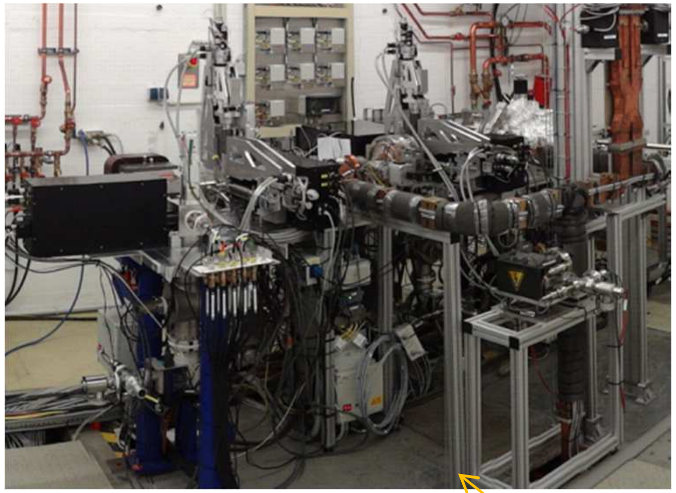
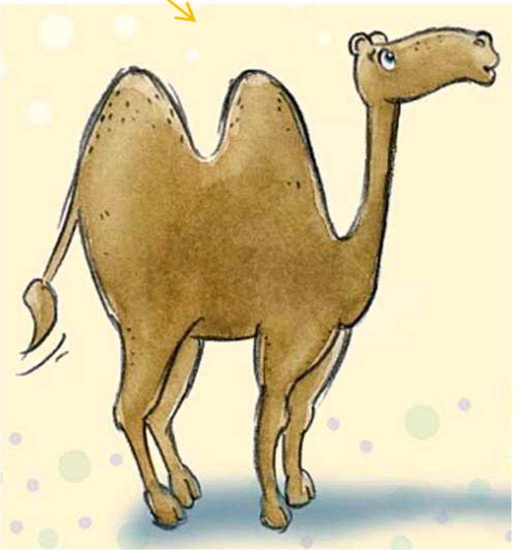
A Transverse Deflecting RF Structure for Sub-Micrometer Bunches at 5 to 50 MeV

LOLA (Greg **Lo**ew, Rudy **L**arsen and Otto **A**ltenmueller)
REGAE (**Re**lativistic **E**electron **G**un for **A**tomic **E**xploration)
a first idea about numbers



REGAE

bunch



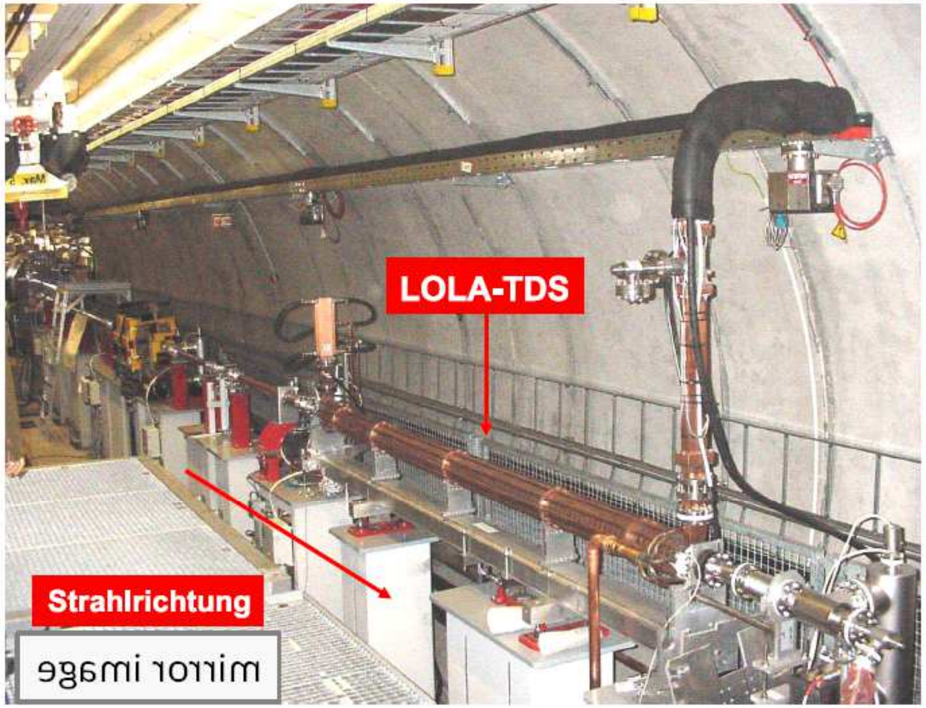
TDS (**Tr**ansverse **D**eflecting **S**tructure) measurement
two examples
rf structures
Remarks / other ideas
literature

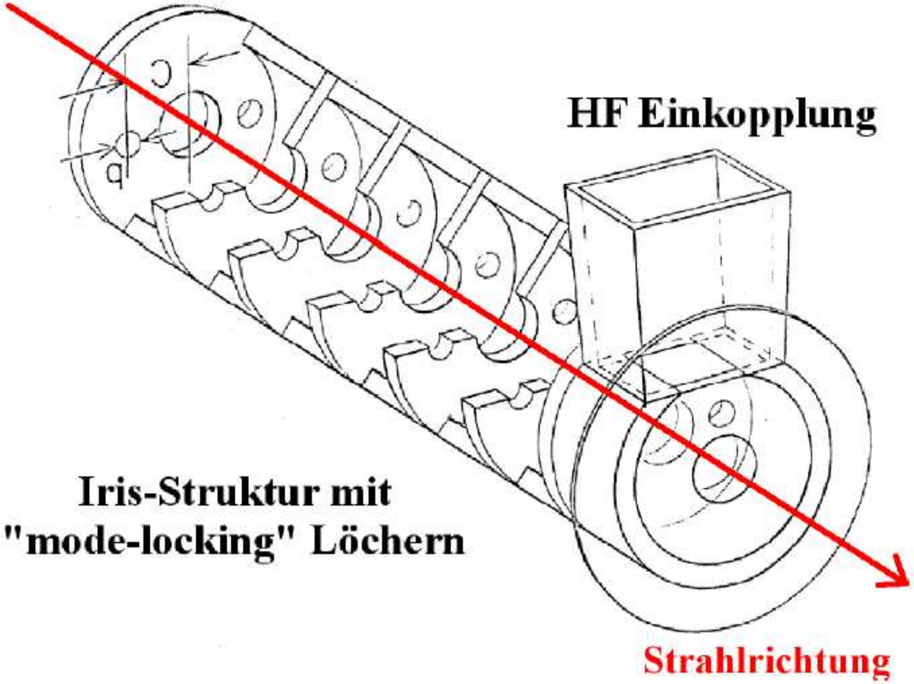
LOLA in the FLASH facility

transverse deflecting structures are standard diagnostic devices in FELS
(there is no FEL without them)

1 TDS	in FLASH
1	in PITZ
x	in LCLS, SACLA, Swiss FEL, FERMI, …
3	in European XFEL

Die transversal ablenkende Struktur "LOLA" bei FLASH.



