

# LWFA-driven Transverse Gradient Undulator-based FEL

Erik Bründermann, KIT

4<sup>th</sup> MT Meeting, HZB, 13.06.2018

Partially based on

A. Bernhard, V. Afonso Rodríguez, S. Kuschel, M. Leier, P. Peiffer, A. Sävert, M. Schwab, W. Werner, C. Widmann, A. Will, A.-S. Müller, M. Kaluza, “Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs,” NIM A, *in press* (2018). DOI: 10.1016/j.nima.2017.12.052 (KIT, HI Jena, Friedrich-Schiller-Universität Jena)

# Acceleration with 5000 times higher gradients

## Today's technology

- Example:  $17.5 \text{ GeV} / 1.7 \text{ km} \approx e \cdot 10 \text{ MV/m}$

**Plasma acceleration**<sup>1)</sup>:  $4.2 \text{ GeV} / 9 \text{ cm} \approx e \cdot 50 \text{ GV/m}$

## Size ↘

- Societal impact: **cost** ↘ **applications** ↗

## Challenges for beams emerging from plasma

- **Divergence** and **pointing instability**
- **Energy spread**

Needed for **real-world** applications

- **Specially designed** electron beam conditioning for FELs
- **Storage** of ultra-short (fs) electron bunches

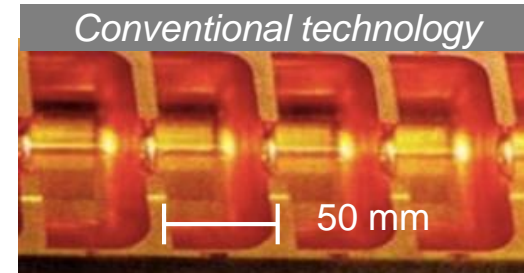
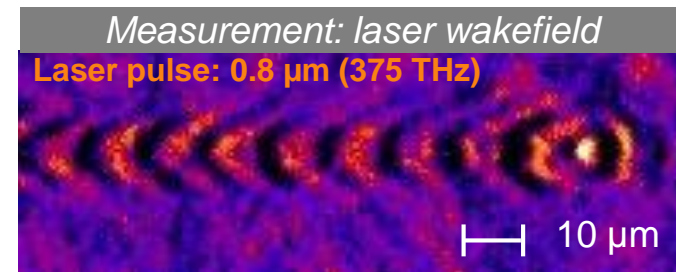
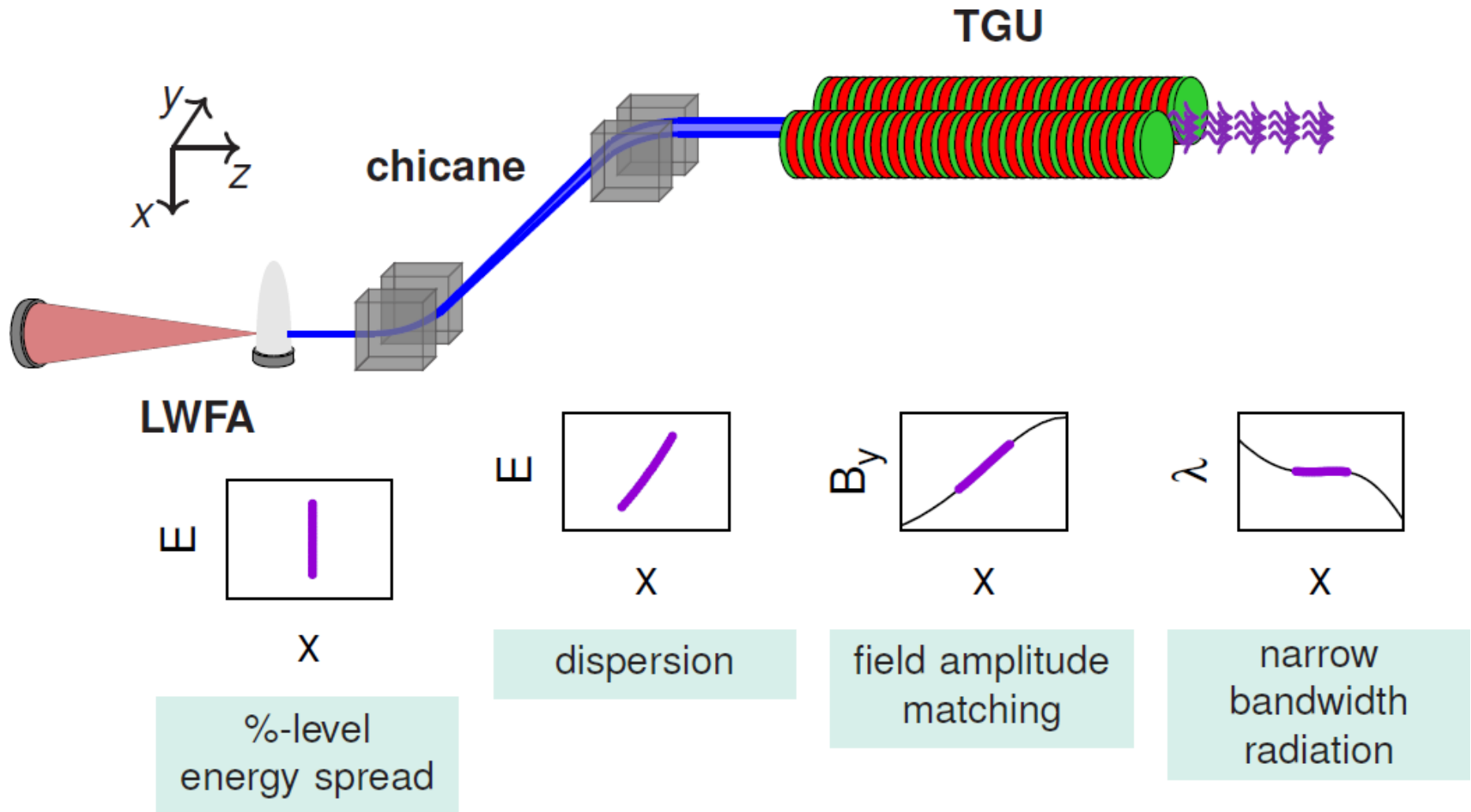


