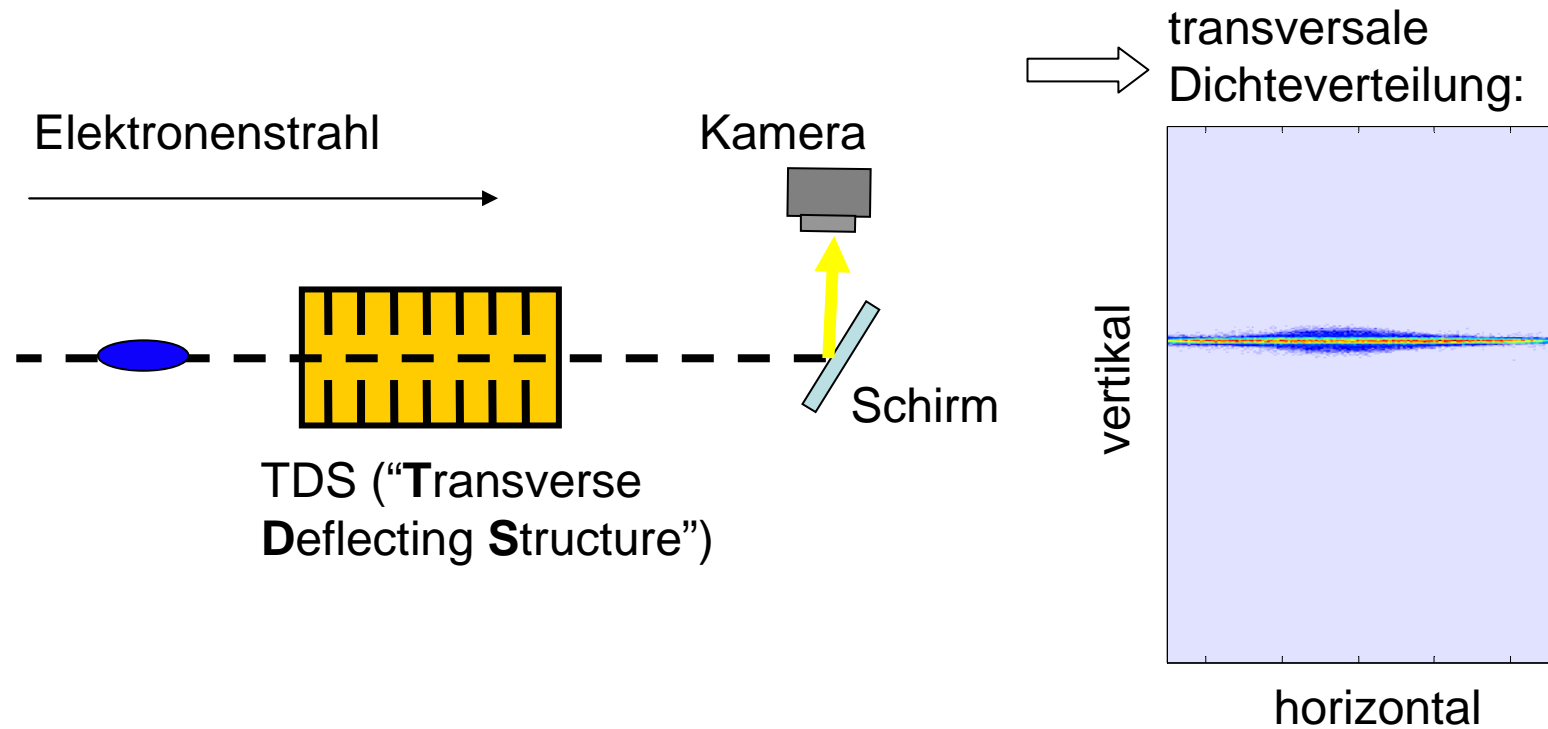
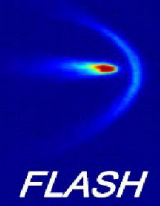


# Untersuchung von Elektronenpaketen am FLASH-Beschleuniger mit einer transversal ablenkenden HF-Struktur

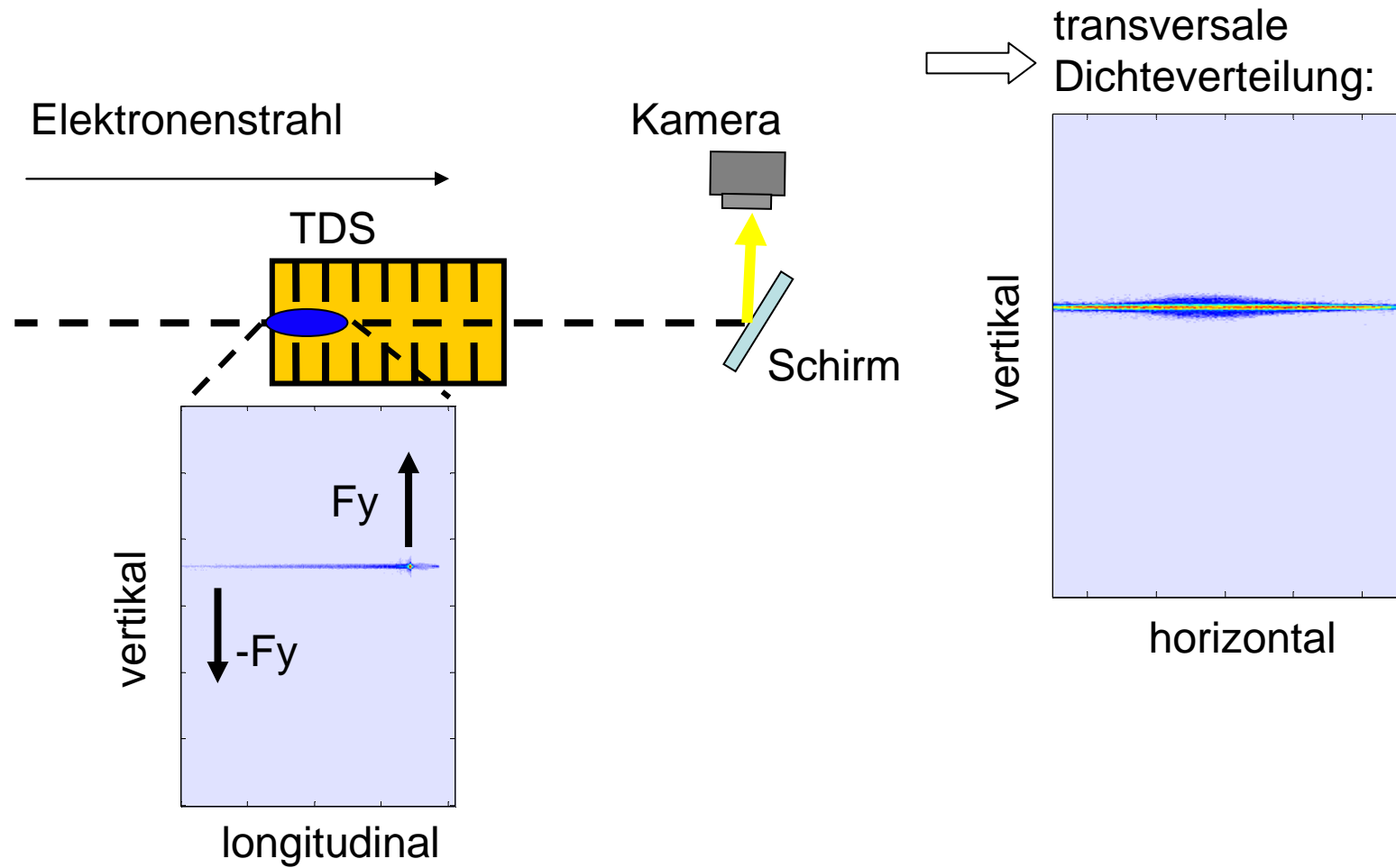
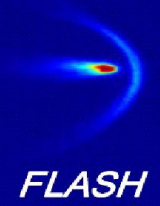
Disputation, 06.05.08

Michael Röhrs

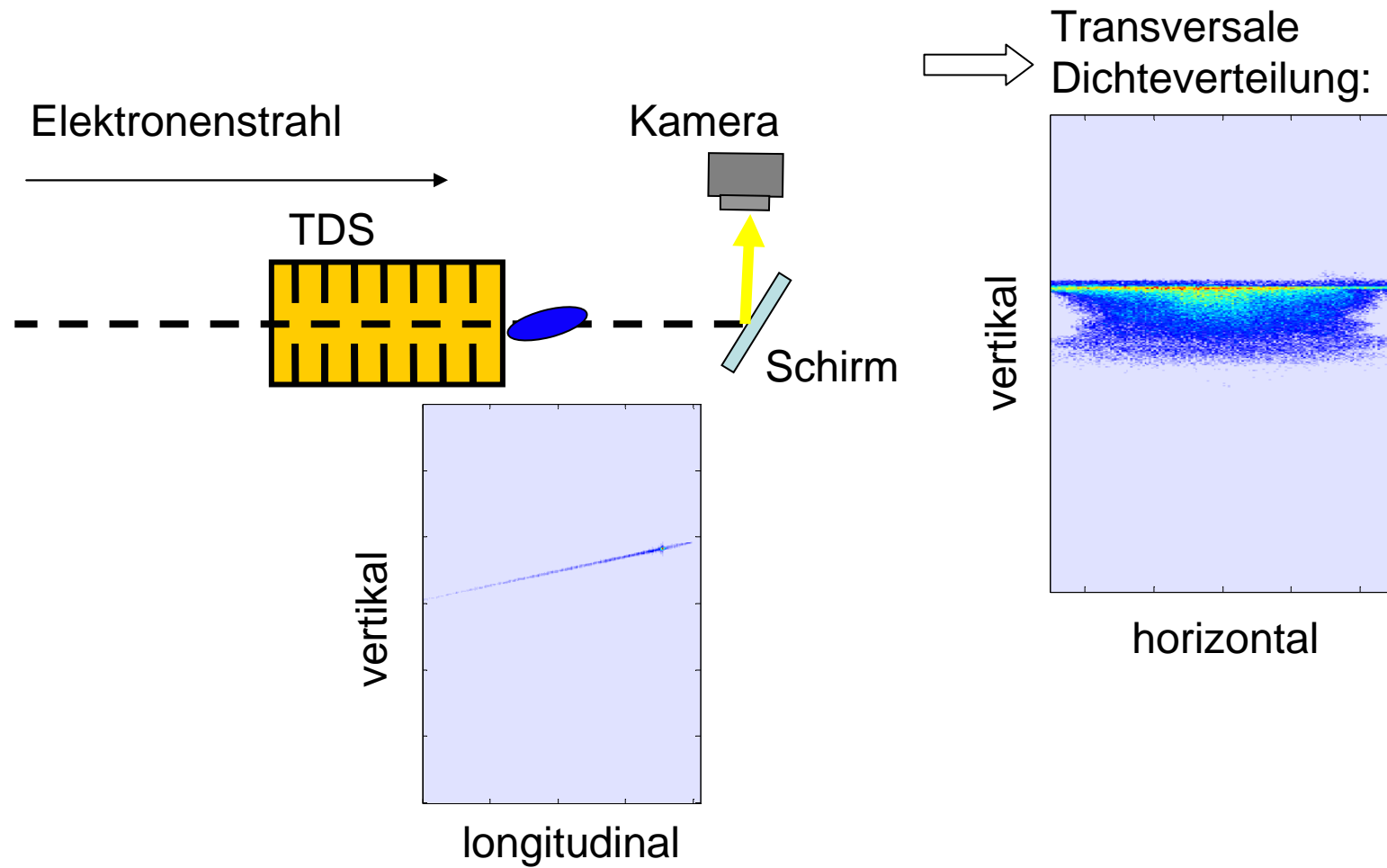
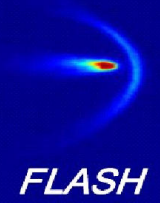
# Einleitung



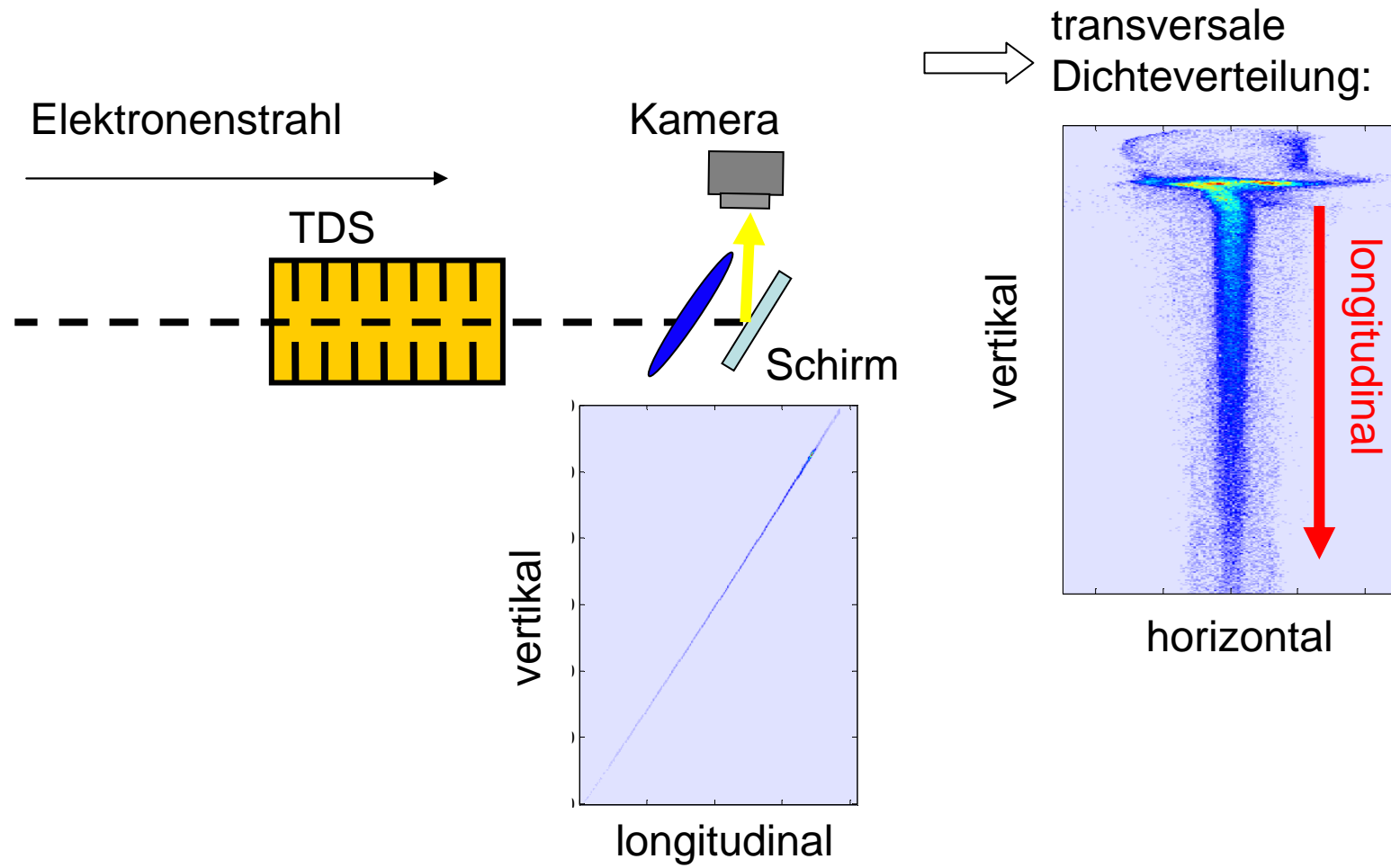
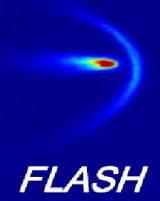
# Einleitung



