S. Bettoni[1], P. Craievich[1], A. Lutman[2] and M. Pedrozzi[1]
[1] Paul Scherrer Institut, Villigen, Switzerland
[2] SLAC National Accelerator Laboratory, Menlo Park, California

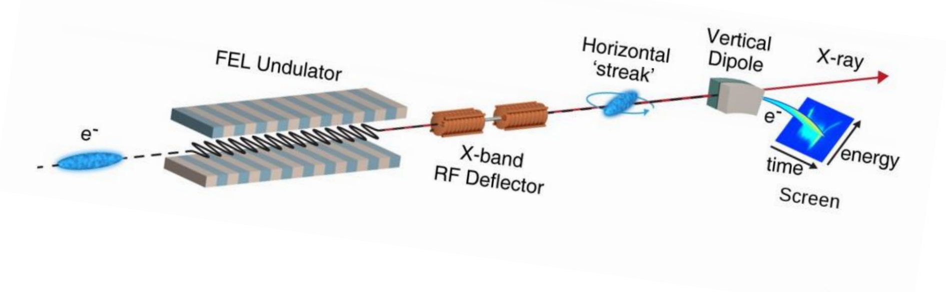
Passive Streaking Using Transverse Wakefield for Ultrashort Bunch Diagnostics

International Particle Accelerator Conference 2017
Copenhagen, 19th May 2017

Talk outline

- Longitudinal beam profile measurement: why?
- Wakefield: a brief recall
- SwissFEL and SwissFEL Injector Test Facility (SITF)
- Passive streaker model and wake potentials
  - Formulas to calculate the beam longitudinal profile at the screen
  - Algorithm to time-resolve the electron beam profile
  - Example of reconstruction from numerical simulations
- Proof-of-principle experiment at SITF
  - Example of reconstruction from experimental data
- Next steps at SwissFEL and at other labs
- Conclusions

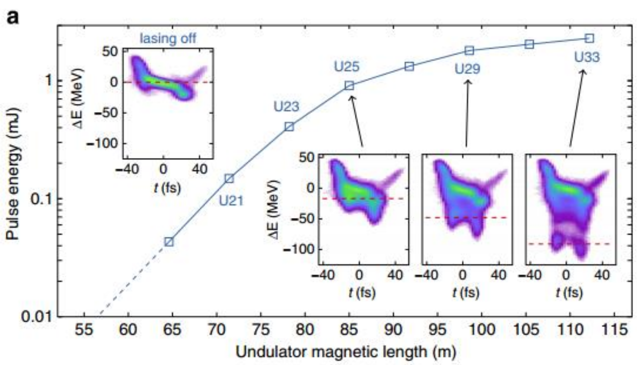
Longitudinal beam profile diagnostics



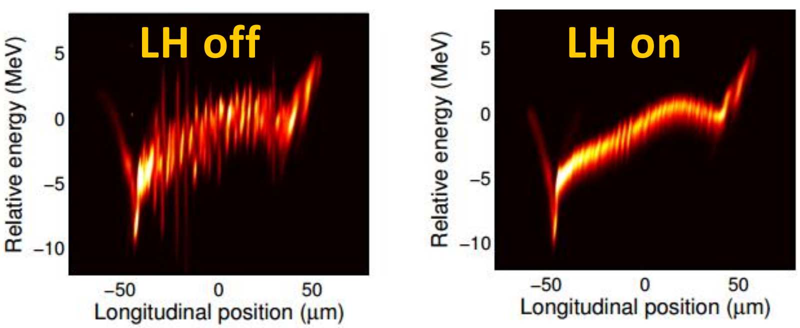
X-band transverse cavity very valuable instrument to:

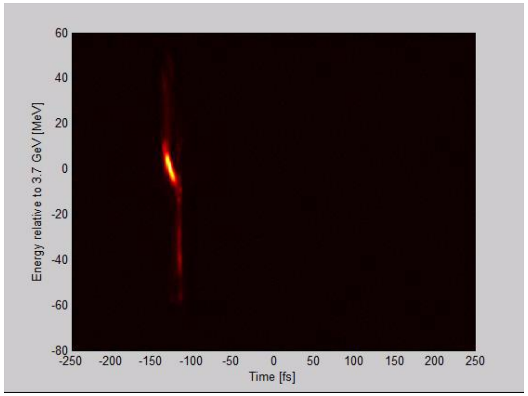
- ❑ Optimize the lasing along the bunch
- ❑ Directly observe the microbunching instability and its mitigation

[Ref. 1] C. Behrens et al.



[Ref. 2] D. Ratner et al.





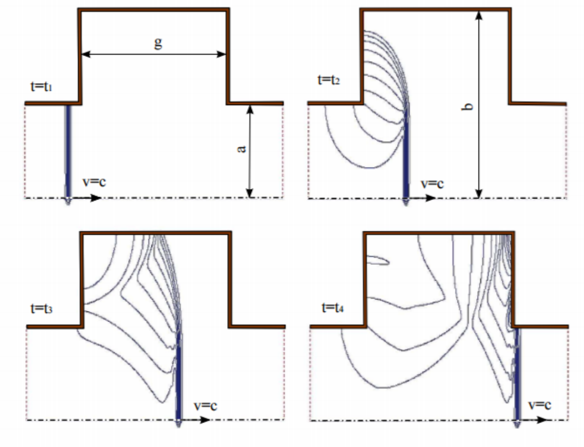
BUT:

- ❑ Expensive manufacture
- ❑ Operation costs (powering, maintenance)
- ❑ It may suffer from jitter issues

Wakefields: from problems...

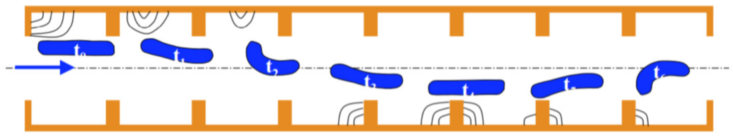
Longitudinal

z-dependendent energy loss



Transverse

z-dependendent deflection



Snapshots of a single bunch traversing a SLAC structure

SHORT-RANGE:

- Wakefield persists only for the duration of a bunch passage
- Particles in the tail can interact with wakes due to particles in the head
- <u>Single bunch</u> instabilities can be triggered → projected emittance growth

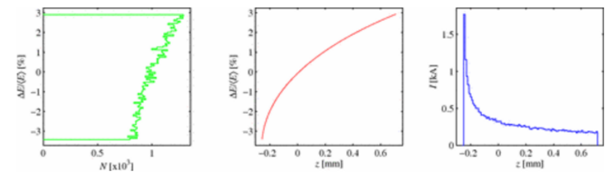
LONG-RANGE:

- The wakefield lasts longer than the time between bunches
- Trailing bunches can interact with wakes from leading bunches to generate <u>multi-bunch</u> instabilities → beam breakup

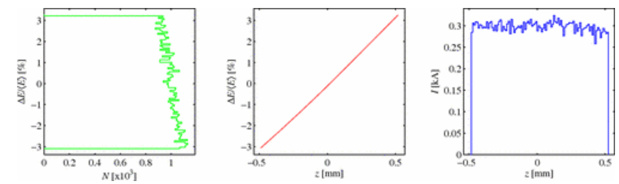
…to resources

LINEARIZER

Linearize the beam longitudinal phase space (equivalent to a high harmonic cavity or non-linear bunch compressor)

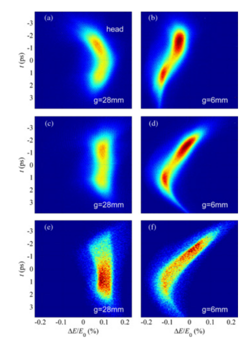


[Ref. 6] P. Craievich

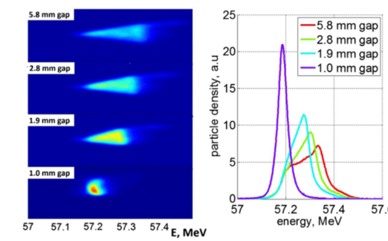


DECHIRPER

Remove the residual correlated energy spread residual from the compression



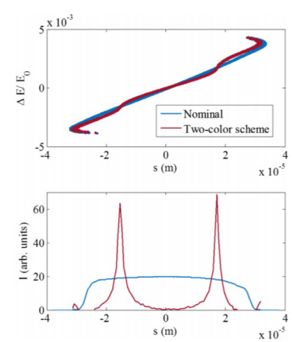
[Ref. w2] P. Emma, et al.



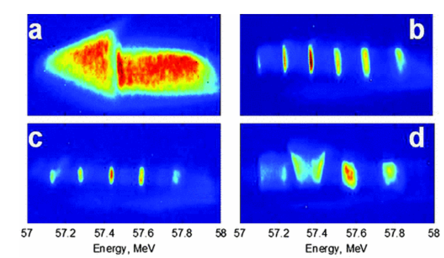
[Ref. w3] S. Antipov, et al.

BEAM TRAIN GENERATION

Modulation of the current profile for THz sources or multi-color operation in FELs or wakefield acceleration schemes



[Ref. 7] S. Bettoni, et al.

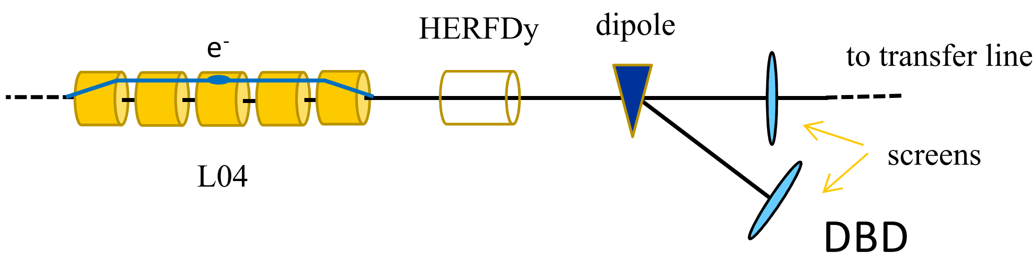


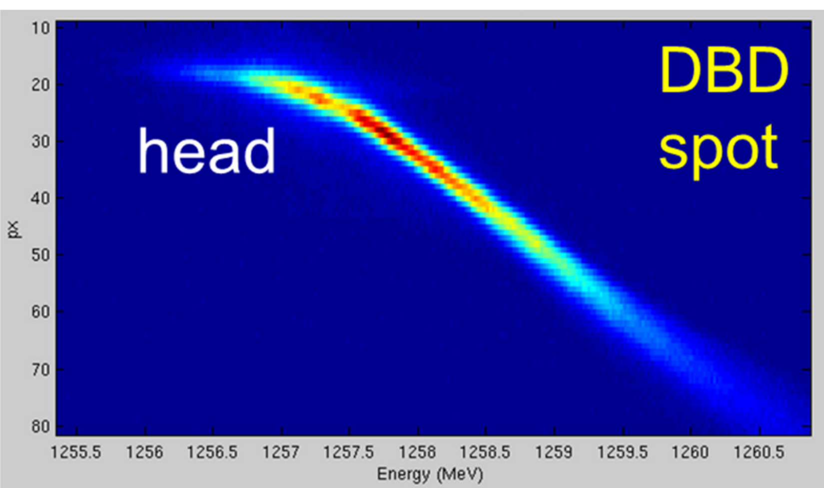
[Ref. w5] S. Antipov, et al.

