LC Beam Diagnostics Key Issues
– Existing and Future Tests in Test Facilities –

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Manfred Wendt
CERN

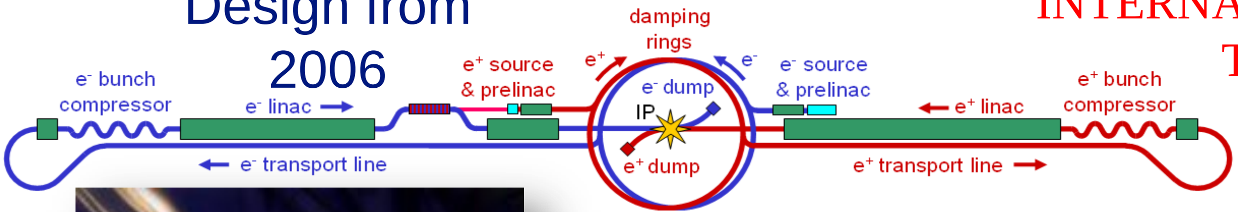
Outline

- **Linear Collider Projects & Beam Test Facilities**
  - **Beam Diagnostics Challenges**
- **Beam Position Monitors based on Cavities**
- **Bunch Length Monitoring based on Electro-Optical Sampling (EOS)**
- **Beam Size / Emittance Measurements**
  - **Laser Wire Scanner**
  - **Optical Transition Radiation**
  - **Optical Diffraction Radiation**
- **Conclusions & Perspectives**

There are many other BI topics worth to be discussed, this is just our personal selection

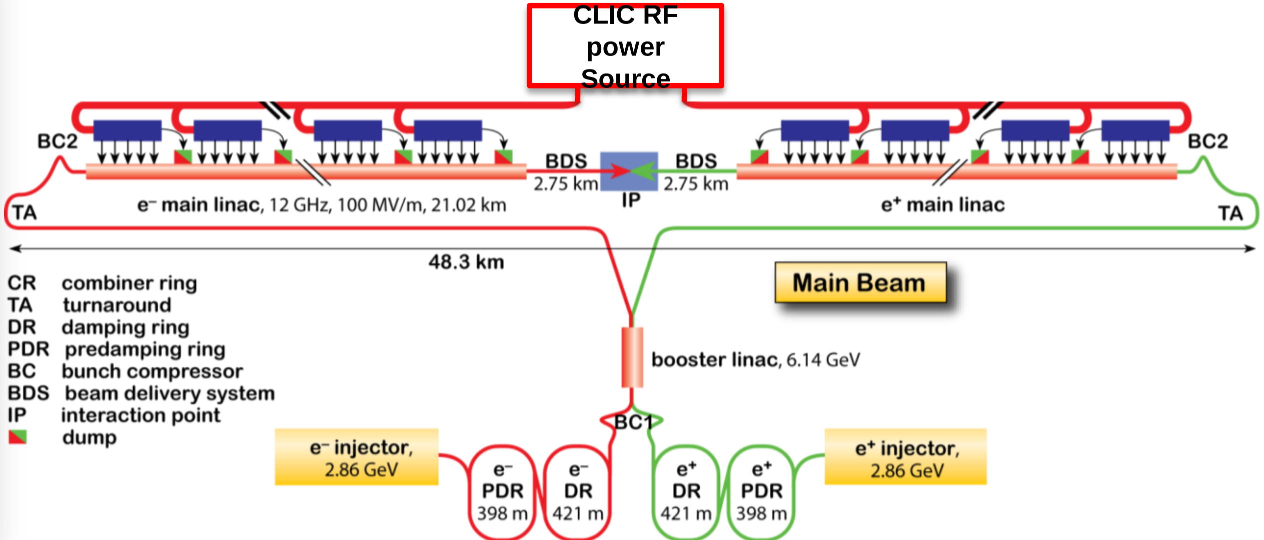
Linear Collider Projects

Design from 2006

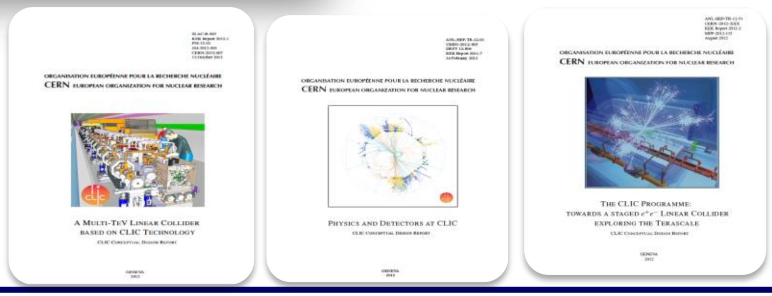


INTERNATIONAL LINEAR COLLIDER
Technical Design Report in 2013

http://www.linearcollider.org/



http://clic-study.org/



COMPACT LINEAR COLLIDER
Conceptual Design Report in 2012

LC Beam Parameters

Parameter		ILC-nom	CLIC-1	CLIC-3
E_{CM}	GeV	500	500	3000
L	$10^{34}cm^{-1}s^{-1}$	2.0	2.3	5.9
N	10^9	20	6.8	3.7
σ_x / σ_y (IP)	nm	474 / 5.9	200 / 2.6	40 / 1
σ_z (IP)	µm	300	72	44
n_{bunch}		1312	354	312
f_{rep}	Hz	5	50	50
Δt_{bunch}	ns	554	0.5	0.5

- **Low emittance preservation!**
  - **High resolution, reproducible beam diagnostics**
- **ILC / CLIC: Different beam formatting**
  - **Temporal / spatial resolution requirements**
  - **Timing, triggering, dynamic range**

Quantity of LC Beam Instruments

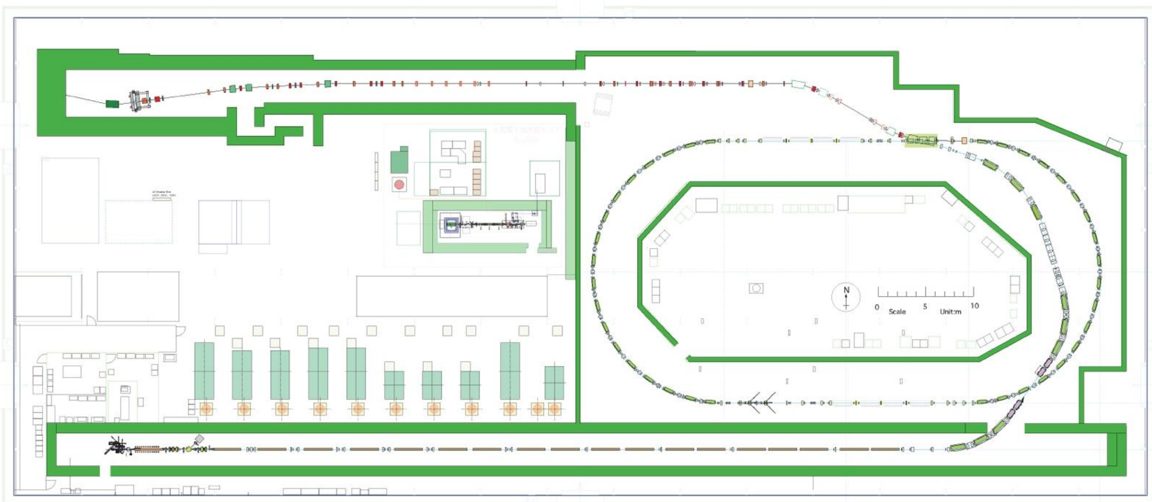
BI Type	ILC-nom (RDR)	CLIC-3-DB	CLIC-3-MB
Intensity	40	278	184
Position	4478	46054	7187
Size	142	800	148
Energy (spread)	13 (13)	210 (210)	73 (23)
Bunch length	13	312	75
Beam loss / halo	1440	45950	7790
Beam phase	14	208	96
Polarization	?		17
Tune	4		6
Luminosity	2(?)		2