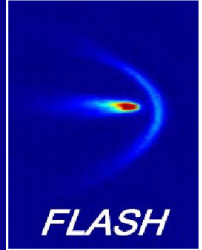
# Einleitung



# Einleitung



# Übersicht

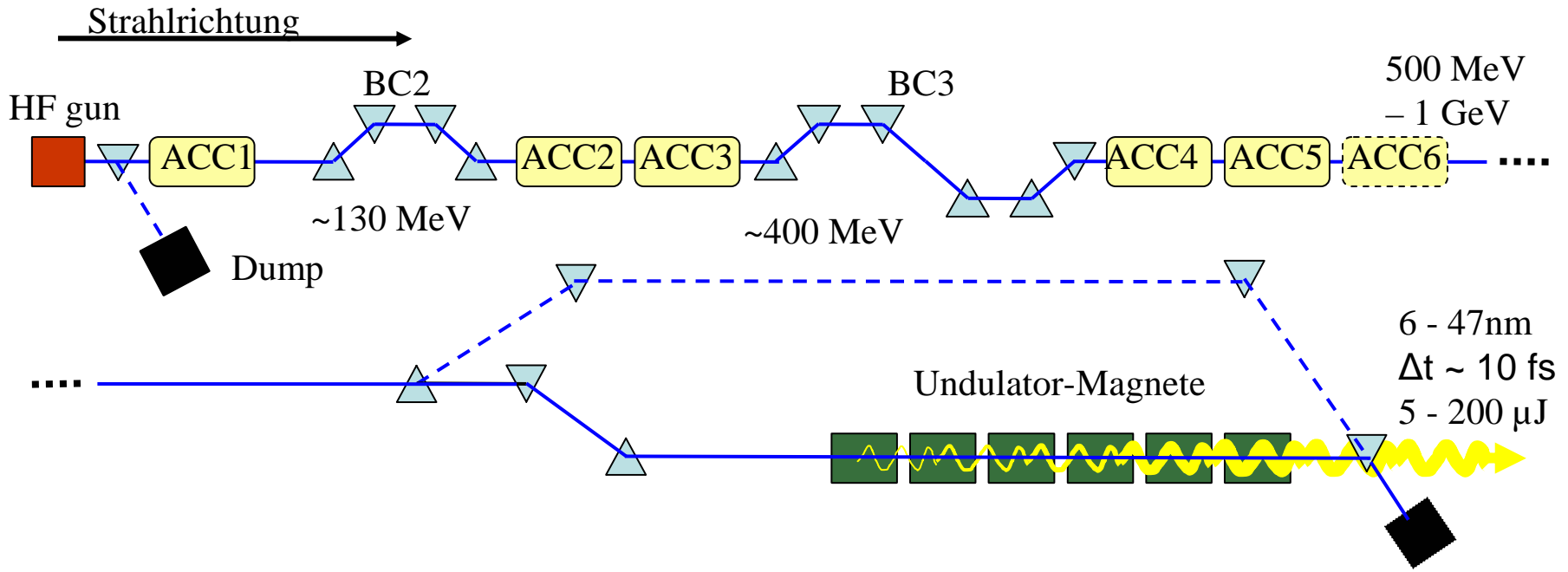
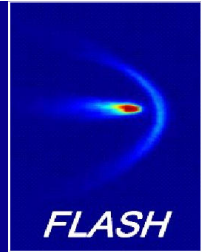


- Motivation
- Die transversal ablenkende HF-Struktur (TDS)
- Messmethoden
- Resultate unter FEL-Betriebsbedingungen
- Zusammenfassung

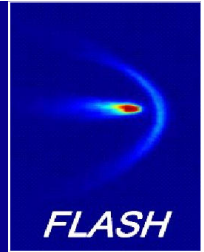
Motivation



# Der Freie-Elektronen Laser in Hamburg (FLASH)

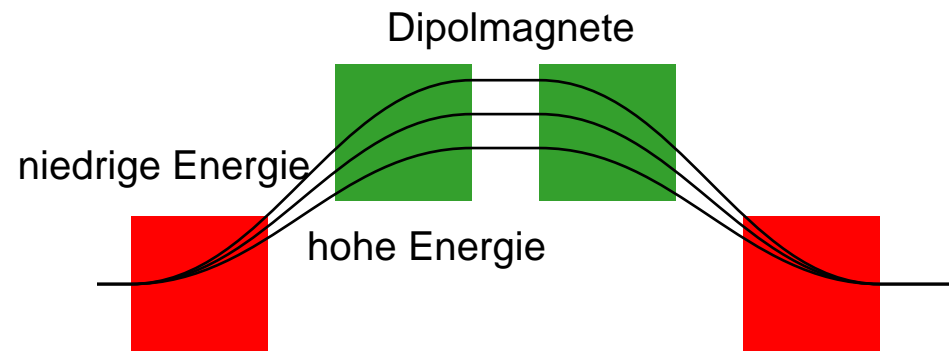
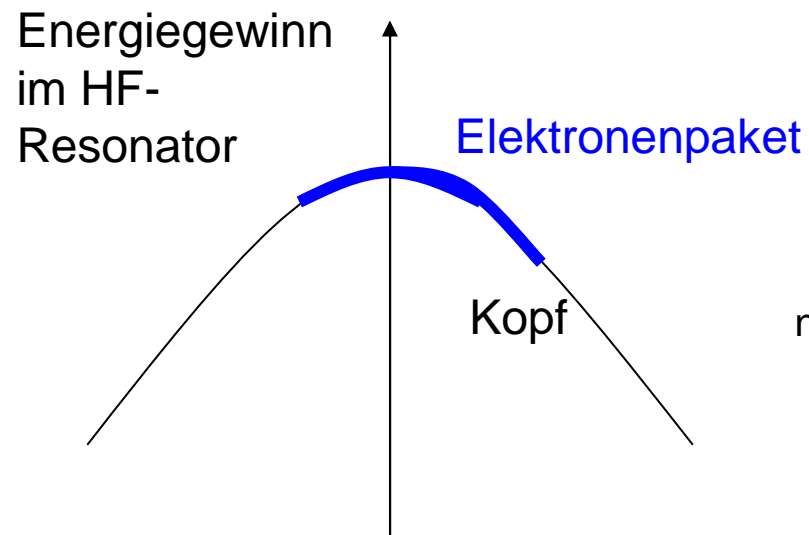


- Elektronenpakete:
- 500 MeV - 1 GeV Elektronenenergie
  - ~1 nC Ladung
  - ~1-3 kA Peakstrom



1. Erzeugung eines Energiegradienten :

2. Energieabhängige Pfadlänge :

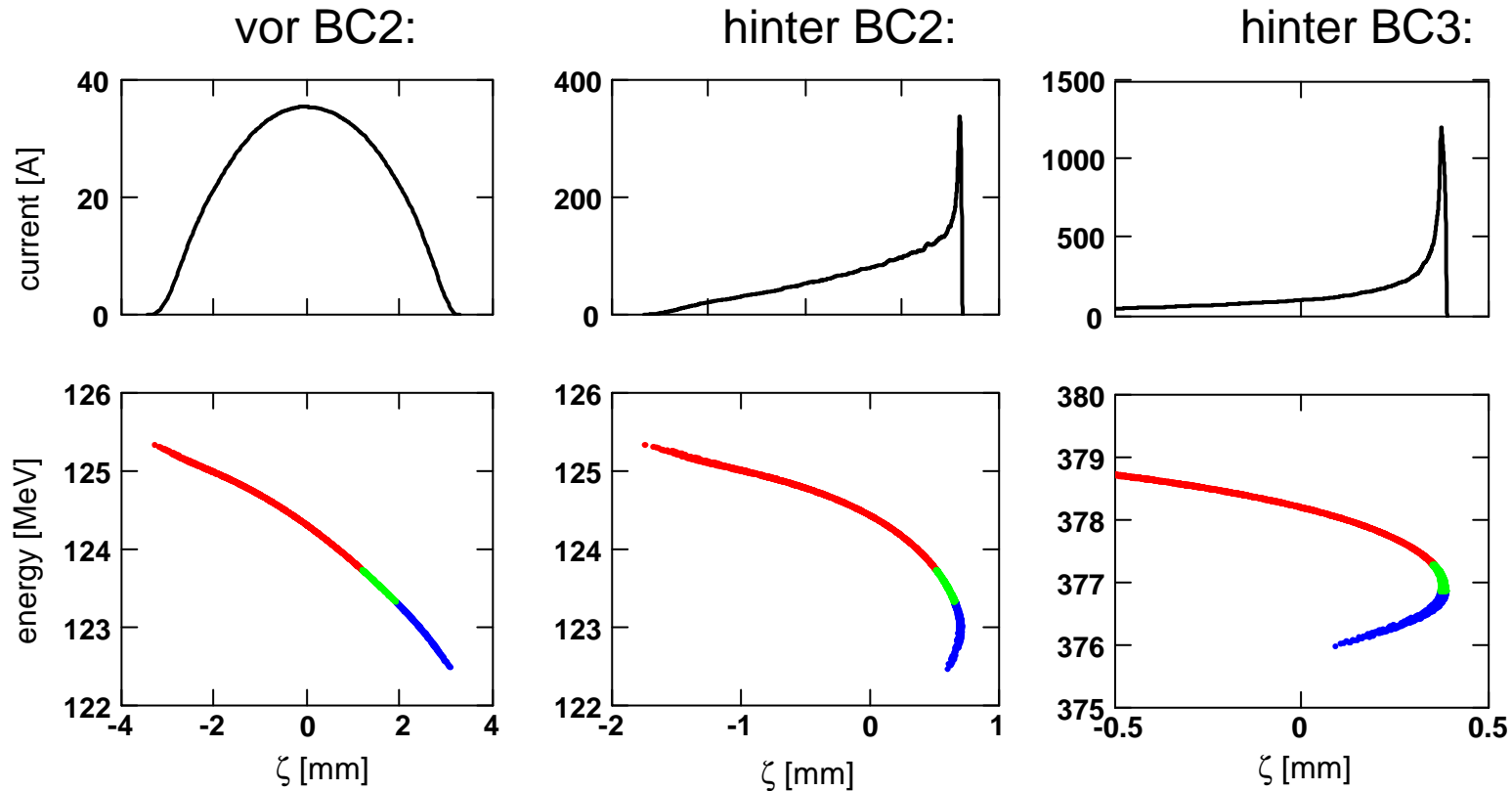
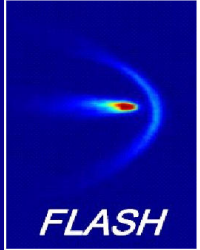




Motivation

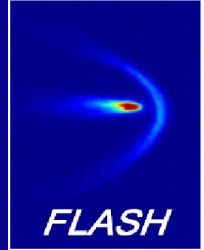


# Longitudinale Kompression

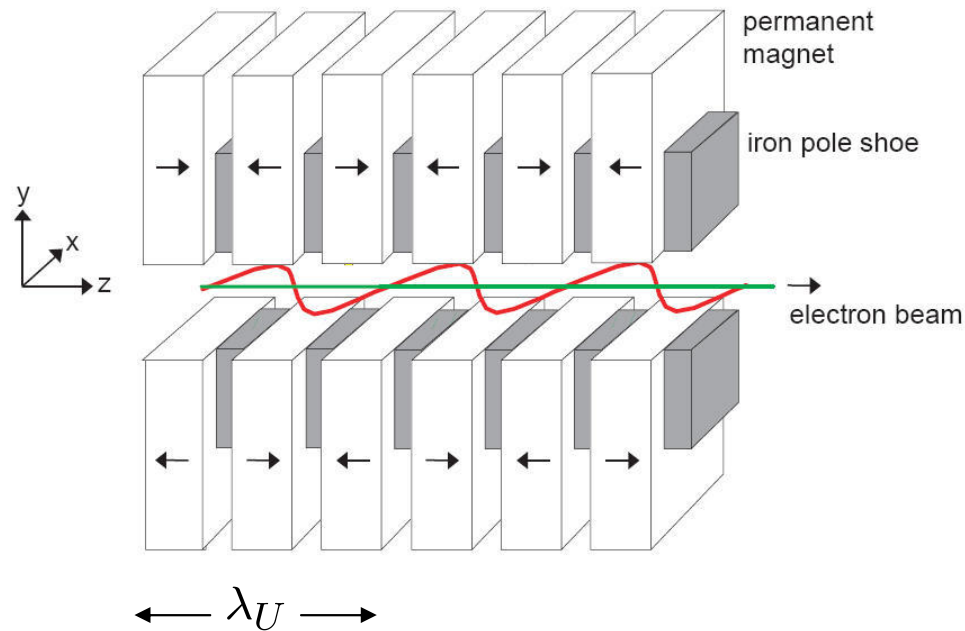


Rechnungen von M. Dohlus

Die TDS erlaubt die Untersuchung der Peakstrom-Region



Undulator-Magnet:



Undulator-Parameter  $K = \frac{eB_0\lambda_U}{2\pi m_e c}$

- spontane Undulatorstrahlung

$$\lambda_L = \frac{\lambda_U}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right)$$

- Energieaustausch zwischen Elektronenstrahl und Strahlung
- Dichtemodulation mit Periode  $\lambda_L$

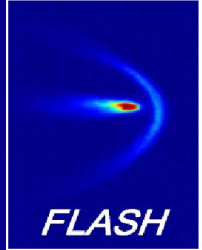


stimulierte Emission

- exponentieller Anstieg der Strahlungsleistung

$$P \propto \exp\left(\frac{z}{L_g}\right)$$

mit Gain-Länge  $L_g$



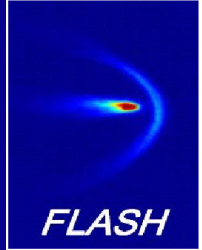
- hohe Teilchendichte  $n_e$  :  $L_g \propto n_e^{-1/3}$ 
  - hoher **Peakstrom** ( $\sim$ kA)
  - kleine transversale Strahlbreite  $\sigma_x = \sqrt{\langle x^2 \rangle}$
- kleine Strahldivergenz  $\sigma_{x'} = \sqrt{\langle x'^2 \rangle}$ ,  $x' = \frac{dx}{dz}$ 

FEL-Kriterium:  $\sigma_x \cdot \sigma_{x'} \leq \frac{\lambda_L}{4\pi}$

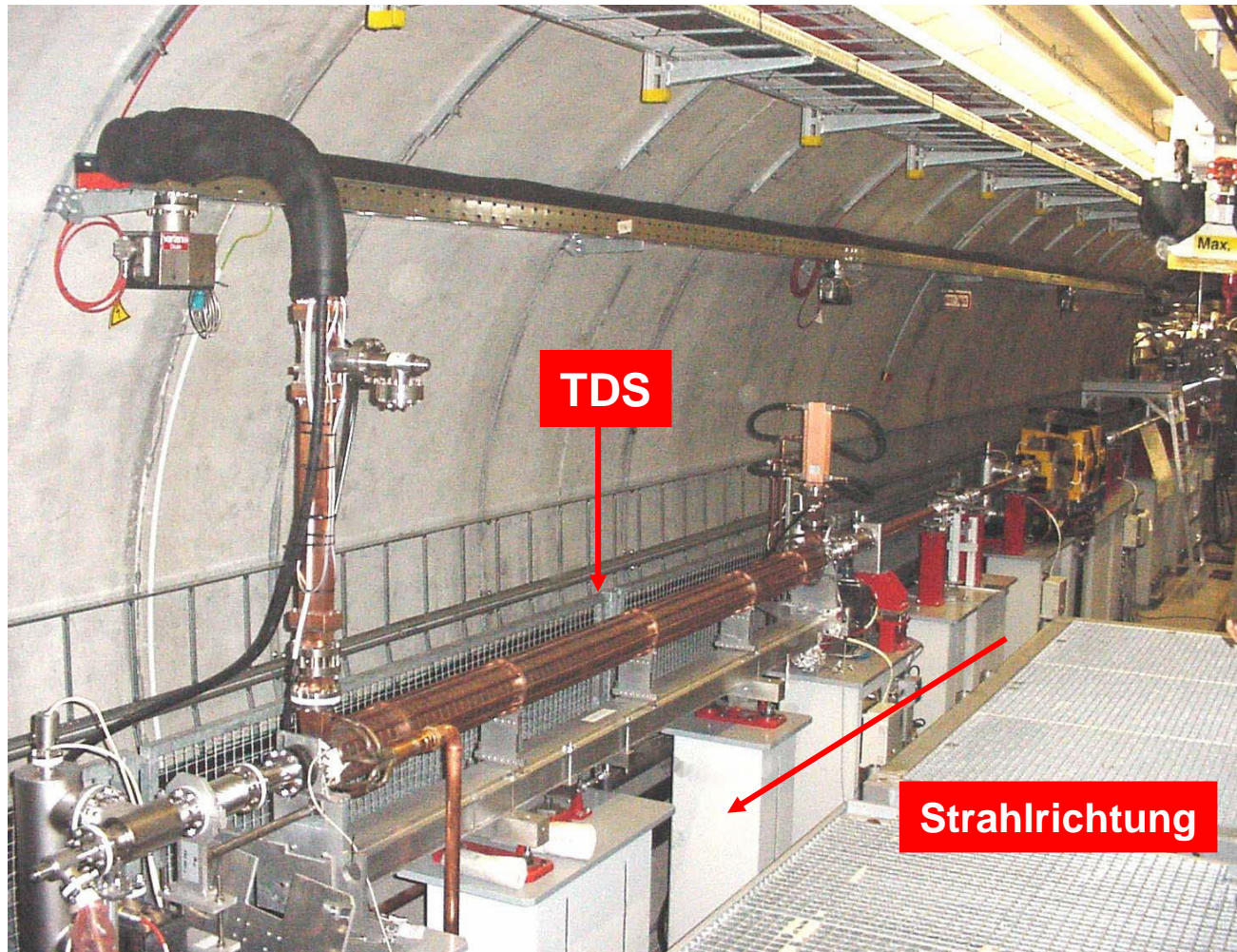
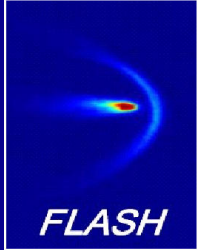
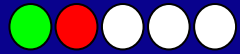
→ **normierte Emittanz**:  $\gamma\epsilon_x = \gamma \cdot \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - 2\langle xx' \rangle} \sim 1 - 4 \mu\text{m}$
- hohe **Energieschärfe**:  $\frac{\sigma_E}{E} < 0.5 \cdot \rho_{FEL}$ ,  $\rho_{FEL} = \frac{1}{4\pi\sqrt{3}} \cdot \frac{\lambda_U}{L_g} \sim 10^{-3}$