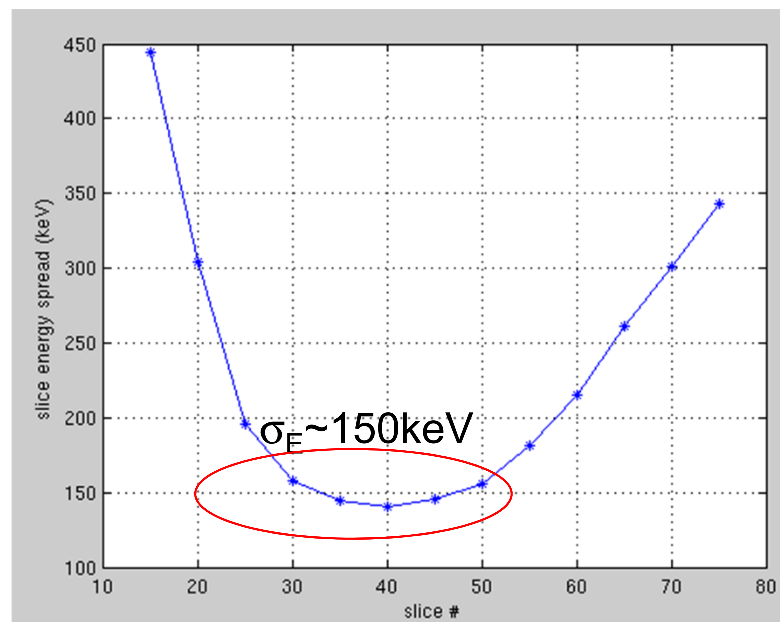
First observation of passive streaking

→ Slice Energy Spread at the FERMI@Trieste spectrometer with BC1+BC2 ($\sigma_t \approx 1$ps)
(…while waiting for High Energy RF Deflector at the end of 2011)

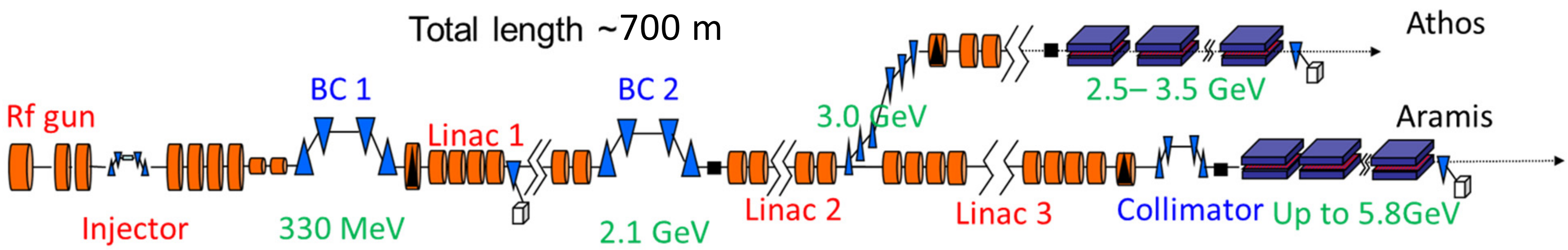
→ Sending the beam off-axis in Linac 4 (high-impedance accelerating structures), used the transverse wakes to create a time-energy correlation







SwissFEL



Electron source

RF gun with CaF_2 laser driven with Cs_2Te photocathode

Undulator beamlines

1. **Aramis**: hard X-ray FEL (1-7 Å). In-vacuum, planar undulators with variable gap, period = 15 mm
2. **Athos**: soft X-ray FEL (6.5-50 Å). Undulators with variable gap and full polarization control, period = 38 mm

Wavelength	1 - 50 Å
Pulse duration rms	3 – 30 fs
Maximum e- beam energy	5.8 GeV
e- beam charge	10 – 200 pC
Repetition rate	100 Hz
Slice emittance (design)	40-150 nm
Slice emittance (expected)	100-300 nm
Slice energy spread	250-350 keV
Saturation length	< 50 m

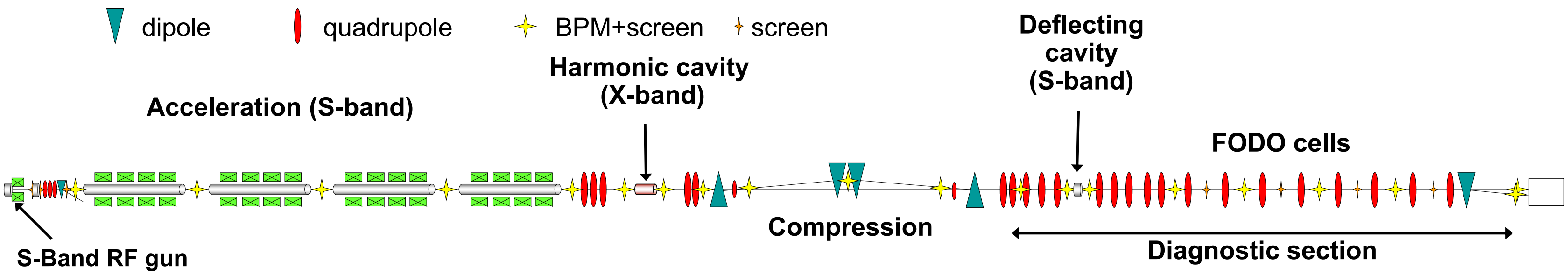
- ❑ Construction started in 2013
- ❑ Commissioning started in Jul 2016
- ❑ Lasing at 24.0 nm (Dec 2016), at 4.1 nm (May 2017)
- ❑ Aramis pilot experiment planned in Dec 2017
- ❑ Athos user operation planned in 2021

See H. H. Braun talk WEZA1

SwissFEL Injector Test Facility (SITF)

Missions

- ❑ Benchmark the simulation expectations and prove the feasibility of SwissFEL
- ❑ Develop and test components/systems and optimization procedures in SwissFEL



Max e- beam charge	200 pC	
Laser longitudinal shape	Flat-top	Gaussian
Laser longitudinal length	9.9 ps FWHM	2.7 ps rms
Laser transverse shape	Cut Gaussian	
Laser transverse RMS	0.18 mm	
Max e- beam energy	266 MeV	
Repetition rate	10 Hz	

Commissioning phases

Phase 1: Electron source and diagnostics (2010)

Phase 2: Phase 1 + two S-band stations (2010-2011)

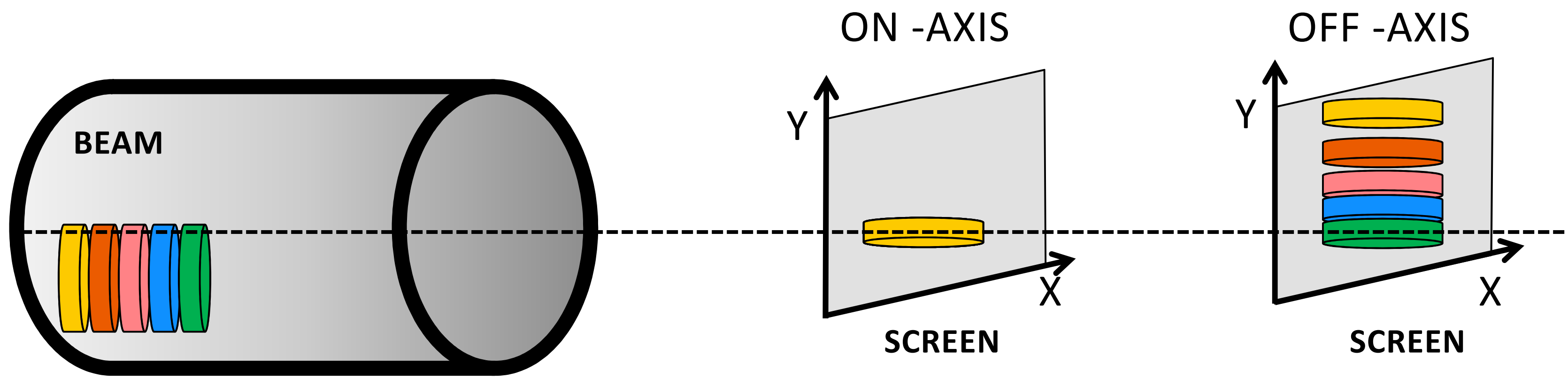
Phase 3: Machine in full configuration: all RF structures operational and bunch compressor installed (2012-2013)

Phase 4: Undulator installed for several weeks (2014)

Phase 4+: PSI gun installed (Oct 2014)

Shut-down: Oct 2014

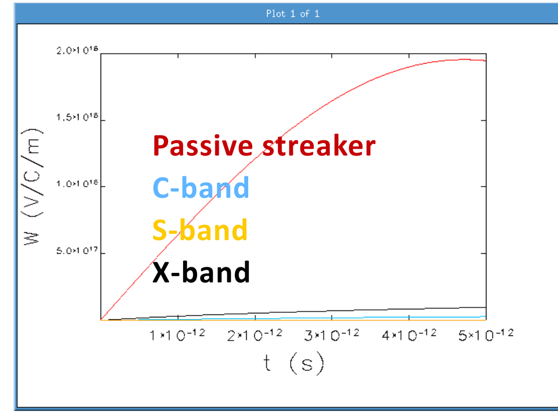
Working principle



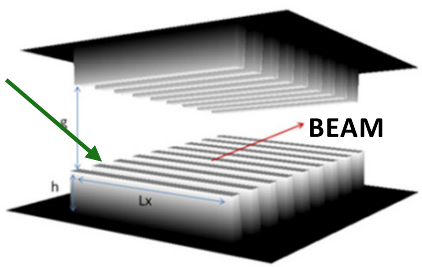
- The method to time-resolve the longitudinal profile is based on the self-transverse-wakefield generation
- A correlation between temporal position of the particle along the bunch and transverse position at a downstream screen is introduced
- The beam passes off-axis through a structure capable of generating a strong monotonic transverse wakefield along the full bunch length
- Cylindrical or planar, corrugated or dielectric-lined geometries may be used without altering the principle
- Potentially sub-fs resolutions achievable

Suitable wakefield sources

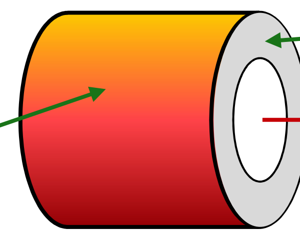
- Several sources can be used to do such a measurements. The requirements are:
  - Function monotone along the full bunch length
  - Amplitude of the wakefield enough to limit the length of the device to a reasonable value (~few meters)



CORRUGATED



DIELECTRIC LINED-WAVEGUIDE

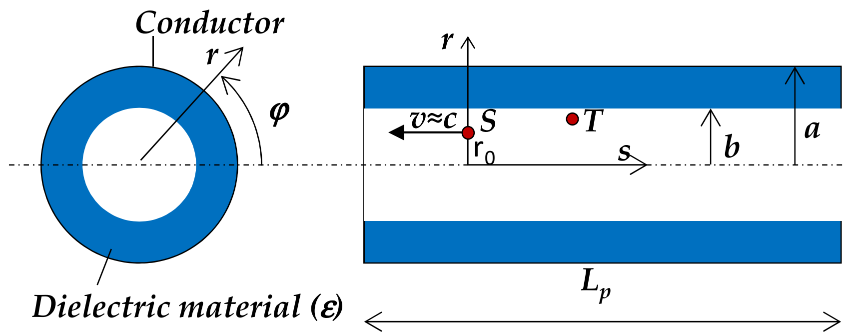


More typically corrugated →

Flat	Round
Easily tunable	More difficult to tune
Reduced amplitude (by $\pi^2/16$)	Maximum amplitude

← More typically dielectric lined

Wakefield model



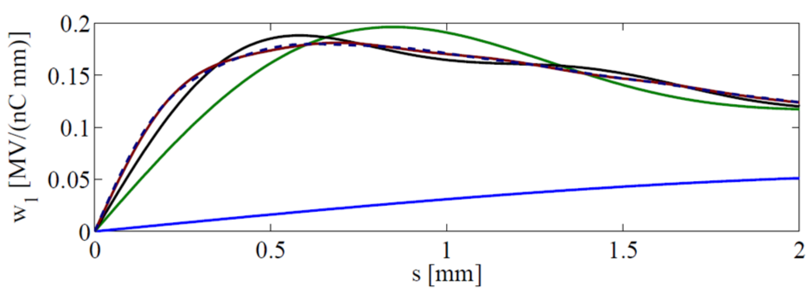
- Wakefield point charge is a linear combination of several sinusoidal functions:

$$w_{r,m}(s,r,r_0,\varphi,\varphi_0) = \frac{Z_0 c}{4\pi a^2}\left(\frac{r}{a}\right)^{m-1}\left(\frac{r_0}{a}\right)^{m}\sum_{i=1}^{\infty} A_{m,i}\sin(k_{m,i}s)\,cos[m(\varphi-\varphi_0)]$$

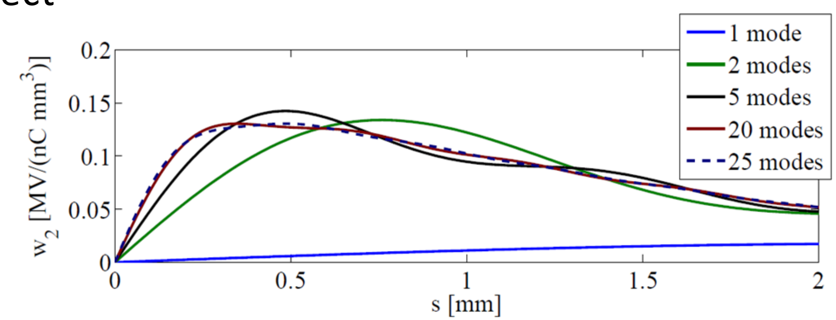
[Ref. 3] K. Y. Ng

$$w_{\varphi,m}(s,r,r_0,\varphi,\varphi_0) = \frac{Z_0 c}{4\pi a^2}\left(\frac{r}{a}\right)^{m-1}\left(\frac{r_0}{a}\right)^{m}\sum_{i=1}^{\infty} A_{m,i}\sin(k_{m,i}s)\,sin[m(\varphi-\varphi_0)]$$

