DIELECTRIC COLLIMATORS FOR BEAM DELIVERY SYSTEMS

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•Wakefield generation by the collimation system is considered a critical linear collider design issue and has to be optimized to achieve the required collider luminosity.

•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 the BDS collimators that reduce the luminosity of the machine.

• Also important is the question of survivability of the collimators in the event of an accidental high intensity beam loss.
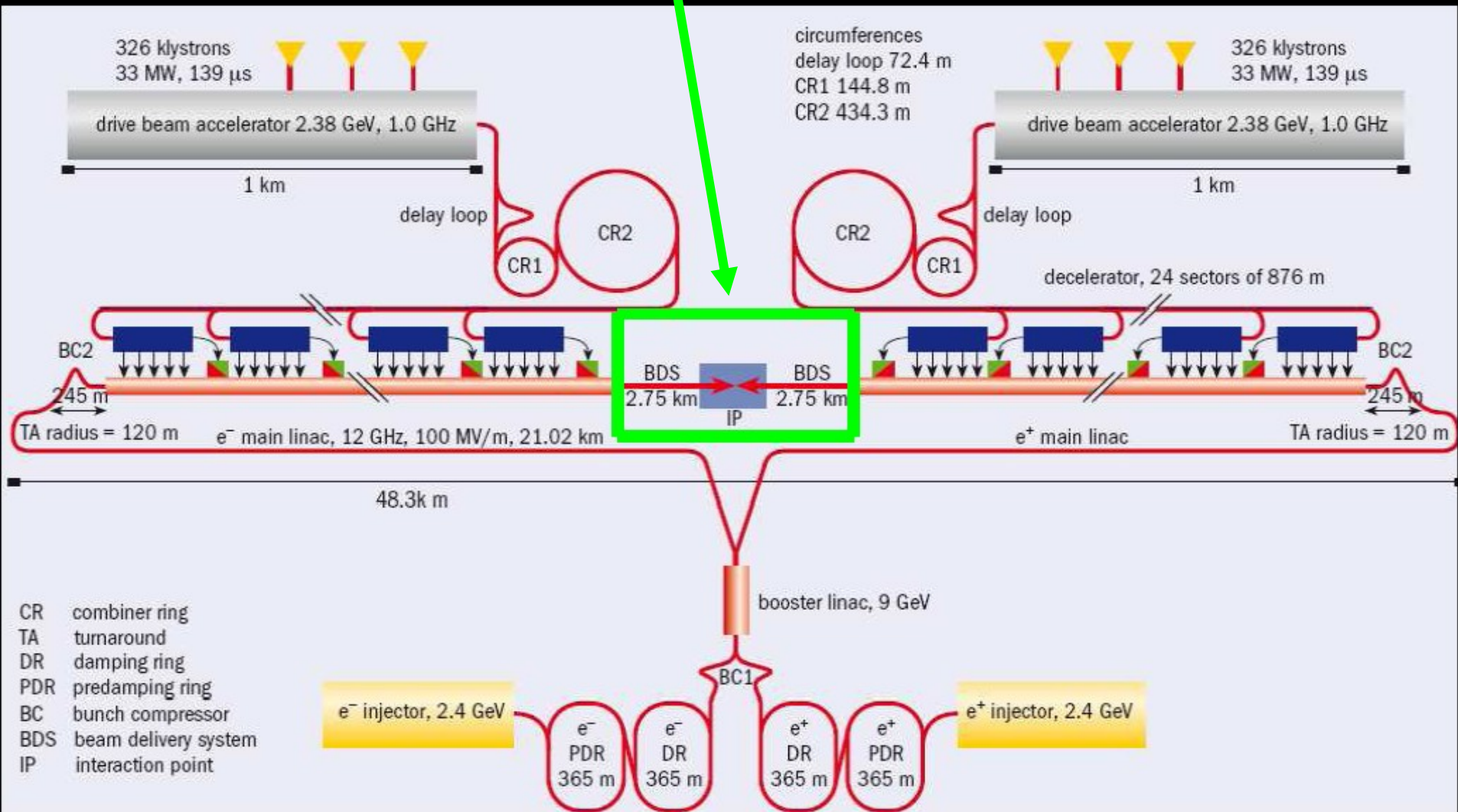
Outline

1. Conventional and dielectric collimators. LHC and CLIC Beam Delivery System

2. Dielectric materials and technologies

3. Numerical modeling of CLIC dielectric collimators

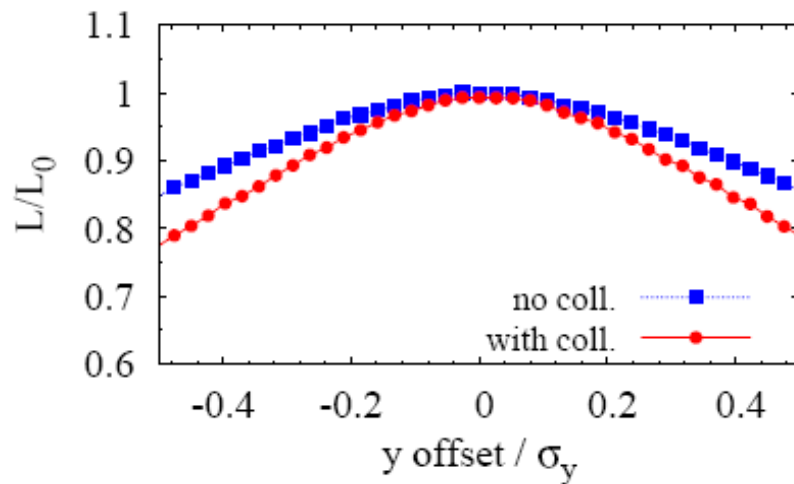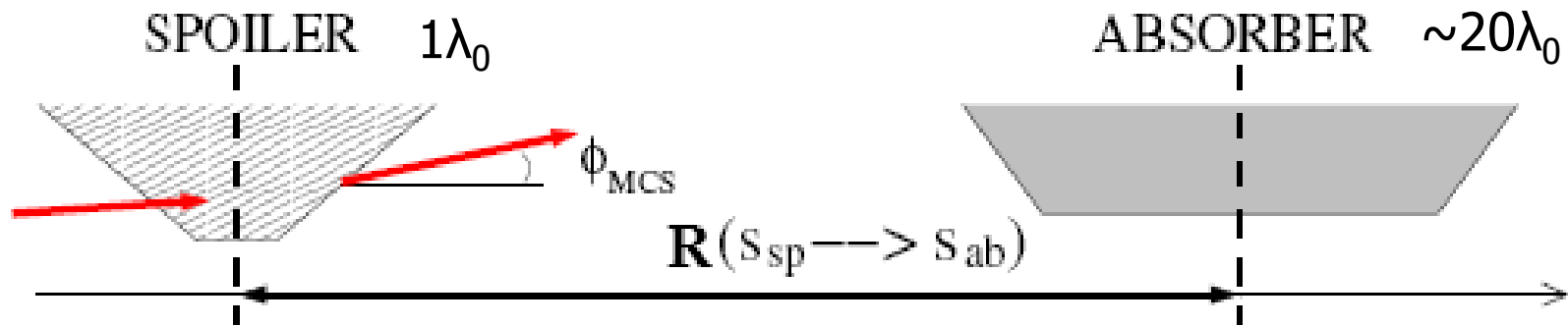4. Dielectric collimator experiments at SLAC/FACET

1. Conventional and dielectric collimators

- The original interest in using dielectric collimators came from the LHC: 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.
- 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.

