PAUL SCHERRER INSTITUT

PSI

Paolo Craievich - Paul Scherrer Institut

Beam manipulations in FEL linacs using self-induced fields

International ICFA mini-Workshop on NOn linear dynamics and Collective Effects in particle beam physics, Arcidosso, Italy, 19-22 September 2017

Outline

- **Dechirping**

  → brief history of passive structures as a dechirper

- **Streaking as a diagnostic tool**

  → experiment at SITF

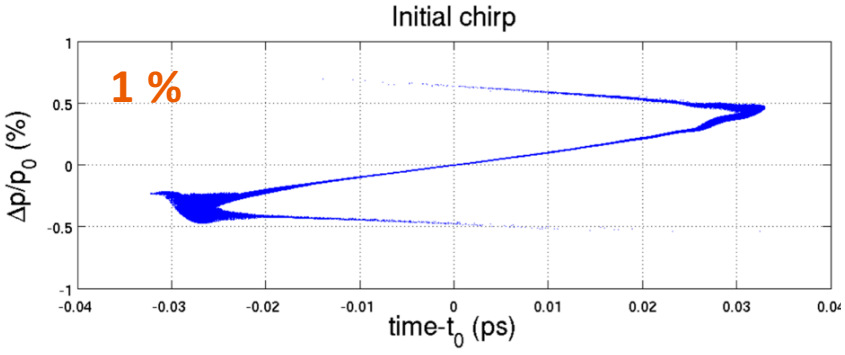
- **Linearization of the compression process**

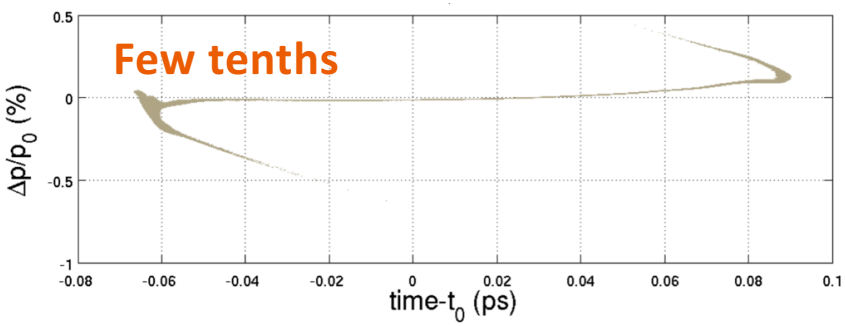
  → experiment at FERMI

- **Activities at SwissFEL**

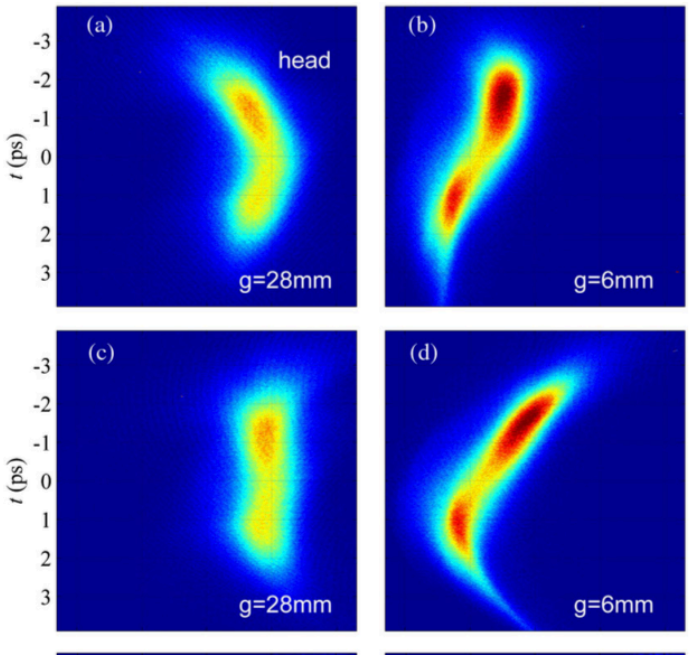
Brief history of passive structures as a Dechirper

Motivation:



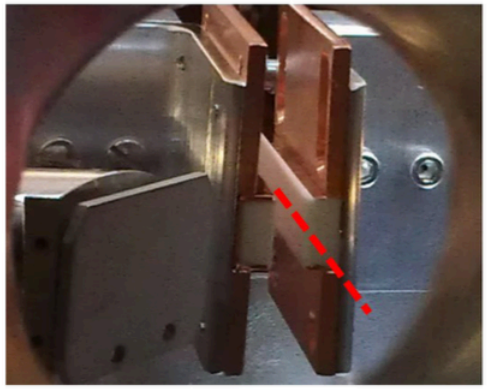


- **Theoretical study for corrugated structure with flat geometry** by K. Bane and G. Stupakov
  - Impedance of a rectangular beam tube with small corrugations, PRAB ST 6, 024401 (2003)
  - Corrugated pipe as a beam dechirper, NIM A, 690, (2012)
  - Dechirper wakefields for short bunches, NIM A, 820, (2016).
- **Simulation codes, i.e. ECHO by I. Zagorodnov**
- **Test with beam at ITF,** PAL on 5-10 August 2013. - P. Emma et al. PRL 112, 034801 (2014)

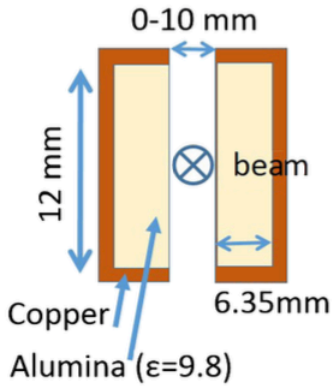


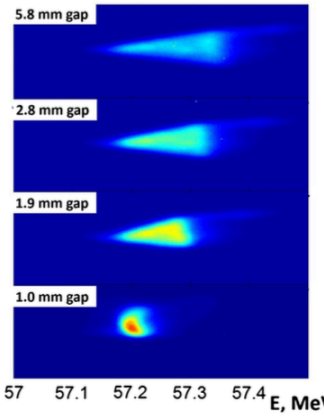
Brief history of passive structures as a Dechirper

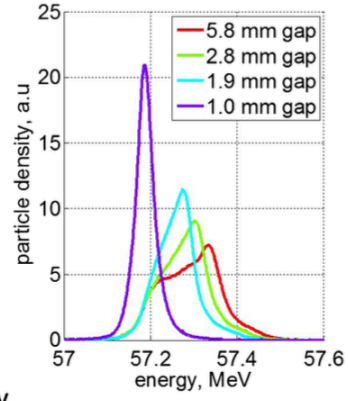
- S. Antipov et al., *Experimental Demonstration of Energy-Chirp Compensation by a Tunable Dielectric-Based Structure*, PRL 112, 114801 (2014)



Experiment in ATF at BNC

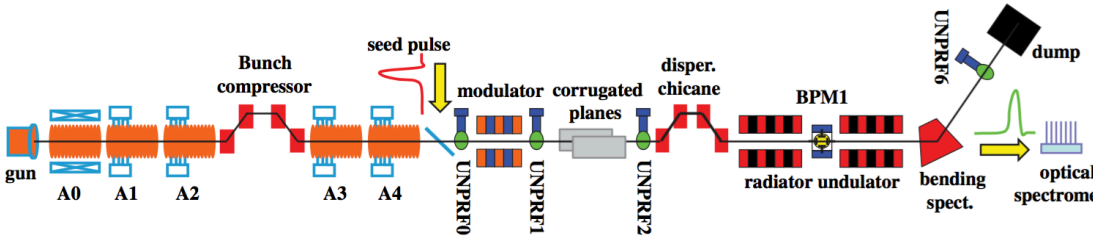


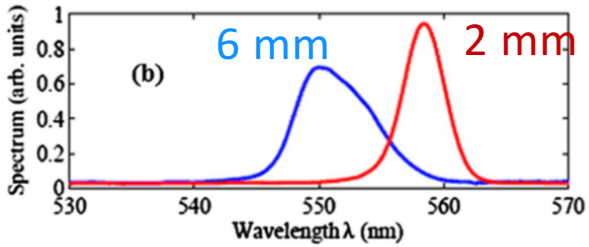




- H. Deng et al., *Experimental Demonstration of Longitudinal Beam Phase-Space Linearizer in a Free-Electron Laser Facility by Corrugated Structures,* PRL 113, 254802 (2014)

FEL (SDUV-FEL) facility in Shanghai

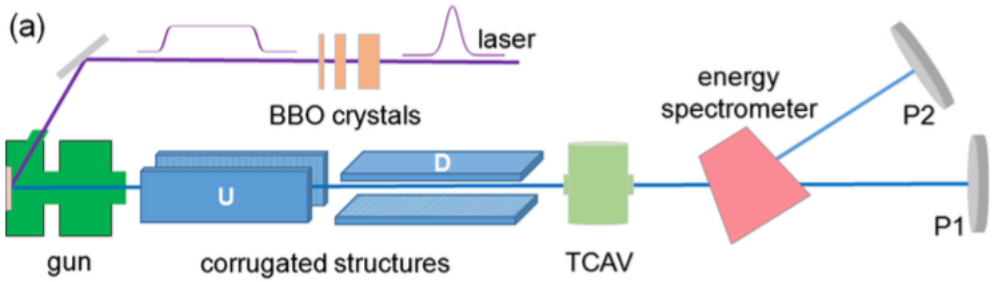


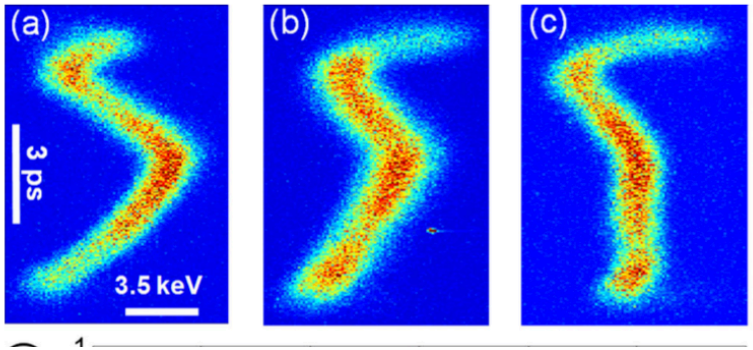


Brief history of passive structures as a Dechirper

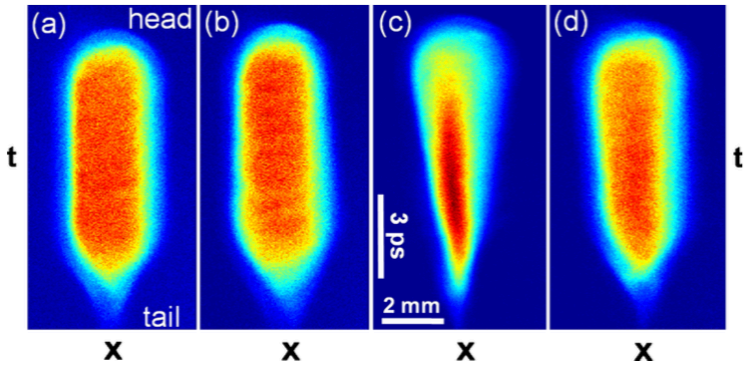
- F. Fu et al., *Demonstration of Nonlinear-Energy-Spread Compensation in Relativist Electron Bunches with Corrugated Structures,* PRL 114, 114801 (2015),

