FEL Seminar | January 2019 | Hamburg | Germany

# Comparative Measurements between CRISP and LOLA-TDS at 13SMATCH.


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on behalf of

E. Hass, N. Lockmann, B. Schmidt, P. Schmüser and P. Winkler

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DESY.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Overview.

> **Introduction CRISP**

> **Coherent Radiation Diagnostics**
  - Frequency domain
  - Reconstruction into time domain

> **Transverse Deflecting Structure**
  - Two Point Tomography

> **Comparison at FLASH1**
  - Experimental setup
  - Data analysis
  - Measurements

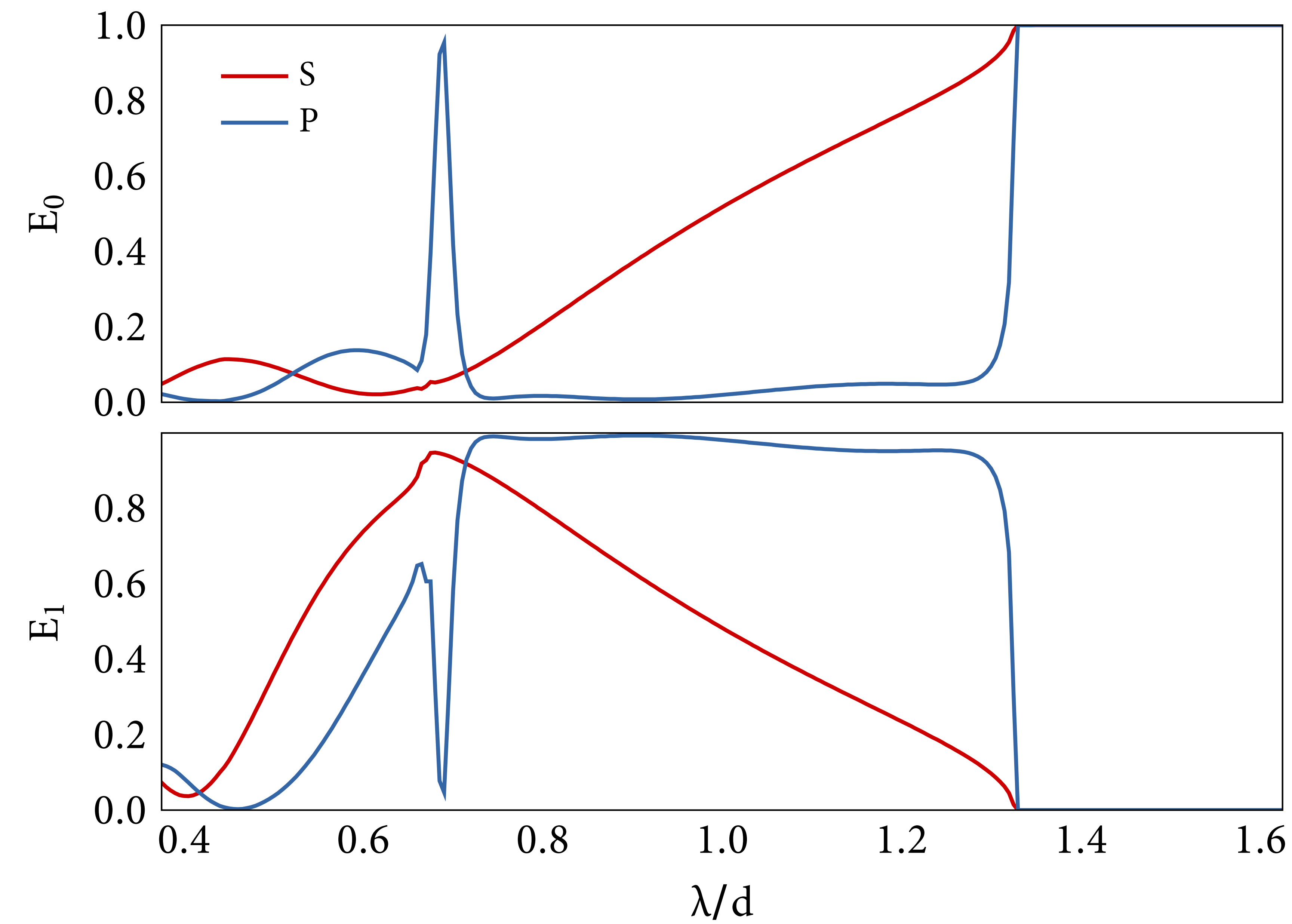
> **Other and new CRISP stations**

> **Summary**

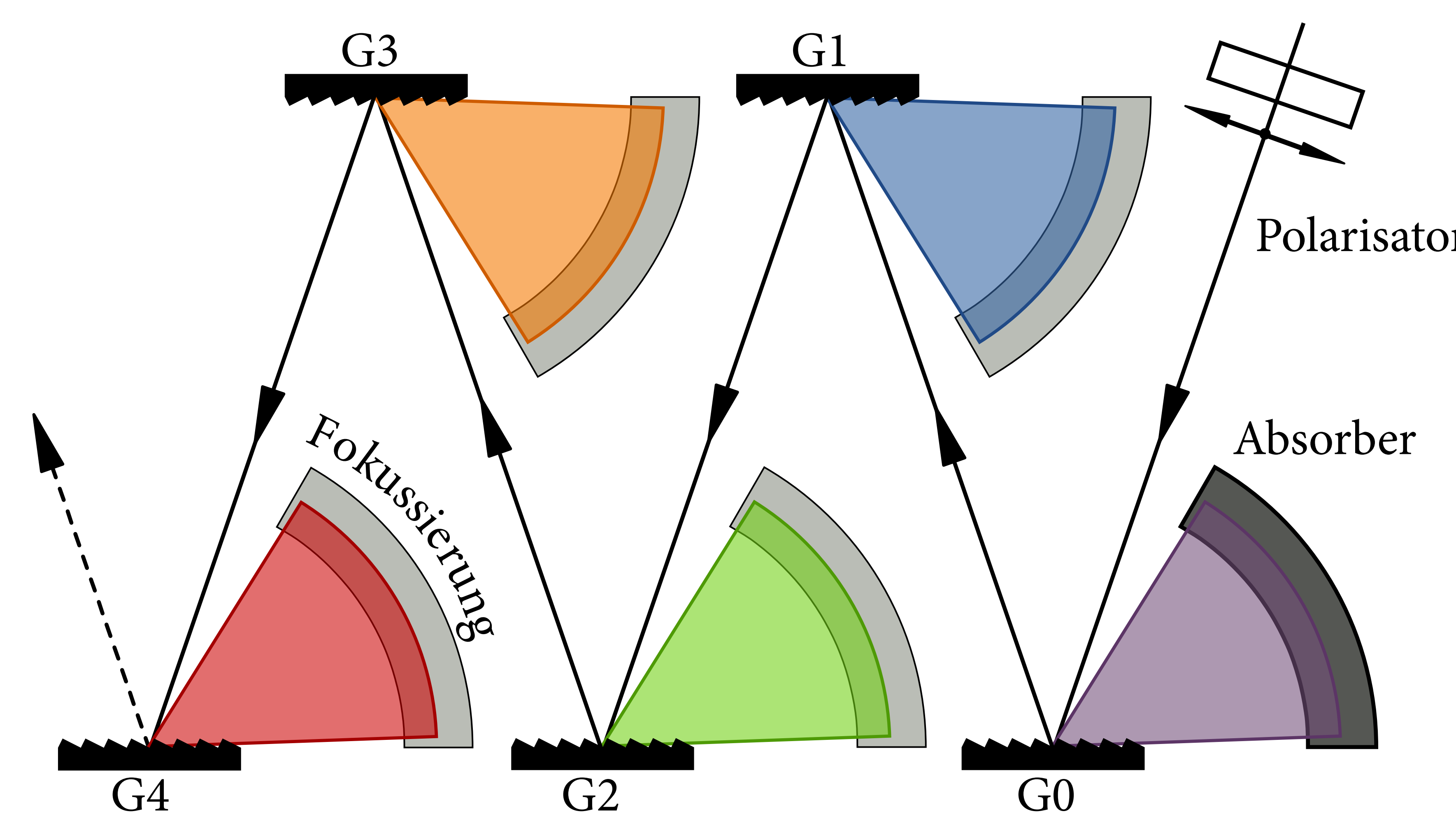
# Introduction.

> **Idea**
- Reflective blazed gratings
- Strong polarization dependency in first and zeroth order
- Acts as low-pass and dispersive element simultaneously

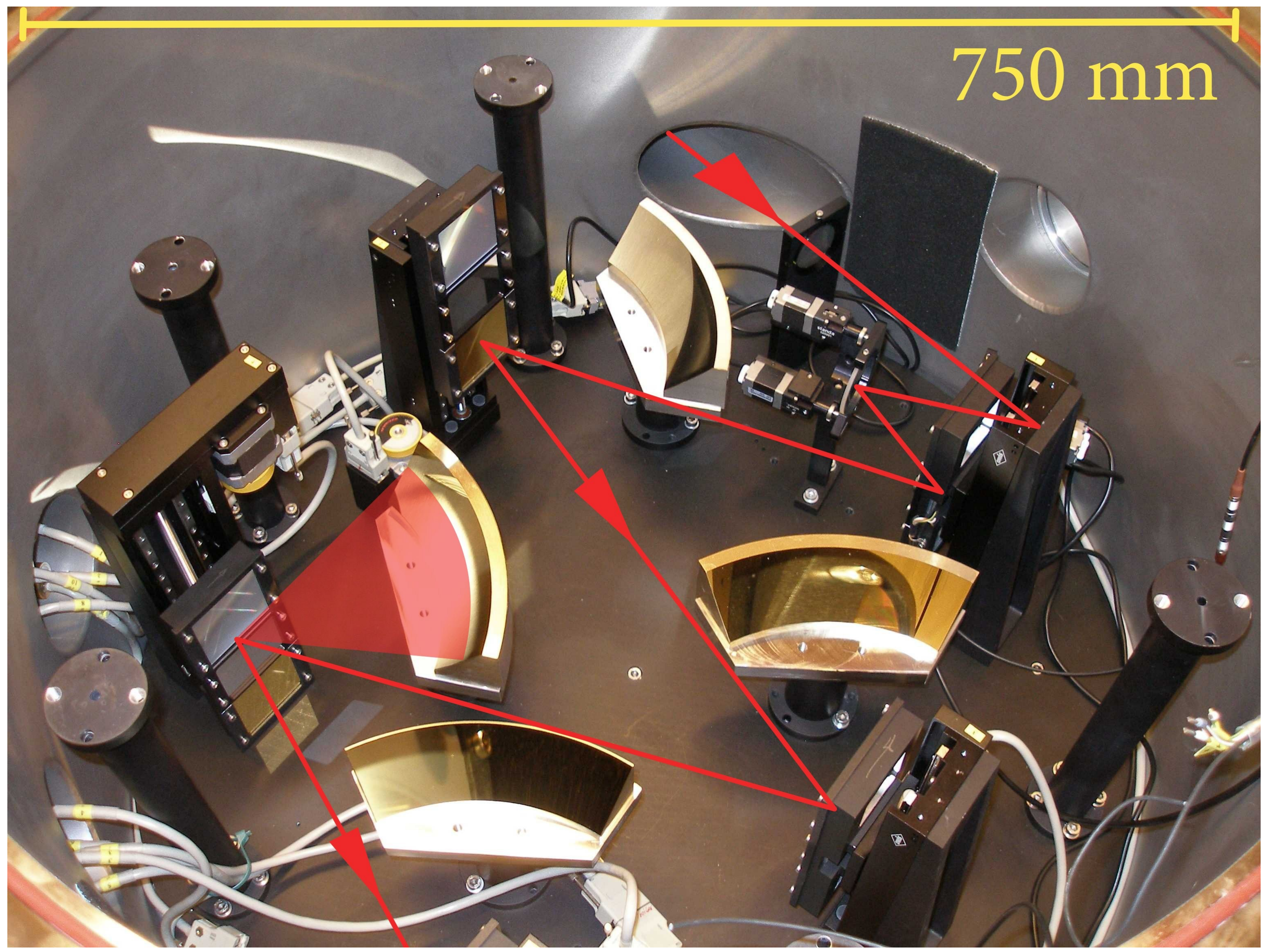
→ Staging to increase band width
→ Broadband single shot spectra



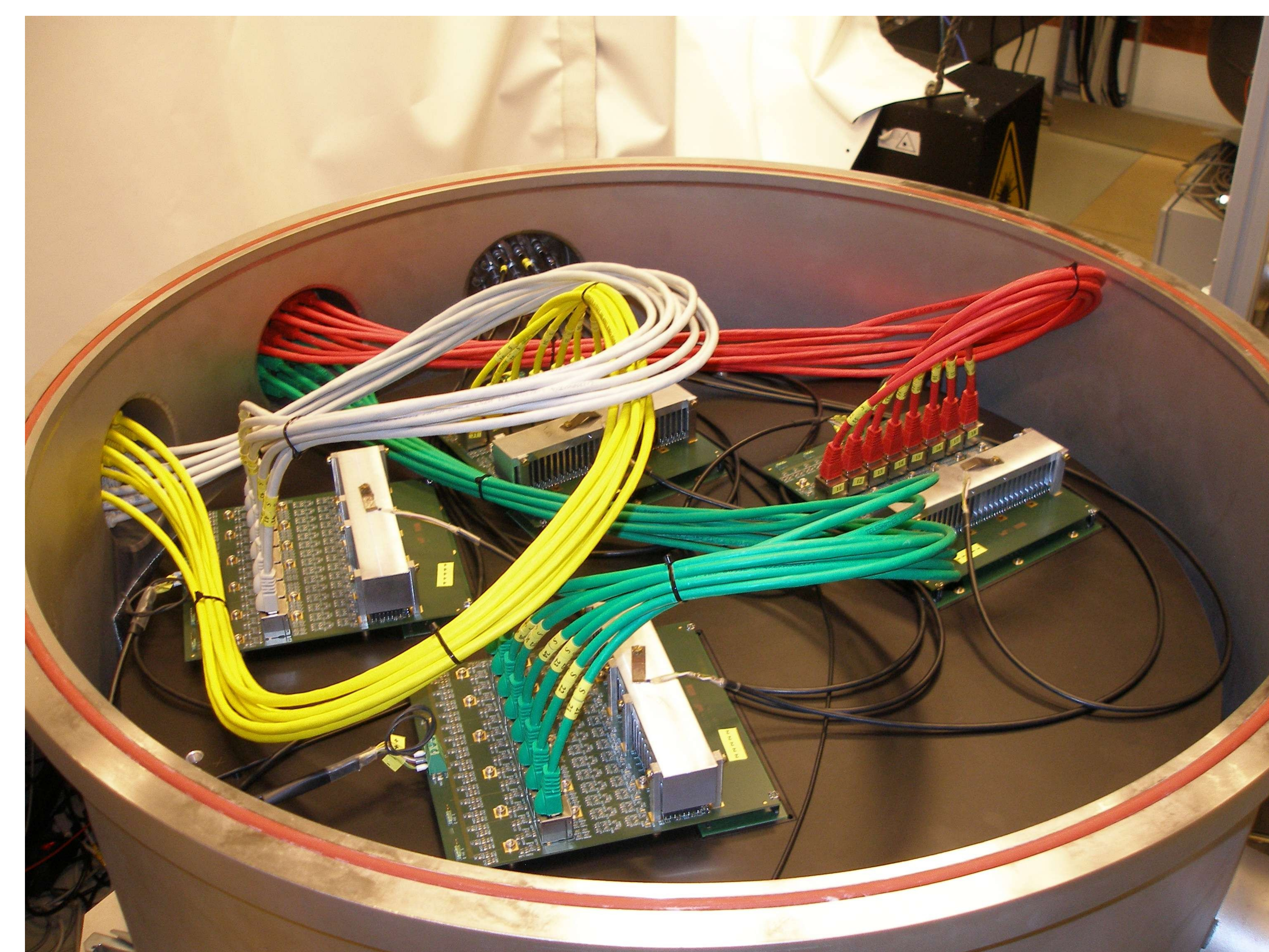

**→ 2-stage prototype by Hossein**
**→ 4-stage „user“ spectrometer**



# Coherent Radiation Intensity SPectrometer.




> **Specs**
- in vacuum
- 2 grating sets
  - 4 – 40 um
  - 40 – 450 um
- focusing ring mirrors
- broadband pyro-electric sensors
- 120 channels
- fast readout on 1 us level