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Beam Delivery System

326 klystrons
33 MW, 139 μs

drive beam accelerator 2.38 GeV, 1.0 GHz

1 km

delay loop

CR1

CR2

circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m

CR2

CR1

delay loop

326 klystrons
33 MW, 139 μs

drive beam accelerator 2.38 GeV, 1.0 GHz

1 km

decelerator, 24 sectors of 876 m

BC2

BDS
2.75 km

BDS
2.75 km

IP

BC2

245 m

TA radius = 120 m

e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km

e⁺ main linac

245 m

TA radius = 120 m

48.3k m

booster linac, 9 GeV

BC1

CR   combiner ring
TA   turnaround
DR   damping ring
PDR   predamping ring
BC   bunch compressor
BDS   beam delivery system
IP   interaction point

e⁻ injector, 2.4 GeV

e⁻
PDR
365 m

e⁻
DR
365 m

e⁺
DR
365 m

e⁺
PDR
365 m

e⁺ injector, 2.4 GeV

Schematic View of the CLIC BDS Collimator

SPOILER $1\lambda_0$

ABSORBER $\sim 20\lambda_0$

ϕ_{MCS}
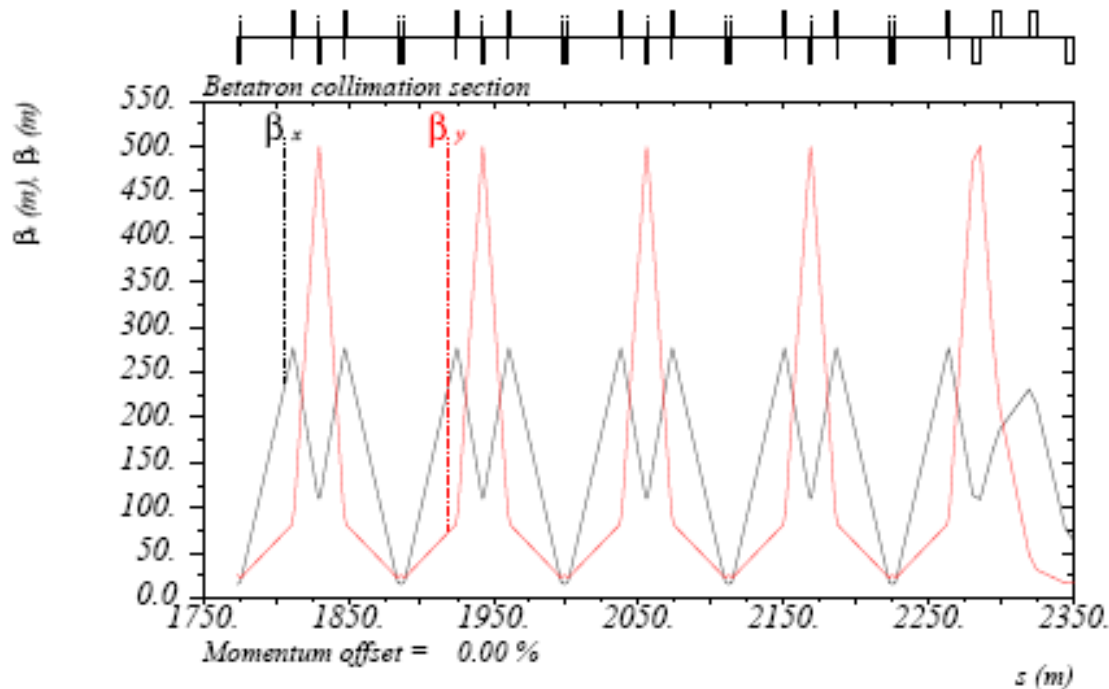
$R(s_{sp} \dashrightarrow s_{ab})$

Relative CLIC luminosity versus initial beam offsets for the cases with and without collimator wakefield effects. (Placet simulation)

spoiler/absorber pairs   2x   2x, 2y

Diagnostics   Energy   Betatron   Final Focus
                collimation collimation   System
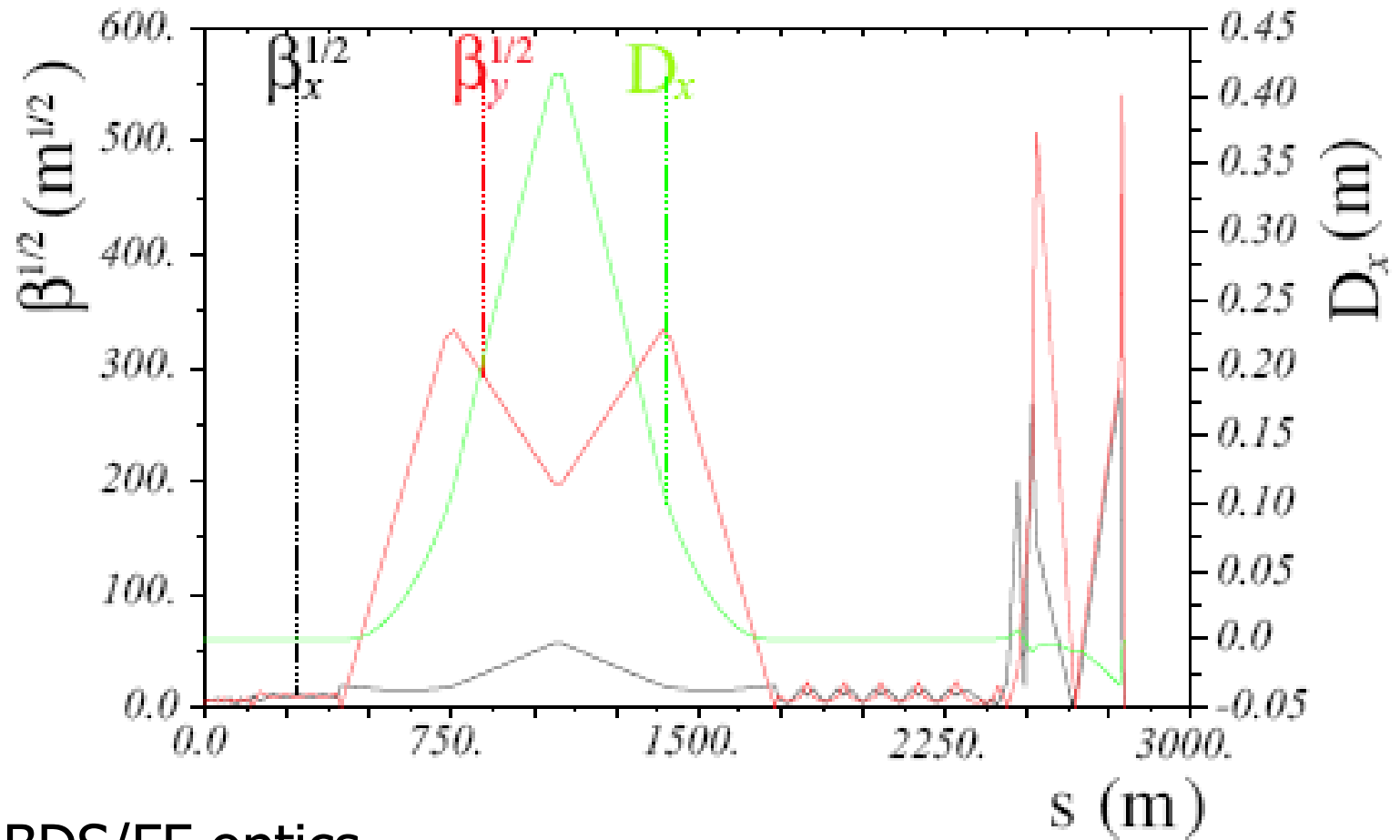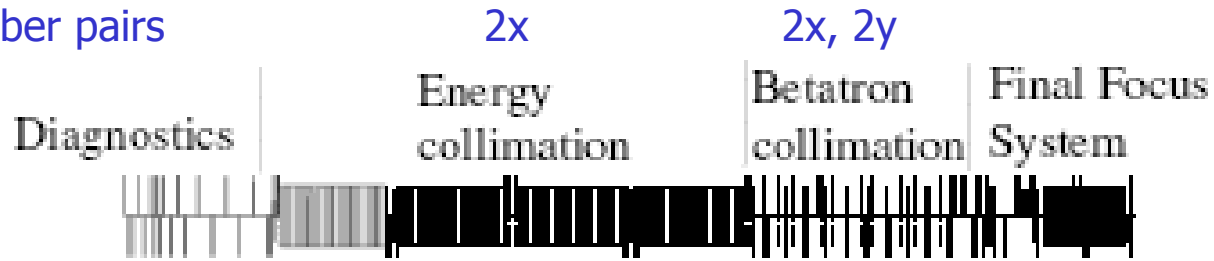
CLIC BDS/FF optics