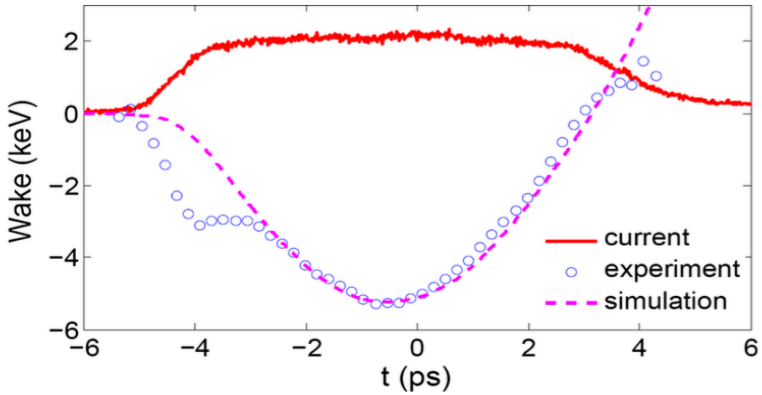
Center for Ultrafast Diffraction and Microscopy at Shanghai Jiao Tong University



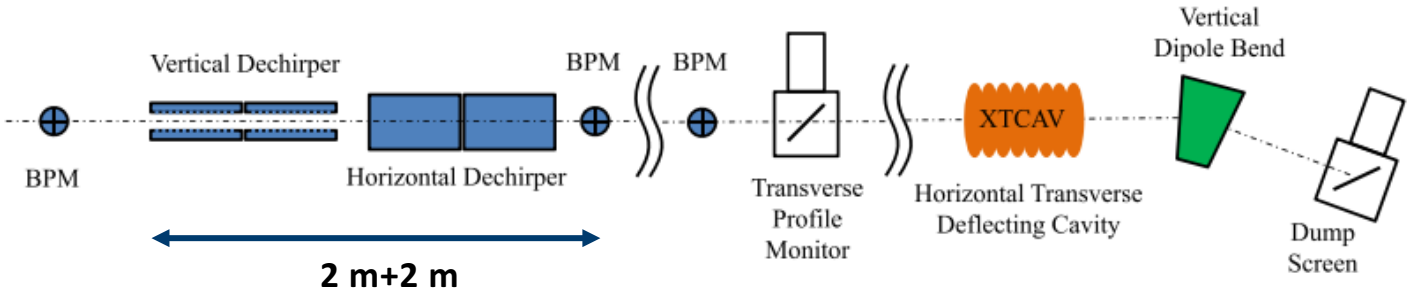


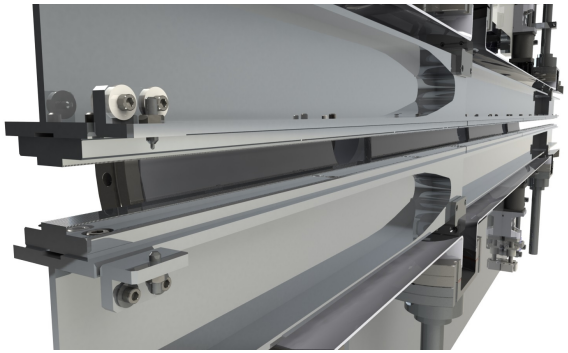
- C. Lu, *Time-resolved measurement of quadrupole wakefields in corrugated structures*, PR AB 19, 020706 (2016)





Dechirper at LCLS





Ref. Z. Zhang, PRST AB 18, 010702 (2015)

LCLS Dechirper by RadiaBeam System

Two talks in this session:

- **Dechirpers design and experimental results, Tim Maxwell**
- **Fresh-slice x-ray FEL schemes for advanced x-ray applications, Alberto Lutman (SLAC) [to be presented by Tim Maxwell]**

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- **Streaking as a diagnostic tool**

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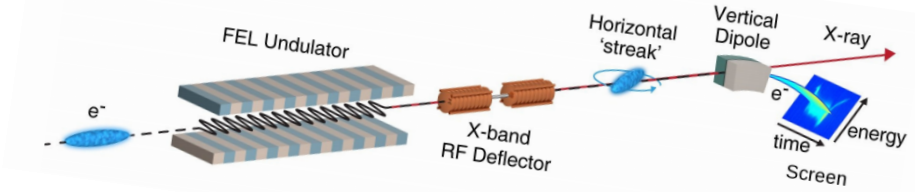
- Linearization of the compression process

  → experiment at FERMI

- Activities at SwissFEL

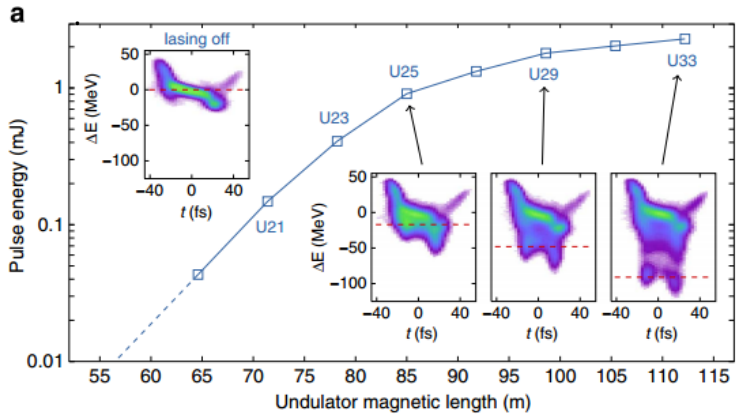
Longitudinal beam profile diagnostics

X-band transverse cavity very valuable instrument to:



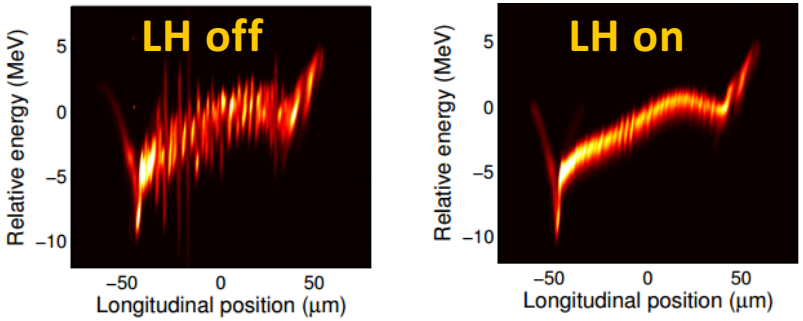
- Optimize the lasing along the bunch

  Behrens et al., Nature Communications, DOI: 10.1038/ncomms4762.



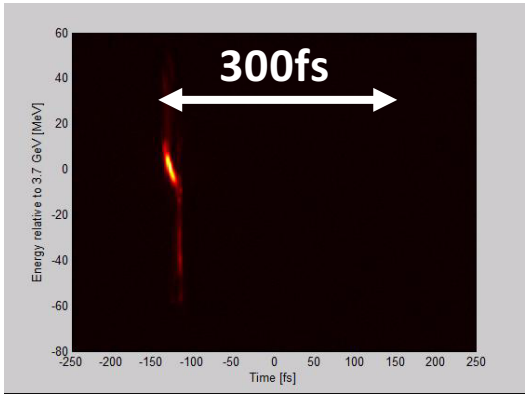
- Directly observe the microbunching instability and its mitigation

  D. Ratner et al., PRST AB 18, 030704 (2015).



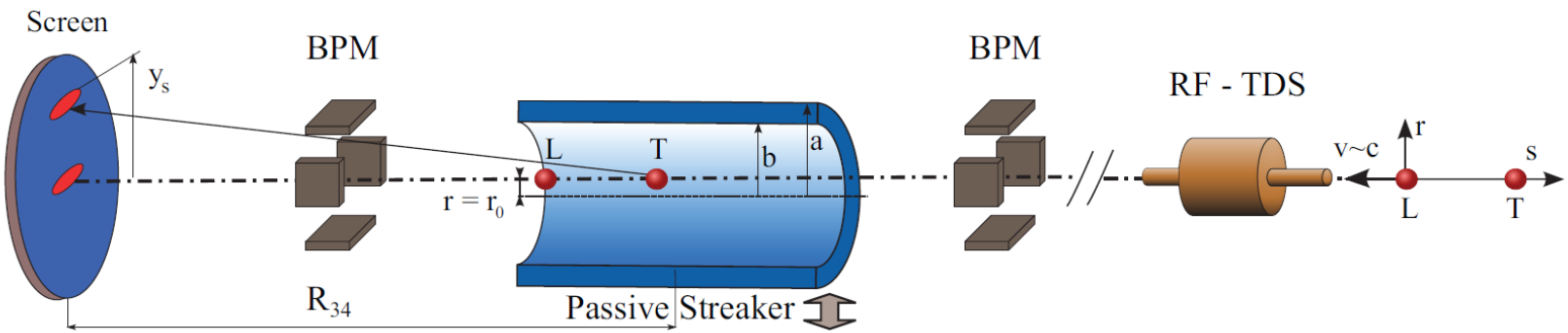
BUT:

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



Courtesy of A. Lutman

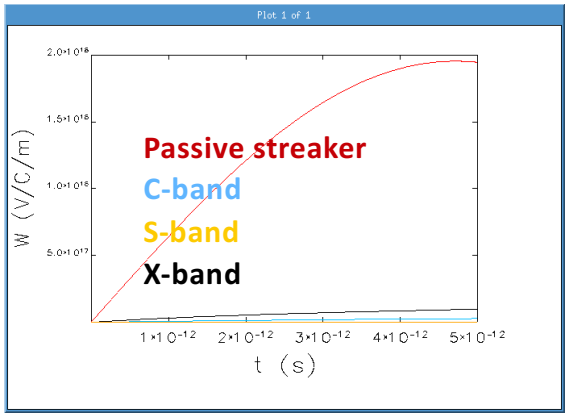
Working principle



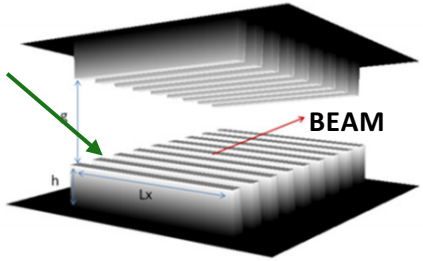
- The method to time-resolve the longitudinal profile is based on the self-transverse-wakefield generation
- A correlation between temporal position of the particle along the bunch and transverse position at a downstream screen is introduced
- The beam passes off-axis through a structure capable of generating a strong monotonic transverse wakefield along the full bunch length
- Potentially sub-fs resolutions achievable

Suitable wakefield sources

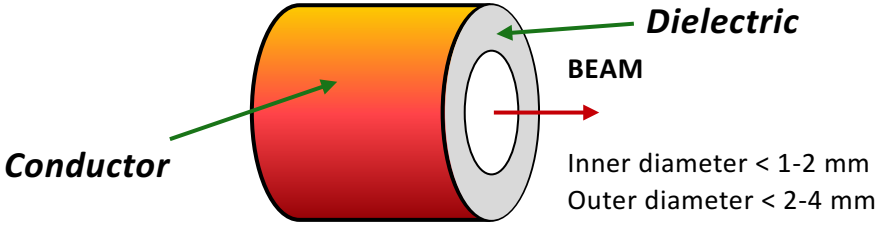
- Several sources can be used to do such a measurements. The requirements are:
  - Wake potential a monotone function along the full bunch length
  - Amplitude of the wakefield enough to limit the length of the device to a reasonable value



