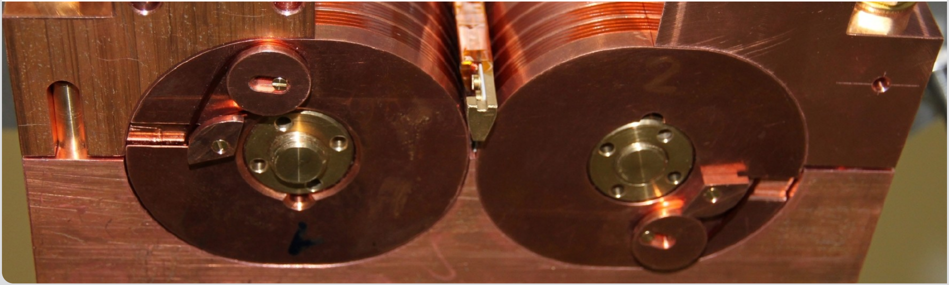
Progress on Experiments towards LWFA/TGU-Based FELs

Axel Bernhard

Laboratory for Applications of Synchrotron Radiation (LAS)



Outline

LWFA-FELs employing Transverse Gradient Undulators (TGU)

Experimental Projects towards LWFA-TGU-FELs

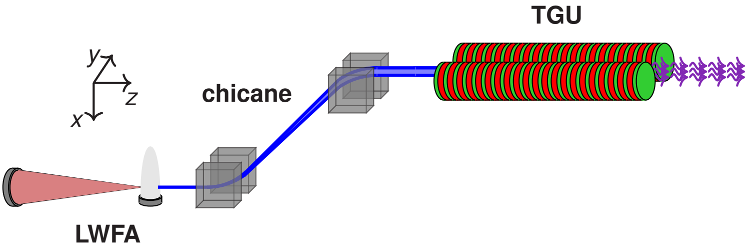
Progress on Experiments at Jena/Karlsruhe

