MeV Ultrafast Electron Diffraction and Microscopy Development at SJTU

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5/8/2015

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

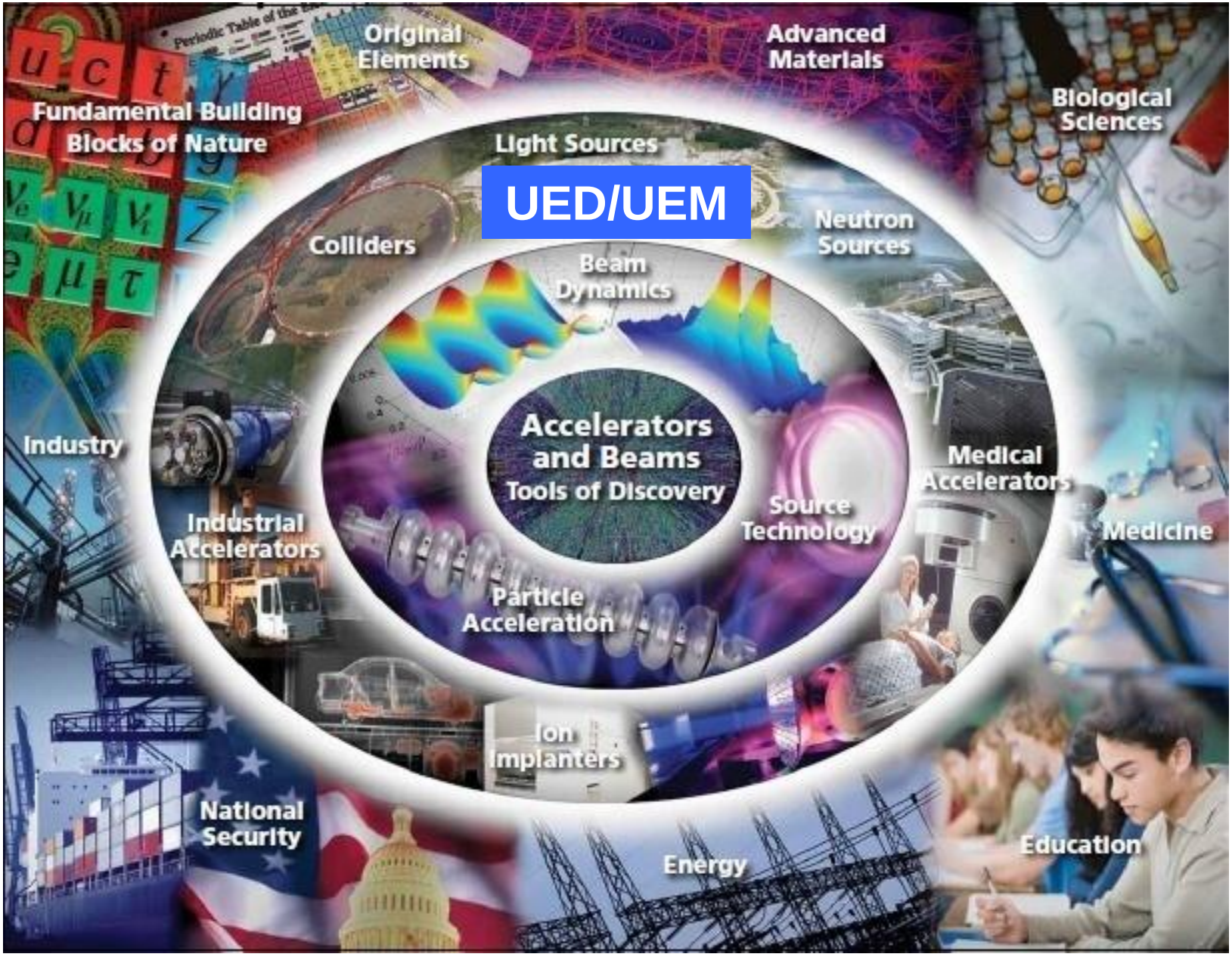
北京大學
PEKING UNIVERSITY

清華大學
Tsinghua University

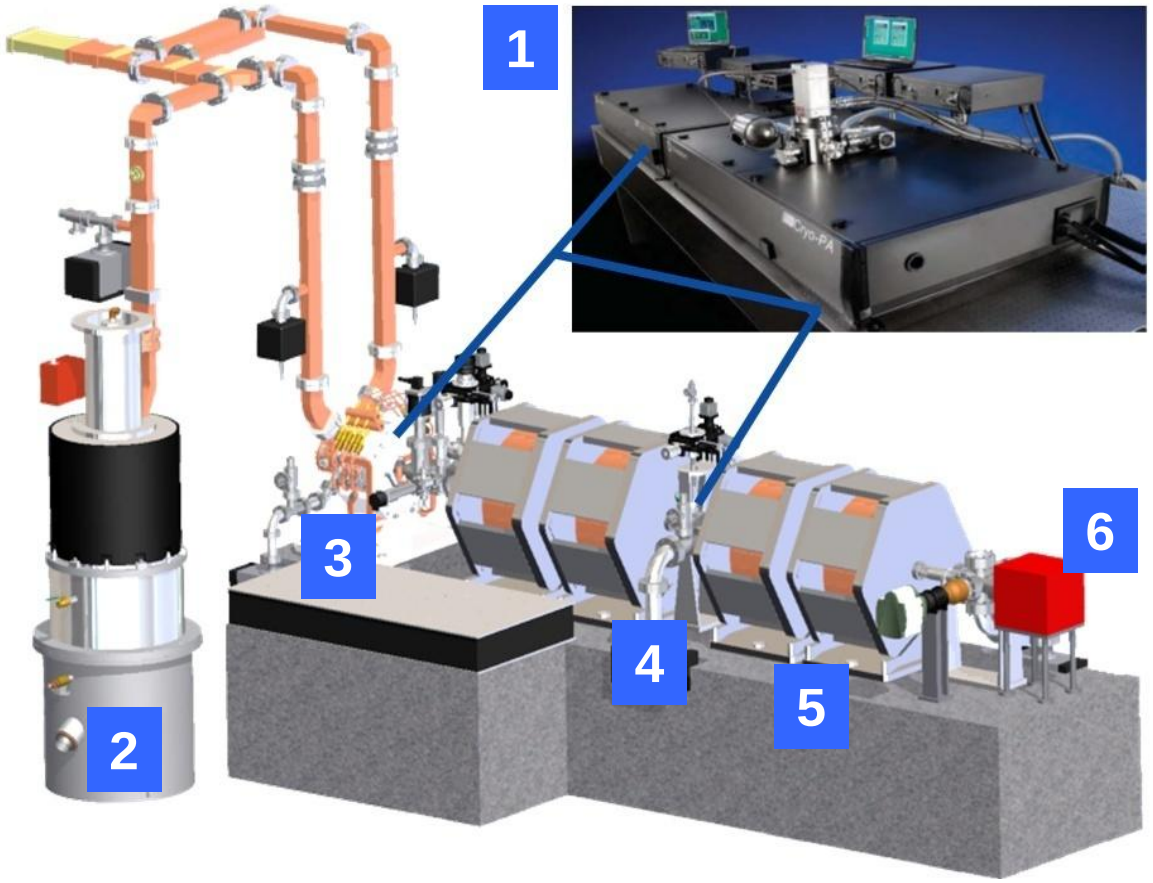
Outline

1. MeV UED/UEM project at SJTU
2. Current status of the UED/UEM project
   - 2.1 Conceptual Design
   - 2.2 Civil construction
   - 2.3 Commissioning UED/UEM test facility
   - 2.4 Improving beam brightness
   - 2.5 Development of high-field objective lens
3. Future plans

Accelerators for shaping the world



Accelerator-based MeV UED/UEM at SJTU



1. Femtosecond laser
2. High rep-rate rf source
3. High rep-rate rf gun
4. Advanced sample chamber
5. Superconducting solenoid
6. Advanced detection system

- ✓ First proposal to NSFC in 03/2011
- ✓ Project funded in 11/2013
- ✓ Construction: 2014 - 2018

Mode	Diffraction	Microscopy	Rep-rate
State-of-the-art	~200 fs	10 ns/10 nm	~100
Goal	~50 fs	10 ps/10 nm	~1000

Strategic plan for a UED/UEM user facility

- ✓ Test critical technologies at the test facility
- ✓ Collaborate with national labs
- ✓ Let the users decide what they want

UED/UEM center at SJTU

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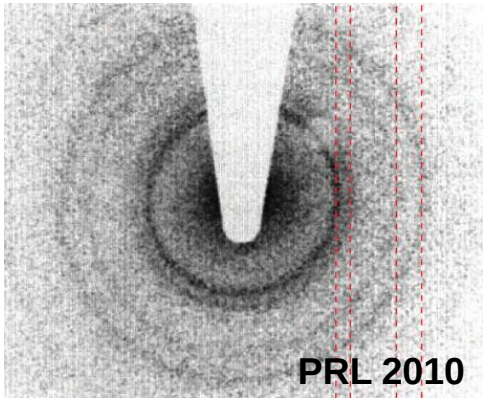
Accelerator based UED

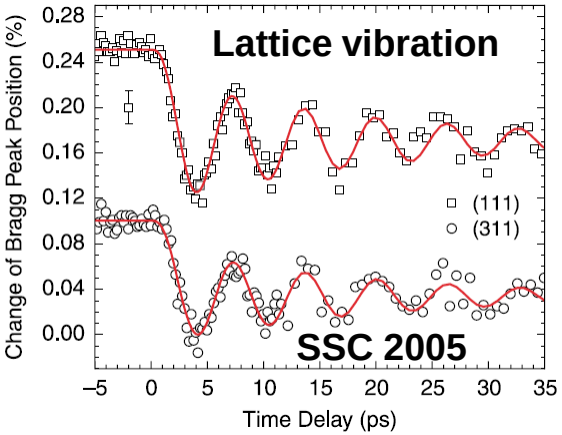
2011 gun — sample

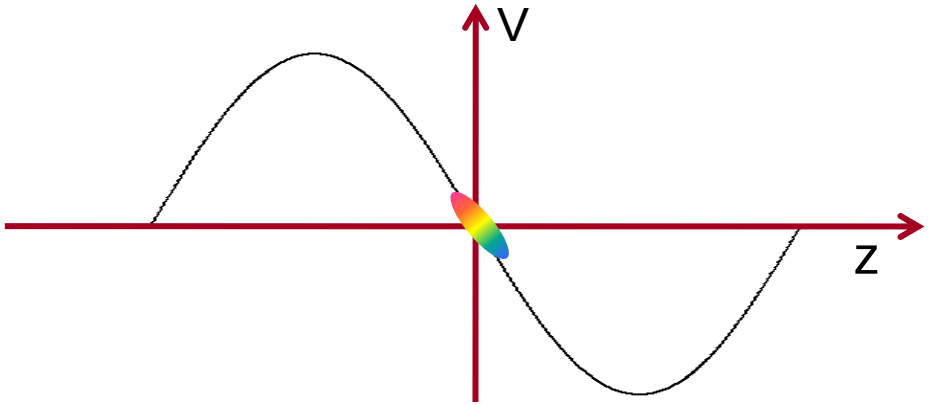
2015 gun — buncher

- ✓ Emittance growth
- ✓ Energy spread growth
- ✓ Timing jitter



Bunch compression reduces bunch length and increases energy spread





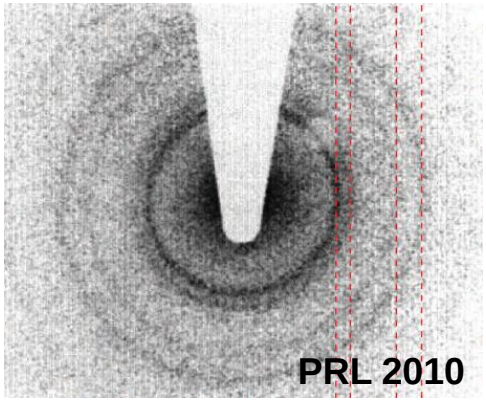
Phase jitter leads to energy and timing jitter

