PAUL SCHERRER INSTITUT PSI

SLAC NATIONAL ACCELERATOR LABORATORY

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Temporal profile measurements using self-induced fields

Physics and Applications of High Brightness Beams Workshop
March 28-April 1, 2016 in Havana, Cuba

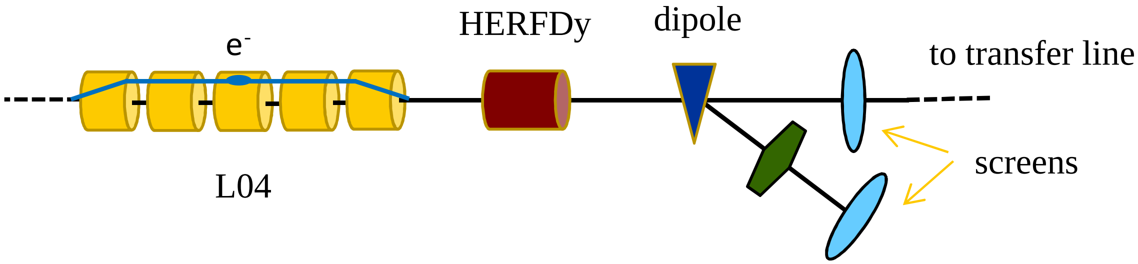
Talk outline

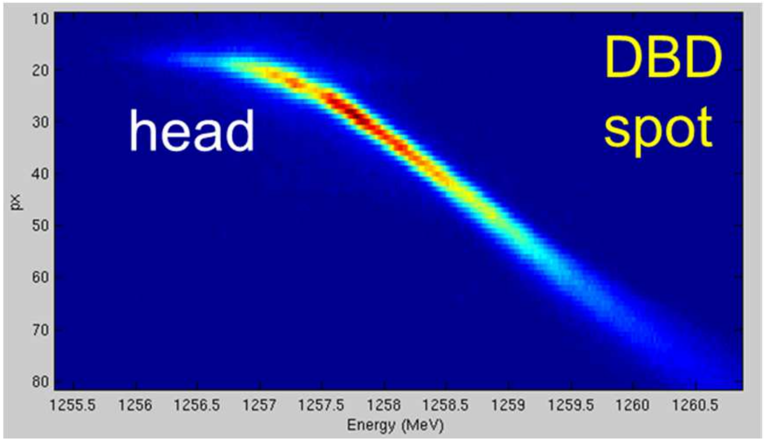
- Passive streaker model and wake potentials
  - Formulas to calculate the profile at the screen
  - Algorithm to time-resolve the electron beam profile
  - Example of reconstruction from numerical simulation
- Experimental setup at SITF
  - Example of reconstruction from experimental data
- Next steps at SwissFEL and passive streaking in other labs

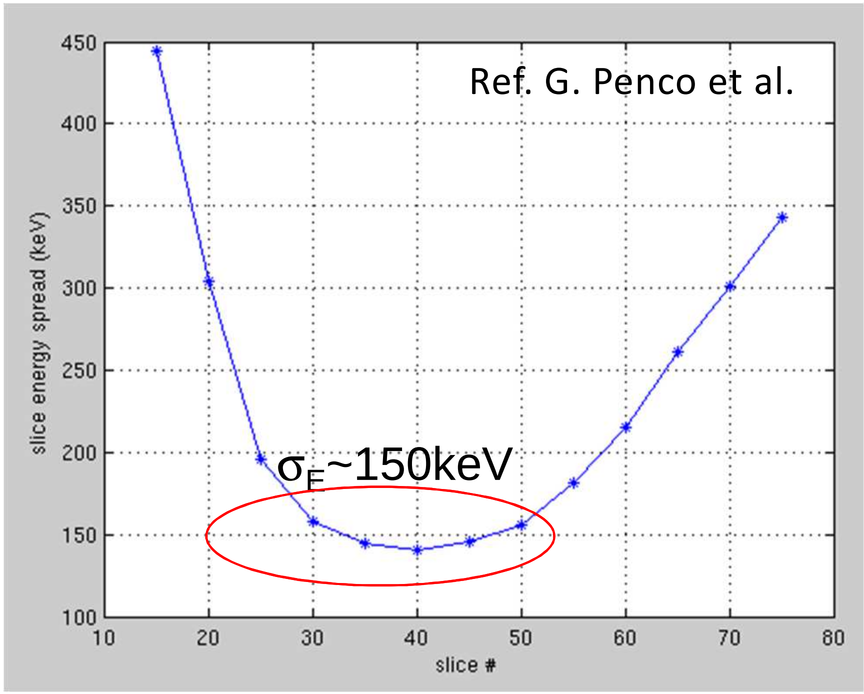
Observation of passive streaking

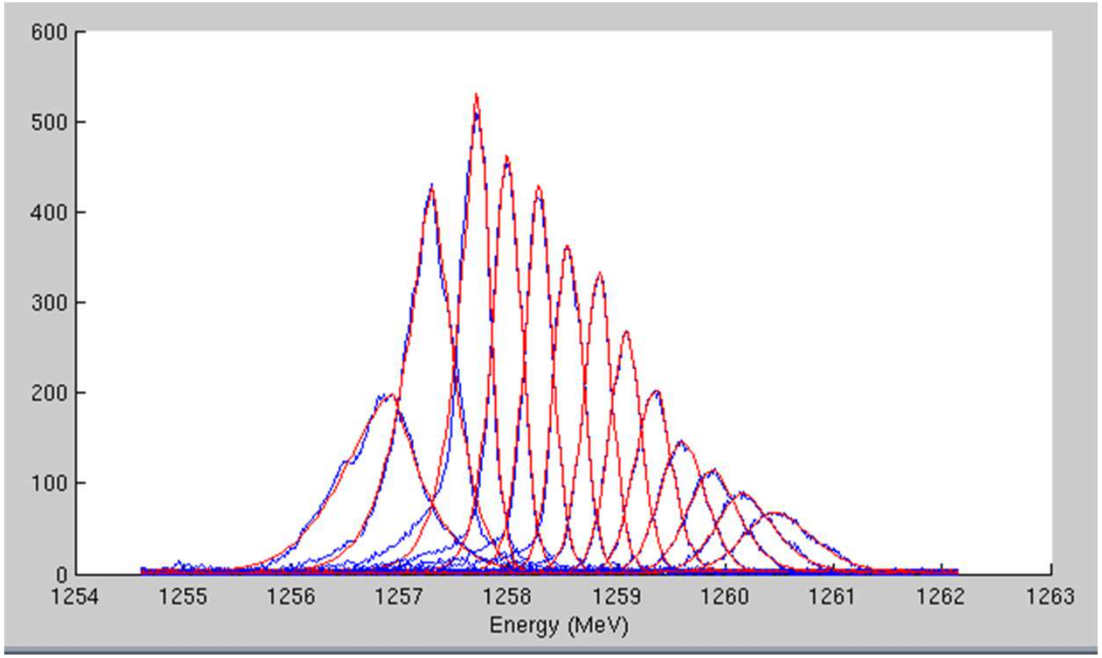
→ Slice Energy Spread at the FERMI@Trieste spectrometer with BC1+BC2 (σ_t≈1ps)
(…while waiting for High Energy RF Deflector at the end of 2011)