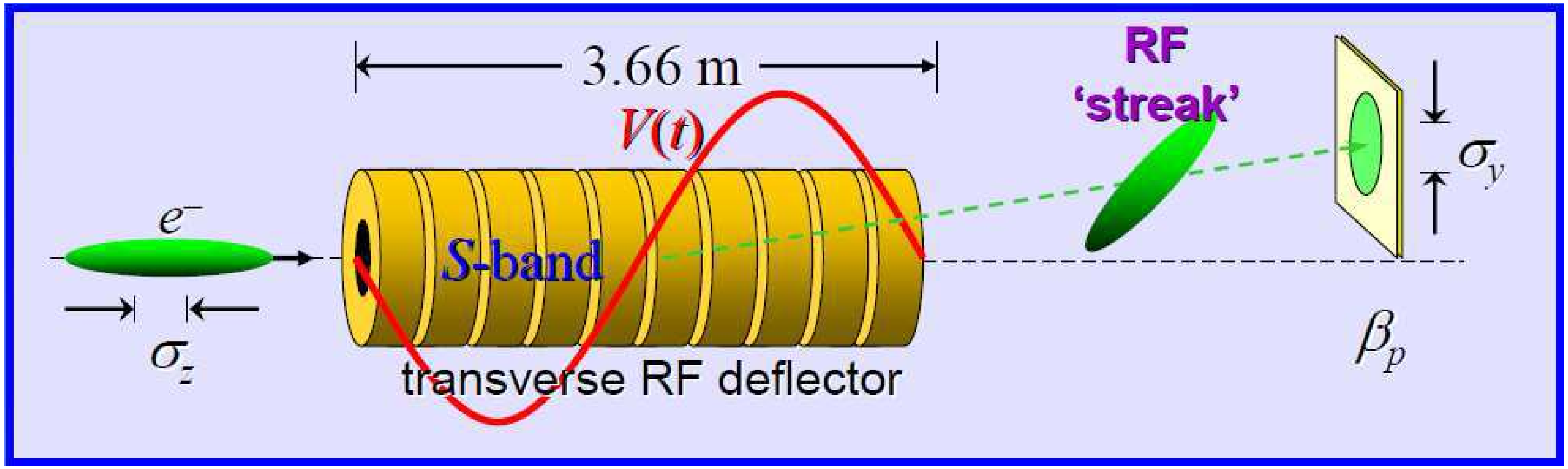


Die LOLA-TDS

- Normalleitende Wanderwellen HF-Struktur aus Kupfer.
- Iris-Struktur mit einer Gesamtlänge von $3.66\,\mathrm{m}$ und Zelllängen von $35\,\mathrm{mm}$.
- Nominale HF-Frequenz von $2856\,\mathrm{MHz}$ (S band) und Phasenänderung pro Zelle von $\frac{2\pi}{3}$.
- Füllzeit von $0.64\,\mu\mathrm{s}$ (bei FLASH: $1\,\mathrm{MHz}$ Mikropuls-Wiederholrate).

from Christopher Behrens, Groemitz 2010, Betriebsseminar

TDS: vertical plane



LOLA setup: horizontal plane

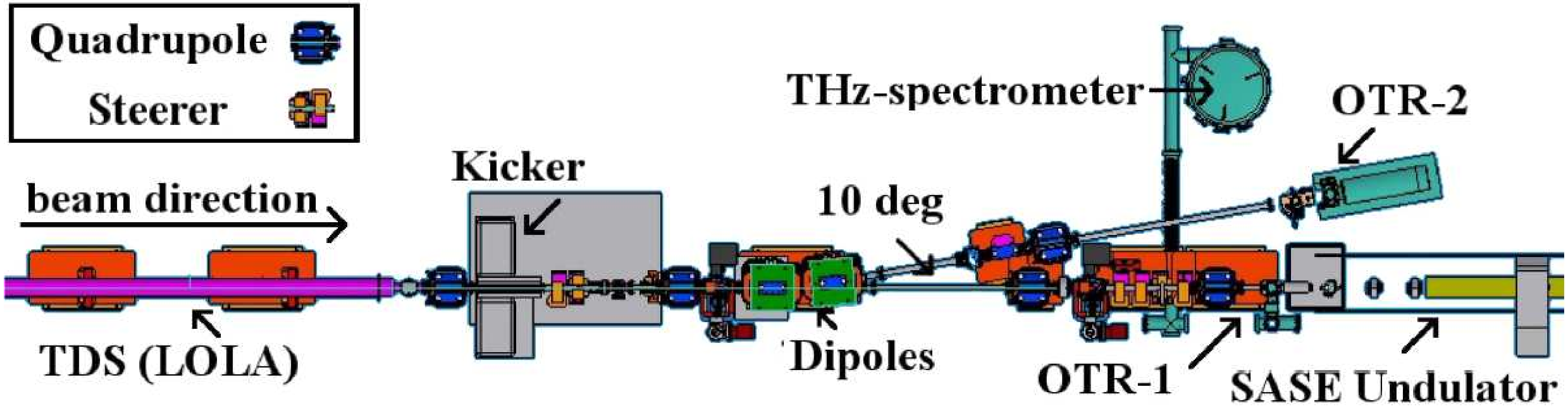
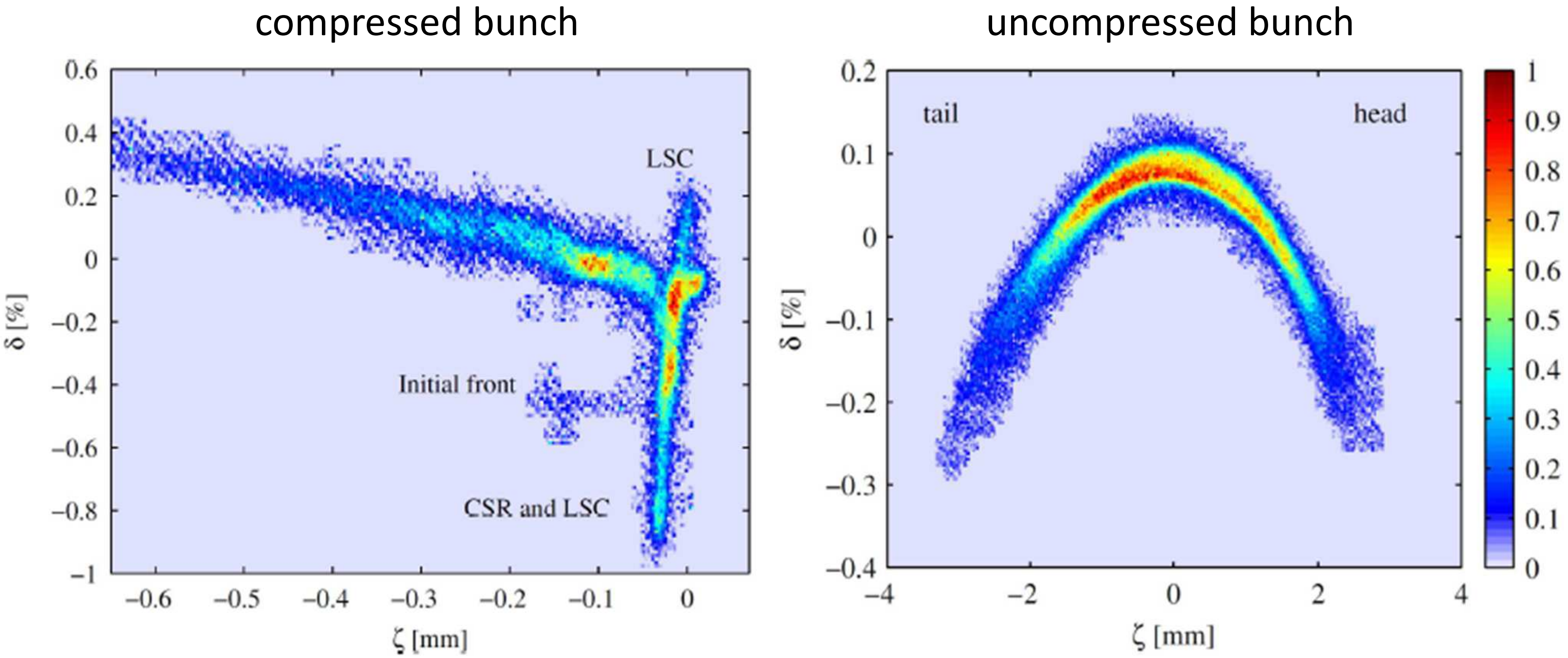


Figure: Aktuelles Design: Installiert im Februar 2010.