- The different modes build up increasing the effect



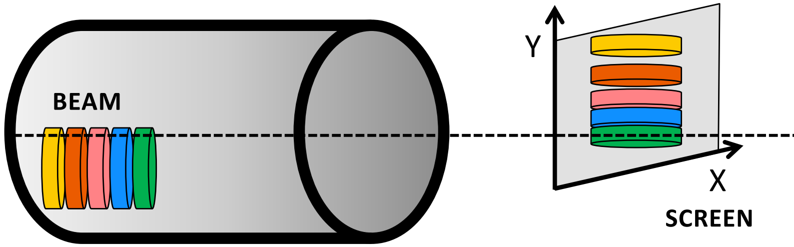
Dipole wake function (m=1)



Quadrupole wake function (m=2)

- Transient effect at the entrance of the tube neglected
- Wake functions were also verified with ImpedanceWake2D code

From the passive streaker to the screen



$\boldsymbol{\rho}_L$ Longitudinal charge distribution at the streaker

$\boldsymbol{\rho}_y$ Vertical charge distribution at the screen

$\boldsymbol{\rho}_{T,y}$ Vertical charge distribution at the screen (finite size)

$\tilde{\boldsymbol{\rho}}_{0,y}$ Vertical charge distribution at the screen (passing on-axis through the passive streaker)

From the charge conservation:

$$\rho_y \, dy = \rho_L \, ds \quad \Rightarrow \quad \rho_y = \rho_L \frac{ds}{dy} \equiv \rho_L \, s'$$

Transverse displacement at the screen

$$y_s(s) \approx \frac{Q L_p R_{34}}{E} \left[W_{r,1}(r_0, s) + W_{r,2}(r, r_0, s) \right]$$

Dipole wake potential: $W_{r,1} \propto r_0$

Quadrupole wake potential: $W_{r,2} \propto {r_0}^2, r$

Wake potentials when the transverse size is much smaller than the offset along the streaker:

$$W_{r,m}(r, s; r_0) = \int_{-\infty}^{s} w_r(r, r_0, s') \, \rho_l(r_0, s - s') ds$$

Finite beam size

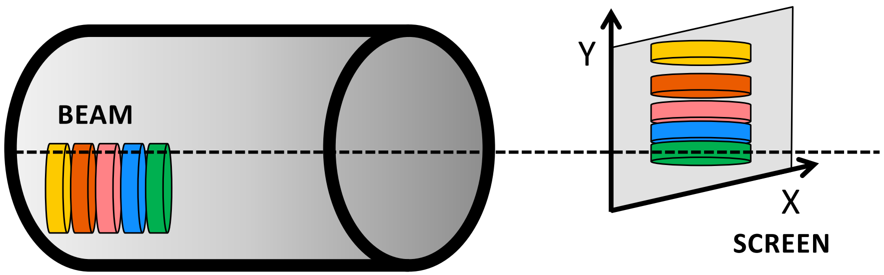
- The beam size is not negligible
- The profile at the screen, $\rho_{T,y}$, is evaluated as:

$$\boxed{\rho_{T,y} = \rho_y \otimes \tilde{\rho}_{0,y}}$$

Assumptions

- The transverse beam parameters are independent of the longitudinal coordinate
- The optics between the tube and the screen is linear

Time-resolving algorithm



ρ_L Charge distribution at the streaker

ρ_y Transverse charge distribution at the screen (off-axis in the streaker) from ρ_L

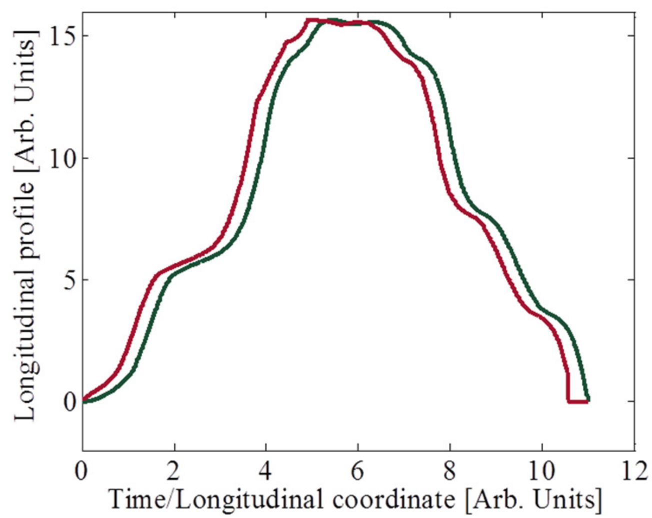
$\tilde{\rho}_L$ Trial charge distribution at the streaker

$\tilde{\rho}_y$ Calculated transverse charge distribution at the screen (off-axis in the streaker) from $\tilde{\rho}_L$

The algorithm minimizes the cost function (neglecting the finite transverse beam size at the passive streaker):

cost function = $|\rho_y - \tilde{\rho}_y|$

changing $\tilde{\rho}_L$, modeled as a piecewise cubic polynomial



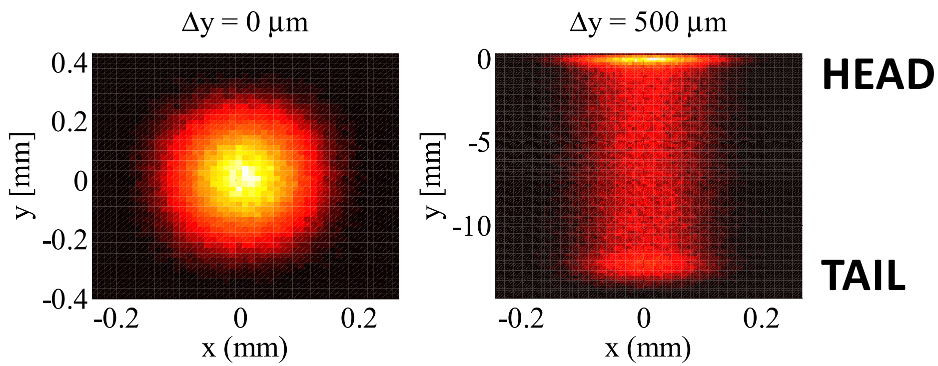
Assumed

Reconstructed

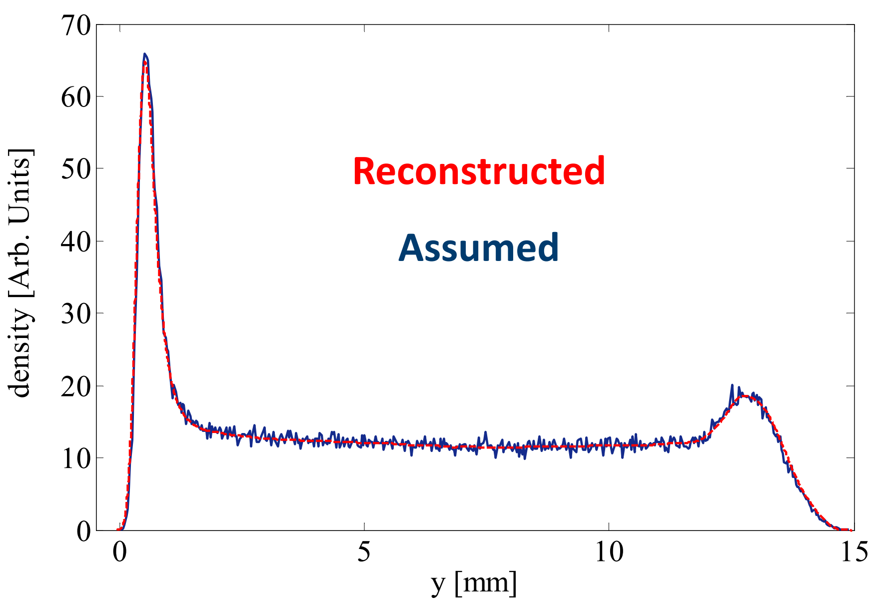
Including the beam transverse size $\rho_{T,y}$ is used in the optimization

Numerical simulations

- Simulated in Elegant [Ref. 4] a wakefield source monotonic along the full bunch length
- Double horn current profile (LCLS undulator like)



- Only the dipole included
- Beam at the head poorly streaked
- Transverse size is a small fraction of the streaked image

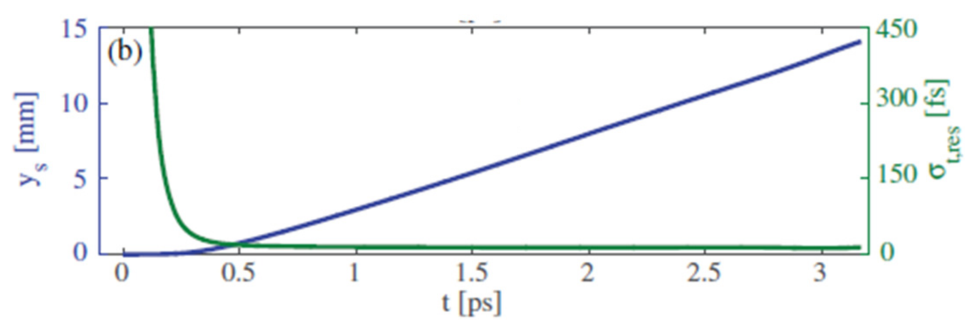


Calibration factor:

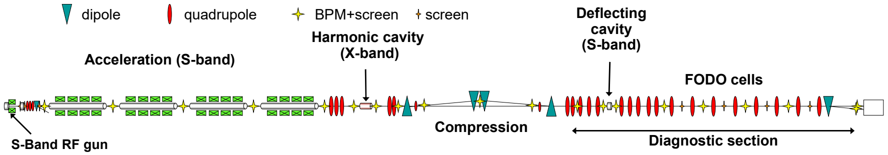
$$S = \frac{dy_s}{ds}$$

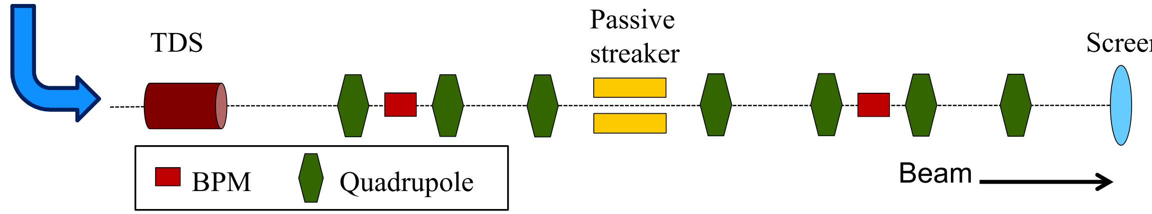
Resolution:

$$\sigma_{s,res} = \frac{\tilde{\rho}_{0,scr}}{S}$$



Experimental setup at SITF

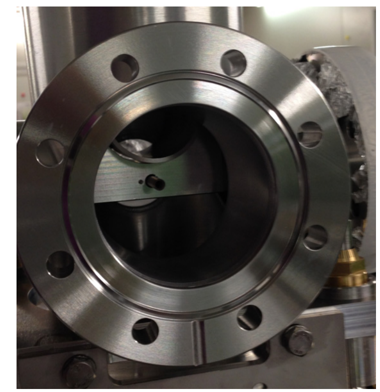




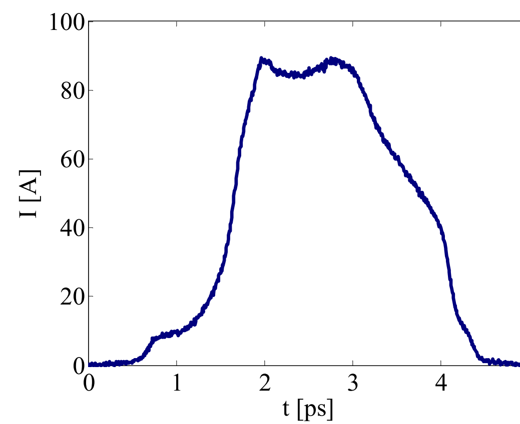
Energy	140 MeV
Charge	200 pC
Laser pulse length	2.7 ps rms
Bunch length	1 ps rms

Material	Alumina
Dielectric constant	10
Metallization	~20 um
Internal diameter	1.65 mm
External diameter	2.40 mm
Length	9.5 cm