- The Superconducting TGU
- The Beam Transport
- Next Steps

Conclusion

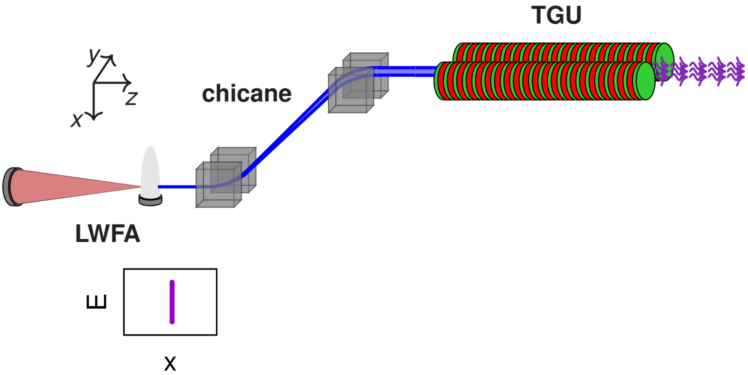
Transverse Gradient Undulator Schemes

The general concept



Transverse Gradient Undulator Schemes

The general concept

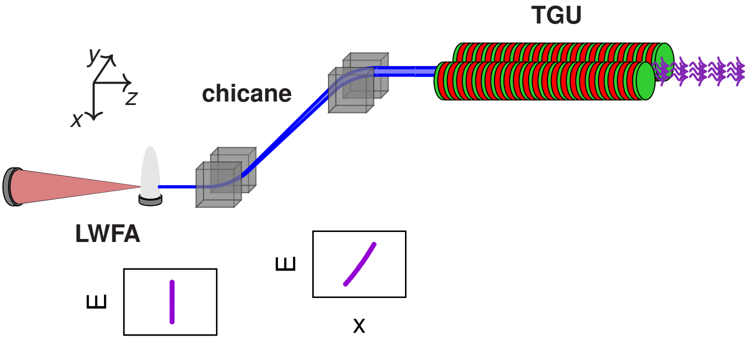


%-level
energy spread

Transverse Gradient Undulator Schemes

Karlsruhe Institute of Technology

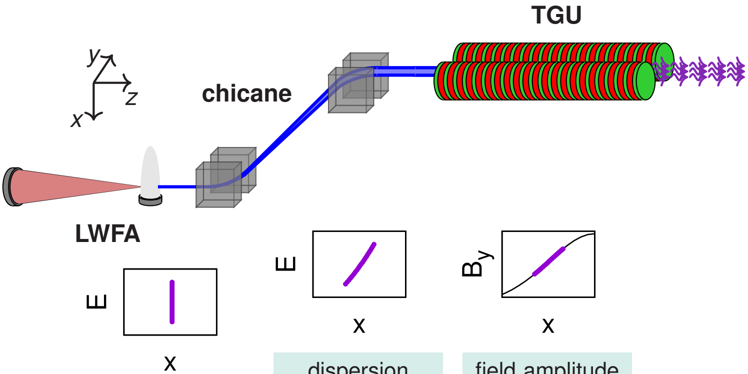
The general concept



dispersion

%-level
energy spread

The general concept



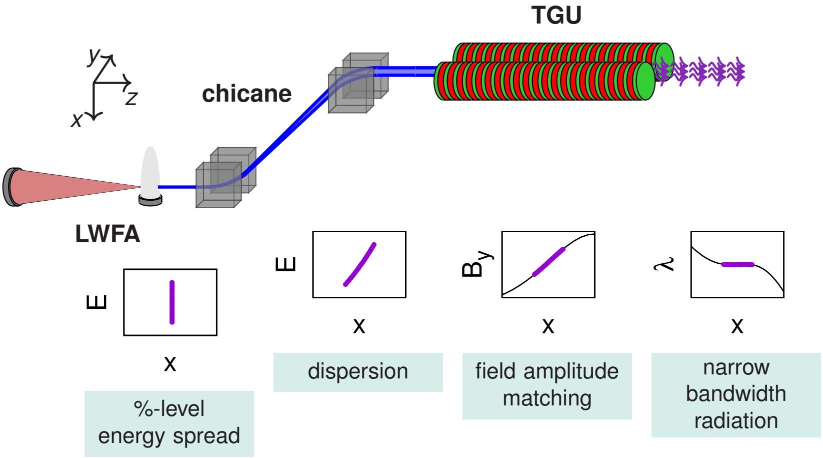
%-level energy spread

dispersion

field amplitude matching

Transverse Gradient Undulator Schemes

The general concept



Extension of the concept towards FELs

Zh. Huang et al., PRL 109 (2012)

P. Baxevanis et al. Pys.Rev.STAB 17 (2014)

Planar undulator

FEL gain suffers from large energy spread. E.g. gain length increase:

$$L_g \approx L_{g0} \left(1 + \frac{\sigma_\delta^2}{\rho_{\mathrm{FEL}}^2} \right)$$

with the Pierce parameter $\rho_{\mathrm{FEL}} \lesssim 10^{-3}$ typically.

TGU modification

Assuming $K(x) = K_0(1 + \alpha x)$, $K_0 = \frac{e}{2\pi m_e c} \lambda_{\mathrm{u}} B_{y\,0}$

and dispersion matching $D_x = \frac{2 + K_0^2}{\alpha K_0^2}$,

FEL performance can be largely enhanced.

Extension of the concept towards FELs

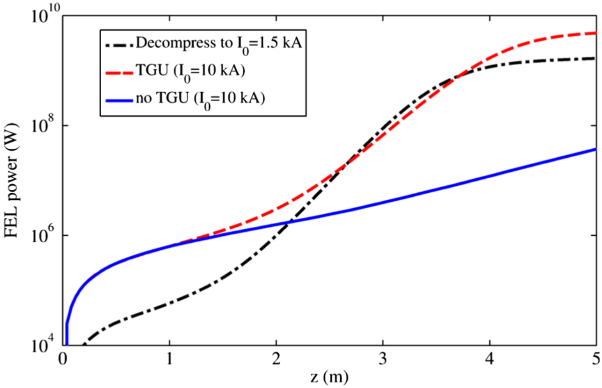


Figure: GENESIS simulation comparing options for a 3.9 nm-FEL, $E_0 = 1\,\text{GeV}$, $\lambda_\text{u} = 10\,\text{mm}$, $K_0 = 2$, $\alpha = 150\,\text{m}^{-1}$

Huang et al., ibd.

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LWFA-TGU experimental projects

Karlsruhe Institute of Technology

SIOM-SINAP-SLAC (China)

Source
SIOM 200 TW laser facility

Design energy	380 MeV
Des. energy spread	1 %

Beam transport scheme
Single deflection

TGU
PMU, transversely tapered

λ_u	20 mm
α	50 m^{-1}

Approach
Direct LWFA-TGU-XFEL demonstration

HI Jena-KIT (Germany)

Source
JETI-40 laser facility

Design energy	120 MeV
Des. energy spread	$\sim$10 %

Beam transport scheme
Achromat-like dogleg

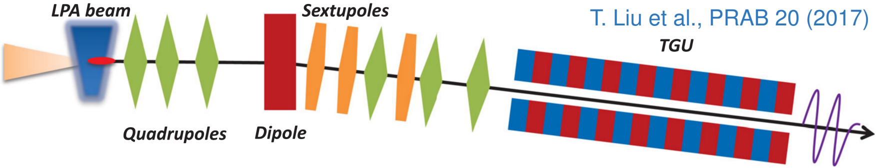
TGU
SCU, cylindric

λ_u	10.5 mm
α	150 m^{-1}

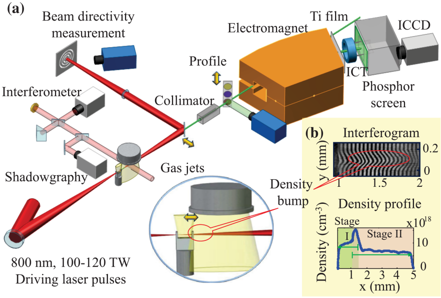
Approach
Intermediate step: spontanous TGU radiation

