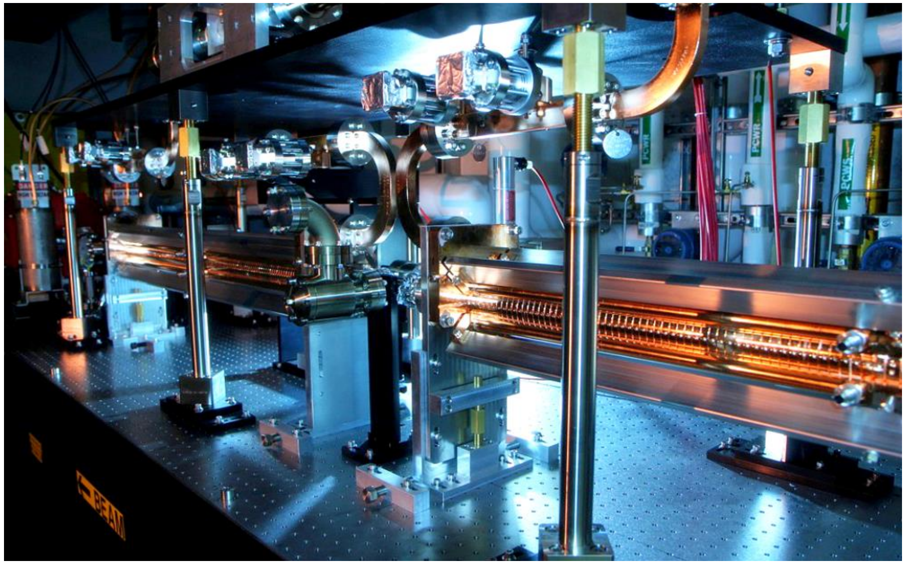
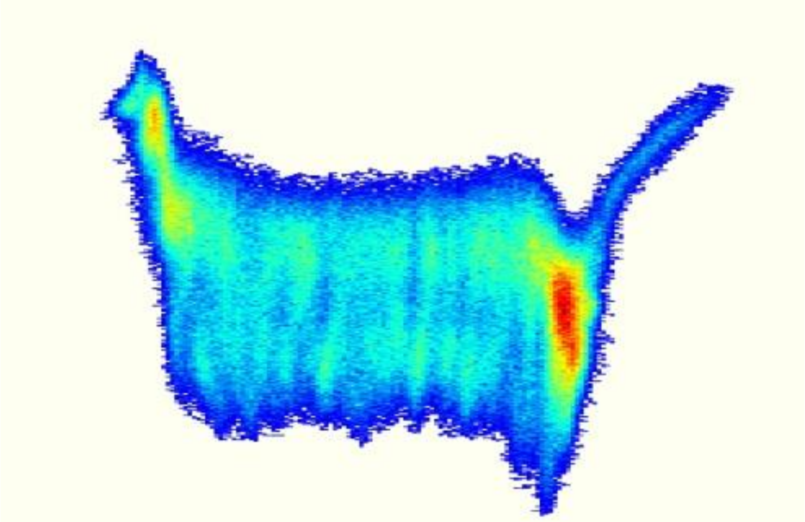
Feasibility Studies on a FLASH II XTCAV



Patrick Krejcik/SLAC



Christopher Behrens

Nils Lockmann, MPY
Feasibility Studies on a FLASH II XTCAV
FEL-Seminar, 7.7.2015

HELMHOLTZ ASSOCIATION

DESY

Outline

- Motivation
- Background of longitudinal phase-space measurements
- XTCAV for FLASH II: basic studies
  - X-Band TCAV
  - Lattice and optics
  - Resolution and optics optimization
  - Jitter
- XTCAV for FLASH II:
  - Bunch simulations and agreement of measurements
  - CSR influence
- Summary and outlook
- Acknowledgments

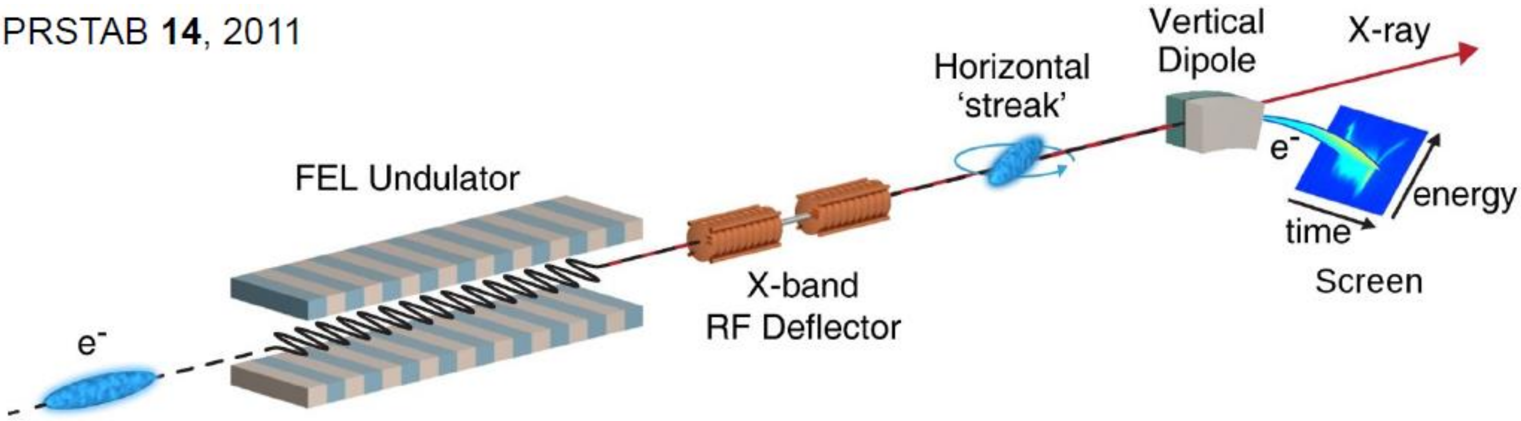
Motivation

- Tendency for shorter FEL x-ray pulses (user)
  - Better time resolution
- Knowledge of temporal x-ray profile
- Conventional streak cameras and photodetectors
  - Response time to slow
- XTCAV + spectrometer (indirect – bunch)
  - Femtosecond regime
  - Single shot
  - Any radiation wavelength
  - No interruption of user operation

Motivation

> **Measuring longitudinal phase-space downstream of undulator**:

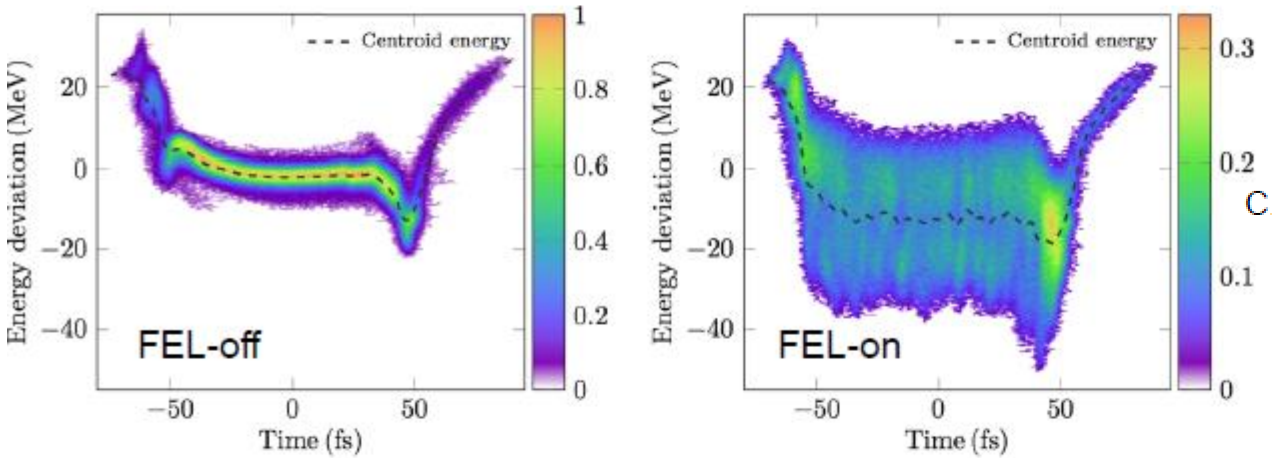
Y. Ding *et al.*, PRSTAB **14**, 2011



- XTCAV: longitudinal coordinate → horizontal coordinate ("streaking")
- Dipole: energy → vertical coordinate (energy spectrometer)

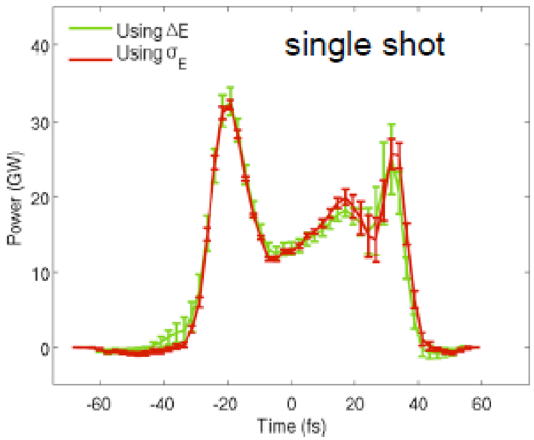
Motivation

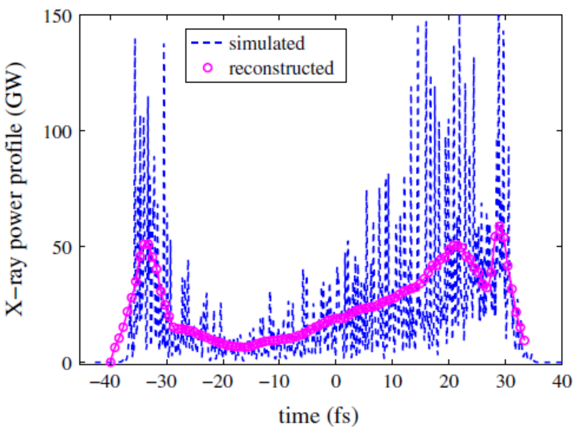
- Measure longitudinal phase-space for FEL-on and FEL-off



C. Behrens *et al.*, Nat. Commun. **5**, 2014

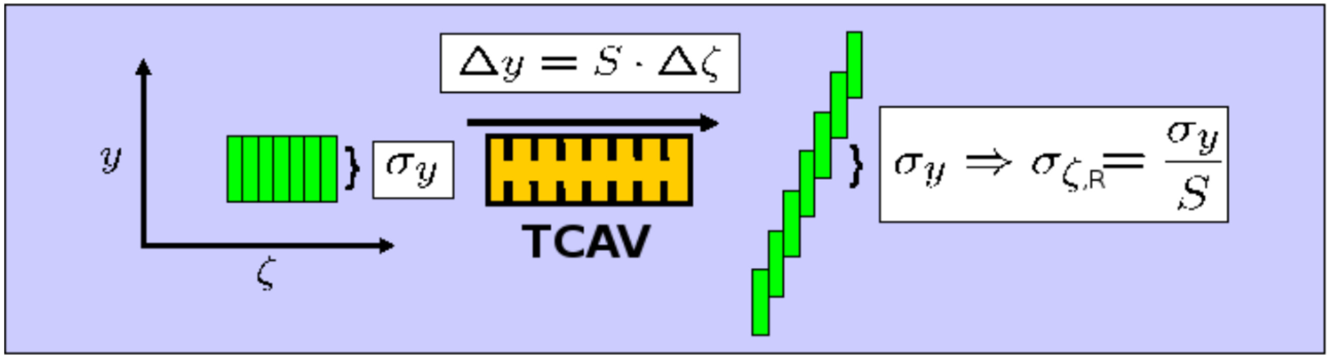
- Extract difference of time-sliced energy loss and energy spread
  - Replica of x-ray FEL-pulse
- Extract current profile
- **Obtain x-ray profile**





