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Dielectric Collimators for Beam Delivery Systems[☆]

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Abstract

Wakefield generation by the collimation system is known to be a critical linear collider design issue. Optimization of the collimators represents a tradeoff between beam quality (halo reduction) and luminosity reduction. The primary objective is to reduce both short range (resonant) and long range (resistive) deflecting wakefields from collimators that reduce the luminosity of the machine. We consider the CLIC BDS (beam delivery system) and examine the potential for using dielectric rather than highly conducting materials for collimation. We present some examples of the flexibility gained by having control over the permittivity and conductivity of the collimator. We discuss simulation efforts with BBU-3000, Arrakis, and other proprietary and commercial codes. We have also proposed impedance measurements of low conductivity and dielectric collimator prototypes at the new FACET facility at SLAC, which provides unprecedented short drive bunches and the availability of a witness beam to probe the induced wakefields.

Keywords: linear collider, collimation, wakefields
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1. Introduction

The collimation system of a future high energy physics accelerator (for example, the Compact Linear Collider (CLIC) or International Linear Collider (ILC)) needs to simultaneously fulfill three different functions. It must (1) provide adequate halo collimation to reduce the detector background, (2) ensure collimator

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[☆] Work supported by the US Dept. of Energy, Grant #DE-SC-0004319 survival and machine protection against missteered beams, and (3) not significantly amplify incoming trajectory fluctuations via the collimator wake fields [1, 2, 3, 4]. The latter has to take in account additional effects such as secondary particle generation, wakefield kicks, and element misalignments. Wakefield generation by the collimation system is considered a critical issue and has to be optimized to achieve the required collider luminosity.

Wakefields in the BDS of the linear colliders can be an important source of emittance growth and beam jitter amplification, consequently degrading the luminosity. The main contributions to wakefields in the BDS are: geometric and resistive wall wakefields of the tapered parts of the collimators; resistive wall wakes of the beam pipe, which are especially important in the regions of the final quadrupoles, where the betatron functions are very large; and electromagnetic modes induced in crab cavities. Other wakefield sources include surface roughness and irregularities in the beam pipe, like pump out apertures, bellows and BPM electrodes.

In the CLIC BDS there are two collimation sections [14]: The first post-linac collimation section is dedicated to energy collimation. The energy collimation depth is determined by failure modes in the linac [15]. A spoiler absorber scheme (Fig. 1), located in a region with non-zero horizontal dispersion, is used for intercepting missteered or errant beams with energy deviation larger than 1.3% of the nominal beam energy. Downstream of the energy collimation section, a dispersion-free section, containing eight spoilers and eight absorbers, is dedicated to clean up of the transverse halo of the beam, thereby reducing the experimental background at the interaction point (IP).

The report [14] was focused on single bunch effects of the collimator transverse wakefields. The main contribution to the collimator wakefields arises from the betatron spoilers, whose apertures (100 μm) are much smaller than the design aperture of the energy spoiler (3.5 mm), and much smaller than the aperture of the nearby vacuum chamber (8–10 mm radius). In order to study the impact of the CLIC collimator wakefields on the beam, a module for the calculation of the collimator wakefields in various regimes has been implemented in the PLACET tracking code [16]. Using this code the effects of the collimator wakefields on the luminosity have been evaluated for the design transverse collimation apertures 15 σ_x and 55 σ_y.

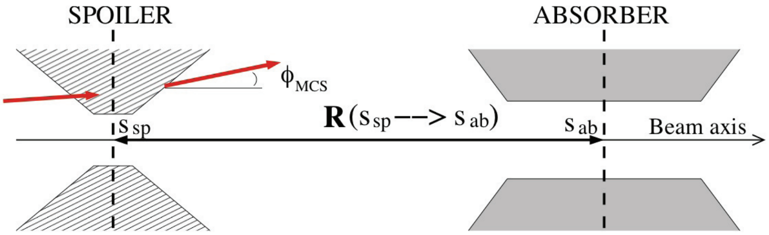


Fig. 1: Schematic view of the CLIC BDS collimator

The relative luminosity degradation has been studied as a function of initial vertical position offsets at the entrance of the BDS with and without collimator wakefields for the conventional (conductive) design. In this calculation the joint effect of all the BDS collimators has been considered. For instance, for beam offsets of 0.4 σ_y, the CLIC luminosity loss was found to amount to as much as 20% with collimator wakefields, and 10% for the case with no wakefield effects. An even smaller aperture would be desirable to further clean up the beams.