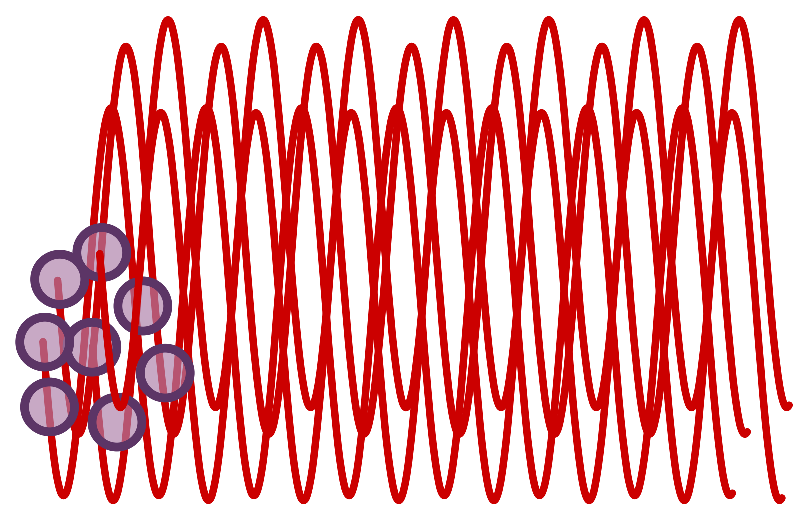


→ **Major design finished in 2010**
→ **Minor changes over last 8 years**

# Coherent Radiation Diagnostic.

> **Radiation emitted by electron bunch**
- Synchrotron, Transition, Diffraction, ...
- Broadband spectrum, deep UV to far infrared / THz
- Small opening angle ~1/γ

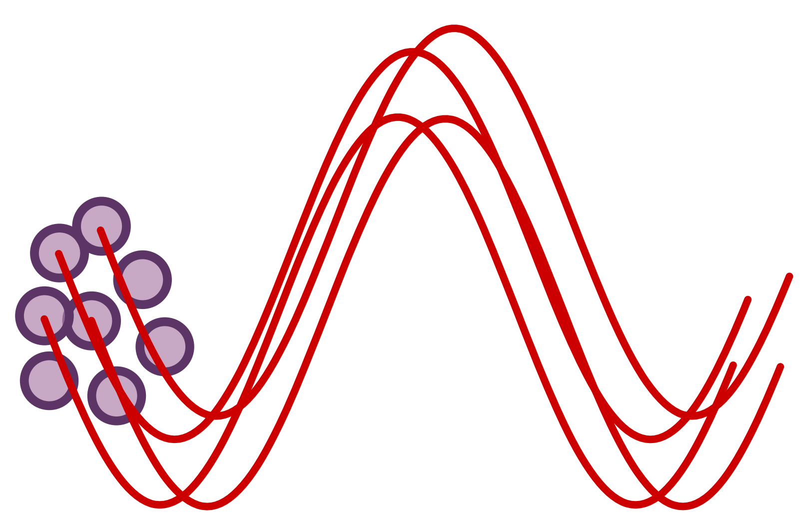
$\lambda \ll \sigma_z$



$$E \propto \sqrt{N}$$
$$I \propto N$$

**fully incoherent** (random interference)

$\lambda \gg \sigma_z$



$$E \propto N$$
$$I \propto N^2$$

**fully coherent** (constructive interference)

→ **Increase of radiated intensity by number of electron in bunch (N ~10^9)**
→ **Frequency dependent**

# Coherent Radiation Diagnostic.

> **Radiated spectral intensity**

$$\frac{dU_{\text{coh}}}{d\lambda} \approx \frac{dU_{\text{sing}}}{d\lambda} \cdot N^2 \cdot |F_{\text{long}}(\lambda)|^2$$

**But phase information is lost!**

> **Form factor == Fourier transform** (transition between extreme cases)

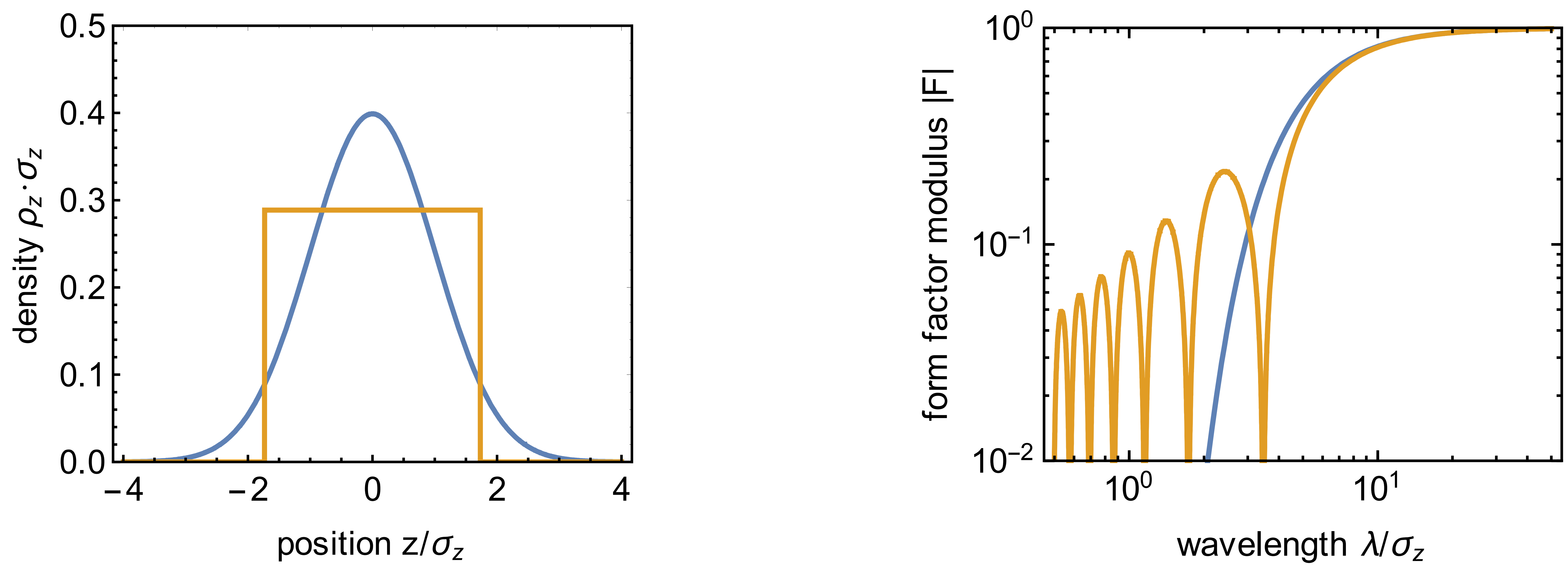
$$F_{\text{long}}(k) = \int \rho_{\text{long}}(z) \; \exp(-\mathrm{i}k \cdot z) \, dz$$

$$F_{\text{long}}(k) = |F_{\text{long}}(k)| \; \exp\left(\mathrm{i}\Phi(k)\right)$$

→ **Get modulus of the form factor by measuring the spectral intensity**

# Coherent Radiation Diagnostic.

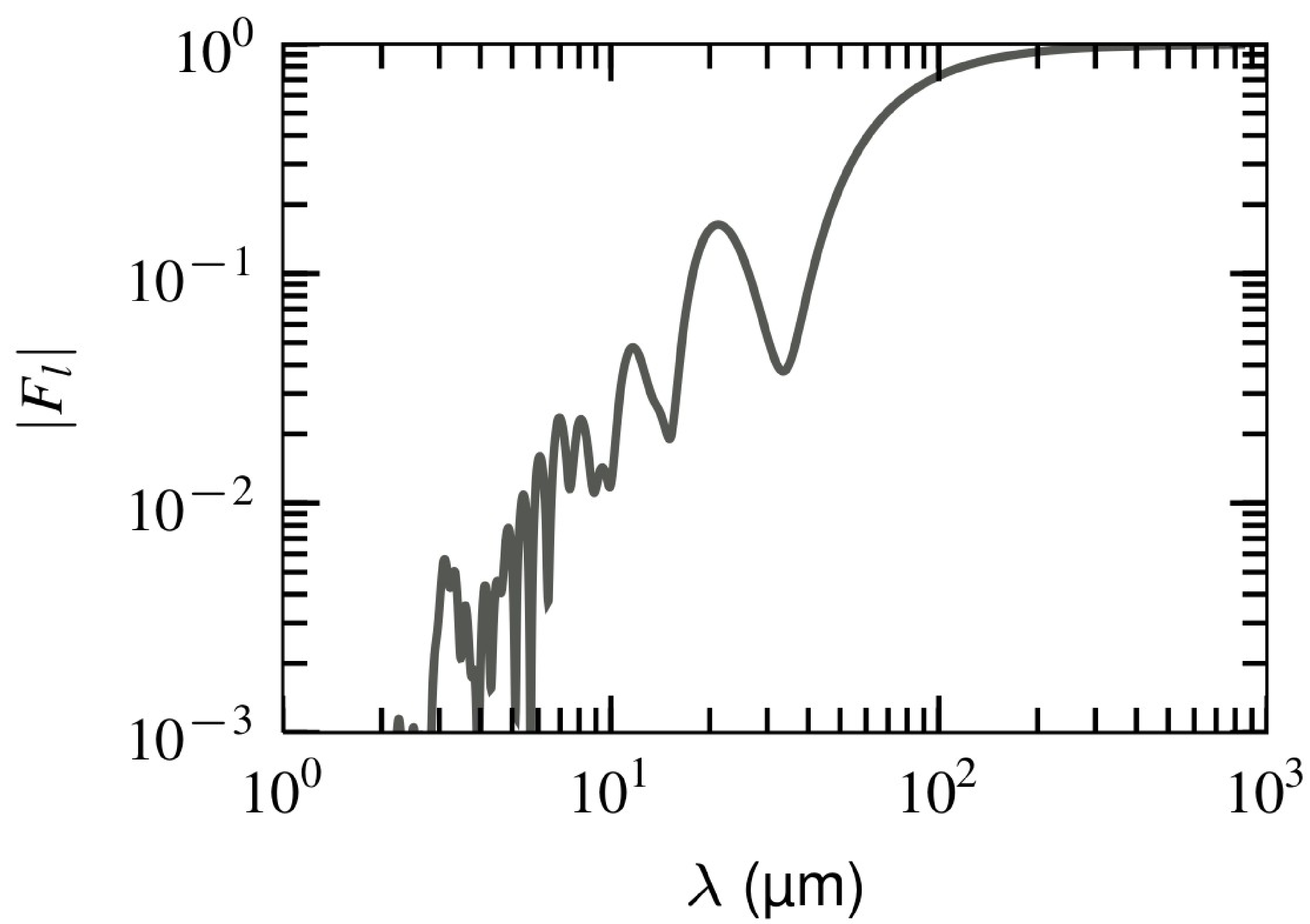
> **Example: Gaussian and rectangular profiles with <u>same</u> RMS lengths**

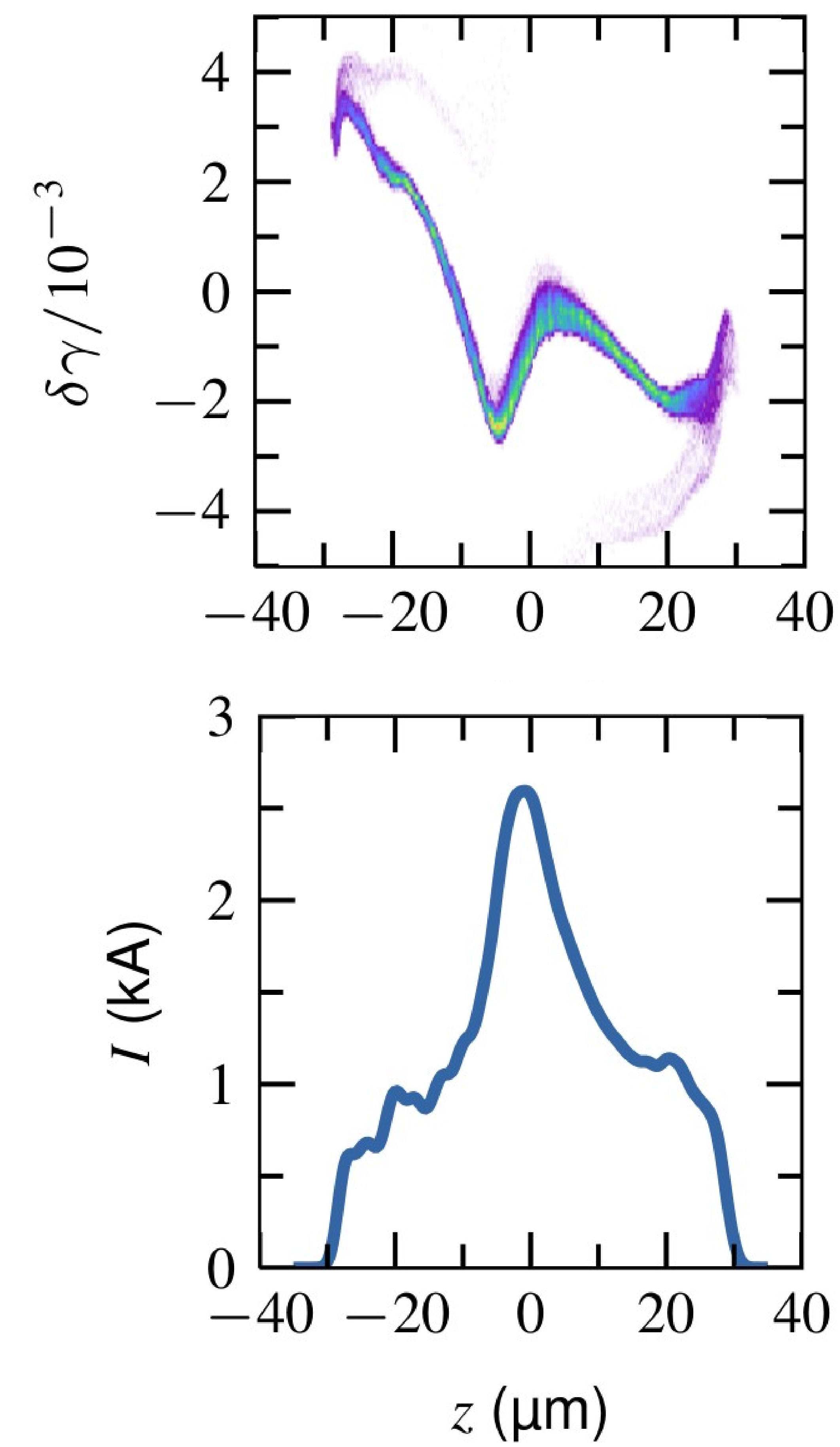



**→ Resolvable with a spectral measurement**

# Coherent Radiation Diagnostic.

**> Example:** I. Zagorodnov, FLASH beam dynamic simulations (www.desy.de/fel-beam/s2e/)




**→ Form factor modulus is a unfamiliar quantity**

# Profile Reconstruction.

Phase information!

$$\rho(z) = \int F(k)\,\exp(ik\cdot z)\,dk = \int |F(k)|\,\exp\left(ik\cdot z + \Phi(k)\right)dk$$

> **Reconstruction out of the form factor modulus**

- Mathematical statement in 1D
  M. H. Hayes, IEEE Transactions on Acoustics, Speech and Signal Processing, Vol. ASP-30, No. 2, April 1982

1. No unique retrieval of the phase information out of the form factor modulus. It is lost!
2. Reconstructed profiles are ambiguous and reflects only **one** potential solution

- General constraints
  Insensitive on absolute arrival time
  Insensitive on time reversal (bunch tail ↔ head)

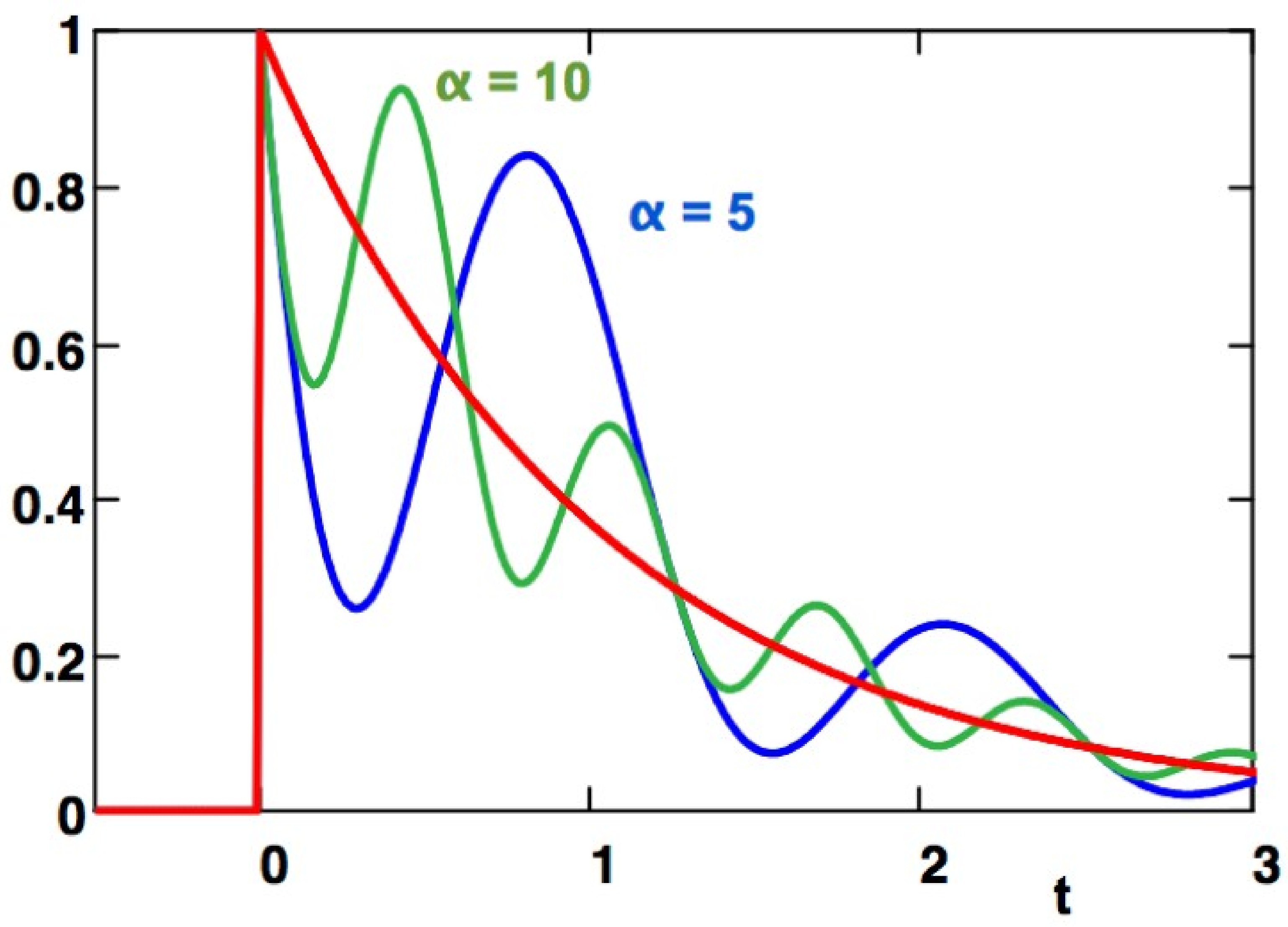
# Profile Reconstruction.