- **Impressive quantities!**
  - **Calls for well though through engineering and optimization**

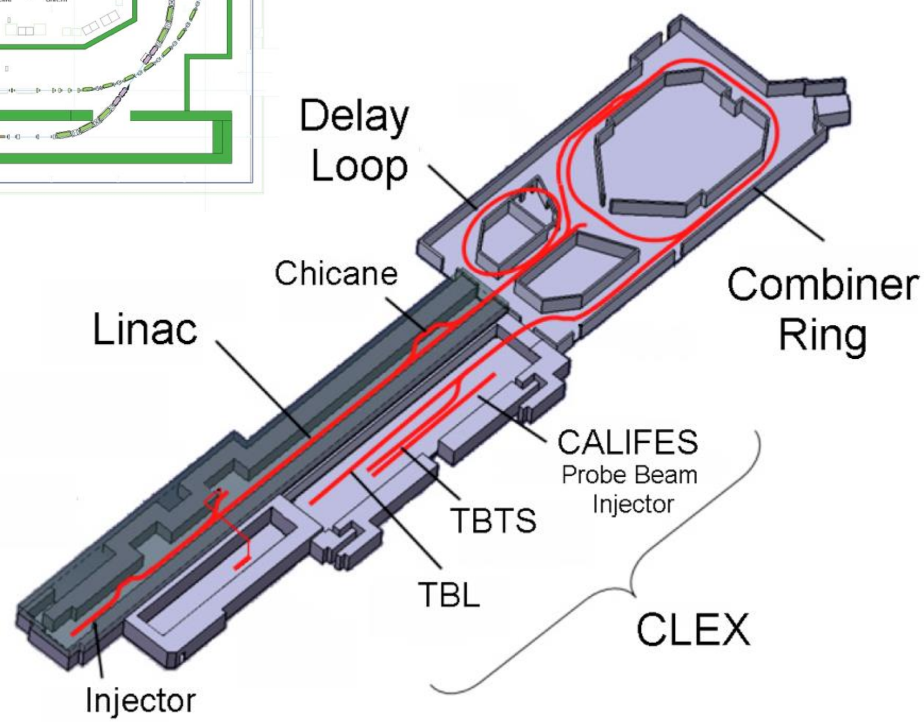
LC Beam Diagnostics Challenges

- **Requirements and quantities for both machines are similar**
  - **Most BI hardware is located in the tunnel**
    - radiation, maintenance
  - **Large quantities,**
    numbers scale with beam energy (tunnel length)
    - CLIC-DB needs additional beam instruments, but with relaxed demands
    - Still need to optimize designs for costs vs. required performance
- **Additional BI challenges**
  - **Measurement of small beam size (emittance), non-interceptive**
    - ~1µm spatial resolution for transverse profile monitors
  - **Measurement of short bunch length**
    - ~20fs time resolution for longitudinal profile monitors
  - **Conversation of low emittance beam over long distances**
    - Beam alignment (golden orbit) relies on high resolution & accuracy BPMs
    - Wakefield effects of cavity BPMs need to be further investigated
  - **ILC SCRF segmentation for warm beam diagnostics?**
    - XFEL may give some hints

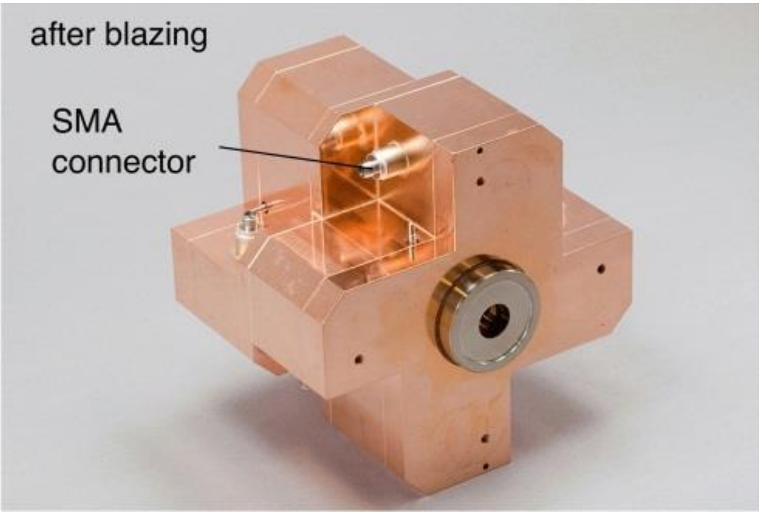
LC Beam Test Facilities

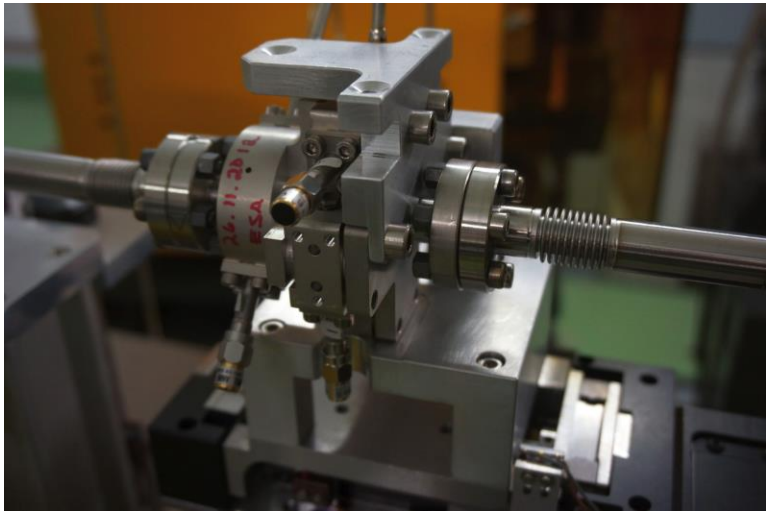


- **Dedicated LC test facilities**
  - **CTF3 (until 2016)**
  - **ATF/ATF2**
- **Many other fest facilities**
  - **FLASH, FACET, CesrTA, STF, NML,…**



High Resolution BPMs





IP BPM (ATF2)

– Aperture: 6mm
– Resolution: 8.72+-0.28(stat)+-0.35(sys) nm
@ 0.7×10^{10} electrons/bunch,
@ 5 μm dynamic range
  ➢ Y. Inoue et.al., Phys. Rev. ST-AB 11, 62801 (2008)

MB BPM (CTF3)

– Aperture: 8mm
– Operating frequency: 15 GHz
– Anticipated resolution: 50 nm, 50 ns
  ➢ To be tested!

