Proposal for Single-Bunch Collimator Wakefield Measurements at SLAC ESTB

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on behalf of the ILC/CLIC collimator wakefield study collaboration

LCWS2012 Workshop
Arlington, USA
October 25 , 2012

Contents

Motivation

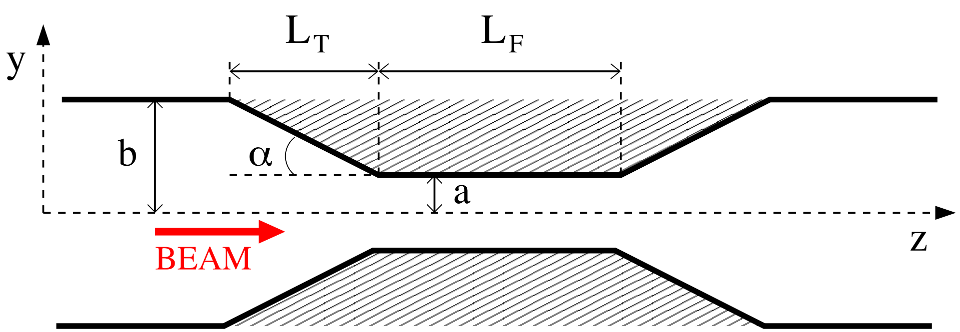
- Collimator wakefields are expected to be an important source of emittance growth and beam jitter amplification in the BDS of future linear colliders (ILC and CLIC)
- It is important to understand and evaluate the collimator wakefield effects for a better estimate of the machine performance.
- Benchmarking between theory, simulations and measurements of collimator wakefield kicks necessary.
- Previous experiments at SLAC ESA (T-480) showed notable discrepancies with theoretical model and simulations. Further investigation needed.
- New set of measurements would be helpful for a better understanding of the collimator wakefield effects (dependence on bunch length, limit of applicability of analytical estimates in the different regimes, etc.)
- ESTB will provide the necessary test beam and an excellent experimental environment for collimator wakefield studies.

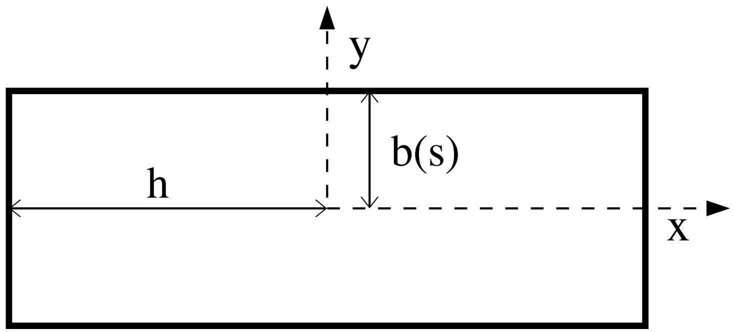
Introduction

Brief theoretical background

- **Geometric wake kick factor for rectangular collimators**

Following Stupakov's prescriptions, assuming "near-centre" approximation:





Dipole mode

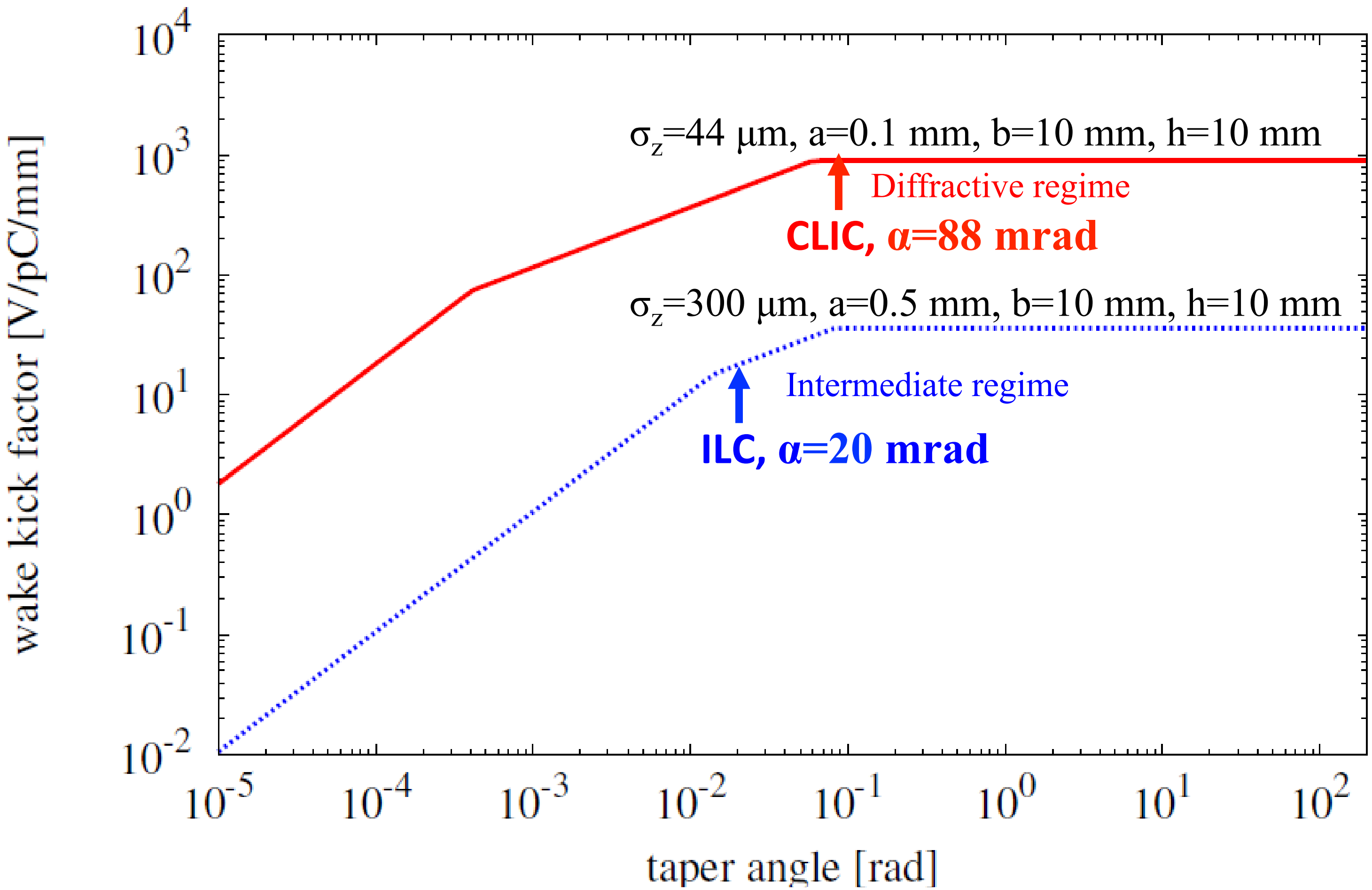
$$\kappa_g \simeq \frac{Z_0 c}{4\pi}\begin{cases} \sqrt{\pi}\alpha h/(4\sigma_z)\left(1/a^2 - 1/b^2\right) & \text{for } \sqrt{\alpha a/\sigma_z} < 6.2a/h\ ; \quad \text{inductive} \\ 8/3\sqrt{\alpha/(\sigma_z a^3)} & \text{for } 0.37 > \sqrt{\alpha a/\sigma_z} > 6.2a/h\ ; \quad \text{intermediate} \\ 1/a^2 & \text{for } \sqrt{\alpha a/\sigma_z} > 0.37\ ; \quad \text{diffractive} \end{cases}$$

[G. V. Stupakov, "High-frequency impedance of small-angle collimators", PAC01]