TDS-Messungen erlauben die Bestimmung dieser Parameter

# Übersicht

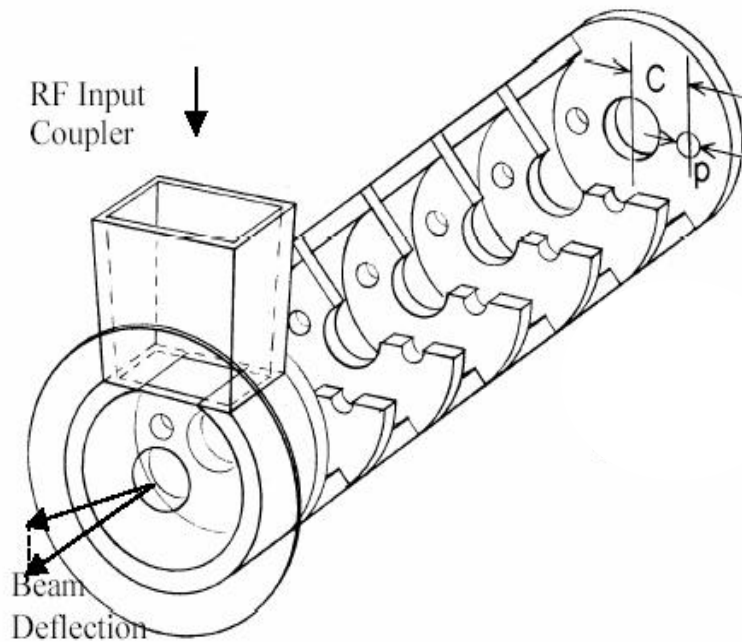
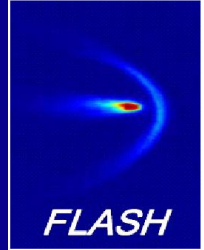
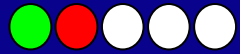


- Motivation
- Die transversal ablenkende HF-Struktur (TDS)
- Messmethoden
- Resultate unter FEL-Betriebsbedingungen
- Zusammenfassung



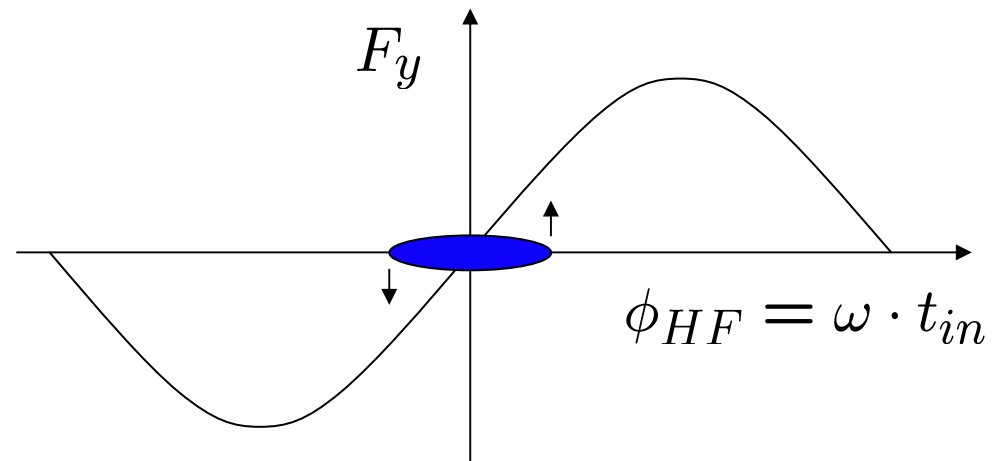
- 2003 installiert, Kollaboration DESY-SLAC
- 1968 gefertigt
- normalleitend (Kupfer)
- Frequenz: 2.86 GHz
- Länge: 3.6 m

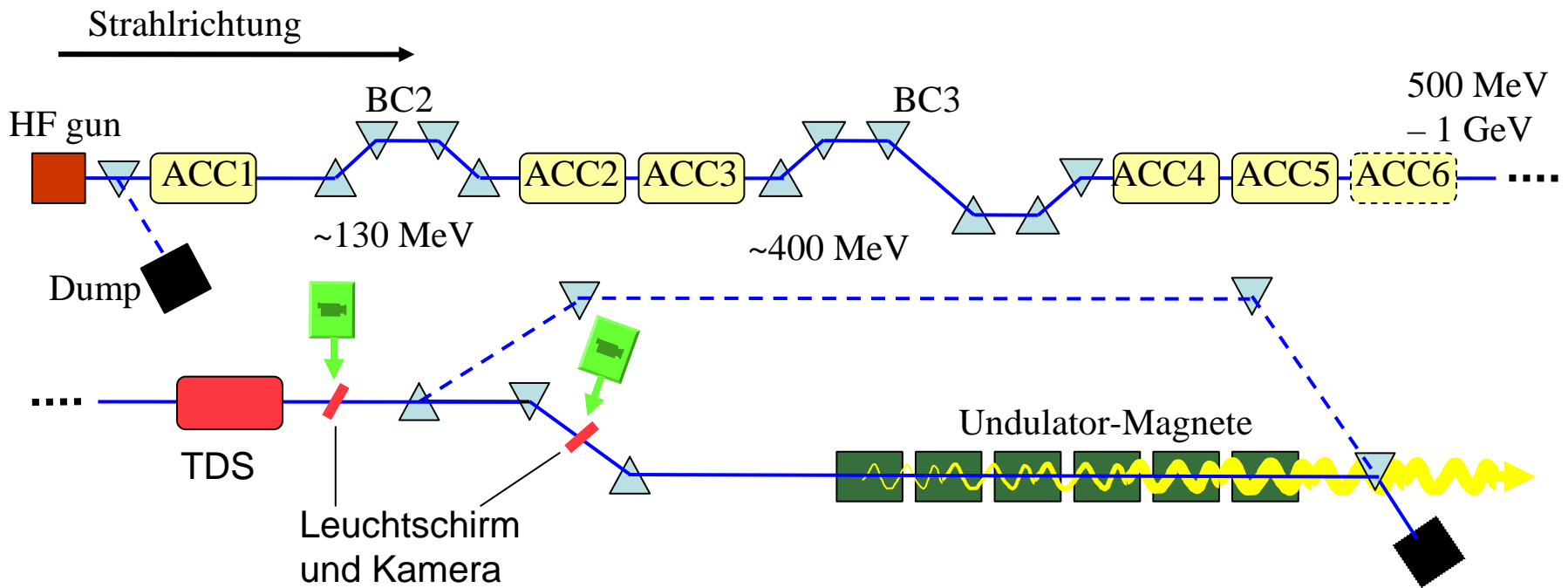
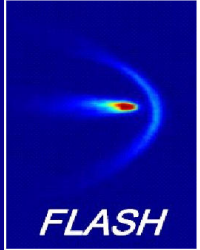
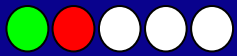




- Zellenlänge: 3.5 cm
- HF-Wanderwellenstruktur
- relativistisches Elektron erfährt konstante Kraft

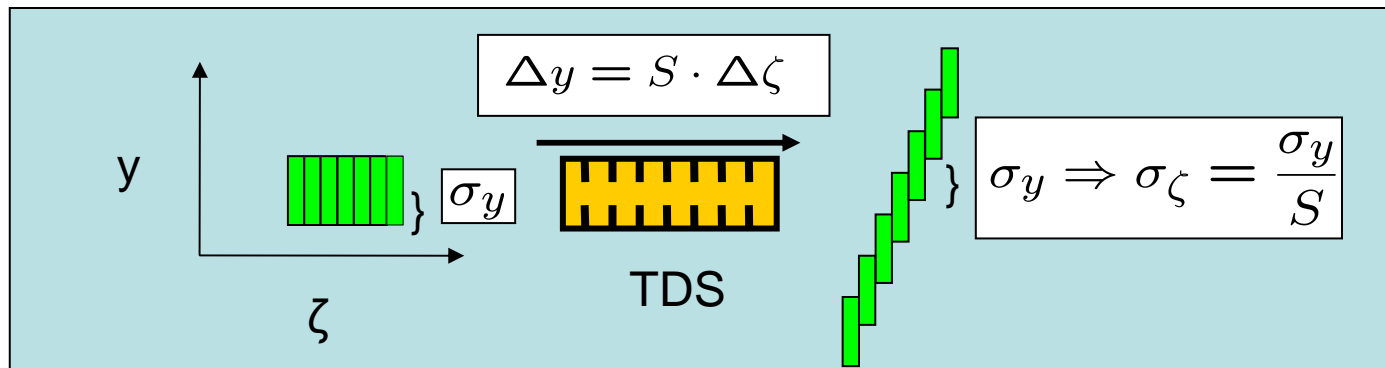
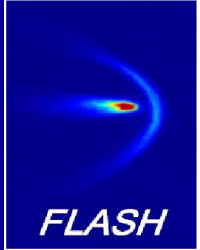
$$F_y = F_0 \cdot \sin(\phi_{HF})$$



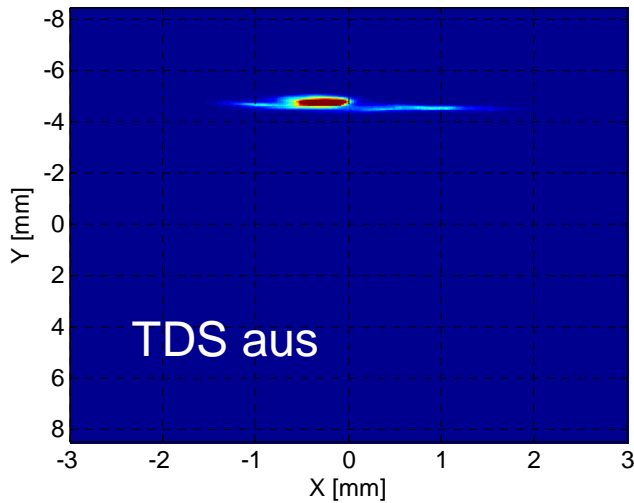




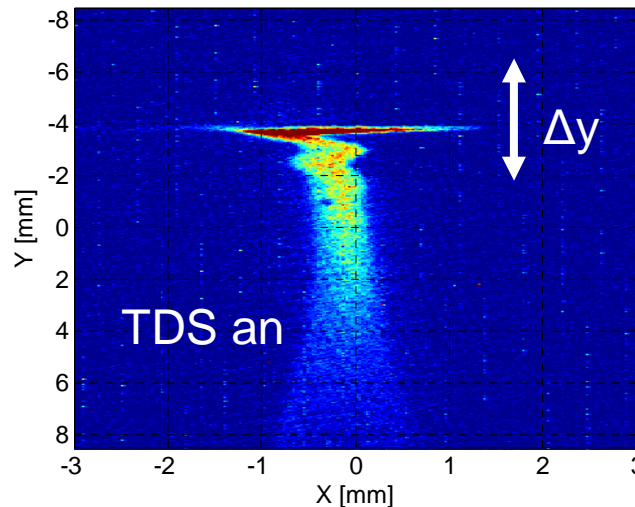
# Longitudinale Auflösung und Kalibration



Abschätzung von  $\sigma_y$



Messung von  $\Delta y$  als Funktion der HF-Phase  $\Rightarrow S$



typisch:

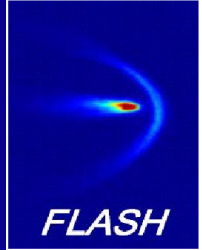
$S = 15$

$\sigma_y = 150 \mu\text{m}$

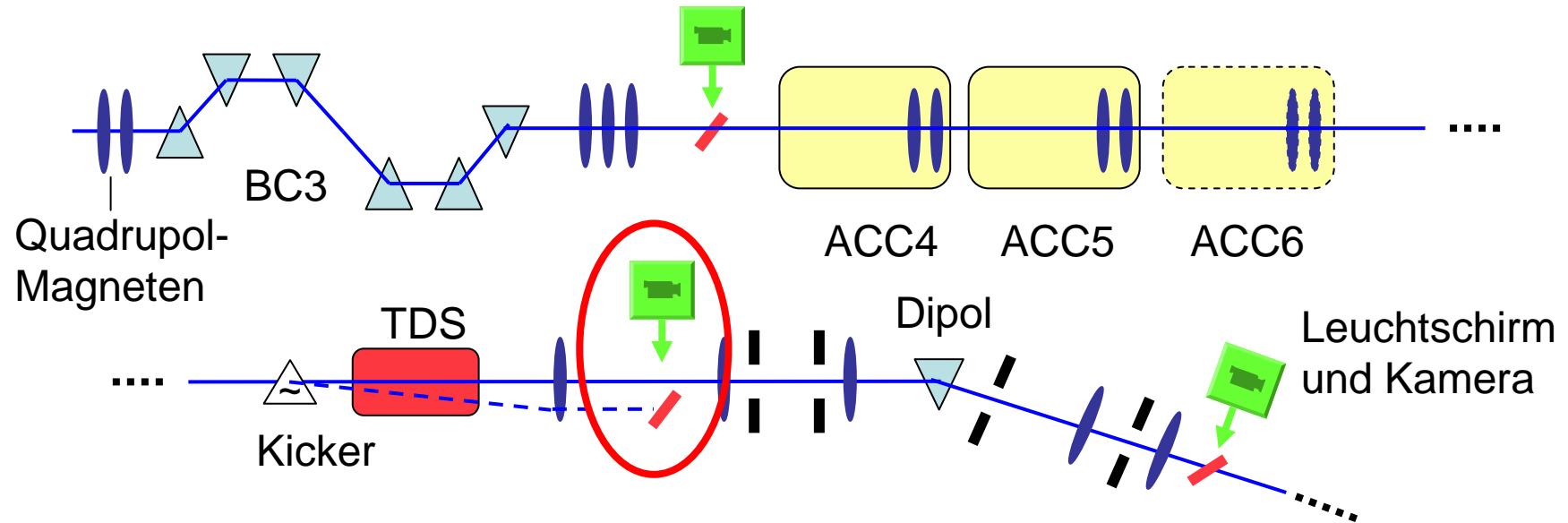
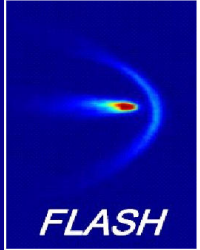
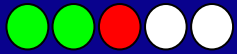
$\Rightarrow \sigma_\zeta = 10 \mu\text{m}$   
(30 fs)



# Übersicht

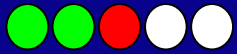


- Motivation
  - Die transversal ablenkende HF-Struktur (TDS)
  - **Messmethoden** →
  - Resultate unter FEL-Betriebsbedingungen
  - Zusammenfassung
- Stromprofil
  - Energieverteilung
  - Scheibenemittanz
  - horizontaler Phasenraum

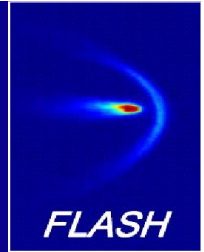


Messung des Stromprofils:

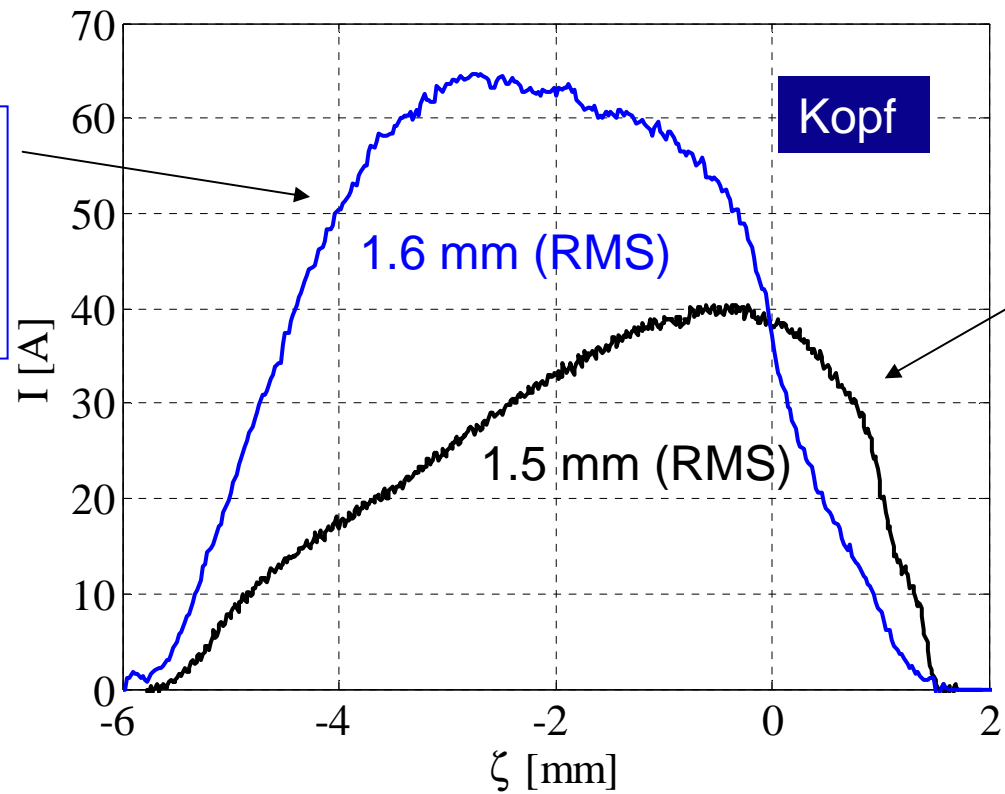
- Kalibration longitudinaler Abstände
- Kalibration der Ladungsdichte