> **Example:** “Akuto”

E. J. Akutowicz, On the Determination of the Phase of a Fourier Integral, Trans. Amer. Math. Soc. 83, 179 (1956)

$$f_1(t) = e^{-\beta t}$$

$$f_2(t) = e^{-\beta t}\left(1 + \frac{4\beta^2(1-\cos(\alpha t))}{\alpha^2} - \frac{4\beta\sin(\alpha t)}{\alpha}\right)$$




$$|\mathcal{F}_1(\omega)| = |\mathcal{F}_2(\omega)| = \frac{1}{\sqrt{\beta^2+\omega^2}}$$

→ **No chance to distinguish between these profiles by measuring |F|**

# Kramers-Kronig Reconstruction.

> **Causal functions**
- Profile / function f → f ($t_0$ < 0) = 0

→ Explicit **analytical** relation

$$\Re(\tilde{f}(\omega_0)) = \frac{1}{\pi} \int \frac{\Im(\tilde{f}(\omega))}{\omega - \omega_0} d\omega$$

$$\Im(\tilde{f}(\omega_0)) = -\frac{1}{\pi} \int \frac{\Re(\tilde{f}(\omega))}{\omega - \omega_0} d\omega$$

> **Adaption to |F|**
- KK phase by using

$$\ln F(\omega) = \ln |F(\omega)| + i\,\Phi(\omega)$$

$$\Phi_{\mathrm{KK}}(\omega) = \frac{2\omega}{\pi} \mathcal{P} \int_0^{\infty} \frac{\ln(|\mathcal{F}(\omega')|) - \ln(|\mathcal{F}(\omega)|)}{\omega^2 - \omega'^2} d\omega'$$

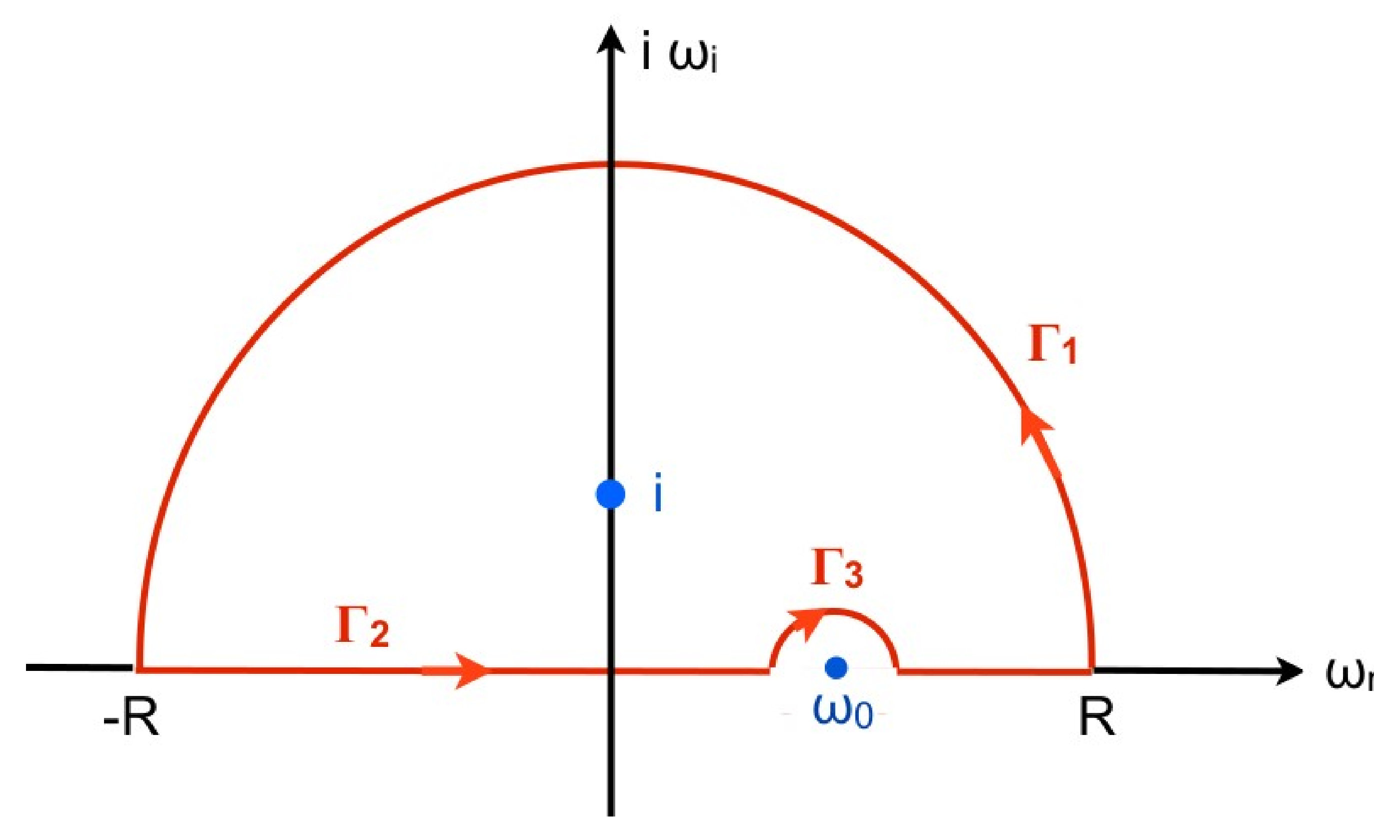
- Solving the principle value in complex plane

  R. Lai, U. Happek, and A.J. Sievers,
  Phys. Rev. E **50**, R4294 (1994)

- |F| may have zeros in the upper half plane

  W. Blaschke, Berichte Math.-Phys.,
  Kl. Sächs. Gesell. der Wiss. Leipzig, 67 (1915), 194-200

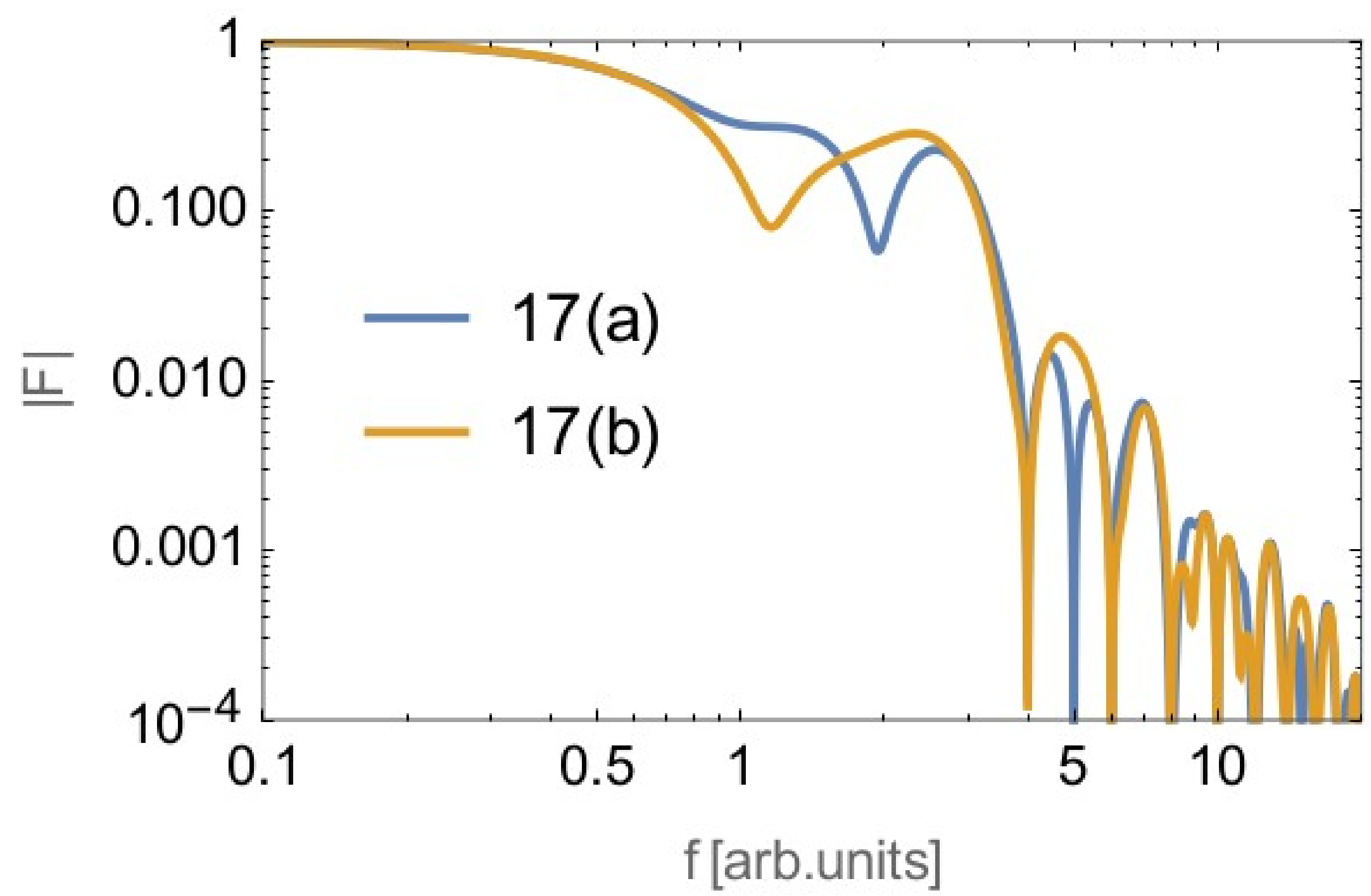
- Contribution of "Blaschke Phase" **inaccessible**



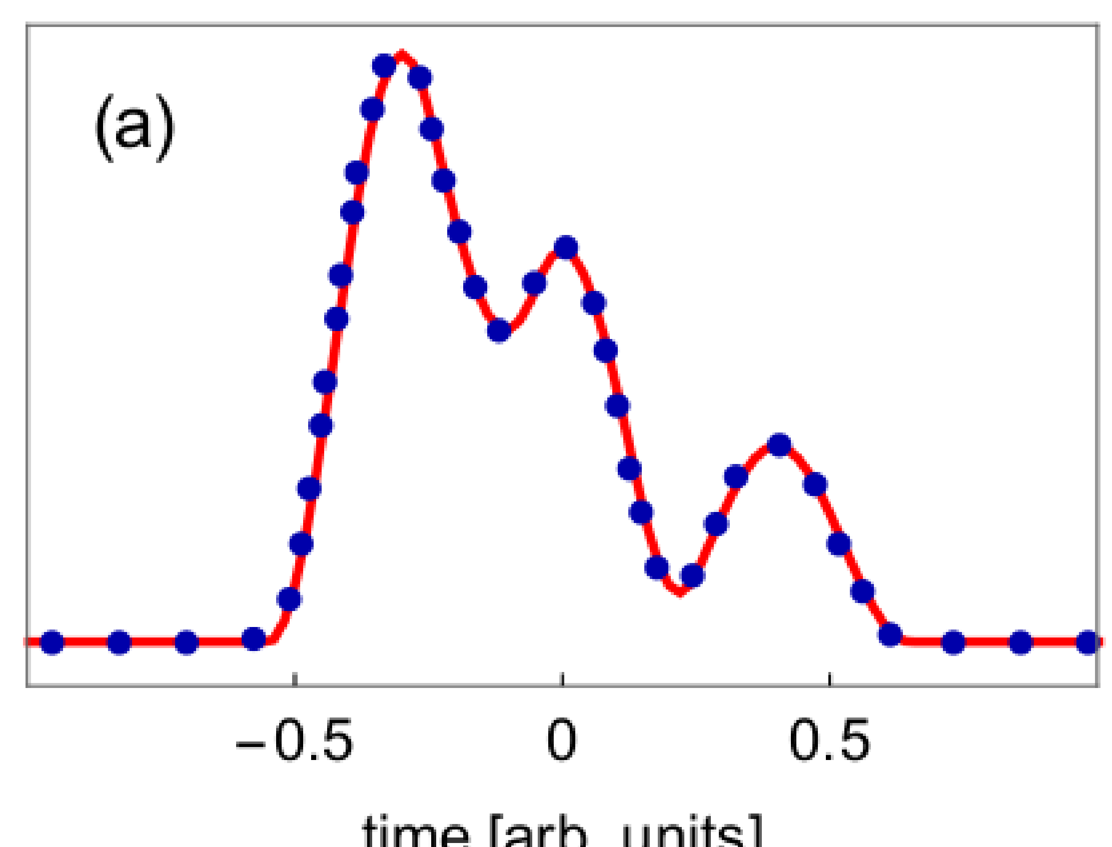

**→ Perfect reconstruction only if the form factor has no complex zeros**

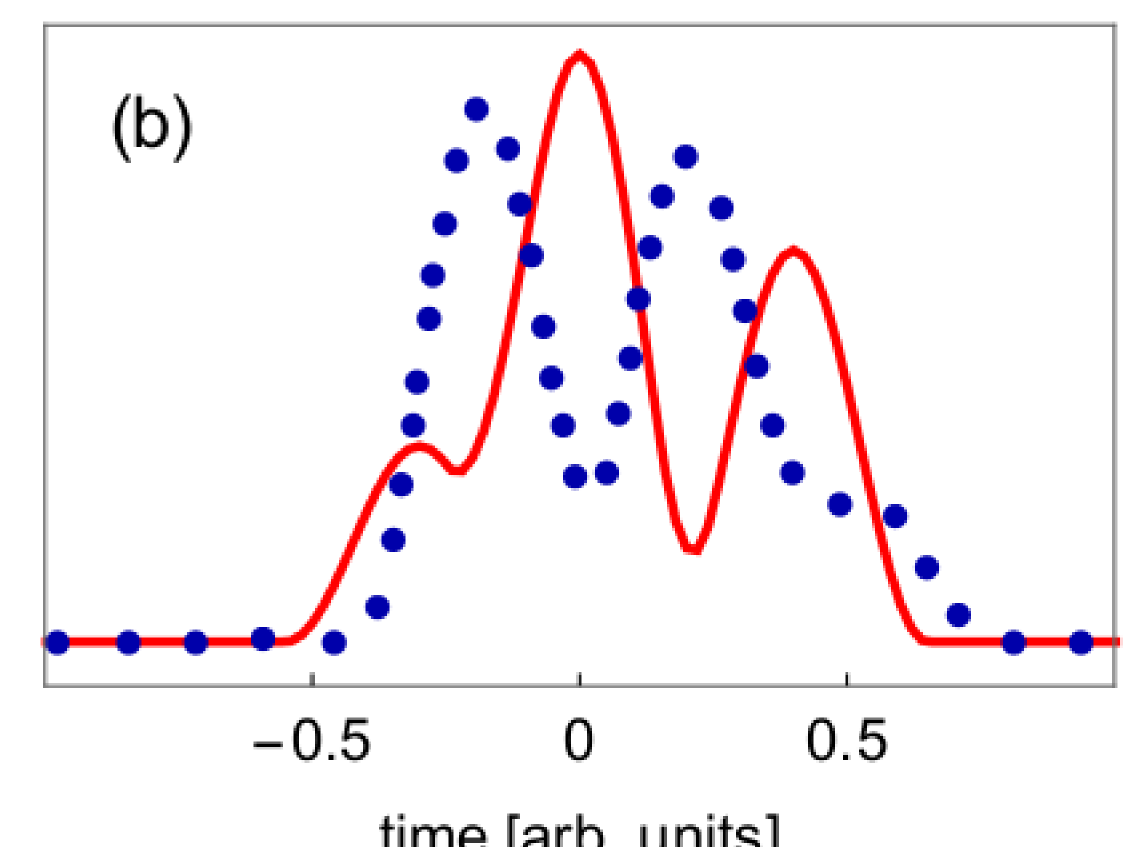
# Kramers-Kronig Reconstruction.