Introduction

Brief theoretical background

- **Geometric wake kick factor for ILC and CLIC betatron spoilers**



Introduction

Brief theoretical background

- **Resistive-wall wakefield for rectangular tapered collimators:**

Long range regime $0.63(2a^2/(Z_0\sigma))^{1/3} \ll \sigma_z \ll 2a^2 Z_0 \sigma$

$$\kappa_r \simeq \frac{Z_0 c}{4\pi}\frac{\pi}{8a^2}\Gamma(1/4)\sqrt{\frac{2}{\sigma_z \sigma Z_0}}\left[\frac{L_F}{a}+\frac{1}{\alpha}\right]$$

where Z_0=376.7 Ω is the impedance of free space, σ the electrical conductivity, L_F the length of the flat part, and $\Gamma(1/4)=3.6256$

[A. Piwinski, DESY-HERA-92-04, 1992]

Short range regime $\sigma_z < 0.63(2a^2/(Z_0\sigma))^{1/3}$

Expression far more complicated!! See for example:

[K. L. F. Bane and M. Sands, SLAC-PUB-95-7074, 1995]

Introduction

Brief theoretical background

- **Resistive-wall wakefield for rectangular tapered collimators:**

Typical parameters of vertical betatron spoilers of CLIC (YSP) and ILC (SP2)

Parameter	CLIC	ILC
Half gap a [mm]	0.1	0.5
Material	Ti-Cu coating	Ti
σ [Ω^{-1}m^{-1}]	6 x 10^7	1.8 x 10^6

For CLIC, σ_z=44 μm:

$$2a^2 Z_0 \sigma \simeq 452\ \mathrm{m}$$

$$0.63\left(2a^2/(Z_0\sigma)\right)^{1/3} \simeq 0.6\ \mu\mathrm{m}$$

For ILC, σ_z=300 μm:

$$2a^2 Z_0 \sigma \simeq 339\ \mathrm{m}$$

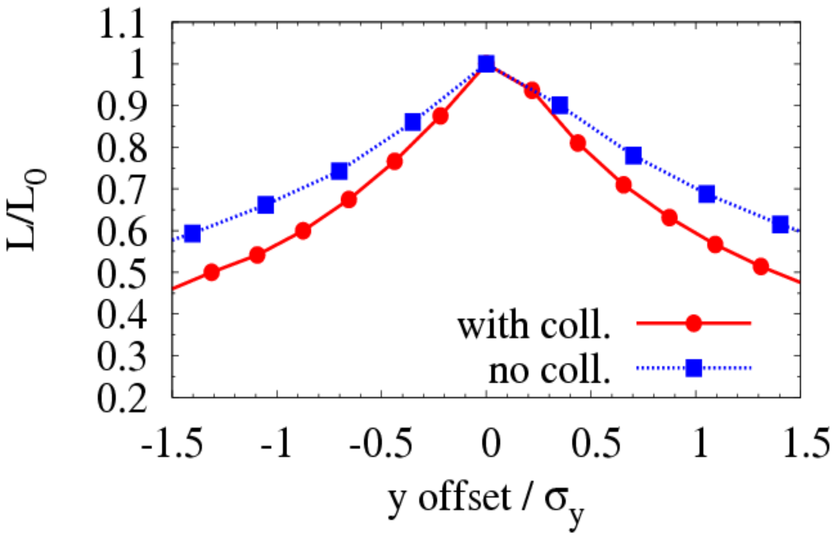
$$0.63\left(2a^2/(Z_0\sigma)\right)^{1/3} \simeq 5.7\ \mu\mathrm{m}$$

Both cases lay in the long range regime

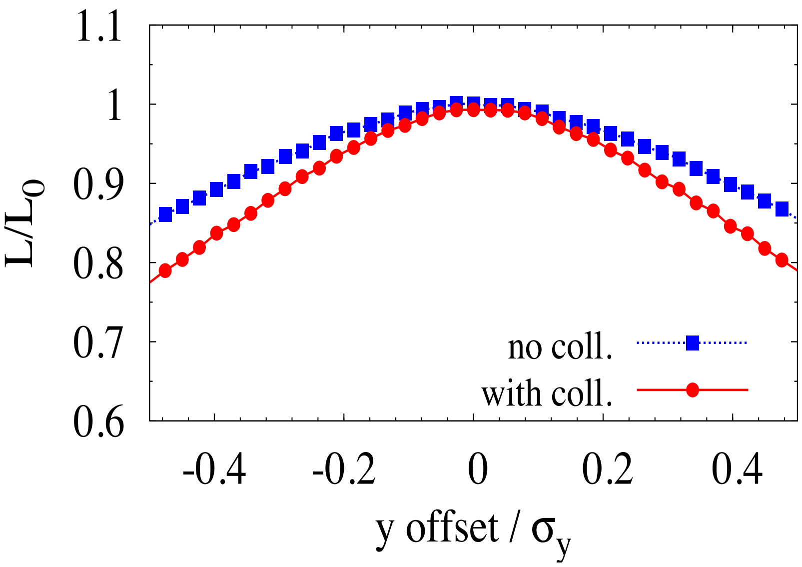
Introduction
Luminosity degradation

- Luminosity loss due to collimator wakefield effects (PLACET + GUINEAPIG based simulations):

ILC (nominal)

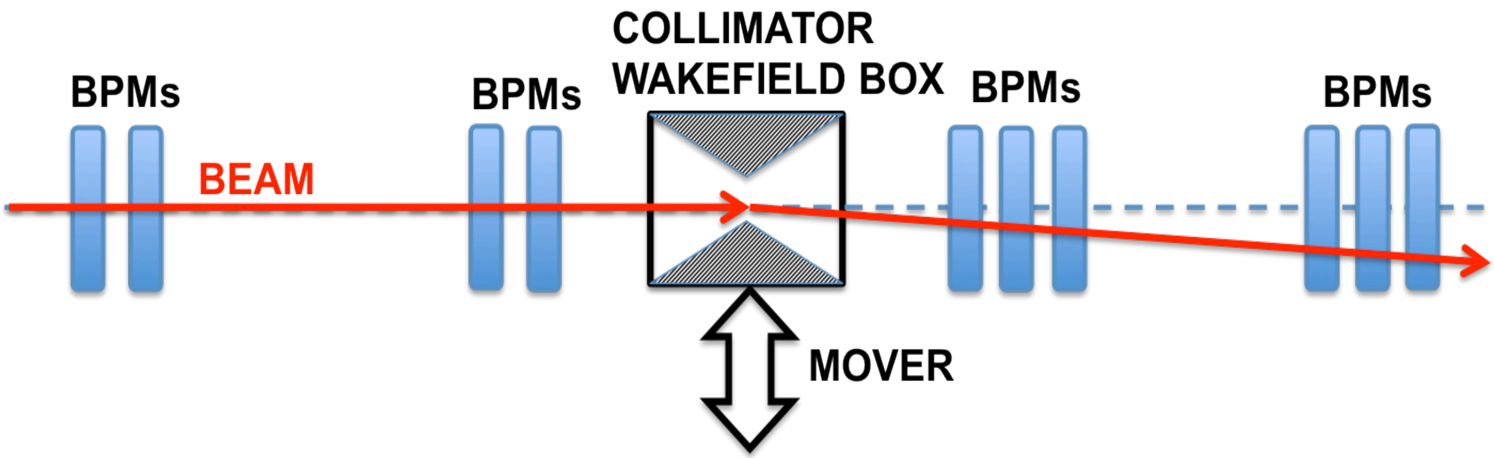


CLIC (nominal)



0.5 σ_y offset: ≈20% luminosity loss with collimators (≈15% w/o collimators)