Background of longitudinal phase-space measurements

> TCAV: longitudinal coordinate → vertical coordinate



- Shear-parameter: $S := R_{34} \frac{\omega e V_0}{c^2 |p|}$
- Calibration: vary phase and measure centroids $t = C_t \cdot y = \frac{1}{S\,\mathrm{c}} \cdot y$
- Non-streaked beam size limits resolution:

$$\sigma_{t,R} = \frac{\sigma_y(s)}{S(s) \cdot \mathrm{c}}$$

$$\text{Goal: } \sigma_{t,R} \approx \text{fs} \leq \frac{L_{coh}}{\mathrm{c}}$$

> Spectrometer: relative energy deviation → horizontal coordinate

- Calibration: vary beam energy/dipole current & measure centroids $\delta E = C_E \cdot x = \frac{1}{D_x} \cdot x$

$$\sigma_{\delta E,R} = \frac{\sigma_x(s)}{D_x(s)}$$

$$\text{Goal: } \sigma_{\delta E,R} \approx 10^{-4} \ldots 10^{-3} \leq \rho_{FEL}$$

XTCAV

- Assuming LCLS-like TCAV for further considerations:

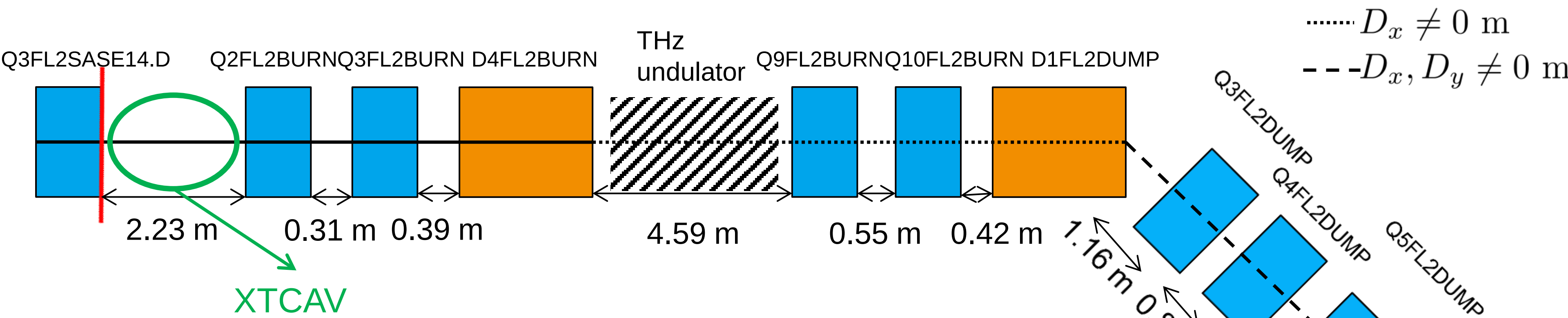
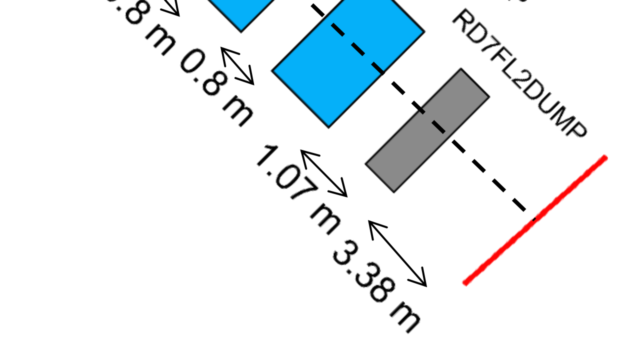
Frequency	11.424 GHz
Beam pipe diameter	10 mm
One cell length	8.747 mm
Phase advance per cell	$2\pi/3$
Kick per meter [MeV/Sqrt [MW]]	31 MeV/m/Sqrt(20 MW)
102 cell structure kick	21.3 MeV/Sqrt(20 MV) (~23MeV@20MW)
Group velocity/ speed of light	3.2 %
Filling time	92 ns
Structure length (with beam pipes)	~94 cm (~1m)

$$V_0 \approx 46 \text{ MV}$$
$$f = 11.424 \text{ GHz}$$

Assuming 2 x 1m @ 20 MW

Lattice and Optics - Current FLASH 2 Lattice

- Starting downstream of undulator
  - Neglecting instruments and monitors (see “~/ttflinac/OPTICS/MAD”)

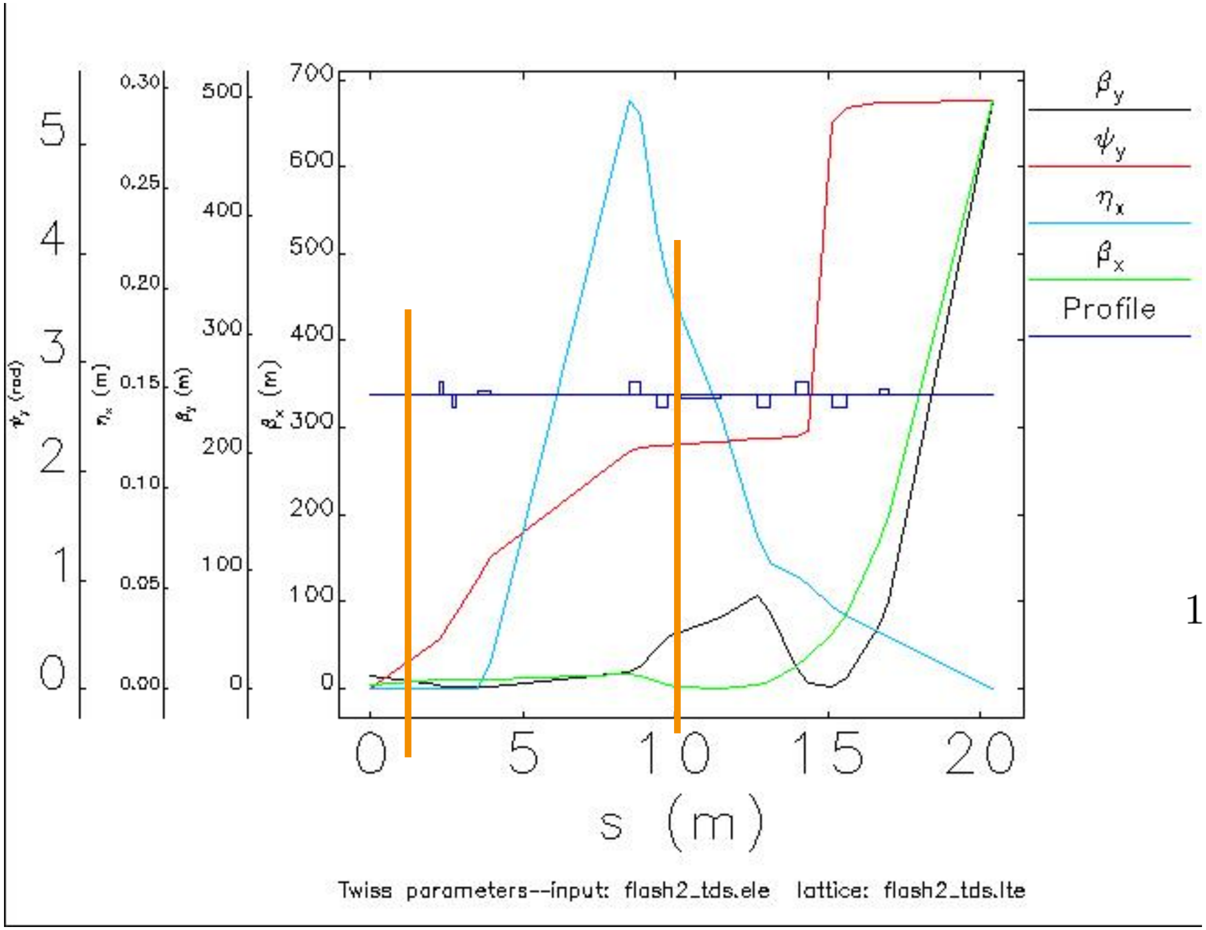



- XTCAV-position
  - Free space >2 m and some downstream for screen
  - Screen: dispersion in non-streaked coordinate, none in streaked coordinate
  - Streak x → useless, streak y → screen between D4FL2BURN and D1FL2DUMP

Lattice and Optics - Current FLASH 2 Lattice

$$\sigma_{t,R} = \frac{\sqrt{\epsilon_y}|p|}{\sqrt{\beta_y(tds)}\sin(\Delta\Psi_y)} \cdot \frac{c}{eV_0\omega}$$

$$\sigma_{\delta E,R} = \sqrt{\epsilon_x}\frac{\sqrt{\beta_x(s)}}{D_x(s)}$$

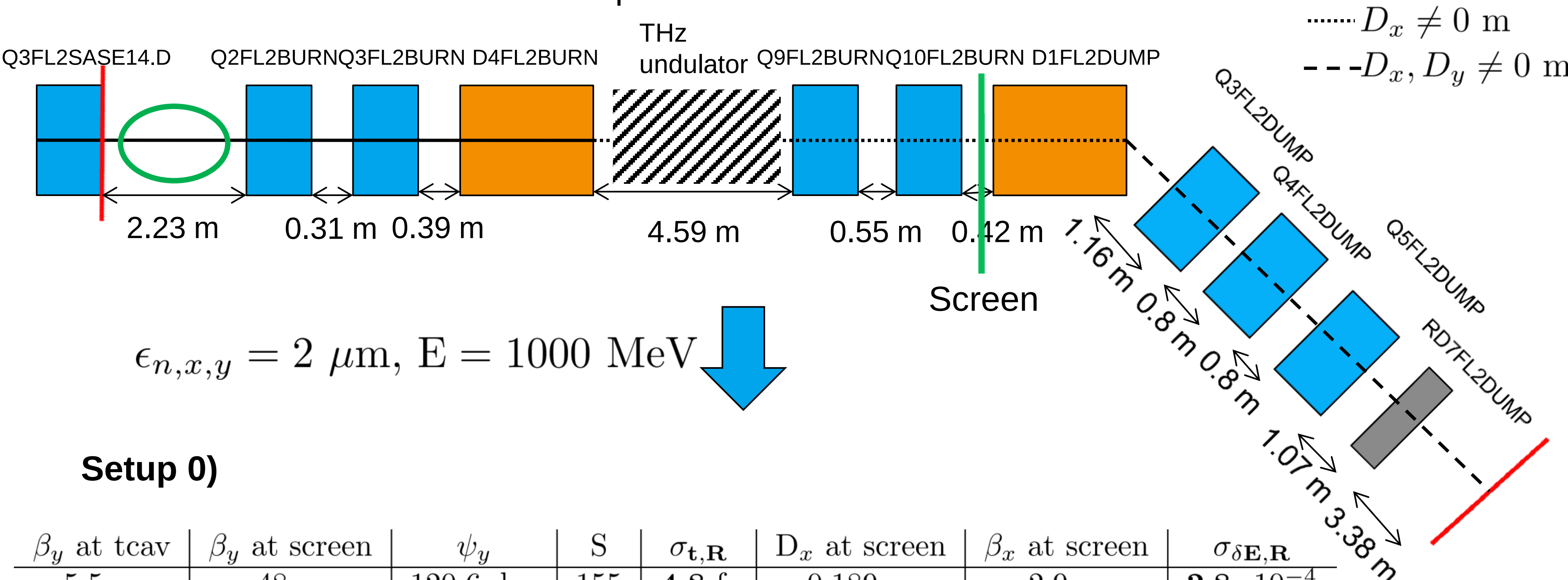


$$70° < \psi_y < 110°$$
$$1.2 \text{ rad} < \psi_y < 1.9 \text{ rad}$$

$\beta_{y,tcav} \approx 5.5$ m Large area with sufficient dispersion and phase advance

