Pushing the limits of ultrafast electron diffraction at Tsinghua University

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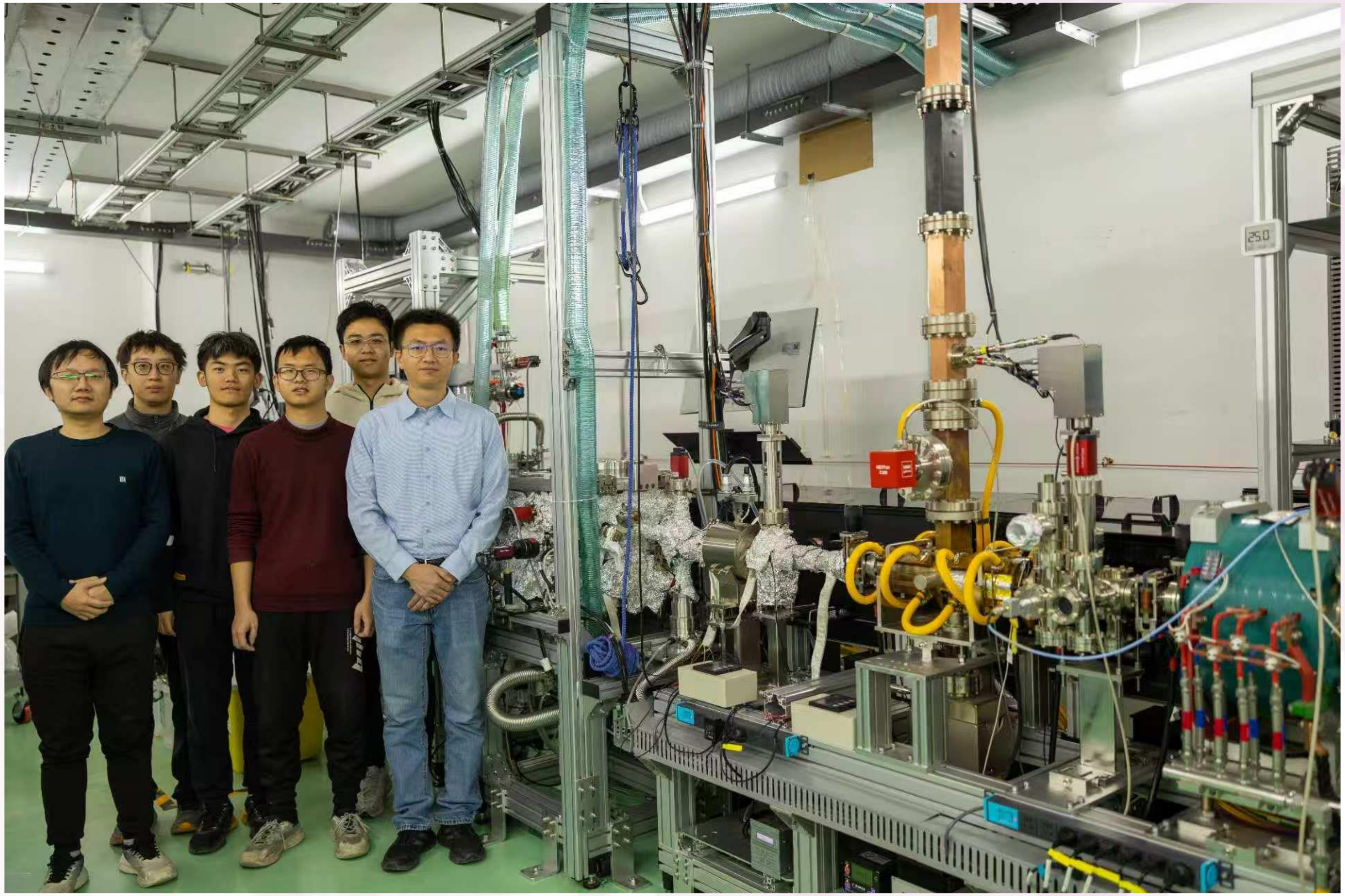
Acknowledgement

