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IMPROVING ENERGY RESOLUTION AND COMPENSATING CHROMATIC ABERRATION WITH A TM010 MICROWAVE CAVITY

C. J. R. Duncan*, P. Cueva, J. M. Maxson, D. A. Muller,
Cornell University, Ithaca, NY, USA

Abstract

The intrinsic energy spread of electron sources limits the achievable resolution of electron microscopes in both spectroscopic and spatially resolved measurements. We propose that the TM010 mode of a single radio frequency (RF) cavity be used to dramatically reduce this energy spread in a pulsed beam. We show with analytic approximations, confirmed in simulations, that the non-linear time-energy correlations that develop in an electron gun can be undone by the RF cavity running near-crest. We derive an expression that gives the required RF field strength as a function of accelerating voltage. We explore multiple applications, including EELS and SEM. By pulsing a photocathode with commercially available, high repetition-rate lasers, our scheme could yield competitive energy spread reduction at higher currents when compared with monochromated continuous-wave sources for electron microscopes.

INTRODUCTION

Motivated by the demands of ultrafast electron diffraction (UED), progress in photoelectron sources over the last decade now makes it possible to produce sub-picosecond electron pulses with femtosecond timing precision. Beyond UED, ultrafast pulses could yield improved beams for microscopy applications that do not aim to make time resolved measurements. Improvement is possible because the pulsed structure gives a handle on the energy-time dimensions of phase-space for experimental manipulation.

The history of attempts to use time dependent fields to correct lens aberrations in electron microscopes date back to the 1940s and the pioneering work of Scherzer [1, 2]. Common to all proposals is the *phase condition*: that the electron pulses be much shorter than the period of the RF wave [3]. Having in mind the use of time dependent fields as transverse lenses, this historical work formulated the phase condition in terms of the lens aberration introduced by a time dependent focal length. Letting ω be the angular RF frequency, the change in focal length during the transit of an electron pulse from its optimal value $f_{\min}$ has the effect of blurring a point focus into a disc of radius r,

$$r = \frac{1}{2}\omega^2 \Delta t^2 f_{\min}\alpha + O\left(\Delta t^4\right), \quad (1)$$

where α is the angular aperture of the beam and Δt is the pulse length. A suitable criterion for the feasibility of using RF fields as a microscope lens is that the right-hand-side of Eq. (1) be less than the aberration of the uncorrected microscope, something never achieved in the 20th century [4]. Considering hypothetical but realistic numbers today, a 100 fs r.m.s. pulse transiting a 3 GHz cavity with an aperture of 100 mrad gives a blur $r/f_{\min} = 9 \times 10^{-9}$, smaller than even the best corrected transmission electron microscopes, which get $r/f \approx 10^{-7}$ [5]. The possibility today of reliably producing pulses shorter than 100 fs is thus a reason to reconsider the use of microwave cavities in electron microscopy, as was done in [6], a work which inspired the line of though that we pursue in this proceeding.

An important metric of beam quality is energy spread. An energy spread of around 10 meV is necessary to resolve phonon spectra [7]. Moreover, chromatic aberration is the leading lens aberration after correcting for spherical aberration. Scanning Transmission Electron Microscopy (STEM) typically uses a probe beam with a 1 eV energy spread; while for Transmission Electron Microscopy, the best monochromated microscopes have an energy spread of 10 meV [7]. Monochromation using an energy filtering slit is not an option in STEM or in Scanning Electron Microscopy (SEM) because of the attendant loss of beam current. At the lower voltages at which SEM and STEM operate compared with TEM, higher current is needed to overcome the signal to noise of particle detectors.

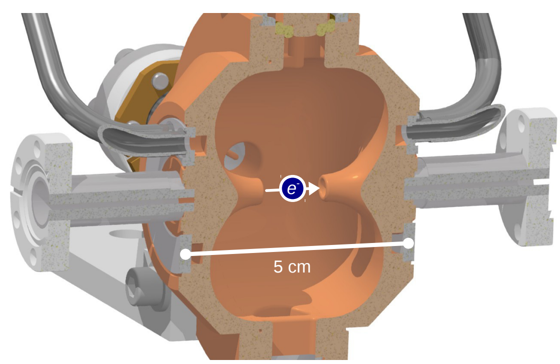

Figure 1: This reentrant cavity design contains a TM010 mode at 3 GHz . The high field gap across which electrons transit is 1 cm long; powered at ~ 50 W the cavity amplitude is 2 MVm^{-1}. The short gap makes the design ideal for time-of-flight based energy correction. The optical properties of a cavity of similar design are studied in [6].