Accelerator based UED

2011 gun ⟷ sample

2015 gun ⟷ buncher ⟷

- ✓ Emittance growth
- ✓ Energy spread growth
- ✓ Timing jitter

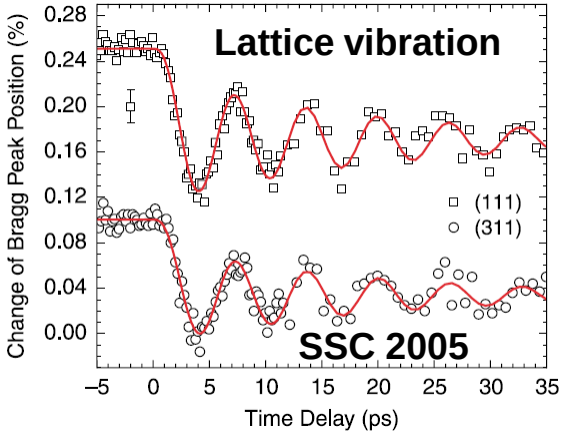


either degrade the sample or mask the structural dynamics[20]. Here we show that a recently developed, ultrabright femtosecond electron source[7–9] makes it possible to monitor the molecular motions in the organic salt $(EDO\text{-}TTF)_2PF_6$ as it undergoes its photo-induced

Miller's group, Nature 2013

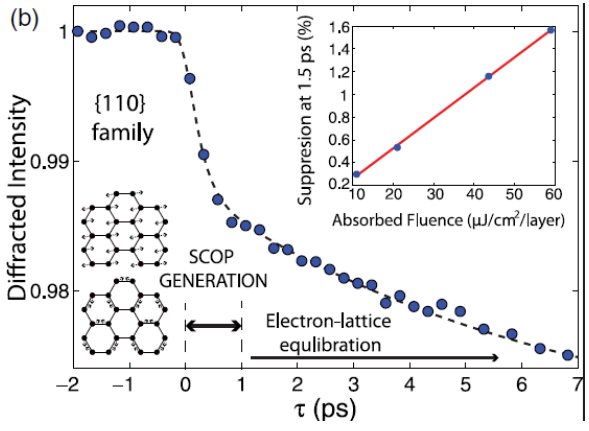
acting degrees of freedom. Here, we demonstrate that recent improvements in ultrafast electron diffraction (UED) instrumentation (*4–7*) provide such a capability by exploring the nature of the semiconductor-to-metal transition in VO_2 (*8*).

Siwick's group, Science 2014



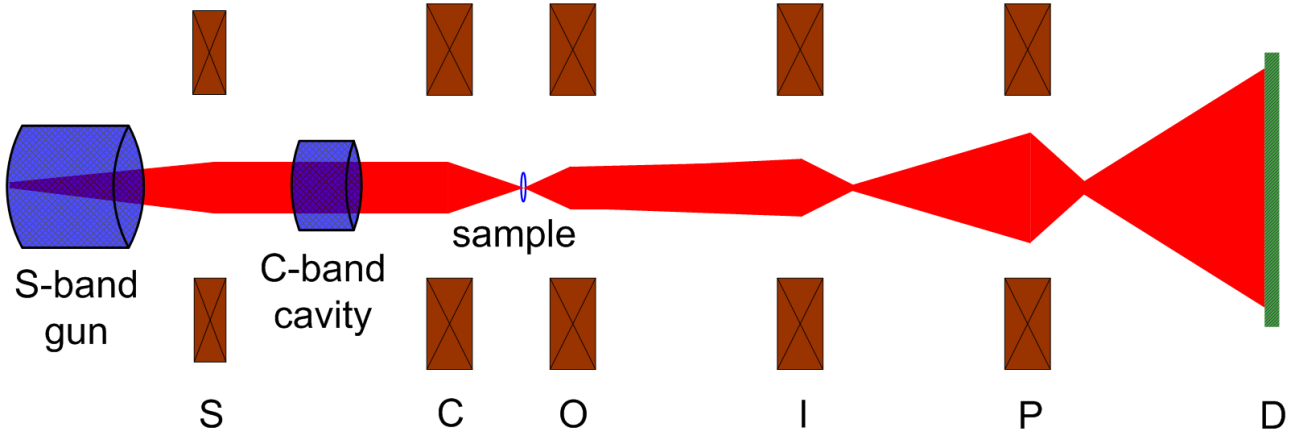
Achieved ~200 fs resolution and excellent S/N with rf compression

PRL 113 235502 (2014)



Accelerator based UEM

A representative design for 10 ps & 10 nm resolution

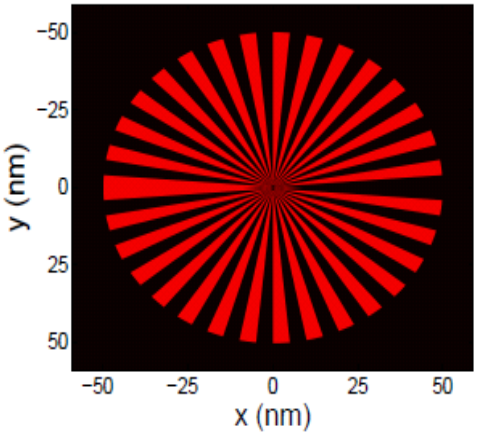


- S: gun solenoid
- C: condenser lens
- O: objective lens
- I: intermediate lens
- P: projection lens
- D: detector

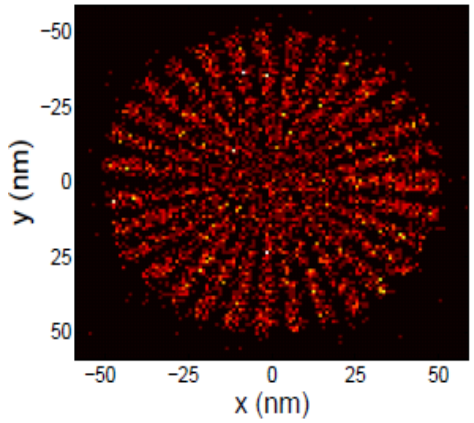
Formulation with accelerator terminology

- Imaging condition: $R_{12}=R_{34}=0$
- Chromatic aberration: T_{126}
- Spherical aberration: U_{1222}

$$T_{ijk} = \sum_{m=1}^{6} R_{im}^{(2)} T_{mjk}^{(1)} + \sum_{m,n=1}^{6} T_{imn}^{(2)} R_{mj}^{(1)} R_{nk}^{(1)}$$



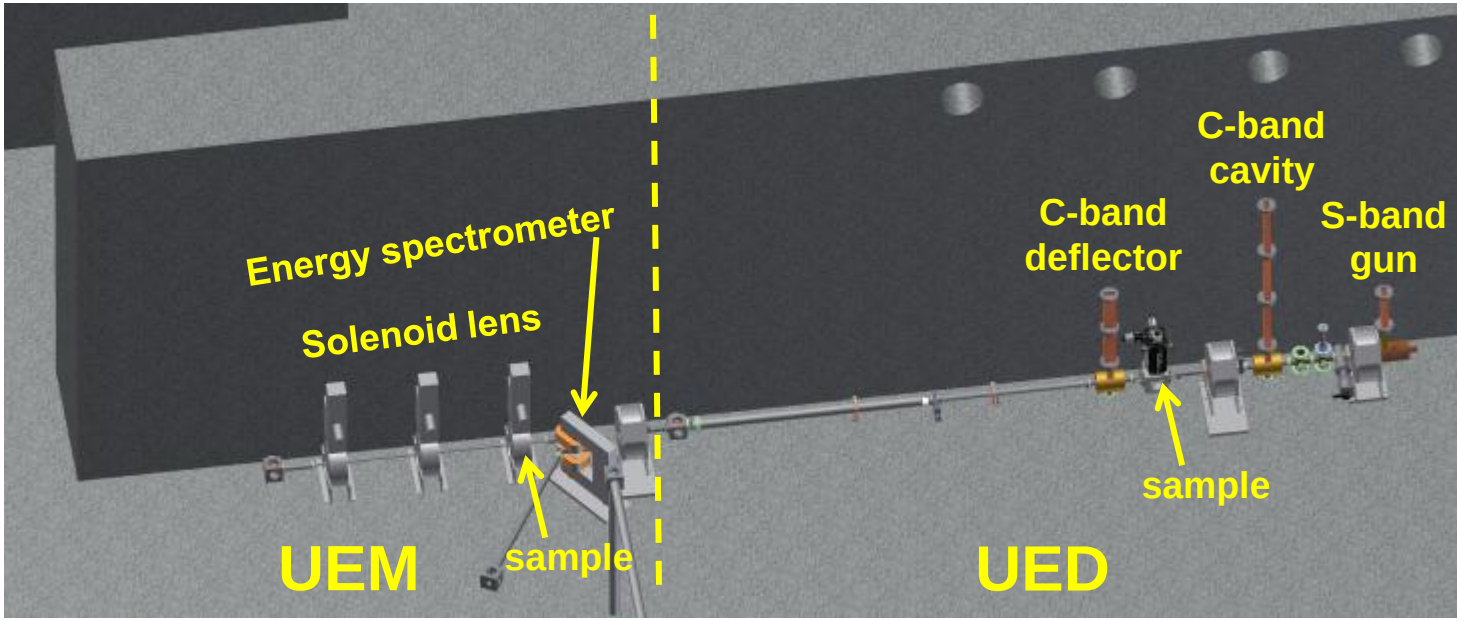
sample



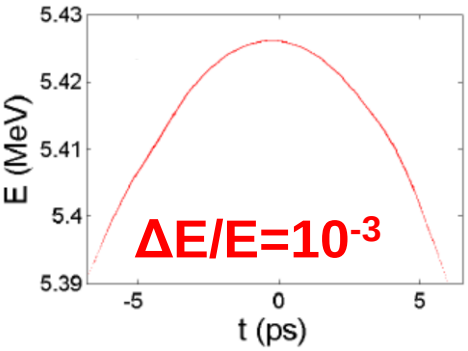
image

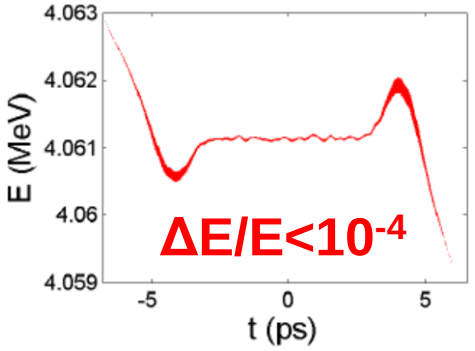
Xiang et al., Nucl. Instru. Meth. A 759, 74 (2014); Li and Musumeci, PR Applied 2, 024003 (2014)

