Beam Instrumentation for Linear Colliders

3hours B-course at the 2013 LC school Antalya,
Hermann Schmickler, CERN-BE-BI

With a big “Thank You” to T. Lefevre for many splendid slides....

- What is special about the beam instrumentation of a Linear Collider ?
- What are the main Instrumentation needs?
- Details on:

- Measurement of nm beam positions
- Measurement of um transverse beam sizes
- Measurement of fs-scale long profiles
- Beam synchronization at the fs-scale
- Keeping the beams in collision

Luminosity of high energy Collider

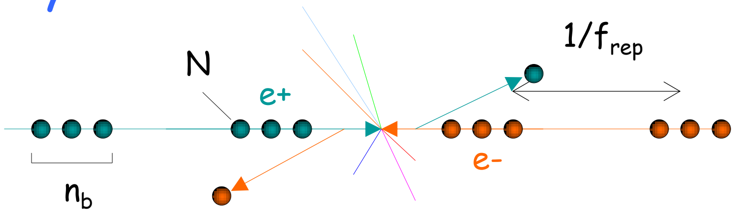
Collider luminosity [$cm^{-2}\, s^{-1}$] is approximately given by

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

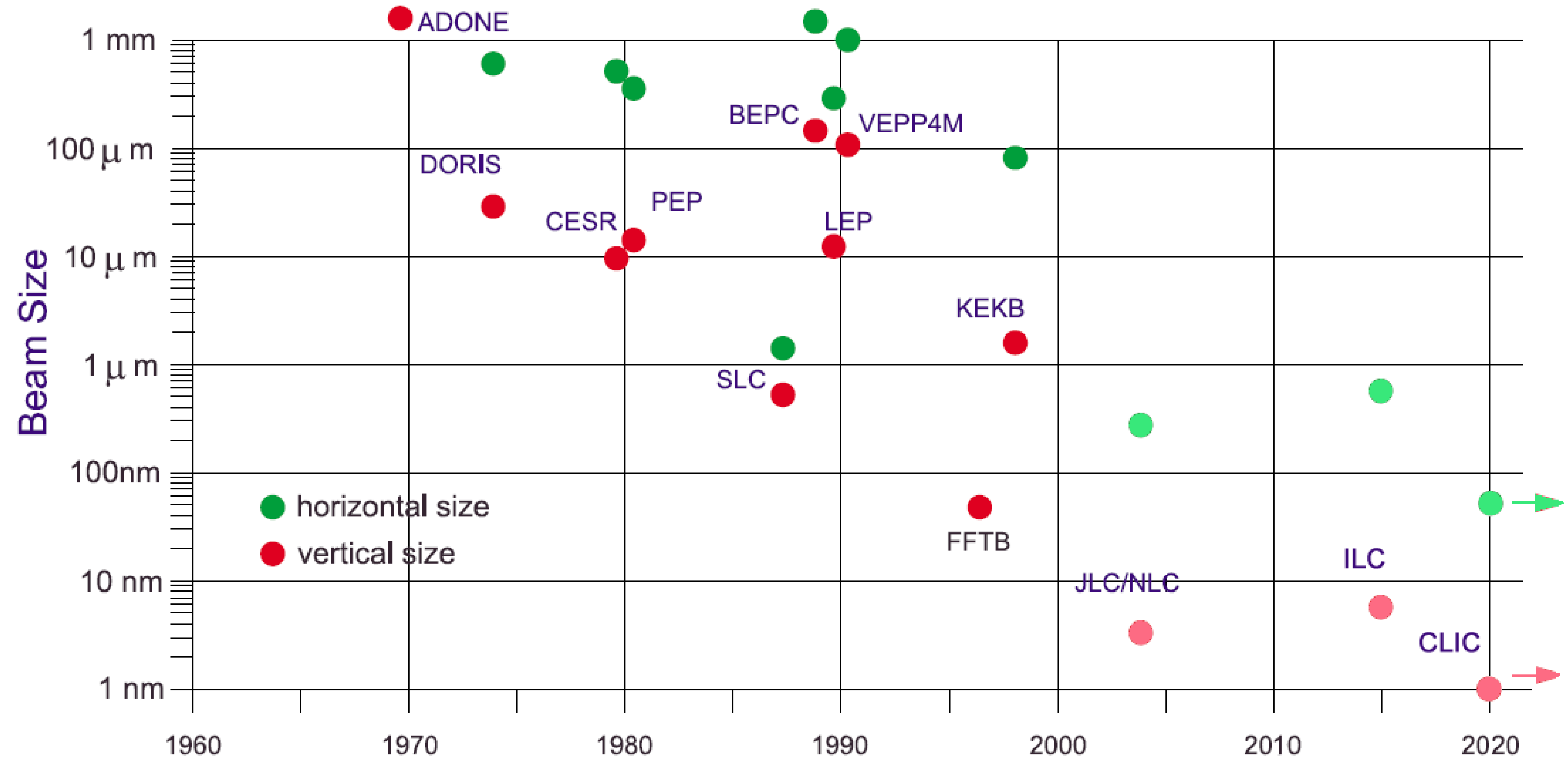
n_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
$\sigma_{x,y}$ = beam size at IP
H_D = beam-beam enhancement factor

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: $\sigma_x \sigma_y \approx 130 \times 6\ \mu m^2$

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:***

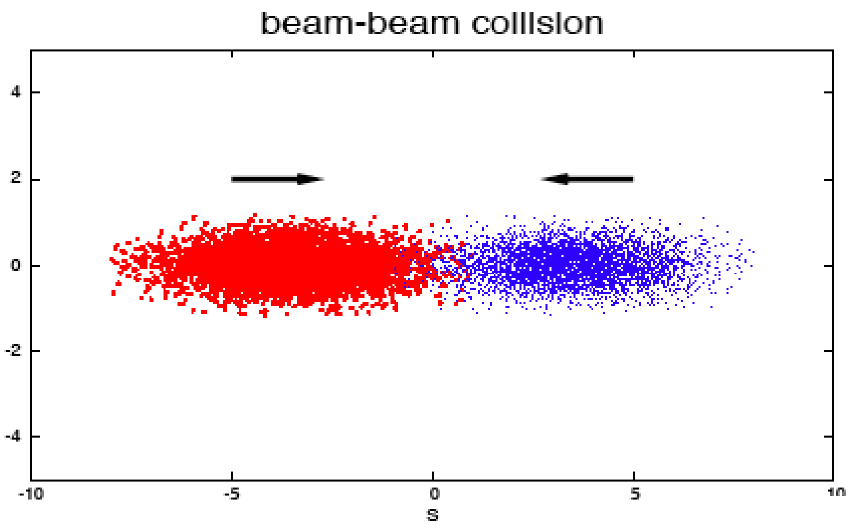
$$D_{x,y} = \frac{2 r_e N \sigma_z}{\gamma \sigma_{x,y} (\sigma_x + \sigma_y)}$$

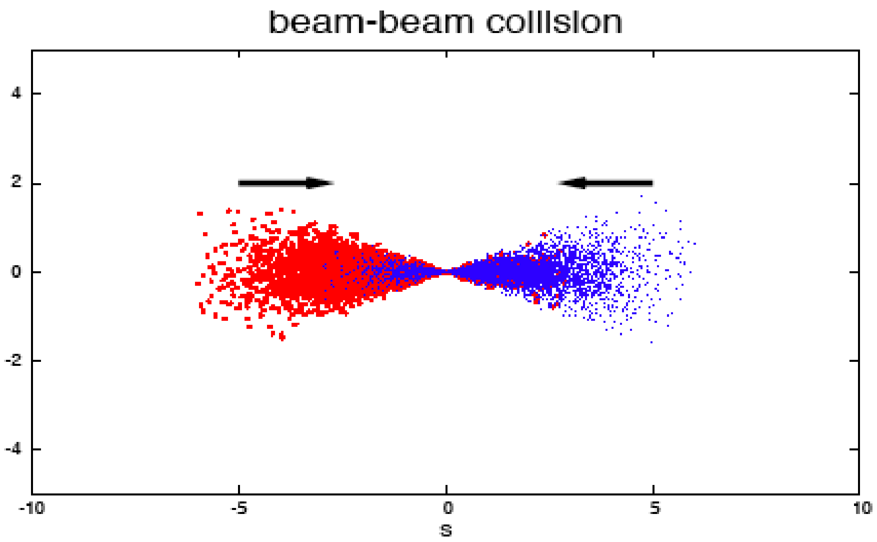
σ_z = bunch length

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

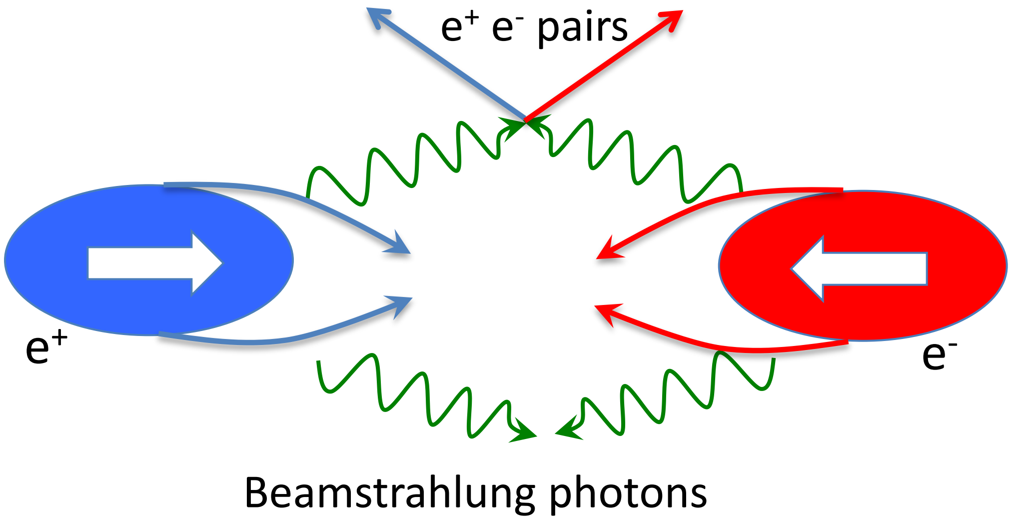




For LC, typical value of HD ~ 1-2

Luminosity issue with intense beams - Beamstrahlung

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



• 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:

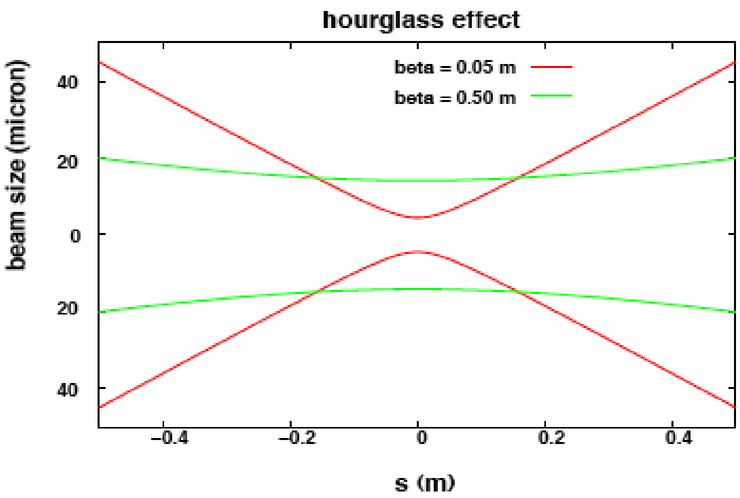
- Make σ_x **large to limit** δ_{BS}
- Make σ_y **as small as possible** to achieve high luminosity.

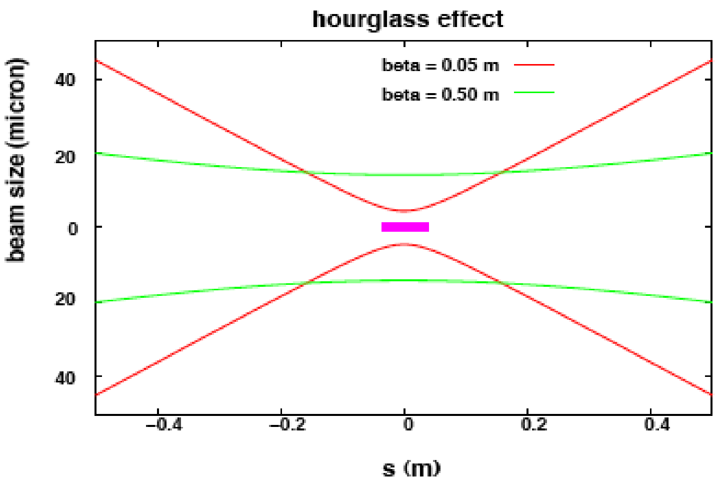
→ δ_{BS} ~ 2.4% @ ILC -- δ_{BS} ~ 29% @ CLIC

Hour glass effect – Bunch length

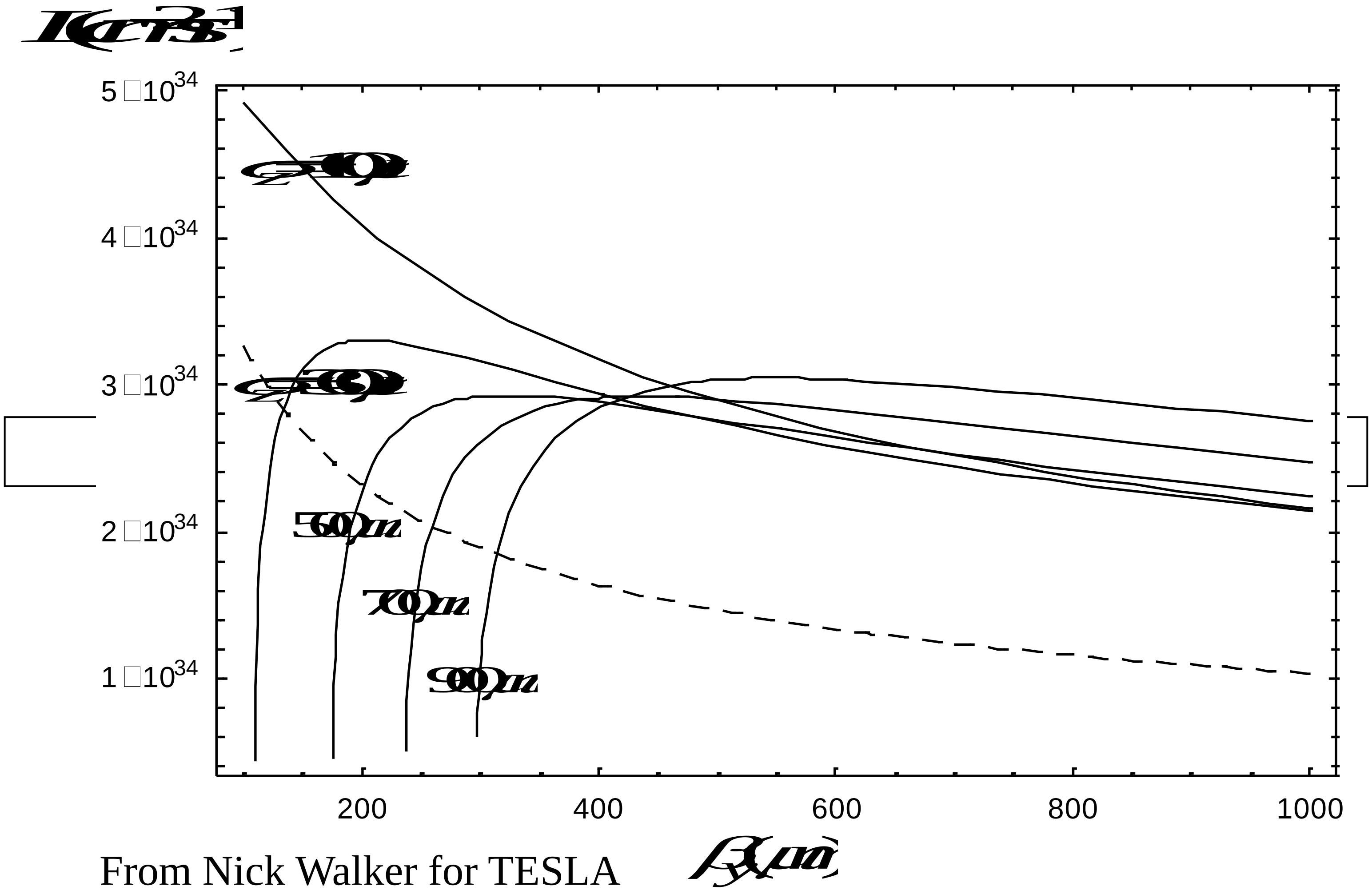
For achieving small Beta function (small beam size) at IP, the beta function rapidly increases as the particle move away from the collision point

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 ?

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

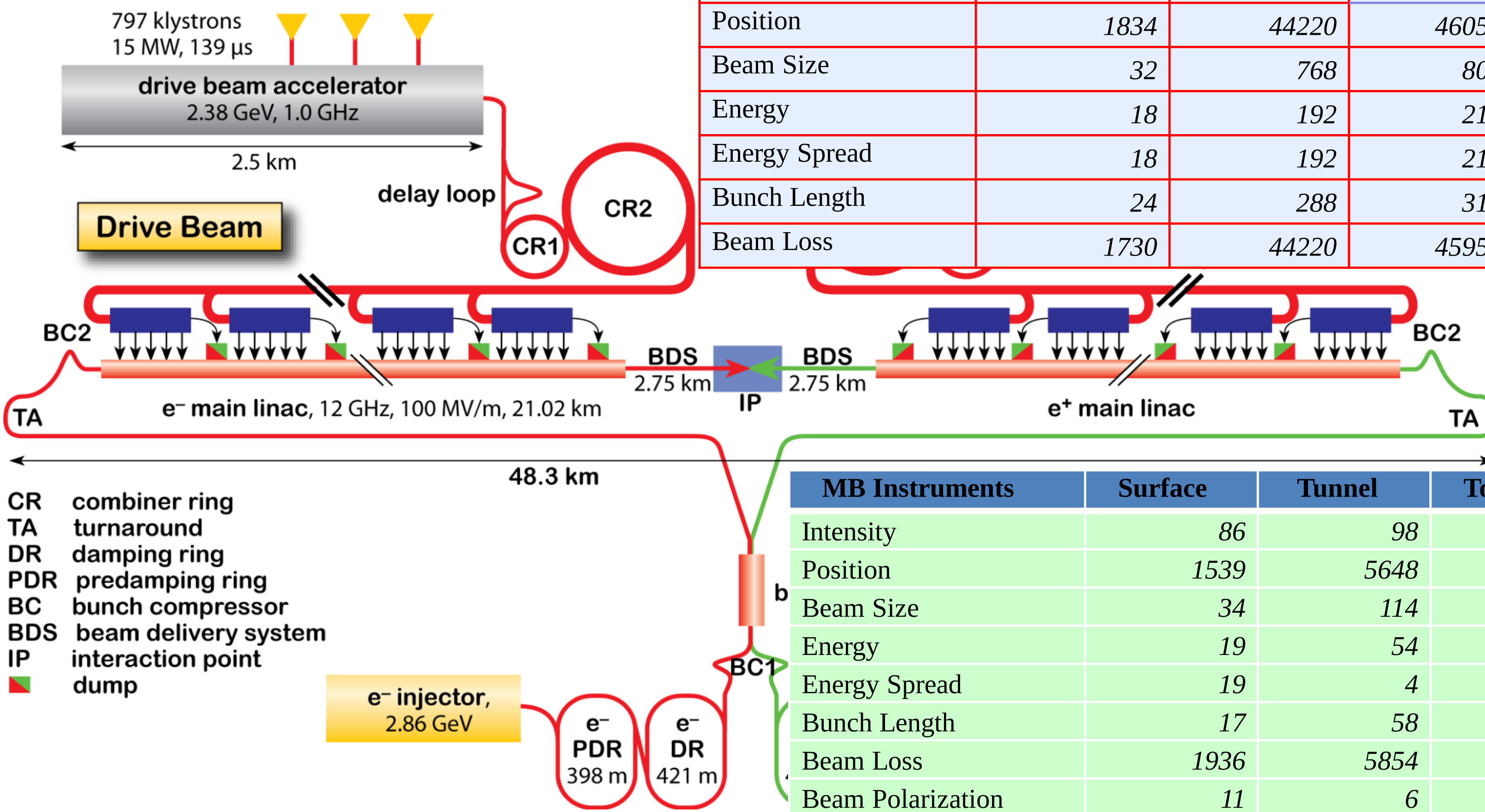
- *high RF-beam conversion efficiency η_{RF} and RF power P_{RF}*
- **small normalised vertical emittance $\varepsilon_{n,y}$**
- **strong focusing at IP (small β_y and hence small σ_z)**

↓

• 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‘s in the CLIC CDR for BI?

DB Instruments	Surface	Tunnel	Total
Intensity	*38*	*240*	*278*
Position	*1834*	*44220*	*46054*
Beam Size	*32*	*768*	*800*
Energy	*18*	*192*	*210*
Energy Spread	*18*	*192*	*210*
Bunch Length	*24*	*288*	*312*
Beam Loss	*1730*	*44220*	*45950*



MB Instruments	Surface	Tunnel	Total
Intensity	*86*	*98*	*184*
Position	*1539*	*5648*	*7187*
Beam Size	*34*	*114*	*148*
Energy	*19*	*54*	*73*
Energy Spread	*19*	*4*	*23*
Bunch Length	*17*	*58*	*75*
Beam Loss	*1936*	*5854*	*7790*
Beam Polarization	*11*	*6*	*17*
Tune	*6*	*0*	*6*
Luminosity		*2*	*2*

Beam Position Monitors - Baseline

Machine Sub-Systems	Intensity (A)	Train duration (ns) / Bunch frequency (GHz)	Accuracy / Resolution (um)	Time Resolution (ns)	Quantity	Beam aperture (mm)
Main Beam						
e^- & e^+ injector Complex	0.5	156 / 1	100 / 50	10	83	40
Pre-Damping Rings	0.5	156 / 1	tbd./ 20	10 Turn by turn	600	20 / 9
Damping Rings	0.5	156 / 1	tbd./ 2	10	600	20 / 9
RTML	1	156 / 2	100 / 10	10	1424	various
Main Linac	1	156 / 2	5 / 0.05	10	4196	
Beam Delivery System	1	156 / 2	5 / 0.05	10	600	
Spent Beam Line	1	156 / 2	tbd / 1000	100	12	various
Drive Beam						
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	660	40
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	210	80
Transfer to Tunnel	100	24 x 240ns / 12	40 / 10	10	872	200
Turn around	100	240ns / 12	40 / 10	10	1920	40
Decelerator	100	240ns / 12	20 / 2	10	41484	26
Dump lines	100	240ns / 12	20 / 2	10	96	40

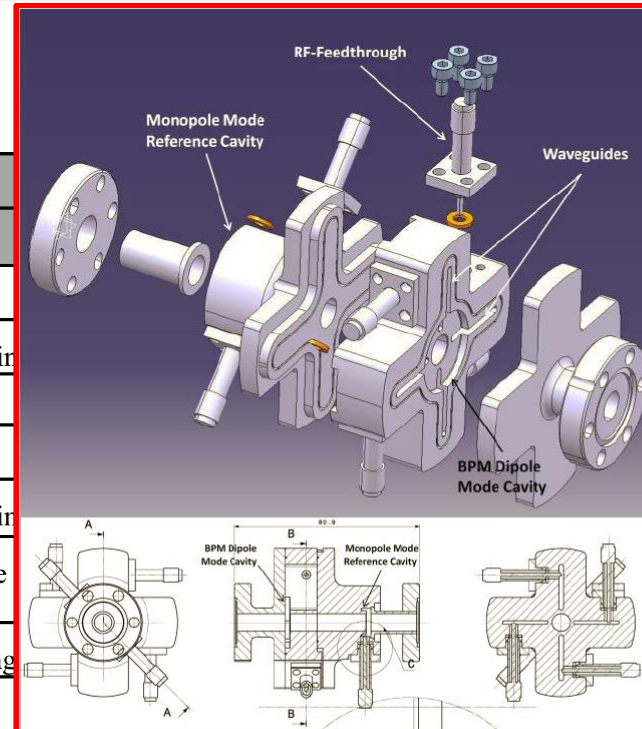
High accuracy (5um) resolution (50nm) BPM in Main Linac and BDS

Various range of beam pipe diameters from 4mm to 200mm all over the complex (to minimize resistive wakefield effects)

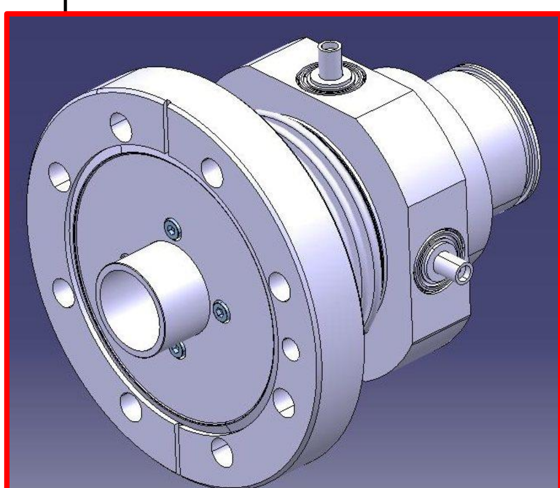
Very high numbers of BPMs for the DB decelerator

Beam Position Monitors - Baseline

Design by Manfred Wendt & co (FNAL)



Machine Sub-Systems	Quantity	Technology choice		
		Pick-up	Processor	
Main Beam				
e^- & e^+ injector Complex	83	Button 6mm	Direct samplin	
Pre-Damping rings	600	Button 6mm	DR type	
Damping rings	600	Button 6mm	DR type	
RTML	1424	Button 6mm	Direct samplin	
Main Linac and Beam Delivery system	4796	14GHz Cavity BPM	Cavity type	
Spent Beam Line	12	Button / Strip line	Direct sampling	
Drive Beam				
	660	Button 6mm	Downconverting	CERN
	210	Button 6mm	Downconverting	CERN
	872	Button 6mm	Direct sampling	CERN
	1920	Button 6mm	Direct sampling	CERN
	41484	Stripline 25mm	Downconverting	CERN
	96	Stripline 25mm	Downconverting	CERN



Designed by Steve Smith

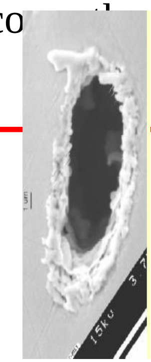
Transverse Profile Monitors - Baseline

Machine Sub-Systems	Emittance (nm.rad)	Energy (GeV)	Resolution (um)	Quantity	Charge dens (nC/cm^2)
Main Beam					
				2	< 5 10^5
				4	< 5 10^5
				2	< 5 10^5
Pre-Damping Rings (H/V)	63000/1500	2.86	50/10	4	< 5 10^6
Damping rings (H/V)	< 500/5	2.86	**10/1**	4	**< 5 10^8**
RTML	510/5	2.86 → 9	**10/1**	70	**< 5 10^8**
Main Linac	600/10	9 →1500	**10/1**	48	**< 5 10^8**
Beam Delivery System	660/20	1500	**10/1**	8	**< 5 10^8**
Spent Beam Line	>660/20	< 1500	1000	6	< 5 10^3
Drive Beam					
		→ 2.37	50	10	**< 40 10^6**
		2.37	50	20	**< 40 10^6**
Transfer to Tunnel	100	2.37	50	2	**< 40 10^6**
Turn around	100	2.37	50	**96**	< 1.5 10^6
Decelerator	150	< 2.37	50	**576**	> 1.5 10^6
Dump lines	> 150	< 2.37	100	**96**	> 1.5 10^6

Critical Issue on micron resolution beam profile measurements (> 100 monitors)

Imaging of high energy spread beams at the end of the decelerator

Charge density limitation problems in many places / **Strong need for non-interceptive devices** : two systems required to co total dynamic range



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

Relatively big number of Instruments ~ 1000

Transverse Profile Monitors - Baseline

Most of the systems based on the combined use of OTR screens and Laser Wire Scanners
- OTR used almost everywhere for commissioning (replaced by synchrotron radiation in rings)
- LWS 1um resolution required for the Main beam
- LWS used in the Drive Beam injector complex for high charge beams (full charge)

Machine Sub-Systems	Quantity	Technology choice		Place to be Tested
		Baseline	Alternatives	
Main Beam				
e^- & e^+ injector Complex	10	OTR		CERN
Pre-Damping and Damping rings	8	XSR	LWS / OSR-PSF	Sync light sources PSI, PETRA, ..
RTML	70	OTR	OTR/OSR PSF	ATF2
		LWS	XDR	CESR-TA
Main Linac and Beam Delivery system	56	OTR	OTR-PSF	ATF2
		LWS	XDR	CESR-TA
Spent Beam Line	6	OTR	Scintillating screens	CERN
Drive Beam				
DB source and Linac	10	OTR / LWS	ODR	FEL's
Frequency multiplication complex	20	OSR	XSR	Sync light sources PSI, PETRA, ..
Transfer to tunnel	2	OTR / LWS	ODR	FEL's
Turn-arounds	96	OSR	XSR	Sync light sources PSI, PETRA, ..
Decelerator and Dump lines	672	OTR		CERN

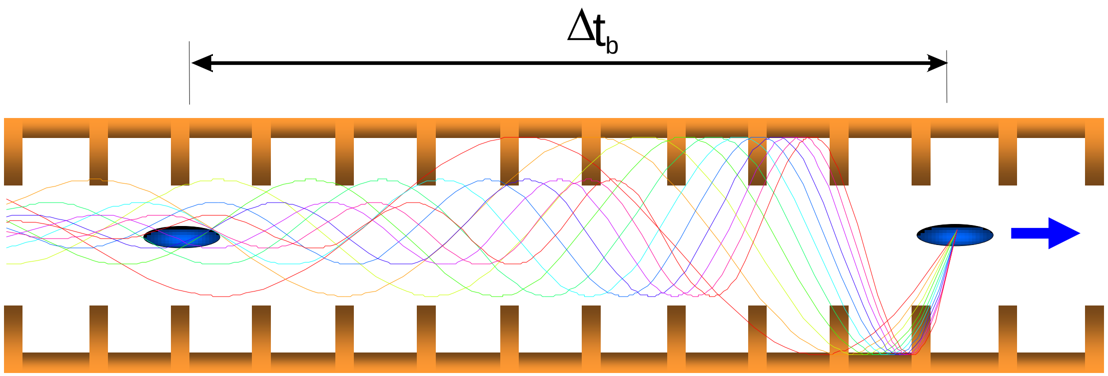
Non-interceptive monitor based on Diffraction radiation as a cheap alternative to LWS for both Drive and Main Beams

Now we treat in detail:

- Measurement of nm beam positions
- Measurement of um transverse beam sizes
- Measurement of fs-scale long profiles
- Beam synchronization at the fs-scale
- Keeping the beams in collision (IP feedback)

Conserving small Emittance along the Main Linac

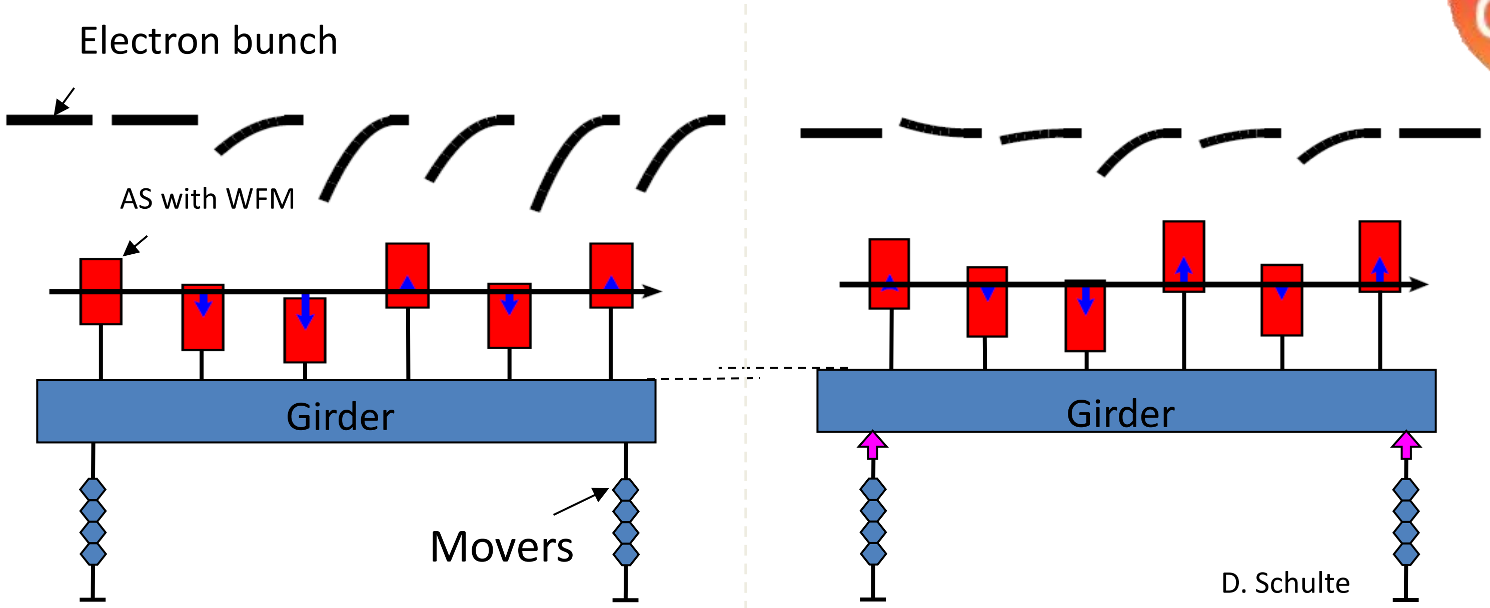
Wakefields in accelerating structures (damping of high order mode)



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

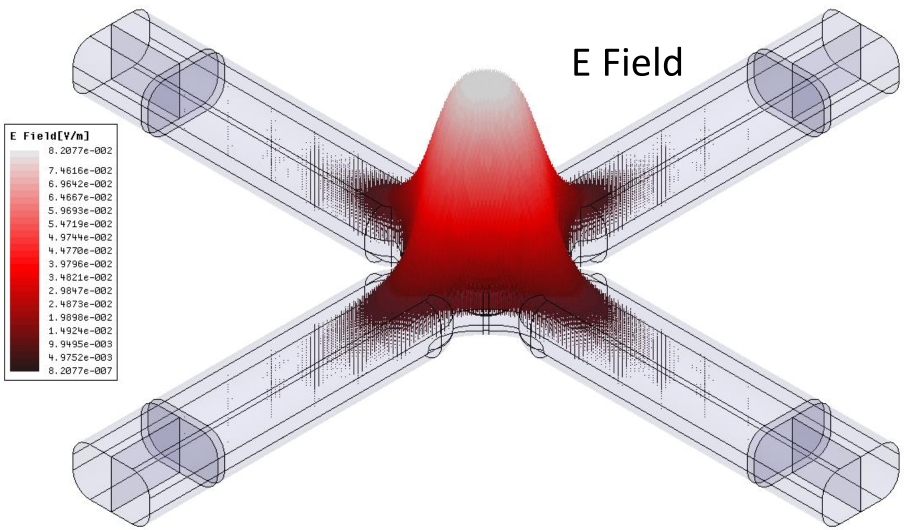
Proposed correction scheme



- 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

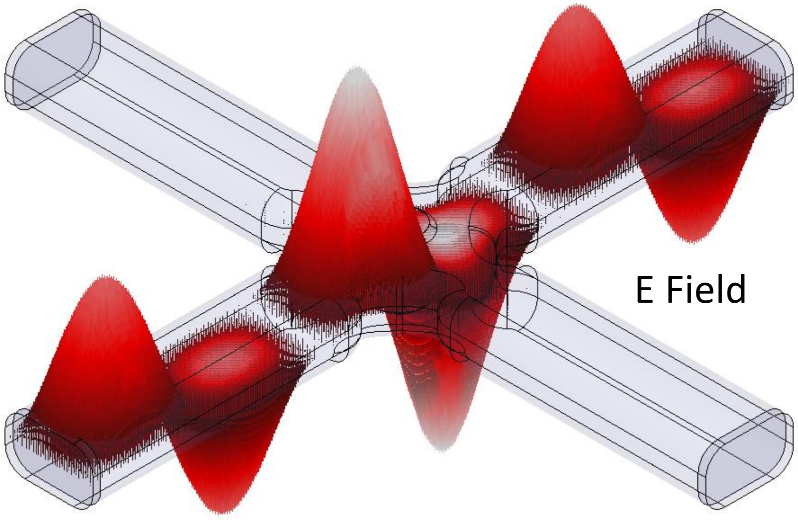
WakeField Monitor design

Monopole mode



Opposite ports signals
are in phase

Dipole mode



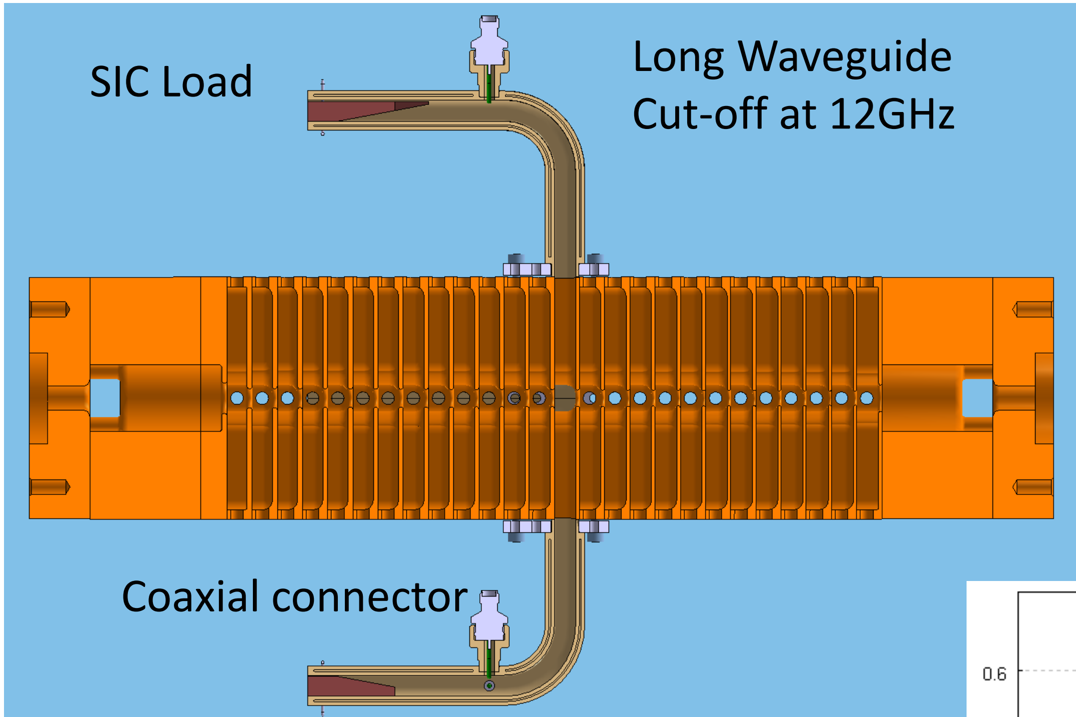
Opposite ports signal
have opposite phase

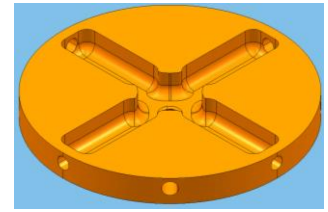
When we substract the opposite port signals, the monopole mode is cancelled and the dipole mode amplitude is increased

F. Peauger

WakeField Monitor design

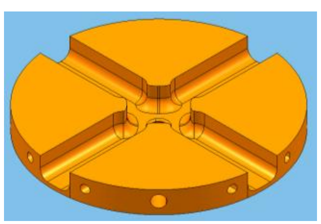
12GHz accelerating cavity



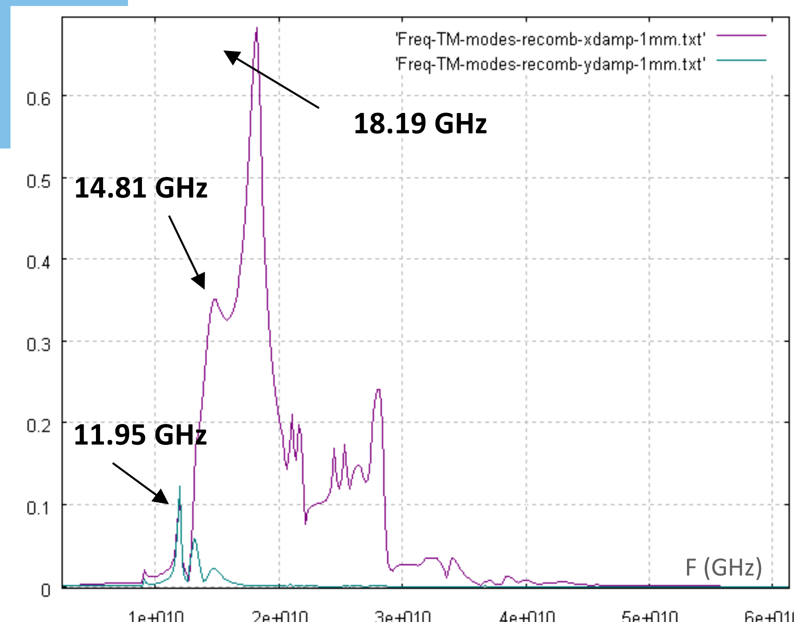


Regular cells with SIC load

Middle cell with WFM



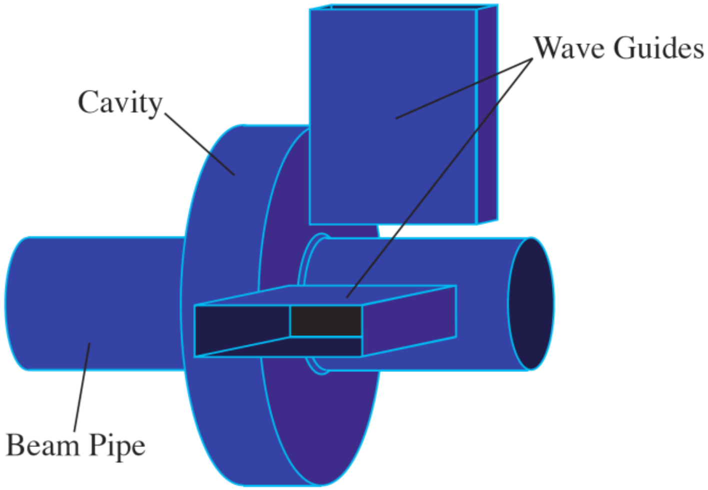
Recombined port
signal amplitude

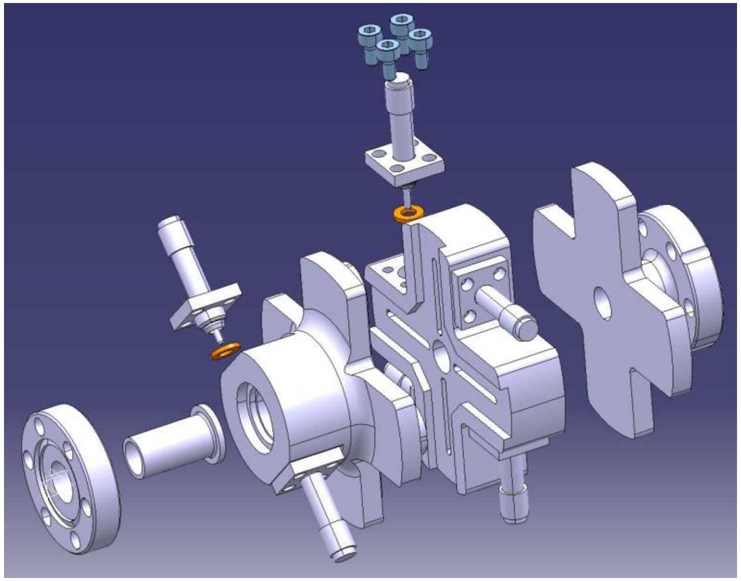


F. Peauger

Conserving small Emittance along the Main Linac

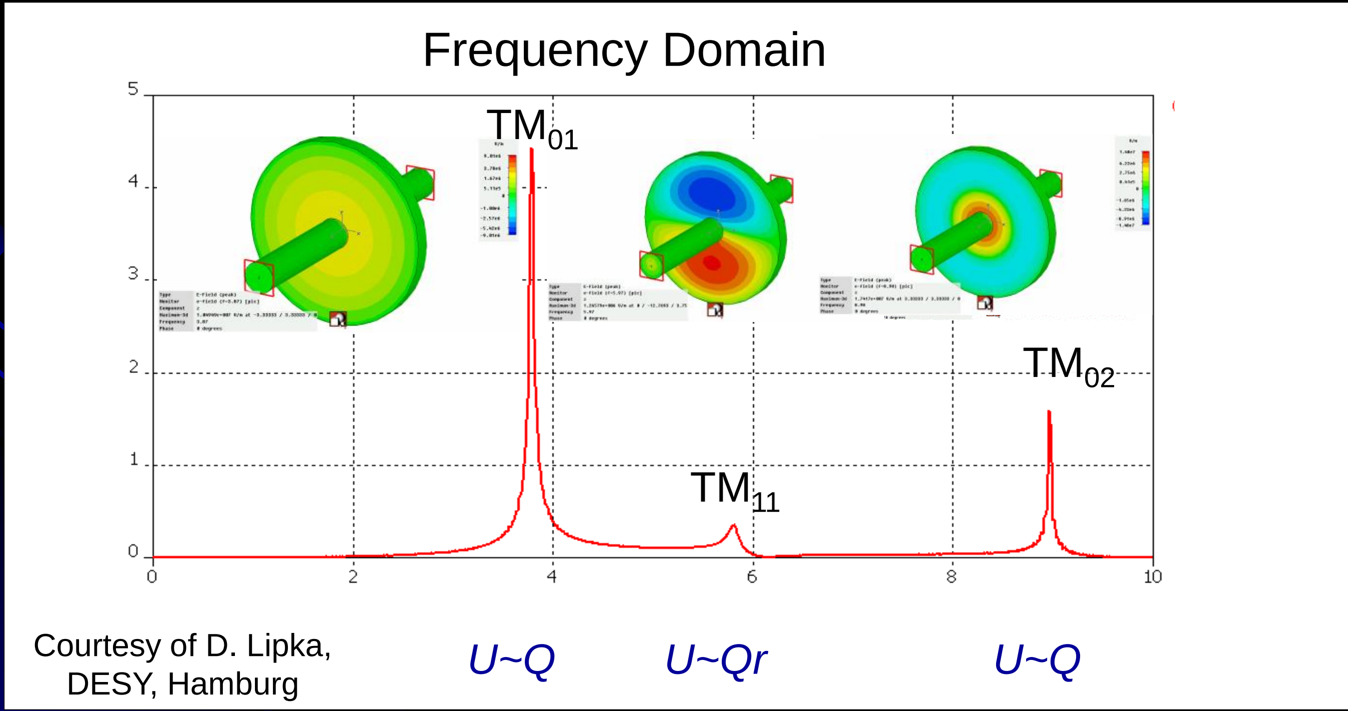
- <u>Dispersive emittance dilutions : offset of quadrupoles</u>
  - Beam based alignment to define a precise reference using high precision BPM (50nm resolution)
  - Dispersion free-steering - Align quadrupoles precisely
  - High resolution cavity BPM (50nm for CLIC)
  - Long linac → large number of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