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 IP

Spoilers		
Parameter	XSP#	YSP#
Geometry	Rectangular	Rectangular
Vert. half-gap a_x [mm]	0.12	8.0
Hor. half-gap a_y [mm]	8.0	0.1
Tapered part radius b [mm]	8.0	8.0
Tapered part length L_T [mm]	90.0	90.0
Taper angle θ_T [mrad]	88.0	88.0
Flat part length L_F [radiation length]	0.2	0.2
Material (other options?)	Be (Ti–Cu coating?)	Be (Ti–Cu coating?)
Absorbers		
Parameter	XAB#	YAB#
Geometry	Circular	Circular
Vert. half-gap a_x [mm]	1.0	1.0
Hor. half-gap a_y [mm]	1.0	1.0
Tapered part radius b [mm]	8.0	8.0
Tapered part length L_T [mm]	27.0	27.0
Taper angle θ_T [mrad]	250.0	250.0
Flat part length L_F [radiation length]	18.0	18.0
Material	Ti alloy–Cu coating	Ti alloy–Cu coating

2. Dielectric materials and technology

Dielectrics in the accelerator environment:

- ❑ Considerable knowledge base from dielectric wakefield acceleration experiments
- ❑ Charging and breakdown not problematic with proper choice of materials
- ❑ Multipactor is important primarily for rf driven dielectric structures— options like machining of surface grooves are under development
- ❑ Beam interaction with dielectric via Cherenkov radiation

Cherenkov radiation in a dielectric structure
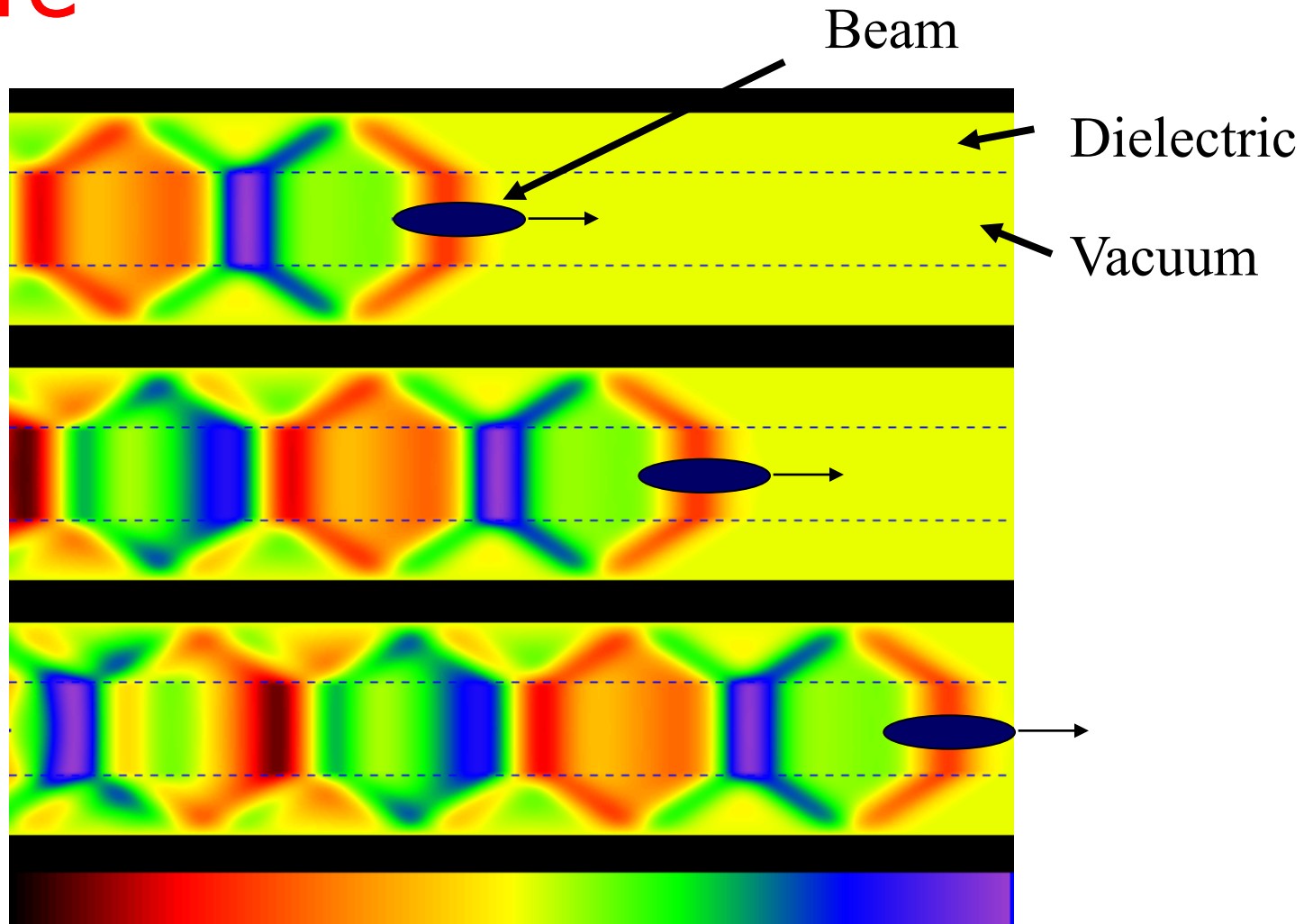
- Graphite, alumina, and aluminum nitride AlN have some attractive properties.
- Graphite is slightly better than Be at scattering and absorbing electrons (radiation length ~19 cm compared to 35 cm for Be) and so allows a reduction in absorber length by ~2/3.
- The relative permittivity of graphite is about 10-15, and its conductivity ranges from $(1-8) \times 10^5$ mho/m.
- Alumina ($\varepsilon = 10$) and AlN ($\varepsilon = 9$) can survive high radiation environments and are inexpensive. Unlike graphite, the conductivity of these ceramics is small, undesirable from the standpoint of damping wakefields (but desired levels of conductivity can be introduced in a composite structure.)

Advantages of dielectrics for collimation

The flexibility afforded by the extra parameters available from a dielectric medium (permittivity, conductivity) to the collimator design allows such interesting possibilities as:

- passive damping of the wakes via bulk conductivity of the collimator;

- adjustment of the frequency of the collimator wake to detune the wakefield so that the maxima of deflecting fields occur away from the beam micropulses;

- use of metamaterial or photonic band gap inspired geometries to suppress particularly harmful frequencies in the wakefield;

- active tuning of the collimator wake through the use of a nonlinear material;

- use of asymmetric conductivity to suppress particular modes of the wakefield.