OTR-2 → longitudinal phase space

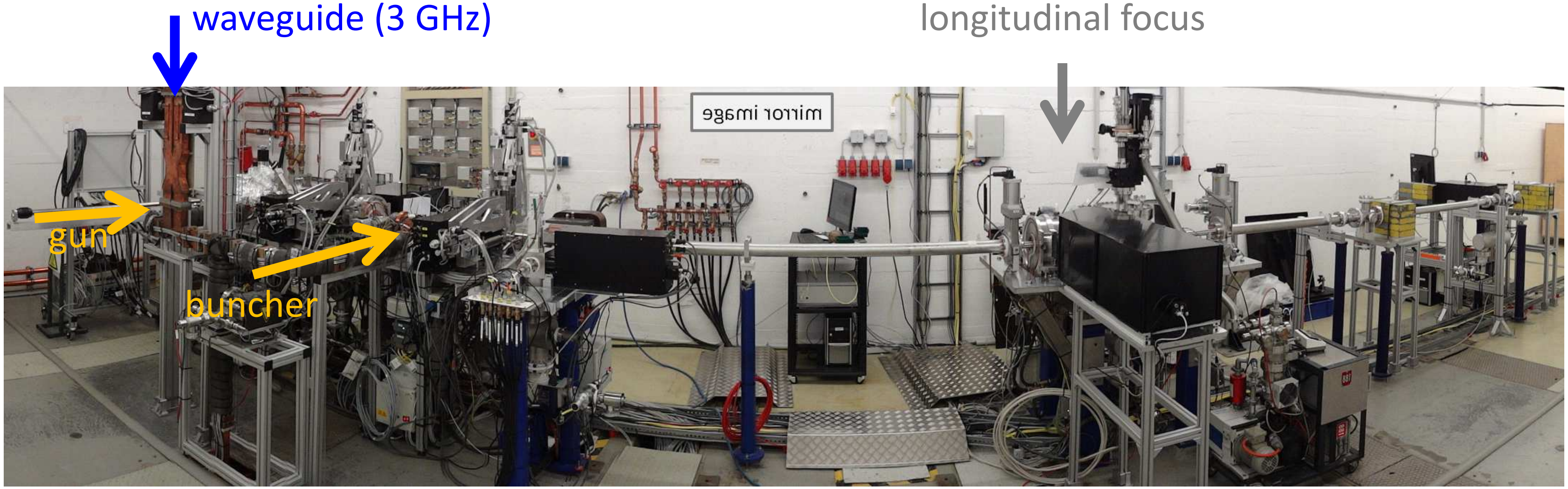

compressed bunch

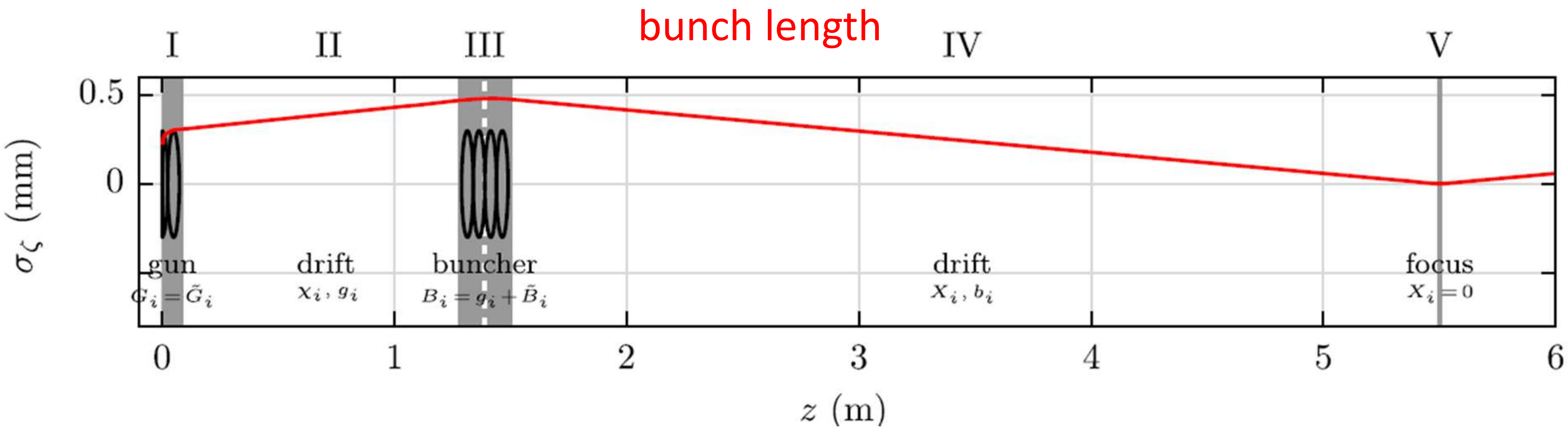
uncompressed bunch

Figure: Long. Phasenraum: mit Kompression (links), ohne Kompression (rechts).

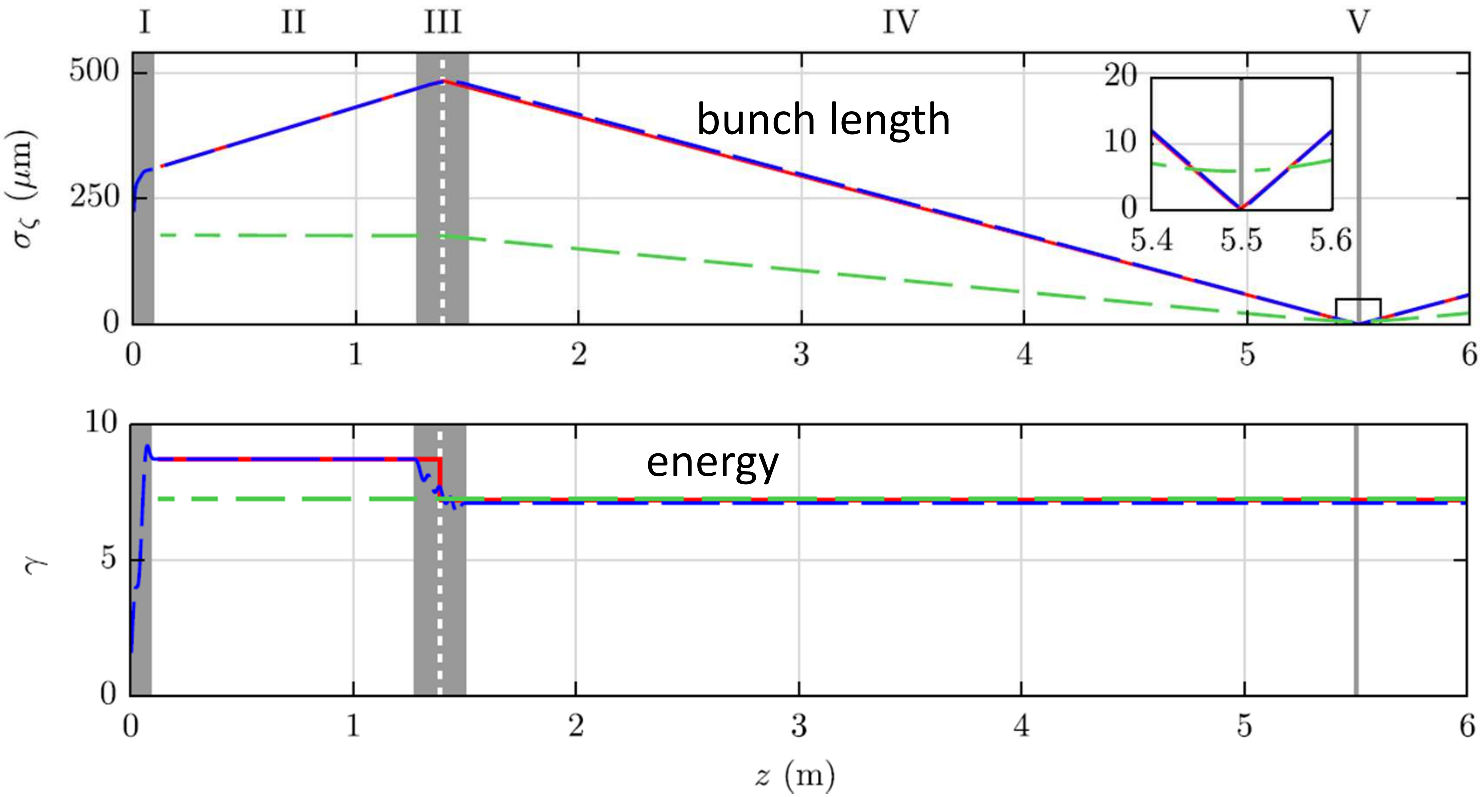
from Christopher Behrens, Groemitz 2010, Betriebsseminar