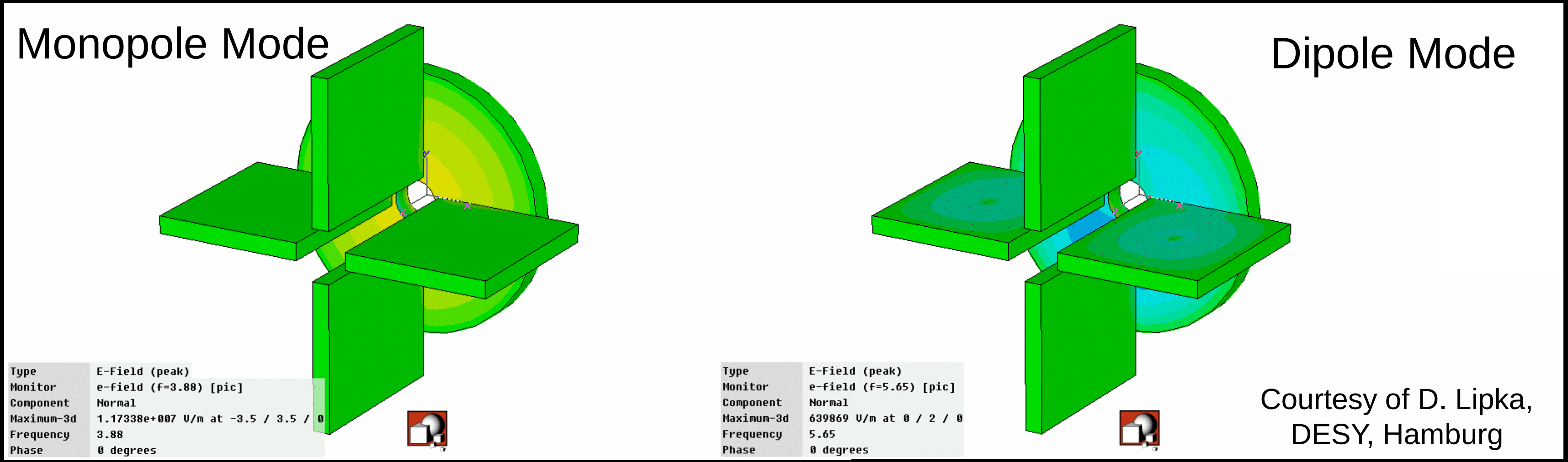
Improving the Precision for Next Generation Accelerators

- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection ⇒ tens micron resolution for typical apertures
- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
    - Dipole Mode TM_{11} proportional to position & shifted in frequency with respect to monopole mode

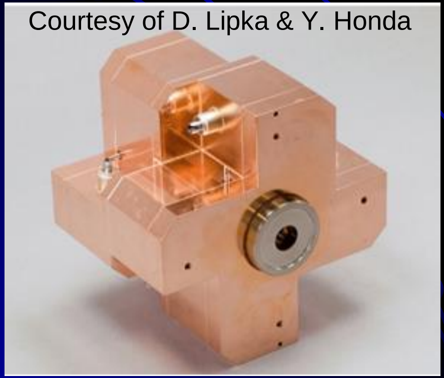


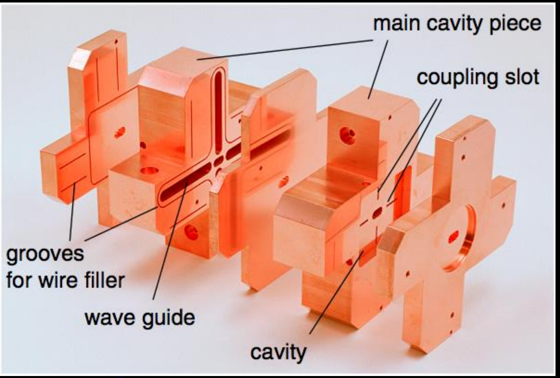
Today's State of the Art BPMs

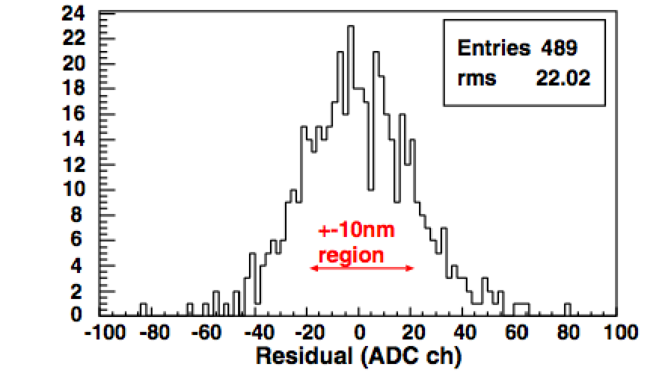
- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode



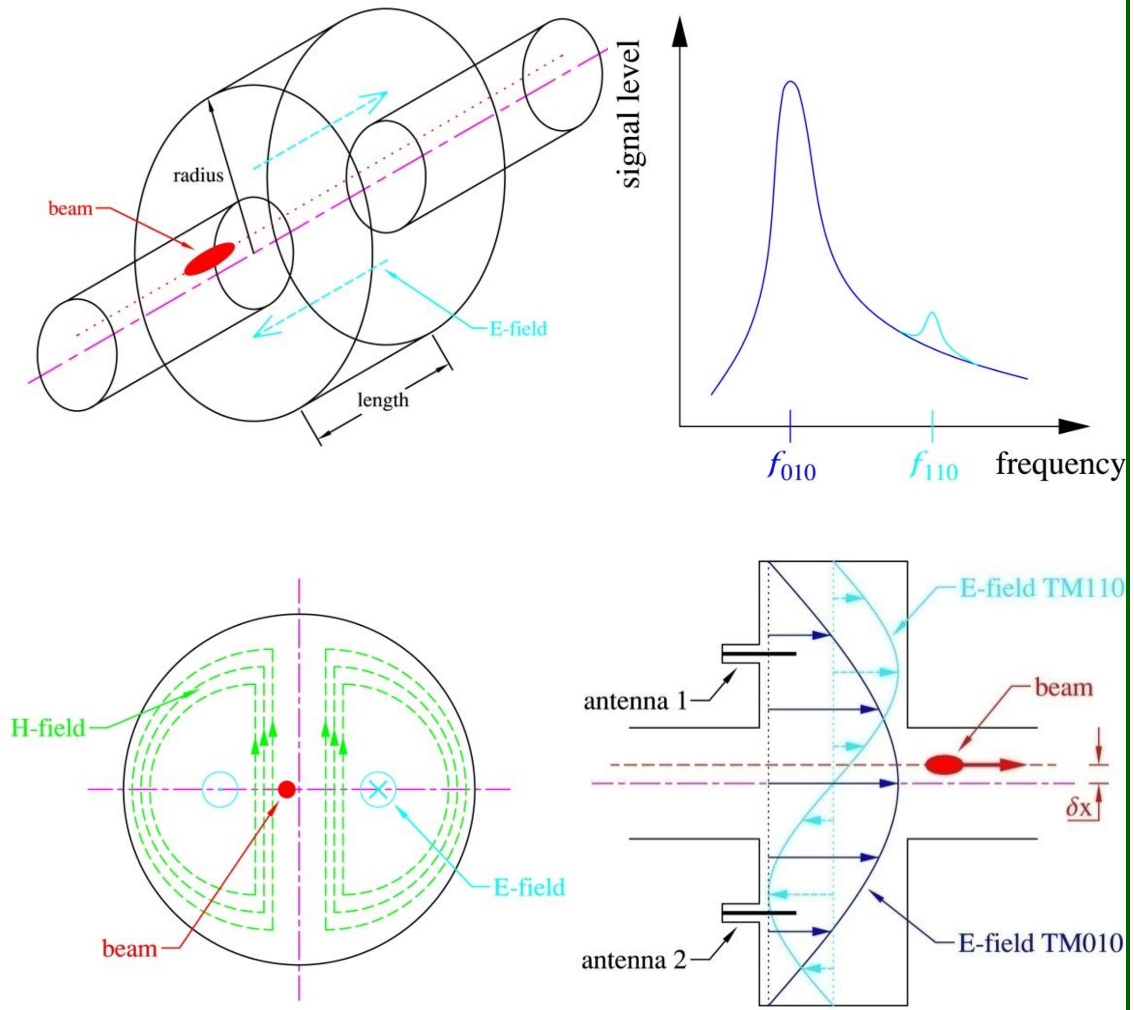
- Prototype BPM for ILC Final Focus
  - Required resolution of 2nm (yes nano!) in a 6×12mm diameter beam pipe
  - Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)







Cavity BPM



- **"Pillbox" cavity BPM**
  - **Eigenmodes:**

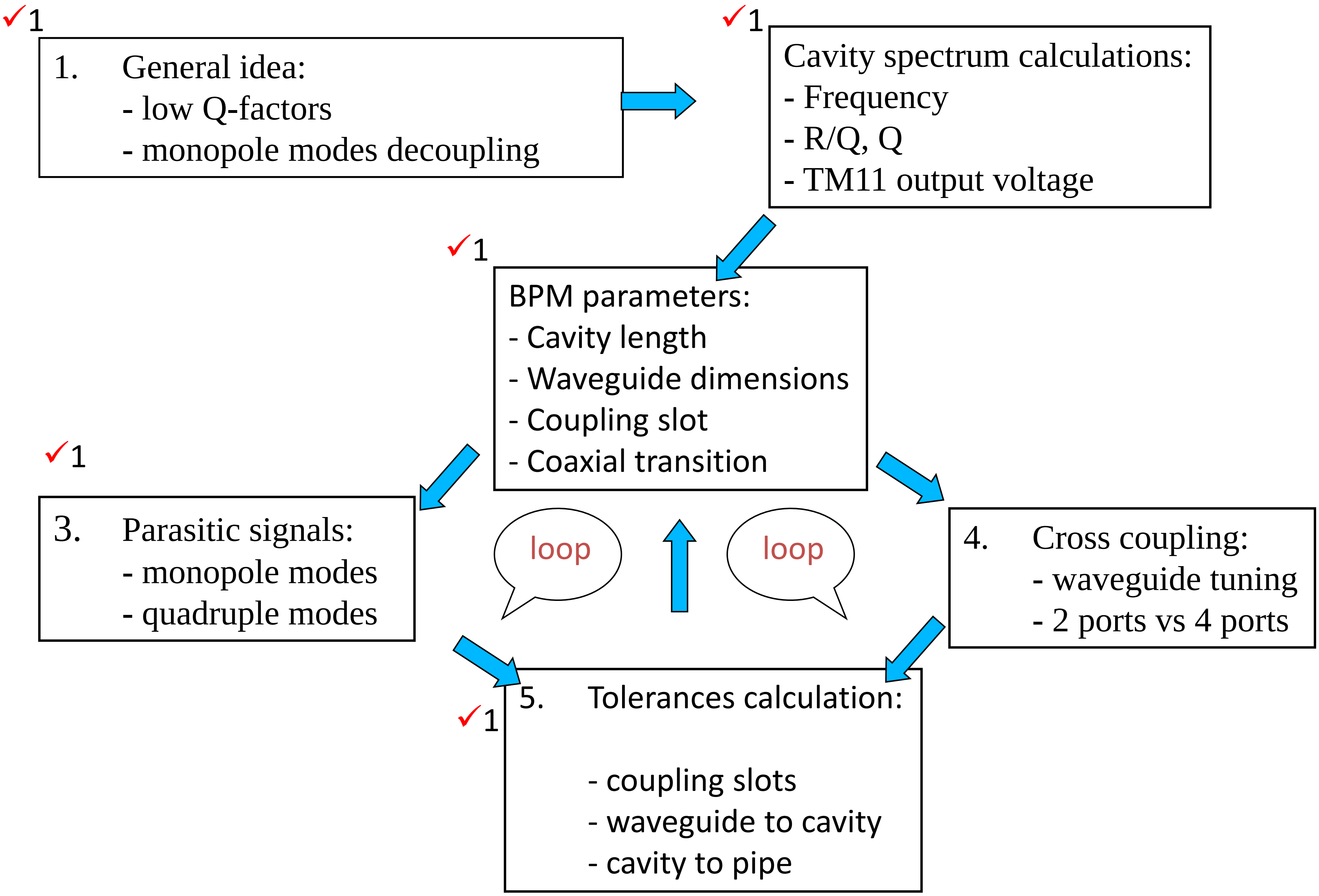
    $$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

  - **Beam couples to**

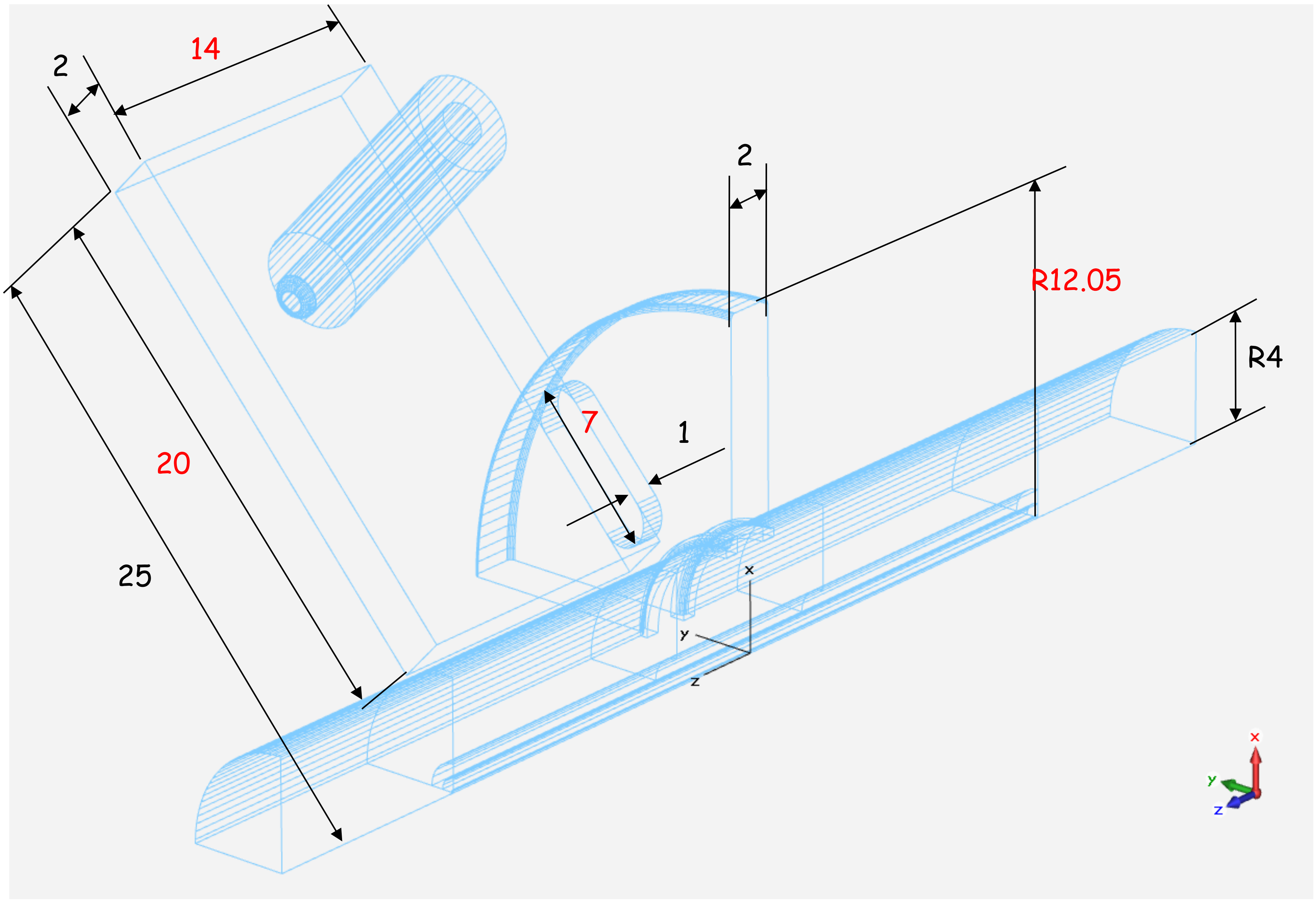
    $$E_z = CJ_1\left(\frac{j_{11}r}{R}\right)\cos\emptyset\, e^{i\omega t}$$

    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**

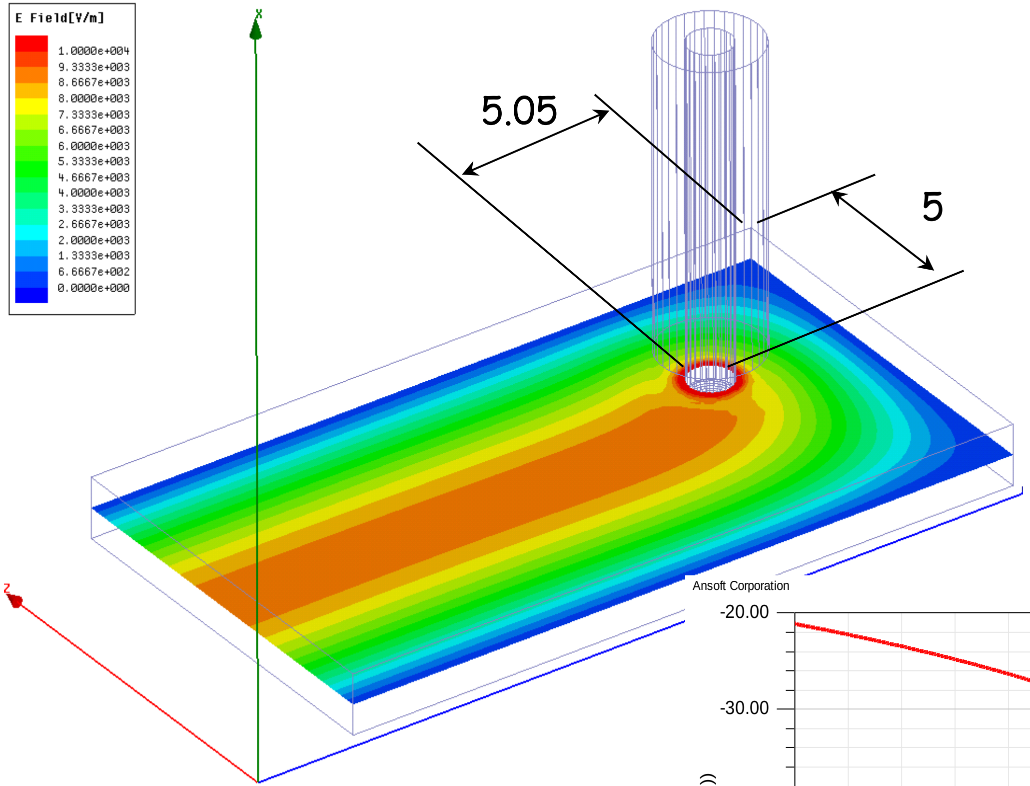
Cavity BPM design steps

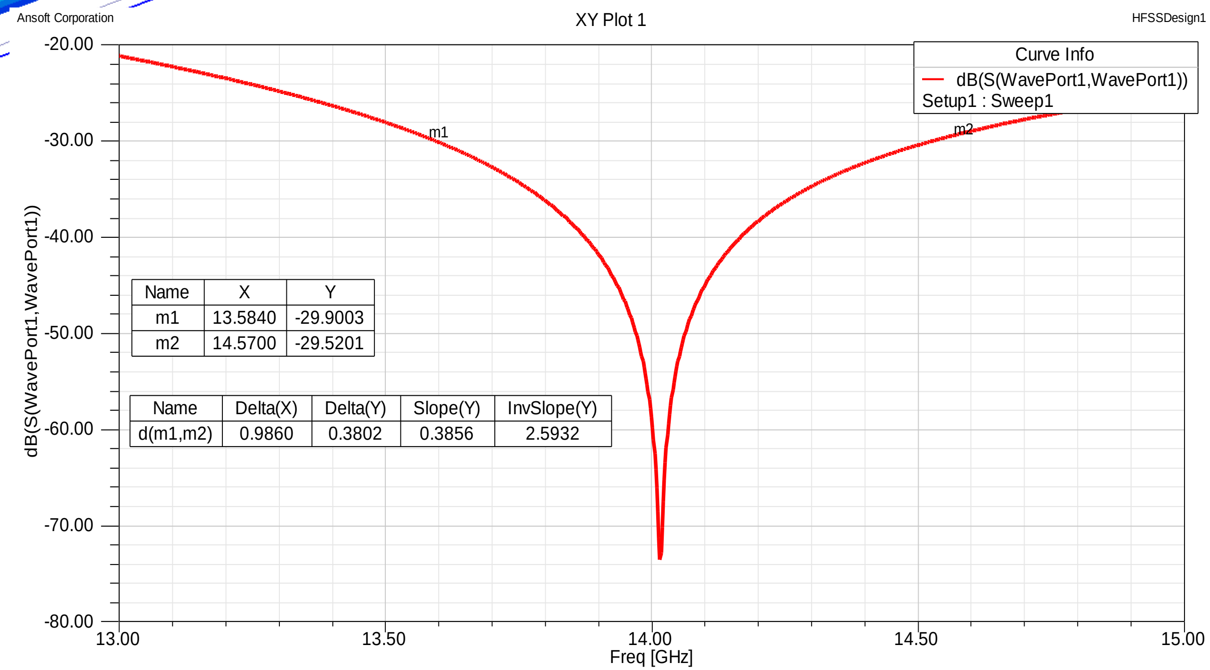


BPM Geometrical Dimensions

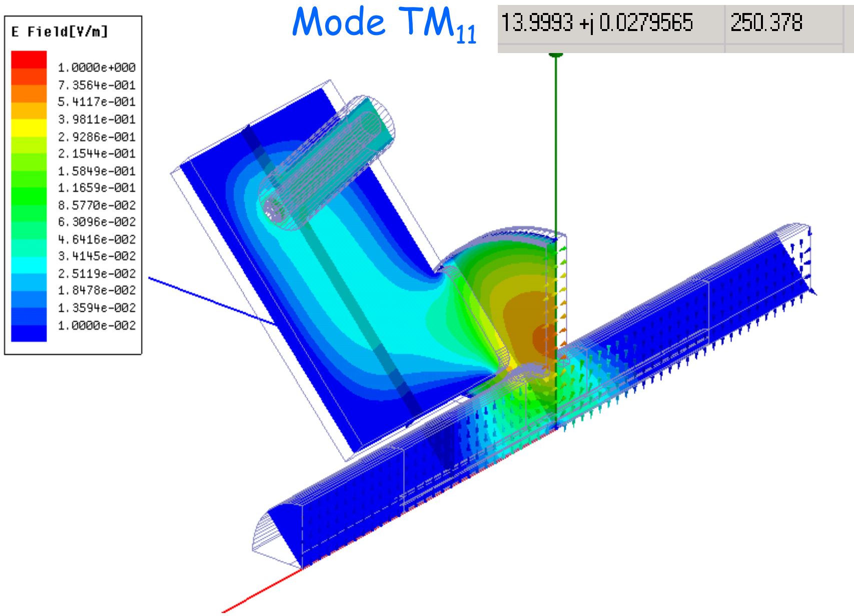


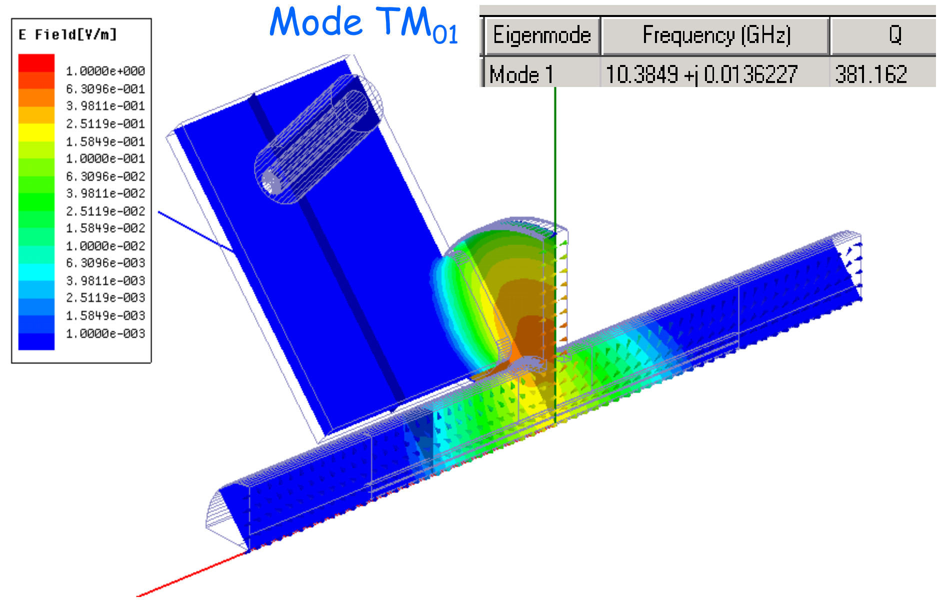
Waveguide to coaxial transition

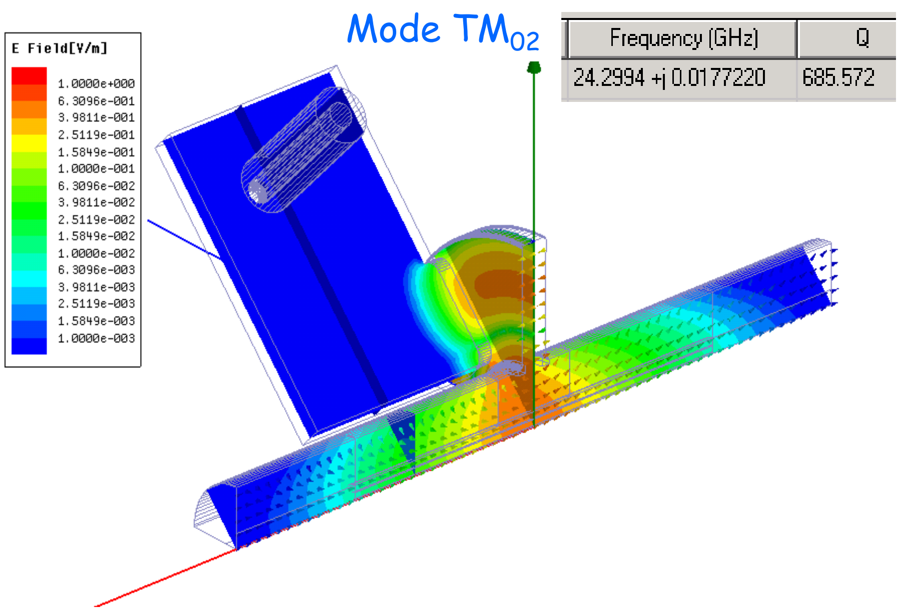


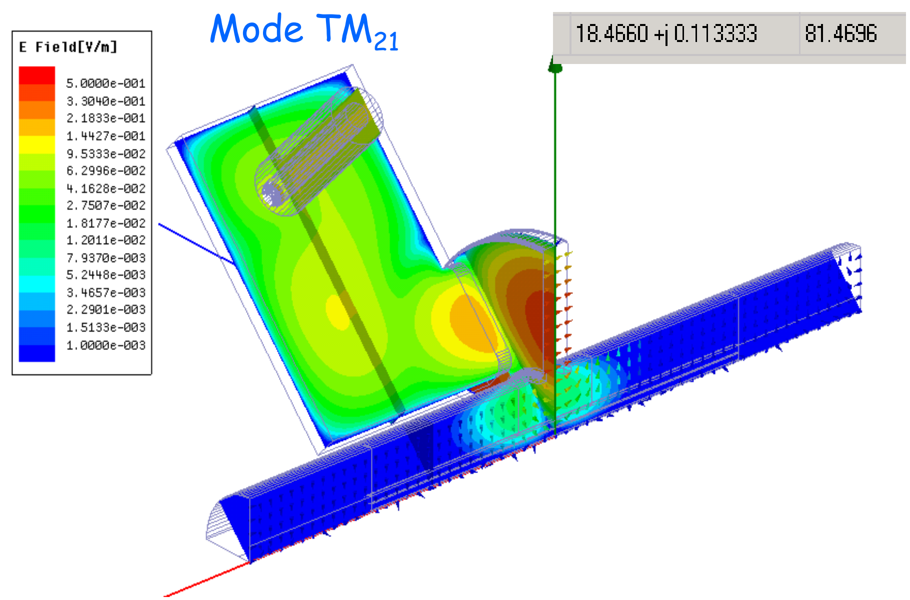


BPM Cavity Modes

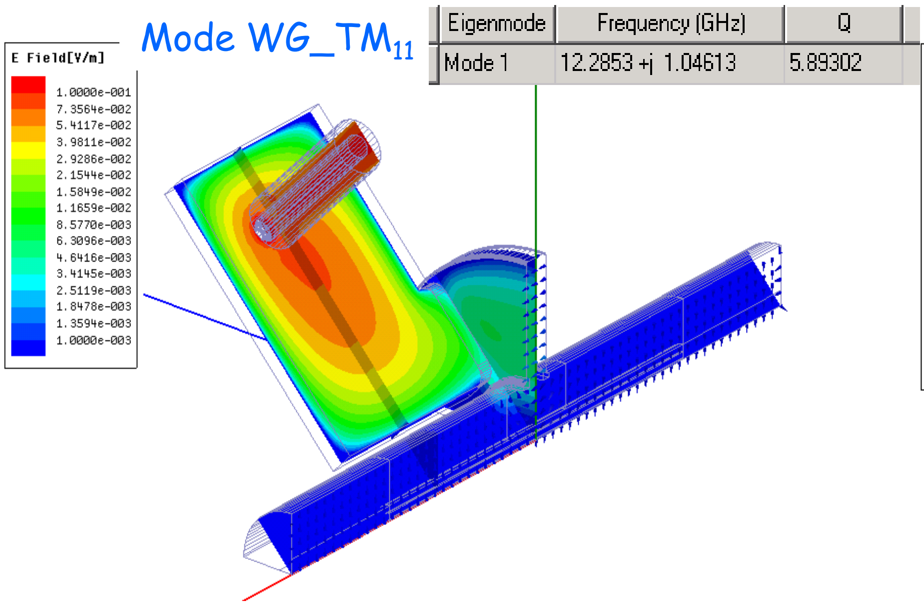


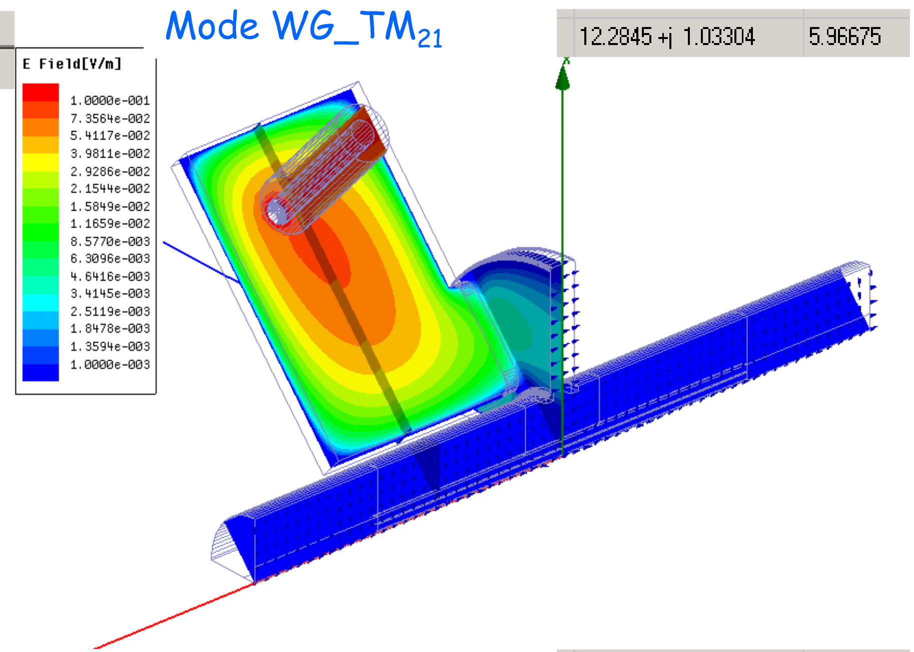


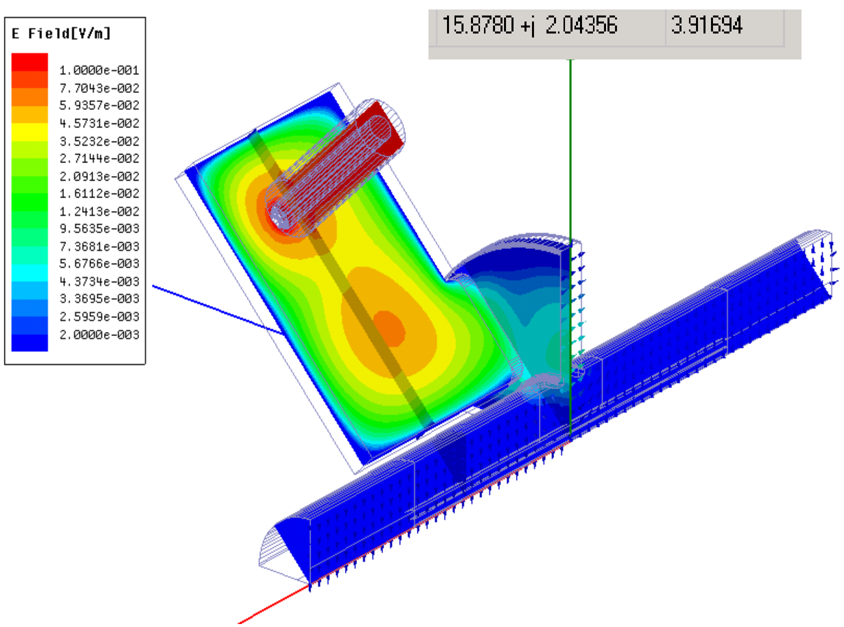


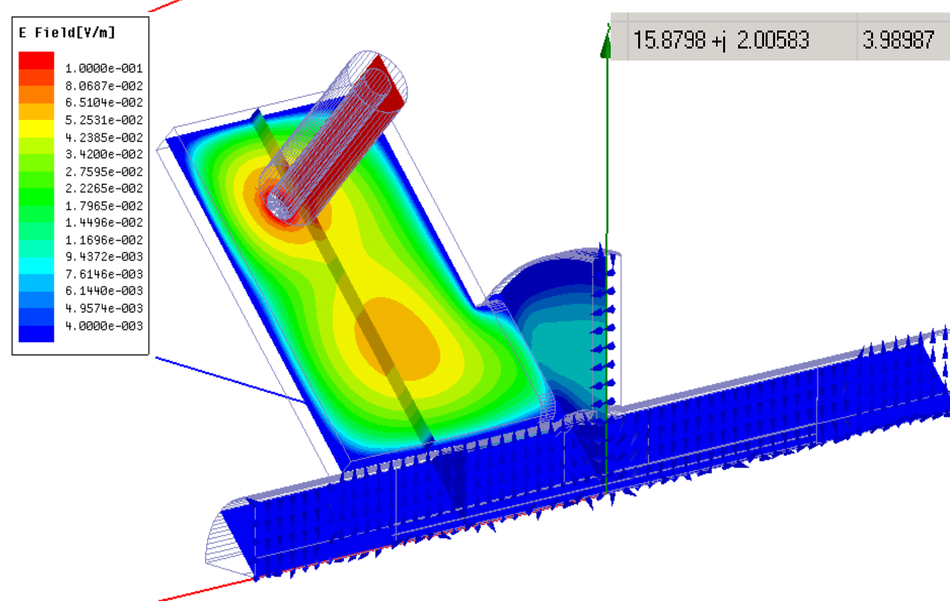


Waveguide Low-Q resonances

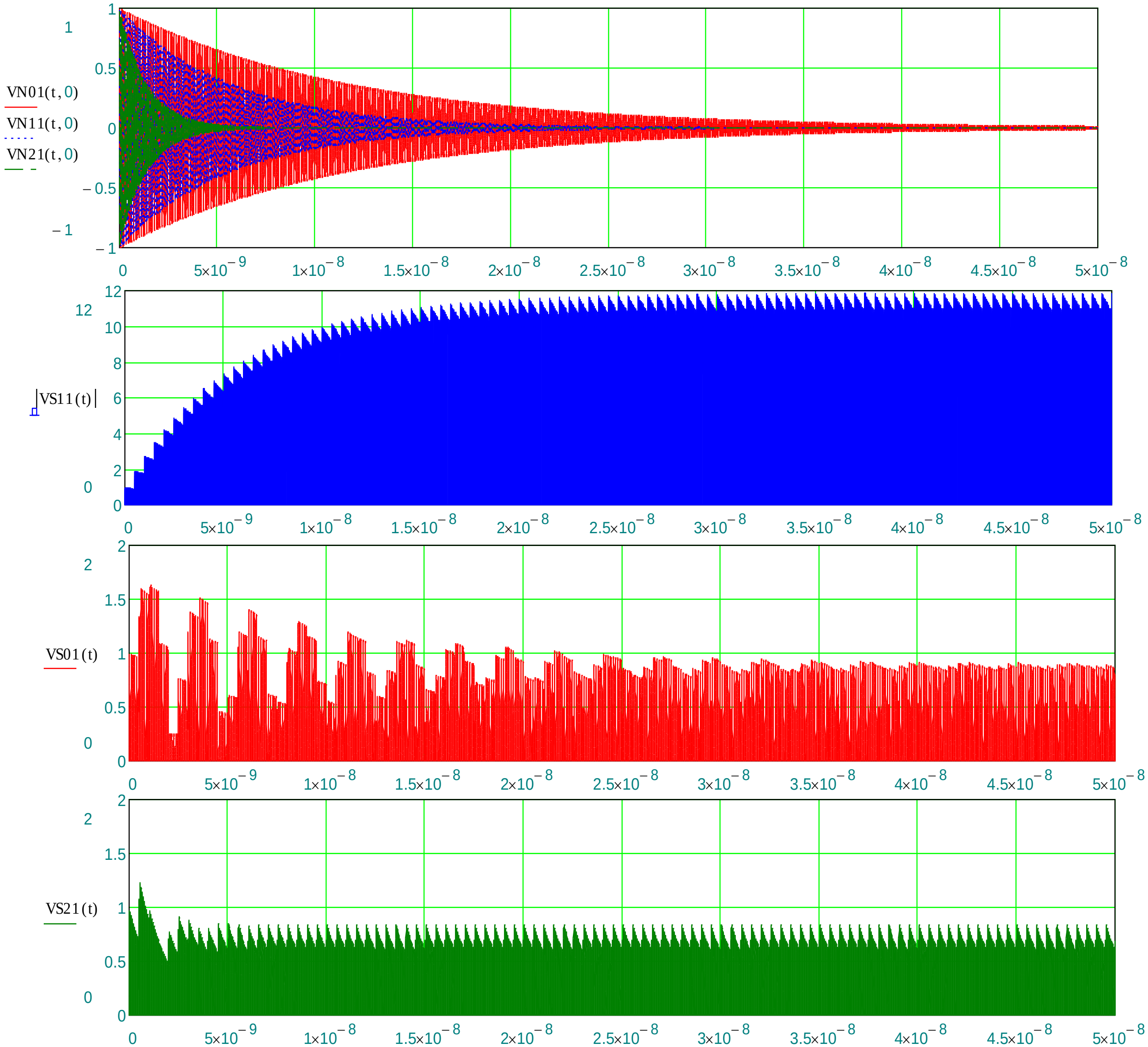








Multi-bunch Regime Rejection



Time, [s]

Single Bunch Signals :

TM_{01}, TM_{11}, TM_{21}

Multi-bunch regime (2 GHz)

TM_{11} signal

$$I11 := \int_{t1}^{t2} |VS11(t)|\, dt$$

TM_{01} signal

$$I01 := \int_{t1}^{t2} |VS01(t)|\, dt$$

Rejection: $\frac{I01}{I11} \approx 0.08$

TM_{21} signal

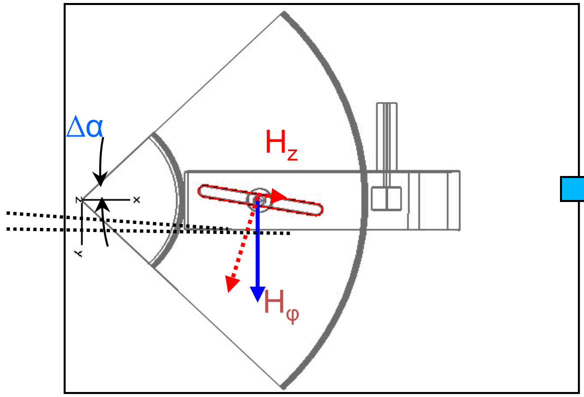
$$I21 := \int_{t1}^{t2} |VS21(t)|\, dt$$

Rejection: $\frac{I01}{I21} \approx 0.07$

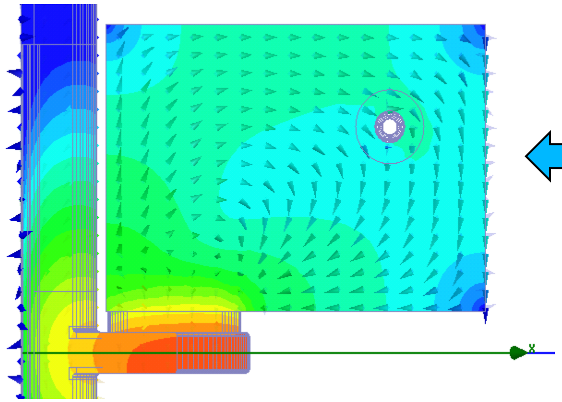
Monopole Mode Coupling due to Mechanical Errors

1. Slot rotation causes the non zero projection of TM01 azimuth magnetic field component (Hφ) in the cavity to a longitudinal one (Hz) of TE10 mode in the waveguide. Small slot shift is equivalent to rotation with angle: $\alpha_x \sim \arctan(\Delta x/Rslot)$. Therefore both slot rotation and shift cause strong magnetic coupling of monopole mode to waveguide.