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3. Numerical modeling of dielectric collimators

- 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.

- We have been using a number of different software tools for treating various aspects of dielectric and conventional collimator simulations.

  - BBU-3000: cylindrical and planar geometry particle-Green's function code.

  - Arrakis/Slab: 2D hybrid pseudospectral code to compute wakefields in rectangular geometry dielectric collimators. In this approach the x-z geometry is addressed using a 2D FDTD analysis with a Fourier decomposition in the y-direction.

  - CST® Microwave studio. 3D FIT, detailed geometry, most realistic simulation but large resource requirements.

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BBU-3000

Euclid Techlabs' in-house particle-Green's function beam dynamics code:

• Simulation of beam breakup effects in linear accelerators, emphasis on DLAs.

• 2D/3D, cylindrical or planar geometries

• Complementary to PIC approach

• Heuristic group velocity effects for multibunch calculations

• Beam Dynamics Simulation Platform; access software via web browser, parallelism (cluster/multicore)
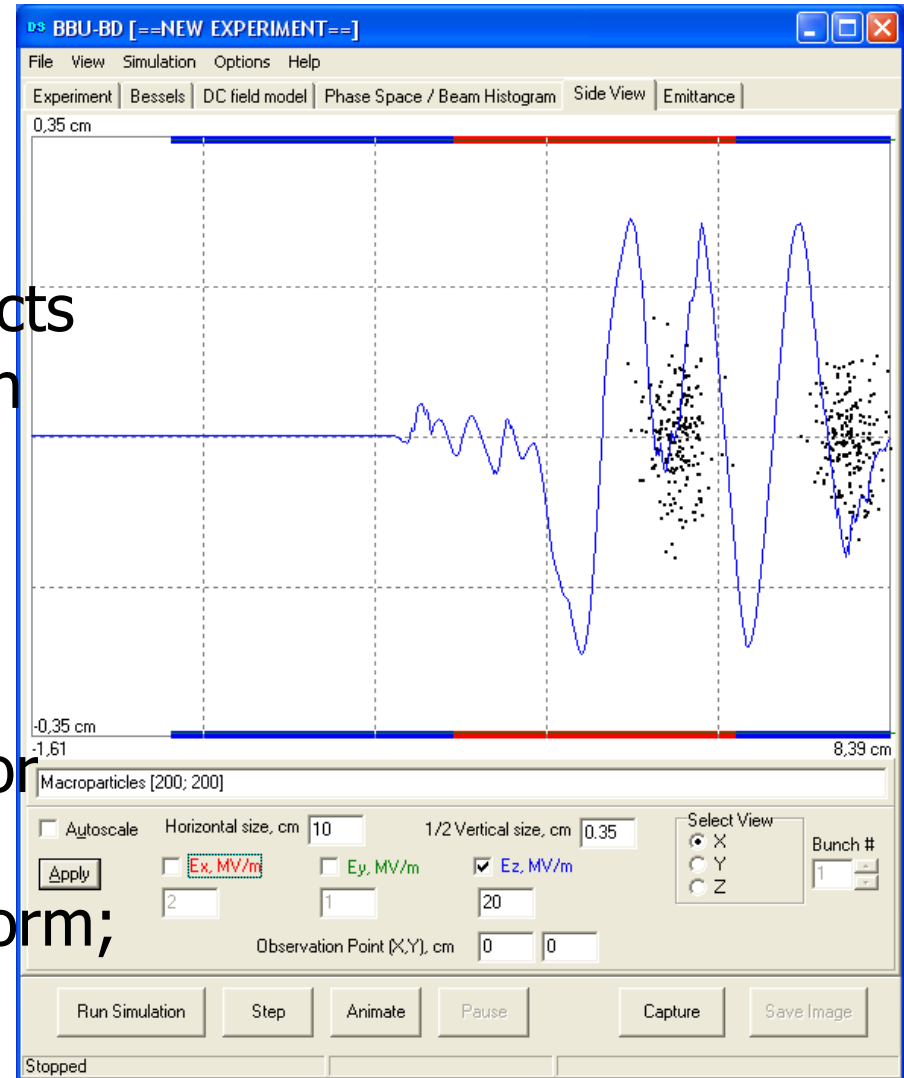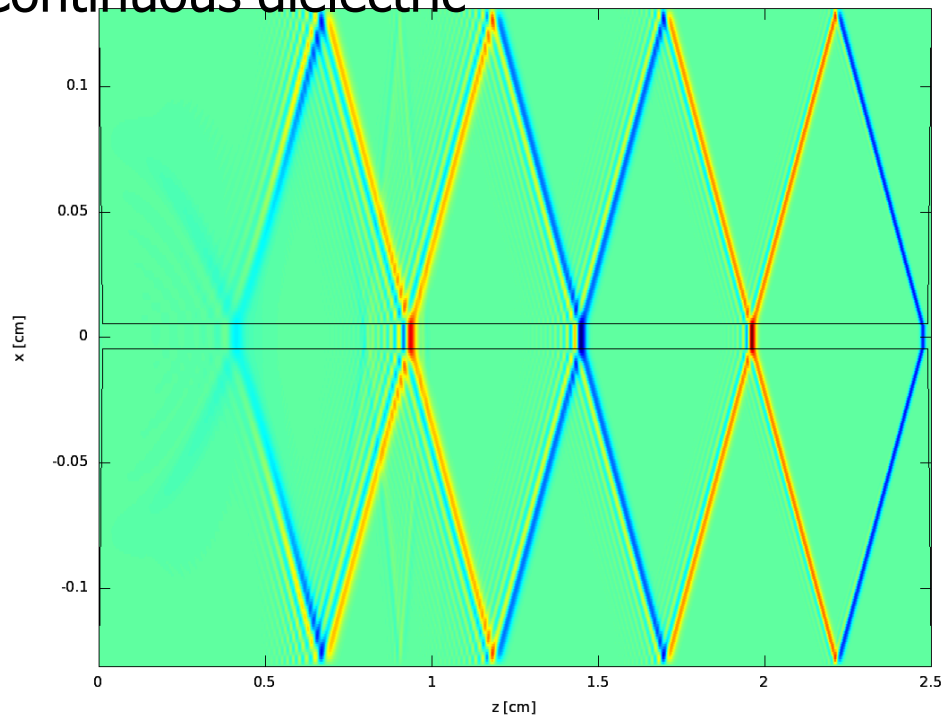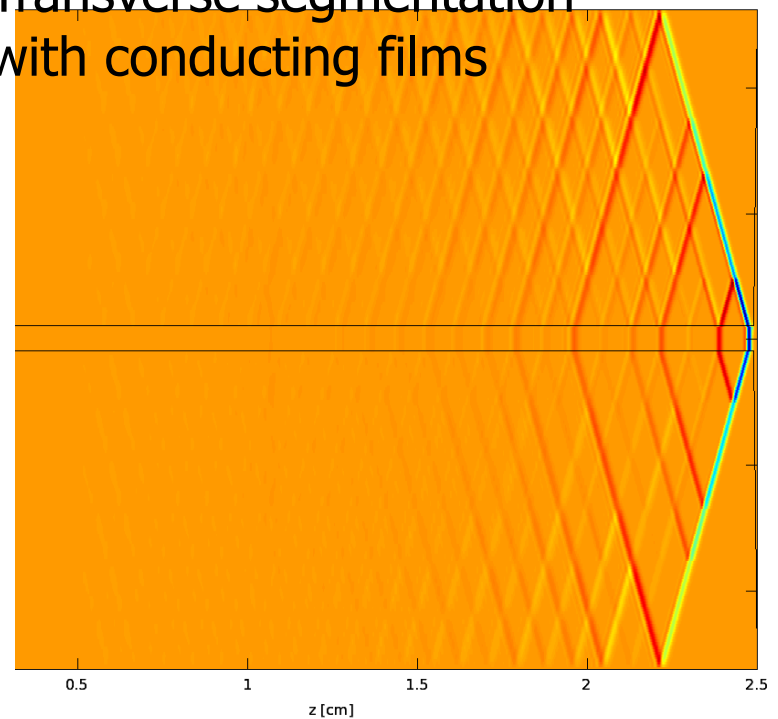
BBU-3000 Collimator simulation