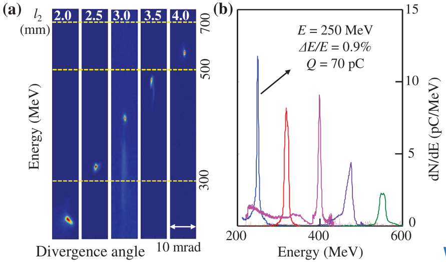
Experiments at SIOM

T. Liu et al., PRAB 20 (2017)



Source: Cascaded LWFA

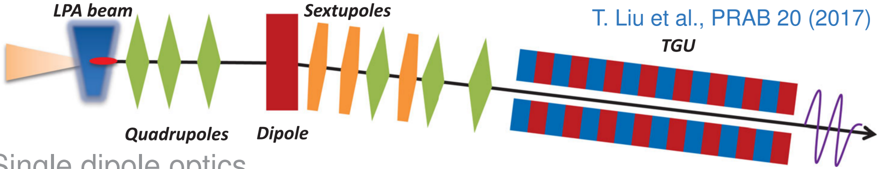




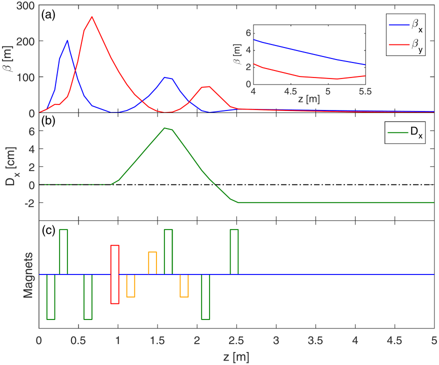
Wang et al., PRL 117 (2016)

Experiments at SIOM

T. Liu et al., PRAB 20 (2017)



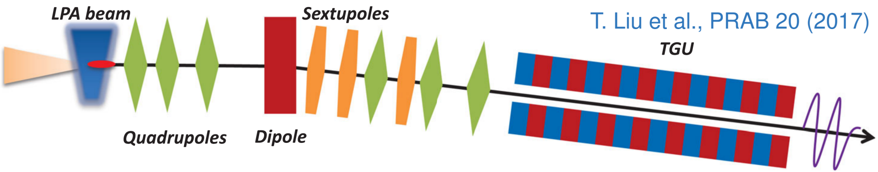
Single dipole optics



In place	*Quadrupoles*	
	L_{eff}	100 mm
	g	$80\,\mathrm{T\,m^{-1}}$
	Dipole	
	θ_{defl}	0.1 rad
devel.	*In-vac. Quadrupoles*	
	g	$150\,\mathrm{T\,m^{-1}}$
	Sextupoles	
	s	$10^4\,\mathrm{T\,m^{-2}}$

T. Liu et al., Proc. IPAC 2016

Experiments at SIOM



T. Liu et al., PRAB 20 (2017)

Transverse Gradient Undulators

Realized: 4 PM-TGUs	
λ_u	20 mm
# periods	40
K_0	1.15
α	$50\,\mathrm{m}^{-1}$

T. Liu et al., Proc. IPAC 2016

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SCTGU: General magnetic design

Design goals

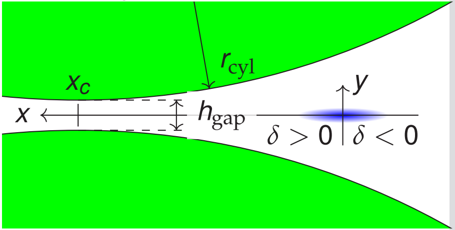
- short period
  (aiming at EUV/X-Rays)
- $K \geq 1$
- high transverse gradient

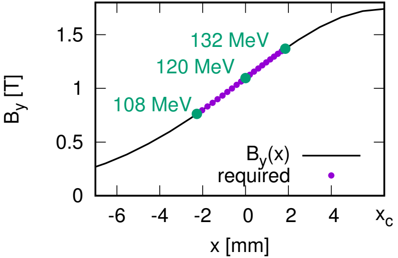
Parameters

period length λ_u	10.5 mm
gap @ symmetry axis h_{gap}	1.1 mm
pole radius r_{cyl}	30 mm
flux density ampl. $B_y(0)$	1.1 T
undulator parameter K_{u0}	1.1
transverse gradient $\frac{\partial K}{\partial x}$	149 m^{-1}
energy acceptance	± 10 %