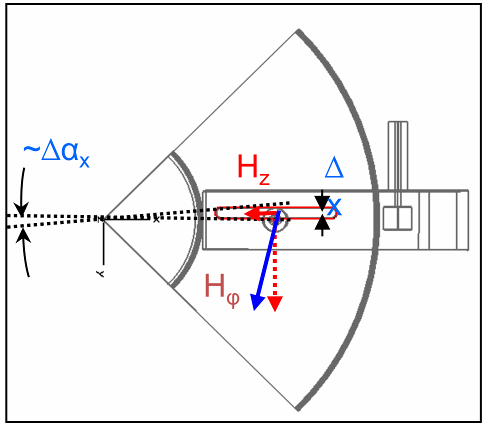
Slot Rotation



Strong Magnetic Coupling

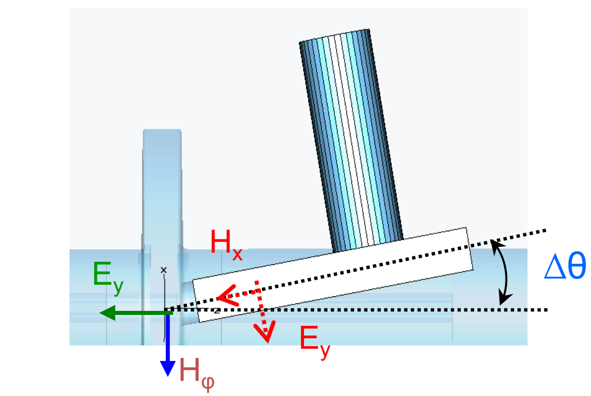


Slot Shift

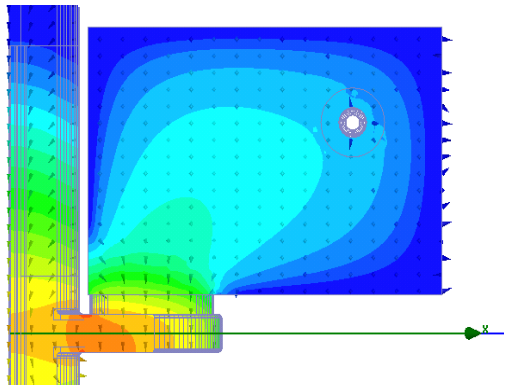


2. Slot tilt causes the non zero projection of TM_{01} azimuth magnetic (H_φ) and longitudinal electric (E_z) filelds components in the cavity to a transverse (H_x) and vertical (E_y) components of TE_{10} mode in the waveguide. Because both H_x and E_y are close to zero near the waveguide wall tilt error causes the weak electric and weak magnetic coupling of monopole mode to waveguide.

Slot Tilt

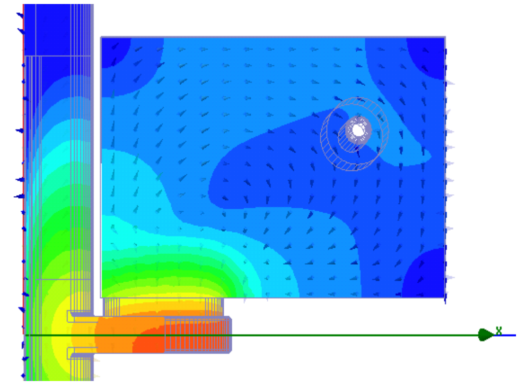


Weak Electric Coupling



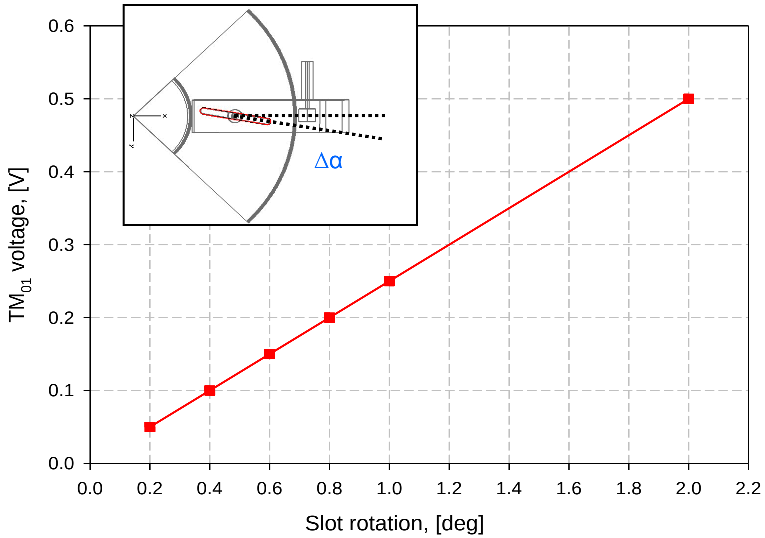
+

Weak Magnetic Coupling

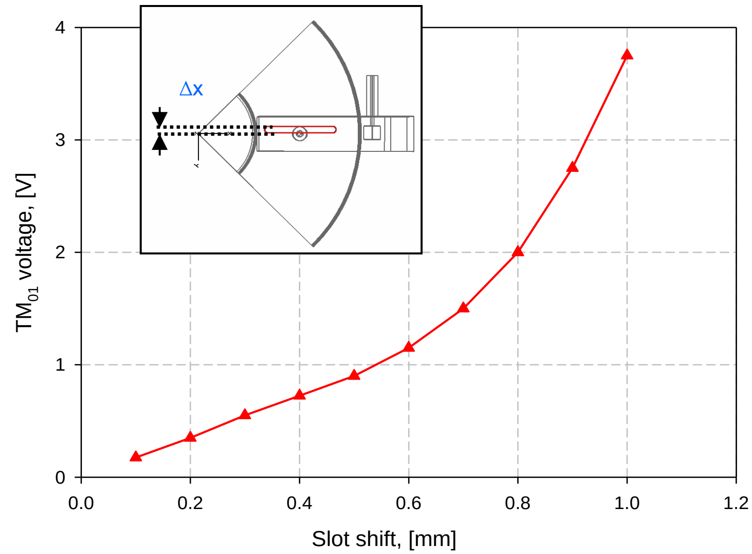


TM_{01} Mode Leak (tolerances calculations)

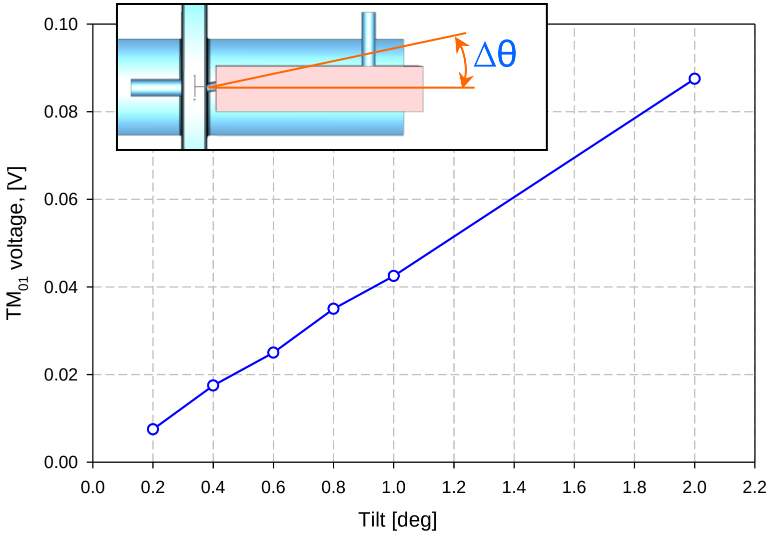
c) Slot Rotation

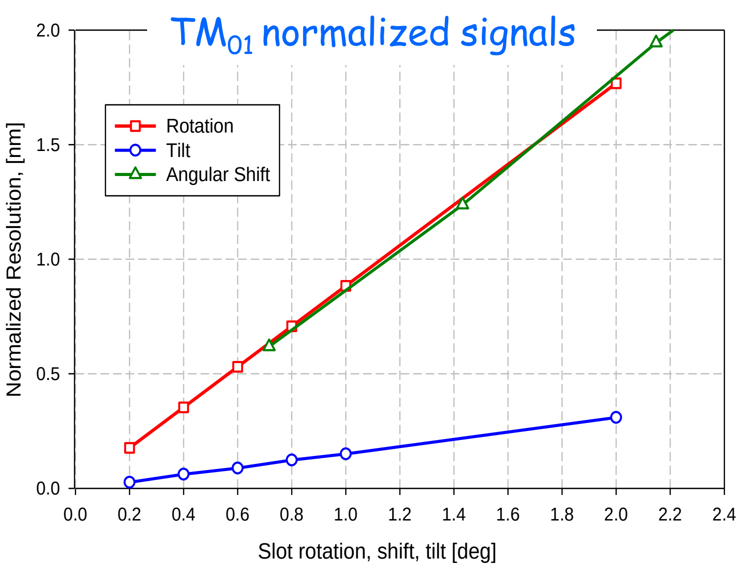


Slot Shift



Waveguide Tilt





Now we treat in detail:

- Measurement of nm beam positions
- Measurement of um transverse beam sizes:
  OTR, ODR, laser wire scanner (LWS)
- Measurement of fs-scale long profiles
- Beam synchronization at the fs-scale
- Keeping the beams in collision (IP feedback)

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

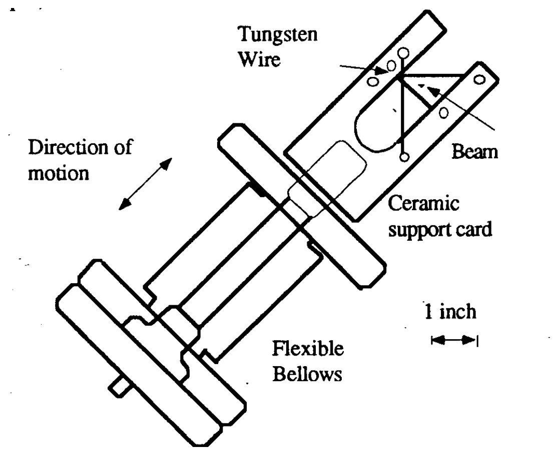
$> 10^{10}$ nC/cm^2

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

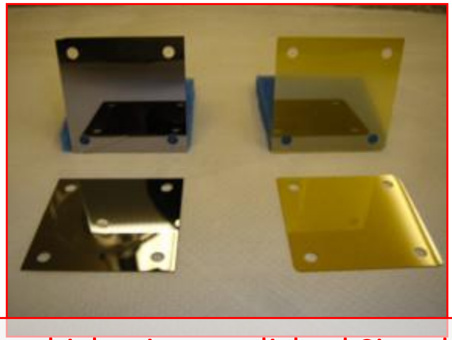
→ *The thermal limit for 'best' material (C, Be, SiC) is 10^6 nC/cm^2*

‘Beam Profile Horror Picture Show’

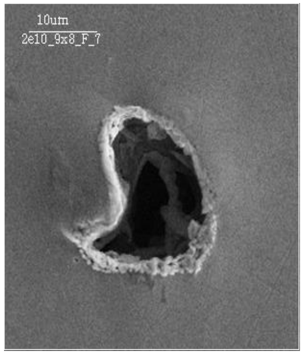
Wire Scanner

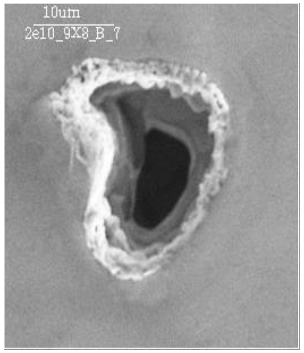


Optical Transition Radiation



200μm thick mirror polished Si and CVD SiC wafer

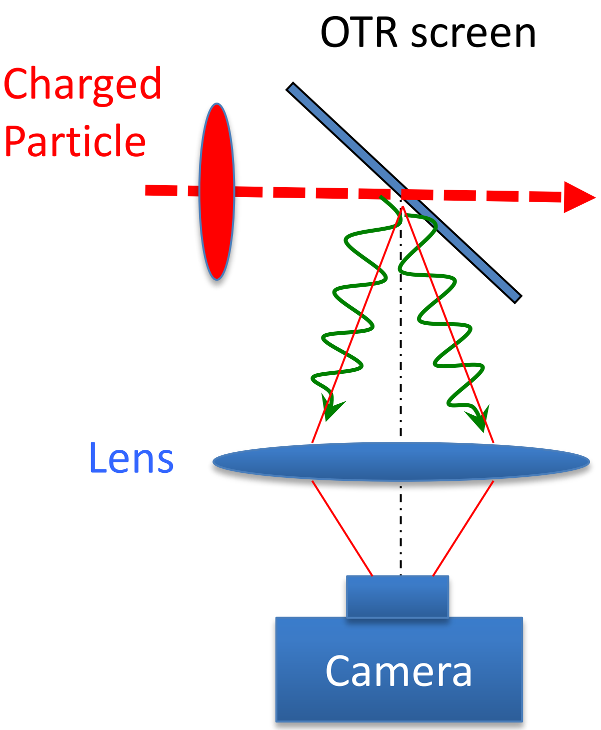




→ <u>Intercepting devices</u> limited to single (or few) bunch mode

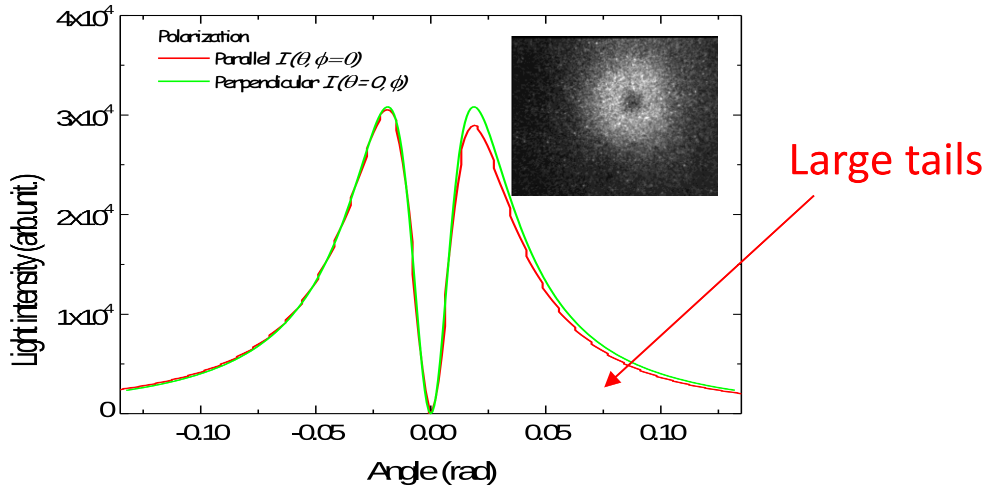
High Resolution Imaging System using OTR

• 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 $1/\gamma$ but large tails
  • Problem for very high energy particles



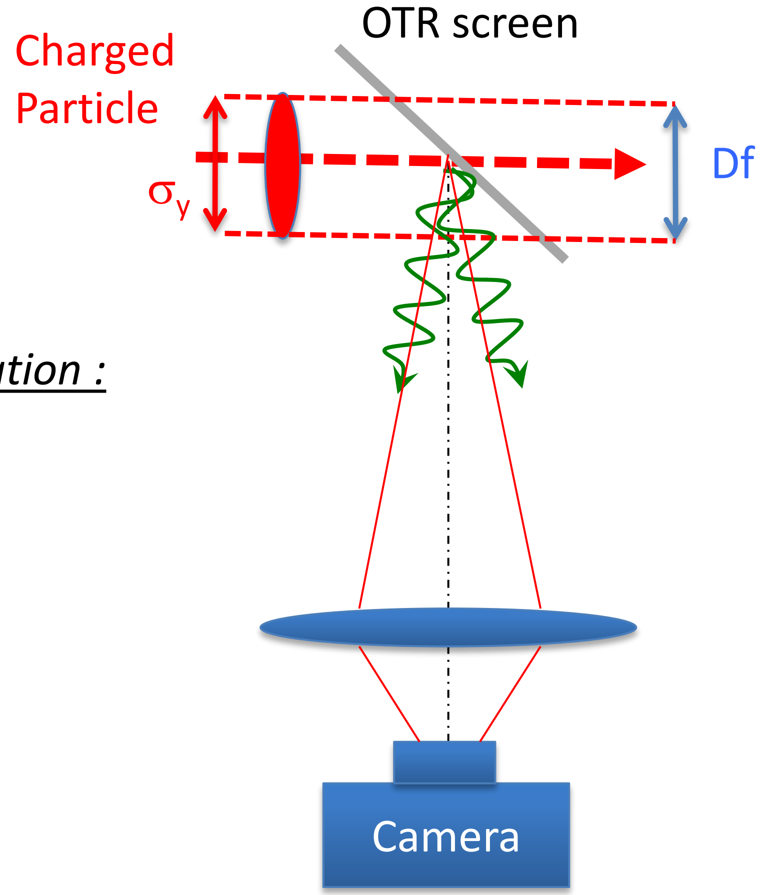
• Aperture of the focussing lens : $\theta \gg 1/\gamma$

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

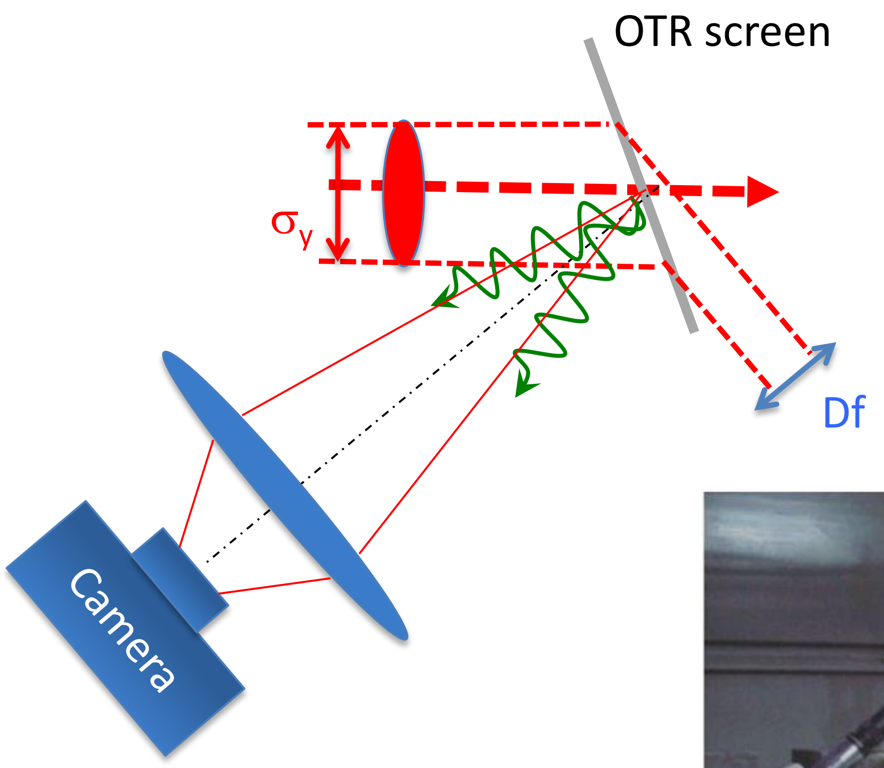


Classical OTR configuration :
90º observation angle

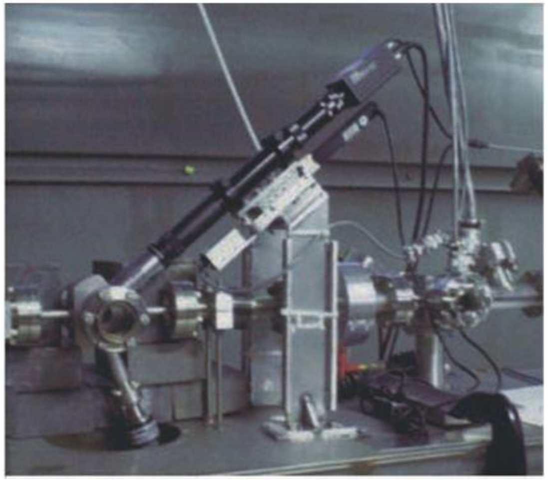
Make Df > σ_y

High Resolution Imaging System using OTR

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

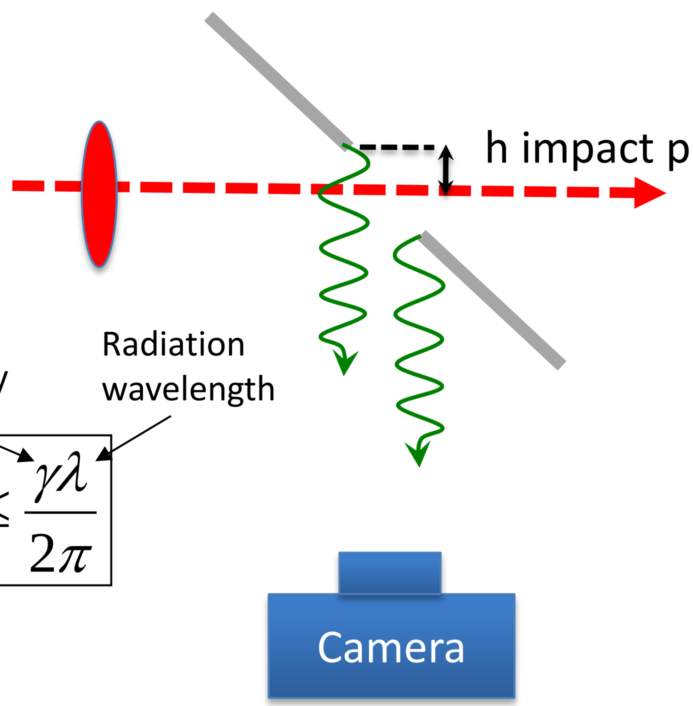


Smaller Df → Tilt the screen



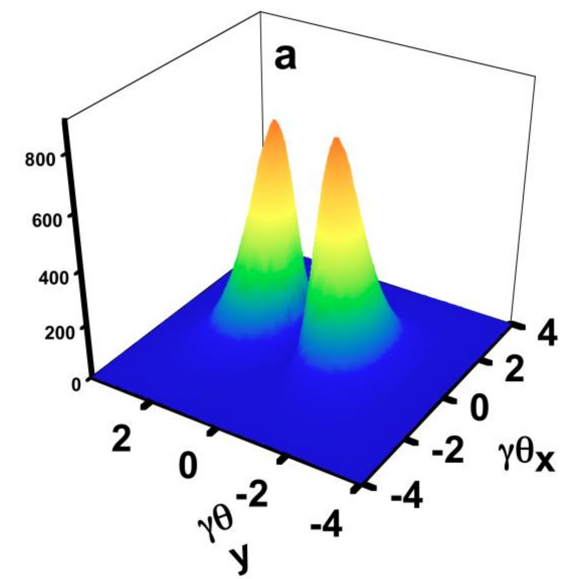
Beam size monitoring with Diffraction Radiation

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



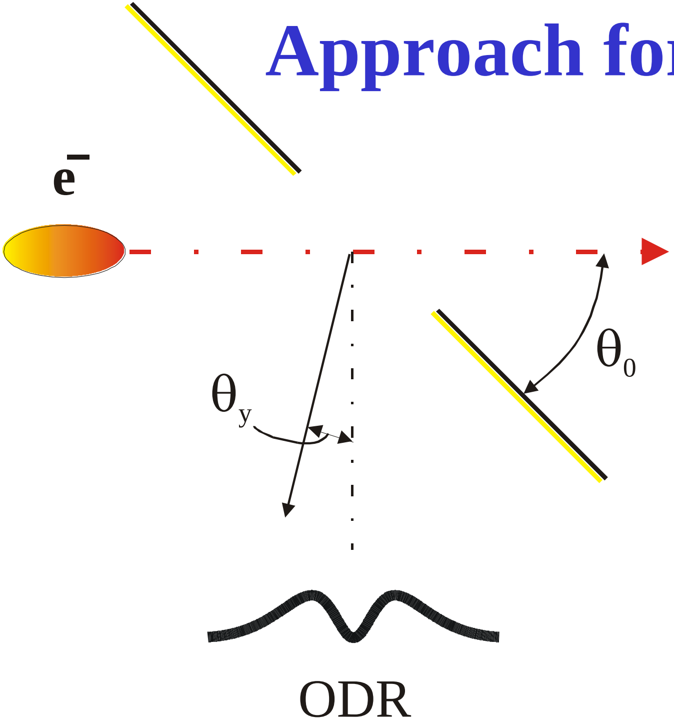
$$h \leq \frac{\gamma\lambda}{2\pi}$$

<u>Measuring the angular distribution of the interference pattern between the DR emitted by the two slits</u>



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

Approach for the beam size measurements



Assume a Gaussian beam profile

$$G(\overline{a}_x, \sigma_y) = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left[-\frac{(\overline{a}_x - a_x)^2}{2\sigma_y^2}\right]$$

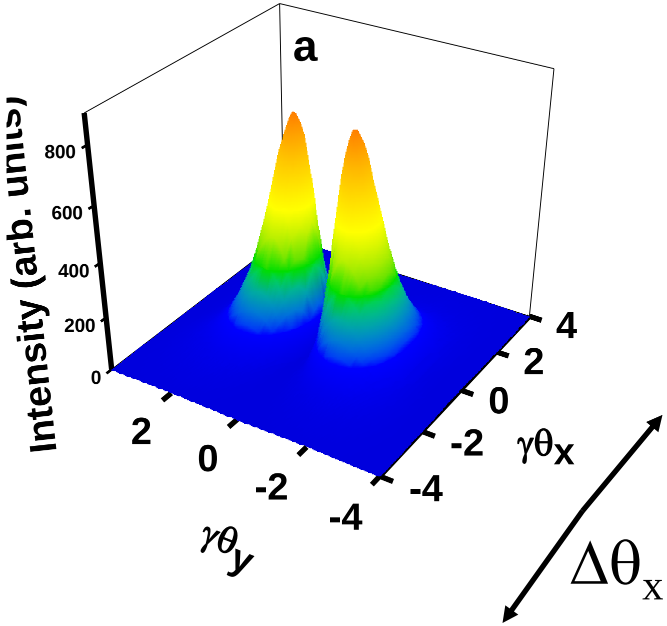
σ_y is the electron beam size and
$\overline{a}_x$ **is its offset with respect to the slit center**

$$\frac{d^2 W_y^{slit}}{d\omega d\Omega} = \frac{\alpha |R_y|^2}{4\pi^2} \frac{\exp\left(-\frac{2\pi a \sin\theta_0}{\lambda}\sqrt{\gamma^{-2} + \theta_x^2}\right)}{\gamma^{-2} + \theta_x^2 + \theta_y^2} \times$$

$$\left\{\exp\left[\frac{8\pi^2\sigma_y^2}{\lambda^2}\left(\gamma^{-2} + \theta_x^2\right)\right] \cosh\left[\frac{4\pi\overline{a}_x}{\lambda}\sqrt{\gamma^{-2} + \theta_x^2}\right] - \cos\left[\frac{2\pi a \sin\theta_0}{\lambda}\theta_y + 2\psi\right]\right\}$$

$$\psi = \arctan\left(\frac{\theta_y}{\sqrt{\gamma^{-2} + \theta_x^2}}\right)$$

Beam size effect

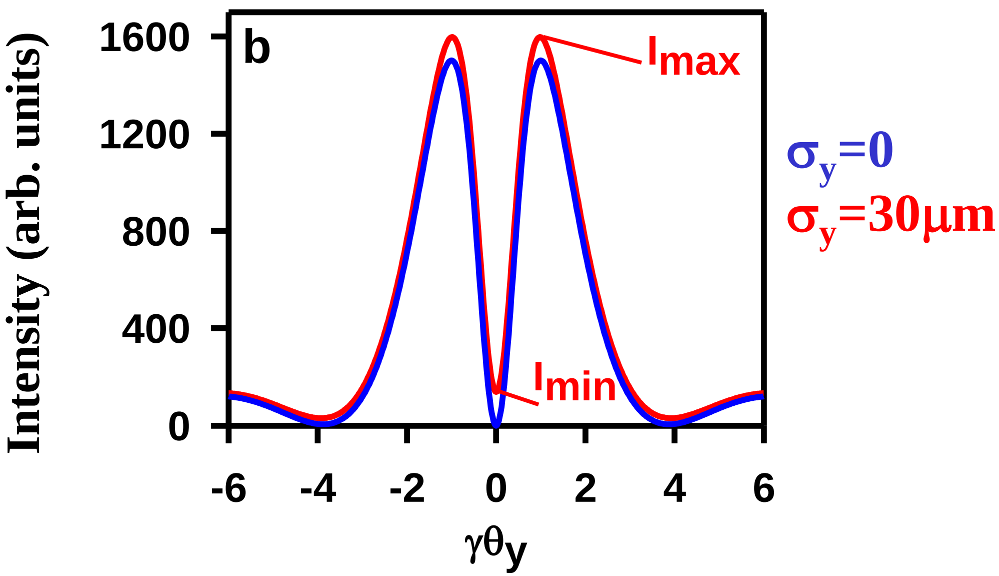


Projected vertical polarization component

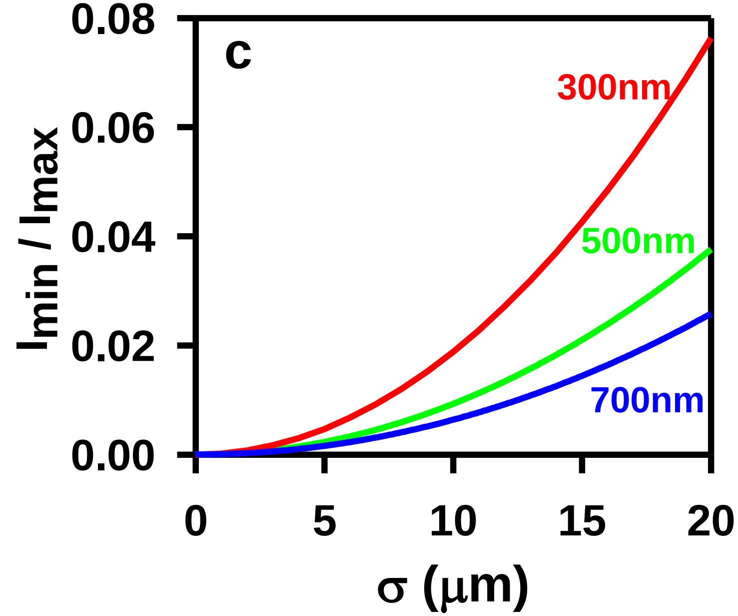
$$\overline{S(\theta_y,\sigma_y)} = \int_{-\Delta\theta_x/2}^{\Delta\theta_x/2} \frac{d^2W(\theta_x,\theta_y,\sigma_y)}{d\omega d\Omega} d\theta_x$$

$\Delta\theta_x$ – x detector angular acceptance

Projection

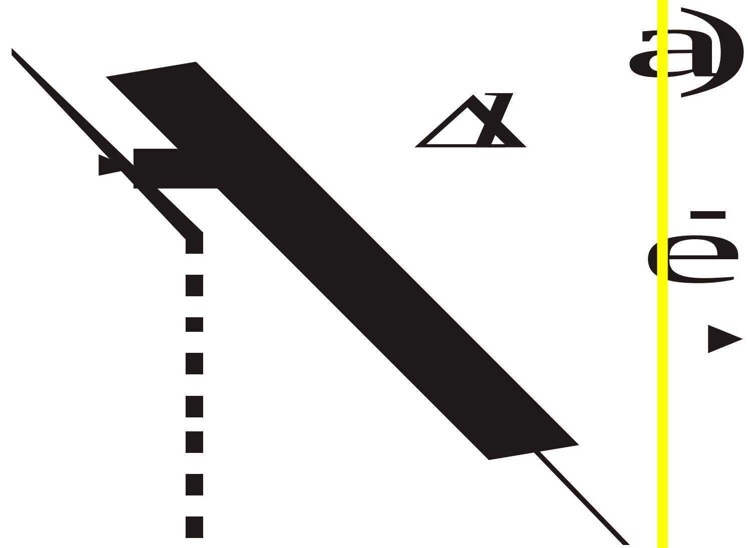


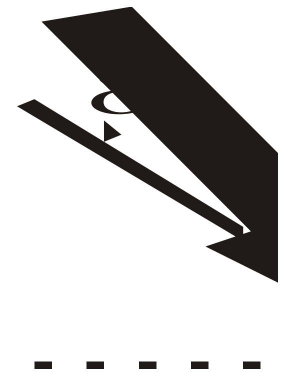
γ = 2500

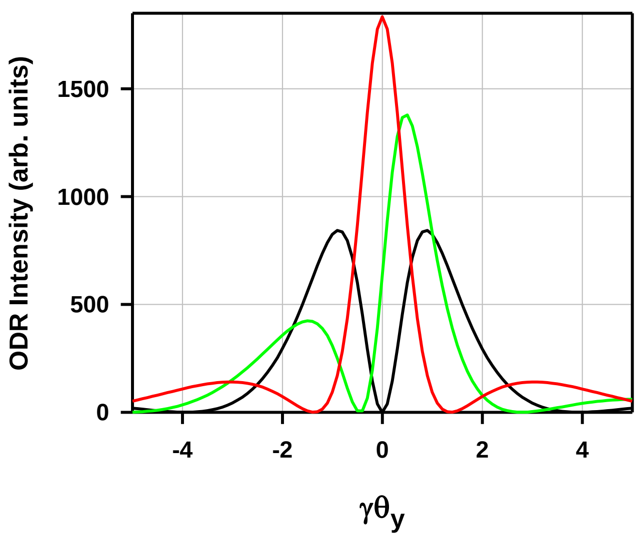


$$E^{slit}_{x,y} = E_{x,y(up)} + E_{x,y(down)} \exp\left(-i\,\frac{4\pi\,\Delta l}{\lambda}\right)$$

$$E^{slit}_{x,y}(\delta) = E_{x,y(up)}(\theta_y + \delta) + E_{x,y(down)}(\theta_y - \delta)$$





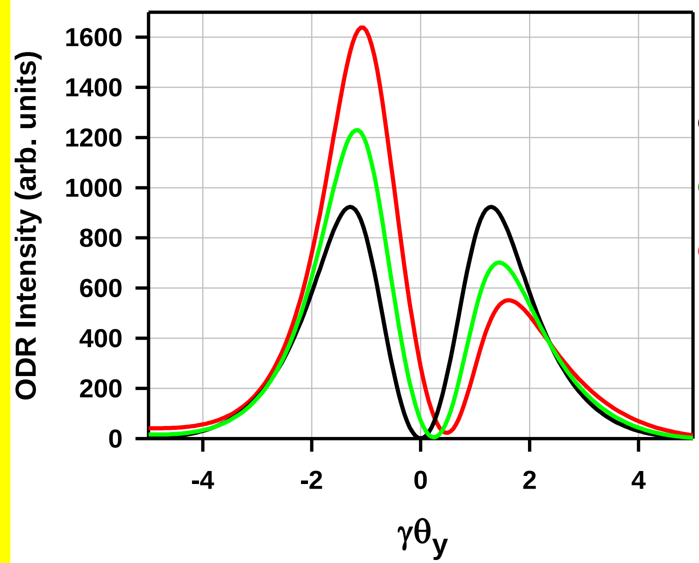


Δl = 0

Δl = λ/10

Δl = λ/4

δ = 1/γ = 0.4mrad



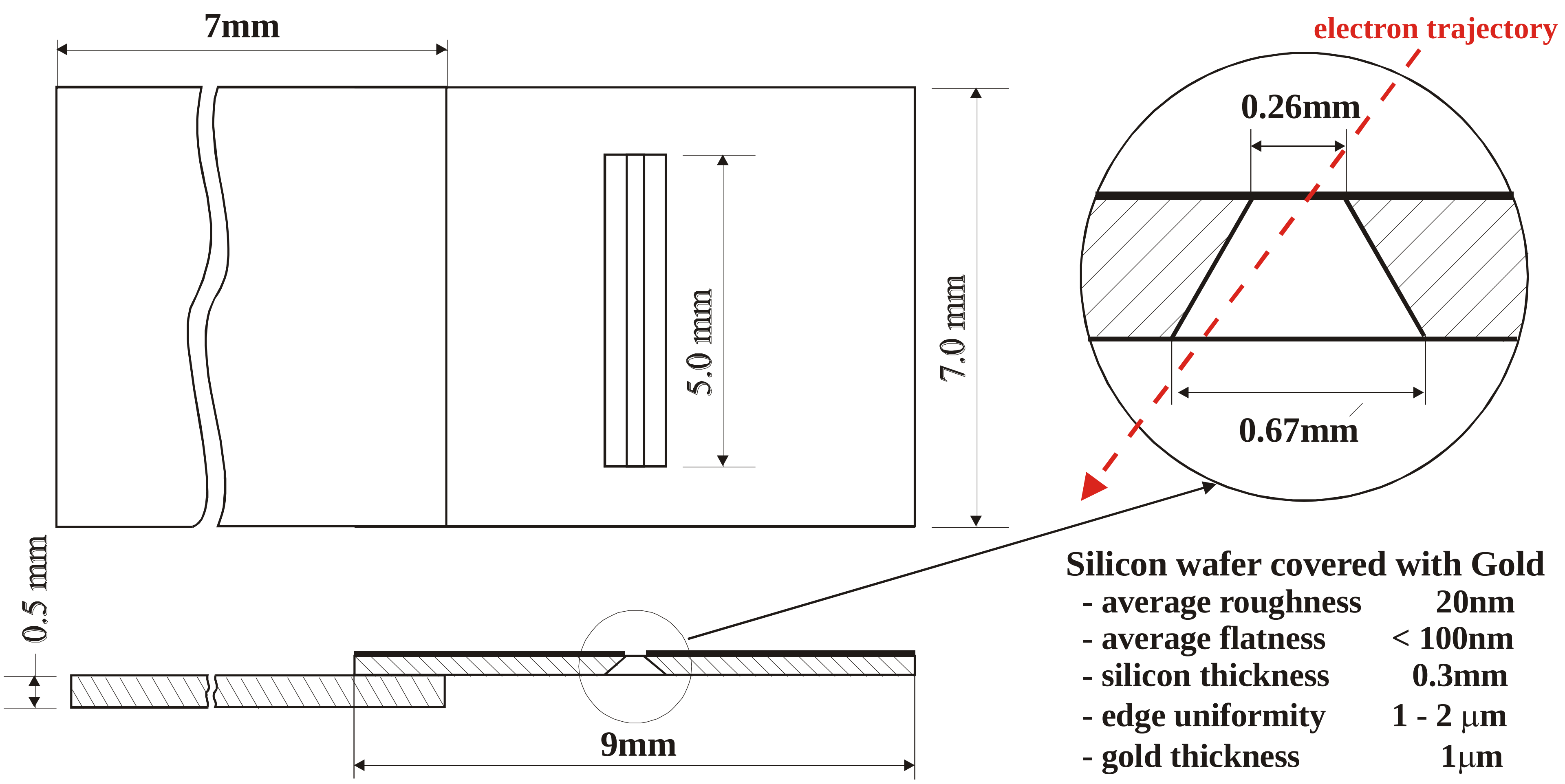
a_x = 0

a_x=0.05mm

a_x = 0.1mm

Target configuration

A silicon wafer covered with a thin gold foil

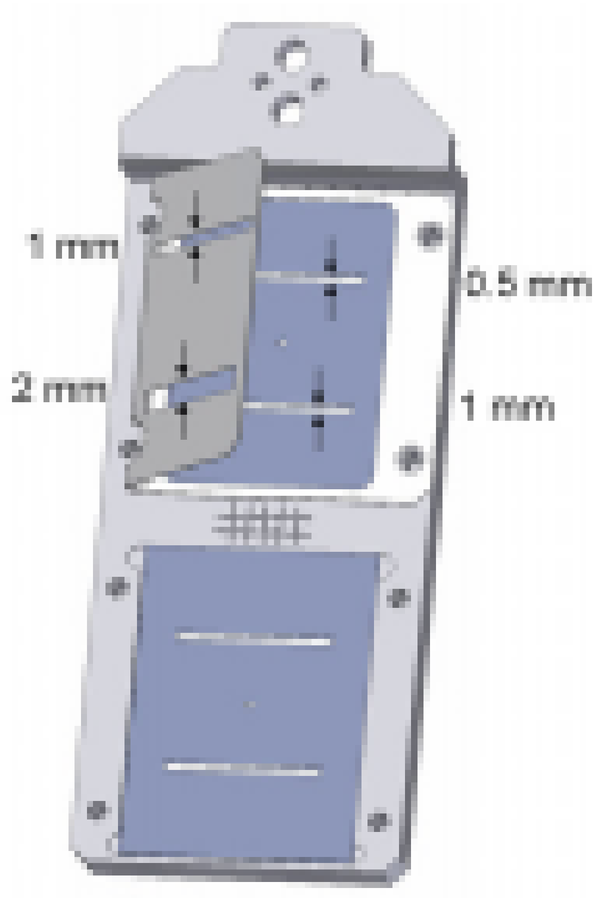


Silicon wafer covered with Gold

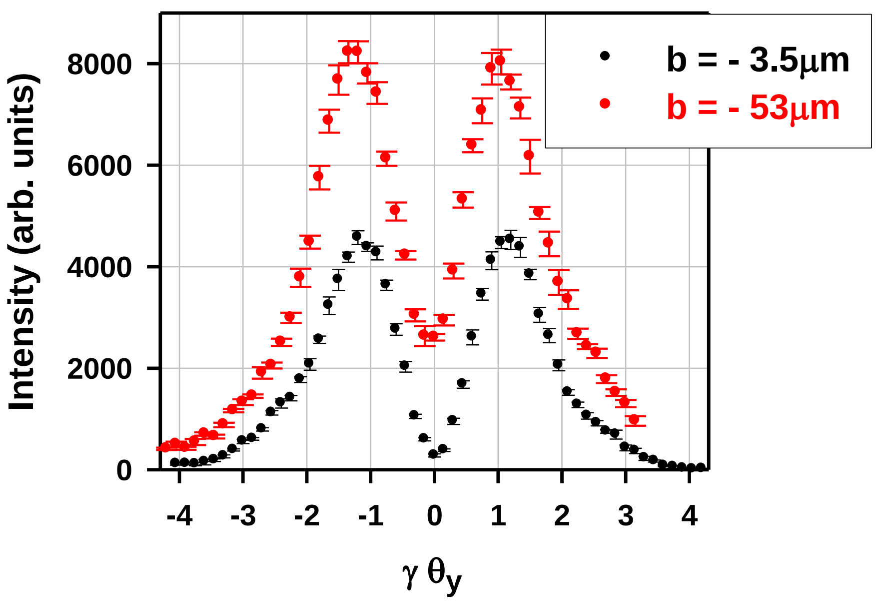
- average roughness	20nm
- average flatness	< 100nm
- silicon thickness	0.3mm
- edge uniformity	1 - 2 μm
- gold thickness	1μm