The current status of the linear collider design efforts requires additional research on wakefield reduction at the collimator section. New materials and new geometries need to be considered [7, 9]. Dielectrics provide an alternate approach for collimation in future accelerators that offers the possibility of higher luminosity with lower backgrounds at the IP. In [5], dielectric collimators for the CLIC Beam Delivery System have been discussed with a view to minimize the BDS collimation wakefields. The dielectric collimator concept was introduced as a result of recent ideas for LHC collimation, where materials with low conductivities have been implemented to reduce the impedance value at low frequencies [8], and using dielectrics as collimator materials has been proposed as an option [9, 10]. As long as composite dielectrics offer a wide range of electrical, mechanical and thermal properties they provide an opportunity to find an optimized solution for the dielectric based collimation system [5, 9, 10].

The interest in using dielectric collimators for the LHC is the possibility of moving the peak impedance experienced by the beam away from the principal frequency component of the beam. The dependence of the impedance on the frequency can be optimized to match the frequency response of the feedback/stability control system and allow smaller collimator apertures and thus cleaner beams at the collision point. The rationale for using dielectric collimators in a linear collider is more complex and is best understood in terms of the direct effects of the wakefields produced by the collimators on the bunch train. The primary objective is to reduce both short range (resonant) and long range (resistive) deflecting wakefields that reduce the luminosity of the machine. A secondary objective is the elimination of hazardous materials (particularly beryllium). This is especially important for consumable or sacrificial collimators that can be destroyed in the case of a beam abort. (It may also be possible to reduce the Be content by using it as a coating material.)

Additionally, there is also the flexibility in collimator design afforded by the extra parameters (relative permittivity, conductivity) available from dielectric media. (Note that for the remainder of the paper, *relative* will be understood when referring to the permittivity.) Some of the interesting approaches that are being investigated include

- passive damping of the wakefields via bulk conductivity of the collimator material;
- adjustment of the frequency of the collimator wake to detune the wakefield;
- use of metamaterial or photonic band gap inspired geometries to selectively transmit or reflect certain frequency components of the wake;
- active tuning of the collimator wake through the use of a nonlinear material;
- Chojnacki suppressor-like [18] schemes (artificial asymmetric conductivity that allow selective transmission of wakefields with particular symmetry characteristics);
- rf absorber techniques from EMC: Salisbury screens etc. [19]. These techniques are based on the principle of destructive interference of a plane wave with itself in an rf absorbing material.

2. Dielectric materials and technology

A considerable knowledge base on dielectrics in the accelerator environment has been accumulated from dielectric wakefield acceleration experiments. A long series of experiments has been carried out at the Advanced Acclerator Test Facility (AATF) [12] and the Argonne Wakefield Accelerator (AWA) facility [13] with a high charge (20–40 nC), short (1–4 mm), electron drive beam generating electromagnetic Cherenkov radiation (wakefields) while propagating down a vacuum channel in cylindrical or planar dielectric structures. Charging and breakdown effects are not problematic with proper choice of materials. Multipactor occurs and is important primarily for rf driven dielectric structures.

Euclid [27] has experimentally tested various dielectric wakefield devices based on ceramics (alumina, forsterite, cordierite, BST(M) ferroelectrics [24, 25]), quartz and CVD diamond [26]. Graphite, alumina, and aluminum nitride AlN have some attractive properties. Graphite is slightly better than Be at scattering and absorbing electrons (radiation length 19 cm compared to 35 cm for Be) and so allows a reduction in absorber length by about a factor of 2/3. The permittivity of graphite is about 10–15, and its conductivity ranges from $(1-8)\times10^5$ mho/m. Alumina ($\epsilon = 10$) and AlN ($\epsilon = 9$) can survive high radiation environments and are inexpensive. Unlike graphite, the conductivity of these ceramics is small, undesirable from the standpoint of damping wakefields. We will discuss in Sect. 3 how a desired level of conductivity can be introduced in a composite structure.