CORRUGATED



DIELECTRIC LINED-WAVEGUIDE



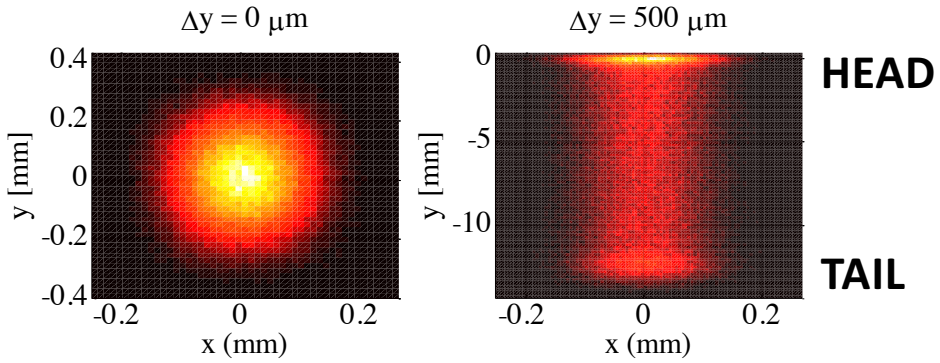
More typically corrugated

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

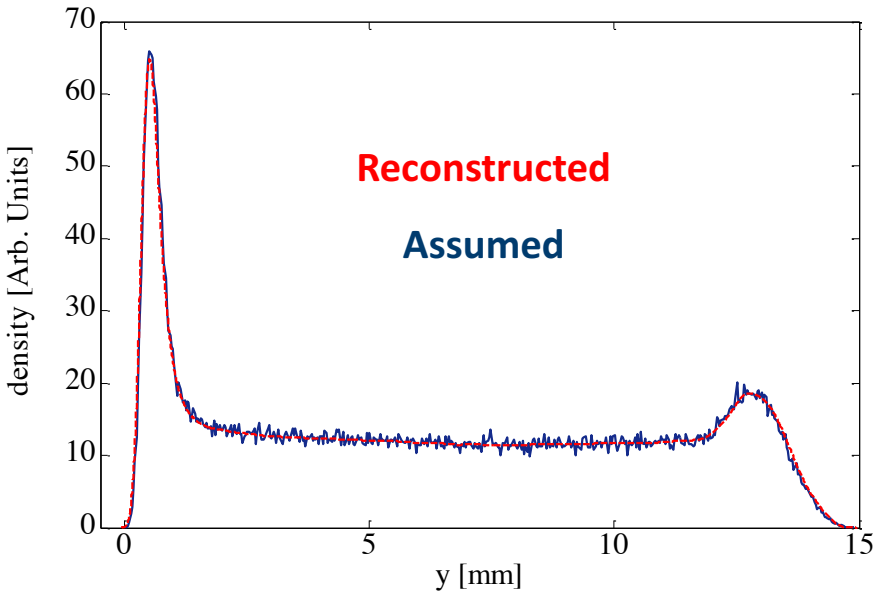
More typically dielectric lined

Numerical simulations

- Simulated in Elegant 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

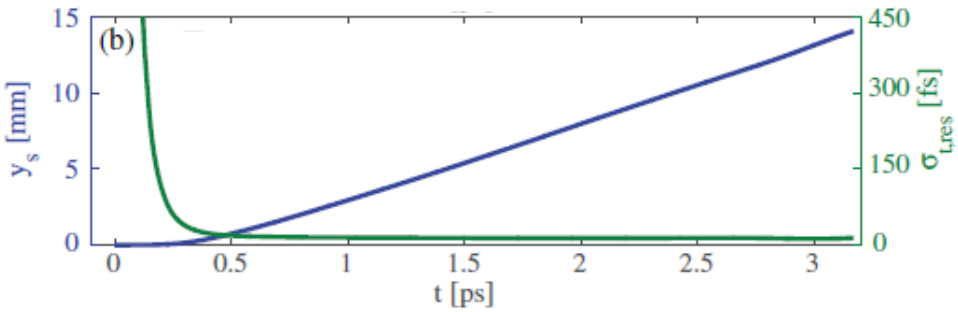


Calibration factor:

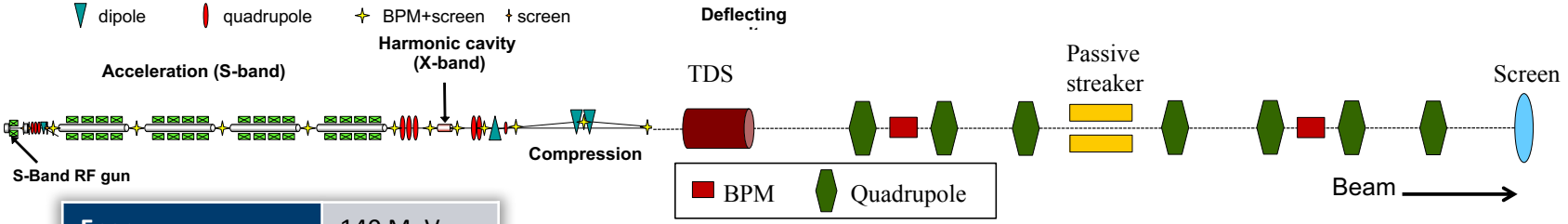
$$S = \frac{dy_s}{ds}$$

Resolution:

$$\sigma_{s,res} = \frac{\sigma_{y0,scr}}{S}$$

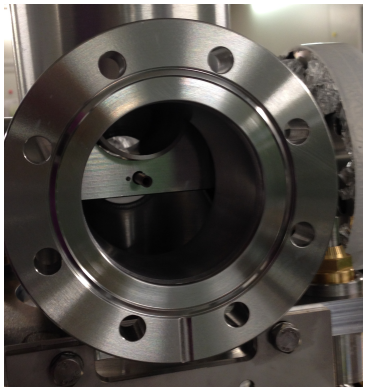


Experimental setup at SITF



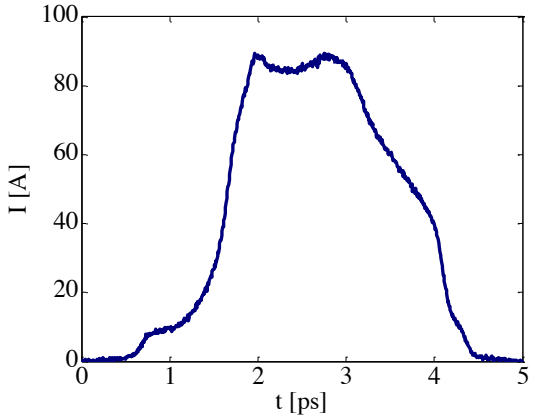
Energy	140 MeV
Charge	200 pC
Laser pulse length	2.7 ps rms
Bunch length	1 ps rms

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



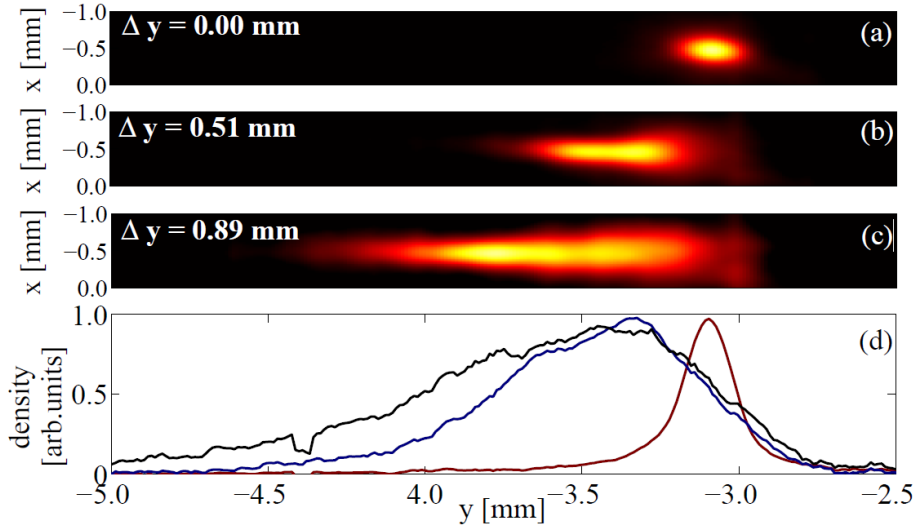
- Streaker mounted on a vertical remotely movable support
- Metallization with Cu layer

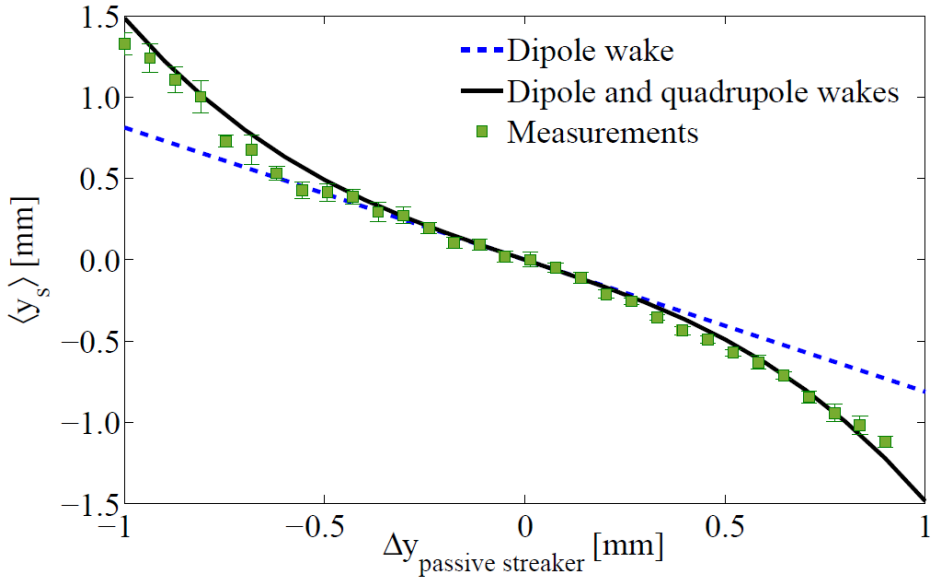
- Beam compressed to have a length compatible with a monotonic wakefield point charge
- Limited space for the streaker ($L_p = 9.5$ cm)
- Lowered the beam energy to enhance the effect ($y_s(s) \propto \frac{1}{E}$)
- Phase advance in the vertical plane between the streaker and the screen to maximize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



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

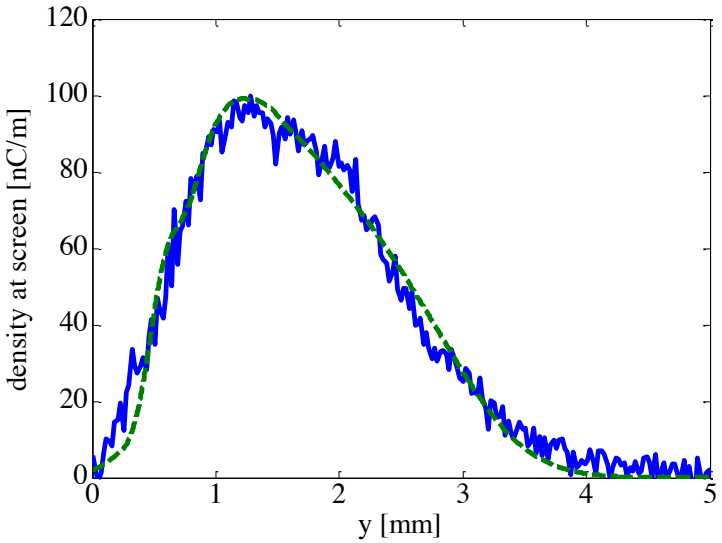
- Quadrupole effect not negligible for Δy>0.3 mm

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:

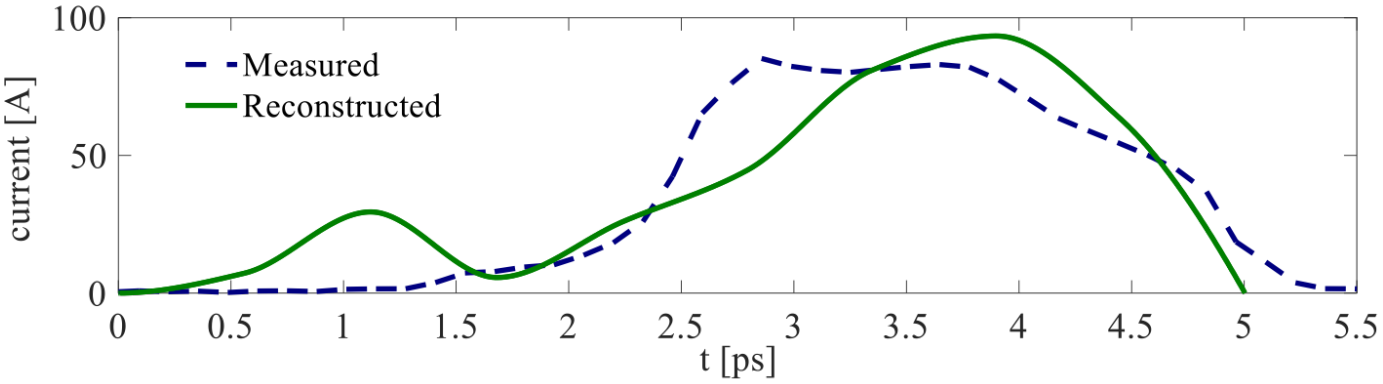
$$\rho_{\mathrm{screen}}(y_s) = \int \rho_{screen}(\tilde{y}_s)\rho_\tau \left[\frac{\Delta y(y_s - \tilde{y}_s)}{y_{sq}(\tilde{y}_s)}\right] \frac{\Delta y}{y_{sq}(\tilde{y}_s)} d\tilde{y}_s$$

- 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

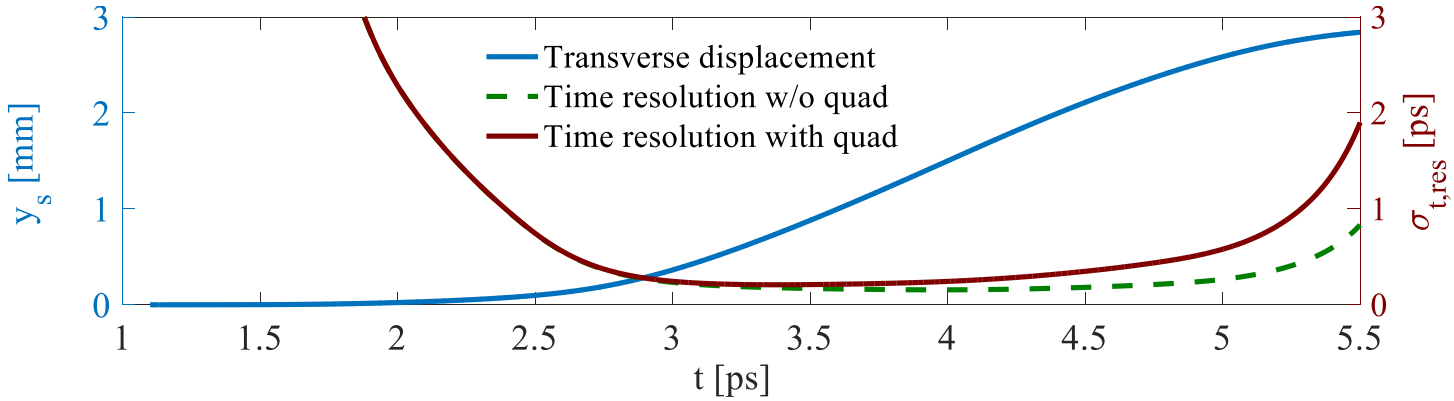


- Green: convolution with dipole and quadrupole wake functions, defocusing effect due to quad and finite emittance
- Blue: measured transverse profile at the screen

Experimental reconstruction



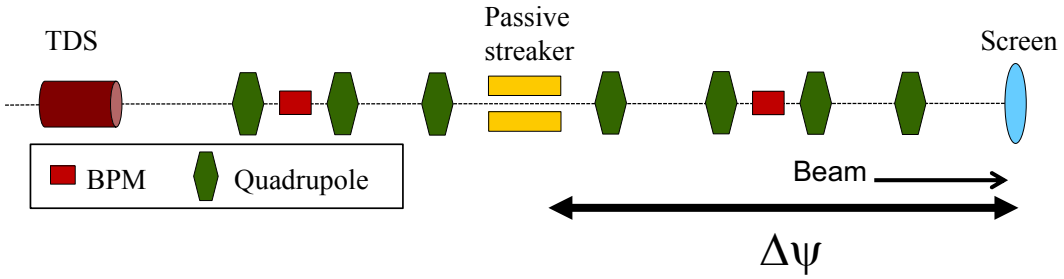
- The method demonstrated to be able to reconstruct the FWHM of the beam experimentally with a limited 9.5 cm length device (space limitations at SITF)



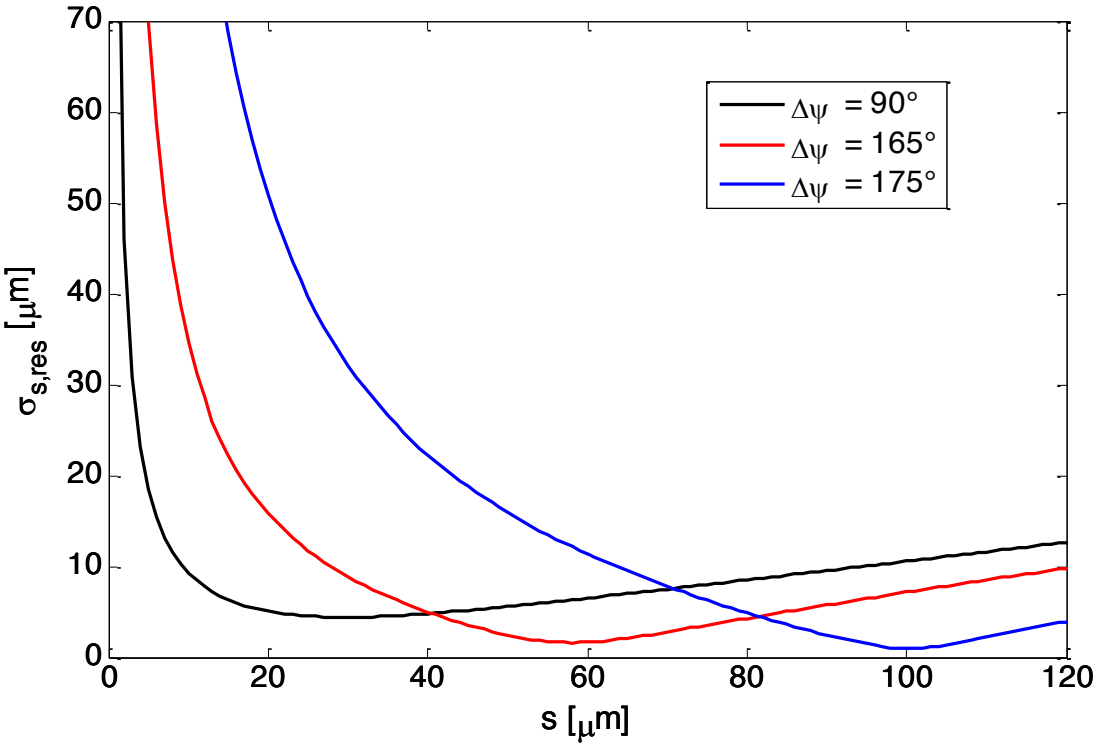
- The resolution of the method is determined by the wakefield source, and the beam size along the streaker:
  - is poor at the head of the beam (no streaking)
  - depends on the quadrupole effect going from the head towards the tail

More details in S. Bettoni et al., PR AB 19, 021304 (2016)

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



P. Craievich, A. A. Lutman, NIM A (2016).

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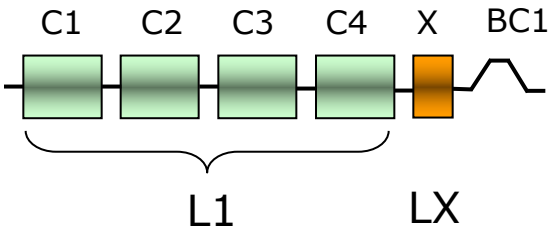
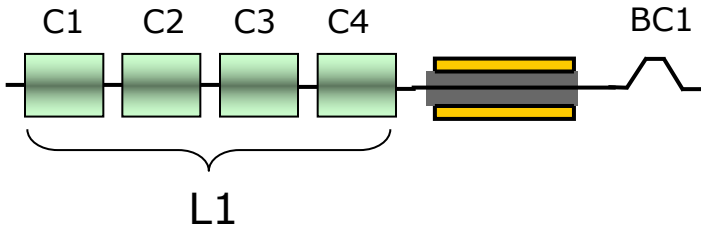
Passive longitudinal phase space linearizer

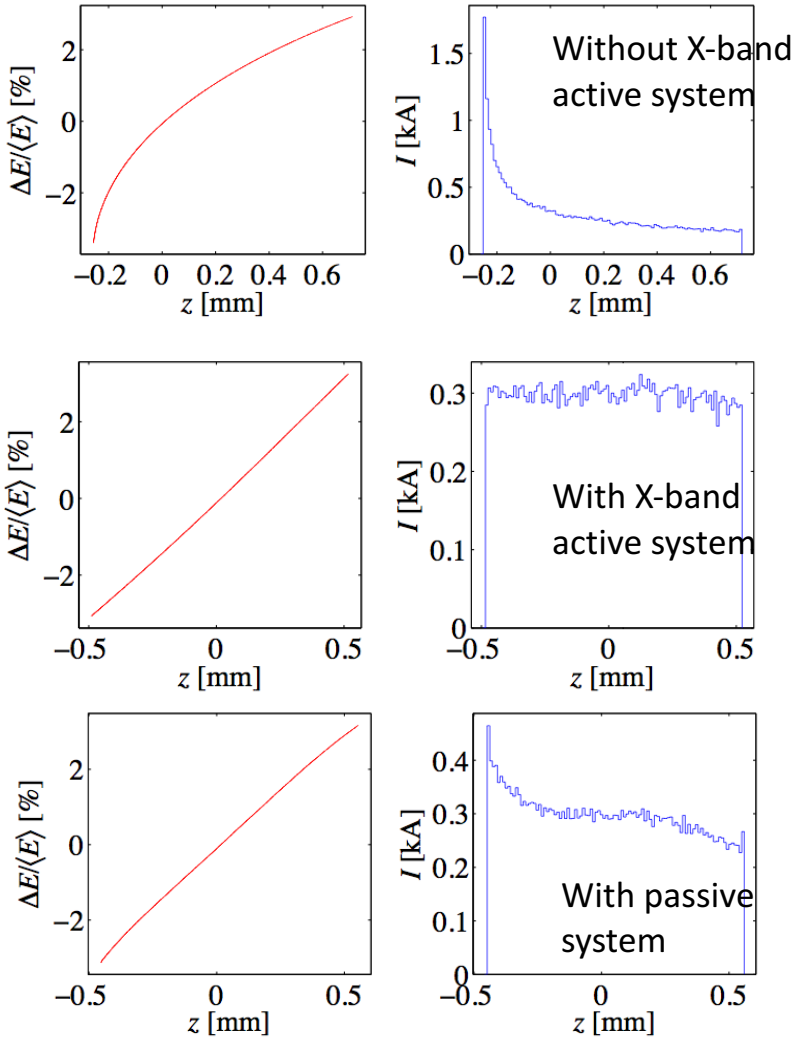
Compression process is strongly affected by non-linear effects such as the sinusoidal RF time curvature and the second-order path-length dependence on particle energy in the magnetic chicane



$$\Delta E_s(z) = -eQL \int_{-\infty}^{z} w_{||}(z-z')\rho_R(z')dz' =$$

$$= \begin{cases} = -eQLA_0 \frac{\sin(\frac{k_s L_b}{2})}{\frac{k_s L_b}{2}} \cos(k_s z) & \text{if } z > \frac{L_b}{2}, \\ -\frac{eQLA_0}{k_s L_b} \sin(k_s z + \frac{k_s L_b}{2}) & \text{if } |z| \le \frac{L_b}{2}, \\ 0 & \text{if } z < -\frac{L_b}{2}. \end{cases}$$