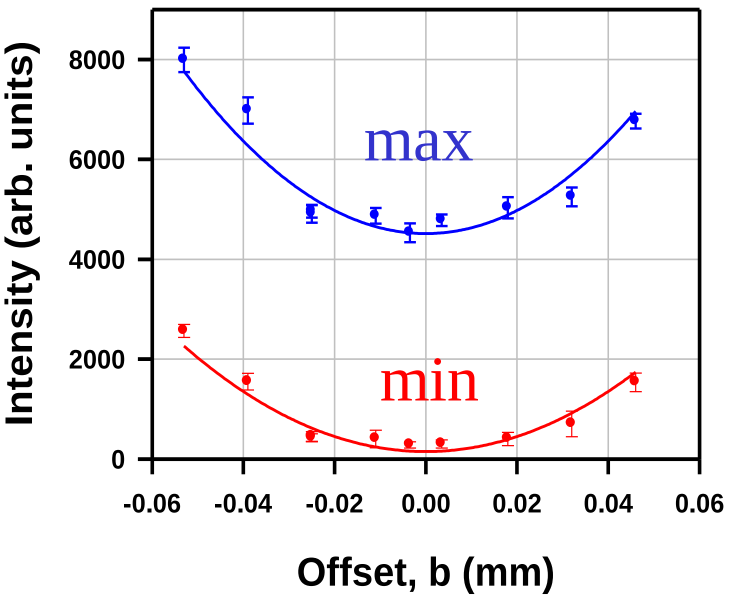
Target configuration

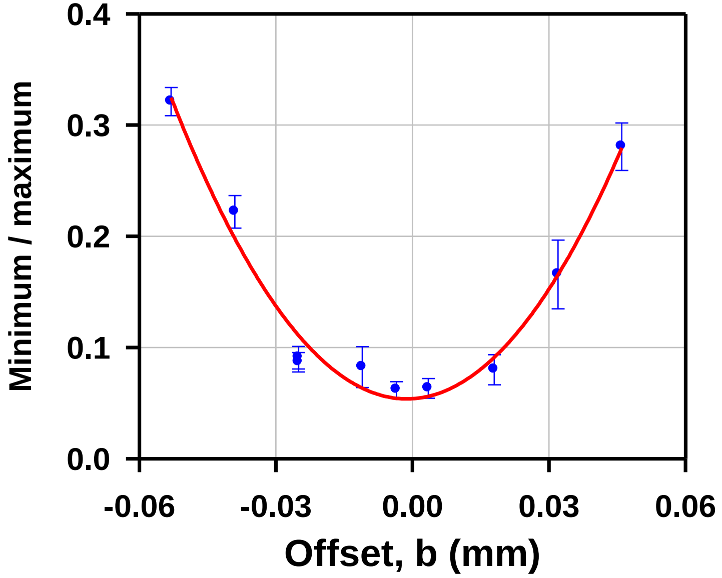
E. Chiadroni, et al., NIM B 266 (2008) 3789
E. Chiadroni, et al., DIPAC'09

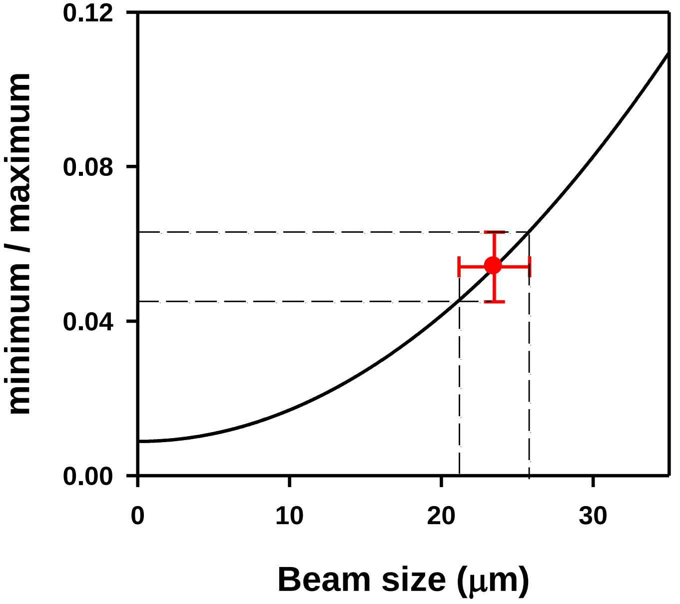


Method for the beam size determination

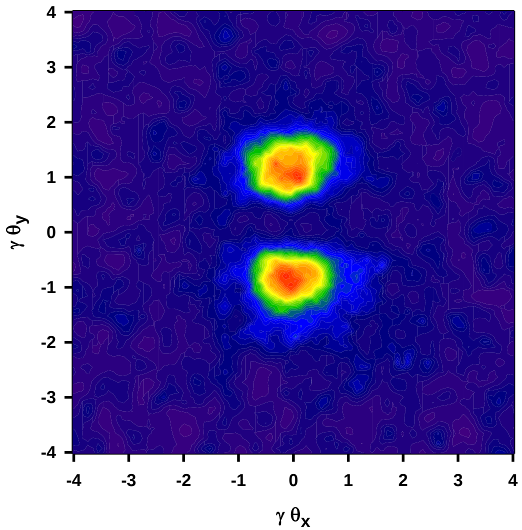






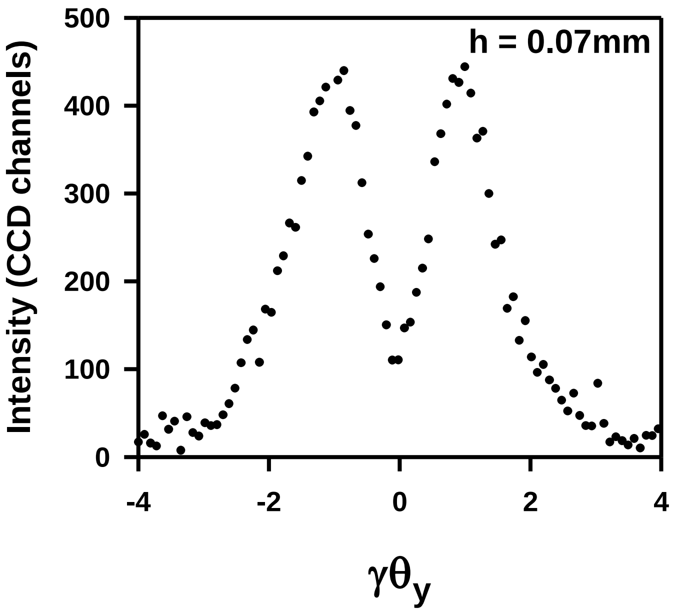


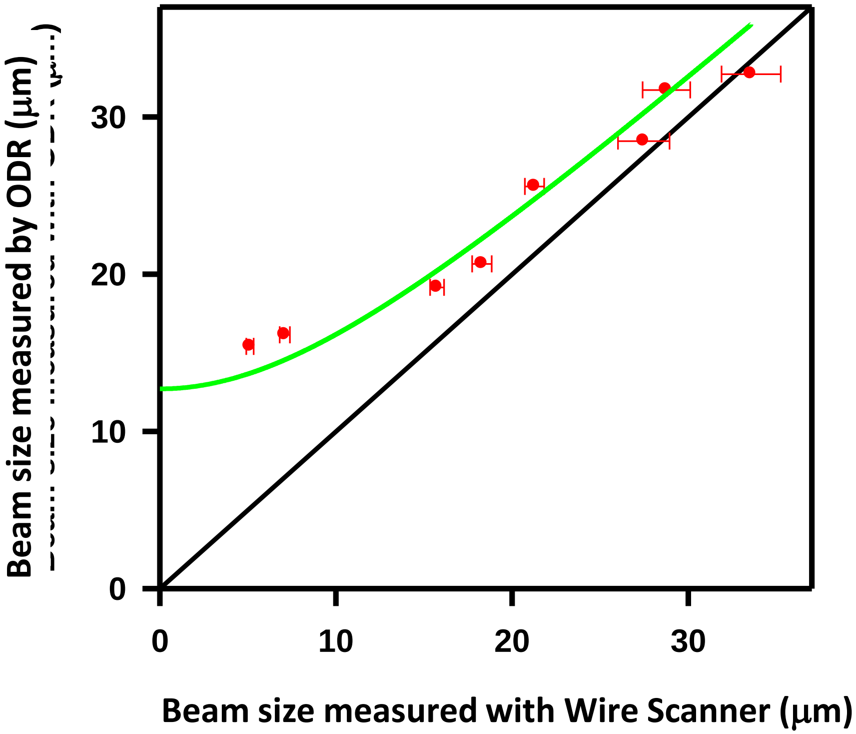
Beam size monitoring with Diffraction Radiation



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

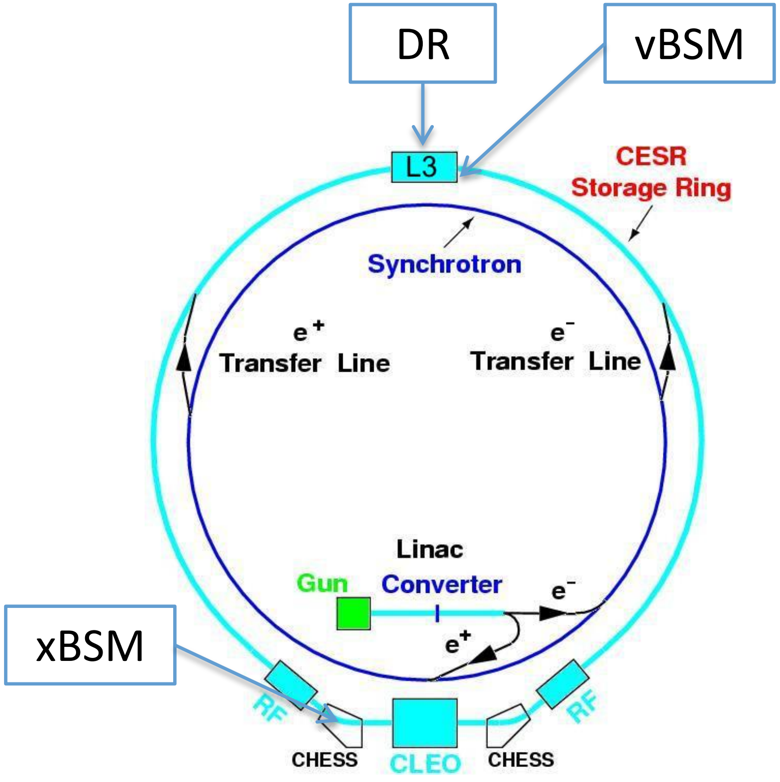
Project aim : Exp. Validation of ODR transverse profile measurements in a circular machine (CESR-Ta, Cornell)

To design and test an instrument to measure on the micron-scale the transverse (vertical) beam size for the Compact Linear Collider (CLIC) using incoherent Diffraction Radiation (DR) at UV/soft X-ray wavelengths.

Cornell Electron Storage Ring Test Accelerator (CesrTA) beam parameters:

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

D. Rubin et al., "CesrTA Layout and Optics", Proc. of PAC2009, Vancouver, Canada, WE6PFP103, p. 2751.



http://www.cs.cornell.edu

Project phases

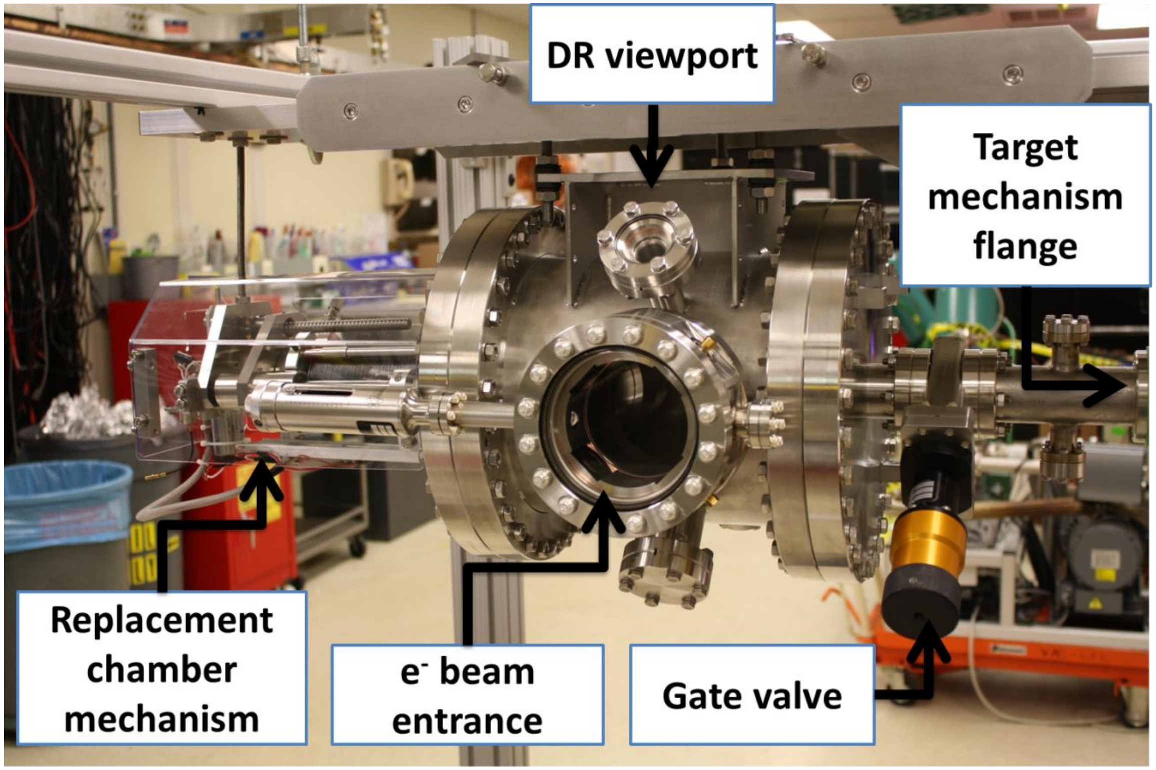
Phase 1: (2013)

- UV - Optical wavelengths
- Measurement of beam size $\sigma_y \leq 50\ \mu m$
- Observation of beam lifetime

Phase 2: (2014-2016)

- Relocate experiment to beam waist in L3 straight section of CesrTA
- Soft x-rays
- Measurement of beam size $\sigma_y \leq 10\ \mu m$

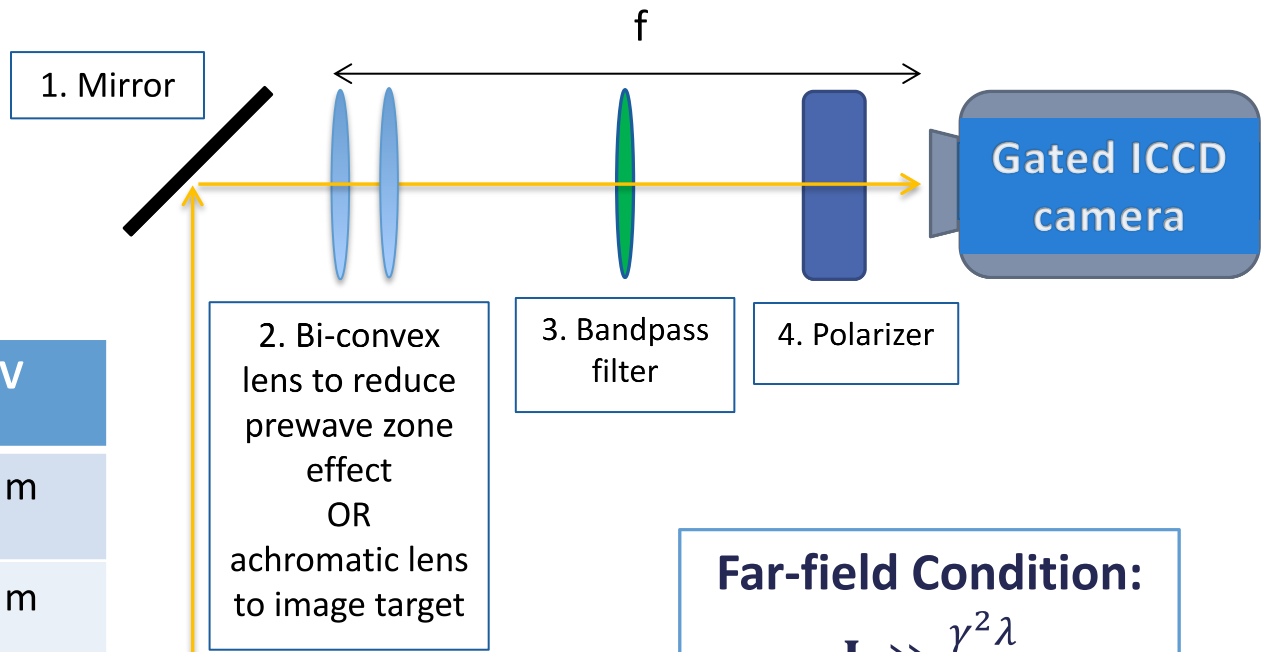
Vacuum chamber assembly



- LHS : CHESS operation
- RHS: DR experiment
- Optical system connected to DR viewport
- Gate valve to disconnect CESR vacuum for target changeover
- Target mechanism: rotation + translation IN/OUT

LHS = Left Hand Side
RHS = Right Hand Side

Optical System

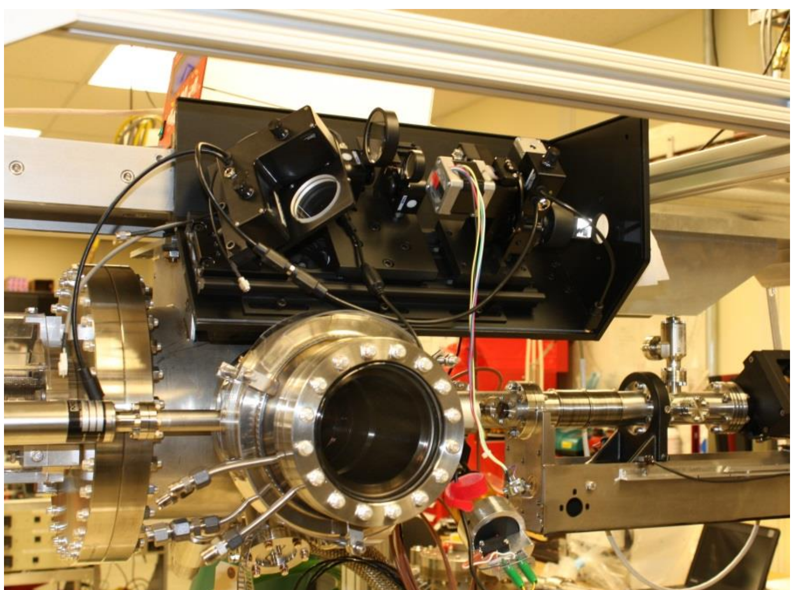


$\frac{\gamma^2 \lambda}{2\pi}$ given γ and λ:

	2.1 GeV	5 GeV
200 nm	0.54 m	3.18 m
400 nm	1.08 m	6.37 m

Far-field Condition:

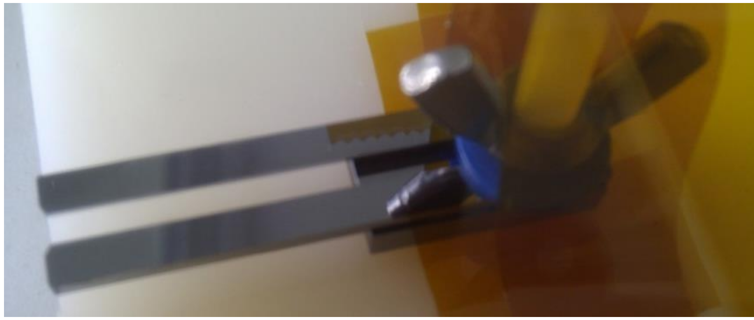
$$\mathbf{L} \gg \frac{\gamma^2 \lambda}{2\pi}$$



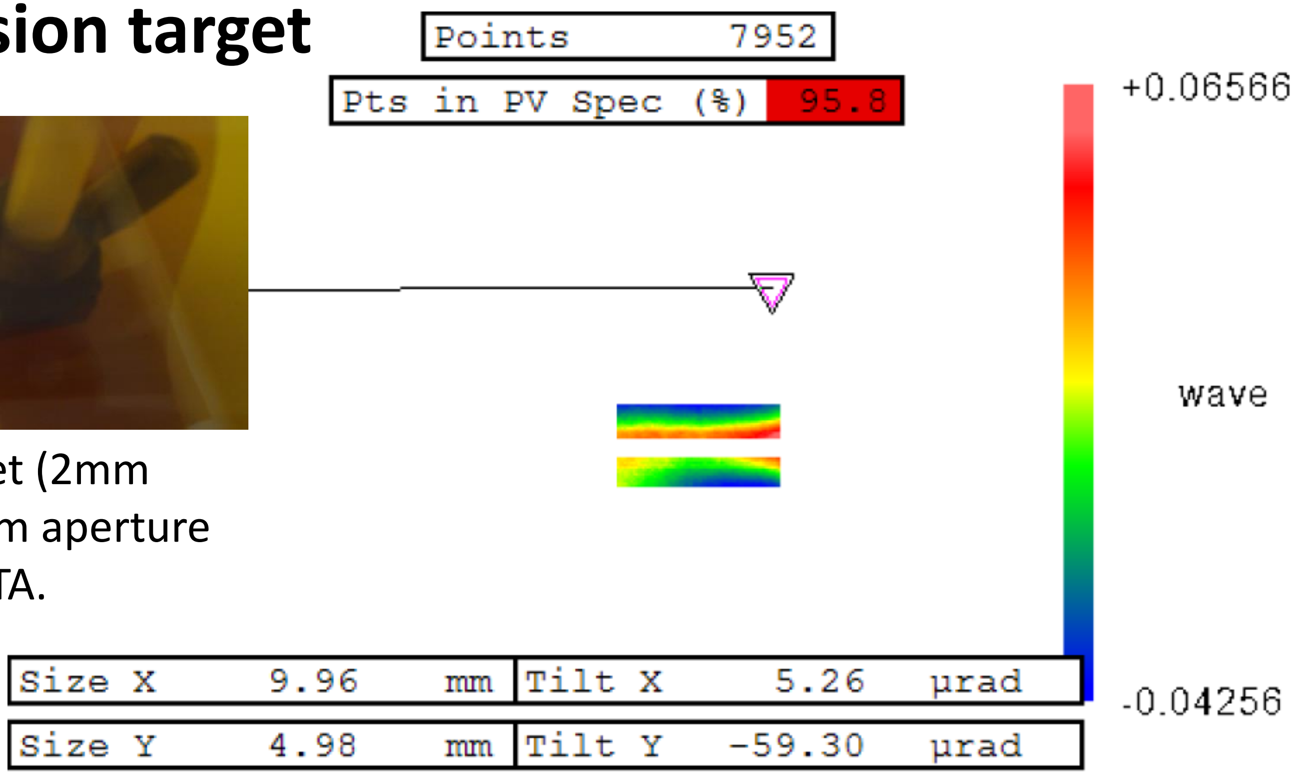
- L = distance from source of DR to detector
- Compact optical system is in the prewave zone therefore a biconvex lens is used with detector in back focal plane to obtain the angular distribution.

(*Pre-wave zone effect in transition and diffraction radiation: Problems and Solutions* -P. V. Karataev).

Molecular adhesion target



Molecular adhesion target (2mm version shown here). 1mm aperture version was used at CesrTA.



“Bonding by molecular adhesion (either ‘direct wafer bonding’ or ‘fusion bonding’) is a technique that enables two substrates having perfectly flat surfaces (e.g., polished mirror surfaces) to adhere to one another, without the application of adhesive (gum type, glue, etc.).”

Patent US 8158013 B2

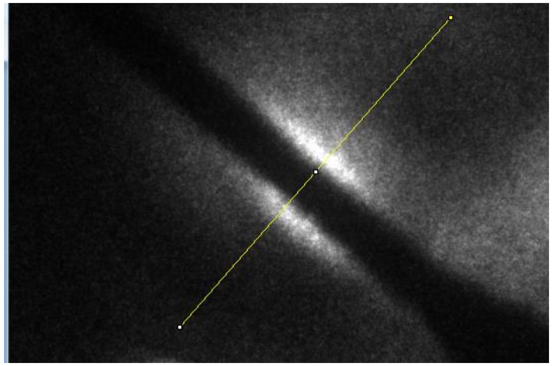
Coplanarity measurement:

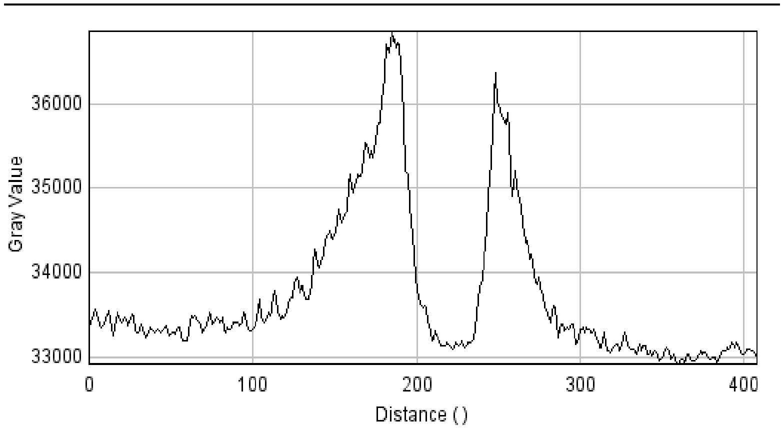
PV	68.479	nm
rms	13.909	nm

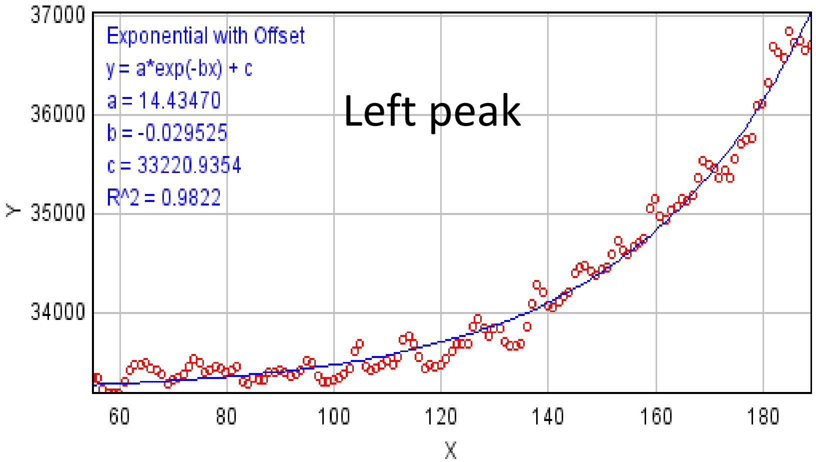
Metrology by Winlight Optics

Identification of DR in target imaging

- DR intensity decays exponentially from slit edge
- SR intensity uniform over small regions
- From simulations, max SR intensity (vert. pol.) does not occur at slit edge







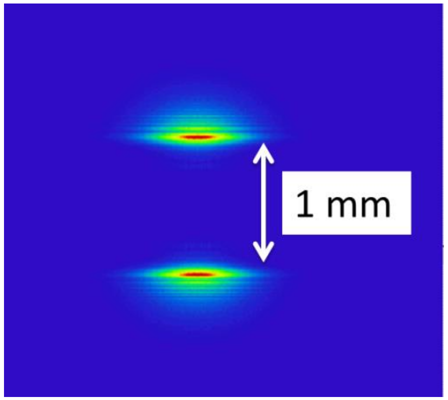
DR intensity [ph/e$^-$]= k * SR intensity [ph/e$^-$]

$k \sim 50$ using real data from TR

$k \sim 25$ using DR images

DR vert. pol. $\sim 4.0 \times 10^{-5}$ ph/e$^-$

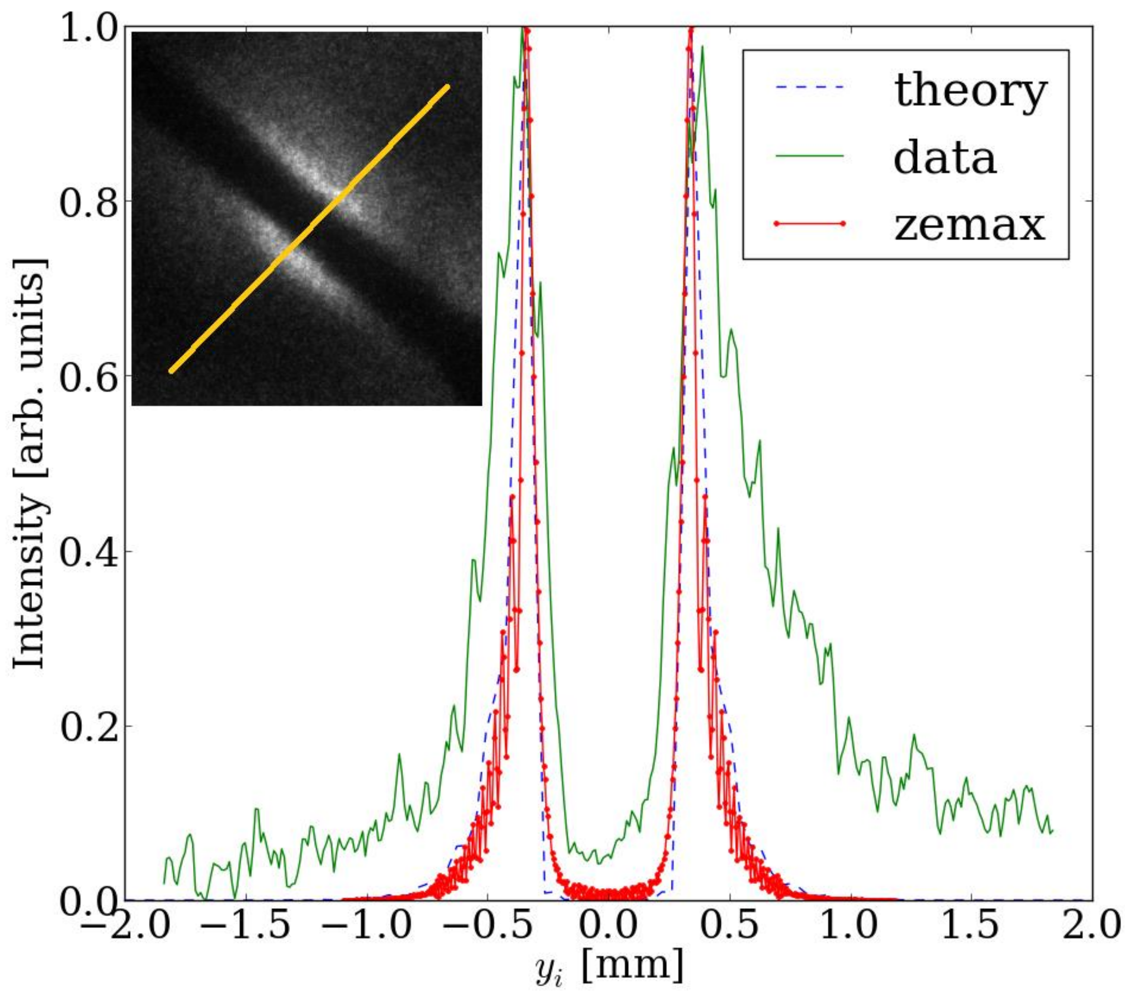
SR. vert. pol. $\sim 6.3 \times 10^{-7}$ ph/e$^-$



T. Aumeyr et al., IBIC2013, WEPF18.

DR target imaging

- 2.1 GeV
- 1 mA single- bunch beam
- 400 nm DR observation wavelength



Theory-
D. Xiang et al., Phys. Rev. ST Accel. Beams, 10 (2007) 062801.

Zemax-
T. Aumeyr et al., IBIC2013, WEPF18.

Data broadening possibly due to:

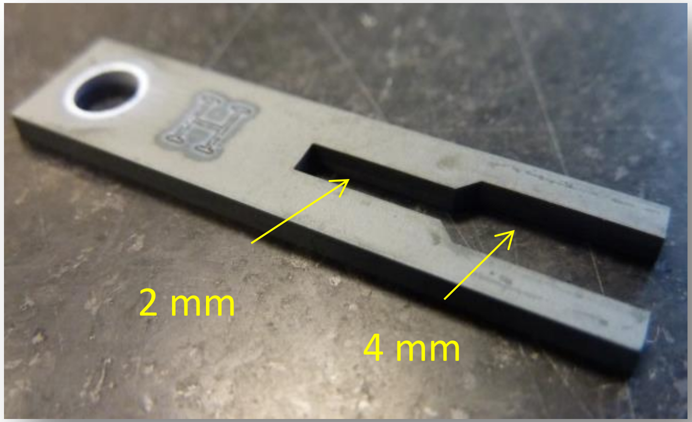
- data taken for $\sigma_y \sim 20\ \mu\text{m}$
  theoretical model and Zemax : single e⁻ $\sigma_y \rightarrow 0$
- Polariser misalignment → some horiz. pol. DR and synchrotron radiation (SR)
- 10 ± 2 nm bandwidth → data smearing (small)
- 15 ms exposure time (CesrTA rev. period $T = 2.56\ \mu\text{s}$) → smearing from beam jitter

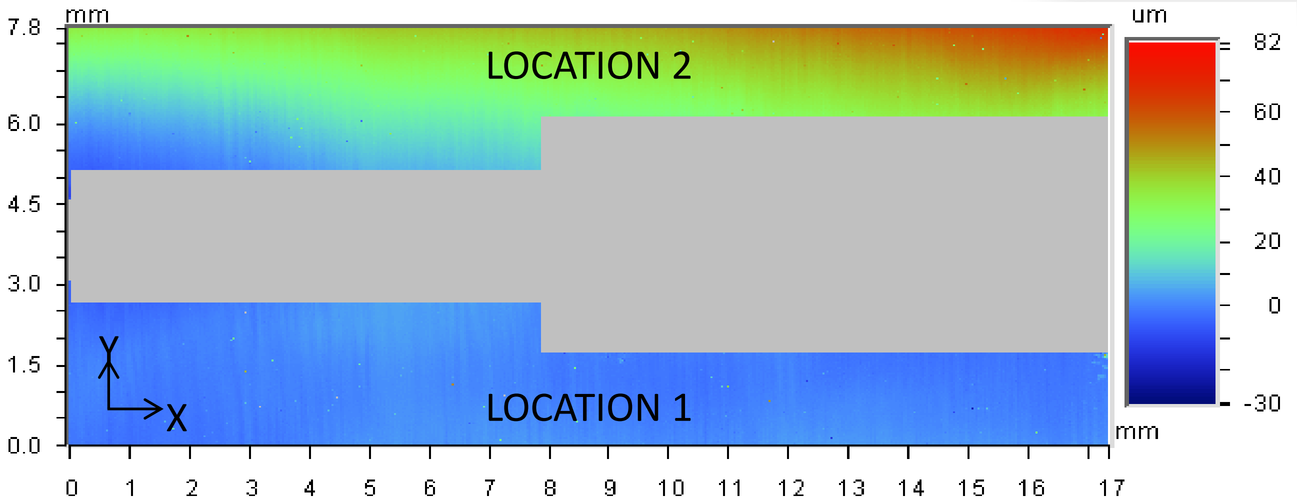
Mask

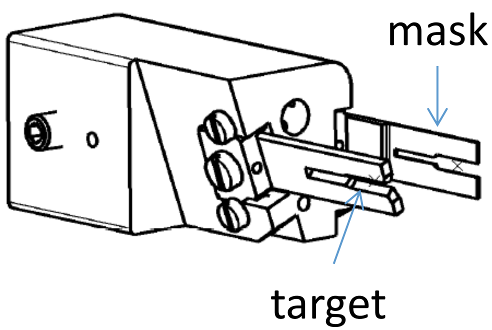
Technical drawings by N. Chritin,
Metrology by L. Remandet

- Silicon Carbide
- Laser machining
- Not etched (orientated perpendicular to beam)
- Mask aperture = 4 * target aperture
  → avoid destructive interference (ODRI)

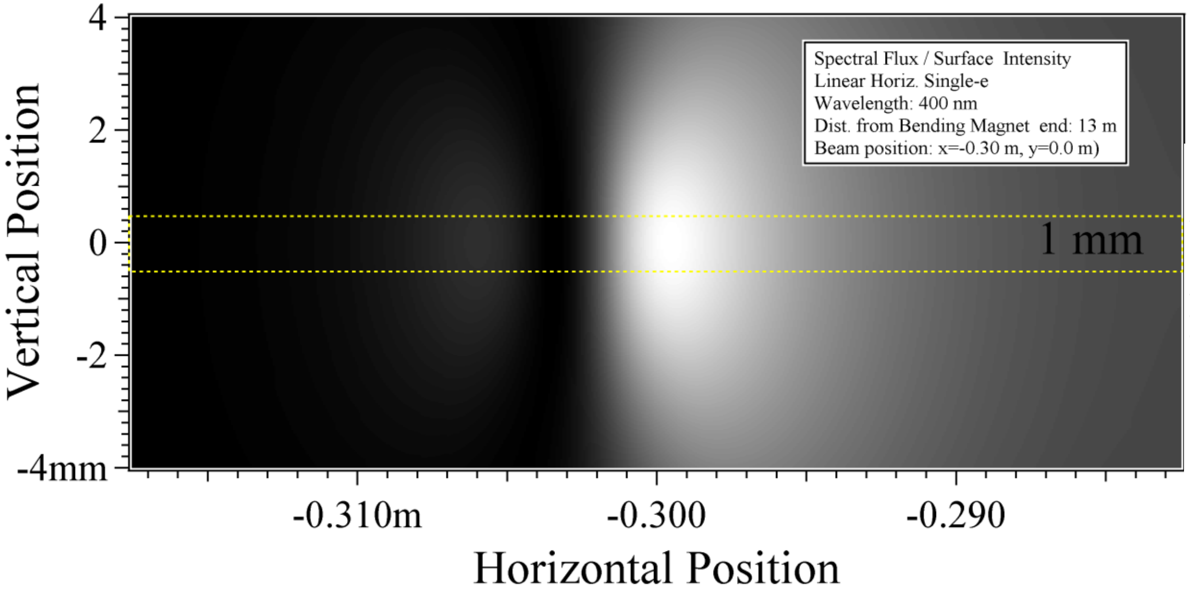
Specification	Location 1 (in µm or in µrad)	Location 2 (in µm or in µrad)
Maximum to minimum	≈ 10 µm	≈ 80 µm
Tilt in X direction	0 µrad	-1897 µrad
Tilt in Y direction	0 µrad	-13913 µrad



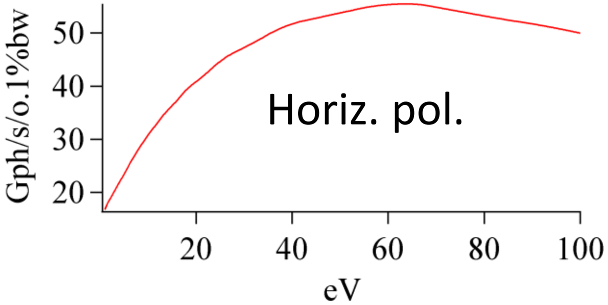


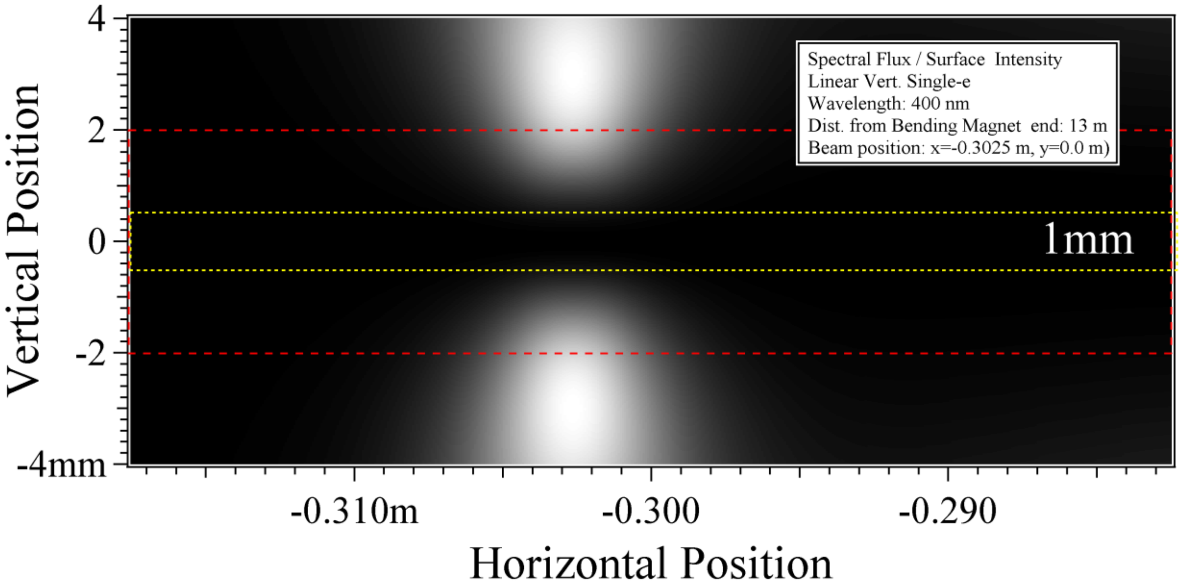


SRW simulations

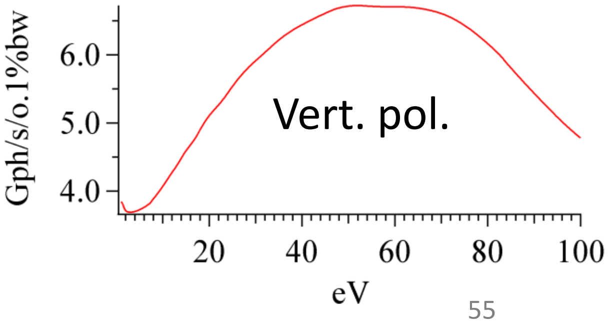


Total intensity at 400nm, 10%bw
= 2.30315e+10 ph/s





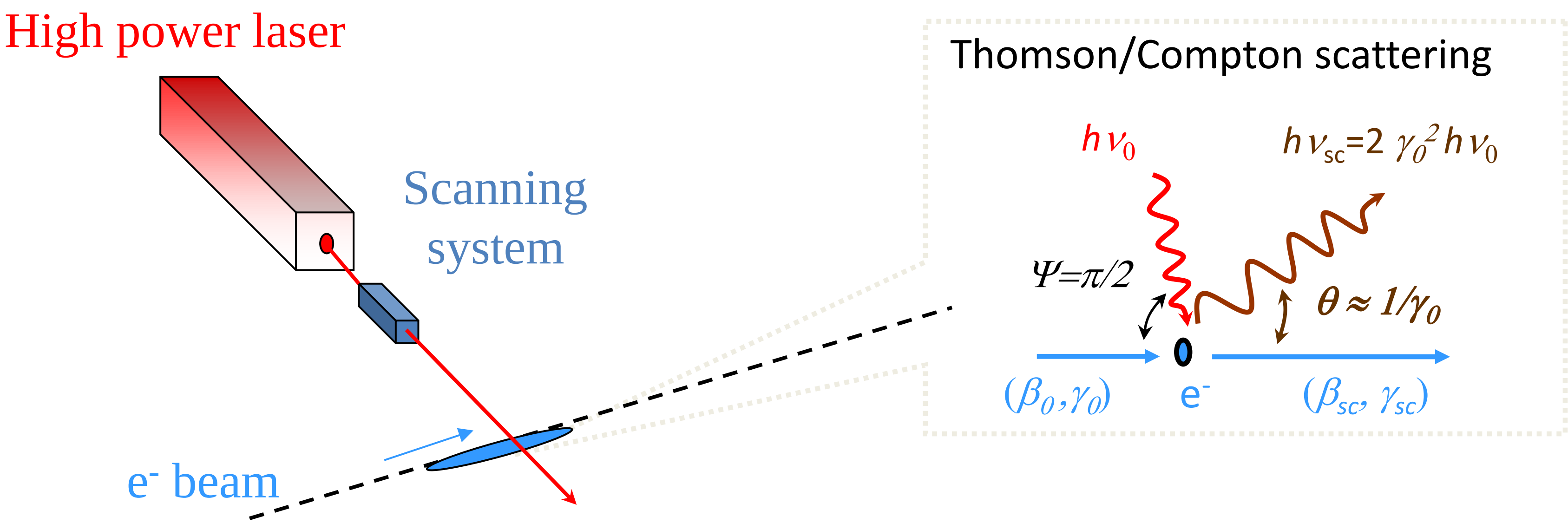
Total intensity at 400nm, 10%bw
= 4.31643e+09 ph/s