Matching

- Done with MADX
- For best resolution in both dimensions (< 1 fs and < e-4 equally)
- Screen position:
  - As close to D1FL2DUMP as possible



$$\epsilon_{n,x,y} = 2\ \mu\text{m},\ \text{E} = 1000\ \text{MeV}$$

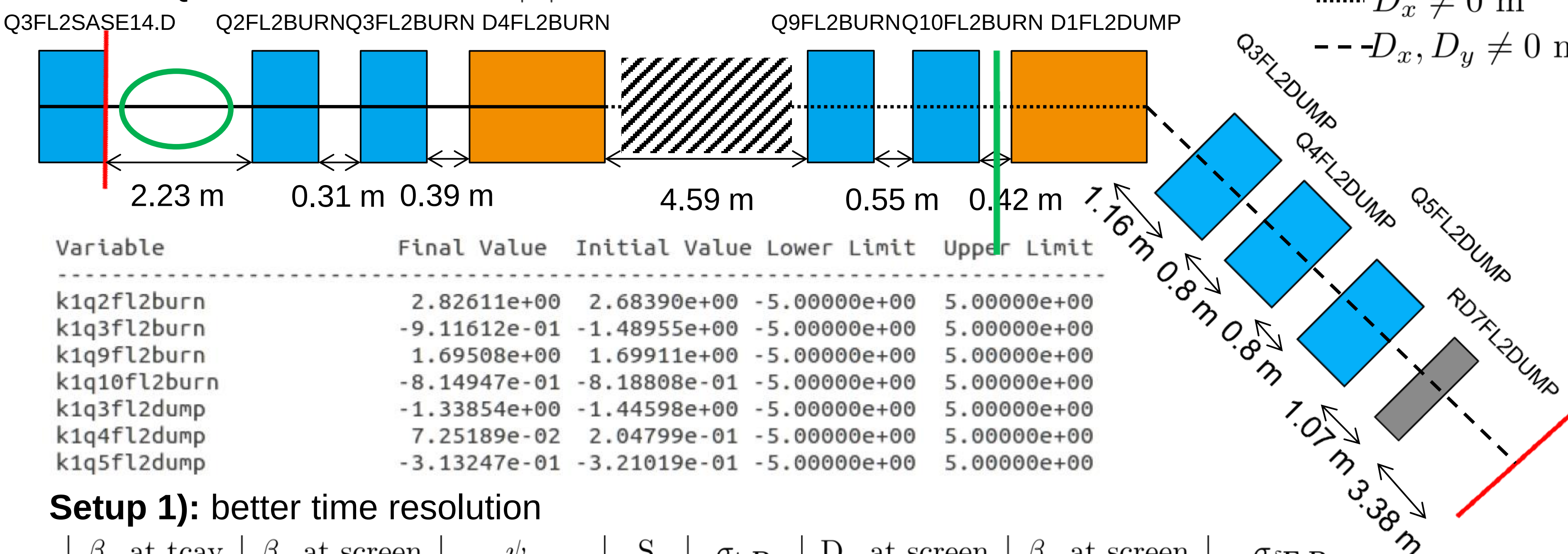
Setup 0)

β_y at tcav	β_y at screen	ψ_y	S	$\sigma_{\mathbf{t,R}}$	D_x at screen	β_x at screen	$\sigma_{\delta\mathbf{E,R}}$
5.5 m	48 m	120.6 deg	155	**4.8** fs	0.189 m	2.9 m	$\mathbf{2.8} \cdot 10^{-4}$

Match Quad strengths

> Matching of all quads in accordance with boundary conditions

- DUMP: $D_x, D_y < 2 \cdot 10^{-3}$ m
  $\beta_x > 600$ m, $\beta_y > 450$ m
- Quads: $|k| < 5$ m^{-2}

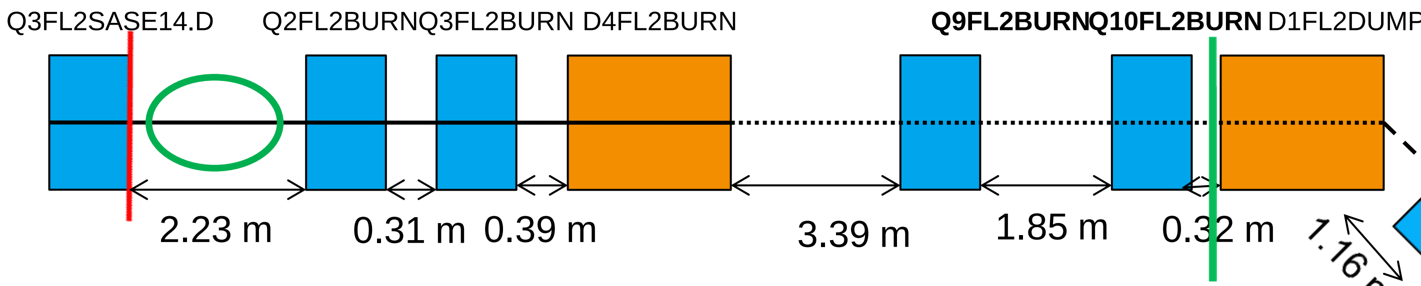


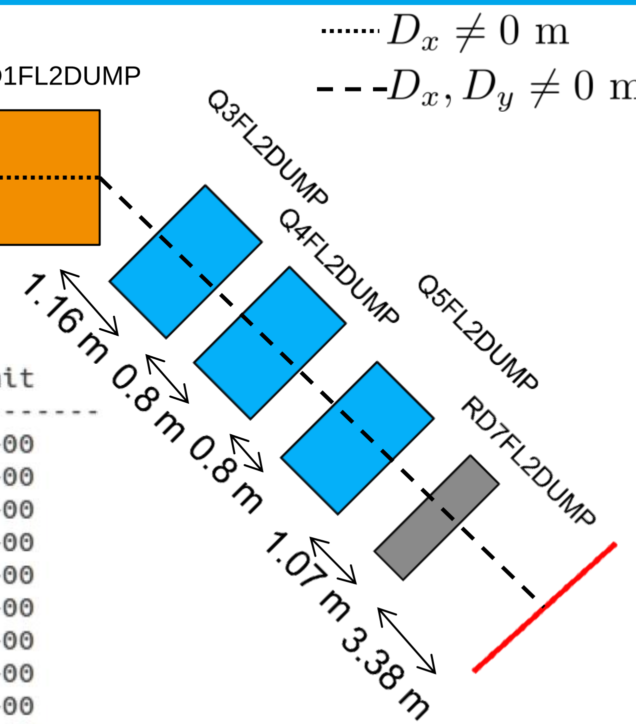

```
Variable            Final Value   Initial Value Lower Limit   Upper Limit
--------------------------------------------------------------------------
k1q2fl2burn          2.82611e+00   2.68390e+00 -5.00000e+00   5.00000e+00
k1q3fl2burn         -9.11612e-01  -1.48955e+00 -5.00000e+00   5.00000e+00
k1q9fl2burn          1.69508e+00   1.69911e+00 -5.00000e+00   5.00000e+00
k1q10fl2burn        -8.14947e-01  -8.18808e-01 -5.00000e+00   5.00000e+00
k1q3fl2dump         -1.33854e+00  -1.44598e+00 -5.00000e+00   5.00000e+00
k1q4fl2dump          7.25189e-02   2.04799e-01 -5.00000e+00   5.00000e+00
k1q5fl2dump         -3.13247e-01  -3.21019e-01 -5.00000e+00   5.00000e+00
```

Setup 1): better time resolution

	β_y at tcav	β_y at screen	ψ_y	S	$\sigma_{\mathbf{t},\mathbf{R}}$	D_x at screen	β_x at screen	$\sigma_{\delta\mathbf{E},\mathbf{R}}$
0.)	5.5 m	48 m	120.6 deg	155	**4.8** fs	0.189 m	2.9 m	$\mathbf{2.8} \cdot 10^{-4}$
1.)	5.5 m	49.2 m	108 deg	172	**4.3** fs	0.189 m	1.32 m	$\mathbf{1.9} \cdot 10^{-4}$

Match Quad strengths and positions





Variable	Final Value	Initial Value	Lower Limit	Upper Limit
k1q3fl2sase14	-2.75769e+00	-3.67505e+00	-5.00000e+00	5.00000e+00
k1q2fl2burn	1.20249e+00	2.68390e+00	-5.00000e+00	5.00000e+00
k1q3fl2burn	-2.41003e+00	-1.48955e+00	-5.00000e+00	5.00000e+00
k1q9fl2burn	1.64118e+00	1.69911e+00	-5.00000e+00	5.00000e+00
posq9fl2burn	7.39840e+00	8.60500e+00	4.01943e+00	9.15930e+00
posq10fl2burn	9.61784e+00	9.51000e+00	9.51000e+00	9.87860e+00
k1q10fl2burn	-1.07771e+00	-8.18808e-01	-5.00000e+00	5.00000e+00
k1q3fl2dump	-1.65019e+00	-1.44598e+00	-5.00000e+00	5.00000e+00
k1q4fl2dump	1.04874e-01	2.04799e-01	-5.00000e+00	5.00000e+00
k1q5fl2dump	2.75627e-01	-3.21019e-01	-5.00000e+00	5.00000e+00

Setup 2) better energy resolution

	β_y at tcav	β_y at screen	ψ_y	S	$\sigma_{\mathbf{t,R}}$	D_x at screen	β_x at screen	$\sigma_{\delta\mathbf{E,R}}$
0.)	5.5 m	48 m	120.6 deg	155	**4.8** fs	0.189 m	2.9 m	$\mathbf{2.8} \cdot 10^{-4}$
1.)	5.5 m	49.2 m	108 deg	172	**4.3** fs	0.189 m	1.32 m	$\mathbf{1.9} \cdot 10^{-4}$
2.)	6.0 m	78.4 m	148.5 deg	125	**7.5** fs	0.09 m	0.14 m	$\mathbf{1.3} \cdot 10^{-4}$

Feasible and desirable? THz-Undulator + worse time resolution...