Our choice of candidate dielectric materials for test collimators was based in part on criteria of availability of commodity materials, radiation hardness, and effectiveness as radiation scatterers and absorbers. The presence or introduction of bulk conductivity into the dielectric has advantages for damping the wakefield and will be fully evaluated.

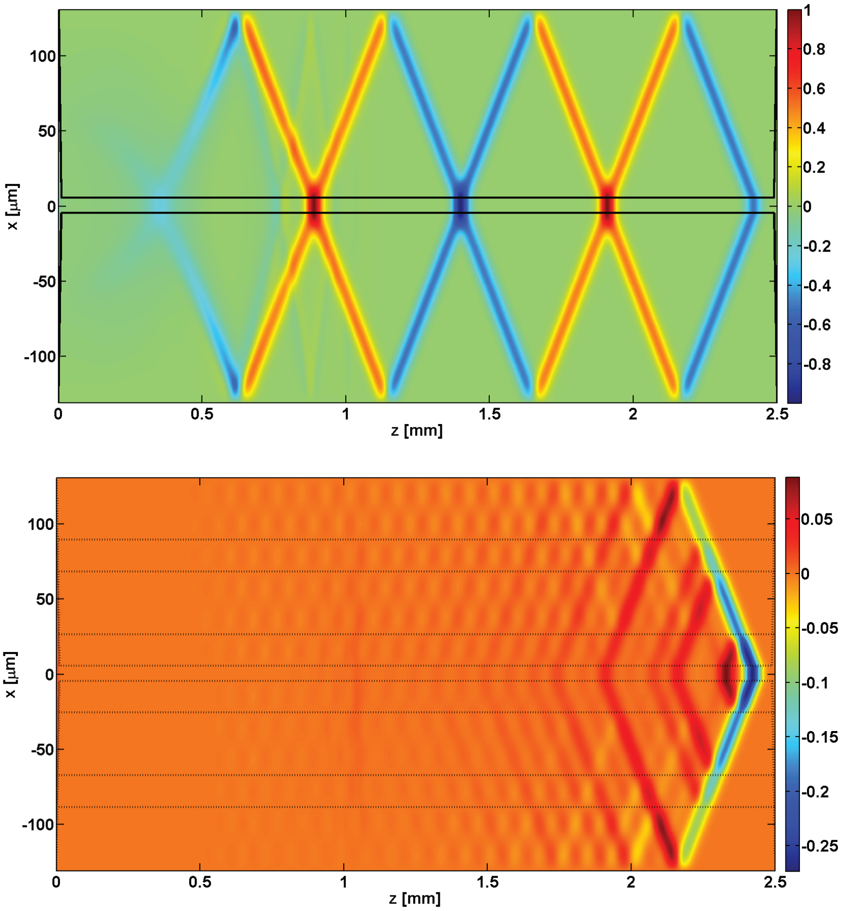
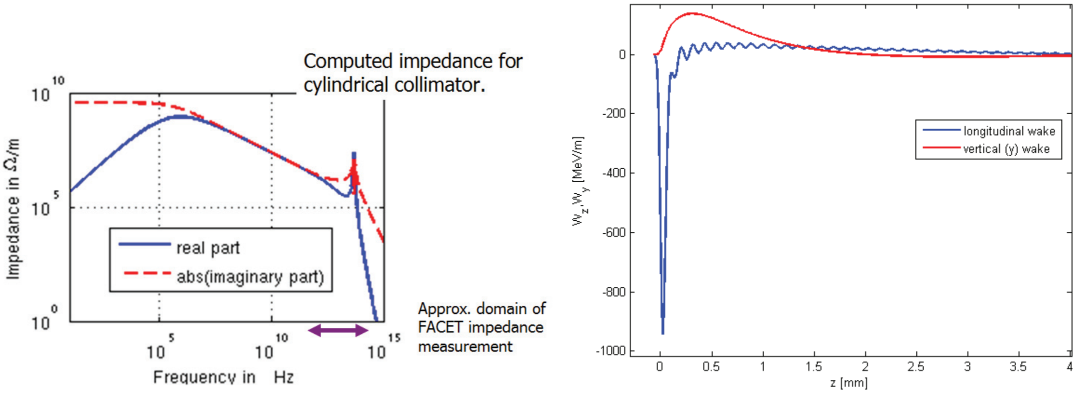