Image from ATHENA slides  
R. Assmann, DESY, 24.2.2015



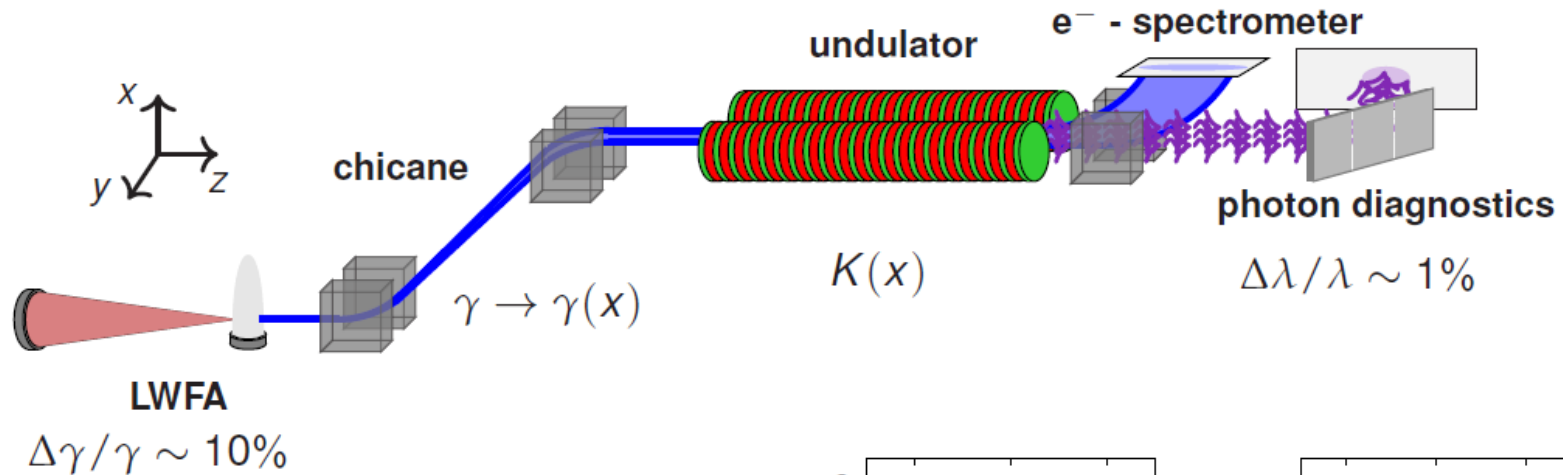
Reference: Schwab (FSU Jena) *et al.*,  
*Appl. Phys. Lett.* 103, 191118 (2013)