Conceptual design of the MeV UED/UEM facility



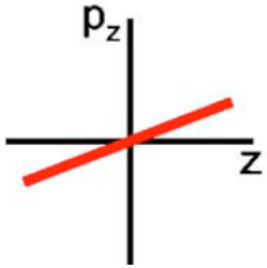
C-band cavity used to remove beam quadratic energy chirp

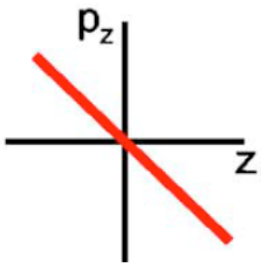




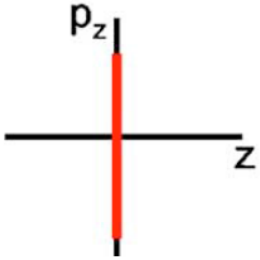
Before and after C-band cavity

C-band cavity used to imprint linear energy chirp for compression





Before and after C-band cavity



At the sample

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Construction of a new experimental hall

06/2014

08/2014

09/2014

10/2014

11/2014

12/2014

Construction of a new experimental hall

Experimental hall

Grounding system

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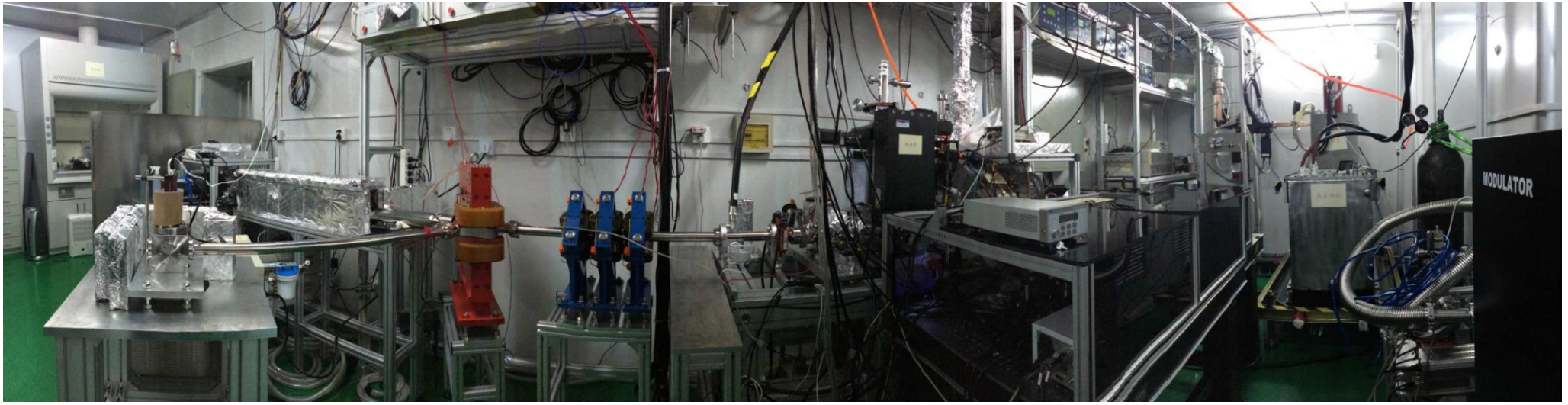
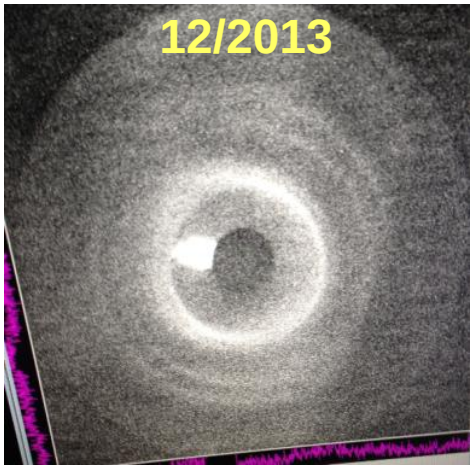
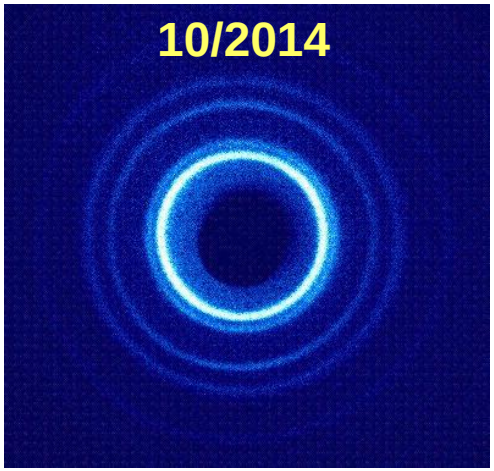
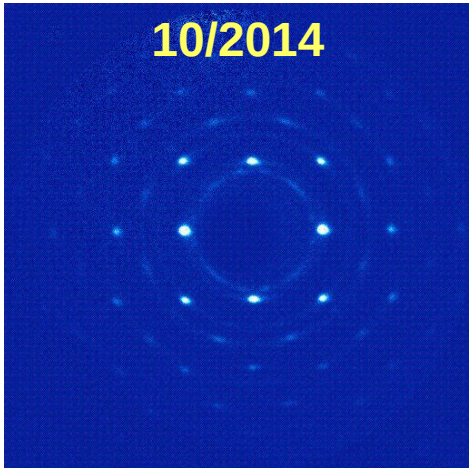
Commissioning the UED test facility



Photocathode rf gun based MeV UED test facility

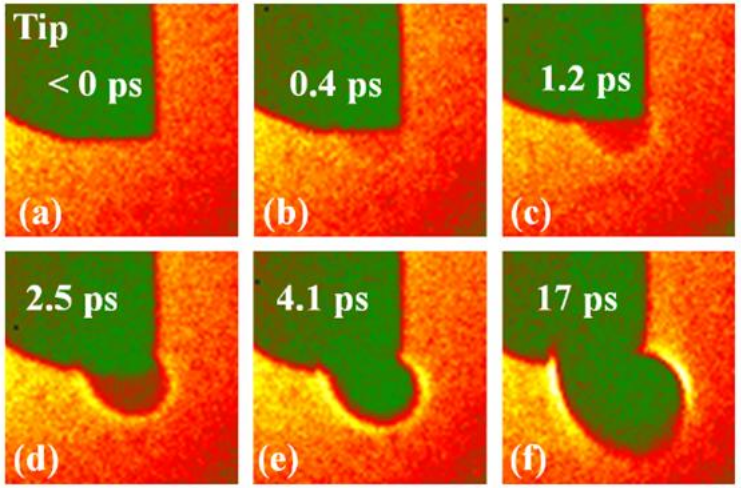


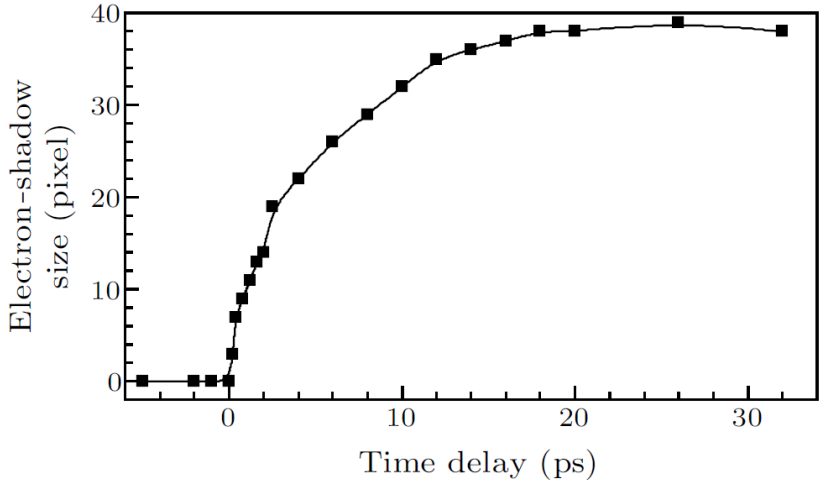




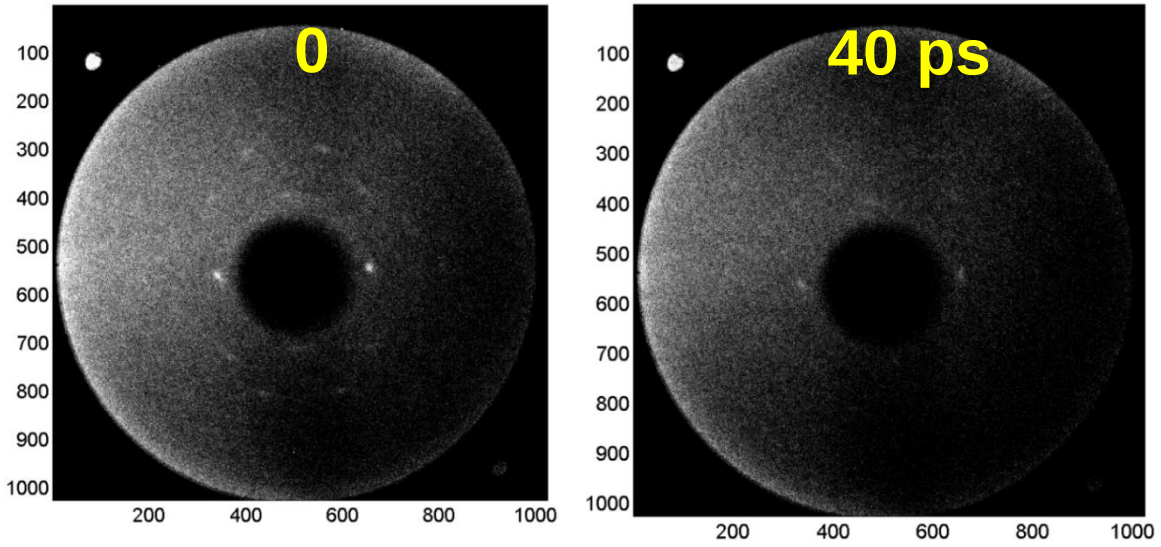
High quality Al and Au diffraction pattern (Fu et al., Rev. Sci. Instru. 2014)

