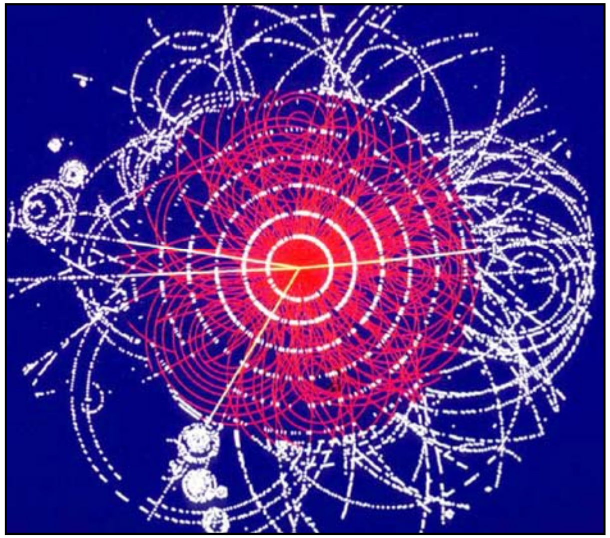
Beam Instrumentation for Linear Collider

T. Lefevre, CERN

- Why Linear Collider ?
- What is special about Linear Collider ?
- What are the main Instruments ?

Why do we need Leptons

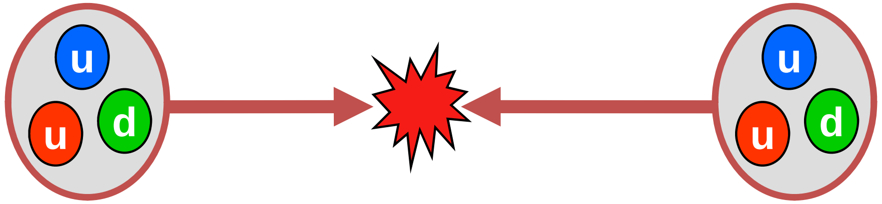
Higgs event Simulation



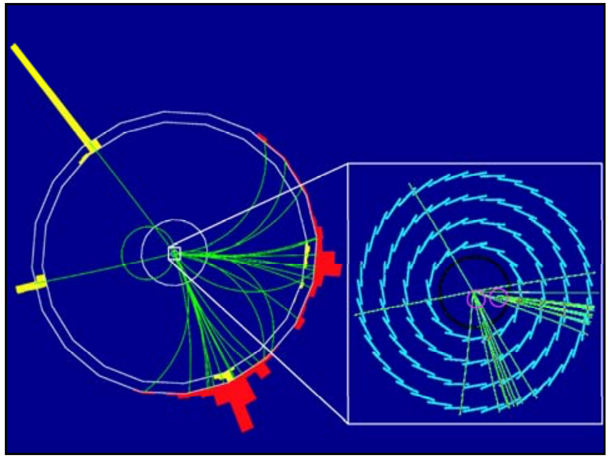
LHC

Hadron Colliders (p, ions):

- Hadrons are composite objects



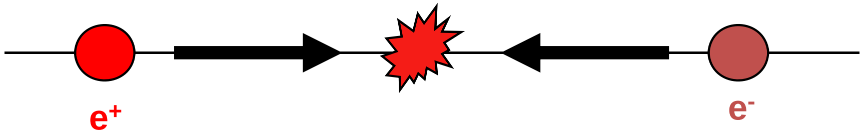
- Only part of proton energy available
- Huge QCD background



ILC

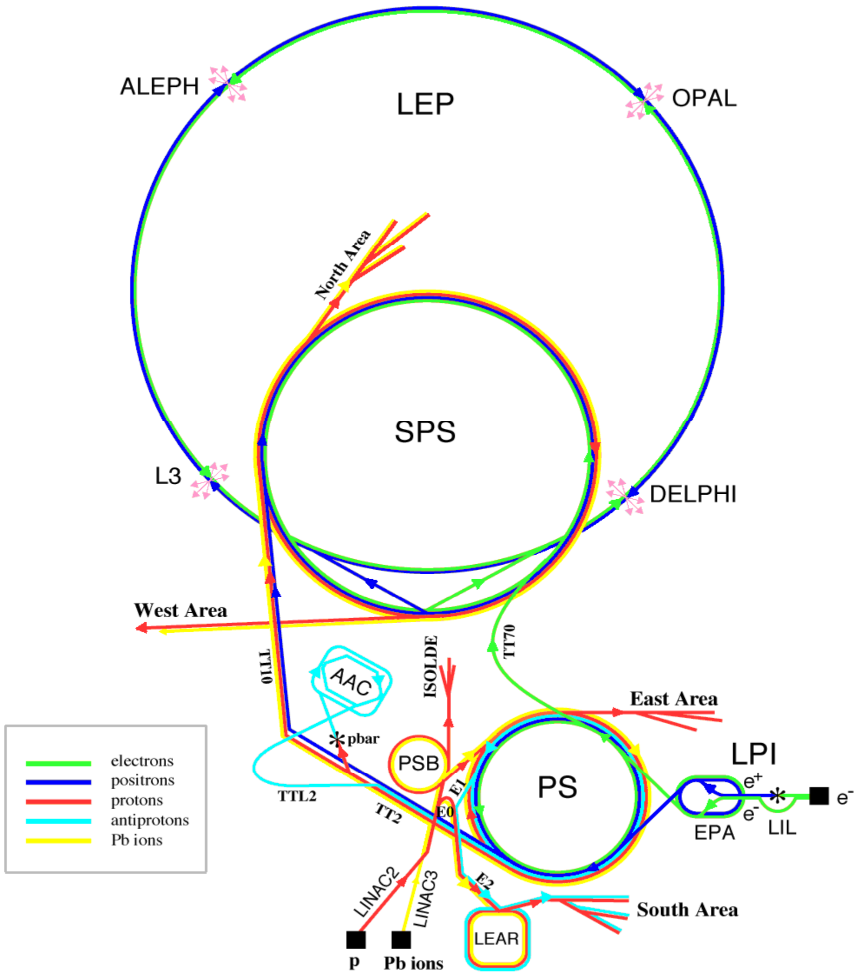
Lepton Colliders:

- Leptons are elementary particles



- Well defined initial state
- Momentum conservation eases decay product analysis
- Beam polarization

No circular e^+e^- collider after LEP



Energy loss dramatic for electrons

$$\Delta E_{SR}[\mathrm{GeV}] = 6\cdot 10^{-21}\cdot \gamma^{4}\cdot {}^{1}\!\big/_{r[km]}$$

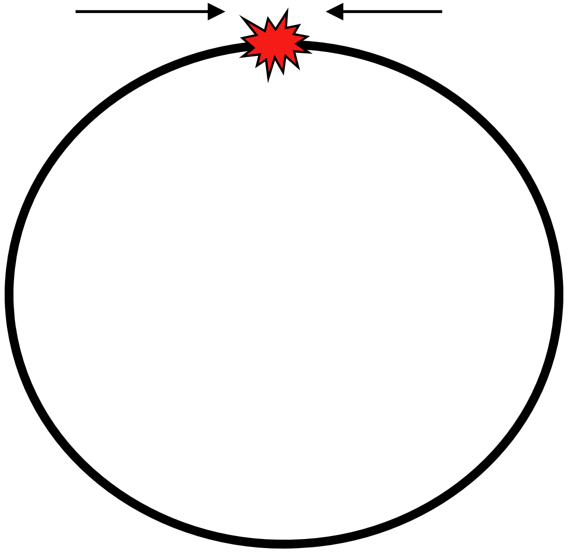
$$\gamma_{\mathrm{proton}} / \gamma_{\mathrm{electron}} \approx 2000$$

Impractical scaling of LEP II to

E_{cm} = 500 GeV and ***L* = 2 · 10^{34}**

- **170 km** around
- **13 GeV/turn** lost
- **1 A** current/beam
- **26 GW RF power**
- **Plug power request > Germany**

What is the difference between Circular and Linear

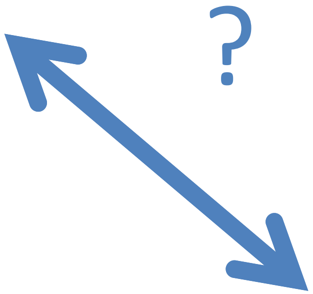


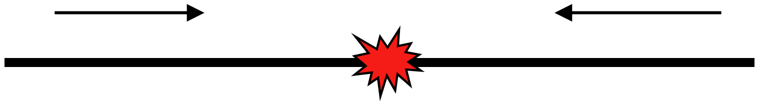
Luminosity (number of collision)
~ Machine repetition rate

LEP f_{rep} = 11 kHz

ILC f_{rep} = 5 Hz

$\Rightarrow$ **factor 2200 in *L* already lost!**

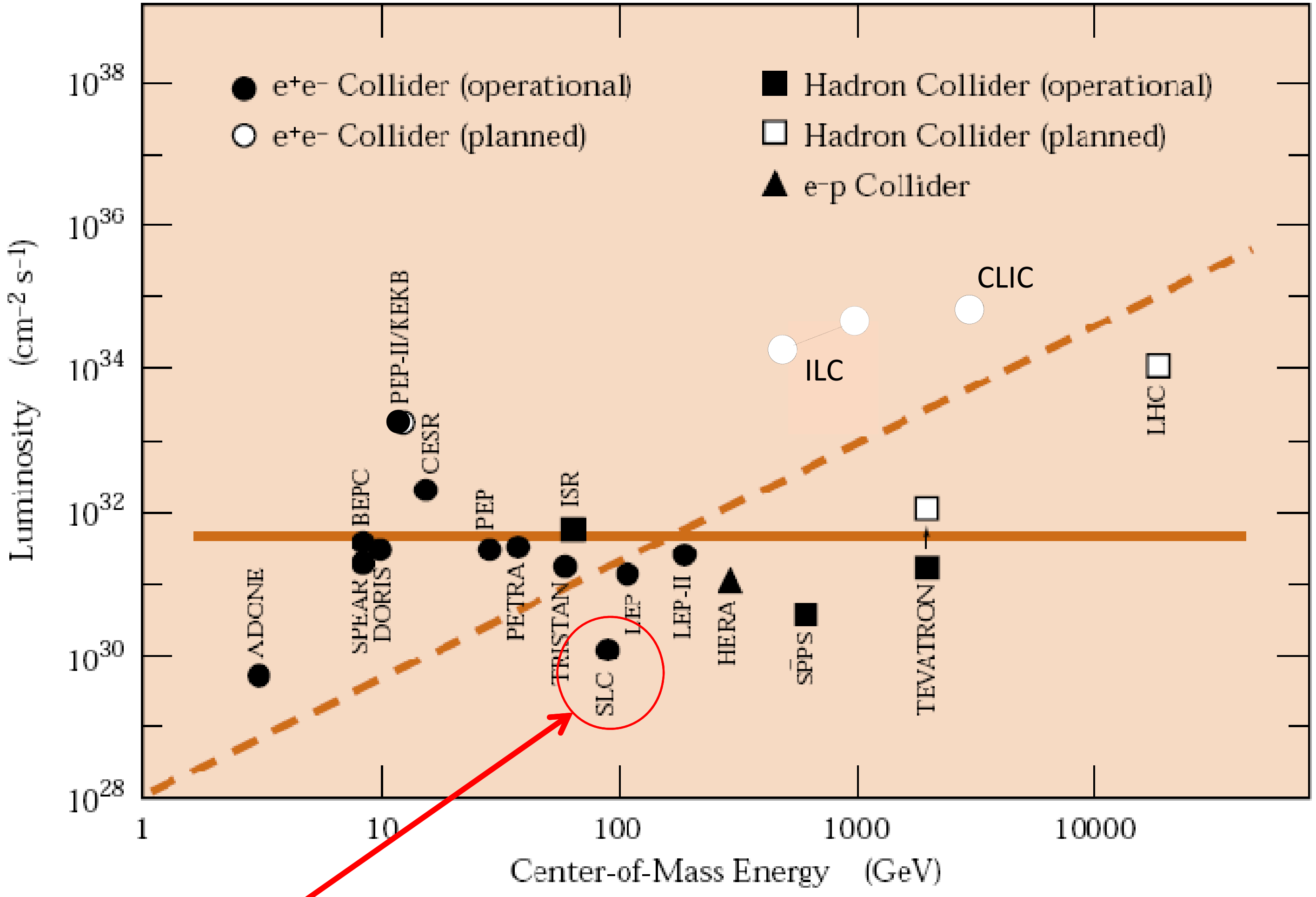




Linear Colliders are pulsed !!

Luminosity of high energy $e^+ e^-$ Collider

Particle physicists ask to increase Luminosity with energy…



SLAC Linear Collider

E_{cm} = 92 GeV

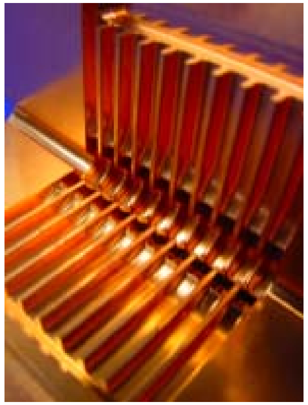
$L = 3 \cdot 10^{30}\ cm^{-2}s^{-1}$

	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	$10^{32}\ cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

What are the projects under-study ?

FRIENDLY RIVALRY

Nature 456,422, 27 Nov 08



- 1.3 GHz supra conducting cavities
- Gradient 32 MV/m
- Energy: 500 GeV, though upgradable to 1.0 TeV

- 12GHz normal conducting cavities
- Gradient 100 MV/m
- Energy : 3 TeV

Luminosity of high energy Collider

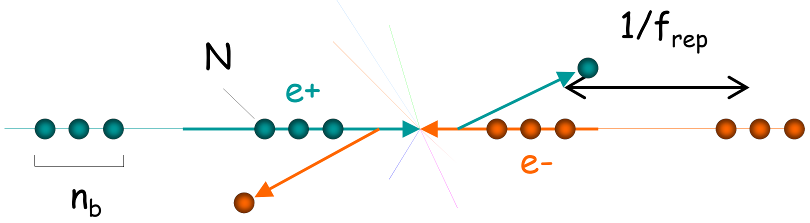
Collider luminosity [$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$] is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D$$

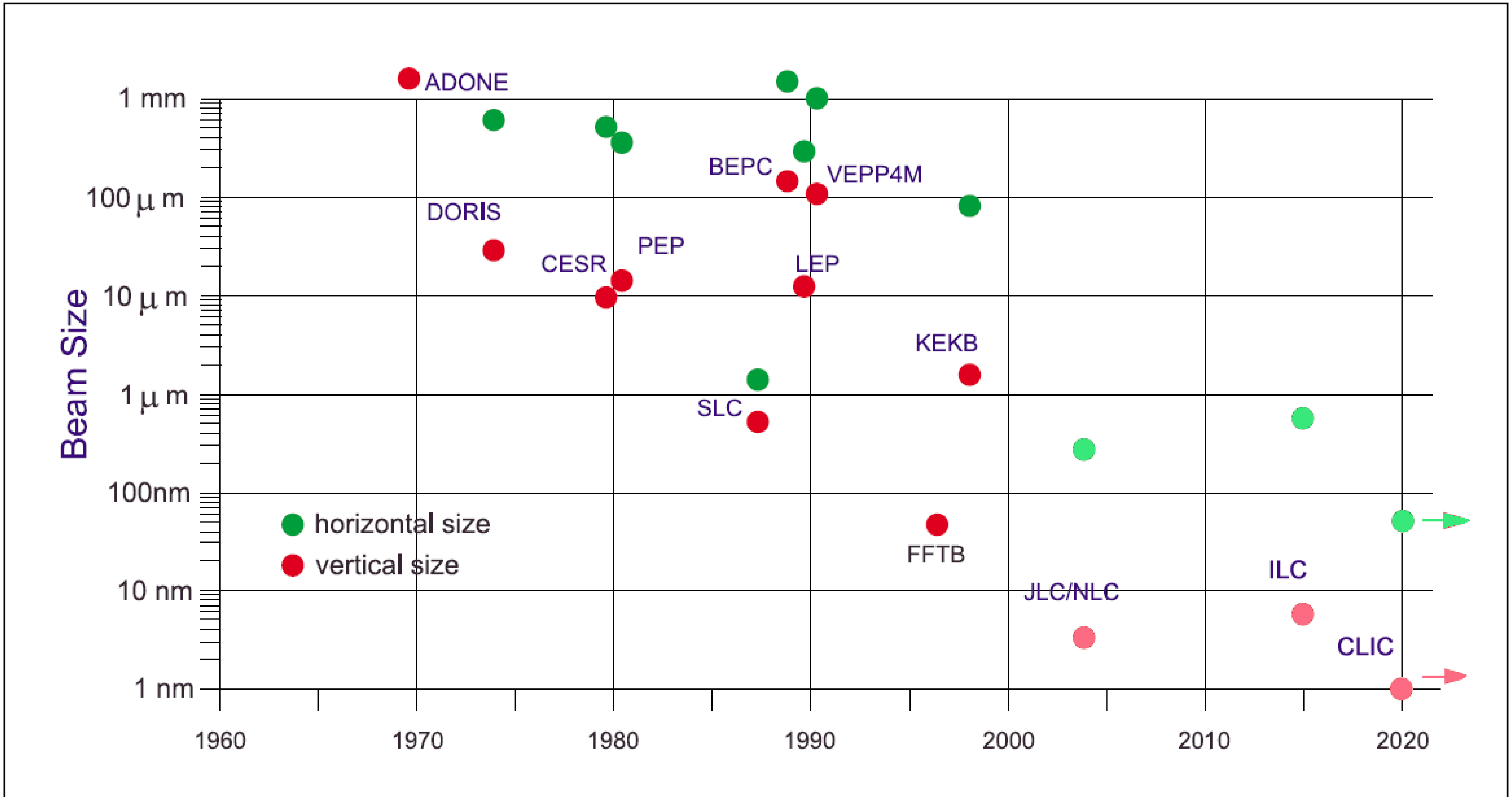
n_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
$\sigma_{x,y}$ = beam size at IP
H_D = beam-beam enhancement factor

A linear collider uses the beam pulses only once:

- Need to accelerate lots of particles
- Need very small beam sizes



The small beam size challenge



Adapded from S. Chattopadhyay, K. Yokoya, Proc. Nanobeam `02

LEP: $\sigma_x\sigma_y \approx 130\times6\ \mu m^2$

ILC: $\sigma_x\sigma_y \approx 500\times(3\text{-}5)\ nm^2$

Luminosity issue with intense beams - Disruption

Field of the opposite particle will distort the other beam during collision:

- Pinch effect (can become instable if two strong)
- Beam-beam deflections – use to adjust beam overlap and luminosity

beam-beam characterised by ***Disruption Parameter:***

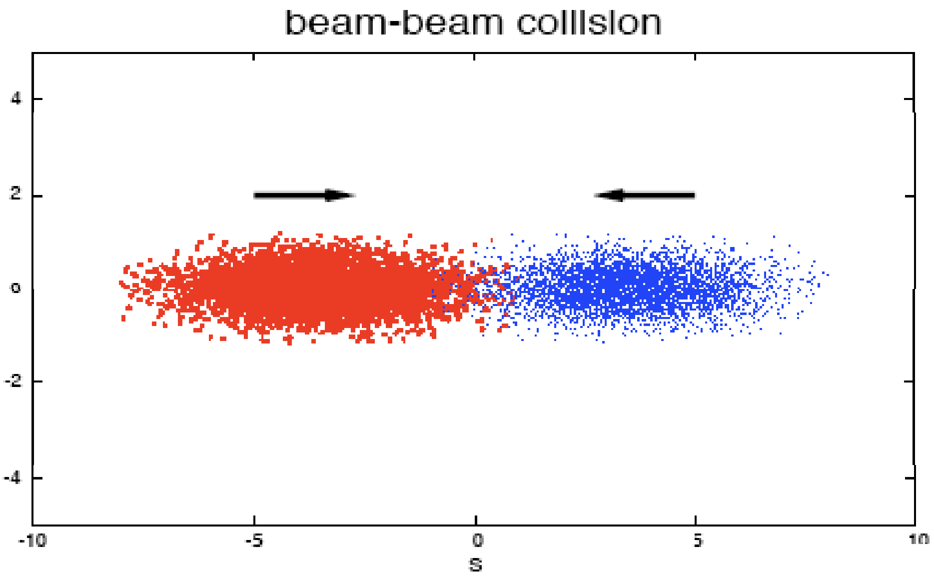
$$D_{x,y} = \frac{2 r_e N \sigma_z}{\gamma \sigma_{x,y} (\sigma_x + \sigma_y)}$$