# Transverse-gradient undulator (TGU)



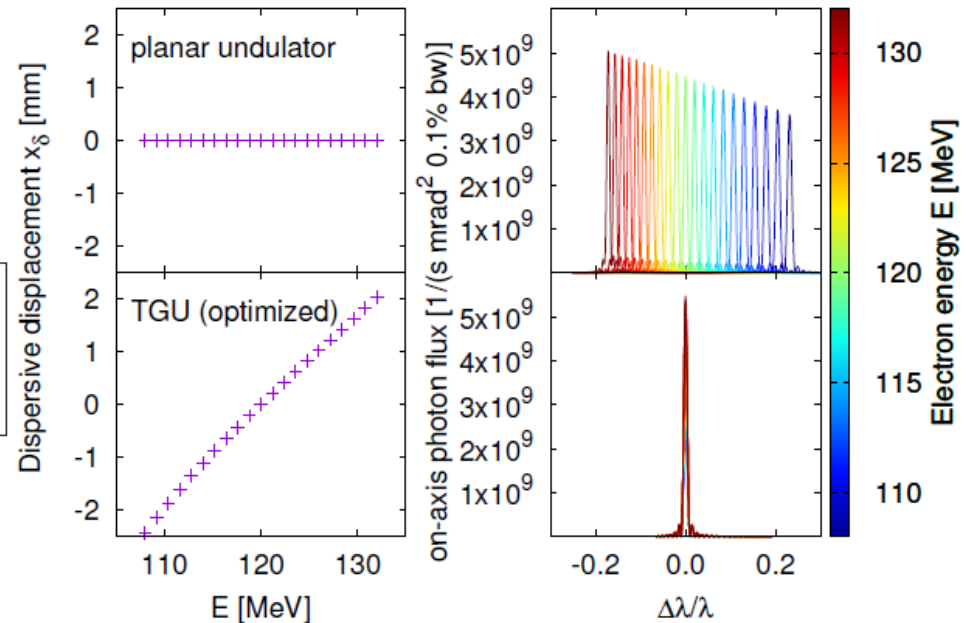
Courtesy: A. Bernhard

# LWFA – TGU concept for an FEL light source



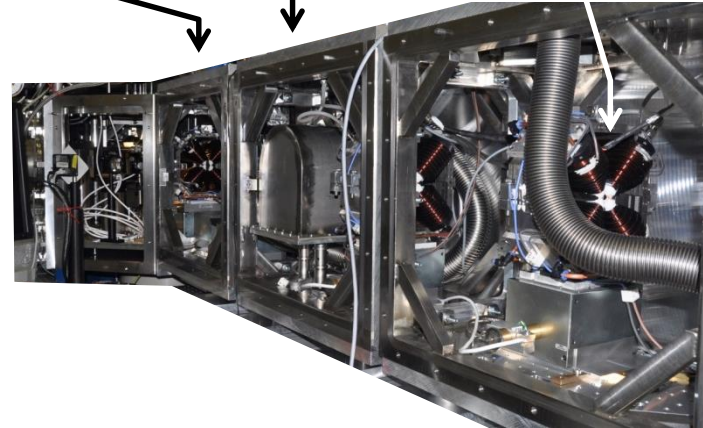
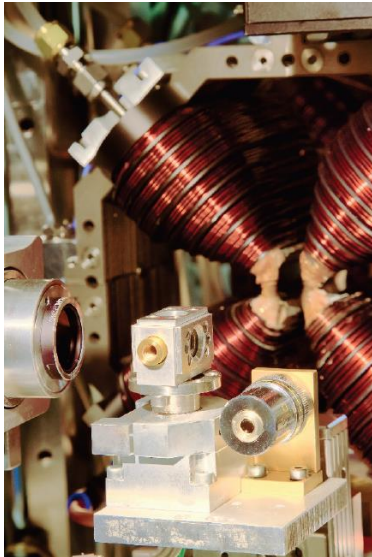
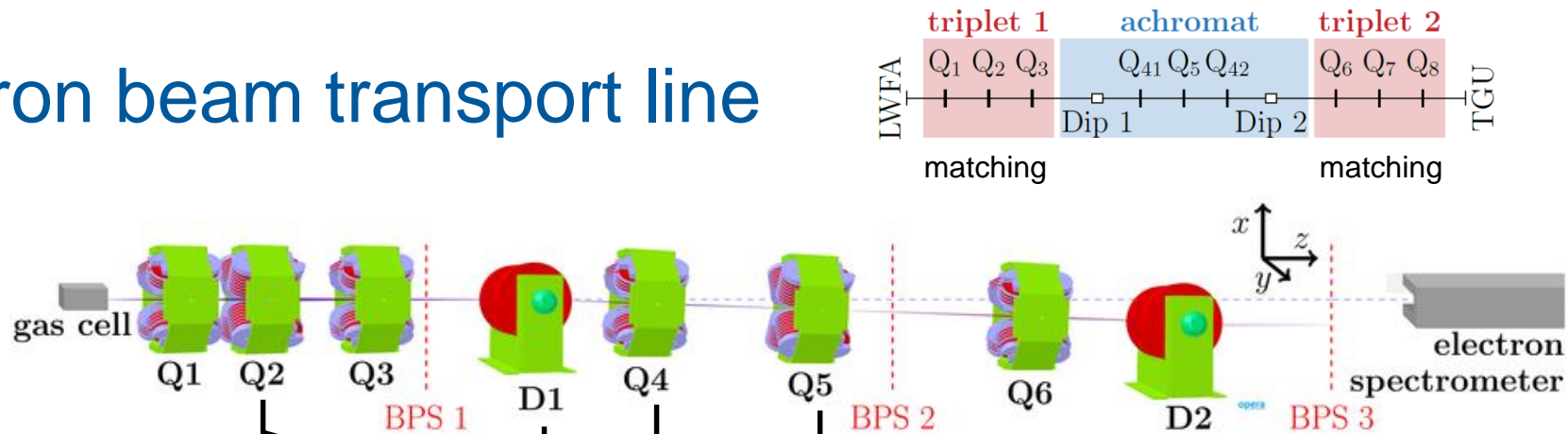
$$\lambda = \frac{\lambda_u}{2\gamma^2(x)} \left( 1 + \frac{K_u^2(x)}{2} \right) = \text{const.}$$

$$K_u(x) = \frac{e}{m_e c} \lambda_u \tilde{B}_y(x)$$



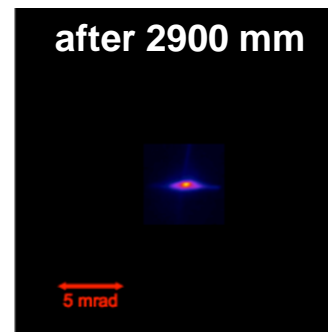
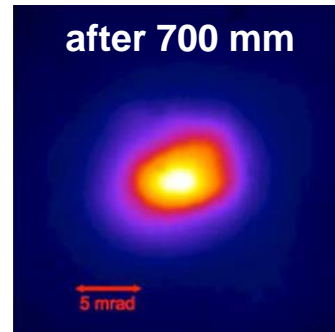
Courtesy: A. Bernhard

# Electron beam transport line



experimental test  
performed at LWFA  
at Jena

**Reference:** A. Bernhard *et al.*,  
“Progress on experiments towards  
LWFA-driven transverse gradient  
undulator-based FELs,” NIM A, *in  
press* (2018)