# Gemessenes Stromprofil unkomprimierter Elektronenpakete

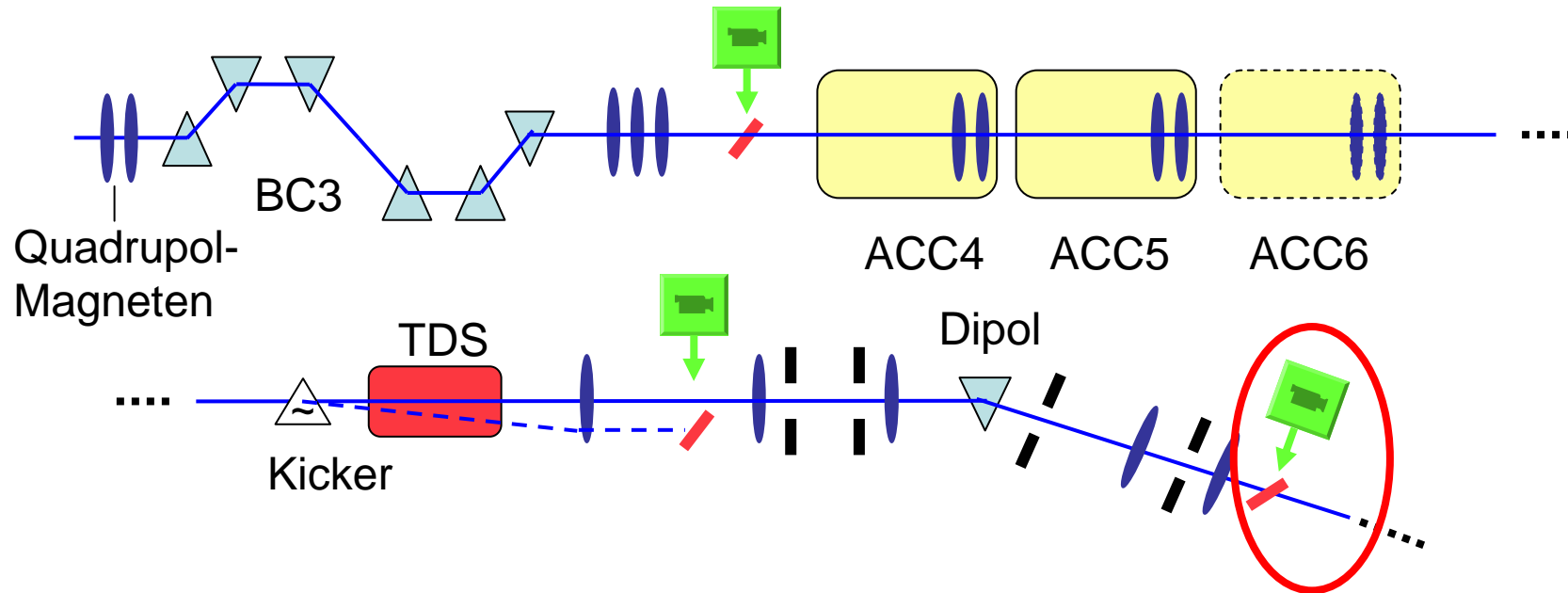
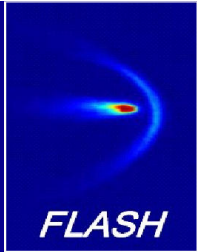
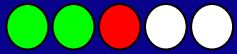


650 MeV, 1.0 nC,  
keine Ablenkung  
in Kompressor-  
Schikanen

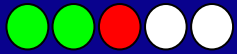


490 MeV,  
0.6 nC

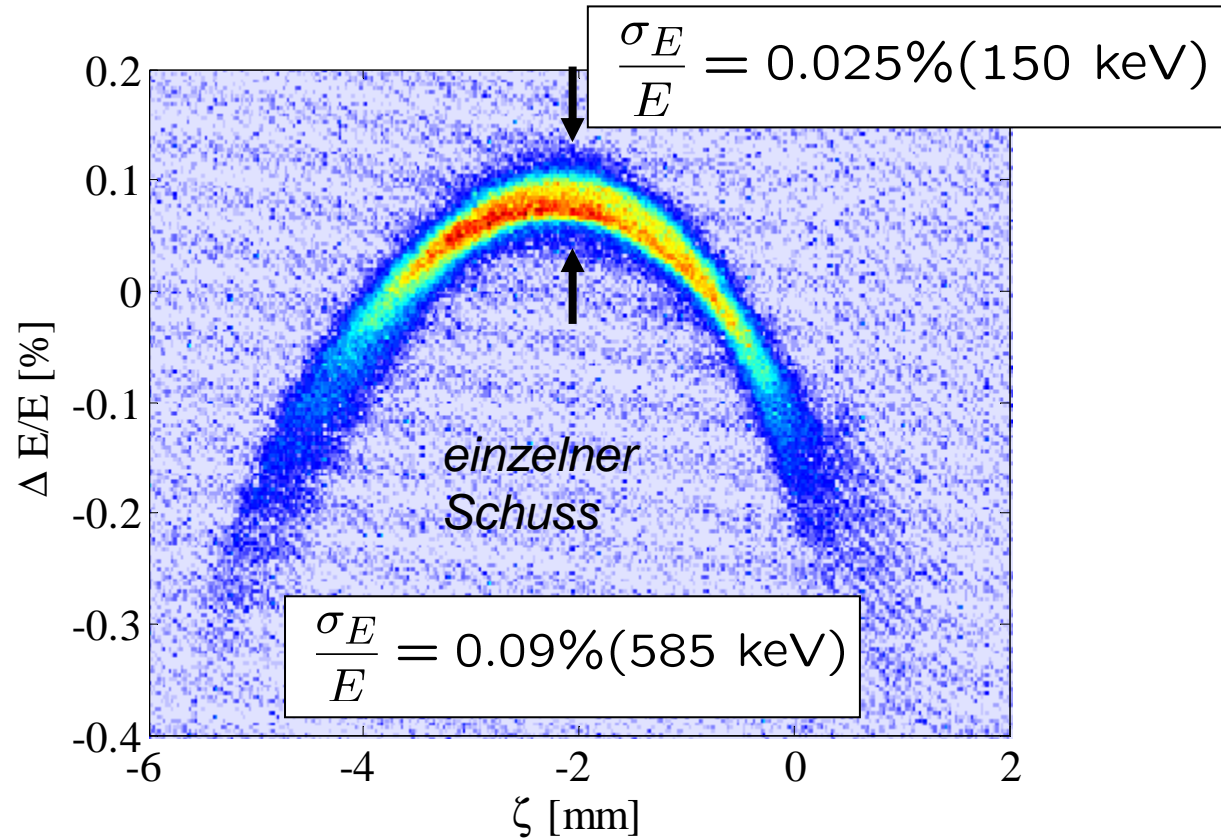
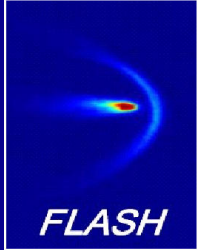
Profile:  
gemittelt über  
30 Schüsse



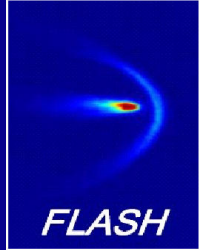
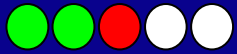
- energieabhängige Position auf dem Schirm:  $\Delta x = D \cdot \frac{\Delta E}{E}$
- typisch:  $D \sim 30 \text{ cm}$ ,  $\sigma_x = 100 \text{ } \mu\text{m}$   $\Rightarrow \frac{\sigma_E}{E} \approx \frac{\sigma_x}{D} \sim 3 \cdot 10^{-4}$



# Gemessene Energieverteilung unkomprimierter Elektronenpakete



650 MeV, 1nC, Kompressor-Schikanen ausgeschaltet

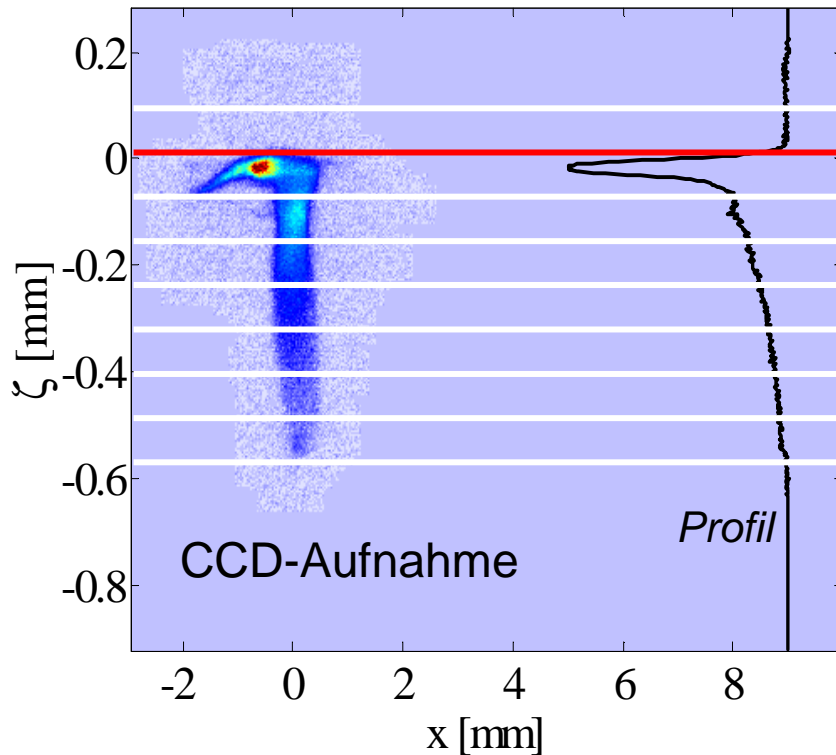
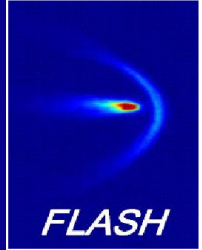
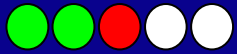


- Emittanz:  $\epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - 2 \langle x x' \rangle} = \det(\sigma_x)$   

$$\sigma_x = \begin{pmatrix} \langle x^2 \rangle & \langle x x' \rangle \\ \langle x x' \rangle & \langle x'^2 \rangle \end{pmatrix}$$
- Strahltransfer:  $\sigma_x(s) = M \cdot \sigma_x(s_0) \cdot M^T$ ,  $M : s_0 \rightarrow s$   

$$\det(M) = 1 \Rightarrow \epsilon_x = \text{const}$$
- Messung von  $\sigma_x^{1,1}(s) = \langle x^2 \rangle(s)$  für verschiedene  $M$   

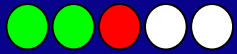
$$\Rightarrow \sigma_x(s_0) \Rightarrow \epsilon_x$$
- typischerweise mehr als 3 Messungen  $\rightarrow$  überbestimmtes Gleichungssystem  $\rightarrow$  [Methode der kleinsten Quadrate](#)
- normierte Emittanz:  $\gamma \epsilon_x$



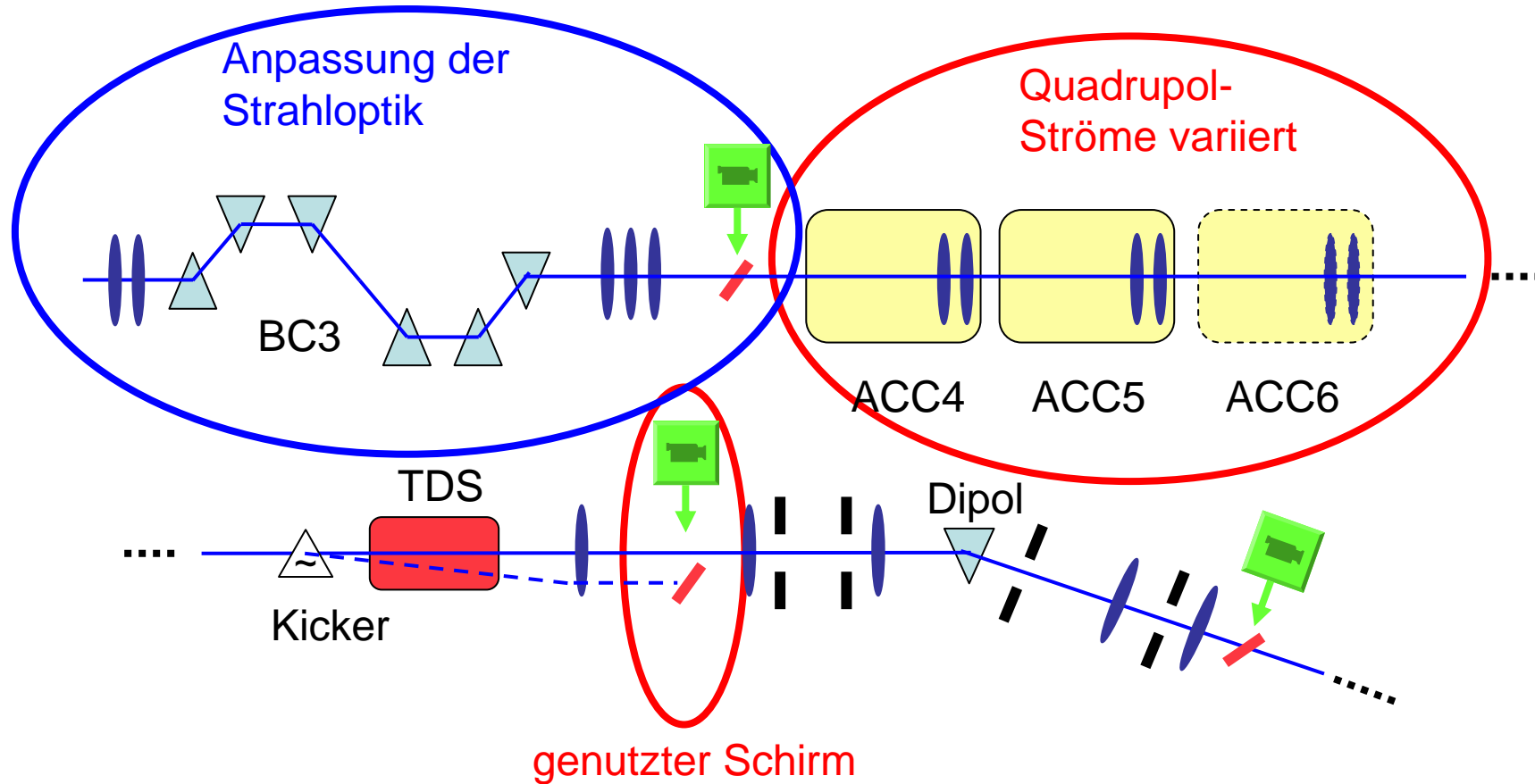
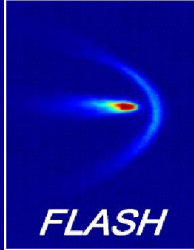
Bildbearbeitung wichtig!