> **Examples**



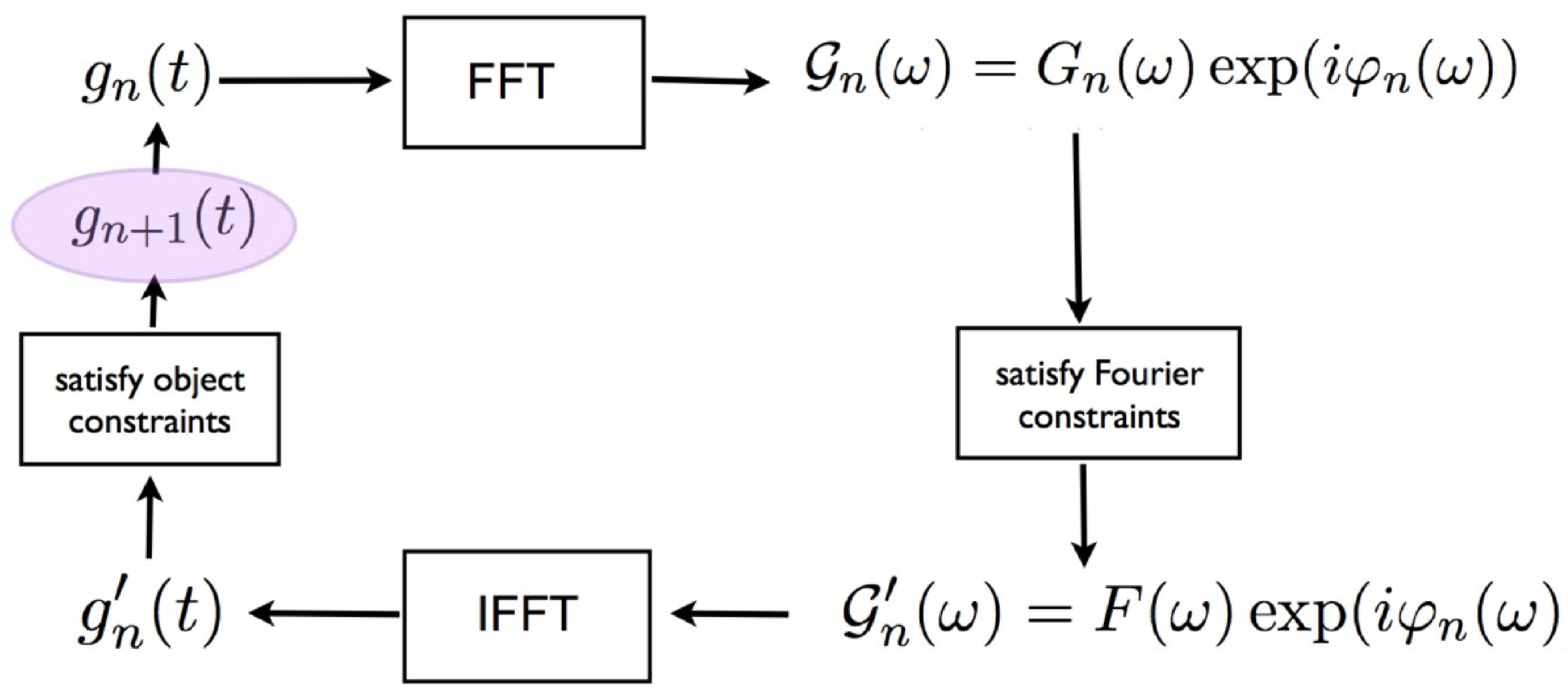

**→ "Blaschke Phase" is not accessible**



# Iterative Reconstruction.

> **Gerchberg-Saxton algorithm**




R.W. Gerchberg and W.O. Saxton, „A practical algorithm for the determination of phase from image and diffraction plane pictures“, Optik 35, 227 (1972)

> **Start phase**
- random

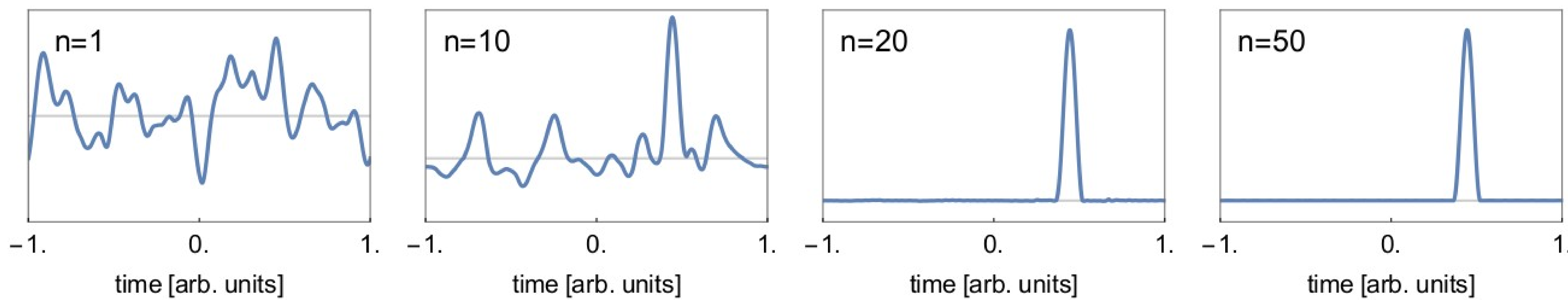
> **Applied constrains**
- Charge density > 0
- Bunch profile is localized

> **Stop criterion**
- Fix number of iterations
- Convergence of profile

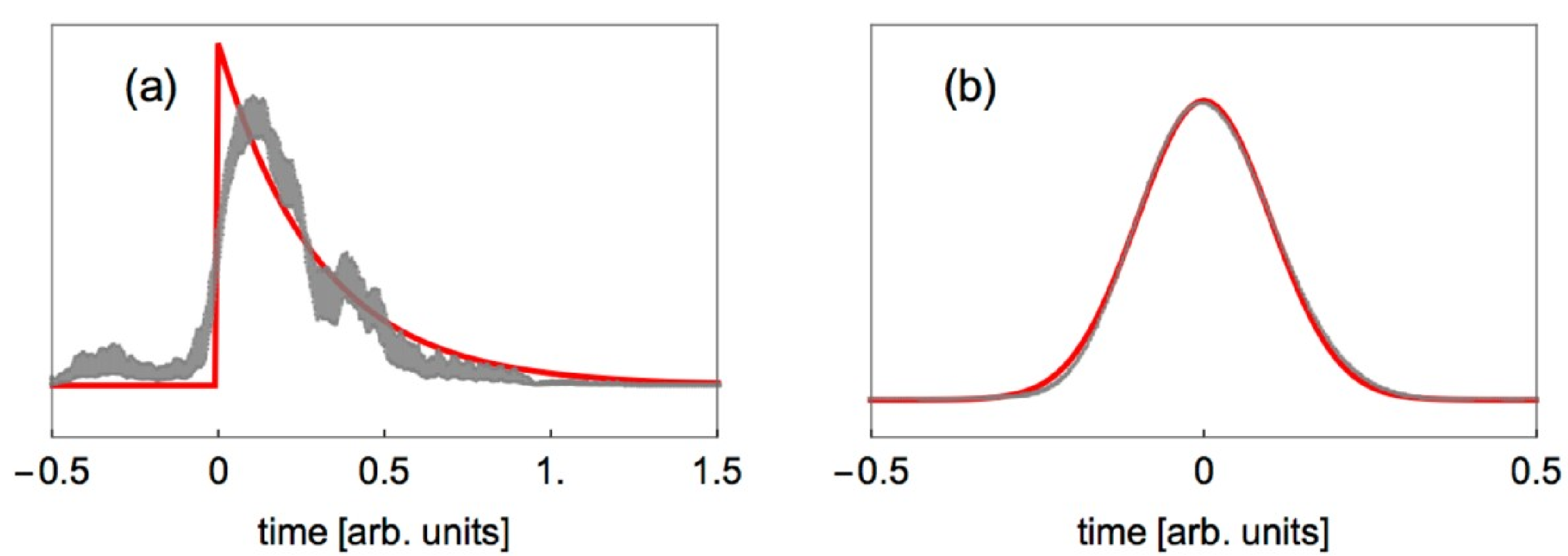
→ **Run multiple times with different starting parameters ...**

# Iterative Reconstruction.

## > Example: Convergence




## > Example: “Akuto“ and Gaussian Profile



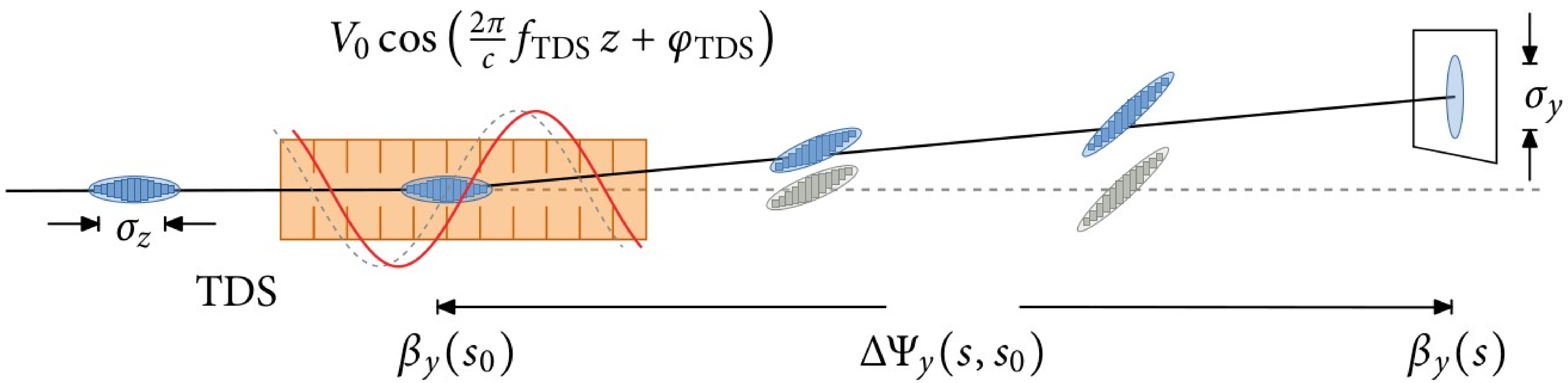

mean profile + error band

# Shift Motivation.

## “Comparative Measurements between CRISP and LOLA-TDS at 13SMATCH“

- → **Test reconstruction methods on real FLASH beam profiles**
- → **Reliable bunch profile measurements by CRISP?**
- → **Measure shortest bunches down to 50 fs rms**

# Transverse Deflecting Structure.




**Offset in zero-crossing**

$$y = y_0 + S \cdot z$$

**Streak** given by optics and TDS

$$S = R_{34}(s, s_0)\, k = \sqrt{\beta_y(s)\beta_y(s_0)}\ \sin \Delta\Psi_y(s, s_0)\ \ \frac{2\pi}{c^2}\, \frac{e}{p}\, V_0\, f$$

**Resolution** given by bunch properties

$$\mathcal{R}_z = \frac{\sigma_{y0}}{S} = \sqrt{\frac{\epsilon_{n,y}}{\beta_y(s_0)}}\, \frac{1}{\sin \Delta\Psi_y(s, s_0)}\, \frac{mc^3}{2\pi e}\, \frac{\sqrt{\gamma - 1/\gamma}}{V_0\, f}$$