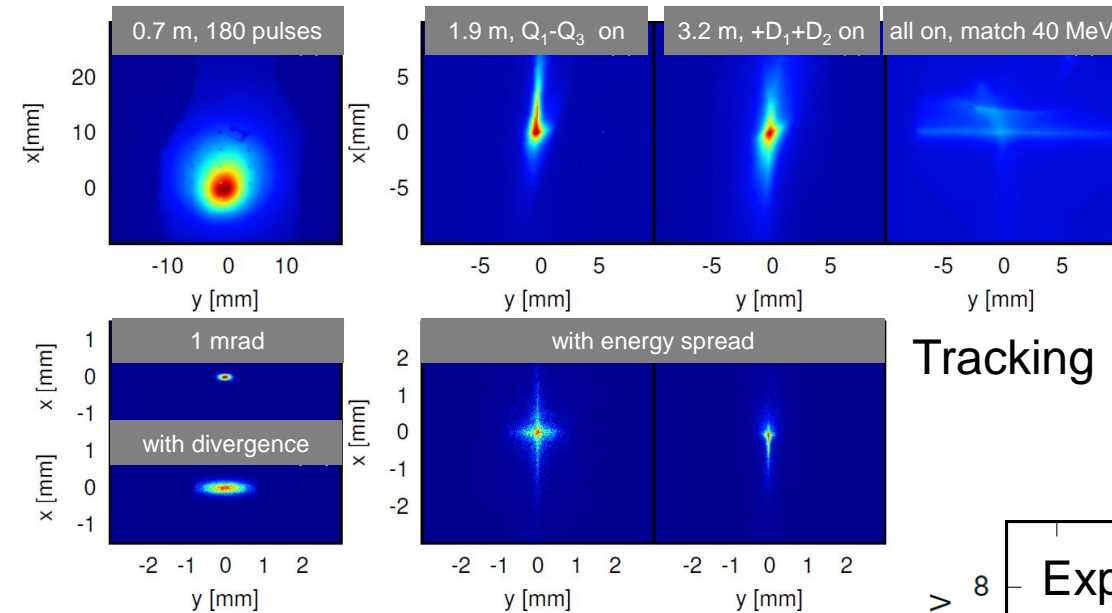
**HI Jena**  
Helmholtz Institute Jena



**KIT**  
Karlsruhe Institute of Technology

**HELMHOLTZ**  
RESEARCH FOR GRAND CHALLENGES

# Experiment: Beam transport towards TGU



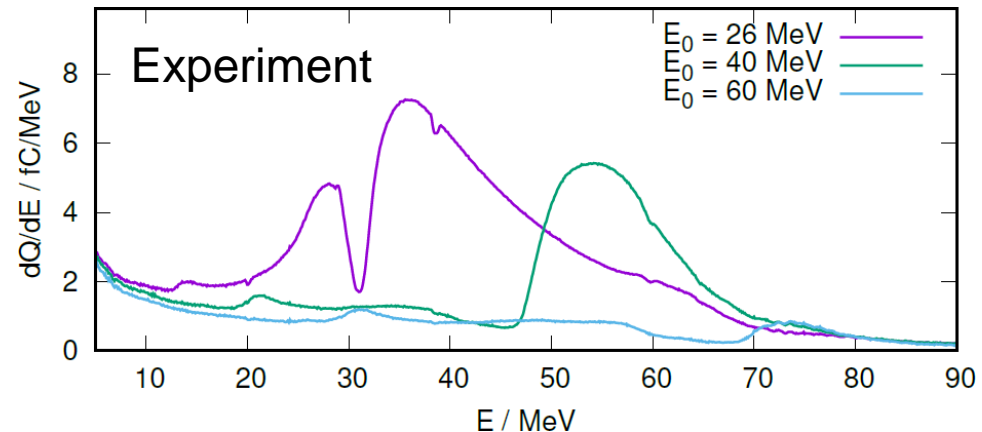
## Experiment & adjustment procedure

0.7 m, 180 pulses

Divergence:  $99.8 \text{ mrad}^2$  ( $9.5 \times 10.5$ , FWHM)

Pointing jitter:  $10 \text{ mrad}^2$  ( $2.4 \times 4.2$ , rms)

## Tracking



## Reference:

A. Bernhard, V. Afonso Rodríguez, S. Kuschel, M. Leier, P. Peiffer, A. Sävert, M. Schwab, W. Werner, C. Widmann, A. Will, A.-S. Müller, M. Kaluza, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs," NIM A, *in press* (2018)



# Superconducting TGU: Magnetic design

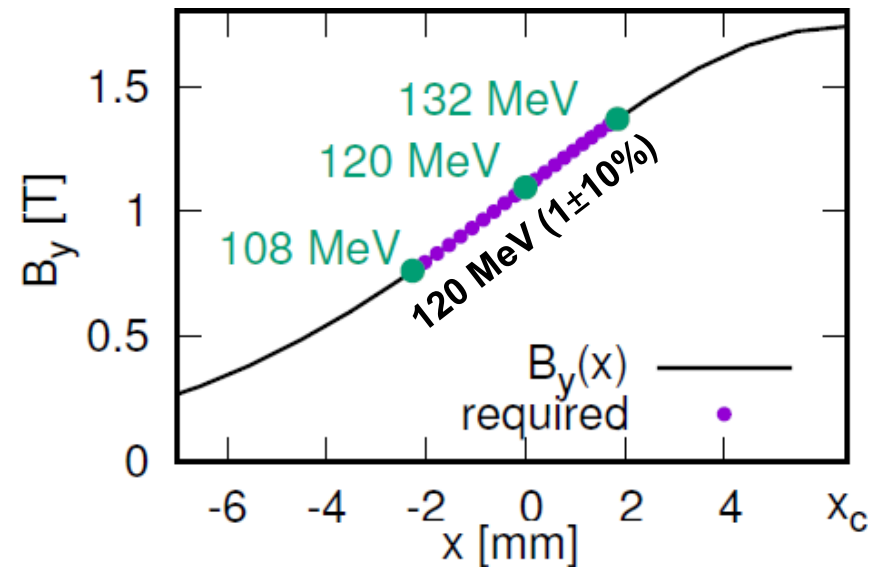
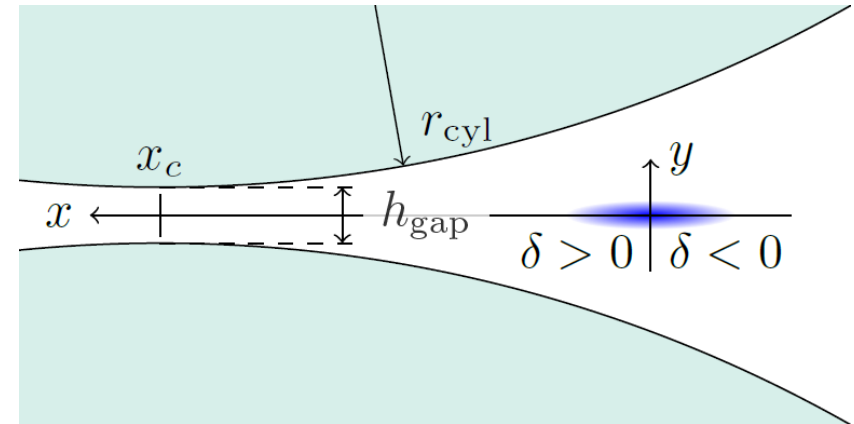
## Design goals

- ▶ Short period (aiming at EUV/X-rays)
- ▶  $K \geq 1$
- ▶ High transverse gradient

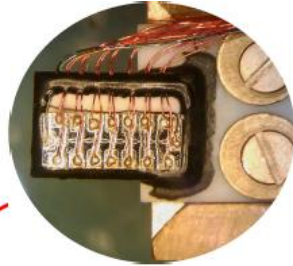
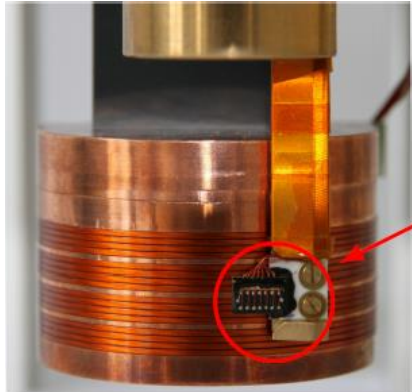
period length $\lambda_u$	10.5 mm
gap @ symmetry axis $h_{\text{gap}}$	1.1 mm
pole radius $r_{\text{cyl}}$	30 mm
flux density ampl. $\tilde{B}_y(0)$	1.1 T
undulator parameter $K_{u0}$	1.1
transverse gradient $\frac{\partial K_u}{\partial x}$	$149 \text{ m}^{-1}$
energy acceptance	$\pm 10 \%$

## Reference:

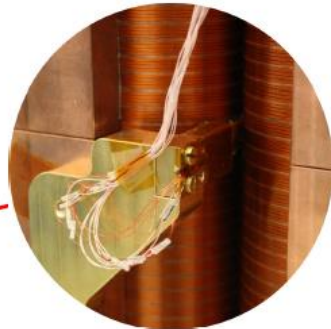
A. Bernhard, V. Afonso Rodríguez, S. Kuschel, M. Leier, P. Peiffer, A. Sävert, M. Schwab, W. Werner, C. Widmann, A. Will, A.-S. Müller, M. Kaluza, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs," NIM A, *in press* (2018)