Experimental concept

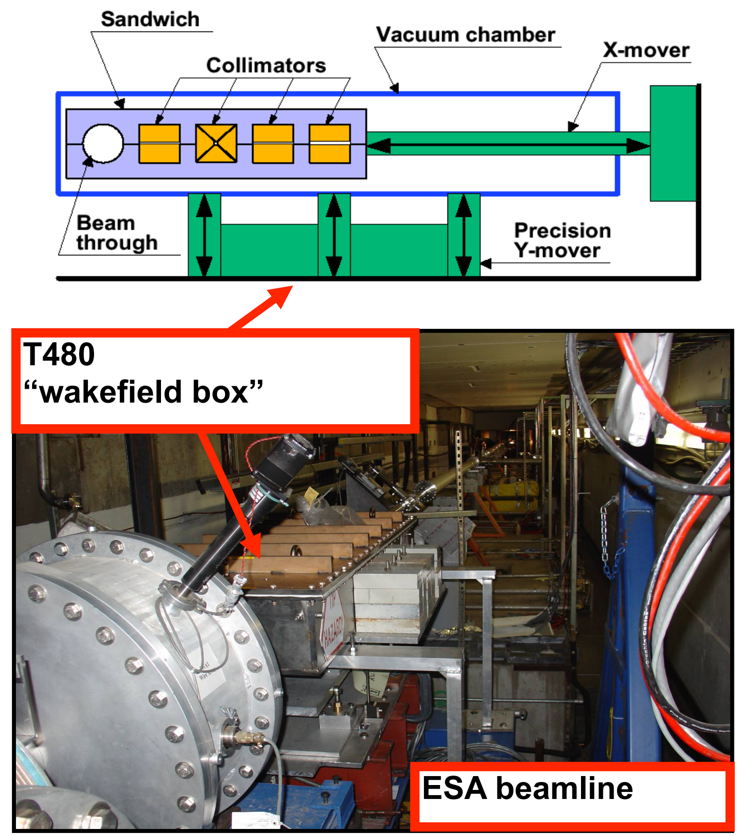


- Move collimators around beam
- Deflection angle is reconstructed using upstream and downstream BPMs
- Measure deflection from wakefields vs. beam-collimator separation

Experimental equipment

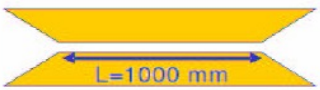
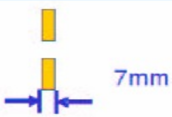
Inheritance of the T-480 experiment [P. Tenenbaum, N. Watson, et al.]

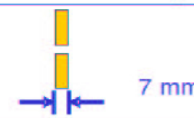
- Different apertures and lengths
- Tests: optimal materials and geometry to minimise wakefields

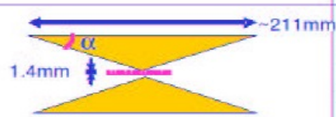
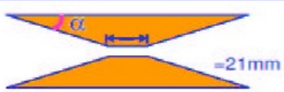
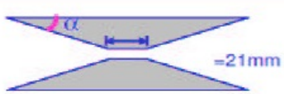
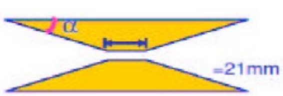


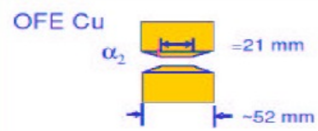
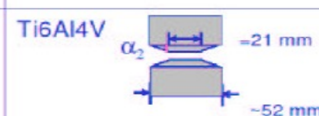
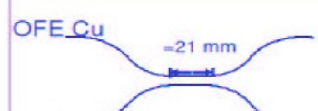
- “Wakefield box” allows swapping of collimators and adjusting jaw aperture
- Magnet mover, y range = ±1.4mm, precision = 1µm

Collimator sets

Collim. #	Side view	Beam view	Revised 4-May-2006
1		38mm h=38 mm	α=324mrad r=2.0mm
2			α=324mrad r=1.4mm
3			α=324mrad r=1.4mm
4			α=π/2rad r=4.0mm

Collim.#	Side view	Beam view	Revised 4-May-2006
8		38mm h=38 mm	r_1 =4.0mm r_2 =1.4mm α_1=289mrad α_2=166mrad
7			α_1=π/2 rad α_2=166mrad r_1=4.0mm r_2=1.4mm
6			α=166mrad r=1.4mm
5			α=π/2rad r=1.4mm

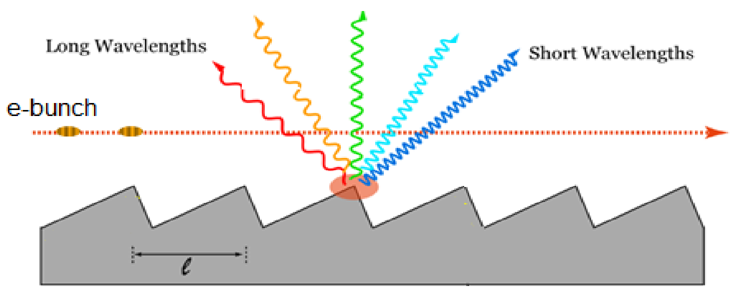
Collim.#	Side view	Beam view	Revised 27-Nov-2006
6		38mm h=38 mm	α=166mrad r=1.4mm (1/2 gap)
10			α=166mrad r =1.4mm
11			α=166mrad r =1.4mm
12			α=166mrad r=1.4mm

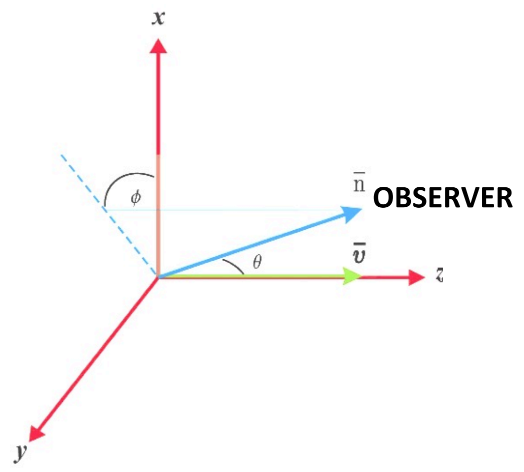
Collim.#	Side view	Beam view	Revised 27-Nov-2006
13		38mm h=38 mm	α_1=π/2 rad α_2=166mrad r_1=4.0mm r_2=1.4mm
14			α_1=π/2 rad α_2=166mrad r_1=4.0mm r_2=1.4mm
15			α_1=π/2 rad α_2=50mrad r_1=4.0mm r_2=1.4mm
16			non-linear taper r=1.4mm

Experimental equipment
Bunch length measurement

Smith Purcell Radiation (SPR) bunch profile monitor:

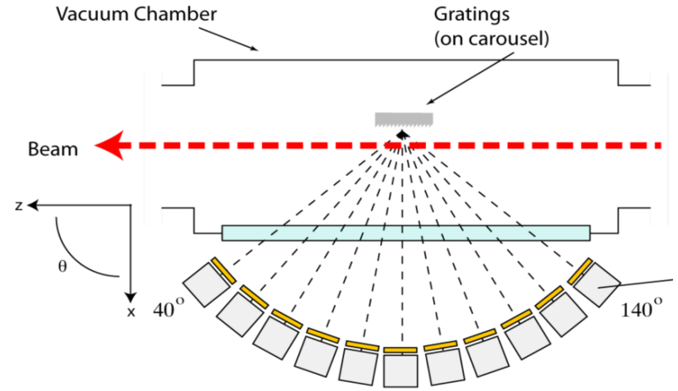
- Non-intercepting, single shot measurement of fs-ps pulses beam
- Beam passes over grating emitting coherent Smith-Purcell radiation
- Grating disperses radiation according to wavelength
- Detector array gives spectrum, which allows to reconstruct the time profile of the electron bunch