V. Afonso Rodriguez et al.,
IEEE Trans Appl SC **23** (2013)

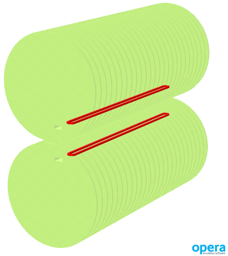
Result: cylindrical SCTGU

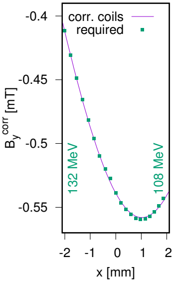




SCTGU: Technical design details

Ponderomotive drift correction

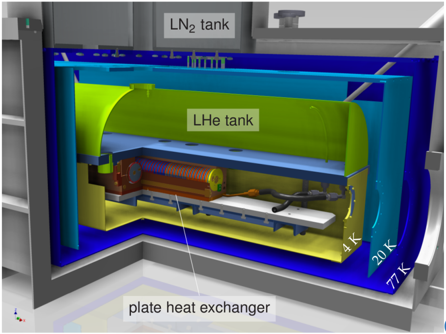




- internal long racetrack coils
- ⇒ iron-free coil former

Cryogenic concept

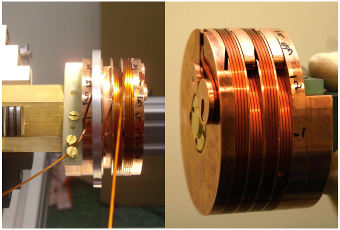
- LTC superconducting coils and HTC current leads
- ⇒ 4.2 K/77 K indirect cooling



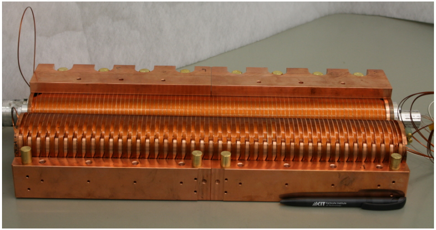
Cryovac GmbH

SCTGU: Realization and quench test

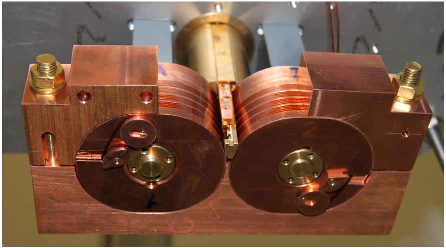
2-period winding test



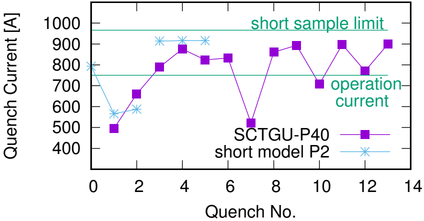
40-period undulator



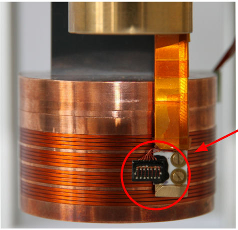
2-period short model

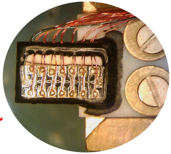


Quench performance (bath)

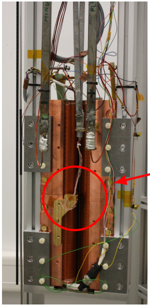


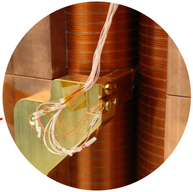
SCTGU: Field measurements at CASPER I





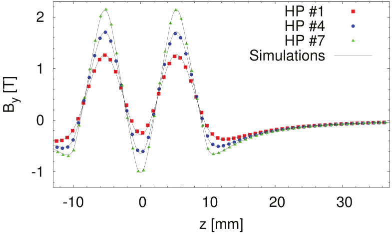
Array of 7 equidistant Hall probes (Arepoc)



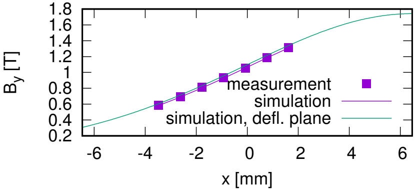


Array mounted at fixed *z*-position

Short model P2, *z*-scan



SCTGU P40, fixed *z*



Outline

Karlsruhe Institute of Technology

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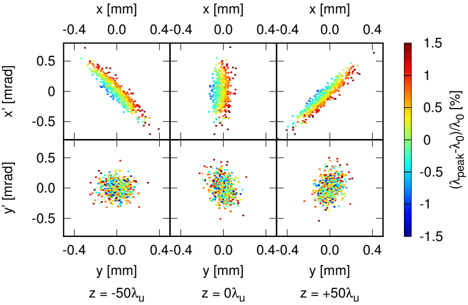
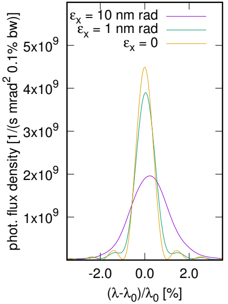
Beam dynamics inside the TGU

