Considerations of an Ultrafast Electron Diffraction experiment at HZB Helmholtz Zentrum Berlin

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Yerevan, Armenia

Ultrafast Beams and Applications workshop

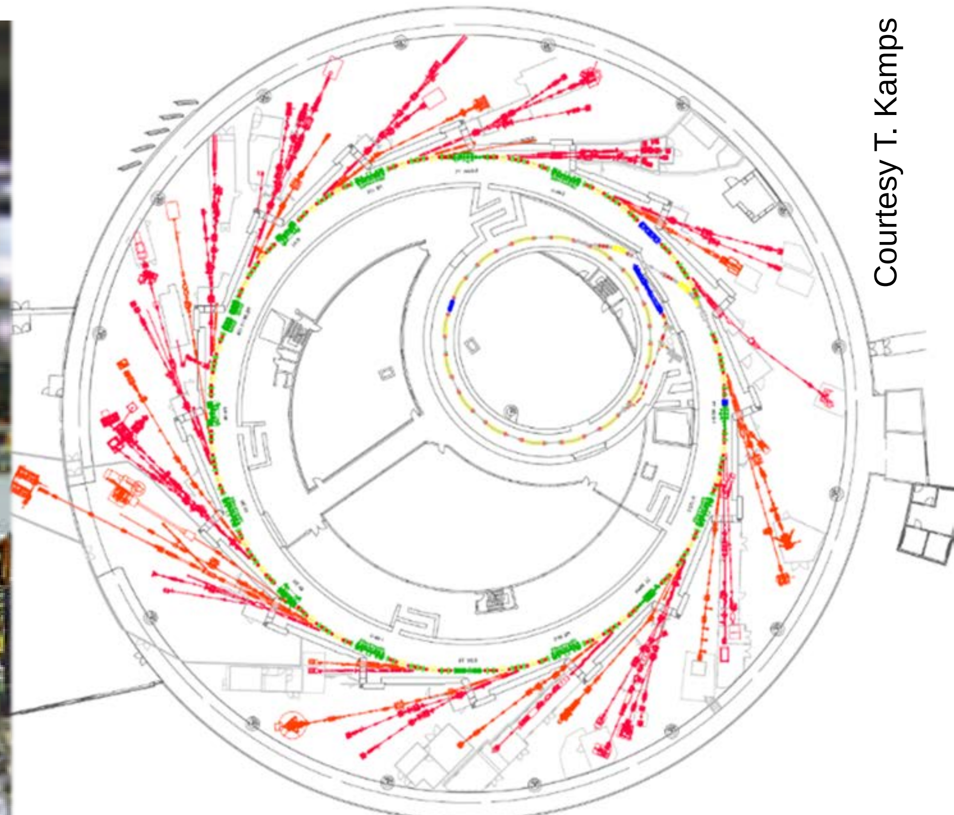
in collaboration with:
Max-Born Institute,
HZB team

Outline

- Accelerator activities at HZB
- MHz MeV Ultrafast Electron Diffraction (UED)
- Probe proof-of-principle experiment at GunLab
- Future pump-probe plans: GunLab II
- Collaborations
- Summary and outlook

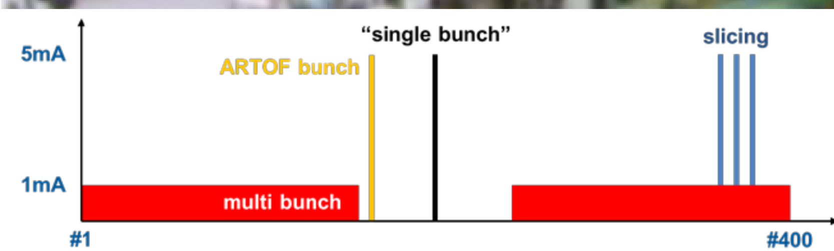
Operation and development of light sources

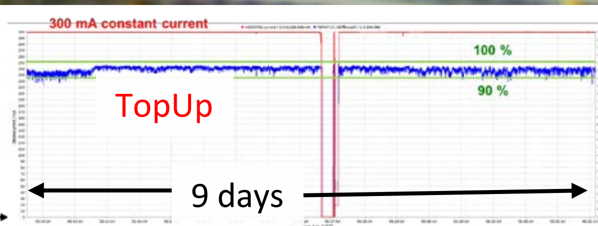
- BESSY II (est. 1999): storage ring for THz to hard X-rays from 50 beamlines (32 IDs + 14 dipoles)
- Top-up operation: 300 mA at 500 MHz with 15 ps bunches
- Specialties: polarized X-rays, low-alpha mode (2 ps), femtoslicing (50 fs)



Courtesy T. Kamps

BESSY II Parameters	
Energy	1.7 GeV
Circumference	240 m
Hor. emittance	5 nm rad
Max RF voltage	2 MV
α low-α	7.5×10^{-4} 3.5×10^{-5}





Shorter pulses while maintaining high average brilliance

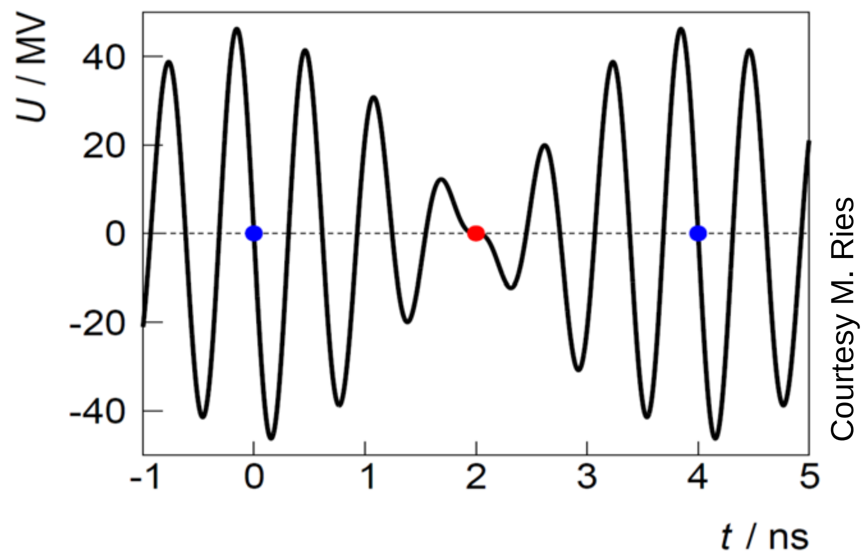
The basic idea:

$$\sigma_t \propto \sqrt{\frac{\alpha}{V'}} \qquad I \propto \alpha$$

Keep same operation parameters –
add overvoltage RF cavities at harmonics of 500 MHz