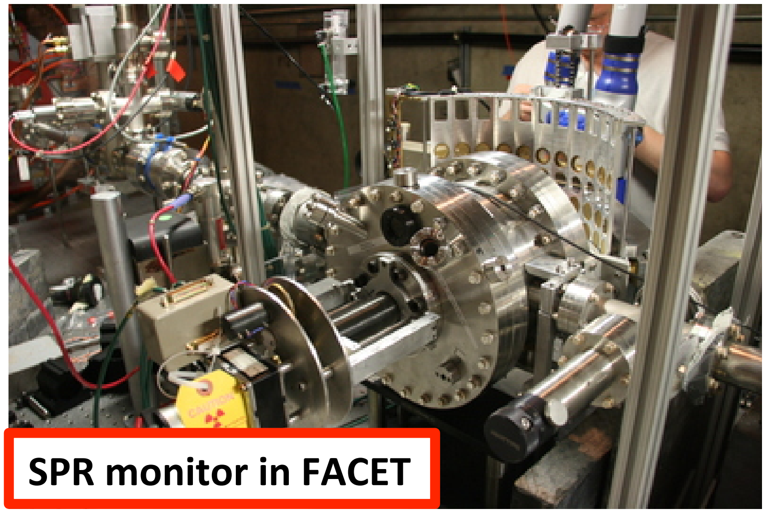
Experimental equipment
Bunch length measurement

Smith Purcell Radiation (SPR) bunch profile monitor:



Last year SPR monitor installed in FACET: aimed to measure in the < 50 micron scale (< 0.2 ps).

2011-2012 experimental campaigns very successful: temporal bunch profiles ~ 100 fs measured.
[R. Bartolini et al. JINST 7 (2012) P01009]



SPR monitor in FACET

(E-203 collaboration)

Experimental equipment
Bunch length measurement

Synergy between the E-203 collaboration and the collimator wakefield collaboration:

- Recently the IFIC-Valencia has joined the E-203 collaboration

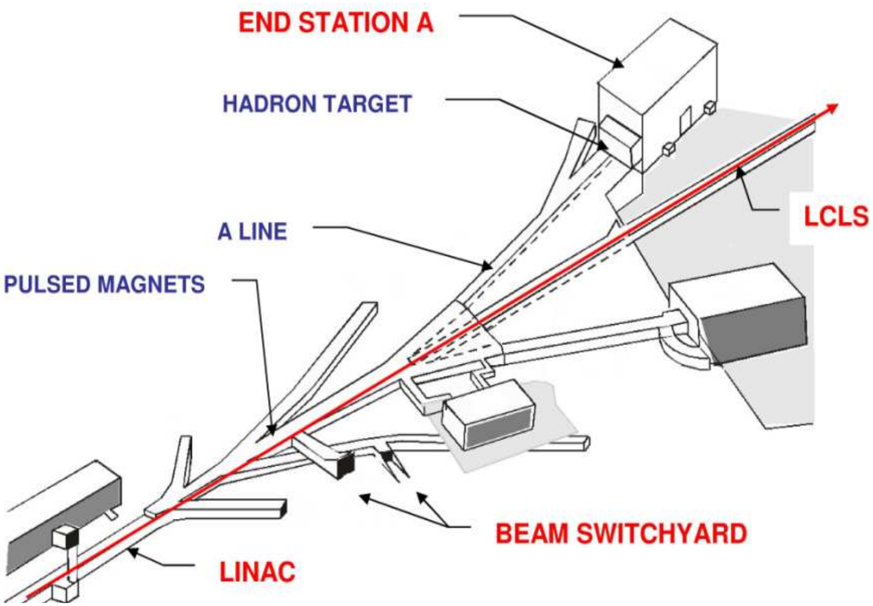
- Aim:
  - Build up a second SPR monitor to measure bunch length at ESTB supporting collimator wakefield studies
  - Build 2^{nd} generation device aimed at single shot capability

- Plan:
  - Fix design by January 2013 based on improved 1^{st} generation SPR device
  - Build up a second SPR monitor ready for use end 2013 at ESTB
  - Including all the accumulated learning from the FACET device that enables single shot capability
  - Get as close as possible to a single shot device in the design stage
  - Evolving in stages from averaging to single shot operation

What is ESTB ?

End Station A Test Beam (ESTB) is a beam line at SLAC using a fraction of the bunches of the 15 GeV electron beam from the Linac Coherent Light Source (LCLS), restoring test beam capabilities in the End Station A (ESA) experimental hall

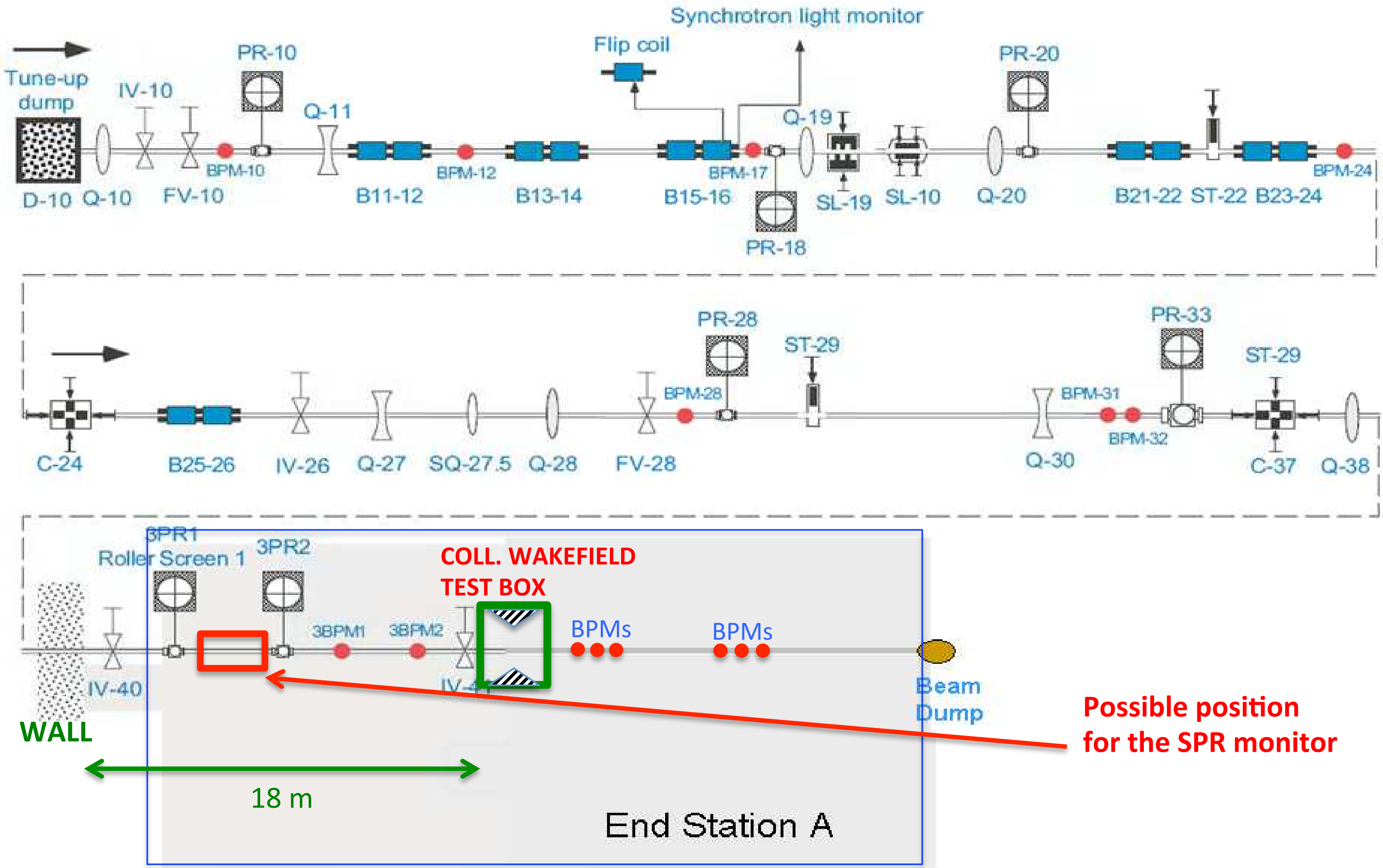
SLAC accelerator complex at the end of the 2-mile linear accelerator:



Parameter	ESTB	ILC BDS	CLIC BDS
Beam energy [GeV]	15	250	1500
Repetition rate [Hz]	1-5 nominal, burts up 120	5	50
Energy spread [%]	0.02	0.1	0.3
Bunch charge [nC]	0.35 (maximum)	3.2	0.6
Bunch length [μm]	100	300	44
Normalised emittance ($\gamma\varepsilon_x$, $\gamma\varepsilon_y$) [μm-rad]	(4, 1)	(10, 0.04)	(0.66, 0.02)

ESTB layout

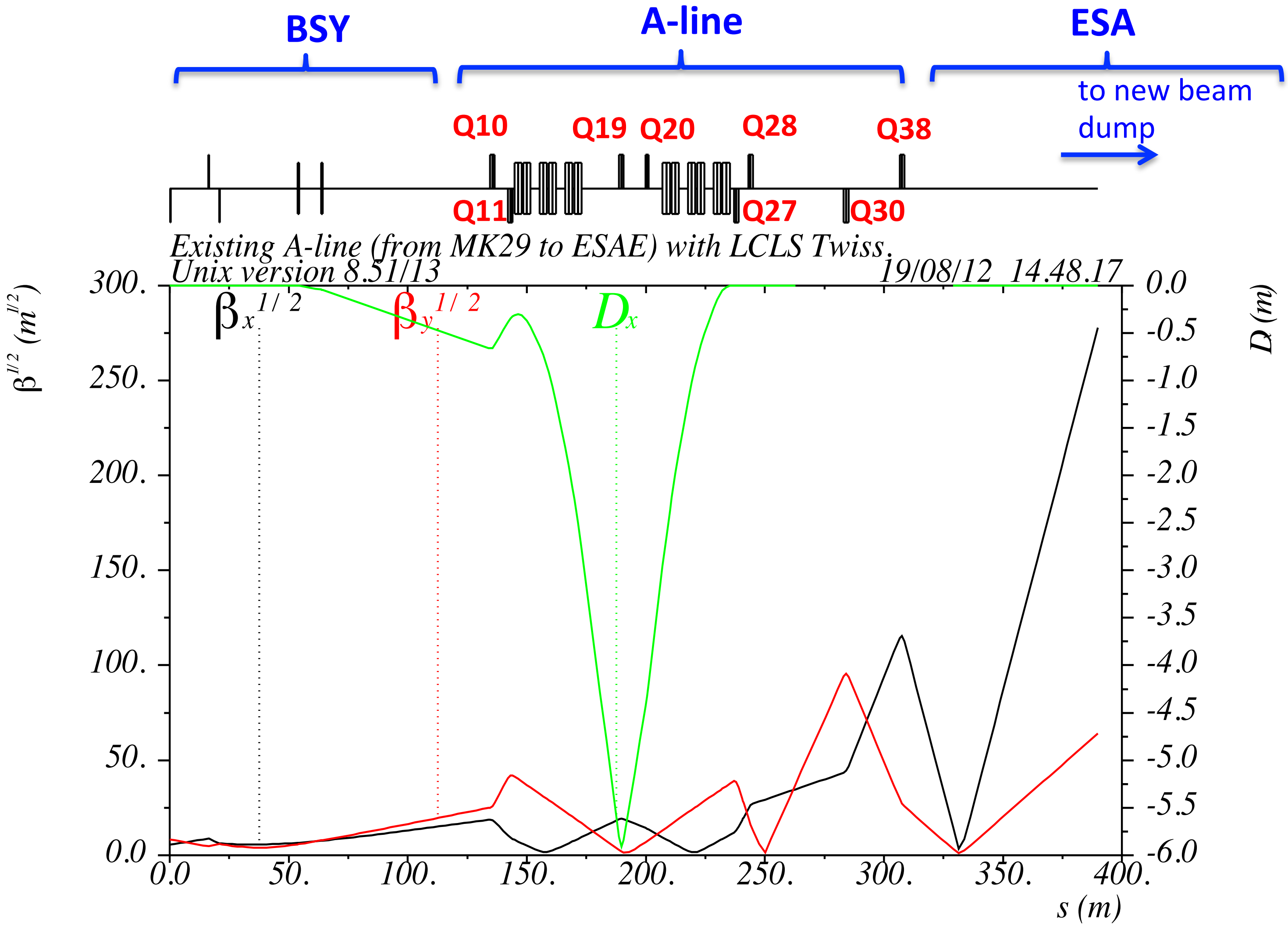
A-line



ESTB optics

From MK29:

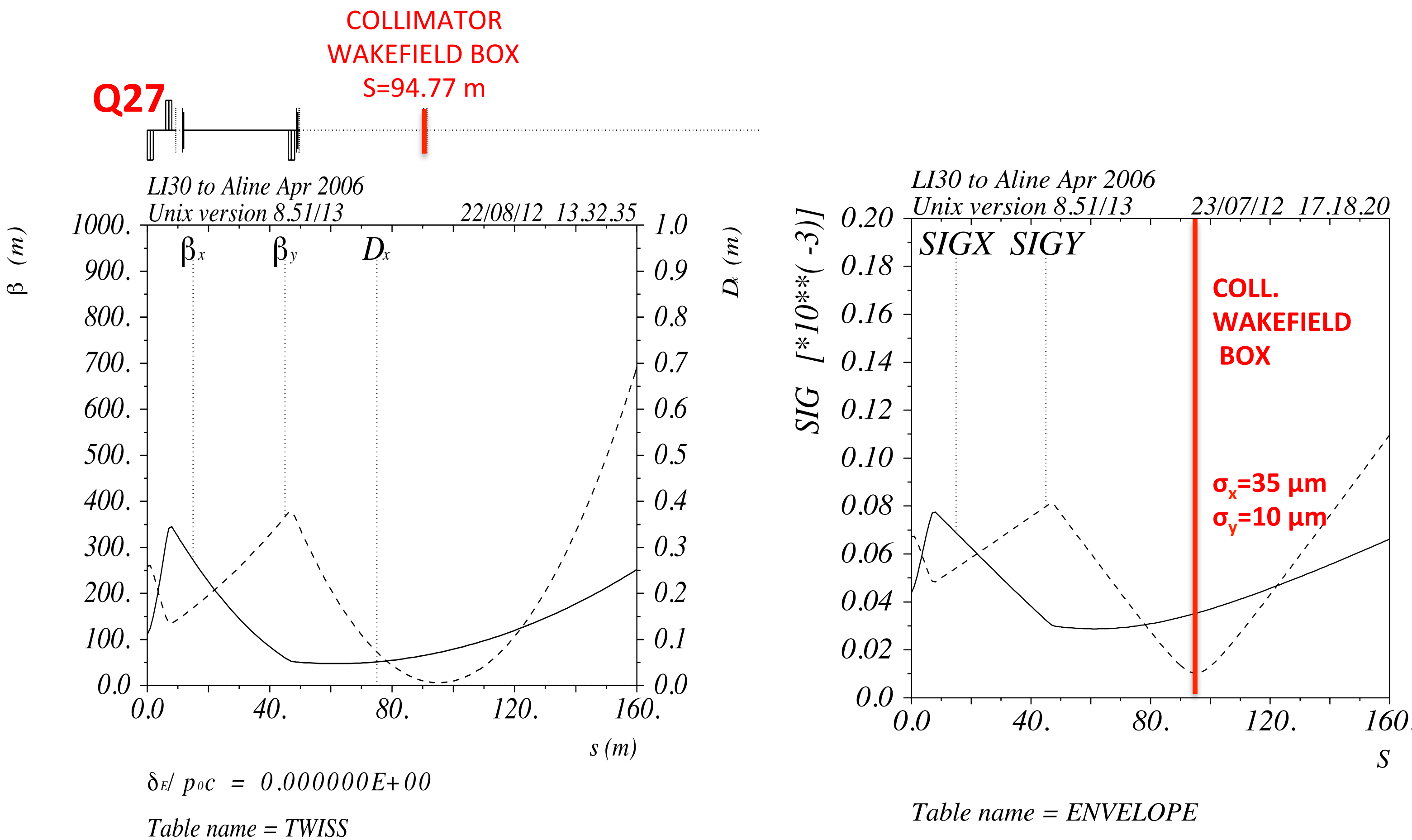
β_{x0}=32.03 m
α_{x0}=0.8
β_{y0}=67.5 m
α_{y0}=-1.5