Fig. 2: Longitudinal electric field component of Cherenkov radiation in a dielectric collimator (a) without losses and (b) a (non optimized) “anti-Bragg” structure made from the same dielectric interspersed with thin conducting layers (dashed lines). The permittivity in both cases is 5. The maximum electric field on axis outside the bunch is about a factor of six larger for the unsegmented case. The color scales for both plots are normalized to the maximum electric field in the nonsegmented case (a).

3. Numerical modeling of dielectric collimators

Currently, the BDS simulation codes do not allow using dielectric based collimation system studies including wakefield effects directly related to the dielectric properties [6, 9]. Full 3D finite difference time domain modelling of the CLIC collimators is a rather demanding problem. The memory requirement for a 3D wakefield analysis of a single dielectric CLIC betatron spoiler is about 5 GB with a marginally coarse mesh spacing. Euclid Techlabs has developed a number of different tools for treating various aspects of dielectric and conventional collimator simulations.

The 2D and 3D simulation codes Waveguide-09, Multibunch-09 and BBU-3000 [20, 21, 22] are used for wakefield and beam dynamics studies in cylindrical and planar dielectric loaded structures. BBU-3000 is Euclid Techlabs’ in-house particle-Greens function beam dynamics code and was designed for simulation of beam breakup effects in linear accelerators, with an emphasis on dielectric loaded structures. It can treat 2D and 3D cylindrical or planar geometries. The BBU-3000 algorithm is complementary to the particle in cell (PIC) approach. Heuristic group velocity effects on the wakefields are implemented for multibunch calculations. A parallel version of the code, the Beam Dynamics Simulation Platform, allows access to the



(a)

(b)

Fig. 3: (a) Example of CLIC dielectric structure impedance simulation [5, 9], showing the expected frequency range that can be covered by FACET witness beam measurements. (b) Longitudinal (blue) and transverse (red) wake potentials in a 200 μm gap alumina collimator. Alumina slab thicknesses are 1.8 mm. Beam charge is 3 nC, beam offset in y is 100 μm. Note that 0.2 mm is the planned maximum delay of the FACET witness beam.

software via web browser on a Linux cluster and can also make use of multicore processors under Linux or Windows environments. Waveguide-09 and Multibunch-09 compute dielectric device modes and wakefields using analytic expressions for the fields and the rigid bunch approximation.

Arrakis/Slab is a Euclid 2D hybrid pseudospectral code to compute wakefields in rectangular geometry dielectric collimators. 2D approaches have been suggested using a moving window to compute the short range wakefields only, although it is not clear in this case how the transverse wake forces would be treated. We follow the approach used in ref [11] for the analysis of planar laser-driven accelerating structures. In the limit of an infinitely wide beam in the y (horizontal) direction, the transverse wake forces vanish, analogous to the cancellation of the radial electric and azimuthal magnetic fields in the TM_{0n} mode of a cylindrical accelerating structure. Writing Maxwell's equations componentwise in rectangular coordinates and assuming an $e^{\pm ik_y y}$ dependence, we obtain a set of equations which are then discretized on a 2D x-z grid using the Yee algorithm [17]. While at first it might appear that there is no saving of memory or computation time with this approach, the large transverse size of the beam means that the beam current is contained within a relatively small range of transverse wave numbers k_y, and thus we can reduce the number of 2D evaluations required. After the code is run for the desired range of transverse wavenumbers, an FFT synthesis can be used to obtain the 3D wake potentials.

Using Arrakis/SLAB, a numerical demonstration of the flexibility of the dielectric collimator concept is shown in Fig.2. Here we compare the longitudinal wakefields from a section of a planar collimator for a continuous dielectric (a) and a transversely segmented dielectric (b). The transverse segments in (b) are separated by thin layers of lossy material (at x=±5, 26, 68, 89 μm) the locations at which the reflection of the Cherenkov wedge can be seen.