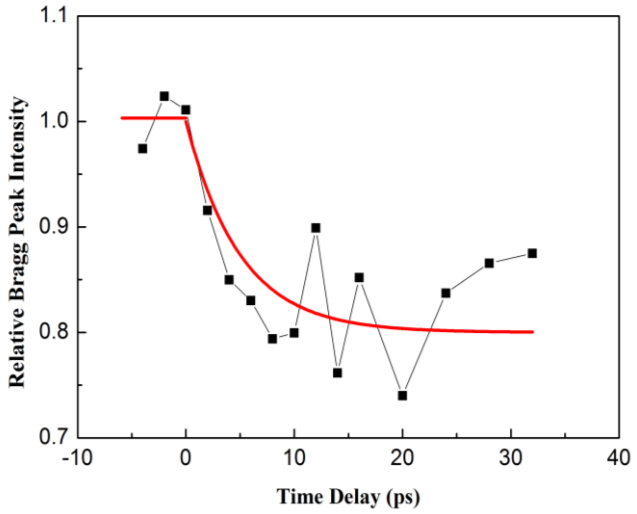
Commissioning the prototype UED machine





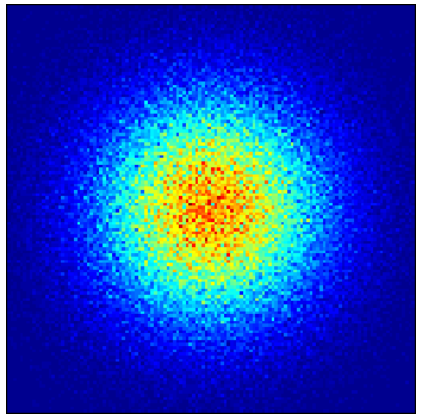
Finding time-zero with the perturbation from laser-induced plasma



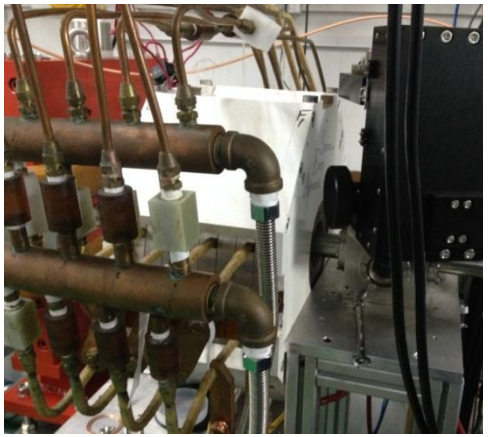


First MeV UED pump-probe experiment in China (Zhu et al., CPL, 2014)

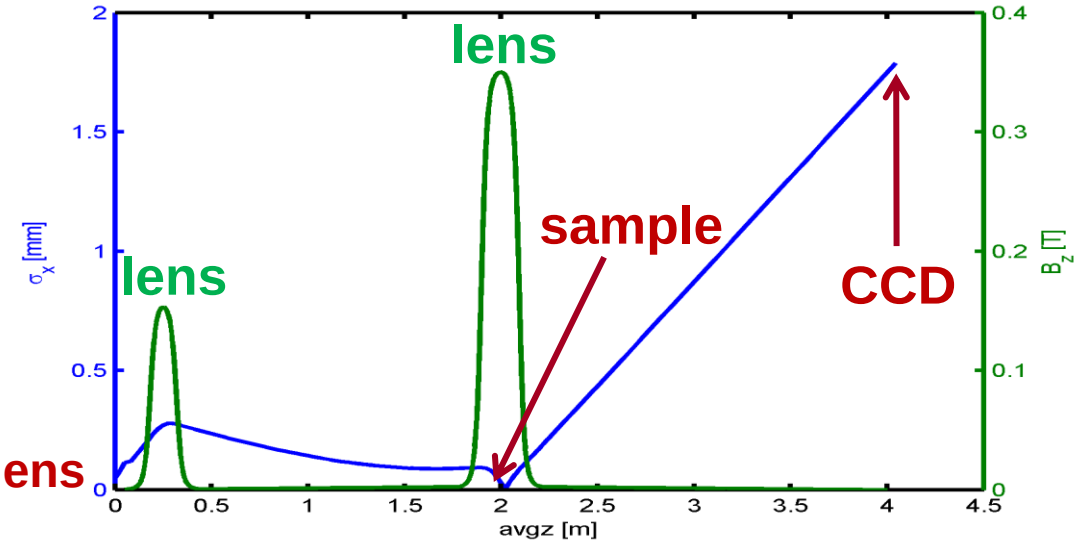
Initial test of a prototype MeV UEM

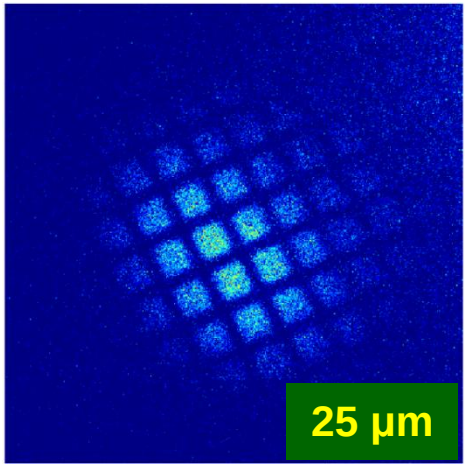


Simulation

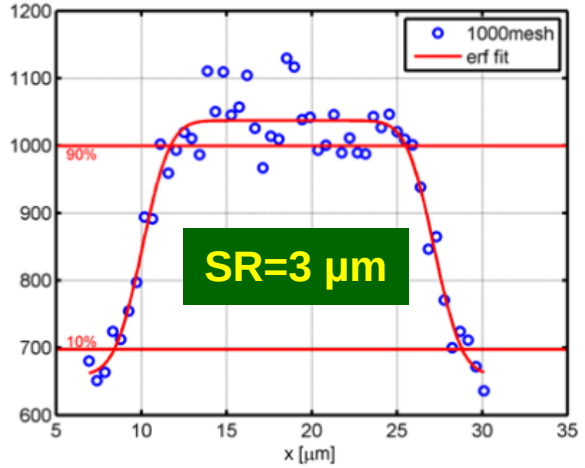


Condenser-objective lens

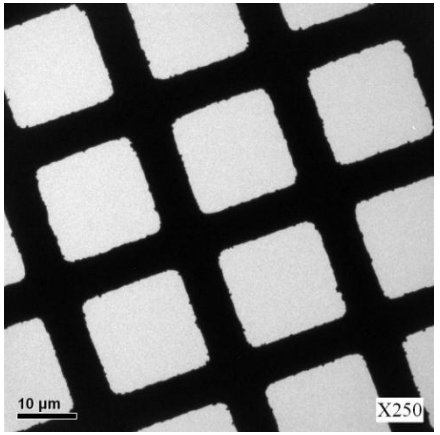




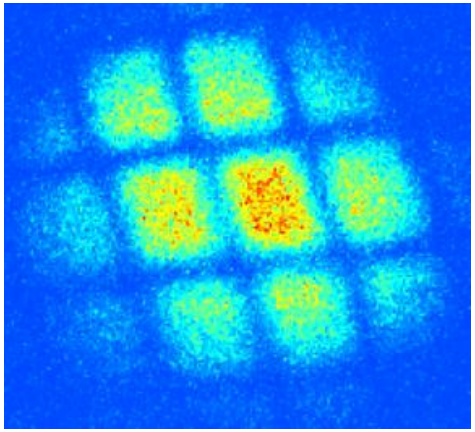
MeV UEM



Resolution



keV TEM

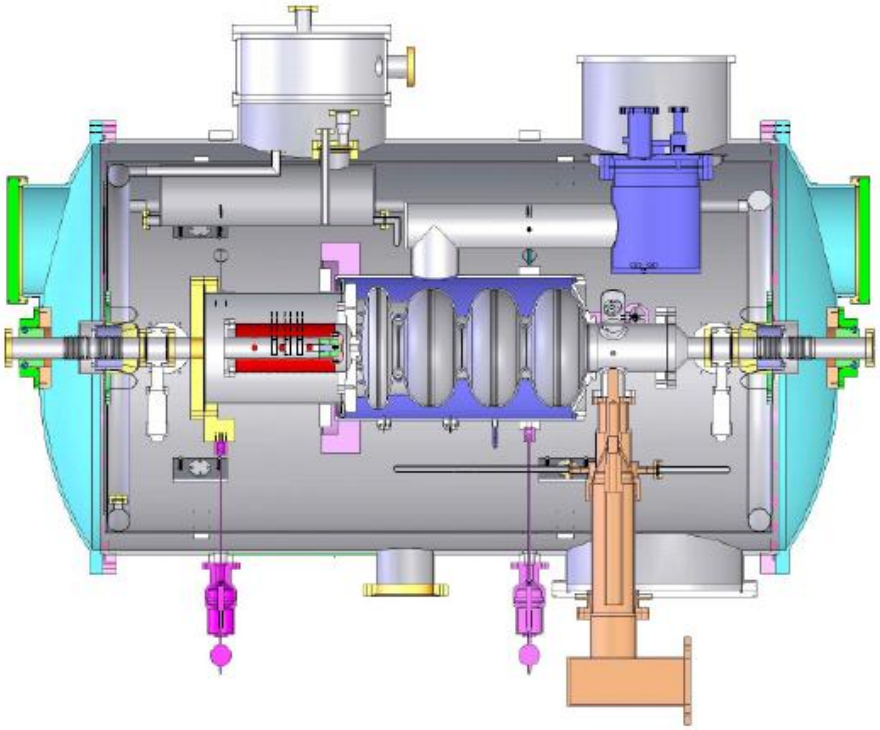


Space charge

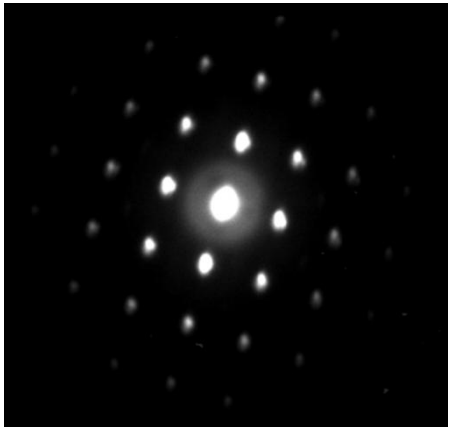
Temporal-spatial resolution (300 fs*3μm=10^{-18} s*m);

