STAGING IN TWO BEAM DIELECTRIC WAKEFIELD ACCELERATORS*

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Abstract

A new experimental program to demonstrate staging in a dielectric two-beam wakefield accelerator (dielectric TBA) is being planned at the Argonne Wakefield Accelerator facility. In dielectric TBA, a drive beam generates acceleration fields in a dielectric decelerating structure to power a dielectric accelerating structure for acceleration of a main beam. This is one of the most promising advanced acceleration methods being pursued for a future high-energy physics linear collider but it remains to demonstrate staged acceleration. Staging is the ability to use two accelerating modules back to back to accelerate a charged particle bunch and it is one of basic requirements of any acceleration method. In this paper, we consider designs for a preliminary beamline consisting of a fast kicker to pick pulses from the drive bunch train and deliver them to the individual acceleration modules.

DIELECTRIC WAKEFIELD ACCELERATION

One of the leading candidates for a high gradient accelerating structure is the dielectric two-beam wakefield acceleration (TBA) [1-3] being pursued at the Argonne Wakefield Accelerator (AWA) [3] facility. In two-beam wakefield acceleration (TBA) [3, 4], a high charge drive beam is passed through a structure to generate high power RF which is then delivered into a second structure to accelerate a low-charge witness beam. Dielectrics structures are potentially an attractive choice due to the simple geometry (a dielectric cylinder with a vacuum hole down the center and surrounded by a metallic jacket), the easy damping of higher order modes, etc.

Previous research has demonstrated many basic requirements for the dielectric scheme. High gradient experiments have shown dielectrics capable of supporting GV/m scale fields in the THz regime [5], 100 MV/m scale fields and 44 MW RF power in the microwave regime [3]. The dielectric two-beam acceleration scheme was successfully demonstrated [6]. However, a fundamental requirement of dielectric TBA that has yet to be demonstrated is the staging of sequential accelerating modules.

STAGING

Linacs are composed of accelerating modules that are staged one after the other in order to accelerate charged particle bunches to high energy. Each accelerating module delivers an increment of energy to a passing charged particle bunch. When many such modules are staged in a row, the charge particle bunch is accelerated to high energy. In its simplest form, a single module can

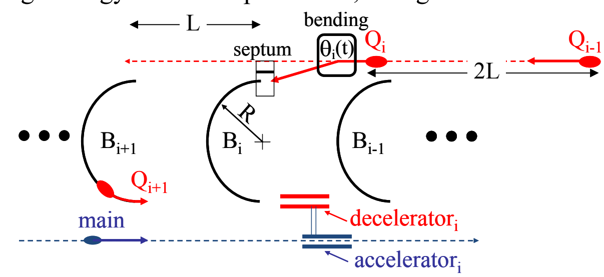

Figure 1: Schematic diagram of a staging beamline.

consist of a single rf cavity powered by a single klystron. Modules that are more complex may have multiple structures powered by a single klystron.

Figure 1 shows a simplified schematic of a staging beamline [7] for the dielectric TBA. The purpose of the staging beamline is to deliver the drive bunches at the appropriate time to the decelerator stages for acceleration of the main beam in the accelerator. We want to deliver a drive beam, Q_i, (i=1..N where N is the number of bunches in the drive train) through an isochronous turn-aound beamline, B_i, and into the decelerating structure, *deceleator*$_i$. Thus, the staging beamline has two main components:

- **fast bending element**, $\theta_i(t)$, to extract the last drive bunch remaining in the train (Q_i) while allowing the leading bunches to pass through
- **isochronous turn-around beamline**, B_i, to deliver the drive beam to the decelerator.

The isochronous beamline is not discussed in this paper but is believed to be reasonably straightforward. In the remainder of this paper, we discuss the general requirements of the fast bending element and consider two designs for the AWA staging beamline: one based on a stripline kicker and the other on a deflecting cavity.

THE GENERAL REQUIRMENTS OF THE BENDING ELEMENT

The requirements for the fast bending element are its time response (rise time, flattop, and fall time) and amplitude ($\theta = \Delta\theta$); they are arrived at as follows. A train of drive bunches, separated by *2L*, where *L* is the separation between stages (Fig. 1), arrives from the drive linac to the staging beamline. The bending element must remain off (θ=0) until the leading bunches (Q_N, Q_{N-1}, … Q_{i+1}) have passed through and then it must turn fully on ($\theta=\Delta\theta$) before the bunch to be extracted (Q_i) arrives. This means the bending element rise time is t_{rise}=2L/c. We note that the fall time is not demanding since we are extracting the last drive bunch in the train. The required amplitude of the bend ($\Delta\theta$) comes from the fact that the drive beam of momentum p_0 must be deflected into the septum