Jitter

- Calibration constants with jitter (worst case)
  - Beam Energy: 0.1% → Energy and Phase scan

    $$\sigma_{x,jit} = D \cdot \sigma_{\delta E,jit}$$

    $$\sigma_{y,jit} = S \cdot c \cdot t \cdot \sigma_{\delta E,jit}$$

  - XTCAV amplitude: 1% → Phase scan

    $$\sigma_{y,jit} = S \cdot c \cdot t \cdot \sigma_{\delta A,jitt}$$

  - Beam arrival time: 50 fs → Phase scan

    $$\sigma_{y,jit} = S \cdot c \cdot \sigma_{t,jit}$$

  - XTCAV phase: 0.1° → Phase scan

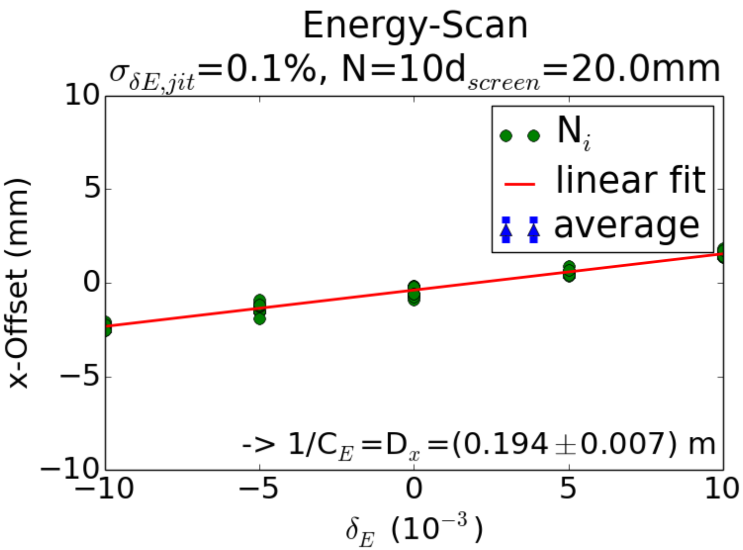
    $$\sigma_{y,jit} = \frac{S \cdot c}{\omega} \cdot \sigma_{\phi,jitt}$$

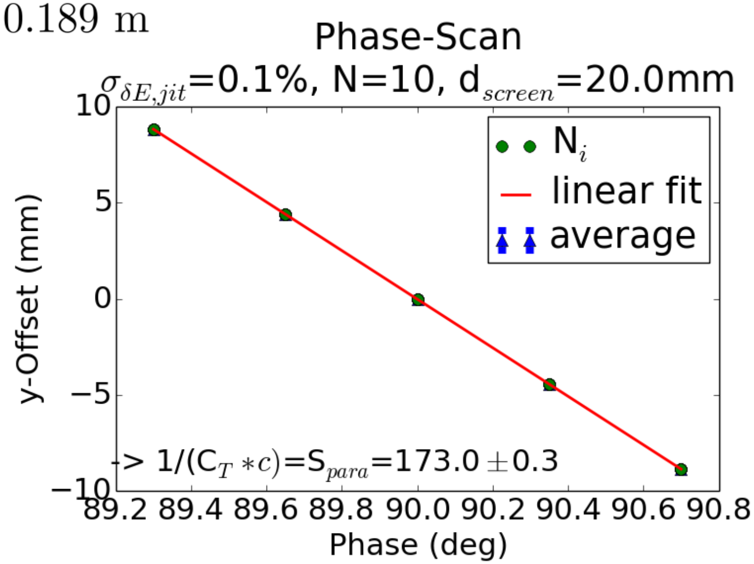
- Setup 1 sufficient, simulations with elegant
  - Largest S and biggest Dispersion
- 2 cm x 2 cm screen
- 10 shots for each step

Jitter

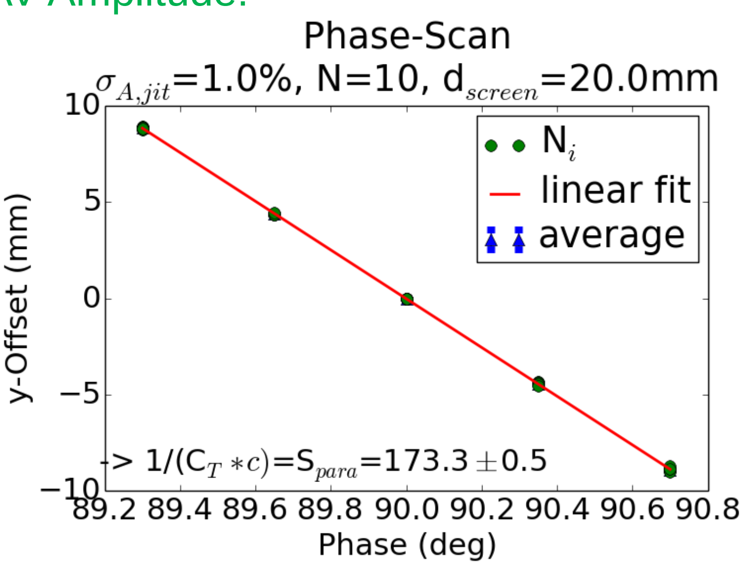
S_{exp}	$D_{x,exp}$ at screen
172	0.189 m

Beam energy:





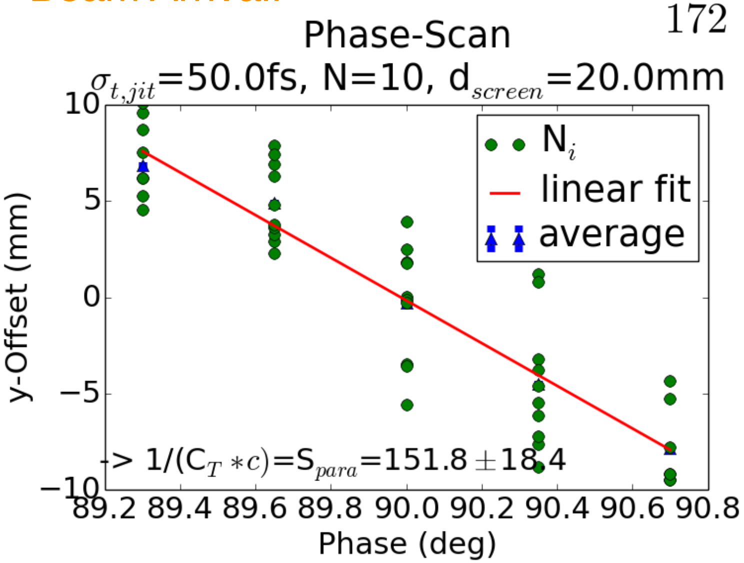
XTCAV Amplitude:



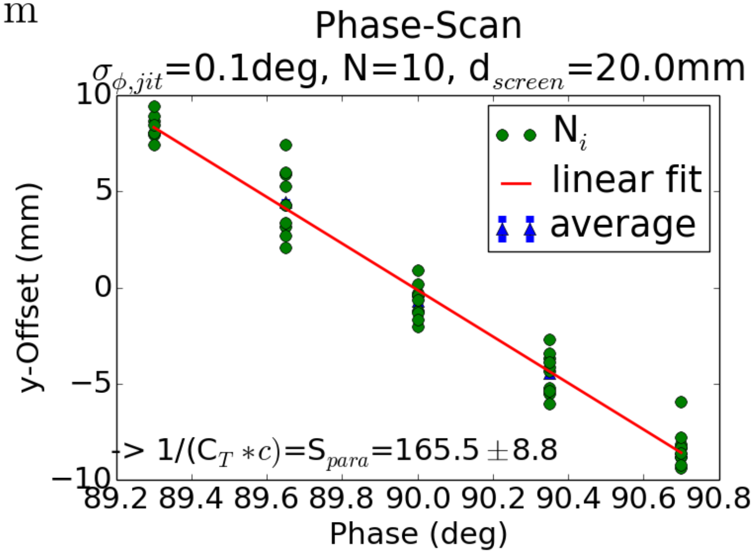
Jitter

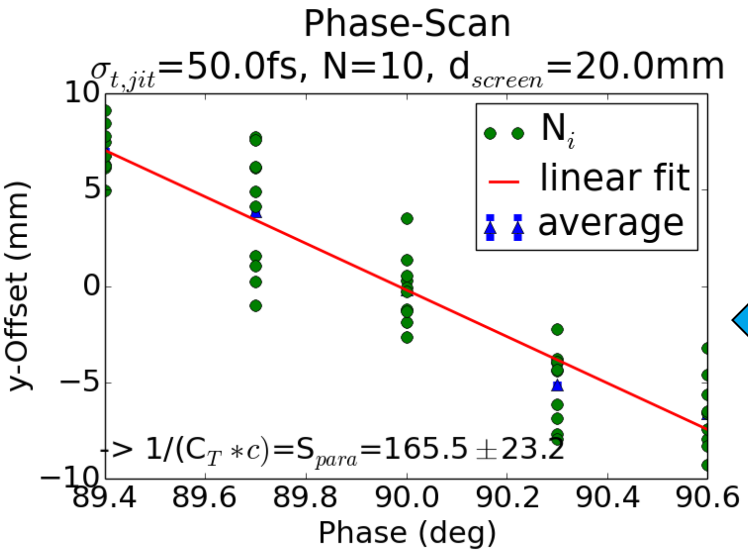
S_{exp}	$D_{x,exp}$ at screen
172	0.189 m

Beam Arrival:



XTCAV phase:





- Smaller scan range or bigger screen
- Calibrate with lower TCAV power and scale

$$S_h = \frac{V_h}{V_l} \cdot S_l$$

Jitter should not be a problem!

