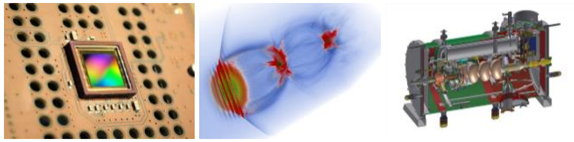


LWFA-driven Transverse Gradient Undulator-based FEL

Erik Bründermann, KIT

4th 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 GeV / 1.7 km ≈ e · 10 MV/m

Plasma acceleration[1)]: 4.2 GeV / 9 cm ≈ e · 50 GV/m

Size ↘

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

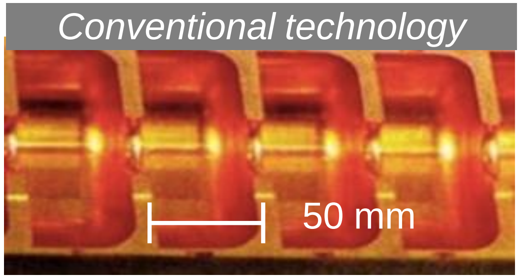
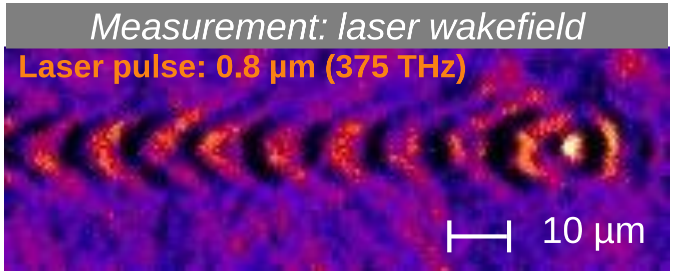


Image from ATHENA slides
R. Assmann, DESY, 24.2.2015

Challenges for beams emerging from plasma

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



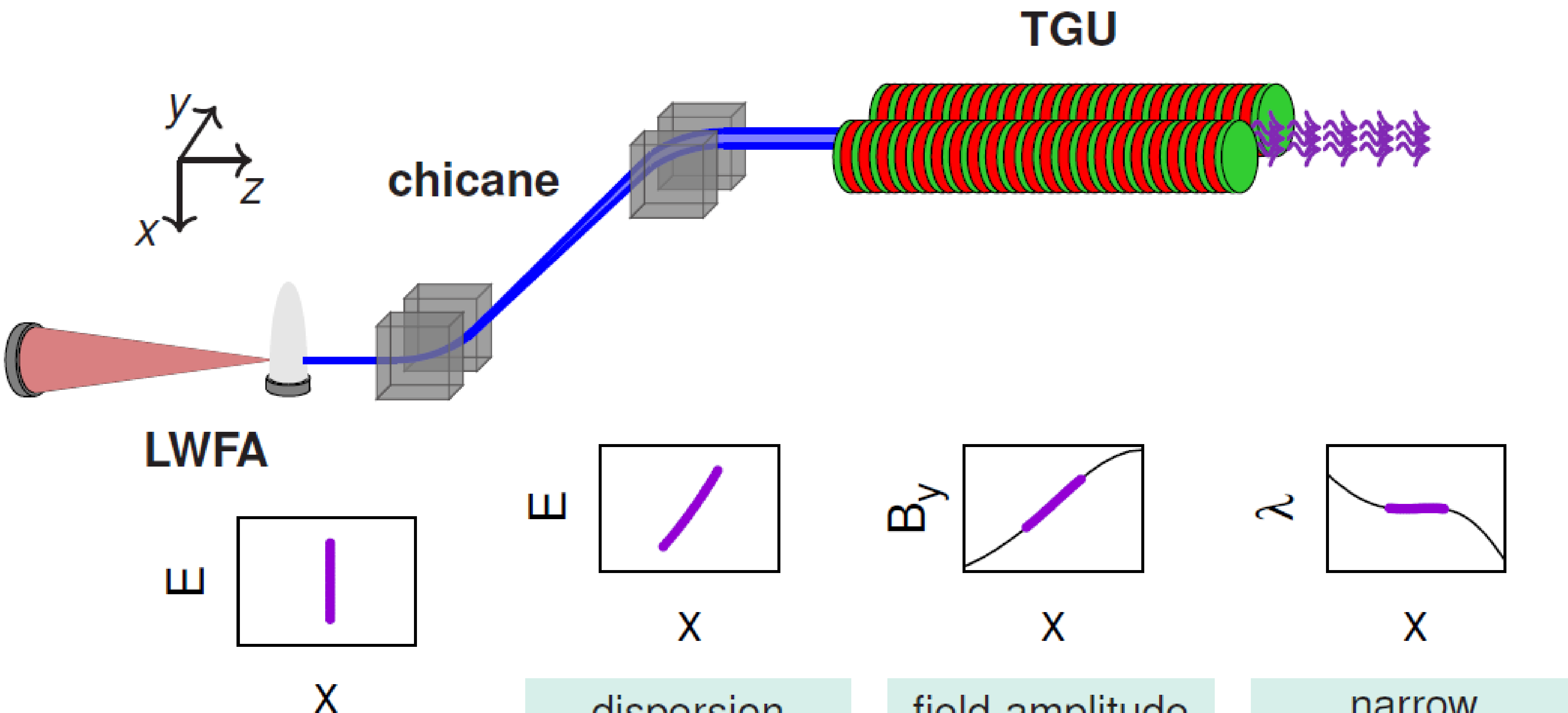
Reference: Schwab (FSU Jena) *et al.*, *Appl. Phys. Lett.* 103, 191118 (2013)

Needed for **real-world** applications

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

Reference LBNL&UCB: [1)]Leemans *et al.*, PRL 113 (2014).