REGAE (**Re**lativistic **E**electron **G**un for **A**tomic **E**xploration)



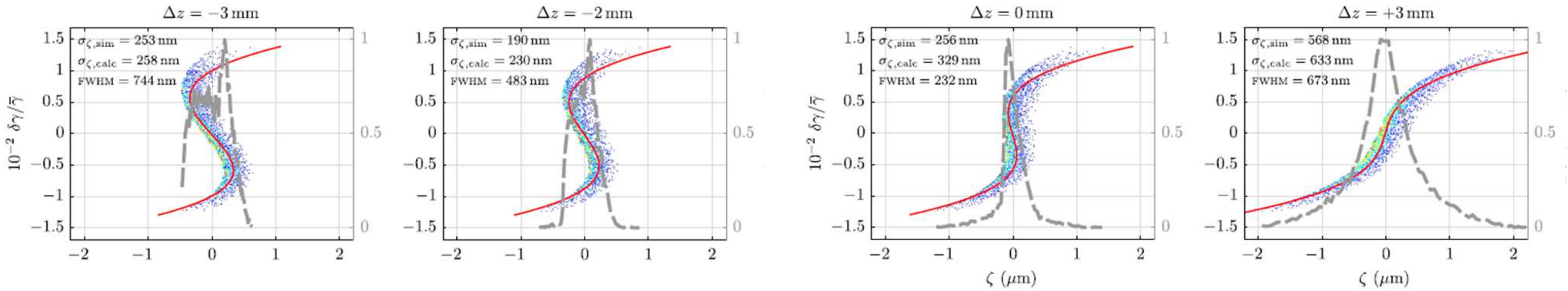


Astra calculation


bunch length

energy

longitudinal phase space



$\sigma_{\mathrm{sim}} = 253$ nm

$\sigma_{\mathrm{sim}} = 190$ nm

$\sigma_{\mathrm{sim}} = 256$ nm

$\sigma_{\mathrm{sim}} = 568$ nm

first idea about numbers

(a first discussion with Klaus Flöttmann)

$f \approx 500$ GHz … 1 THz

$\lambda = 0{,}6$ mm … 0,3 mm

resolution $\Delta_t \approx 100 \cdot 10^{-18}$ sec

$\hat{=}$ 30 nm

$\mathcal{E} = 5$ MeV

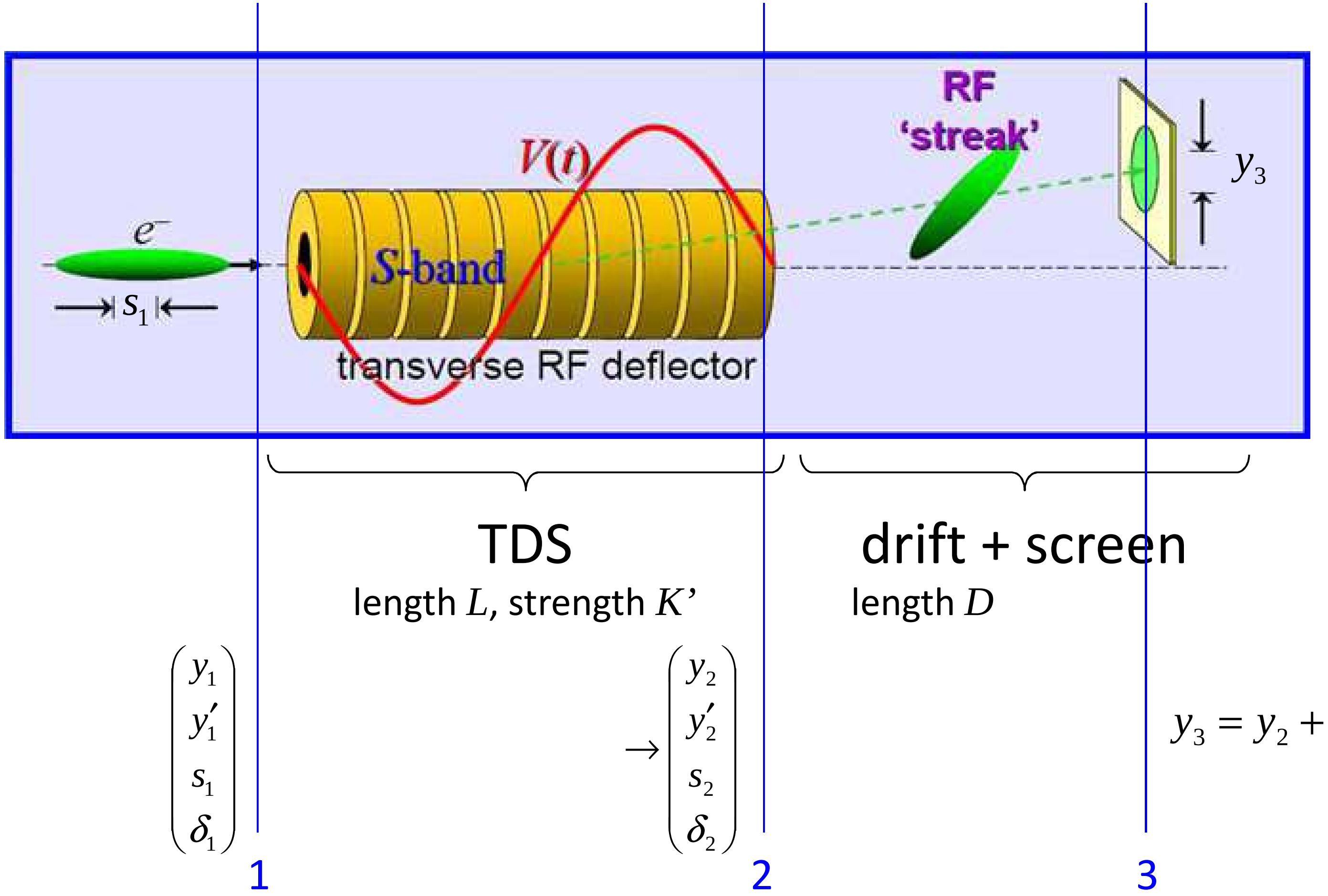
$\mathcal{E}_t \approx 10$ nm

length < 20 cm

$Q \approx 100$ fC

not the last!