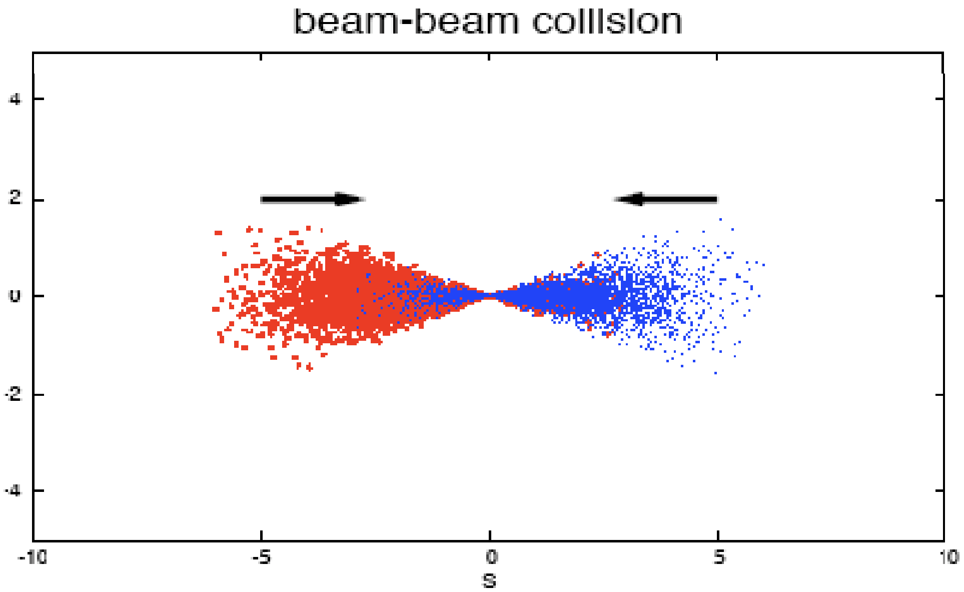
σ_z = bunch length

Enhancement factor (typically $H_D \sim 1.5 \div 2$) is given by:

$$H_{Dx,y} = 1 + D_{x,y}^{1/4} \left(\frac{D_{x,y}^3}{1 + D_{x,y}^3} \right) \left[\ln\left(\sqrt{D_{x,y}} + 1 \right) + 2 \ln \left(\frac{0.8 \beta_{x.y}}{\sigma_z} \right) \right]$$

Luminosity issue with intense beams - Disruption

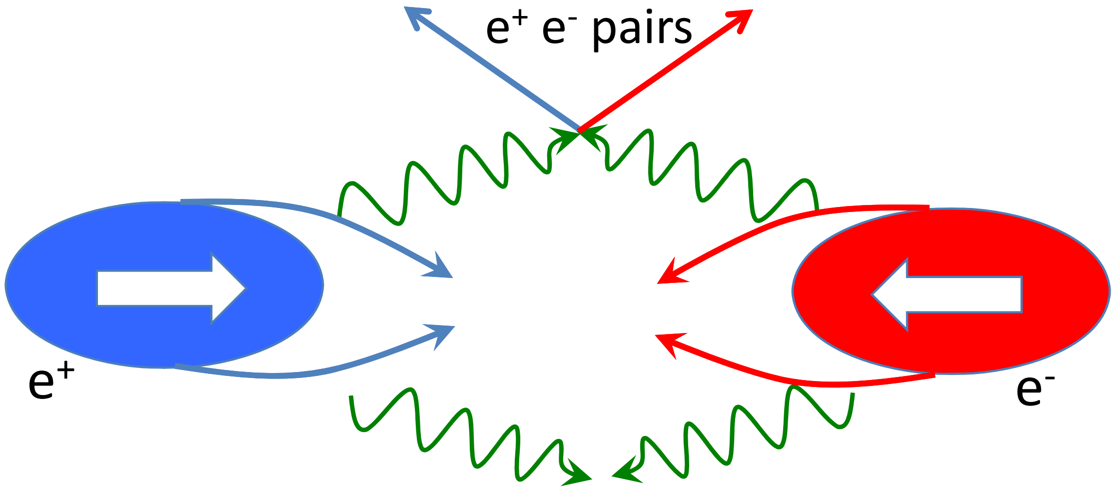




For LC, typical value of HD ~ 1-2

Luminosity issue with intense beams - Beamstrahlung

- Generation of Synchrotron Radiation photons of particles in the strong EM field of the opposite bunch



Beamstrahlung photons

- High energy Beamstralung photons can convert in strong field into e^+/e^- pairs: background for the detector

Coherent e^+e^- pairs

  - Direct photons conversion in strong fields
  - Negligible for ILC but high for CLIC : Few 10^8 particles per Bunch crossing

Incoherent e^+e^- pairs

  - Photons interacting with other electron/photon
  - Few 10^5 particles/Bunch crossing

Beam size for minimizing beamstrahlung

rms relative energy loss induced by Beamstrahlung

$$\delta_{BS} = 0.86 \frac{e r_e^3}{2 m_0 c^2} \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

we would like to make $(\sigma_x \sigma_y)$ small to maximise luminosity

and keep $(\sigma_x + \sigma_y)$ large to reduce δ_{SB}

$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$$

Trick: use "flat beams" with $\sigma_x >> \sigma_y$

Rule:

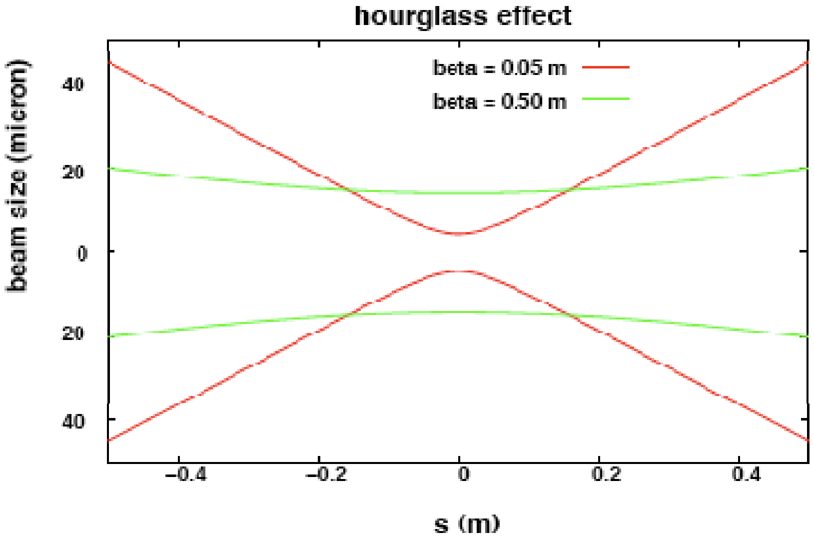
- Make σ_x **large to limit** δ_{BS}
- Make σ_y **as small as possible** to achieve high luminosity.

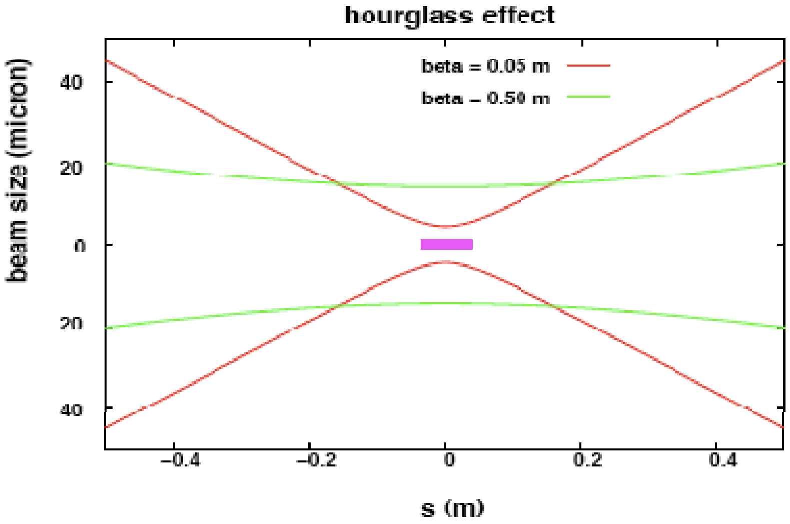
→ δ_{BS} ~ 2.4% @ ILC -- δ_{BS} ~ 29% @ CLIC

Hour glass effect – Bunch length

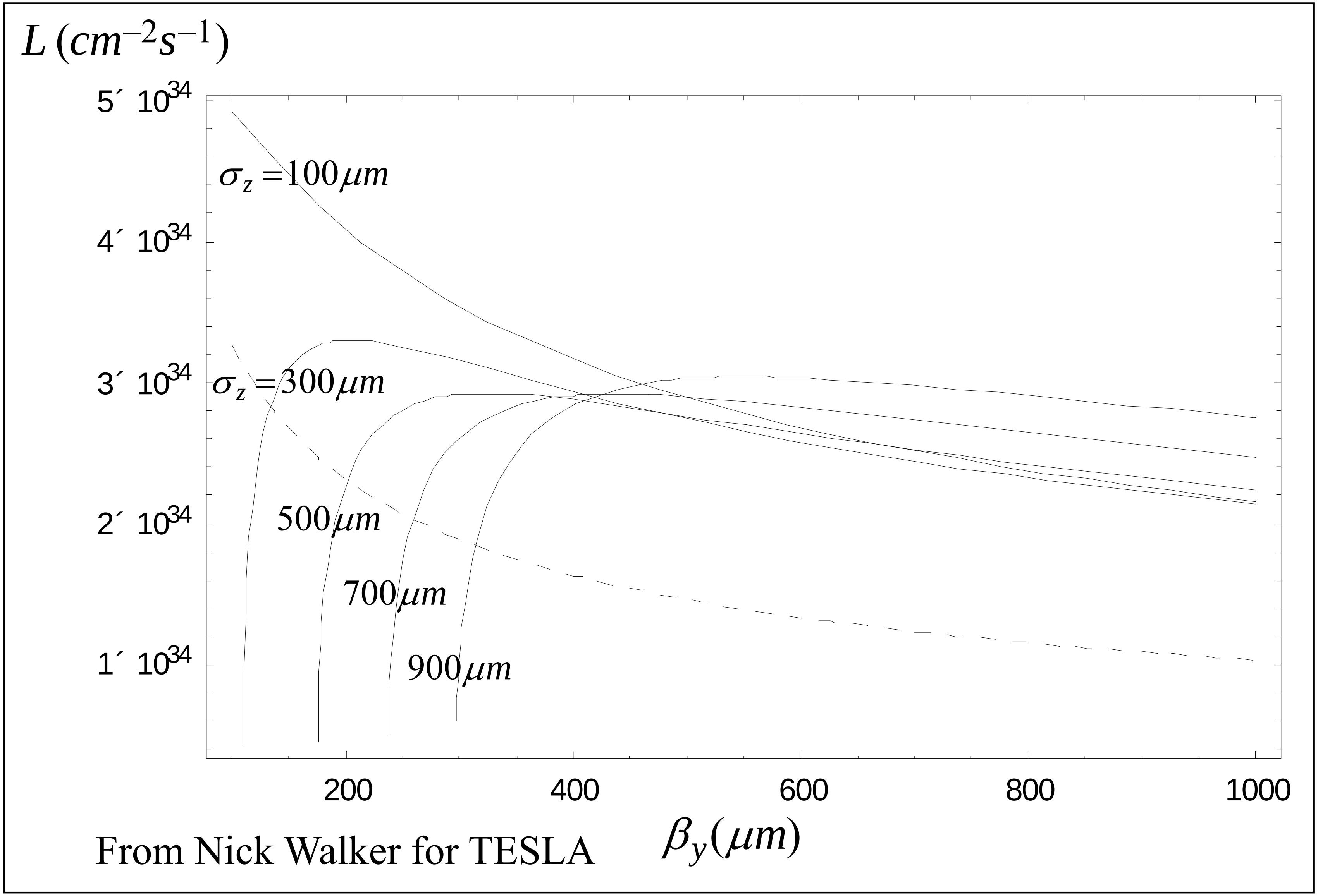
For achieving small Beta function (small beam size) at IP, the beta function rapidly increases as the particle move away from the collision point

Variation of beam size along the bunch





Hour glass effect – Bunch length



From Nick Walker for TESLA

Rule: Keep $\beta_y \sim \sigma_z$

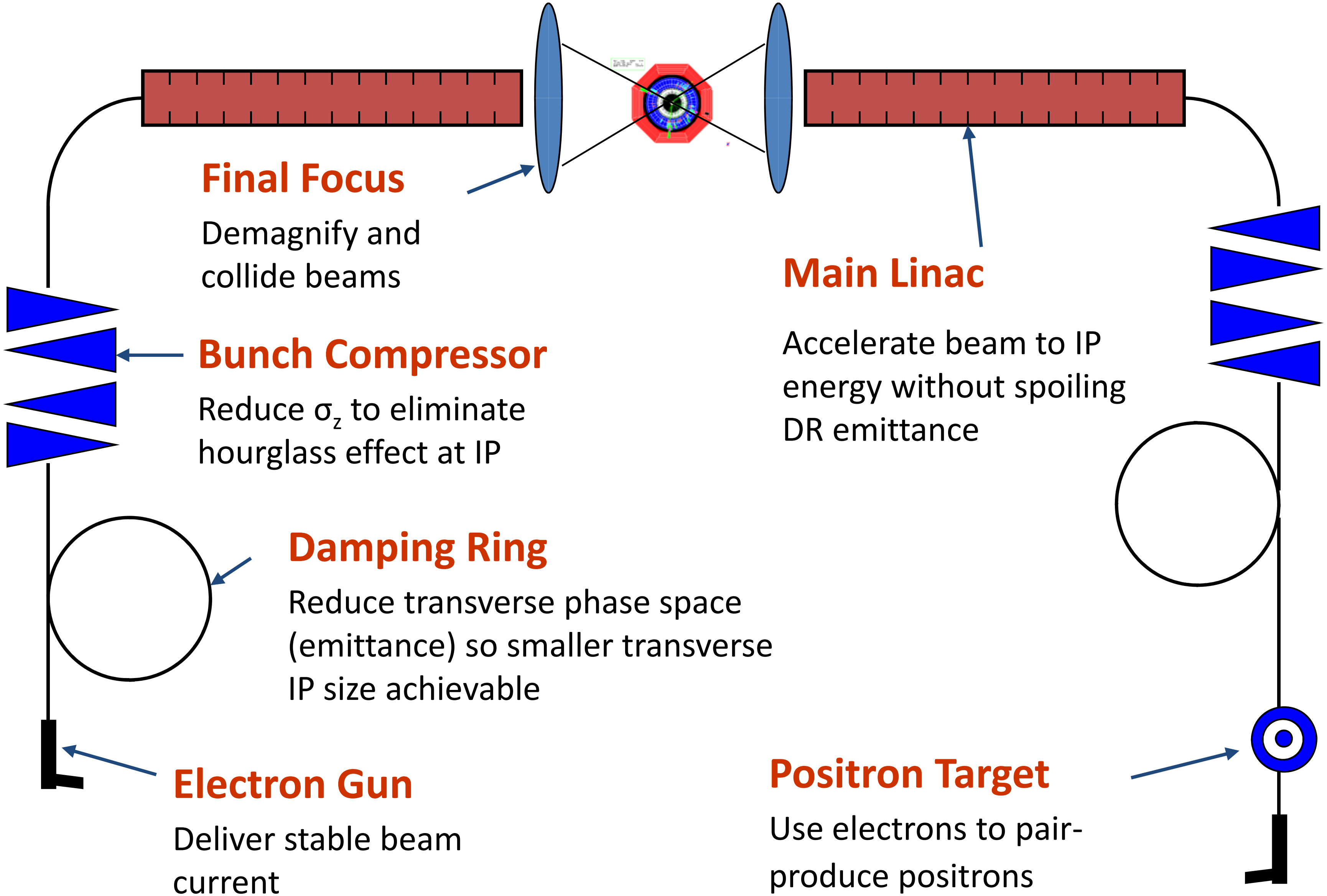
A final luminosity scaling for Linear collider ?

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D \quad \textit{with} \quad \beta_y \approx \sigma_z$$

- *high RF-beam conversion efficiency η_{RF} and RF power P_{RF}*
- **small normalised vertical emittance $\varepsilon_{n,y}$**
- **strong focusing at IP (small β_y and hence small σ_z)**

• Extremely small beam spot at Interaction Point	beam delivery system, stability
• Generation of small emittance	damping rings
• Conservation of small emittance	wake-fields, alignment, stability
• Generation and acceleration of short bunches	Bunch compressor

What would a future Linear collider look like ?



Final Focus

Demagnify and
collide beams

Bunch Compressor

Reduce σ_z to eliminate
hourglass effect at IP

Damping Ring

Reduce transverse phase space
(emittance) so smaller transverse
IP size achievable

Electron Gun

Deliver stable beam
current

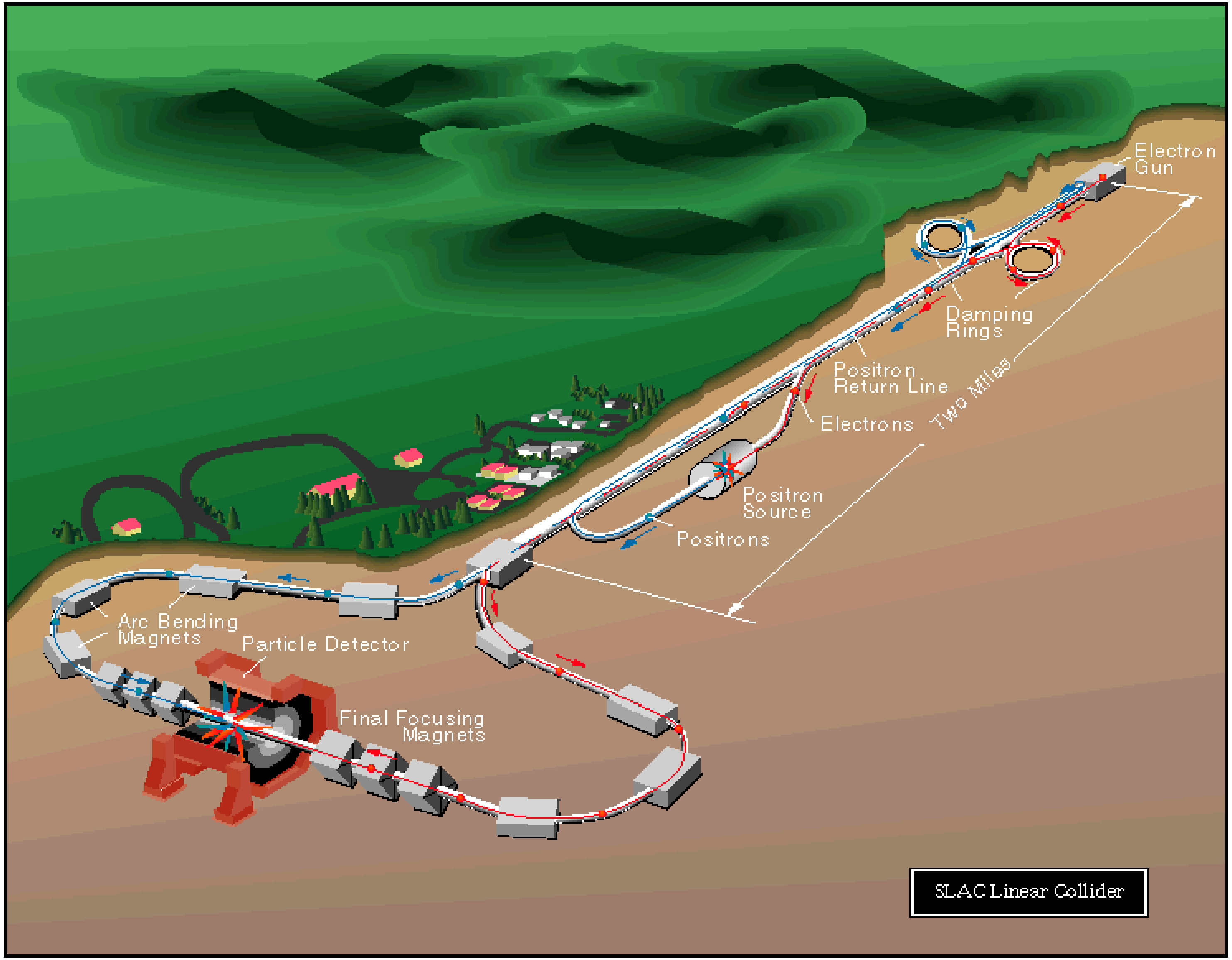
Main Linac

Accelerate beam to IP
energy without spoiling
DR emittance

Positron Target

Use electrons to pair-
produce positrons

Lesson from the first Linear collider : SLC



Built to study the Z_0 and demonstrate linear collider feasibility

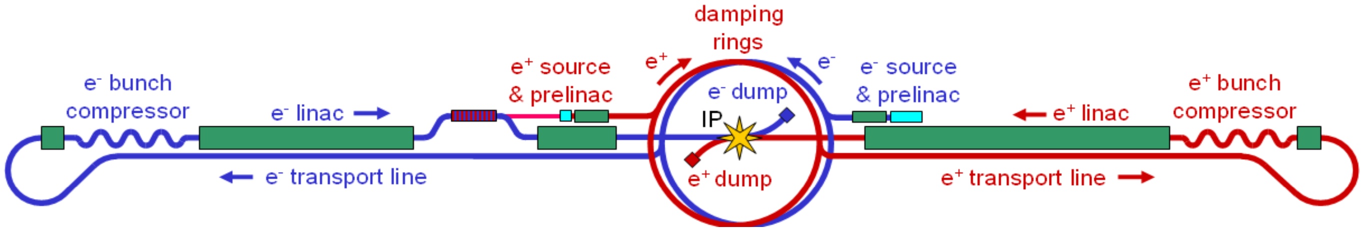
Single bunch

Energy = 92 GeV

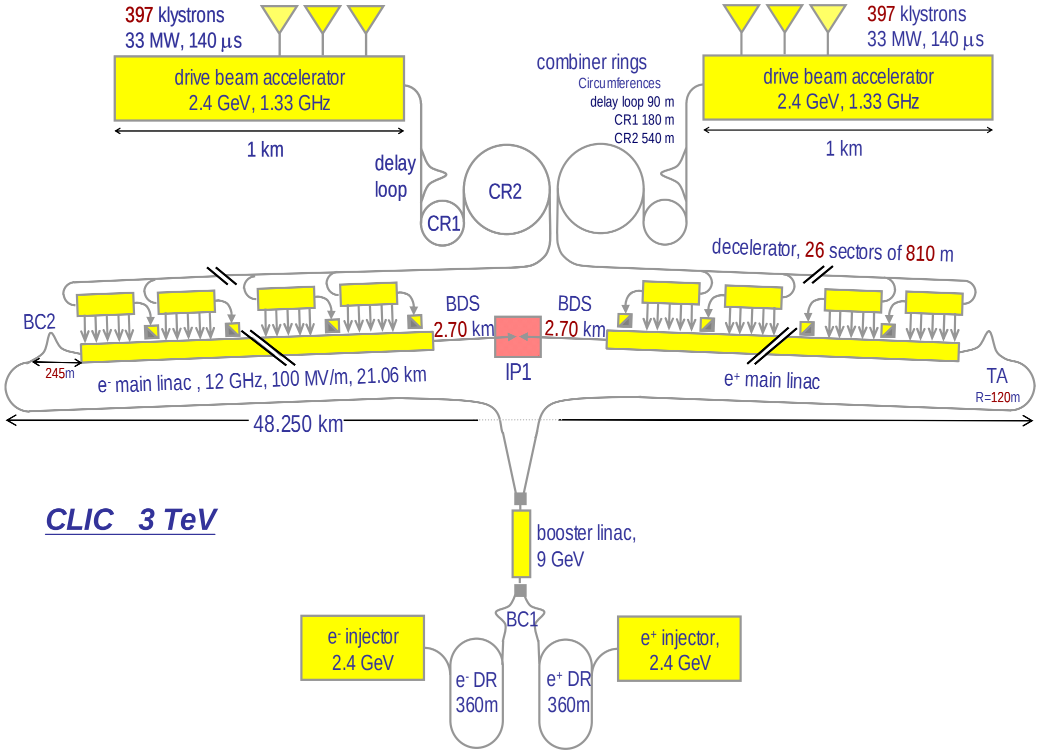
Luminosity = 3e30

Had all the features of a 2nd gen. LC except both e+ and e- shared the same linac