Matching conditions for finite-emittance beams

$x - x'$	$y - y'$
TGU = FODO structure $\tilde{\beta}_x = 2.2\,\mathrm{m}$ *better:* outer focusing to centre, $\beta_{x\,w} = 0.2\,\mathrm{m}$	natural focusing: const. $\beta_y = 0.7\,\mathrm{m}$



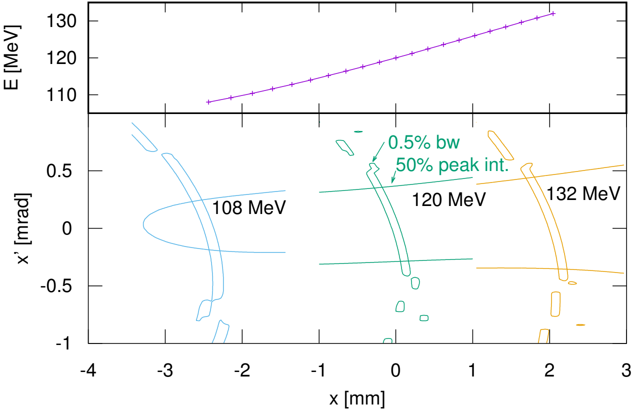


A. Bernhard et al., PRAB **19** (2016)

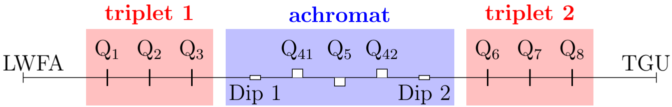
Particle tracking and analysis of spontanous radiation ($E = 120\,\mathrm{MeV}$, SCTGU10.5-P100)

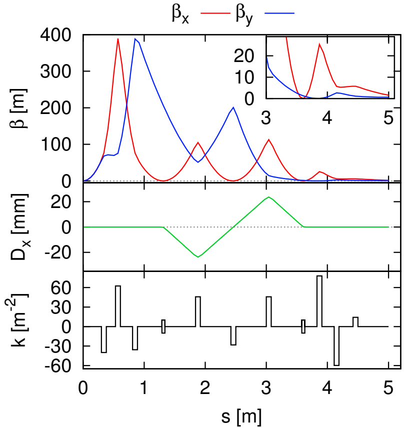
Complete Matching Condition

Strategy: From spontanous radiation spectra deduce optimum dispersion and dynamic acceptance for each energy.
Example: Beam energies 120 MeV ± 10 %, acceptance contours for 0.5 % wavelength deviation and 50 % peak intensity reduction.



Beam transport: design strategy

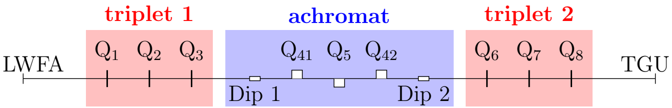


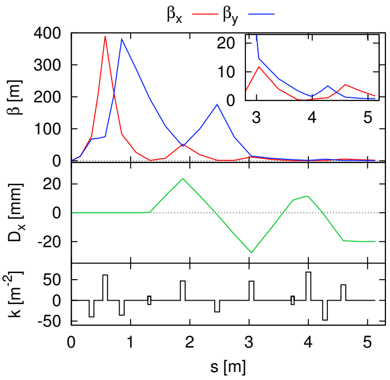


- start with achromatic dogleg
- matched to estimated initial and TGU matching conditions:

	initial	final
E_0	120 MeV	
$\epsilon_{x,y}$	10 nm rad	
β_x	1.6×10^{-3} m	1.6 m
α_x	0	2.6
β_y	1.6×10^{-3} m	0.7 m
α_y	0	0

Beam transport: design strategy



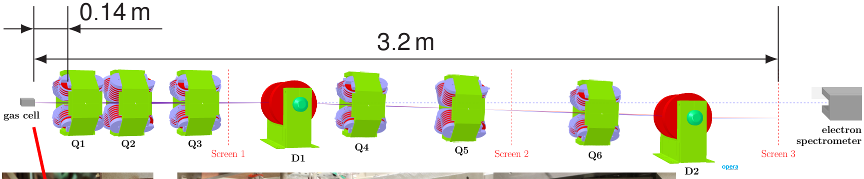


- adjust "achromat" to finite dispersion
  $D_{x\,\mathrm{TGU}} = 20\,\mathrm{mm}$, $D'_{x\,\mathrm{TGU}} = 0$
- chromatic correction: combined function quad-sext at Q_{41}, Q_{42}, Q_6, Q_8
- remark: bunch length grows moderately (by 40 %, $R_{56} = -3.6 \times 10^{-4}$ m),
  potential to make the transport nearly isochronous.