- Long & short pulses simultaneously
- Low-α mode down to 400 fs

SRF system for continuous operation at high voltage
(A. Tsakanian, Wed. 09:50)



4 x 500 MHz cavities → 15 ps
+ 2 x 1.5 GHz → 2.4 ps
+ 2 x 1.75 GHz → 1.7 ps and 15 ps

Accelerator Physics at HZB : bERLinPro

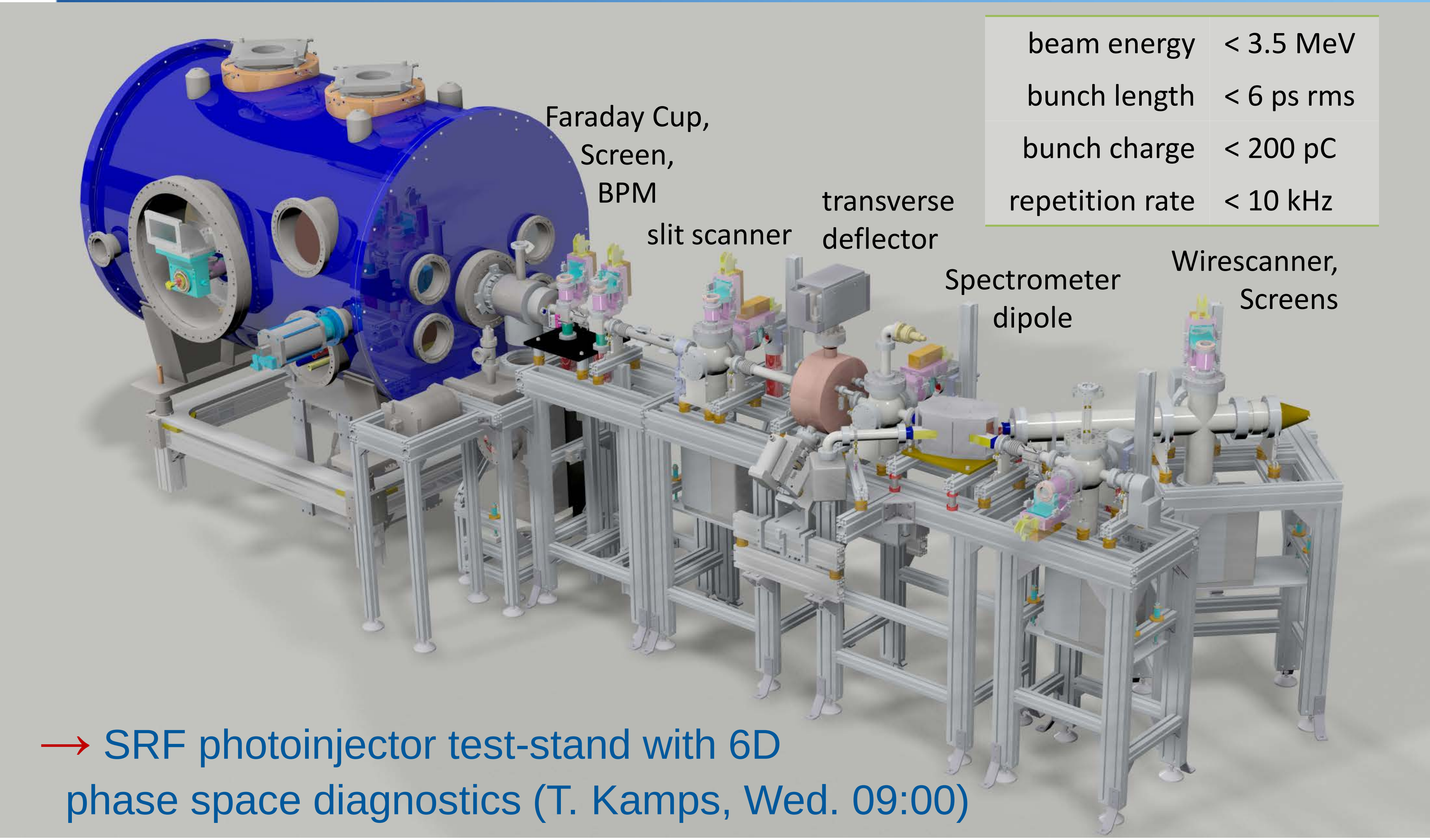
Single-pass Energy-Recovery Linac: tunable parameters + high current using 100% duty cycle, suitable for EUV photons

repetition rate	1.3 GHz
max beam current	100 mA
Bunch length	< 2 ps
norm. emittance	< 1 µm·rad
max beam energy	50 MeV

Operation expected in 2018

→ Performance determined at source

Accelerator Physics at HZB : GunLab



beam energy	< 3.5 MeV
bunch length	< 6 ps rms
bunch charge	< 200 pC
repetition rate	< 10 kHz

→ SRF photoinjector test-stand with 6D phase space diagnostics (T. Kamps, Wed. 09:00)

→ Demonstrator of UED potential at HZB!

(U)ED at HZB

- Electrons, a supplement to photons
    - More suitable for surfaces, thin films, gas-phase samples, due to:
      - larger scattering cross-section (shorter elastic mean free path)
    - Considerably less damage in biological samples:
      - Elastic/inelastic scattering ratio 3 times smaller
    - Overall gain in efficiency of > 10^8 potentially possible
    - Facility of smaller size and cost (compared to 3rd-4th generation light sources) with higher flexibility in beam parameters (control with EM fields)

Citing: P. Musumeci, T.van Oudheusden, G. Sciaini and RJD. Miller

MeV UED at HZB

- Novel properties from relativistic beam energies

  - few MeV e- beams allow:
    - mÅ wavelengths
    - improved velocity mismatch for gas-phases
    - better beam manipulation from suppressed space charge

  - Short pulses (< 100 fs) possible: time-resolved structural dynamics → movies of atomic motions!