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

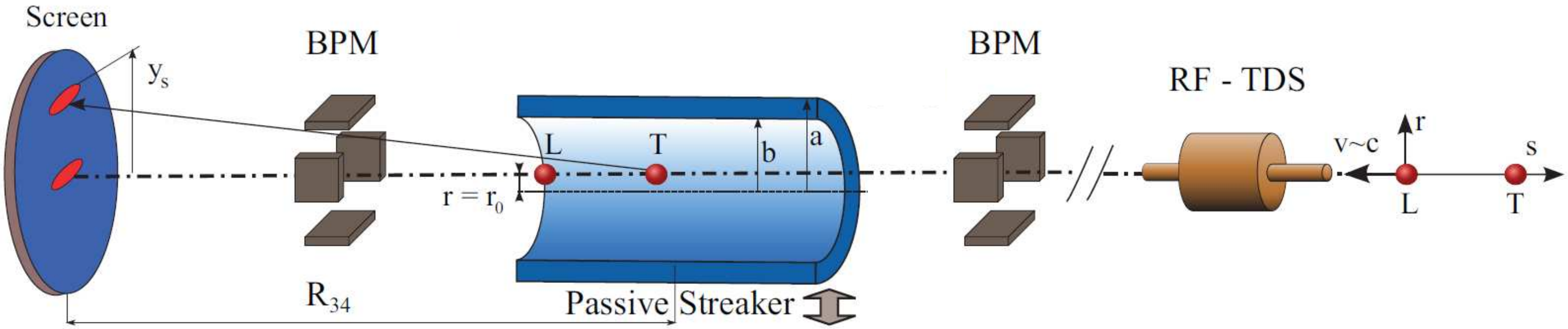




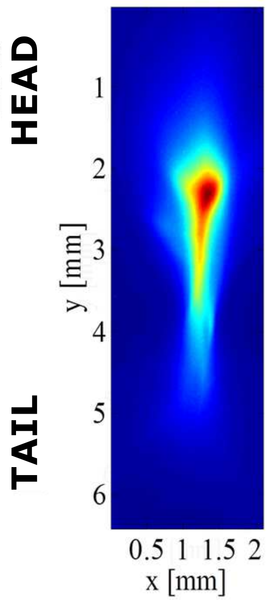




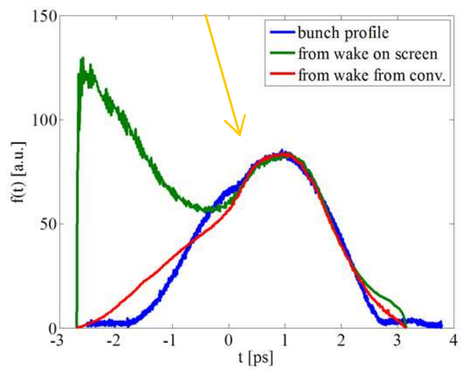
Working principle



August 2014: first attempt



Parabolic approximation of the wake effects



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

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Wakefield model

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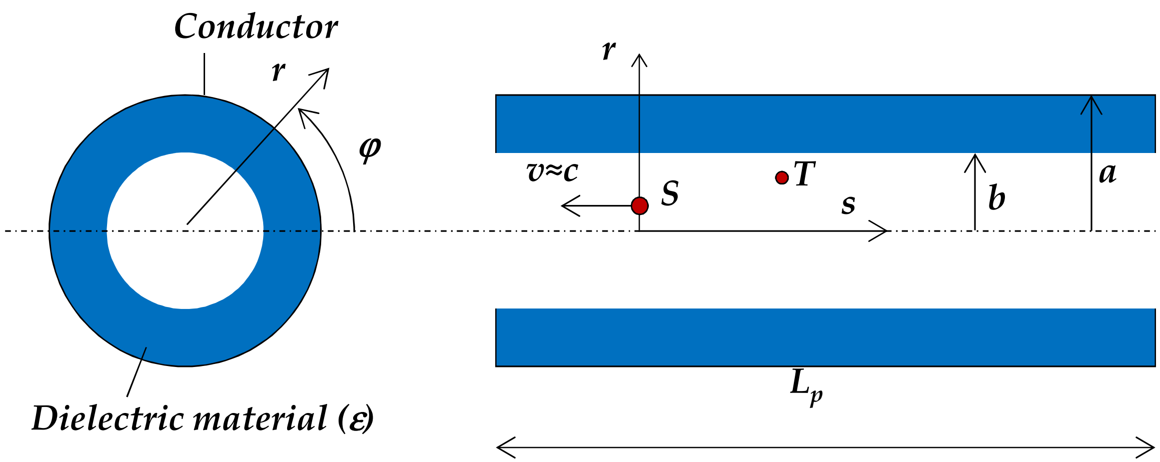
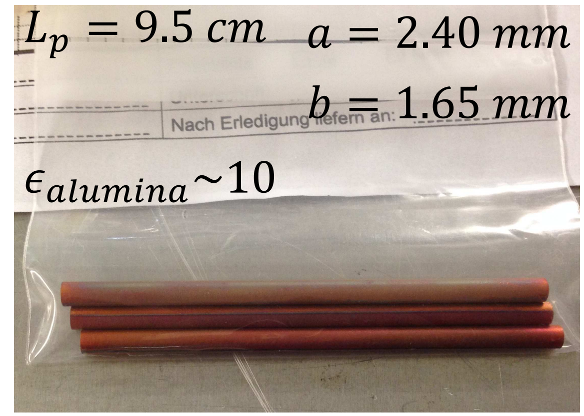


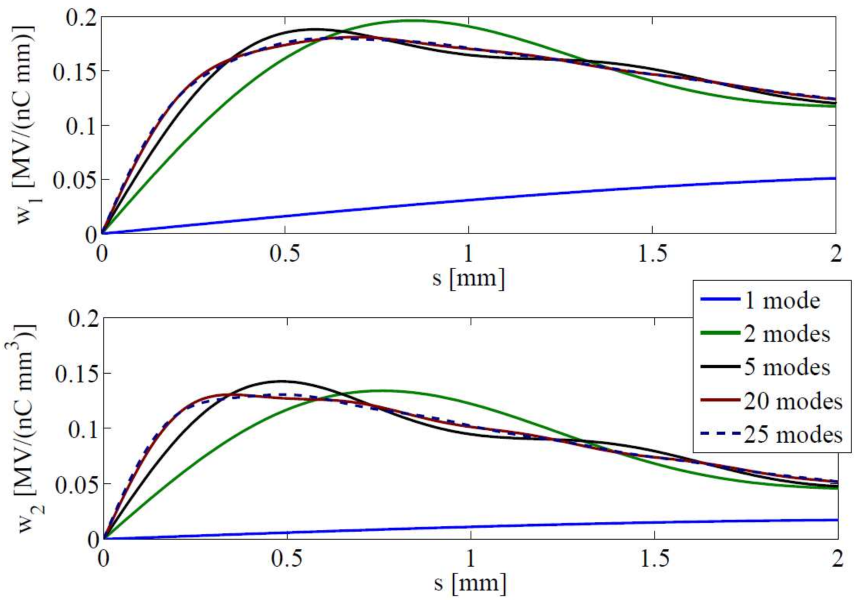


$$w_{r,m}(s,r,r_0,\varphi,\varphi_0) = \frac{Z_0 c}{4\pi a^2}\left(\frac{r}{a}\right)^{m-1}\left(\frac{r_0}{a}\right)^{m}\sum_{i=1}^{\infty} A_{m,i}\sin\left(k_{m,i}s\right) cos[m(\varphi-\varphi_0)]$$

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

- Wake function model from King-Yuen Ng, “Wake fields in a dielectric-lined waveguide” Phys. Rev. D, Vol 42 Issue 5 (1990);
- transient effect at the entrance of the tube neglected;
- wake functions were also verified with ImpedanceWake2D code (N. Mounet, CERN-ATS-Note-2010-056).

From time to vertical position

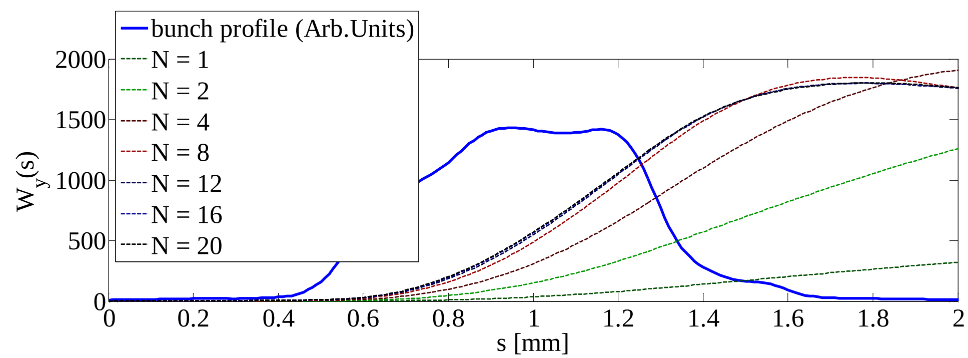


Dipole wake function (m=1)

Quadrupole wake function (m=2)

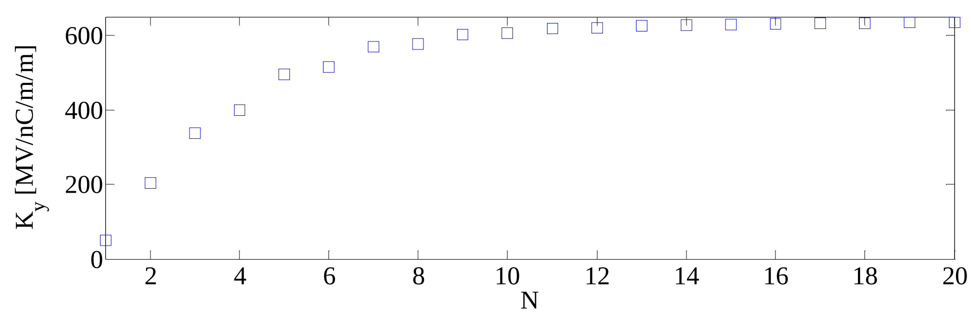
Wake potentials when the transverse size is much smaller than the offset r_0 ($r \approx r_0$ and $\varphi = \varphi_0$):

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



Transverse displacement at the screen location

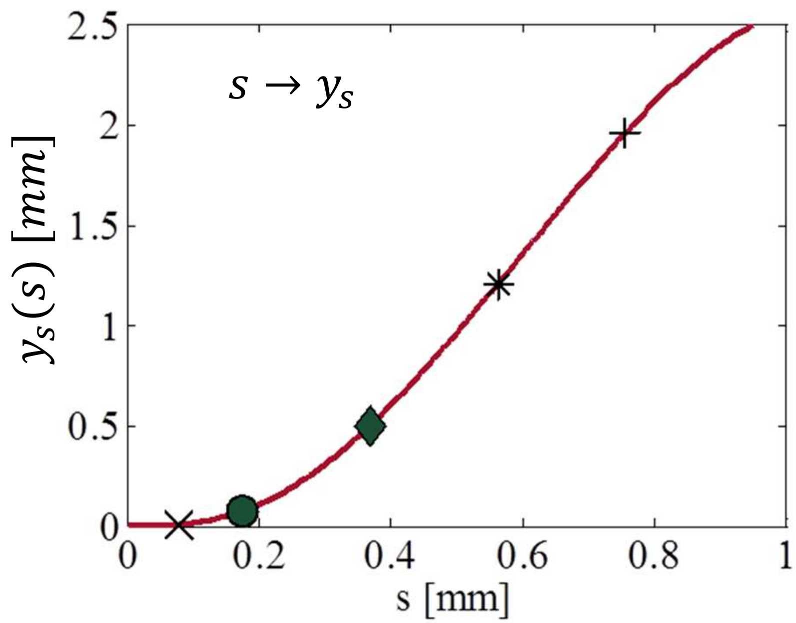
$$y_s(s) \approx \frac{Q L_p R_{34}}{E}\left[W_{r,1}(r_0,s) + W_{r,2}(r,r_0,s)\right]$$