International Linear Collider / Compact Linear Collider



		CLIC	CLIC	ILC
E_{cms}	[TeV]	0.5	3.0	0.5
f_{rep}	[Hz]	50	50	5
f_{RF}	[GHz]	12	12	1.3
G_{RF}	[MV/m]	80	100	31.5
n_b		354	312	2625
Δt	[ns]	0.5	0.5	369
N	$[10^9]$	6.8	3.7	20
σ_x	[nm]	202	40	655
σ_y	[nm]	2.26	1	5.7
ϵ_x	[μm]	2.4	0.66	10
ϵ_y	[nm]	25	20	40
$\mathcal{L}_{total}$	$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	2.3	5.9	2.0
$\mathcal{L}_{0.01}$	$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	1.4	2.0	1.45



CLIC 3 TeV

Main Instrumentation challenge for Linear Collider

- Measuring small emittance and small beam size

  ~ 1um spatial resolution Transverse Profile Monitors

- Measuring Short bunch length

  ~ 20fs time resolution Longitudinal Profile Monitors

- Conservation of emittance over long distances relies on precise alignment

  high accuracy (5um) high resolution (50nm) Beam Position Monitor

Not talking about Damping rings Beam size monitor (lectures by Volker) using Synchrotron radiation (Interferometer, P-Polarisation, X-ray imaging systems)

Measuring small beam size in a Linear Collider

- Required high precision from the Damping ring to the Interaction Point (IP)
  - Beam energy ranges from 2.4GeV → 1.5TeV
  - Tens of km of beam lines – Big number of instruments

- Flat Beams ($\varepsilon_x >> \varepsilon_y$) : Think of a flat noodle !

- Small beam size
- High beam charge

→ High Charge Densities

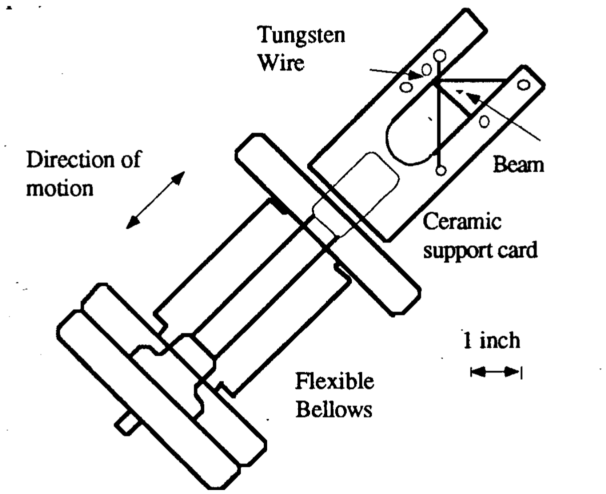
$> 10^{10}$ nC/cm^2

	ILC	CLIC
Beam Charge (nC)	7875	190
Hor. Emittance (nm)	655	40
Ver. Emittance (nm)	5.7	1

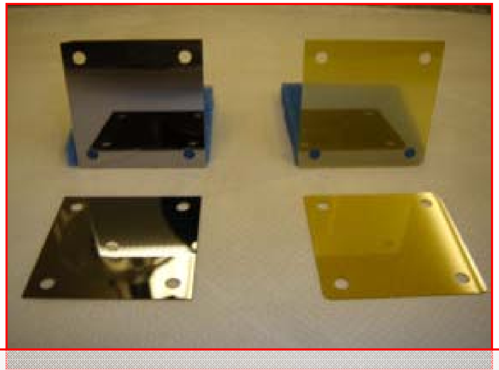
→ *The thermal limit for 'best' material (C, Be, SiC) is 10^6 nC/cm^2*

‘Beam Profile Horror Picture Show’

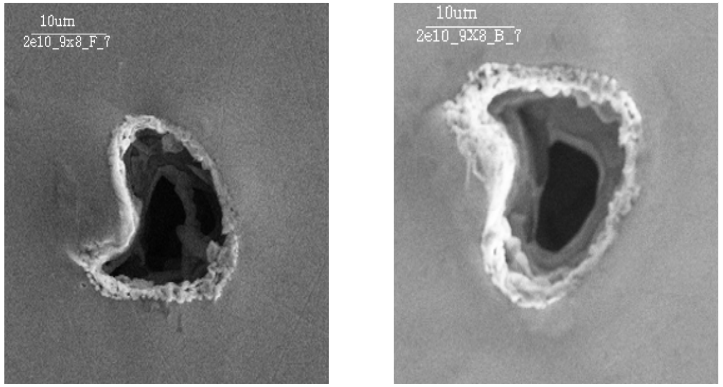
Wire Scanner



Optical Transition Radiation



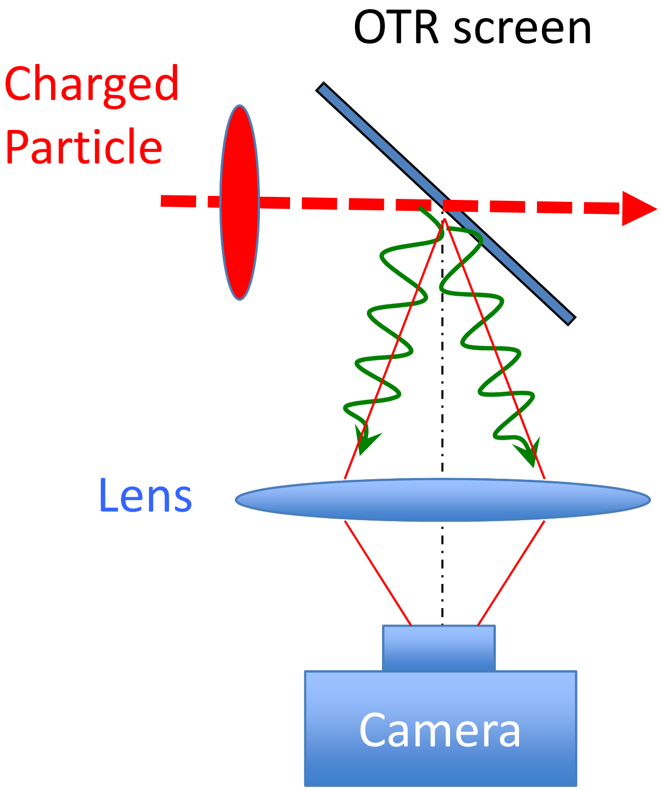
200μm thick mirror polished Si and CVD SiC wafer



<ins>Intercepting devices</ins> limited to single (or few) bunch mode

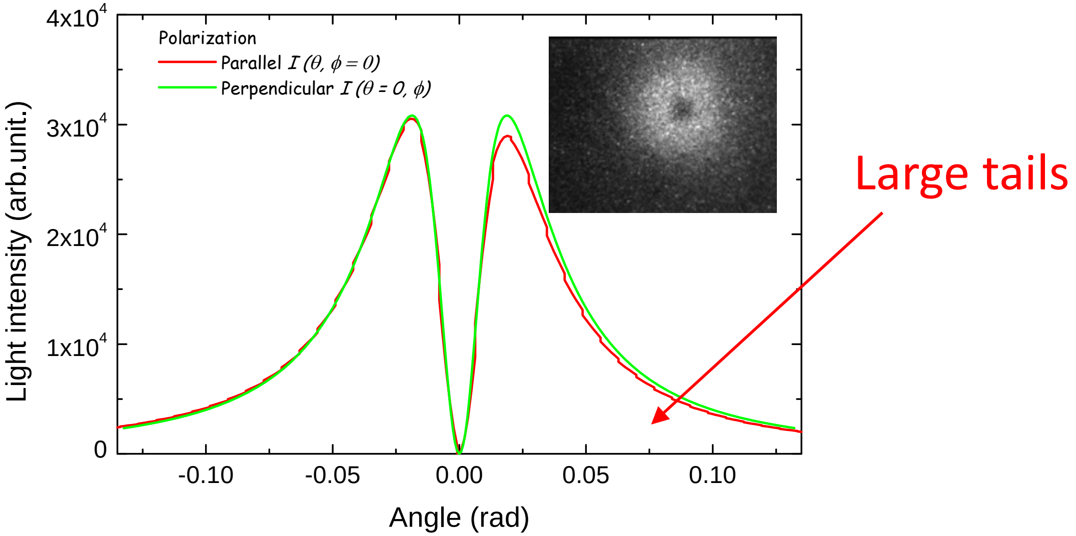
High Resolution Imaging System using OTR

- Diffraction effect would determine the resolution limit of the measurements



$$\Delta x \geq \frac{\lambda\,(\text{wavelength})}{\theta\,(\text{useful opening angle})}$$

- OTR angular distribution: Peak at 1/γ but large tails
  - Problem for very high energy particles



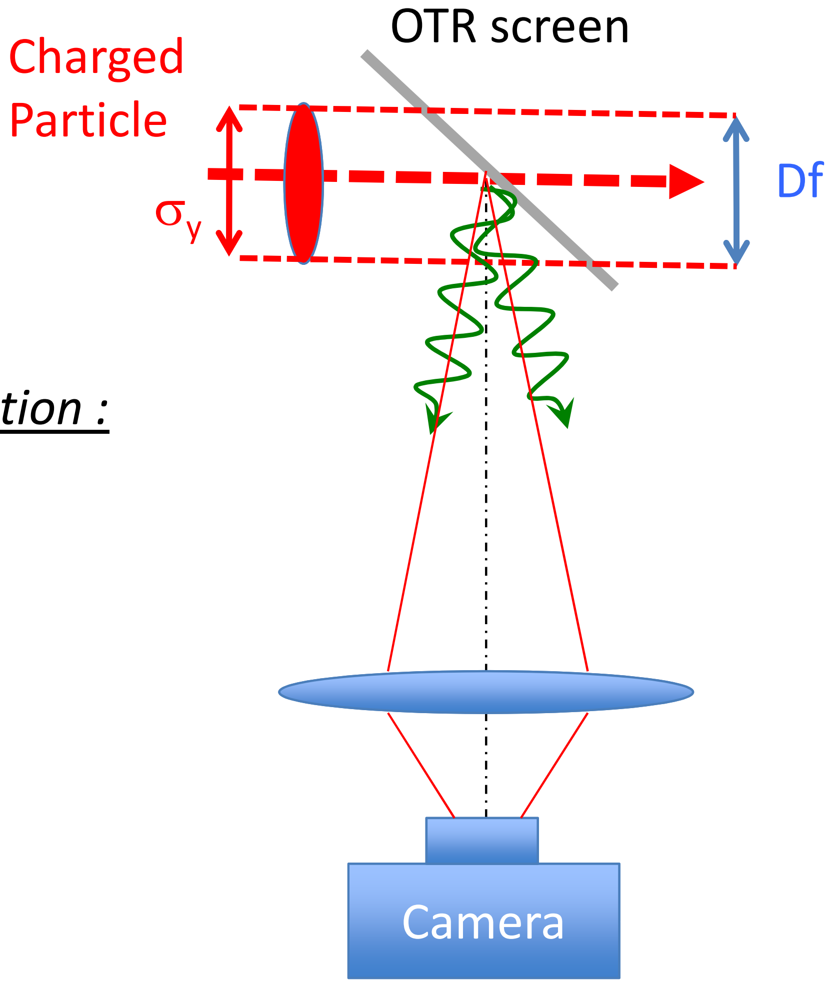
- Aperture of the focussing lens : θ >> 1/γ

X. Artru et al, **NIM AB 145 (1998) 160-168**

C. Castellano and V.A. Verzilov, **Physical Review STAB 1, (1998) 062801**

High Resolution Imaging System using OTR

- Depth of field limits the resolution because the image source is not normal to the optical axis

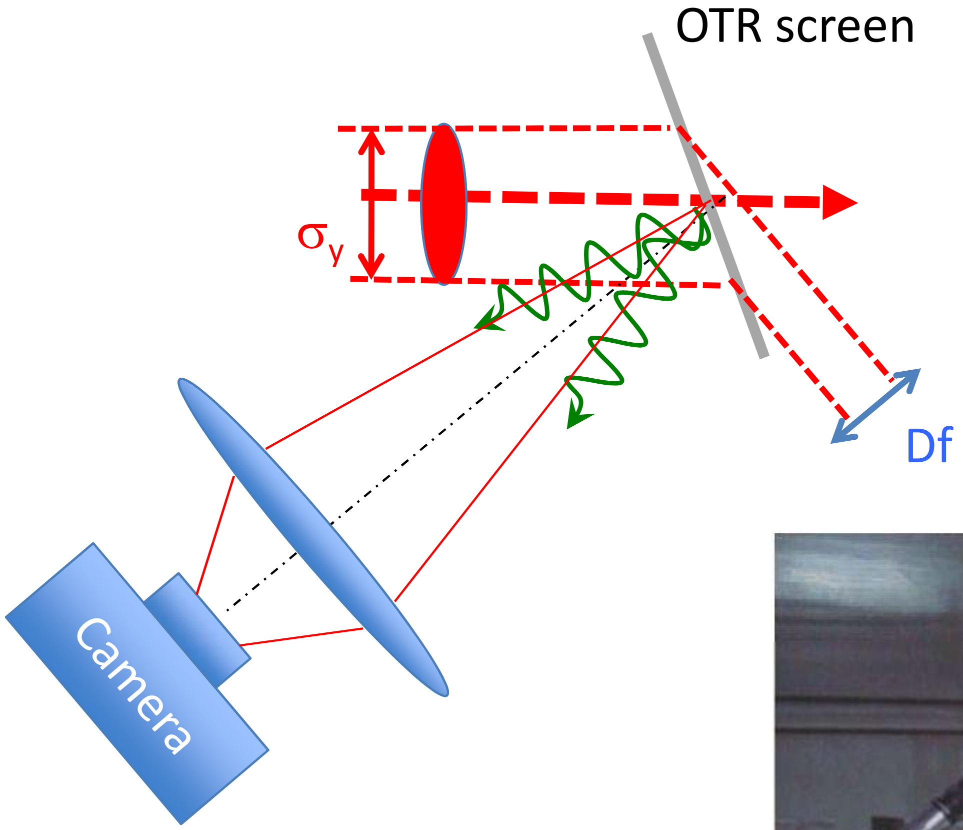


Classical OTR configuration :
90^o observation angle

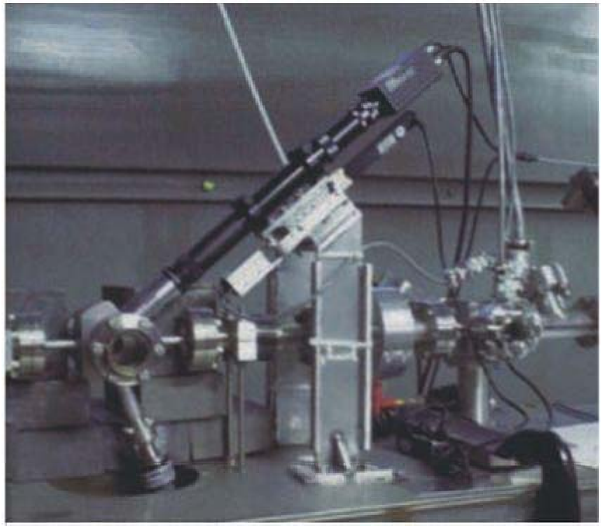
Make Df > σ_y

High Resolution Imaging System using OTR

- Imaging small beam size → large magnification → short Depth of field (Df)

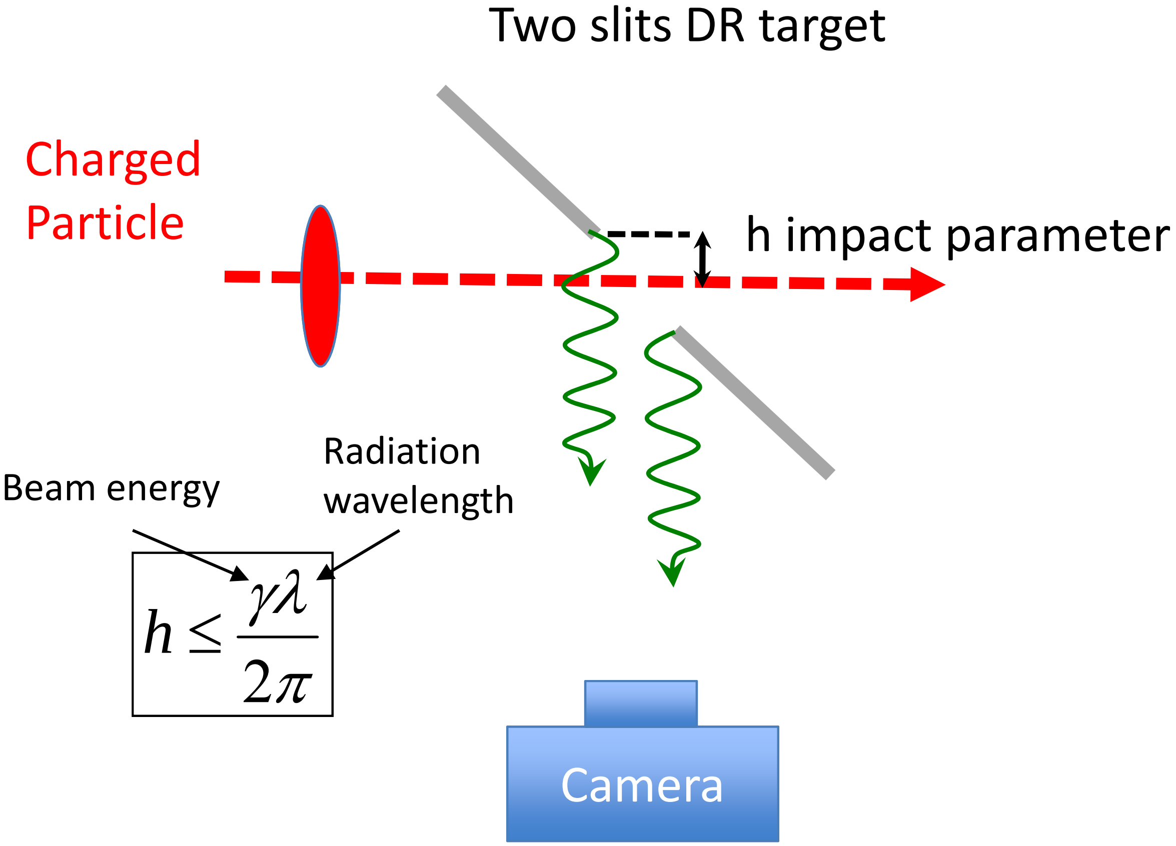


Smaller Df → Tilt the screen



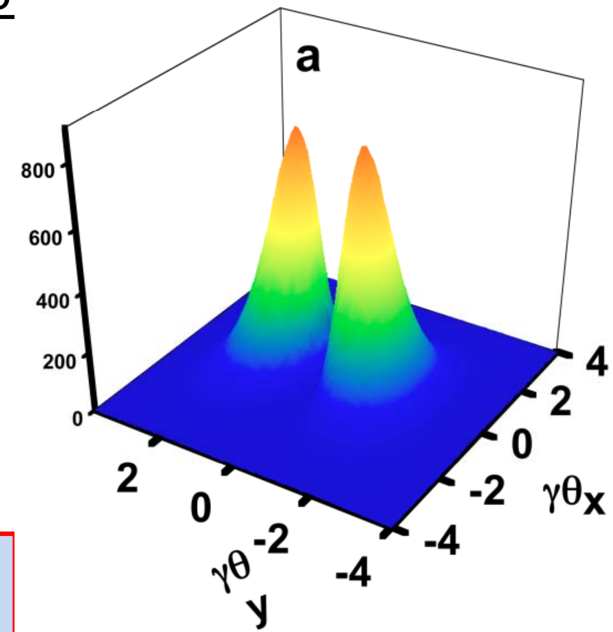
Beam size monitoring with Diffraction Radiation