  - higher charge and lower emittance →
    - higher brightness for single-shot measurements (~100 fC @ 100 µm)
    - improved longitudinal and transverse coherency (tens of nm)

  - Possibilities: polarized probe electrons and Microscopy (UEM)

Citing: G. Sciaini and RJD. Miller doi:10.1088/0034-4885/74/9/096101

MHz MeV UED at HZB

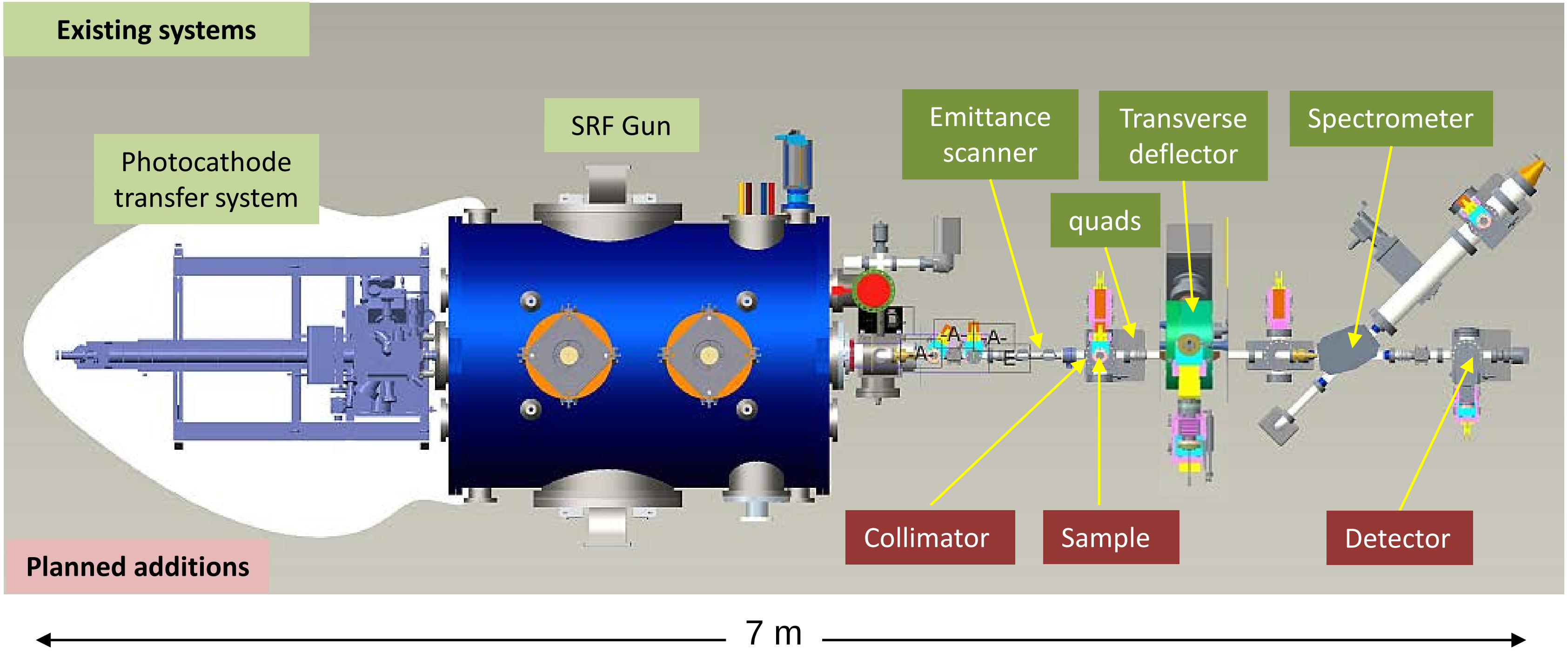
- High repetition rates and stability from CW SRF technology
  - Improved stability + temporal resolution from Continuous Wave operation:
    - amplitude and phase RF jitter much smaller compared to pulsed mode

$$\tau^2 = \tau_{pl}^2 + \tau_{pe}^2 + \tau_{VM}^2 + \tau_T^2$$

  - MHz repetition rate of equally spaced pulses (not burst mode):
    - reduced measurement time for multi-shot experiments
    - especially suited for gas (and other) samples
  - Ultra-high vacuum (UHV) conditions (< 10^{-9} mbar)
- Target scientific cases
  - Interactions of e-, phonons and spins in photo-induced excitations / phase transitions: CDW materials, heterostructures, manipulation of magnetization in garnets, WDM, …
  - … linked with high-temperature superconductivity, colossal magnetoresistance, ferrimagnetism and ferromagnetism