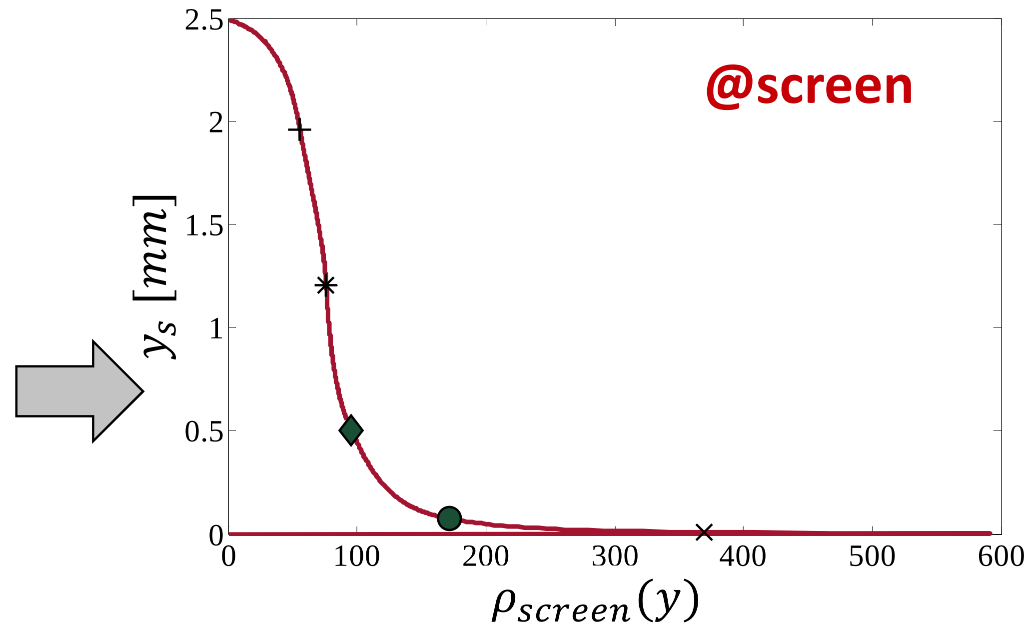


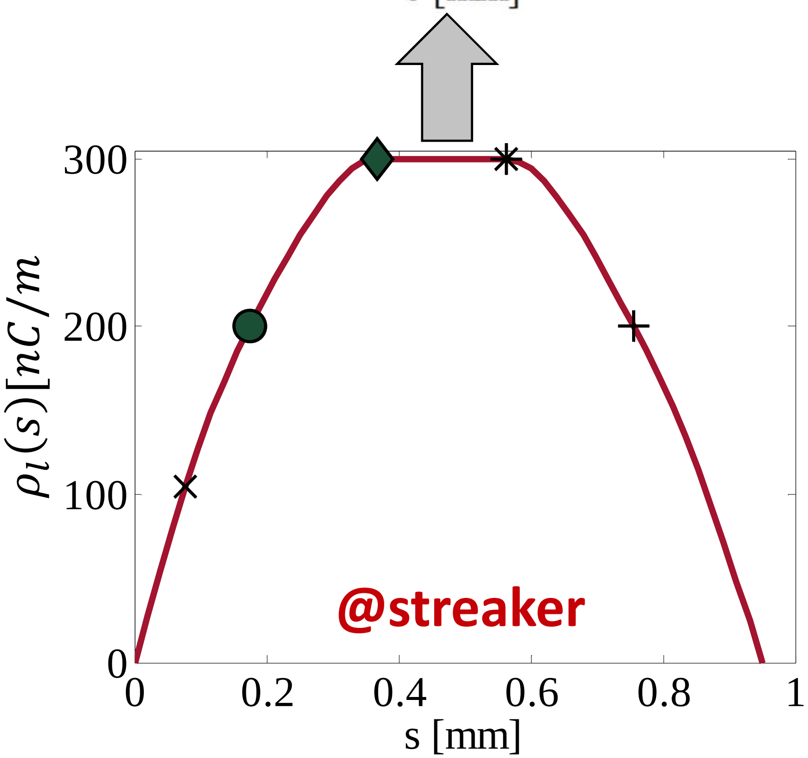
Dipole wake potential: $W_{r,1} \propto r_0$

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

Relation between charge distributions







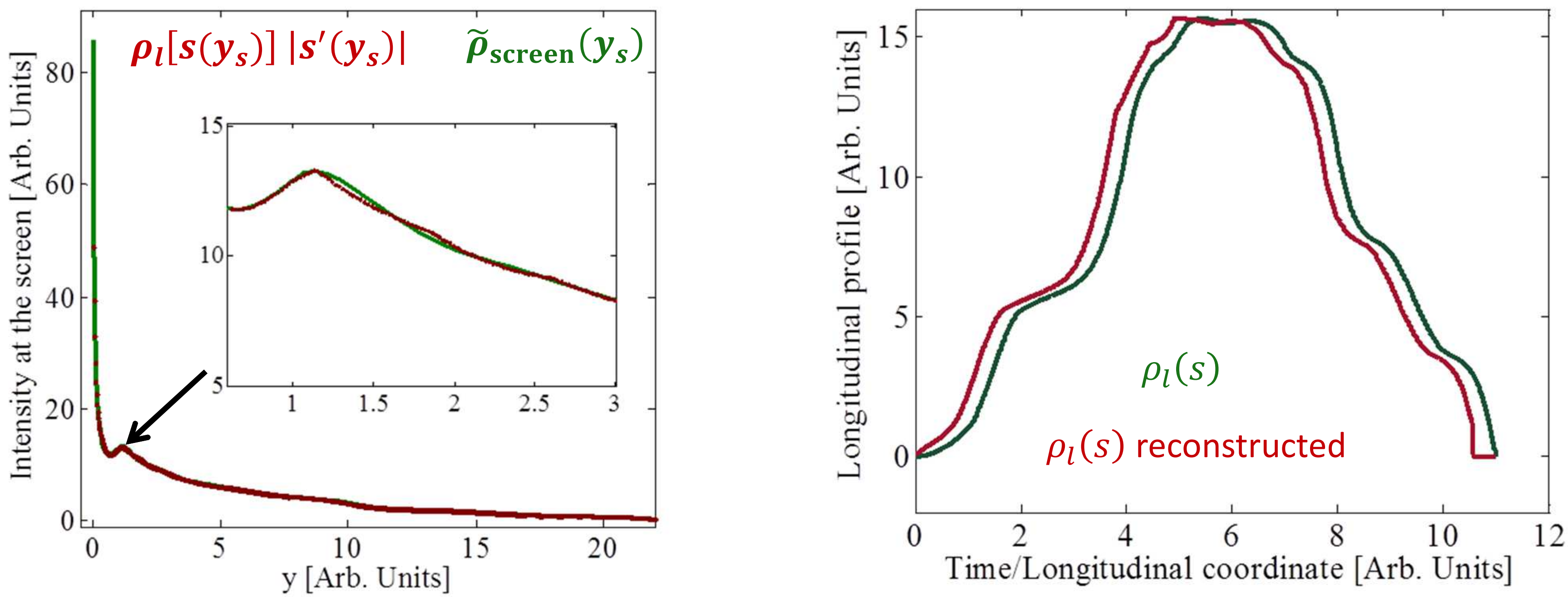
$$y_s(s) \approx \frac{QL_pR_{34}}{E}\left[W_{r,1}(r_0,s) + W_{r,2}(r,r_0,s)\right]$$

$$\boldsymbol{\rho_{screen}(y_s) = \rho_l[s(y_s)]\,|s'(y_s)|}$$

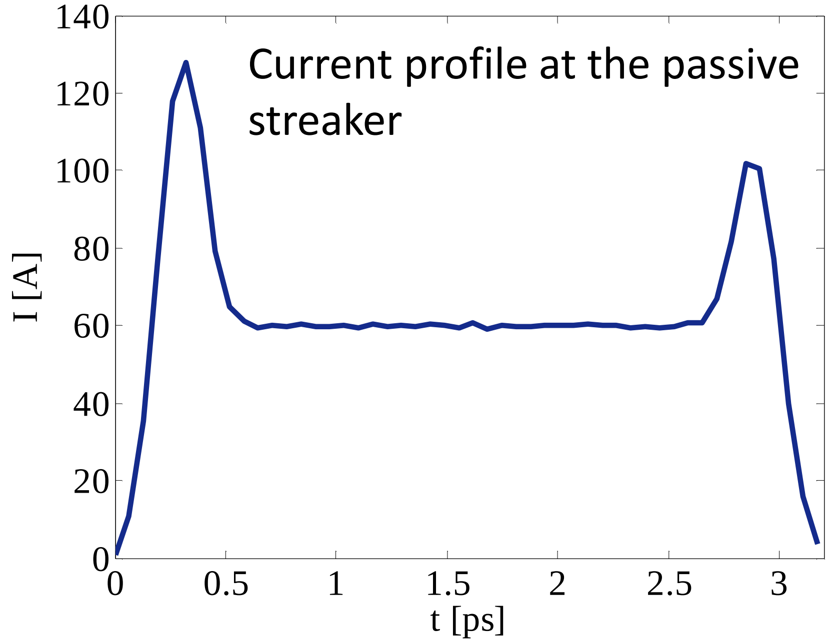
$s(y_s)$ is the *inverse relation* $y_s \to s$

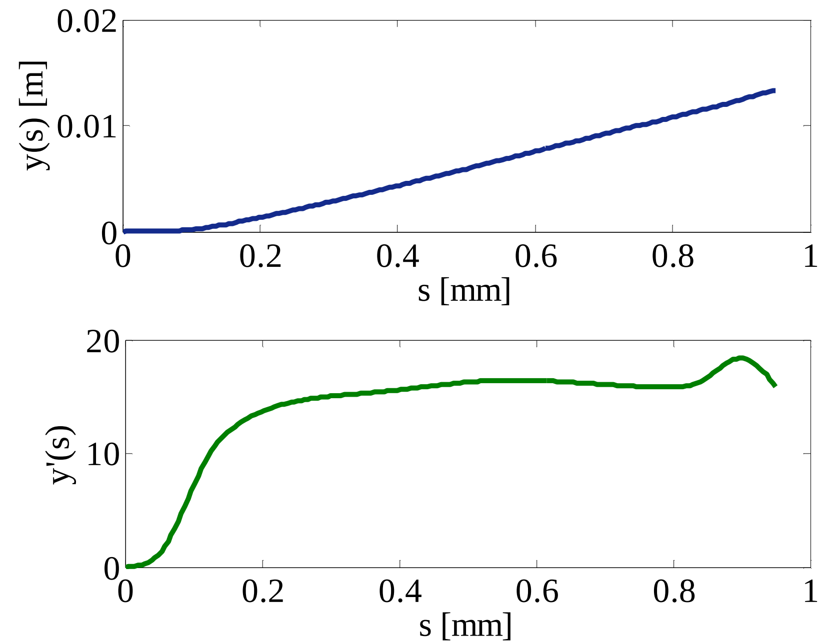
Time-resolving algorithm(s)

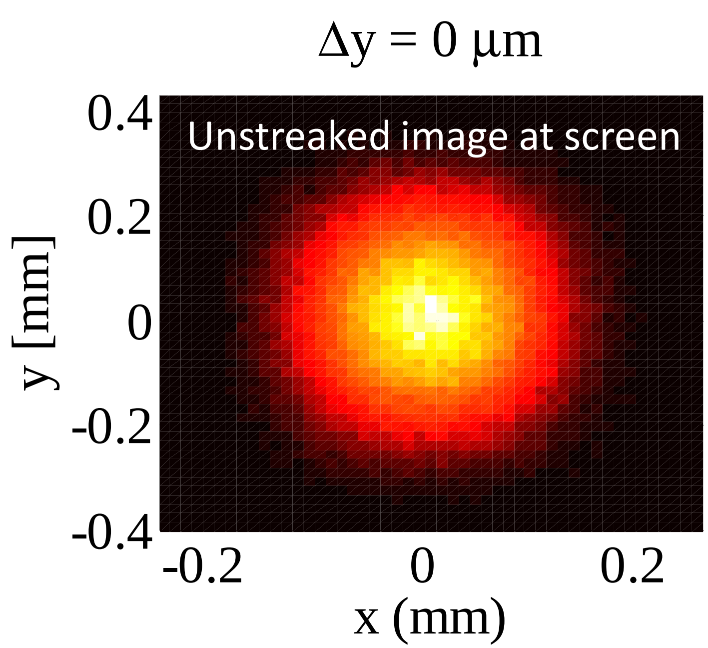
- A possible algorithm iteratively minimizes the distances between the measured profile $\tilde{\rho}_{screen}(y_s)$ and that obtained using the inverse relation to reconstruct the profile at the screen itself $\rho_{screen}(y_s) = \rho_l[s(y_s)]\,|s'(y_s)|$ calculated from current solution $\rho_l(s)$;
- distance is calculated using $||\rho_{screen}(y_s) - \tilde{\rho}_{screen}(y_s)||$ **(cost function)**;
- $\rho_l(s)$ is modeled as a piecewise cubic polynomial (class C1 and avoiding overshoot);
- $y_s(s)$ (and $y'_s(s)$) are evaluated analytically from the polynomial coefficients and the wake function expression;
- $y_s(s)$ is numerically inverted to obtain $s(y_s)$;
- the time-resolving algorithm can move knots and coefficients on a subset (or all) the intervals. After stopping into a local minimum, it can increase number of knots.