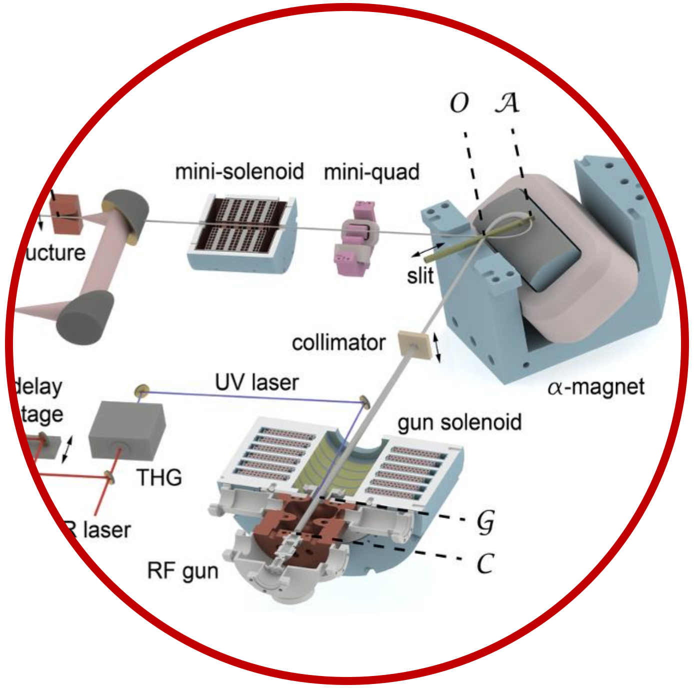
- Collaboration and discussions with many colleagues, especially at Cornell, UCLA, and SLAC
- Colleagues at Tsinghua & team members: P. W. Huang, Z. C. Dong, Y. M. Tan, Y. A. Wang, X. Y. Zhang, Y. N. Yang, P. Lv, Z. Y. Wang, B. T. Song, Z. X. Liu etc.
- Funding agencies