- Streaker mounted on a vertical remotely movable support
- Metallization with Cu layer

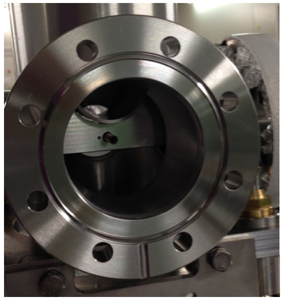


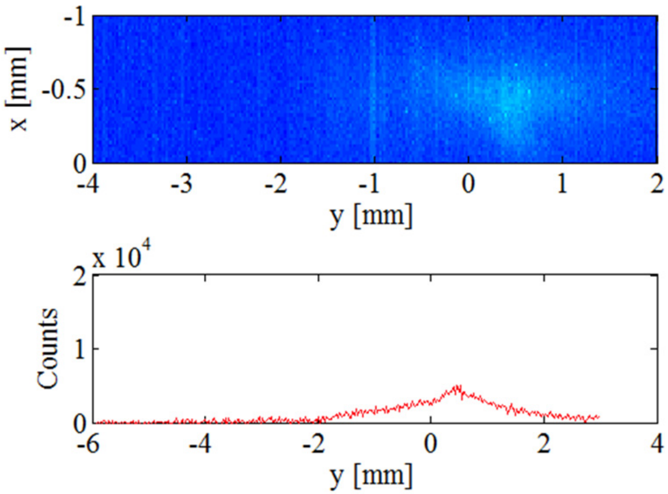
- Beam compressed to have a length compatible with a monotonic wakefield point charge
- Limited space for the streaker ($L_p = 9.5$ cm)
- Lowered the beam energy to enhance the effect ($y_s(s) \propto \frac{1}{E}$)
- Phase advance in the vertical plane between the streaker and the screen to maximize the resolution (270 deg)



Measurements at SITF

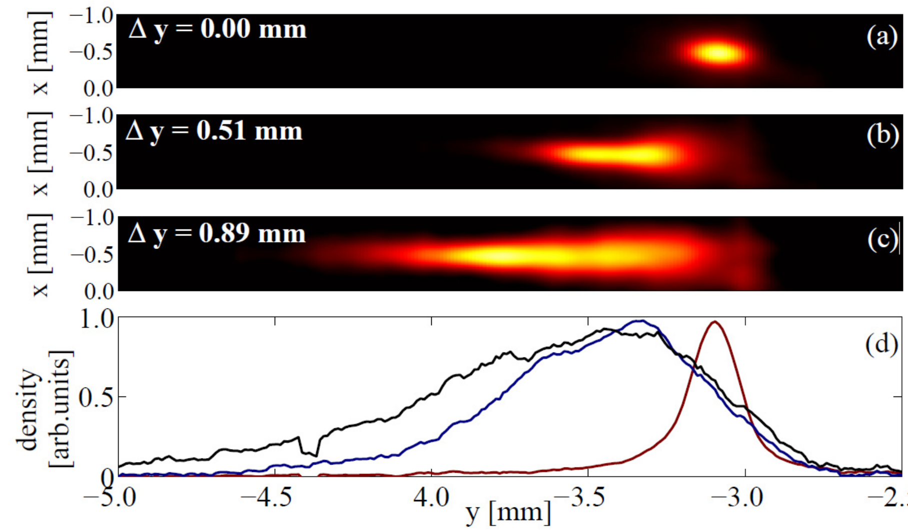
- Shifted the position of the tube
- Measured the centroid of the beam on a downstream screen
- Centroid kick calculated

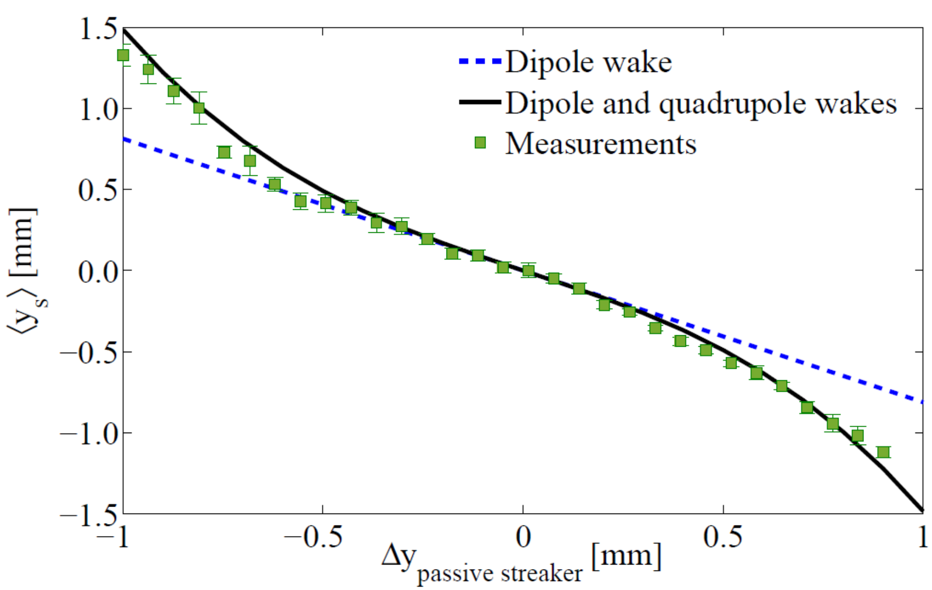




Measurements at SITF

- Shifted the position of the tube
- Measured the centroid of the beam on a downstream screen
- Centroid kick calculated





- The kick factor can be expressed as:

$$K = C_1 \Delta y + C_3 \Delta y^3$$

	Model	Measured
C_1 [MV/(nC·m·mm)]	0.62	0.63
C_3 [MV/(nC·m·mm^3)]	0.52	0.43

- Quadrupole effect not negligible for Δy>0.3 mm

Defocusing due to the quadrupole

- More important if the beam size is large compared to the aperture of the device or the beam is more off-centered
- The charge distribution at the screen used for the convolution, to include the defocusing effects for a transverse beam distribution at the streaker is given by the expression:

$$\mathrm{\rho_{screen}}(\mathrm{y_s}) = \int \rho_{screen}(\tilde{y}_s)\rho_\tau\left[\frac{\Delta y(y_s-\tilde{y}_s)}{y_{sq}(\tilde{y}_s)}\right]\frac{\Delta y}{y_{sq}(\tilde{y}_s)}d\tilde{y}_s$$

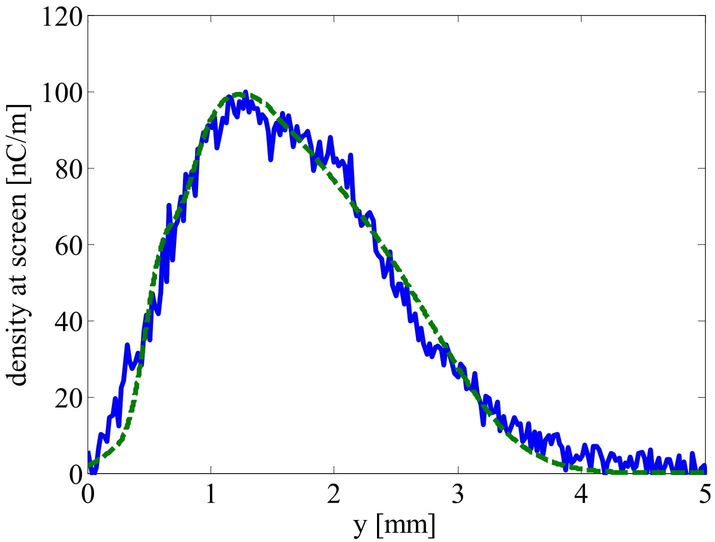
- y_{sq} is the transverse displacement of the beam at the screen due to the quadrupole wake only, for a particle at offset Δy at the passive streaker, and that is deflected to the coordinate y_s at the screen

Defocusing due to the quadrupole

- More important if the beam size is large compared to the aperture of the device or the beam is more off-centered
- The charge distribution at the screen used for the convolution, to include the defocusing effects for a transverse beam distribution at the streaker is given by the expression:

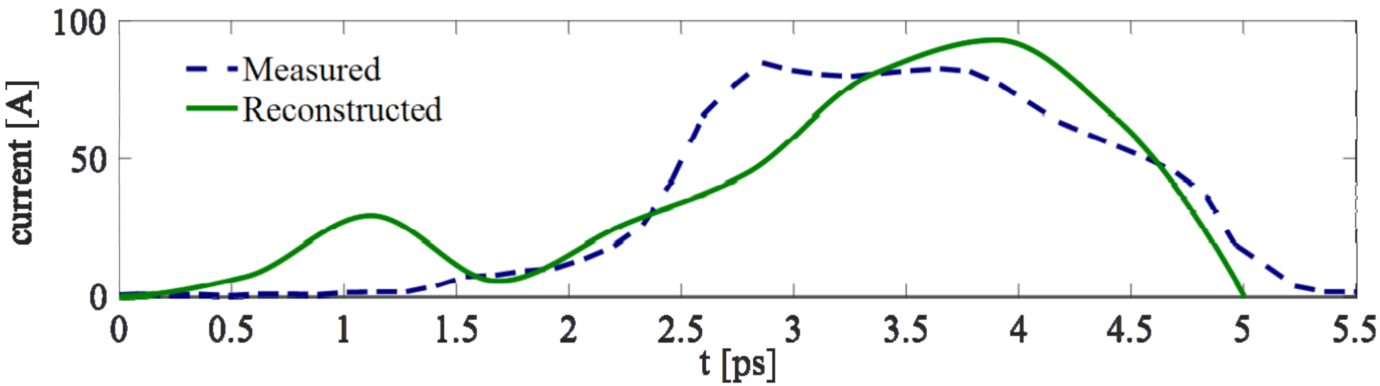
$$\rho_{screen}(y_s) = \int \rho_{screen}(\tilde{y}_s)\rho_\tau\left[\frac{\Delta y(y_s - \tilde{y}_s)}{y_{sq}(\tilde{y}_s)}\right]\frac{\Delta y}{y_{sq}(\tilde{y}_s)}\,d\tilde{y}_s$$

- y_{sq} is the transverse displacement of the beam at the screen due to the quadrupole wake only, for a particle at offset Δy at the passive streaker, and that is deflected to the coordinate y_s at the screen

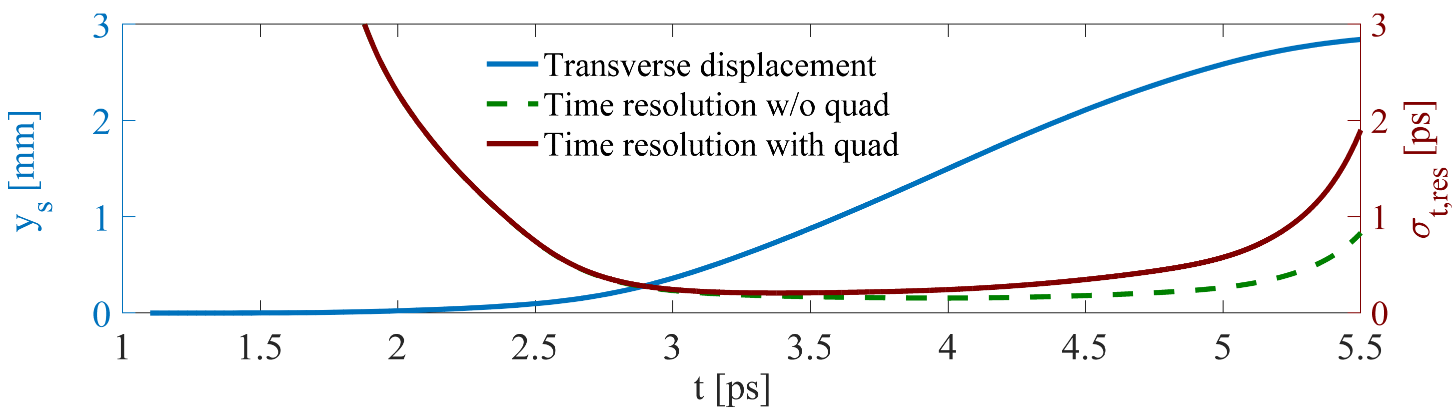


- Green: convolution with dipole and quadrupole wake functions, defocusing effect due to quad and finite emittance
- Blue: measured transverse profile at the screen