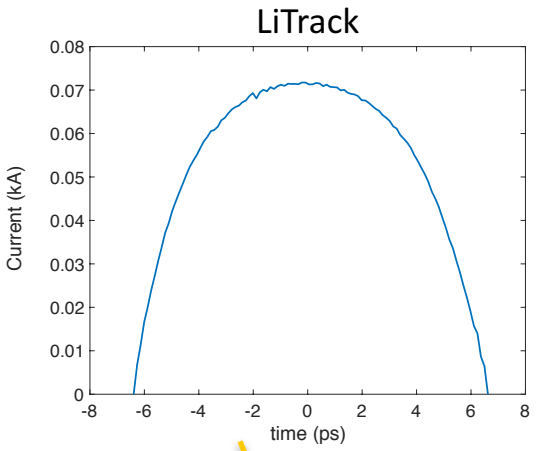


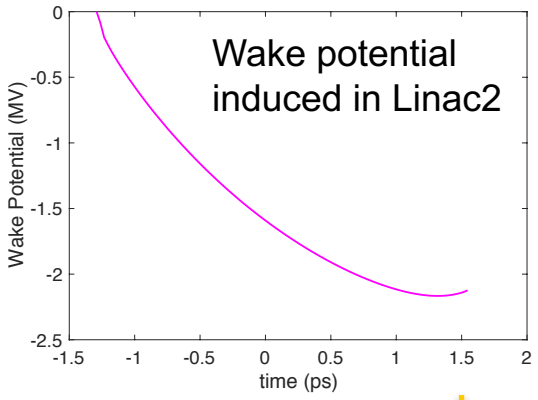


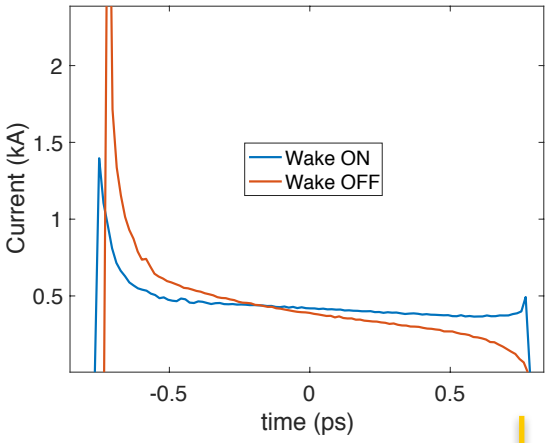
P. Craievich, PRST AB 13, 034401 (2010)

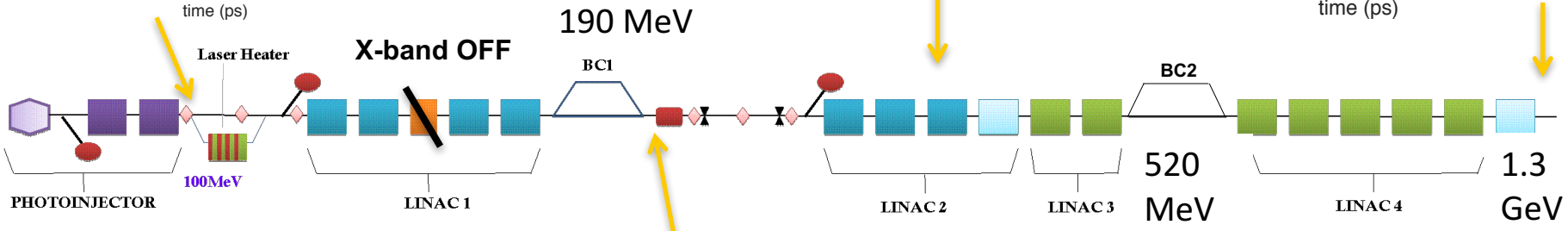
Activities at FERMI@Elettra

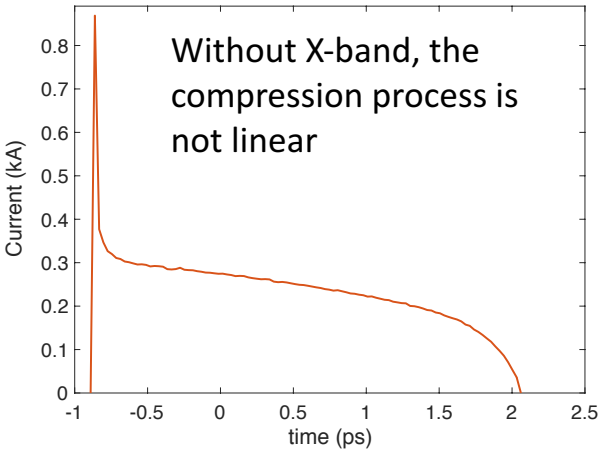
Elettra Sincrotrone Trieste

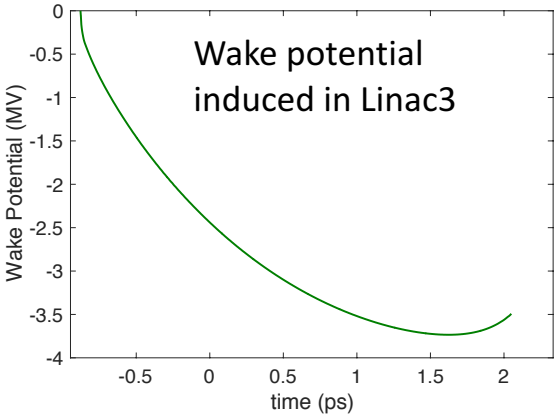








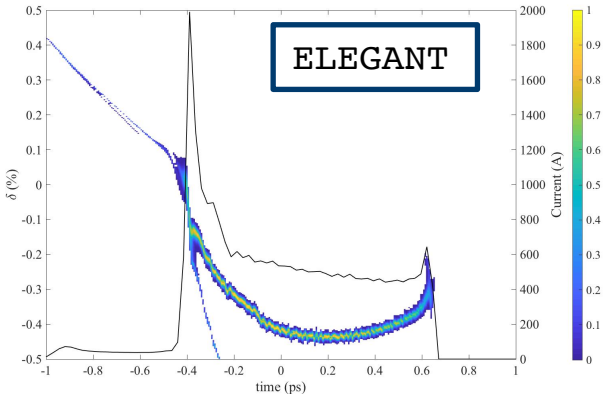


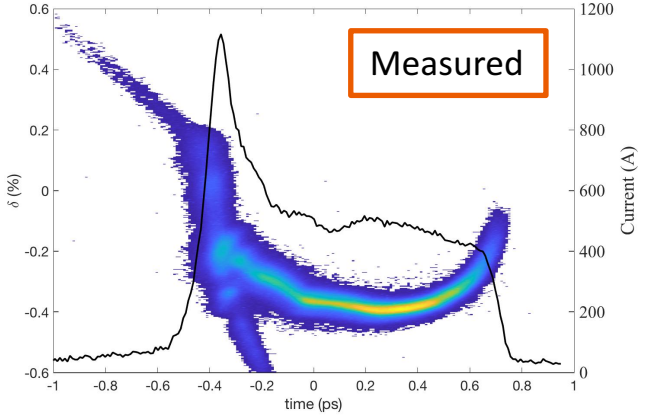


G. Penco et al.

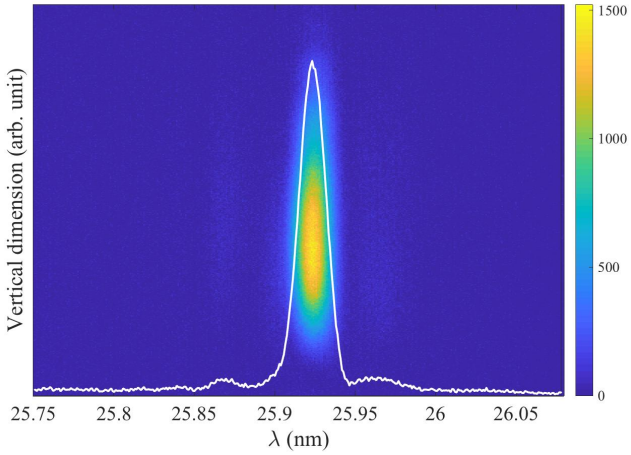
Activities at FERMI@Elettra

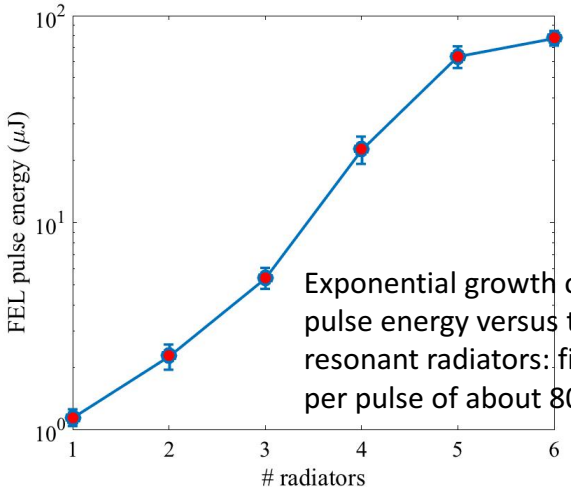
- **Experiment using the linac longitudinal wakes to linearize**
- Double-stage compression and without the X-band cavity, 700 pC





- Lasing in FEL-1 line in high-gain harmonic generation mode
- Intensity and spectral purity comparable to the ones in the nominal conditions.