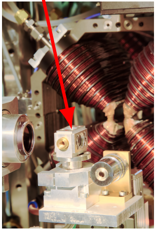
Laboratory for Applications of Synchrotron Radiation (LAS)

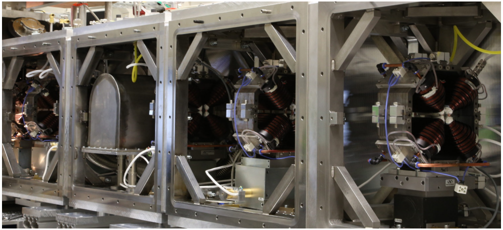
Beam transport: experimental setup at Jena

Karlsruhe Institute of Technology



Courtesy J. Polz



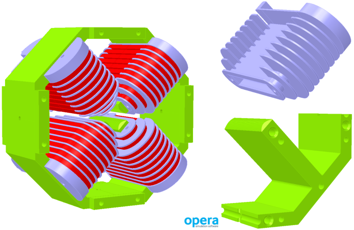


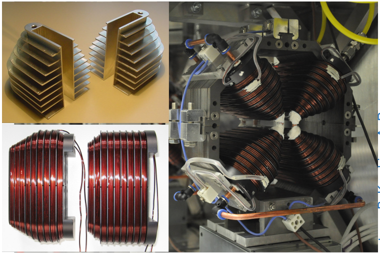
C. Widmann et al., IPAC 2015; C. Widmann, Dissertation, KIT (2016)

Laser: JETI 28 fs 1.2 J $\sim 10^{19}$ W cm^{-2}	**LWFA: Gas cell** $\varnothing$1 mm $\times$ 3 mm 95 % He, 5 % N_2	**Beamline** triplett 1 + achromat in vacuum	**Diagnostics** 3$\times$ LANEX screen e^- spectrometer

Experiment: In-vacuum Quadrupoles

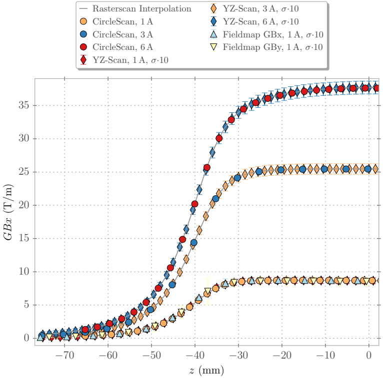
Magnets were designed and manufactured in-house (KIT/Jena)





Courtesy: B. Kumbies, A. Rose

Characterization

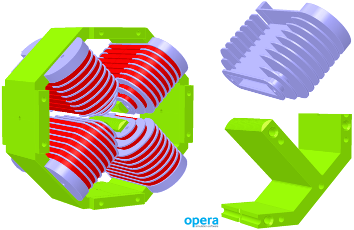


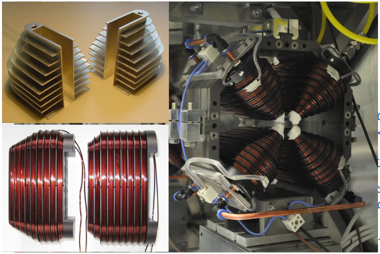
A. Will, Master's Thesis, KIT, 2016

Field gradient along axis for different operation currents and different scan methods

Experiment: In-vacuum Quadrupoles

Magnets were designed and manufactured in-house (KIT/Jena)





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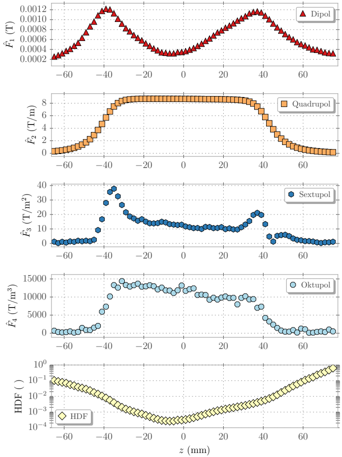
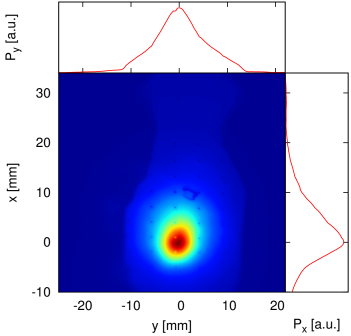


A. Will, Master's Thesis, KIT, 2016

Multipole strengths along axis for 1 A determined by circular Hall-probe scans

Experiment: Initial beam



- Screen1, 0.7 m from source
- average over 180 shots
- 9.5 mrad × 10.5 mrad (FWHM)
- Pointing 2.4 mrad × 4.2 mrad (rms)

