HIGH-GRADIENT MULTI-MODE TWO-BEAM ACCELERATING STRUCTURE

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Abstract

A two-beam accelerating structure which aims to provide an acceleration gradient >150 MeV/m for a next generation multi-TeV linear collider is suggested. The structure is based on a periodic system of multi-mode cavities. Each cavity is excited in several equidistantly-spaced eigenmodes by the 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 the cavities, thus exposing the cavity surfaces to strong fields for only a small fraction of time; this feature is expected to raise the breakdown and pulse heating thresholds. It is also shown that selective cavity detunings can lead to large effective transformer ratios between the accelerator and drive beam channels of the structure.

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 [1-3]. 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. This principle is illustrated in Fig. 1, where particles are accelerated in a periodic system of cavities that are decoupled from one another. RF power that flows in the longitudinal direction is, for purposes of this discussion, neglected due to assumed small cutoff holes that are only large enough for beam transmission.

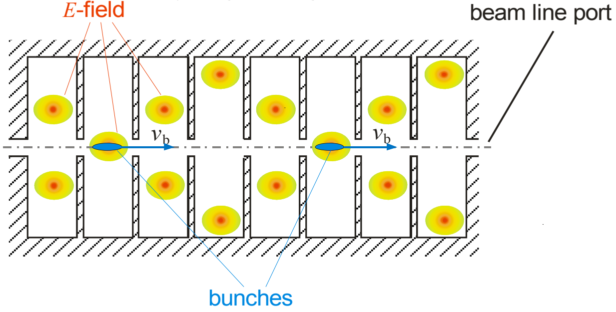

Figure 1: Acceleration of moving periodic bunches by uncoupled cavities operated with synchronized eigen modes.

The ideal electric field as seen by bunches along the structure is sketched in Fig 2 (curve 1 – in green), in comparison with the field in a single-frequency structure (curve 2 – in red). In the case of a limited number of modes used in the proposed accelerating structure the resulted field looks like that in curve 3 – in blue. One notes that in the latter case the field is only strong during the short time intervals where bunches are localized.

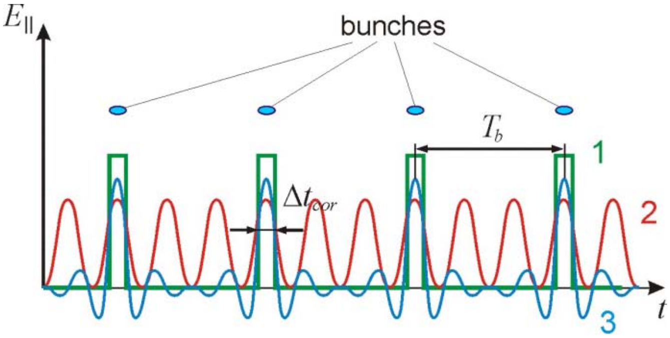

Figure 2: Time dependence of field in accelerating structures:
1 - ideal (desirable) field dependence on time;
2 - field dependence in conventional single-frequency accelerating structure;
3 - field in multi-frequency accelerating structure operated with a limited number of modes.

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

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

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:

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

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:

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

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.

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COMPARISON OF MULTI-FREQUENCY 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 $\omega = \pi/\Delta t_{cor}$.

SIMULATION OF TWO-BEAM TWO-SECTION 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:

$$f_{n,2n,0} = \frac{n \cdot c}{\sqrt{2} \cdot a}, \tag{5}$$

where c is the light velocity.