# scTGU: Field measurements at CASPAR I at KIT

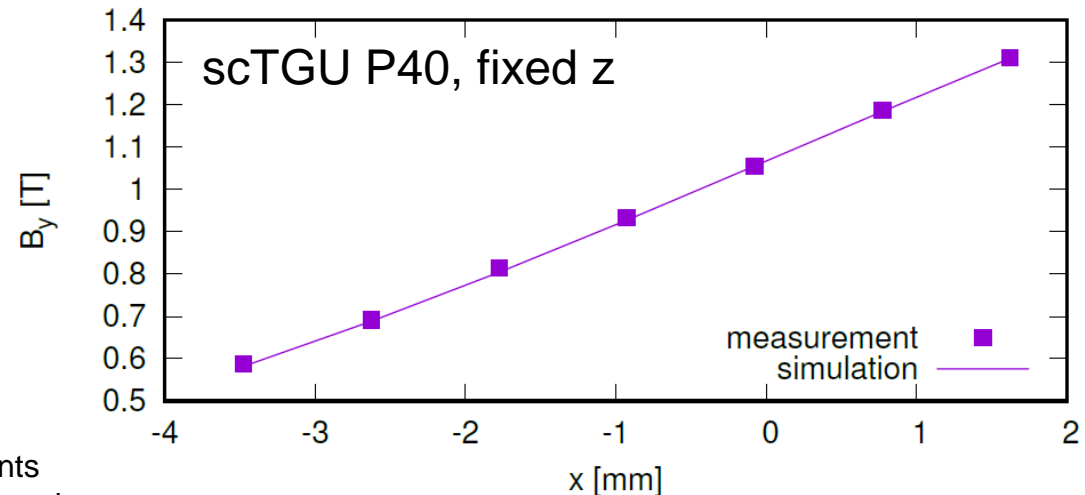
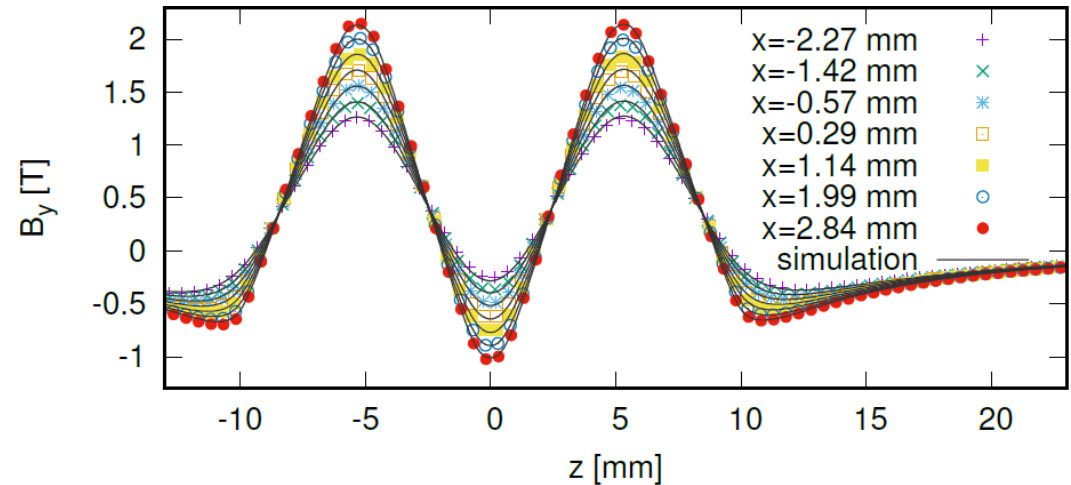