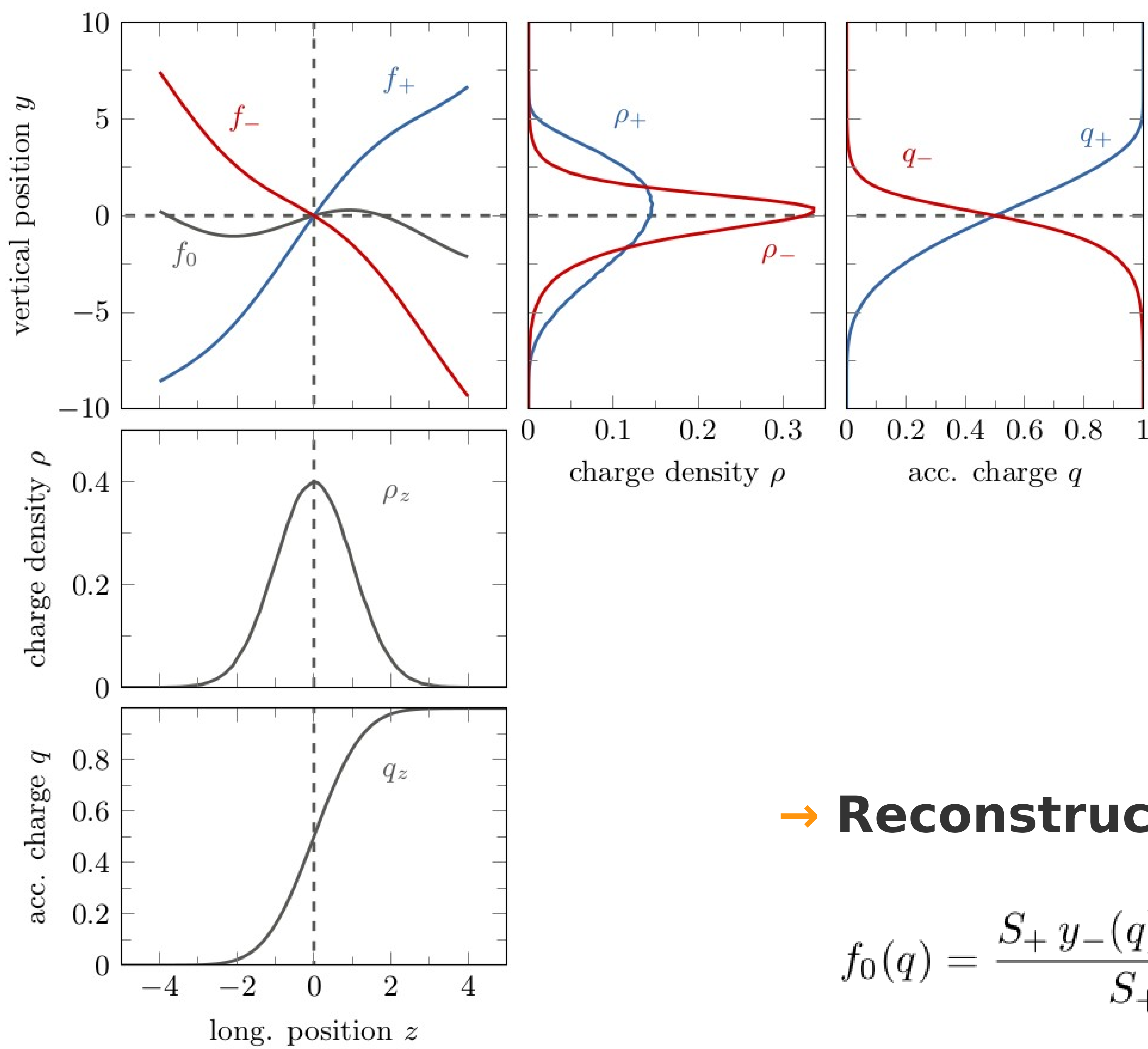
→ **LOLA-TDS available at FLASH**

# Two Point Tomography.

Idea by Hendrik Loos

> **Intrinsic centroid correlation <y>(z)**

$$f_\pm(z) = \langle y \rangle_\pm(z) = f_0(z) + S_\pm\, z$$




- Accumulated charge

$$q_+(y) = \int_{-\infty}^{y} \rho_+(y^*)\, dy^*$$

$$q_-(y) = \int_{y}^{\infty} \rho_-(y^*)\, dy^*$$

- Map

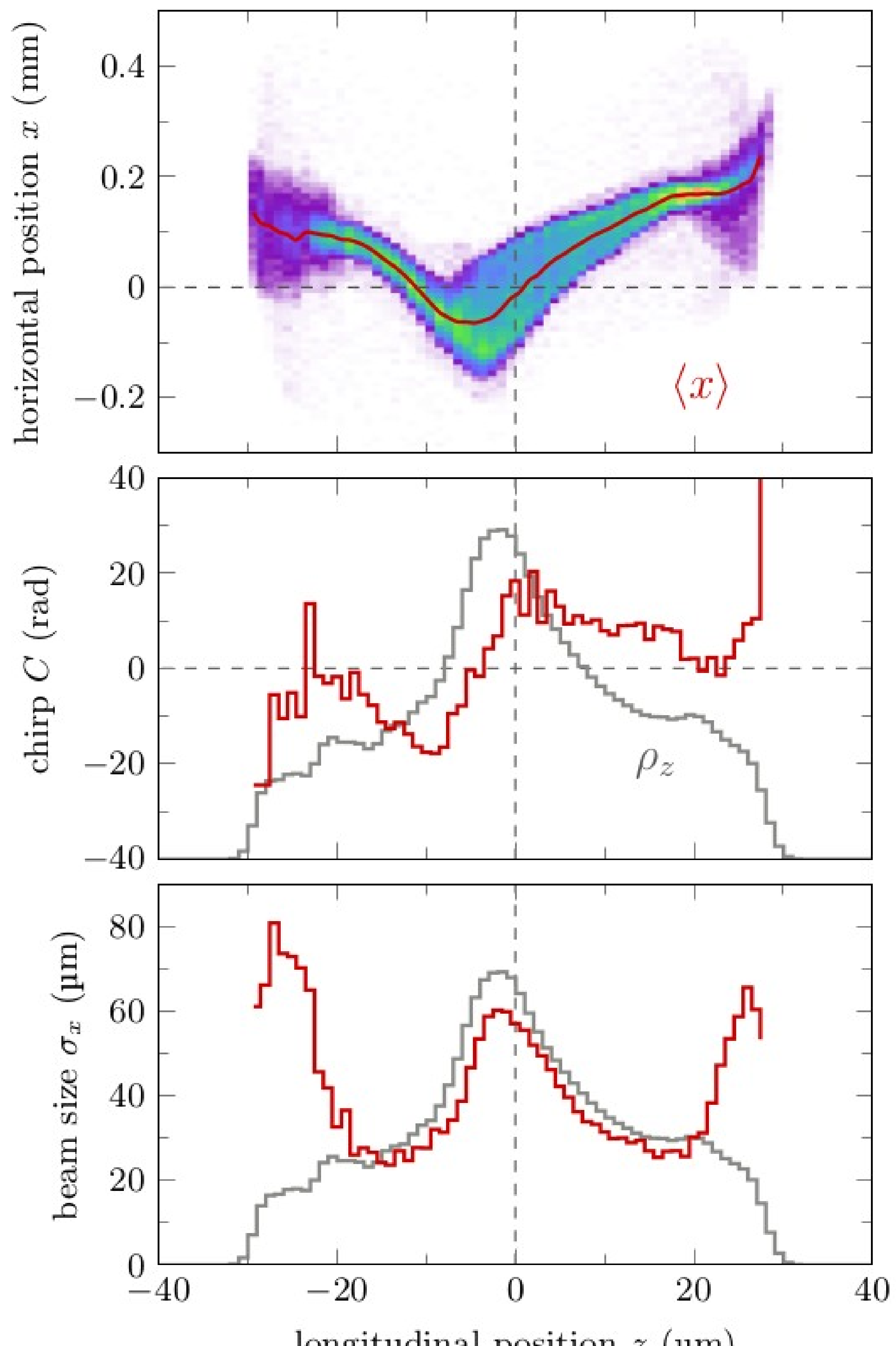
$$z(q) = \frac{y_+(q) - y_-(q)}{S_+ - S_-}$$

→ **Reconstruction of correlation and profile**

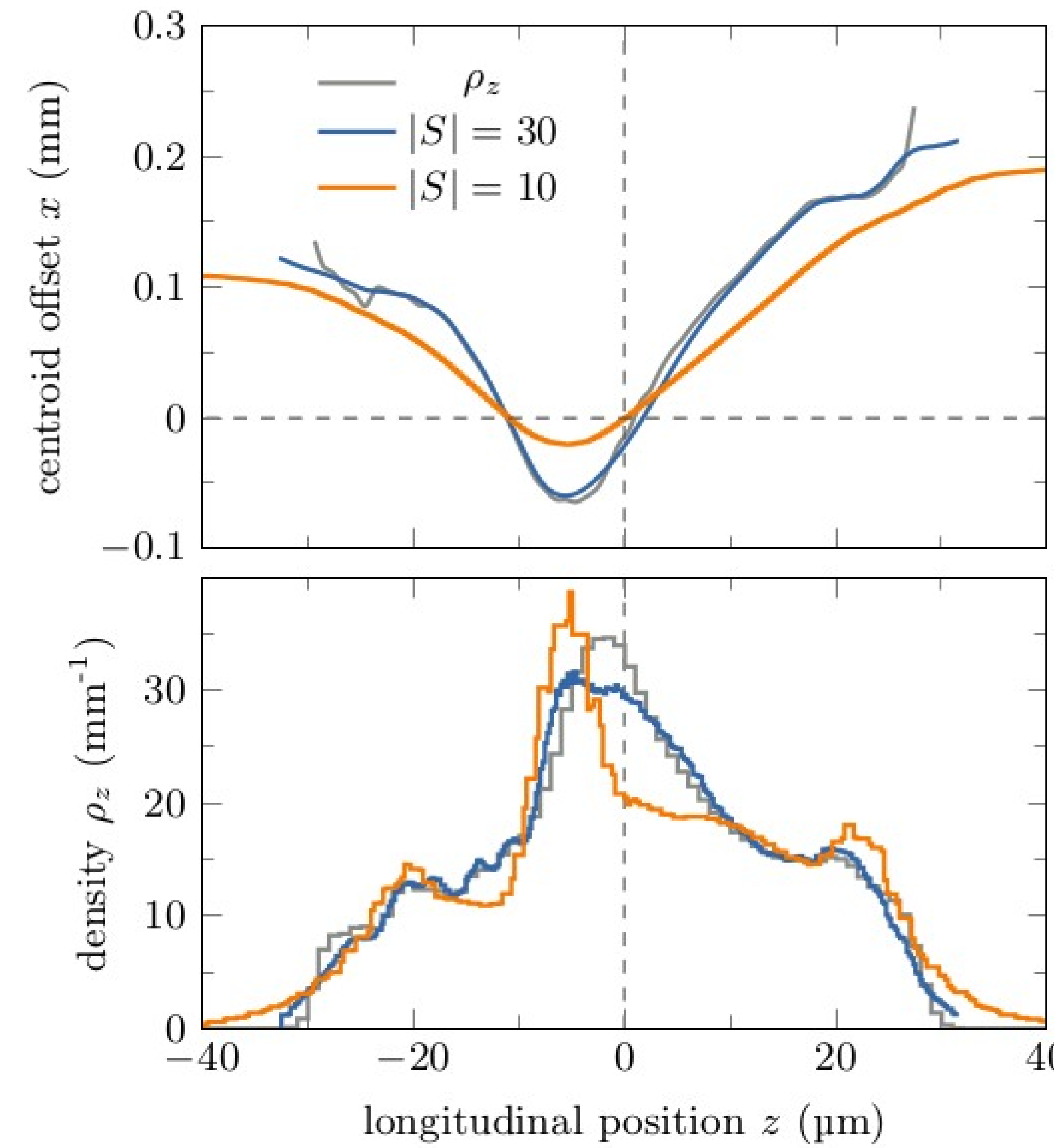
$$f_0(q) = \frac{S_+\, y_-(q) - S_-\, y_+(q)}{S_+ - S_-} \qquad \rho_{z,\mathrm{r}}(z) = \frac{d}{dz}\, q(z)$$

# Two Point Tomography.

> **Example:** I. Zagorodnov



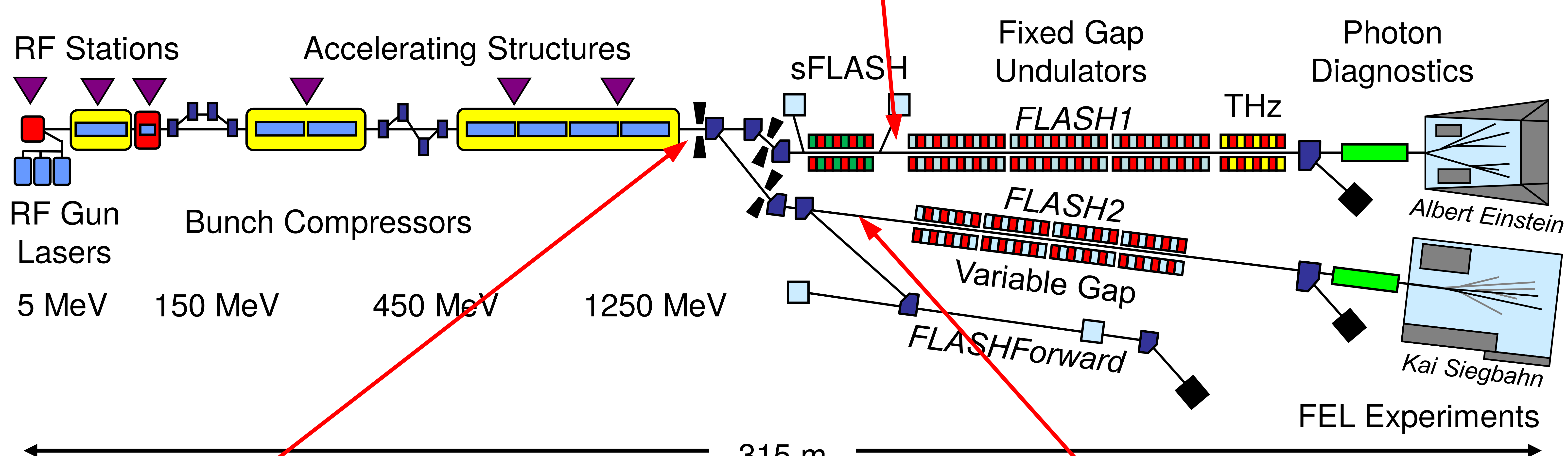

TDS measurement
+
Reconstruction




→ **Successful with sufficient streak**

# CRISP@FLASH.

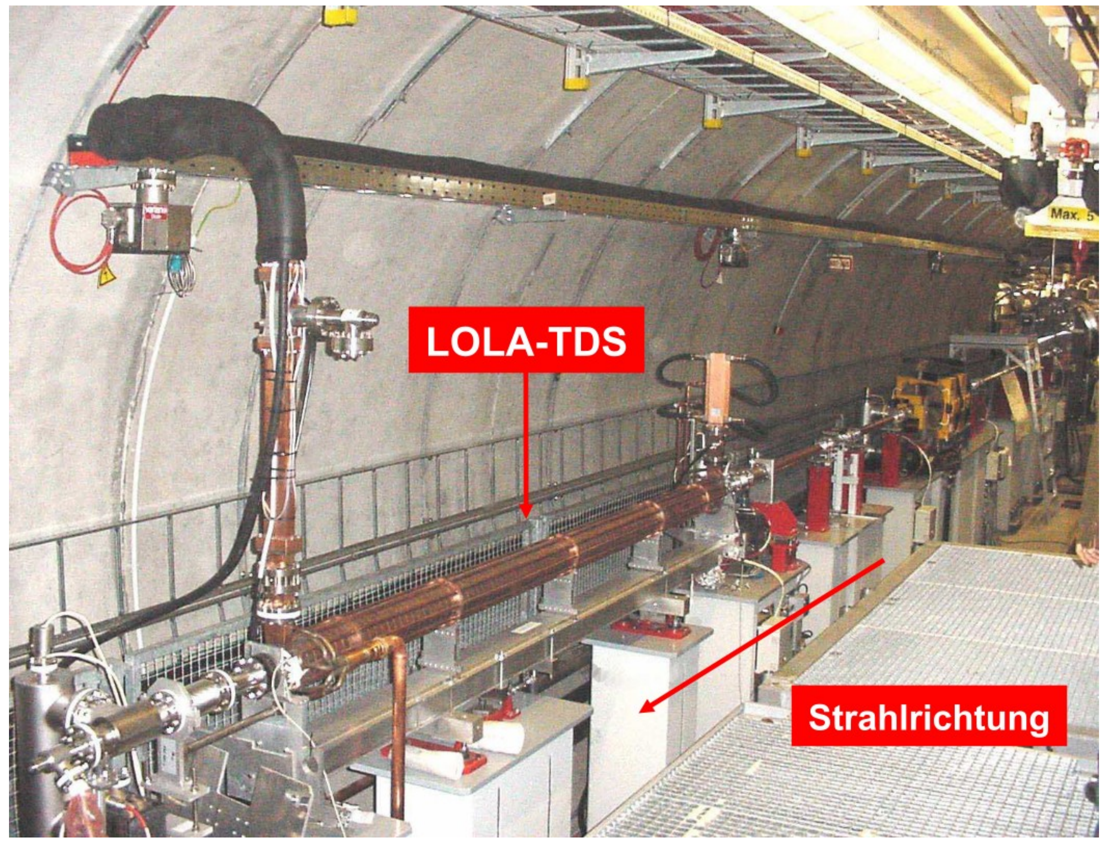
> **CRISP@202m (@FL1)**
- inside tunnel
- delays: BLM masking, kicker, screen, detectors, …
- exchange complete spectrometer in 2015

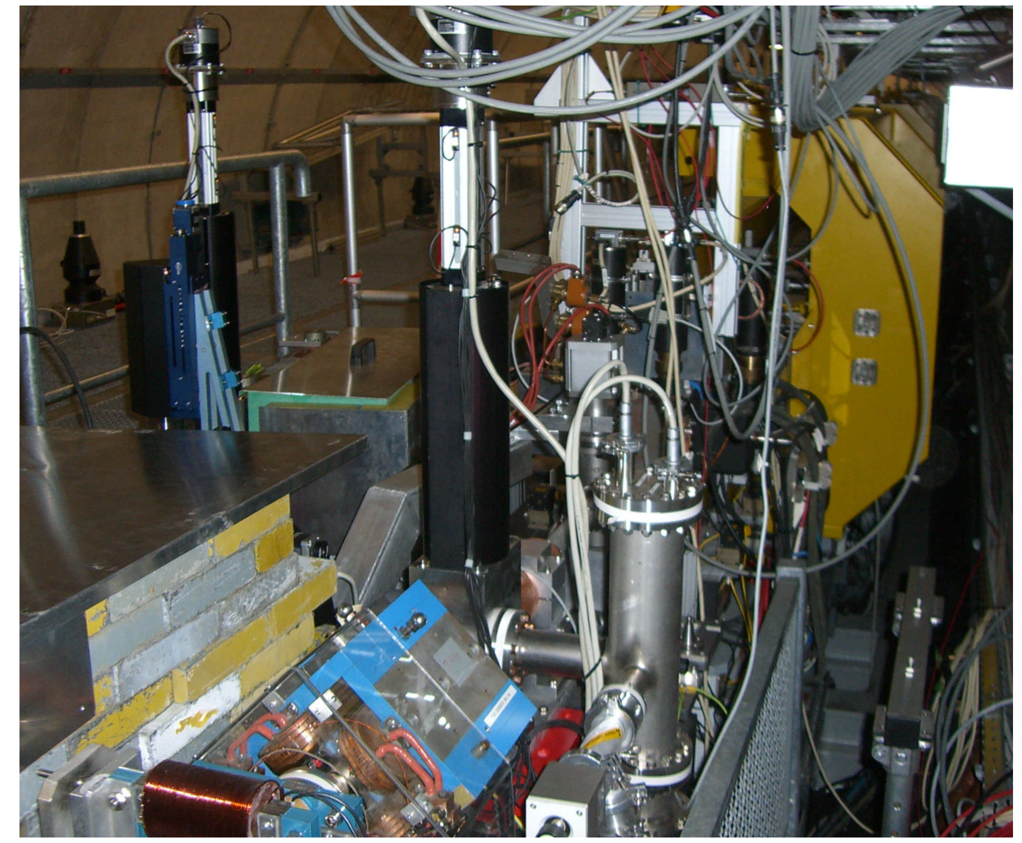


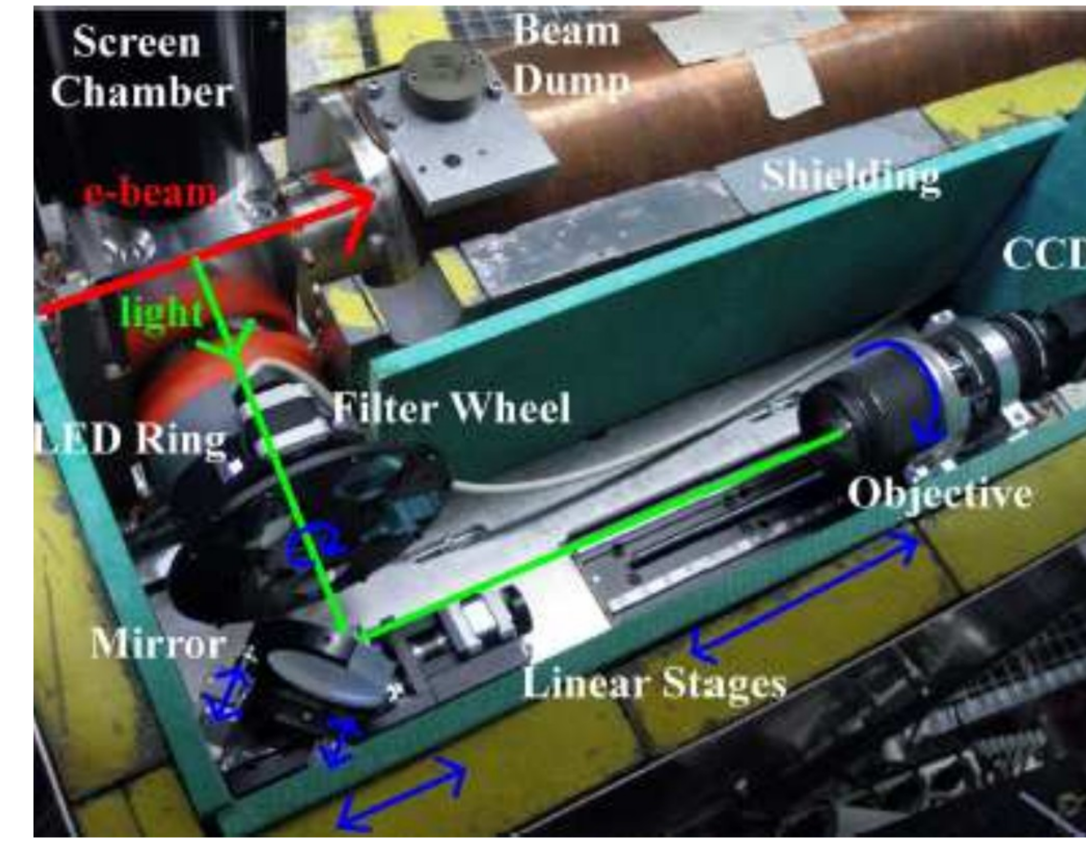

> **CRISP@141m (@LINAC)**
- beamline to external lab 28g
- commissioning of the 1st CRISP
- first comparisons with LOLA-TDS