TDS measurement without spectrometer magnet



TDS
length L, strength K'

drift + screen
length D

$$\begin{pmatrix} y_1 \\ y_1' \\ s_1 \\ \delta_1 \end{pmatrix} \rightarrow \begin{pmatrix} y_2 \\ y_2' \\ s_2 \\ \delta_2 \end{pmatrix}$$

$$y_3 = y_2 + Dy_2'$$

drift + screen $\rightarrow$ $\boxed{y_3 = y_1 + (L + D)y_1' + (L/2 + D)LK's_1}$

1→2: (period averaged) equation of motion in TDS

$$\frac{dy}{dZ} = y' = \frac{p_y}{p_z}$$

$$\left\langle \frac{dp_y}{dZ} \right\rangle \approx \frac{1}{v_z} \left\langle F_y(s) \right\rangle \approx \frac{1}{v_z} e \left\langle E_y \right\rangle \sin\left(\frac{2\pi}{\lambda} s \right) \approx p_z K's \qquad \text{with} \quad K' = \frac{2\pi}{\lambda} \frac{e\left\langle E_y \right\rangle}{\mathcal{E}}$$

$$\frac{d}{dZ} \begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix} \approx \begin{pmatrix} & 1 & & \\ & & K' & \\ & & & 0 \\ K' & & & \end{pmatrix} \begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix}$$

notation: uppercase Z for beam line coordinate
lowercase s for bunch coordinate

transport matrix

$$\rightarrow \begin{pmatrix} y_2 \\ y_2' \\ s_2 \\ \delta_2 \end{pmatrix} = T \begin{pmatrix} y_1 \\ y_1' \\ s_1 \\ \delta_1 \end{pmatrix} \qquad \text{with} \quad T = \begin{pmatrix} 1 & z & K'L^2/2 & 0 \\ 0 & 1 & K'L & 0 \\ 0 & 0 & 1 & 0 \\ K'L & K'L^2/2 & K'^2L^3/6 & 1 \end{pmatrix}$$

$$y_3 = y_1 + (L+D)y_1' + (L/2+D)LK's_1$$

more general

$$y_3 = w\begin{pmatrix} y_1 \\ y_1' \\ s_1 \\ \delta_1 \end{pmatrix}$$ with coefficients $w = \begin{pmatrix} w_1 & w_2 & w_3 & w_4 \end{pmatrix}$

measured

ν is particle index

what we want to know

$$\sigma_3^2 = \left\langle y_{3,\nu}^2 \right\rangle = w\underbrace{\left\langle \begin{pmatrix} y_{1,\nu} \\ y_{1,\nu}' \\ s_{1,\nu} \\ \delta_{1,\nu} \end{pmatrix}\begin{pmatrix} y_{1,\nu} \\ y_{1,\nu}' \\ s_{1,\nu} \\ \delta_{1,\nu} \end{pmatrix}^t \right\rangle}_{C} w^t = f\times\left(\sigma_e^2 + \boxed{\sigma_m^2}\right)$$ with $\boxed{\sigma_m^2 = \left\langle s_{1,\nu}^2 \right\rangle}$ and $f = \left((L/2+D)LK'\right)^2$

correlation matrix

systematic error

vertical optics (~ spot size without deflection)

$$\sigma_e^2 = \boxed{\underbrace{\cdots C_{yy} + \cdots C_{yy'} + \cdots C_{y'y'}}_{\sigma^2_{e,\mathrm{vert}}}} + \boxed{\underbrace{\cdots C_{ys} + \cdots C_{y's}}_{\sigma^2_{e,\text{long-vert}}}} + \boxed{\begin{array}{l}\cdots \quad \cdots C_{\delta\delta} \\ \text{correlations with energy}\end{array}}$$

vertical - longitudinal correlation

error from vertical phase space

$$\boxed{\sigma_{e,v} = \frac{\sqrt{\boxed{\varepsilon_y\left(\beta_y^2\right.}-2\boxed{\alpha_y}(L+D)+\left.(L+D)^2\boxed{\gamma_y}\right)}}{(L/2+D)LK'}}$$

vertical emittance and Twiss parameters

velocity effects: additional error from uncorrelated energy spread

$$\boxed{\sigma_{e,\delta} \approx \frac{L}{2\gamma_r^2}\frac{D+L/3}{D+L/2}\boxed{\sigma_\delta}}$$

uncorrelated (relative) energy spread $\sigma_\delta^2 = C_{\delta\delta}$

period averaged equation of motion in TDS with velocity effects (γ^{-2} terms)

$$\frac{d}{dZ}\begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix} \approx \begin{pmatrix} & 1 & & \\ & & K' & \\ & & & \boxed{\gamma_r^{-2}} \\ K' & & & \end{pmatrix}\begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix}$$

$$T = \begin{pmatrix} 1 & L & K'L^2/2 & 0 \\ 0 & 1 & K'L & 0 \\ 0 & 0 & 1 & 0 \\ K'L & K'L^2/2 & K'^2L^3/6 & 1 \end{pmatrix} + \frac{1}{\gamma_r^2}\begin{pmatrix} K'^2L^4/24 & K'^2L^5/120 & K'^3L^6/720 & K'L^3/6 \\ K'^2L^3/6 & K'^2L^4/24 & K'^3L^5/120 & K'L^2/2 \\ K'L^2/2 & K'L^3/6 & K'^2L^4/24 & L \\ K'^3L^5/120 & K'^3L^6/720 & K'^4L^7/5040 & K'^2L^4/24 \end{pmatrix} + O\left(\gamma_r^{-4}\right)$$

two examples

bunch

aperture $A \propto \lambda_{\mathrm{rf}}$ $\quad A \approx A_{\mathrm{fac}}\lambda$

$\sigma_{x,y} < A$ $\quad \sigma_{x,y} < A/N_{\sigma}$

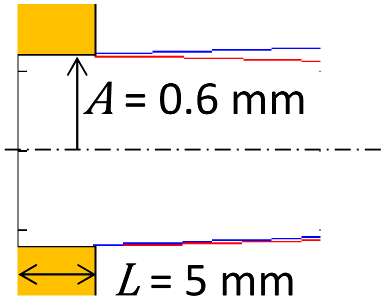
strength $K' = \dfrac{2\pi}{\lambda_{\mathrm{rf}}}\dfrac{e\langle E_y\rangle}{\mathcal{E}}$

Example 1:
(not optimized)

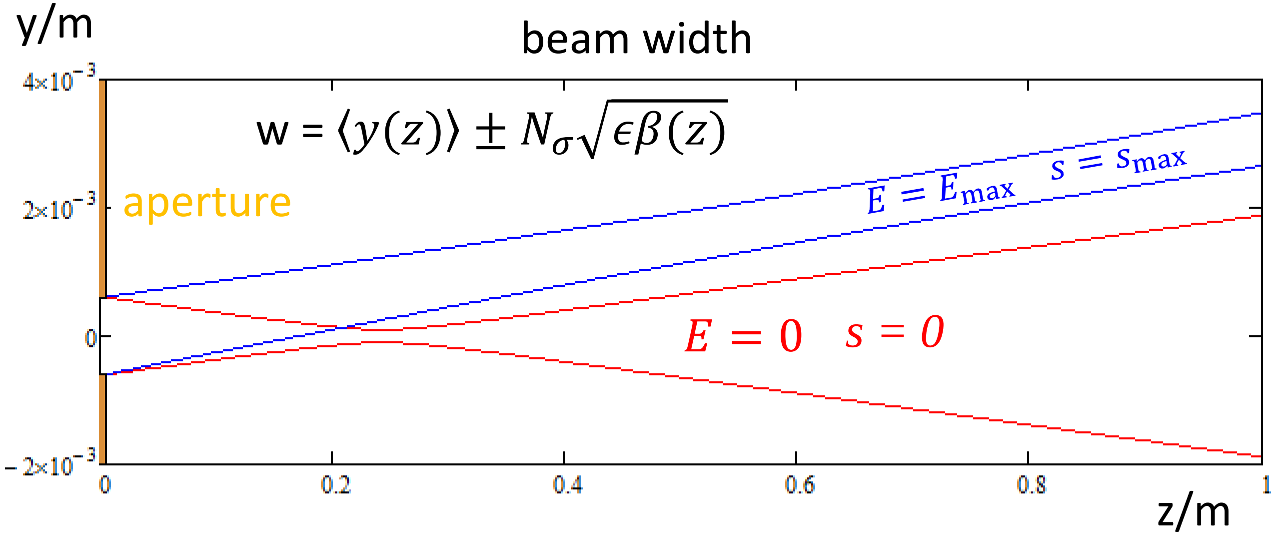
γ		10
$\epsilon \cdot \gamma\beta$	nm	100
σ_δ		0.005
$s_{\max}$	μm	5
A_{fac}		0.2
N_σ		5
f	GHz	100
$E_{\max}$	MV/m	300
L	mm	5
D	mm	1000
$\sigma_{\text{e,vert}}$	nm	136
$\sigma_{\text{e},\delta}$	nm	125