A. Jeff

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

<u>Laser Beam</u>

λ_0 : Laser wavelength

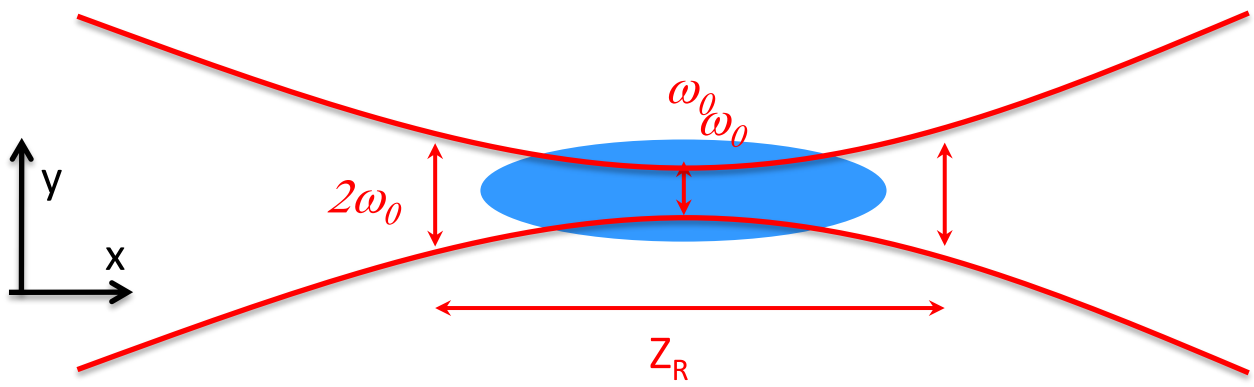
ω_0 : Laser waist size

Z_R : Rayleigh range

<u>Electrons Beam</u>

σ_y : ver. beam size

σ_x : hor. beam size



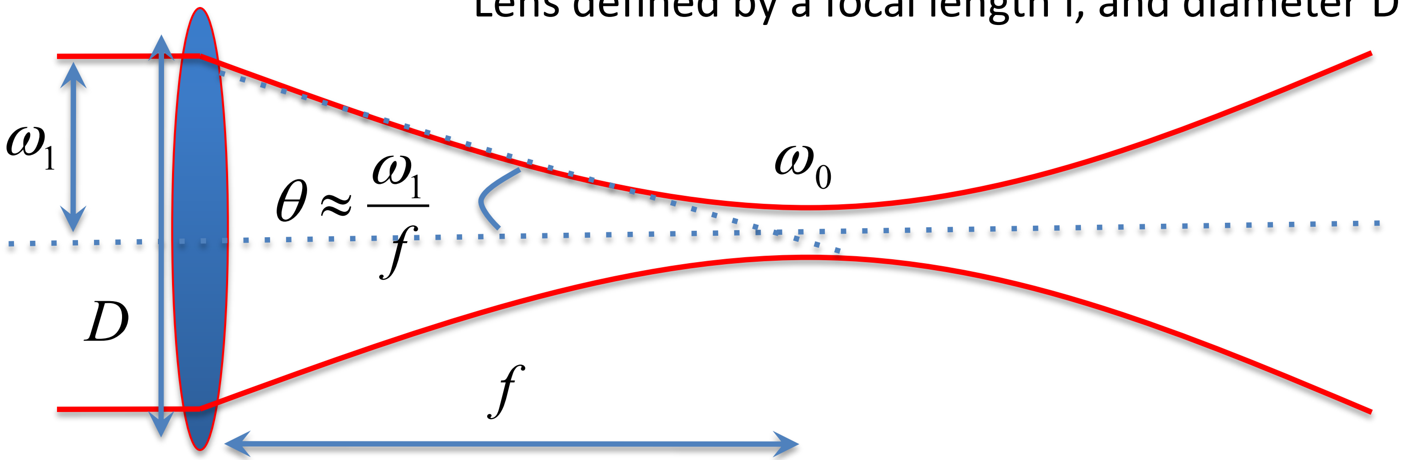
- The number of X-rays produced is given by $$N_{\text{interaction}} \approx \frac{\sigma \cdot N_e \cdot N_{laser}}{A}$$

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

$F\# = 2$

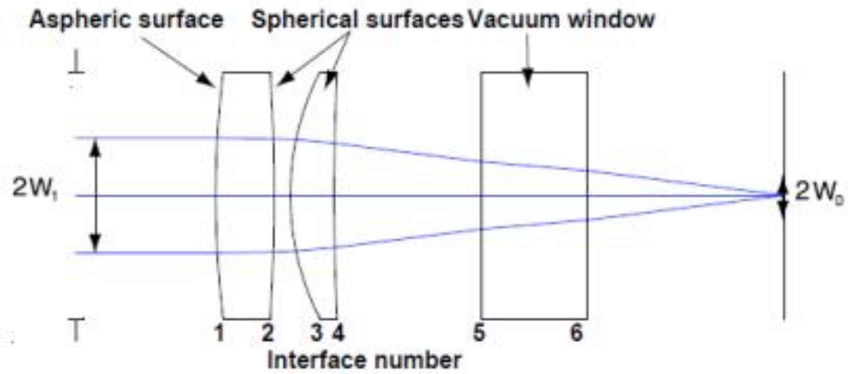
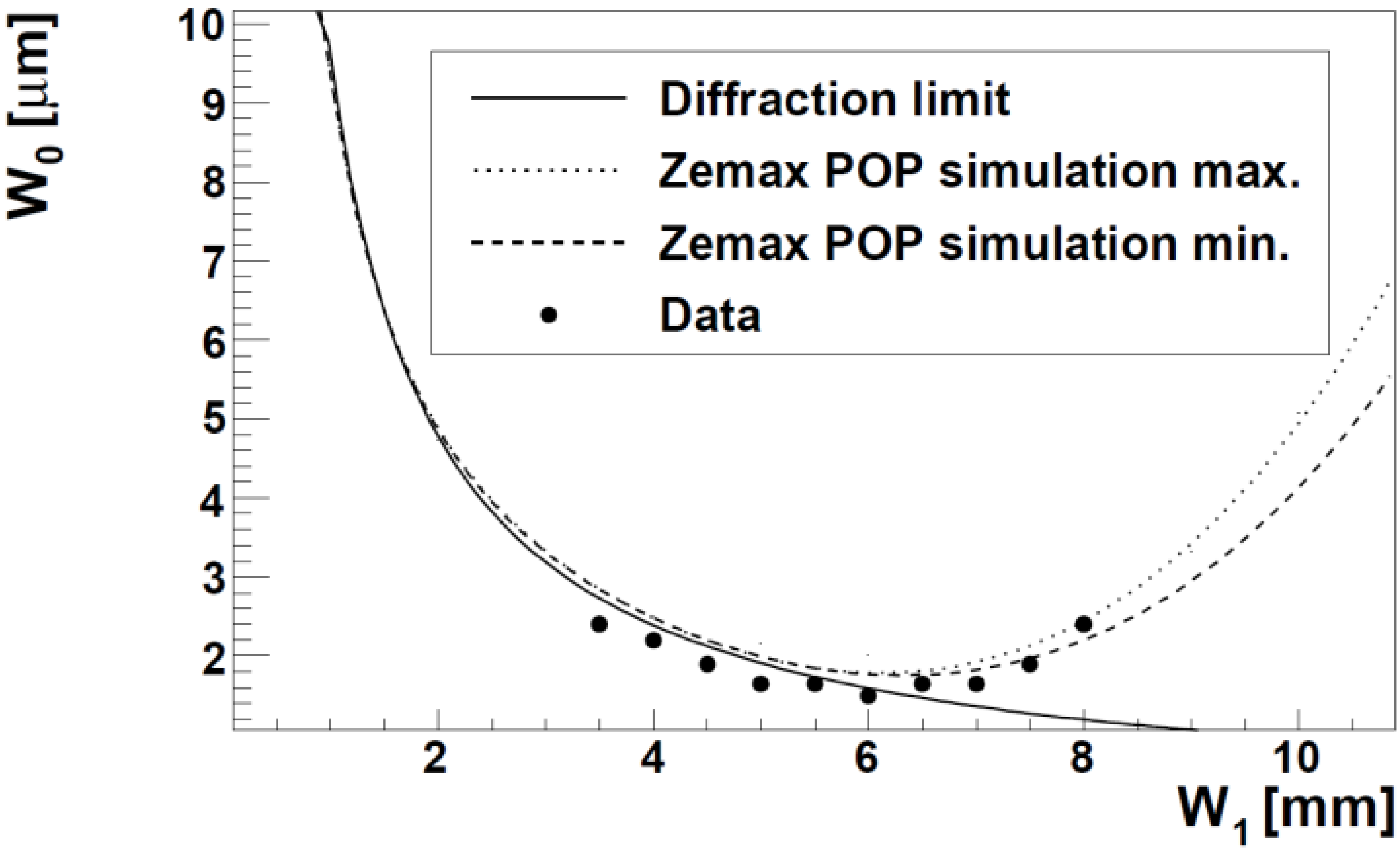


FIG. 7. Color online. Diagram of the final focus lens.

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

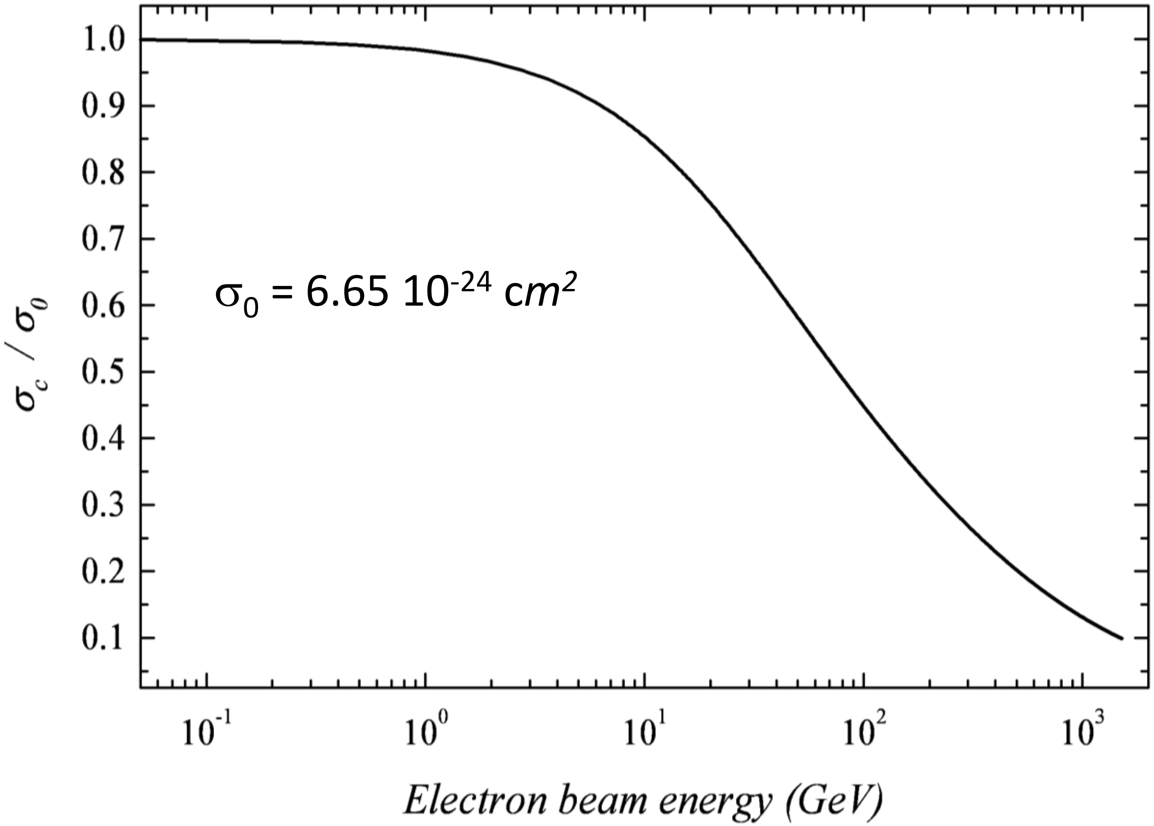
<u>*Design for ATF2 LWS by G. Blair et al*</u>



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

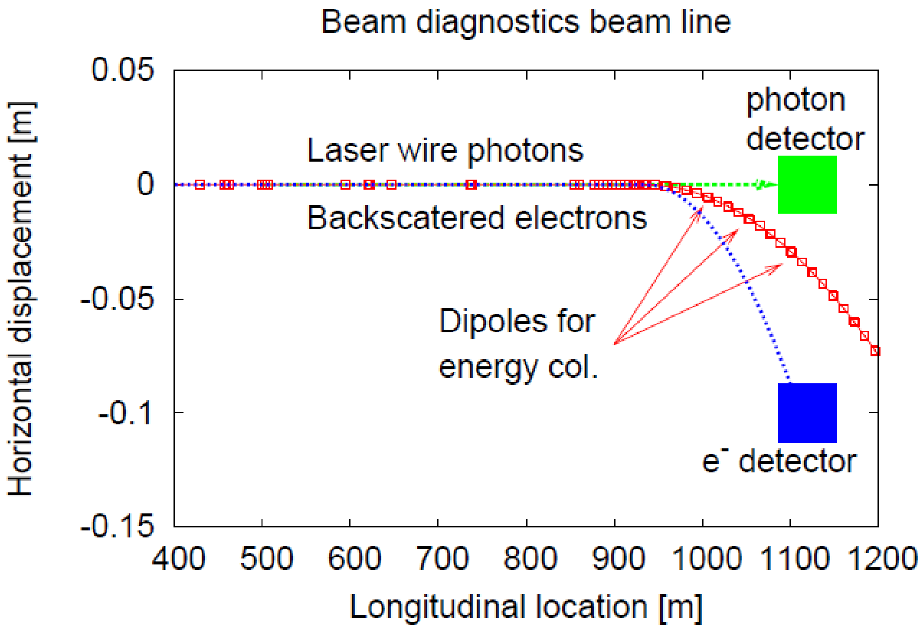


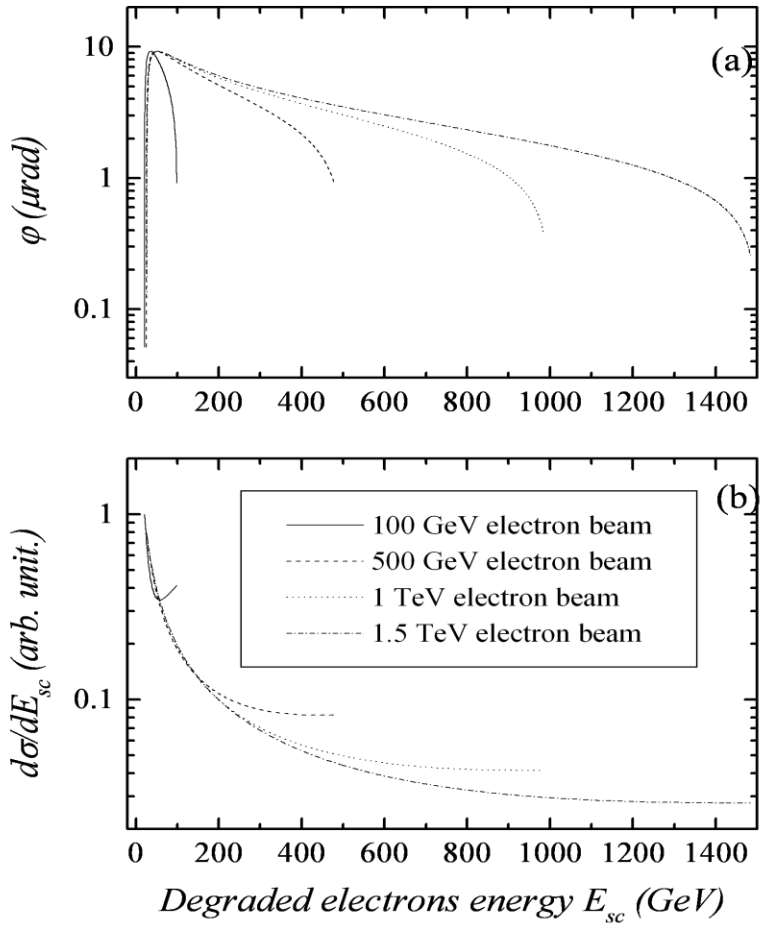
- The number of interaction produced is given by $N_{interaction} \propto \sigma \cdot N_e \cdot N_{laser}$

→ *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





Now we treat in detail:

- Measurement of nm beam positions
- Measurement of um transverse beam sizes
- **Measurement of fs-scale long profiles**
- Beam synchronization at the fs-scale
- Keeping the beams in collision (IP feedback)

	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

Short bunch length measurements

Radiative techniques

Optical Method

1. Produce visible light
2. Analyse the light pulse using dedicated instruments

Bunch Frequency Spectrum

The shorter the bunches, the broader the bunch frequency spectrum

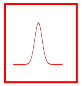
RF manipulation

Use RF techniques to convert time information into spatial information

Laser-based beam diagnostic

Using short laser pulses and sampling techniques

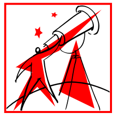
Beam instrumentation

1- Longitudinal Profile  ← → σ RMS or FWHM values

- *More precise information on the beam characteristic*

2- Single shot measurements 1 ← → n! Sampling measurements

- *Do not care about the beam reproducibility*
- *No additional problem due to timing jitter*

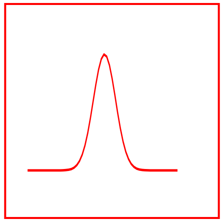
3- Non interceptive  ← →  Destructive Devices

- *Can be used for beam study and beam control for on-line monitoring*
- *Beam Power : No risk of damage by the beam itself*

Beam instrumentation

Can we do non intercepting, single shot, beam profile measurement in an easy way ?

+ 1 +



=

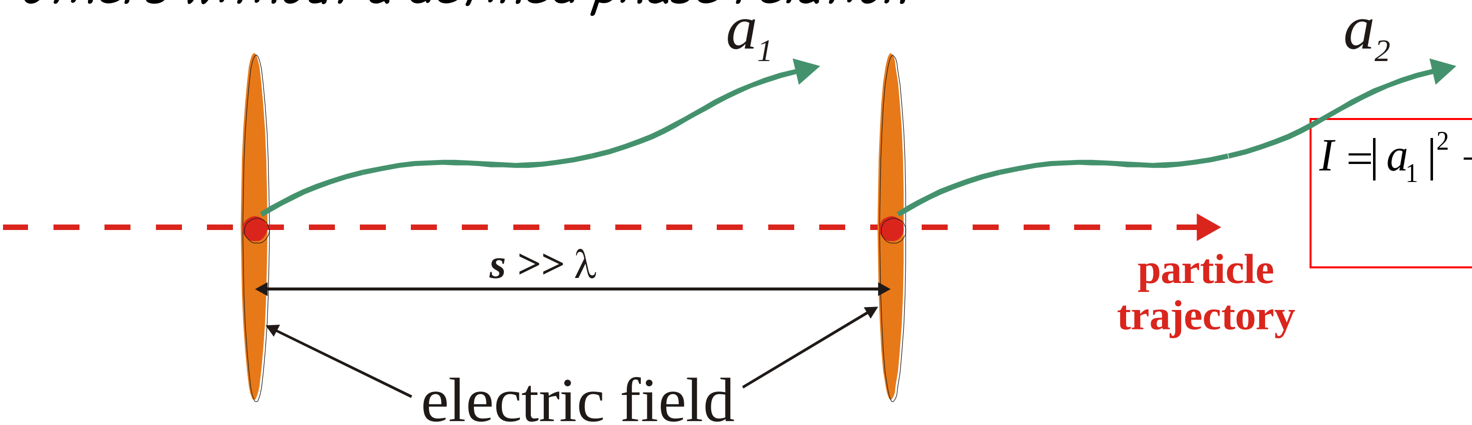
All in red → 'perfect system'

Radiative techniques

'Convert particles into photons'

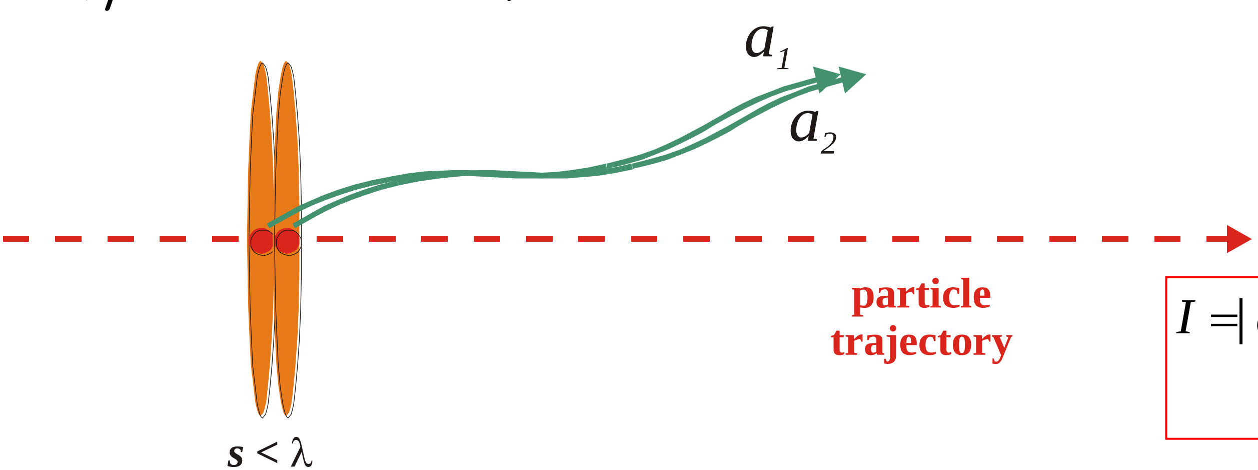
Coherent / Incoherent Radiation

- *At wavelength much shorter than the bunch length, the radiation is emitted incoherently because each electron emits its radiation independently from the others without a defined phase relation*



$$I = |a_1|^2 + |a_2|^2 = 2|a|^2 \rightarrow N|a|^2$$

- *A coherent enhancement occurs at wavelengths which are equal to or longer than the bunch length, where fixed phase relations are existing, resulting in the temporal coherence of the radiation*



$$I = |a_1 + a_2|^2 = |2a|^2 = 4|a|^2 \rightarrow N^2|a|^2$$

Radiation Spectrum

Incoherent term ↘ Coherent term ↙

$$S(\omega) = S_p(\omega)\left[N + N(N-1)F(\omega)\right]$$

$S(\omega)$ – radiation spectrum

$S_p(\omega)$ – single particle spectrum

N – number of electrons in a bunch

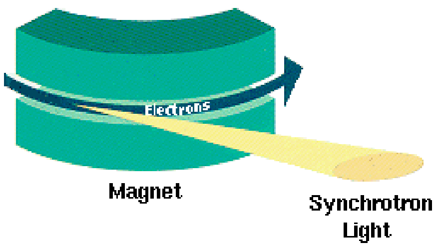
$F(\omega)$ – longitudinal bunch form factor

$$F(\omega) = \left| \int_{-\infty}^{\infty} \rho(s)\, e^{-i\frac{\omega}{c}s}\, ds \right|^2$$

$\rho(s)$ – Longitudinal particle distribution in a bunch

Optical Synchrotron Radiation

SR appears when a charged particle is bent in a magnetic field



$$P_\gamma = \frac{1}{6\pi\varepsilon_0}\frac{q^2 c}{\rho^2}\gamma^4$$

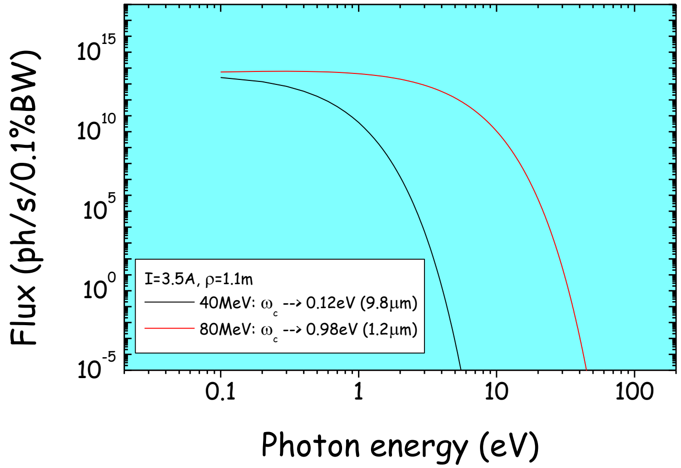
γ charged particle Lorentz-factor

ρ is the bending radius

Critical frequency :

$$\omega_c = 3\gamma^3 \frac{c}{2\rho}$$

Beam energy (γ) — Beam curvature (ρ)



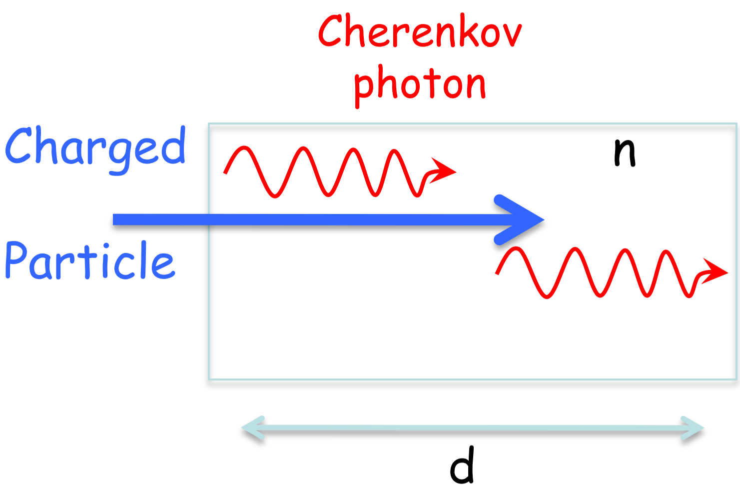
Limitations :

- Use a lot on electrons (for visible light: E > 100 MeV)
- Limited to very high energy proton or heavy ion beams

Cherenkov radiation

'Equivalent to the supersonic boom but for photons'

Threshold process: Particles go faster than light $\beta > 1/n$



- n is the index of refraction (n>1)
- β is the relative particle velocity
- θ_c is the Cherenkov light emission angle

$$\cos(\theta_c) = \frac{1}{\beta n}$$

- d the length of the cherenkov radiator

The total number of photons proportional to the thickness of the Cherenkov radiator

$$N_{ph} = 2\pi\alpha \cdot d \cdot \left(\frac{1}{\lambda_a} - \frac{1}{\lambda_b}\right)\left(1 - \frac{1}{(\beta n)^2}\right)$$

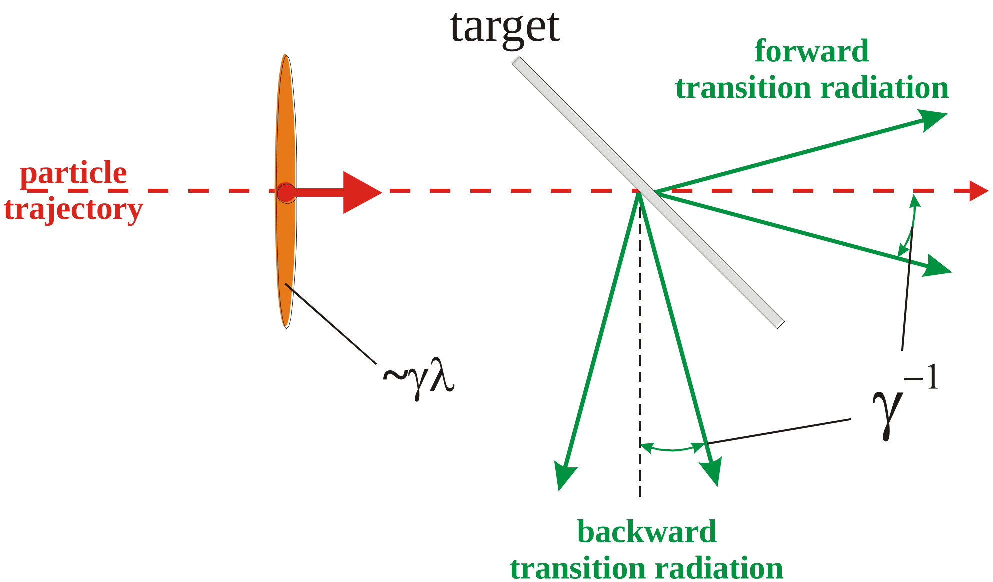
Limitations :

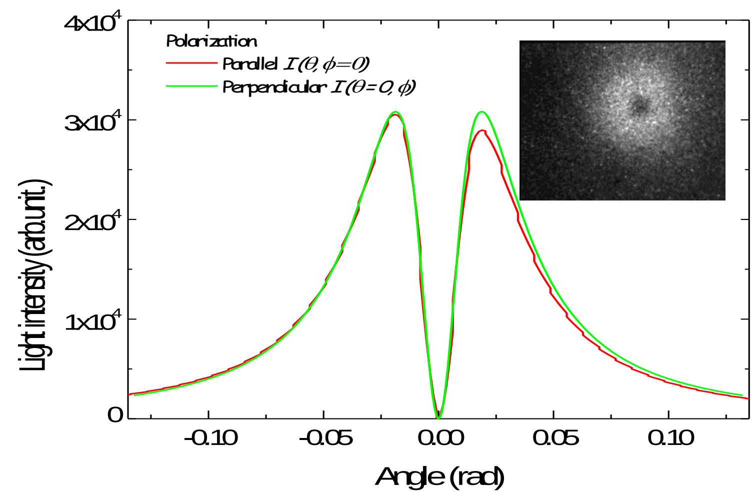
•Using transparent material (Glass n=1.46) : thermal and radiation hardenss issues

•Time resolution limited by the length of the radiator

Optical Transition Radiation

'TR is generated when a charged particle passes through the interface between two materials with different permittivity (screen in vacuum)'





Number of OTR photons per charge particle

$$N_{ph} = \frac{2\alpha}{\pi} \cdot \ln\left(\frac{\lambda_b}{\lambda_a}\right)\left(\ln(2\gamma) - \frac{1}{2}\right) \quad \sim 5\ 10^{-3} \text{ in [400-600]nm}$$

Radiation wavelength — Beam energy

Using good reflecting material

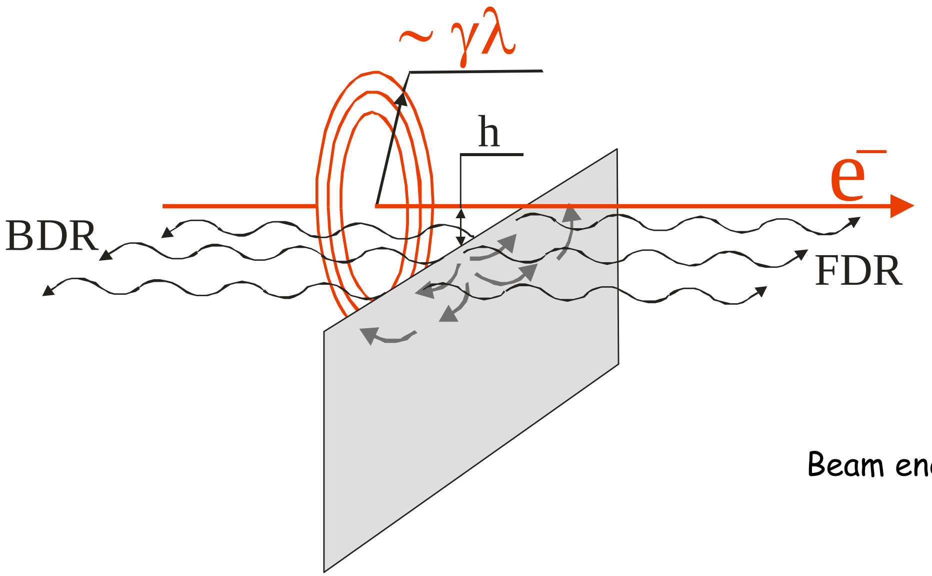
The thermal limit for 'best' screens (C, Be, SiC) is ~ 1 10⁶ nC/cm²

$$\Delta T(r) = \frac{dE}{dx}\frac{N_{tot}}{2\pi\sigma^2 c_p \rho} e^{-\frac{r^2}{2\sigma^2}}$$

M. Castellano and V. Verzilov, Phys. Rev. ST-AB 1, 062801 (1998

Optical Diffraction Radiation

'DR is generated when a charged particle passes through an aperture or near an edge of dielectric materials, if the distance to the target h (impact parameter) satisfies the condition :



Beam energy

Radiation wavelength

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

Limitations :

- Not enough photons in the visible for low energy particles : E < 1 GeV for a decent impact parameter (100μm)

T. Muto et al, ***Physical Review Letters 90 (2003) 104801***

Optical method with Incoherent radiation

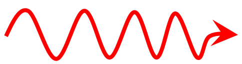
'Convert particles into visible photons'

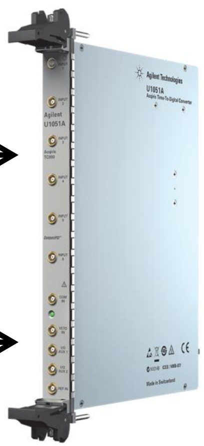
Time Correlated Single Photon Counting

n!

Geiger-mode Avalanche photodiode converts photon to electrical pulse

Visible photon





Time to Digital converter records pulse arrival time

Precise trigger synchronized with the beam

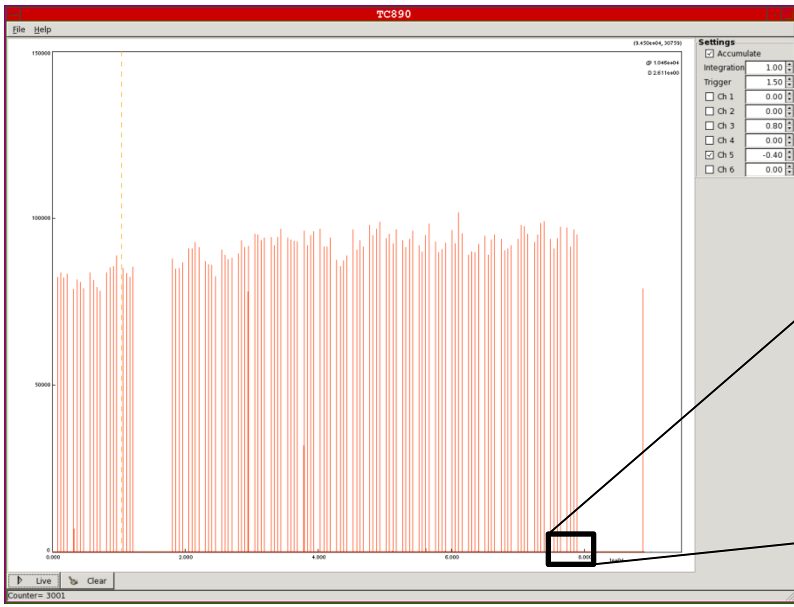
- Sampling Method allowing very high dynamic range if you measure long enough

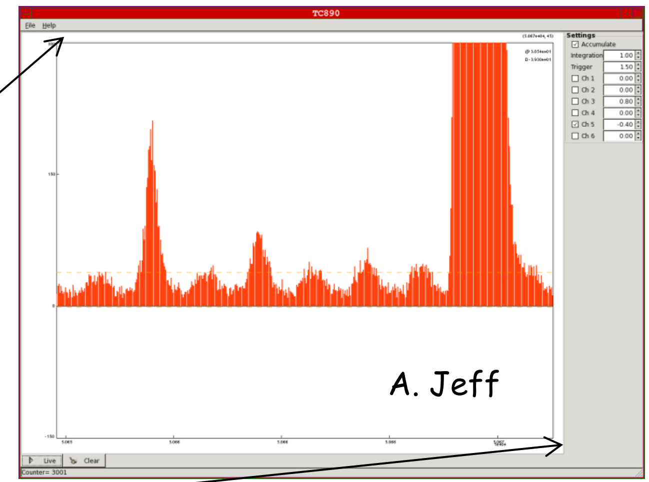
- Avalanche photodiode have deadtime and are subject to afterpulsing
- State of the art TDC typically limited to 10ps sampling

D.V. O'Connor, D. Phillips, Time-correlated Single Photon Counting, Academic Press, London, 1984
C.A. Thomas et al., Nucl. Instr. and Meth. A566 (2006) p.762

Time Correlated Single Photon Counting

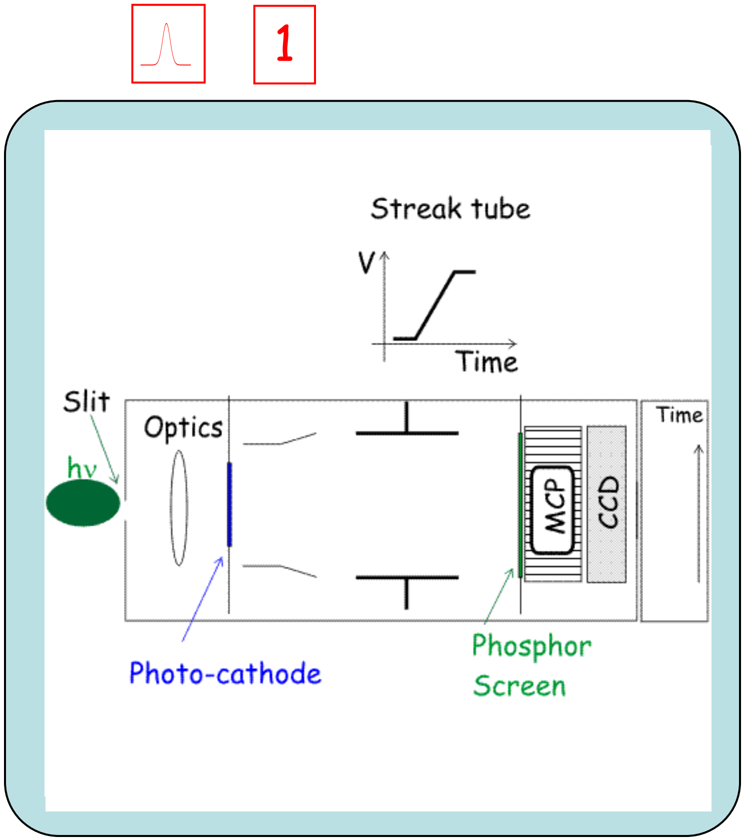
Longitudinal profile of the entire LHC ring (89us)
with 50ps resolution using SR light





A very large dynamic range should make it possible to see ghost bunches as small as 5e5 protons / 50ps with long integration

Streak Camera



'Streak cameras uses a time dependent deflecting electric field to convert time information in spatial information on a CCD'

Mitsuru Uesaka et al, ***NIMA 406 (1998) 371***

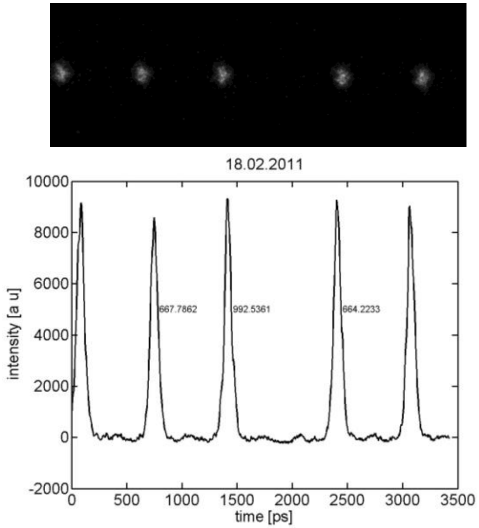
200fs time resolution obtained using reflective optics and 12.5nm bandwidth optical filter (800nm) and the Hamamatsu FESCA 200

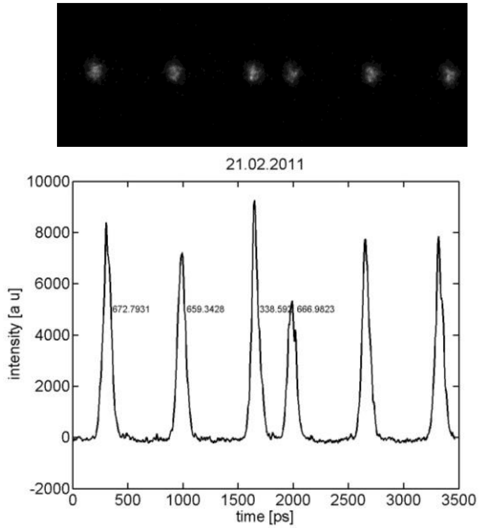
Limitations : Time resolution of the streak camera :

(i) Initial velocity distribution of photoelectrons : *narrow bandwidth optical filter*
(ii) Spatial spread of the slit image: *small slit width*
(iii) Dispersion in the optics