Transverse-gradient undulator (TGU)



%-level energy spread

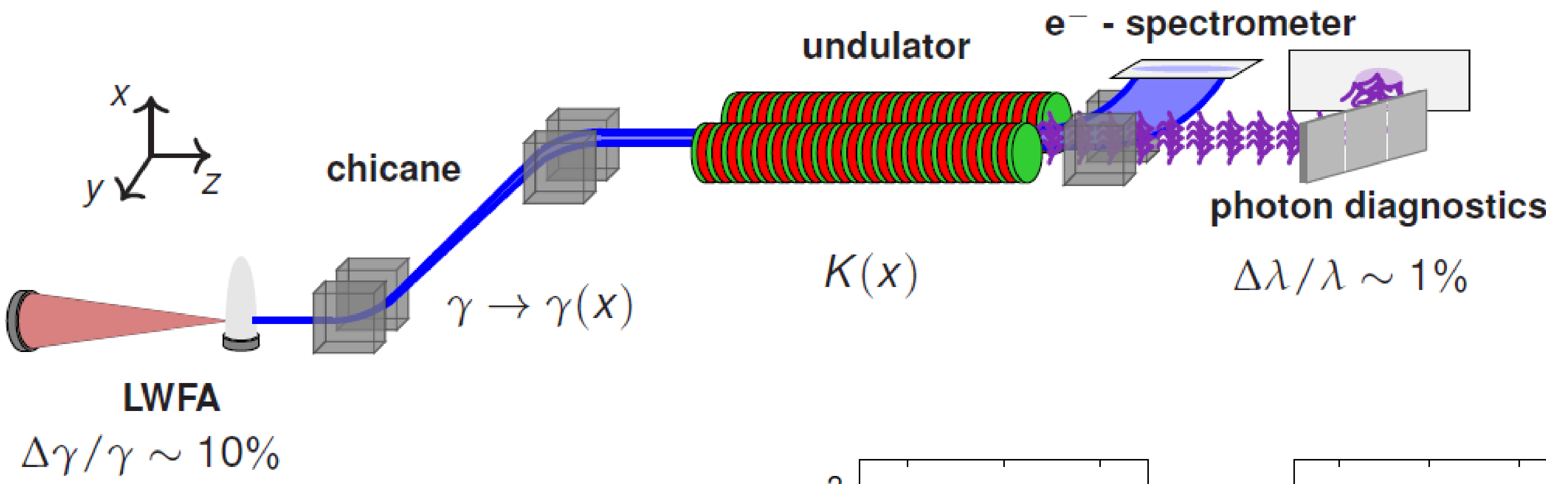
dispersion

field amplitude matching

narrow bandwidth radiation

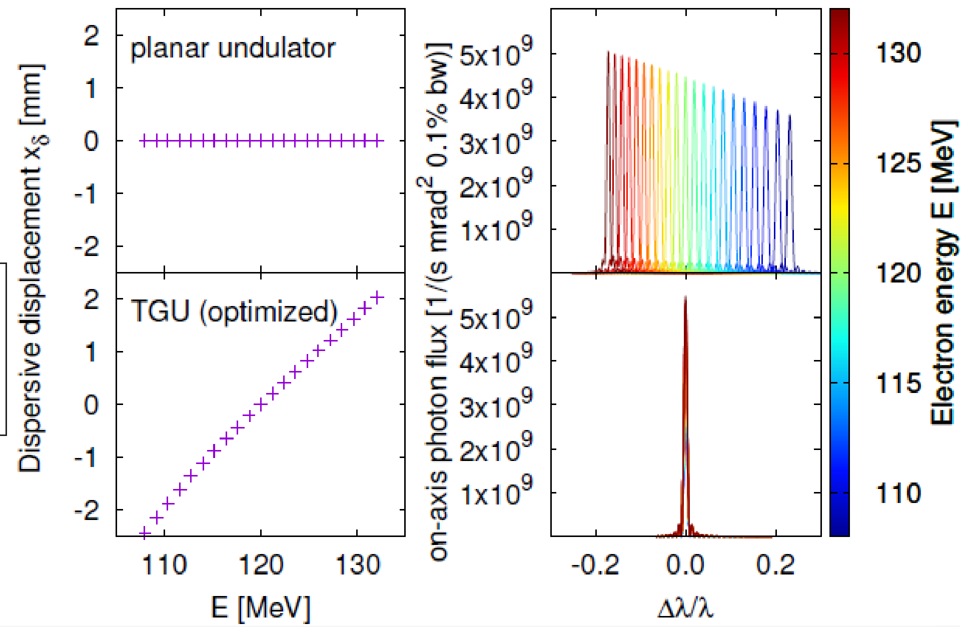
Courtesy: A. Bernhard

LWFA – TGU concept for an FEL light source



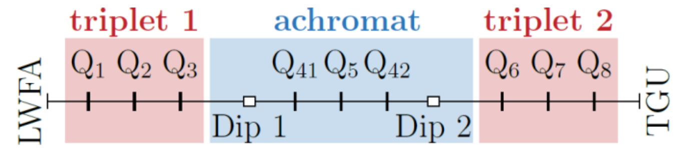
$$\lambda = \frac{\lambda_\mathrm{u}}{2\gamma^2(x)}\left(1 + \frac{K_\mathrm{u}^2(x)}{2}\right) = \mathrm{const.}$$