In reducing energy spread, RF cavities are a potential alternative or complementary technology to monochromation using energy filtering slits. When a TM010 mode is operated such that the maximum accelerating phase coincides with the arrival of the lowest energy particle in a pulse, the effect of the cavity is to reduce the overall energy spread of the pulse. By *pulse* in this context is meant an ensemble of single-particle shots: the low emittance required in mi-

* cjd257@cornell.edu

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croscopy can only be achieved by eliminating space-charge. At a repetition rate of 1 GHz, the average current single particle pulses of 160 pA is an order of magnitude larger than the average current of the highest resolution monochromated continuous wave sources [7].

A reentrant cavity of a design such as is shown in Fig. 1 can produce a large RF field for low RF power, 2 MVm^{-1} at ~ 50 W, over a short distance, ~ 1cm, meaning that the complication of transit time effects inside the cavity can be ignored. Thus, the energy gain delivered by the cavity is well approximated as a sinusoidal function of time of arrival. The two leading questions for the feasibility of this scheme are:

- i. whether there is a choice of phase offset such that the time dependent energy gain can undo the up-stream non-linear time-energy correlation, and;
- ii. whether the time of arrival of pulses at the cavity can be made sufficiently precise to avoid introducing a new source of energy spread to the beam.

We treat the effect of the energy-compensating cavity on transverse phase-space in a forthcoming paper. Here we answer i. and ii. using a simplified model of an electron gun that ignores the transverse dimension.

EVOLUTION OF TIME-ENERGY CORRELATIONS IN A DC GUN

To evaluate the threshold feasibility of cavity-based energy correction, we use a simple model that treats the DC gun as a region of space of length d in which particles with initial kinetic energy K_C undergo uniform acceleration across a potential difference V_G. Inverting the kinematic equations to find the initial energy as a function of the time of arrival at the gun exit t_G, we obtain,

$$K_C = \frac{1}{2m_e}\left(\frac{eV_G}{d}\right)^2 t_G^2 + O\left(t_G^3\right), \tag{2}$$

where we define $t_G = 0$ to be the time that a particle with initial kinetic energy $K_C = 0$ exits the gun. The quadratic coefficient in Eq. (2) does not depend on the position of the gun exit when re-expressed in terms of the field strength, the interpretation being that time-of-arrival correlations mostly develop near the cathode where particle velocities are low, as shown in Fig. 2. For that reason, time of arrival *relative to the bunch* is insensitive to gun voltage fluctuations at the 10^{-6} level. Initial energy spread is much more important in determining time of arrival because the initial energy spread is of the same order as the initial average energy.

ENERGY SPREAD DOWNSTREAM OF THE CAVITY

We imagine the cavity to be placed downstream of the gun exit, on the order of centimeters. To obtain a time dependent expression for the energy gain delivered by the cavity, we

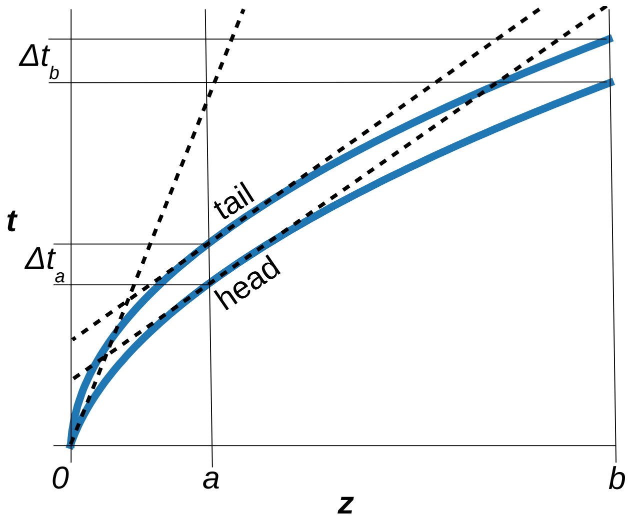

Figure 2: Evolution of energy-time correlations in an electron bunch accelerated through a DC gun over a distance b. The bunch is an ensemble of many single electron shots and hence space-charge is ignored. The pulse length $\Delta t(z)$ fixes the quadratic coefficient in Eq. (2), the dependence of initial kinetic energy on time of arrival $t(z)$. The bunch tail is shown here with zero initial velocity. The initial velocity of the head is shown by the dashed tangent line. By the point a, located 25% of the distance to the gun exit, the tangents to the two curves are roughly parallel. Hence, the pulse length Δt_b at b is approximately equal to the pulse length Δt_a at a.