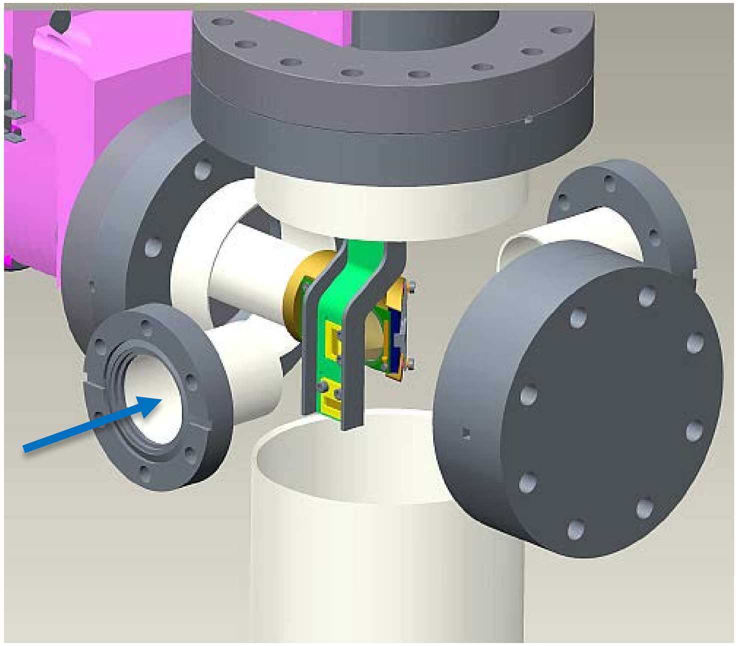
Proof-of-principle experiment

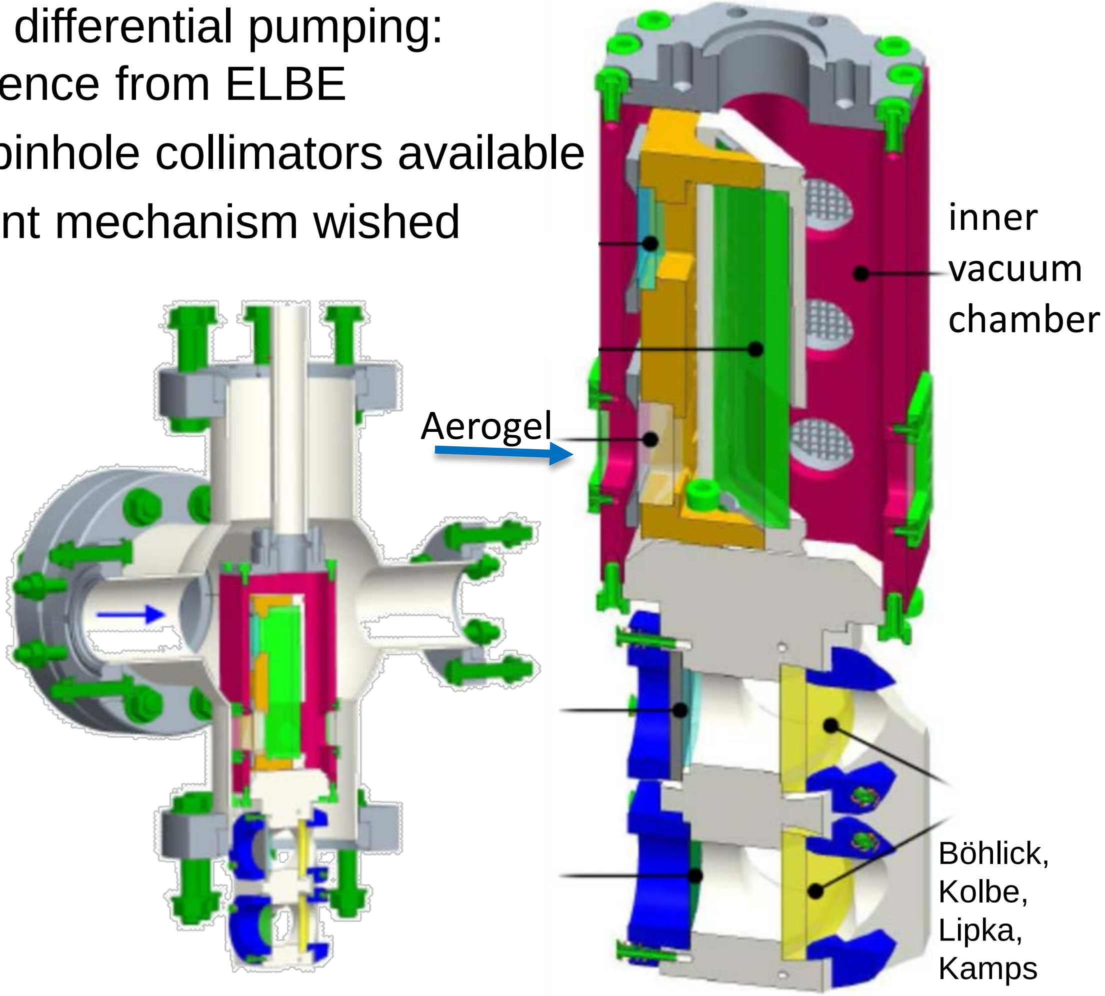
- Static MeV diffraction experiment at GunLab is planned
  - Demonstrate first diffraction pattern from SRF gun (10 nm thick Au sample)
  - Additions / modifications to existing beamline:
    - sample holder
    - collimators
    - detector



Proof-of-principle experiment: sample chamber

- Modification of existing diagnostic station at 2.5 m
  - UHV conditions require differential pumping:
    - existing design experience from ELBE
  - Additional actuator for pinhole collimators available
  - Transverse 4D alignment mechanism wished

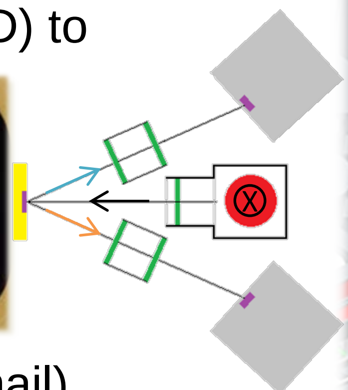




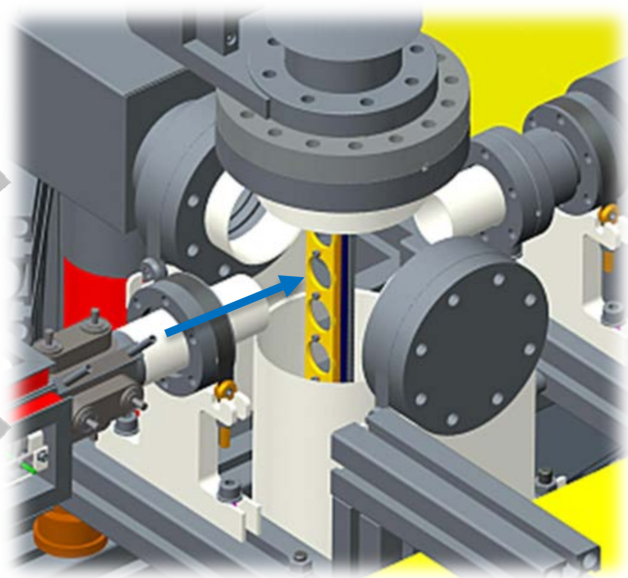
Proof-of-principle experiment: detector

- EMCCD Detector from MBI
  - Andor iXon 888 Camera with single-photon sensitivity
  - 26 fps read-out for 1 MP resolution,
    670 fps for 128x128 Crop
    with 30 MHz pixel clock speed

- Multiscreen station after 1.7 m drift
  - Digital Micromirror Device (DMD) to deflect 0^{th} peak for high dynamic range readout