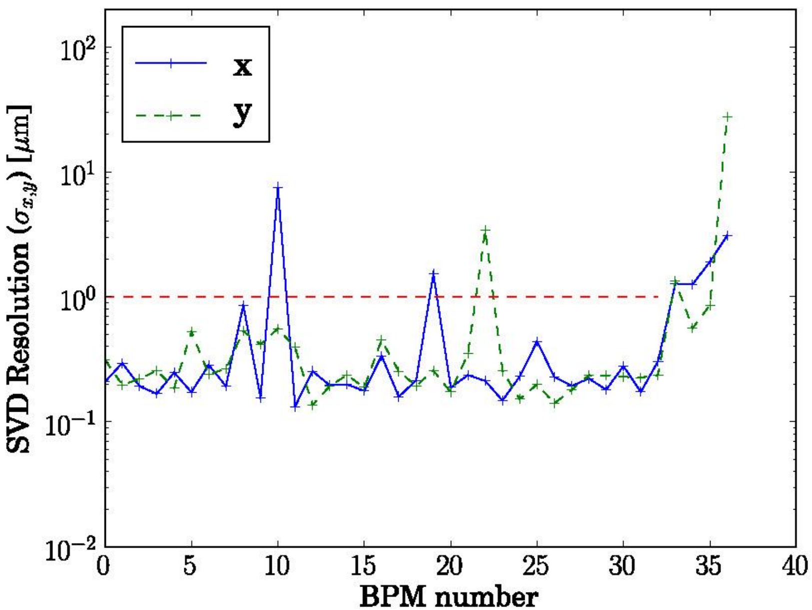
Collaboration KNU / PAL / KEK / RHUL / SLAC

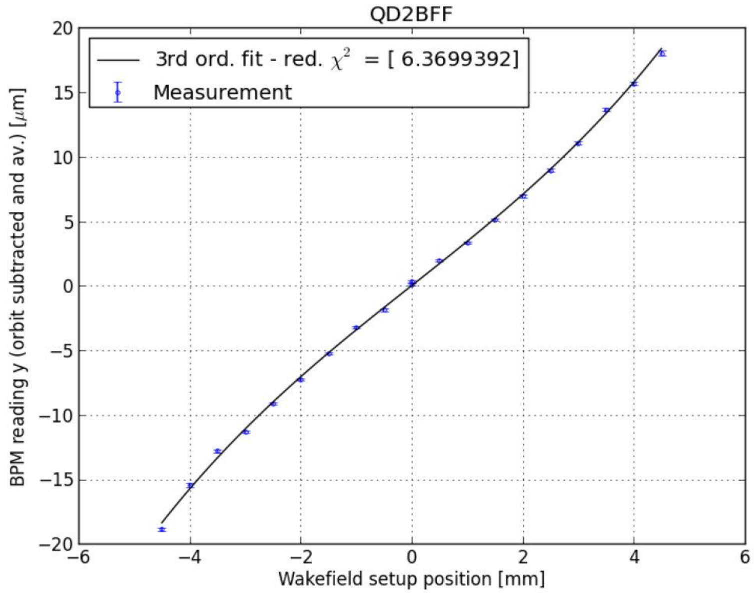
Royal Holloway University of London Fermilab CERN

S. Boogert, F. Cullinan, A. Lunin, A. Lyapin, S. Smith, L. Soby, J. Towler, M Wendt

High Resolution BPMs

- **Nanometer resolution cavity BPMs have been successfully developed at ATF2 over the last 15 years**
  - **Spin-off to FEL linacs (LCLS, FERMI, XFEL, FLASH, SwissFEL,…)**
  - **Miniworkshop on cavity BPM systems following the IBIC2013**
- **Need to study the impact on the cavity BPM wakepotential**
  - **Wakefield kick effect has been measured at ATF2**

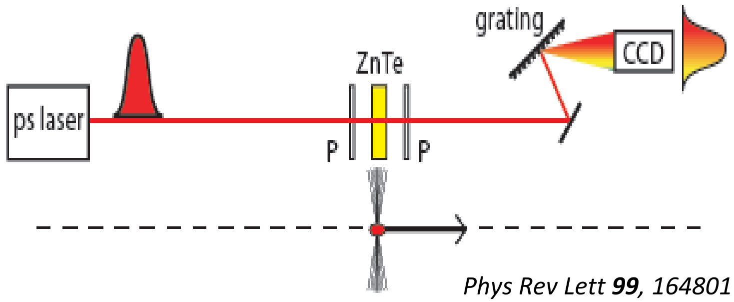




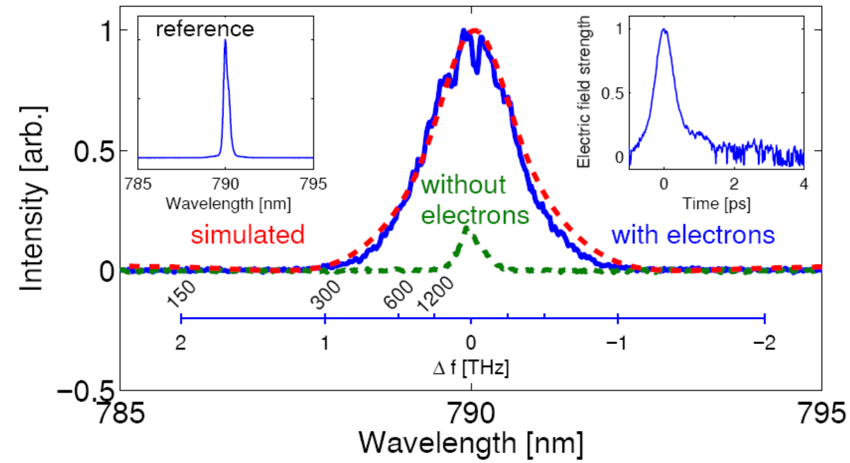
EOS Bunch Length Monitors

EOS-spectral up-conversion techniques

– Convert far…mid-IR spectrum to optical wavelength
– Bandwidth reduction 10µm…1mm -> 740…800nm



Phys Rev Lett ***99****, 164801 (2007)*
Phys. Rev. ST, ***12****, 032802 (2009)*



- **Laser-generated THz pulses as mimic of electron bunch (Daresbury)**
- **Plan for beam tests at test facilities with short bunches (PSI)**

- **EOS detection solution based on advance materials**
  – **Very high bandwidth material (phonon resonances in the far THz)**
    ➢ Materials, Photonics & Smart Systems (PAPS) Group at Dundee
  – **Fabrication & applications of nanocomposites**

Science & Technology Facilities Council

University of Dundee

W. A. Gillespie, D. A. Walsh, S. P. Jamison , R. Pan, T. Lefevre

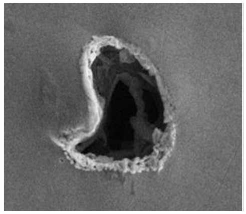
High-Rez Beam Size Monitors

- **High resolution is required from DR to IP**
  - **Large beam energy range (2.4GeV -> 1.5TeV)**
  - **Large quantities!**

	ILC	CLIC MB	CLIC DB
Beam Charge (nC)	7875	190	1.2 10^6
Hor. Emittance (nm.rad)	10^4	660	10^8
Ver. Emittance (nm.rad)	40	20	10^8