Array of 7  
equidistant  
Hall probes



Array mounted  
at fixed z

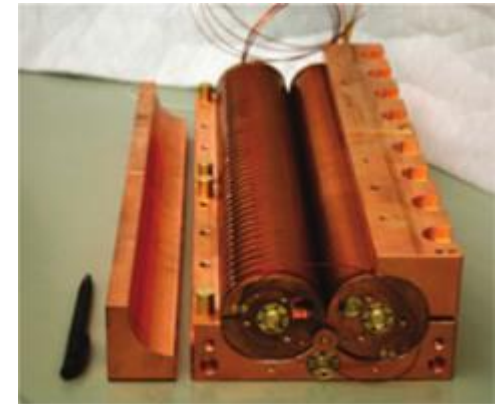
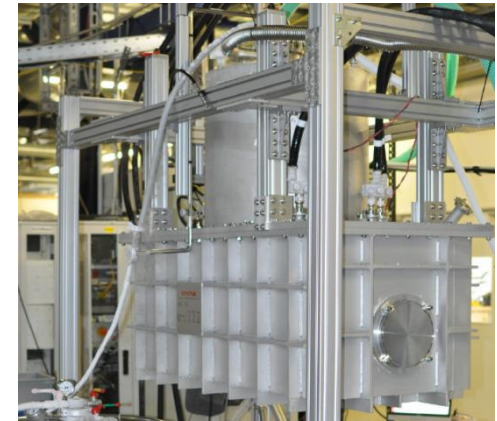
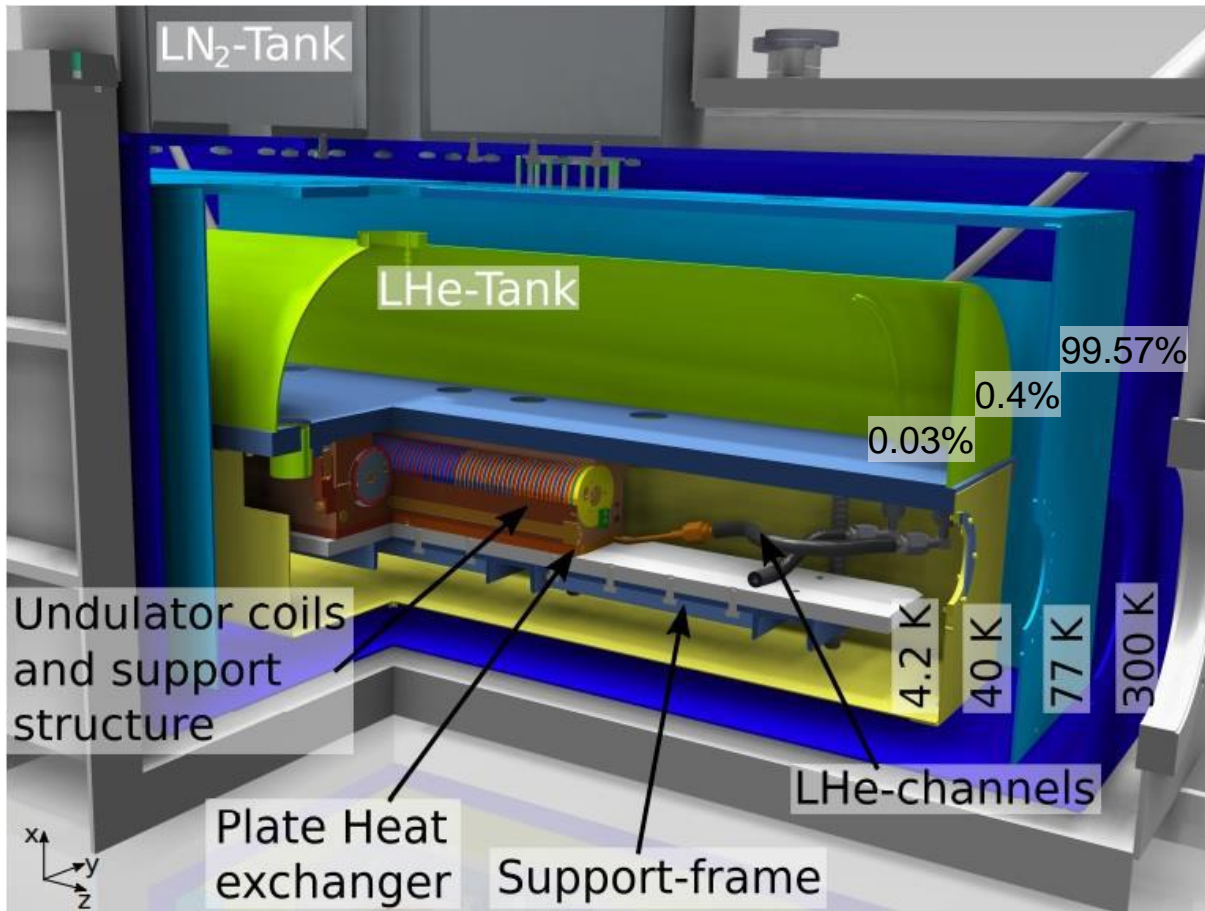
Short model P2, z-scan



**Reference:** A. Bernhard *et al.*, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs," NIM A, *in press* (2018)



# Transverse-gradient undulator (TGU) in cryostat



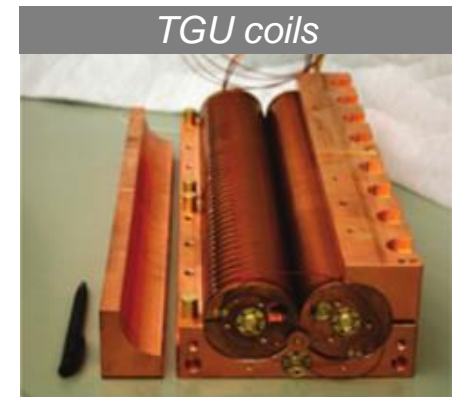
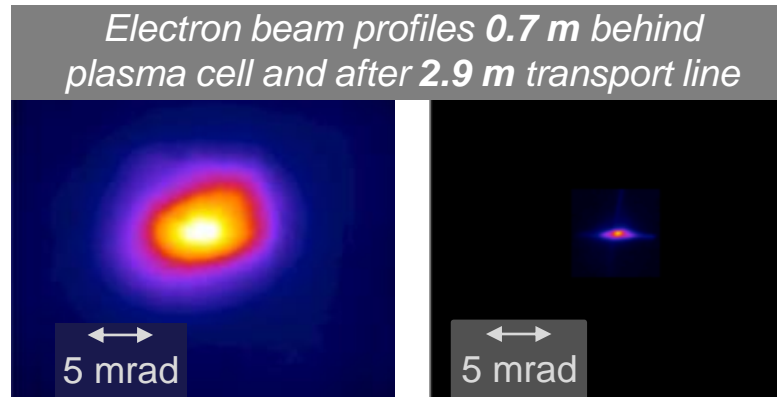
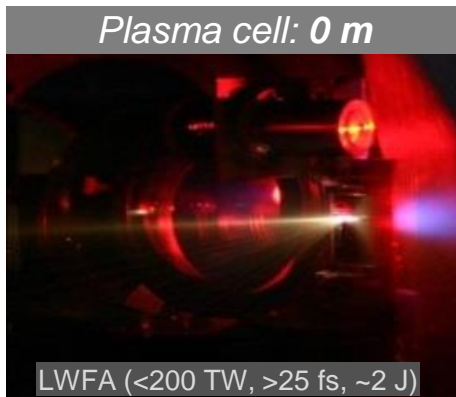
$$\partial_t Q \sim T_{\text{hot}}^4 - T_{\text{cold}}^4$$

4.2 K / 77 K indirect cooling

Low- $T_C$  superconducting coils, high- $T_C$  current leads

# Status

- **Divergence, pointing**: e-beam conditioning incl. transport was installed<sup>1,2)</sup>
- **Energy spread**: superconducting TGU was built<sup>3)</sup>
- Concept of LWFA-driven TGU-based free electron laser, article *in press*<sup>4)</sup>



**Compact**

## References:

- <sup>1)</sup> C. Widmann *et al.*, Proc. IPAC2014, THOBA03 (2014).
- <sup>2)</sup> C. Widmann, Ph.D. thesis; KIT (2016).
- <sup>3)</sup> A. Bernhard *et al.*, Phys. Rev. Accel. Beams 19 (2016).
- <sup>4)</sup> A. Bernhard *et al.*, NIM A *in press* (2018).