Copper coated cylindrical dielectric collimator (ε = 5, 16 mm diameter) with vacuum channel diameter of 0.2 mm, and the nominal CLIC beam parameters. Perfectly insulating dielectric.

spectrum
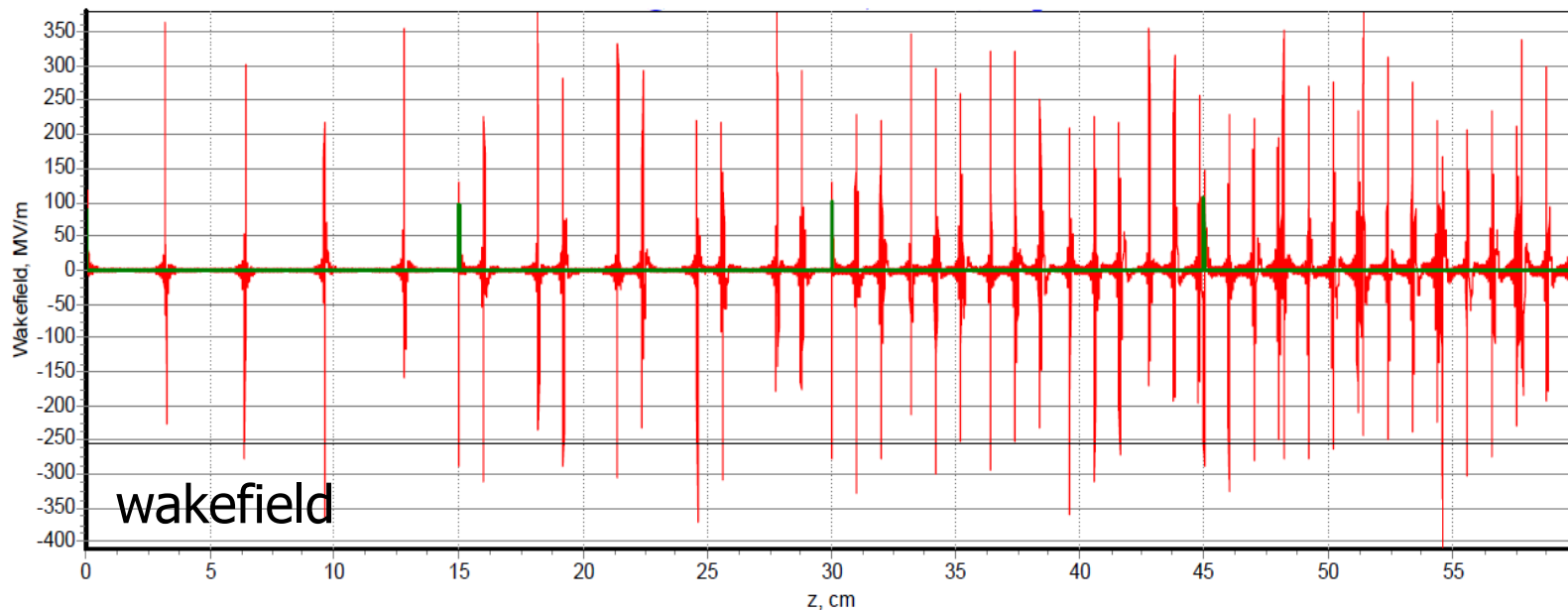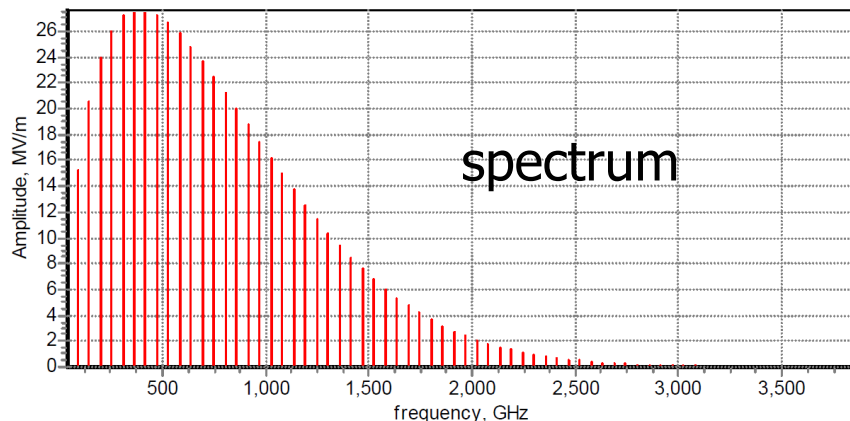
wakefield

