

## ELECTRON MICRO-ACCELERATOR

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### Abstract

Here we discuss an open resonator-based electron micro-accelerator, which, if realized in hardware, could have accelerating gradients of  $\sim 1$  GeV/m. We analyze the optics of a  $\beta = 1$  structure and the beam dynamics of a graded- $\beta$  injector with an auto-emission cathode.

### 1 INTRODUCTION

Selectively placed perturbing metal strips in an open resonator cavity cause the **E**lectro**M**agnetic field to vary strongly and periodically. Charged particles passing through holes in these strips can interact with the electric field and be accelerated, velocity modulated, and bunched [1]. Such a resonator can produce a large accelerating gradient using a variety of sources, including lasers.

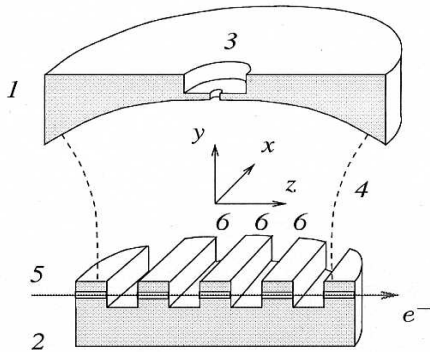


Figure 1: Modified Fabry-Perot open resonator.

In our open quasi-optical Fabry-Perot resonator, seen in Fig. 1, the field variation along the beam path is produced by a special mirror geometry. Here spherical (1) and plane (2) mirrors allow the standing wave, excited through a coupling slot (3), to be limited by a caustic surface (4). A pre-accelerated and pre-bunched electron beam (5), injected parallel to the alternating electric field component, passes through holes in the strips (6) that are perpendicular to both the electric field and the beam.

The strip thickness and spacing are such that during acceleration the beam is in the gap, otherwise the strips shield it. Thus in the limiting relativistic case, the strip thickness and spacing are half the EM wavelength,  $\lambda/2$ . The mirror surface is also located a distance  $\lambda/2$  from the base. The beam holes have a diameter less than  $\lambda/2$  and are located  $\lambda/4$  from the base. The lowest EM field mode, a paraxial standing wave concentrated between mirrors, has an amplitude Gaussianly distributed in  $x$  and  $z$ .

For a  $\lambda = 10 \mu\text{m}$  EM source with 10 ps, 120 MW pulses and for a resonator with  $Q \sim 3,000$ , a 300  $\mu\text{m}$  inter-mirror distance, and 300 gaps, an electron will gain  $\sim 9$  MeV and the structure energy gradient will be  $\sim 3$  GeV/m.

Here we report on: (a) Experiments using a 7-mm prototype resonator whose fields we are measuring while developing a protocol for accelerating an electron beam; (b) A possible open resonator as a high-energy linear collider booster; (c) Development of a micro-accelerator injector using an auto-emission cathode; and (d) A sketch of a prototype multi-resonator accelerator design.

### 2 PROTOTYPE RESONATOR

#### 2.1 Resonator field



Figure 2: 7-mm resonator (a) prototype and (b) mirrors.

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We have constructed in brass a prototype resonator, seen in Fig. 2(a) with the exciting horn (top) and a receiving horn (bottom) attached respectively to the input and accelerating structure mirrors seen in Fig. 2(b). The resonator is excited by a 7-mm **R**adio**F**requency source. We made the  $140 \times 88 \text{ mm}^2$  input mirror cylindrical with a 76.9 mm radius to provide a more uniform field distribution along beam path between gaps. The accelerating structure mirror has a 7 mm pitch with a 3.5 mm gap depth and 1.2 mm diameter beam holes.

We measure a fundamental mode  $Q$  of 850 at a 7.4 mm resonance wavelength with a 2 mm diameter plasticine-graphite sphere sliding on a 0.25 mm diameter fishing-line that diffuses and absorbs EM energy to perturb the cavity field. We excite the resonator by sweeping the frequency of a backward-wave tube signal, which we channel through a waveguide, attenuator, wave meter, exciting horn, and coupling holes in the cylindrical mirror. The EM radiation is then transmitted through the open resonator volume, into holes in the accelerating structure gap bottoms, through the receiving horn, and into the waveguide where it hits a square picked-off detector whose output signal is amplified and directed to an oscilloscope. By moving the perturbing probe, we obtain the electric field distribution from the height of the oscilloscope trace as seen in Fig. 3 for the fundamental  $(0,0,18)$  mode.

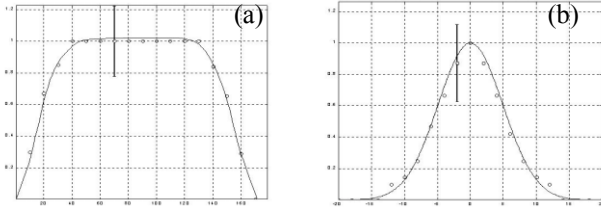


Figure 3: Field distribution along (a)  $z$  and (b)  $x$ .