# Transverse-gradient undulator (TGU) progress

- TGU cool-down
- TGU powering test

Program Matter and Technologies

**Study of a Superconducting Transverse Gradient Undulator for a Laser Plasma Accelerator-Driven FEL**

K. Damminsek, A. Bernhard, E. Bründermann, A.-S. Möller

### Introduction

The application of Laser Wakefield Acceleration (LWFA) is a potential key for realizing extremely compact Free Electron Lasers (FEL) due to an unprecedented high longitudinal electric field inside the laser-driven plasma wave. LWFA-based electron beams exhibit challenging initial conditions in terms of beam divergence and large energy spread. The superconducting transverse gradient undulator (TGU) scheme is a viable option to compensate the challenging properties of the LWFA electron beam and to enable FEL amplification.

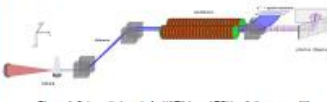


Figure 1: Schematic layout of a LWFA-based TGU radiation source [1]

Electron energy (keV)	120	MeV
Energy spread (ΔE/E <sub>0</sub> )	2/10	%
Electron current (pA)	40	
Period length	10.50	mm
Pole radius	30.00	mm
Gap width @120 MeV	2.40	mm
Peak field on axis	1.54	T
Undulator parameter @120 MeV	1.10	
Superconducting wire material	NbTi	
Superconductor wire dimension (mm)	1.00 x 0.50	
Cable type	1-36/1	
Operating temperature	4.2	K
Average current density	3000	A/mm <sup>2</sup>
Radiation wavelength (μm)	150	nm
Radiation bandwidth (Δλ/λ)	0.5	%

Table 1: Design electron beam and undulator parameters [2]-[4]

### TGU cool-down

The crystal structure has an external recipient at 300 K and three shielding plates for a liquid nitrogen temperature at 77 K, for a helium gas temperature at 40 K and for a liquid helium temperature at 4.2 K, respectively. The first TGU cooling process to 4.2 K was successful.

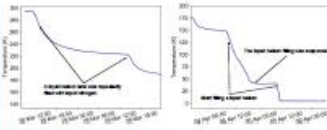


Figure 4: Relationship between time and temperature of the TGU coil during the cooling process.

### Status of the projects

The TGU is placed in vacuum and conduction-cooled inside a specially designed crystal. A first test of the TGU was performed in the crystal of KTi at liquid Helium temperature (4.2 K).

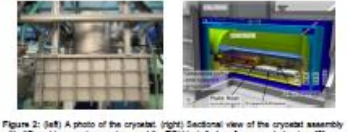


Figure 2: (left) A photo of the crystal; (right) Sectional view of the crystal assembly with different temperature regions and the TGU installed on the support structure [2]




Figure 3: Installation of the undulator on the support structure inside the crystal with (left) a part of the magnetic field measurement system and (right) a plate heat exchanger.

### Transverse Gradient Undulator powering test

In this study, a preliminary magnet powering test was performed by using one of the two undulator coils. The preliminary results show that quenches occur when a current of around 410 A is applied. The current was limited by the low-temperature superconductor (LTS) connection which are not in their final stage.

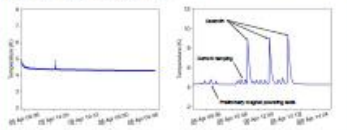


Figure 5: (left) Stability of the TGU coil temperature during the cooling process; (right) The TGU coil temperature during ramping and when a quench occurs.

### Conclusion


The cool-down process of the TGU inside the crystal was investigated. The temperature of the TGU was reduced to around 4.2-4.3 K. The TGU coil reaches the superconducting state. A magnetic field measurement system for the TGU inside the crystal will be installed in order to measure the field.

### Next steps

Additional superconducting wire connectors will be used to finalize the LTS connection between the superconducting wire and the current lead of the crystal. A further step is to install a magnetic field measurement system which will be used for measuring the transverse field distribution along a longitudinal axis of the TGU.

### Reference

- [1] Wörnlein, C., PhD Thesis, Karlsruhe Institute of Technology (2016)
- [2] Alonso Rodríguez, V., PhD Thesis, Karlsruhe Institute of Technology (2017)
- [3] Bernward, A. et al., NIMA A, ArXiv in press.
- [4] Alonso Rodríguez, V. et al., Superconductor in Appl. Supercond., vol. 2017, arXiv:1607.00117 (2017)

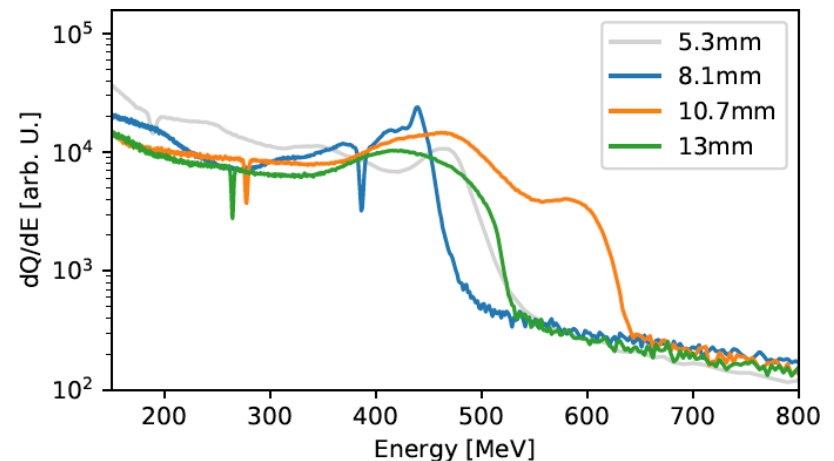
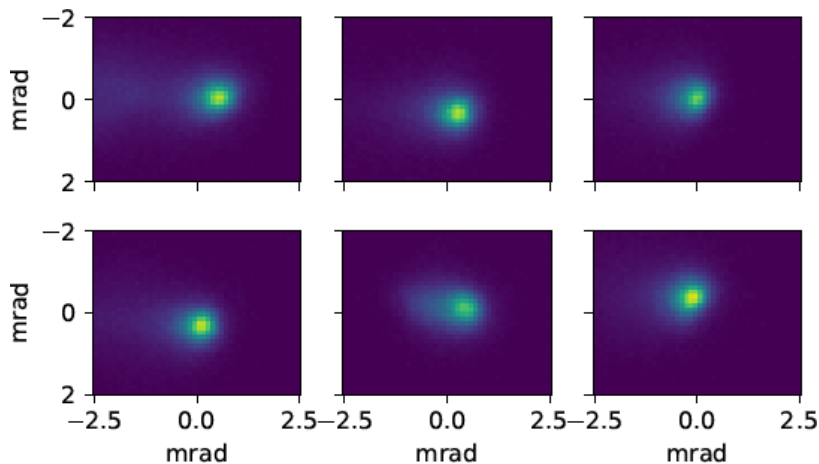
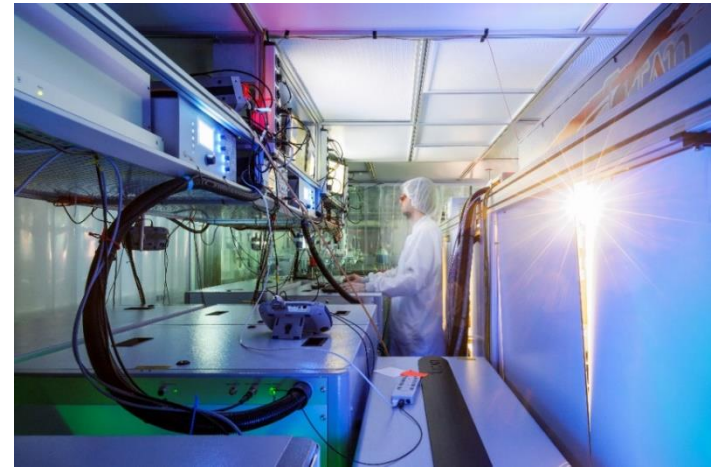