  - **Flat beams (σ_x>>σ_y)**
  - Small beam size
  - High beam charge

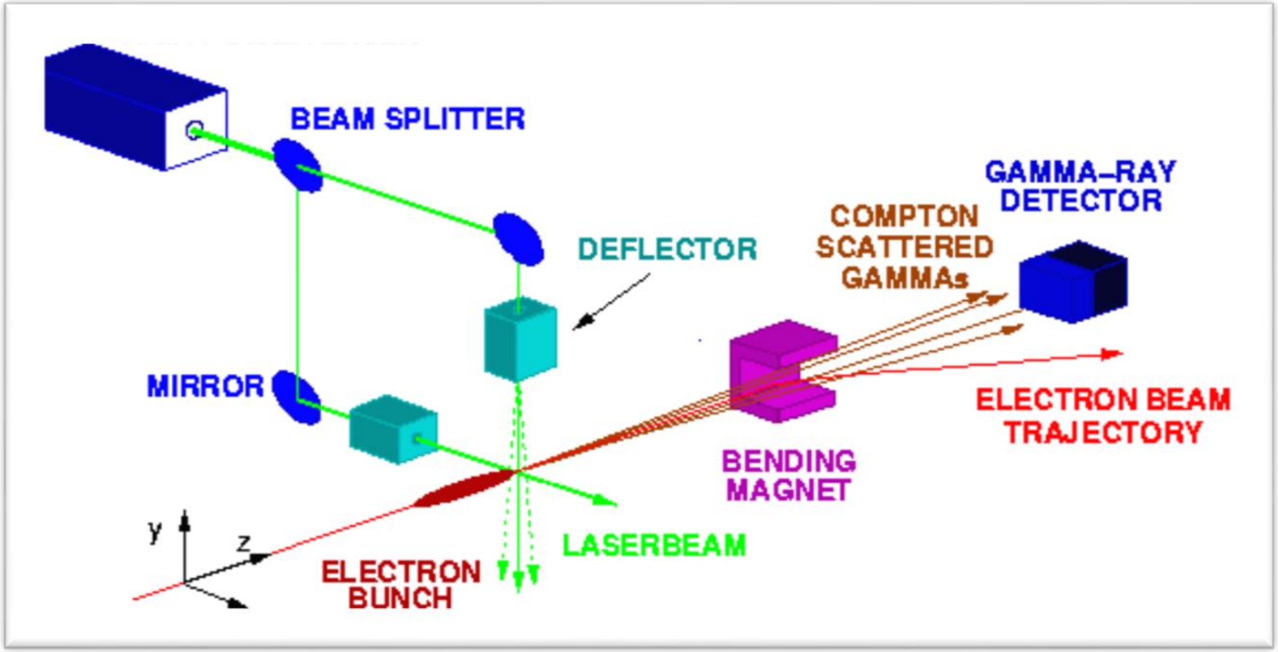
High Charge Densities > 10^{10} nC/cm^2
Thermal limit for 'best' screen materials (C, Be, SiC) is 10^6 nC/cm^2



- Intercepting devices limited to single (or few) bunch (no micro-bunching instabilities assumed!)
- Strong need for non-intercepting devices
- Require two different systems to cover the large beam intensity dynamic range (commissioning and production beams)

Laser Wire Scanner

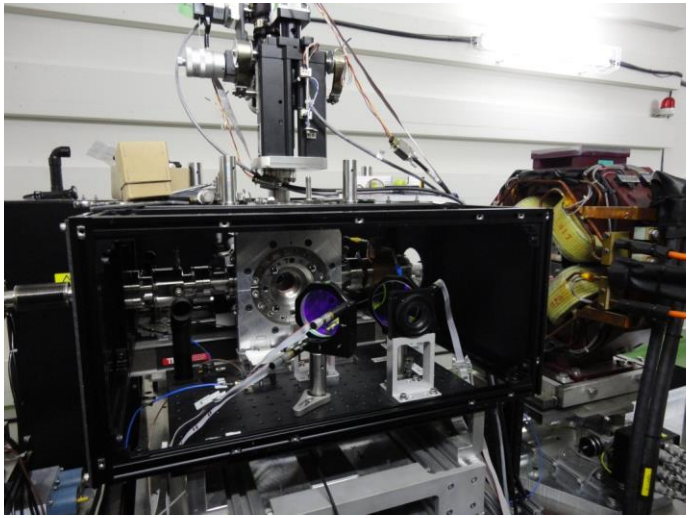
- **High resolution non-interceptive transverse beam profile measurement**
  - **Goals to detect 1µm beam size (resolution was demonstrated at SLC)**
  - **Small Compton scattering cross section -> High power laser (10MW)**



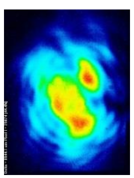
10 Years of R&D

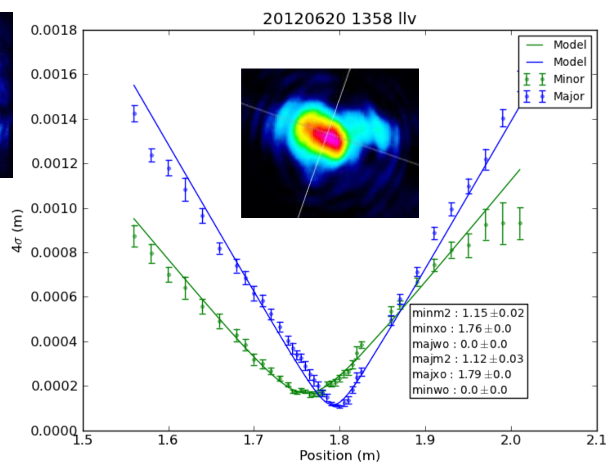
  - **Spatial resolution requires strong focusing**
    - High quality fiber laser & optics, diffraction limited spot size using large F#
  - **Complexity and reliability: "Still not easy to operate"**

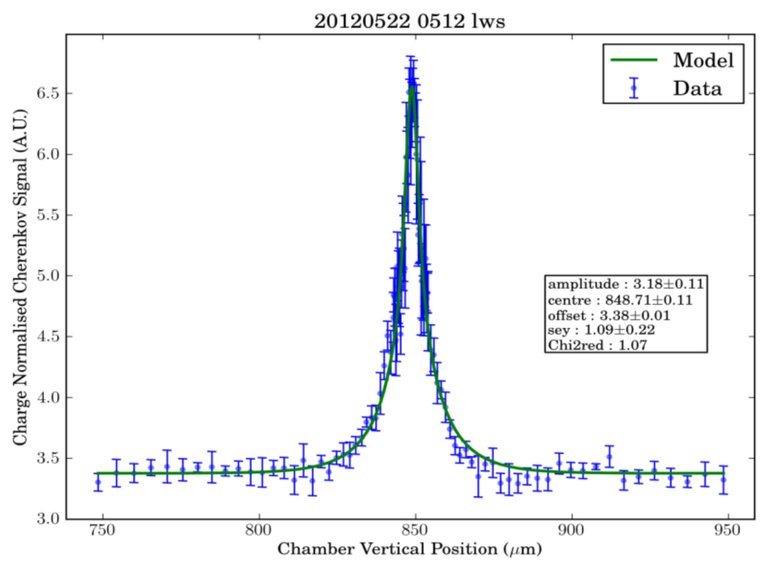
Laser Wire Scanner



- **ATF2 Laser-wire @ KEK in 2012**
  - LW moved during 2011 shutdown
  - e^- optics: V=1µm x H=200µm
  - Reduced background
  - Detailed investigation of the laser focus
  - Further analysis in progress!