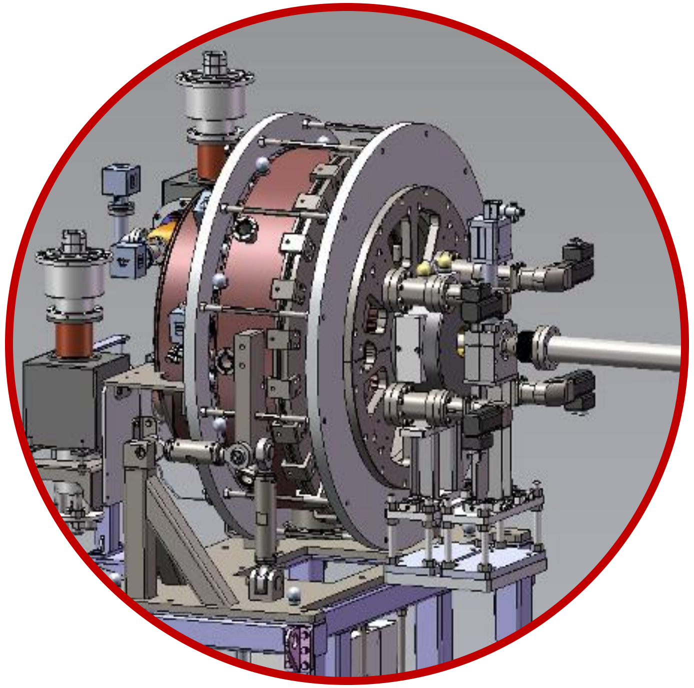
Outline

FORTRESS
stable & flexible

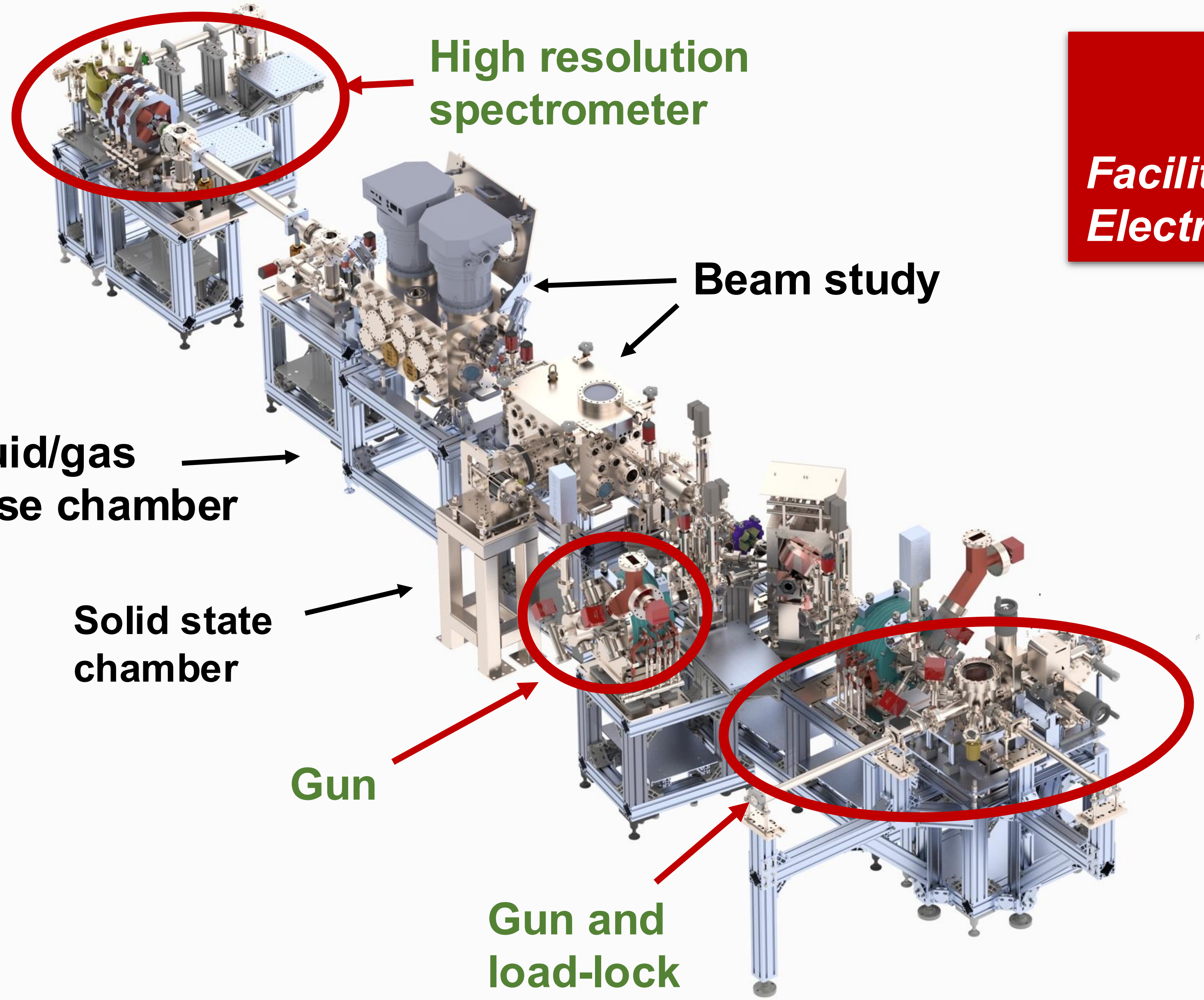
~5-fs
temporal control



High rep-rate
UED and imaging



New beamline for bright beams research

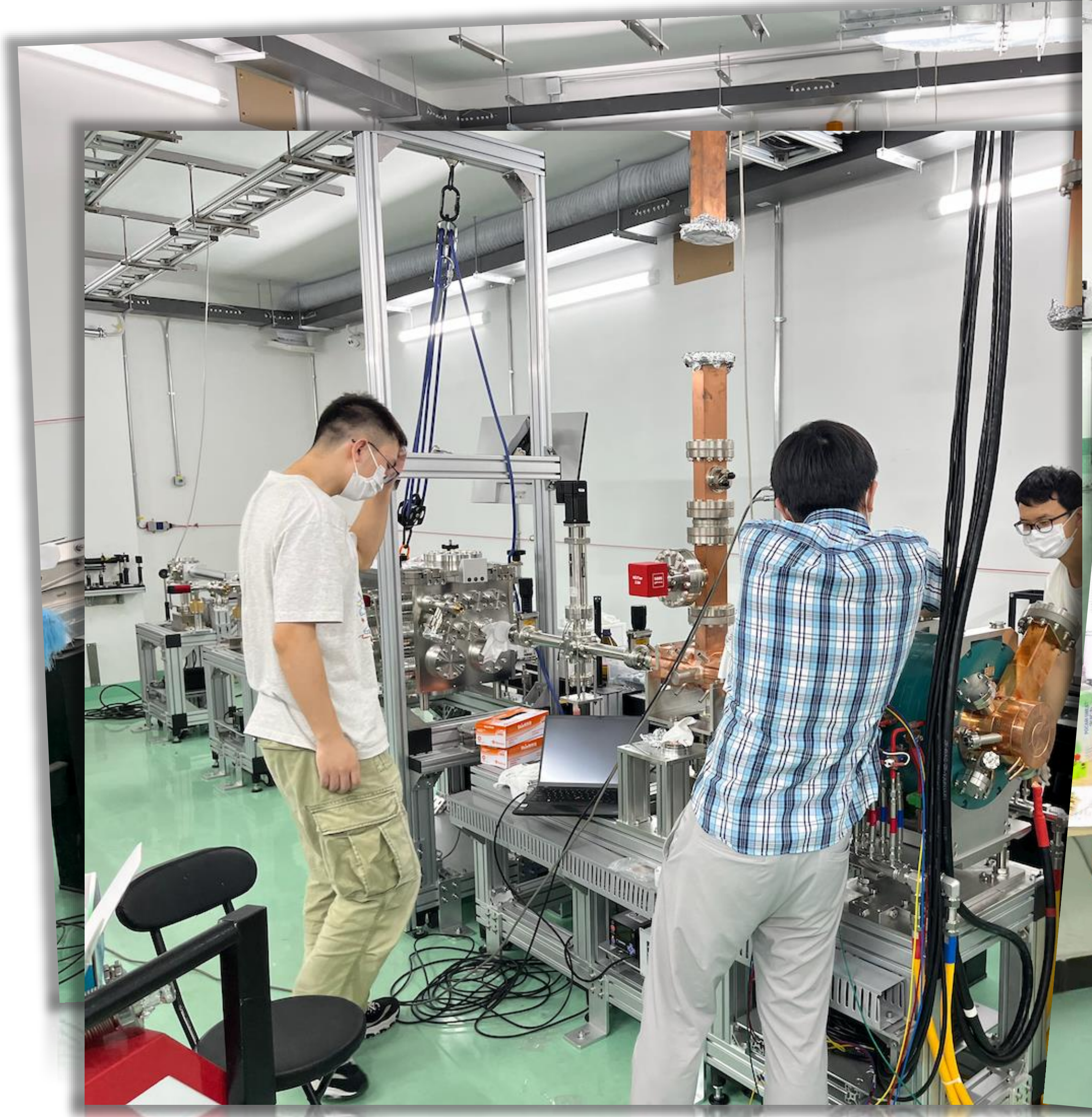


FORTRESS

Facility of Relativistic Time-Resolved Electron Sources and Scattering

- **Sources and cathodes**
- **Low emittance**
- **fs bunch and timing**
- **Advanced diagnostics**
- **UED/UEM**
- **Training students**