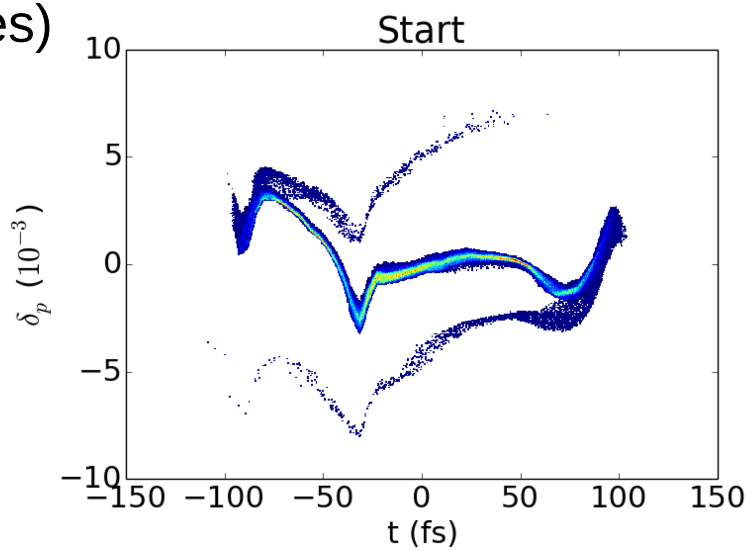
Bunch simulations

- FEL-off (start to end simulation)

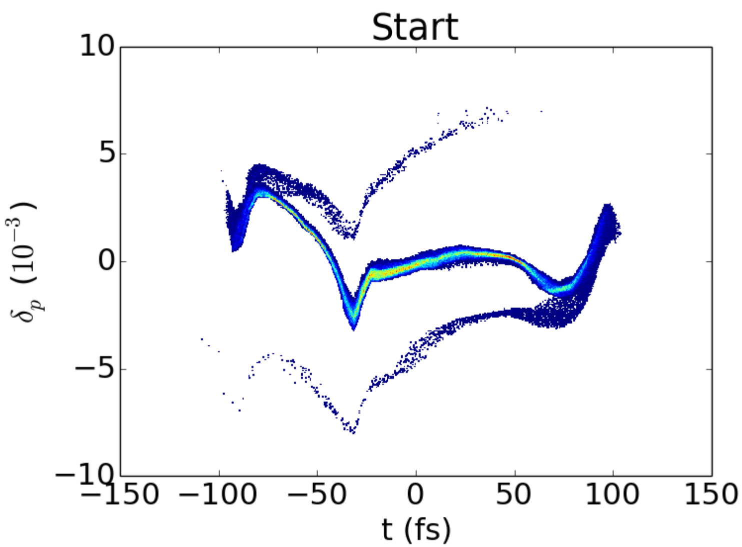
$$Q = 0.25\ \text{nC};\ I_p = 2.5\ \text{kA};\ E = 1000\ \text{MeV};\ \epsilon_{n,x} = 0.82\ \mu\text{m};\ \epsilon_{n,y} = 0.75\ \mu\text{m}$$

	β_y at tcav	β_y at screen	ψ_y	S	$\sigma_{\mathbf{t},\mathbf{R}}$	D_x at screen	β_x at screen	$\sigma_{\mathbf{E},\mathbf{R}}$
0.)	5.5 m	48 m	120.6 deg	155	**2.9** fs	0.189 m	2.9 m	$\mathbf{1.8} \cdot 10^{-4}$
1.)	5.5 m	49.2 m	108 deg	172	**2.67** fs	0.189 m	1.32 m	$\mathbf{1.2} \cdot 10^{-4}$
2.)	6.0 m	78.4 m	148.5 deg	125	**4.6** fs	0.09 m	0.14 m	$\mathbf{0.9} \cdot 10^{-4}$

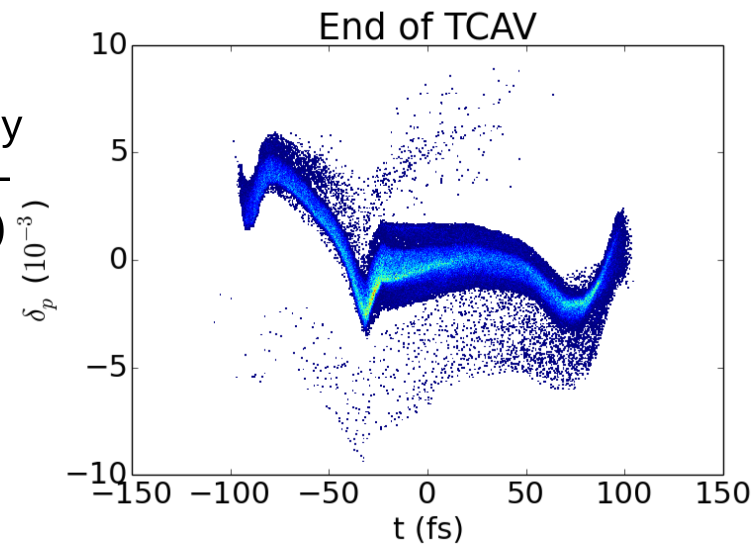
- Elegant simulations (250 000 macroparticles)
- Proceed as in experiment
  - Calibration: Scans
  - Temporal resolution: non-streaked beam size

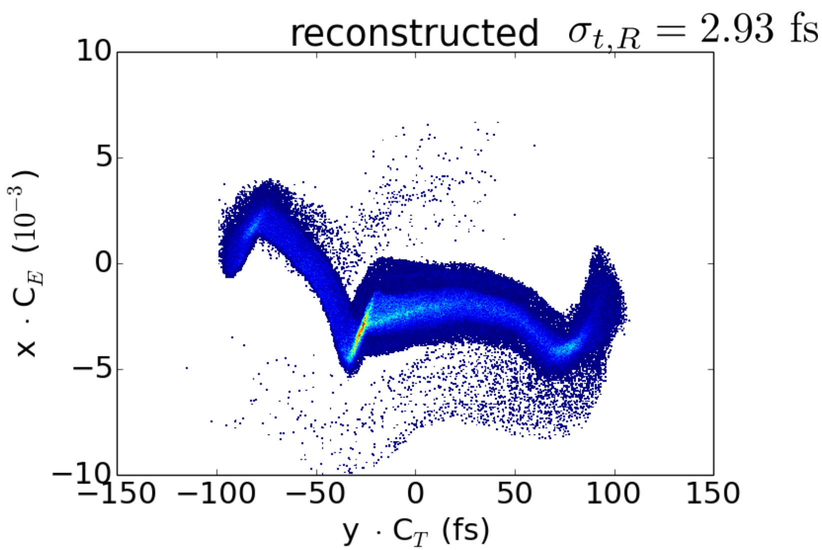


Setup 0



TCAV adds energy spread (Panofsky-Wenzel-Theorem)

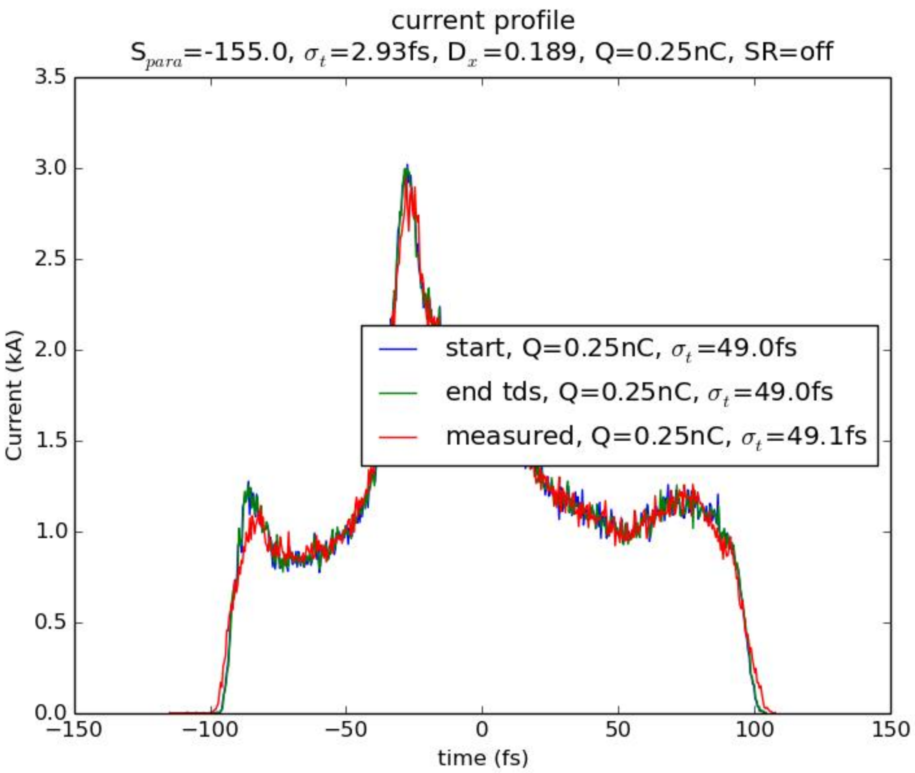




Setup 0)

