HIGH-GRADIENT TWO-BEAM ACCELERATING STRUCTURE

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Abstract

A new accelerating structure, which is aimed to provide gradient >150 MV/m for next generation of multi-TeV linear colliders, is suggested [1-3]. The structure is based on periodic system of quasi-optical cavities, which are not coupled with each other. Each of these cavities is excited in several equidistantly-spaced eigen modes by the spatially bunched drive beam in such a way that the RF fields reach peak values only during the short time intervals when an accelerating bunch is resident in a cavity, thus exposing the cavity surfaces to strongest fields for only a small fraction of time. This feature is expected to raise the breakdown and pulse heating thresholds.

The proposed structure has smaller ratio α of maximal surface field to accelerating gradient (1<α<2) in comparison with usual single-frequency structure, where this ratio is close to factor 2. Due to all cavities of new accelerating structure are uncoupled, the structure is very reliable, i.e. possible breakdown in a separate cavity does not spoil the whole accelerator.

High efficiency and transformer ratio of drive beam power to accelerating beam power are expected to be provided by means of a so-called idea of frequency detuning. In accordance with this idea high-current drive beam leaves its power in a distributed way (at long distance along accelerator). This is achievable due to detuning of eigen frequencies of a structure cavity out of drive bunch frequency.

Calculations of a new two-beam accelerating structure consisted of multi-mode rectangular cavities with the parallel driving and accelerated beams, show that high gradient (~150 MV/m), low surface field (~190 MV/m), and high efficiency (~30%) are achievable under beam parameters close to those projected for CLIC (CERN). This structure embodies most of additional attractive properties: the cavity is an all metallic structure, no transfer or coupling structures are needed between the drive and acceleration channels, the cavity fields are symmetric around the axes of the drive beam and the accelerated beam.

ACCELERATION BY CHAIN OF MULTI-FREQUENCY MULTI-MODE CAVITIES

We suggest a new accelerating structure which is based on chain of multi-mode cavities with nearly equidistant eigenfrequencies. A multi-mode superposition of fields localized in space is caused to bounce between the structure axis and wall at the bunch period and thereby to accelerate the particles. Strong accelerating RF field appears, when a bunch enters the resonator. All the time while the resonator is empty (till next bunch comes), strong field at the resonator axis is not necessary. This principle is illustrated in Fig. 1, where particles are accelerated in a periodic system of uncoupled cavities.

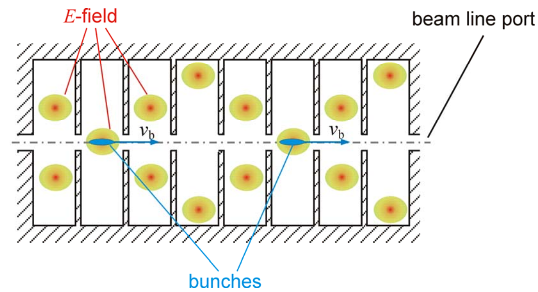

Figure 1: Acceleration of moving periodic bunches by uncoupled cavities operated with superposition of the synchronized eigenmodes.

The ideal electric field as seen by bunches along the structure is sketched in Fig 2 (curve 1), in comparison with the field in a single-frequency structure (curve 2). In the case of a limited number of modes used in the proposed accelerating structure the actual field looks like that in curve 3.

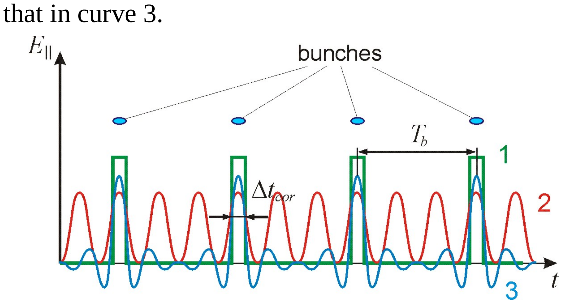

Figure 2: Time dependence of field in accelerating structures. 1 – ideal (desirable) field dependence on time; 2 – field dependence in conventional single-frequency accelerating structure; 3 – field in multi-frequency accelerating structure operated with a limited number of modes.