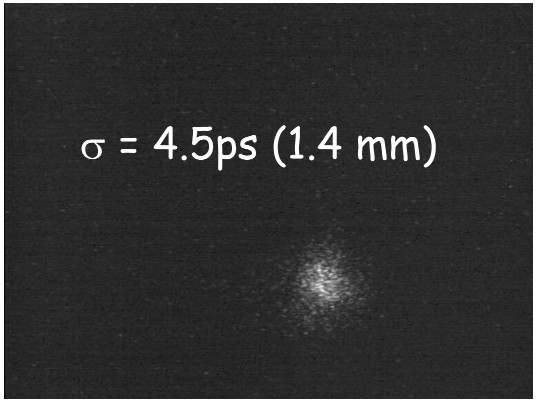
Streak camera examples

Observation of 5MeV electron bunch train using cherenkov
Sweep speed of 250ps/mm

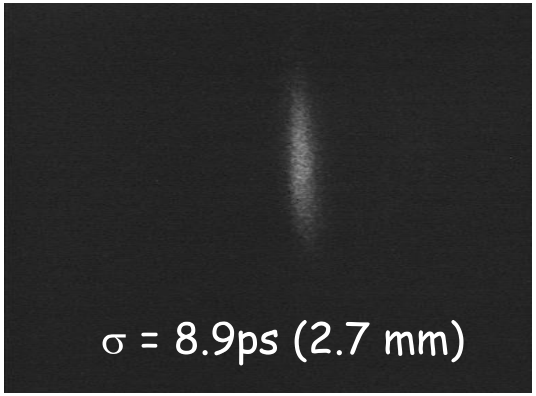




Measure of bunch length using OTR and OSR



Sweep speed of 10ps/mm



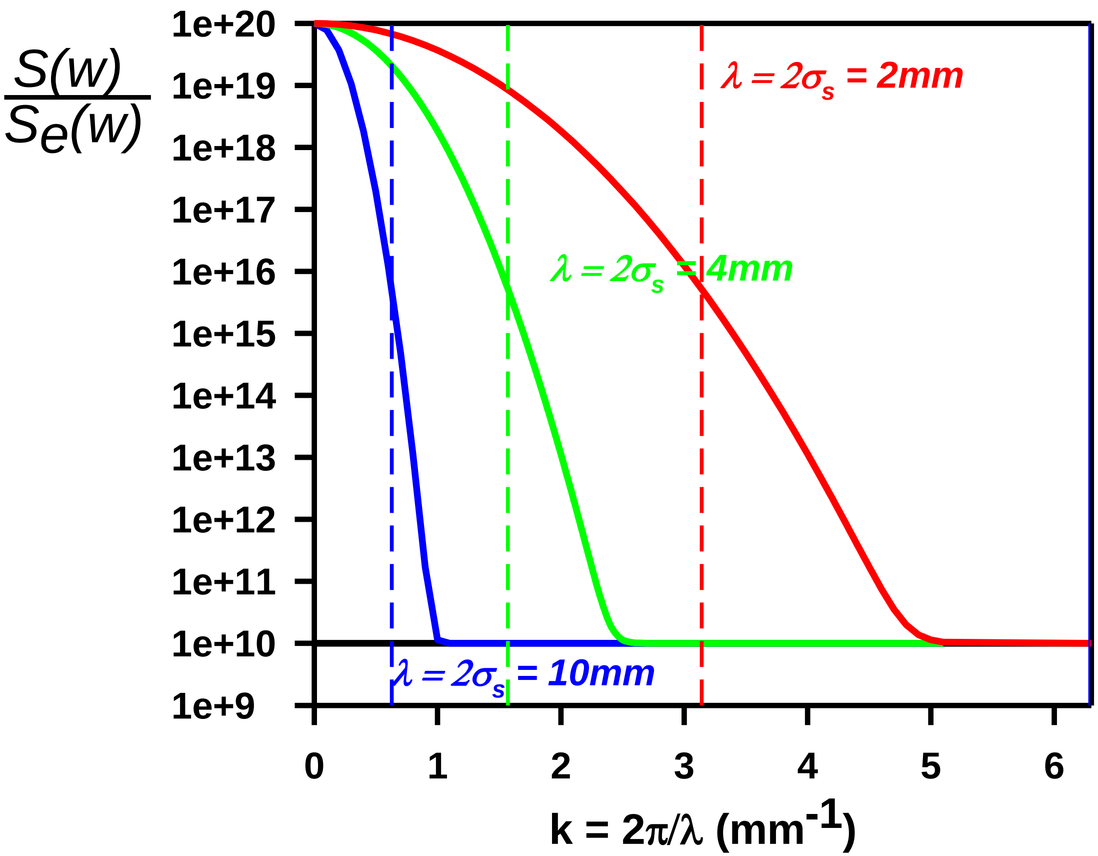
Bunch Length measurement with Coherent Radiation

'The shorter in time, The broader in frequency'

Bunch Form Factor for Gaussian distribution

$$F(\omega) = \left| \frac{1}{\sigma_s\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{s^2}{2\sigma_s^2}} e^{-i\frac{\omega}{c}s} ds \right|^2 = e^{-\frac{\omega^2\sigma_s^2}{c^2}} = e^{-k^2\sigma_s^2}$$

Assume $N = 10^{10}$ e/bunch



Coherent radiation appears when the bunch length is comparable to or shorter than the emitted radiation wavelength

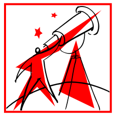
Measuring Radiation Spectrum

$$S(w) \text{ » } N^2 S_p(w) F(w)$$

- ✓ S(ω)– radiation spectrum ((known in the experiment)
- ✓ N – number of electrons on the bunch (known from the experiment)
- ✓ F(ω) – bunch form factor (what you want to find out)
- ✓ S_p(ω) – single particle spectrum (should be known)

Coherent Transition Radiation (CTR)

P. Kung et al, **Physical review Letters 73 (1994) 96**



Coherent Diffraction (CDR) or Coherent Synchrotron (CSR)

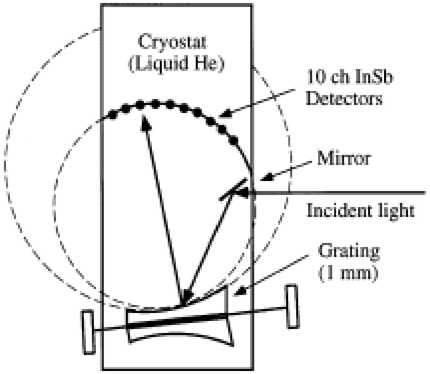
B. Feng et al, **NIM A 475 (2001) 492-497** ; A.H. Lumpkin et al, **A 475 (2001) 470-475** ; C. Castellano et al, **Physical Review E 63 (2001) 056501**

T. Watanabe et al, **NIM A 437 (1999) 1-11 & NIM A 480 (2002) 315-327**

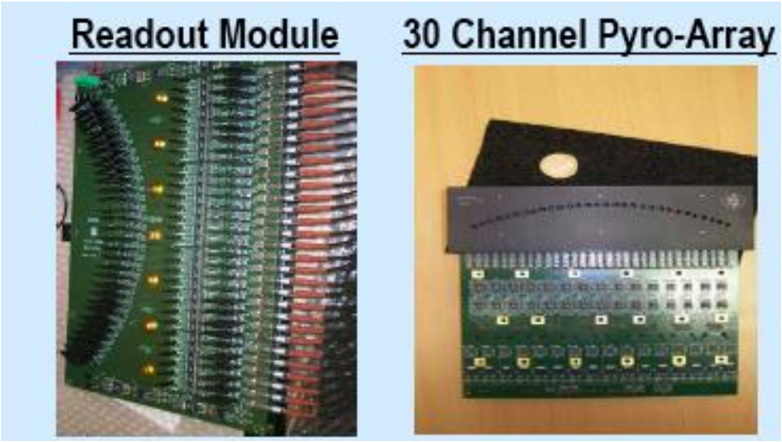
Bunch Frequency Spectrum by Coherent Radiation

1

*'The **polychromator** enables to get the spectrum directly by a single shot. The radiation is deflected by a grating and resolved by a multi-channels detector array'*



T. Wanatabe et al., NIM-A 480 (2002) 315-327
H. Delsim-Hashemiet al., Proc. FLS, Hamburg 2006, WG512



B. Schmidt, DESY

Bunch Frequency Spectrum by Coherent Radiation

Frequency Domain

Spectral Intensity
$A(\omega)$

Extrapolation
(high and low frequencies)

Correction
(transfer function of detection system)

Long Form Factor
$|F(\omega)|$

Inverse Fourier Transform for
symmetric bunch distribution

Long. Bunch profile
$S(z)$

Kramers-Kronig relation
for non symmetric bunches

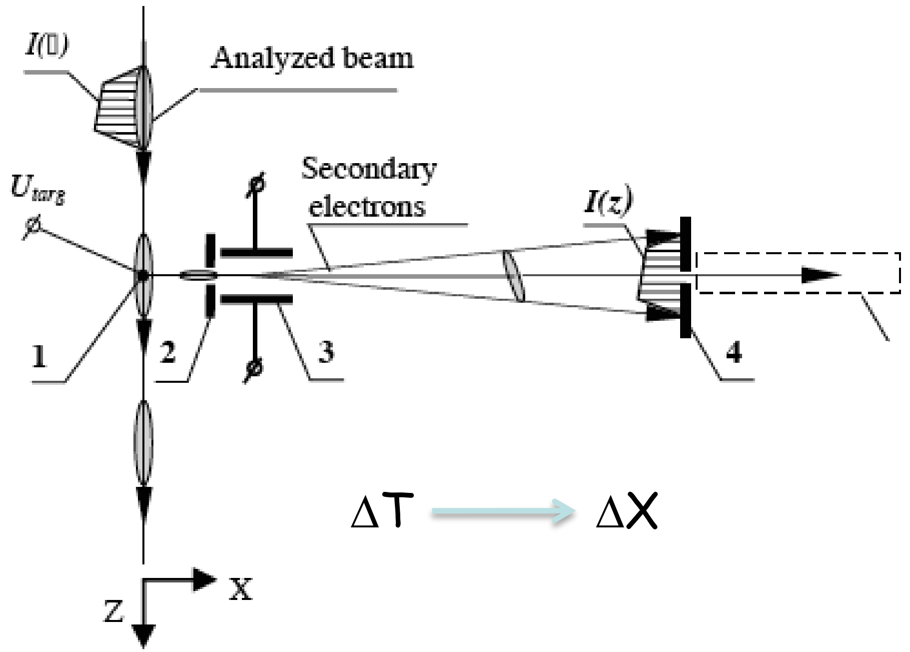
Time Domain

R. Lai and A.J. Sievers, NIM-A 397 (1997) 221 -231

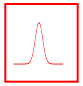
RF techniques

'How to transform time information
into spatial information'

Bunch Shape Monitor - Feschenko monitor



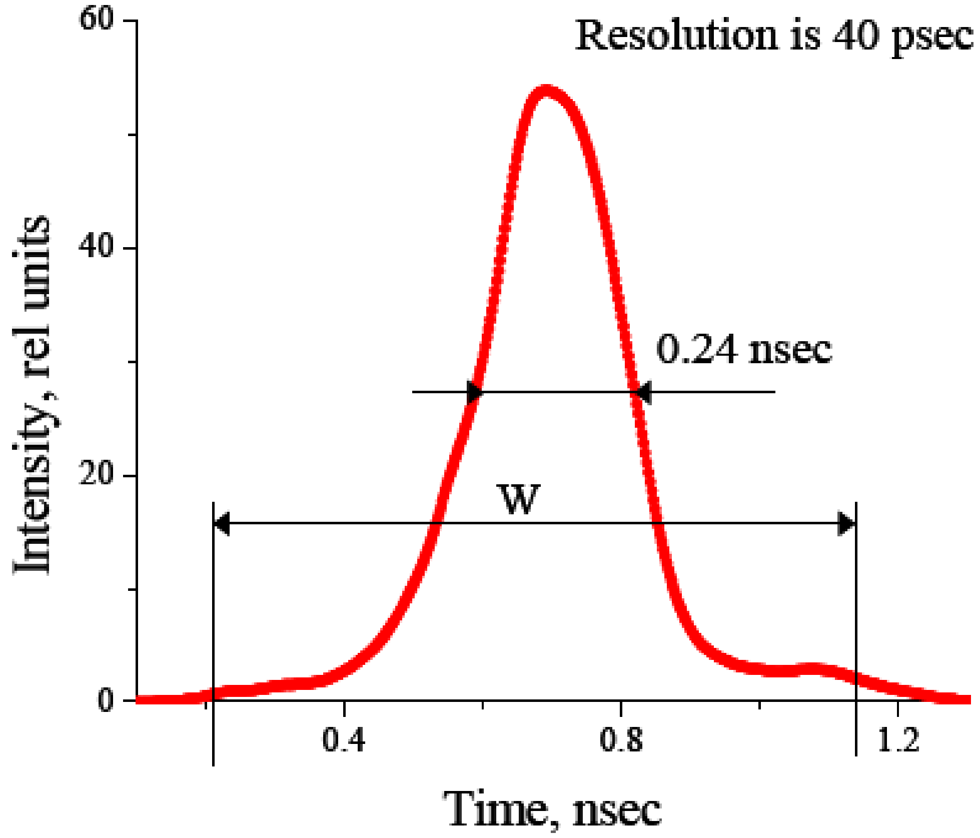
1 - Target (wire, screen, laser for H^-) : Source of secondary electrons
2 - Input collimator
3 - RF deflector (100MHz, 10kV) combined with electrostatic lens
4 - Electron Beam detector (electron multiplier, ..)



1

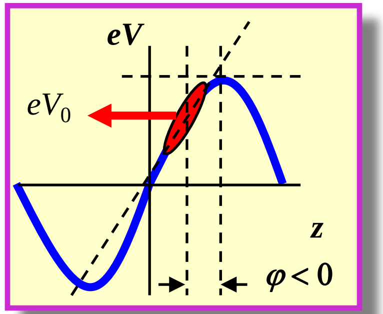
Bunch Shape monitor - Feschenko monitor

Longitudinal Bunch profile @ SNS

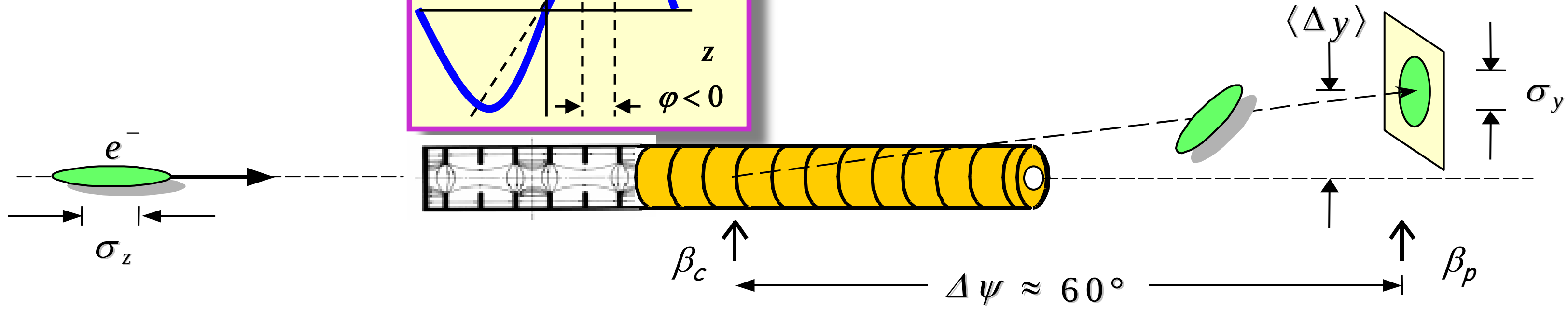


A. Feschenko *et al*, Proceedings of LINAC 2004, Lübeck, p408

RF Deflecting Cavity



- *Old idea from the 60's*
- *RF Deflector ~ relativistic streak tube*



Beam profile RF on

$$\sigma_y = \sqrt{\sigma_{y_0}^2 + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi}{\lambda} \frac{eV_0}{E_0} \sin(\Delta\Psi) \cos(\varphi) \right)^2}$$

Beam profile RF off ($\sigma_{y_0}^2$)

Deflecting Voltage (eV_0)

Bunch length (σ_z^2)

Beta function at cavity and profile monitor ($\beta_c \beta_p$)

RF deflector wavelength (λ)

Beam energy (E_0)

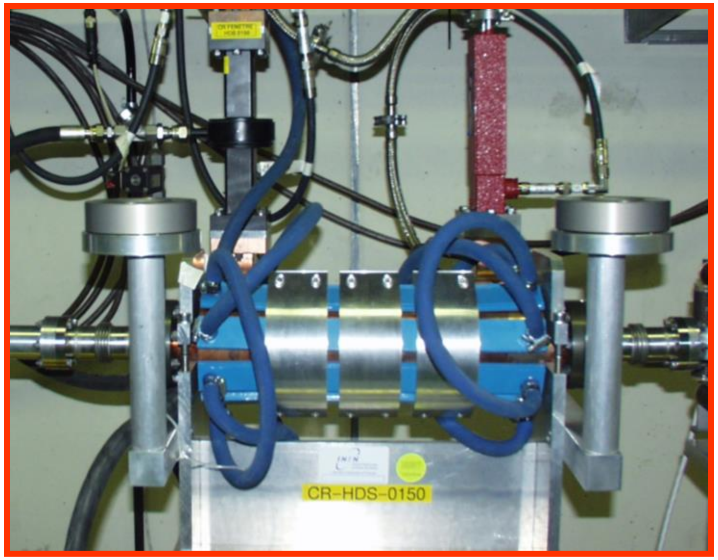
Betatron phase advance (cavity-profile monitor)

$\sin\Delta\psi = 1$, β_p small
Make β_c large

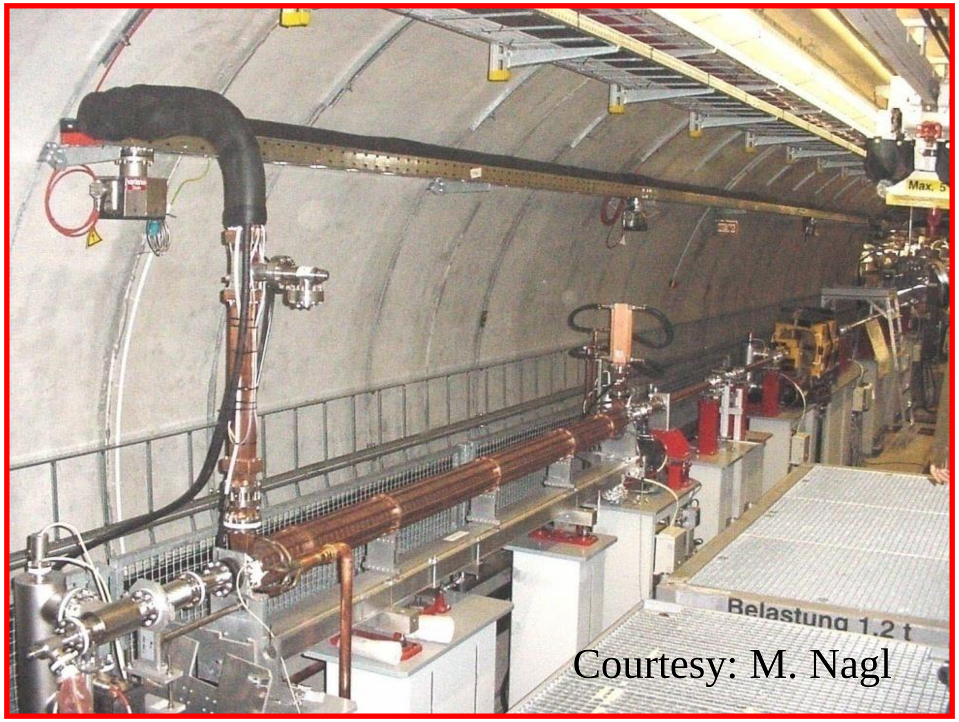
P. Emma et al, LCLS note LCLS-TN-00-12, (2000)

RF Deflecting Cavity

CTF3



LOLA @ Flash

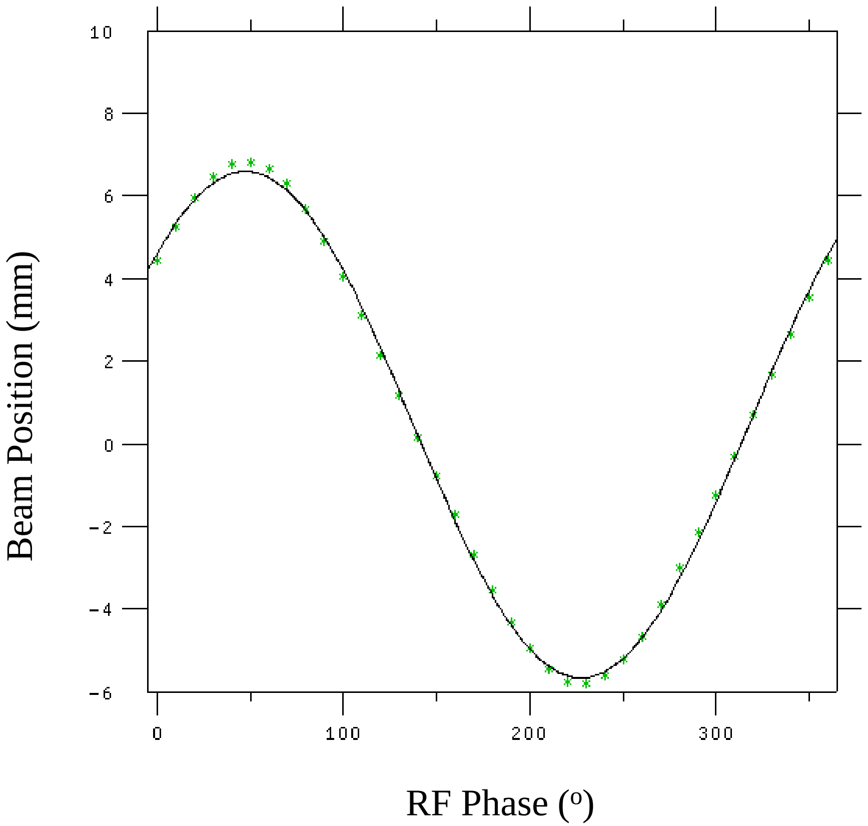


Courtesy: M. Nagl

RF Deflecting Cavity

Calibration of RF Deflector

ΔX(mm) → $\Delta\varphi(^\circ)$
ΔT(ps)



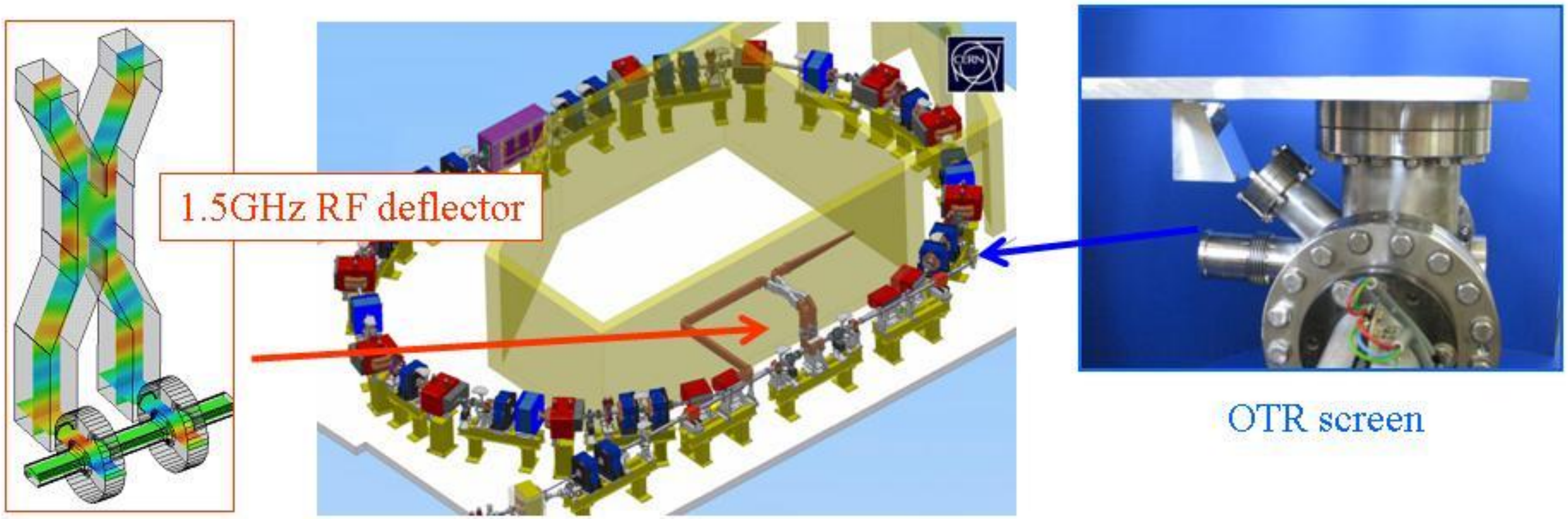
Monitor the Beam Position on (or close to) the Profile monitor to calibrate the deflection angle

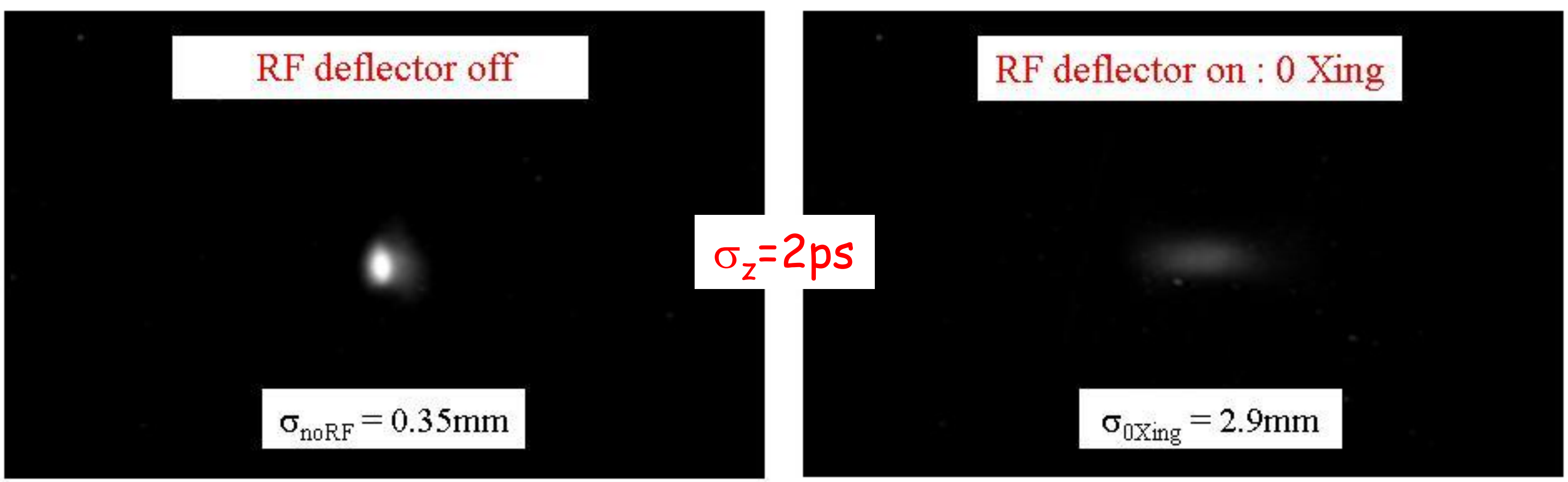
RF deflector phase

Beam offset on the screen

$$\Delta y(z) \approx \frac{eV_0}{E_0} \cdot \sqrt{\beta_c \beta_p}\, \sin(\Delta\Psi)\left(\frac{2\pi}{\lambda} - z\cos(\varphi) + \sin(\varphi)\right)$$

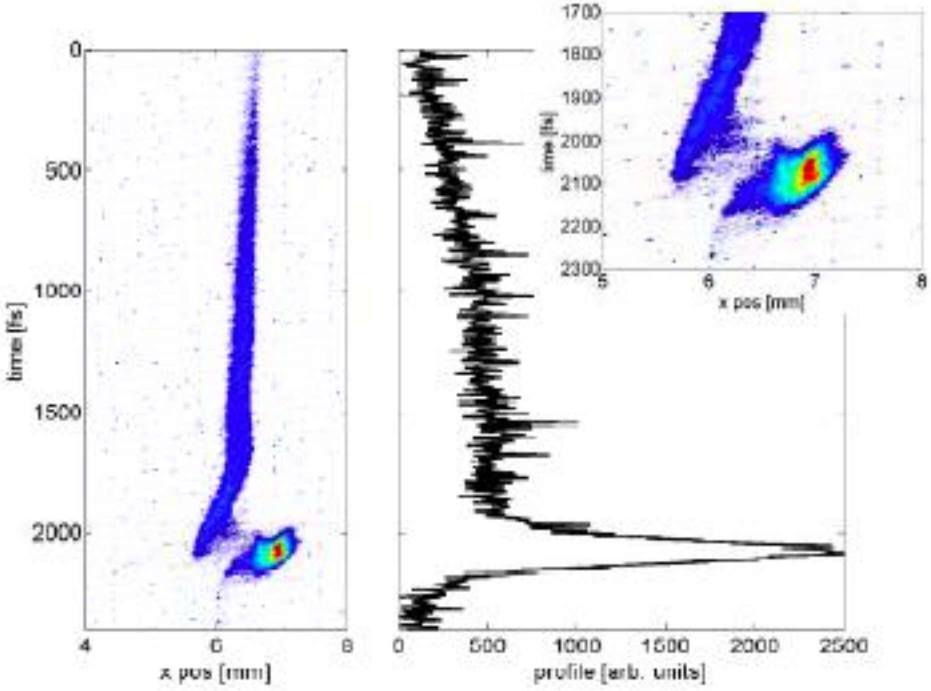
RF by Deflecting Cavity



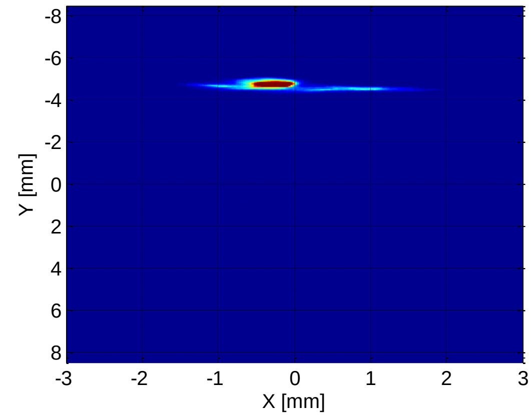


RF by Deflecting Cavity

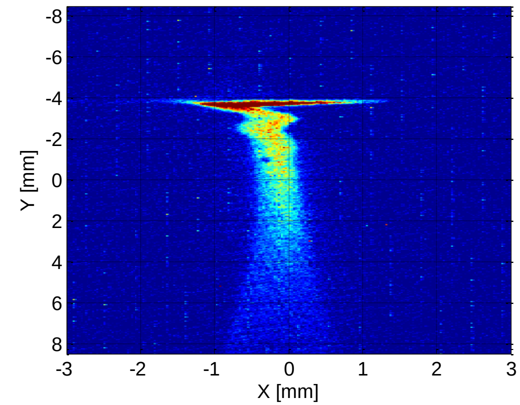
Bunch length measurement @ Flash



LOLA off:



LOLA on:

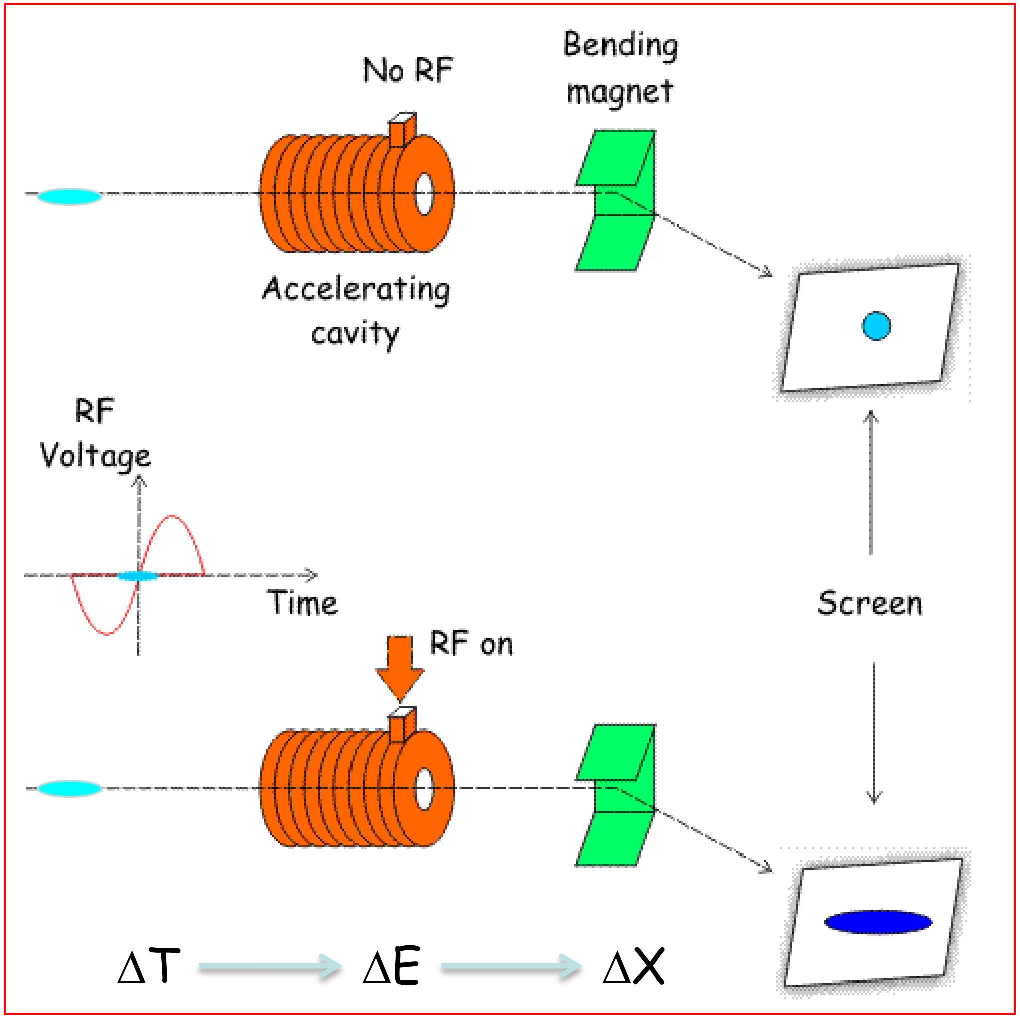


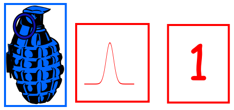
→ Resolution of 4fs/pixels

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

RF accelerating structures

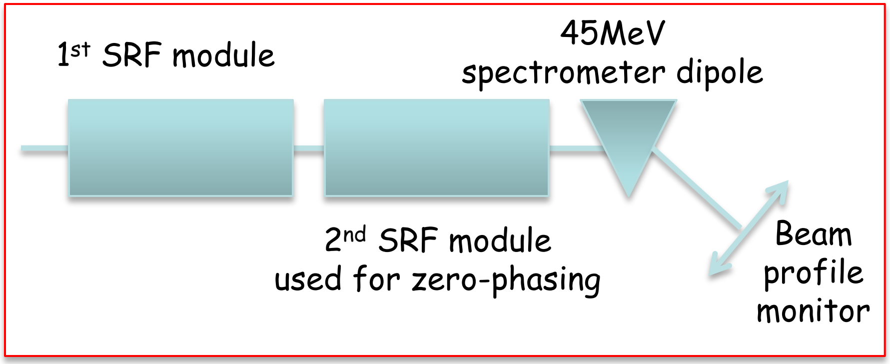
'The electron energy is modulated by the zero-phasing RF accelerating field and the bunch distribution is deduced from the energy dispersion measured downstream using a spectrometer line'





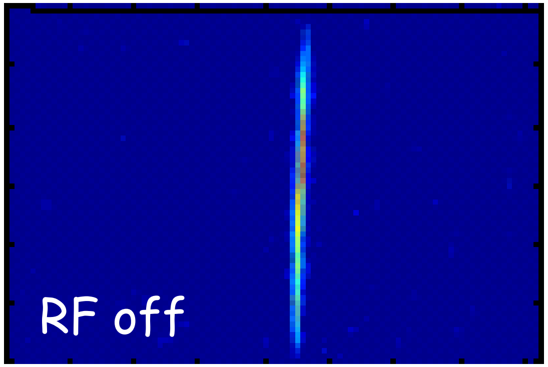
RF accelerating structures

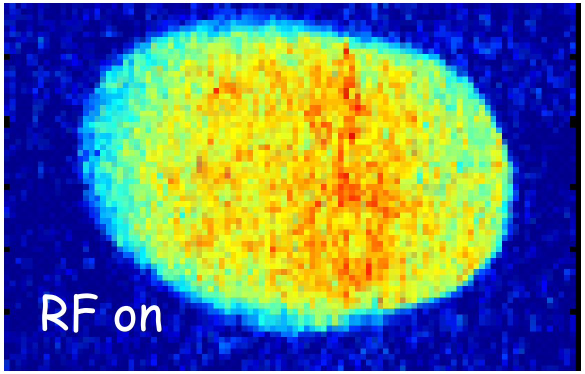
CEBAF injector, Newport News



D. X. Wang *et al*, Physical Review E57 (1998) 2283

84fs, 45MeV beam but low charge beam





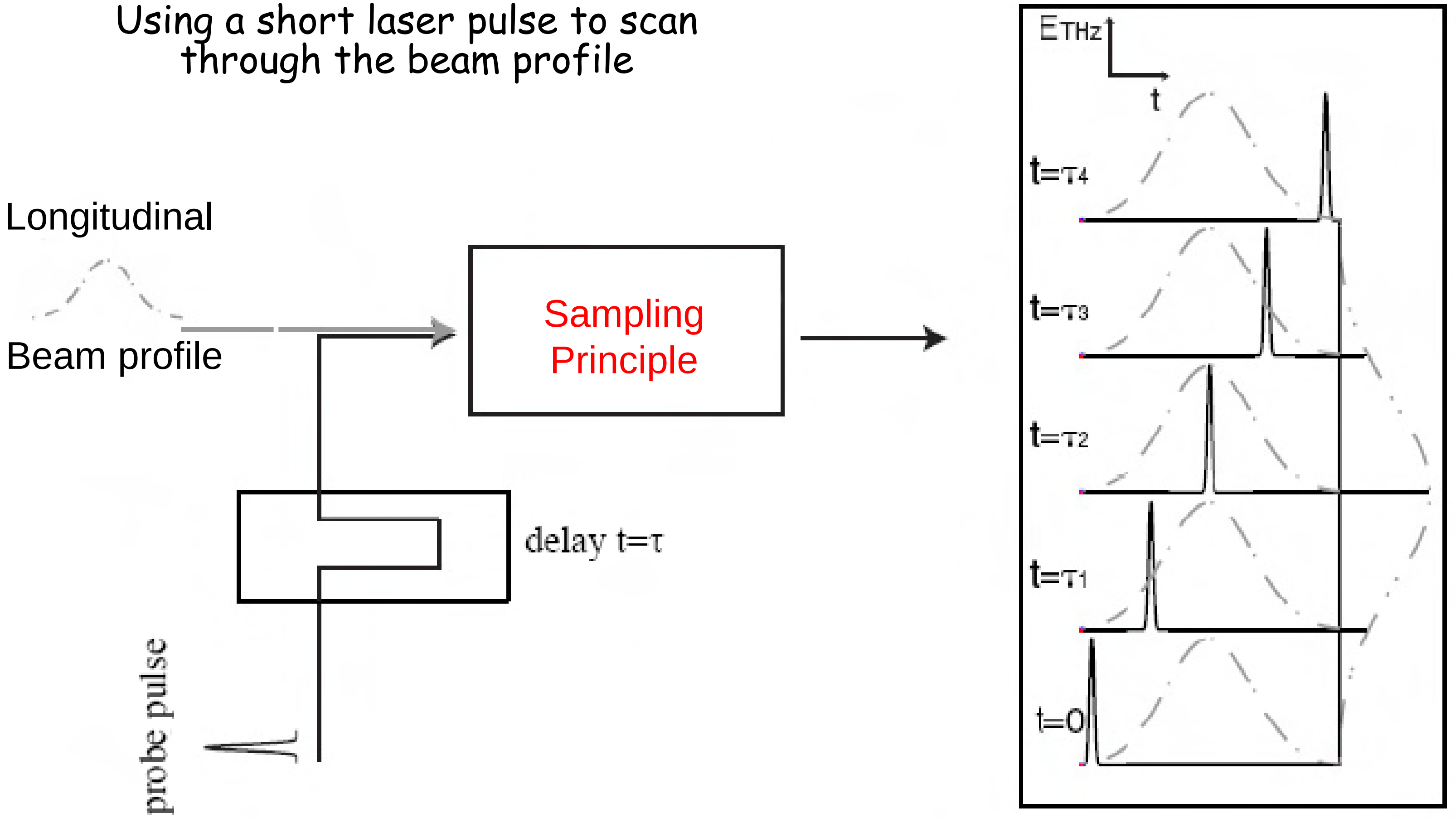
Limitations

RF non linearities
Beam loading and wakefield for high charge beam

Laser based techniques

Sampling Techniques

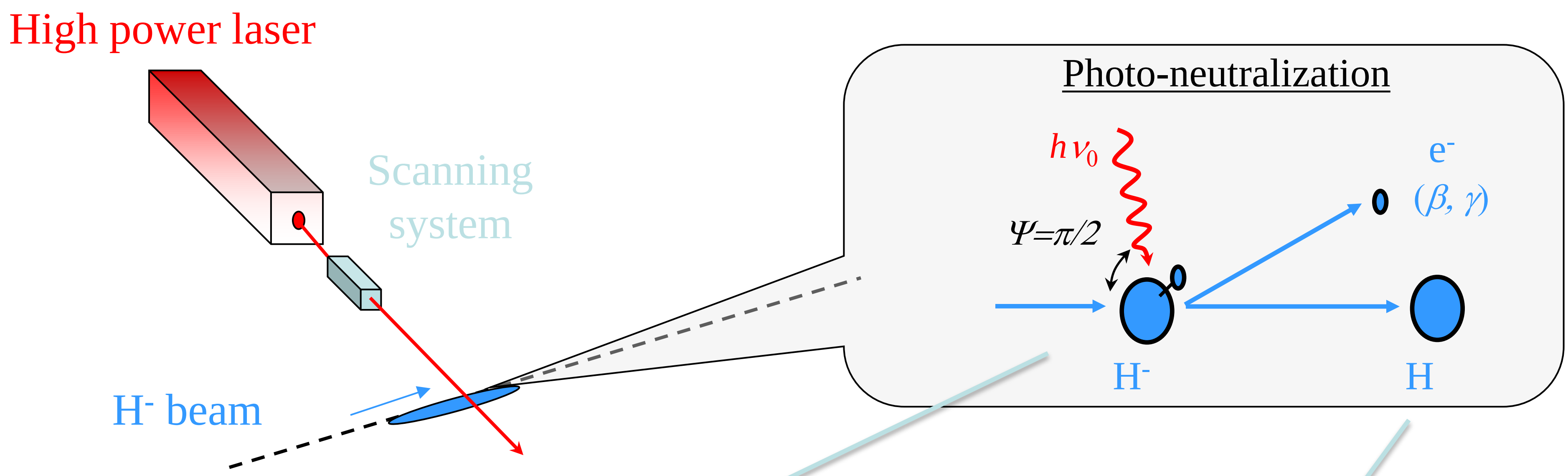
Using a short laser pulse to scan through the beam profile



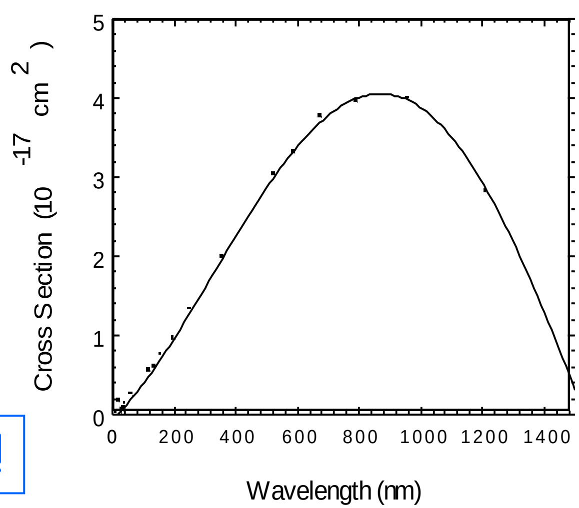
Limitation

Laser-beam synchronization jitter (50fs)

Laser Wire Scanner : Photo-neutralization



- First ionization potential for H^- ions is 0.75eV
- Photo-neutralization cross section : $\sigma \sim 4.10^{-17}\ cm^2$