Continuous dielectric

Transverse segmentation
with conducting films

Numerical (Arrakis/SLAB) demonstration of the suppression of wake fields in a dielectric collimator. Here we compare the longitudinal wakefields from a section of a planar collimator for a continuous dielectric (l) and a transversely segmented dielectric (r). The transverse segments are separated by thin layers of lossy material, and the depth of the layers is chosen to provide a half wavelength phase difference between pairs of segments, approximately cancelling the fields on axis. The permittivity in both cases is 5.
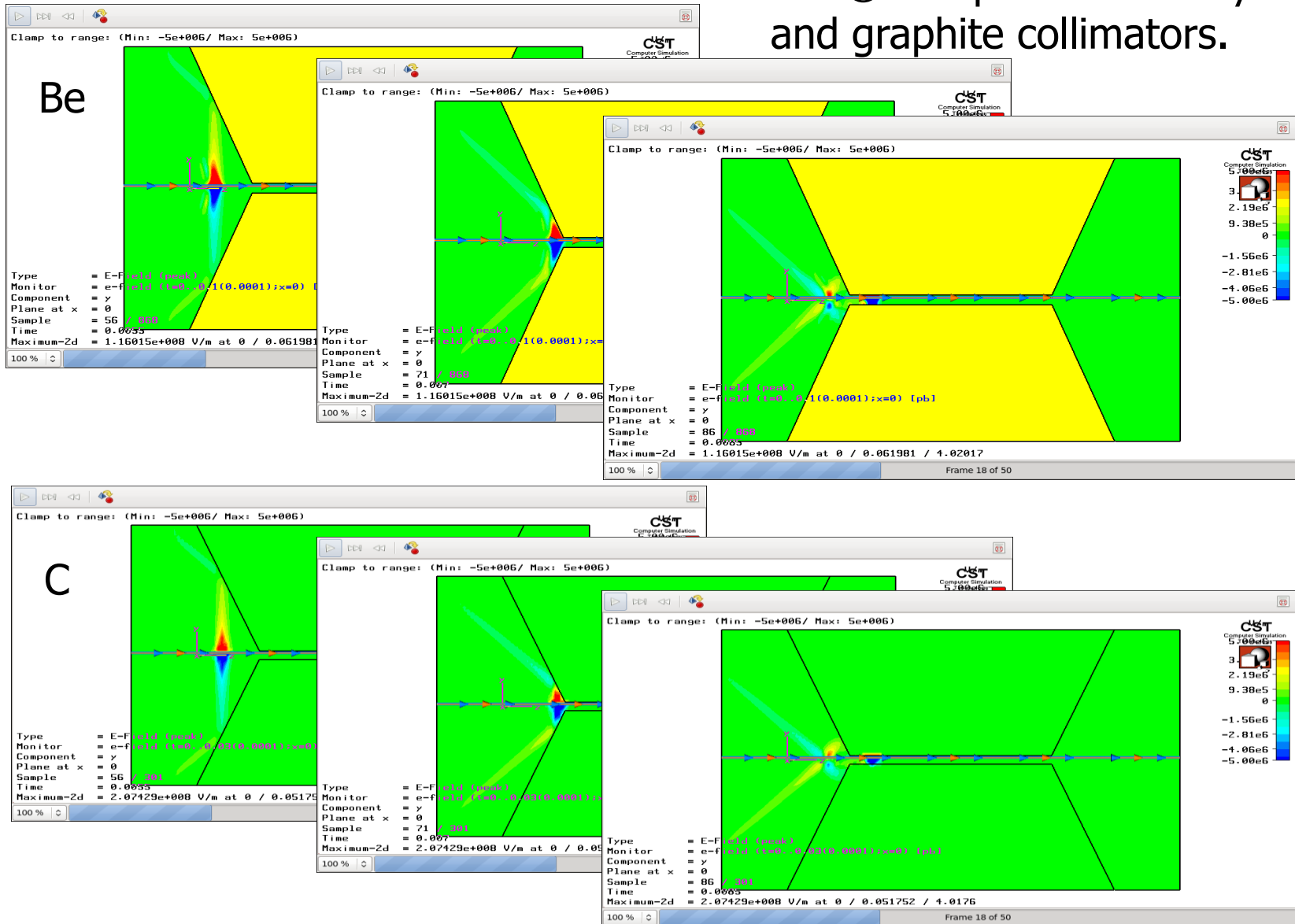
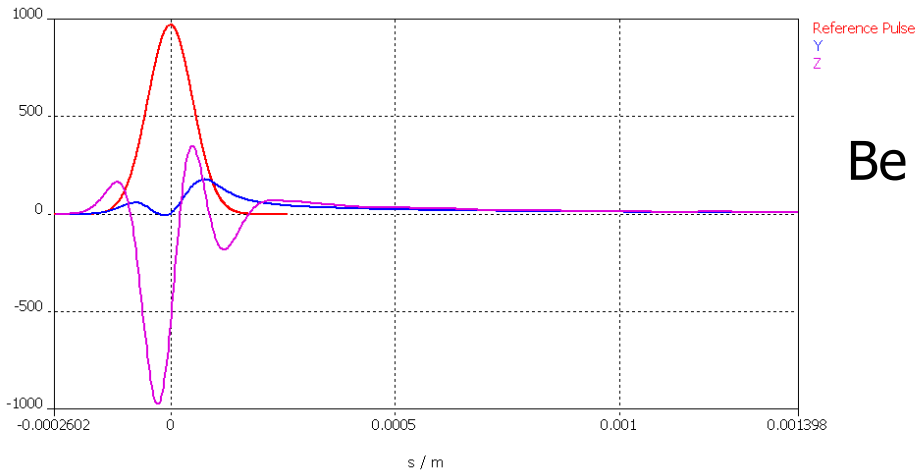# Electric fields in midplane, continuous vs segmented
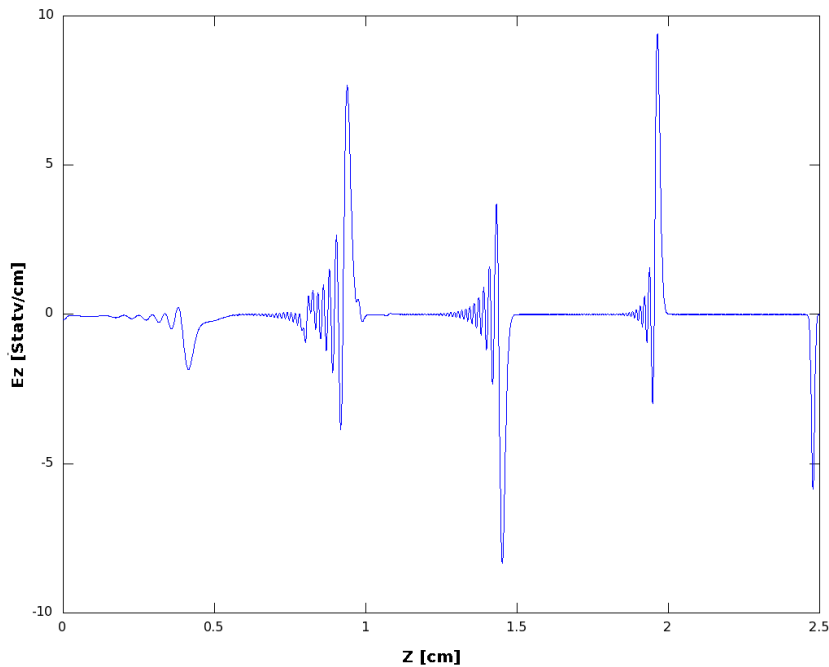
Lineouts of the axial electric field in the midplane for unsegmented (above) and transversely segmented (left). The maximum electric field on axis outside the bunch is about a factor of five larger for the unsegmented case.
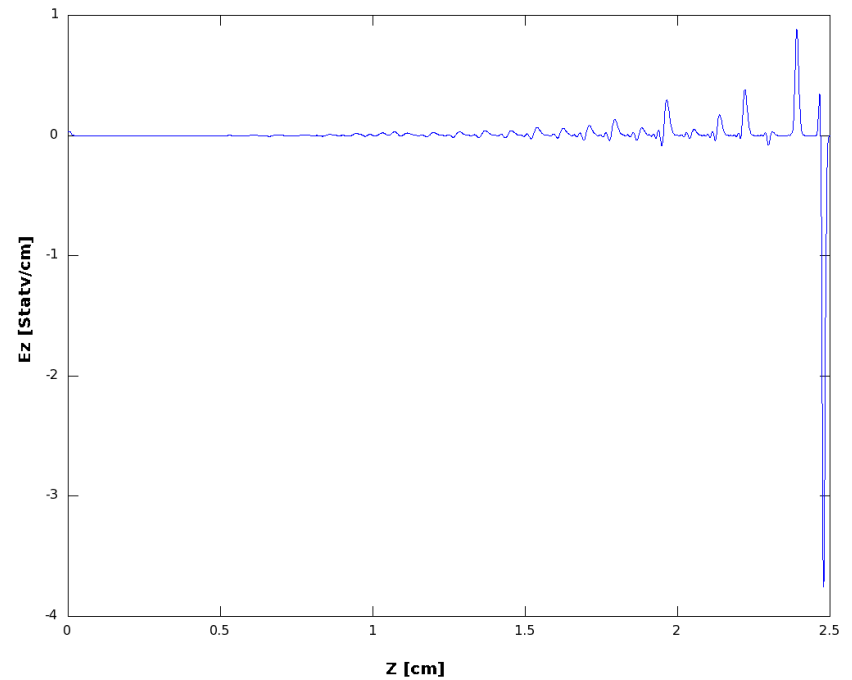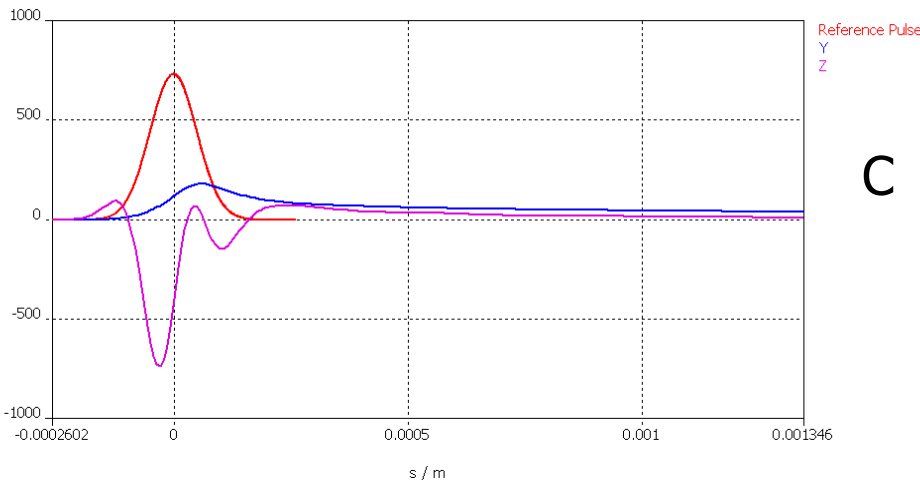
CST® comparison of beryllium and graphite collimators.