	S	$\sigma_{t,R}$	$\sigma_{\delta E,R}$
0.)	155	2.9 fs	$1.8 \cdot 10^{-4}$

Setup 0



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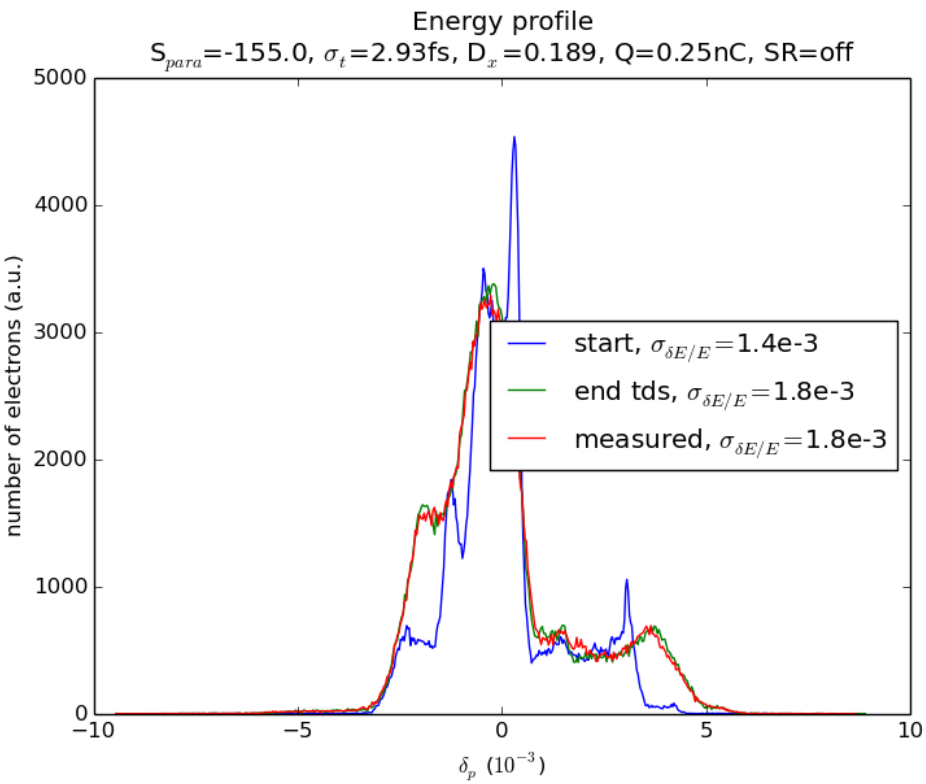
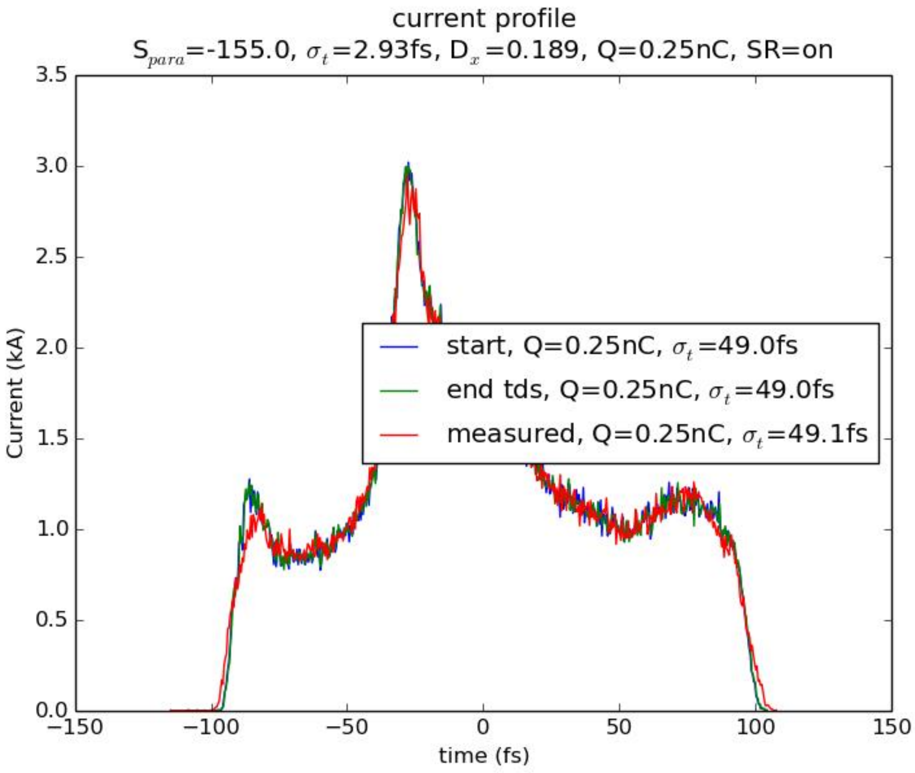
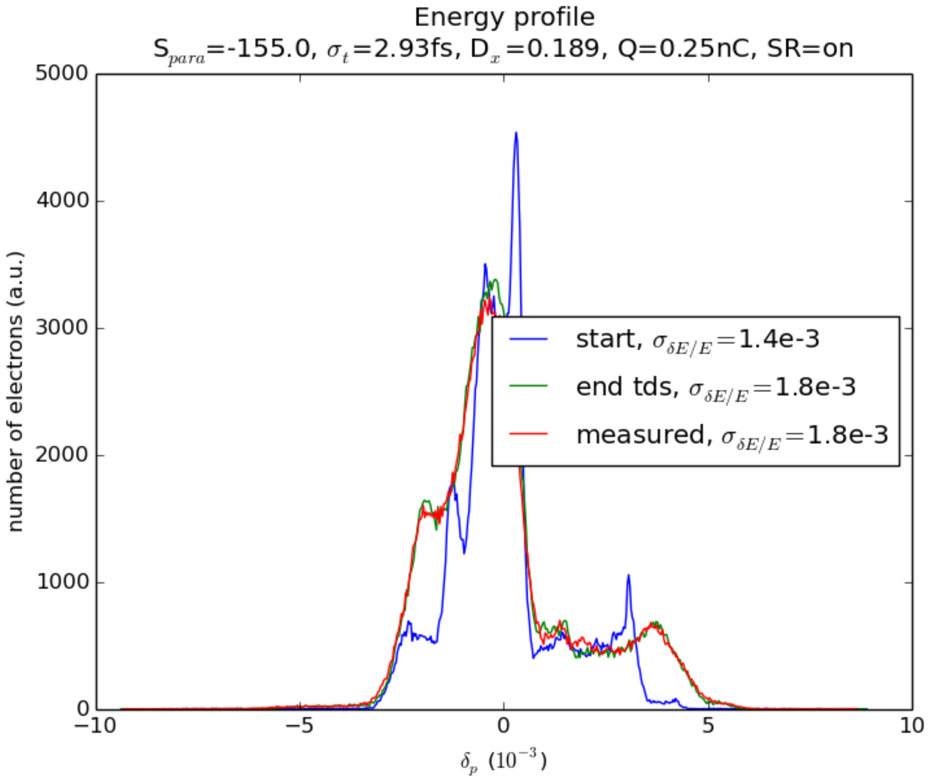


CSR influence

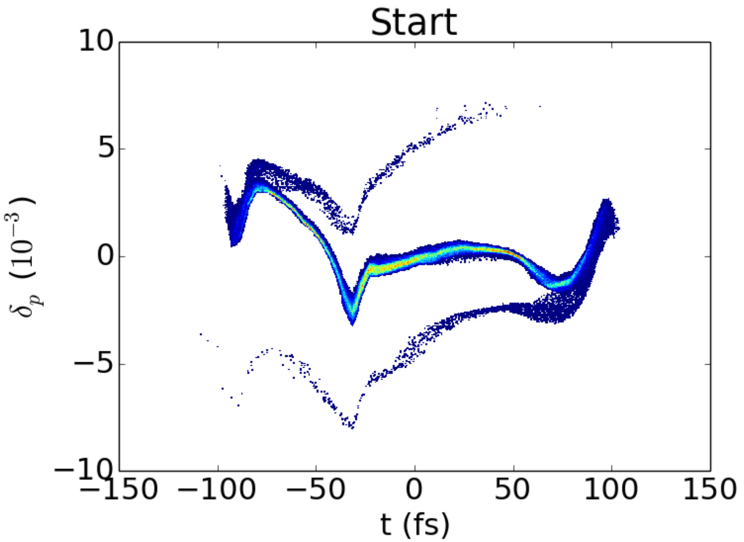
- CSR because of dipole could have influence on measurements

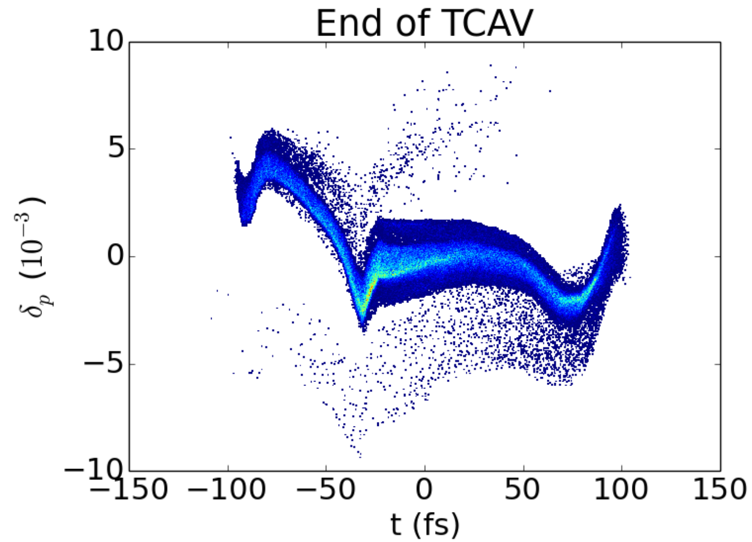


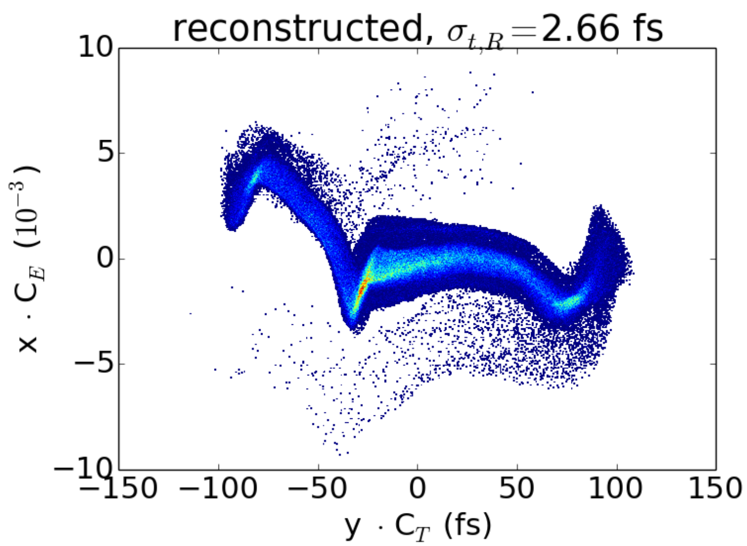


No relevant influence ☺

Setup 1







Setup 1)

	S	$\sigma_{t,R}$	$\sigma_{\delta E,R}$
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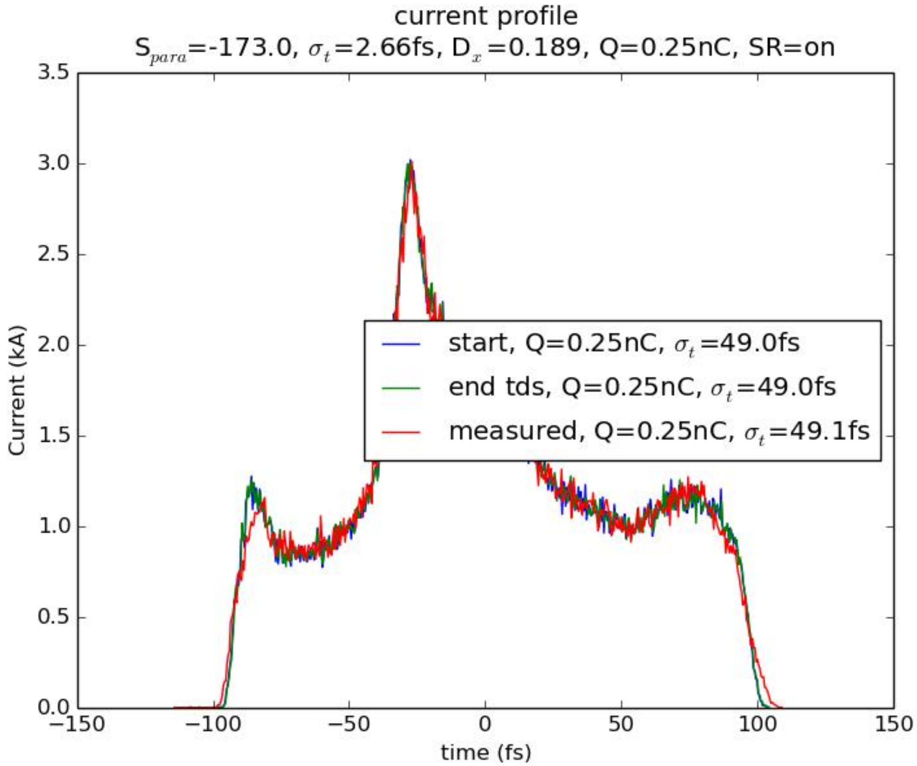
1.)	172	2.67 fs	$1.2 \cdot 10^{-4}$