aperture: $\lambda \approx 3\,\text{mm}$

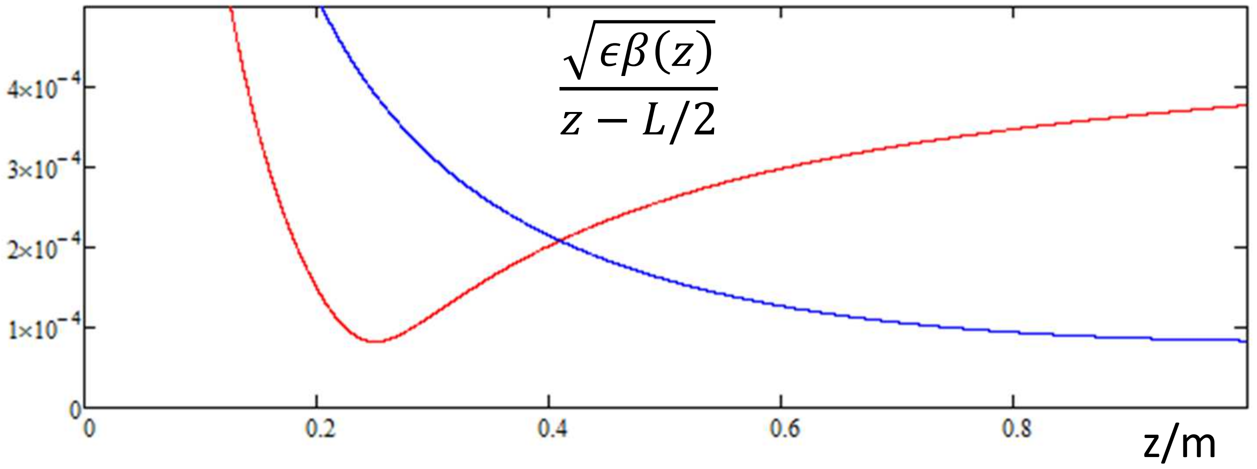
$$A = \lambda A_{\text{fac}}$$



beam width

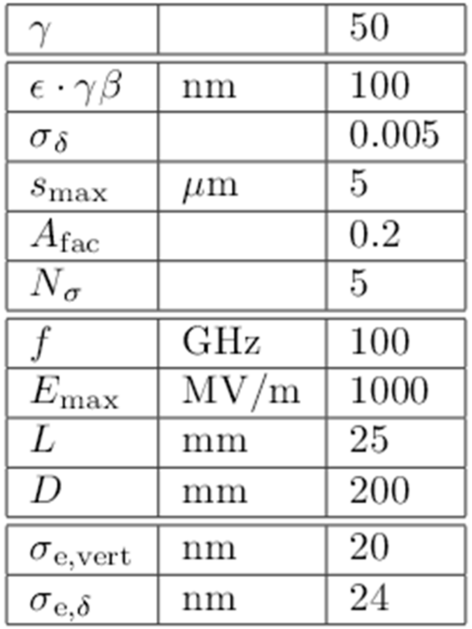


relative focus



Example 2:

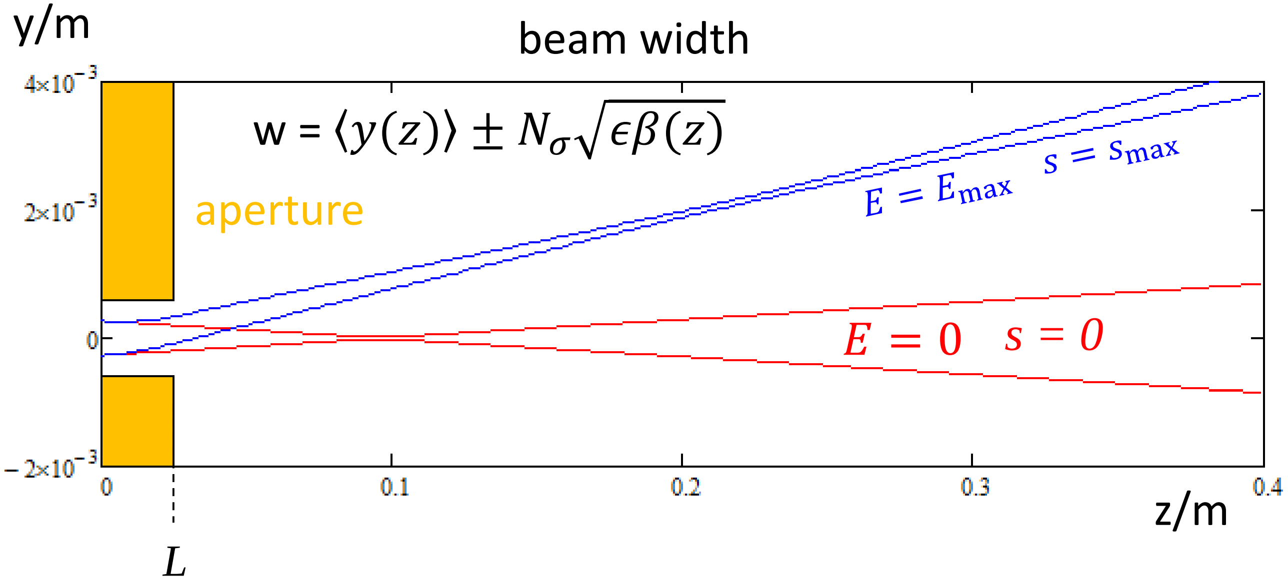
(not optimized)



