben proposed, but have in general lower impedance ratios. In particular, elliptical cavities with unequal apertures around the two focal points were already mentionned in the original proposal[1]. A single elliptic cavity (with equal apertures around the foci) has been tested recently in Japan[3]. Unfortunately, the experiment was abandonned because the beam to be accelerated was strongly deflected and did not pass the cavity.

It should be easy to overcome the deflection of the accelerated beam simply by increasing the injection energy, which was only a few tens of kilovolts in the experiment. The overall deflection could also be cancelled by disposing groups of cavities with two drivers alternating on two sides[1]. However, the impedance ratios in elliptic cavities are rather limited. The impedances can be estimated with a special 3-dimensional computer program for wakefields in elliptical cavities [4].

2. MULTI-STAGE ACCELERATORS

High accelerating gradients in a structure can be achieved also when the driving beam passes through a high-impedance aperture but is replaced periodically. Since the driver then only provides the acceleration of a single stage, it may loose its energy at a high rate. One no longer needs to rely on the gain in accelerating field due to impedance transformation, although it could be combined with it.

The elliptic cavity geometry appears particularly well suited for such a scheme : by rotating subsequent groups of cavities, the spent drivers can be easily disposed and new ones introduced in the next stages (see Fig. 1). The driver pulses may all be created as a single pulse train, which have to be split, e.g. by a time-dependent deflection, into single bunches which are steered to the various accelerating stages. By proper timing one can obtain correct synchronism and even overcome any "slippage" problem between driver and accelerated beam if one of them is not fully relativistic.

Because of this possibility, one may also use proton beams as drivers for the acceleration of electrons. In this it resembles the "proton klystron"[5] which, however, has driver and accelerated beam in the same aperture and therefore is difficult to stage. In addition, it is limited by just this slippage problem.

For colliding beams, only much lower energy electrons are required to obtain the same experimental results, compared to protons which distribute the energy amongst their constituents. Hence, it would be sufficient to accelerate electrons to the same energy as that of the driving proton beam and still gain a large advantage. If one can increase the gradient, one obtains furthermore a shortening of the structure required to obtain this energy.

The principal limitation to achieving a high acceleration rate by particle excitation of a structure is due to breakdown and electrical discharges which may damage the metallic surfaces. However, we shall not concern ourselves with this problem here about which only little is known yet. Another difficulty is the production of very short pulses with high charge, i.e. the achievement of extremely high peak currents. Normal RF linacs may have difficulties in reaching these values, but there are a number of studies using laser-excited cathodes to obtain extremely short pulses. It may furthermore be possible to use induction linacs or storage rings to reach the peak current levels required. Other limitations are caused by the total power requirements of a full-scale accelerator which makes high efficiency desirable. Both heating by energy dissipation and total energy requirements can be controlled by reducing the repetition rate, which on the other hand should be kept high in order to obtain a large interaction rate in colliding linacs.

3. A NUMERICAL EXAMPLE

As a simple illustration, we shall use the computed values of the loss-factor in a disk-loaded waveguide to show what gradients could be achieved. The total energy loss per unit length of a Gaussian bunch of RMS-length σ can be written

$$\Delta U' = - k'(\sigma) \cdot Q^2$$

when Q is the total charge in the bunch. The energy gain per unit charge and length, also called gradient, is then simply $G = k' \cdot Q$. The loss factor per unit length for disk-loaded waveguides of various radii and periods is shown in Fig. 2. Over a reasonable range of parameter values it can be approximated by

$$k' = \frac{1}{4\pi\varepsilon_0} \frac{1}{4a^{1/2}\,\sigma^{3/2}}$$

and reaches typically values of a few hundred V/pCm for a few millimeters beam-hole radius. In order to achieve an energy gain of several hundred MeV/m, one thus needs charges of the order of micro Coulombs in a bunch length of a few millimeters RMS. For example, a structure with an inner radius a = 2 mm, an outer radius b = 20 mm, a gap length g = 5 mm and a period p = 6 mm has about k' = 450 V/pCm for σ = 2 mm. Hence a charge of 1 μC which corresponds to about 6×10^{12} particles per bunch or a peak current of nearly 60 kA, would yield a gradient of 450 MV/m.

4. CONCLUSIONS

A particle-driven wakefield accelerator not relying on the impedance-transformer principle appears possible if short stages are used with new driving pulses in each stage. This has the distinct advantages that the degradation of beam quality due to interaction of the driver with the structure is of little concern, and furthermore permits re-adjustment of the acceleration phase in each stage so that (slower) protons could be used as drivers. However, one does require quite high charges in short bunches for the driver which exceed the values which can be obtained in present RF linacs by quite a large factor. However, peak currents of the required amount have been achieved in induction linacs, and may also be obtainable in circular machines. The development of laser-pulsed cathodes, which is actively pursued in several laboratories around the world, may allow a simpler solution to this problem.