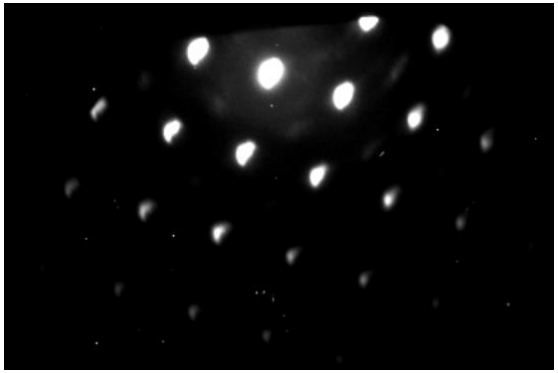
Shoot for 10^{-19} s*m with our user facility

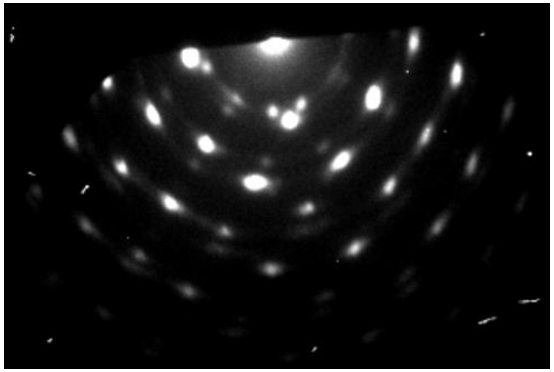
Test of MHz MeV UED (PKU-SJTU collaboration)



DC-SRF 3.5 cell 1.3 GHz gun







- ✓ Beam energy: 3.4 MeV； Rep-rate: 81.25 MHz
- ✓ Beam current: up to ~1 mA (~10^{16} e/s)
- ✓ Permanent damage induced by 81.25 MHz beam;
- ✓ Forbidden peaks are observed;
- ✓ Likely due to heat-stress related distortion (surface bulging; 2.2 microsecond recovery time).

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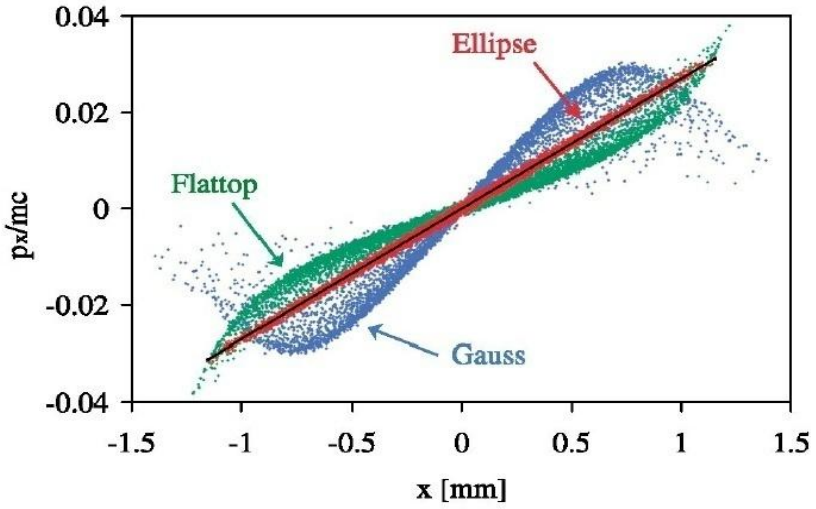
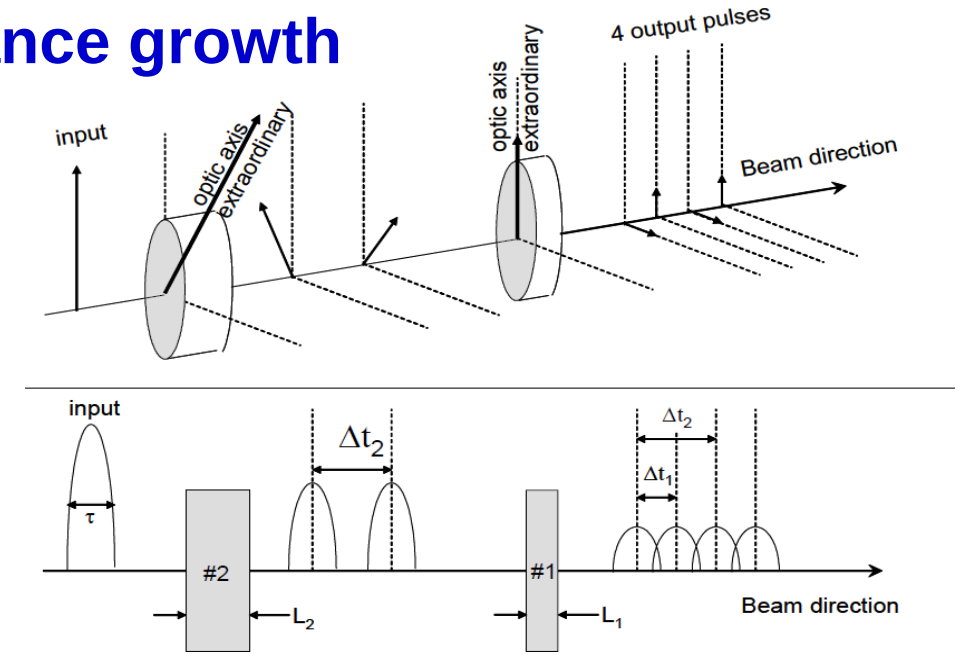
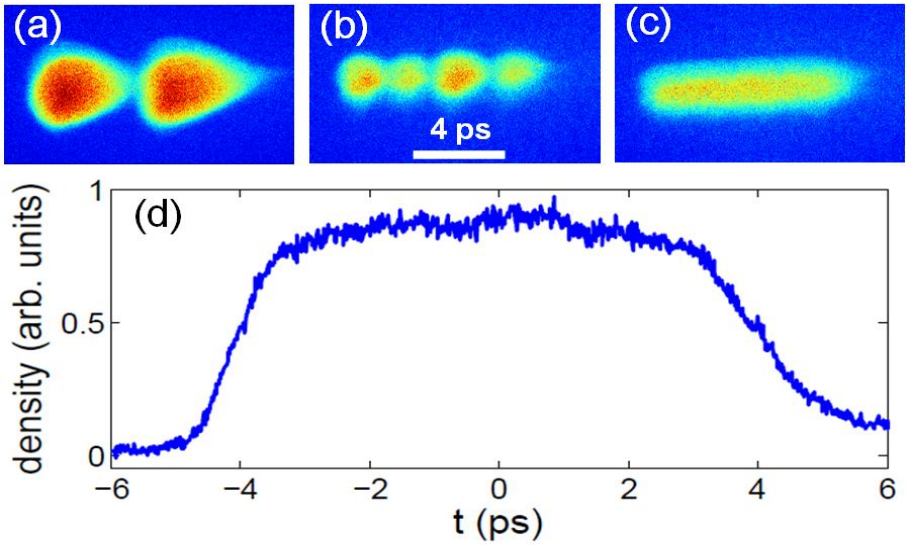
Improving beam brightness

1. Laser shaping to reduce emittance growth



Beam transverse phase space for various laser distribution (PRL 2004)

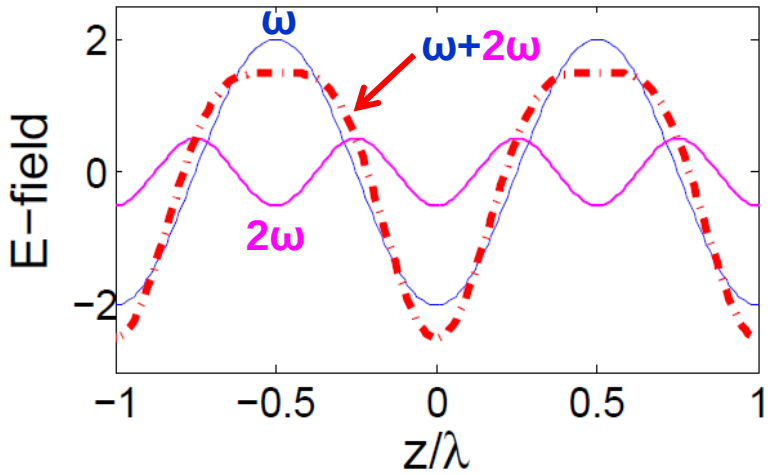




- ✓ **3 alpha-BBO crystals to produce 8 laser pulse trains**
- ✓ **Pulse separation < pulse width**
- ✓ **Nearly flat-top distribution**

Improving beam brightness

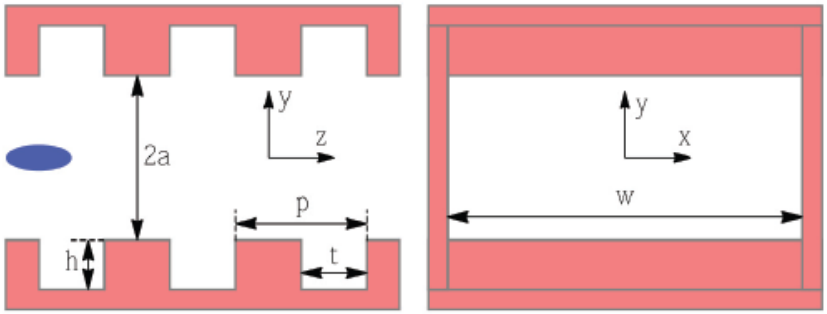
2. Corrugated structure to reduce beam energy spread