- Fehlerquellen:
  - statistische Fehler
  - Kalibrationsfehler
  - Auflösung des optischen Systems
  - Fehler der Transfermatrizen (Energiefehler)
- Fehler der Emittanz hängt ab von
  - Beschleuniger-Optik (optimiert)
  - Strahleigenschaften
- hier:

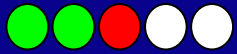
$$\sigma_{\epsilon_x} / \epsilon_x < 20\%$$



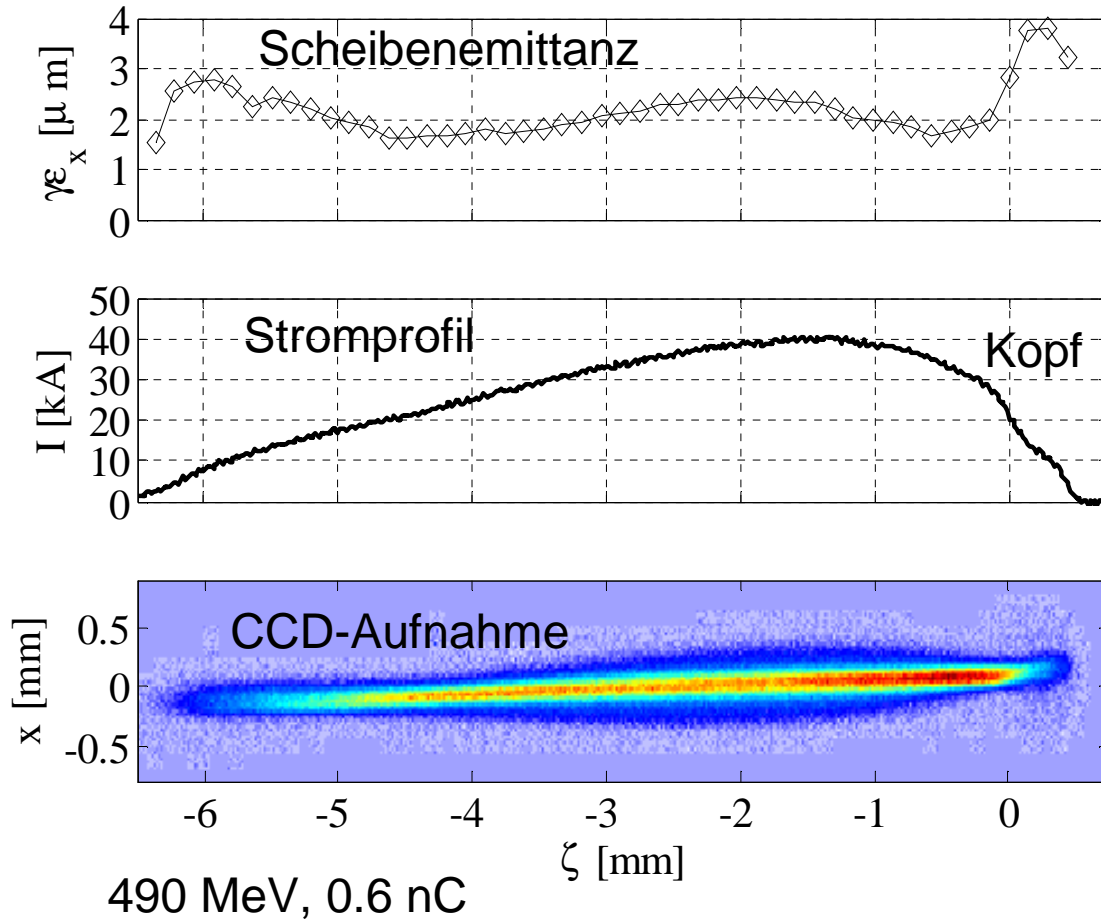
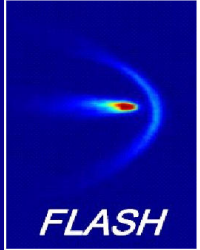
# Messung der Scheibenemittanz: Quadrupolmagneten und Schirm



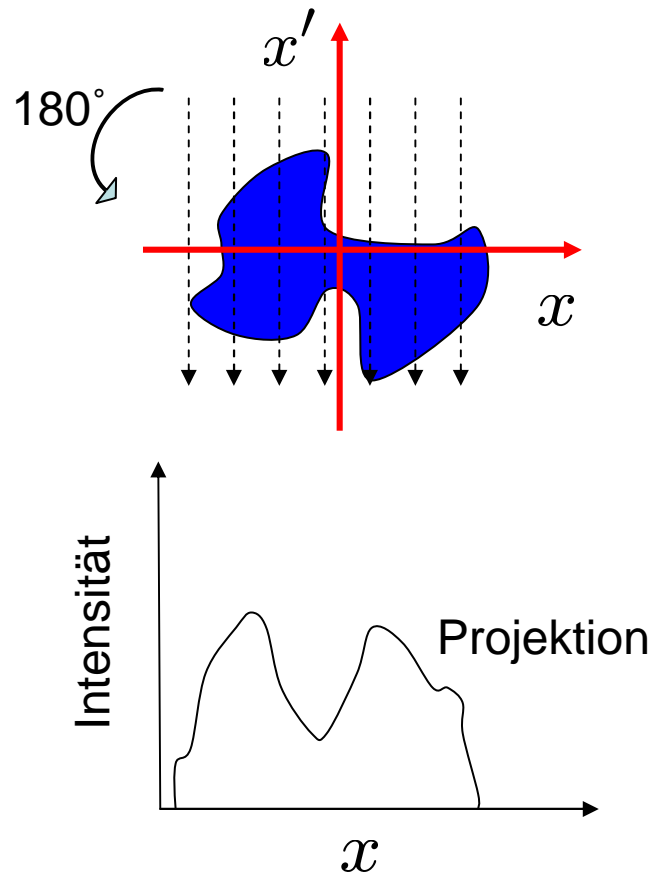
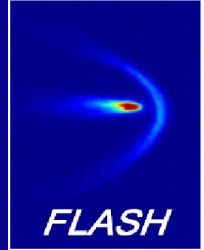
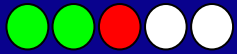




# Gemessene Scheibenemittanz unkomprimierter Elektronenpakete



- Mittelwert der Scheibenemittanz: **2.1  $\mu\text{m}$**
- projizierte Emittanz: **3.8  $\mu\text{m}$**
- Differenz durch
  - Zentroidenversätze  $\langle x \rangle(\zeta)$
  - Deformation der Phasenraumverteilung



Methode der maximalen Entropie (MENT)

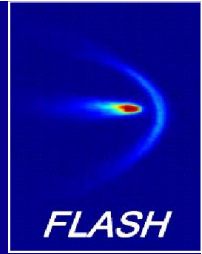
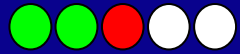
Entropie  $E(f)$ :

$$E(f) = \int -f(x, x') \ln f(x, x') dx dx'$$

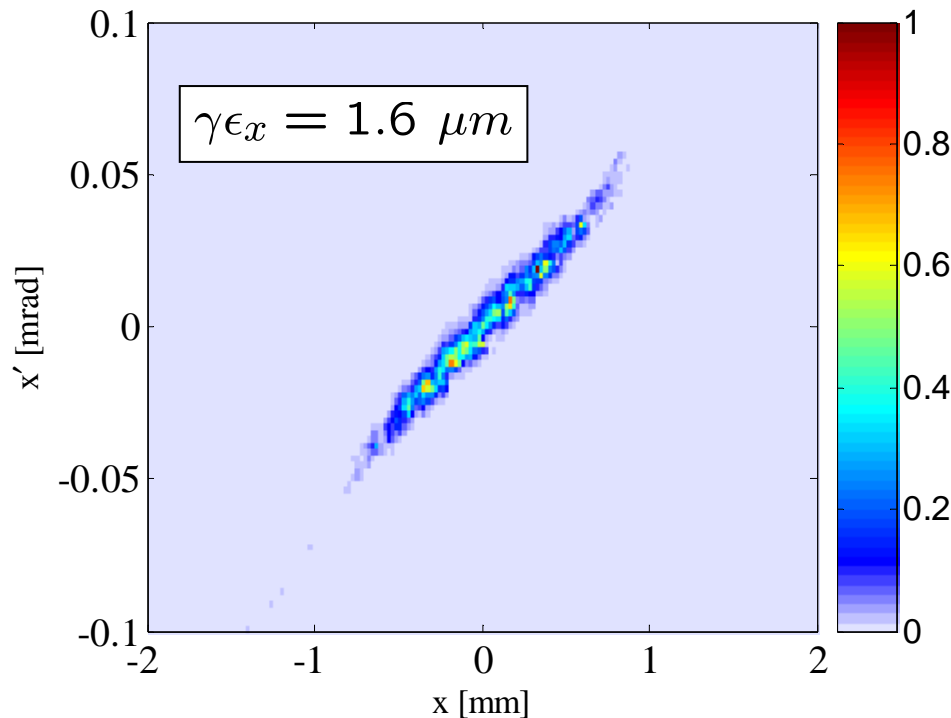
(Implementation: J. Scheins, 2004)

TDS erlaubt **3D-Tomographie**:  
Rekonstruktion des horizontalen  
Phasenraums in longitudinalen Scheiben  $\Delta z$

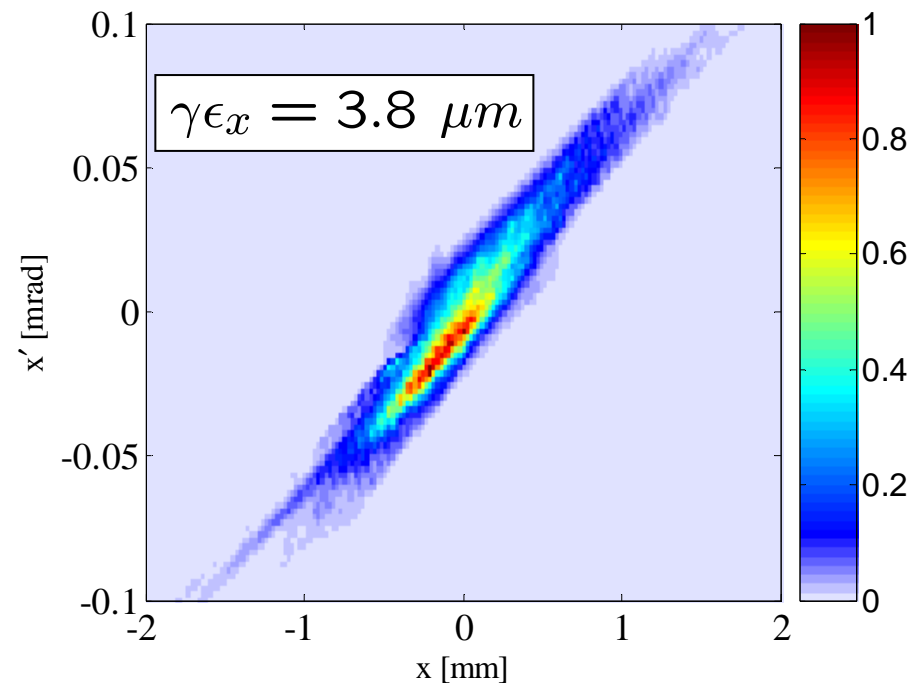
Messmethoden Rekonstruierte Dichteverteilungen im horizontalen Phasenraum



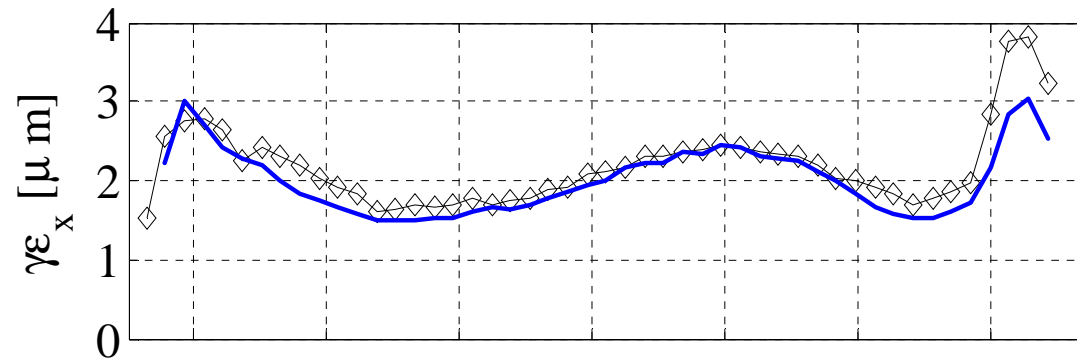
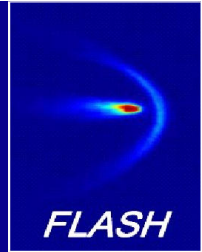
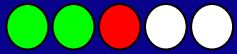
einzelne Scheibe,  $\Delta\zeta = 150\mu\text{m}$



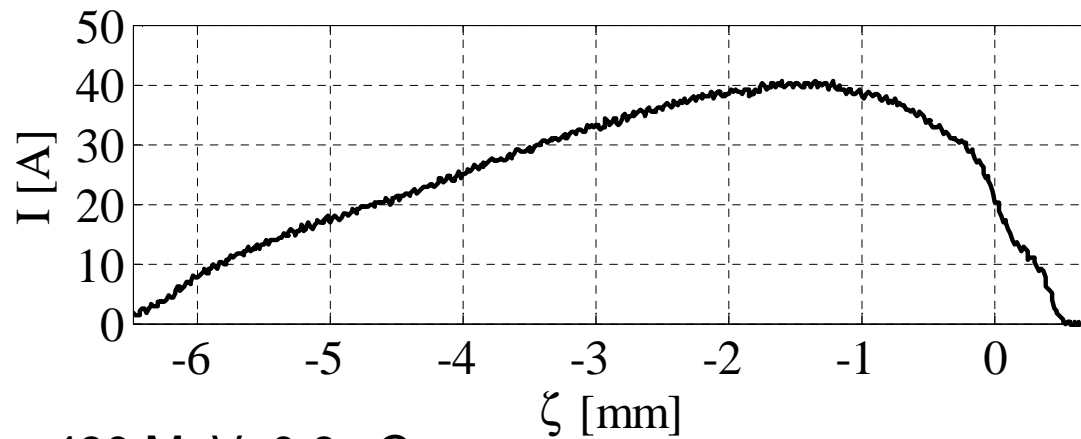
gesamtes Elektronenpaket



490 MeV, 0.6 nC, keine Kompression

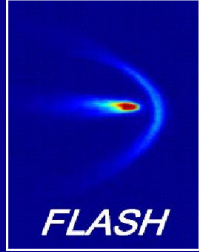


Tomographie  
kleinste  
Quadrate

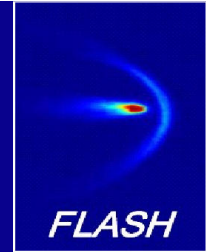
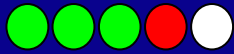


490 MeV, 0.6 nC

# Übersicht

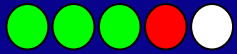


- Motivation
- Die transversal ablenkende HF-Struktur (TDS)
- Messmethoden
- **Resultate unter FEL-Betriebsbedingungen**
- Zusammenfassung

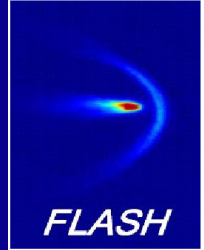


- Messungen bei
  - 494 MeV (27 nm)
  - 677 MeV (13.7 nm)
  - 964 MeV (6.8 nm)
- mittlere Strahlungsenergie pro Puls:
  - 0.5  $\mu$ J (964 MeV)
  - 5  $\mu$ J (677 MeV)
  - 10  $\mu$ J (494 MeV)
  - nicht gesättigt !
- Beschleuniger-Optik und Strahlführung hinter den Kompressor-Schikanen geändert → keine FEL- Strahlung, aber:  
Energieverteilung, Emittanz und Stromprofil unverändert!

Resultate

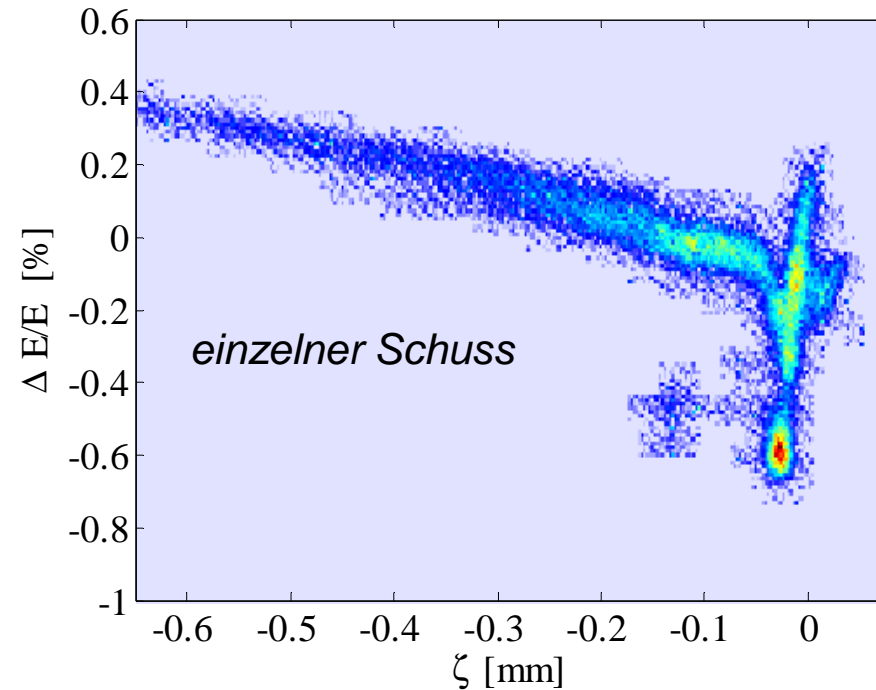
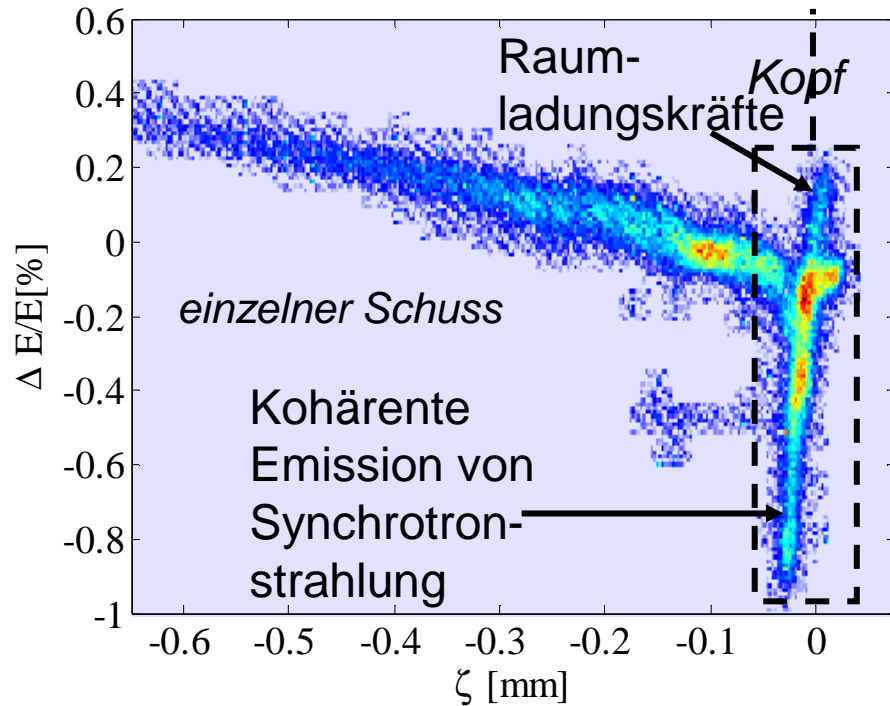