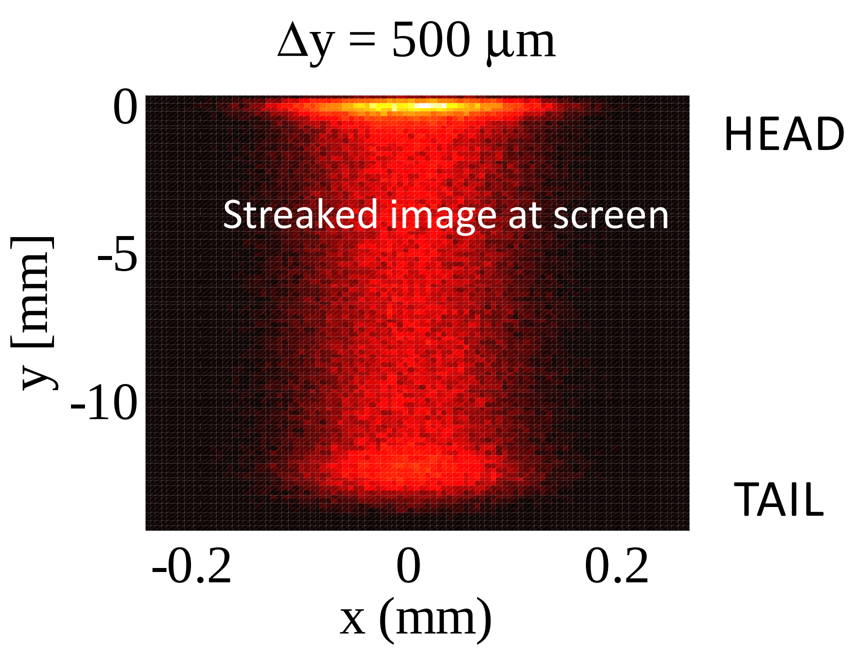


Elegant simulations

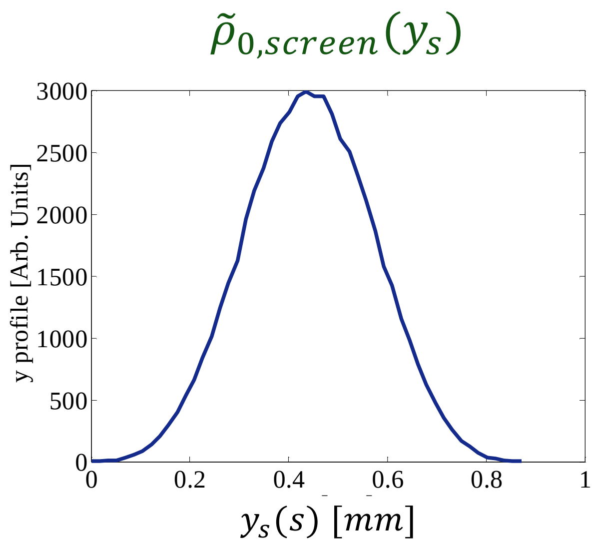






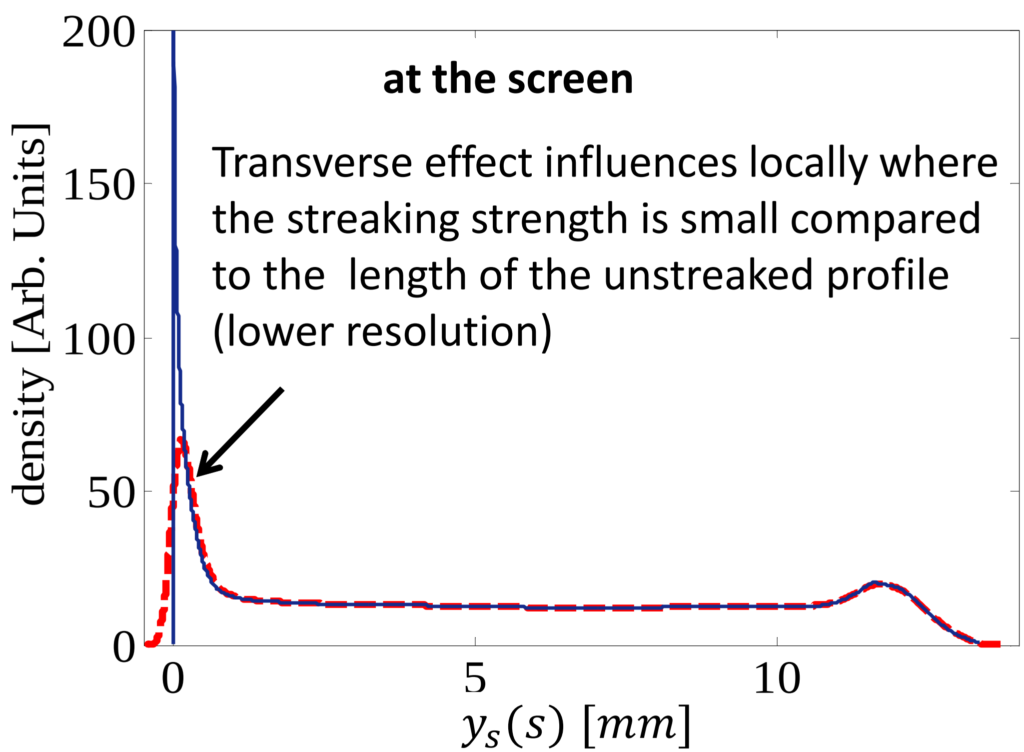


Finite emittance

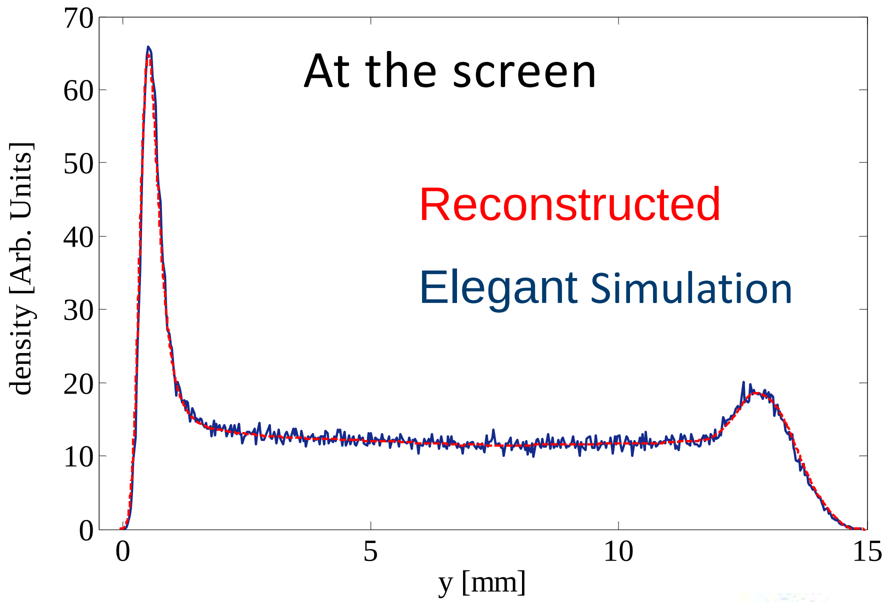


- A real beam has finite size at the screen (even at offset 0 mm);
- for the model used in the reconstruction we consider that the transverse beam parameters are independent of the longitudinal coordinate : $\rho(r,\varphi,s) = \rho_t(r,\varphi)\rho_l(s)$
- optics between the tube and the screen is linear;
- the profile at the screen is evaluated as the convolution of the measured normalized transverse profile when the beam transits the streaker on-axis $\tilde{\rho}_{0,screen}$ and $\rho_s(y_s)$ (zero emittance):