define an effective DC voltage across the reentrant cavity gap:

$$V_{RF} := \int_{-\infty}^{\infty} E(z)\cos\left(\frac{\omega_{RF} z}{c\beta_z}\right) dz. \tag{3}$$

The optimal value of V_{RF} as a function of gun voltage — the value that cancels the quadratic term in Eq. (2) — is then:

$$V_{RF} = \frac{eV_G^2}{m_e c^2}\left(\frac{c}{\omega_{RF} d}\right)^2. \tag{4}$$

The final energy spread after the cavity is bound from below by the laser pulse length Δt_ℓ :

$$\Delta E_{\min} \geq eV_{RF}\omega_{RF}^2 \Delta t \Delta t_\ell + O\left(\Delta t_\ell^2\right), \tag{5}$$

where Δt is the bunch length at the cavity. Figure 3 compares these formula with simulation results, showing excellent agreement.

The final energy spread is broadened by phase uncertainty in the RF cavity. The dominant source of this uncertainty is changes in the cavity resonance frequency due to thermal expansion [6]. Letting κ be the thermal expansion coefficient, the quality factor of the cavity Q and ΔT the uncertainty in temperature, the uncertainty in RF phase $\Delta\phi$ is,

$$\Delta\phi = 2Q\kappa\Delta T. \tag{6}$$

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The corresponding contribution to the uncertainty of the final energy of the beam is,

$$\Delta E_{\text{phase}} = eV_{\text{RF}}\left(\omega\Delta\phi\Delta t + \frac{1}{2}\Delta\phi^2. + \mathcal{O}\left[\Delta\phi\Delta t^3\right]\right), \quad (7)$$

With reference to the simulation parameters shown in Fig. 3, taking a copper cavity to have $Q = 10^4$, $\kappa = 1.6 \times 10^{-5}\text{K}^{-1}$ and a pulse length of 350 fs, the uncertainty in the final energy given a temperature uncertainty of one millikelvin is $\Delta E_{\text{phase}} = 27$ meV. This uncertainty scales like V_G, inspecting Eq. (7), because $V_{\text{RF}} \sim V_G^2$, $\Delta t \sim V_G^{-1}$, as shown in Eq. (4) and Eq. (2) respectively. Hence, at gun voltages between 1, 10 kV, an uncertainty of 1 meV is feasible.

CONCLUSION

By investigating an analytic model of a pulsed laser photoemitter, we have shown that correlations between initial kinetic energy and time of arrival enable a single TM010 cavity to eliminate initial kinetic energy as a source of energy spread, down to a bound imposed by the laser pulse length. Our model also shows that correlations between time of arrival and fluctuations in accelerating voltage are much weaker; hence, fluctuating accelerating voltage is a source of energy spread that cannot be touched by a correcting cavity. Our model neglects the transverse dimensions of phase space: we treat the transfer optics required to mitigate the introduction of energy-space correlations in a future work.

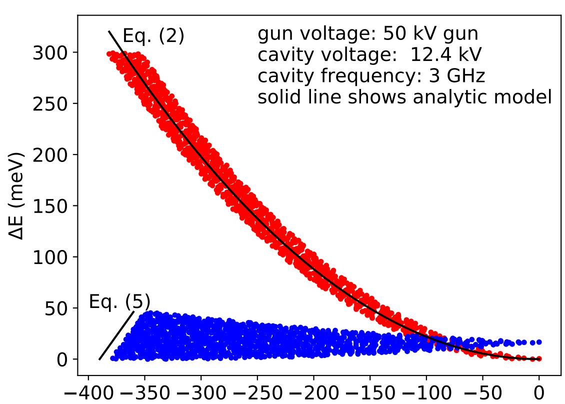

Figure 3: General Particle Tracer (GPT) [8] simulation results showing energy as a function of time of arrival at the cavity entrance (red) compared with cavity exit (blue). Simulations ignore space-charge and transverse spatial dimensions. The analytic prediction Eq. (2) is shown as a solid line, as is the analytic prediction for the final energy spread Eq. (5). The final energy spread line is shown offset the particle ensemble to improve legibility. The analytic model matches the simulations well, in particular predicting the final energy spread of 47 meV from the laser pulse length of 30 fs.

ACKNOWLEDGEMENTS

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