Experimental reconstruction

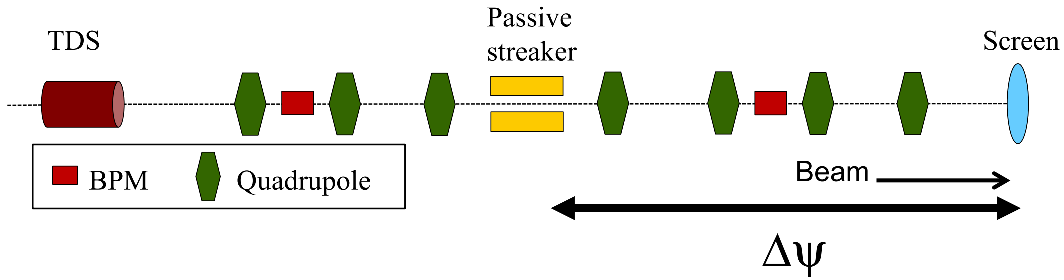


- The method demonstrated to be able to reconstruct the FWHM of the beam experimentally with a limited 9.5 cm length device (space limitations at SITF)

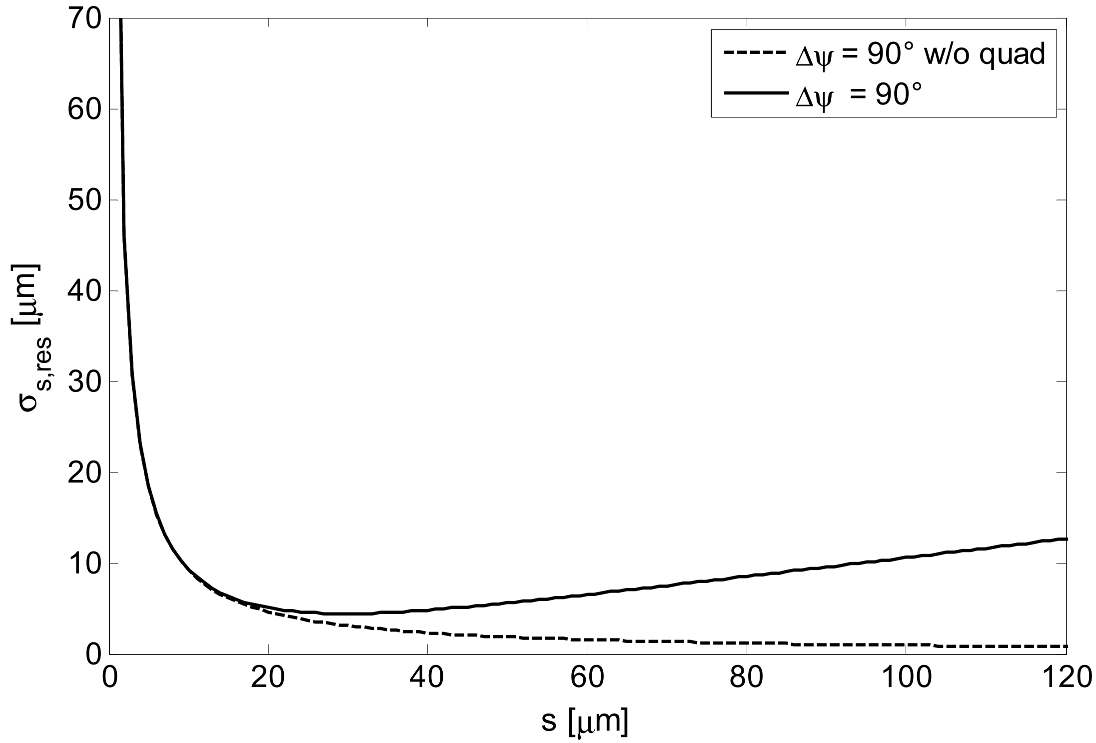


- The resolution of the method is determined by the wakefield source, and the beam size along the streaker:
  - is poor at the head of the beam (no streaking)
  - depends on the quadrupole effect going from the head towards the tail

Resolution optimization

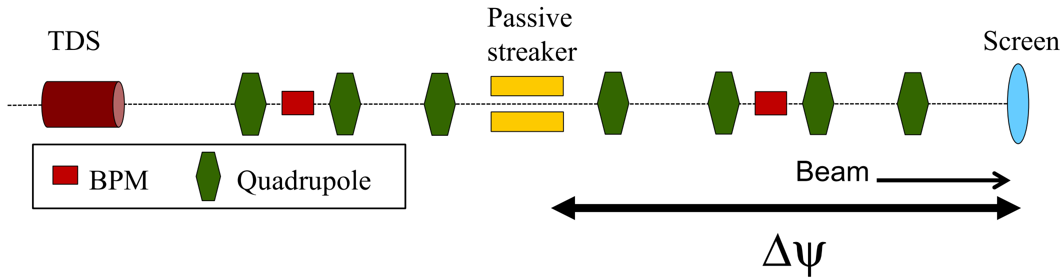


Scan of the phase advance between the passive streaker and the profile monitor may be an efficient way to optimize the resolution of the measurement

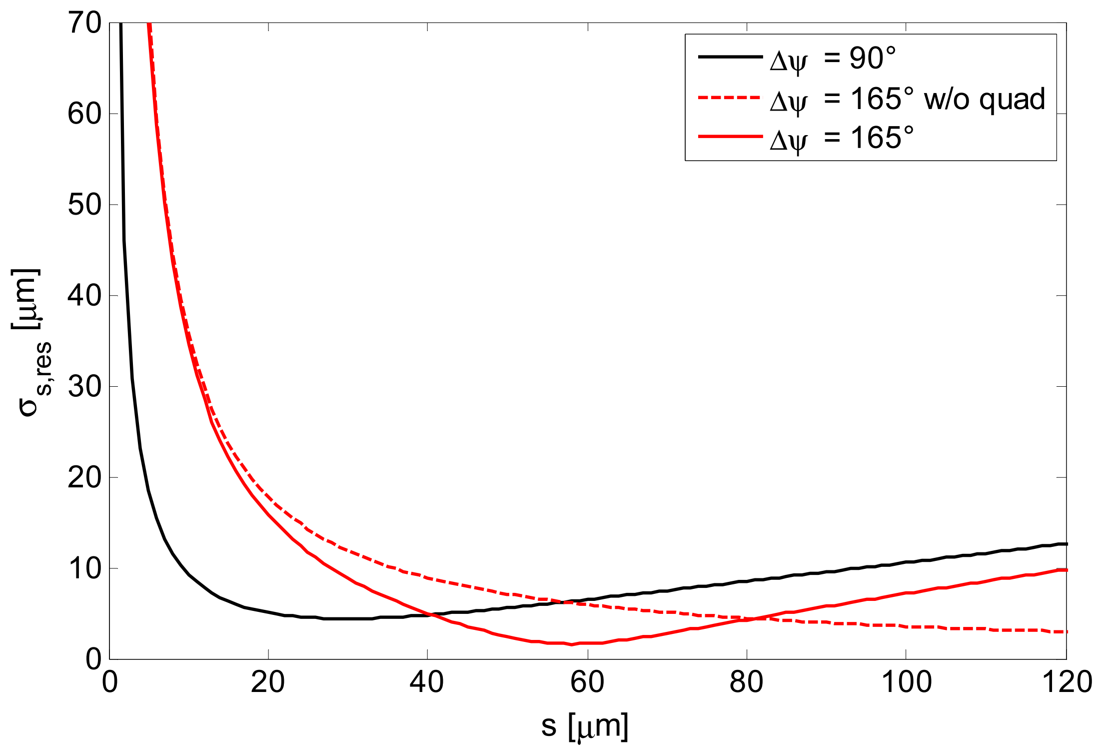


[Ref. 5] P. Craievich, A. A. Lutmann

Resolution optimization

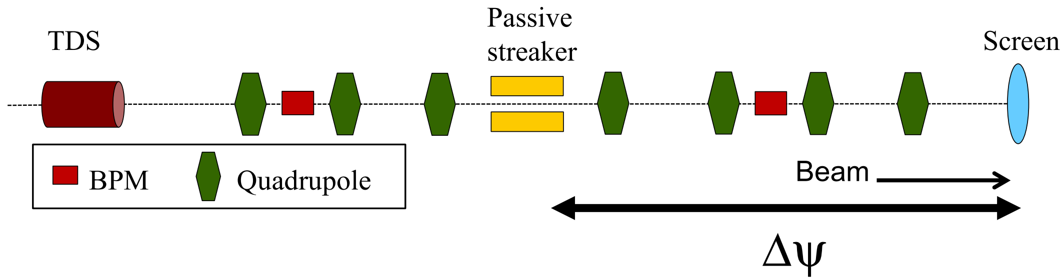


Scan of the phase advance between the passive streaker and the profile monitor may be an efficient way to optimize the resolution of the measurement

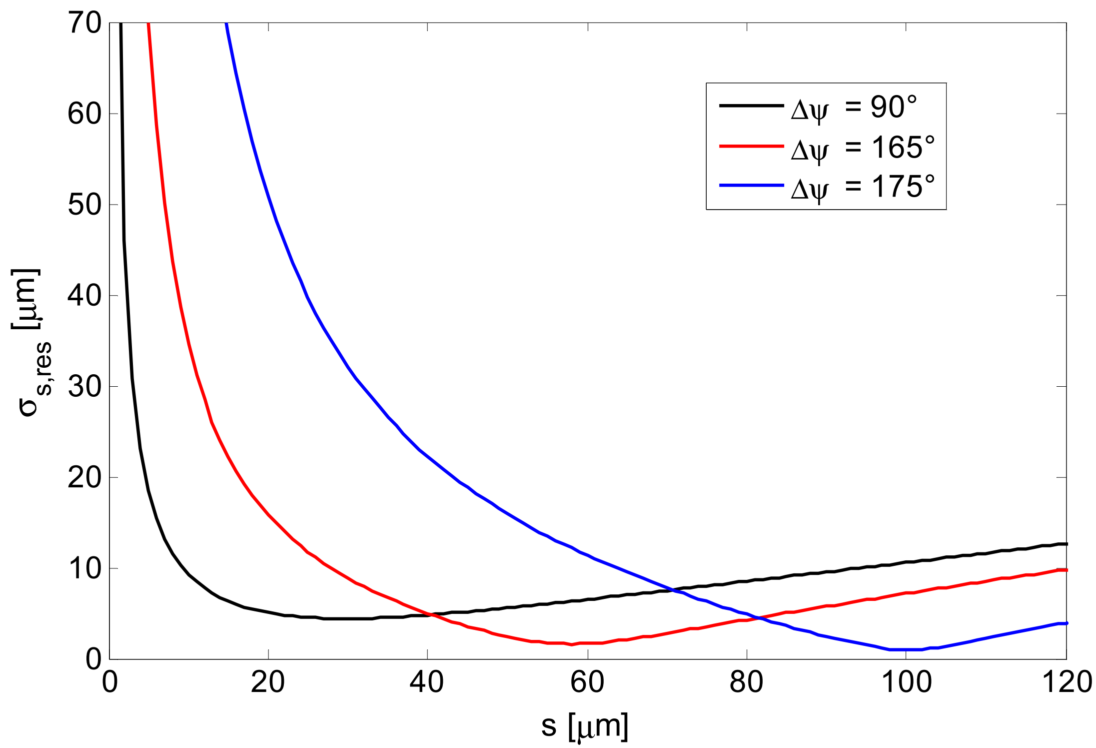


[Ref. 5] P. Craievich, A. A. Lutmann

Resolution optimization

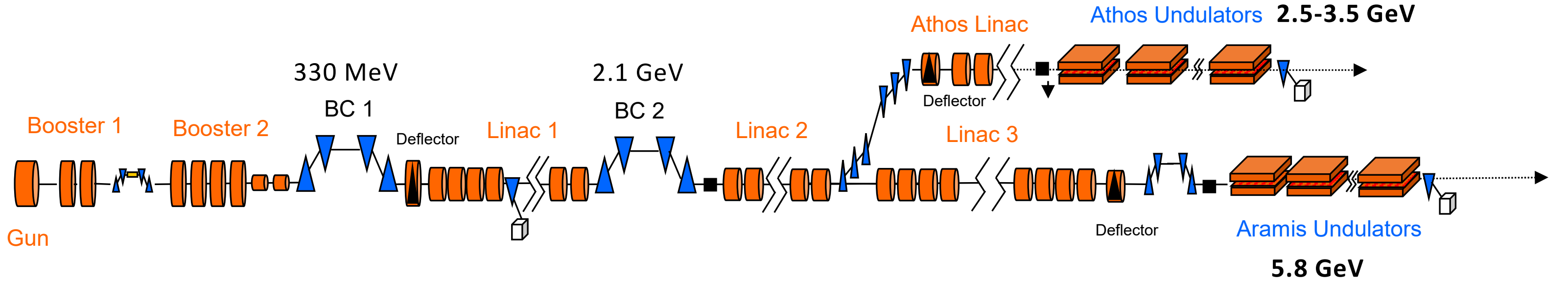


Scan of the phase advance between the passive streaker and the profile monitor may be an efficient way to optimize the resolution of the measurement