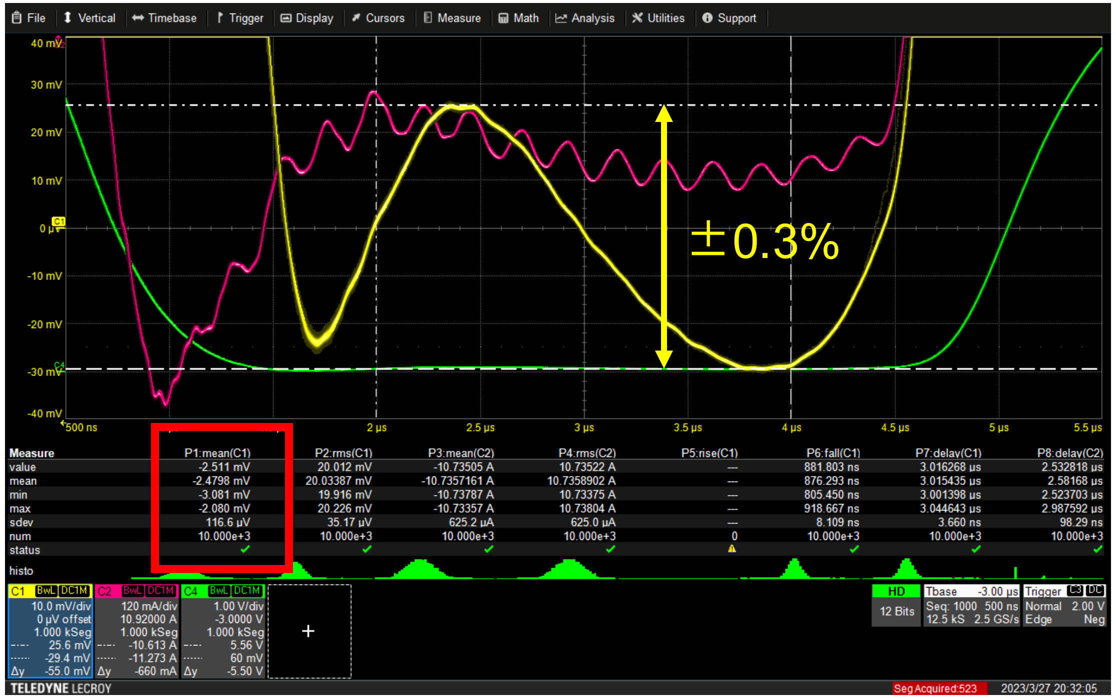
Construction of FORTRESS



Key components for high stability

❑ Solid state modulator

- HV shot-to-shot fluctuation <20 ppm, with drift feedback for long-term stability