Setup 1



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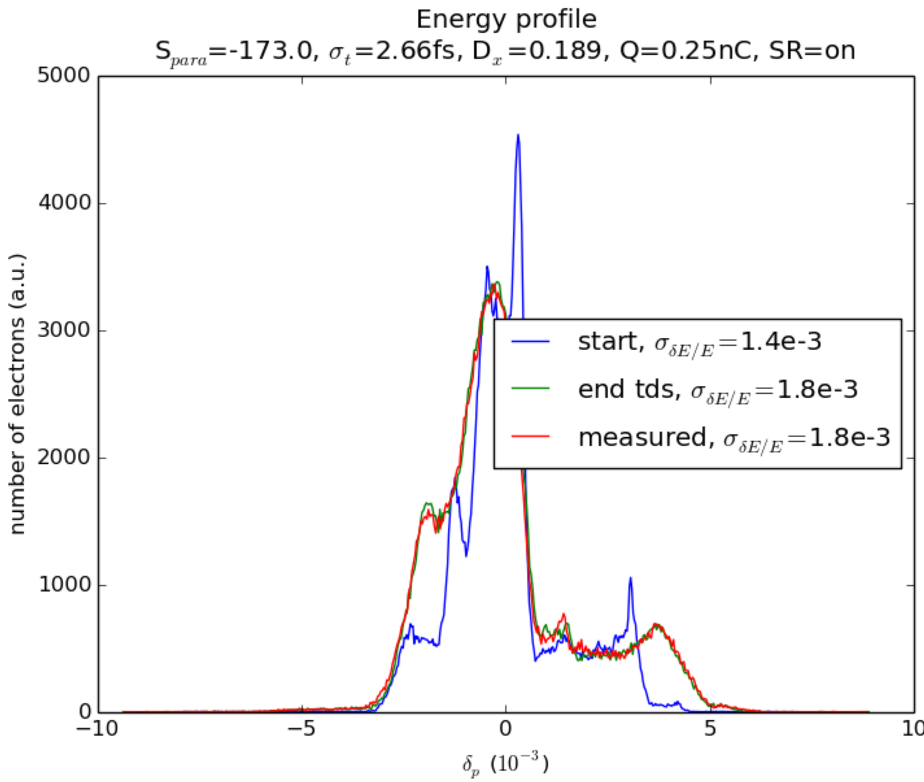
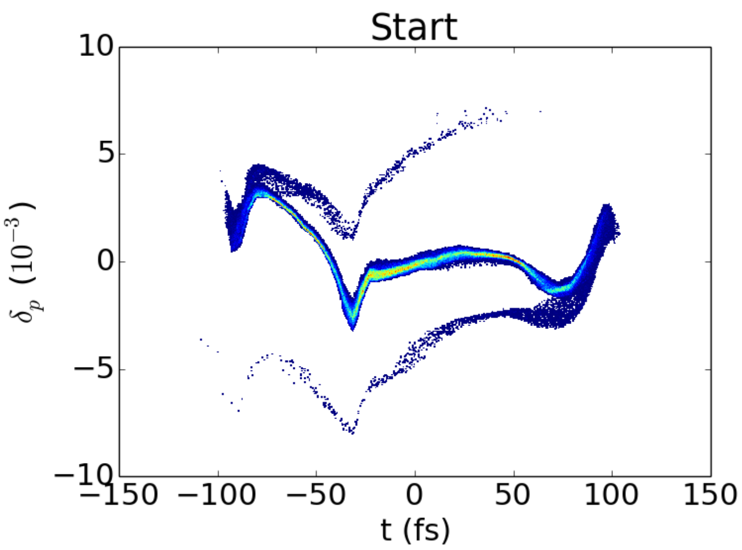
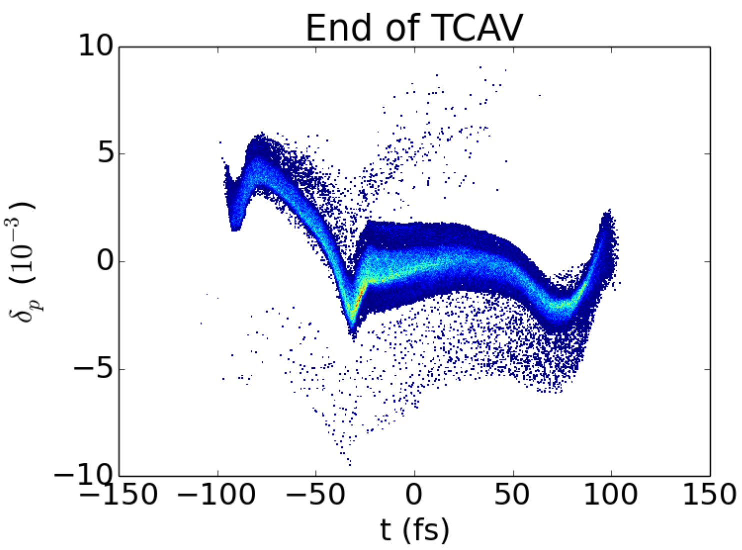
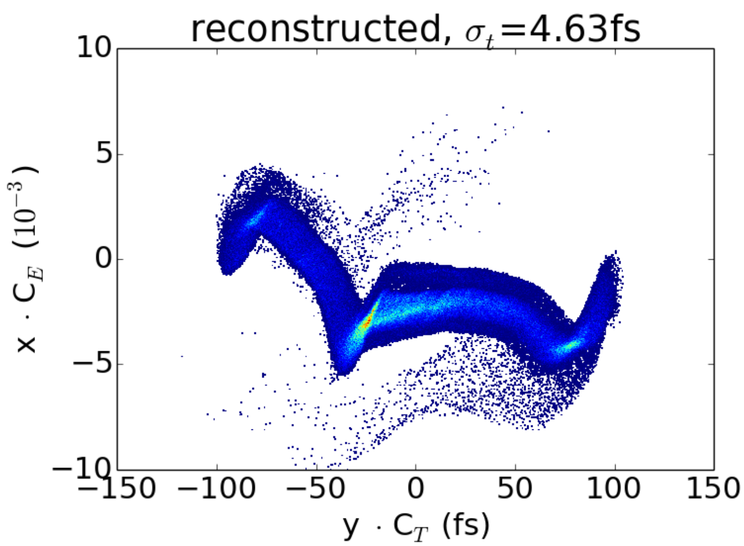


Setup 2



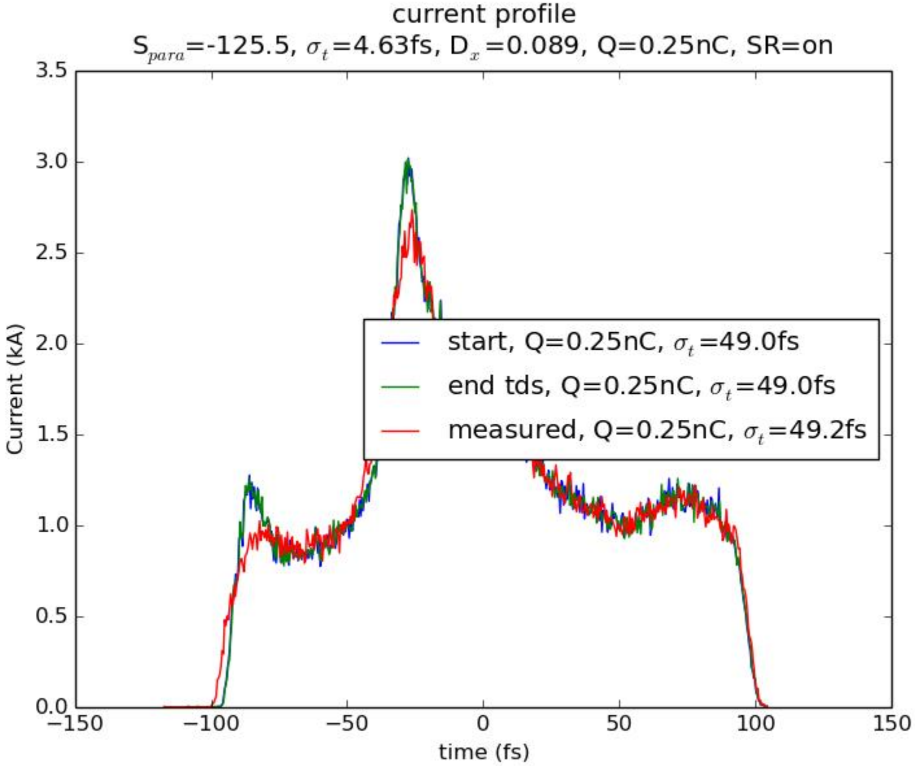




Setup 2)

	S	$\sigma_{t,R}$	$\sigma_{\delta E,R}$
0.)	155	2.9 fs	$1.8 \cdot 10^{-4}$
1.)	172	2.67 fs	$1.2 \cdot 10^{-4}$
2.)	125	4.6 fs	$0.9 \cdot 10^{-4}$

Setup 2



Setup 2)

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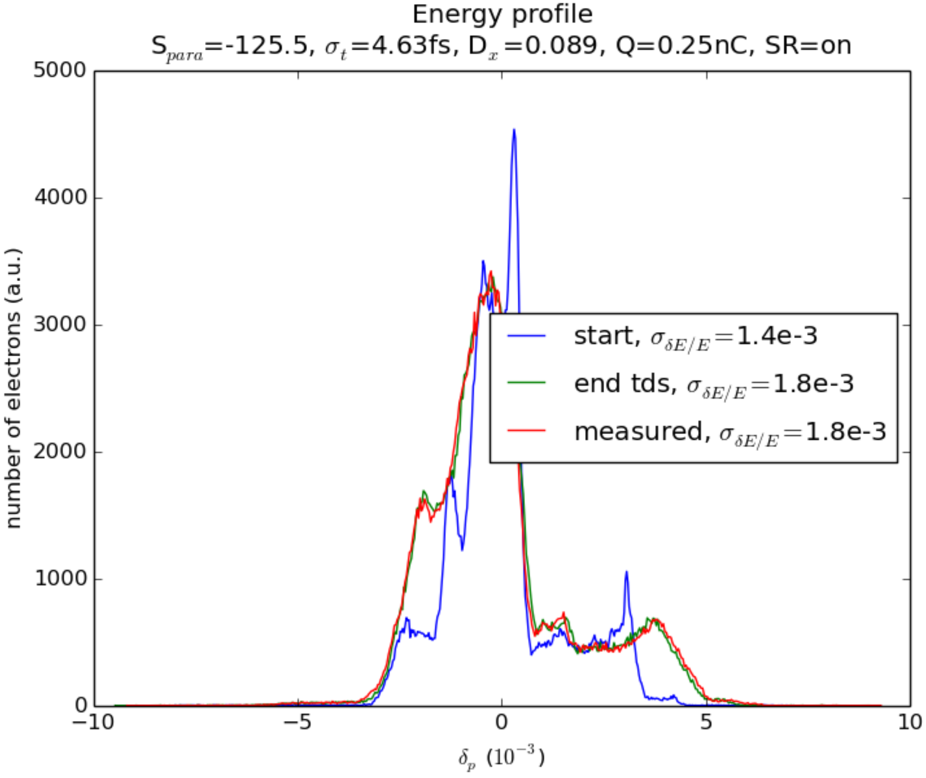


Summary and Outlook

- 3 different setups
  - Screen position; + quad strengths (better time resolution); + quad positions (better energy resolution)
- Jitter can be dealt with
- CSR has no influence
- Sufficient results for all 3 setups
  - Should be able to resolve FEL effects

	S	$\sigma_{t,R}$	$\sigma_{\delta E,R}$
0.)	155	2.9 fs	$1.8 \cdot 10^{-4}$
1.)	172	2.67 fs	$1.2 \cdot 10^{-4}$
2.)	125	4.6 fs	$0.9 \cdot 10^{-4}$

- FEL - pulse
- Comparison simulated x-ray pulse and reconstruction
- Which setups are feasible and which is best suited?
- Changing optics before TCAV could highly improve resolution
  - Larger $\beta_{y,tds} \rightarrow \beta \approx 200 \text{ m} \rightarrow \sigma_t < 1 \text{ fs}$

Thank you for your attention!