L. Nevay, L. Corner, S. Boogert, P. Karataev, A. Aryshev

Alternatives to the LWS?!

- **Study of a cheaper, and easier to manage alternative to the LWS!**

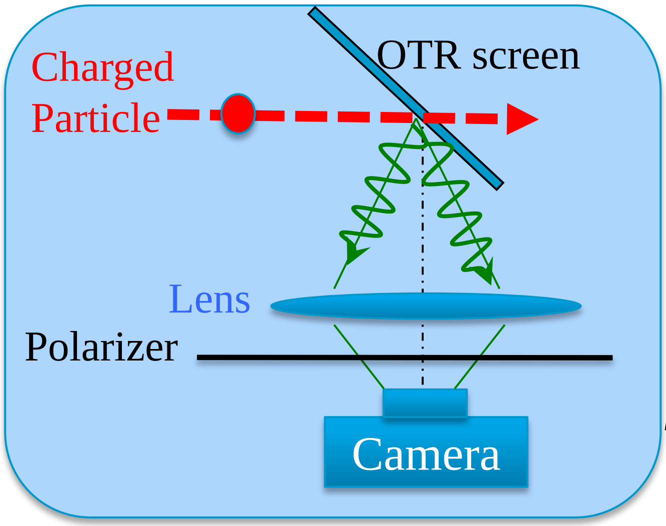
- **Plan: Make use of Transition and Diffraction Radiation!**
  - **OTR for single bunch of low charge beams**
    - Anyway foreseen to use OTR screens during machine commissioning with lower charge, high emittance beams
  - **ODR for observation of the full bunch train**

- **Required R&D:**
  - **Development of a high resolution TR monitor with µm resolution**
  - **Development of a high resolution DR monitor with similar resolution**

High-Rez OTR Measurements

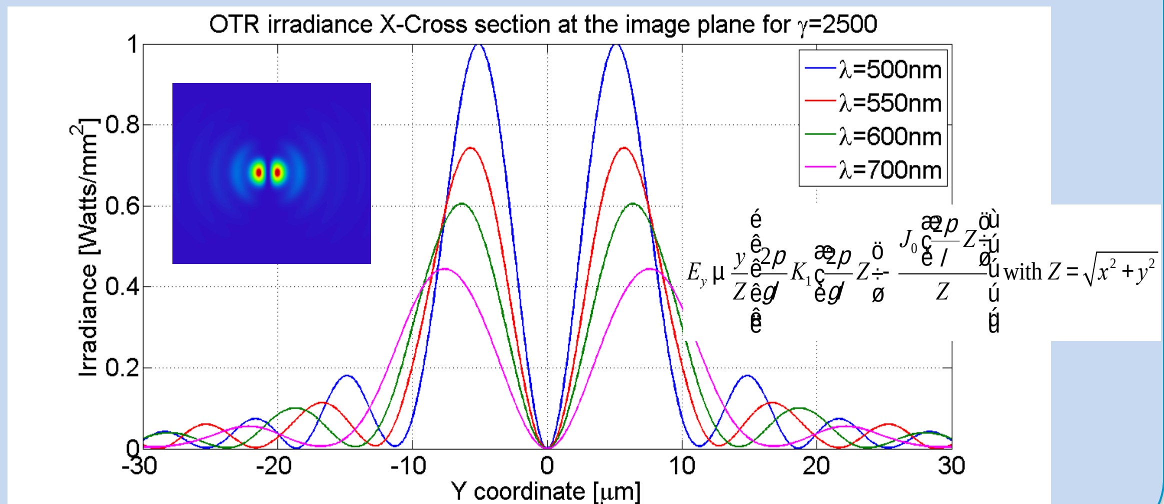
Optical Transition Radiation

- **Charged particle passing a media boundary**
  - dielectric screen (high reflectivity)
- **Interceptive method limited to single bunches**
- **Simple, cheap & reliable!**



Point spread function of OTR imaging system

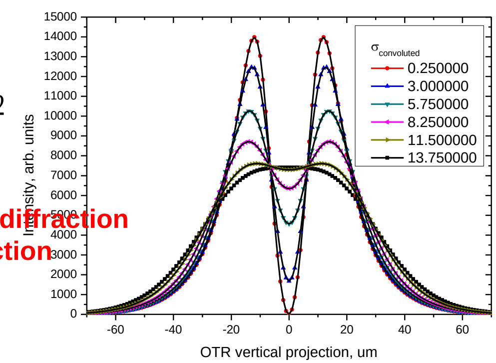
~ Image generated by a single electron (Zemax simulations)



PSF: convolution integral of

$$f^2(\theta_m,\gamma,\varsigma)=\left[\int_0^{\theta_m}\frac{\theta^2}{\theta^2+\gamma^{-2}}J_1(\varsigma\theta)\,d\theta\right]^2$$

OTR response — **Point charge diffraction stimulus function**

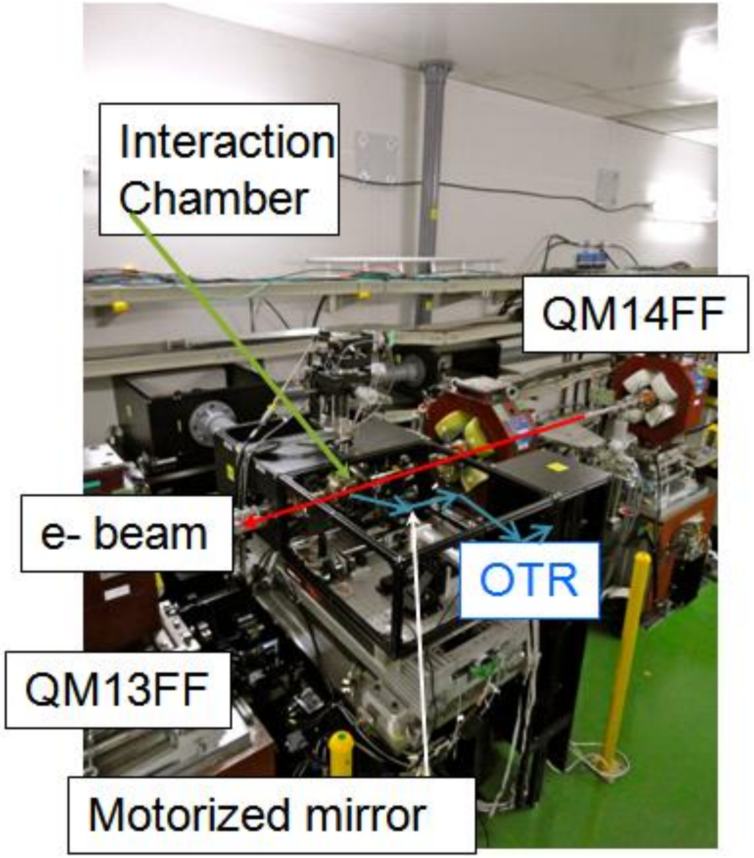


Considering the physical beam size, the resulting image on the camera is the convolution of the beam spatial distribution with the optical system PSF