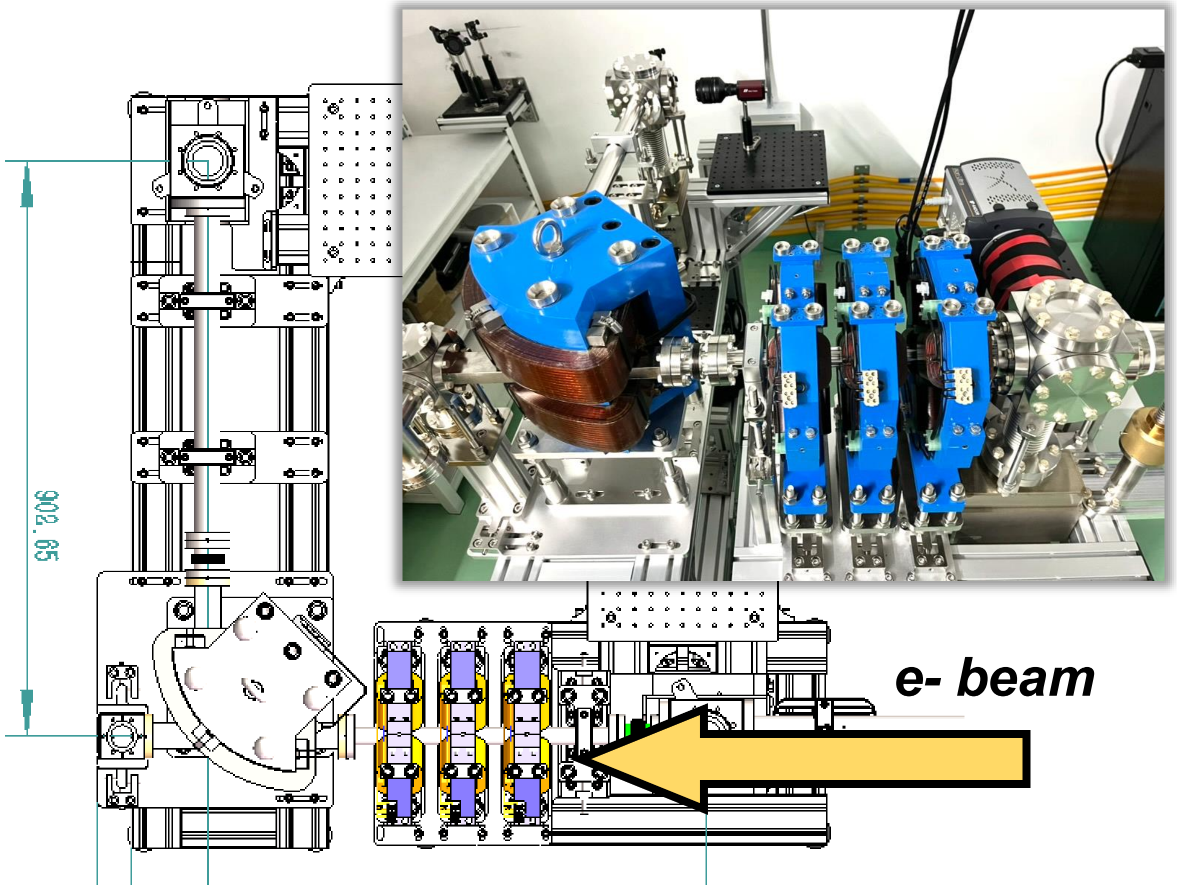


- **Best shot-to-shot stability measured 13 ppm (10,000 shots)**

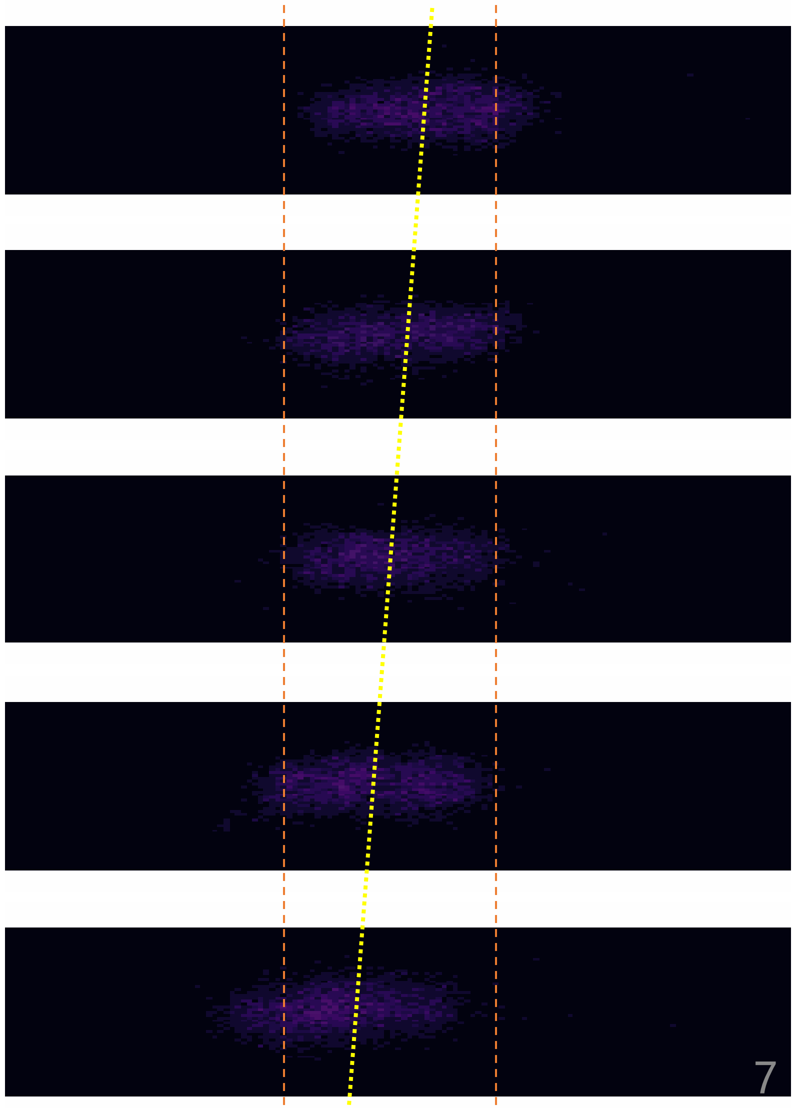
- **Routinely under 20 ppm for many hours**