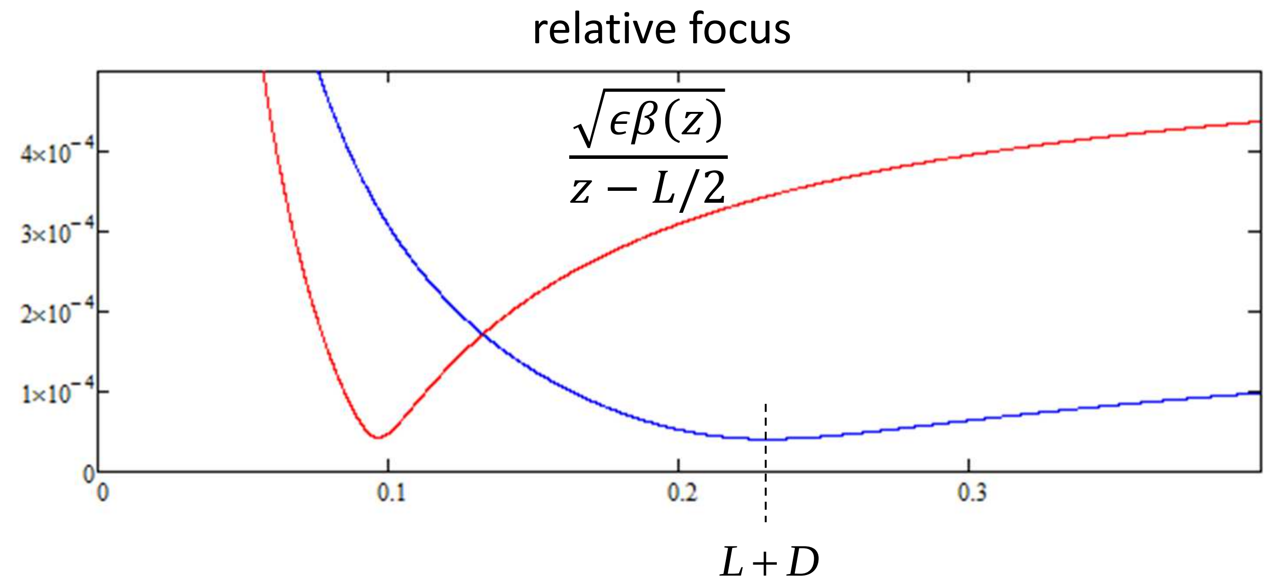
γ		50
$\epsilon \cdot \gamma\beta$	nm	100
σ_δ		0.005
$s_{\max}$	μm	5
A_{fac}		0.2
N_σ		5
f	GHz	100
$E_{\max}$	MV/m	1000
L	mm	25
D	mm	200
$\sigma_{\mathrm{e,vert}}$	nm	20
$\sigma_{\mathrm{e},\delta}$	nm	24

aperture:

$A = \lambda A_{\mathrm{fac}}$



beam width



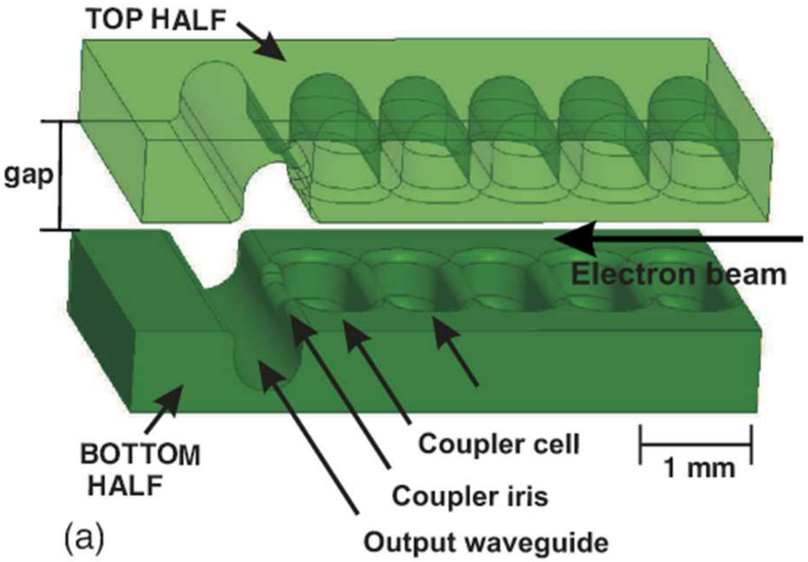
relative focus

rf structures

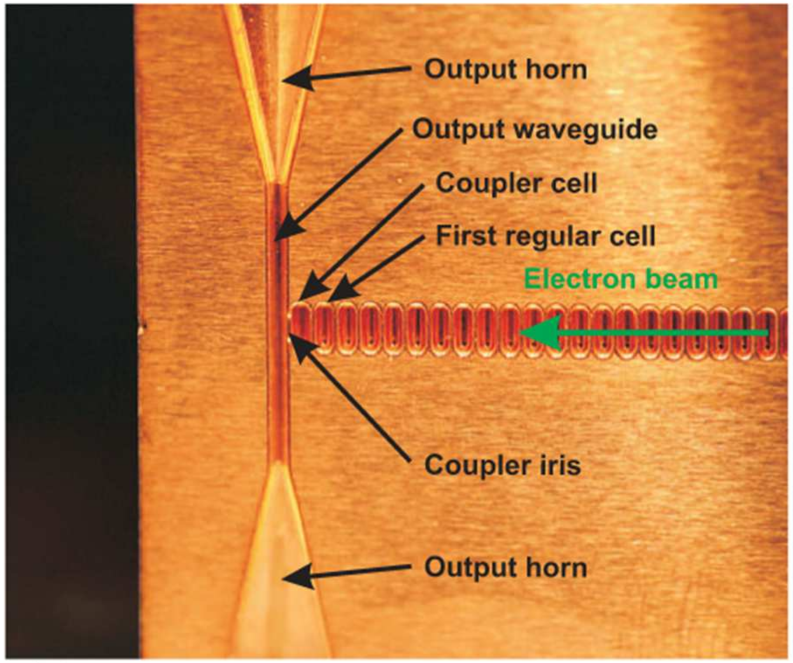
accelerating structure from

Massimo Dal Forno, et. Al.
rf breakdown tests of mm-wave metallic accelerating structures
Phys. Rev. Accel. Beams 19, 011301 – Published 6 January 2016

f = 115 .. 140 GHz
$E_{acc} < 0.3$ GV/m
$E_{surface} < 1.5$ GV/m
pulse length 2.4 nsec



(a)



(b)

H-type groove waveguide from

P. Arcioni, M. Bressan, F. Broggi, G. Conciauro, L. Perregrini, P. Pierini:
The Groove Guide as an Interaction Structure for Microwave FEL
Nuclear Instruments and Methods in Physics Research, Section A 358, pp. 108-111, 1995

might overcome the aperture limitation (for x direction)
but: linear range is still small!

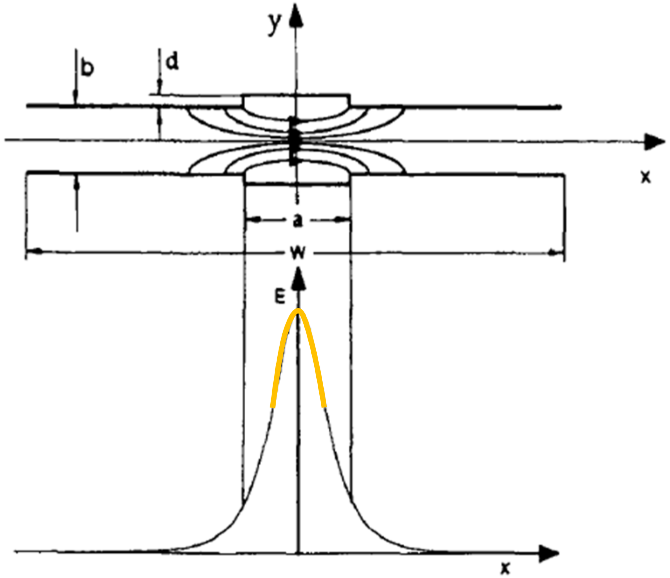


Fig. 1. Cross section of the groove-guide with the field lines and the electric field amplitude in the x direction at $y = 0$.

remarks

TDS focus changes with K’

time resolution limited by: maximal field
length/γ^2 and
aperture

increase energy (ACC+TDS?) or reduce resolution

open: working point, frequency, SW or TW regime
structure technology
rf source
couplers
even the method

other ideas ???