The proposed solution implies that fields are periodic functions of time:

$$\vec{E}(\vec{r}, t + T_b) = \vec{E}(\vec{r}, t), \qquad (1)$$

where T_b is the time interval between bunches. This requires the RF field in each cavity to be represented as superposition of equidistantly spaced eigenmodes:

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$$\vec{E}(\vec{r},t)=\sum_n a_n\cdot\vec{F}_n(\vec{r})\cdot\exp(i\omega_n t),\qquad(2)$$
$$\omega_n=\omega_0+n\cdot\Delta\omega,\quad T_b=q2\pi/\Delta\omega,$$

where $\omega_0/\Delta\omega=p/q$; n, p, and q are positive integers.

Duration of each power peak is determined by a condition that the phase difference between the lowest and highest modes is π:

$$\Delta t_{cor}\approx\pi/(\omega_N-\omega_0).\qquad(3)$$

We assume below that the ratio of peak's width to time interval between peaks $\Delta t_{cor}/T_b$ is a small parameter. Hence, the field at an arbitrary point is pulsed in time with significant intervals between peaks.

COMPARISON OF MULTI- AND SINGLE-FREQUENCY STRUCTURES

Dark current limitations

In a single-frequency structure the accelerating gradient is limited to that field magnitude which leads to dark current capture. For a multi-frequency structure the capture condition requires that the particles reach the phase velocity of the slow accelerating wave within a time interval Δt_{cor}. Therefore, the limiting gradient for a multi-frequency structure equals the limiting gradient in a single-frequency structure at a frequency $\omega=\pi/\Delta t_{cor}$. If we consider that all particles are caused by cold emission, magnitude of dark current in a multi-frequency structure will be then smaller:

$$I^{dark}_{mult}\approx I^{dark}_{\omega}\cdot\frac{\Delta t_{cor}}{T_b}.\qquad(4)$$

Pulse heating limitations

Surface degradation in high-gradient structures strongly depends on pulsed temperature rise due to pulsed surface heating by the RF magnetic field H_s. For the same pulse duration and accelerating gradient in a multi-frequency structure with $\Delta t_{cor}=\pi/\omega$, the temperature rise ΔT during one pulse is smaller in proportion to the factor $(\Delta t_{cor}/T_b)^{1/2}$.

$$\Delta T_{mult}\approx\Delta T_{\omega}\cdot(\Delta t_{cor}/T_b)^{1/2}\qquad(5)$$

Breakdown limitations

RF breakdown is believed to strongly depend on a combination of surface electric field and time of exposure. Recent experimental data show that scaling law for threshold value follows the empirical law

$$E_S^r\times\tau\le const,\qquad(6)$$

where E_s – is the surface field, and τ is the exposure time. Various models for RF breakdown invoke exponents r ranging from 2 to 6 [4-5]

In accordance with this criterion it is expected that the breakdown field threshold in a multi-frequency structure could be higher by a factor $(T_b/\Delta t_{cor})^{1/r}$ than in a single-frequency structure at frequency $\omega=\pi/\Delta t_{cor}$.

SIMULATION OF TWO-BEAM ACCELERATING STRUCTURE

We propose a two-beam accelerating structure where a high-current drive beam excites fields which accelerate a low-current beam, much as in the CLIC scheme. The structure consists of rectangular cross-section cavities with approximate sizes $a\times 2a\times l_r$ which have an infinite number of equidistant $TM_{n,2n,0}$ (n = 1,3,5,…) modes at frequencies:

$$f_{n,2n,0}=\frac{n\cdot c}{\sqrt{2}\cdot a},\qquad(7)$$

where c is the light velocity.

The bunches in either e^+e^- or e^-e^- combinations move in parallel direction as in Fig. 3 with different spacings L_b.

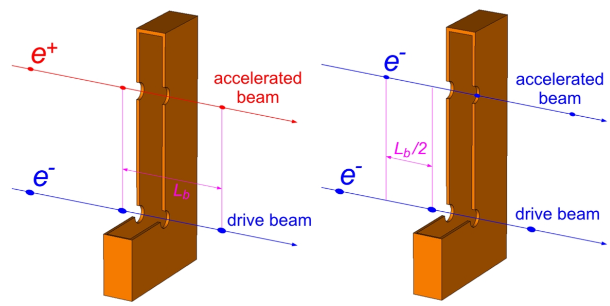

Figure 3: Two-beam two-section accelerating structure with aspect ratio 1:2 (frequency detuning is not shown).