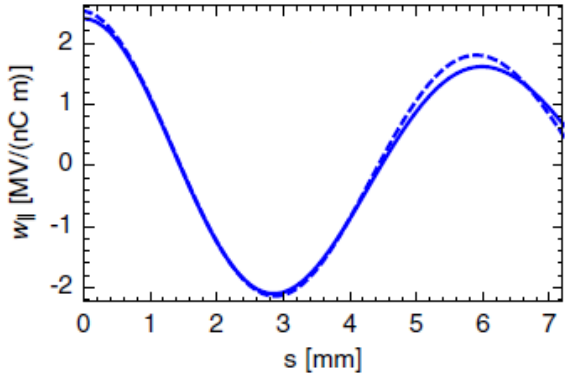
Quadratic chirp removal with an rf cavity

- ✓ Requires one more rf station
- ✓ Requires accurate control of the phase
- ✓ Beam energy reduces by $1/n^2$

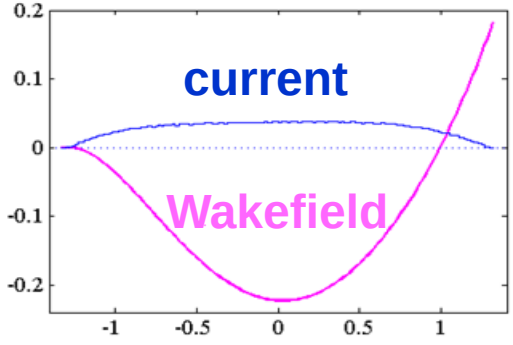
Quadratic chirp removal with a passive device



$$W(z) = \frac{\pi^2}{16}\frac{Z_0 c}{\pi a^2} F e^{-\frac{kz}{2Q}} \cos(kz)$$



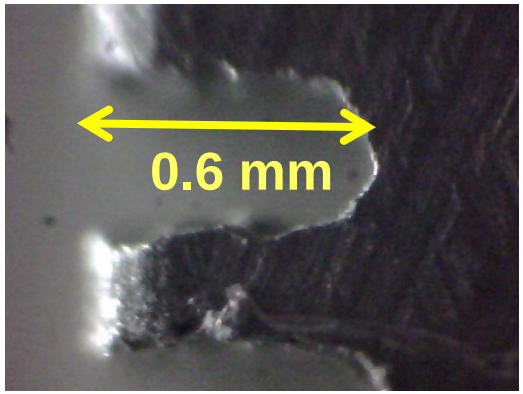
Green function

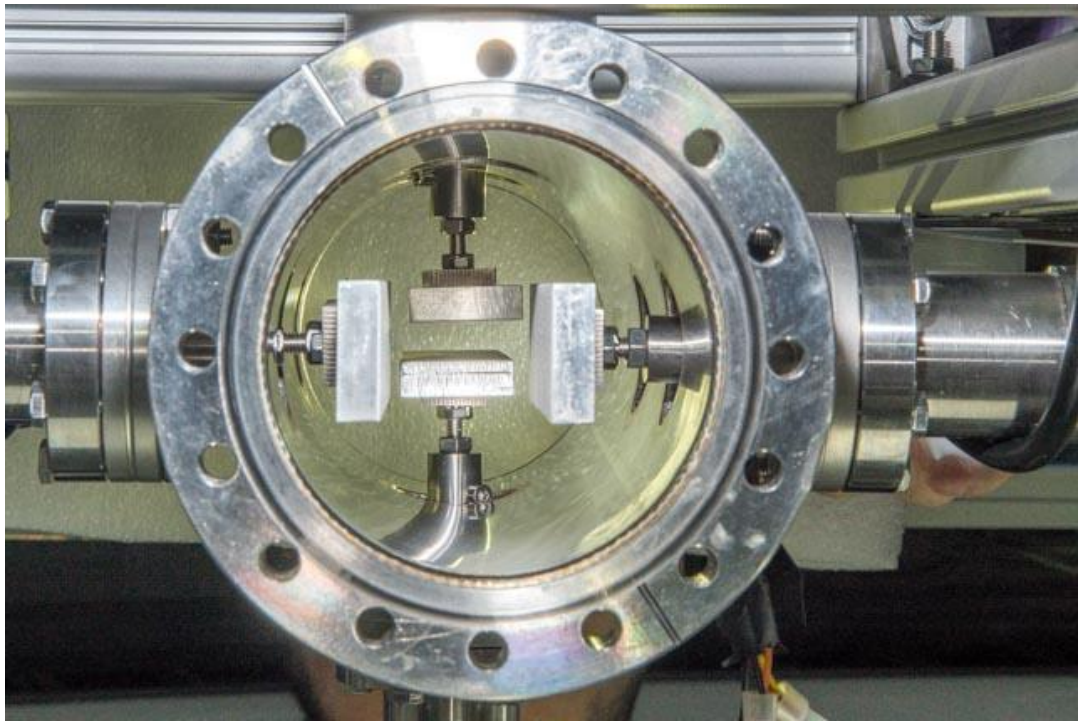


E-beam wakefield

Improving beam brightness

2. Corrugated structure to reduce beam energy spread





Improving beam brightness

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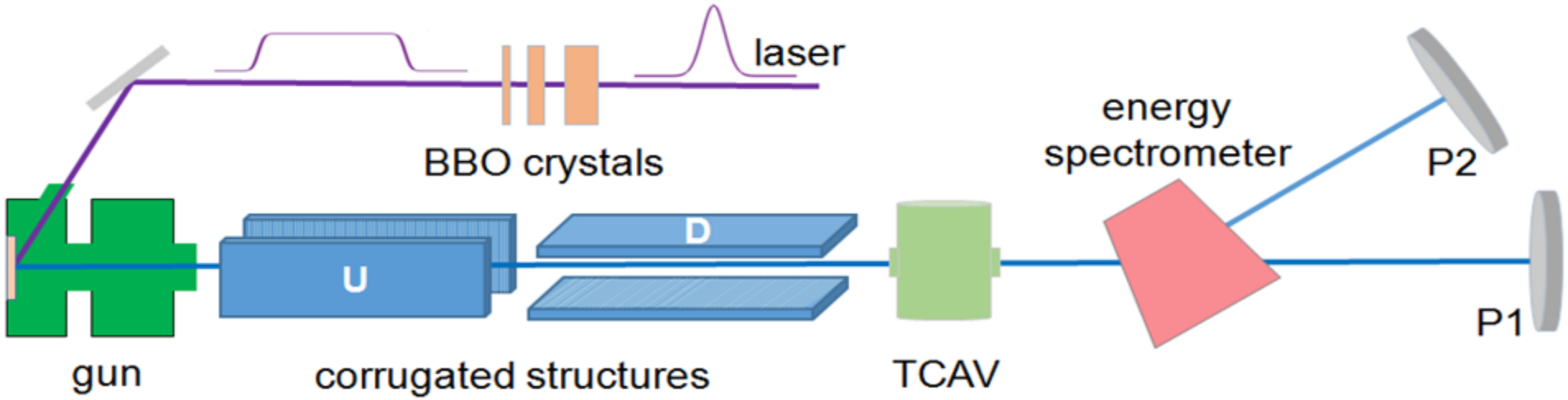

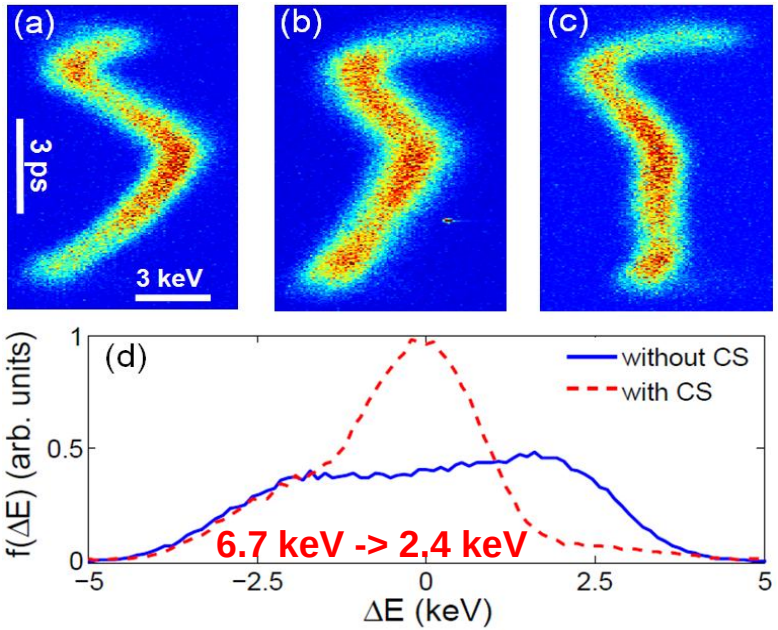

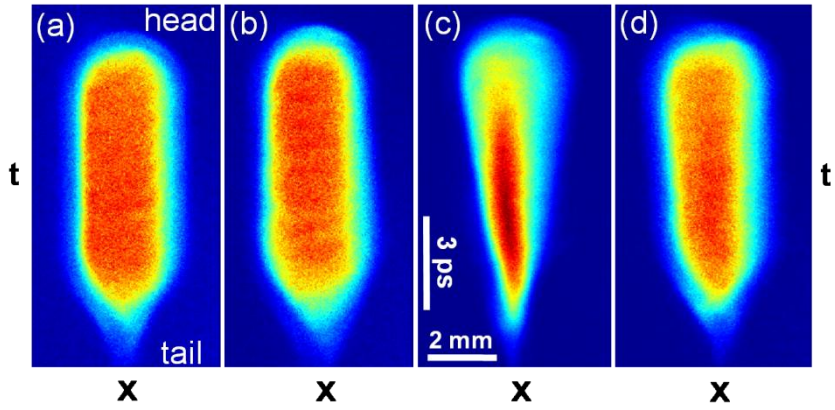

Quadrupole wake cancellation

Fu et al., PRL 114, 114801 (2015)

Outline

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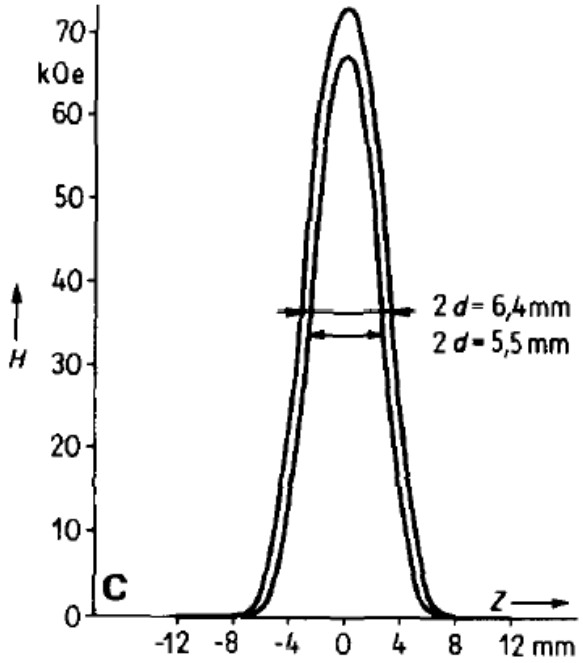
Development of high-field objective lens