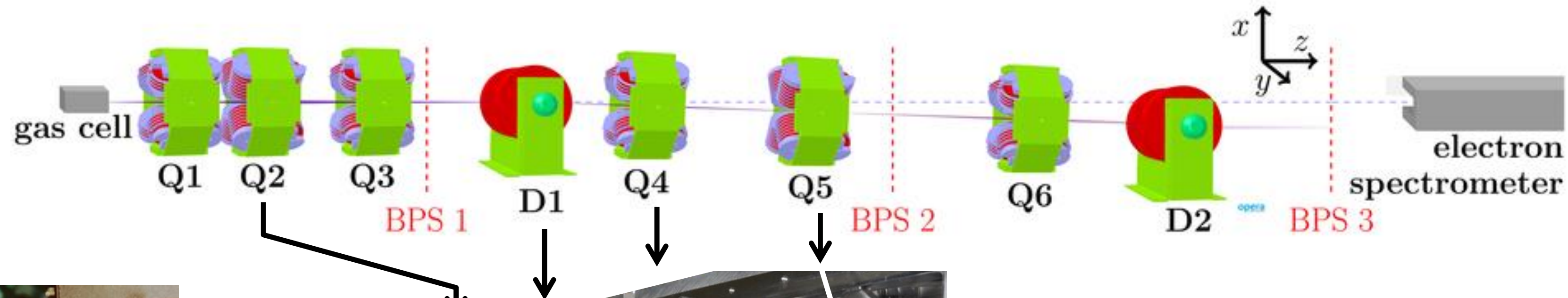
$$K_\mathrm{u}(x) = \frac{e}{m_e c}\lambda_\mathrm{u}\tilde{B}_y(x)$$

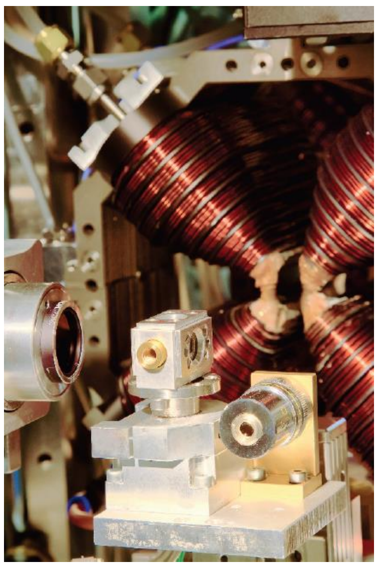


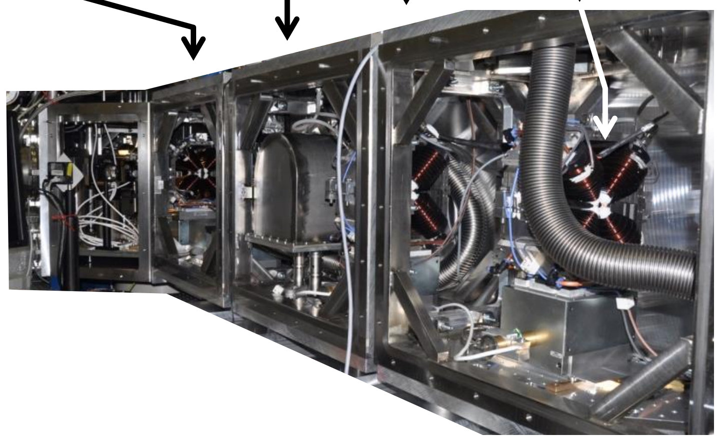
Courtesy: A. Bernhard

Electron beam transport line

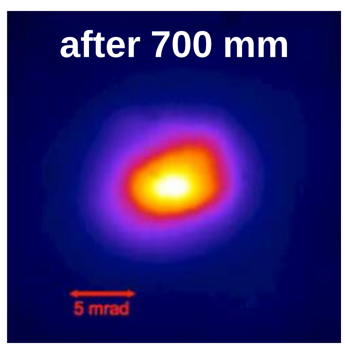


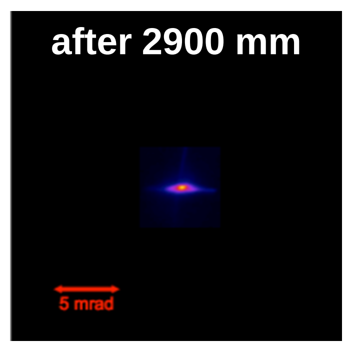






experimental test performed at LWFA at Jena





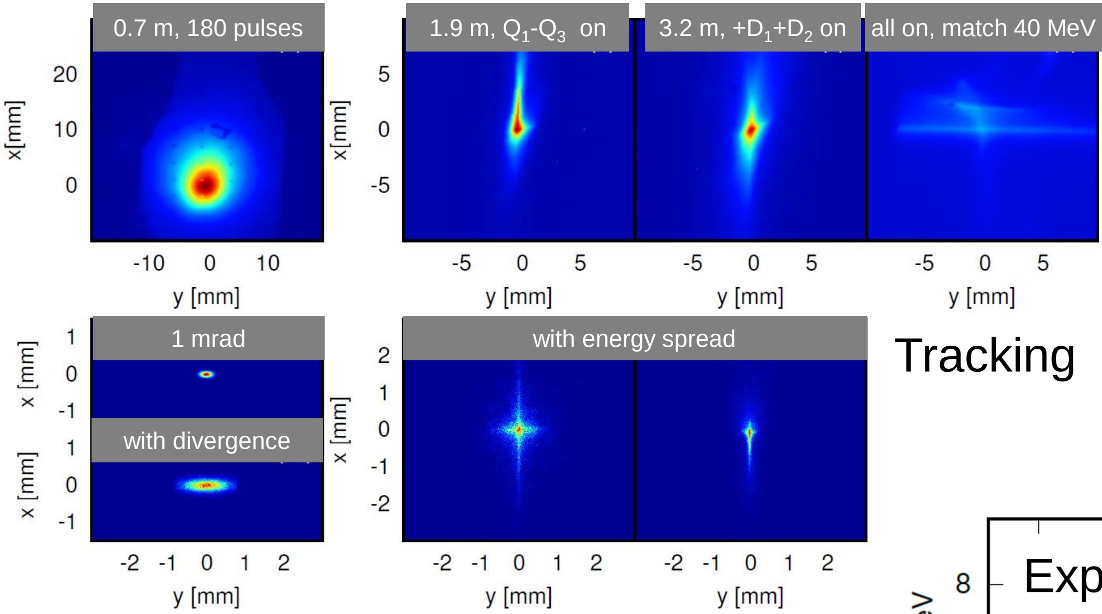
Reference: A. Bernhard *et al.*, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs," NIM A, *in press* (2018)