$$\rho_{T,s}(y_s) = \rho_{screen}(y_s) \otimes \tilde{\rho}_{0,screen}(y_s)$$



Example of time-resolved profile

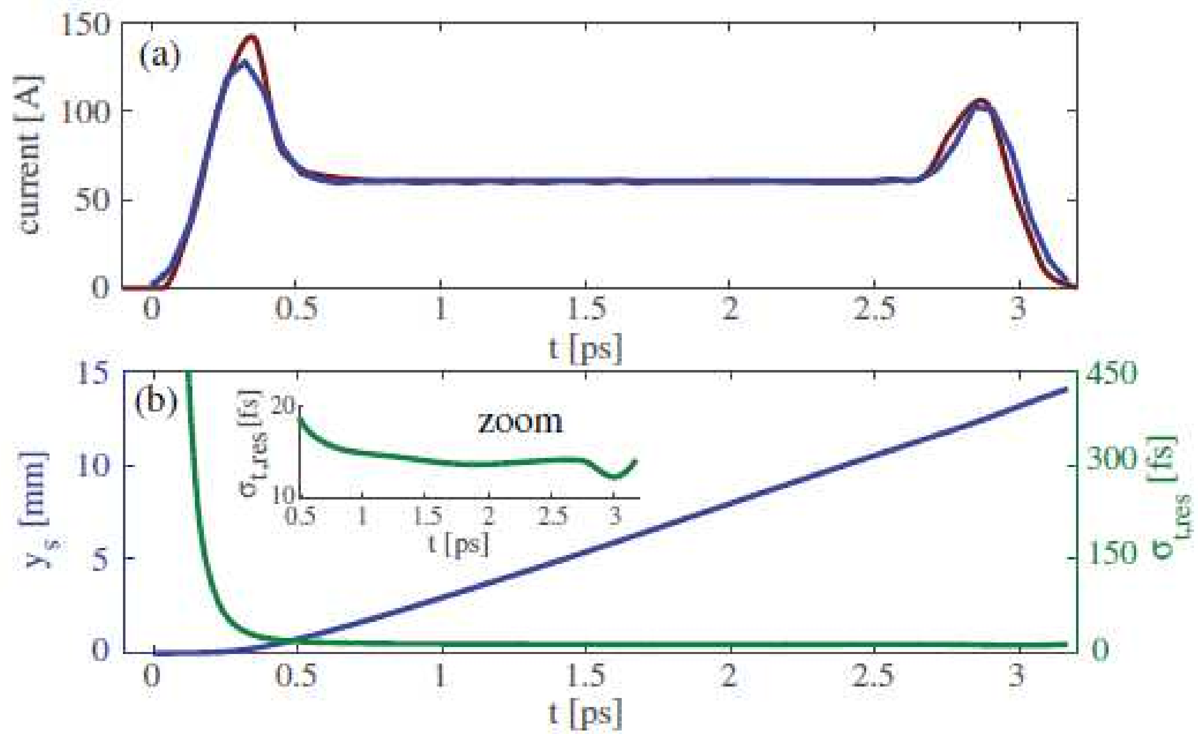


Calibration factor:

$$S(s) = \frac{dy_s(s)}{ds}$$

Resolution:

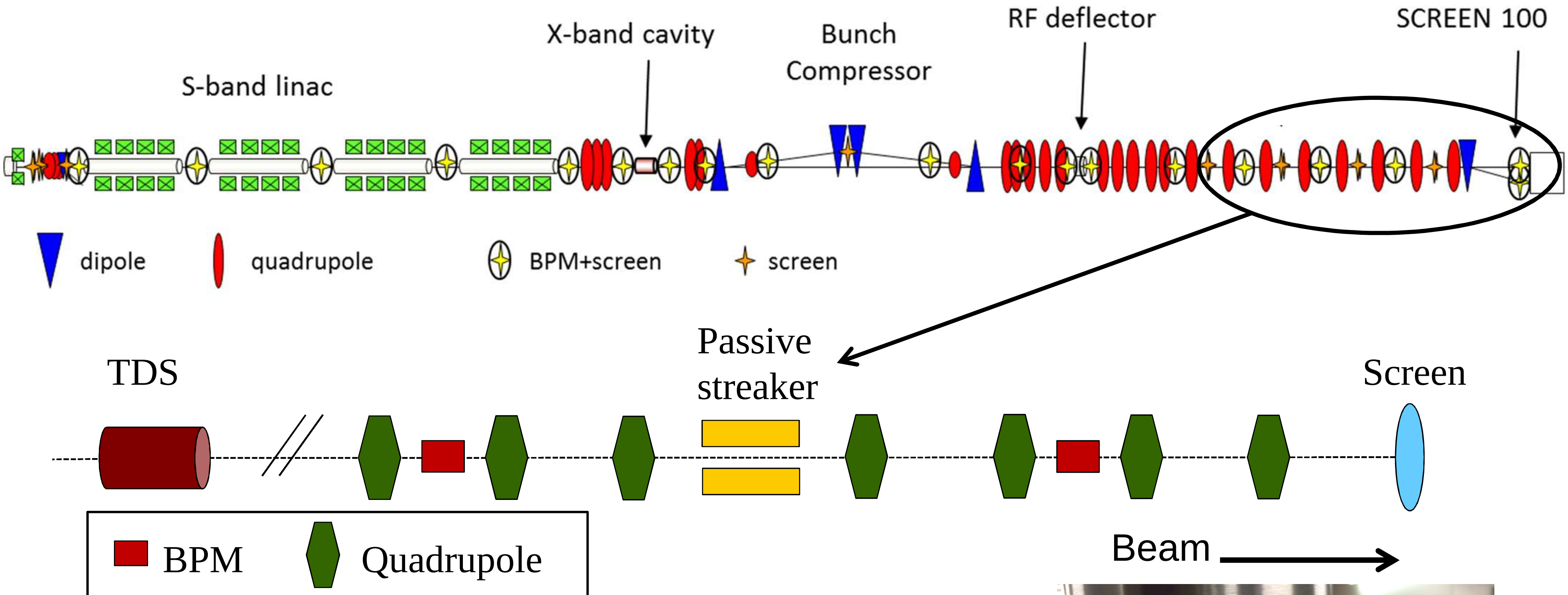
$$\sigma_{s,res}(s) = \frac{\sigma_{y0}}{S(s)}$$



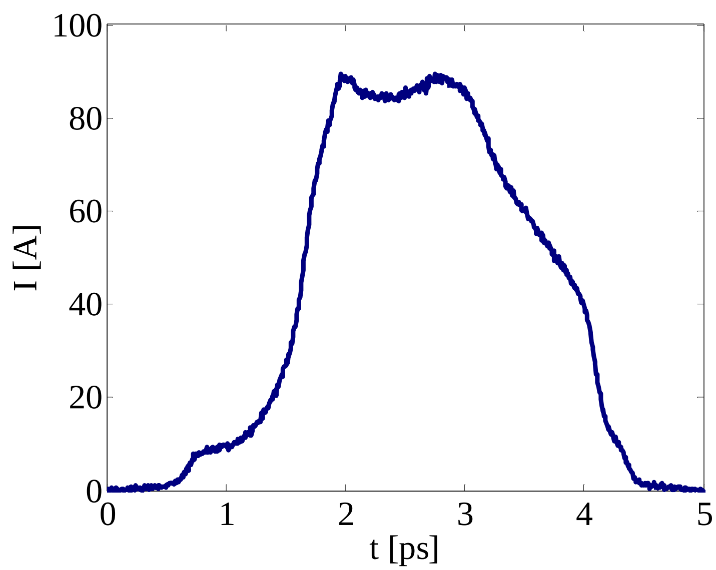
Note again:

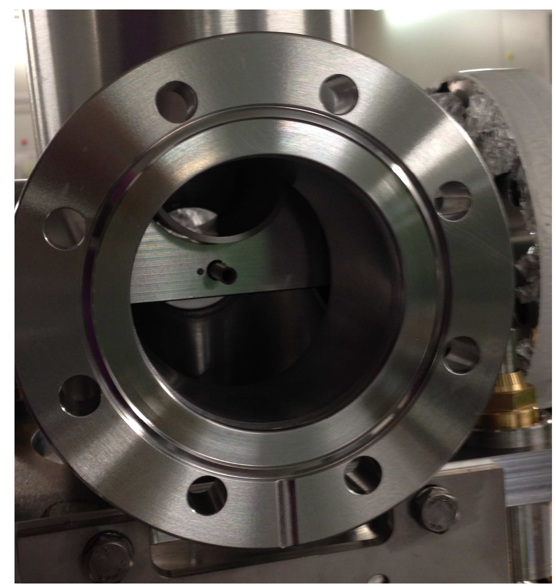
unambiguous reconstruction → wake potential along the bunch ***must be*** a strictly monotonic function of the longitudinal coordinate