- Non destructive alternative for beam size measurement (not imaging anymore)



$$h \leq \frac{\gamma\lambda}{2\pi}$$

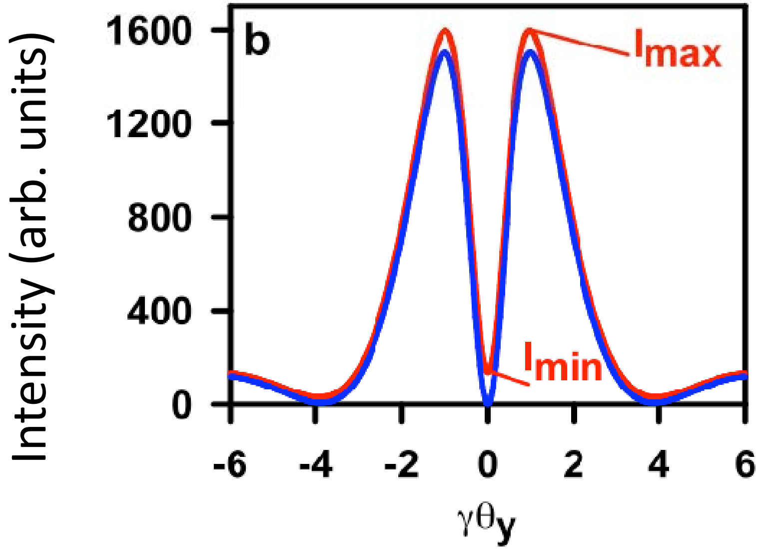
Measuring the angular distribution of the interference pattern between the DR emitted by the two slits



After the Damping ring the beam has few GeV and ODR is generated for reasonable values of h

Beam size monitoring with Diffraction Radiation

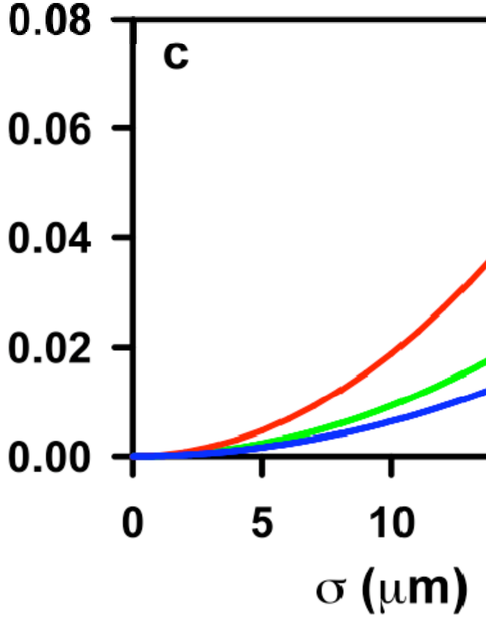
- Sensitivity to beam size is given by the visibility of the interference pattern
- Vertical (hor) polarization component depends on the vertical (hor) beam size



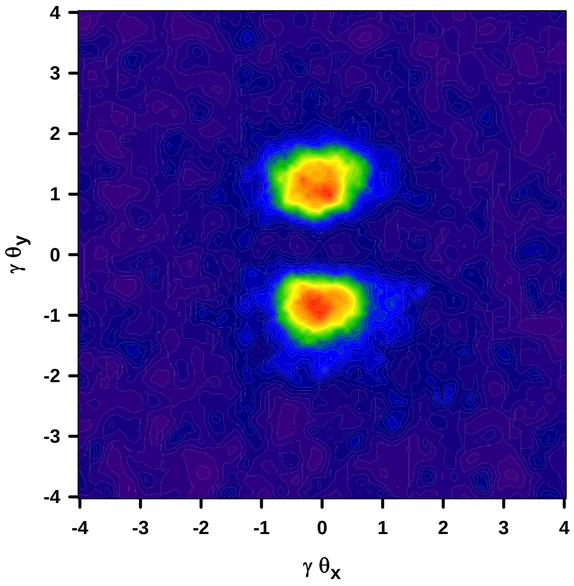
- The visibility strongly depends on the wavelength with an beam size sensitivity limit as follows

$$\boxed{\sigma > 0.05\frac{\gamma\lambda}{2\pi}}$$

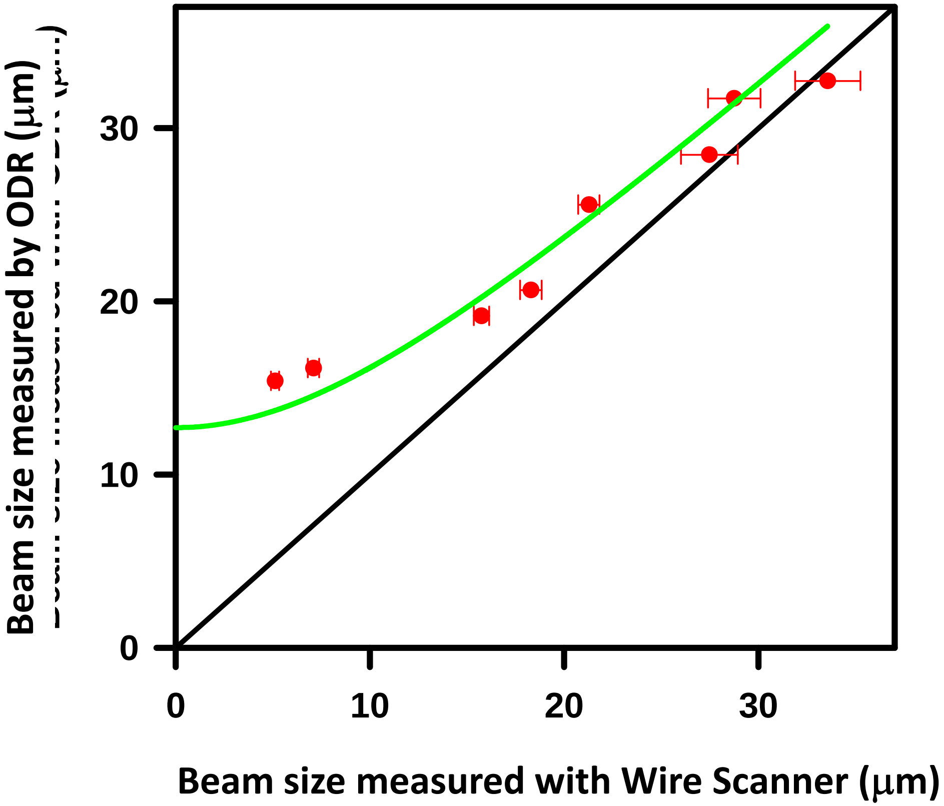
GO for short wavelength

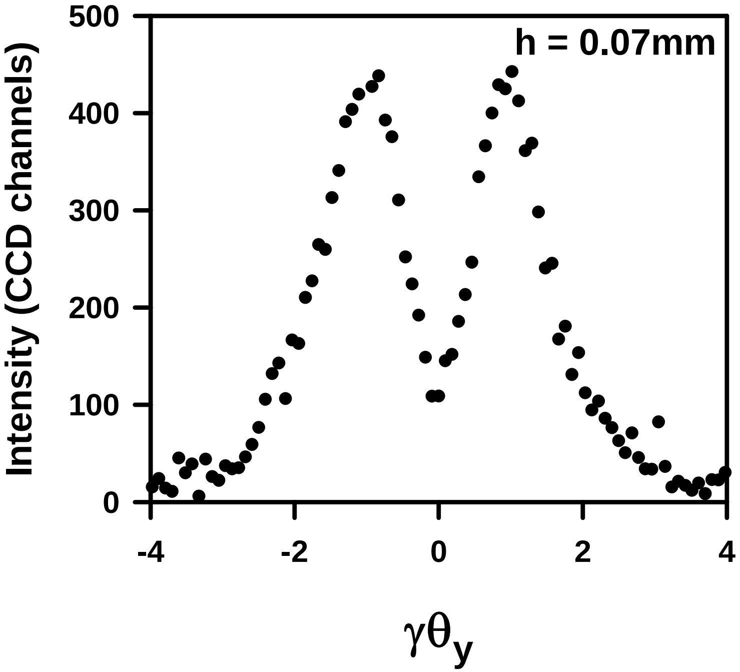


Beam size monitoring with Diffraction Radiation



Investigation on the low emittance beam at ATF, KEK, Japan
E=1.28GeV ; λ=445nm ; h=70μm





P. Karataev et al., Physical Review Letters **93** (2004) 244802
P. Karataev et al, Physical Letters **A345** (2005) 428

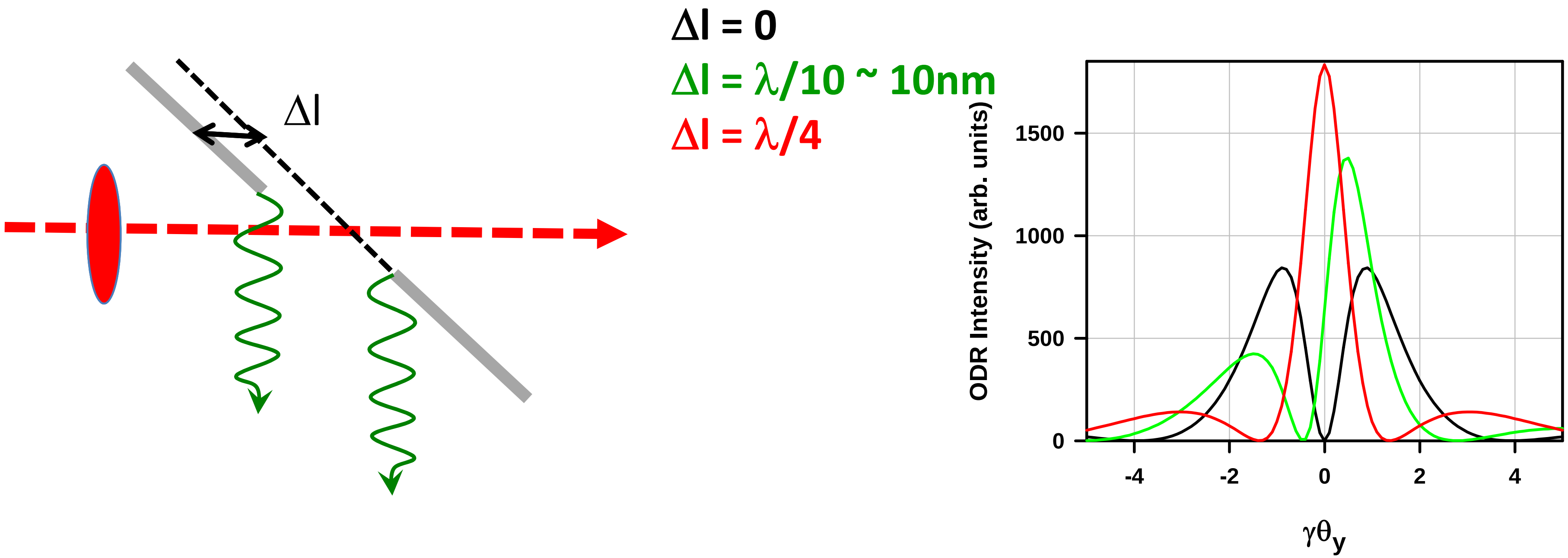
Beam size monitoring with Diffraction Radiation

- Push the technology in the EUV regime (~100nm) to bring the resolution in the 1-10μm range

- Not usable for ultra-high beam energy : >10GeV

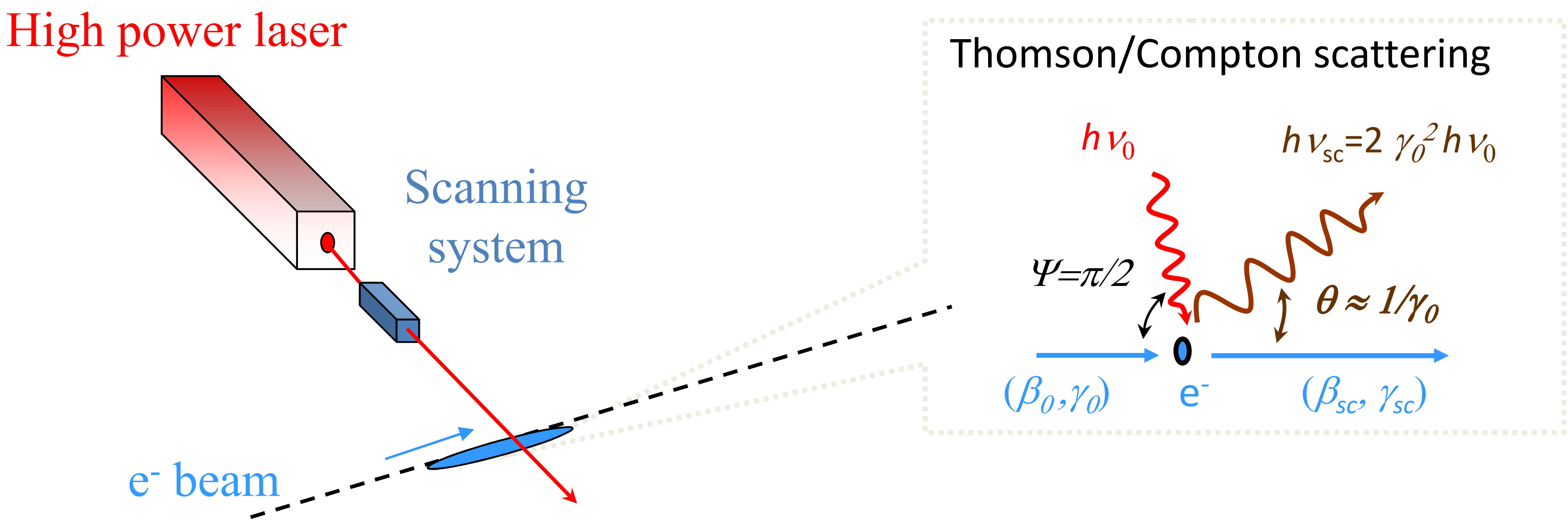
Used in Linear collider from the Damping to the Main Linac (40kms of beam line - ~70 Devices in CLIC)

- Mechanical challenge for the slit technology



Beam size monitoring with Laser Wire Scanner

Baseline solution for linear collider: high spatial resolution would rely on Laser Wire Scanner



Beam size monitoring with Laser Wire Scanner

Laser Beam

λ_0 : Laser wavelength

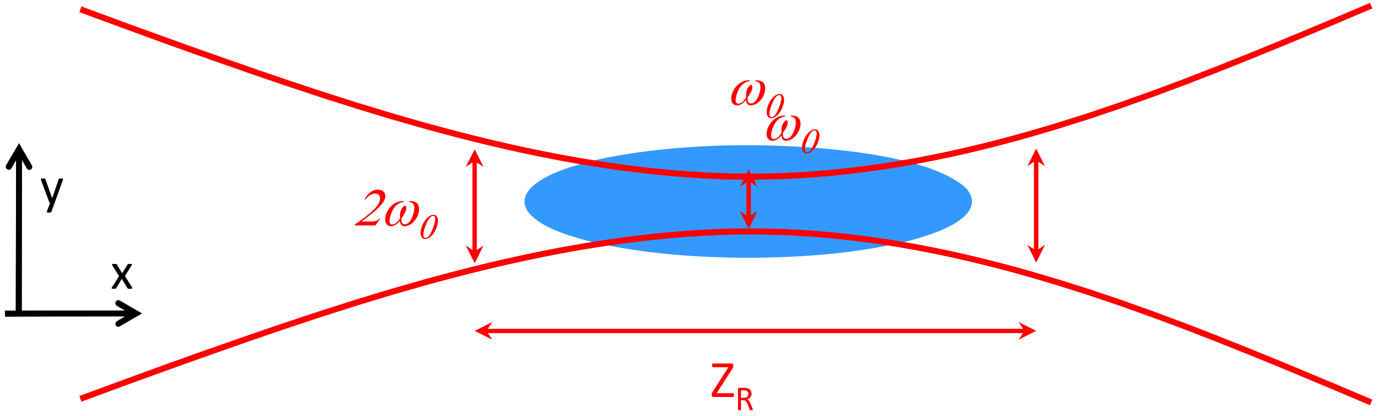
ω_0 : Laser waist size

Z_R : Rayleigh range

Electrons Beam

σ_y : ver. beam size

σ_x : hor. beam size



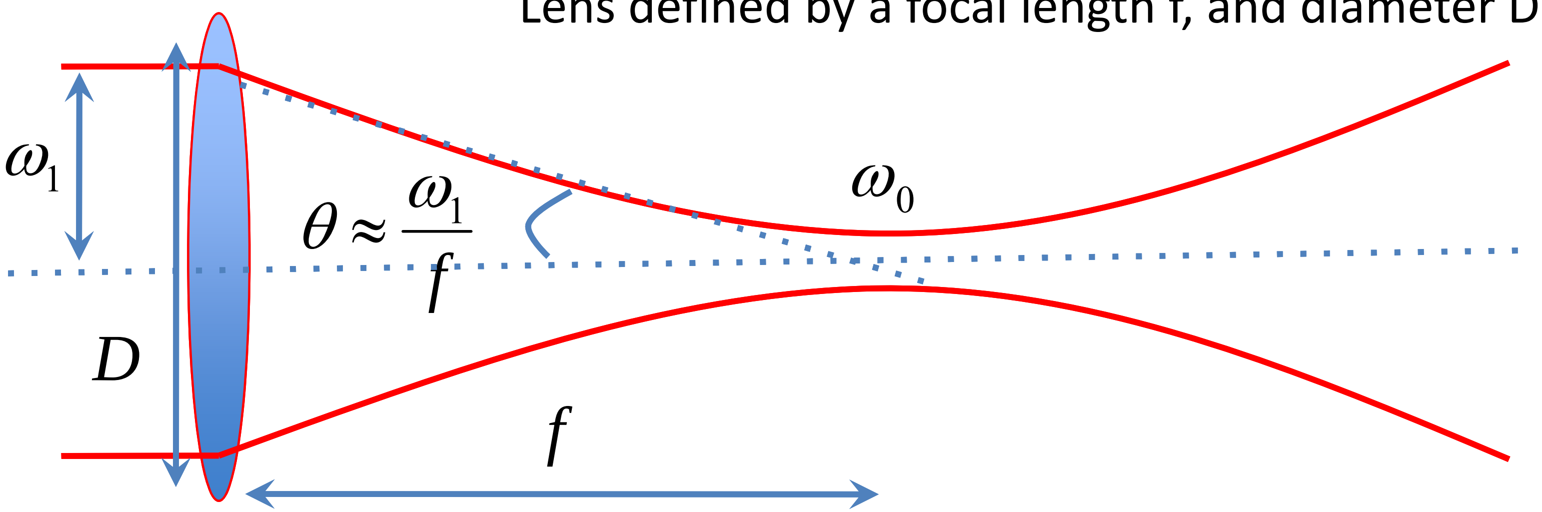
- The number of X-rays produced is given by $$N_{\text{interaction}} \approx \frac{\sigma \cdot N_e \cdot N_{laser}}{A}$$

with A the interaction area, N_e and N_{laser} are the number of electrons and photons in *A*

Beam size monitoring with Laser Wire Scanner

- High spatial resolution need very focused laser beam: Need a optimum Focusing system

Lens defined by a focal length f, and diameter D : $F\# = \frac{f}{D}$



Performance of Laser : M^2=1 for pure Gaussian distribution

- Diffraction $\omega_{diffraction} = \frac{M^2\lambda}{\pi\theta} \approx \frac{M^2\lambda}{\pi} F\#$

Smaller F# is better

- Spherical aberration $\omega_{spher} \propto \frac{D}{2F\#^2}$

For the single lens,
small F# makes spherical aberration large.