Frequency Detuning

In order to not have an unreasonable number of drive beams along the accelerator, the structure should exhibit a high transformer ratio T (ratio of the magnitudes of fields felt by the accelerated particles to those felt by the drive particles). High T values can be achieved only when the cavity eigenfrequencies are detuned slightly away from the frequency of the drive bunches, in which case the electric field of the operating modes can be close to zero during the times when drive bunches pass through the cavity, as shown in Fig. 4. With multi-mode operation, different detuning is required for each mode. Moreover the steady-state situation as depicted in Fig. 4 evolves in time from the start of the drive bunch train, where the peak fields occur right at the bunches; the evolution time depends upon detuning, beam current, and cavity Q.

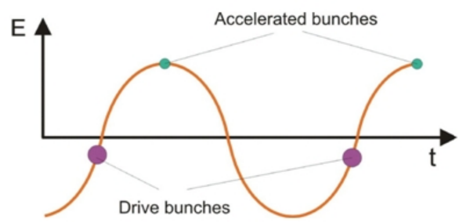

Figure 4: Location of drive and accelerated bunches in the steady-state, relative to the wave field in the cavity.

Three-Cell Model

Simulation of the accelerating structure was carried out in a three-cell model (Figs. 5-6) with parameters of the drive and accelerated beams as given in the CLIC project. Each cell with sizes 70 × 140 mm^2 had 10 mm length and 3 mm iris thickness operated with first three modes at frequencies 3 GHz, 9 GHz, and 15 GHz.

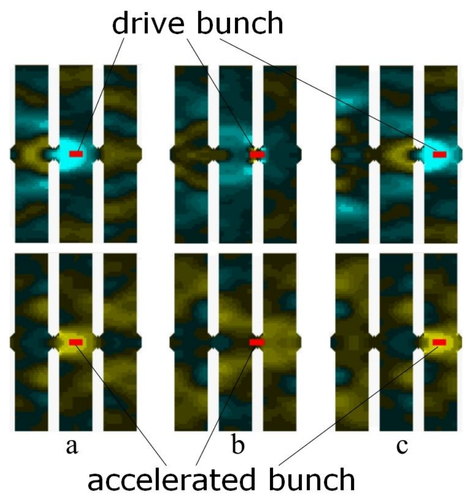

Figure 5: Instant $E_{||}$-field structures in drive beam plane (above) and accelerated beam plane (below): a – bunches are in the centre of middle cell; b – bunches are between the cells; c – bunches are in next cell.

Results of simulations are depicted in Fig. 5 where cross-sections of drive and accelerated beams are shown at three subsequent times, and Fig. 6 where fields in the plane perpendicular to the beams in the central cell are shown. Times in Fig. 6 a, b, c are the same as those in Fig. 5 a, b, c, respectively.

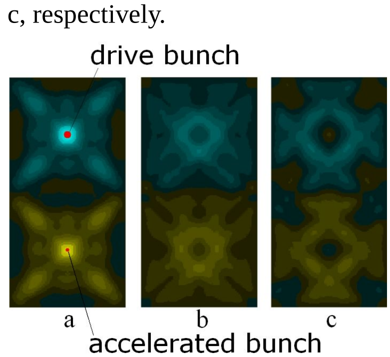

Figure 6: Instantaneous field structures in transverse cross-section of the middle cell at three times.

The optimized parameters of the structure are summarized in Table 1 for accelerating gradients G = 100 MeV/m and G = 150 MeV/m. Note that the ratio of maximum surface electric field to accelerating gradient is ~1.5:1, i.e. less than the typical value of 2:1 in single-frequency structures.

Table 1: Summary of optimization

	Q_0=33.6 nC G = 100 MV/m	Q_0=33.6 nC G = 150 MV/m
I_{drive}	100.8 A	100.8 A
I_{acc}	1.2 A	1.2 A
T	28.0	21.2
Efficiency	33.2 %	21.2 %
E_s max	146 MV/m	220 MV/m

CONCLUSION

The idea of a high-gradient two-beam accelerating structure has been described. The structure is based on a periodic system of uncoupled multi-mode cavities, each excited in several equidistantly-spaced eigenmodes by the drive beam. Preliminary analysis shows that the structure exhibits a number of attractive properties:

- High gradient due to decreased values of surface fields as well as decreased time of exposition by these fields,
- High efficiency and transformer ratio from drive beam to accelerating beam.

In addition the proposed structure uses all metallic cavities, requires no transfer or coupling structures between the drive and acceleration channels, and has cavity fields that are symmetric around the axes of the drive beam and the accelerated beam.

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