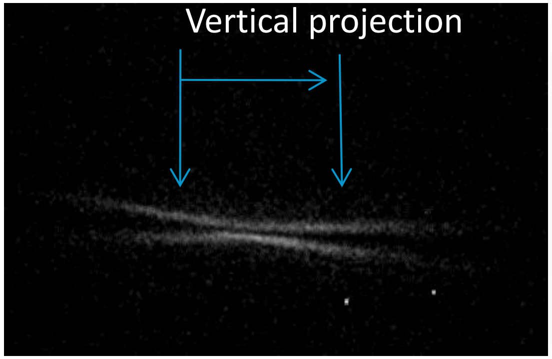
Royal Holloway University of London
John Adams Institute for Accelerator Science
A. Aryshev, N. Terunuma, J. Urakawa, S. Boogert, P. Karataev, L. Nevay, S. Mazzoni, T. Lefevre, B. Bolzon

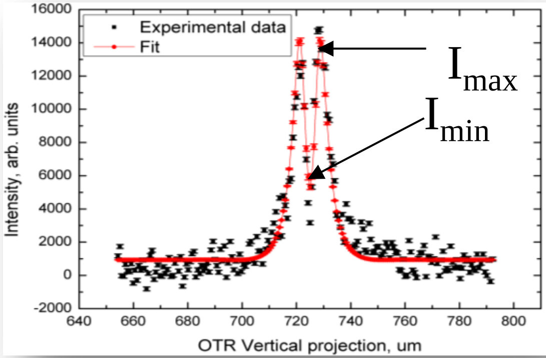
High-Rez OTR Measurements

ATF2 OTR PSF @ KEK in 2013



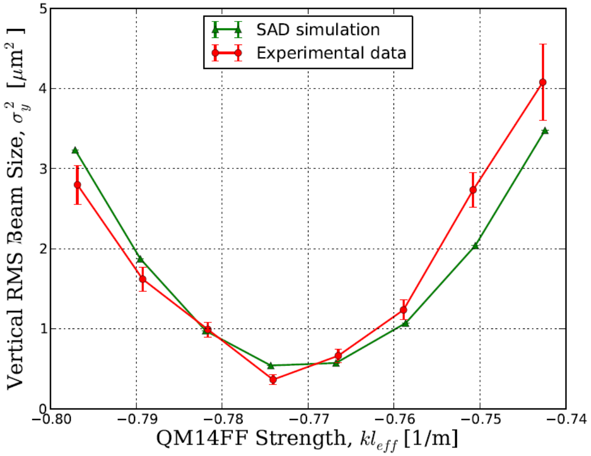
Newly installed optical system designed using Zemax simulations





$$f(x) = a + \frac{b}{1+[c(x-\Delta x)]^4}\left[1 - e^{-2c^2\sigma^2}\cos[c(x-\Delta x)]\right]$$

Minimum measured beam size was: 0.754±0.034 μm

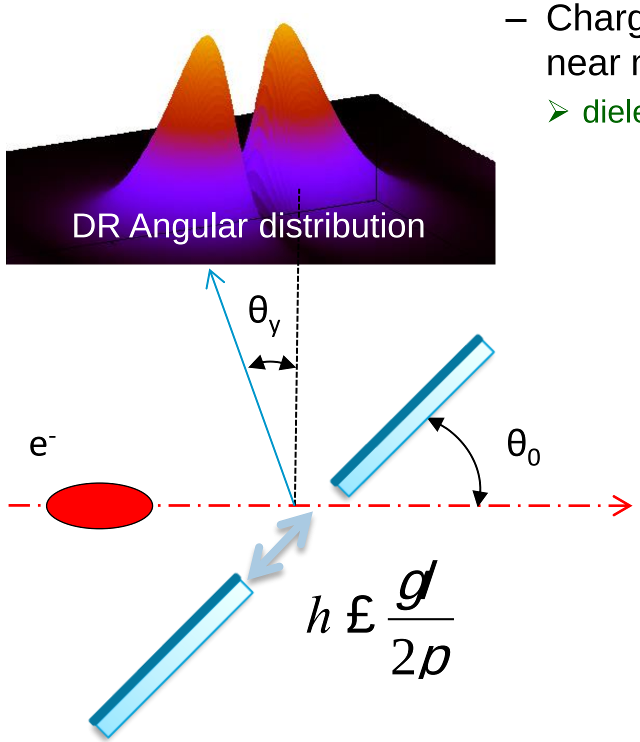


P. Karataev et.al, Phys. Rev. Letters ***107****, 174801 (2011)*
A. Aryshev, et.al, Journal of Physics: Conference Series ***236 (2010) 012008***

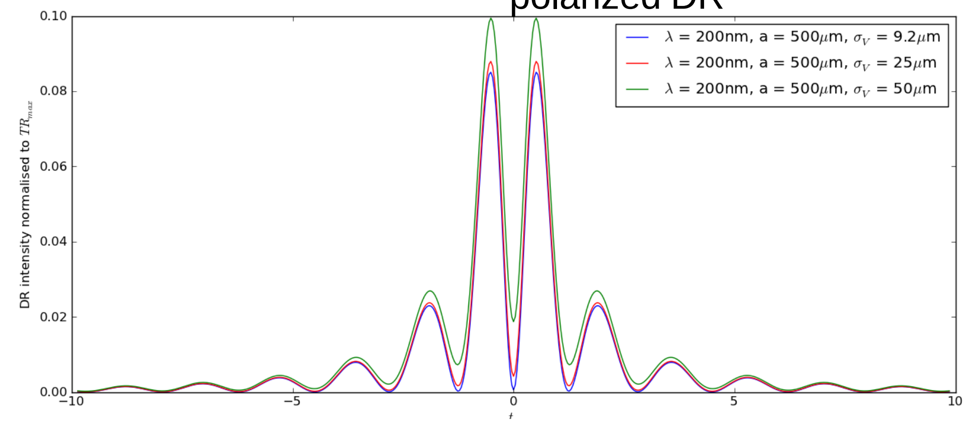
Diffraction Radiation for Beam Size

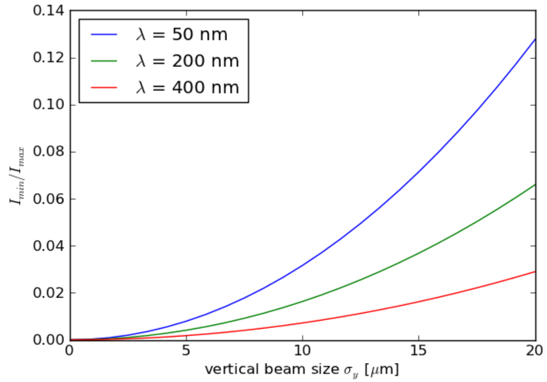
Optical Diffraction Radiation

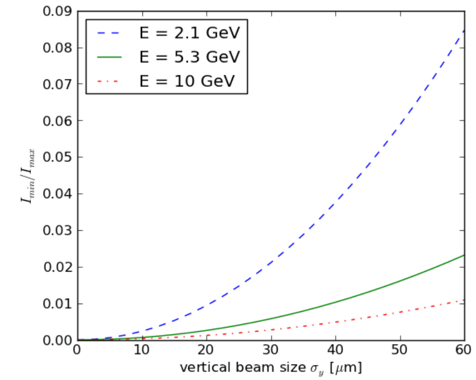
- Charged particle passing near media boundary
  - ➢ dielectric slit (high reflectivity)
- Non-interceptive method
- Interference pattern from the edges of the slit
- Vertical beam size gives vertically polarized DR