→ *Minimize spherical aberration using several lenses*

Beam size monitoring with Laser Wire Scanner

Design for ATF2 LWS by G. Blair et al

$F\# = 2$

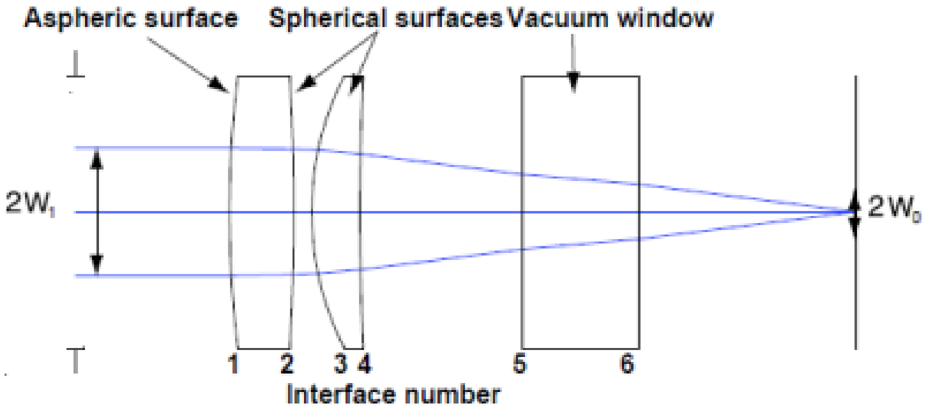
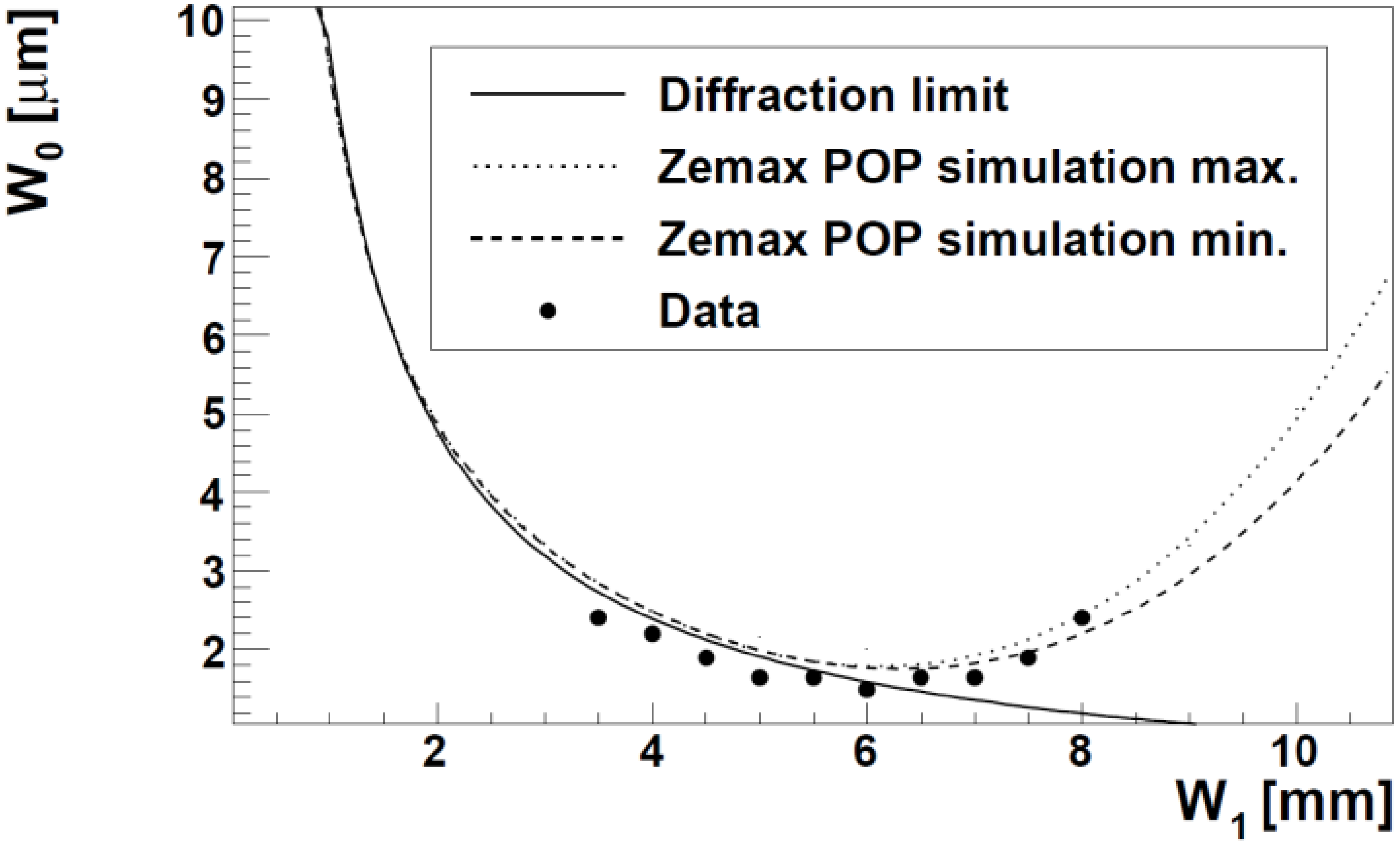


FIG. 7. Color online. Diagram of the final focus lens.

Interface number	Shape	Radius [mm]	Thickness [mm]	From	To
1	Even asphere	117.126106	7.093310	Air	Silica
2	Spherical	−250.070725	1.987140	Silica	Air
3	Spherical	33.118324	5.309160	Air	Silica
4	Spherical	274.998672	17.985135	Silica	Air
5	Spherical	Infinity	12.700000	Air	Silica
6	Spherical	Infinity	24.075710	Silica	Vacuum

Beam size monitoring with Laser Wire Scanner

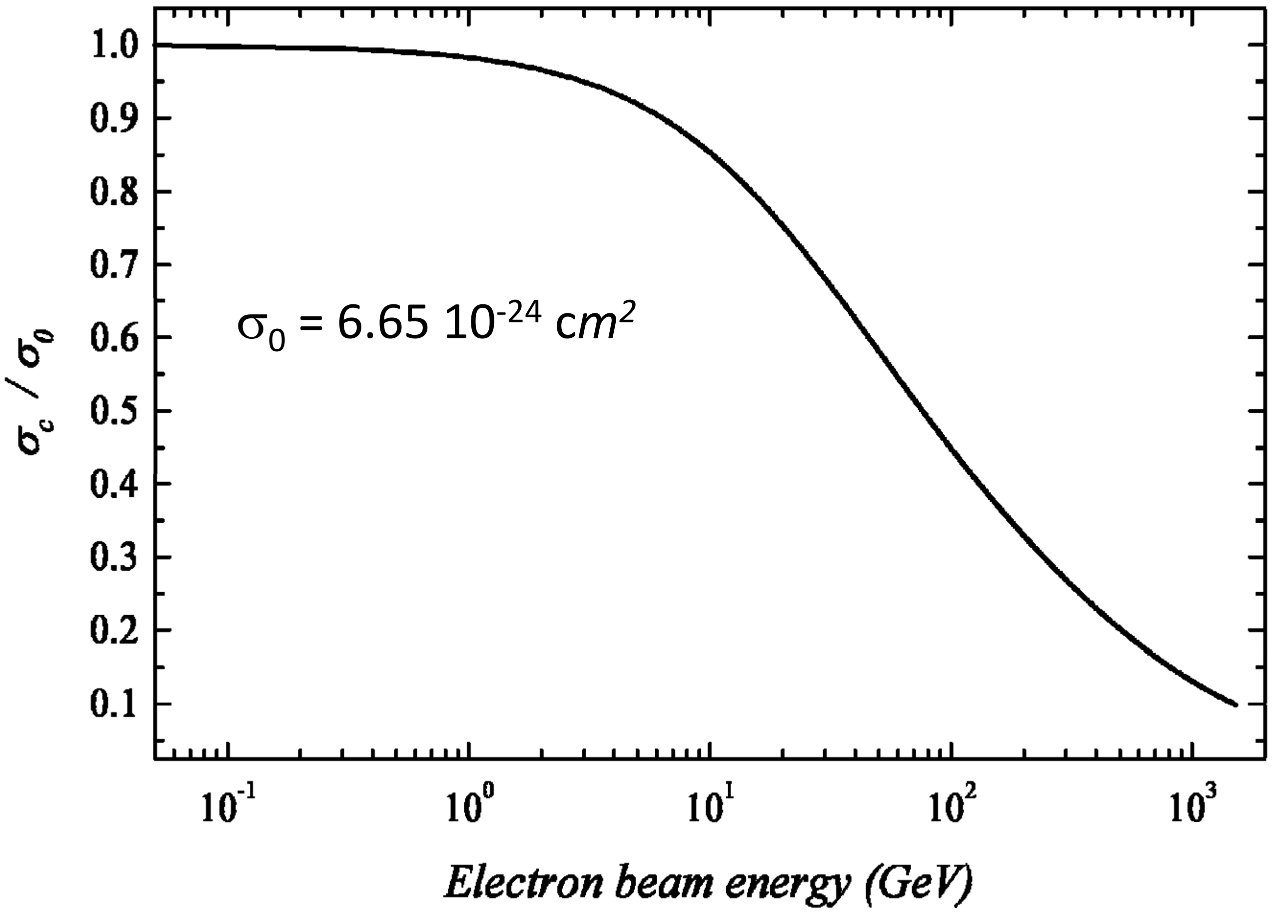
Design for ATF2 LWS by G. Blair et al



GO to smaller wavelength to do better (green → UV)

Beam size monitoring with Laser Wire Scanner

- At high energy, the Compton cross section gets smaller

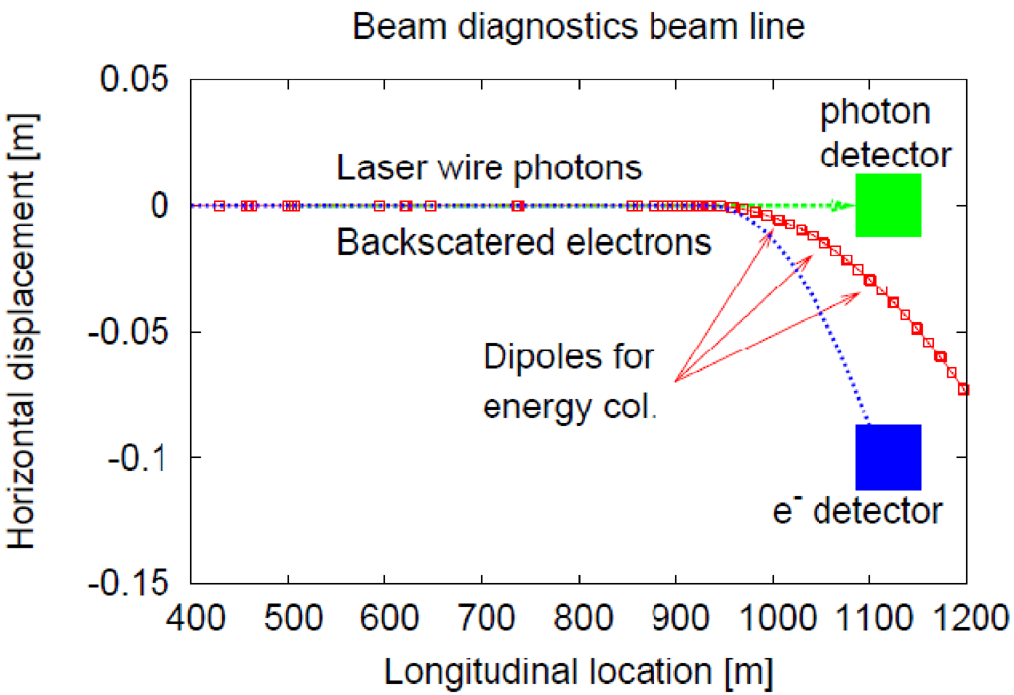


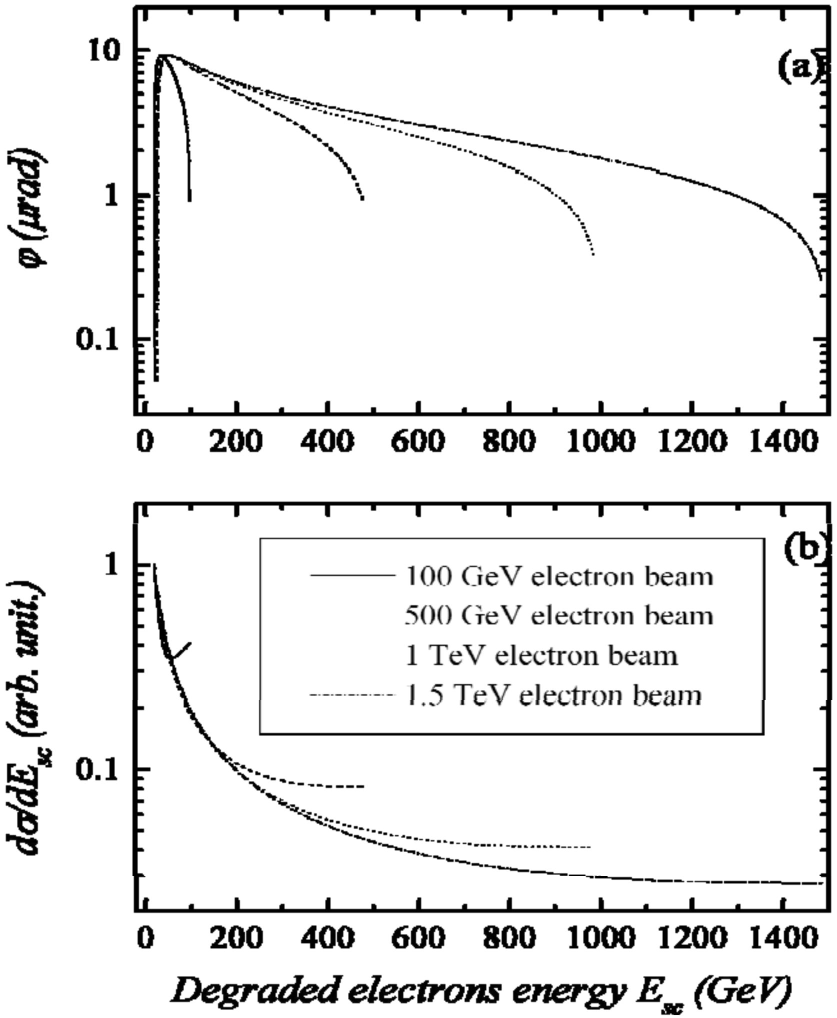
- The number of interaction produced is given by $N_{\text{interaction}} \propto \sigma \cdot N_e \cdot N_{laser}$

→ *Increase the Laser Power (10MW and more)*

Beam size monitoring with Laser Wire Scanner

- At high energy (>10GeV) the detection system can be easily done either using the scattered photons or the scattered electrons





Measuring Short bunches with femtosecond time resolution

- Want capability of compressing by a factor 50: Done in two steps to avoid emittance dilution

	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

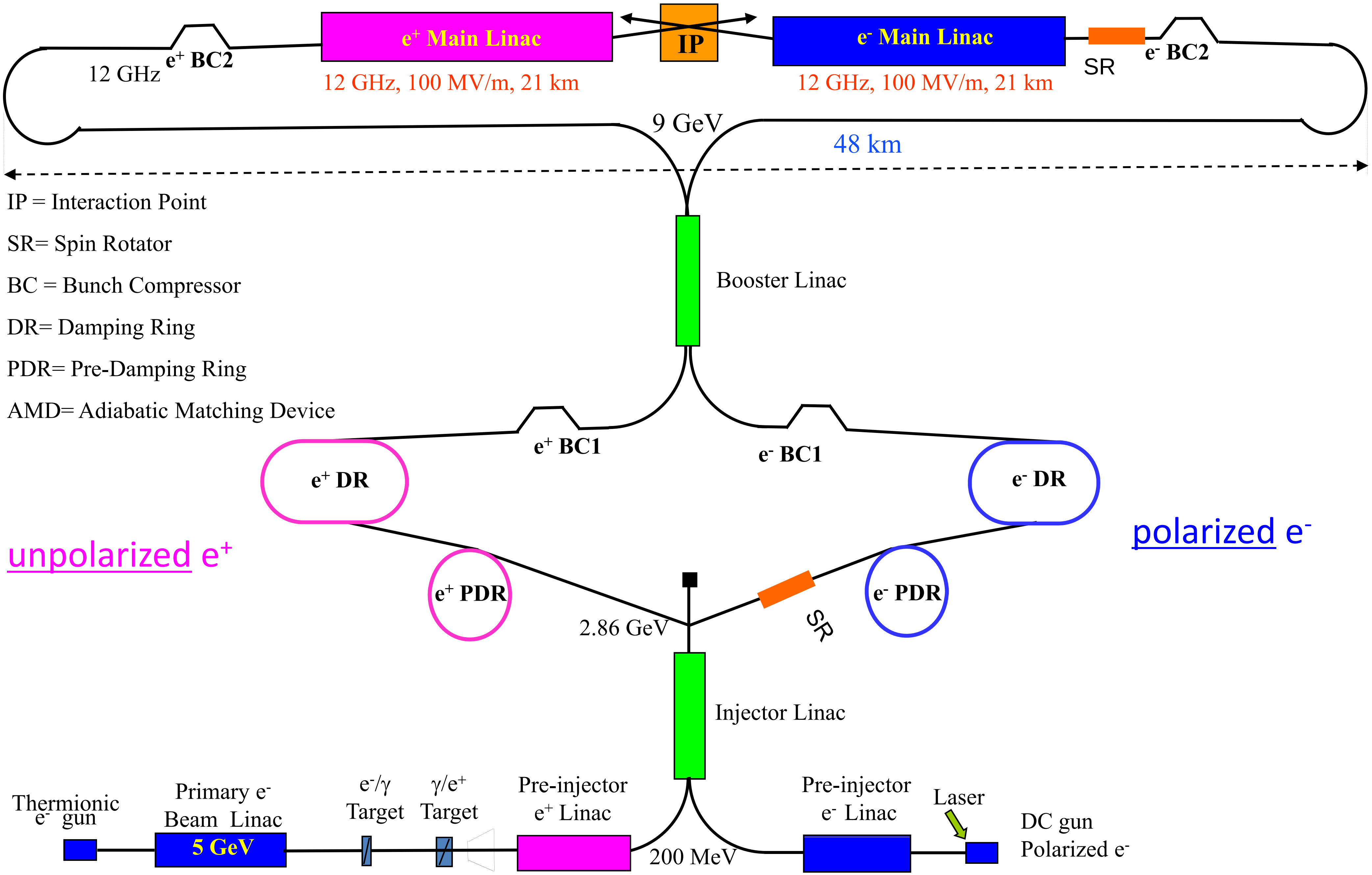
- High resolution monitor for single shot measurement