HI Jena
Helmholtz Institute Jena

Karlsruhe Institute of Technology

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

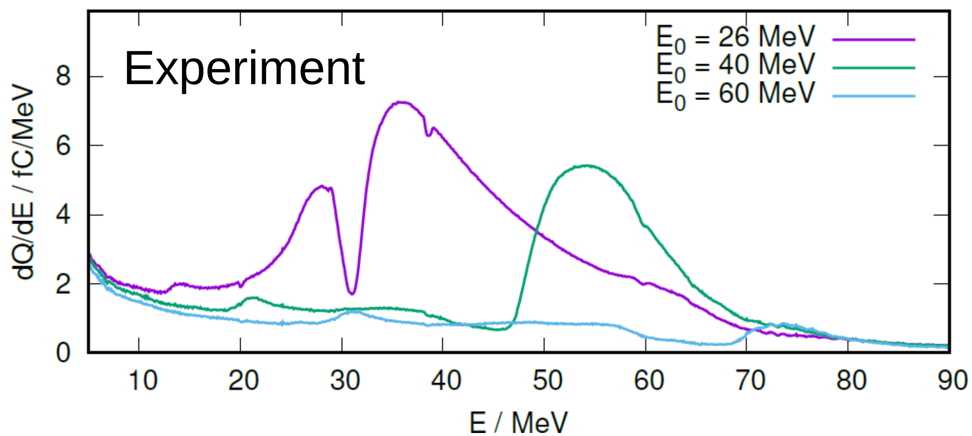
Experiment: Beam transport towards TGU



Experiment & adjustment procedure

0.7 m, 180 pulses
Divergence: 99.8 mrad² (9.5 x 10.5, FWHM)
Pointing jitter: 10 mrad² (2.4 x 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)

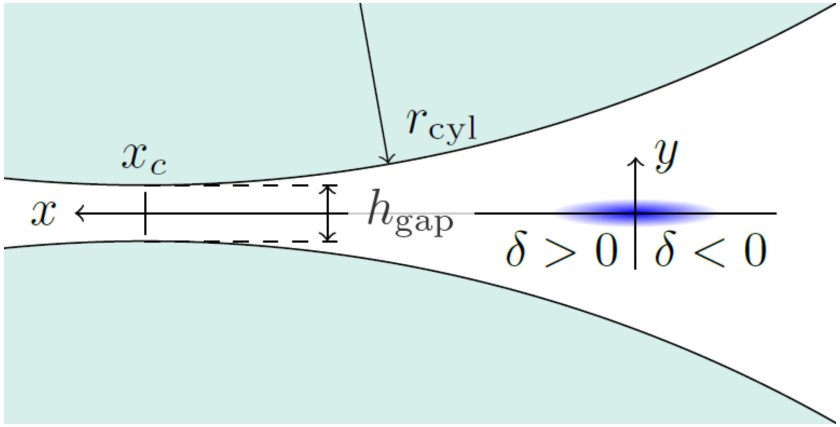
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

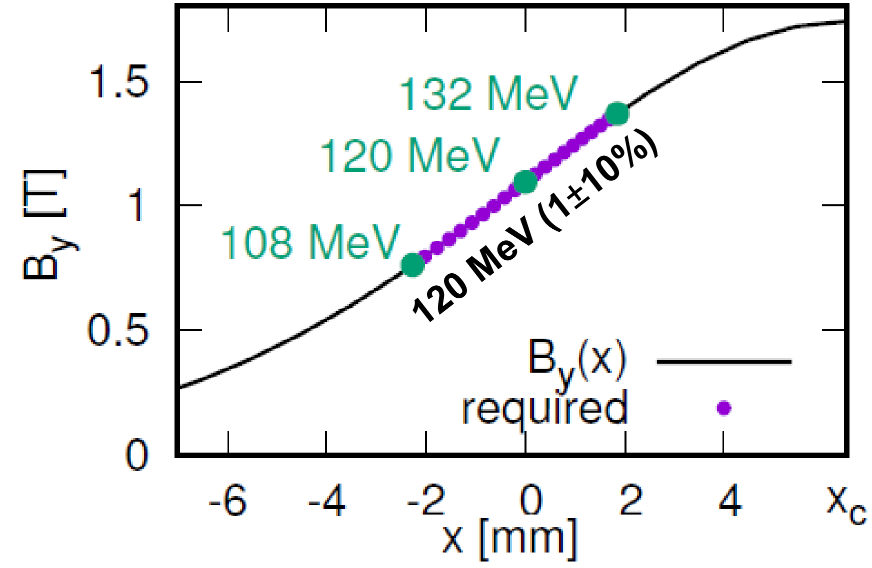
Superconducting TGU: Magnetic design

Design goals

- Short period (aiming at EUV/X-rays)
- K ≥ 1
- High transverse gradient

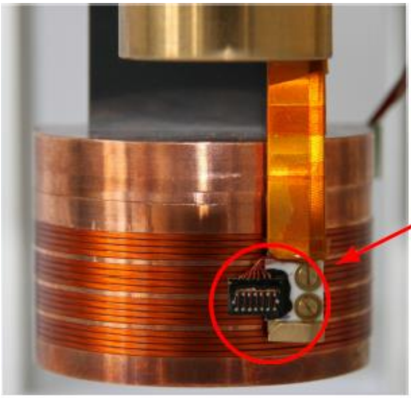
period length λ_u	10.5 mm
gap @ symmetry axis h_{gap}	1.1 mm
pole radius r_{cyl}	30 mm
flux density ampl. $\tilde{B}_y(0)$	1.1 T
undulator parameter K_{u0}	1.1
transverse gradient $\frac{\partial K_u}{\partial x}$	149 m^{-1}
energy acceptance	±10 %