Exponential growth of the FEL pulse energy versus the number of resonant radiators: final energy per pulse of about 80 μJ

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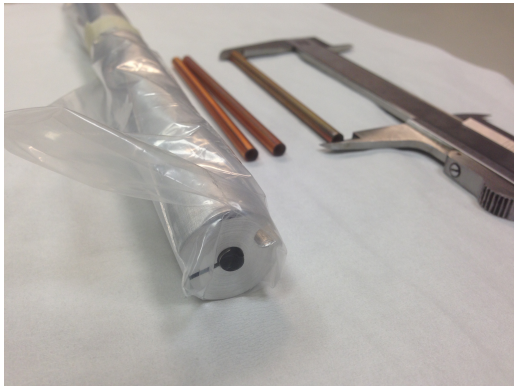
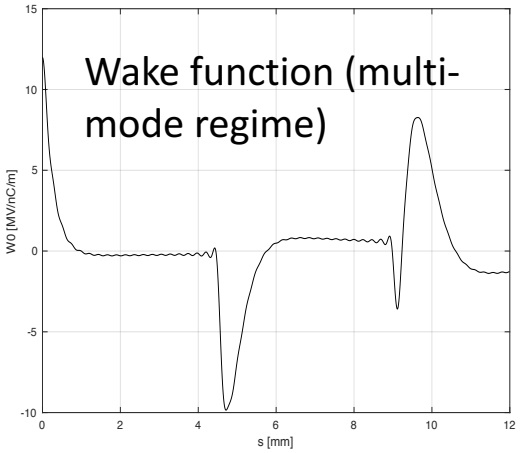
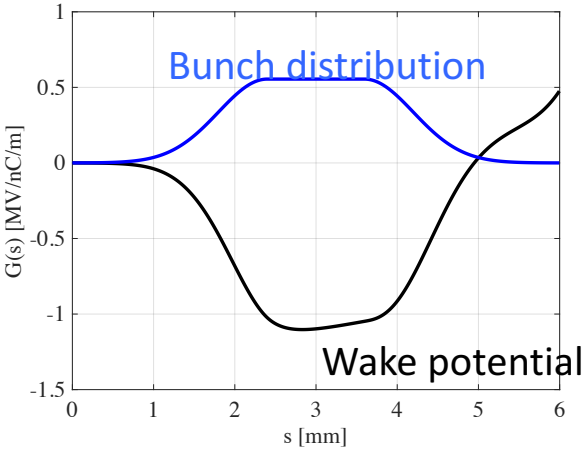
Activities at FERMI@Elettra

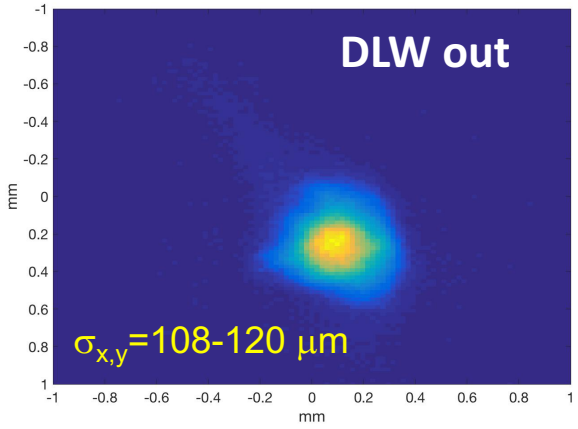
Experiment using passive dielectric-lined waveguides installed downstream BC1

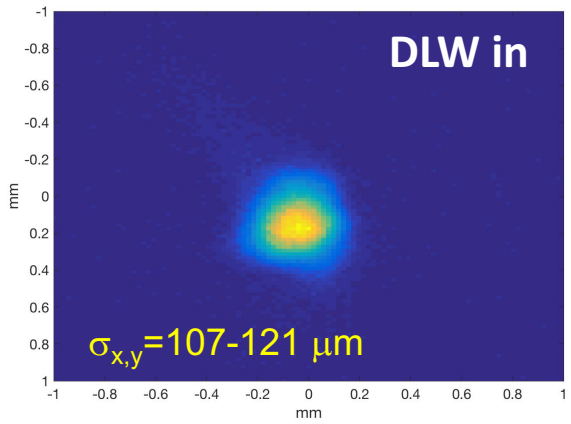






- Alumina pipe with 20 μm Cu coating (inner radius: 1.65 mm, outer radius: 2.4 mm, total length: 28.5 cm), realized by the PSI and already tested as passive streaker
- Trajectory steering to minimize the transverse wakes. Beam Optics in BC1 preserved ($\varepsilon_{x,y} \approx 1.35$)





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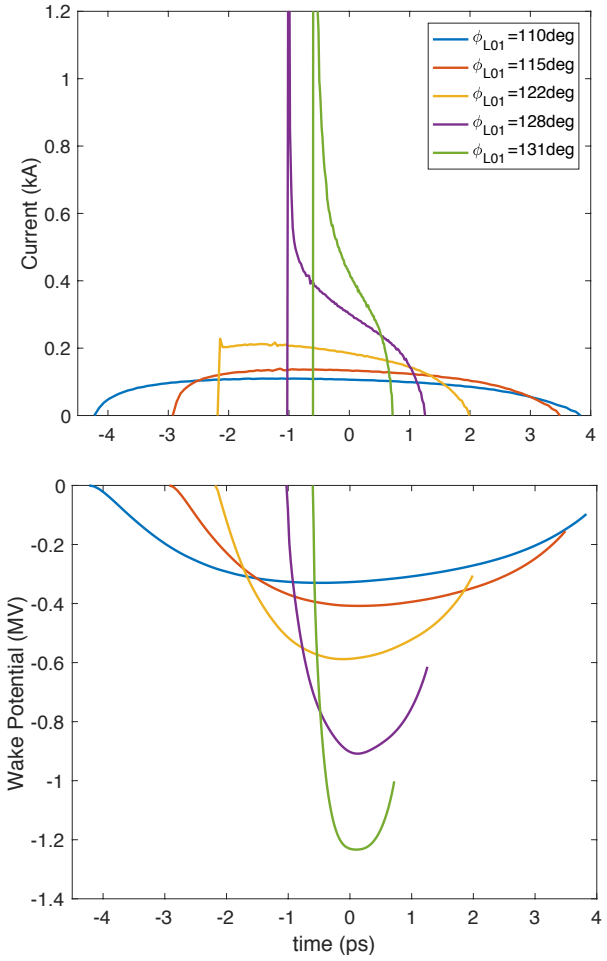
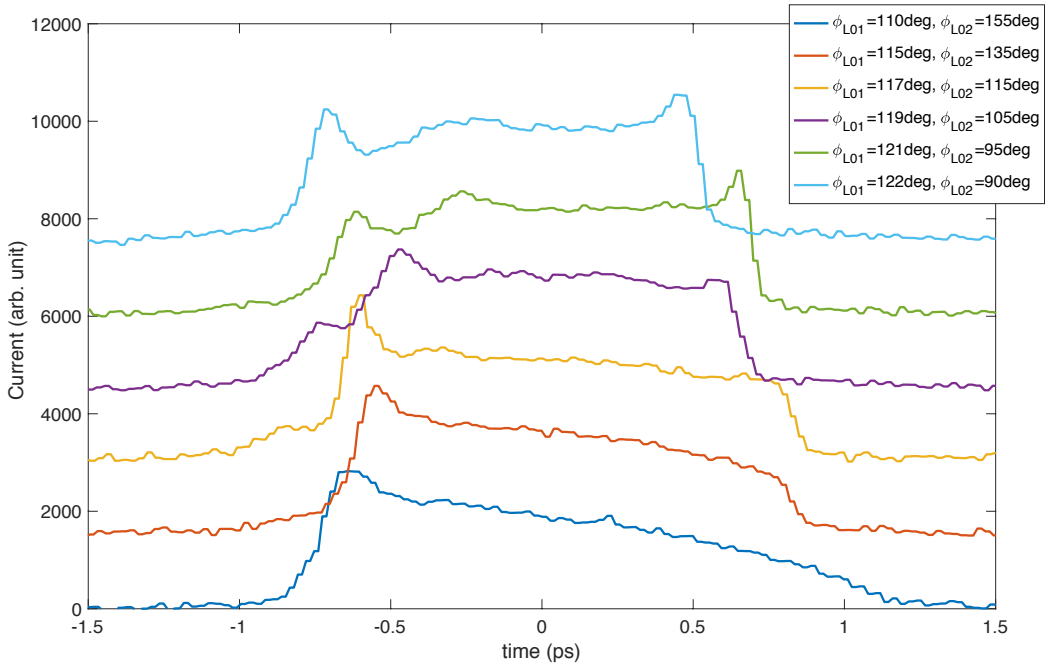
Activities at FERMI@Elettra

- Bunch length at linac-end fixed
- We varied the compression ratio between the two stages using the RF phase in linac 1 and linac 2 in order to tune the compression factors in BC1 and BC2, respectively





Beam temporal profiles measured at the linac end as a function of ϕ_{L01} and ϕ_{L02}, keeping constant the bunch length after BC2.

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Outline

- Dechirping

  → brief history of passive structures as a dechirper

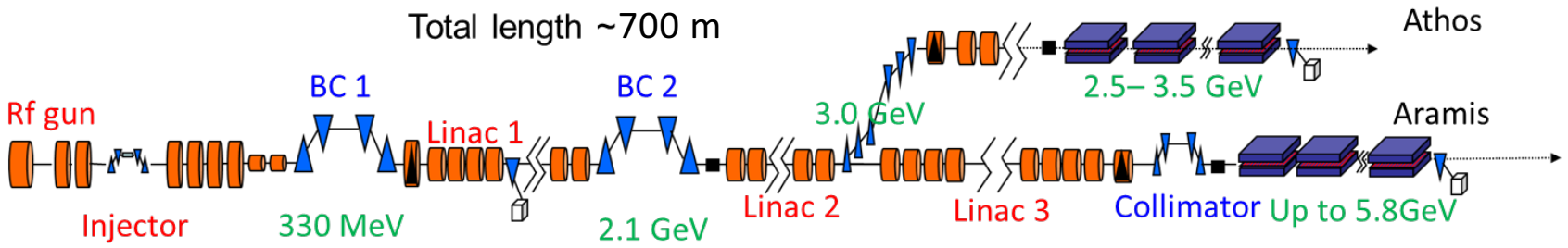
- Streaking as a diagnostic tool

  → experiment at SITF

- Linearization of the compression process

  → experiment at FERMI

- **Activities at SwissFEL**



Electron source

RF gun with Cs_2Te photocathode

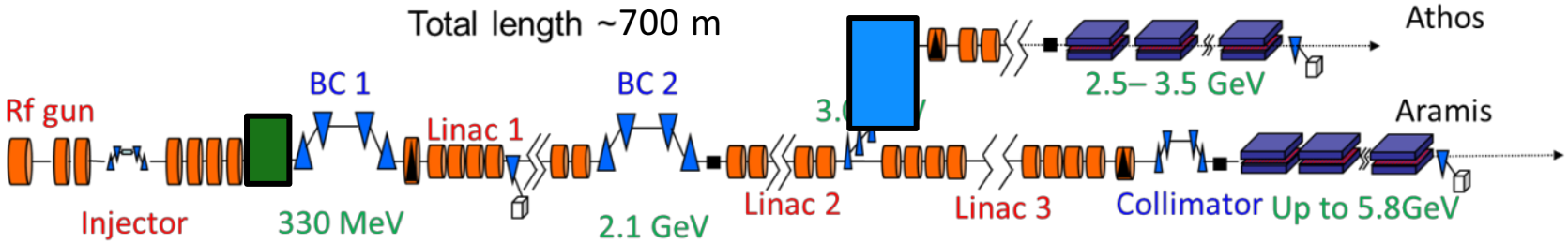
Undulator beamlines

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

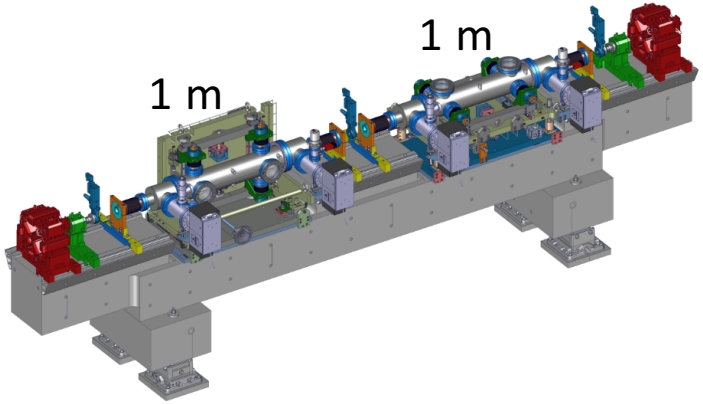
Wavelength	1 - 50 Å
Pulse duration	3 – 20 fs
Maximum e- beam energy	5.8 GeV
e- beam charge	10 – 200 pC
Repetition rate	100 Hz
Slice emittance (expected performances)	200 nm (10 pC) 300 nm (200 pC)
Slice energy spread	250-350 keV
Saturation length	< 50 m