  - RF deflector : Excellent time resolution but destructive

  - *Coherent Diffraction radiation for online measurement and feedback system*

  - EO techniques for single shot longitudinal profile monitoring

Compact Linear Collider



e+ Main Linac

IP

e- Main Linac

12 GHz

e+ BC2

12 GHz, 100 MV/m, 21 km

12 GHz, 100 MV/m, 21 km

SR

e- BC2

9 GeV

48 km

IP = Interaction Point

SR= Spin Rotator

BC = Bunch Compressor

DR= Damping Ring

PDR= Pre-Damping Ring

AMD= Adiabatic Matching Device

Booster Linac

e+ BC1

e- BC1

e+ DR

e- DR

unpolarized e+

polarized e-

e+ PDR

e- PDR

2.86 GeV

SR

Injector Linac

Thermionic e- gun

Primary e- Beam Linac

5 GeV

e-/γ Target

γ/e+ Target

Pre-injector e+ Linac

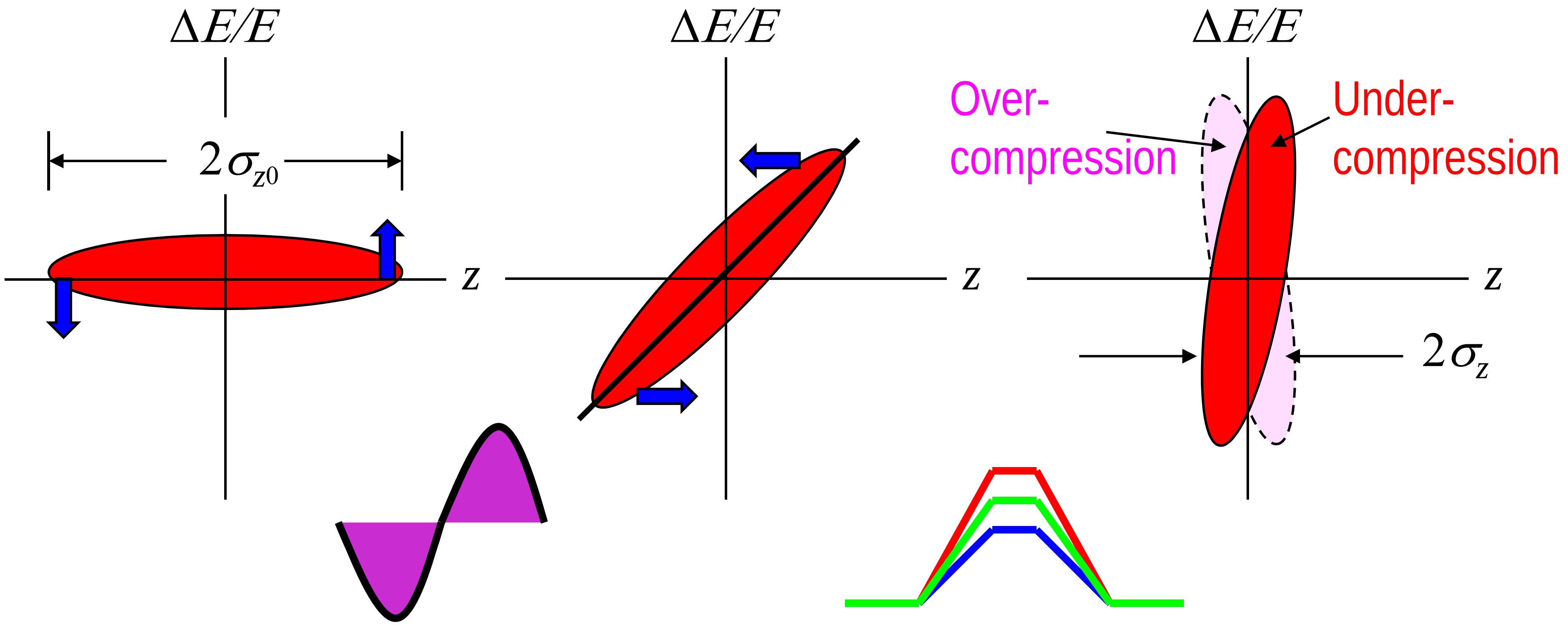
200 MeV

Pre-injector e- Linac

Laser

DC gun Polarized e-

Bunch compressors



$V = V_0 \sin(\omega\tau)$

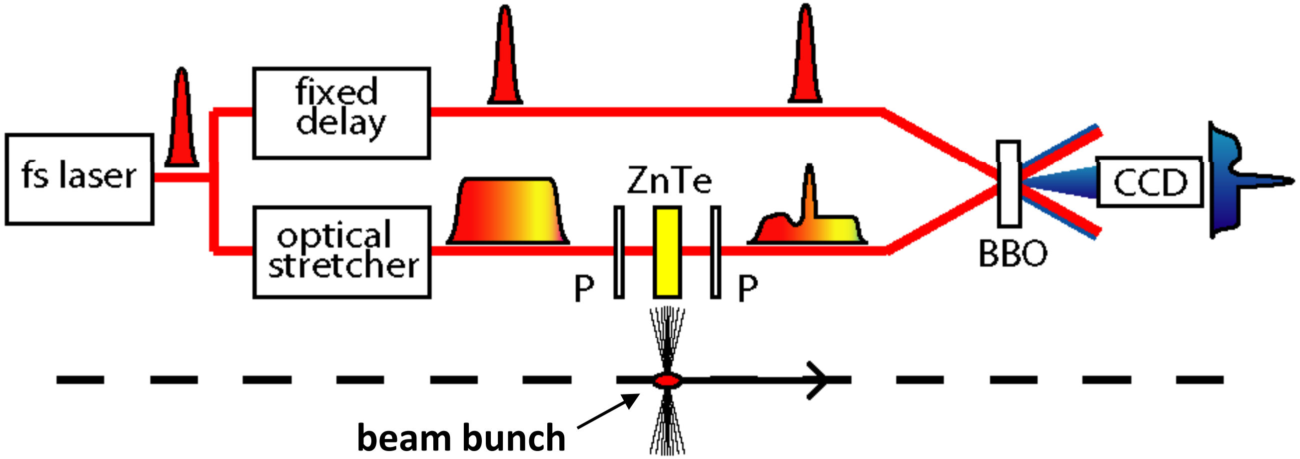
$\Delta z = R_{56} \Delta E/E$

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

EO Temporal decoding

Single shot high-resolution



- *Encoding the bunch long. Profile in an intensity modulation of a laser pulse amplitude*

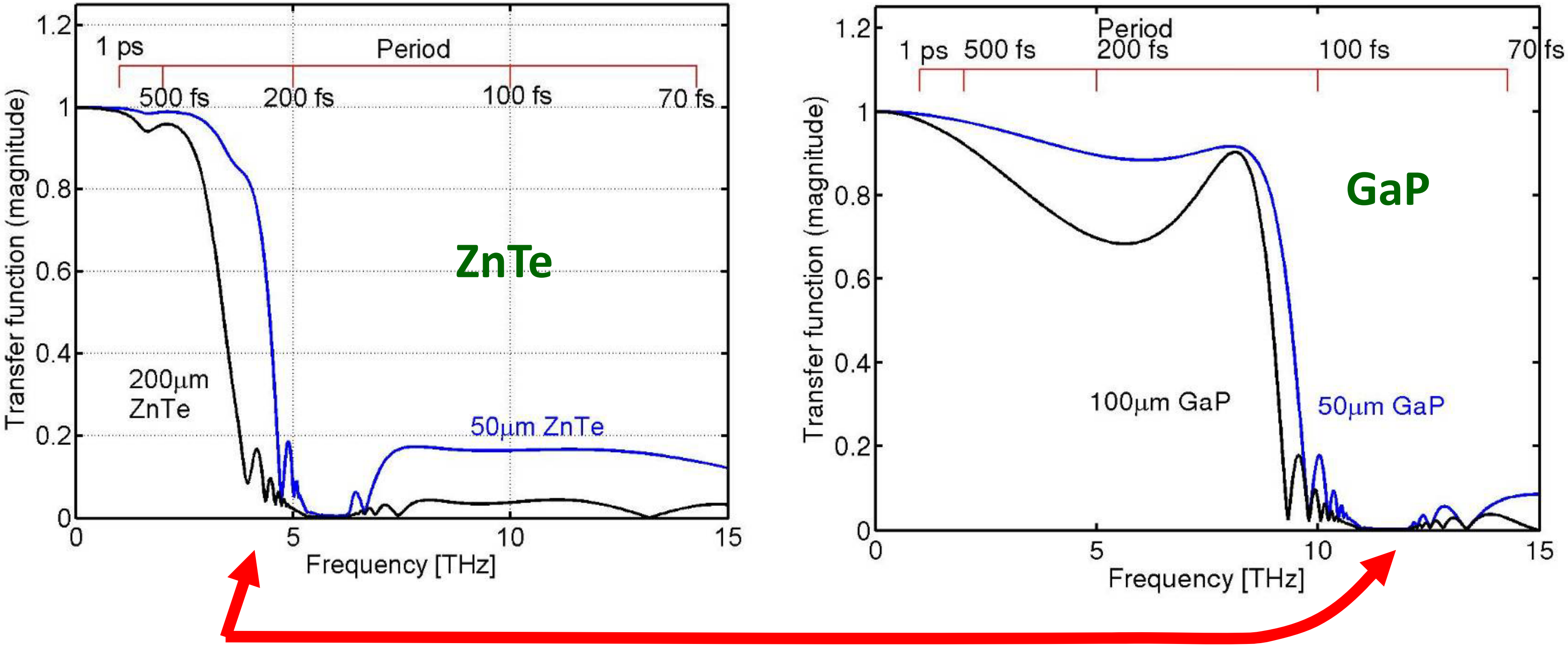
- *Measured the* laser pulse leaving EO crystal via single-shot cross correlation in BBO using a short laser pulse

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

W.A. Gillespie & S. Jamison

Encoding Time resolution

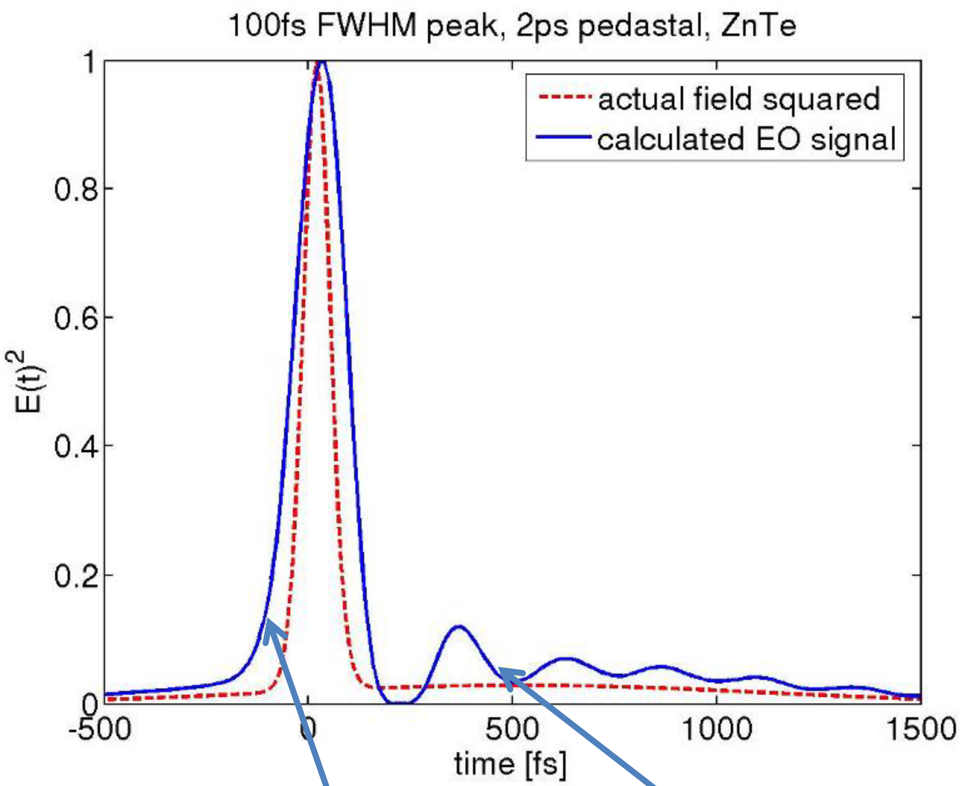
Spectral limitations of the Crystal

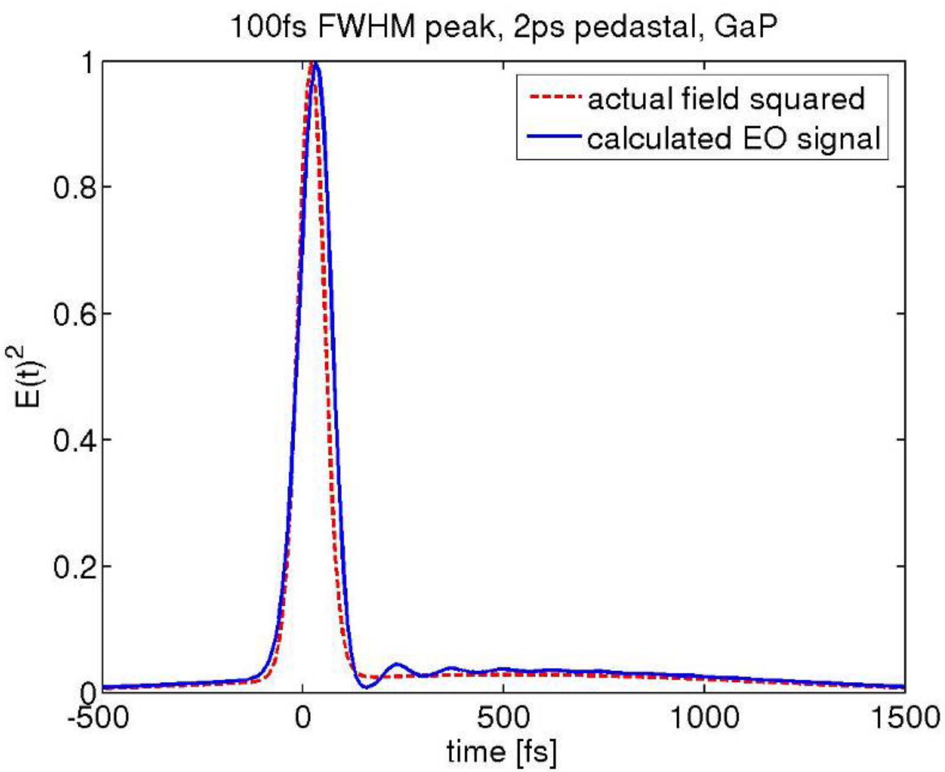


Phonon resonances

W.A. Gillespie & S. Jamison

Encoding Time resolution





Bandwidth limitation

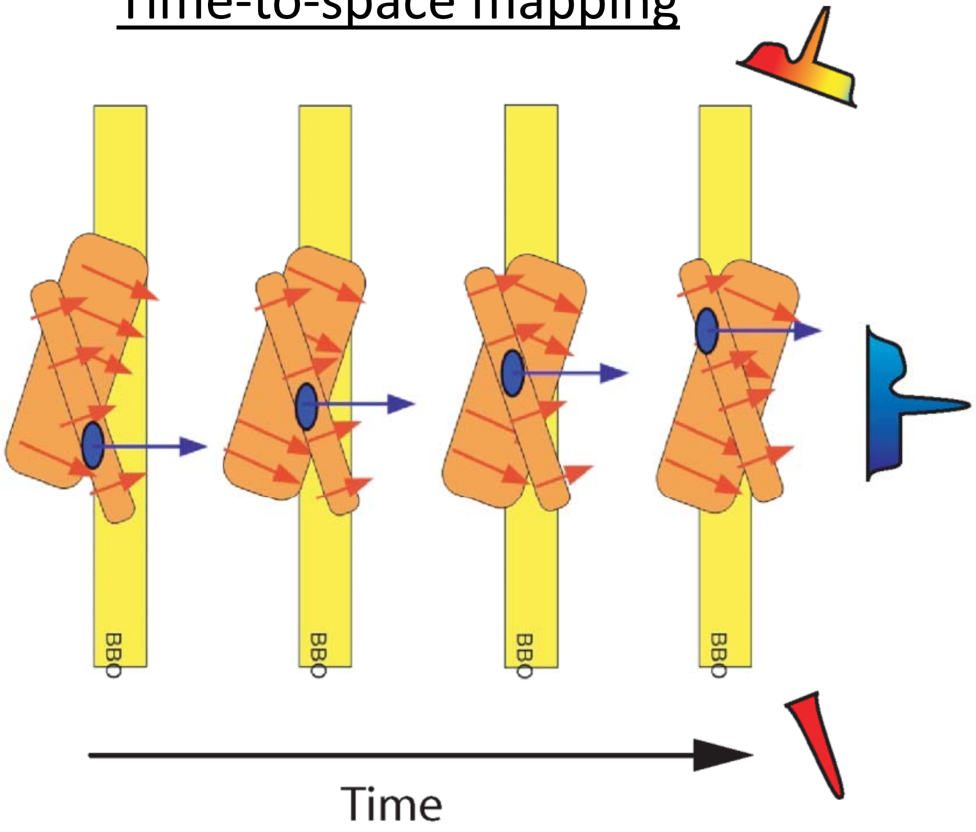
ringing artefacts

- *Thin crystal (>10μm)*
- *Consider new materials* GaSe, DAST, MBANP ….. or poled organic polymers?

W.A. Gillespie & S. Jamison

Temporal decoding

Time-to-space mapping



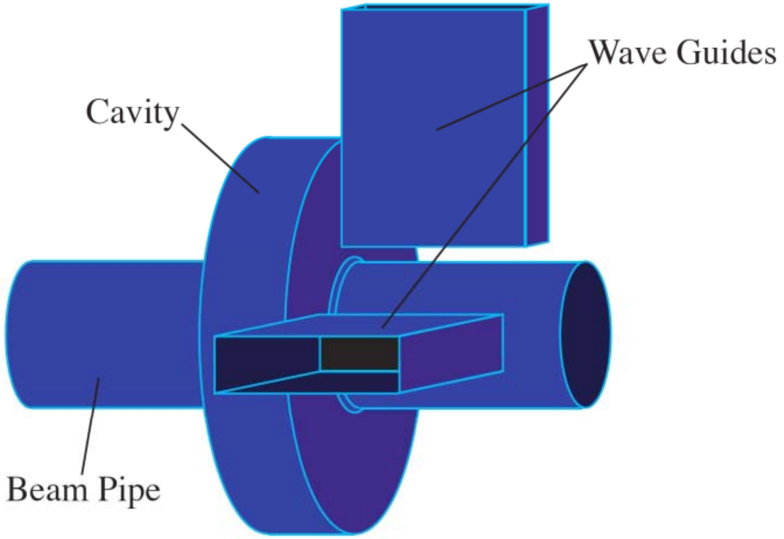
The non-collinear nature of the cross correlation geometry provides a mapping of time to spatial position in the BBO crystal and the CCD

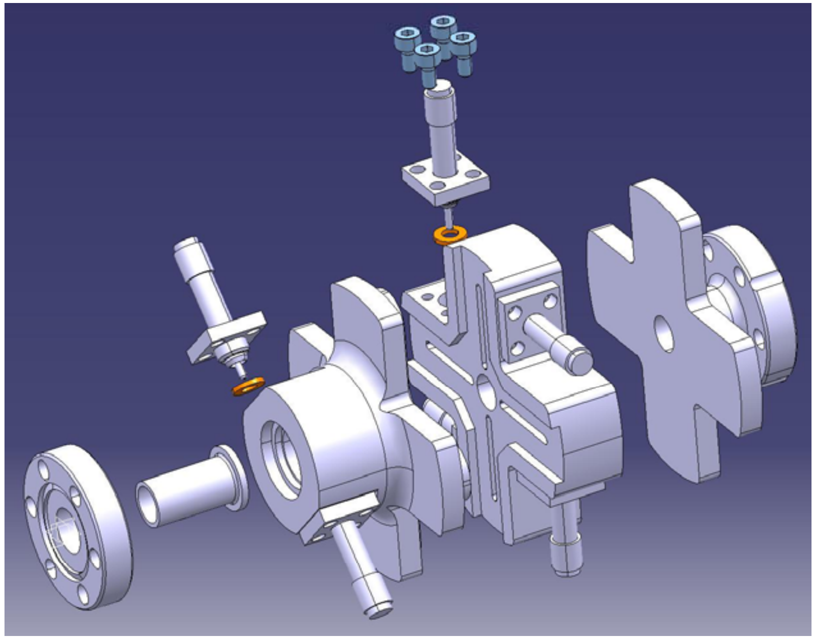
- *Very short laser pulse for time resolution*
- *High laser energy (1mJ) for frequency doubling efficiency*

W.A. Gillespie & S. Jamison

Conserving small Emittance along the Main Linac

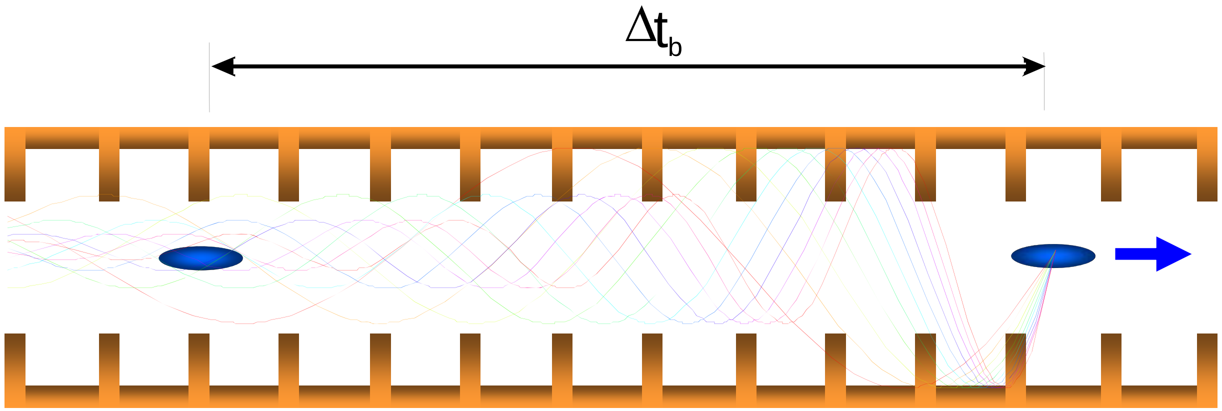
- Dispersive emittance dilutions : offset of quadrupoles
  - Beam based alignment to define a precise reference using high precision BPM (50nm resolution)
  - Dispersion free-steering - Align quadrupoles precisely
  - High resolution cavity BPM (50nm for CLIC)
  - Long linac → large number of BPMs: 2000@ILC – 4000@CLIC