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magnet. If the bending element is placed after the turn-around arc of radius, R, then the distance between the bending element and the septum magnet is approximately L-R. Therefore, the offset at the septum is,

$$\Delta x = \Delta\theta * (L - R) \quad (1)$$

If the deflecting element imparts a transvserse momentum $\Delta p_\perp$ to a beam with momentum p_0 then the bend angle is,

$$\Delta\theta = \Delta p_\perp / p_0 \quad (2)$$

Staging at the AWA Facility

Demonstration of staging in a dielectric TBA is being planned after completion of the upgrade to the AWA facility [3]. The 75 MeV drive linac will be capable of delivering a variety of bunch trains of up to 32 electron bunches and up to 100 nC per bunch, although not simultaneously. However, due to the limited space in the facility's bunker there is only enough room for a two-stage demonstration. Initial estimates show that two stages separated by L=8 m will fit into the bunker with a turn-around beamline of R=4 m. The 100 nC drive beam has a large transverse size, approximately 6*σ = 25 mm, and therefore needs to be kicked off axis by a correspondingly large amount. For an offset Δx = 50 mm and separation L-R = 4m, then the required bend (Eq. 1) is **Δθ = 12.5 mrad**.

A STRIPLINE KICKER AS THE BENDING ELEMENT

We consider a stripline kicker [8] consisting of a pair of parallel plate striplines of length S and gap separation d. A transverse voltage $V_\perp$ applied across the plates produces an electric field of $E = V_\perp / d$. Solving the equation $dp/dt = eE$ and substituting $dt = ds/c$, then the transverse momentum imparted to the beam is,

$$\Delta p_\perp = \frac{1}{c}\frac{eV_\perp S}{d}$$

and therefore the bend angle is,

$$\Delta\theta = \frac{eV_\perp}{T_0}\frac{S}{d} \quad (3)$$

Where T_0 is the kinetic energy of the beam and the approximation $p_o c \approx T_0$ was used.

In order to achieve the required amplitude of the bend (Δθ = 12.5 mrad) we substitute into Eq.(3) with S=30 cm, d=50 mm, and T_0=75 MeV to find the required transverse voltage, $V_\perp = 156\,\mathrm{kV}$. This is a large voltage and the options for reducing it are limited to increasing S or decreasing d. The former is problematic because the separation between the kicker and the septum is only 4 m while the later is difficult since the 100 nC beam has a large transverse envelope. We will consider using focusing elements to reduce the transverse size of the drive beam to reduce the required kick. The risetime of the kicker, as outlined above is, t_{rise}=2L/c. For a drive bunch separation of 2L=16m the corresponding risetime is, $t_{rise} \approx 50$ ns. Taken together, this would require the development of a very challenging power supply to provide a high voltage (156 kV) and fast rise time (50 ns) output.

A DEFLECTING CAVITY AS THE BENDING ELEMENT

We next consider an RF deflecting cavity ("deflector") [9] for the bending element. The deflector operates in a TM_{110}-like mode and according to the Panofsky-Wenzel theorem [10] the transverse momentum imparted to the bunch is given by,

$$\Delta p_\perp = \left(\frac{je}{\omega}\right)\int_0^L \nabla_\perp E_z dz$$

No simple expression equivalent to Eq. (3) exists and an evaluation of the integral based on numerical simulations of the cavity fields is required. To estimate the requirements of the deflector we scale the values from an existing AWA deflector [11]. The transverse deflection voltage ($eV_\perp \approx \Delta p_\perp c$) corresponds to maximum deflection voltage provided by the cavity when the beam pass through the cavity "on-crest". (This is as opposed to applications where the beam passes through the cavity at "zero-crossing" to be streaked by the cavity.) The AWA deflector normalization is $V_\perp$=3.4 MV at P=4.2 MW. Since the voltage scales with the square root of the power, then the power required for $V_\perp$=156 kV is only P = 8.8 kW. This is a very modest amount of RF power.

Achieving a large amplitude kick from an RF deflector is trivial as the previous analysis shows. The challenge in using an RF deflector is not the magnitude of the kick but the timing of the kick. The difficulty is that the deflector must allow an arbitrary number of beams to pass through at the zero-crossing (so that the bunches are NOT deflected) and then kick the last one. This prevents the use of a simple subharmonic or harmonic cavity based scheme. Consider the use of harmonic cavities, n*f_0. The problem is (Fig. 2) when all drive bunches have the same phase (on crest in Fig. 2) of f_0, they will also have the same phase ϕ_i of f_i. And while one can shift the value of ϕ_i, all drive bunches will still receive the same kick.