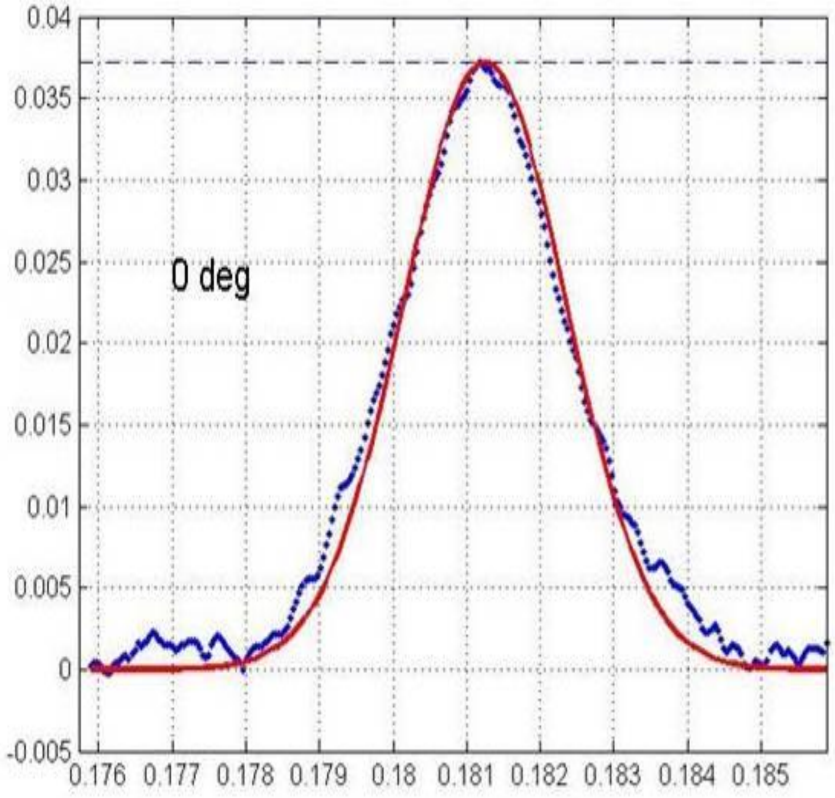
Detection system based on

- The measurement of released electrons using a magnet and a collector (faraday cup, MCP,..)
- *Measured the conversion of H^- into H with a current monitor*

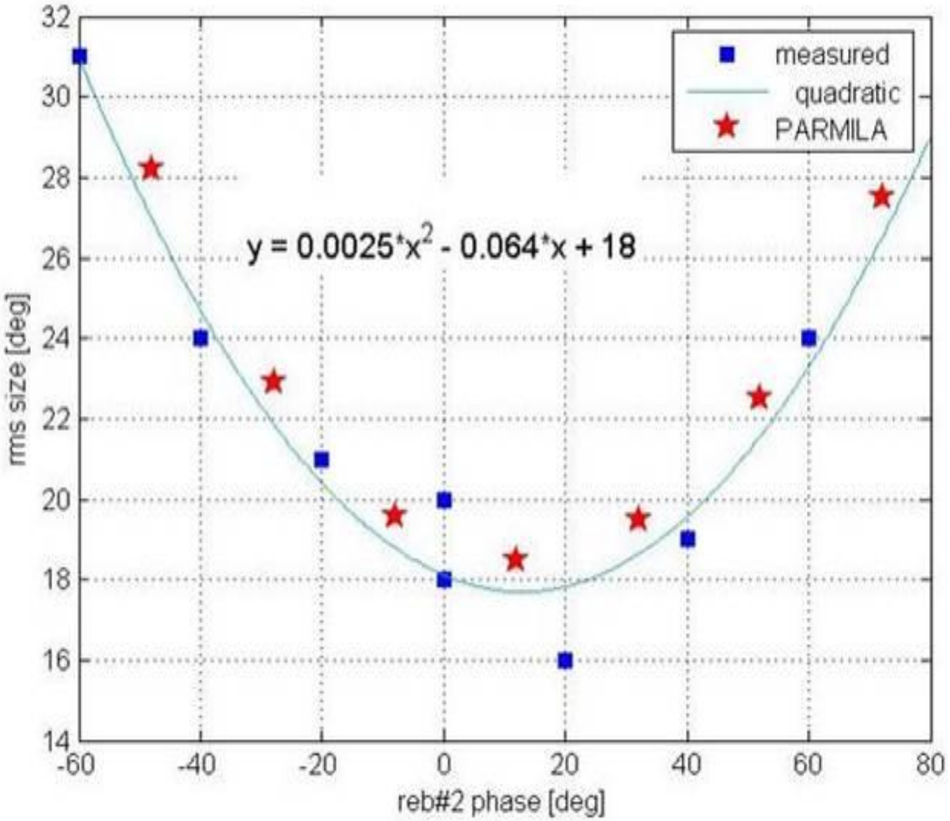
Laser Wire Scanner : Photo-neutralization

Mode Locked Laser Longitudinal Measurements @ SNS

2.5 MeV H^-, 402.5 MHz bunching freq, Ti-Sapphire laser phase-locked @ 1/5th bunching frequency



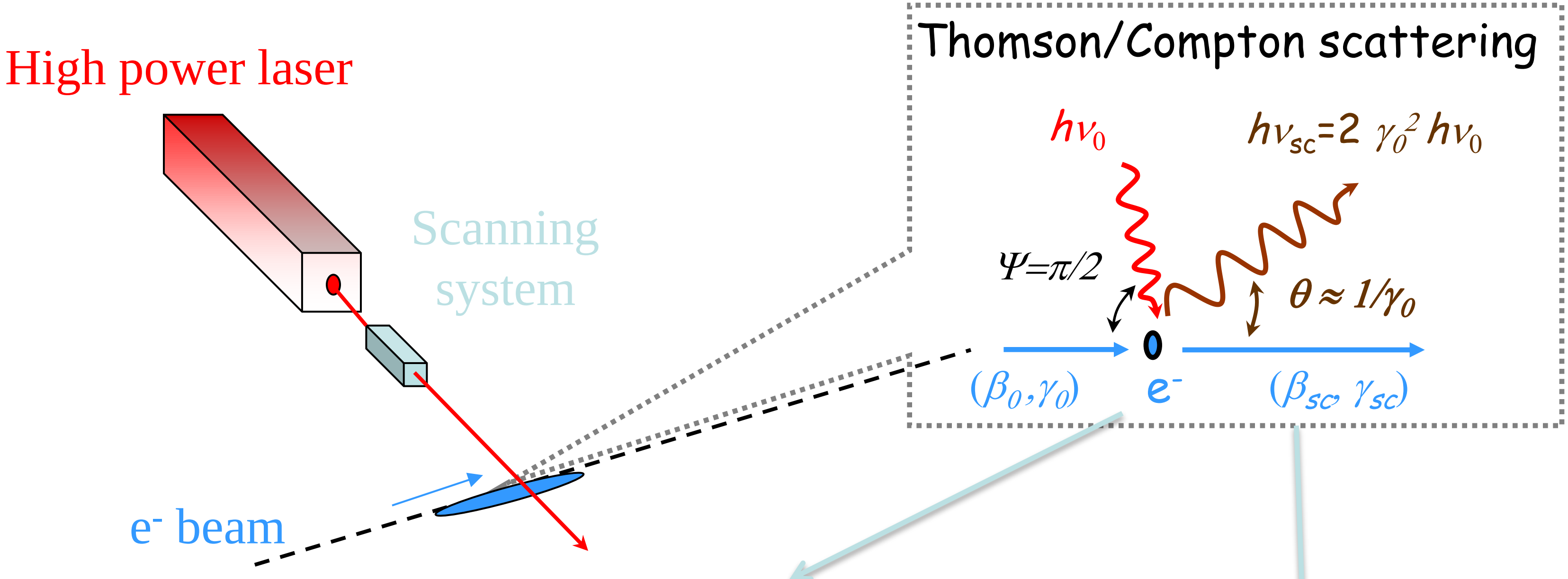
Collected electron signal plotted vs. phase

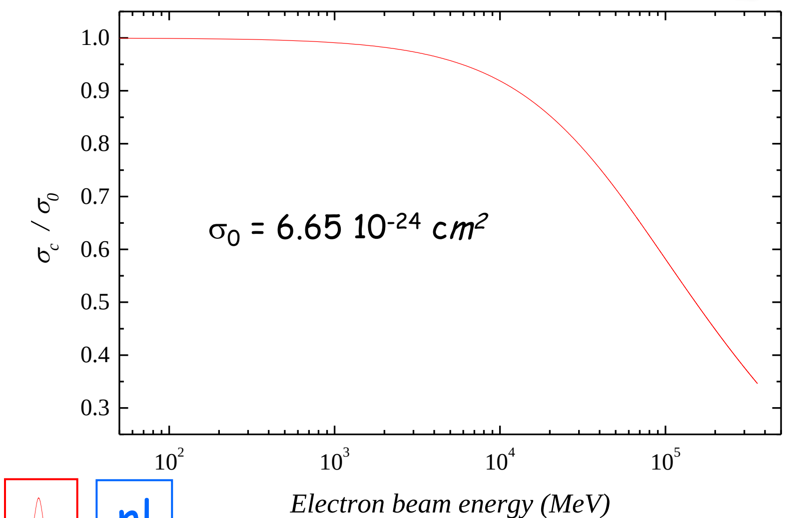


Measured and predicted bunch length vs. cavity phase setting

S. Assadi *et al*, Proceedings of EPAC 2006, Edinburgh, pp 3161

Laser Wire Scanner - Compton scattering



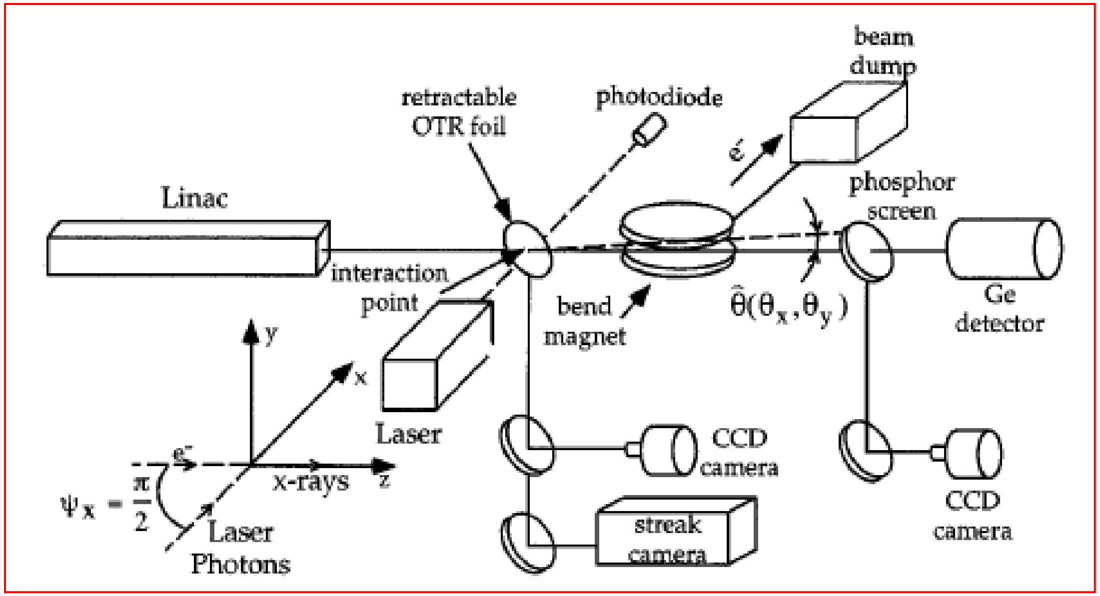


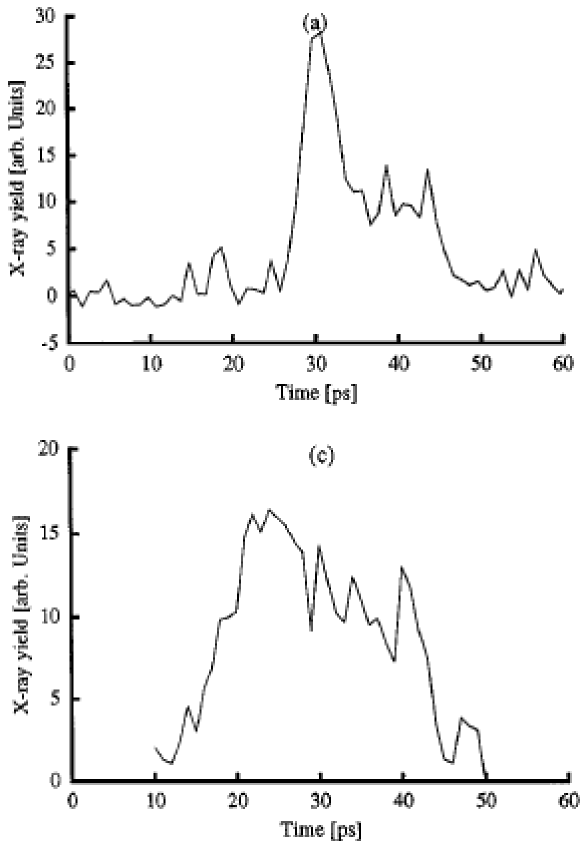
Detection system based on

- The measurement of the scattered photons
- The measurement of degraded electrons

Laser Wire Scanner – Compton scattering

ALS @ LBNL



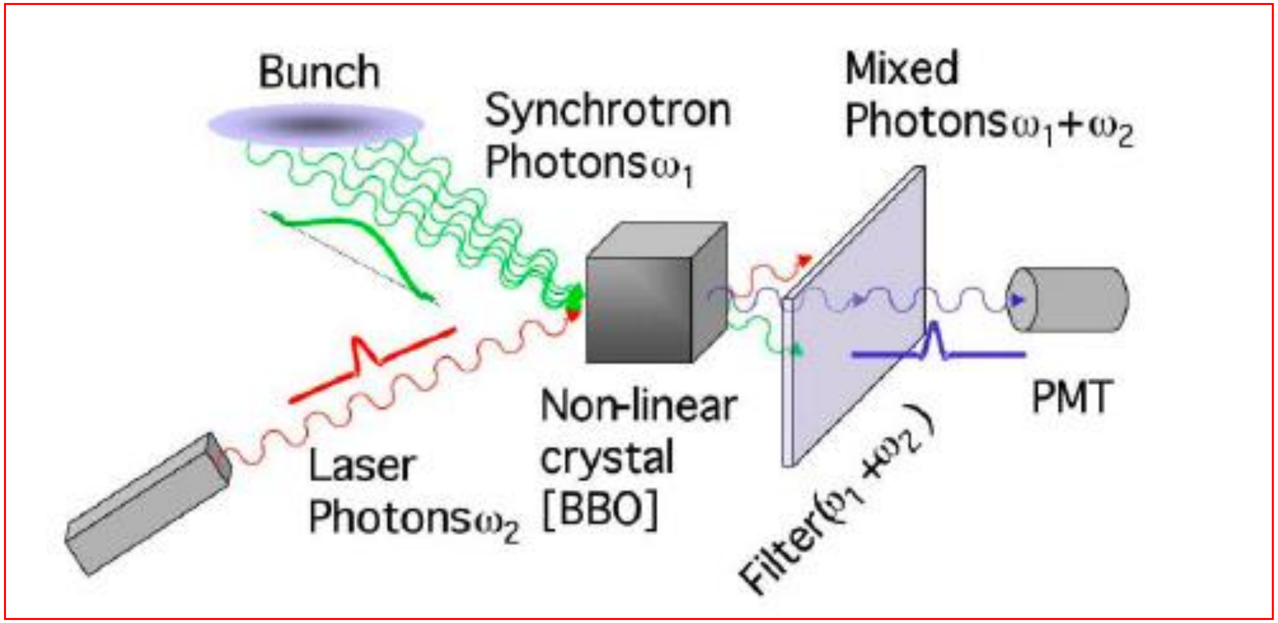


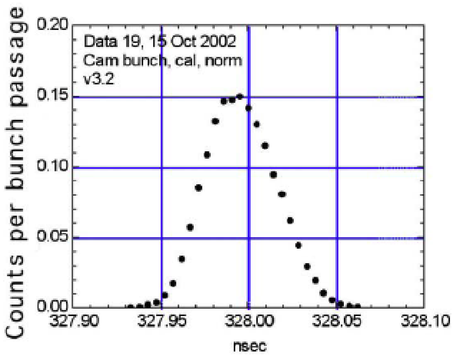
Using a 10TW Ti:Al_2O_3 laser system. Detecting 5.10^4 10-40 keV X-rays using either an X-ray CCD and Ge detector.

W.P. Leemans *et al*, PRL 77 (1996) 4182

Non linear mixing

'Non linear mixing uses beam induced radiation, which is mixed with a short laser pulse in a doubling non linear crystal (BBO,..). The resulting up frequency converted photons are then isolated and measured'





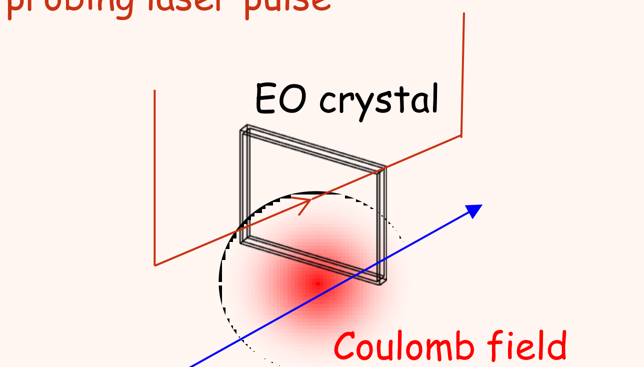
M. Zolotorev *et al*, **Proceeding of the PAC 2003, pp.2530**

15-30ps electron bunches (ALS, LBNL) scanned by a 50fs Ti:Al_2O_3 laser

Electro Optic Sampling

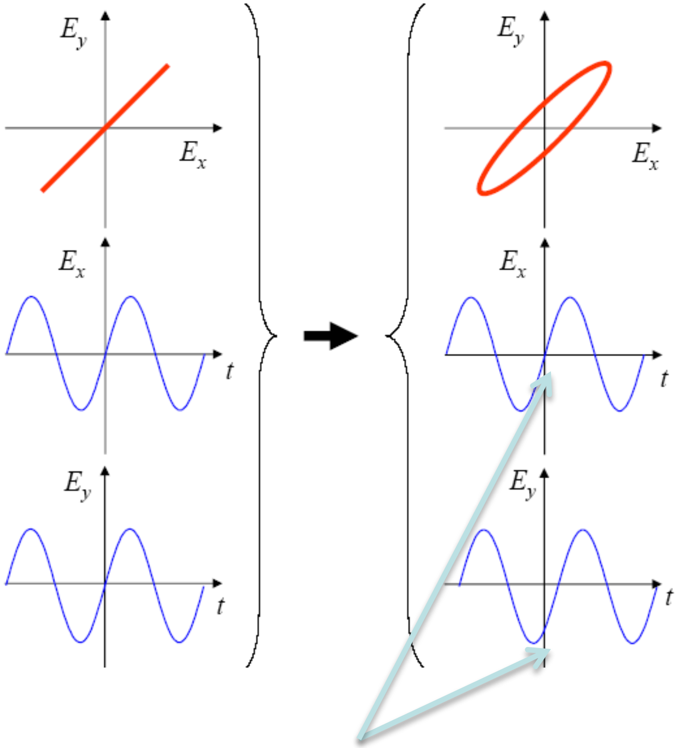
'This method is based on the polarization change of a laser beam which passes through a crystal itself polarized by the electrons electric field'

E-field induced birefringence in EO-crystal : Pockels effect



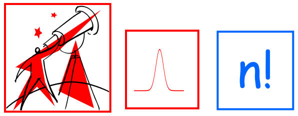
$$E_r \approx \frac{q}{\sqrt{2\pi}\left(\varepsilon_0 \sigma_z r\right)}$$

- Polarization diagram
- electric field of the horizontal polarization
- electric field of the vertical polarization

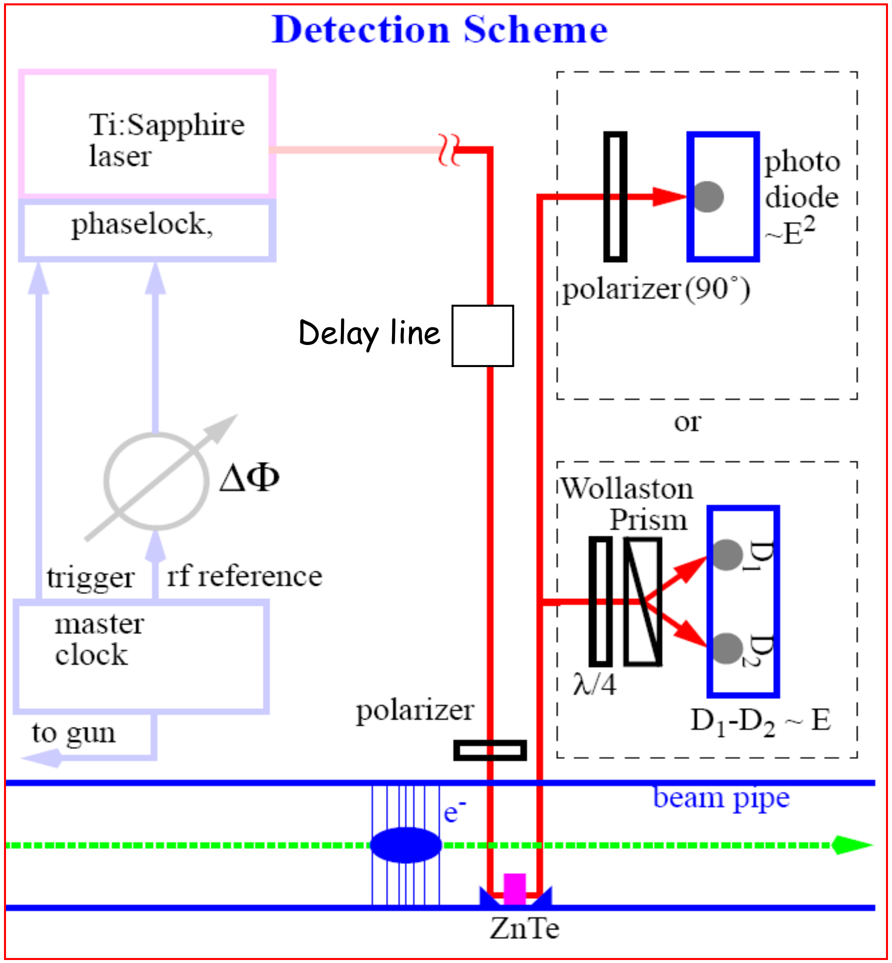


$$\Gamma = \frac{2\pi d}{\lambda_0}\left(n_x - n_y\right) = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_r$$

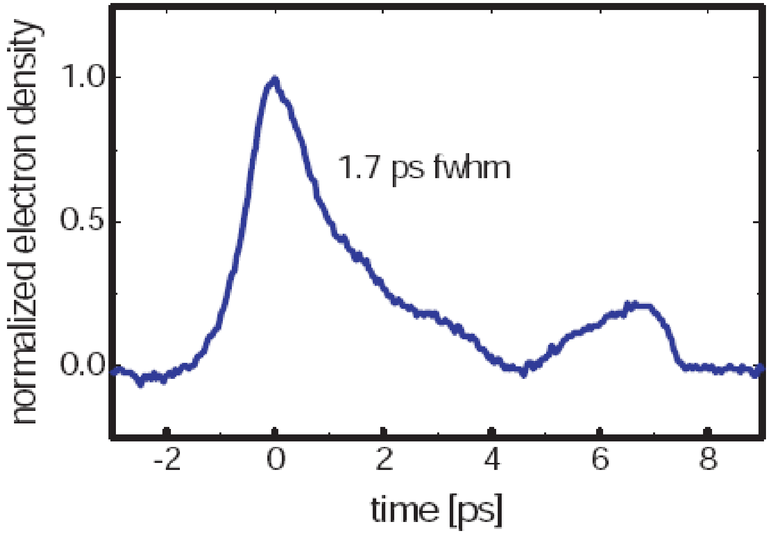
Relative phase shift between polarizations increases with the beam electric field



Electro Optic Sampling



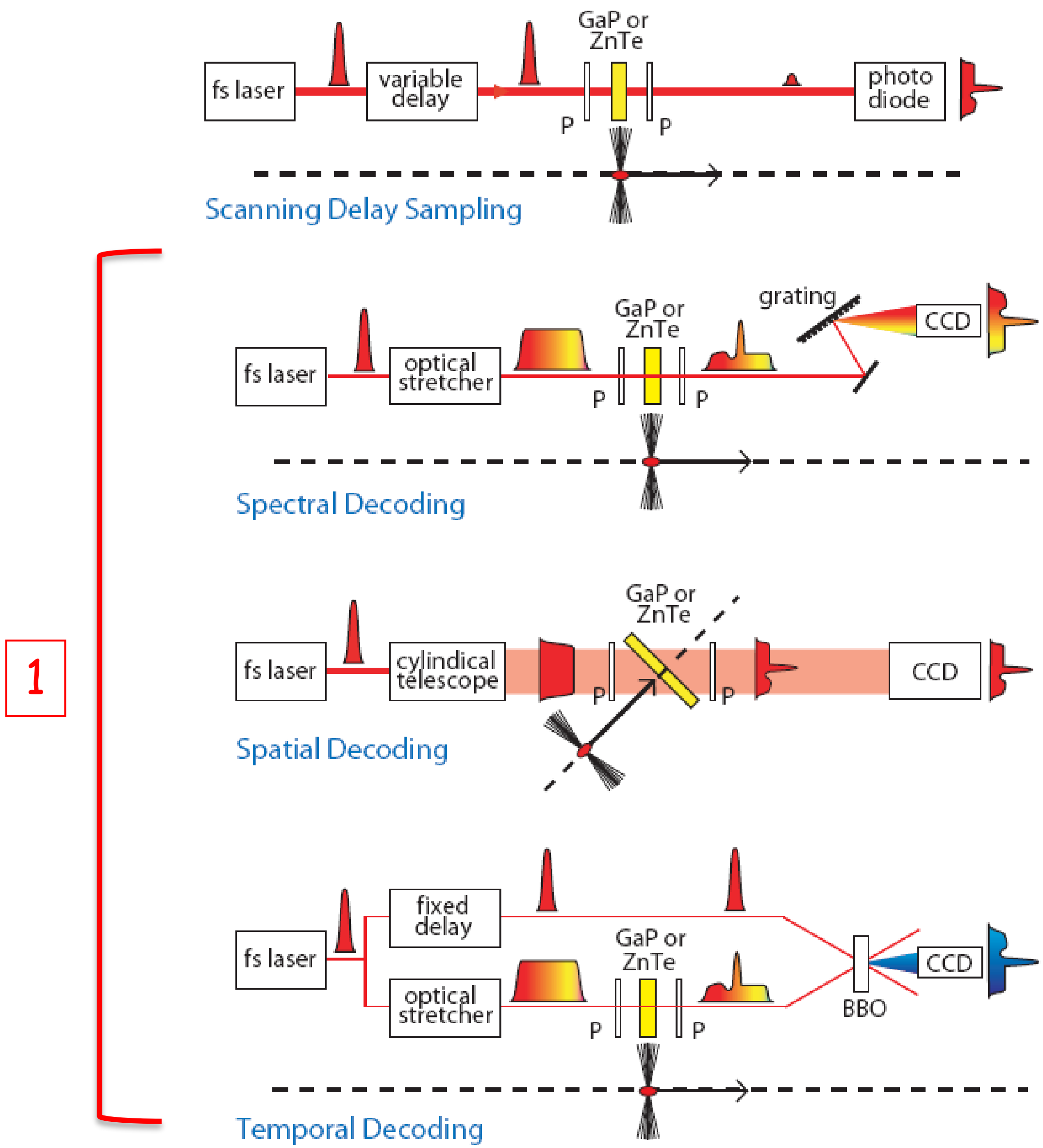
EOS @ FELIX



Using 12fs Ti:Al2O3 laser at 800nm and ZnTe crystal 0.5mm thick and a beam of 46MeV, 200pC, 2ps.

X. Yan *et al*, PRL 85, 3404 (2000)

Electro Optic based bunch length monitors



1. Sampling:
- multi-shot method
- arbitrary time window possible

2. Chirp laser method, spectral encoding
- laser bandwidth limited~ 250fs

Wilke *et.al.*, PRL 88 (2002) 124801

3. Spatial encoding:
- imaging limitation ~ 30-50 fs

Cavalieri *et. al*, PRL 94 (2005) 114801

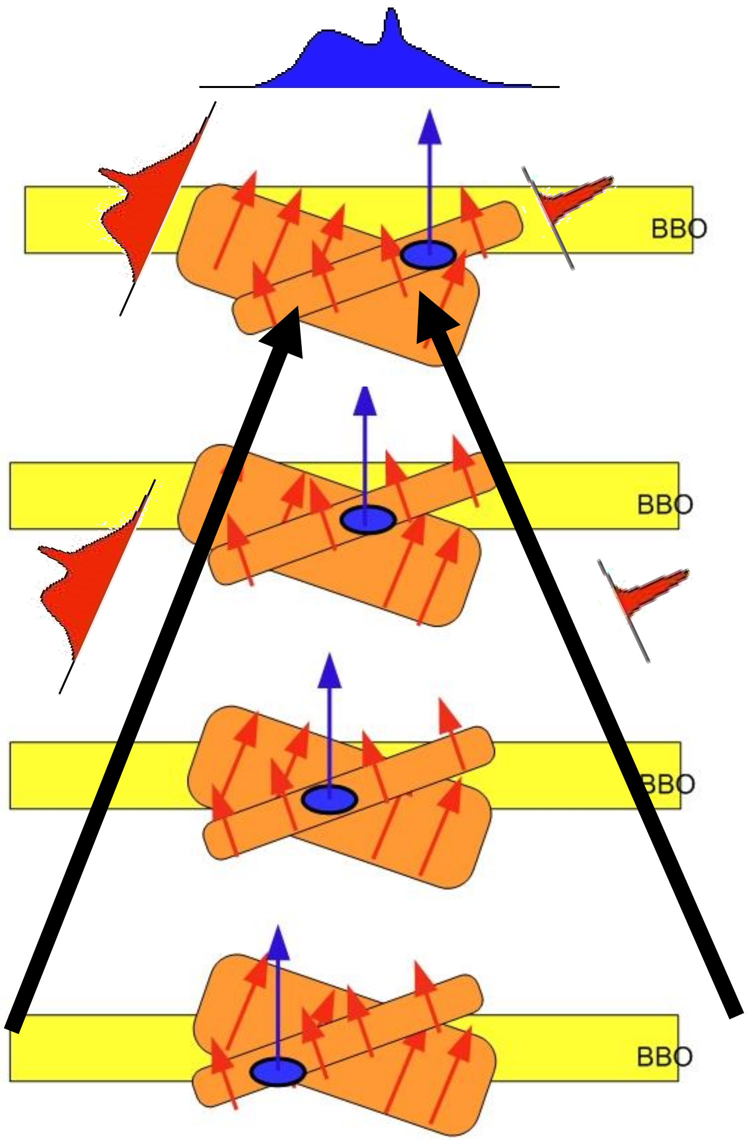
Jamison *et. al*, Opt. Lett. 28 (2003) 1710

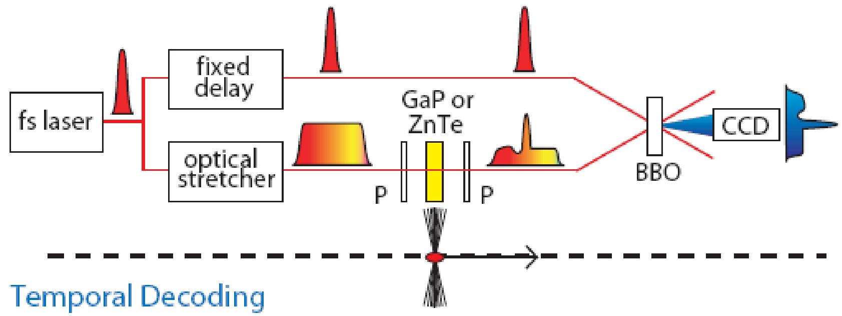
Van Tilborg *et. al*, Opt. Lett. 32 (2007) 313

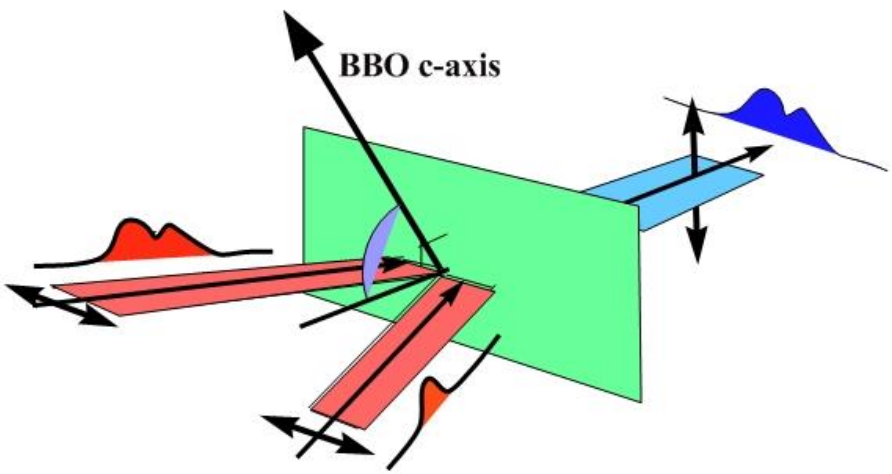
4. Temporal decoding:
- laser pulse length limited ~ 30fs

Berden *et.al*, PRL 93 (2004) 114802

Electro Optic Temporal decoding

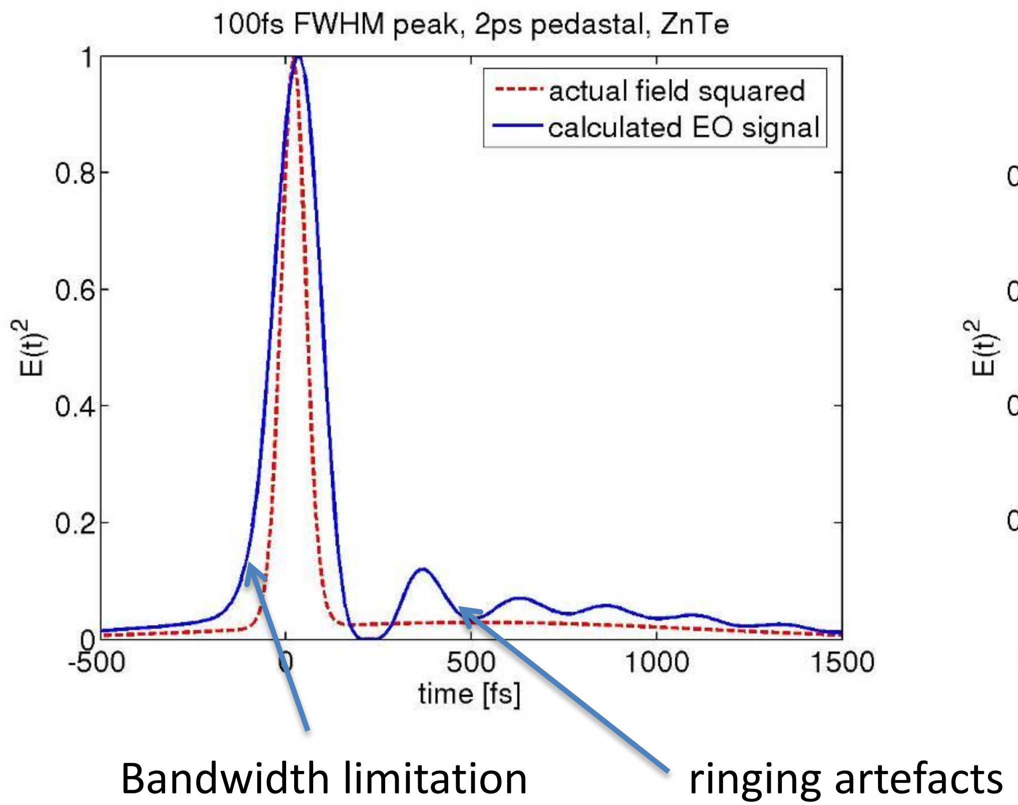


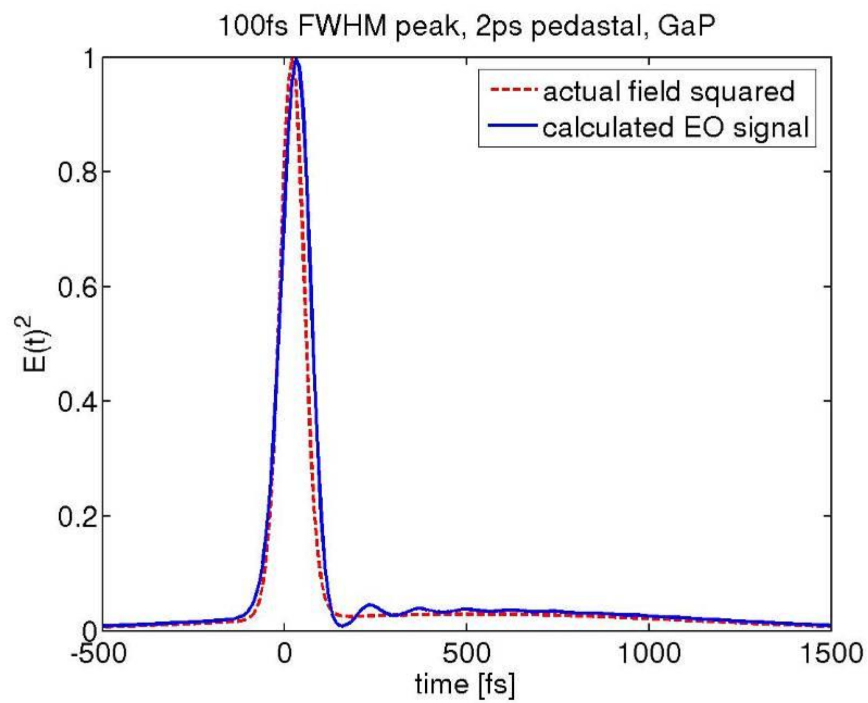




Courtesy: S. Jamison et al.

Encoding Time resolution



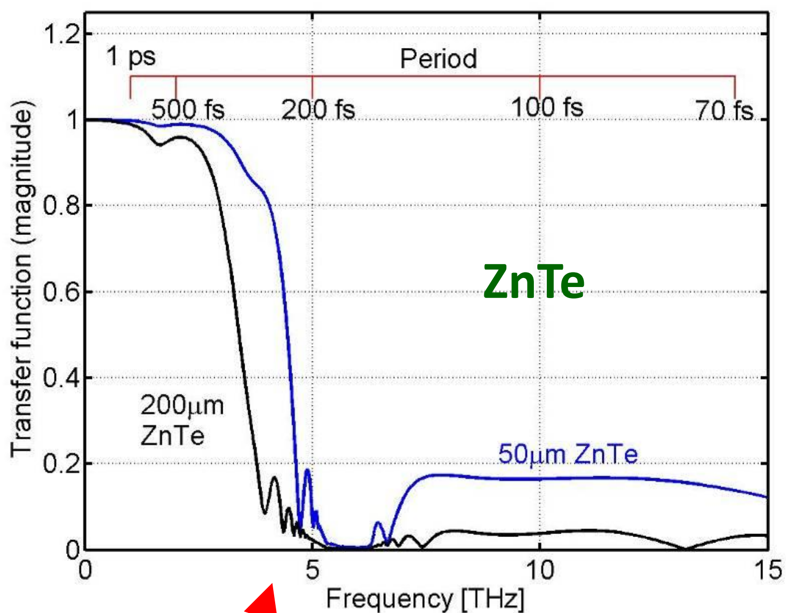


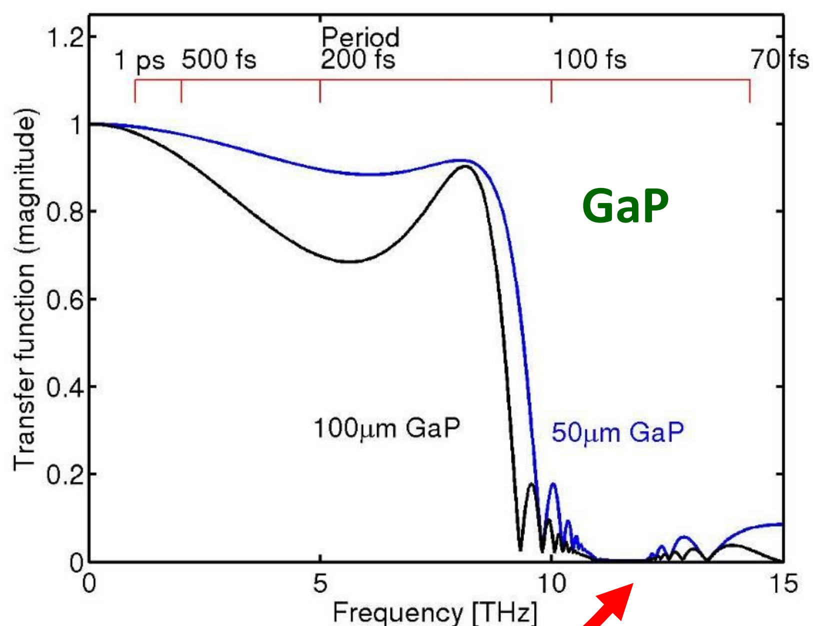
- *Thin crystal (>10μm)*
- *Consider new materials* GaSe, DAST, MBANP ….. or poled organic polymers?