Courtesy
J. Völker



  - Additional intensity collimator (nail) or phosphor screen with hole

Proof-of-principle experiment: simulations

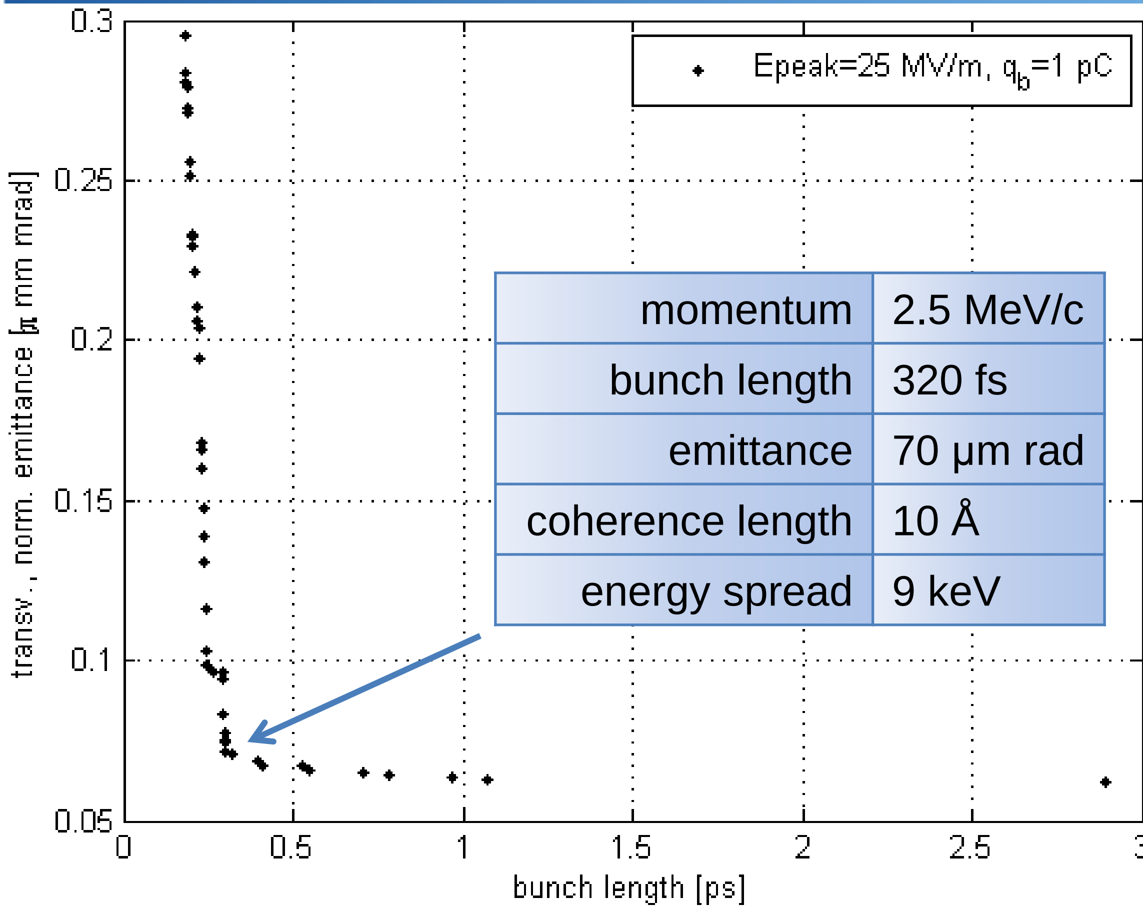
- ASTRA simulations for the expected e- beam parameters

  - Multi-objective optimization of photo-injector settings, judging on…

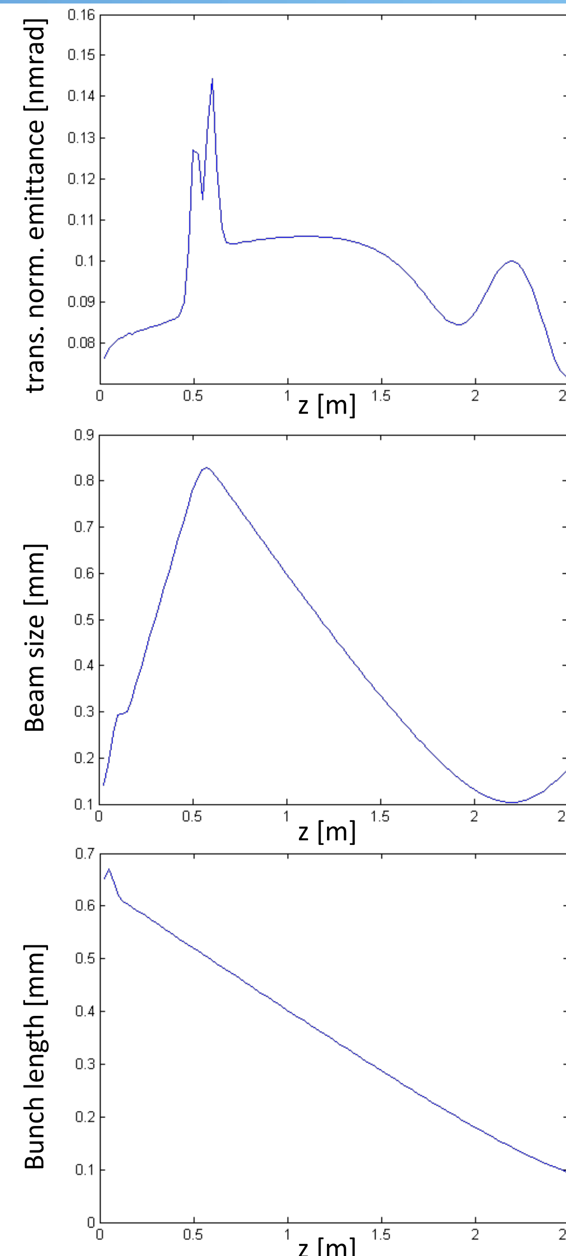
  - … compromise between various conflicting beam parameters:
    - charge (↕)
    - momentum (↕)
    - bunch length (↓)
    - emittance (↓)
    - momentum spread (↓)
    - transverse coherence length (↑)
    - beam size (↑)

  - For a specific bunch charge and momentum, the optimization is based on a trade-off between emittance and bunch length, while evaluating the rest parameters…