The depth of the layers is chosen to provide a half wavelength phase difference between pairs of segments, approximately cancelling the fields on axis. One could think of this configuration as an "anti-Bragg" structure, although the larger effect is still from losses in the conducting layers. This configuration also suggests a method of introducing a controlled amount of loss into a nonconducting ceramic collimator, by stacking layers of metallized ceramics.

4. Dielectric collimator experiments at SLAC/FACET

FACET, the Facility for Advanced aCcelerator Experimental Tests at SLAC [23], is a new beamline for wakefield acceleration (and other) studies. The initial collimator experiments require a relatively simple apparatus; diagnostics are part of the FACET facility. A vacuum chamber, the "Kraken" is a (T-481-like) vacuum chamber provided for outside users to set up their experiments.

Initially we plan to evaluate, graphite, and alumina or AlN as collimator materials. These are common, commercially available materials. Graphite is a material with bulk conductivity and has also been studied for use in LHC collimators. We plan to metallize the surfaces of some of the ceramic slabs to study the damping properties of multilayer collimators. The idea here is that by introducing sub-skin depth metal interfaces a low loss dielectric stack can be made lossy. We also have some evidence that interference effects from reflections of the Cherenkov wedge at the interfaces may help partially cancel the wakefield. (Sect. 3) We have had considerable experience in successfully metallizing electrodes on ceramic surfaces for control of nonlinear rf phase shifters and switches. We will also machine tapers on the entrance and exit edges of some of the slabs to evaluate the effect of the tapers on geometric wakefields.

We plan to test several planar collimator configurations. These experiments will use the same mounting hardware, vacuum chamber etc. and will differ only in the test collimator used. In each case the maximum axial length L of the collimator will ultimately be determined by the available space. Given the results of the simulations (see below) the length of the structure (and hence the energy loss in the collimator) should be as large as possible. L=20 cm is about the maximum size possible. The difficulty is separating the energy change of the drive bunch from its intrinsic $\Delta E/E = 1.3\%$ (≃300 MeV) energy spread.

The impedance of the test collimator structures will be estimated using the FFT of the wakefield measured using the witness beam. This technique for measuring wakefields and the analysis of sampled wakefield data were originally developed at Argonne's Advanced Accelerator Test Facility. At FACET, the maximum delay of the witness beam relative to the drive beam (maximum sampling distance for the wake) is 200 μm ($\Delta f \simeq 0.75$ THz). A delay sampling increment of 0.2 μm will provide a maximum frequency ≃325 THz. Figure 3a shows the frequency range covered compared to the spectrum of a cylindrical collimator as computed using the CERN code [5, 9]. While not ideal (one would like a very long witness delay measurement to be able to resolve lower frequencies) this measurement should be adequate for comparison and validation of the various simulation codes.

Figure 3 shows the longitudinal phase space of drive beams (one centered, one off axis) exiting a 2 cm 200 μm aperture alumina collimator in the absence of a drive beam energy spread. While the maximum energy difference (about 9.2 MeV) between the two beams is apparent, inclusion of the energy spread in the drive beam completely washes out the effect. Increasing the length of the structure to 20 cm would result in a maximum energy difference of 92 MeV, sufficient to be detected by the centroid shift within the energy spread of the pulses (Fig. 3). The witness bunch has a narrower energy spread than the drive and will be the main diagnostic tool for these measurements. From Figure 3b it can be seen that the peak energy loss and transverse deflection are within the range of the 0.2 mm maximum witness beam delay; thus long range wakes cannot be studied directly by this technique.

Based on the results of the initial FACET collimator measurements we plan to develop a second set of dielectric collimator structures. Measurements of these devices would also be made at FACET in a later run. We are interested in working with FACET staff to develop new diagnostics that are better suited to impedance measurements. These include beam deflection diagnostics. (The present diagnostic system measures beam energy only.) One possibility for obtaining long range wake measurements is to accelerate the witness bunch on later rf cycles than the drive bunch. While this would not provide a continuous delay, and would require a different mechanism for producing the witness beam, one could get delays of 0–200 μm + integer multiples of 10.5 cm.