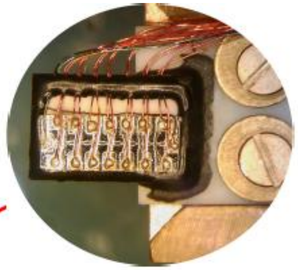




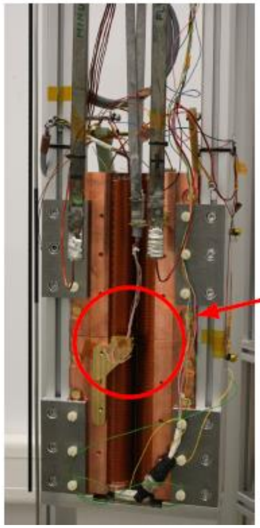
Reference:
A. Bernhard, V. Afonso Rodríguez, S. Kuschel, M. Leier, P. Peiffer, A. Sävert, M. Schwab, W. Werner, C. Widmann, A. Will, A.-S. Müller, M. Kaluza, "Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs," NIM A, *in press* (2018)

scTGU: Field measurements at CASPAR I at KIT



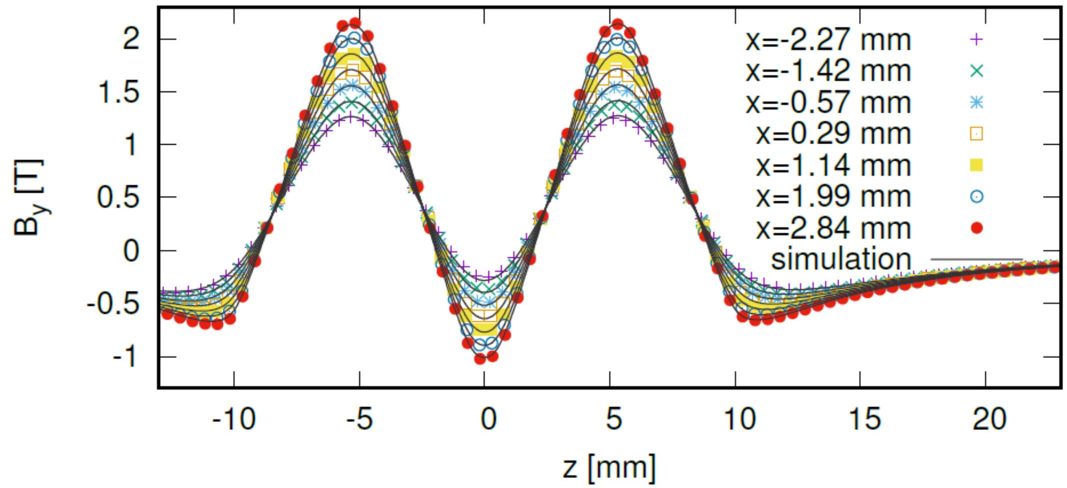