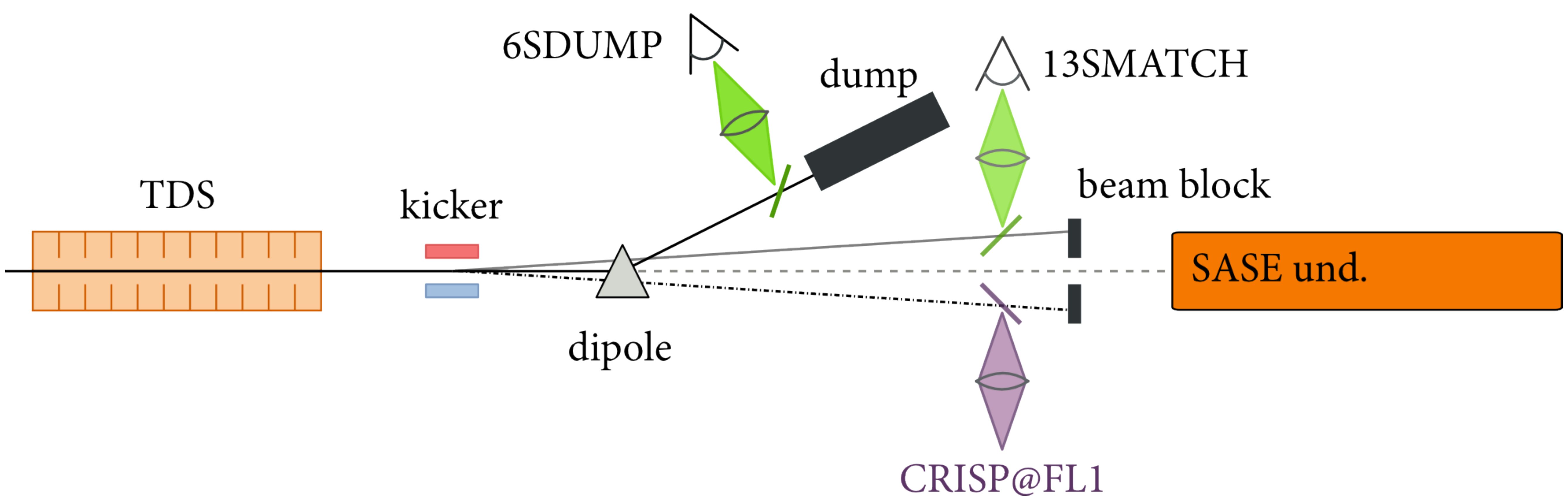
> **CRISP@FL2**
- inside FLASH2 tunnel
- later in this talk ...

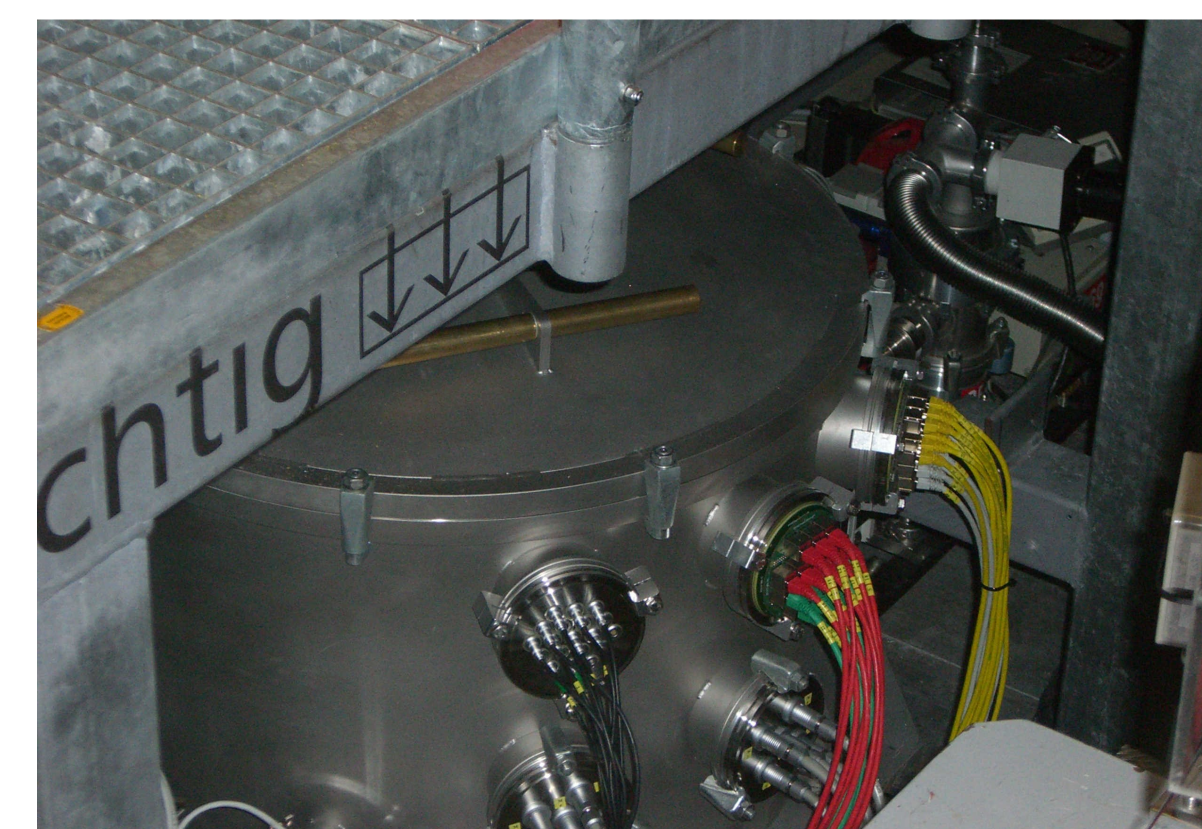
# Experimental Setup SDUMP/SMATCH.





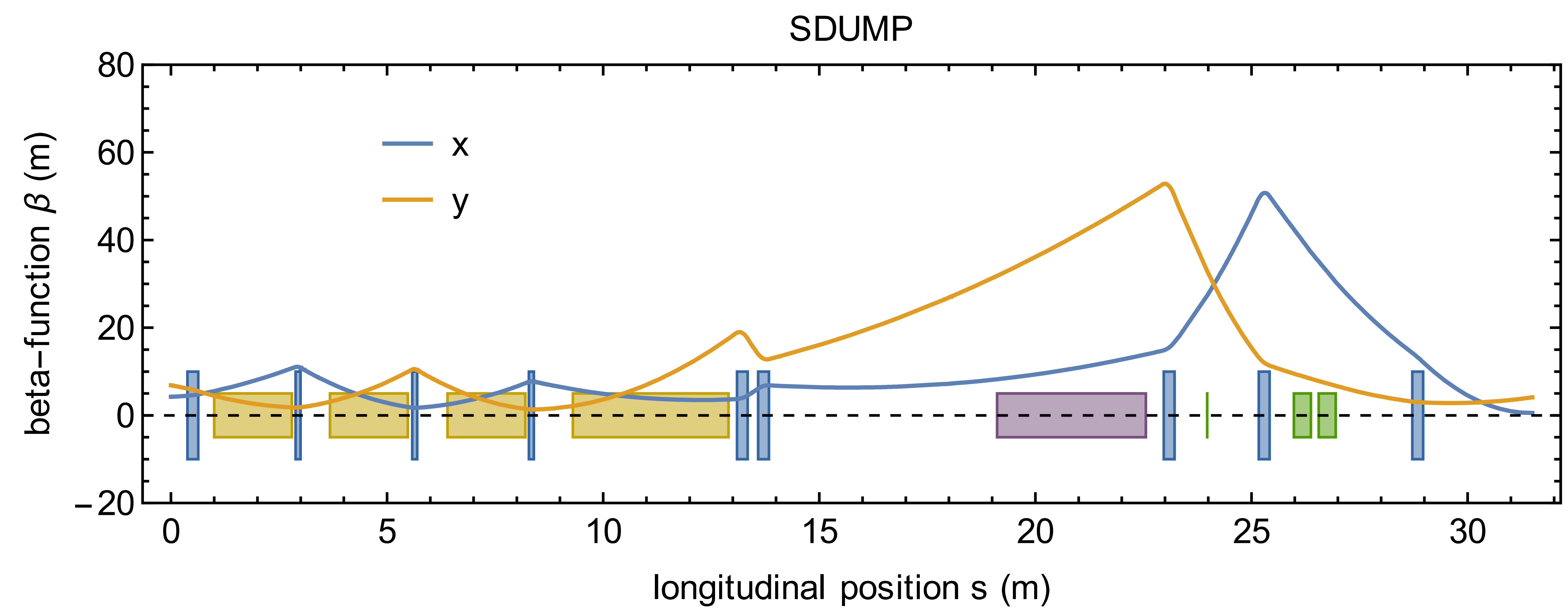



→ **Designed to compare both diagnostics**

# Experimental Setup SDUMP/SMATCH.

> **SDUMP special optics**
- Based on FLASH1 theory optics
- Streak in y:
  - $\beta_{TDS}$ = 41 m,
  - $\beta_{SCR}$ = 4 m,
  - $\psi$ ~ $\pi/2$
- Energy x:
  - $\beta$ = 0.54 m,
  - $\eta$ = 0.77 m
- Works for 13SMATCH as well




> **Resolution**

(for 20 MV and 1 GeV/c, 1 um·rad)

**S = 15**

**$R_z$ = 3 um (rms)**

**$R_\delta$ = 2 x $10^{-4}$ (rms, dominated by TDS)**

→ **Excellent time resolution (matched beam in SFUND needed)**

# Machine Setup.

> **Check list: Machine**

- Virtual cathode
- Phase scans
- Set minimum energy spread downstream BC2
- Match in DBC2 (4 screen method)
- Set minimum energy spread downstream BC3
- Close dispersion in dogleg
- Match in SFUND (4 screen method)
- Set special SDUMP optics

> **Check list: Measurement**

- Set compression (sum voltage control, intuitive)
- Measure longitudinal phase space with TDS
- Switch to 13SMATCH (dark current tuning)
- Measure spectra with CRISP
- Switch back to 6SDUMP
- Set new compression ...

x **Optics in SFUND**

- Small beam sizes on screens
- Weird beam shapes
- Matching somehow random

x **Switching to 13OTRSMATCH**

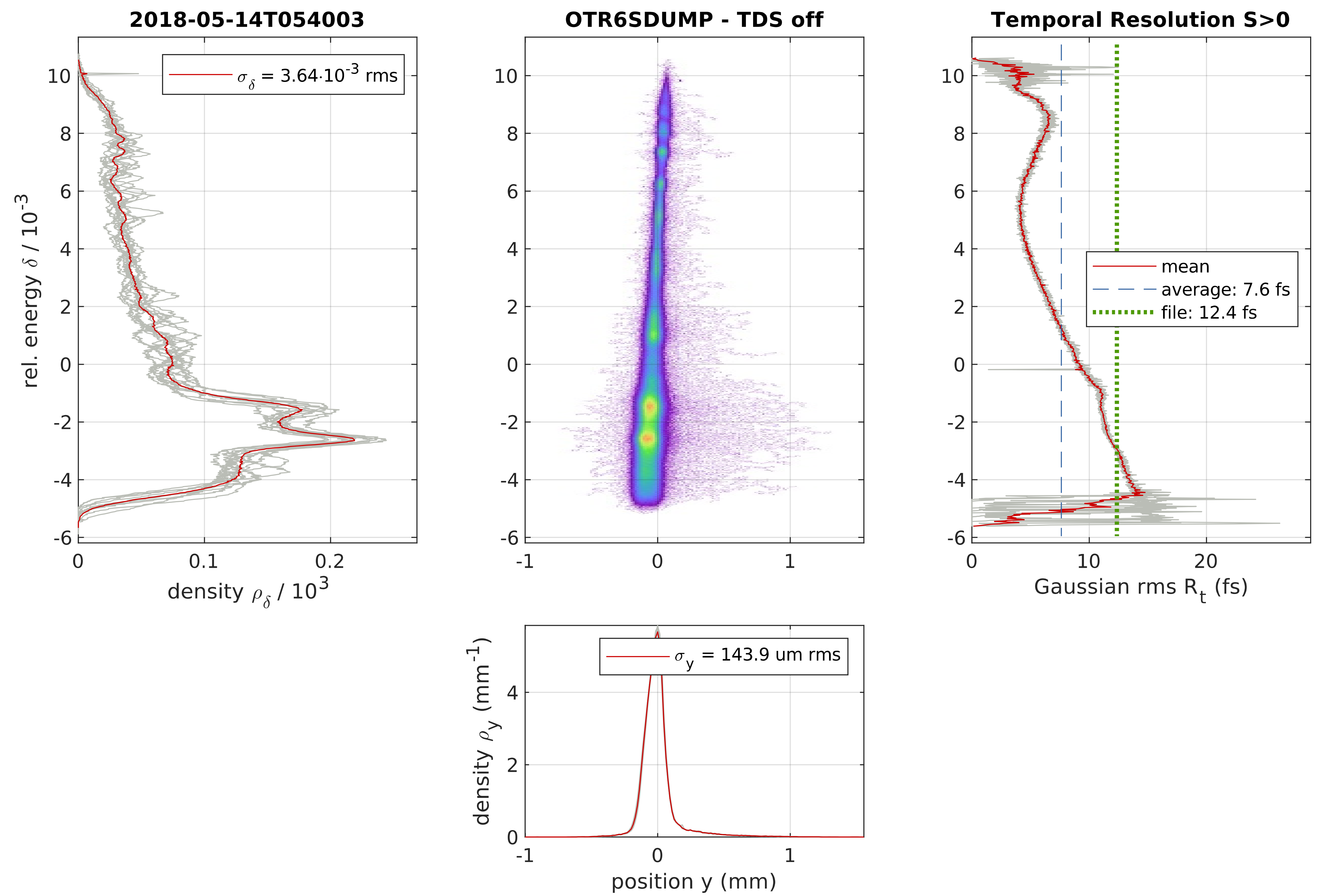
- Upstream killer steerers
- Attention to DC in undulators

→ **Spent a lot of time to prepare the machine**

# TDS Measurement.

> **Data taking for both zero-crossings**
  - Time calibrations
  - Single image
  - 20 images

> **Time calibration analysis** (update)
  - Based on energy slices
  - Better understanding of resolution