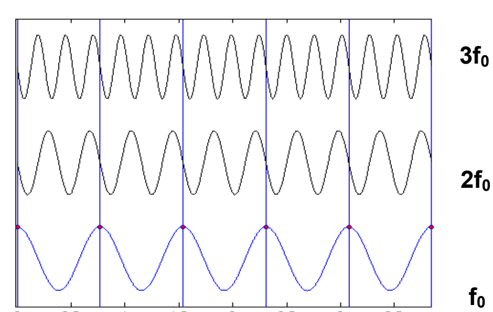

Figure 2: Harmonic Cavity does not work.

Non-Harmonic RF Deflecting Cavities

A solution to the above problem of using RF deflectors as the bending elements in the staging beamline has been found based on the use of non-harmonic RF deflecting cavities. We first analyze the simplest case (2 stages) and then show the general results. Given the fundamental accelerating frequency of the drive bunch train, f_0, we choose an RF deflecting cavity operating at $f_1=(1+1/4)*f_0$ (Fig. 3). If the first beam Q_1 (filled circle) is placed at normalized time, $t/T_0=0$ (where $T_0=1/f_0$) and the trailing bunch Q_2 (empty circle) is placed 1(5) fundamental RF period later ($t/T_0=1,\ 5$), then Q_1 will pass through the cavity undeflected while Q_2 will get kicked. In general, the separation between the bunches must satisfy $d=(2m+1)*\lambda_0$ where $m=0,1,\ldots\infty$. This separation in turn imposes a restriction on the distance between stages so that $2*L = (2m+1)*\lambda_0$.

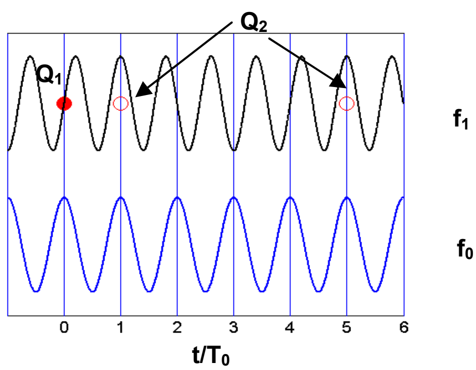

Figure 3: Timing relationship of the fundamental cavity frequency (f_0) and the non-harmonic cavity frequency (f_1) for the *2* bunch case.

Briefly, we state the results for the general case of N bunches (Fig. 4). The frequency of the i^{th} deflecting cavities (C_i) is,

$$f_i = f_0 * \left(1+1/2^{1+i}\right) \quad \{i=1,2,\ldots,N\} \tag{4}$$

From Eq. (4), we see that the frequencies could be called fractional harmonics of the fundamental. In the simplest case, the minimum separation (d_i) between bunches i and $i+1$ and the separation between the stages ($L_{i,i+1}$) is,

$$d_{i,i+1} = \lambda_0 * 2^{N-i} \quad \{i=1,2,\ldots,N\} \tag{5}$$

$$L_{i,i-1} = 2*d_{i,i-1}. \tag{6}$$

This separation is the minimum but can be increased as long as it is a multiple of the minimum distance. In the future we will investigate whether it is possible to find a solution similar to Eq. (4) that operates at a higher harmonic of f_0 but still modified by the same fractional part shown in parenthesis.

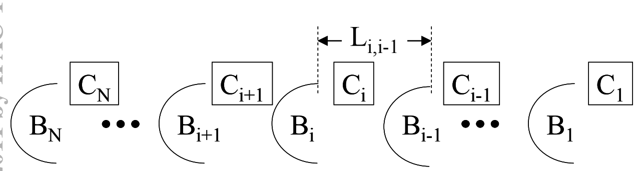

Figure 4: Schematic of the complete staged beamline.

SUMMARY

A plan to demonstrate staged acceleration using dielectric structures in the two-beam accelerator configuration has begun at the Argonne Wakefield Accelerator. The critical technological choice for the staged beamline will be the bending element that picks off one of the drive beams for extraction into the decelerator. We are considering both a stripline kicker and a deflecting cavity. Due to the limited space in the AWA bunker a large transverse kick is required from the bending element. This large kick and associated fast turn on time makes the stripline kicker option difficult. The deflecting cavity option can easily achieve the transverse kick required but is difficult to use due to its inability to turn the kick on at arbitrary times. A solution to overcome this difficulty based on a fractionally harmonic cavity is under investigation.

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