Proof-of-principle experiment: 1 pC case study



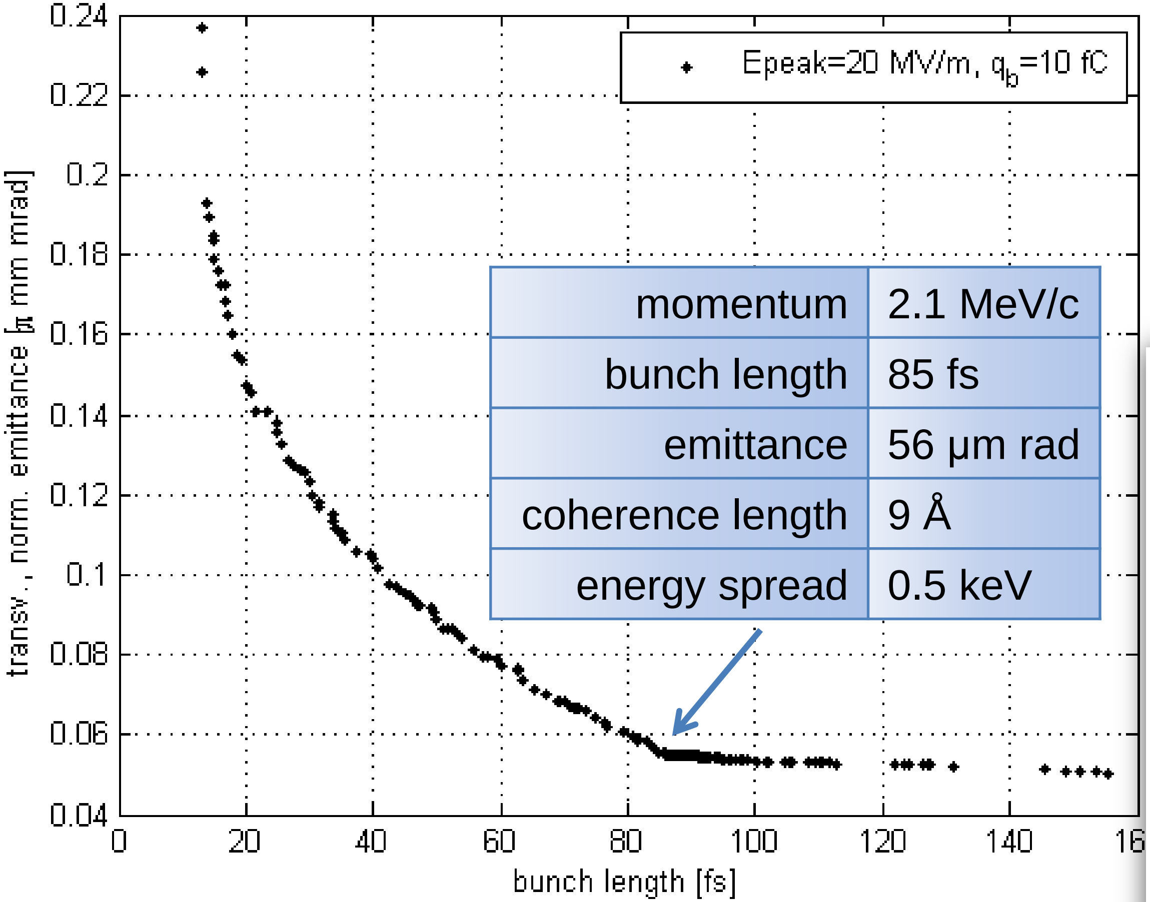
momentum	2.5 MeV/c
bunch length	320 fs
emittance	70 µm rad
coherence length	10 Å
energy spread	9 keV



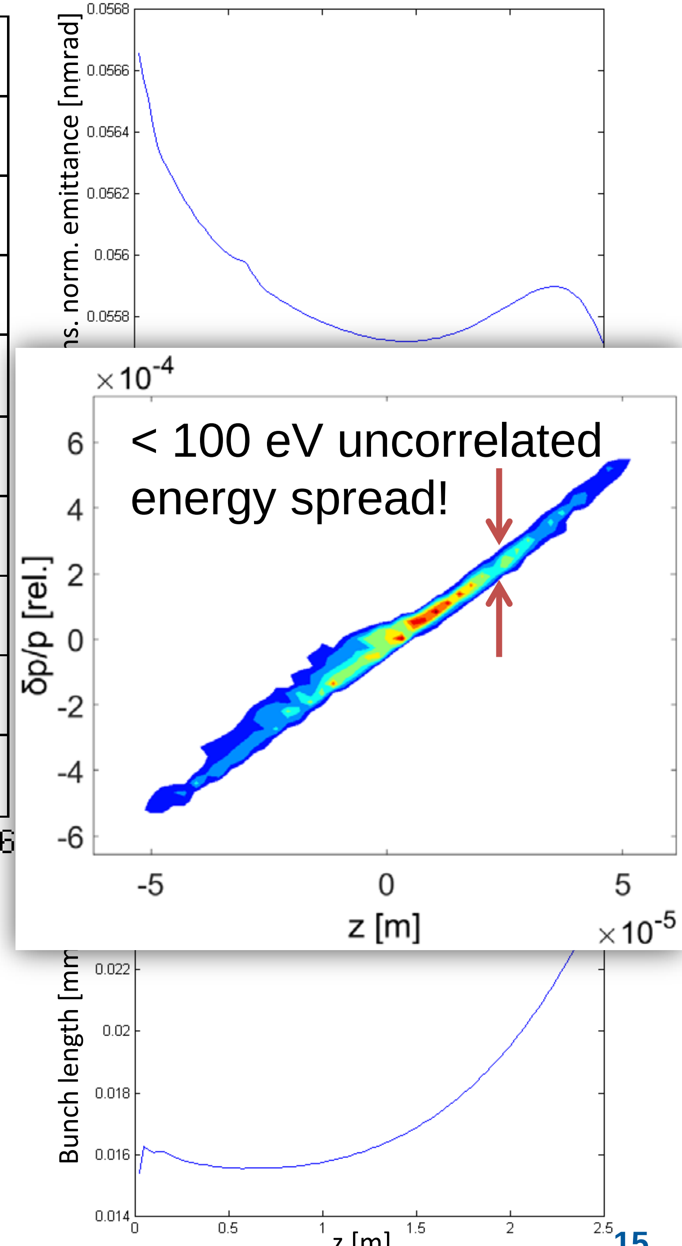
Courtesy E. Panofski

- 15 Å coherence length @ 250 fs → certainly sufficient for Au (> 3 x 4 Å)
- 1.1 mm spacing / peak without focusing

Future plans: 10 fC case study with 100 fs laser



momentum	2.1 MeV/c
bunch length	85 fs
emittance	56 µm rad
coherence length	9 Å
energy spread	0.5 keV