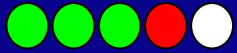
# Gemessene Energieverteilung unter FEL-Betriebsbedingungen



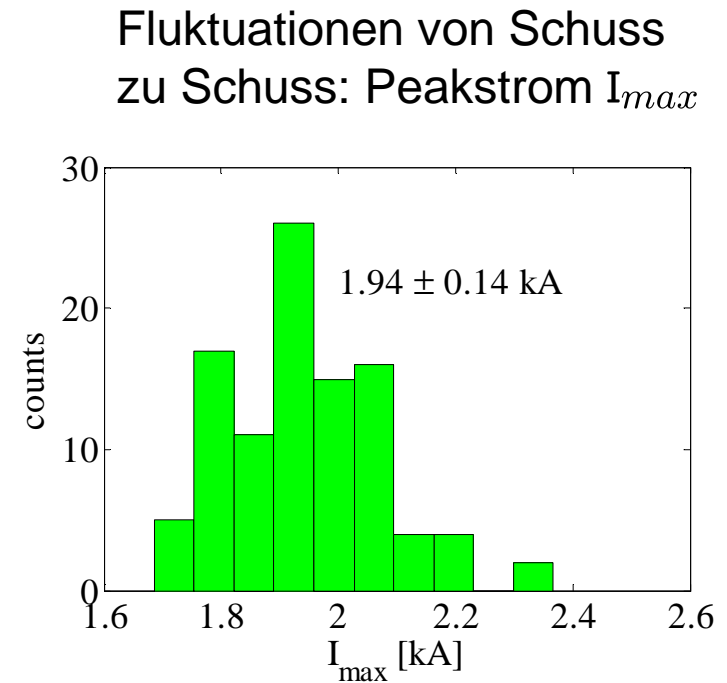
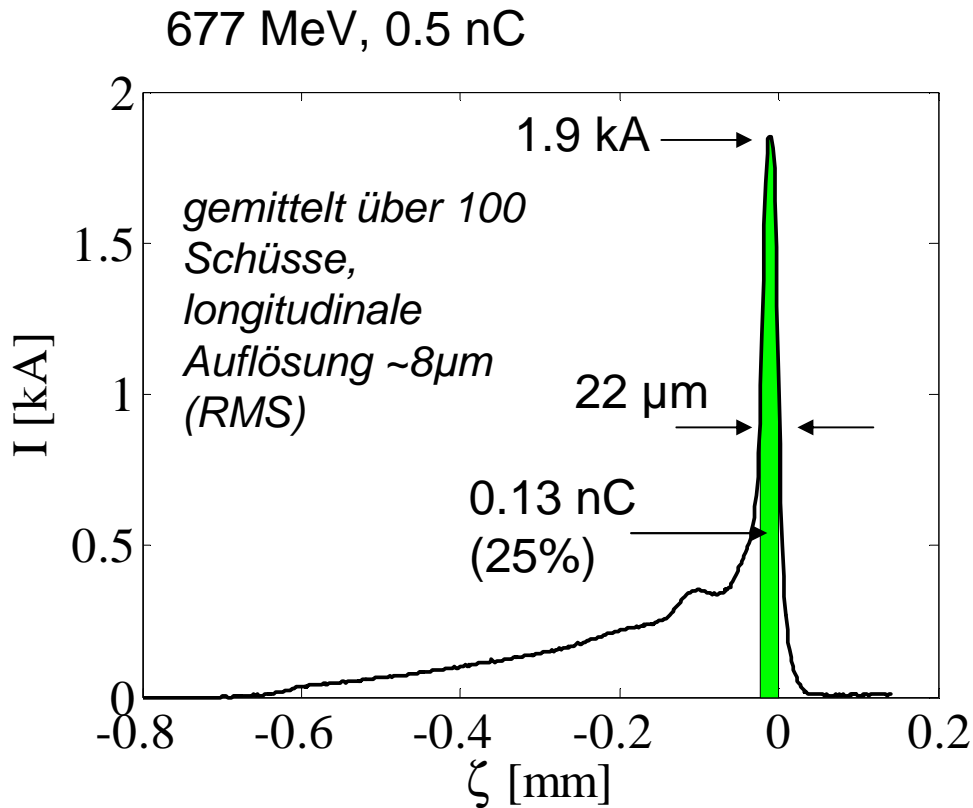
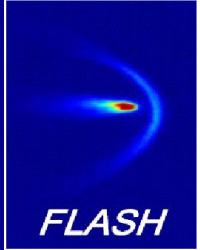
Energieunschärfe im  
Kopf : 0.25 %,  
1.7 MeV (RMS)

677 MeV, 0.5 nC

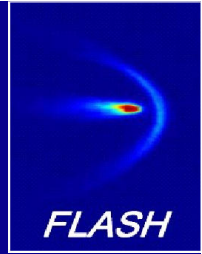
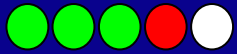




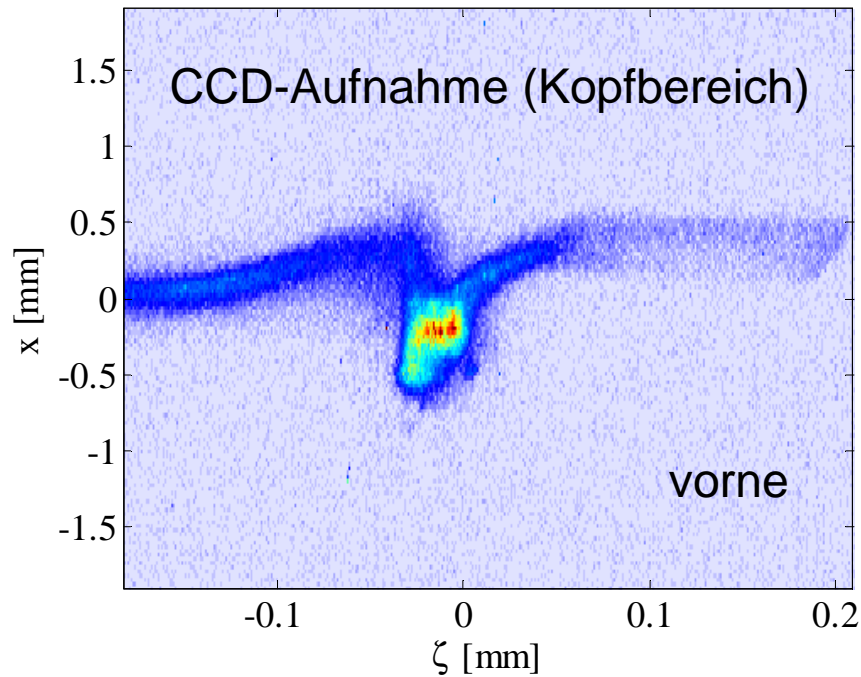
# Gemessenes Stromprofil unter FEL-Betriebsbedingungen



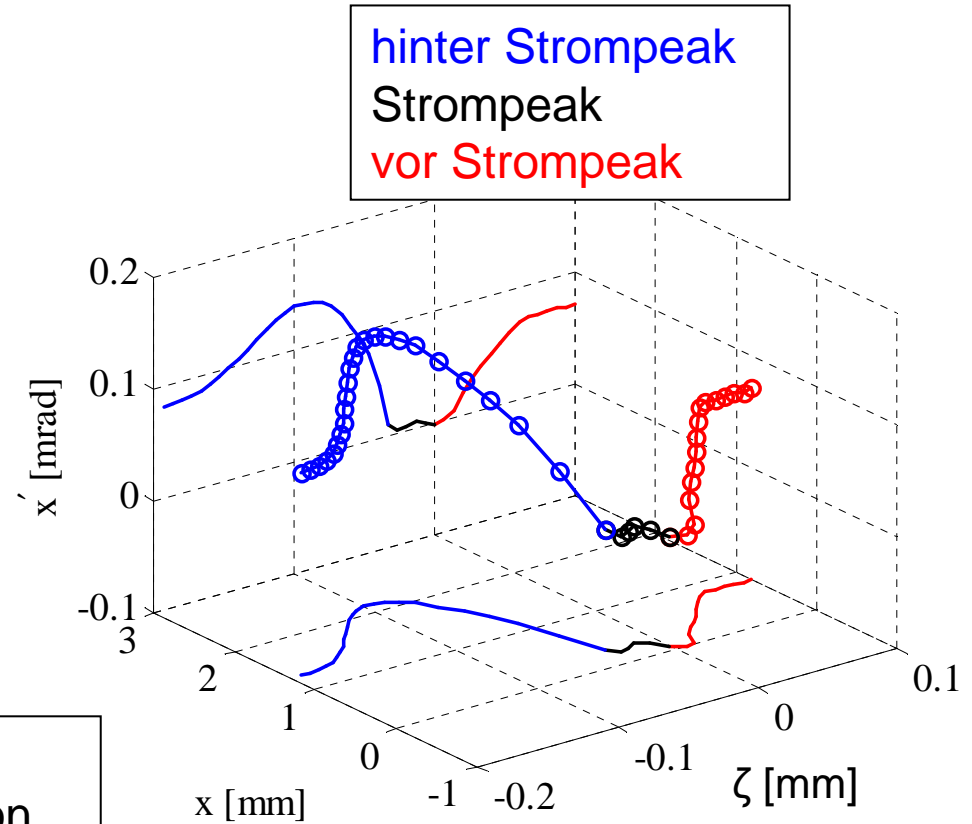


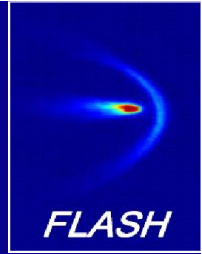
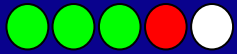


494 MeV, 0.7 nC

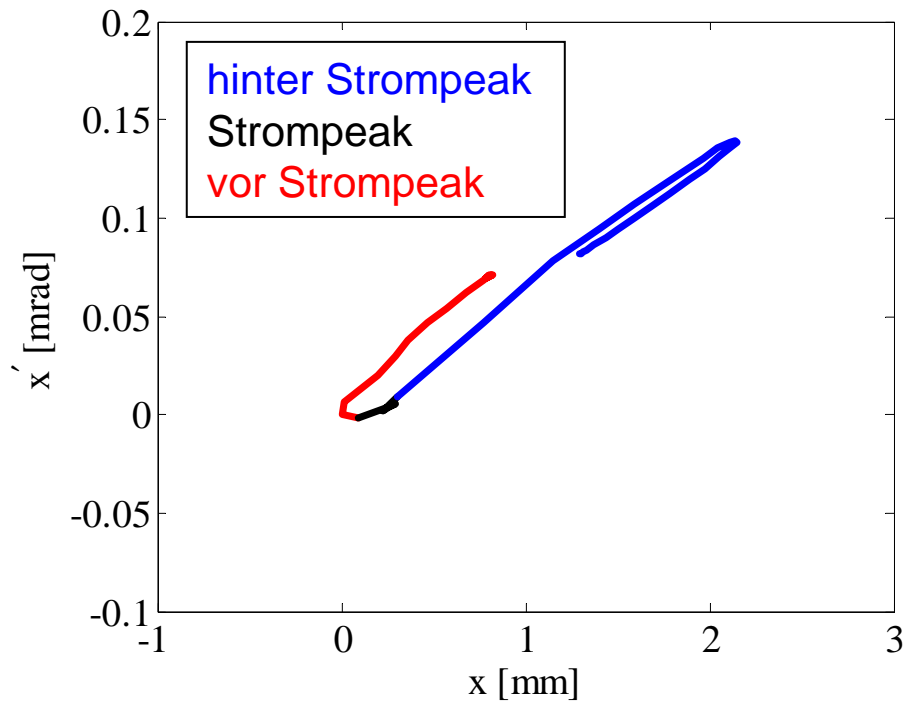


horizontaler Versatz der Peakstrom-Region durch kohärente Emission von Synchrotron-Strahlung in Kompressor-Schikanen



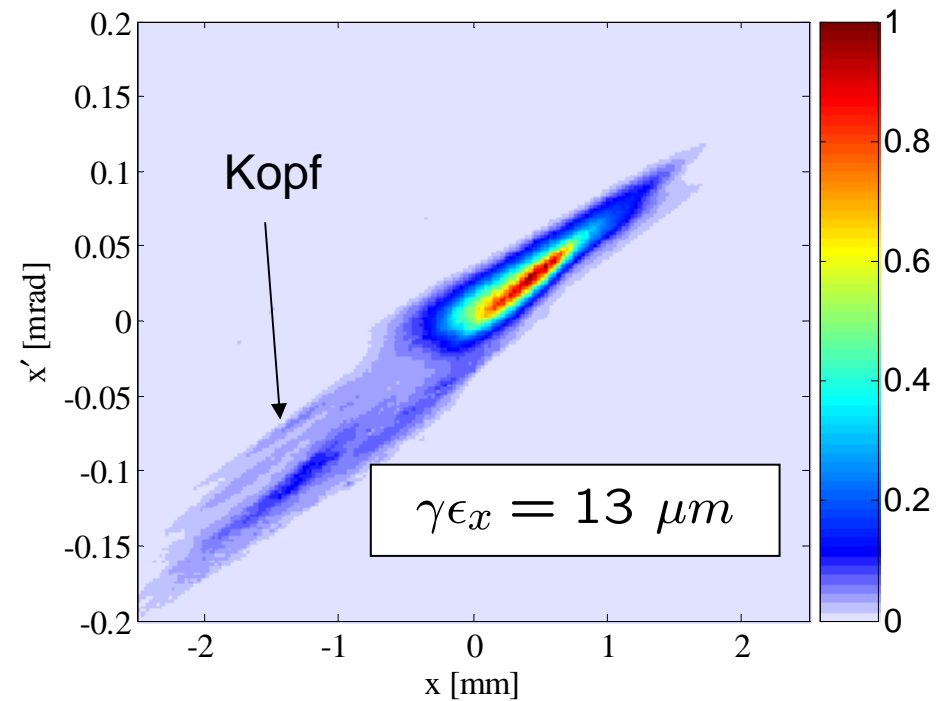


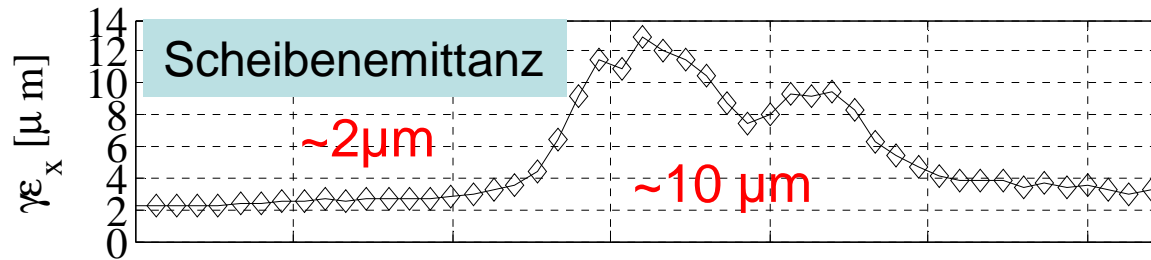
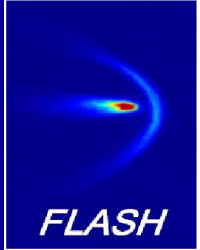
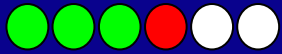
Zentroidenkurve:



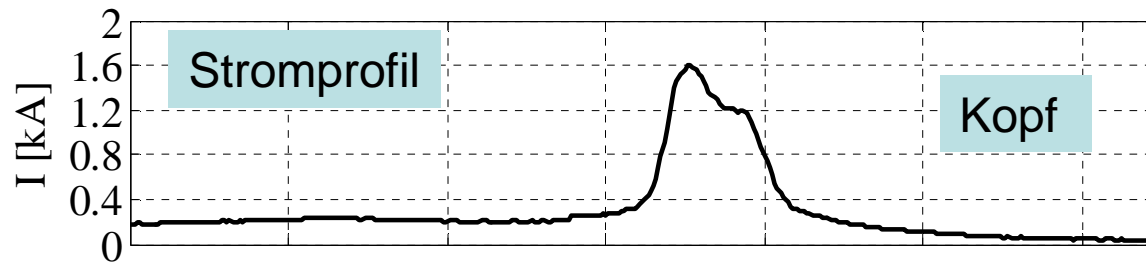
494 MeV, 0.7 nC

gemittelte Phasenraumverteilung,  
gesamtes Elektronenpaket:



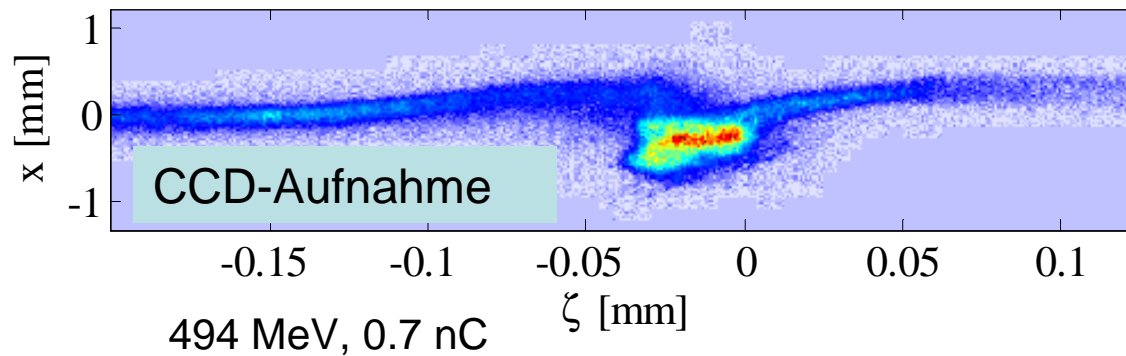


longitudinale  
Auflösung  $\sim 8 \mu\text{m}$   
(RMS)

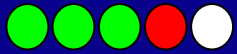


Anstieg der  
Scheibenemittanz in  
der Peakstrom-  
Region:

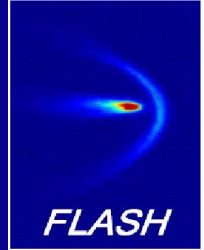
- Ursache?
- FEL-Kriterium?