ESTB optics for collimator wakefield experiment

From Q27:

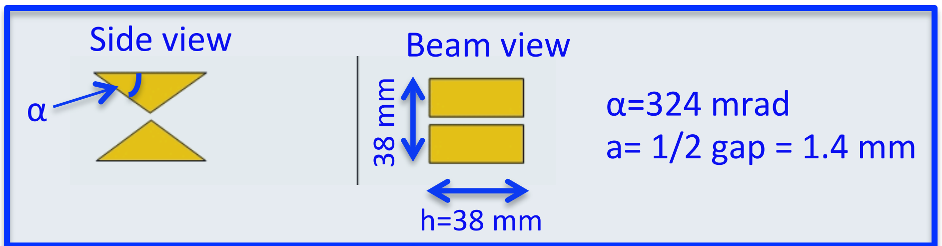
β_{x0}=110.2 m
α_{x0}=-4.9
β_{y0}=258.8 m
α_{y0}=-6.0



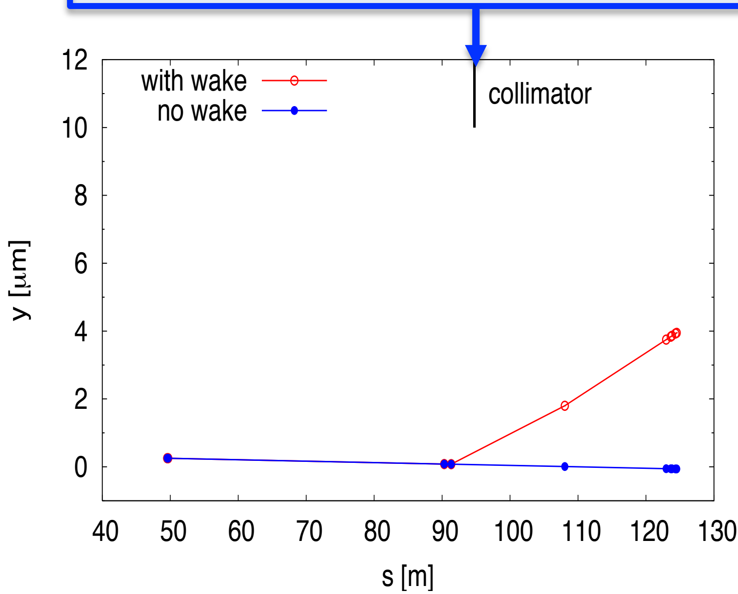
Quads. Q27, Q28, Q30 and Q38 matched to obtain a vertical beam waist of σ_y=10 µm at the collimator position

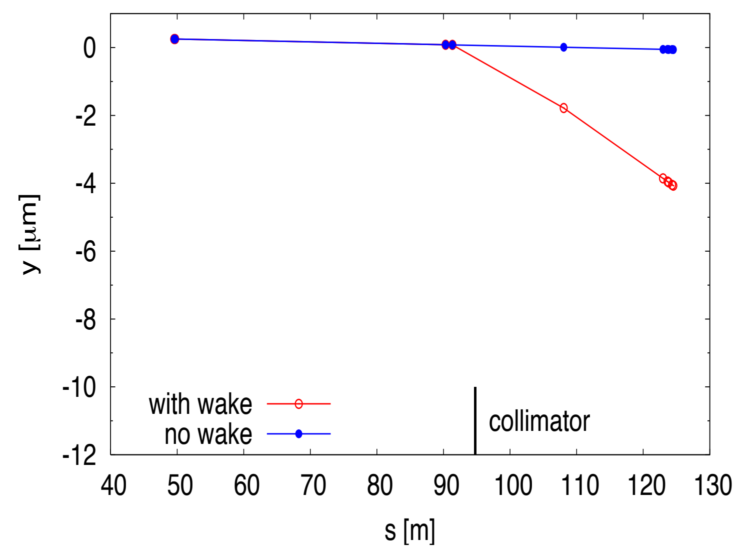
Beam tracking simulations

- Example of beam trajectories for collimator offsets -1390 µm and 1390 µm



Simulations using the code PLACET,
- Assuming σ_z= 100 µm
- Assuming only the linear regime (up to quadrupolar component of the wakefield)

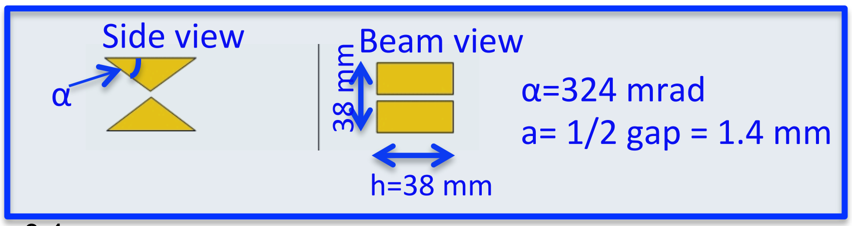


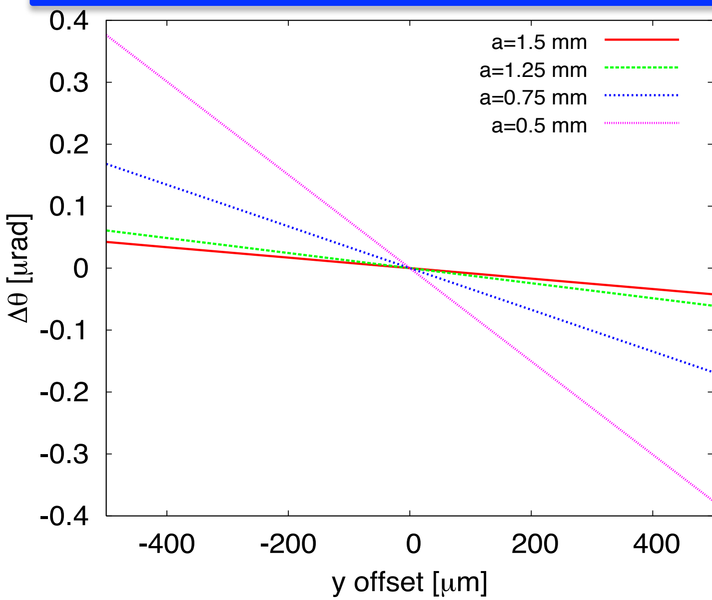


Trajectory reconstruction using 4 BPMs upstream of the collimator and 6 BPMs downstream of the collimator