High resolution spectrometer

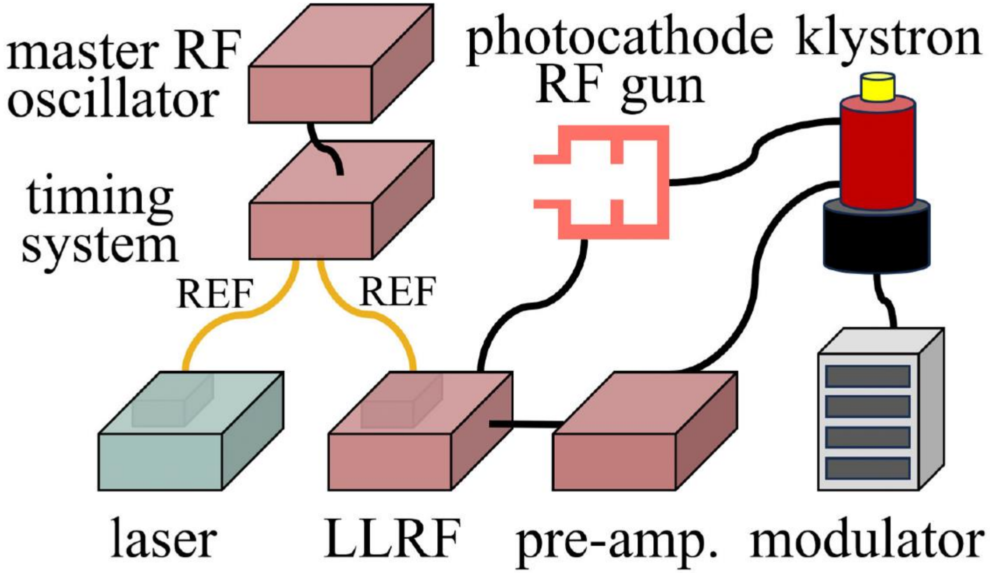
- Dispersion $D = 0.89\ m$
- Beam centroid ~ 10 μm
- ~10^{-5} energy resolution



rf amp. setting	Spectrometer images
-2.30×10^{-4}	
-1.15×10^{-4}	
Nominal	
$+1.15 \times 10^{-4}$	
$+2.30 \times 10^{-4}$	