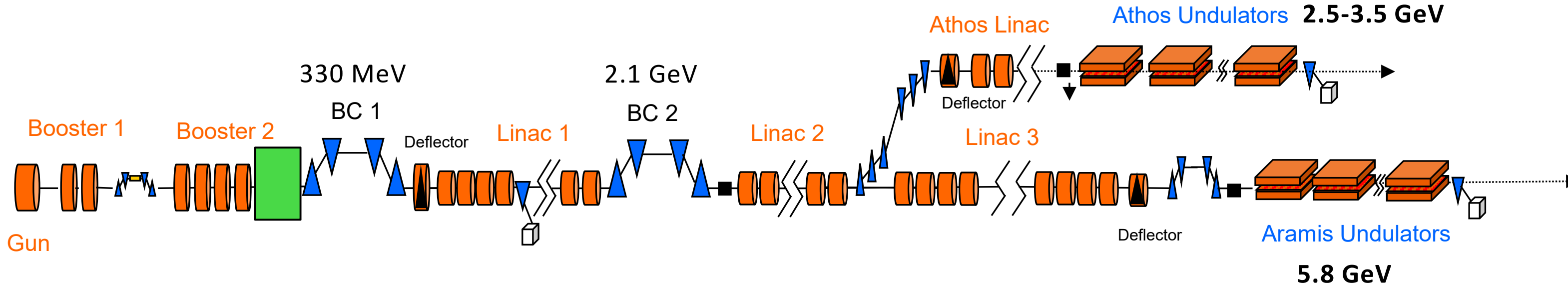


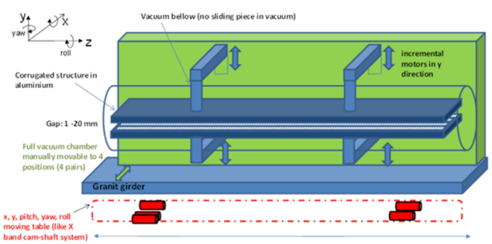
[Ref. 5] P. Craievich, A. A. Lutmann

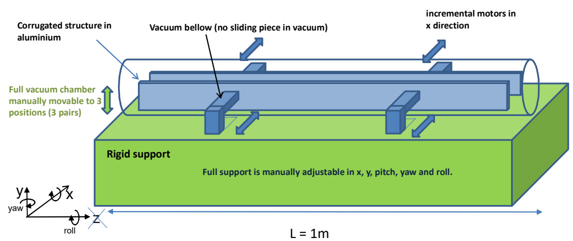
Next steps at SwissFEL: beam manipulation

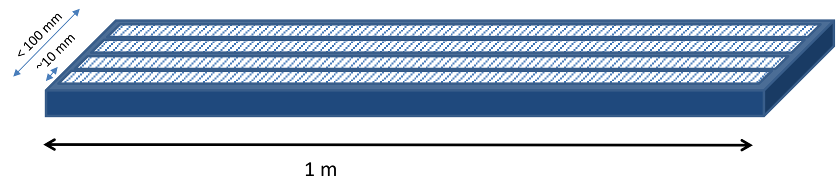


Next steps at SwissFEL: beam manipulation







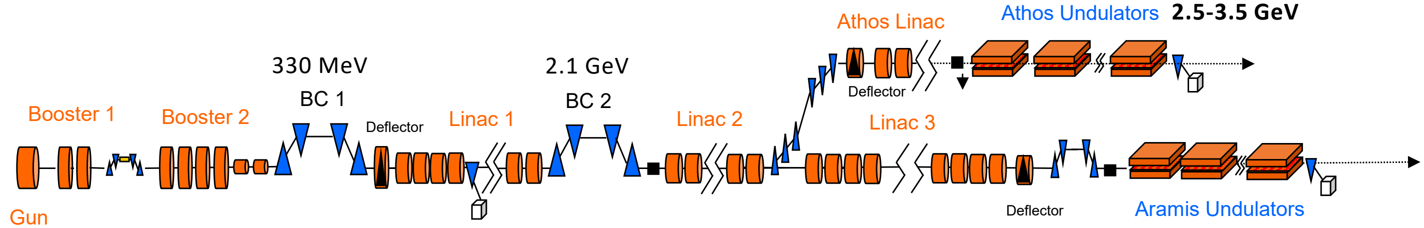


- Installation of two passive structures 1 m length each upstream of BC1 to:
  - Measure the wakefield in view of the dechirper installation for Athos: λ ~ 2 mm
  - Alternatively linearize (following idea in [Ref. 6]): λ ~ 6 mm
  - Test the two-color generation via wakefield excitation [Ref. 7]: λ ~ 1 mm

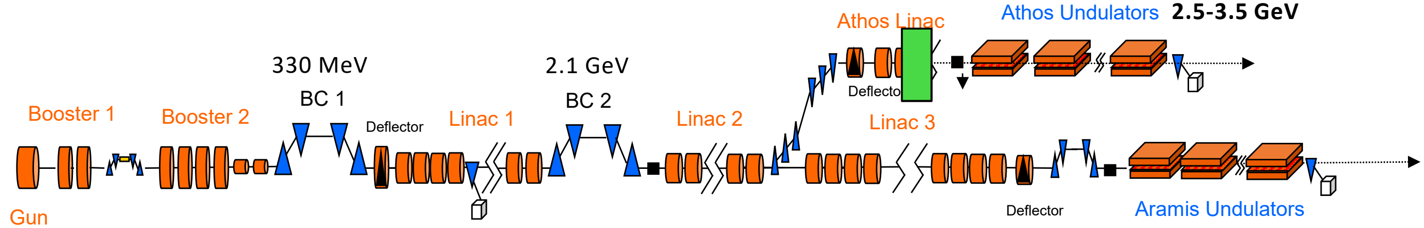
Continue the streaking and reconstruction experience with a longer device with corrugated surface, equivalent to the dielectric line waveguide in terms of beam dynamics

[Ref. 6] P. Craievich, [Ref. 7] S. Bettoni et al.

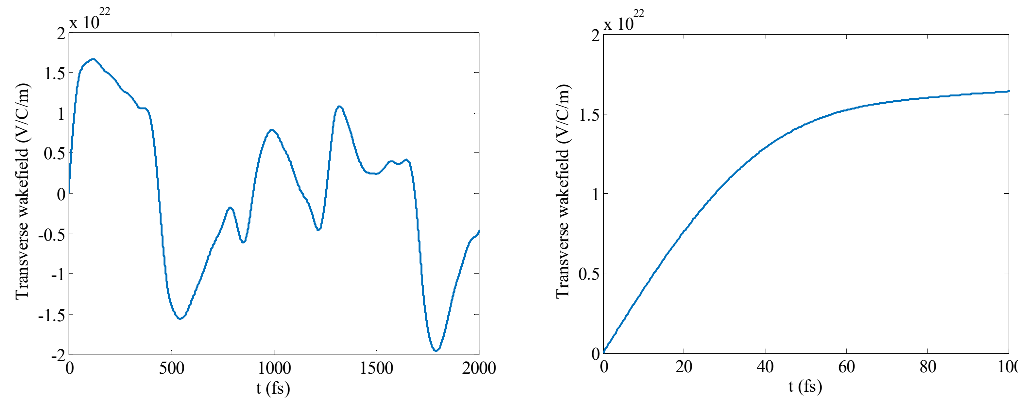
Next steps at SwissFEL: high energy activity

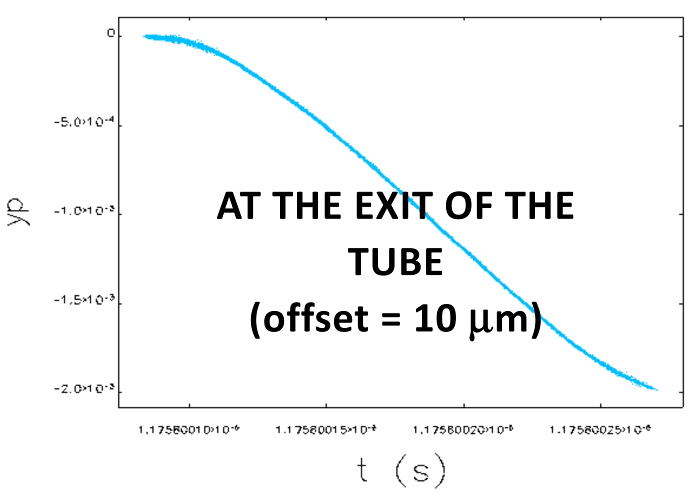


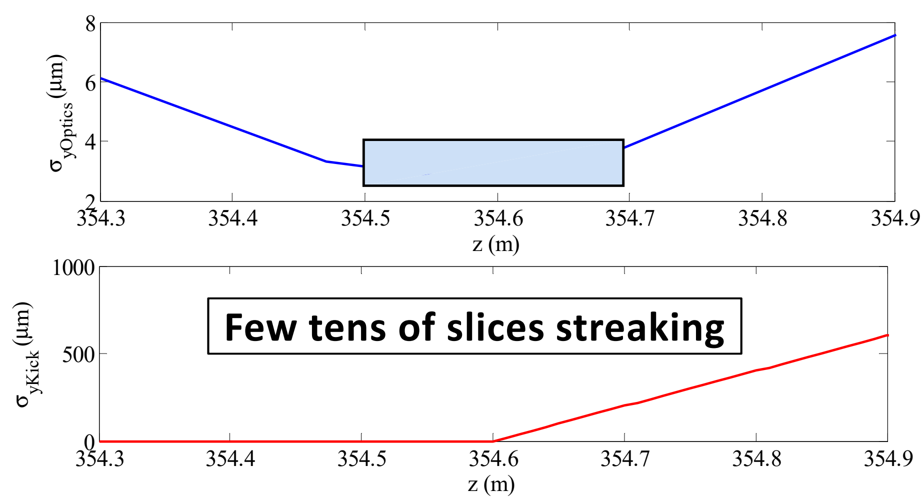
Next steps at SwissFEL: high energy activity



Material	Fused silica
Dielectric constant	4.8
Internal diameter	160 µm
External diameter	200 µm
Length	20 cm
Beam Q	200 pC
Beam energy	3 GeV
Bunch length	80 fs FWHM



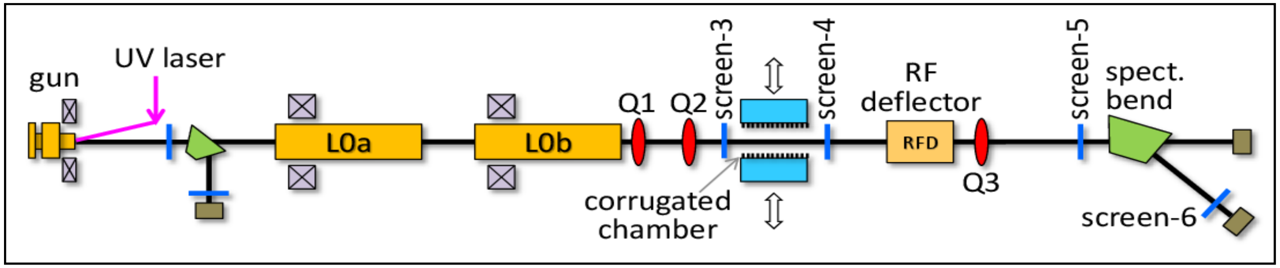




Passive streaking at PAL

A longitudinal phase space measurement by corrugated structure

[Ref. 8] J. Hong, C. H. Kim, H.-S. Kang



e^- beam:

$E = 85$ MeV

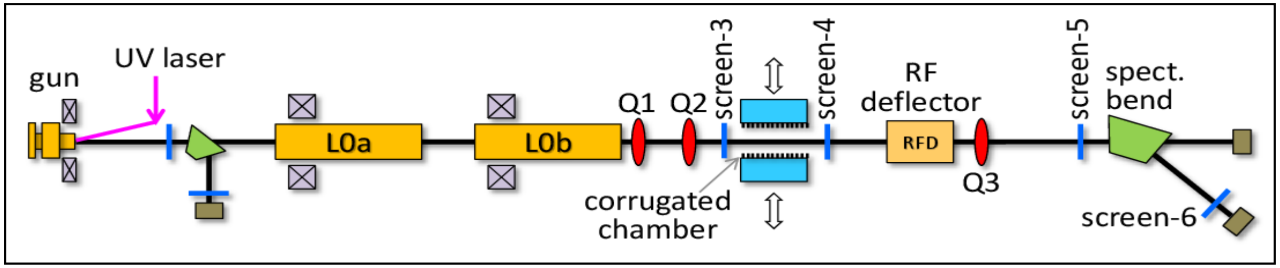
$\sigma_z = 0.45$ mm

$Q = 200$ pC

Passive streaking at PAL

A longitudinal phase space measurement by corrugated structure

[Ref. 8] J. Hong, C. H. Kim, H.-S. Kang



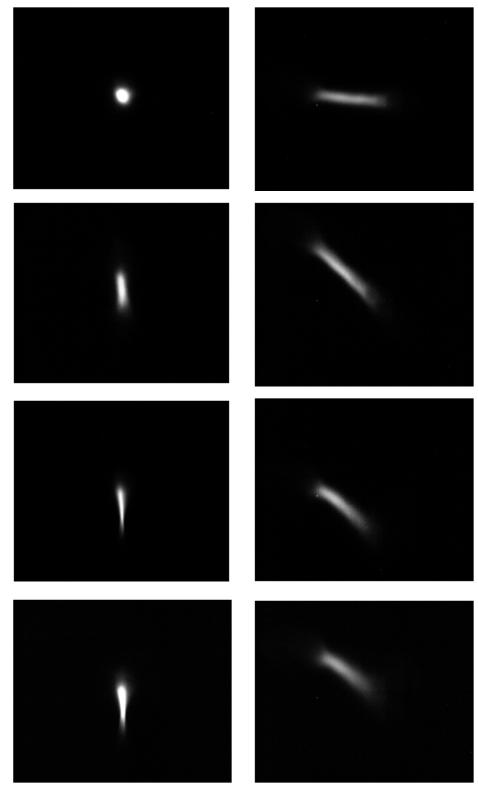
e^- beam:

$E = 85$ MeV

$\sigma_z = 0.45$ mm

$Q = 200$ pC

screen-5 screen-6



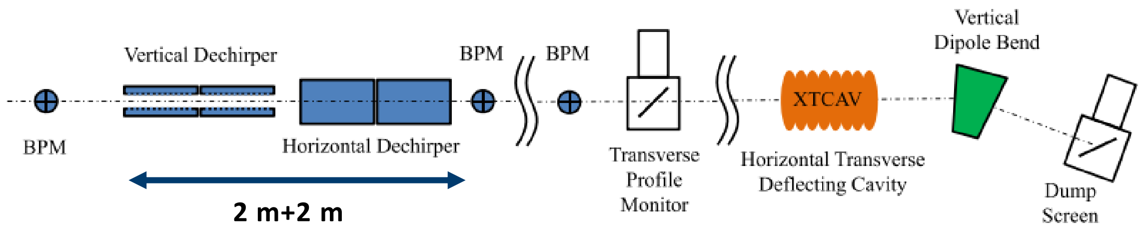
Dechirper gap 28 mm (OUT), deflector OFF

Dechirper OUT, deflector ON

Dechirper gap 8 mm, offset 2 mm, deflector OFF

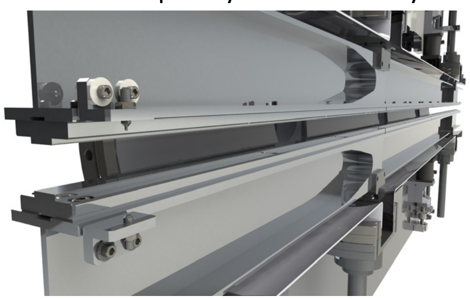
Dechirper gap 6 mm, offset 1 mm, deflector OFF

Passive streaking at LCLS



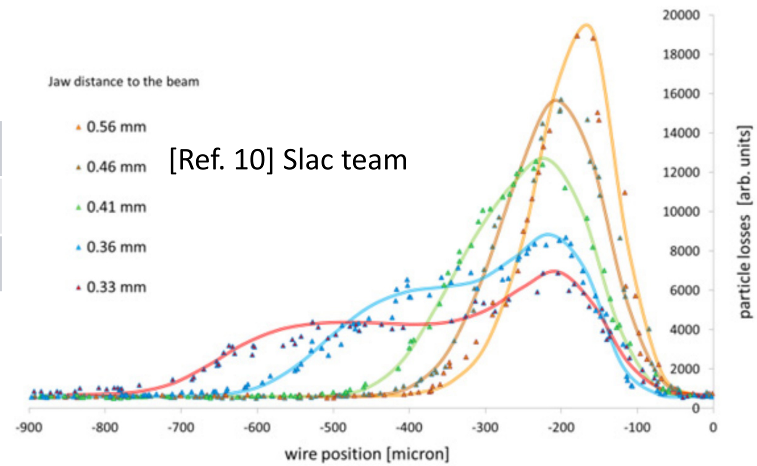
Measurement

LCLS Dechirper by RadiaBeam System



[Ref. 9] K. Bane, G. Stupakov

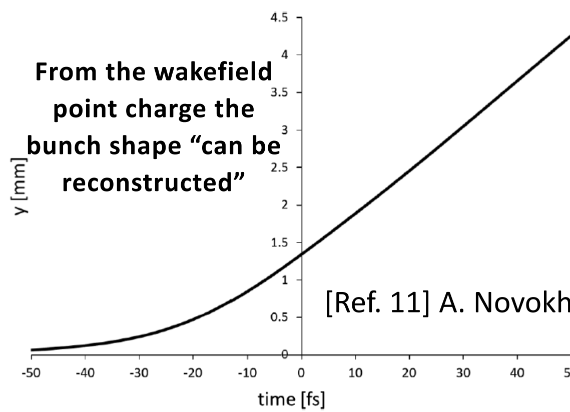
E	13.3 GeV
σ_t	50 fs (FWHM)
Q	185 pC



[Ref. 10] Slac team

Simulation

E	4 GeV
σ_t	10 fs (rms)
Q	100 pC
Gap	3 mm
offset	1 mm

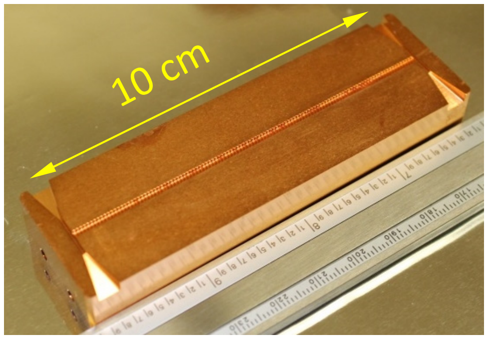


[Ref. 11] A. Novokhatski et al.

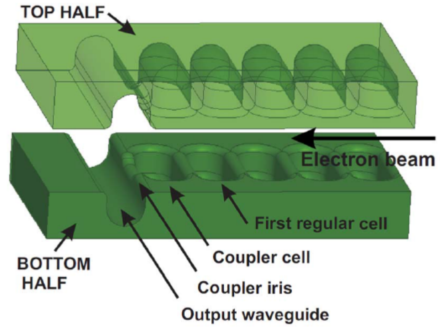
$$\sigma_{t,res}(s) \approx 1fs$$

SLAC/FACET E204 experiments

Accelerating structure at 100 GHz

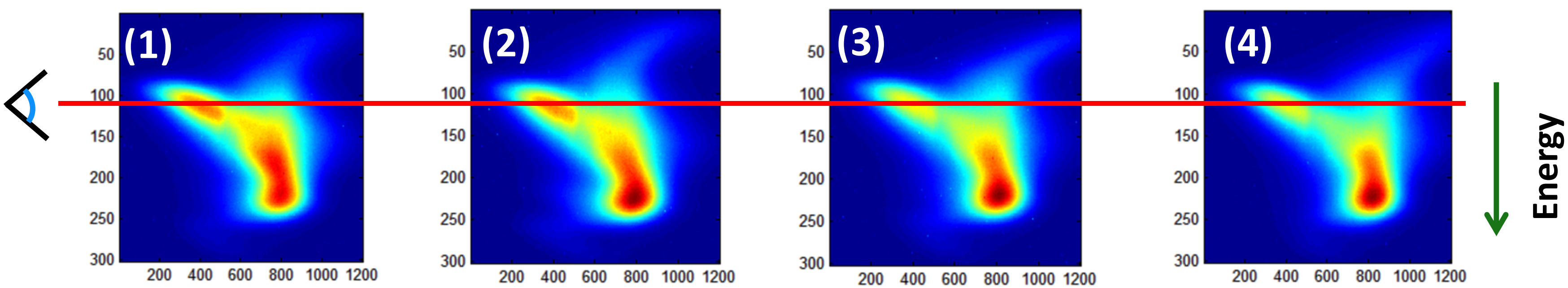


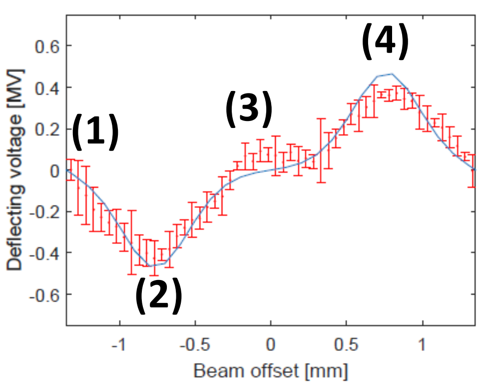
[Ref. 12] M. Dal Forno et al.