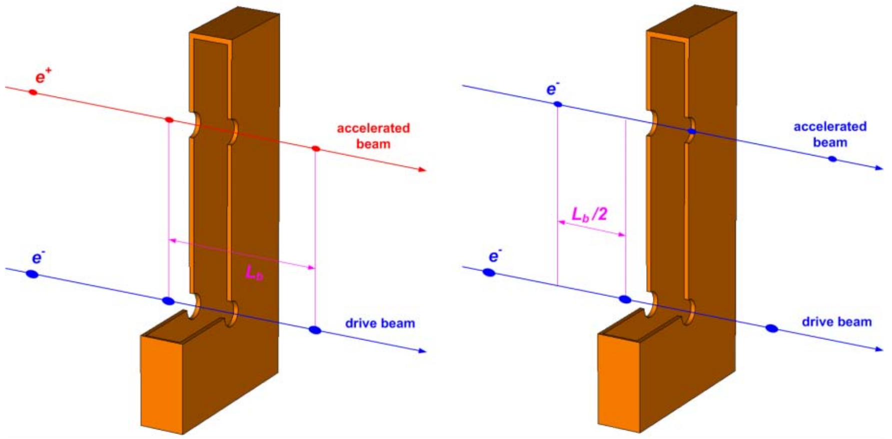

Figure 3: Two-beam two-section accelerating structure with aspect ratio 1:2 (frequency detuning is not shown).

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. For the same pulse duration and accelerating gradient in a multi-frequency structure with $\Delta t_{cor} = \pi/\omega$, the temperature rise during one pulse is smaller in proportion to the factor $(\Delta t_{cor}/T_b)^{1/2}$.

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

$$E_s^r \times \tau \le const, \tag{4}$$

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 $\omega = \pi/\Delta t_{cor}$.

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

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.

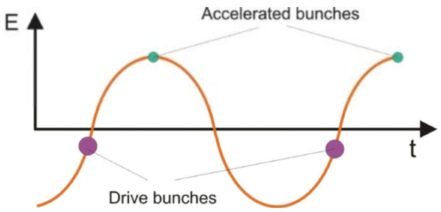

Figure 4: Location of drive and accelerated bunches in the steady-state, relative to the wave field in the cavity.

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.

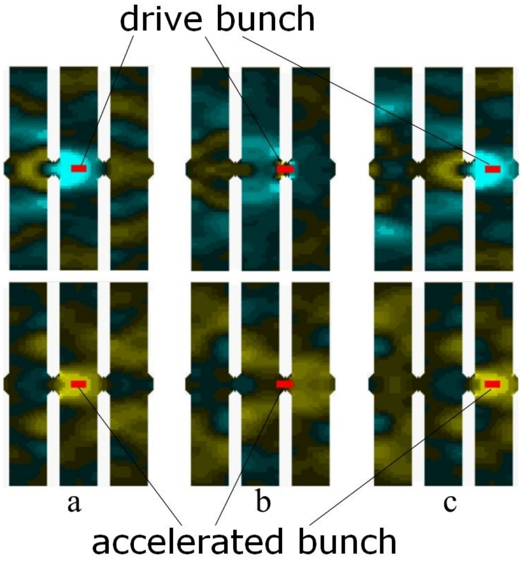

Figure 5: Instant $E_{||}$-field structures in drive beam plane (left) and accelerated beam plane (right): a – bunches in center of middle cell, b – bunches between cells, c – bunches in next cell.

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.

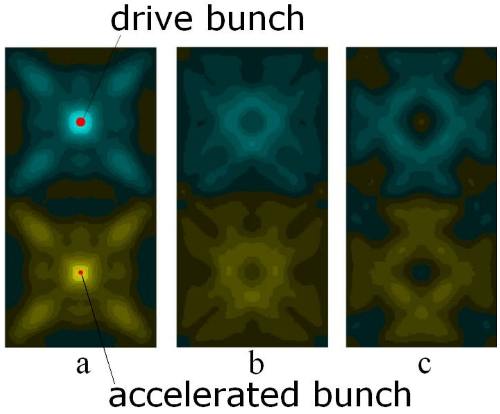

Figure 6: Instantaneous field structures in transverse cross-section of the middle cell at three times.

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 multi-mode two-beam accelerating structure is described. 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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