Conserving small Emittance along the Main Linac

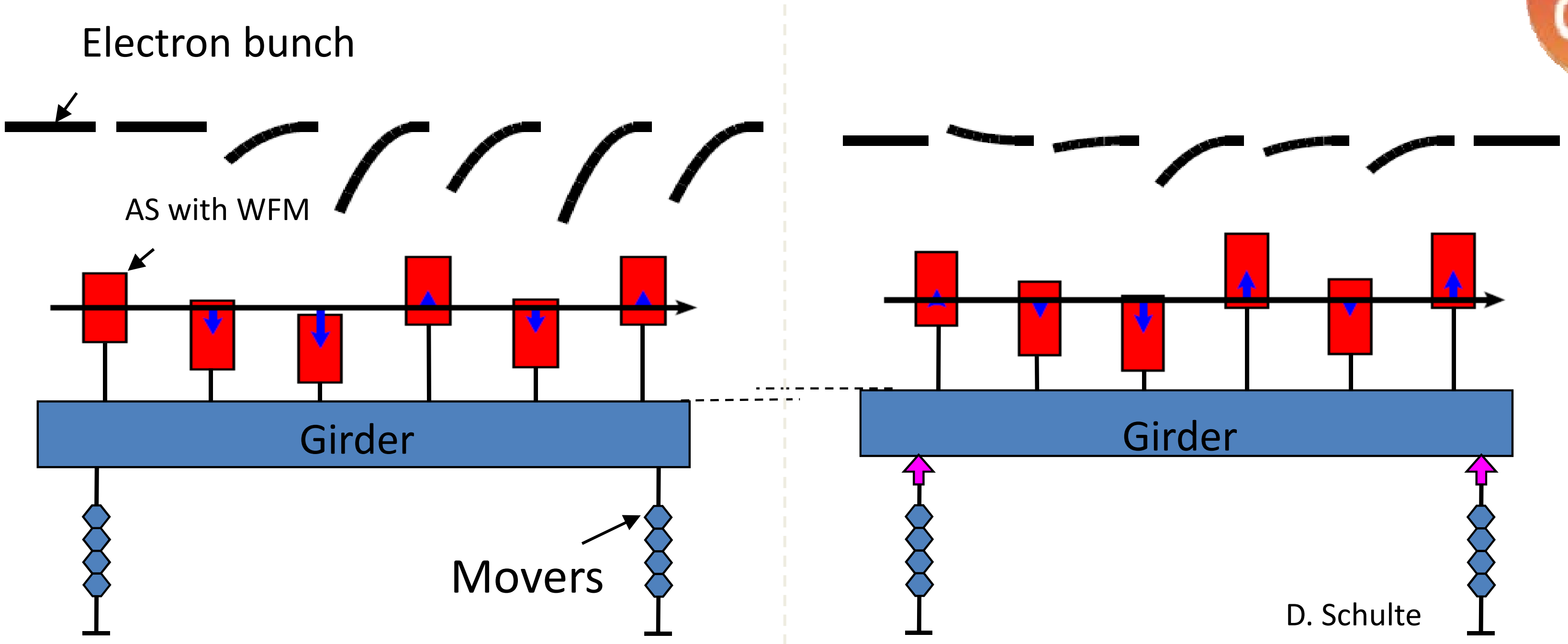
Wakefields in accelerating structures (damping of high order mode)



Bunches passing through an accelerating structure off-centre excite high order modes which perturbs later bunches

- Tolerances for acc. Structures alignment
- Cavity alignment at the 300 μm level @ ILC compared to 5 μm @ CLIC
- Need wakefield monitor to measure the relative position of a cavity with respect to the beam

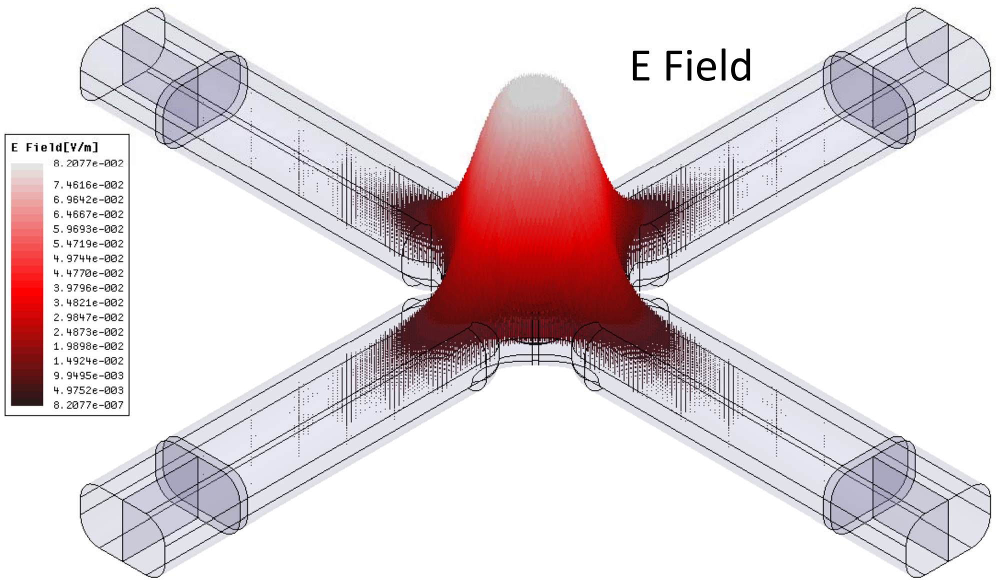
Proposed correction scheme



- ➢ Wakefield kicks from misaligned AS can be cancelled by another AS
- ➢ One WFM per structure (142000 monitors) and mean offset of the 8 AS computed
- ➢ WFM with 5um resolution
- ➢ Need to get rid of the 100MW of RF power at 12GHz present in the structures

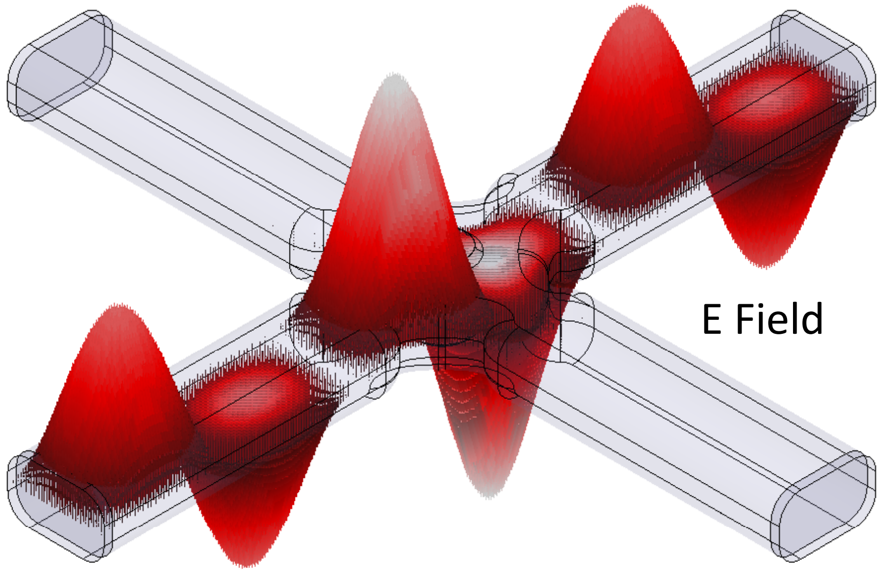
WakeField Monitor design

Monopole mode



Opposite ports signals
are in phase

Dipole mode



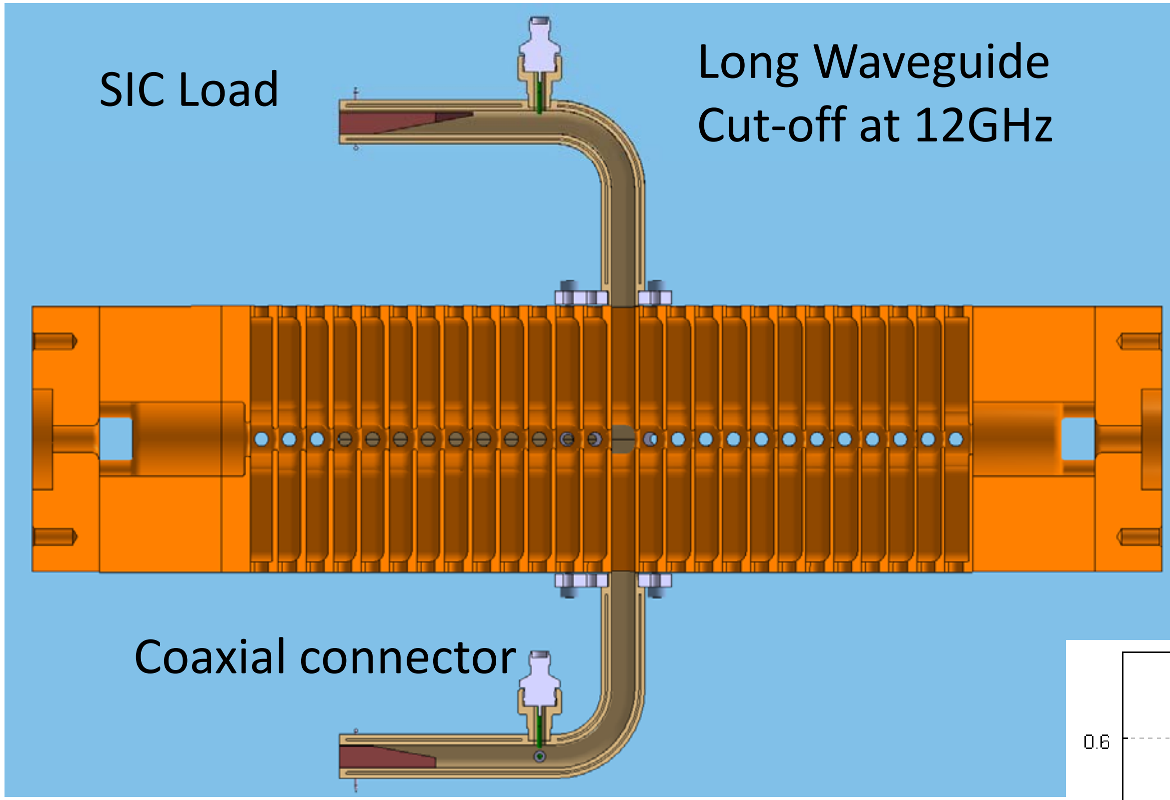
Opposite ports signal
have opposite phase

When we substract the opposite port signals, the monopole mode is cancelled and the dipole mode amplitude is increased

F. Peauger

WakeField Monitor design

12GHz accelerating cavity

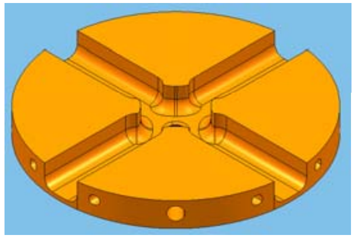


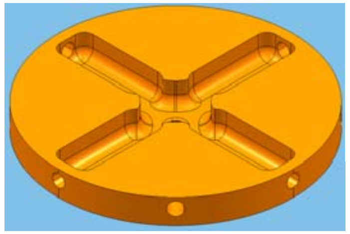
SIC Load

Long Waveguide
Cut-off at 12GHz

Coaxial connector

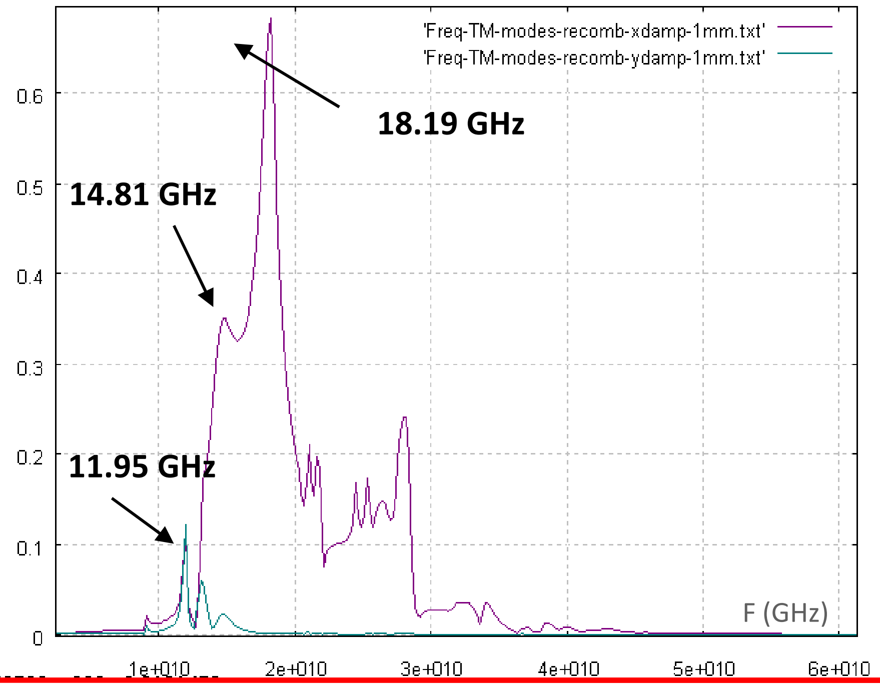
Middle cell with WFM





Regular cells with SIC load

Recombined port
signal amplitude

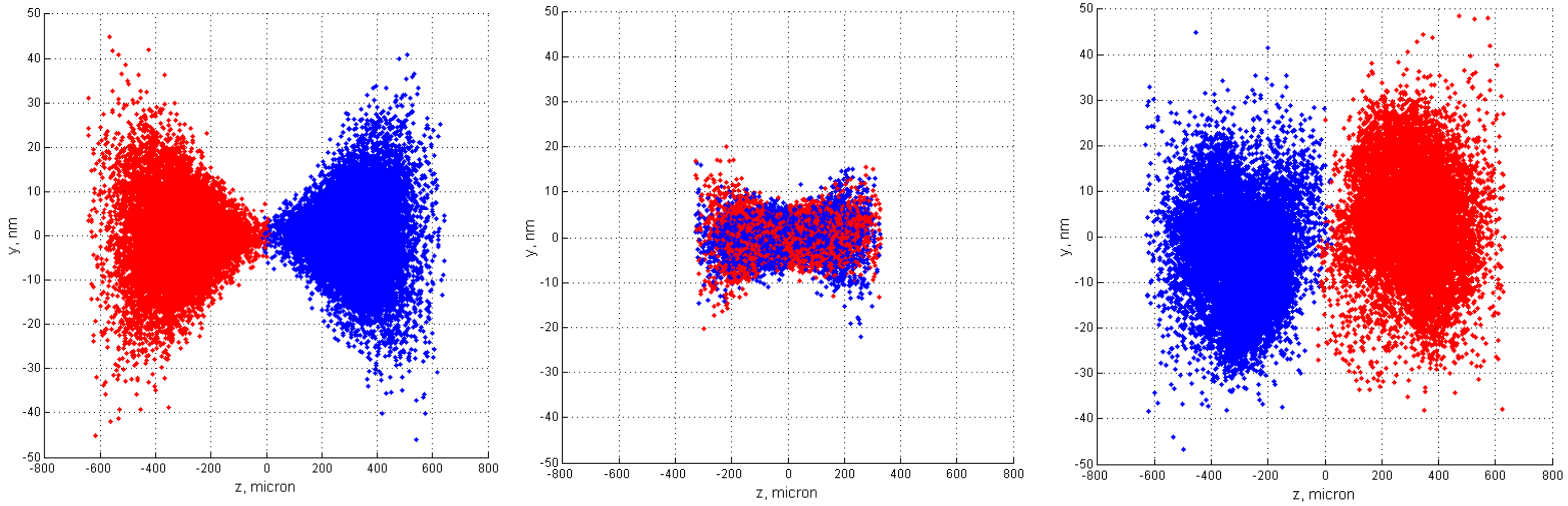


F. Peauger

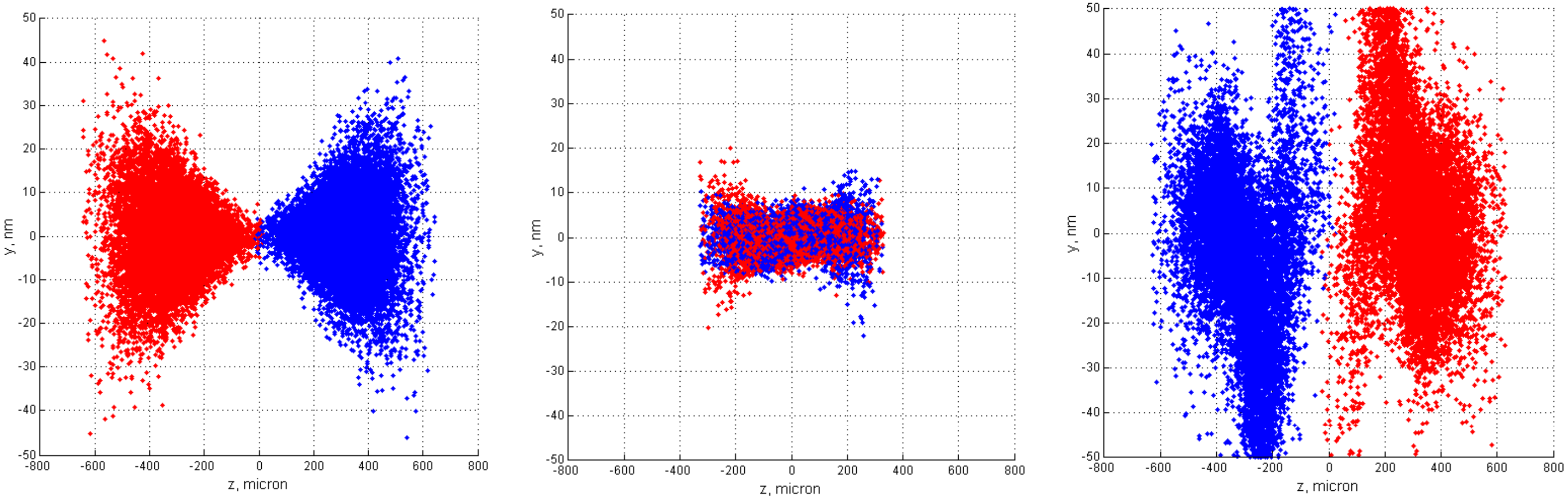
Thanks for your attention

Luminosity issue with intense beams - Disruption

due to 1% initial offset between beams



$D_y = 12$



$D_y = 24$

Damping Ring : the mandate ?

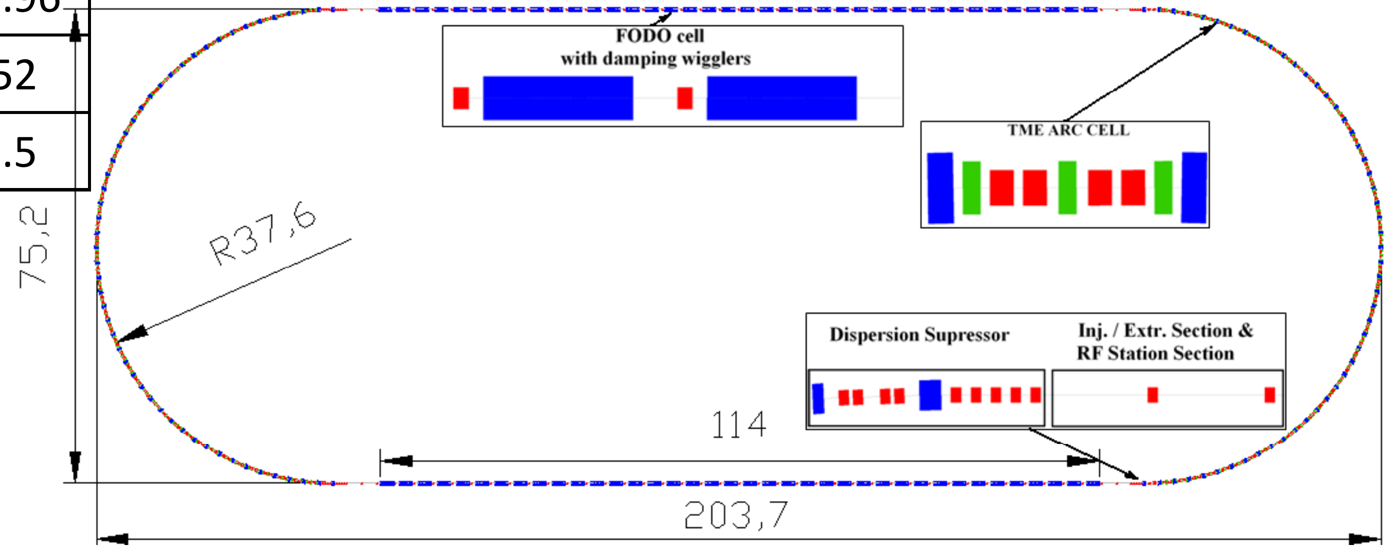
Damping ring necessary to “cool” the beam to an extremely low emittance in all three dimensions

- High-bunch density
  - Emittance dominated by **Intrabeam Scattering**, driving energy, lattice, wiggler technology choice and alignment tolerances
  - **Electron cloud** in e^+ ring imposes chamber coatings and efficient photon absorption
  - **Fast Ion Instability** in the e^- ring necessitates low vacuum pressure
  - **Space charge** sets energy, circumference limits
- Repetition rate and bunch structure
  - Fast damping achieved with wigglers
  - RF frequency reduction considered due to many challenges @ 2GHz (power source, high peak and average current)
- Output emittance stability
  - Tight jitter tolerance driving kicker technology
- Positron beam dimensions from source
  - Pre-damping ring challenges (energy acceptance, dynamic aperture) solved with lattice design

PARAMETER	**NLC**	**CLIC**
bunch population (10^9)	7.5	4.1
bunch spacing [ns]	1.4	0.5
number of bunches/train	192	312
number of trains	3	1
Repetition rate [Hz]	120	50
Extracted hor. normalized emittance [nm]	2370	<**500**
Extracted ver. normalized emittance [nm]	<30	<**5**
Extracted long. normalized emittance [keV.m]	10.9	<**5**
Injected hor. normalized emittance [μm]	150	63
Injected ver. normalized emittance [μm]	150	1.5
Injected long. normalized emittance [keV.m]	13.18	1240

Damping Ring : the mandate ?