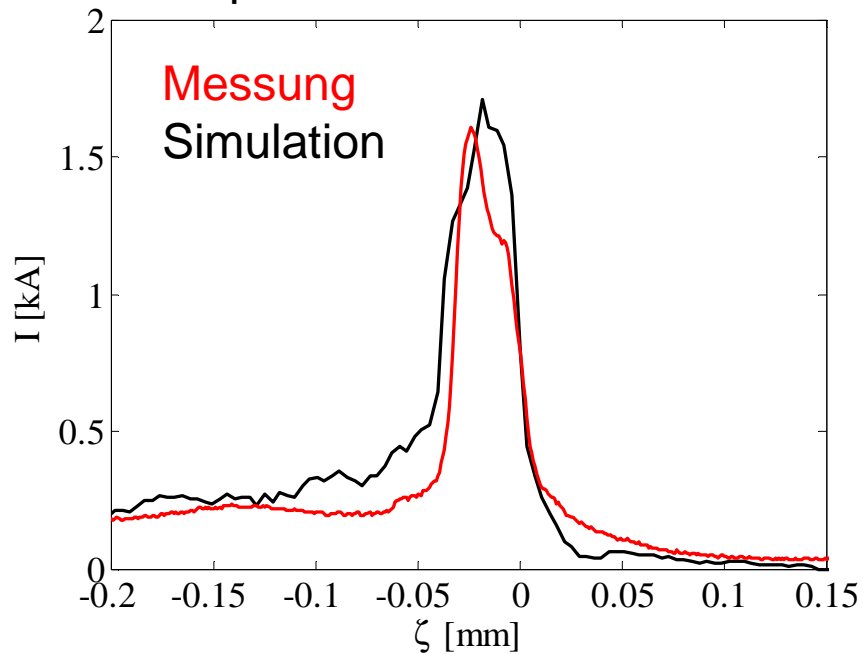
Resultate



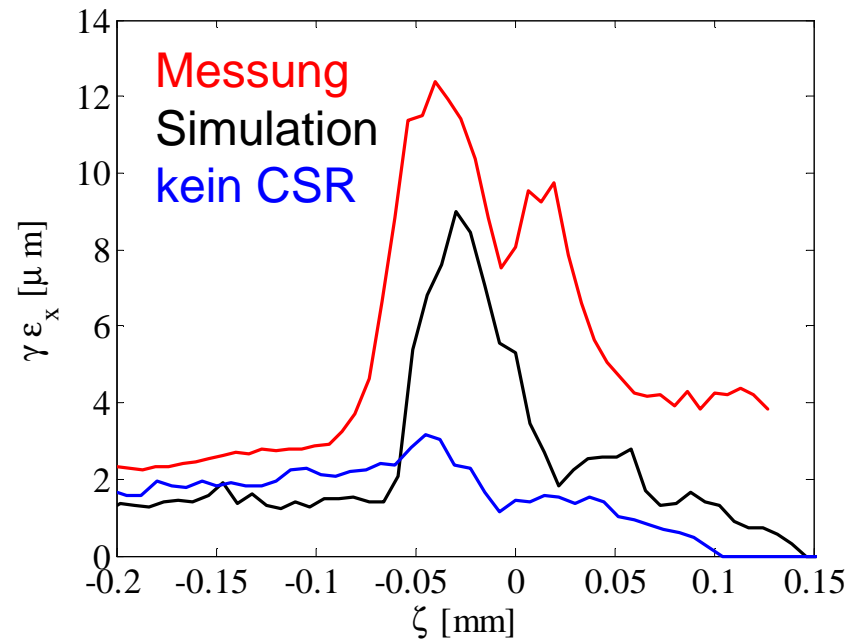
# Vergleich mit numerischen Simulationen



Stromprofil:

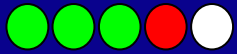


Scheibenemittanz:

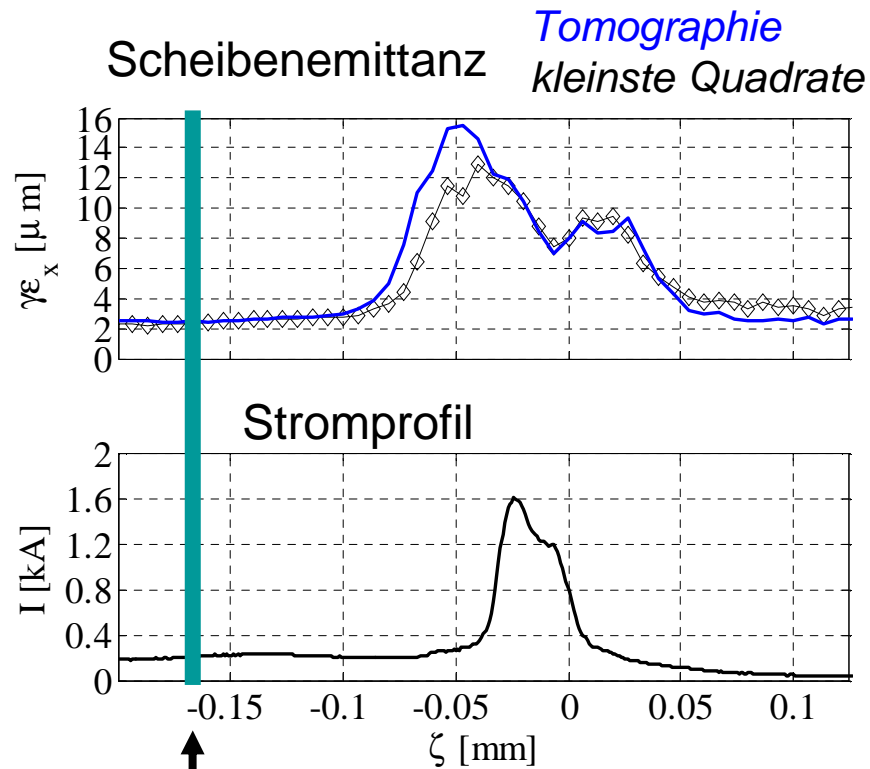
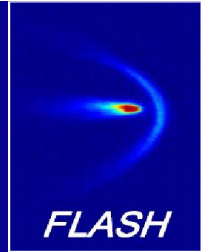


Simulationen mit ASTRA (K. Flöttmann) und CSRTrack (M. Dohlus)

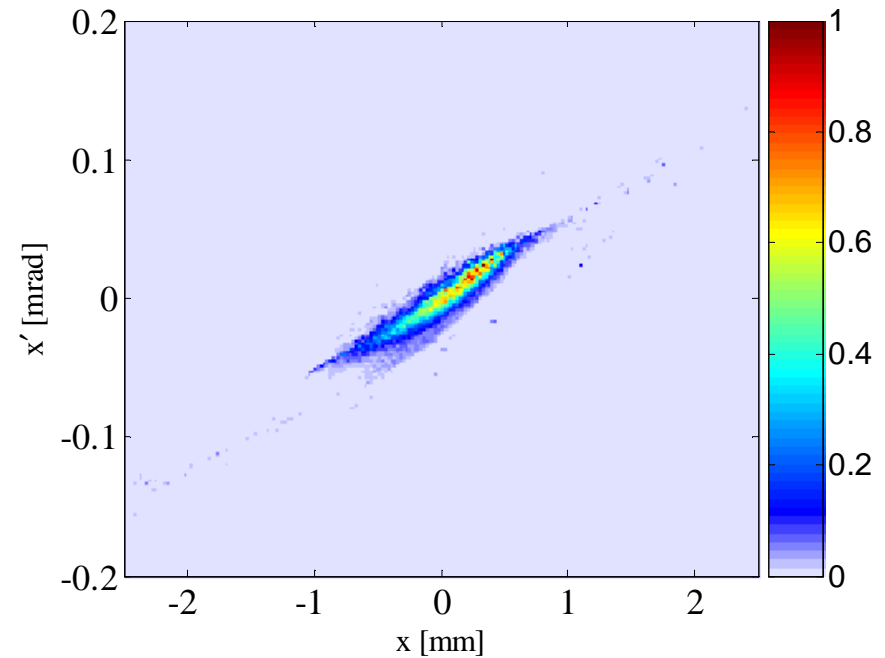
Resultate



# Rekonstruierte Phasenraumverteilung

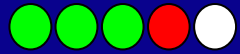


rekonstruierter Phasenraum:

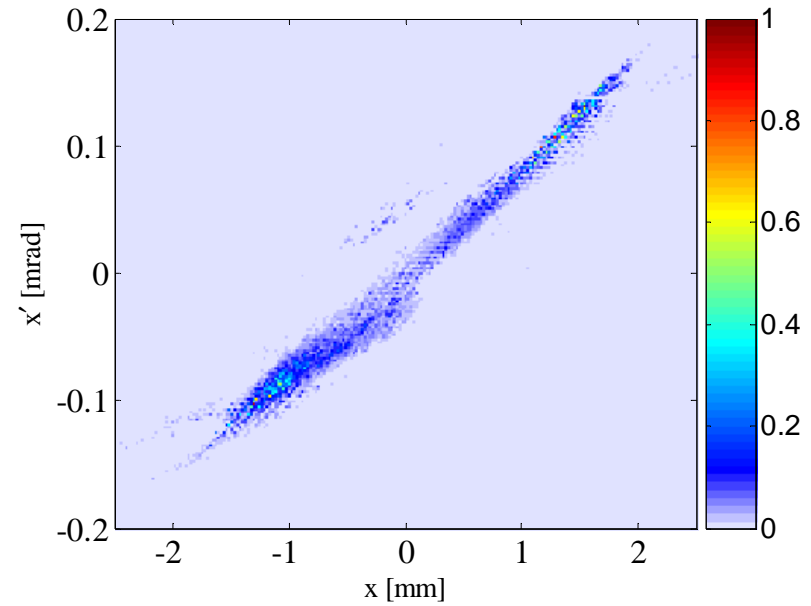
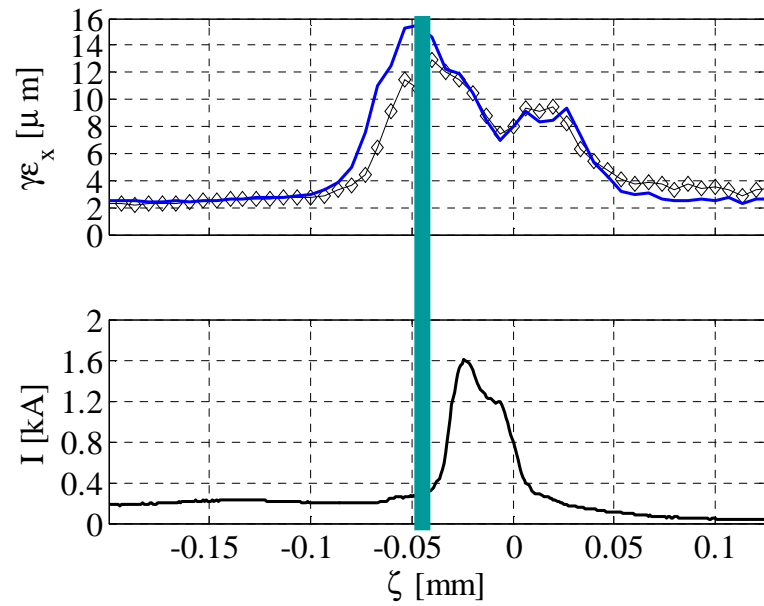
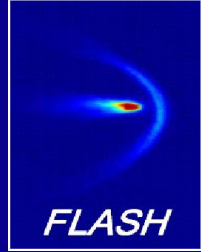


longitudinale Position der Scheibe,  
Dicke  $\Delta\zeta = 8 \mu\text{m}$

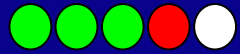
Resultate



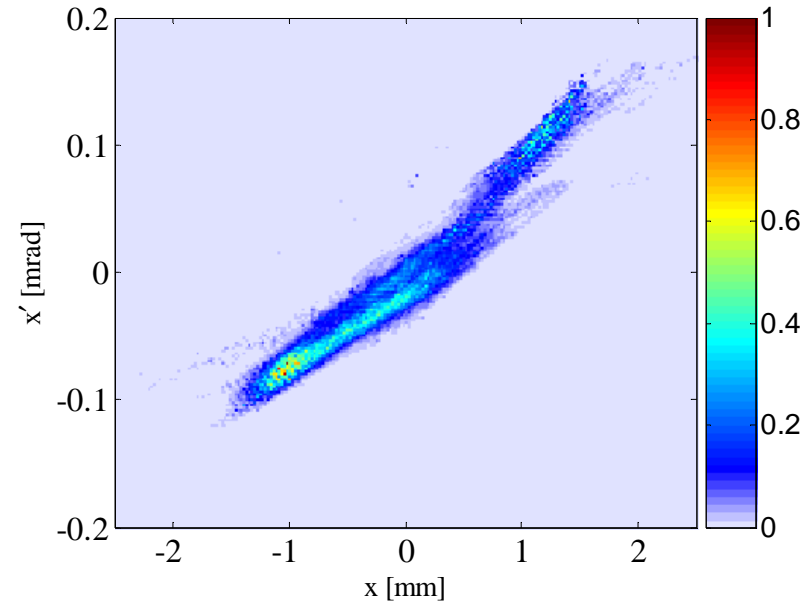
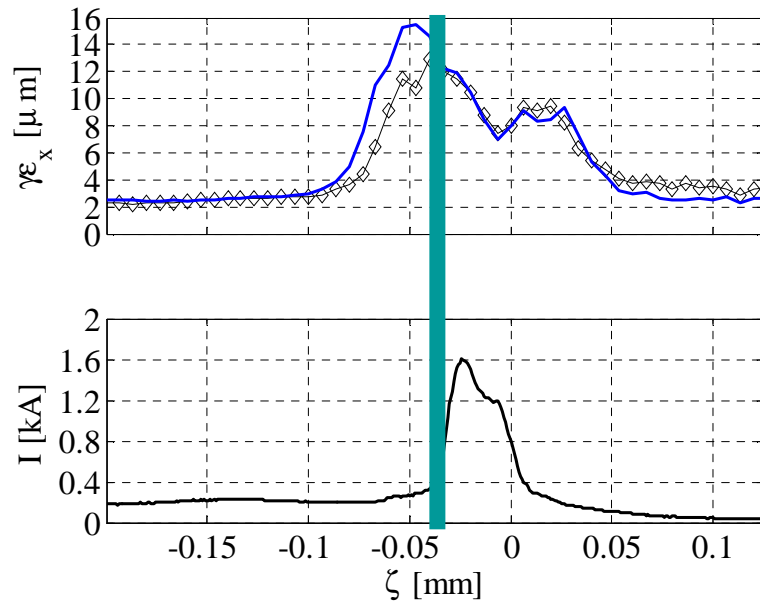
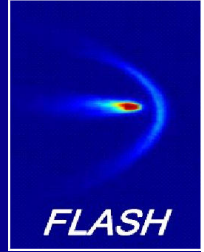
# Rekonstruierte Phasenraumverteilung