Experimental setup at SITF



Electron beam temporal profile measured with the RF deflector

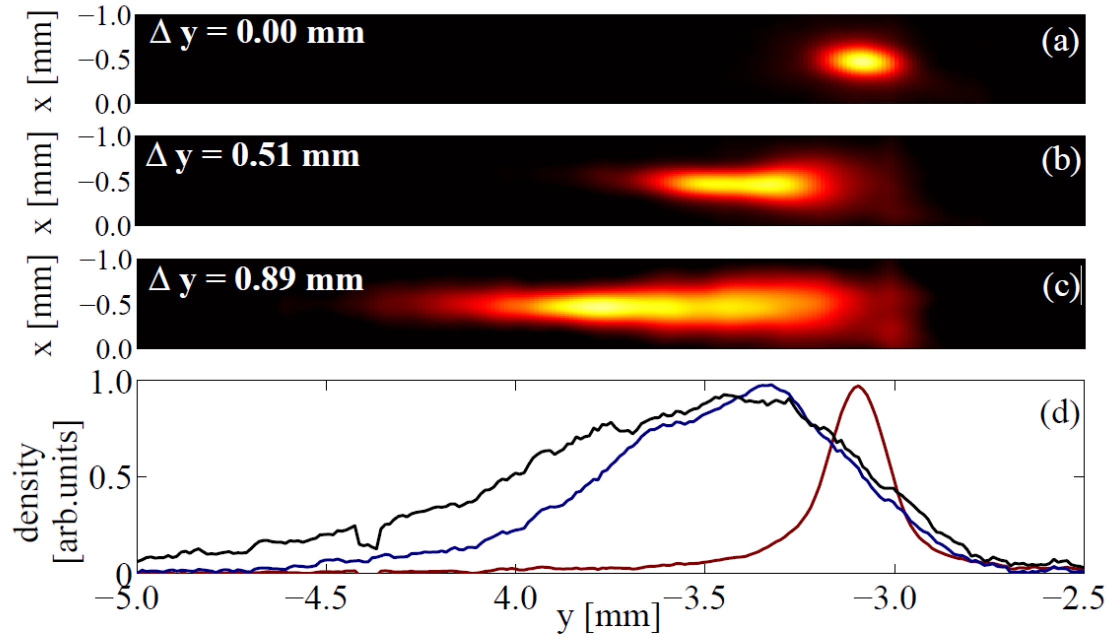


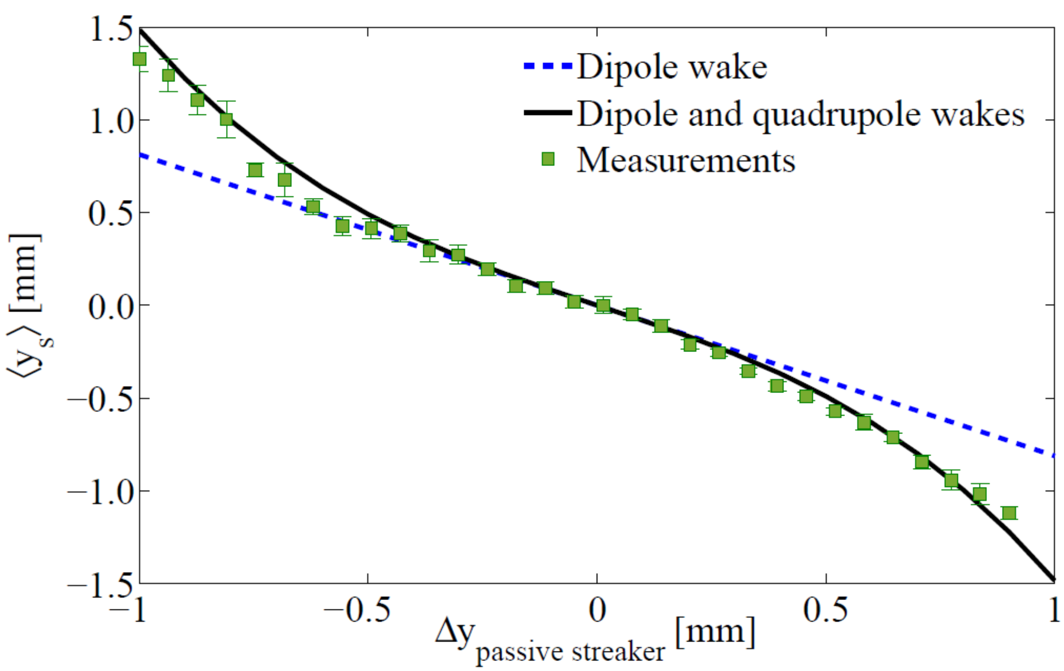


Energy 140 MeV
Bunch charge 200 pC
Bunch length ~1ps (rms)

Streaking on screen

Transverse beam images at screen for different offsets of the passive streaker and corresponding vertical profiles.





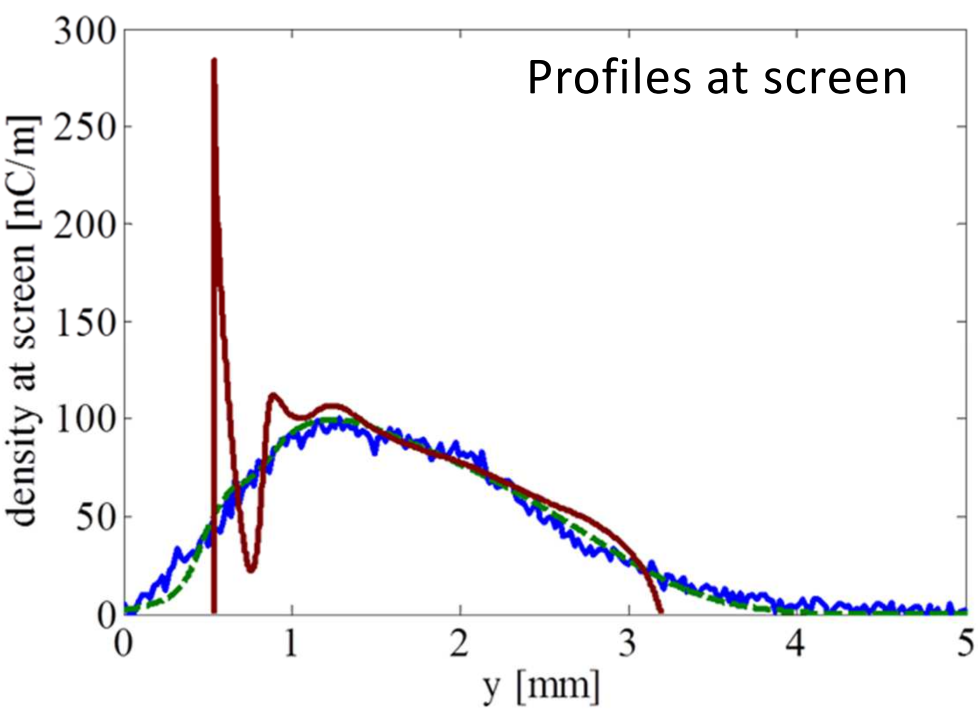
- Measured average vertical beam centroid on the screen as a function of the vertical offset;
- linear kick factor from the model is 0.62 MV/(nC·m·mm);
- cubic kick factor from the model is 0.52 MV/(nC·m·mm^3);
- Fitting with a cubic polynomial:
  linear kick factor 0.63 MV/(nC·m·mm) ,
  cubic kick factor 0.43 MV/(nC·m·mm^3).

Defocusing due to the quadrupole

- Transverse beam size at the passive streaker : 360 um (rms) → *too large to neglect the defocusing effect from the quadrupole wake;*
- The charge distribution at the screen used for the convolution, to include the defocusing effects for a transverse beam distribution at the streaker $\rho_\tau(y)$ is:

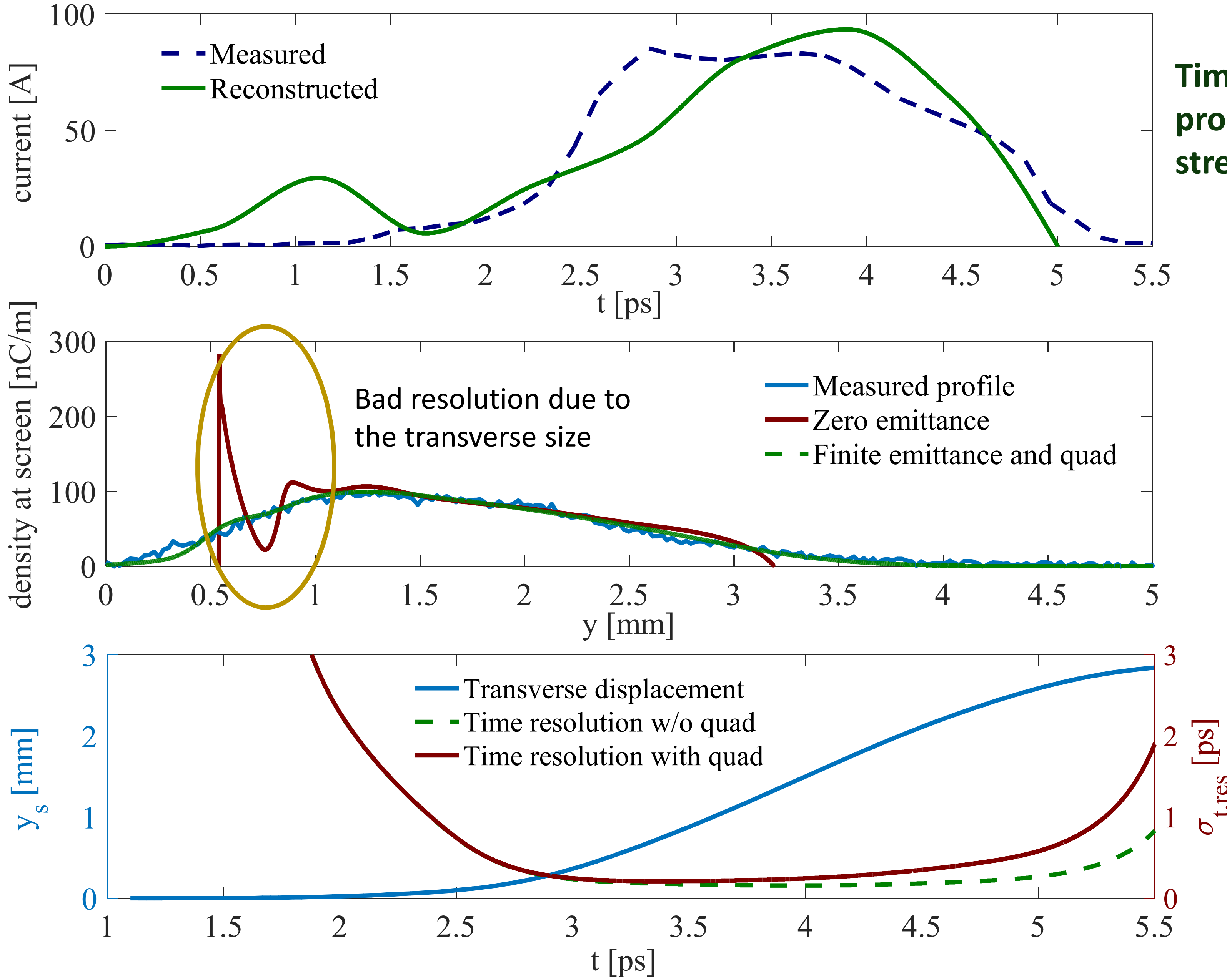
$$\rho_{\text{screen}}(y_s) = \int \rho_{screen}(\tilde{y}_s)\rho_\tau\left[\frac{\Delta y(y_s - \tilde{y}_s)}{y_{sq}(\tilde{y}_s)}\right]\frac{\Delta y}{y_{sq}(\tilde{y}_s)}d\tilde{y}_s$$

- y_{sq} is the transverse displacement at the screen due to the quadrupole wake only, for a particle at the offset Δy at the tube that is deflected to the coordinate y_s at the screen.



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

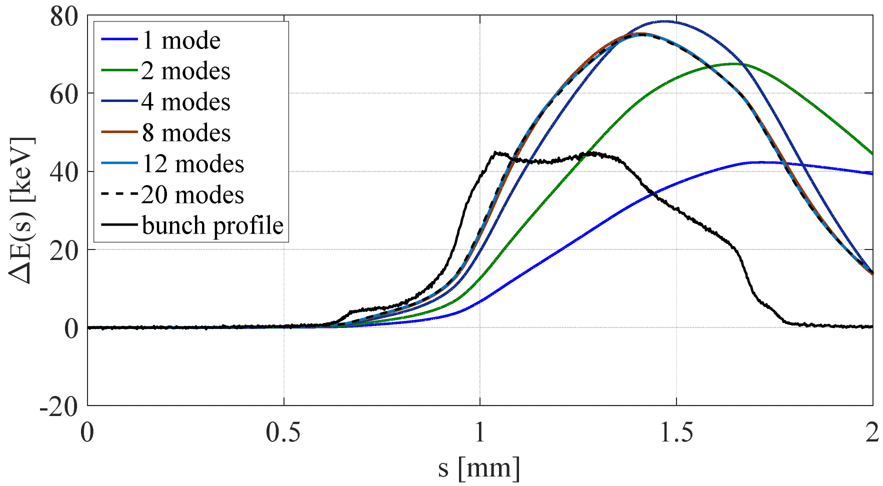
Time-Resolved profile from exp.