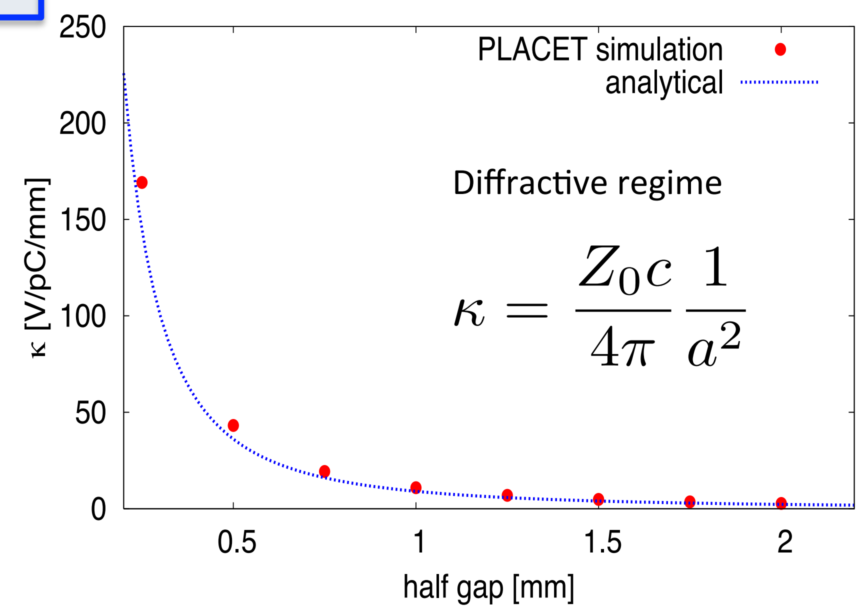
Beam tracking simulations

- Deflection angle of the bunch centroid due to collimator wakefield effects for different collimator half gaps.





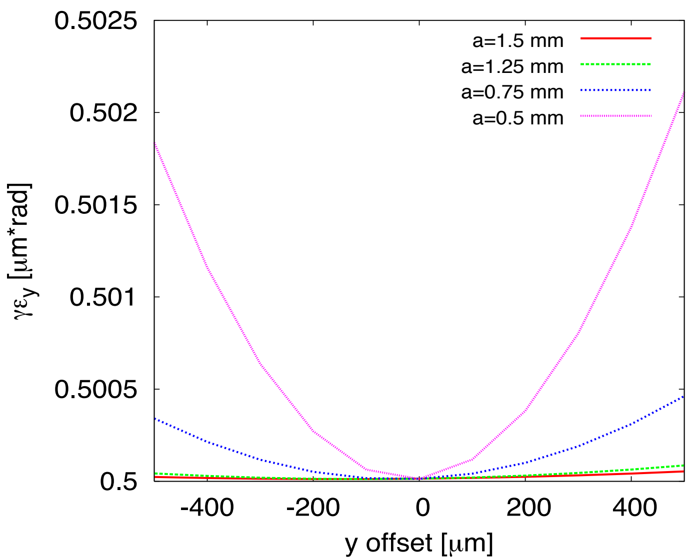
Geometric wake kick factor as a function of the collimator half gap



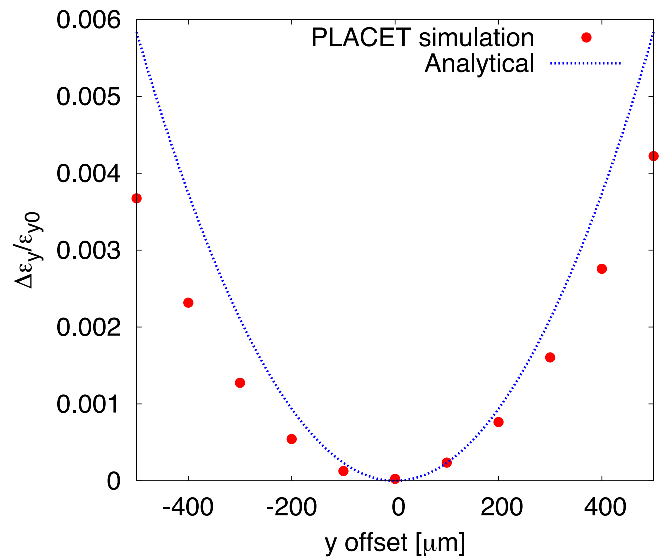
- To reconstruct the kick the slope from the linear fit to the upstream data is subtracted from the slope of a linear fit from the BPM downstream data

Beam tracking simulations

- Emittance growth due to collimator wakefield effects for different collimator half gaps as a function of beam offset.



a=0.5 mm



Emittance dilution (analytical estimate): $\frac{\Delta\varepsilon_y}{\varepsilon_{y0}} = \sqrt{1+\frac{\beta_y}{\varepsilon_{y0}}\langle y'^2_c\rangle} - 1$

Very small emittance dilution expected!
~0.1% in the worst cases

RMS centroid´s kick: $\langle y'^2_c\rangle = \left(\frac{N_e r_e}{\gamma}\kappa_\perp^{\text{rms}} y\right)^2$

The spread of the kick for a Gaussian bunch: $\kappa_\perp^{\text{rms}} = \frac{\kappa_\perp}{\sqrt{3}}$ where $\kappa_\perp$ is the kick factor in m^{-2} units

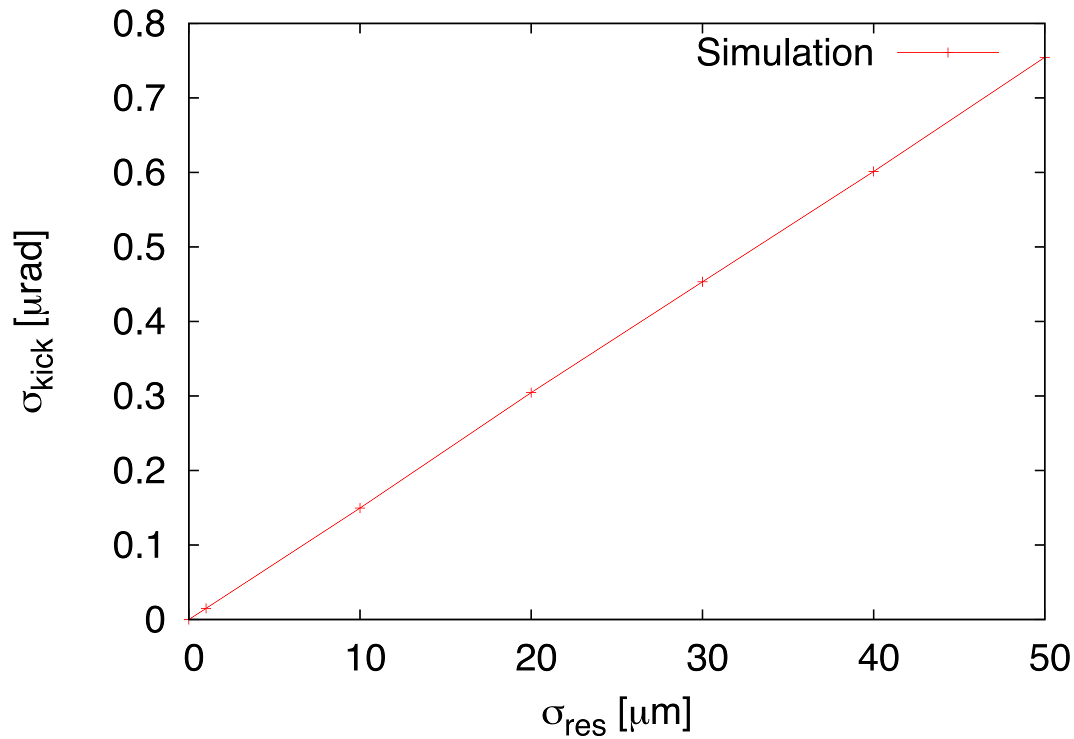
Beam tracking simulations

BPM resolution

[A. Latina]