A. Sävert, internal report, 2014

- rather instable pointing implied that averaging over $\sim$ 30 shots was necessary throughout the experiment

Experiment: Iterative beam based alignment

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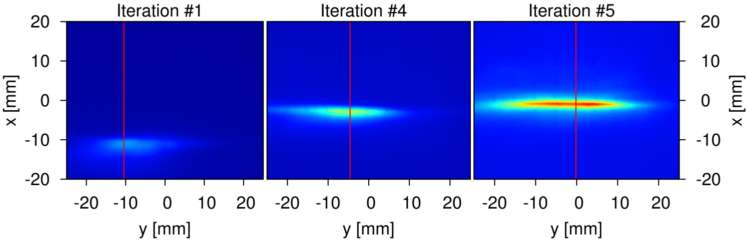
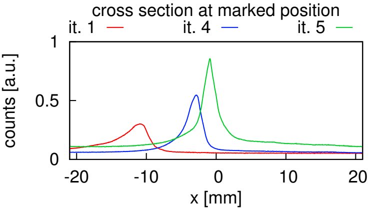
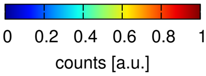
Q1 vertical alignment with averaged images on Screen1



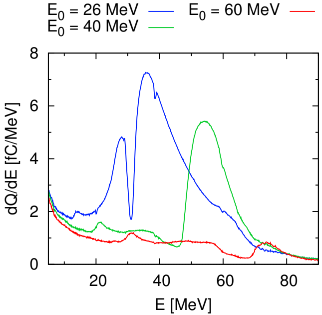




C. Widmann, Dissertation, KIT, 2016

Experiment: Transport to spectrometer screen

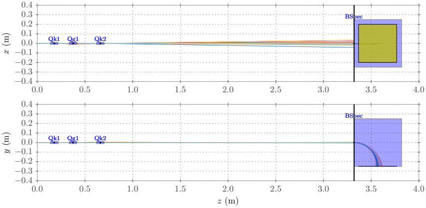
Measurement

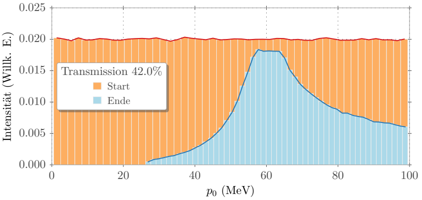


- beam focused to spectrometer screen for different energies
- slight miscalibration and shadowing effects observed

C. Widmann, Dissertation, KIT, 2016

Tracking simulations

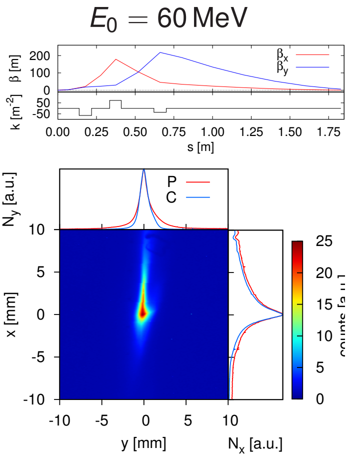




Transmission for 60 MeV-setting

A. Will, Master's thesis, KIT, 2016

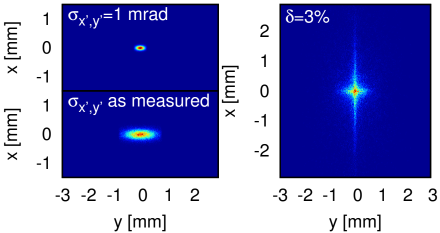
Experiment: Beam transport to TGU



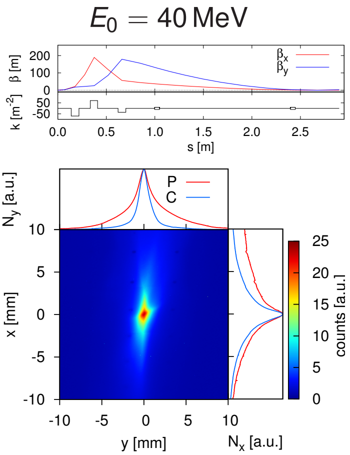
Screen 2 (1.9 m), Q1-Q3

- align first triplet (Screen 2)

Tracking simulations



Experiment: Beam transport to TGU



- align first triplet (Screen 2)
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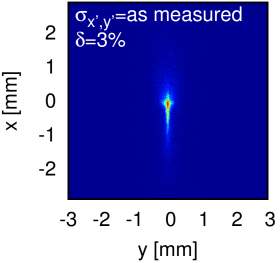
Tracking simulations