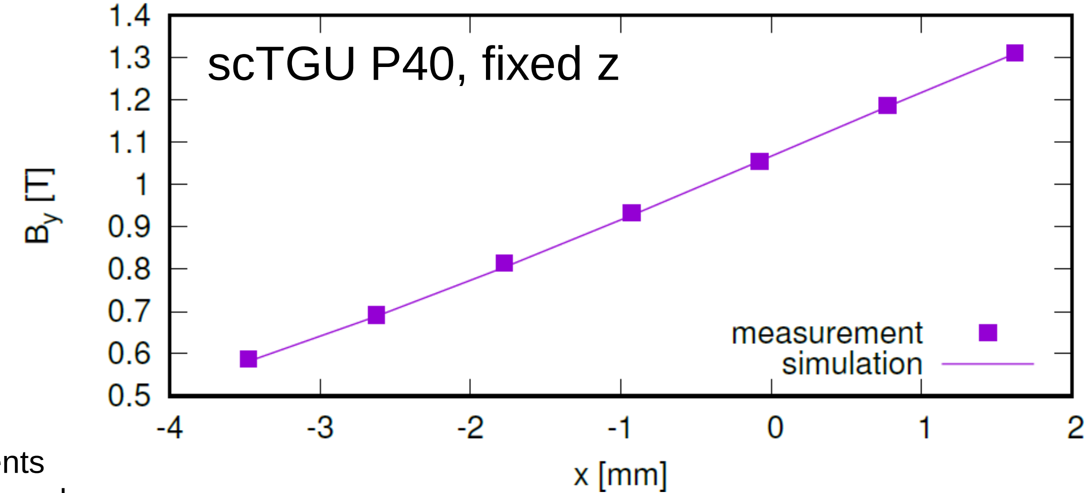
Array of 7 equidistant Hall probes



Array mounted at fixed z

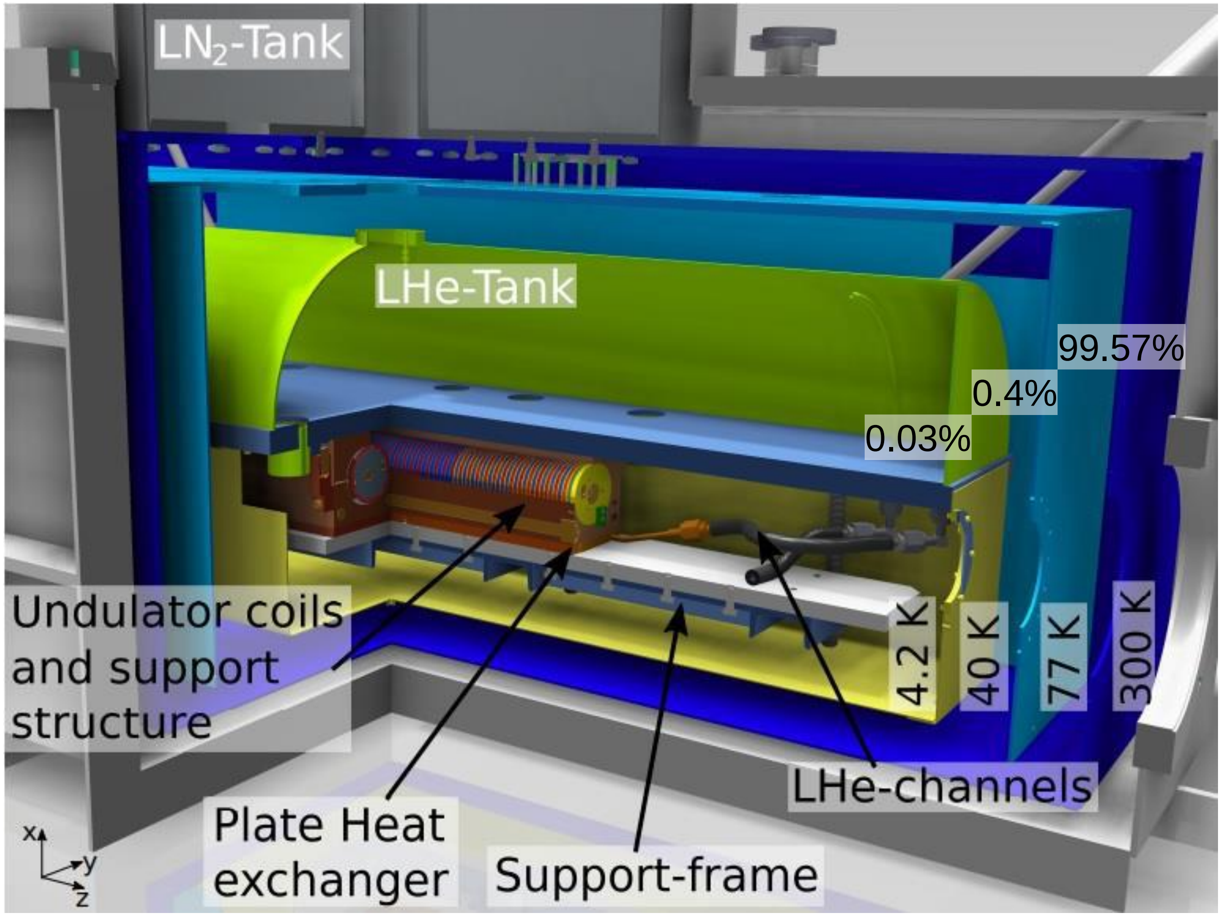
Short model P2, z-scan

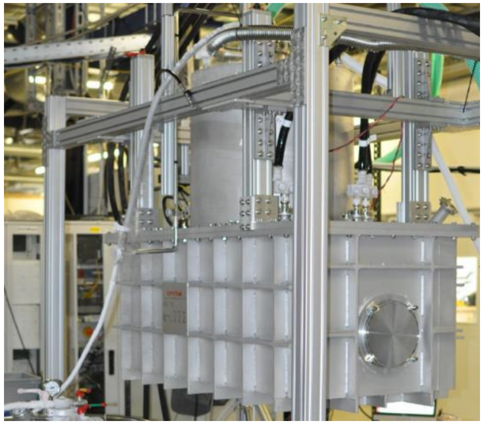


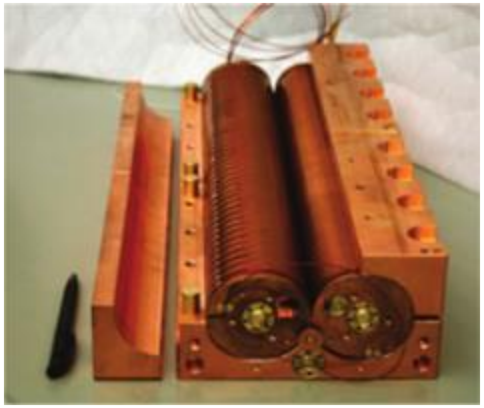


Reference: A. Bernhard *et al*., “Progress on experiments towards LWFA-driven transverse gradient undulator-based FELs,” NIM A, *in press* (2018)

