We present detailed development of the linear theory of wakefield amplification by active medium and its possible application to a two-beam accelerator (TBA) is discussed. A relativistic train of triggering microbunches traveling along a vacuum channel in an active medium confined by a cylindrical waveguide excites Cherenkov wake in the medium. The wake is a superposition of azimuthally symmetric transverse magnetic modes propagating along a confining waveguide, with a phase velocity equal to the velocity of the triggering bunches. The structure may be designed in such a way that the frequency of one of the modes is close to active-medium resonant frequency, resulting in amplification of the former and domination of a single mode far behind the trigger bunches. Another electron bunch placed in proper phase with the amplified wakefield may be accelerated by the latter. Importantly, the energy for acceleration is provided by the active medium and not the drive bunch as in a traditional TBA. Based on a simplified model, we analyze extensively the impact of various parameters on the wakefield amplification process.

I. INTRODUCTION

Classification of a novel acceleration paradigm distinguishes between plasma-based and structure-based schemes. In the former case, a laser or an e-beam pulse injected in plasma generates a space-charge wake that in turn may accelerate electrons or positrons. Both methods have demonstrated gradients of the order $100 \text{ GV/m}$—more than 3 orders of magnitude the operating gradient in existing linear accelerators. However, there are a few other important characteristics (repetition rate, emittance, beam transport, etc.) that are yet to be determined or improved before the plasma-based schemes become a realistic alternative to the International Linear Collider (ILC).

A less drastic change in the acceleration approach is adopted in the structure-based schemes. In this case, an electromagnetic wave is injected or generated inside an electromagnetic structure which is designed to support a TM$_{01}$ mode propagating at the speed of light and whose longitudinal electric field may accelerate electrons or positrons. Several approaches are relevant to the study that follows, therefore we briefly describe them. The compact linear collider (CLIC) [1] is developed at CERN and its essence is to extract microwave power from a drive beam (high-current medium-energy) using a periodic metallic structure. This power is injected in a regular, room-temperature, metallic structure which accelerates a low-current high-energy main beam. The two electron beams move along parallel lines which do not coincide. At Argonne National Laboratory (ANL) [2] and Yale University (Omega P) [3] a similar program is pursued except that extraction units consist of a dielectric loaded waveguide—thus the name dielectric wakefield accelerator (DWA). In another configuration of DWA a Cherenkov wake produced by the drive beam traveling along the dielectric-loaded waveguide may be used to accelerate a trailing beam in the same structure. In this case both drive and accelerated beams move along the same axis. The theory of a wakefield in a dielectric-loaded waveguide is presented in Ref. [4].

At optical frequencies, Ohm loss makes the metallic acceleration structures irrelevant and they must be replaced by equivalent dielectric structures [5–7]. A general treatment of a wakefield confined by a dielectric structure is given in Ref. [8]. Preliminary results from dielectric acceleration structures driven by laser were recently reported [9], indicating gradients in excess of 0.25 GV/m.

In the present study we propose a novel paradigm that combines two concepts: (i) the well-known two-beam accelerator (TBA) and the recently proposed (ii) enhanced Cherenkov wake amplification by active medium [10]. Its essence is two trains of microbunches propagating along the same axis of a structure that contains active medium. In a specific module of the TBA, the first train contains the trigger bunches which generate Cherenkov radiation that in turn is amplified by the active medium (AM). Slightly after the medium reaches saturation ($L_{sat}$), the amplitude of the Cherenkov wake is constant and it is there where we place the trailing train in antiphase with the former such that its bunches are accelerated. In both trains, the spacing between two adjacent microbunches is the resonant wavelength of the medium. By the active medium we mean a medium...