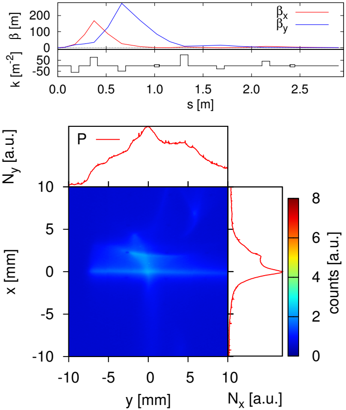


Screen 3 (3.2 m), Q1-Q3, D1, D2

Experiment: Beam transport to TGU

Karlsruhe Institute of Technology

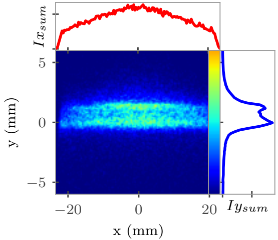
$E_0 = 40\,\text{MeV}$



Screen 3 (3.2 m), Q1-Q6, D1, D2

- align first triplet (Screen 2)
- switch on dipoles, focus to Screen 3
- adjust dispersion and focusing to TGU centre with second triplet

Tracking simulations



$\delta = 10\,\%$, $\sigma_{x',y'} = 2\,\text{mrad}$

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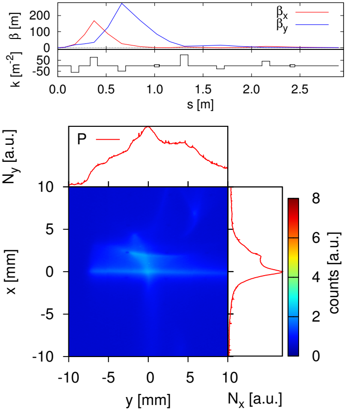

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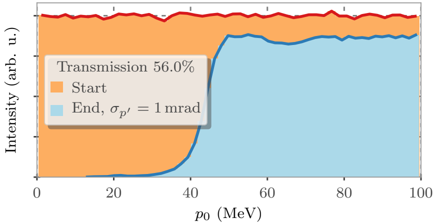

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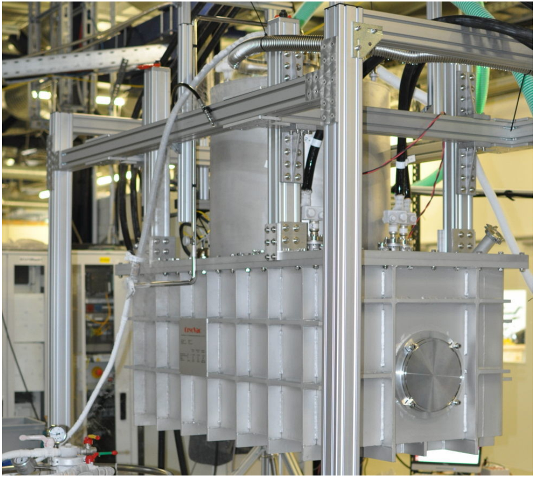
Next steps

SCTGU

- installation in own cryostat
- measurement of 2D field map
- test with beam



SCTGU cryostat system test (2017)

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Karlsruhe Institute of Technology

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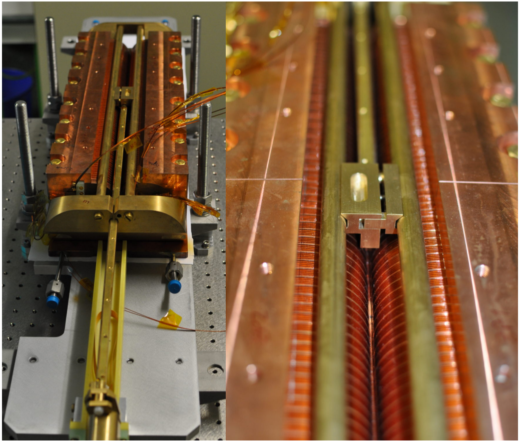

SCTGU with Hall probe sliding system

Next steps

SCTGU

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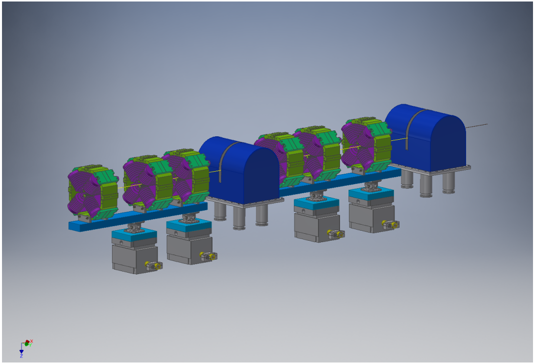
Beam transport

- improved magnet alignment
  - pre-aligned groups
  - movable in 4 degrees of freedom
- test with beam
- chromatic correction



Conclusion

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- so far no showstoppers, lots of work remain to be done

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