Transverse-gradient undulator (TGU) in cryostat







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

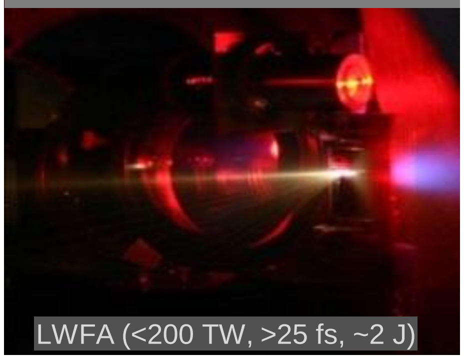
4.2 K / 77 K indirect cooling

Low-T_C superconducting coils, high-T_C current leads

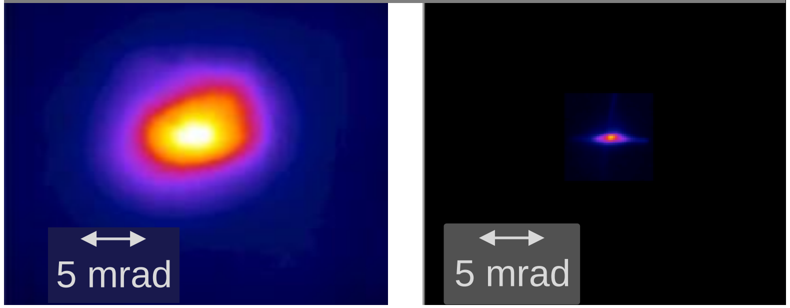
Status

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

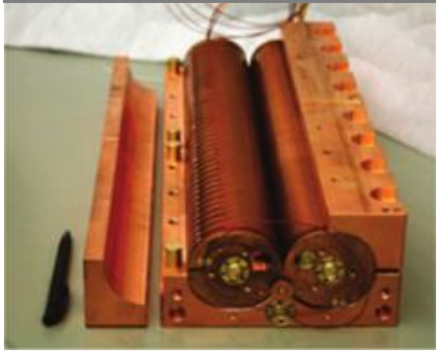
*Plasma cell: **0 m***



*Electron beam profiles **0.7 m** behind plasma cell and after **2.9 m** transport line*

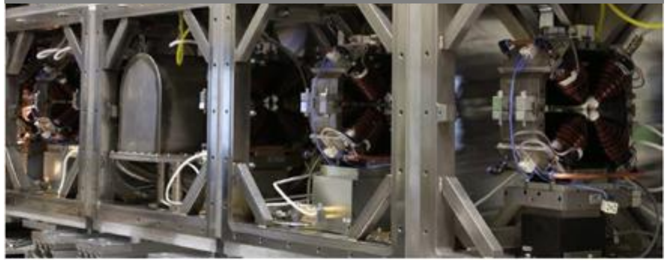


TGU coils



Compact

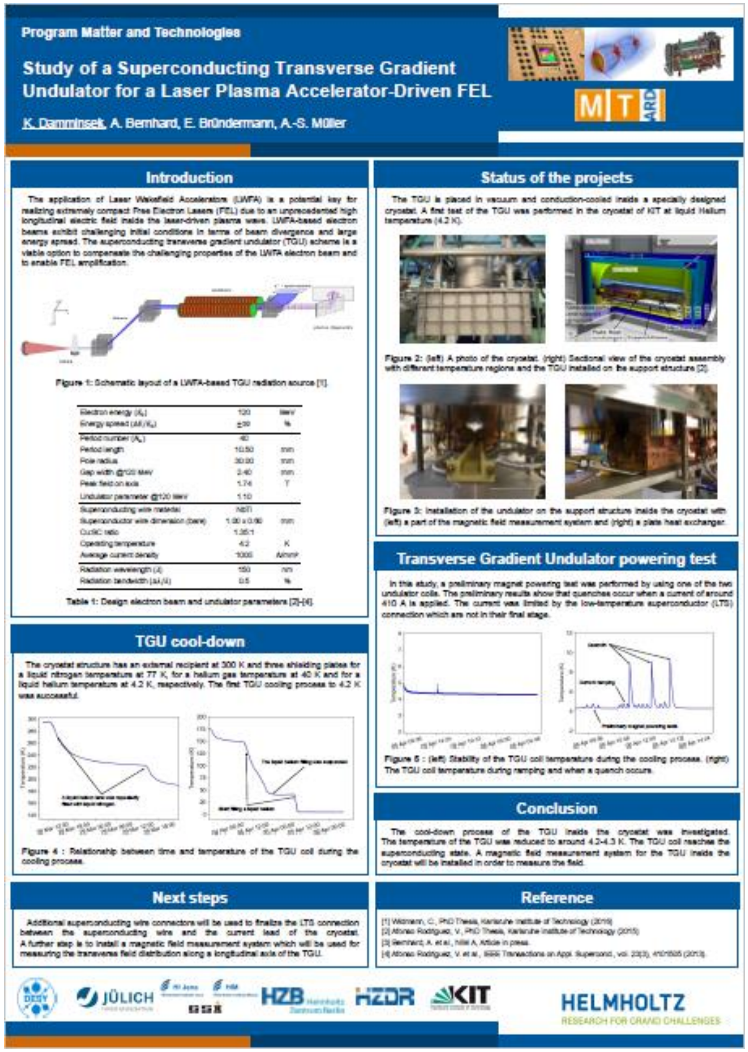
installed at LWFA Jena



References:
[1] C. Widmann *et al.*, Proc. IPAC2014, THOBA03 (2014).
[2] C. Widmann , Ph.D. thesis; KIT (2016).
[3] A. Bernhard *et al.*, Phys. Rev. Accel. Beams 19 (2016).
[4] A. Bernhard *et al.*, NIM A *in press* (2018).