Be

C

The reflected wakefield is considerably lower from the graphite collimator.

The longitudinal wake is smaller in the graphite structure, while the transverse wakes are comparable in amplitude.

4. Dielectric collimator experiments at SLAC/FACET

- FACET—Facility for Advanced aCcelerator Experimental Tests at SLAC. New beamline for wakefield acceleration (and other) studies

- Experiments require a relatively simple apparatus; diagnostics are part of the FACET facility

- "Octopus" (T-481)-like vacuum chamber

- Transverse positioning of wakefield device
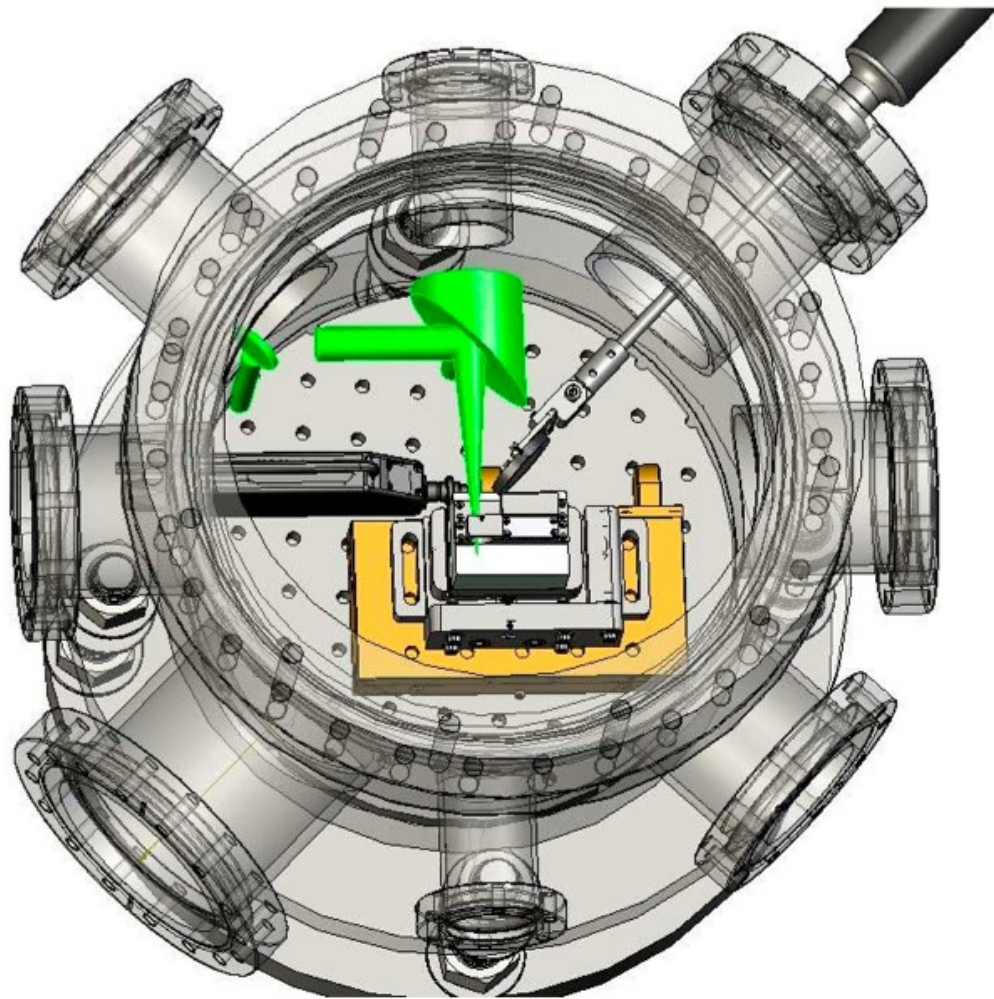
- Aperture adjustment for planar devices

Collimator geometries

Region 1 : Vacuum (r < a)
Region 2 : Dielectric (a < r < b)
Region 3 : yet to define (r > b)

200um

2mm
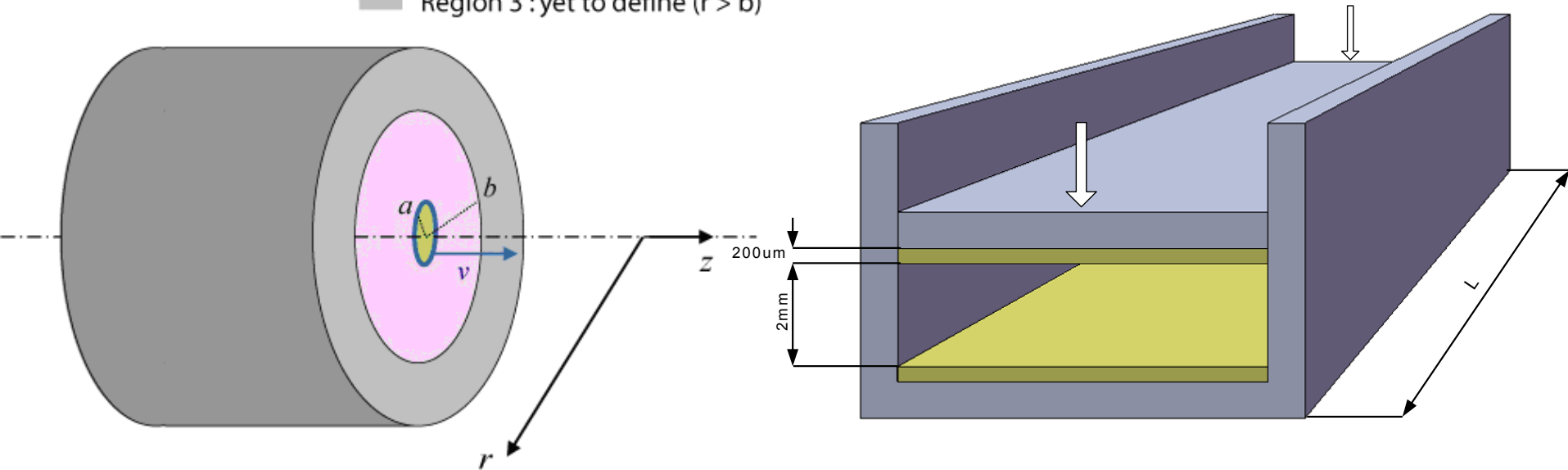
Cylindrical. Outer layer may be dielectric or copper.