- If at least 0.01 µrad per pulse resolution is required on the reconstructed wakefield angle, then single-pulse BPM resolution < 0.6 µm

- For example, Cavity BPM with ~100 nm resolution could be used



Plans:

1) Coll. wakefield measurements with bunch length in the range [100-300] μm

- For a precise benchmarking between experimental results, theory and simulations
- Investigate coll. wakefields with ILC-like bunches
- We can use the instruments which are already installed in the ESTB beamline: wakefield box, BPMs
- 2^{nd} generation SPR monitor at ESTB (aimed at single shot capability)

2) Push to smaller bunch length (< 50 μm)

- Investigate coll. wakefields with CLIC-like bunches
- SPR monitor at ESTB: precise measurement of bunch length for CLIC studies (~ 100 fs scale)

Collaboration

- C. Hast, M. C. Clarke, SLAC
- J. Barranco, A. Latina, G. Rumolo, D. Schulte, R. Tomas, CERN
- R. M. Jones, Cockcroft Institute, University of Manchester, UK
- J. Smith, Lancaster University and Tech-X UK Ltd, UK
- G. Doucas, R. Bartolini, I. Konoplev, C. Perry, A. Reichold, A. Seryi JAI, Oxford University, UK
- N. Delerue, LAL, Orsay
- A. Faus-Golfe, N. Fuster-Martinez, J. Resta-Lopez, IFIC, CSIC-Valencia University, Spain

E-203

Thank you all !

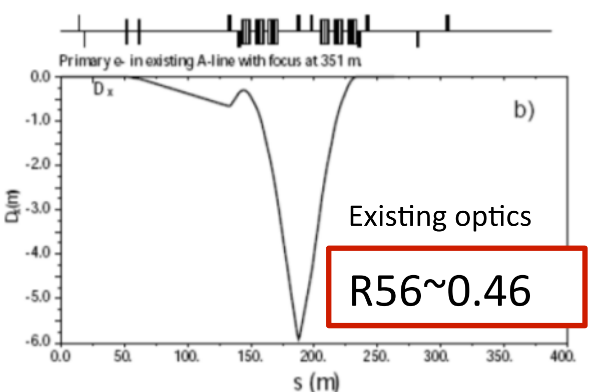
Supporting slides

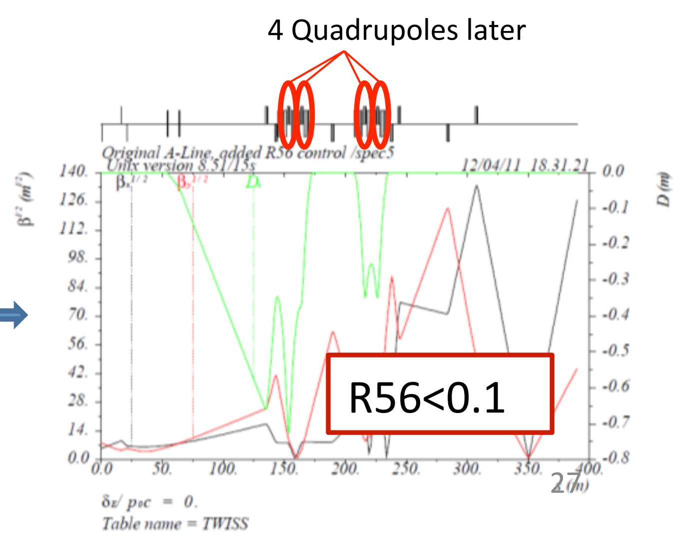
Bunch length measurement
Diagnostic methods

- **RF deflector**: using a deflecting RF cavity (e.g. LOLA at SLAC)
  - Pros: mature technique; single shot measurement; resolution < 50 fs
  - Cons: expensive, destructive technique
- **Smith-Purcell Radiation monitor** (G. Doucas et al.):
  - Pros: relatively cheap device; resolution < 50 fs; non-destructive technique
  - Cons: not yet mature technique; not yet single shot experiment; more work still needed in the radiation protection aspect
  - System to be upgraded during 2012 (in FACET)
- **Electro-optical method** (S. Jamison et al.): currently being developed as part of the CLIC-UK collaboration
  - Pros: useful for very short bunch length measurements (e.g. CLIC-like bunches and FEL bunches); <~20 fs resolution goal (program 2011-2014); non-destructive technique
  - Cons: relatively complex system; for <~20 fs resolution it requires high power laser; pretty costly

Development: Short bunch length

- Interest to short bunches ~44μm (CLIC, accel. R&D..)
- LCLS beam: 10 μm and smaller
- In the A-line, bunch length increases to 100 μm due to 24° bend, large dispersion and large R56
- Solution: installation of 4 available QUADs in A-line
  - to reduce R56 (T. Fieguth)
  - with LCLS beam σ_E~0.02% (Z. Huang)
  - **bl = 50 μm or shorter in ESA**





Historical review

Tests in the SLAC linac Sector 2:

- P. Tenenbaum et al., "Transverse wakefields from tapered collimators: measurements and analysis", SLAC-PUB-8937, 2001:
  - 1.19 GeV
  - Test designed to test the geometric wakefield of a tapered aperture
  - Measurements with both electron and positron beams
  - 3 rectangular collimators
    - subset 1: RMS σ_z=650 µm; 2 x 10^{10} particles per pulse
    - subset 2: RMS σ_z=1.2 mm; 1 x 10^{10} particles per pulse
  - The measure wakefields typically agree well with simulation results (using MAFIA), and show agreement at the level of a factor 2 with improved analytic models

- D. Onoprienko, M. Seidel, P. Tenenbaum, "Measurement of resistive dominated collimator wakefield kicks at the SLC", Proc. of EPAC 2002.
  - 1.19 GeV
  - Study of resistive wakefields for graphite collimators
  - While the geometric kick tends to be overestimated by the simple diffraction theory, better agreement is found for the resistive part

Historical review

- P. Tenenbaum, D. Onoprienko, "Direct measurement of the resistive wakefield in tapered collimators", SLAC-PUB-10578, 2004; Proc. of EPAC 2004.
  - RMS σ_z=0.5 mm; 2 x 10^{10} particles per pulse
  - For high resistivity Ti collimators: results in good agreement with theoretical prediction
  - For low-resistivity Cu collimators: resistive deflections appears to be larger than predicted by a factor 3
  - In both cases the resistive wake kick scaled as expected with the bunch length

- P. Tenenbaum et al., "Direct measurement of the transverse wakefields of tapered collimators", Phys. Rev. ST-AB, 10 (2007), 034401
  - 1.19 GeV
  - Test designed to test the geometric wakefield of a tapered aperture
  - Test of 4 different tapered collimator configurations
  - Simulations using MAFIA, ECHO3D
  - In the case of flat collimators, qualitative agreement between theory and measurement observed, but in many cases there was discrepancy as large as factor 2
  - Numerical electromagnetic simulations were able to predict the measured wakefield kick with typical agreement at the level of 20%

Historical review

Tests at ESA:

- S. Molloy et al., “Measurements of the transverse wakefields due to varying collimator characteristics”, Proc. of PAC 2007
- J. L. Fernandez-Hernando et al., “Measurements of collimator wakefields at End Station A”, Proc. of EPAC 2008
  - 28.5 GeV electron beam
  - $\sigma_z \in [0.5, 1.5]$ mm
  - 16 different collimator configurations
  - Simulations with 3D modeling (GdfidL)
  - While good qualitative agreement could be found between simulation, measurement and theory, the bunch length was not well known, and given the functional dependence on bunch length of the wakefield kicks, that directly meant that there was somewhat large uncertainty introduced in the consequent kick factors

Summary, T-480 wakefield measurements

Analysis 2007-2008

[N. Watson et al.]