Since both the plane mirror and the gap bases are located at standing wave nodes, the resonator field alone determines the gap field amplitude, phase, and spatial distribution. So the gap field along the particle path is almost constant and nearly that of the standing wave maximum above the gap. The field decays exponentially in the beam holes.

## 2.2 Proposed beam experiments

In experiments with an electron beam, our 5 MeV racetrack microtron injector [2] will provide a sequence of  $\sim 22$ , 2,856 MHz electron bunches with 0.1 to 1.0 nC/bunch. We match the beam and resonator at the 15<sup>th</sup> harmonic of 2,856 MHz, 42.84 GHz, whose corresponding wavelength is 6.998 mm. These bunches will arrive every 350 ps and the field will be excited by the bunch decays as  $Q/\pi f$ . For  $Q > 1,000$  this is  $> 7.4$  ns so we neglect the field decay between bunches. The total energy, transferred to the fundamental resonator mode by  $N$  bunches, is  $\Delta W_N = 76.3fnNQ_b^2/q$  (J), where  $q$  is the

resonator height in half-wavelengths, with a corresponding power of  $P = \Delta W_N / (NT_b) = 763fnNQ_b^2/qT_b$  (W) and electron energy change of  $\Delta E = \Delta W_N / (NQ_b) = 76.3fnQ_b/q$  (eV). For 42.84 GHz,  $N = 20$ ,  $Q_b = 1$  nC, and  $q = 18$ ,  $P = 10.4$  kW and  $\Delta E = 3.6$  keV.

## 3 ULTRA-RELATIVISTIC BEAMS

One application of our resonator is as a linear collider booster of which we have studied two aspects: (1) beam optics for a 500 GeV maximum energy using RF quadrupole focusing and (2) wake field effects.

### 3.1 Beam optics

Approximating the gap with beam holes by a rectangular cavity with  $\lambda/2$  height and width in the beam direction and  $\gg \lambda/2$  in the transverse direction, the normalized focusing gradient is

$$G_x(x,0)_n = \frac{\partial^2 E_{z1}(x,0)/E_{z1}(0,0)}{\partial x^2}, m^{-2}, \quad (1)$$

$$G_y(0,y)_n = \frac{\partial^2 E_{z1}(0,y)/E_{z1}(0,0)}{\partial y^2}, m^{-2}$$

where  $\varphi$  is the bunch phase with respect to the RF. Thus, a relativistic particle with  $\varphi = 0$  will gain the maximum energy.  $E_{z1}(x,y)$  is the 1<sup>st</sup> longitudinal electric field  $E_z(x,y,z)$  Fourier spatial harmonic and the focusing strength is

$$S_{x,y}(x,y) = -\frac{\lambda^2 \sin \varphi}{8\pi} G_{x,y}(x,y)_n E_{z1}(0,0). \quad (2)$$

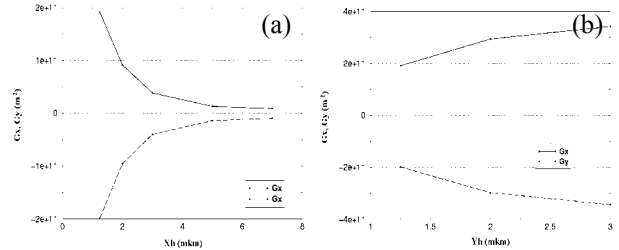


Figure 4:  $G(x,y)$  with beam (a) width and (b) height.

These calculations, seen in Fig. 4, show that the normalized focusing gradient can be varied about an order of magnitude by elongating the beam hole. This will not change the sign of  $G$  since the transverse cavity dimension is much larger than its height. Thus, to get quadrupole focusing in both planes, we use the focusing strength dependence on phase, or “phase focusing”. For a 1 GeV/m,  $\lambda = 10 \mu\text{m}$  accelerator with 500 GeV maximum energy, we consider an elementary periodic focusing channel cell consisting of three structures, each with 100 gaps, the 1<sup>st</sup> operating at  $\varphi > 0$ , the 2<sup>nd</sup> at  $\varphi = 0$ , and the 3<sup>rd</sup> at  $\varphi < 0$ . In Fig. 5(a) we present the  $\beta$ -function dependence on particle momentum for two phases and a  $1.25 \times 3 \mu\text{m}^2$  beam hole.

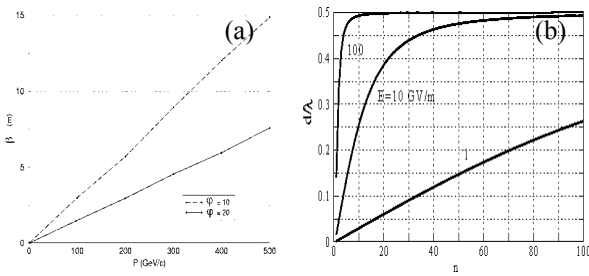


Figure 5: (a)  $\beta$ -function with beam momentum and (b) graded- $\beta$  structure gap width with gap number.