stimulate observe	external field	self-field + geometry
observe beam effect	TDS + screen	wake + instability +screen ~ Q^2
observe field	undulator → radiation	resonator → radiation

undulator → radiation

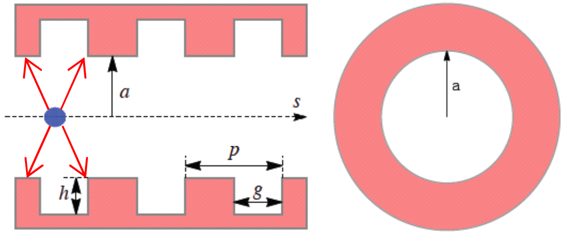
$$2\pi\sigma_s \sim \lambda_{\mathrm{ph}} = \frac{1+K^2/2}{2\gamma^2}\lambda_u \approx \frac{\lambda_u}{\gamma^2}$$

required undulator period $\lambda_u \sim 2\pi\gamma^2\sigma_s$

$$2\pi \cdot 10^2 \cdot 100\,\mathrm{nm} \approx 60\,\mu\mathrm{m}$$

100^2 6mm yes!

resonator → radiation



$a/\gamma << \sigma_s$ but $1\,\mathrm{mm}/10 >> 100\,\mathrm{nm}$

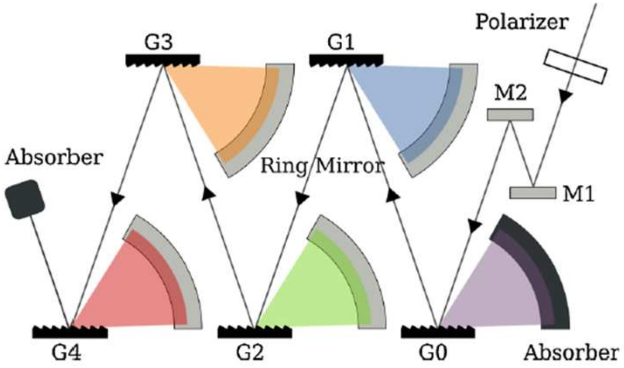
1mm/100

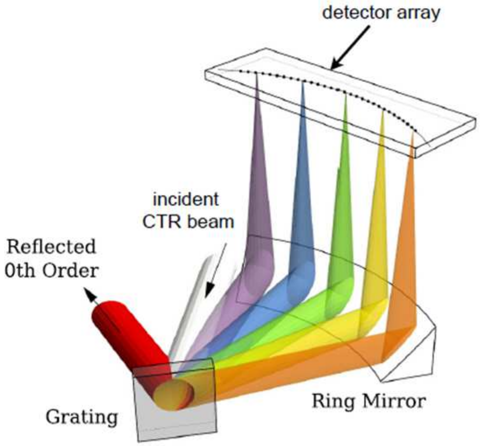
no!

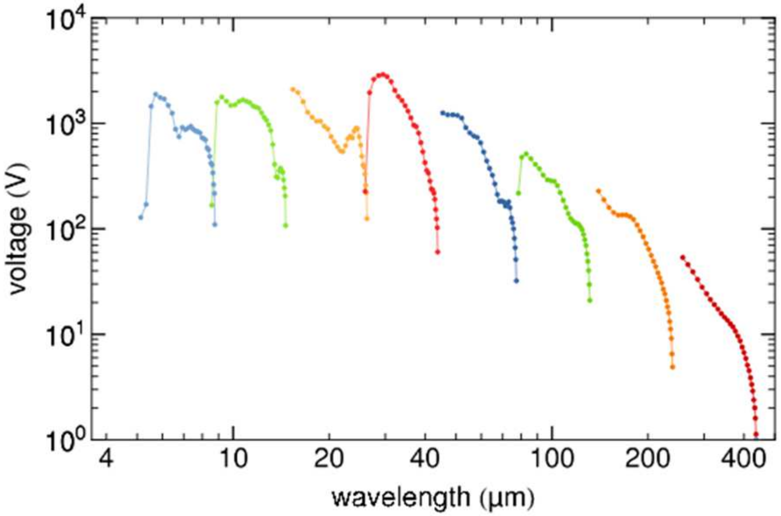
short magnet + spectrometer

take one magnet from the undulator → coherent short magnet radiation

multichannel infrared spectrometer







$$200\,\mathrm{nm} < 2\pi\sigma_s \sim \lambda_{\mathrm{ph}}$$

optical spectrometer

literature

tds:

R. Akre, L. Bentson, P. Emma, P. Krejcik
Bunch length measurements using a transverse rf deflecting structure in the SLAC linac
SLAC-PUB-9241, PAC2002

Klaus Floettmann and Valentin V. Paramonov
Beam dynamics in transverse deflecting rf structures
Phys. Rev. ST Accel. Beams 17, 024001 – Published 5 February 2014

ragae:

Benno Zeitler, Klaus Floettmann, and Florian Grüner
Linearization of the longitudinal phase space without higher harmonic field
Phys. Rev. ST Accel. Beams 18, 120102 – Published 30 December 2015

structures:

Massimo Dal Forno, et. Al.
rf breakdown tests of mm-wave metallic accelerating structures

P. Arcioni, M. Bressan, F. Broggi, G. Conciauro, L. Perregrini, P. Pierini:
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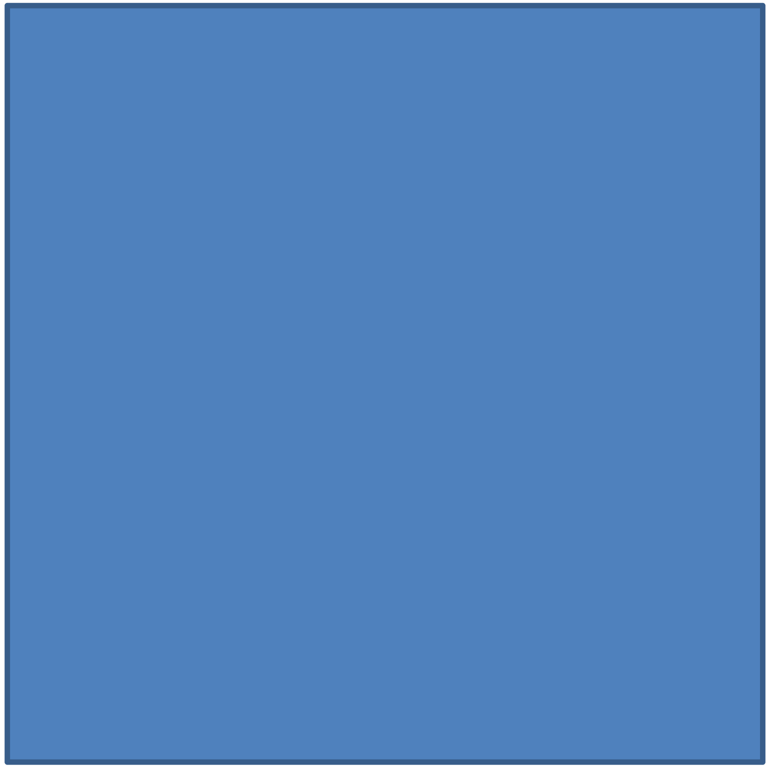

funny beam dynamics:

parameters as for example 2

$$\frac{d}{dZ}\begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix} \approx \begin{pmatrix} & 1 & & \\ & & K' & \\ & & & \gamma_r^{-2} \\ K' & & & \end{pmatrix}\begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix}$$

$$T = T_\infty + \frac{1}{\gamma_r^2} T_\gamma + O\xcancel{\left(\gamma_r^{-2}\right)}$$

$$X(Z) = T(Z) X_1$$

$$\frac{d}{dZ}\begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix} \approx \begin{pmatrix} & 1 & & \\ & & K' & \\ & & & 0 \\ K' & & & \end{pmatrix}\begin{pmatrix} y \\ y' \\ s \\ \delta \end{pmatrix}$$