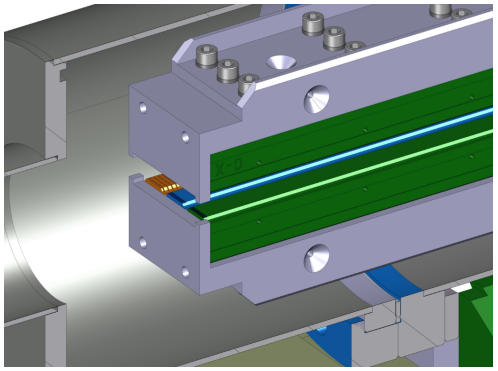
- ❑ Construction started in 2013
- ❑ Commissioning started in Jul 2016
- ❑ Pilot experiment in Aramis planned in Dec 2017
- ❑ Athos user operation planned in 2021

Beam manipulation in SwissFEL linac



- Passively streak the beam (1-10 ps bunch length): 1 mm ≤ λ_w ≤ 6 mm
- Test the two-color generation via wakefield excitation: λ_w = 1 mm
- Alternatively linearize: λ_w = 6 mm
- Remove the chirp residual from the compression: λ_w = 2 mm
- Passively streak the beam at higher energy and shorter bunch length (~10-500 fs)





Assembly	Nov 2017
Delivery	Jan 2018
Operational	Jul 2018

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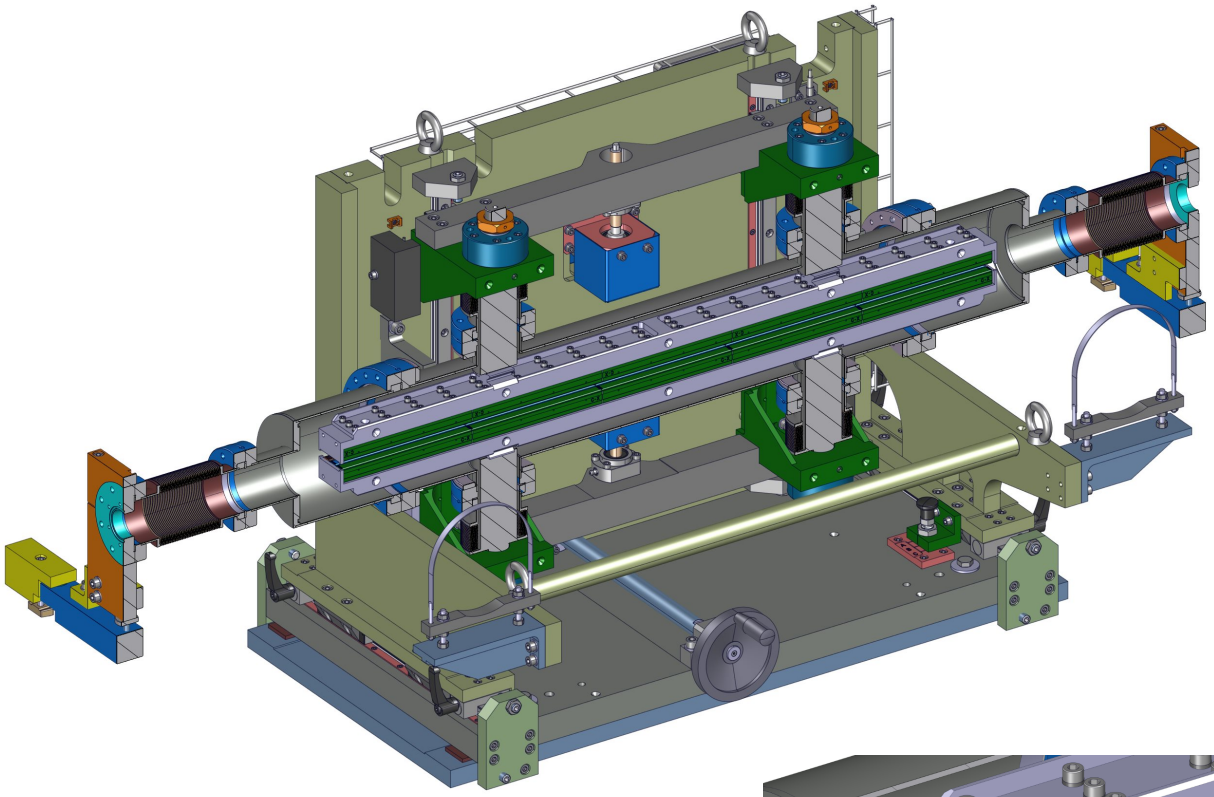
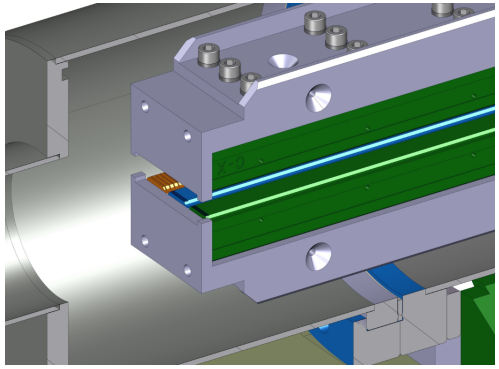
PSI Dechirper



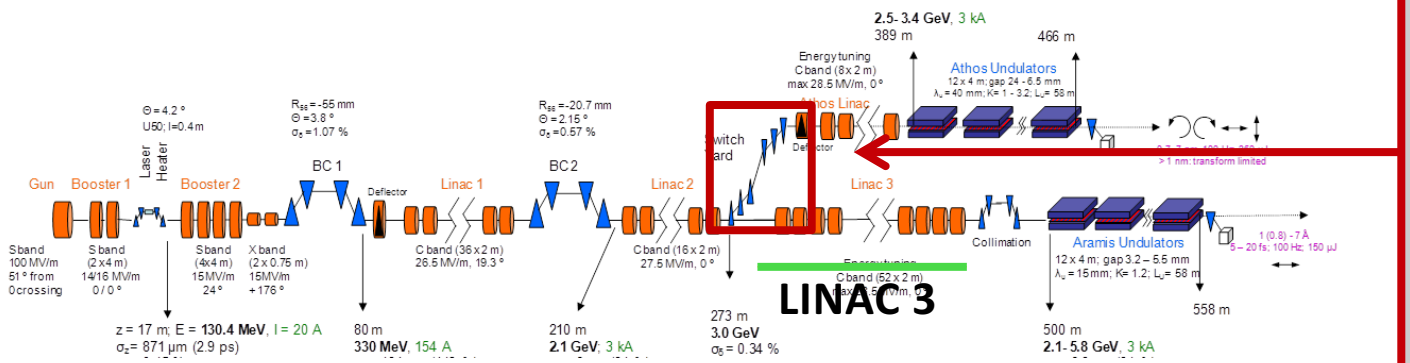


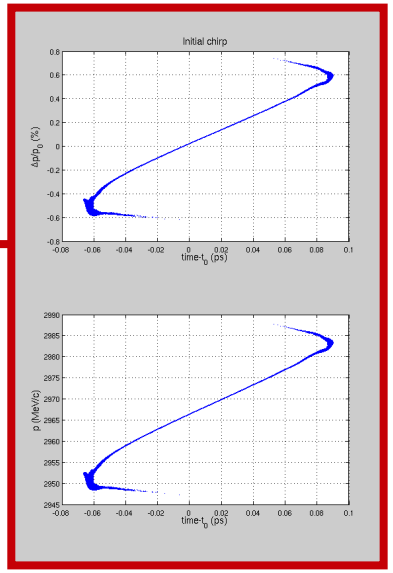
General parameters	
Gap_dechirper length: D4_Gap	**1 m**
Corrugation design	Table 3.2
Flatness over 1 m (p.t.p.)	‹50 µm
Material for corrugated surface	Al or Cu
Number of units	1
Overall system positioning	**(manual)**
X, pitch, yaw and roll positioning	Manually adjustable by survey to within 100 um.
X minimum motion range (to select 3 different pairs of dechirper)	+/– 25 mm
Beam Height	1.2 m
Motorized Gap and height (in y direction)	
Y gap range	1 to 20 mm
Y minimum step for alignment (when going in one direction)	‹ 10 µm
Height moving range	+/- 2 mm
Y Encoder precision	1 µm
Speed in gap change	‹ 1 mm /s
Limit switches	yes
Manually Selectable dechirper pair	To test 3 different corrugations
Number of pairs	3
Motion range in X (not motorized but with tunnel access)	+/– 25 mm

	Struktur A	Struktur B	Struktur C
g [um]	1500	250	220
p [um]	2000	500	500
Delta [um]	1500	250	100
a [um]	1500	1250	1500

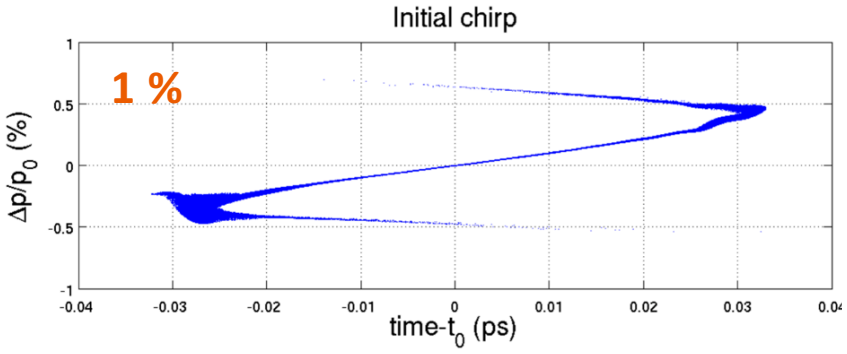
Courtesy of P. Heimgartner

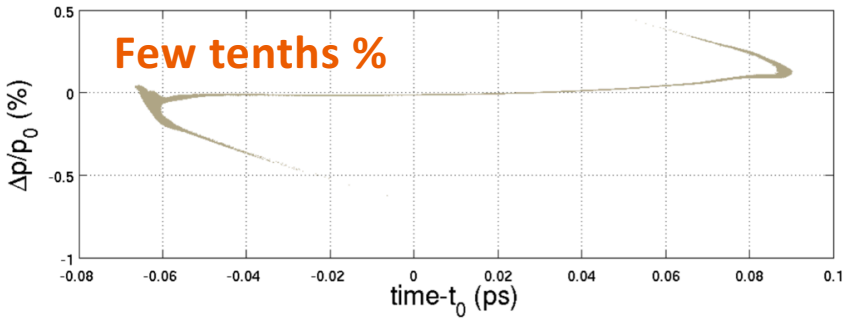
Dechirping for Athos line





- Aramis line → we compensate for the residual energy chirp at the Aramis line with the wakefield of LINAC 3
- Athos line → we have a residual chirp of 1.1% at 3 GeV (and 0.7% in the new lattice)
- Beam parameters: energy 3 GeV, FW bunch length 50µm, peak current 3 kA, relative energy chirp 1.1 %- 0. 7%