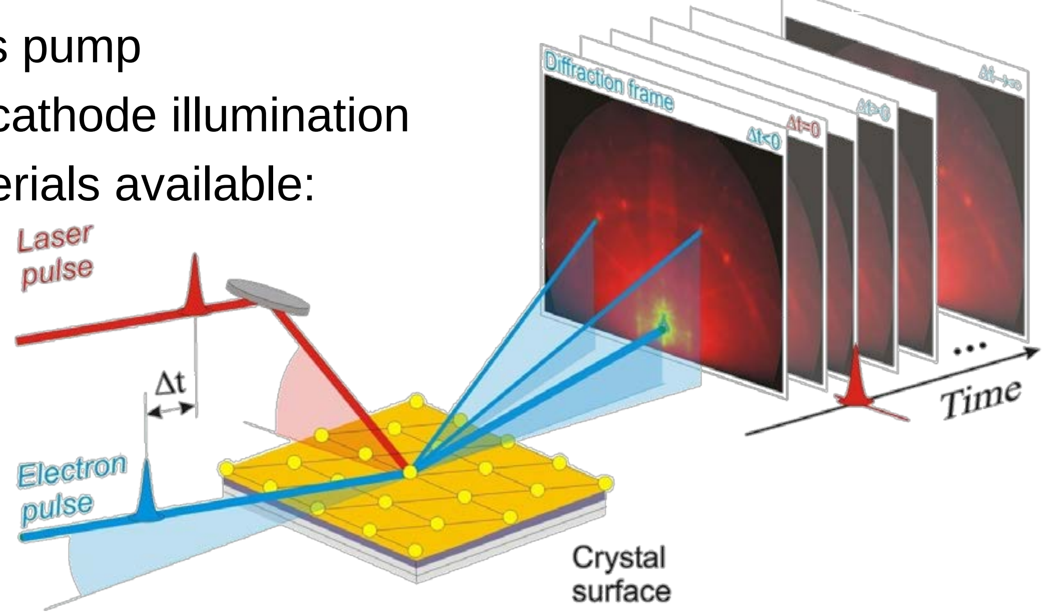


- Sub-50 fs bunches achievable but not as coherent
- Further improvement expected with the use of collimators and focusing

Future plans: pump-probe experiment

- Laser upgrade
  - 10 – 100 fs IR laser as pump
  - Conversion to UV for cathode illumination
  - Different cathode materials available: Cu, Mo, CsK_2Sb, etc.

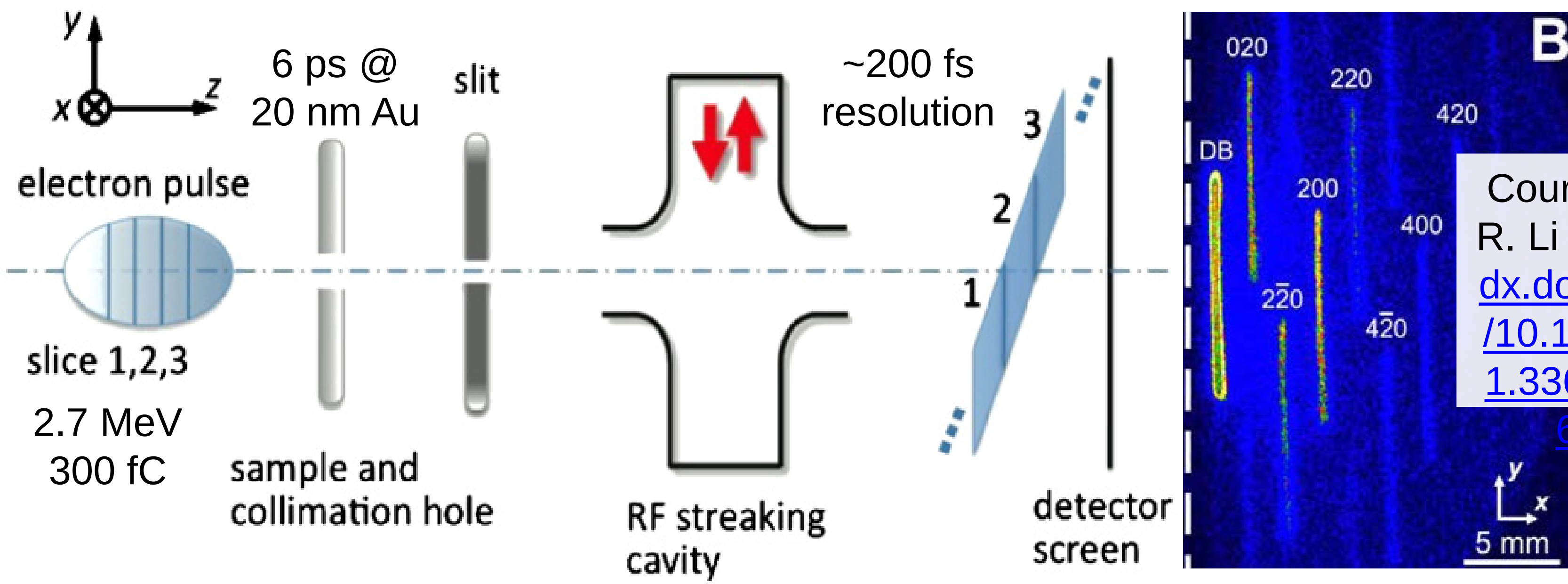
Courtesy
Nuh Gedik



- Arrival time monitors considered:
  - Plasma lens, as simpler but less accurate technique (ps resolution)
  - Grating enhanced ponderomotive scattering, as a more elaborate solution (down to fs + bunch length measurement)
  - … more ideas welcomed

Future plans: alternative approaches (CTR)

- Continuously Time Resolved UED
  - truly single-shot measurement: continuous diffraction image which can be temporally-resolved using a transverse RF deflector