DR intensity ⇧ as slit size ⇩





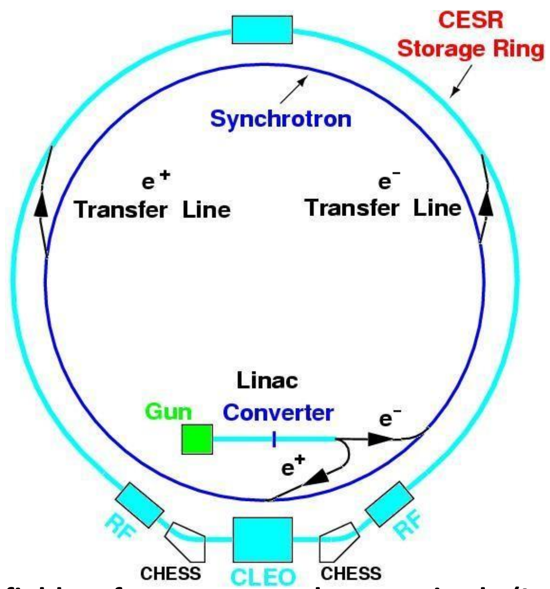


A. Cianchi et al., Phys. Rev. ST Accel. Beams 14 (10) 102803 (2011)
A.H. Lumpkin et al, Phys. Rev. ST Accel. Beams 10, 022802 (2007)
P. Karataev et al, Phys. Rev. Lett. 93, 244802 (2004)

L. Bobb, T. Aumeyr, M. Billing, D. Rubin, N. Chritin, P. Karataev, S. Mazzoni, T. Lefevre

Diffraction Radiation for Beam Size

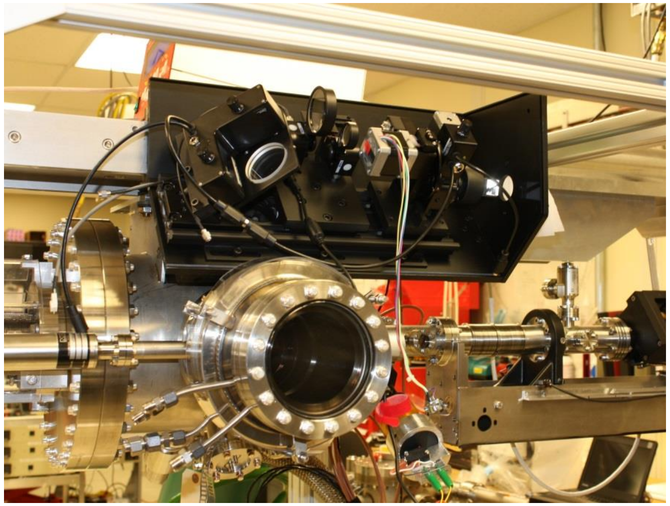
Test foreseen on Cornell Electron Storage Ring in 2012/13

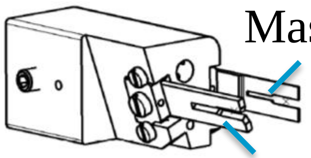


E (GeV)	σ_H (µm)	σ_V (µm)
2.1	320	~9.2
5.3	2500	~65

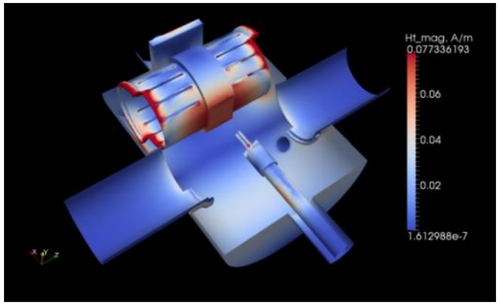
Target Assembly

- SiC Mask to suppress background from Synchrotron radiation
- Si Target for Diffraction Radiation: *λ/100* roughness, *λ/10* coplanarity





H-field surface tang complex magnitude (Loss map)
Mode Fr = 1.19 GHz, Q = 3309, Ploss = 0.075 W



Total power loss for single bunch = 0.6 W

- First DR images obtained in April 2013
- Next test in December 2013

Conclusions & Perspectives

- LC beam diagnostics is a very active R&D area, relying of large collaborations
- No fundamental feasibility issues, but many technical challenges in a wide range of disciplines
  - Electronics, RF, sensors, radiation hardness, lasers & optics, high precision manufacturing & polishing,…
- Baseline choices have been made, but R&D is going on in many areas
  - Good chances to replace LWS by OTR/ODR in may locations – costs and simplicity
  - Development of EOS-based bunch length monitor to replace costly, invasive RF deflector
  - Do cavity BPMs play a role on the impedance budget of the linac?
    - Do we need a new design?
  - EMC issues in the CLIC main linac?
    - Observation of EMI noise from the drive beam limits resolution of the MB diagnostics!
  - No R&D without test facilities!!
- Large amount of devices to be build and operate
  - Far beyond what was already realized in our field
  - Realistic integration of beam instruments in the machine layout
    - The delve lies in the details!
  - Radiation hardness and operational / maintenance aspects need to be investigated as well!

Thanks all the ILC/CLIC contributors to this talk

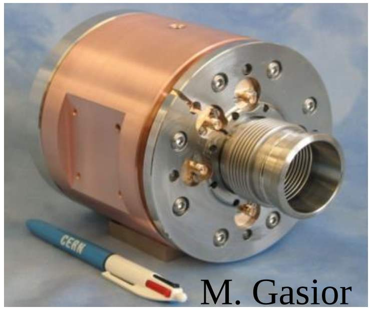
Thanks for your attention!

CLIC Drive Beam BPM

Requirements:

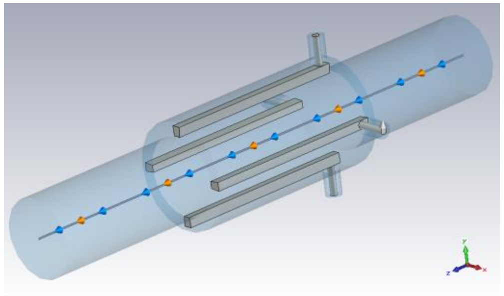
- **High current 100A – high bunch frequency 12GHz**
- **In the vicinity of an RF structure producing 100MW @12GHz**
- **Temporal resolution of 10ns**
- **2µm resolution over an aperture of 23mm (accurate calibration)**
- **Simple and Cheap ~ 40k units**

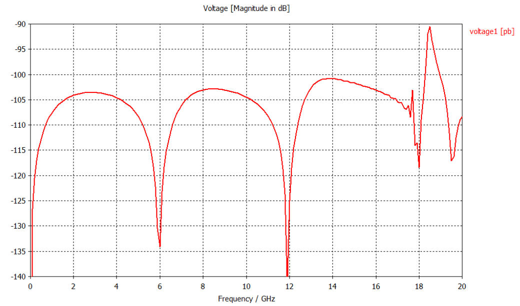
CLIC TEST FACILITY 3 uses Inductive Pick-ups
~60 Units ~ 5um resolution measured