5. Summary

Collimation systems are an essential part of high-energy colliders. Beam collimation systems must reduce the background in the detectors, removing the beam halo, and ensure machine protection by minimizing the activation and damage of sensitive accelerator components. A careful design of a collimation system has to take into account not only the particles traversing the collimators but also additional effects such as secondary particle production, deflecting kicks induced by wakefields in the collimators, and response to element misalignments [6]. Wakefields in the BDS can cause severe single or multibunch effects leading to luminosity loss. Jitter amplification and emittance growth can be driven by wakefields and degrade the electron or positron beam quality at the IP with a consequent luminosity drop.

We have begun investigations of the use of dielectric collimators in linear colliders to reduce the wakefields and therefore allow higher luminosity and possibly the use of smaller apertures, resulting in cleaner beams at the IP. The small collimator gap compared to the overall dimensions of the structure requires a fine mesh that makes 3D wakefield computations challenging. Compounding these difficulties is the need for long integration times to compute long range wakefields. Finally, more accurate models of frequency dependent conductivity need to be incorporated into the codes. We have been working with a number of alternative analytic and numerical approaches using codes developed by Euclid. The versatility of options available with dielectric collimators makes this approach worth pursuing. We have also proposed an extensive series of dielectric collimator measurements for the new SLAC FACET facility. The schedule for these experiments is contingent on the availability of further funding.

References

[1] ILC Reference Design Report, `http://ilcdoc.linearcollider.org/record/6321/files/ILC_RDR_Volume_3-Accelerator.pdf`

[2] Updated CLIC Parameters 2005, `http://cdsweb.cern.ch/record/1132079/files/CERN-OPEN-2008-021.pdf`

[3] CLIC 2008 Parameters, `http://cdsweb.cern.ch/record/1132079?ln=fr`

[4] R. Assmann et al. "Overview of the CLIC Collimation Design", Proceedings of the 2001 Particle Accelerator Conference, Chicago, p.4071.

[5] E. Metral, A. Grudiev, G. Rumolo, B. Salvant, R. Tomas. Robert Siemann Symposium and ICFA Mini-Workshop, 2009.

[6] Agapov I. et al., Phys. Rev. ST-Accelerators and Beams, 12, 081001 (2009).

[7] R. Tomas. ILC-CLIC Beam Dynamics Workshop. CERN, Geneva, 23-25 June, 2009. http://indico.cern.ch/getFile.py/access%3FcontribId=9&sessionId=3&resId=0&materialId=slides&confId=56133

[8] E. Metral et al. "Transverse Impedance of LHC Collimators". LHC-PROJECT-Report-1015. `http://cdsweb.cern.ch/record/1056724/files/lhc-project-report-1015.pdf`

[9] E. Metral, F. Caspers, A. Grudiev, T. Kroyer, F. Roncarolo and B. Salvant. "Impedance Studies for the Phase 2 LHC Collimators". PAC09. `http://cdsweb.cern.ch/record/1208361/files/CERN-ATS-2009-040.pdf`

[10] E.Metral, Conceptual Design Review LHC Phase II Collimation. CERN, 2009. `http://indico.cern.ch/getFile.py/access?contribId=7&resId=0&materialId=slides&confId=5515`

[11] A. Tremaine, J. Rosenzweig, P. Schoessow, "Electromagnetic wake fields and beam stability in slab-symmetric dielectric structures", Phys.Rev.E56:7204-7216, 1997.

[12] W. Gai et al., "Experimental Demonstration of Wakefield Effects in Dielectric Structures", Phys. Rev. Lett. 61 2756 (1988).

[13] P. Schoessow et al . "High Power RF Generation by Relativistic Beams in Dielectric Structures", J. Appl. Phys. 84 663 (1998).

[14] J. Resta-Lopez, D. Angal-Kalinin, B. Dalena, J. L. Fernandez-Hernando, F. Jackson, D. Schulte, A. Seryi and R. Tomas. "Status report of the baseline collimation system of the compact linear collider", 2011, pp.1-41, unpublished.

[15] J. Resta-Lopez, "Design and Performance Evaluation of Nonlinear Collimation Systems for CLIC and LHC", Doctoral Thesis, U. Valencia (2007) Ch. 2.