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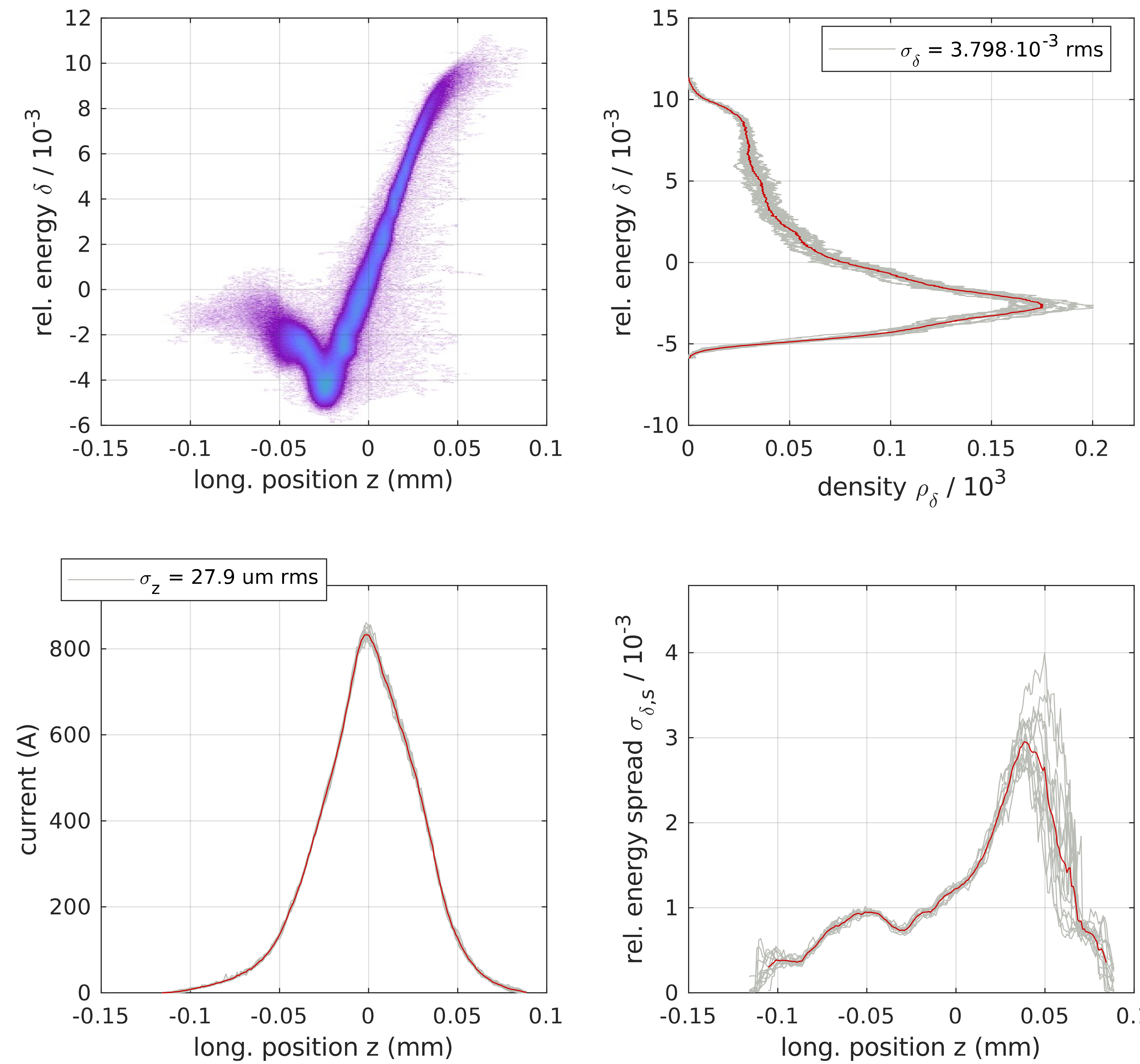
> **Image analysis**
- Correct for center of mass shifts
- Scale all profiles to the mean bunch length
- Averaging profiles
  … potentially wash out micro-structures



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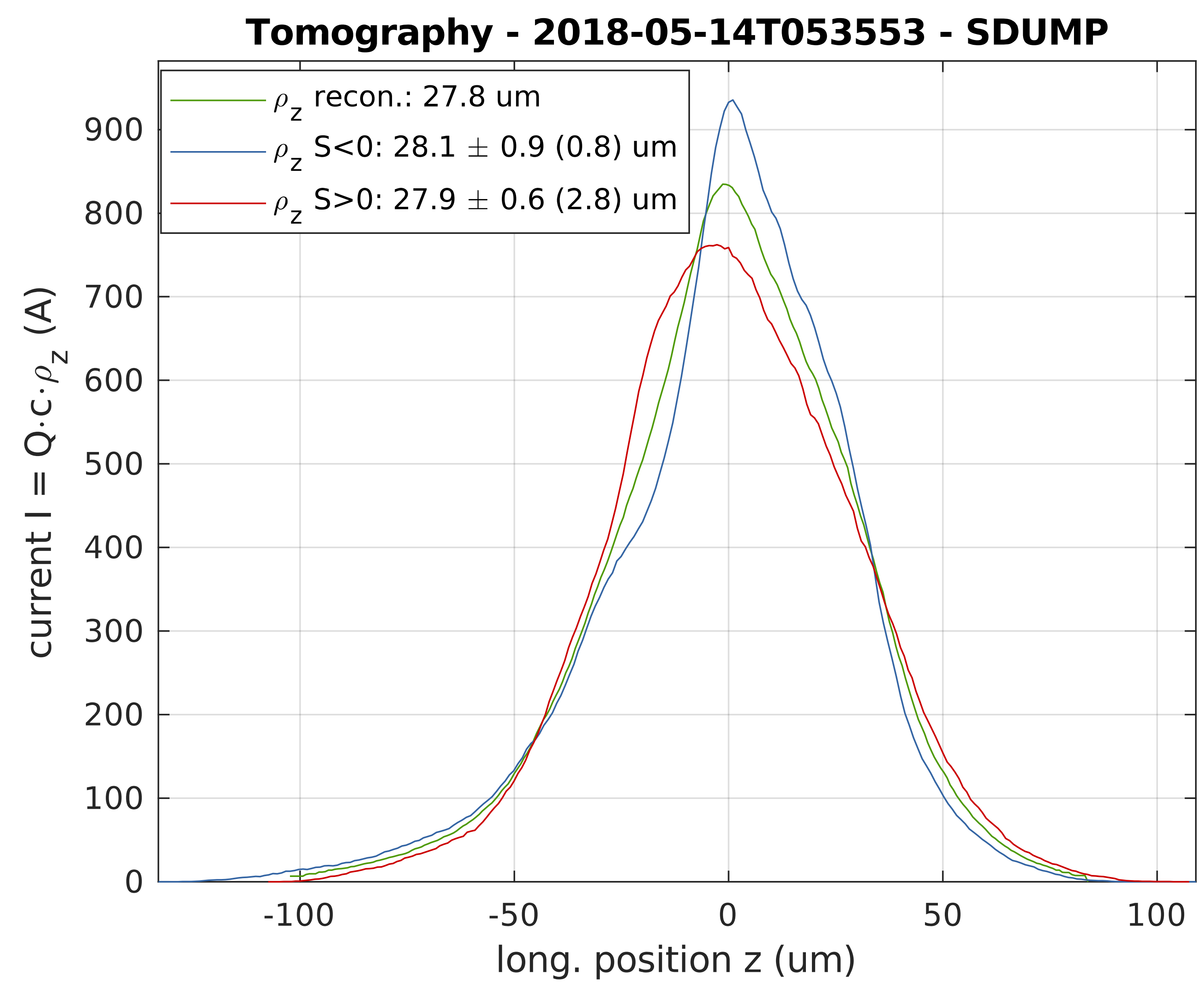
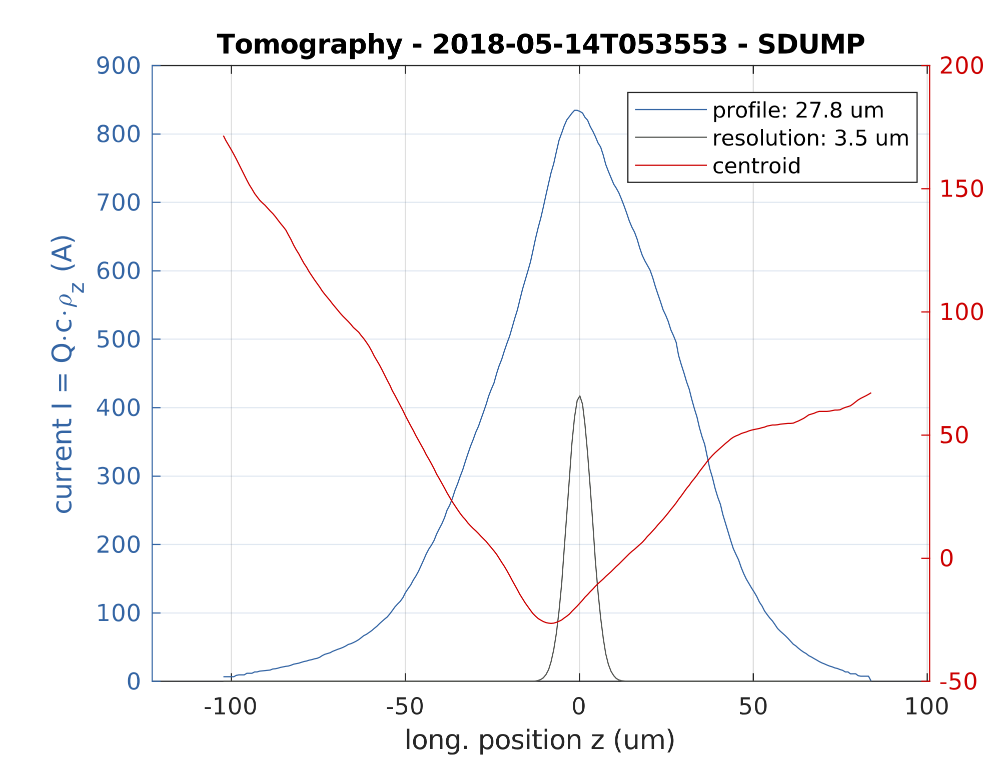
> **Two point tomography**
- Most likely profile
- Centroid shift



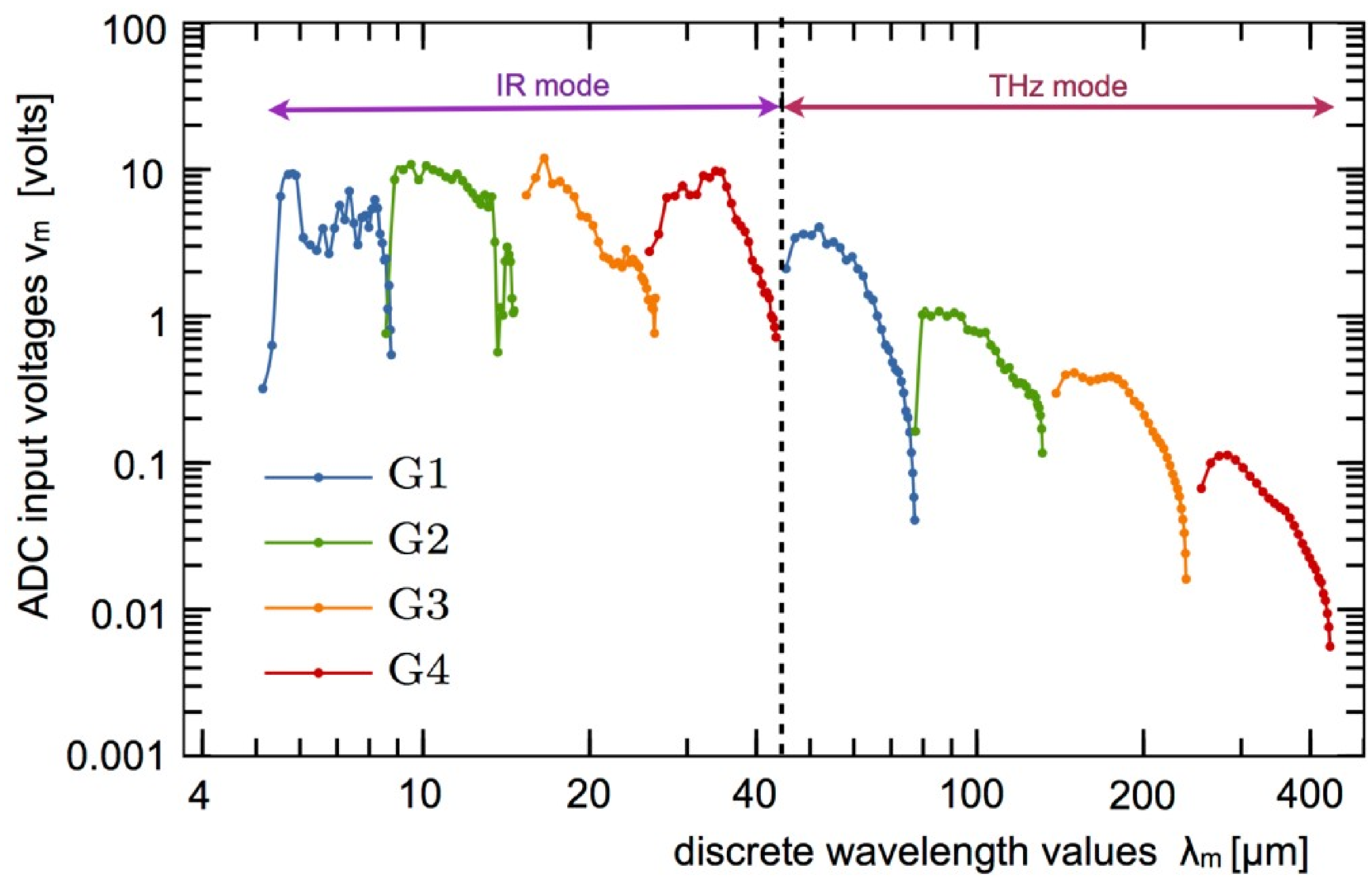



# CRISP Measurement.

> **Data taken**
- 200 shots
- 2 grating sets

> **Measure form factor**
- Average of all shots (for now)
- Well calibrated device (source → electronics)
- Characterization by response
  (infinitesimal short bunch)
- ADC signal → form factor

$$|F_l| = \left( \frac{adc\ signal[\mathrm{V}]}{charge[\mathrm{nC}]^2 \cdot response[\mathrm{V}]} \right)^{1/2}$$