1. Superconducting solenoids

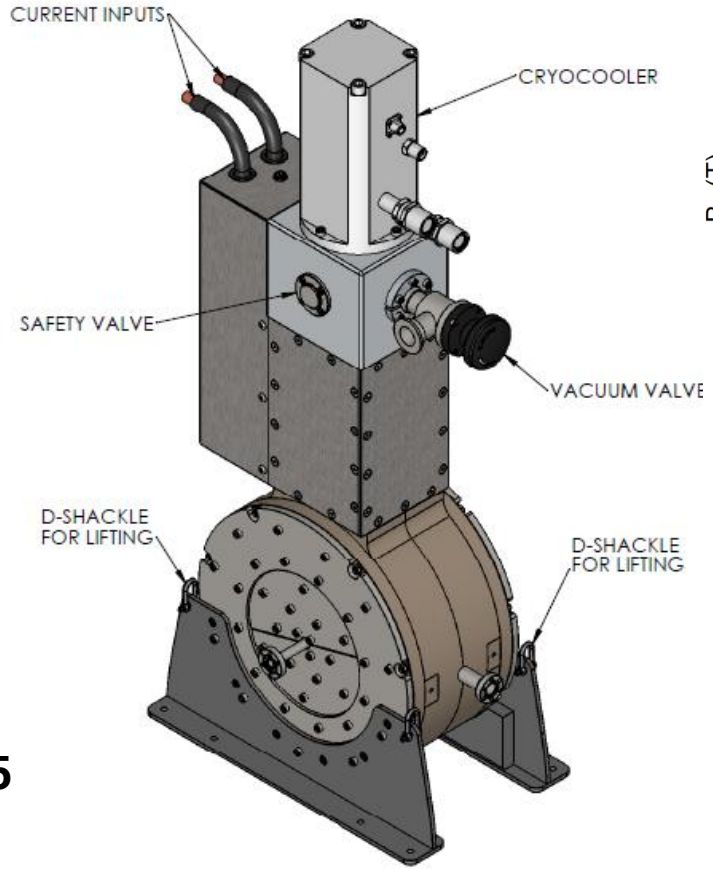
$$\frac{1}{f} = \frac{e^2}{4\gamma^2 m^2 v_z^2} \int B_z^2 \mathrm{d}z$$

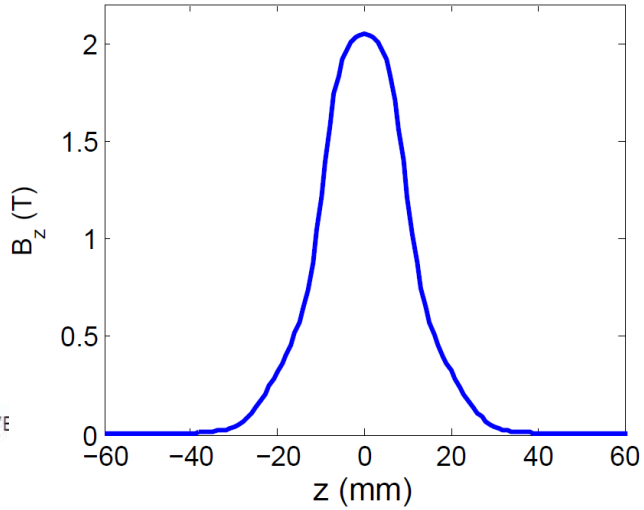
$C_c \sim C_s \sim f$

High-field lens needed for MeV UEM



A shielding lens with >7 T field provides *f*=2 mm for a 1.5 MV TEM (Dietrich et al., 1967)





Magnetic field of the HTS solenoid

To be delivered to SJTU in 09/2015

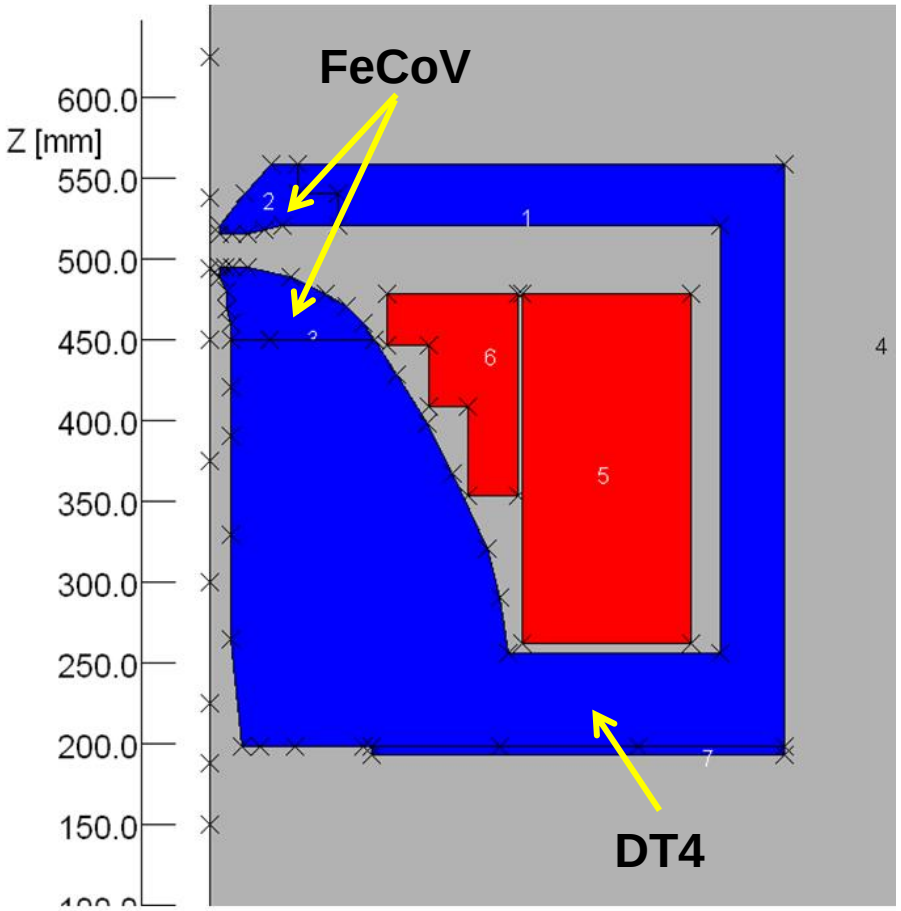
Development of high-field objective lens

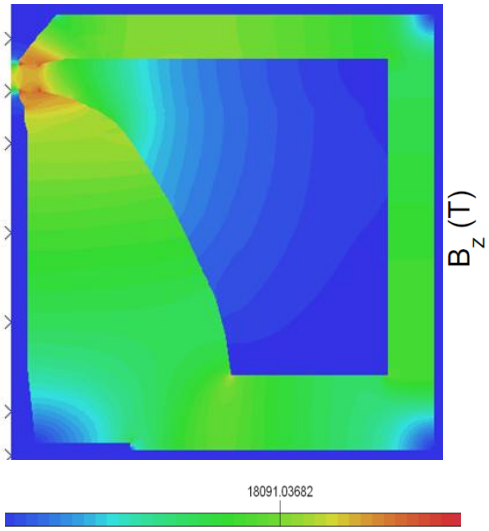
2. Room-temperature electromagnetic solenoids

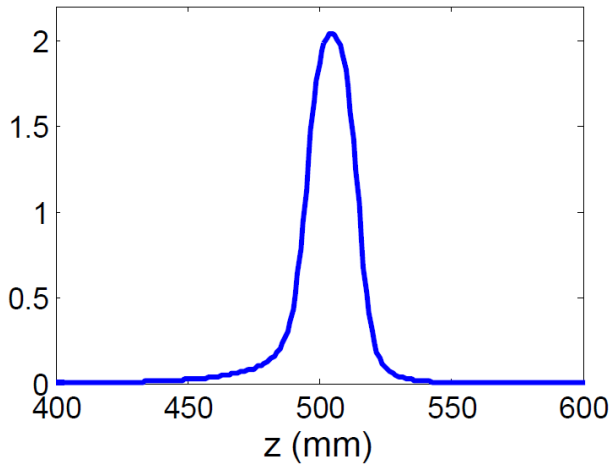
$$\frac{1}{f} = \frac{e^2}{4\gamma^2 m^2 v_z^2} \int B_z^2 \mathrm{d}z$$

$C_c \sim C_s \sim f$

High-field lens needed for MeV UEM







Magnetic field of the conventional solenoid
B_p=2.1 T when J=1.6 A/mm^2

Diameter: ~75 cm
Height: ~37 cm
Weight: ~1 ton

To be delivered to SJTU in 12/2015

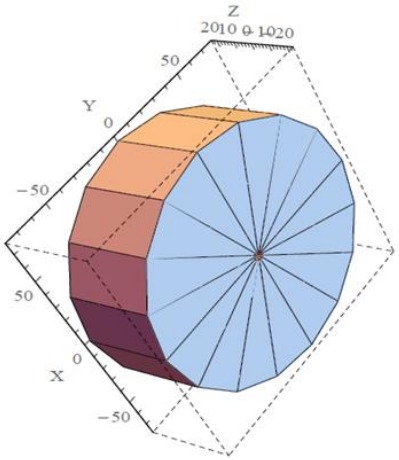
Development of high-field objective lens

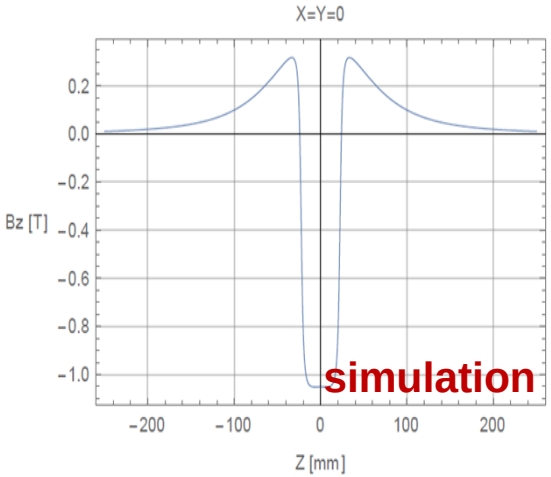
3. Permanent magnet solenoid (PMS) and quadrupole (PMQ)