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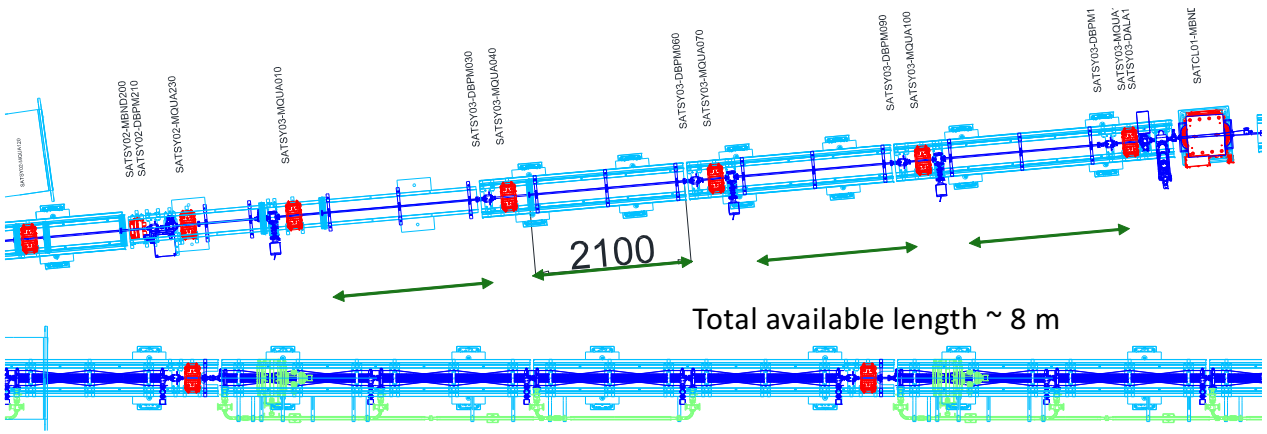
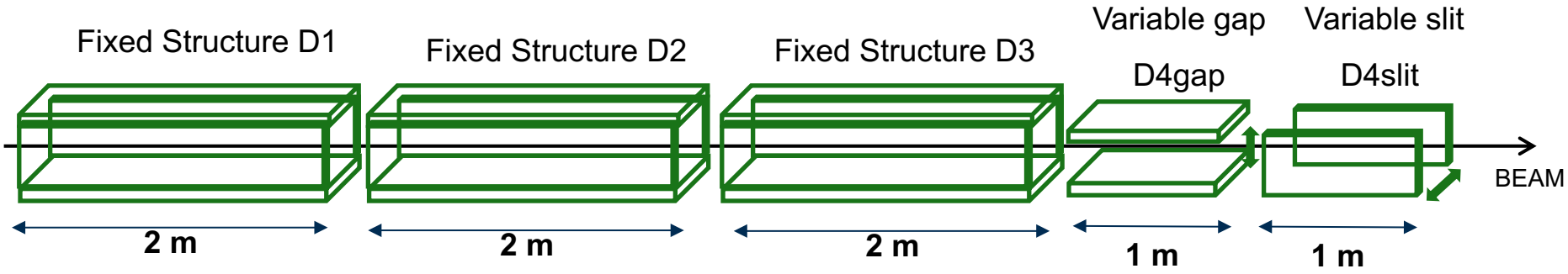
Solution for Athos line

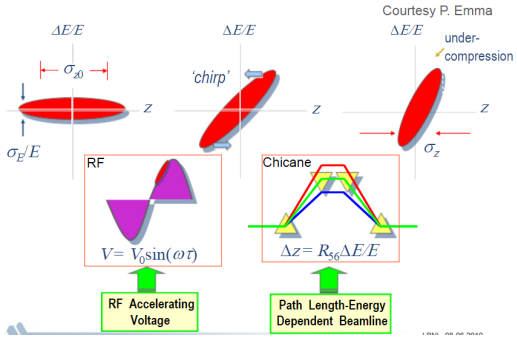




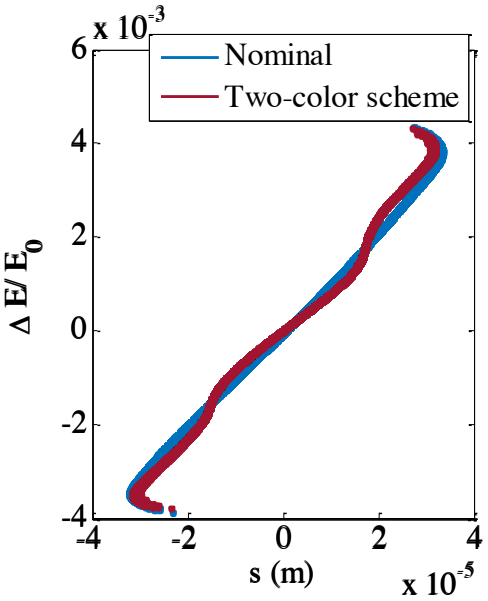
- 3 modules 2-m long each, corrugated and square section 2.5 mm x 2.5 mm (fixed)
- 2 modules (H and V) 1-m long each: variable gap (1-20 mm)

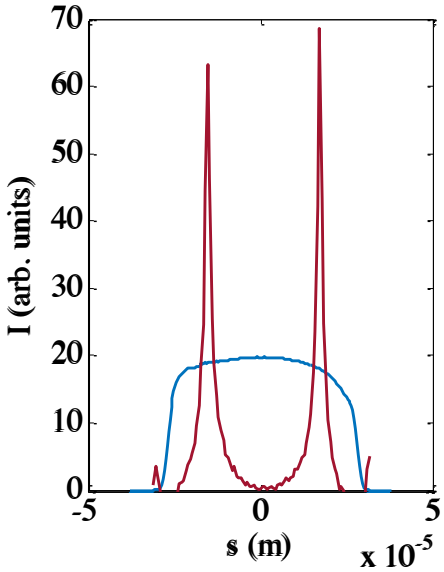
Two-Color Beam Generation

A well known and used way to compress the beam is to impose a (time,energy) correlation and to use the energy dependence of the trajectory in a dispersive section (typically chicane, dogleg).



- Superimpose a (time,energy) correlation at two locations along the beam using a longitudinal wakefield on top of the nominal chirp
- Compress the beam using the downstream compression stages





- What it is important is the **relative** energy chirp, therefore better to apply this scheme at the lowest compression stage
- Possible to swap the order of the sub-pulses inverting the sign of the global chirp

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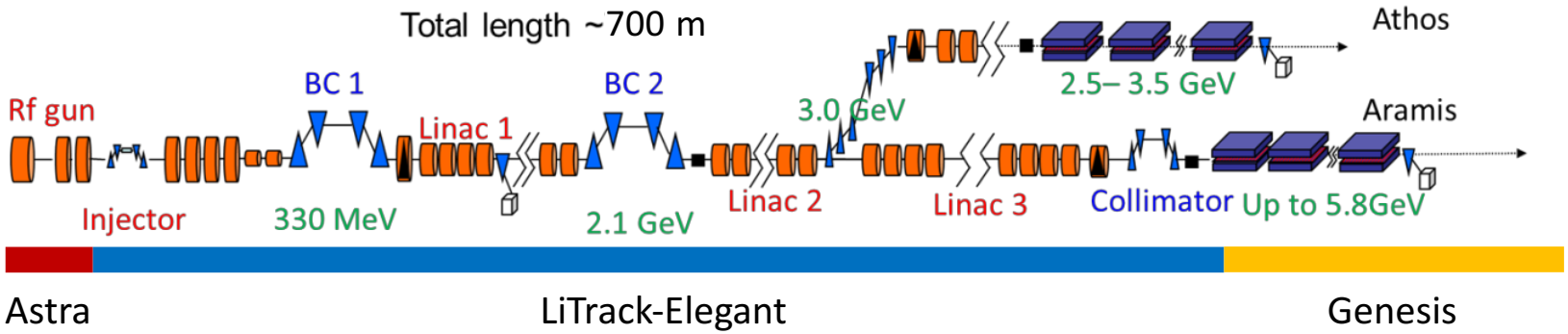
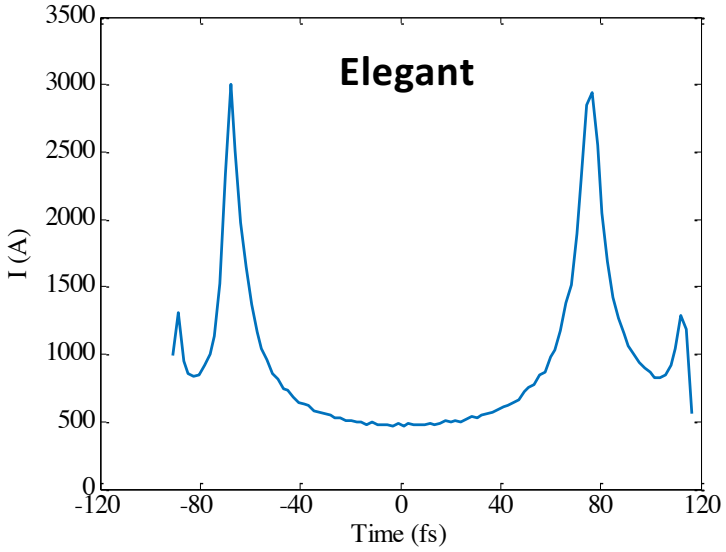
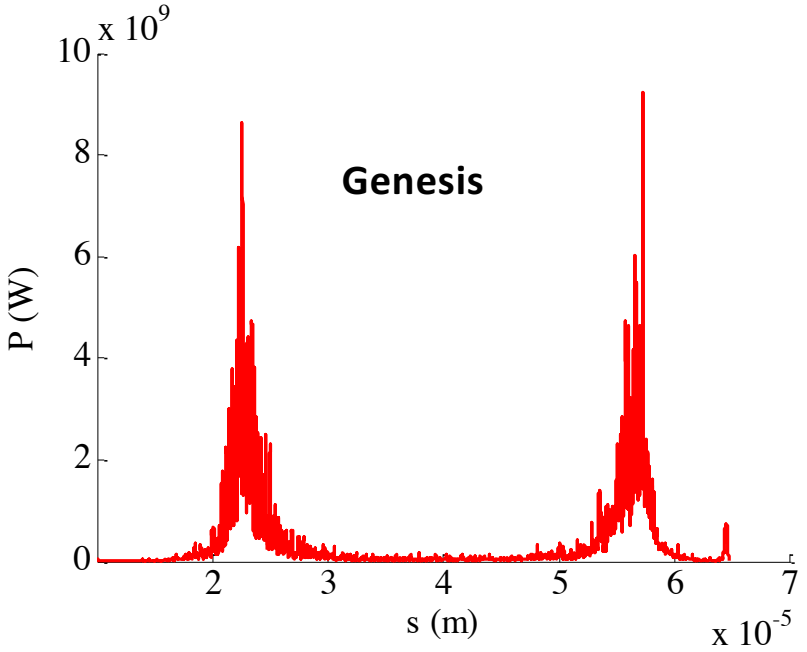
Start-to-end simulations







- Beam quality preserved → nominal SwissFEL laser power assuming the installed undulators
- Relatively easy setup
- Tunability knobs: λ_w changing the gap and RF phase of downstream linac

S. Bettoni et al. PR AB 19, (2016)

Conclusions

- Brief history of passive structures as a Dechirper
- Passive streaking

Pros:

- ✓ Single shot measurement
- ✓ Self-synchronized with the beam
- ✓ Cheaper to manufacture and operate[d] to other existing devices
- ✓ Potentially fs or sub-fs resolu[tion]

Cons:

- Necessary [k]gy, charge and optics
- Tempo[ral] [is] not constant along the beam
- If relation [be]tween beam at the device and beam at the screen is non-linear, inversion requires more complicated computation

- Passive linearization of the compression process at FERMI
  - an alternative for C-band or X-band injector?
- Activities at SwissFEL: dechirper 8-m long!!!

Thank you for the attention!!