### 3.2 Wake field effects

Wake fields limit the bunch charge that can pass through an accelerating structure with acceptable emittance growth. Although the wake field amplitude grows with decreasing wavelength, decreasing the bunch spacing maintains the luminosity while the higher accelerating gradient favors small wavelengths [3]. For our resonator, in contrast to ordinary accelerating structures, only single bunch wake field effects are important because the generated wake fields are effectively damped by radiation to free space. In a  $10 \mu\text{m}$  resonator,  $\sim 0.1 \text{ pC/bunch}$  could be accelerated.

### 4 INJECTOR

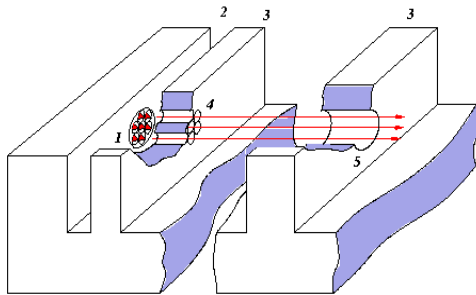


Figure 6: Injector field cathode (1) 1<sup>st</sup> gap (2), metal strips (3) beam holes for low- $\beta$  (4) and  $\beta = 1$  (5) beams.

The injector for our accelerator will have a field emission cathode [4] at the 1<sup>st</sup> accelerating gap wall. Despite the high accelerating gradient, the energy gain per gap is limited to  $\sim 10 \text{ keV}$ . Thus the injector section will be a graded- $\beta$  structure with the gap length following the changing electron velocity. The longitudinal beam dynamics for several accelerating gradients in which the gap width changes with the gap number are seen in Fig. 5(b). We also study the beam dynamics with space charge in the injector structure using an axially symmetric approximation. To provide the effective gap width defined by the field distribution, the beam hole diameter and gap width must be comparable to but much less than that for a  $\beta = 1$  structure. We sketch a possible injector design in Fig. 6, where initially the single beam hole is replaced by several smaller diameter holes that provide the necessary field distribution. With our  $\sim 10^{10-11} \text{ V/m}$

electric field amplitude, the auto-emission current density can reach  $10^{9-10} \text{ A/cm}^2$ , which can provide  $\sim 0.5 \text{ pC/bunch}$  extracted in a half-period.

### 5 MULTI-STRUCTURE

We can replace the resonator top concave mirror by a transparent plate with appropriate permittivity and thickness and place a lens before the top mirror to get additional resonance wave focusing. A possible multi-resonator micro-accelerator, seen in Fig. 7, combines the resonators in series. The laser beam (1) passes through a vacuum window (8) and encounters a succession of semi-transparent mirrors (2) whose reflections are directed through focusing lenses (3) to Fabry-Perot resonators consisting of top (4) and bottom accelerating structure mirrors (5). A set of piezoelectric elements (6) adjust the resonator heights, while another set (7) adjusts the accelerating structures longitudinal positions, thus providing in-phase acceleration of the injected beam (9) through an exit window (10). The unused laser beam power is dumped in a carbon absorber (11).

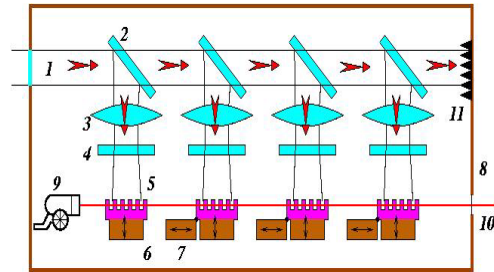


Figure 7: Possible multi-resonator micro-accelerator.

### 6 REFERENCES

- [1] Yu.K. Alekseev and V.I. Shvedunov, "An Open Resonator Particle Accelerator," in Proc. EPAC 2000 Conf., J.-L. Laclare, W. Mitaroff, Ch. Petit-Jean-Genaz, J. Poole, and M. Regler, eds. (World Scientific, Singapore, 2000) p. 892.
- [2] R. Barday, V.P. Gorbachev, A.M. Gorokhov, E.A. Knapp, V.I. Shvedunov, N.P. Sobenin, A.A. Sulimov, W.P. Trower, A. Vetrov, and D.A. Zayamy, "High-brightness RaceTrack Microtron Injector," in these proceedings.
- [3] J.-P. Delahaye, G. Guignard, I. Wilson, and T. Raubenheimer, "Scaling Laws for Normal Conducting  $e^+e^-$  Colliders," in Proc. XIX Inter. Linac Conf., C.E. Eyberger, R.C. Pardo, and M.M. White, eds. (Fermilab, Batavia, 1998) p. 13.
- [4] R.H. Fowler and L. Nordheim, "Electron Emission in Intense Electric Fields," Proc. Royal Soc. A119 (1928) 173.