> Special thanks to:

- C. Behrens, B. Marchetti, J. Zemella, G. Feng, S. Schreiber, M. Vogt, S. Duesterer

BACKUP SLIDES

Dependencies

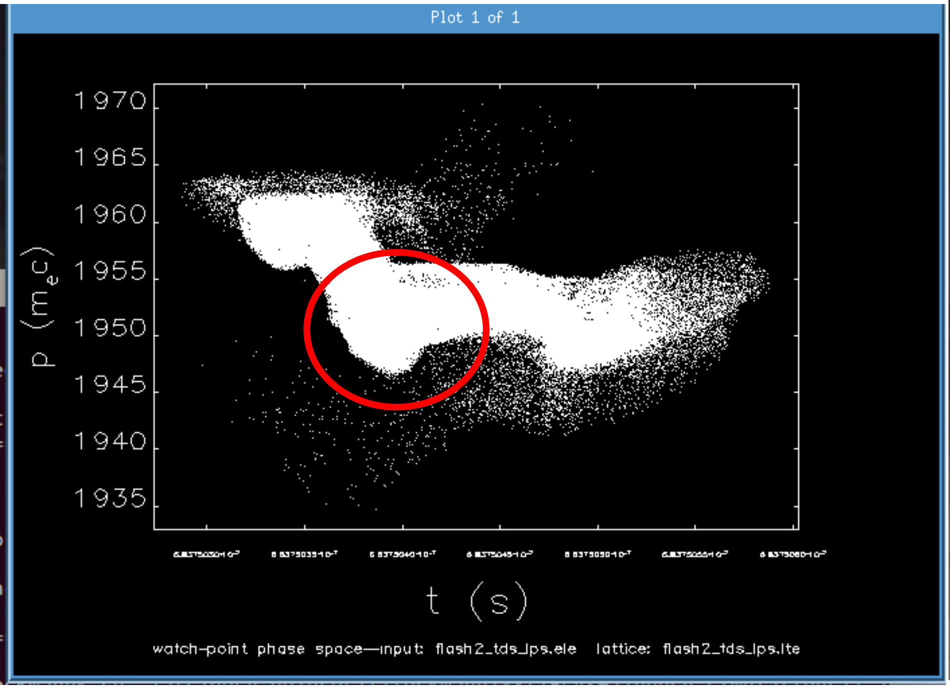
Shear Function S and Longitudinal Resolution $\sigma_{\zeta,R}$

- $S = \sqrt{\beta_x(s_0)\beta_x(s)} \cdot \frac{eV_0k}{E} \cdot \sin(\Delta\Phi_x)$ $\quad \boxed{\sim 1/E}$
- $\sigma_{\zeta,R} = \frac{\sigma_{x_\beta}}{S} = \sqrt{\epsilon_{N,x}/\gamma} \cdot E \cdot \frac{1}{\sqrt{\beta_x(s_0)} \cdot \sin(\Delta\Phi_x)} \cdot \frac{1}{eV_0k}$ $\quad \boxed{\sim \sqrt{\epsilon_{N,x} \cdot E}}$

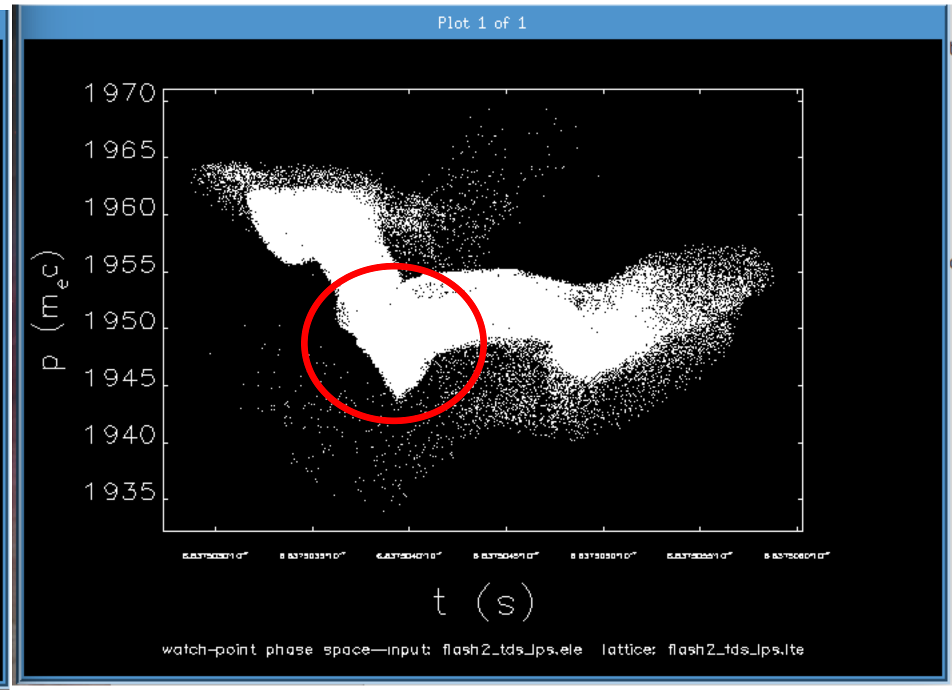
Relative Energy Resolution $\sigma_{\delta,R}$

- $\sigma_{\delta,R} = \frac{\sigma_{y_\beta}}{D_y} = \sqrt{\epsilon_{N,y}/\gamma} \cdot \frac{\sqrt{\beta_y}}{D_y}$ $\quad \boxed{\sim \sqrt{\epsilon_{N,y}/E}}$
- Absolute Energy Resolution: $\sigma_{E,R} = \sigma_{\delta,R} \cdot E$ $\quad \boxed{\sim \sqrt{\epsilon_{N,y} \cdot E}}$

CSR off



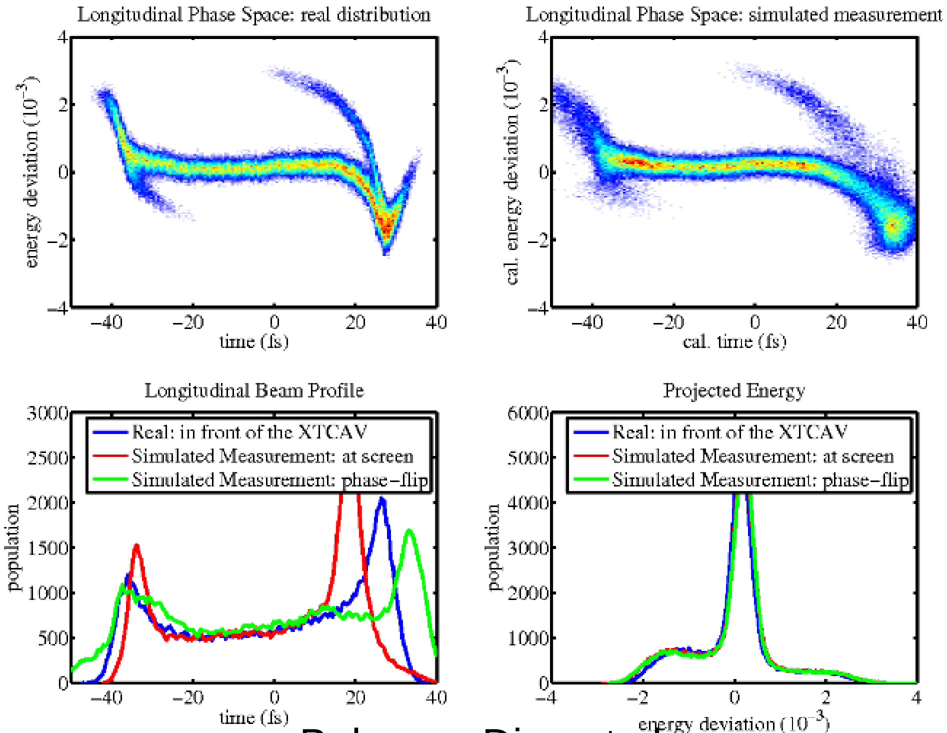
CSR on



Simulated longitudinal phase space at screen

Correlations

- Intrinsic effects can lead to initial t-yp correlation
- Systematic error on measurements
- Can be corrected by a second measurement changing the TCAV phase by 180°
- However was not observed here!



Behrens, Ding et al.

Reconstruction of temporal x-ray profile

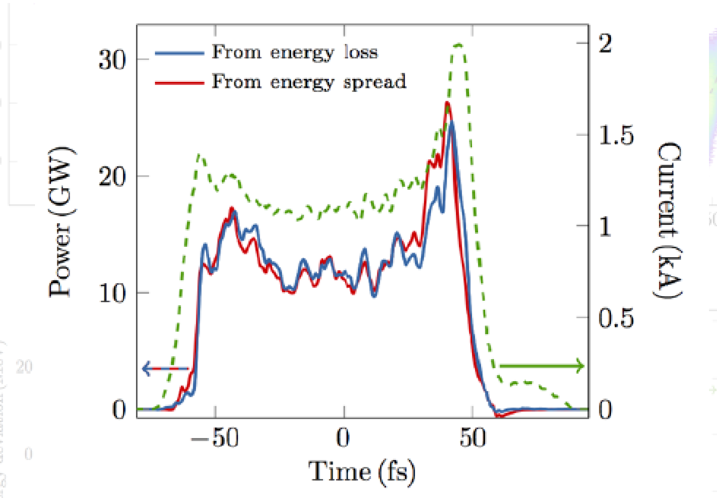
- PRSTAB 2011:
  - absolute with ΔE
  - relative with σ_E
- T. Maxwell
  - calculations

- The 2011 PRSTAB implies the x-ray profile $P_{xray}(t)$ can be inferred from either the shift in the slice mean energy or the slice energy spread as either

$$P_{xray}(t) \propto I(t)\left[\langle E_{off}(t)\rangle - \langle E_{on}(t)\rangle\right]$$

$$P_{xray}(t) \propto I(t)\sqrt{\sigma_{off}^2(t) - \sigma_{off}^2(t)}$$

$$P_{xray}(t) \propto I^{2/3}(t)\left[\sigma_{off}^2(t) - \sigma_{off}^2(t)\right]$$



DESY