See Poster by K. Damminsek

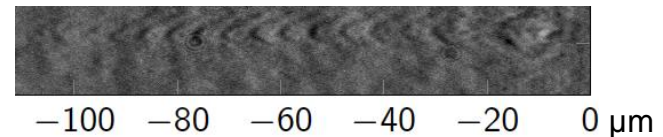


# Status of LWFA @ HI-Jena

- ▶ JETI: sub-20 fs Ti:Sapphire laser with  $P = 200$  TW
- ▶ First LWFA experiments @ 130 TW in 2017/18 using gas cell
- ▶ very stable e-beam, pointing:  $0.7 \text{ mrad}^2$ , low divergence:  $0.5 \text{ mrad}^2$ , up to 600 MeV



- ▶ Few-cycle-probe for wakefield imaging:
- ▶ **Next steps:** increase  $P$  to 300 TW, shift probe-pulse wavelength to mid-IR for lower densities



Courtesy: S. Kuschel, A. Seidel, C. Wirth, A. Sävert,  
M. B. Schwab, D. Hollatz, M. C. Kaluza, M. Zepf

# Outlook

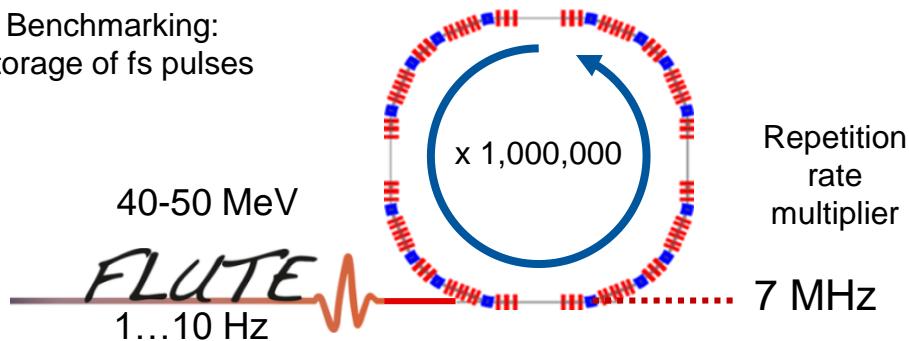
*compact Storage Ring for Accelerator Research and Technology*



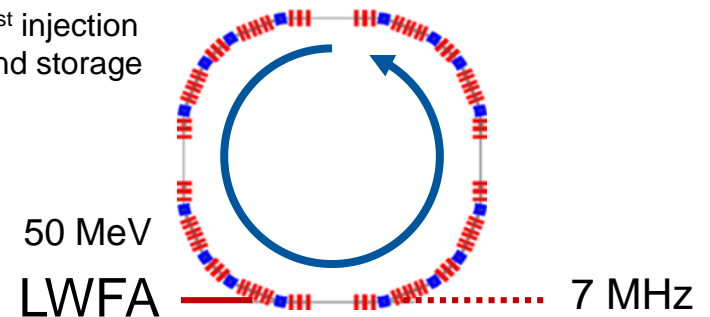
## Storage of ultra-short (fs) electron bunches

- ▶ 1<sup>st</sup> study<sup>1,2</sup>): LWFA injection in ring-based light sources
- ▶ Unique design<sup>3</sup>): non-equilibrium ring with **very large momentum acceptance**
- ▶ Goal: world-wide 1<sup>st</sup> **injection & storage** of a LWFA beam in a storage ring

Benchmarking:  
Storage of fs pulses



1<sup>st</sup> injection  
and storage



## References

1. S. Hillenbrand, Ph.D. thesis, KIT (2013)
2. S. Hillenbrand, R. Assmann, A.-S. Müller, O. Jansen, V. Judin, A. Pukhov, "Study of laser Wakefield accelerators as injectors for synchrotron light sources", NIM A 740, 153-157 (2014)
3. A. Papash, E. Bründermann, A.-S. Müller, "An Optimized Lattice for a Very Large Acceptance Compact Storage Ring", Proc. IPAC2017, TUPAB037 (2017)



**HELMHOLTZ**  
RESEARCH FOR GRAND CHALLENGES



# Summary

## Challenges

- ▶ Capture, transport and match beams with pointing instability, divergence and energy spread
- ▶ Recover ultra-short bunches
- ▶ Diagnostics
  - Helmholtz President's strategic fund, IVF-Project "Plasma accelerators" (HZDR, DESY / UHH, HI Jena / GSI, KIT)

## Methods

- ▶ Combined tracking and magnet simulations
- ▶ Unconventional and compact magnet geometries
- ▶ Improvement of LWFA at HI Jena
  - low divergence and low pointing instability

## Outlook

- ▶ Matching LWFA to TGU
- ▶ cSTART at KIT
- ▶ LWFA (50 MeV) injection into very large acceptance compact storage ring (VLA cSR in ATHENA)
- ▶ TGUs for other applications / X-band, Horizon 2020: **Compact** 