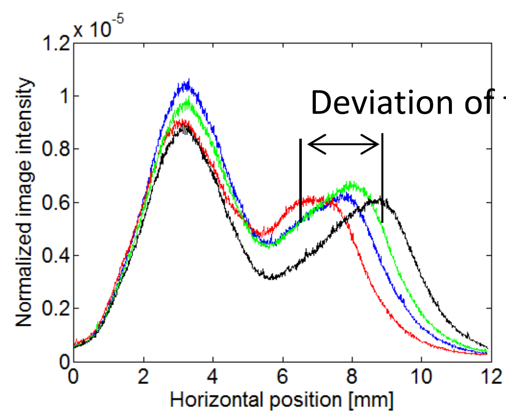


Beam parameters at FACET

- beam energy E = 20.35 GeV
- bunch charge q = 3.2 nC
- bunch length σ_z = 50 µm

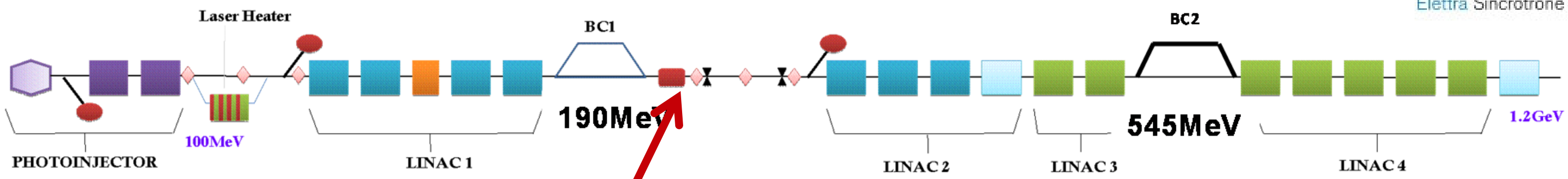


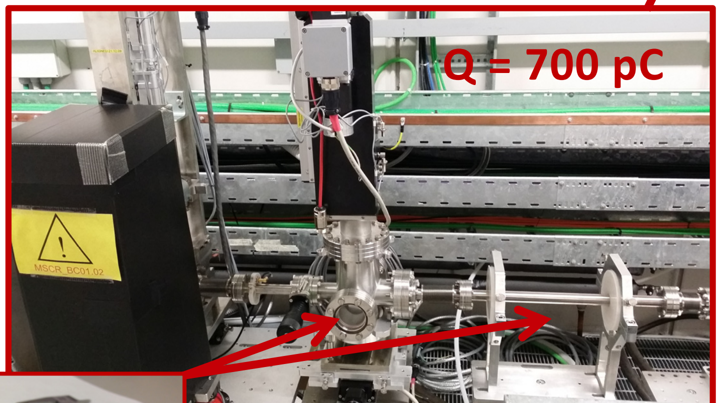


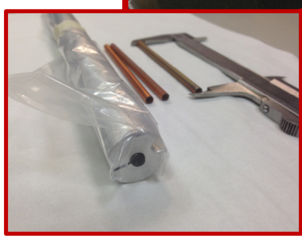


Deviation of the tail is ~±0.8 mm

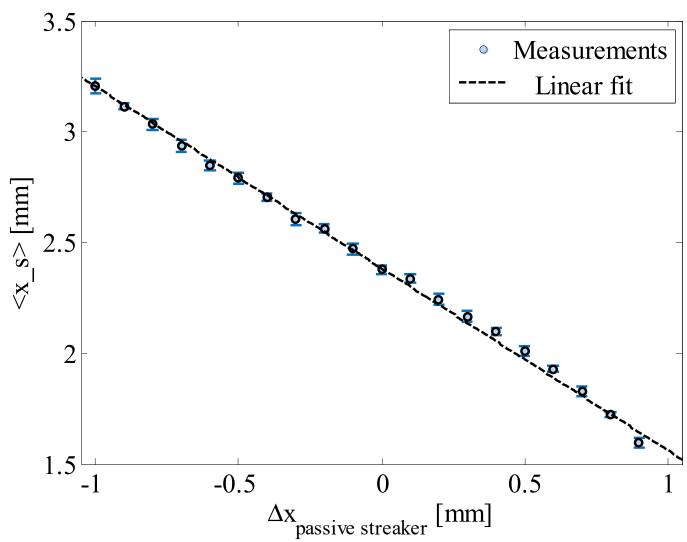
FERMI experiment







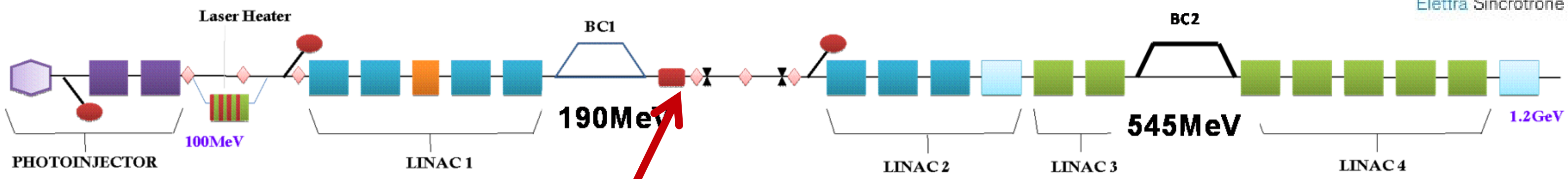
- SITF passive streaker and chamber shipped to Fermi for an experiment of beam manipulation carried on by Fermi team
- Fermi team built a second dedicated system to install 3 more passive streaker

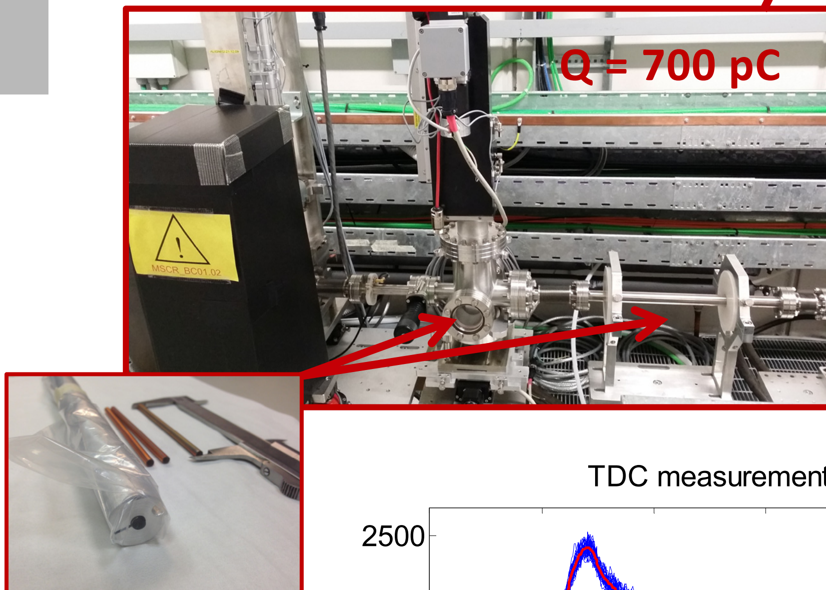


- Small transverse beam size along the tube (σ_x,σ_y<150 μm)
- No quadrupole component observed

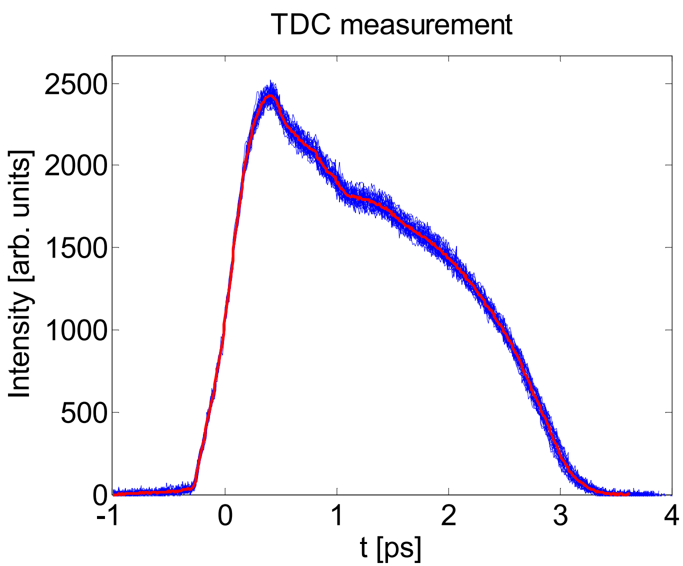
G. Penco, P. Craievich,
S. Bettoni, E. Ferrari, E. Roussel

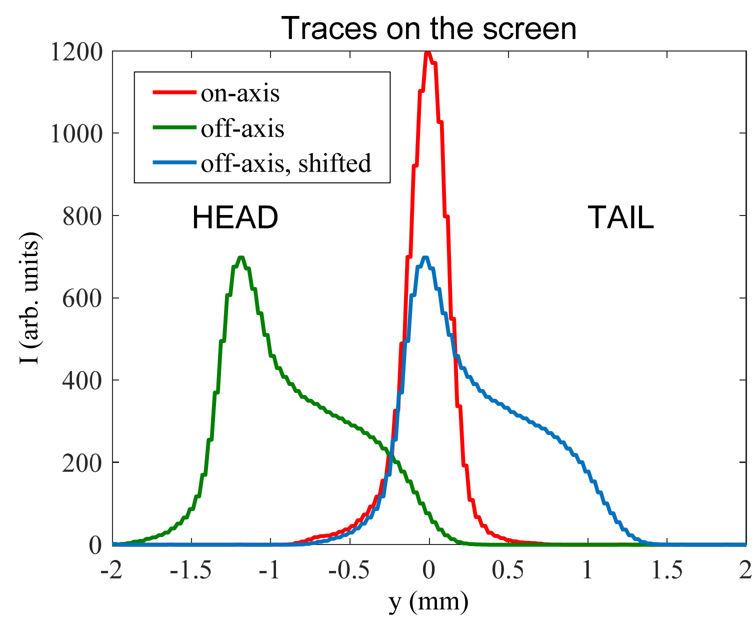
FERMI experiment





- SITF passive streaker and chamber shipped to Fermi for an experiment of beam manipulation carried on by Fermi team
- Fermi team built a second dedicated system to install 3 more passive streaker



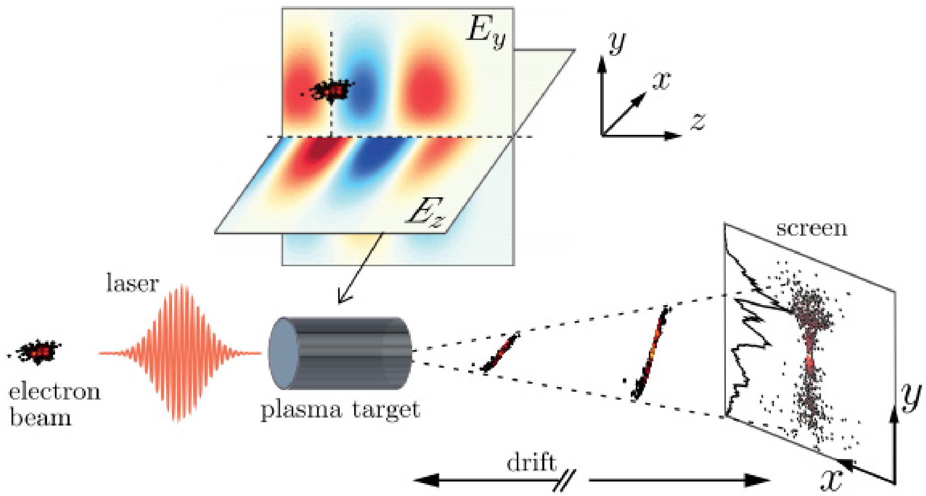


G. Penco, P. Craievich,
S. Bettoni, E. Ferrari, E. Roussel

Plasma-driven bunch diagnostics

A short-pulse laser drives a linear wakefield in a plasma target. The electron bunch is situated off-axis at the transverse maximum and longitudinal zero-crossing of the transverse fields

[Ref. 13] I. Dornmair et al.



Q	0.5 pC
σ_z	7.5 fs (rms)
E	110 MeV
σ_{TRANSV}	17 um

- Simulated resolution ~0.1 fs in the core of the beam
- Second order dependence of the electric field on the transverse coordinate degrade the resolution at the head and tail

- Plasma generation complex
- High power laser
- Synchronization with the beam

Conclusions

- A *passive streaker* based on the self-transverse-wakefield can be used to effectively streak the electron beam
- An algorithm to reconstruct the electron bunch longitudinal profile has been proposed and verified with simulations
- A proof-of-principle experiment was performed at SITF
- More activities are undergoing in several laboratories
- Passive streaking presents pros and cons compared to a standard RF deflectors:

Pros:

- ✓ Single shot measurement
- ✓ Self-synchronized with the beam
- ✓ Cheaper to manufacture and operated (passive) compared to other existing devices
- ✓ Potentially fs or sub-fs resolutions achievable

Cons:

- Necessary to know beam energy, charge and optics
- Temporal resolution is not constant along the beam
- If relation between beam at the device and beam at the screen is non-linear, inversion requires more complicated computation

More details in PR AB 19, 021304 (2016)

References

[1] C. Behrens et al., Nature Communications, DOI: 10.1038/ncomms4762.

[2] D. Ratner et al., Phys. Rev. ST Accel. Beams 18, 030704 (2015).

[w3] S. Antipov, et al., Phys. Rev. Lett. 112, 114801 (2014).

[w2] P. Emma, et al., Phys. Rev. Lett. 112, 034801 (2014).

[w5] S. Antipov, et al., Phys. Rev. Lett. 108, 144801 (2012).

[3] King-Yuen Ng, "Wake fields in a dielectric-lined waveguide",Phys. Rev. D, Vol 42 Issue 5 (1990).

[4] M. Borland, Advanced Photon Source LS-287, (2000).

[5] P. Craievich, A. A. Lutmann, NIM-A (accepted), (2016).

[6] P. Craievich, Phys. Rev. ST Accel. Beams 13, 034401 (2010).

[7] S. Bettoni, E. Prat, S. Reiche, Phys. Rev. ST Accel. Beams 19, 050702 (2016).

[8] J. Hong, C. H. Kim, H.-S. Kang, PAL, Pohang. To be published.

[9] K. Bane and G. Stupakov, NIM A 690, 106 (2012).

[10] M. Guetg et al., private communication.

[11] A. Novokhatski, PRST AB 18, 104402 (2015).

[12] M. Dal Forno et.al, PR AB 19, 011301 (2016).

[13] I. Dornmair, C. B. Schoeder, K. Floettmann, B. Marchetti. A. R. Maier, PR-AB, 19, 062801 (2016).

Conclusions

- A *passive streaker* based on the self-transverse-wakefield can be used to effectively streak the electron beam
- An algorithm to reconstruct the electron bunch longitudinal profile has been proposed and verified with simulations
- A proof-of-principle experiment was performed at SITF
- More activities are undergoing in several laboratories
- Passive streaking presents pros and cons compared to a standard RF deflectors:

Pros:

- ✓ Single shot measurement
- ✓ Self-synchronized with the beam
- ✓ Cheaper to manufacture and operated (passive) compared to other existing devices
- ✓ Potentially fs or sub-fs resolutions achievable

Cons:

- Necessary to know beam energy, charge and optics
- Temporal resolution is not constant along the beam
- If relation between beam at the device and beam at the screen is non-linear, inversion requires more complicated computation

More details in PR AB 19, 021304 (2016)