Planar. Aperture is remotely adjustable.

"Octopus" vacuum chamber showing the position of the T-481 sample holder and micropositioner.

beam entrance port

Witness beam impedance measurements

- 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.
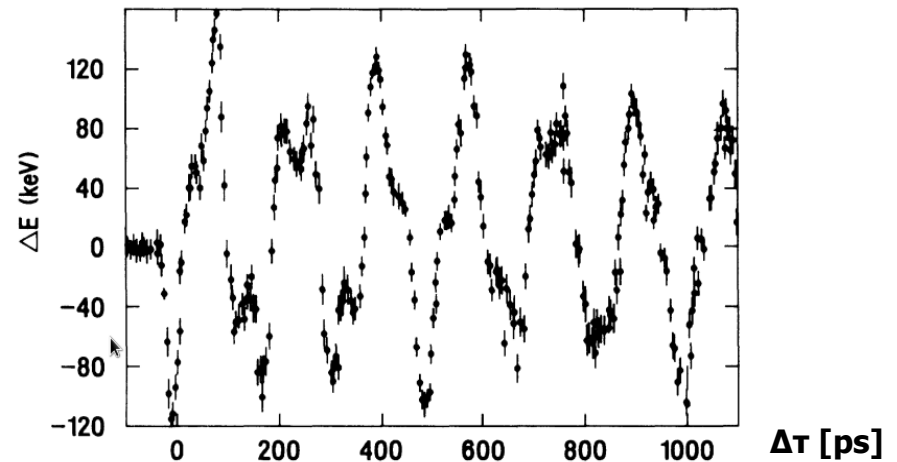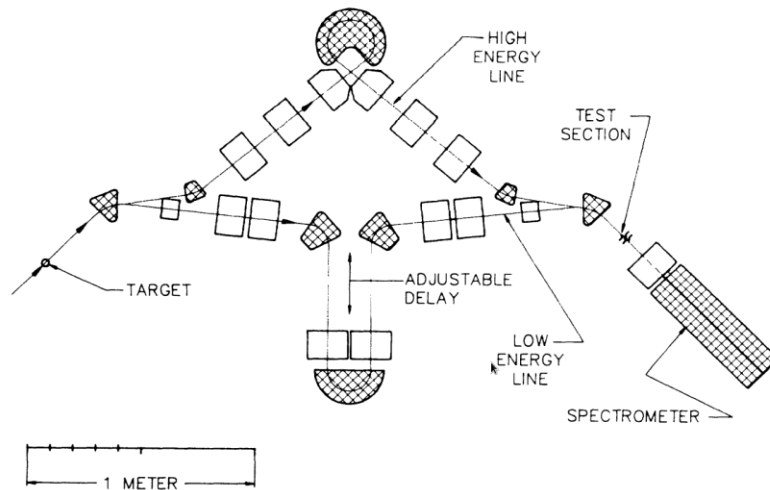
- At FACET, can sample the wake over 200 μm (Δf~0.75 THz). A delay sampling increment of 0.2 μm will provide a maximum frequency ~325 THz for the cylindrical collimator, adequate for comparison and validation of the simulation codes.
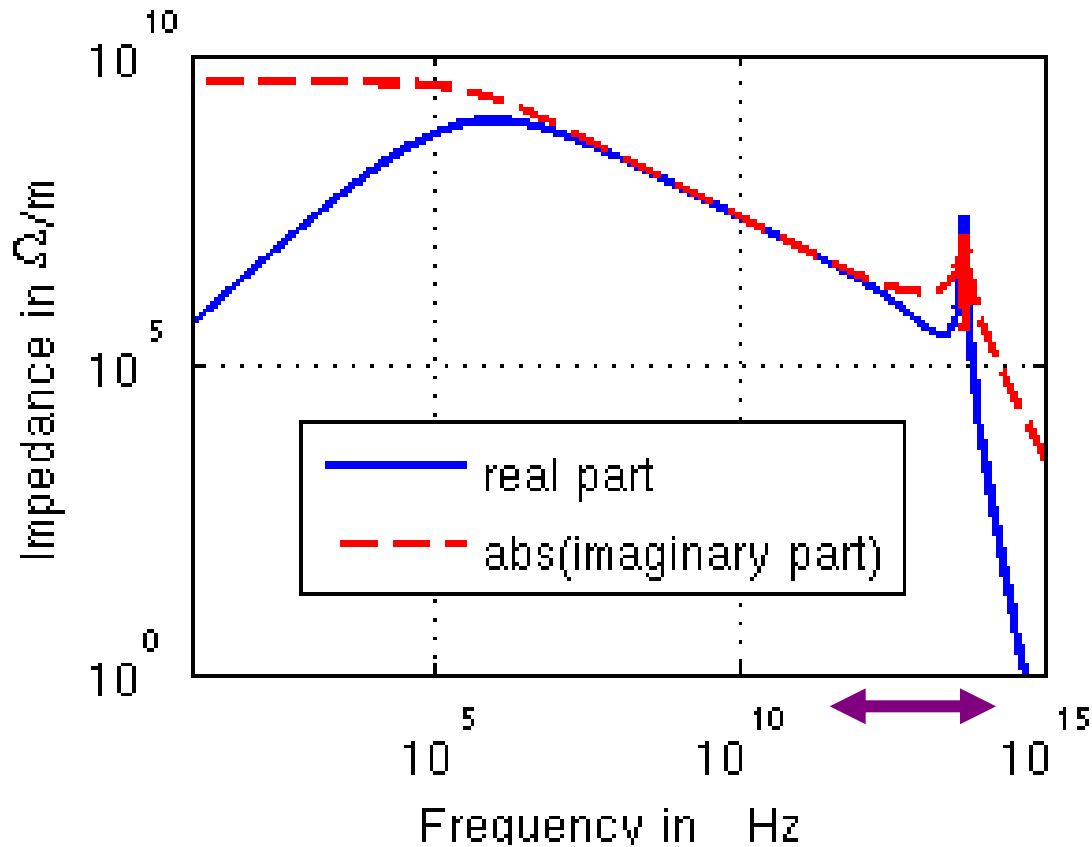
Computed impedance for cylindrical collimator, showing range accessible for FACET measurements.

Proposed FACET collimator experiments

Measurement category	Dielectric	Configuration	Comments
Electrically conductive collimator	graphite	Plain slabs, thickness > 30 µm	Bulk resistivity. Slab minimum thickness needs to be only a few skin depths at these frequencies.
	alumina or AlN	Stacks of thin slabs (0.1 mm) separated by metallized interfaces	Composite dielectric-metal structures. Test of multilayer concept.
Nonconducting dielectric	alumina or AlN	Plain slabs, ~2 mm	Scan over beam offsets from center of structure and varying gap sizes.
Boundary condition modifications	alumina or AlN	Segmented boundary	interrupt currents on outer surface of collimator.
geometric wakes	alumina or AlN	Dielectric slabs with edge tapers.	Scan over beam offsets from center of structure and varying gap sizes.

SUMMARY

- 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 proposed an extensive series of dielectric collimator measurements for the new SLAC FACET facility.