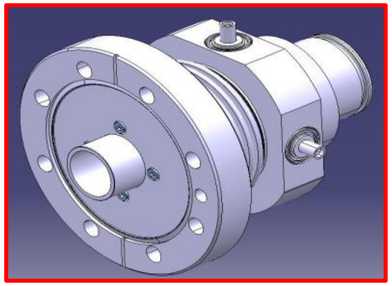


M. Gasior

Cheaper alternative based on Stripline Pick-ups *(A. Benot-Morell, S. Smith, M. Wendt, L. Soby)*



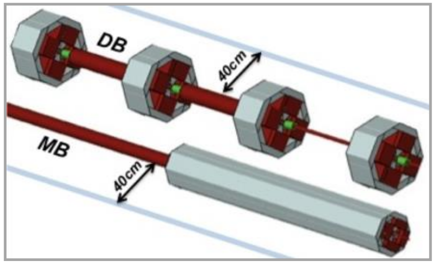




To be tested on CTF3 in 2013

CLIC Beam Loss Monitors

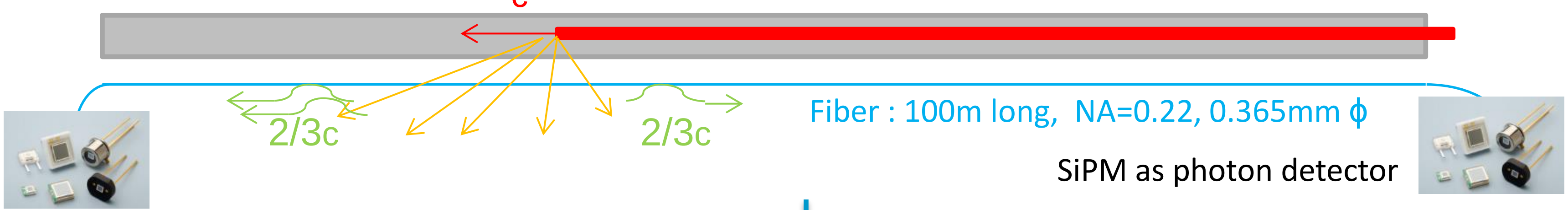
FLUKA model to simulate secondary particle shower distributions requirements

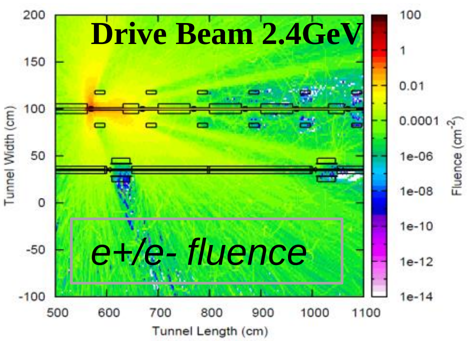


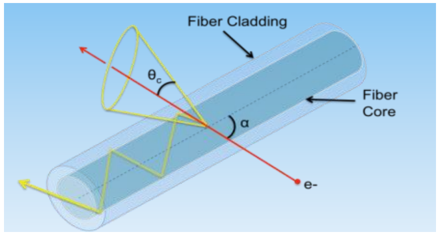
- Large dynamic 10^5 to cover destructive and operational losses
- Annual dose ≤ 50 kGy at detector location
- Ionization chambers as baseline choice : 1 detector/quadrupole

Based on LHC ionization chamber and readout electronics with dynamic range 10^5 (10^6 under investigation) and sensitivity $7e10^{-9}$ Gy

Considering long distributed system based of optical fibers used as Cherenkov detectors







Analytical model

≈ 50% more photons downstream

Sensitivity requirements: ≈ $10^4 - 10^5$ N_{ph}/train

Dynamic range: ≈ 10^4

Cherenkov model validated on beam tests (angular dependence)

Loss longitudinal localization works for single bunch

Quartz fibers tested ok up to 22 MGy

Length cannot be longer than 100m (attenuation)

CERN UNIVERSITY OF LIVERPOOL *E. B. Holzer, J. van Hoorne, S. Mallows*

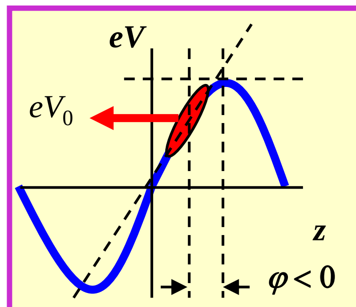
Bunch Length RF Deflector

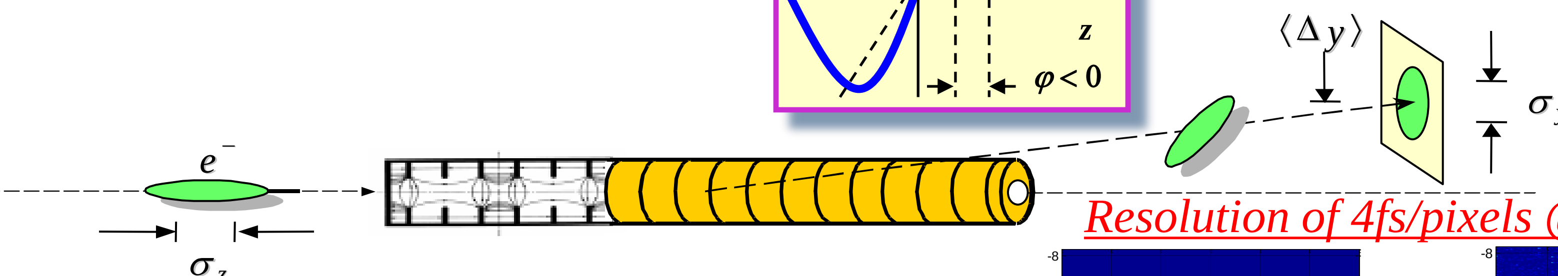
	ILC	CLIC linac	XFEL	LCLS
Beam Energy (GeV)	250	1500	20	15
Linac RF Frequency (GHz)	1.3	12	1.3	2.856
Bunch charge (nC)	3	0.6	1	1
Bunch Length (fs)	700	150	80	73

- High resolution, single shot longitudinal measurement:

  - Baseline solution using RF deflector: Excellent time resolution, well calibrated

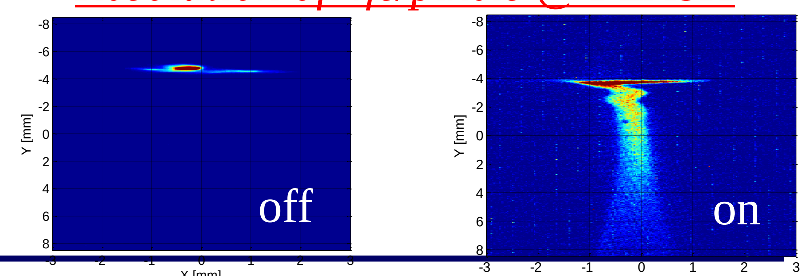
- *Old idea from the 60's*
- *RF Deflector ~ relativistic streak tube*
- *Used in almost all short bunch length facility*





!! But destructive method !!

Resolution of 4fs/pixels @ FLASH



P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

M. Hüning *et al*, Proceeding of the27th FEL conference, Stanford, 2005, pp538