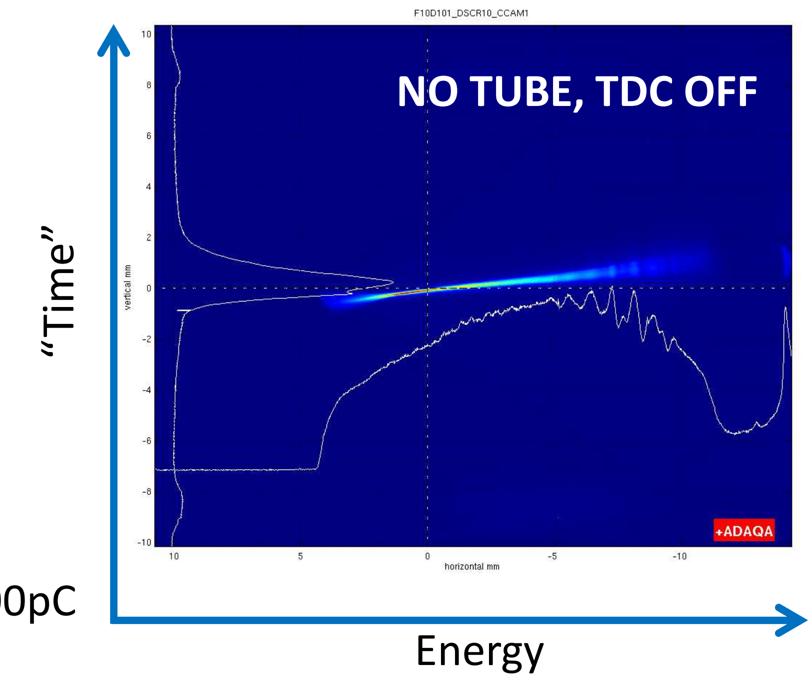
Time-Resolved profile at the streaker

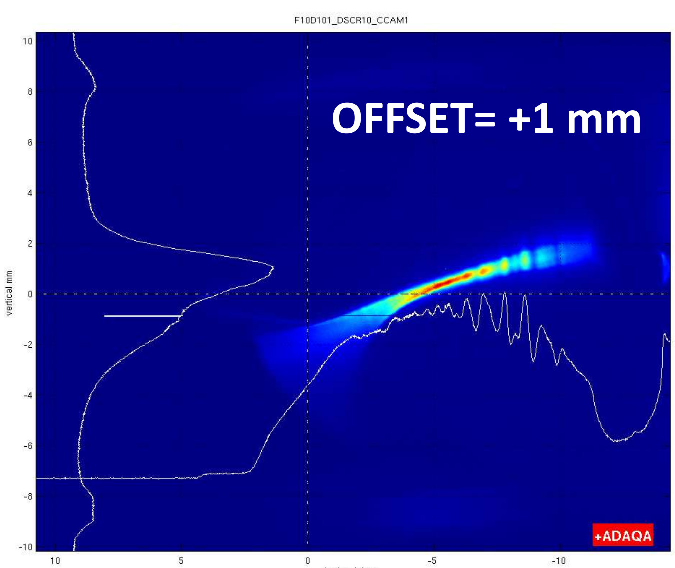
Resolution

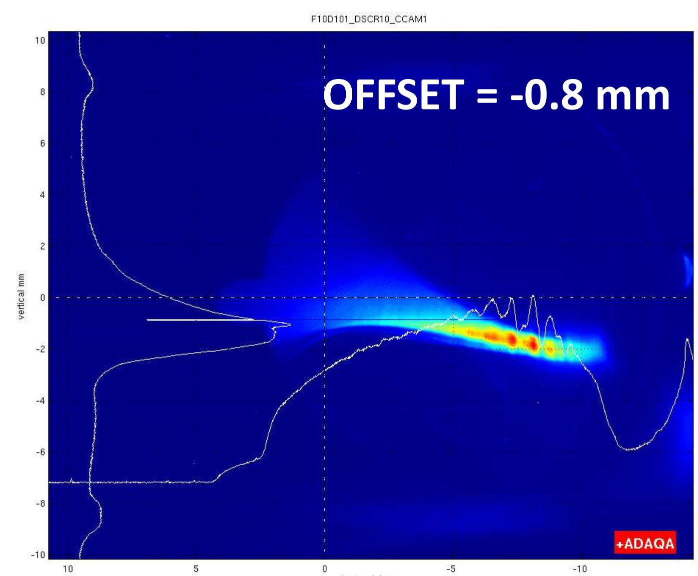
Images at spectrometer



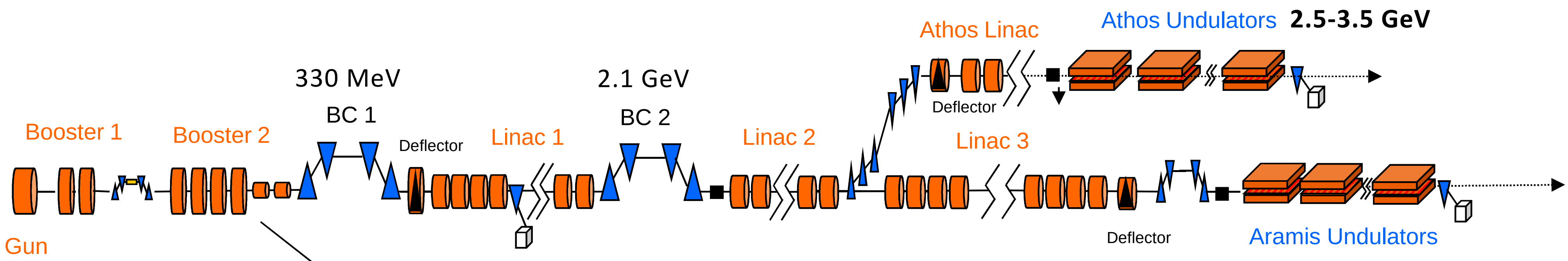
Calculated Loss factor: **2.8 MV/nC/m** → 53 keV @200pC





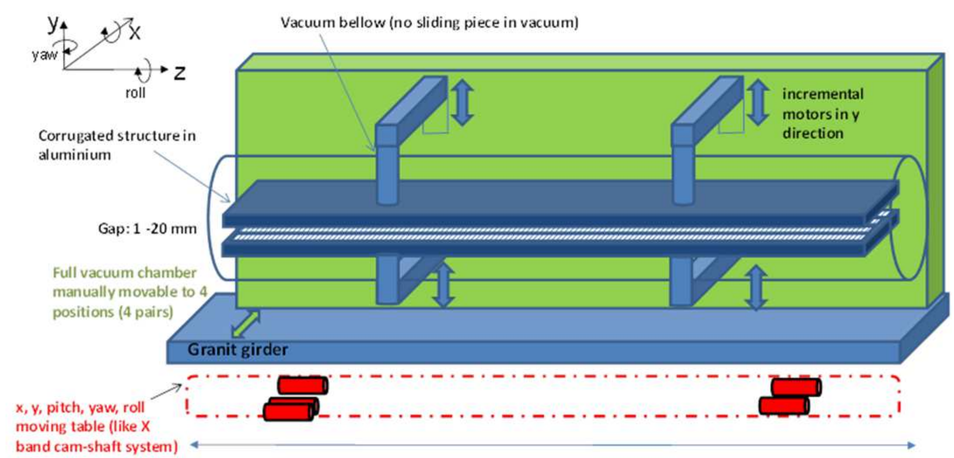


Next steps at SwissFEL



There are ~8 m of space available between Booster 2 and X-band structures

- ❑ Installation of two passive structures multi-purpose
- ❑ Vertical and horizontal orientation in order to study and compensate the defocusing due to the quad components
- ❑ Planar structures with different corrugations and (maybe) dielectric layers

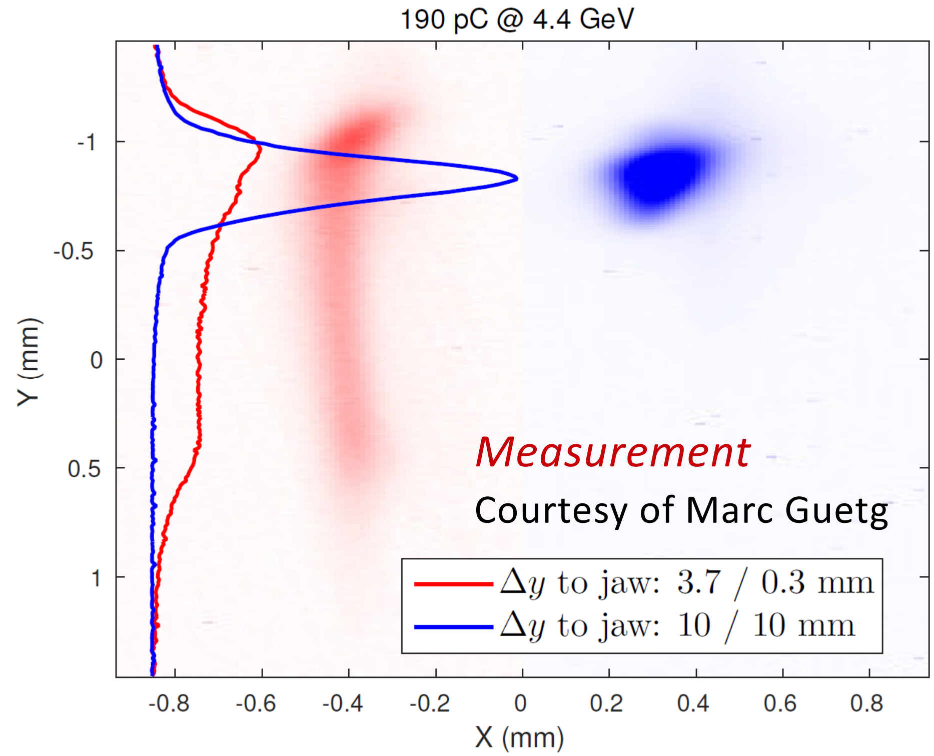


- ❑ Continue on passive streaking activities
- ❑ Study of energy dechirping for the Athos beamline (residual energy chirp is 30 MeV)
- ❑ Passive linearization
- ❑ Two-colors beam based on wakefields generation (see poster by S. Bettoni)
- ❑ Bunch train generation based on wakefield excitation (ref. S. Bettoni)