Transverse-gradient undulator (TGU) progress

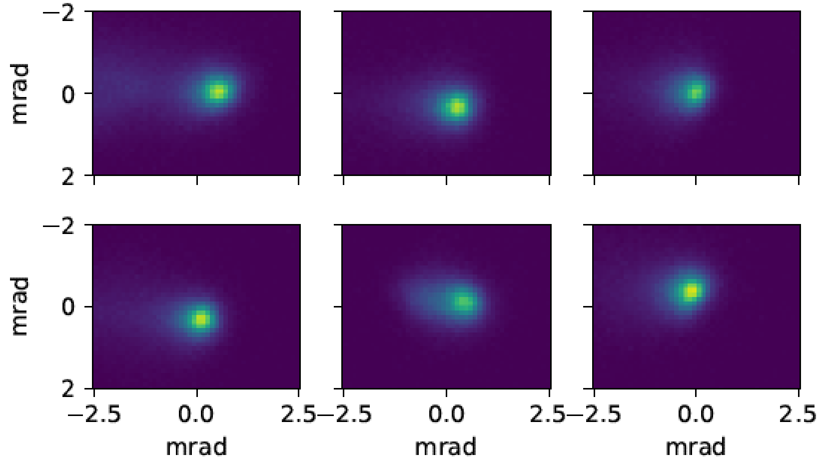
- TGU cool-down
- TGU powering test

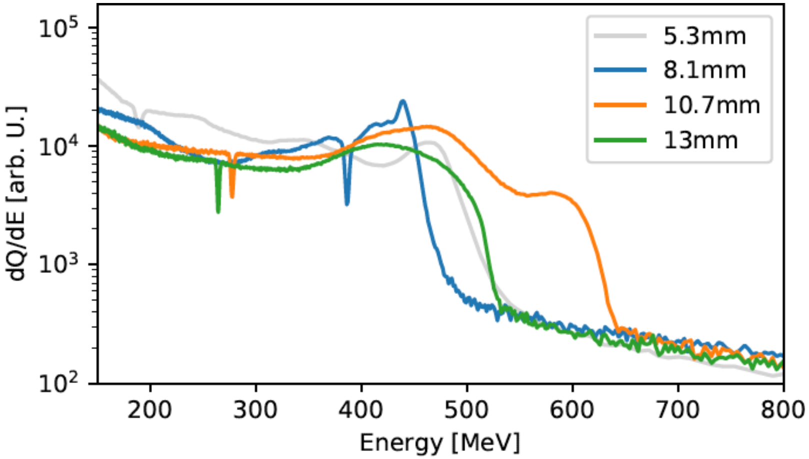


See Poster by K. Damminsek

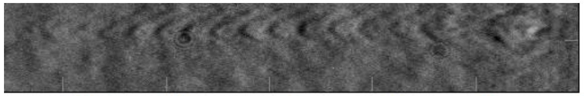
Status of LWFA @ HI-Jena

- 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 $mrad^2$, low divergence: 0.5 $mrad^2$, 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

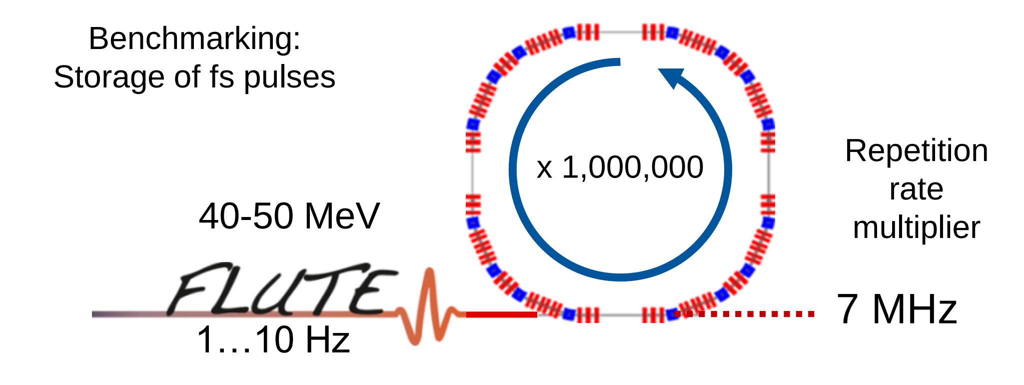
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

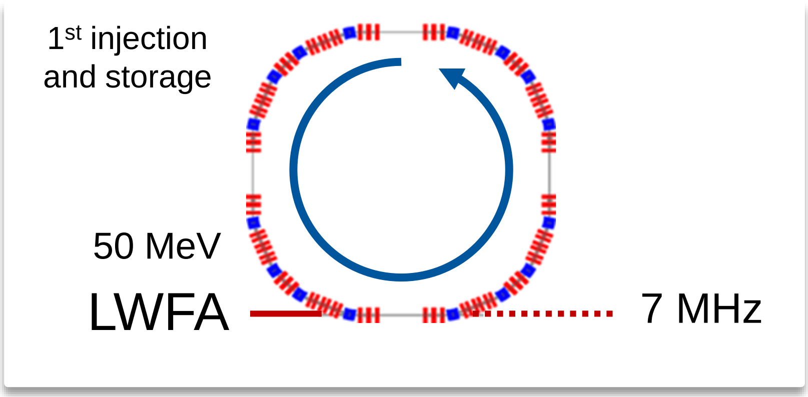
Outlook

compact Storage Ring for Accelerator Research and Technology

Storage of ultra-short (fs) electron bunches

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



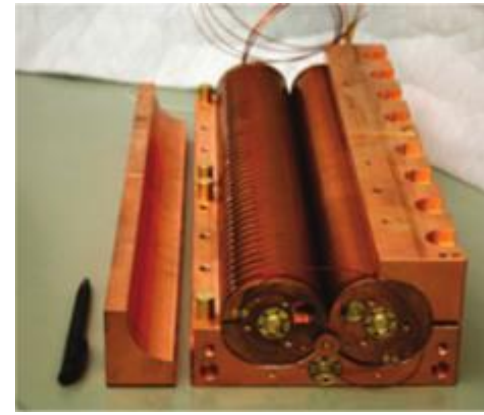


References

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

cSTART

ATHENA
Accelerator Technology Helmholtz Infrastructure

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