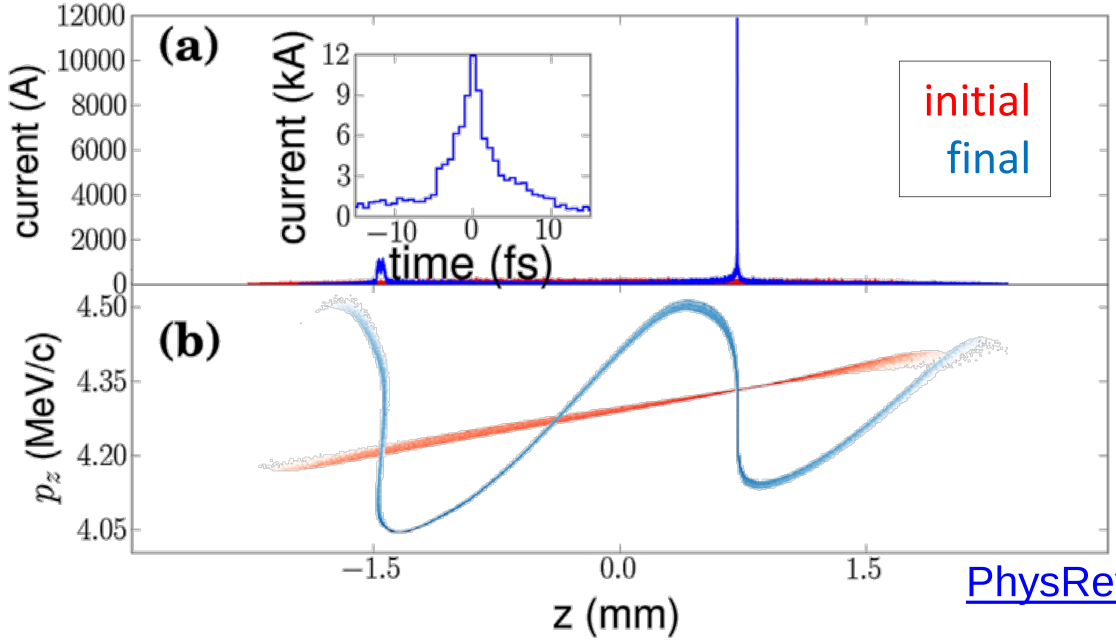
Courtesy R. Li et al. dx.doi.org/10.1063/1.3361196

+ no compression needed, single pump pulse → no jitter term in resolution...
- … determined by deflector instead: sub-100 fs resolution possible with 35 kW deflecting power and optimized beam dynamics

– convolution with energy spread, more complicated analysis, less explored

Future plans: alternative approaches (DLW)

- Passive bunching with Dielectric-Lined Waveguides
  - use wake-fields to modulate the energy and thus the particle density → 7% of the bunch squeezed in few fs after 0.5 m



F. Lemery, P. Piot
PhysRevSTAB.17.112804

\+ low-cost, no need for bunching synchronization (free of RF jitter)

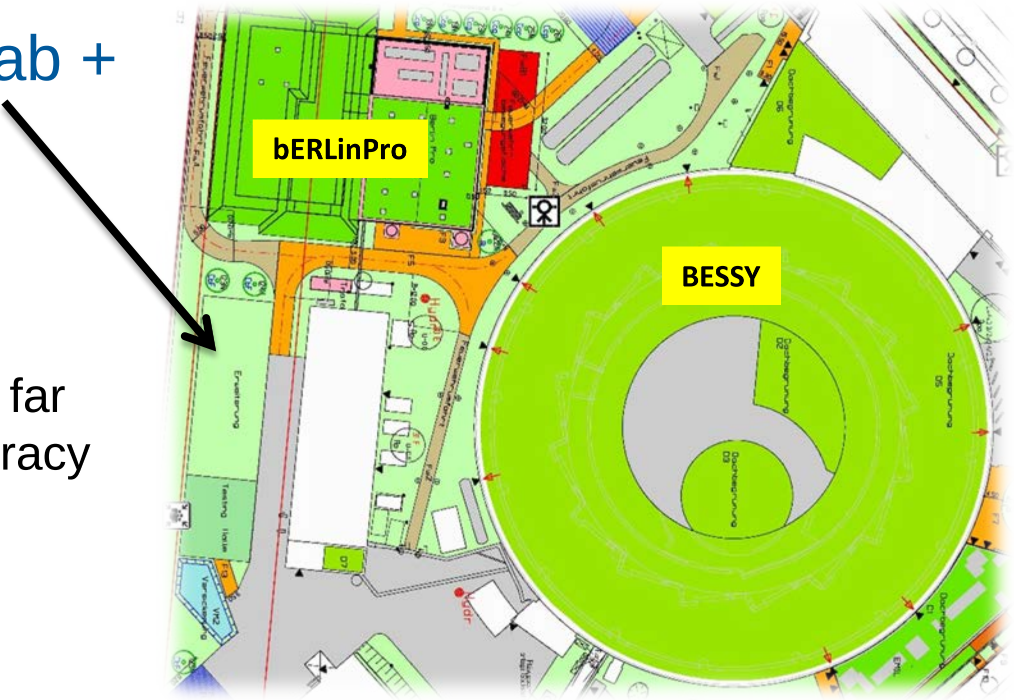
– challenging for low charges: tiny transverse dimensions of structure, very precise alignment needed

– collimation of the low-density tails required

Future plans: facility upgrade

- Traditional bunching approaches also considered:
  - RF cavity for ballistic bunching
  - Dogleg for magnetic compression
  - But in principle: beamline as simple as possible! → additional components complicate beam dynamics and introduce sources of error

- GunLab II: existing GunLab + extended drift
  - UED and FEL mode up to 200 pC @ 1 MHz
  - Sufficient drift for additional focusing lenses and near + far detector for increased accuracy
  - Underground bunker for radiation protection



Collaborations

- Established
  - MBI (S. Eisebitt, M. Schnuerer, I. Will) : samples, detector, laser development
- In contact with
  - Mainz University (J. Demsar)
  - Fritz Haber Institute – Max-Planck (R. Ernstorfer)
- Looking for new collaborators and users!

Summary and outlook

- Summary
  - UED is a complementary tool for atomic observation with novel features for the established community at HZB and beyond
  - Static proof-of-principle experiment at GunLab on schedule, using the existing experience on CW SRF photo-injectors
  - Facility upgrade is planned: new building with fs laser for pump-probe experiment at 1 MHz repetition rate

- Outlook
  - Optimize probe beam parameters, adjust them to user needs
  - Acquire / develop cutting-edge beam diagnostics
  - Investigate the possibility of Ultra-fast Electron Microscopy

- We are looking forward to your feedback and collaboration

THANK YOU FOR YOUR ATTENTION