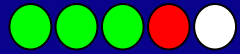
Resultate



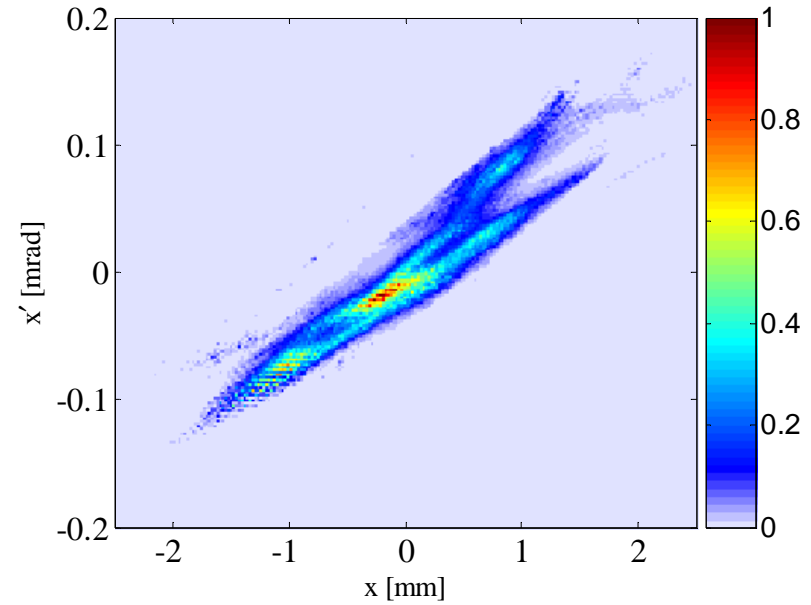
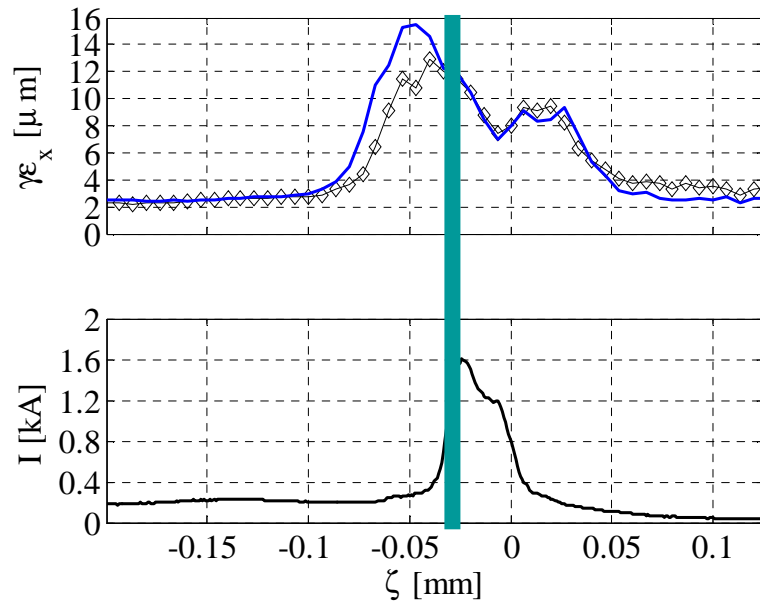
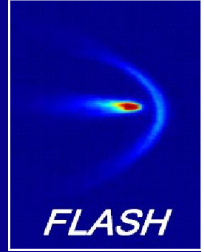
# Rekonstruierte Phasenraumverteilung



Resultate

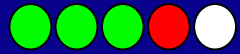


# Rekonstruierte Phasenraumverteilung

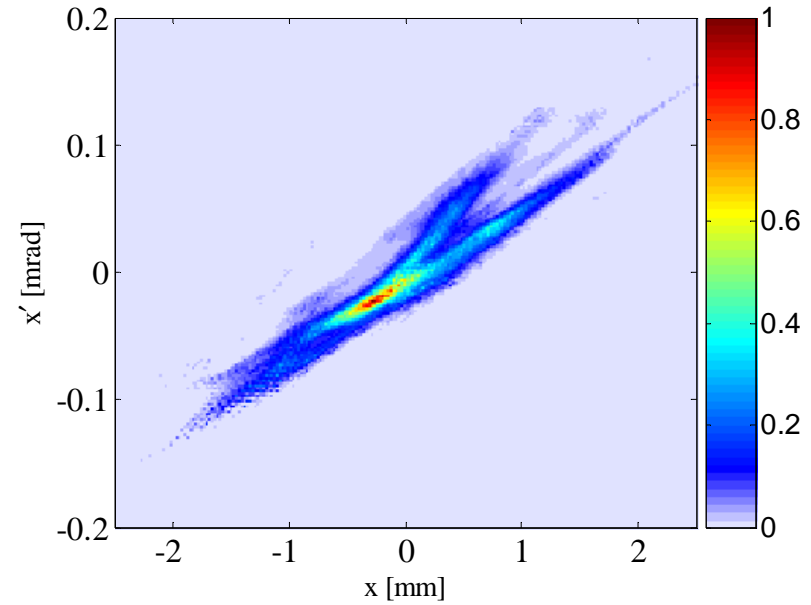
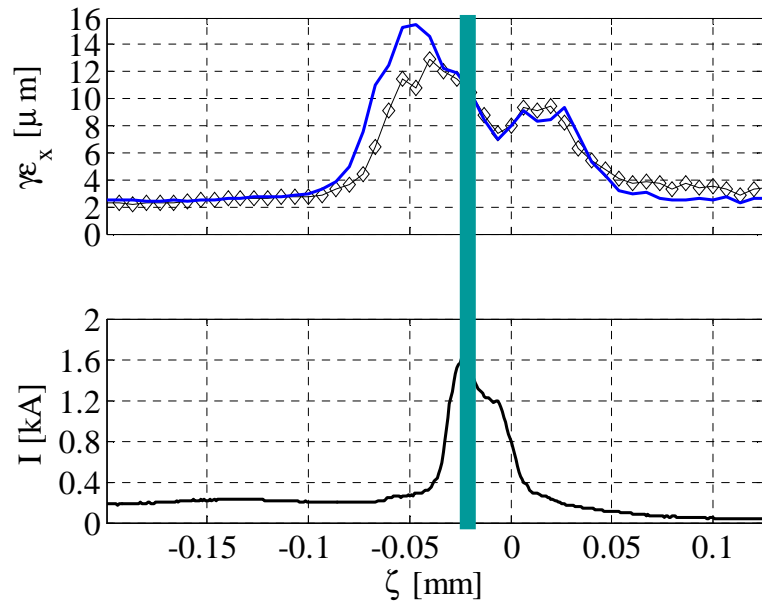
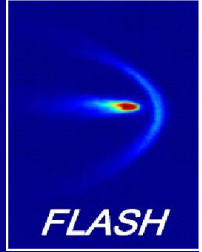




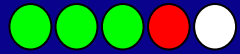
Resultate



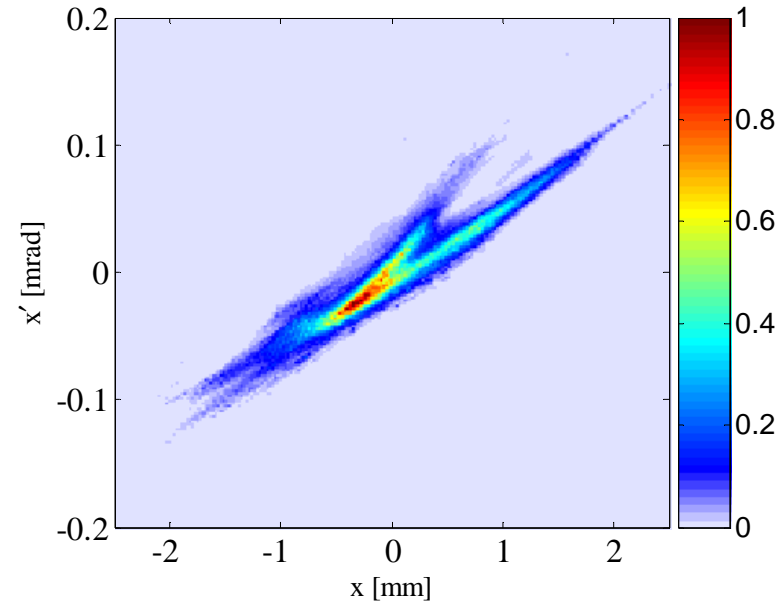
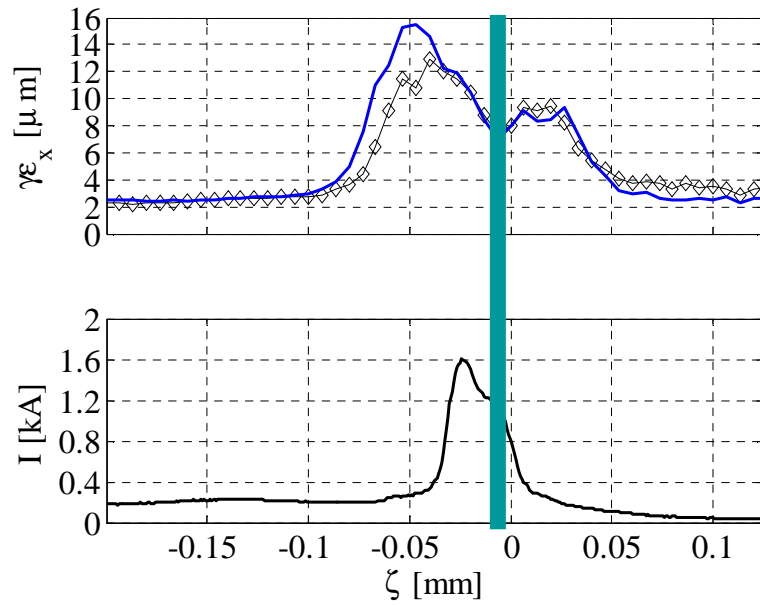
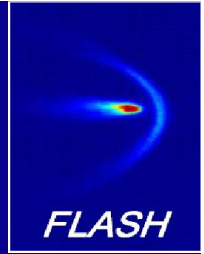
# Rekonstruierte Phasenraumverteilung



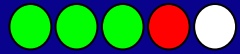
Resultate



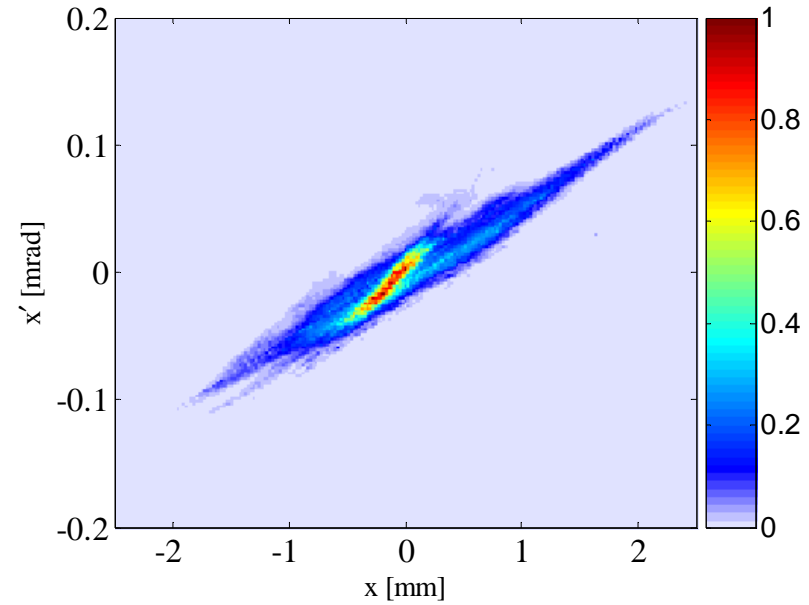
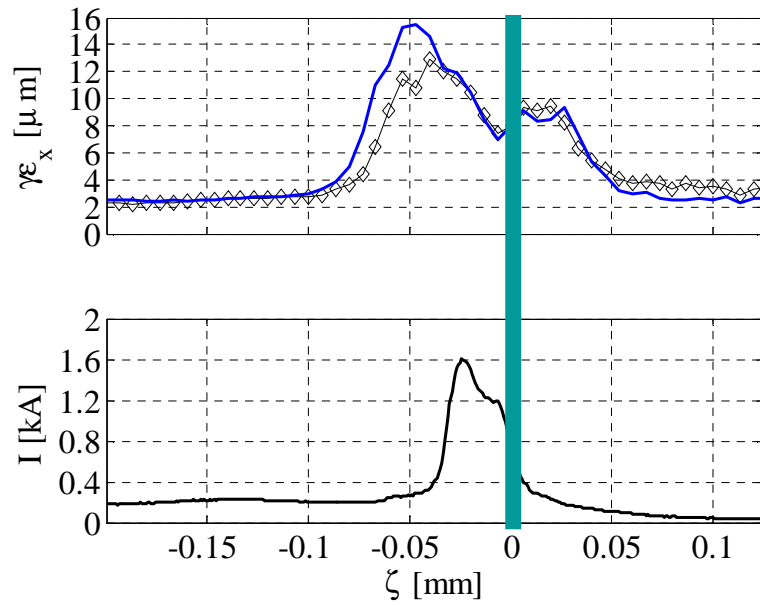
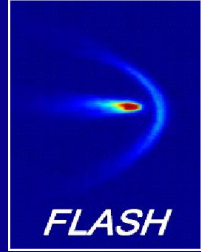
# Rekonstruierte Phasenraumverteilung

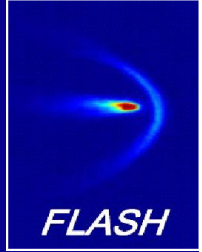
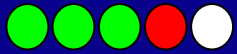


Resultate

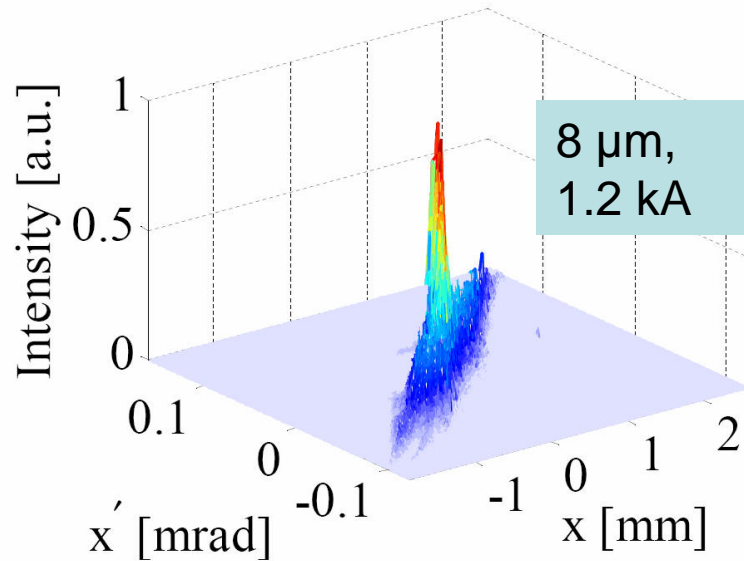


# Rekonstruierte Phasenraumverteilung

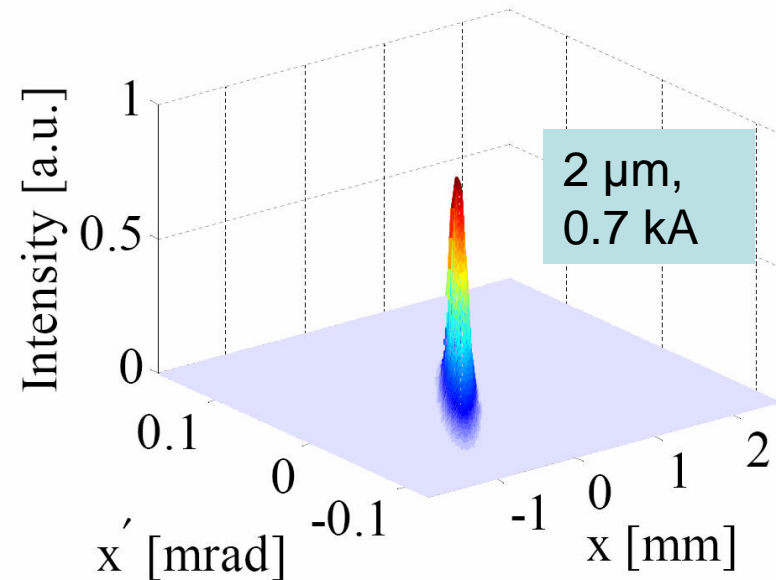




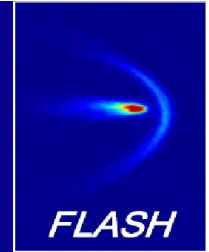
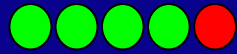
gemessene Verteilung  
innerhalb der  
Peakstrom-Region:



Gauss-Fit an den  
Bereich hoher Dichte:

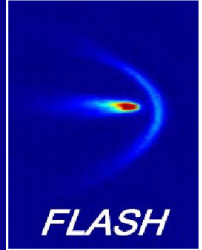


typisch: 2-4  $\mu\text{m}$  normierte Emittanz, 0.5 – 1.0 kA Peakstrom



- TDS erfolgreich eingesetzt zur Messung von Stromprofil, Energieverteilung, Scheibenemittanz und horizontaler Phasenraumverteilung mit einer longitudinalen Auflösung von  $\sim 10 \mu\text{m}$
- tomographische Rekonstruktion der Phasenraumverteilung notwendig zur Bestimmung der transversalen Emittanz des “lasenden” Bereichs, Scheibenemittanz nicht aussagekräftig
- kohärente Synchrotronstrahlung von entscheidender Bedeutung für die Verteilung in horizontalem und longitudinalem Phasenraum unter FEL-Betriebsbedingungen

# Ich danke...



Peter Schmüser, Gerhard Mack, Holger Schlarb, Bernhard Schmidt, Christopher Gerth, Florian Löhl, Bart Faatz, Ernst-Axel Knabbe, Gerhard Grygiel, Hossein Delsim-Hashemi, Ingrid Nikodem, Jörg Rossbach, Markus Hüning, Siegfried Schreiber, Thomas Bruns, Uschi Djuanda, Vitaly Kocharyan, Bolko Beutner, Martin Dohlus, Thorsten Limberg, Axel Winter, Klaus Flöttmann, Winfried Decking, Lars Fröhlich, Eduard Prat, Evgeny Schneidmiller, Benjamin Polzin, Katja Honkavaara, Igor Zagorodnov, Kirsten Hacker, Michail Yurkov, dem gesamten FLASH-Team,

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