W.A. Gillespie & S. Jamison

Encoding Time resolution

Spectral limitations of the Crystal

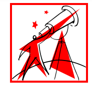
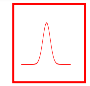




Phonon resonances

W.A. Gillespie & S. Jamison

Summary

				σ	1	n!	Limitations
• Optical radiation							
• Cherenkov / OTR radiation		X					
• ODR / OSR Radiation	X						
• Streak camera			X				200fs
• Coherent radiation : Bunch spectrum							
• Interferometry				X		X	
• Polychromator				X	X		
• RF techniques							
• 'Feschenko' monitor	X		X		X		Hadron, 20ps
• RF Deflector		X	X		X		10fs
• Zero phasing techniques		X	X		X		10fs
• Laser based Method							
• Sampling						X	Jitter (50fs)
• Non linear mixing			X				
• Thomson/Compton scattering	X		X				Electron
• Photo-neutralization	X		X				H^-
• Electro-Optic Sampling	X		X				
• E-O Spectral decoding	X		X		X		~ 200fs
• E-O Spatial decoding	X		X		X		~ 50fs
• E-O Temporal decoding	X		X		X		~ 50fs

Now we treat in detail:

- Measurement of nm beam positions
- Measurement of um transverse beam sizes
- Measurement of fs-scale long profiles
- Beam synchronization at the fs-scale
- Keeping the beams in collision (IP feedback)

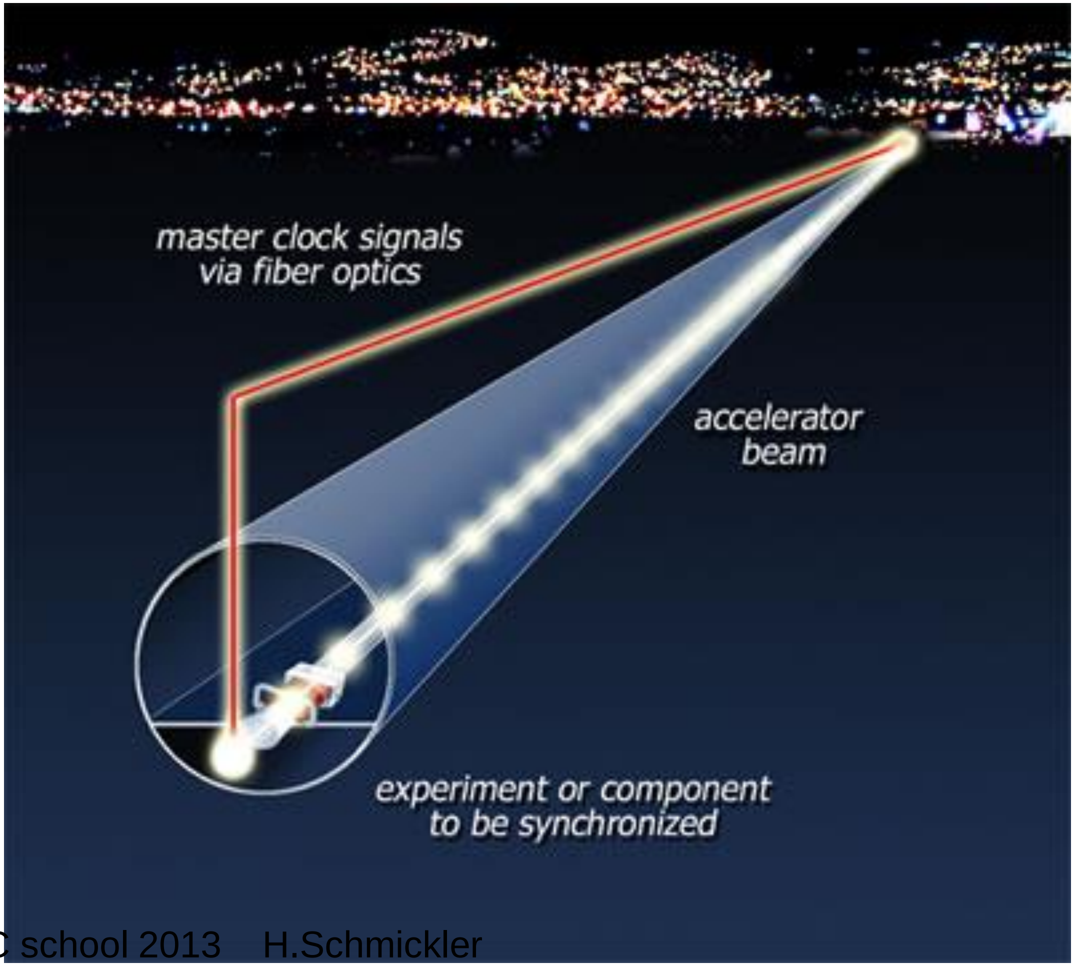
Synchronization of (distant) accelerator components down to the femtosecond

Speed of light:

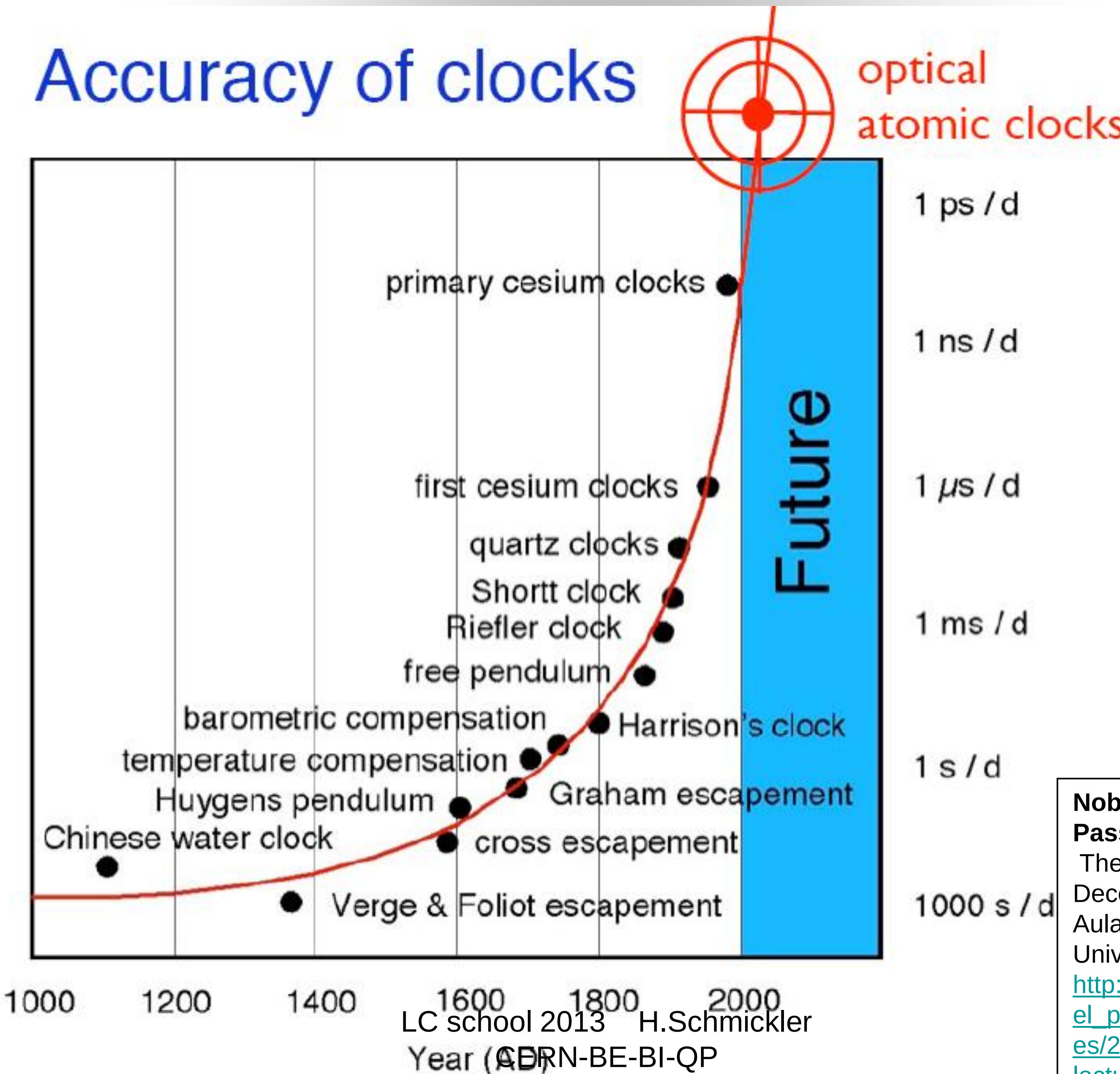
= 3*10^8 m/s

= 0.3 um/ fs

1) Clock stability
2) Distribution over length

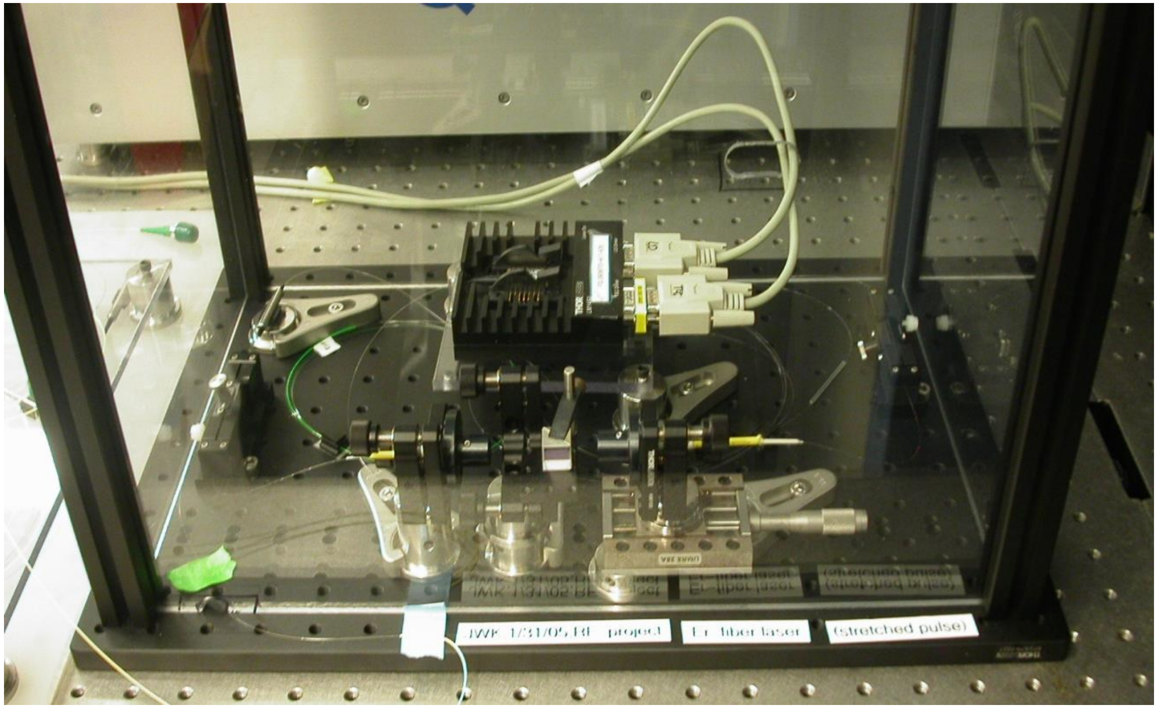


Accuracy of clocks

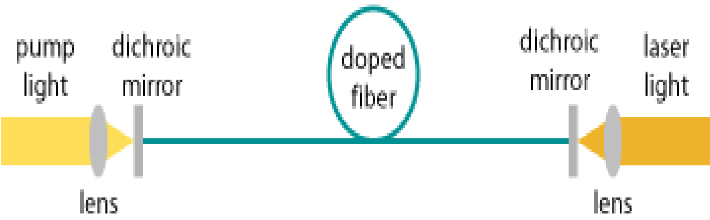


Nobel Lecture
Passion for Precision
Theodor W. Hänsch
December 8, 2005, at Aula Magna, Stockholm University.
http://nobelprize.org/nobel_prizes/physics/laureates/2005/hansch-lecture.html

Master Oscillator: Passively Mode-Locked Er-fiber lasers



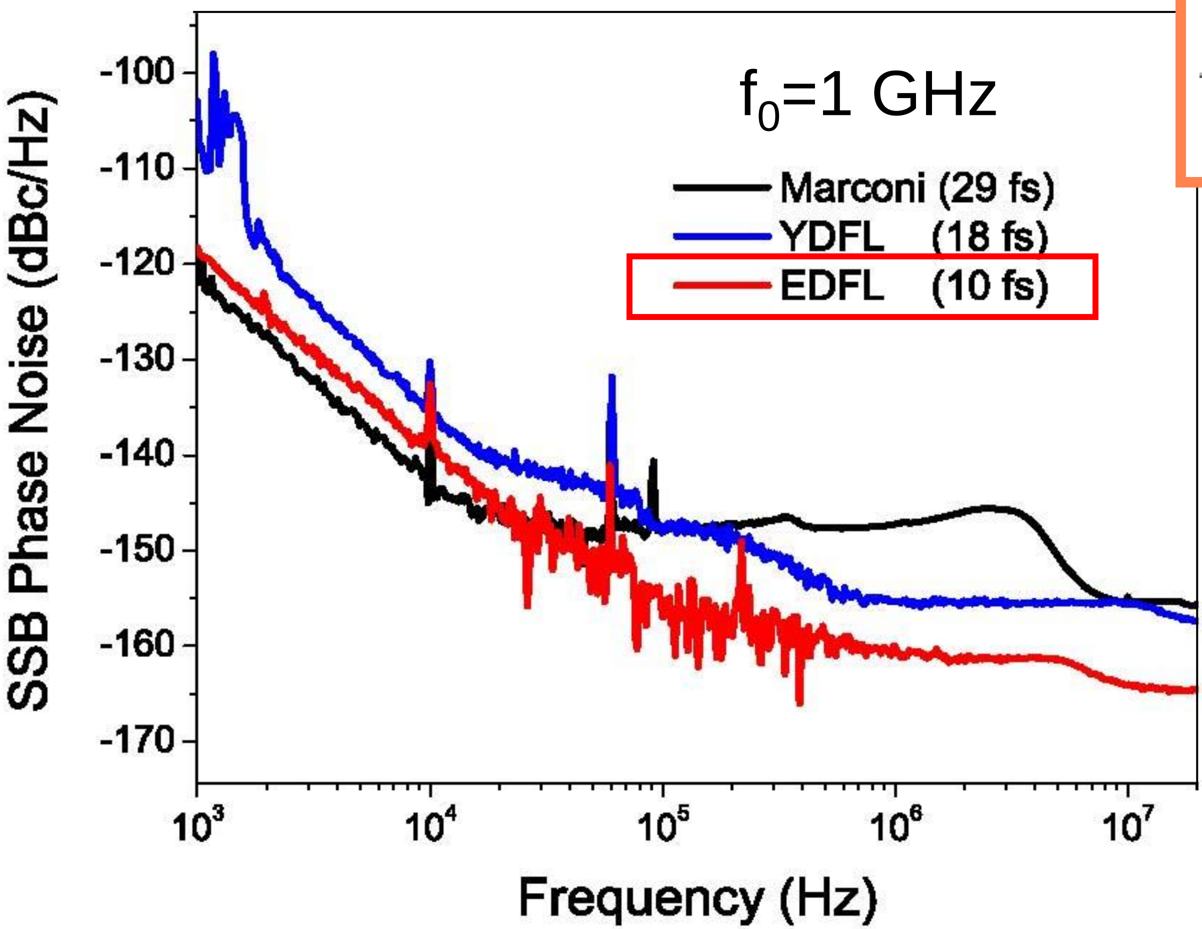
Ippen et al. Design: Opt. Lett. 18, 1080-1082 (1993)



- diode pumped
- sub-100 fs to ps pulse duration
- 1550 nm (telecom) wavelength for fiber-optic component availability
- repetition rate 30-100 MHz

Master Oscillator Timing Jitter

Agilent Signal Analyzer 5052a



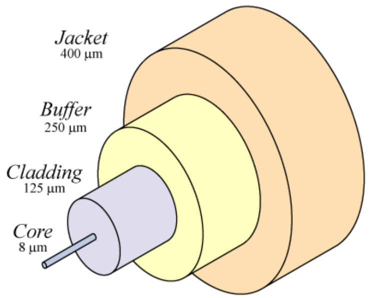
$$\Delta t_{rms} = \frac{\sqrt{2\int_{f_1}^{f_2} L(f)\,df}}{2\pi f_0}$$

- **Scaled to 1 GHz**
- **Limited by photo**
- **detection**
- **Theoretical limit ~1 fs**

Very stable operation over weeks !

Why fiber transmission?

- Fiber offers THz bandwidth, immunity from electromagnetic interference, immunity from ground loops and very low attenuation
- However, the phase and group delay of single-mode glass fiber depend on its environment
  - temperature dependence
  - acoustical dependence
  - dependence on mechanical motion
  - dependence on polarization effects



- These are corrected by reflecting a signal from the far end of the fiber, compare to a reference, and correct fiber phase length.
- Two approaches: CW and pulsed

Stabilized fiber link

Frequency-offset Optical Interferometry

Technique used at ALMA

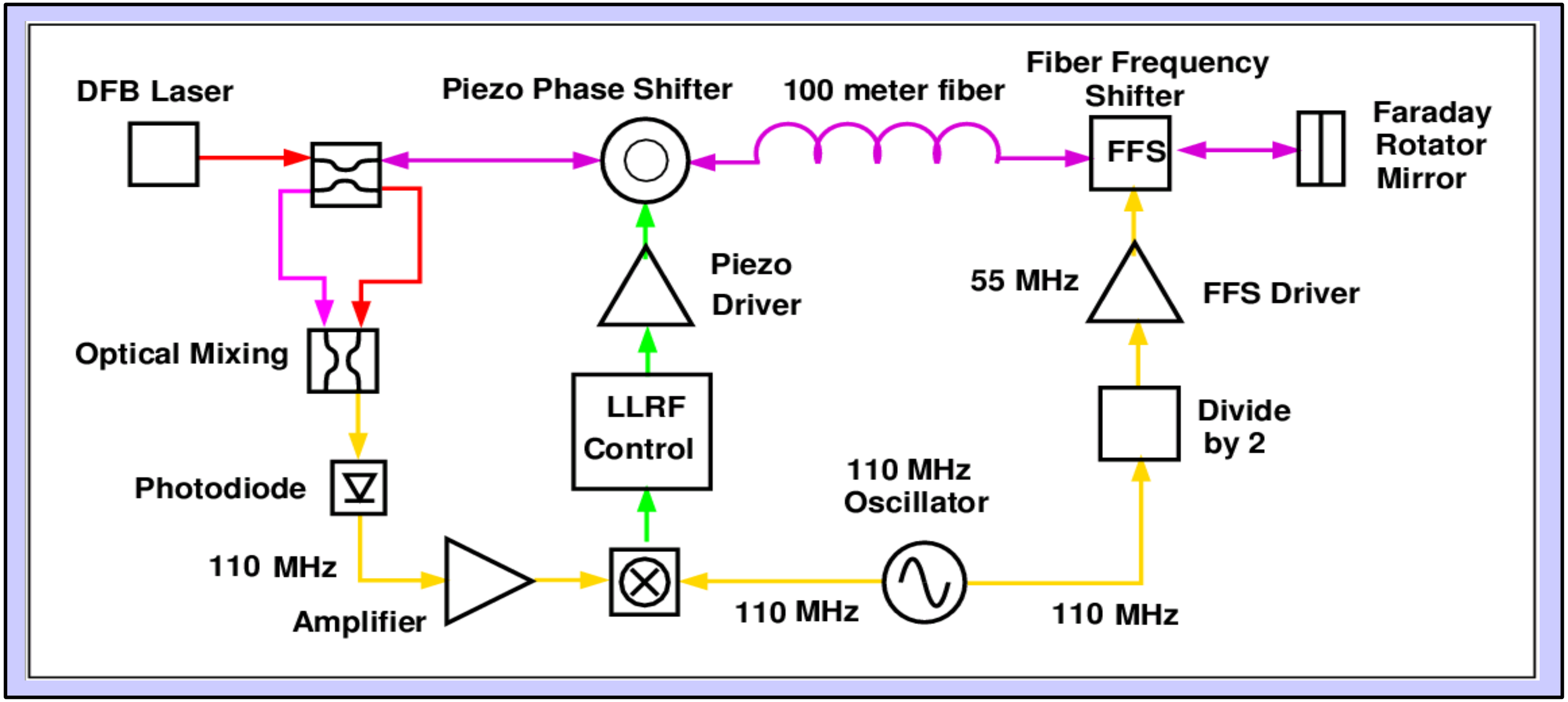
64 dishes over 25 km footprint, 37 fsec requirement

Principle: Heterodyning preserves phase relationships

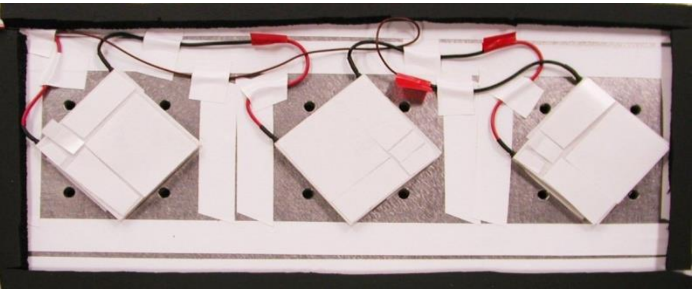
1 degree at optical = 1 degree RF

1 degree at 110 MHz = 0.014 fsec at optical

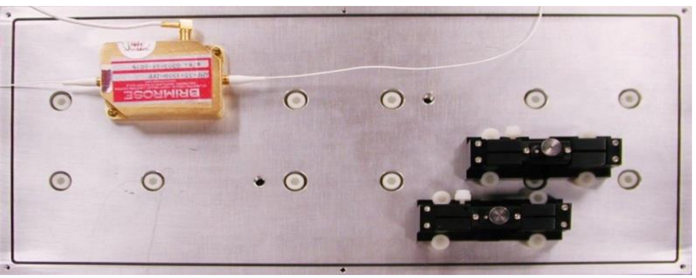
Gain 10^5 leverage over RF-based systems in phase sensitivity



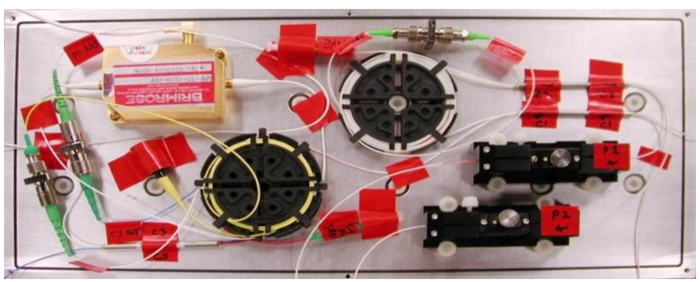
Thermal control of critical components



Peltier Coolers

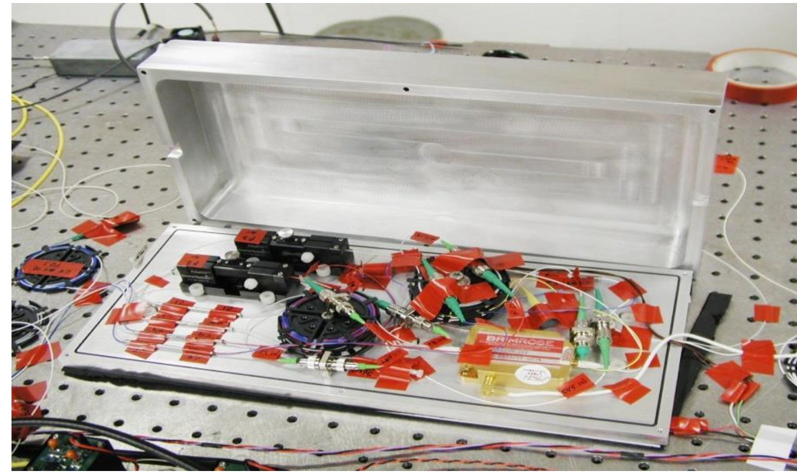


Baseplate

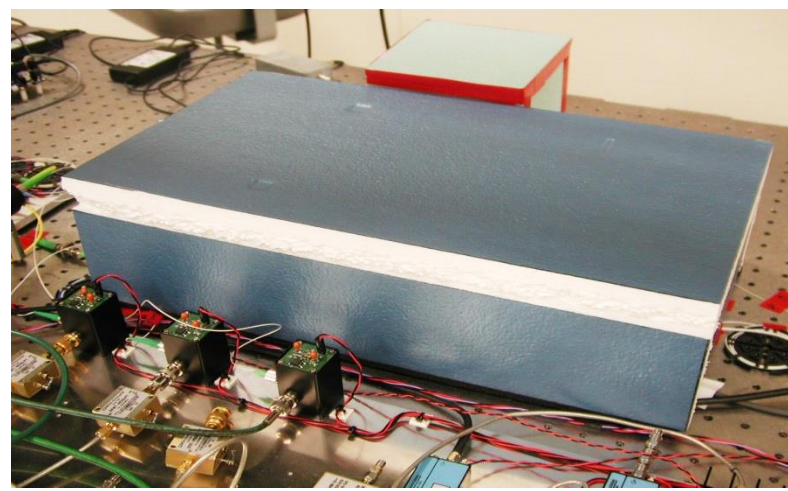


Some components

Complete

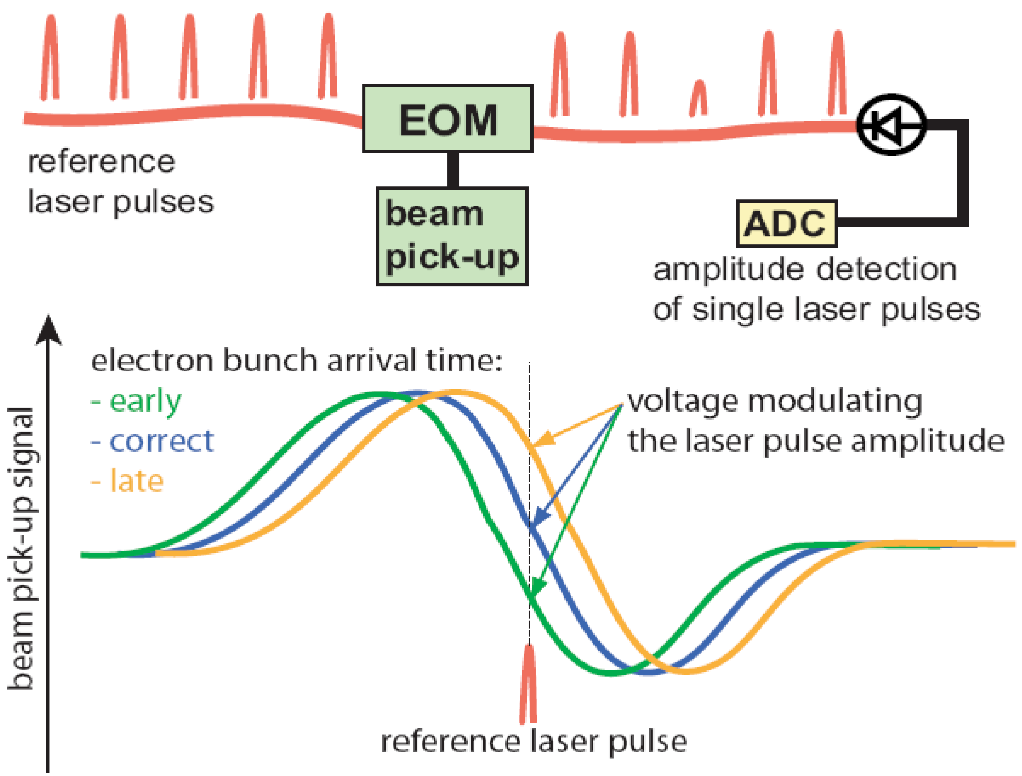


Aluminum Chamber

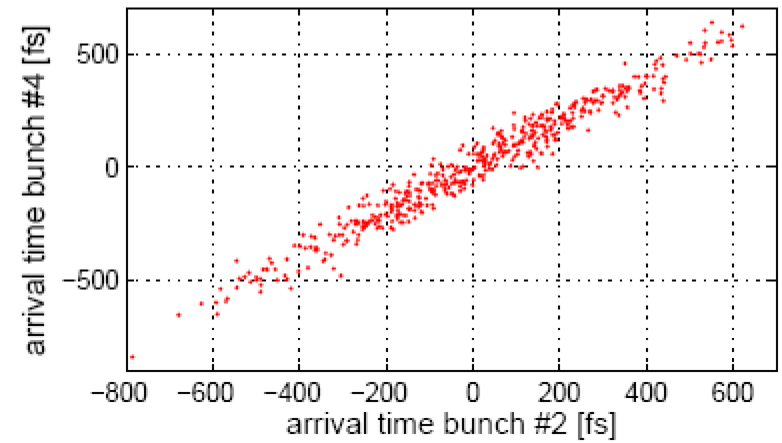


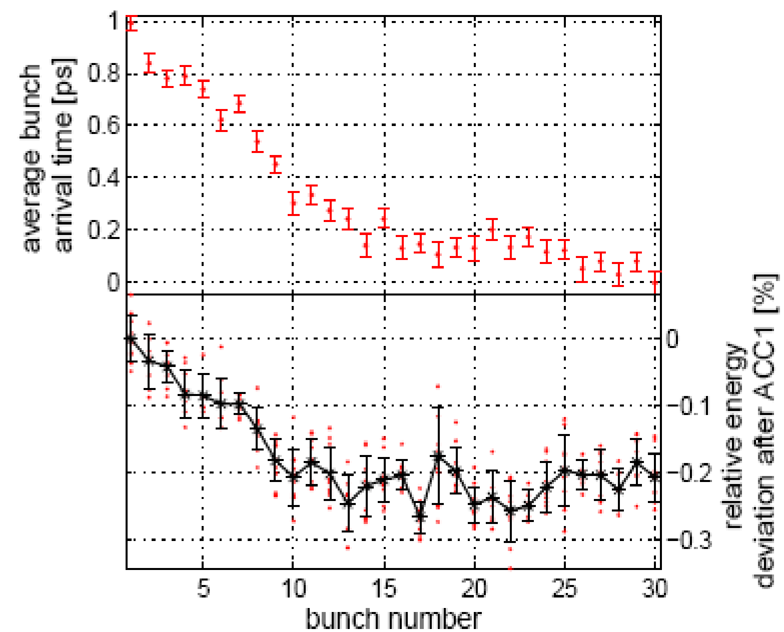
Insulating Jacket

Measurement: Bunch arrival monitor (Σ)



Principle of the arrival time detection. Reference laser pulses traverse an electro-optical modulator which is driven by the signal of a beam pick-up (top). Arrival time changes of the electron beam cause different modulation voltages at the laser pulse arrival time (bottom), leading to laser amplitude changes that are detected by a photo detector.





Comparison of the average bunch arrival time over the bunch train at the end of the machine with the average beam energy after the first accelerating module ACC1.

A Sub-50 Femtosecond bunch arrival time monitor system for FLASH; F. Loehl, Kirsten E. Hacker, H. Schlarb (DESY, Hamburg) DIPAC07

Now we treat in detail:

- Measurement of nm beam positions
- Measurement of um transverse beam sizes
- Measurement of fs-scale long profiles
- Beam synchronization at the fs-scale
- Keeping the beams in collision (IP feedback)

Beam Control Stability Issues

- Degradation of the luminosity due to IP beam jitter
- Sources of IP beam jitter: ground motion, additional local noise (e.g. cooling water)
- IP jitter control:

"Cold-RF" based LC (e.g. ILC)

- A fast intra-train FB systems at the IP can in principle recover > 90% of the nominal luminosity
- The linac+BDS elements jitter tolerance and tolerable ground motion are not determined from IP jitter, but from diagnostic performance and emittance preservation

"Warm-RF" based LC (e.g. CLIC)

- IP beam stability mainly provided from:
  - Selection of a site with sufficiently small ground motion
  - Pulse-to-pulse FB systems for orbit correction in linac and BDS
  - Active stabilisation of the FD quadrupoles
- In this case a fast intra-train FB system is thought as an additional line of defence to recover at least ~ 80% of nominal luminosity in case of failure of the above stabilisation subsystems.
- A fast FB system can also help to relax the FD subnanometer position jitter tolerance

IP-FB Systems

ILC (500 GeV)

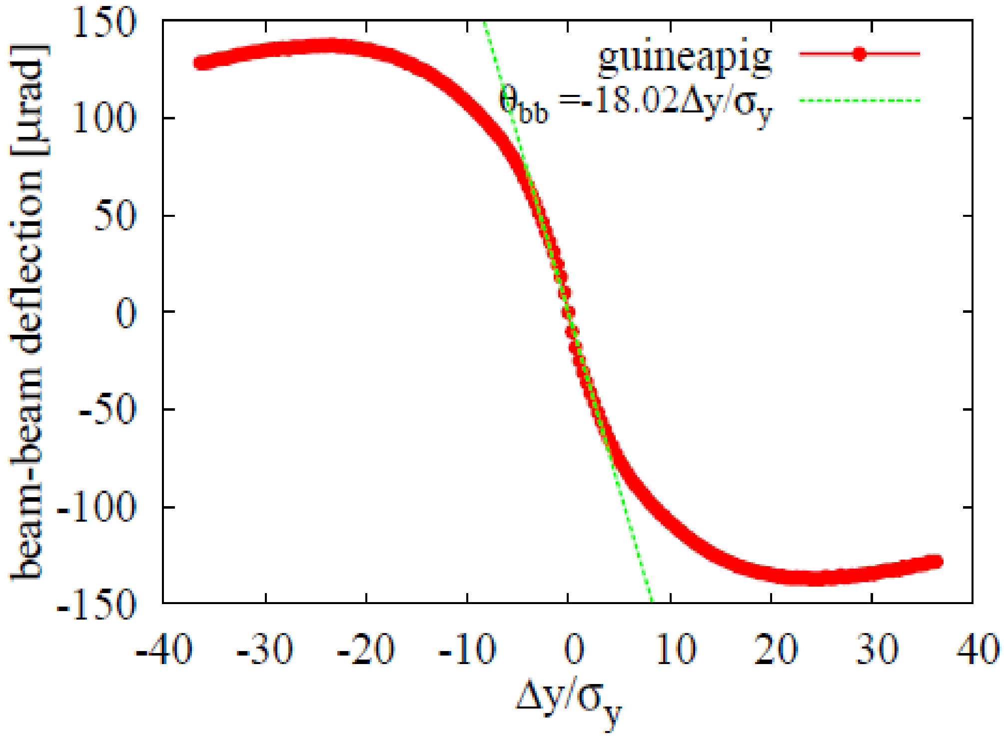
- Beam time structure:
  - Train repetition rate: 5 Hz
  - Bunch separation: 369.2 ns
  - Train length: 969.15 µs
- Intra-train (allows bunch-to-bunch correction)
- Digital FB processor (allows FPGA programming)
- Large capture range (10s of σ)
- IP position intra-train FB system + Angle intra-train FB system (in the FFS)

CLIC (3 TeV)

- Beam time structure:
  - Train repetition rate: 50 Hz
  - Bunch separation: 0.5 ns
  - Train length: 0.156 µs
- Intra-train (but not bunch-to-bunch)
- Analogue FB processor
- No angle intra-train FB system due to latency constraints

Beam-beam deflection curve

The analysis of the beam deflection angle caused by one beam on the other is a method to infer the relative beam-beam position offset at the IP



Linear approximation in the range [-10, 10] σ^*_y: $$\theta_{b-b}(\Delta y^*) = -18.02\frac{\Delta y^*}{\sigma^*_y}\ [\mu\text{rad}]$$

The convergence range is limited by the non-linear response of beam-beam deflection

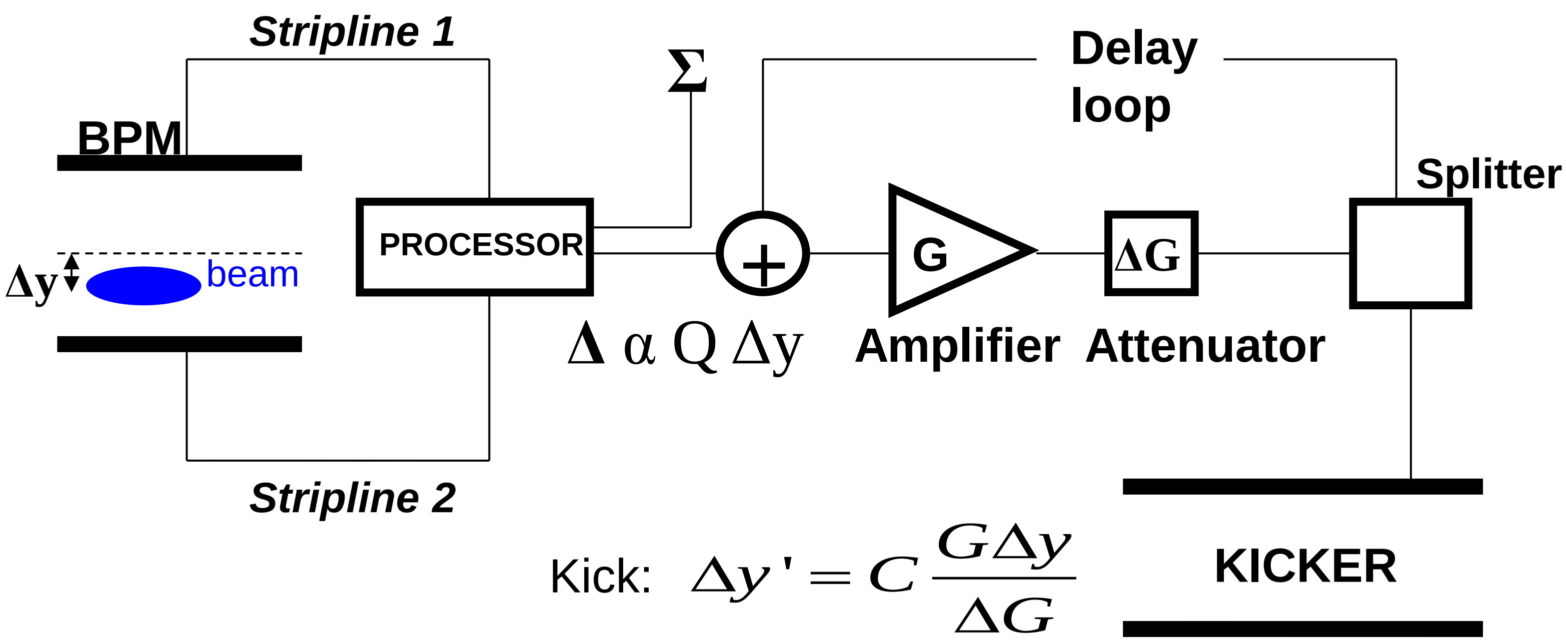
Bunch train structure comparison

	Cold LC	Warm LC	
Property	**ILC 500 GeV**	**CLIC 3 TeV**	units
Electrons/bunch	2.0	0.37	10^{10}
Bunches/train	2625	312	
Train Repetition Rate	5	50	Hz
Bunch Separation	369.2	0.5	ns
Train Length	969.15	0.156	μs
Horizontal IP Beam Size (σ_x)	639	45	nm
Vertical IP Beam Size (σ_y)	5.7	0.9	nm
Longitudinal IP Beam Size	300	45	μm
Luminosity	2.03	6.0	$10^{34}\text{cm}^{-2}\text{s}^{-1}$

For CLIC 738 times smaller bunch separation and 6212 times smaller bunch train length than for ILC !
IP intra-pulse FB is more challenging.

Analogue FB system

Basic scheme



Kick: $$\Delta y' = C \frac{G \Delta y}{\Delta G}$$

Equipment:

- BPM: to register the orbit of the out-coming beam
- BPM processor: to translate the raw BPM signals into a normalised position output
- Kicker driver amplifier: to provide the required output drive signals
- Fast kicker: to give the required correction to the opposite beam

CLIC IP-FB system latency issues

- Irreducible latency:
  - Time-of-flight from IP to BPM: t_{pf}
  - Time-of-flight from kicker to IP: t_{kf}
- Reducible latency:
  - BPM signal processing: t_p
  - Response time of the kicker: t_k
  - Transport time of the signal BPM-kicker: t_s

Study and test of an analogue FB system for 'warm' linear colliders: FONT3:

P. Burrows et al. "PERFORMANCE OF THE FONT3 FAST ANALOGUE INTRA-TRAIN BEAM-BASED FEEDBACK SYSTEM AT ATF", Proc. of PAC05.

Comparison of tentative latency times for a possible CLIC IP-FB system with the latency times of FONT3

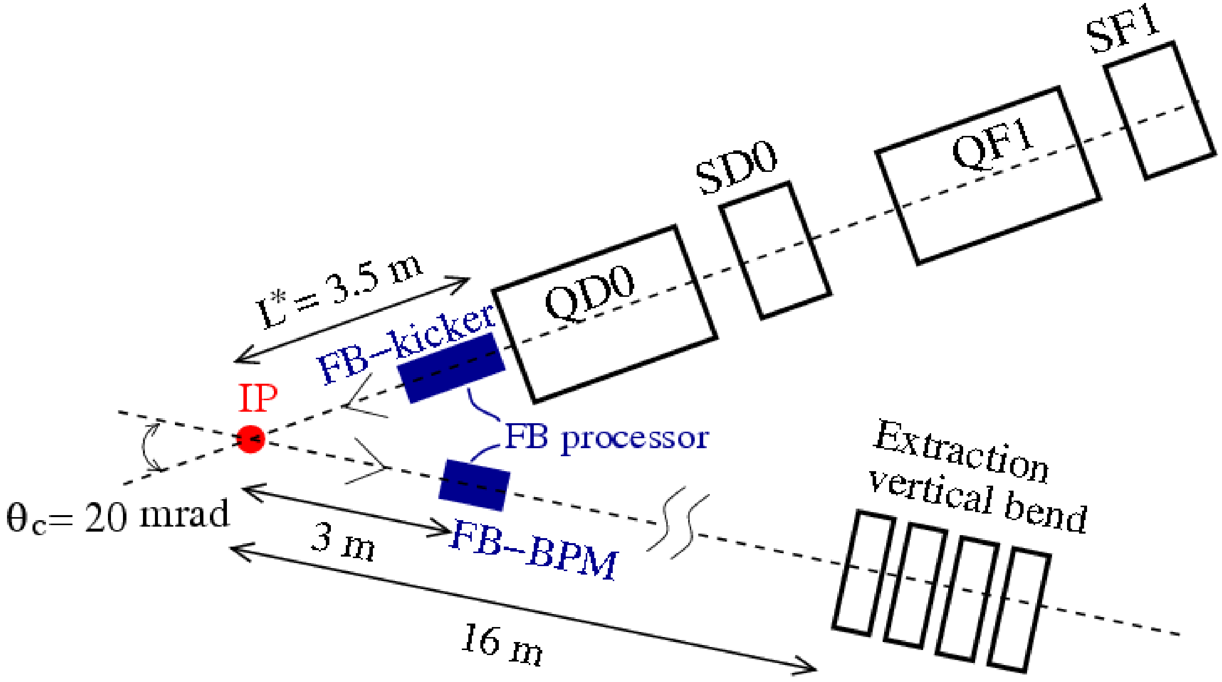
Source of delay	Latency FONT3 [ns]	Latency CLIC [ns]
$t_{pf} + t_{kf}$	4	20
t_s	6	7
t_p	5	5
t_k	5	5
Total t_{FB}	20	37

CLIC IR

IP-FB BPM and kicker positions

The choice of the position of the IP-FB elements is a compromise between:

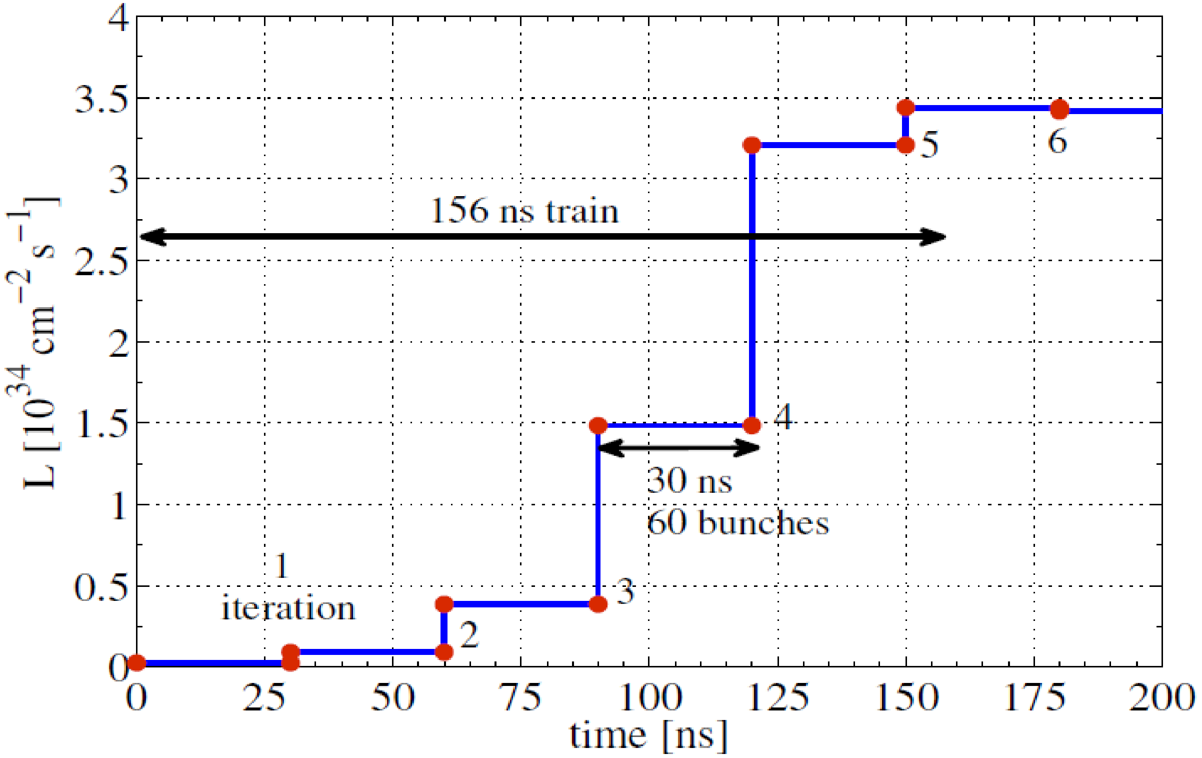
- Reduction of latency
- Avoiding possible degradation of the BPM response due to particle background/backsplash and possible damage of electronics components



If FONT elements 3 m apart from IP, then beam time-of-flight = 10 ns

Luminosity performance

Simulation time structure:
Simulation applying a single random seed of GM C



•For the simulations we have considered a correction iteration every 30 ns. The systems performs approximately a correction every 60 bunches (5 iterations per train)