Design Parameters	CLIC
Energy [GeV]	2.86
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Compaction factor	8x10^{-5}
Damping time x / s [ms]	1.88/0.96
No bends / wigglers	100/52
Dipole/ wiggler field [T]	1.4/2.5

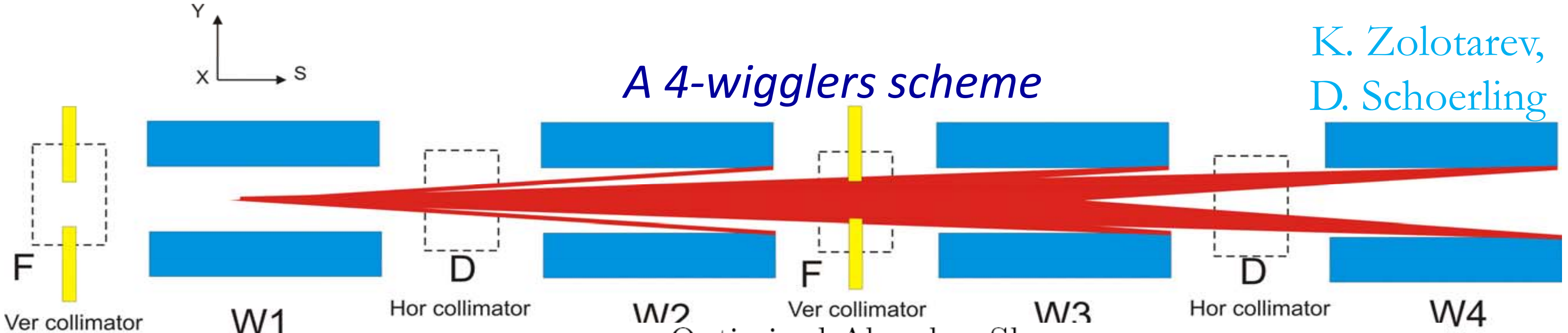


- Racetrack shape with
  - 96 TME arc cells (4 half cells for dispersion suppression)
  - 26 Damping wiggler FODO cells in the long straight sections (LSS)
  - Space reserved upstream the LSS for injection/extraction elements and RF cavities

Damping Ring : the Challenge ?

Radiation parameters	DR
Power per dipole [kW]	1.3
Power per wiggler [kW]	18.7
~~Total power [MW]~~	~~0.61~~
Critical energy for dipole [keV]	19.0
Critical energy for wiggler [keV]	40.7
Radiation opening angle [mrad]	0.11

- 90% of radiation power coming from the 52 SC wigglers
- Design of an absorption system is necessary and critical to protect machine components and wigglers against quench
- ~~Radiation absorption equally important for PDR~~ (but less critical, i.e. similar to light sources)



A 4-wigglers scheme

K. Zolotarev,
D. Schoerling

Optimized Absorber Shapes

Element	Length [m]	V [mm]	H [mm]	Shape
Horizontal Absorber	0.5	13.5	12.3	Rectangular
Vertical Absorber	0.5	9.5	12.5	Rectangular

- Gap of 13mm (10W
- Combination of collimators and absorbers (PETRAIII type, power density of up to 200W/cm)
- Terminal absorber at the end of the straight section (10kW)

Damping Ring Instrumentation

Very high synergy with

	CLIC DR	SLS	Diamond	Soleil
Beam Energy (GeV)	2.86	2.4	3	2.75
Ring Circonfrence (m)	493	288	561.6	354
Bunch charge (nC)	0.6	1	1	0.5
Energy Spread (%)	0.134	0.09	0.1	0.1
Damping times (x,y,E) (ms)	2,2,1	9,9,4.5	-	6.5,6.5,3.3
Orbit stability (um)	1	1	1	1

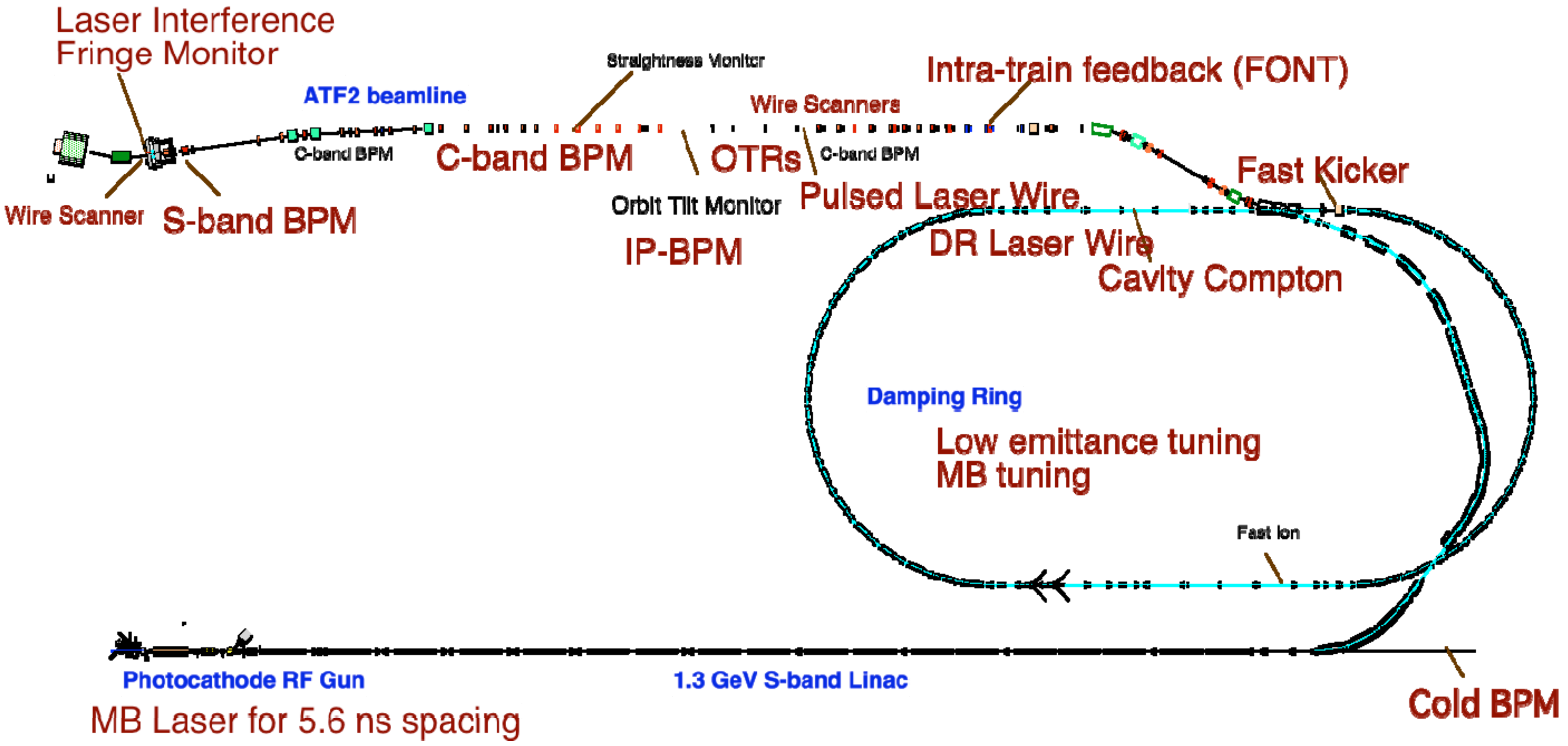
300PUs, turn by turn (every **1.6µs**)

- **10µm** precision, for linear and non-linear optics measurements.
- **2µm** precision for orbit measurements (vertical dispersion/coupling correction + orbit feedback).

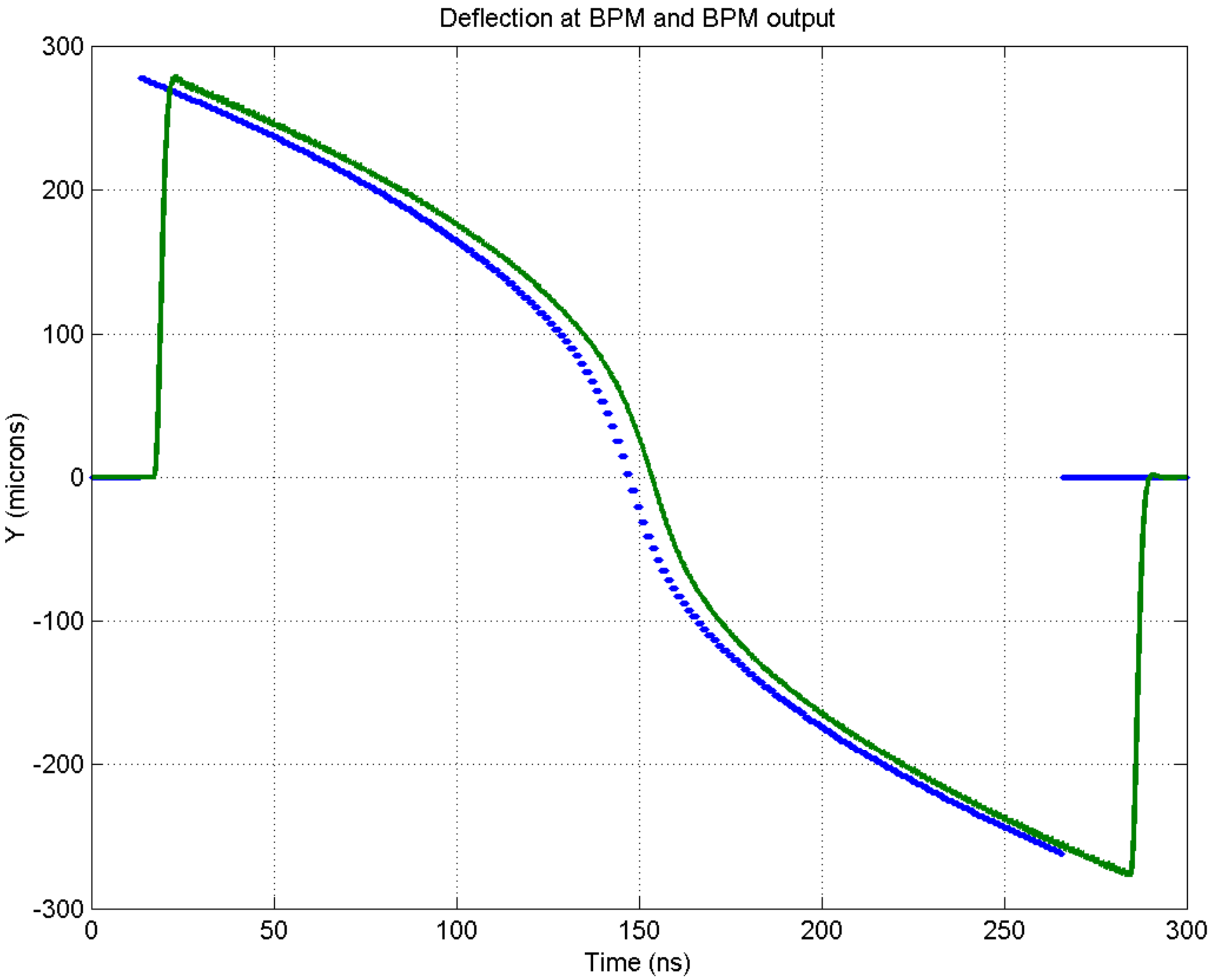
WB PUs for bunch-by-bunch (bunch spacing of **0.5ns** for **312** bunches) and turn by turn position monitoring with high precision (**~2µm**) for injection trajectory control, and bunch by bunch

Damping Ring Instrumentation

- Turn by turn transverse profile monitors (X-ray?) with a wide dynamic range:
  - ☐ Hor. geometrical emittance varies from 11nm.rad @ injection to 90pm.rad @ extraction and the vertical from 270pm.rad to 0.9pm.rad.



Beam - Beam scan at IP

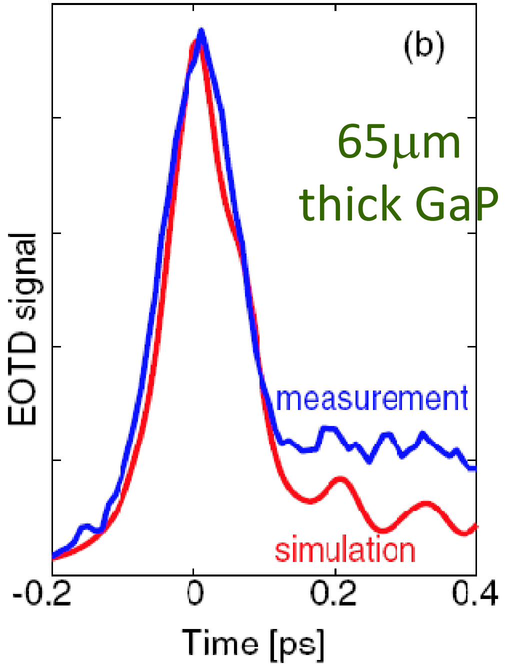


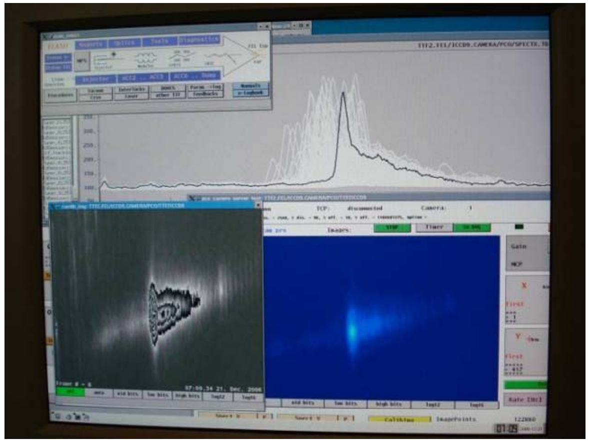
Beam bunches at IP: blue points

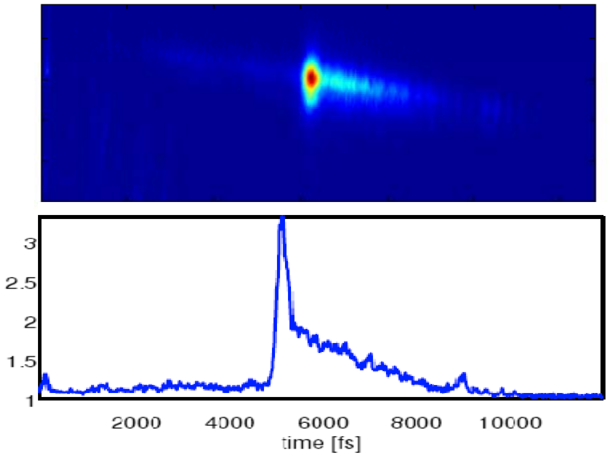
BPM analog response: green line

Temporal decoding

high time resolution (+ wakefields ?)

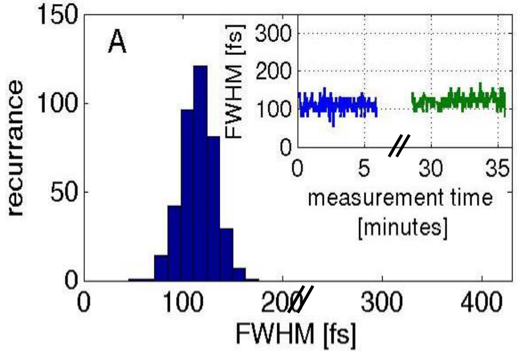




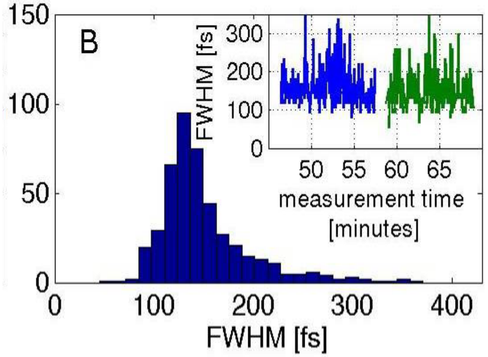


observing stabilising effect of slow feedback

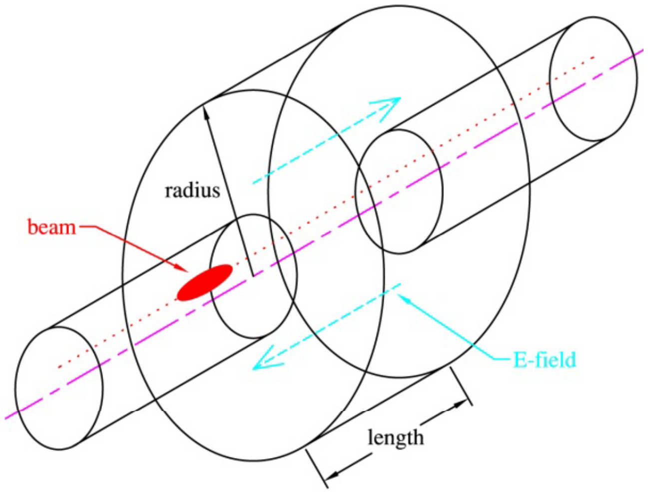
CDR feedback on

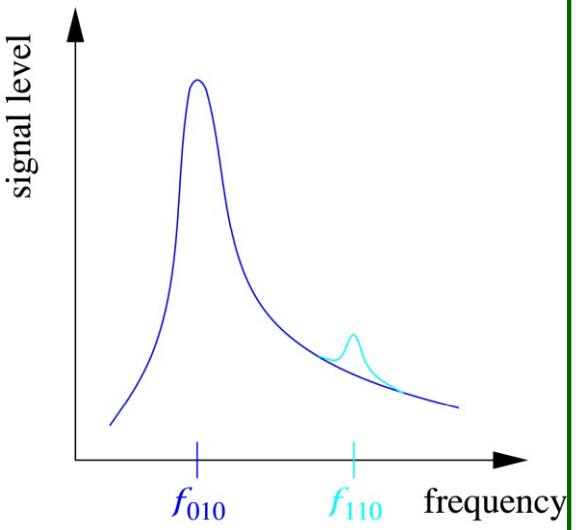


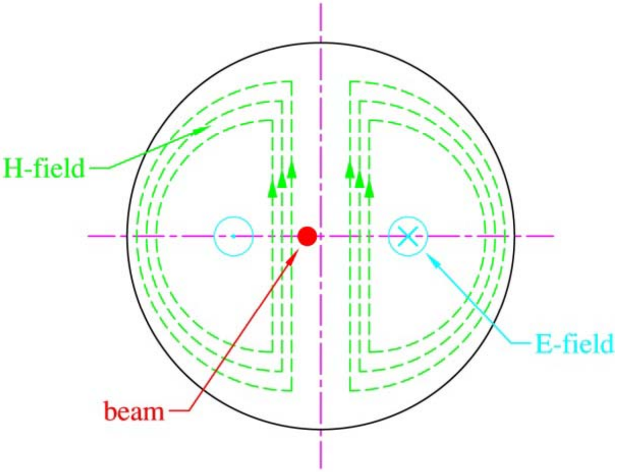
CDR feedback off

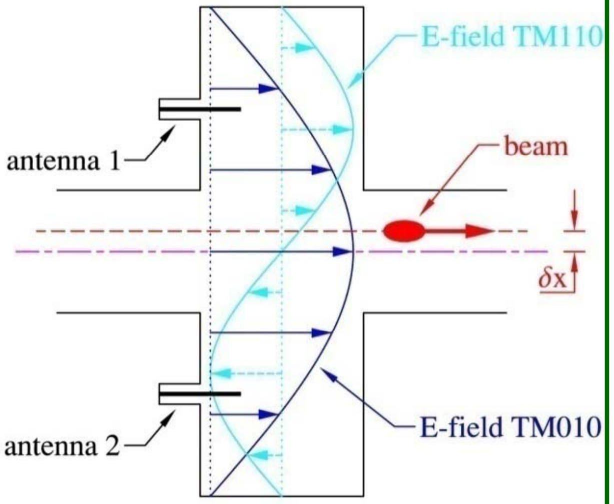


Cavity BPM









- **“Pillbox” cavity BPM**
  - **Eigenmodes:**

    $$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

  - **Beam couples to**

    $$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)\cos\phi\, e^{i\omega t}$$

    dipole (TM_{110}) and monopole (TM_{010}) modes
  - **Common mode (TM_{010}) suppression by frequency discrimination**
  - **Orthogonal dipole mode polarization (xy cross talk)**
  - **Transient (single bunch) response (Q_L)**
  - **Normalization and phase reference**

No circular e^+e^- collider after LEP

Cost of Circular Accelerator : Length + Energy lost replaced by RF power ~ E^2

Cost of Linear Accelerator : Length ~ E