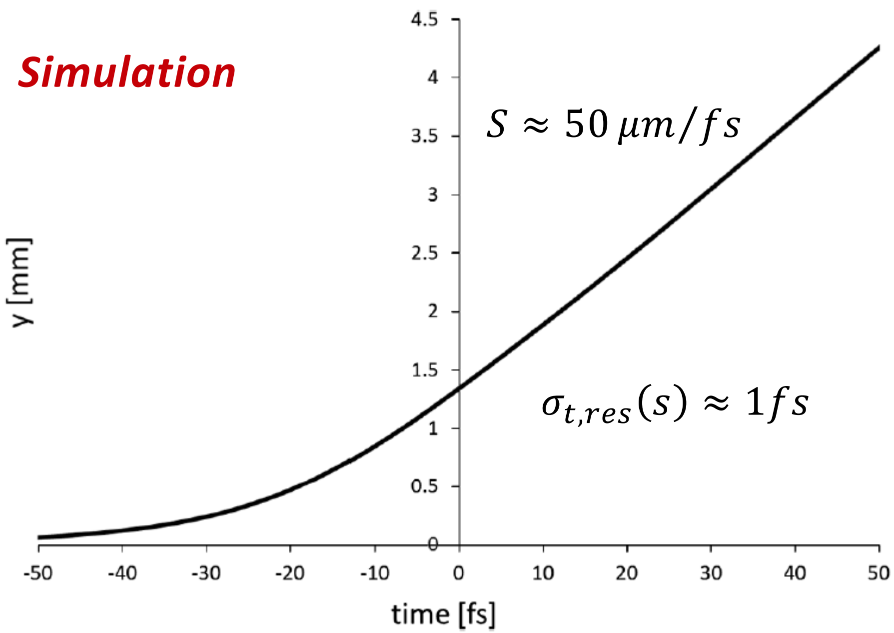
Passive streaking at LCLS

LCLS Dechirper by RadiaBeam System

References: K. Bane and G. Stupakov, NIM A 690, 106 (2012)
Z. Zhang et al. PRST AB 18, 010702 (2015)



Simulation

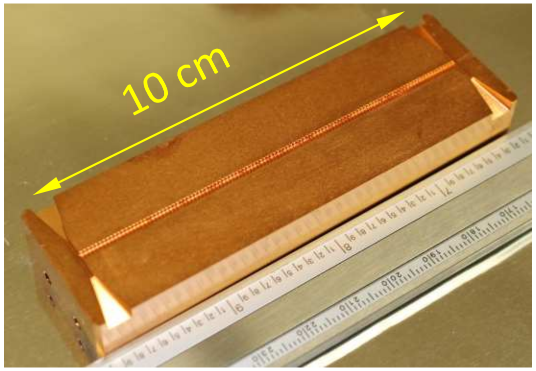


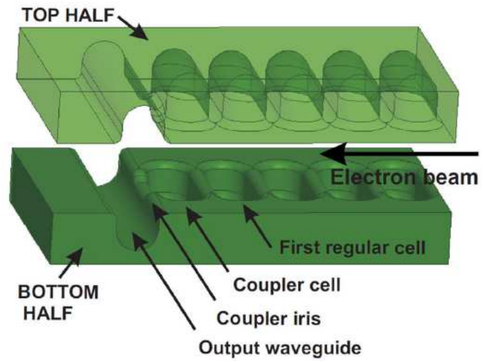
E = 4 GeV
σ_t = 10 fs (rms)
Q = 100 pC

gap = 3 mm
offset = 1 mm

Reference: A. Novokhatski, PRST AB 18, 104402 (2015)

SLAC/FACET E204 experiments

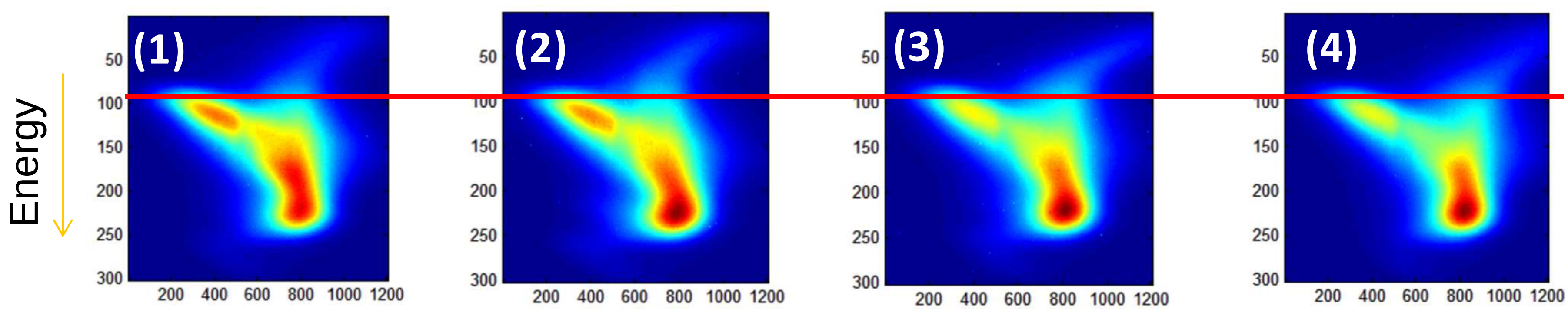


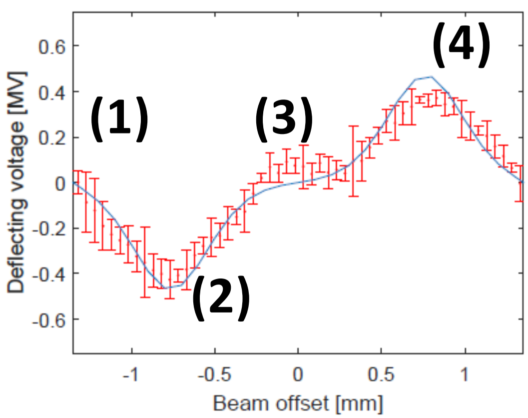


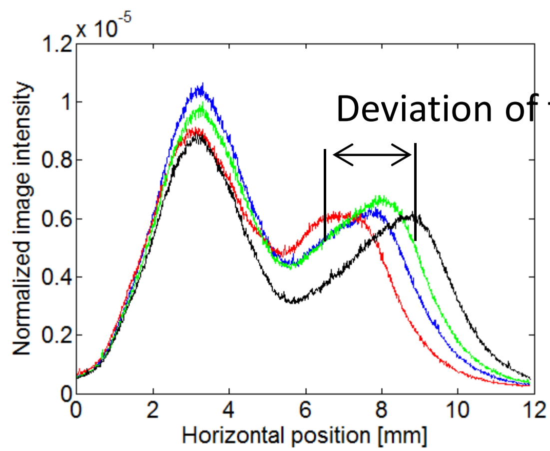
Accelerating structure at 100 GHz

Beam parameters in 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

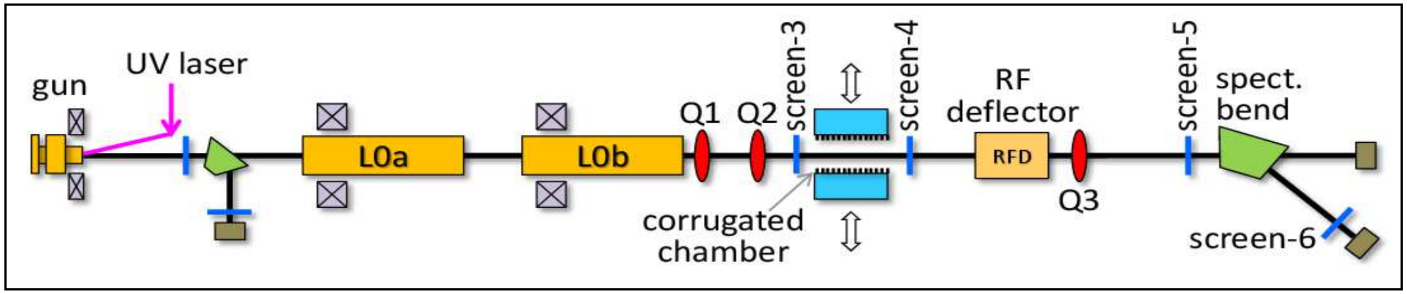
References:

V. Dolgashev, proceeding of FEIS-2 (2015)

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

Passive streaking at PAL

A longitudinal phase space measurement by corrugated structure
J. Hong, C. H. Kim, H.-S. Kang, PAL, Pohang. To be published.



***e⁻* Beam:**

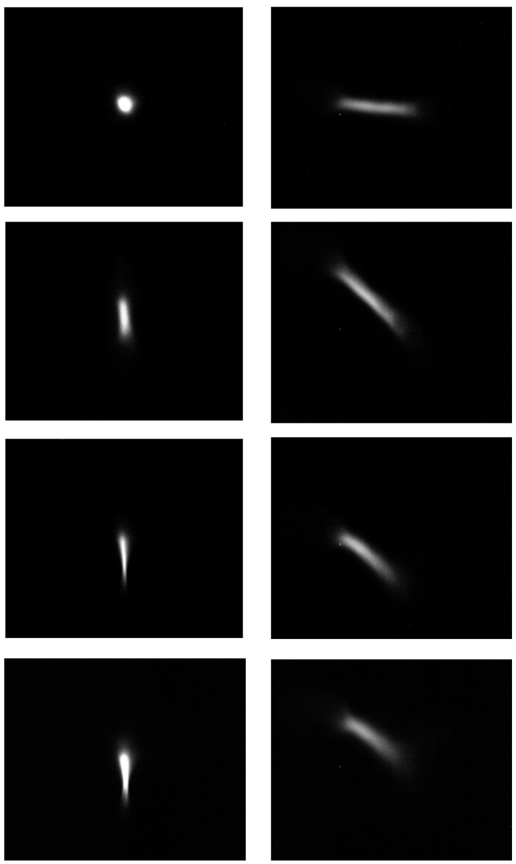
E = 85 MeV

σ_z = 0.45 mm

Q = 200 pC

Ref. for dechirper: P. Emma et al., PRL 112, 034801 (2014)

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

Conclusion

- A passive streaker based on the self-transverse-wakefield can be used to effectively streak the electron beam.
- An algorithm to time-resolve the electron beam has been proposed and verified with simulations .
- A proof-of-principle experiment was performed in SITF.
- Passive streaking presents advantages and disadvantages compared to a standard RF deflectors:

Advantages

- cheaper
- no need of power supplies
- self-synchronized

Disadvantages

- 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)