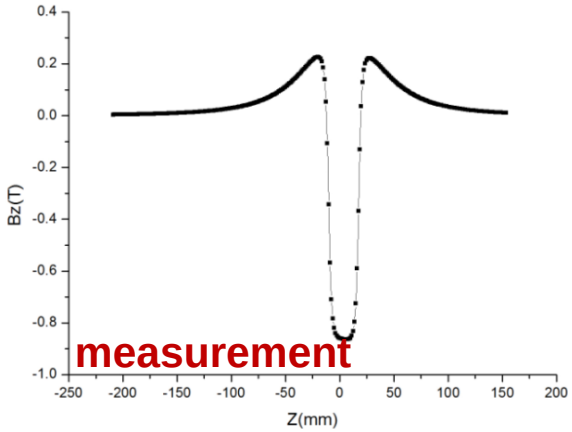
$$\frac{1}{f} = \frac{e^2}{4\gamma^2 m^2 v_z^2} \int B_z^2 \mathrm{d}z$$

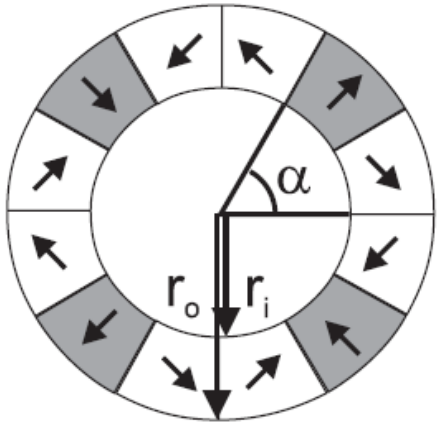
$C_c \sim C_s \sim f$

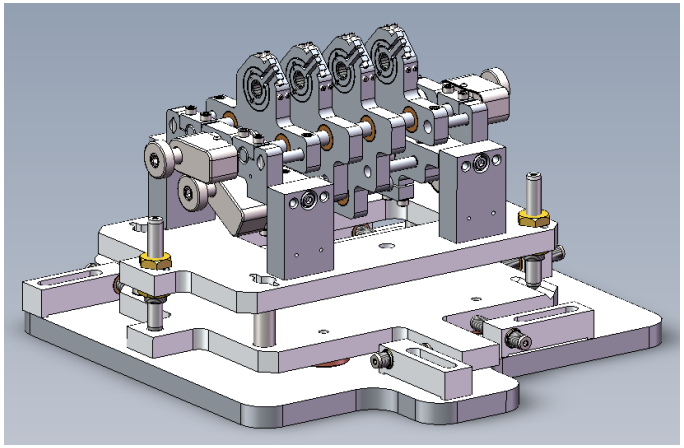
High-field lens needed for MeV UEM











- ✓ Russian quadruplet (FDFD)
- ✓ X/Y back focal planes coincide
- ✓ Movable with in-vacuum motors

PMQ to be delivered to SJTU in 06/2015

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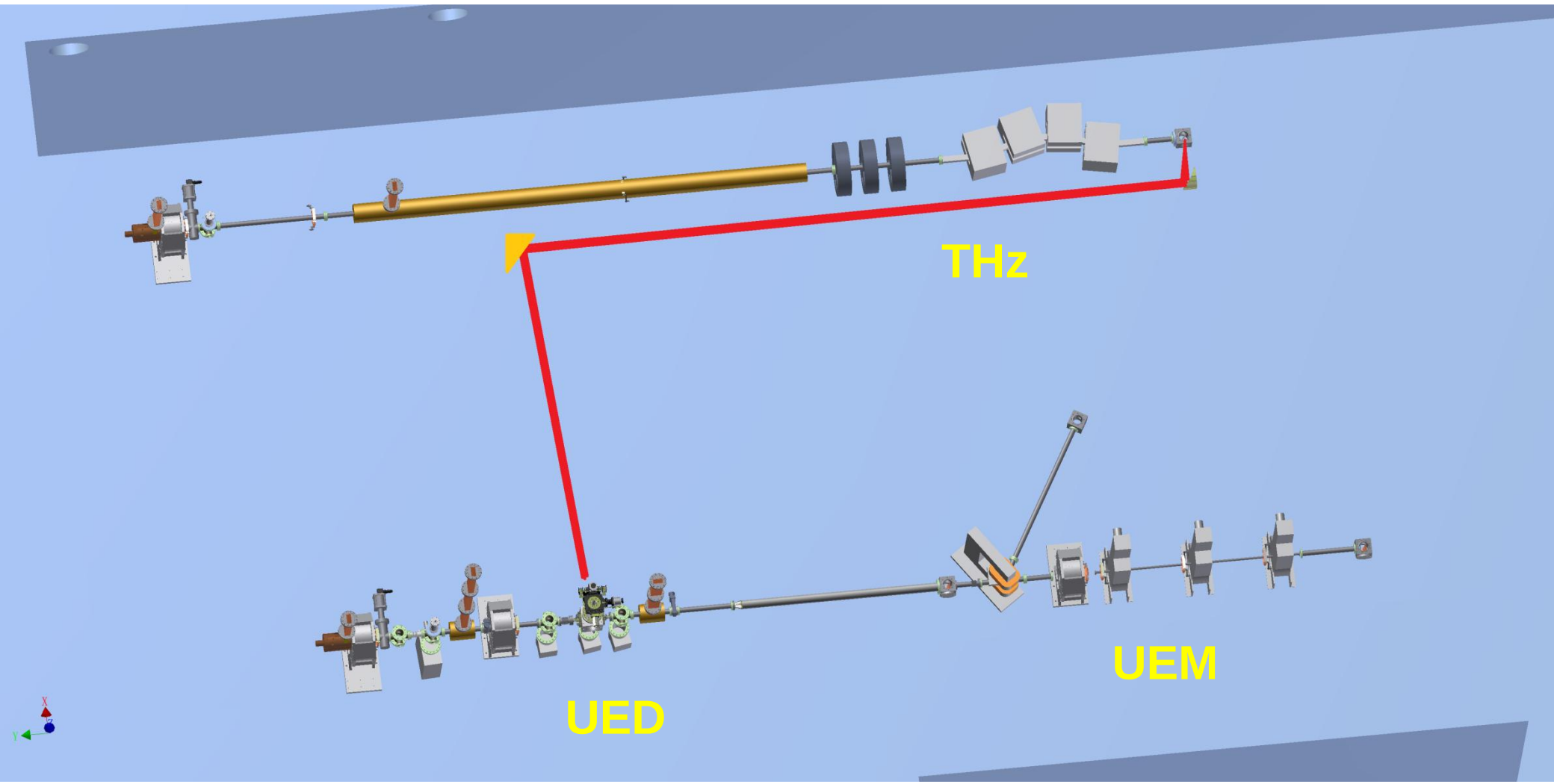
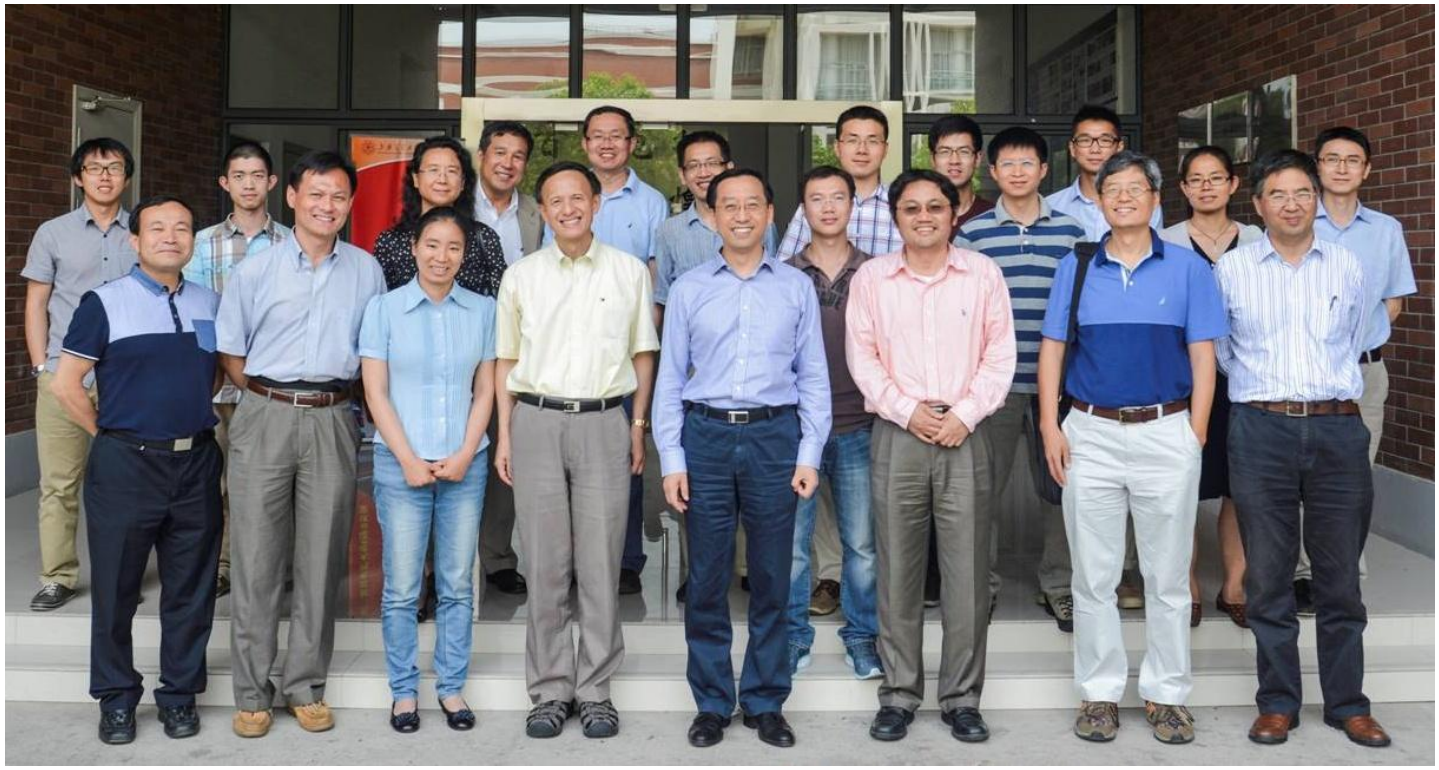
Future plans



- ✓ Gatan K2 detector;
- ✓ A dedicated intense THz source for THz-pump UED-probe.



Thanks !

Everyone is welcome to use our UED/UEM facility.