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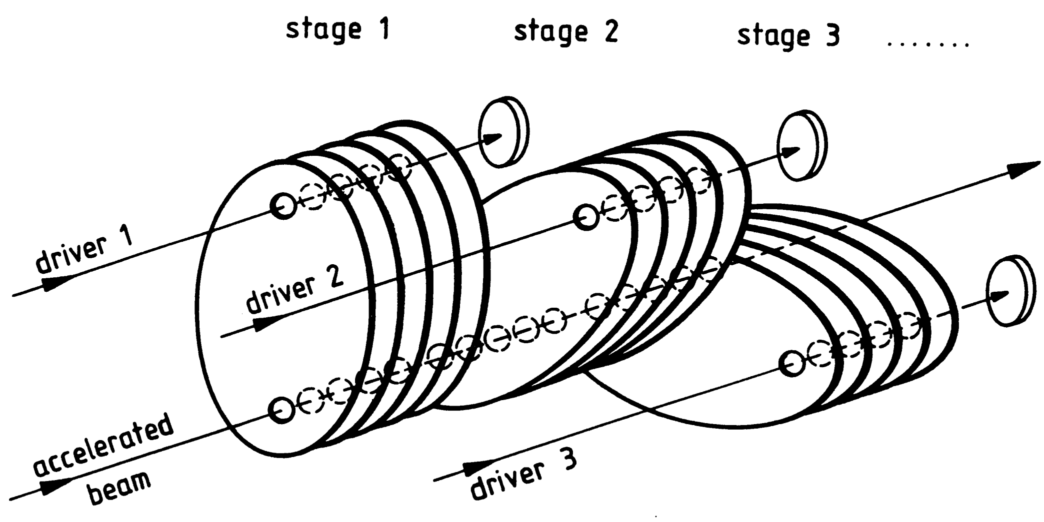

Fig. 1 Schematic geometry of staging accelerator with elliptical cavities.

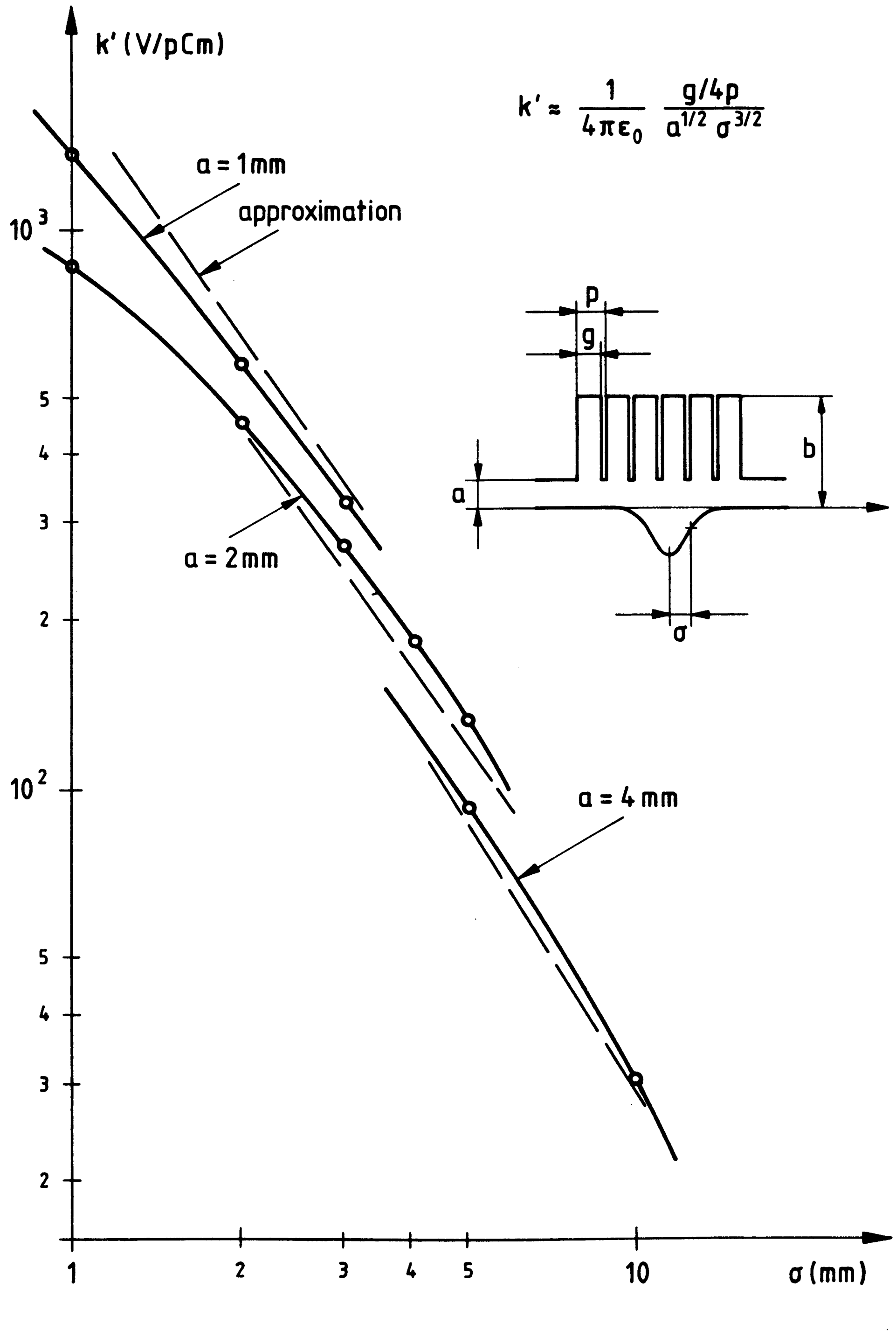

Fig. 2 Loss-factor as function of bunchlength for disk-loaded waveguide.