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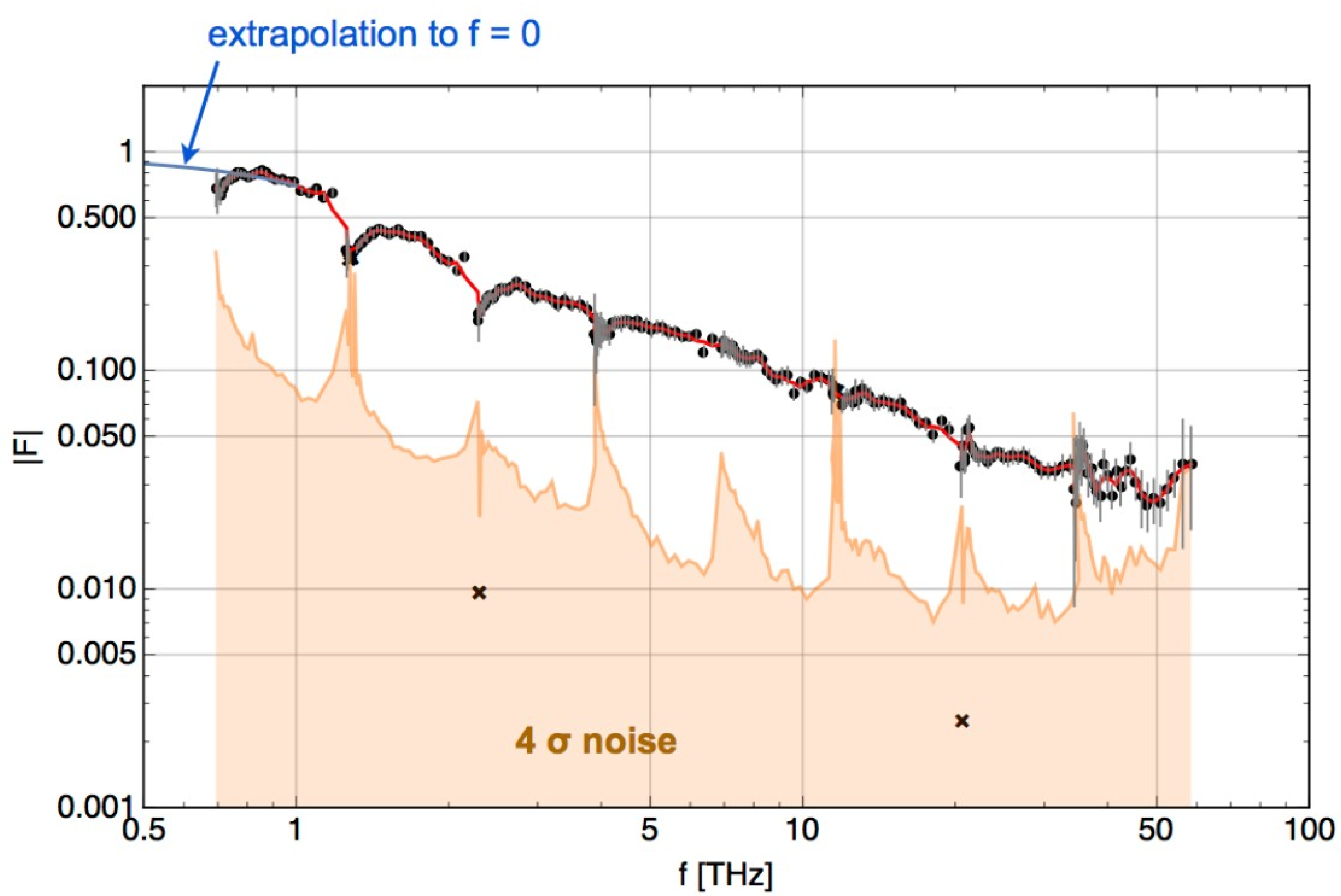
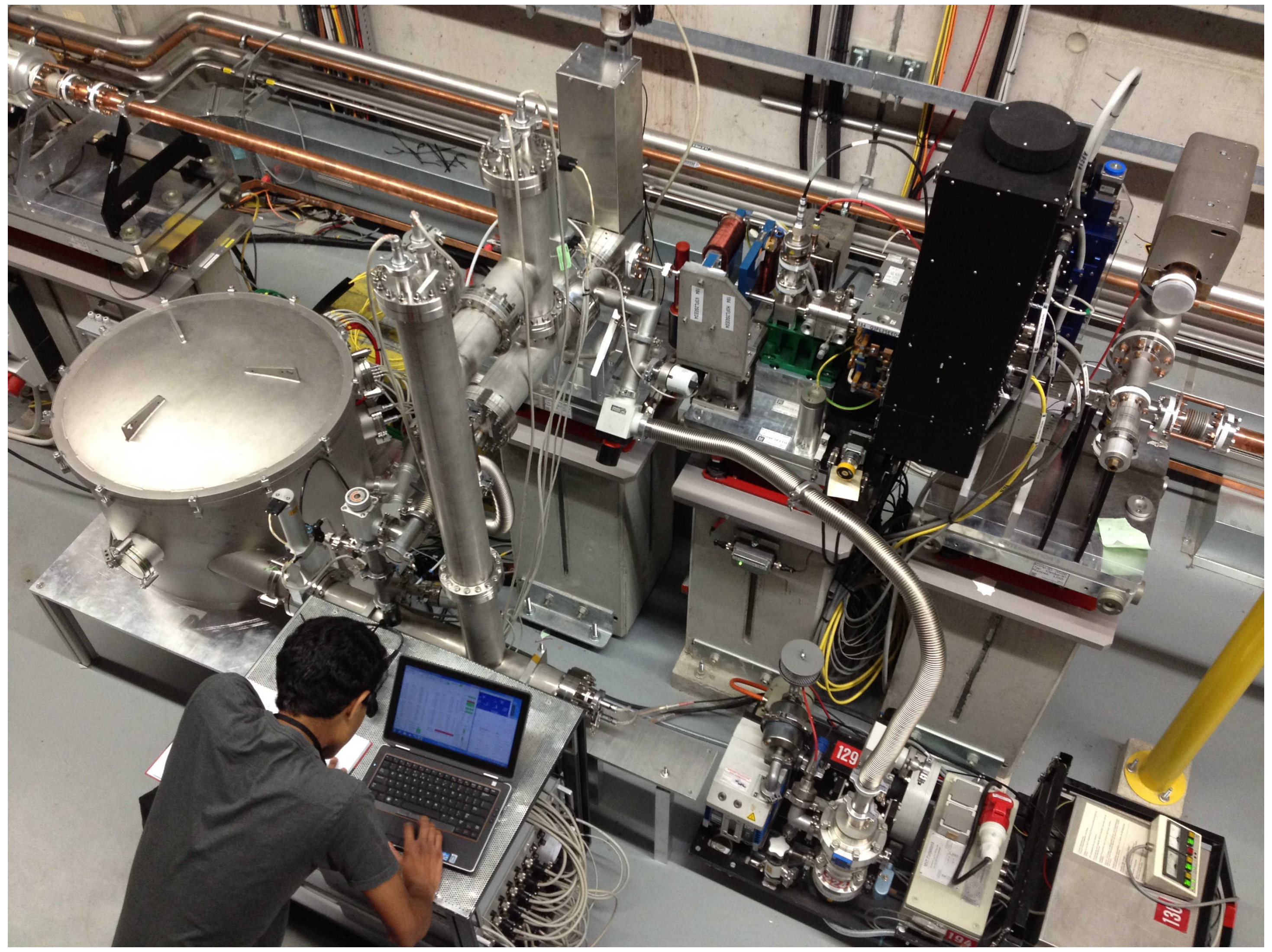
> **Analyse form factor**
- Errors statistical
- Sensitivity by ADC noise level



# CRISP@FL2.

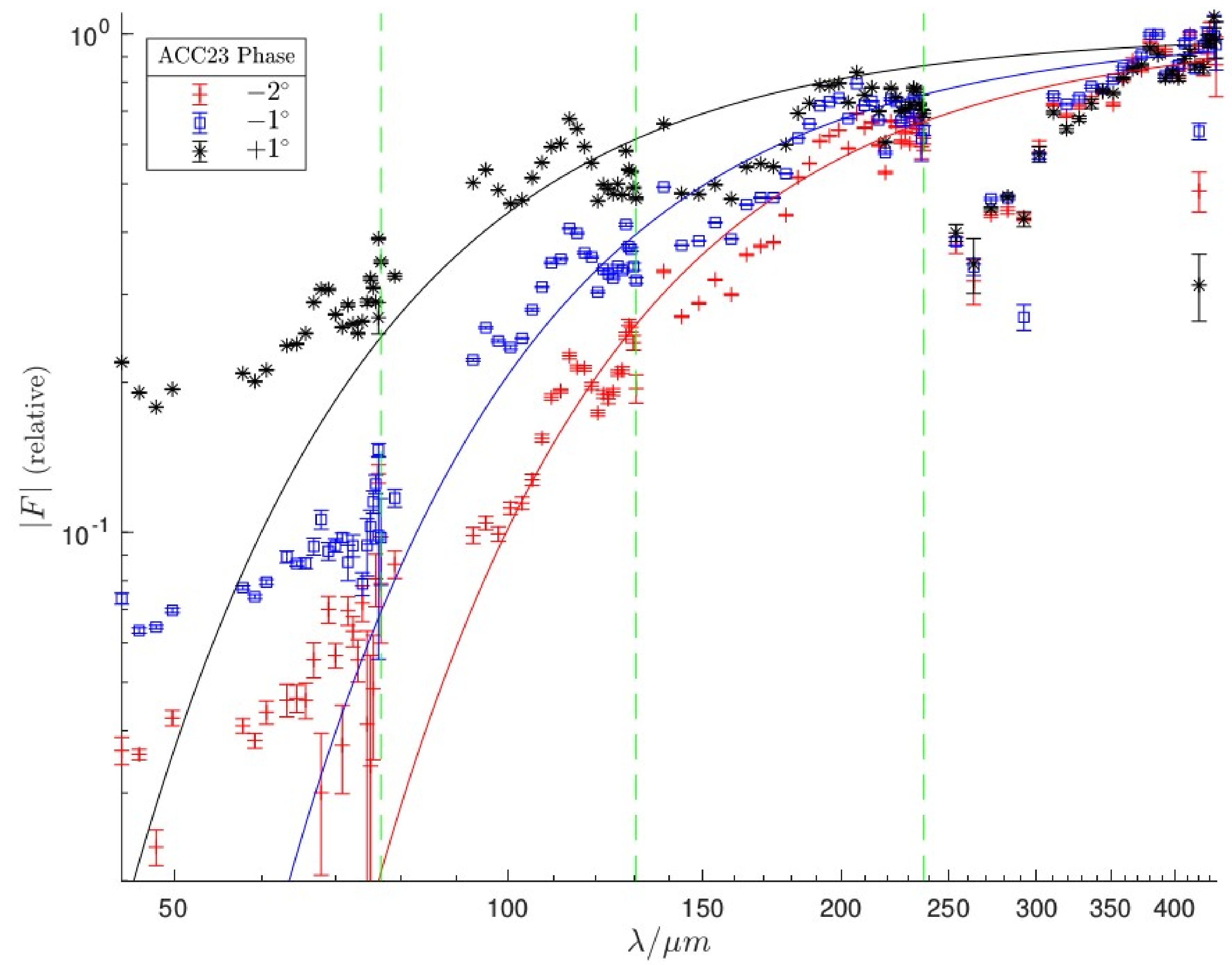
## > Delays

- **Solved:**
  new uTCA electronics
  over-heating of electronics
  wrong THz beamline focussing mirror
  no off-axis screen
- **Missing:**
  lead shielding for parallel operation



## > Status

- Beamline and spectrometer aligned
  (laser- and ebeam-based)
- First bunch spectra by Tanish Satoor
  (summer student 2017)
- Kicker characterization
- Problems
  a.) extremely fluctuating signal on alignment pyros
  b.) other time consuming projects




**→ Station is alive**
**→ Next measurements planned in Feb**

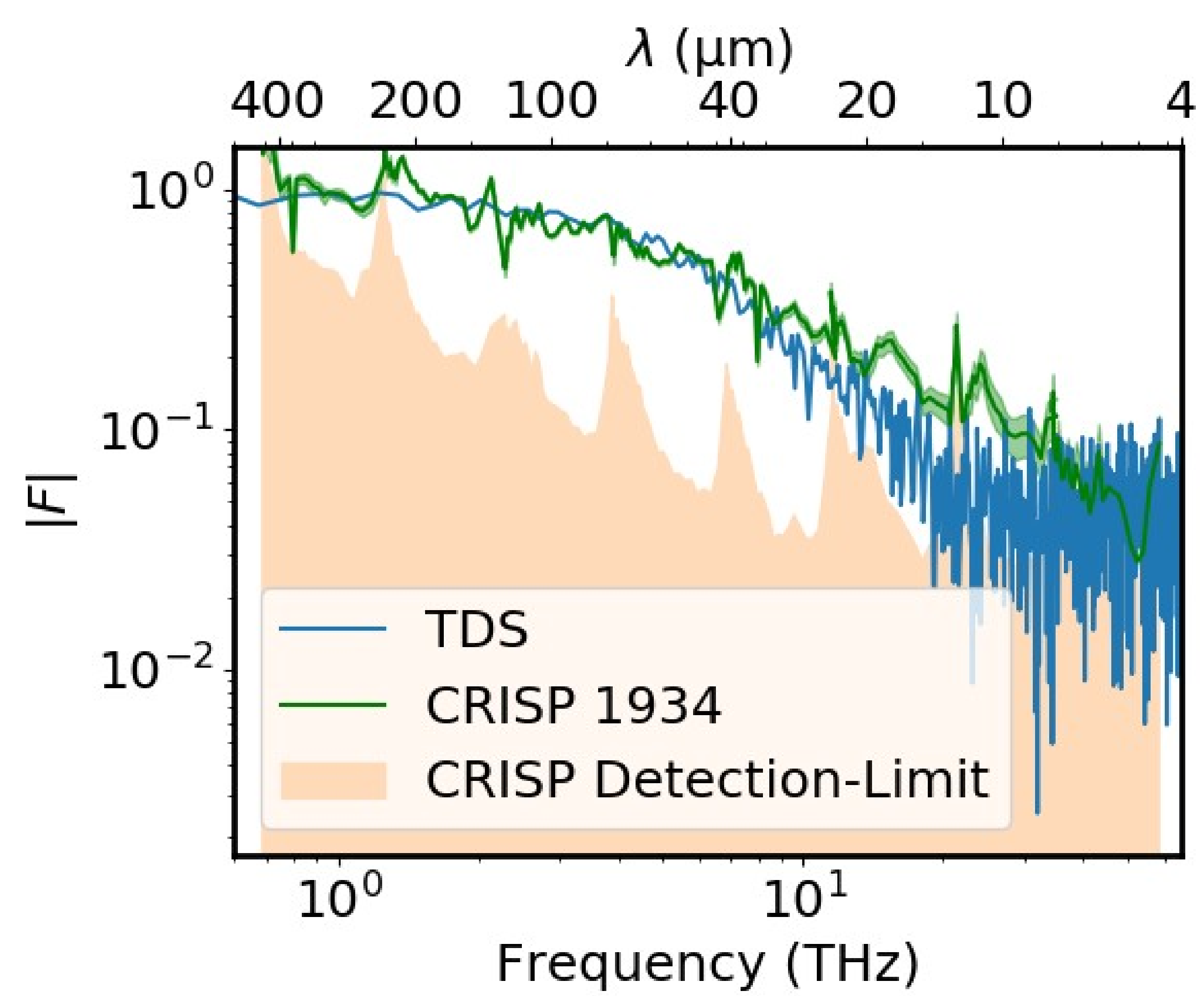
# CRISP@EuXFEL.

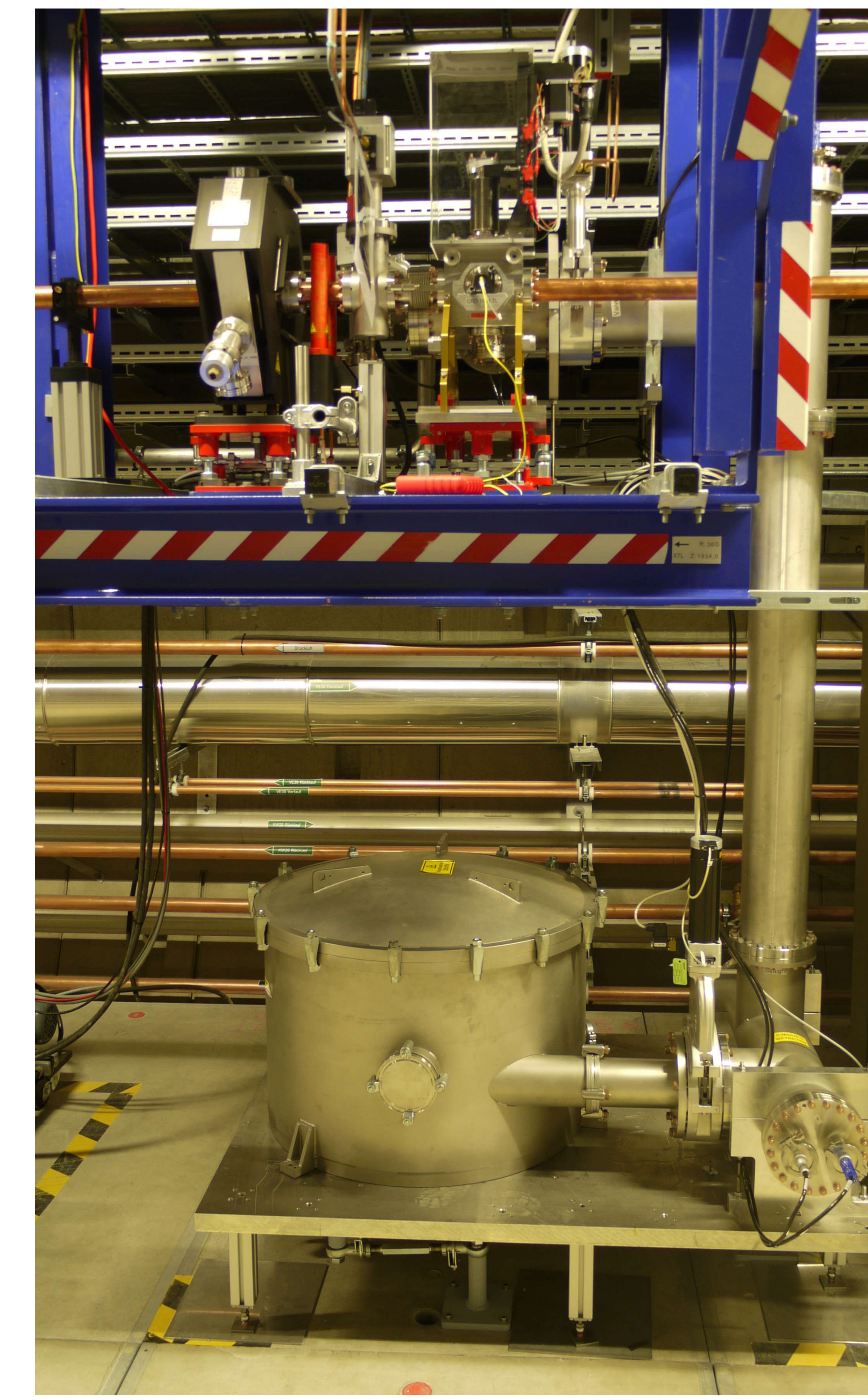
> **Setup**
- In XTL at 1934 m (17.5 GeV = final energy)
- Non-invasive diffraction radiator

> **Goals**
- Monitoring all bunches simultaneously
- Feedback on pulse-train bunch profiles

> **Status**
- Installed
- Technical commissioned
- First spectra taken
- First cross-checks with TDS
- DOOCS server by O. Hensler

→ **PhD student Nils Lockmann**
**with C. Gerth and J. Röver (MSK)**



# Summary.

> **CRISP very well understood and characterized during the past years**

> **Comparisons with TDS show impressive agreements**

> **Stations at FLASH2 and EuXFEL**

> **Seamless integration into DOOCS has been started …**

**… CRISP as a regular bunch profiles monitor**

> **Further reading**

- PhD Thesis, **DESY-THESIS-2012-052**
- 'CRISP', NIMA **665** (2011) 40–47
- 'Reconstruction', **DESY 18-027**