[16] G. Rumolo, A. Latina and D. Schulte, Proceedings of EPAC 2006, Edinburgh, Scotland, UK, 2006;

[17] A.Taflove, S.Hagness (eds.), Computational Electrodynamics: The Finite-Difference Time-Domain Method, Third Edition, Artech House 2005

[18] "Measurement of deflection mode dampening in an accelerating structure", E. Chojnacki, W. Gai, C. Ho, R. Konecny, S. Mitingwa, J. Norem, M. Rosing, P. Schoessow, J. Simpson, J.Appl.Phys.69:6257-6260,1991.

[19] `http://www.microwaves101.com/encyclopedia/absorbingradar3.cfm#salisbury`

[20] P. Schoessow et al., Proc. 2009 Particle Accelerator Conference, paper WE6RFP063, p.2939.

[21] P. Schoessow et al., Proc. IPAC 2010, paper TUPEC081, p.1904.

[22] P. Schoessow et al., "Beam Dynamics Simulation Platform and Studies of Beam Breakup in Dielectric Wakefield Structures", 2010 Advanced Accelerator Concepts Workshop, AIP Conf. Proc.1299, 262 (2010)

[23] "FACET Conceptual Design Report", SLAC-R-930, September 14, 2009.

[24] A. Kanareykin, "New Advanced Dielectric Materials for Accelerator Applications", AIP Conf. Proc. Volume 1299, pp. 286-291, doi:10.1063/1.3520329

[25] C. Jing et al., "Experimental Demonstration of Wakefield Acceleration in a Tunable Dielectric Loaded Accelerating Structure", Phys. Rev. Lett. 106, 164802 (2011)

[26] Sergey Antipov et al., "Diamond-Based Dielectric Loaded Accelerating Structures", AIP Conf. Proc. 1299, 359 (2010)

[27] `http://www.euclidtechlabs.com`

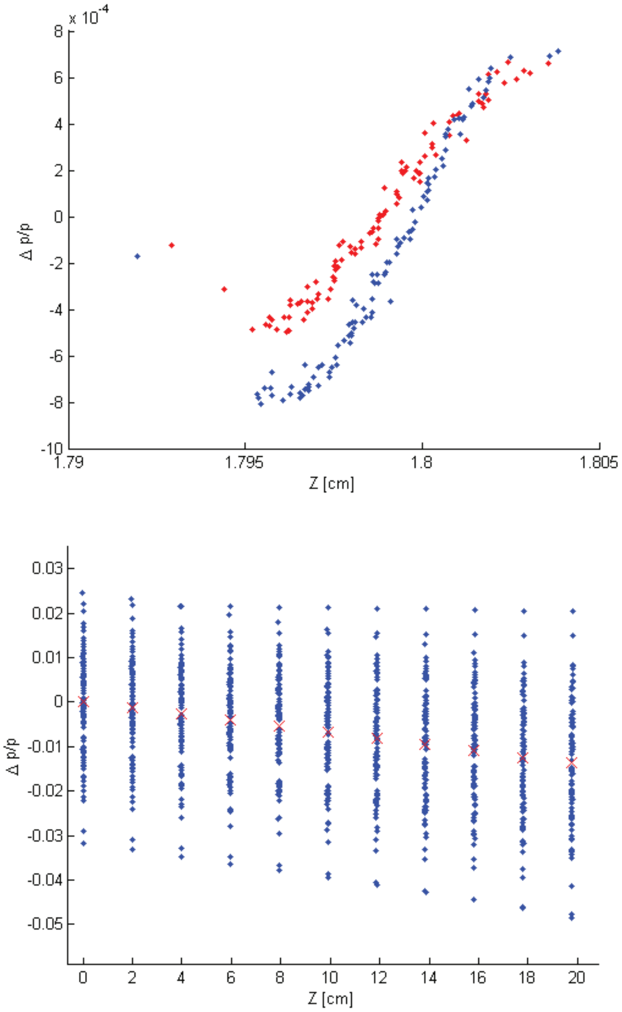


Fig. 4: (a) Longitudinal phase space for FACET bunch exiting 200 μm planar collimator. (Red points, beam on axis; blue points 100 μm vertical offset.) (b) Evolution of the drive beam longitudinal phase space through 20 cm structure. Centroids are indicated by (x). (BBU-3000 simulations.)