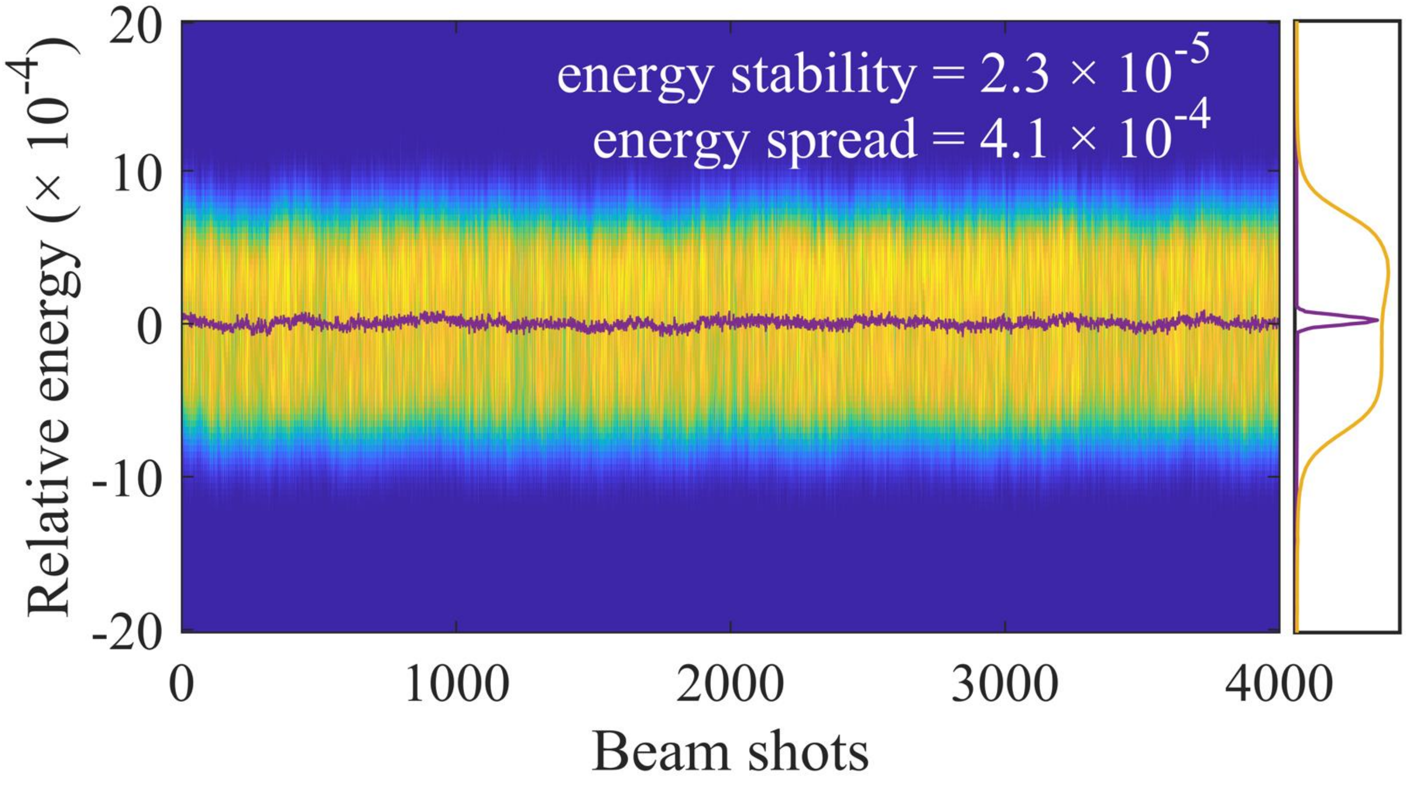
Energy stability



rf amp. stability $\sim 6 \times 10^{-5}$ rms (limited by electronics readout)

rf phase jitter $\lesssim$ 30 fs rms

Energy stability 2.3×10^{-5} rms



P. Lv et al., submitted

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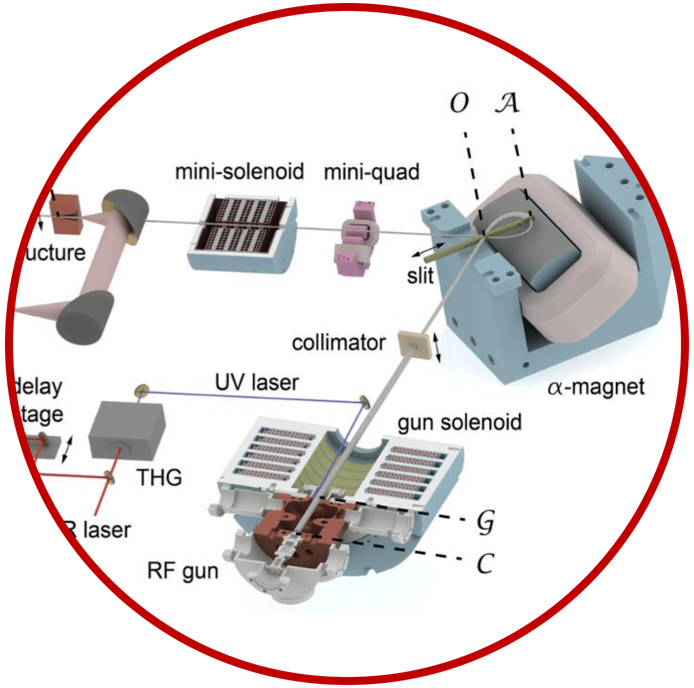
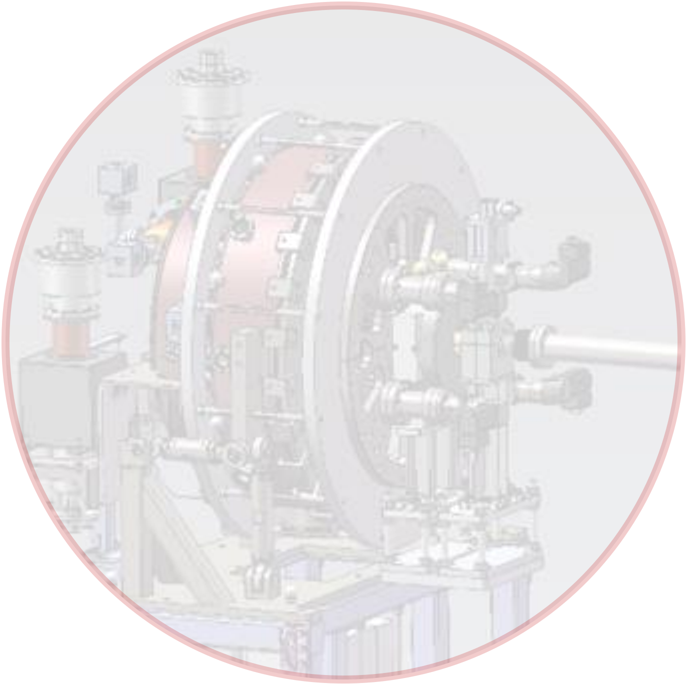
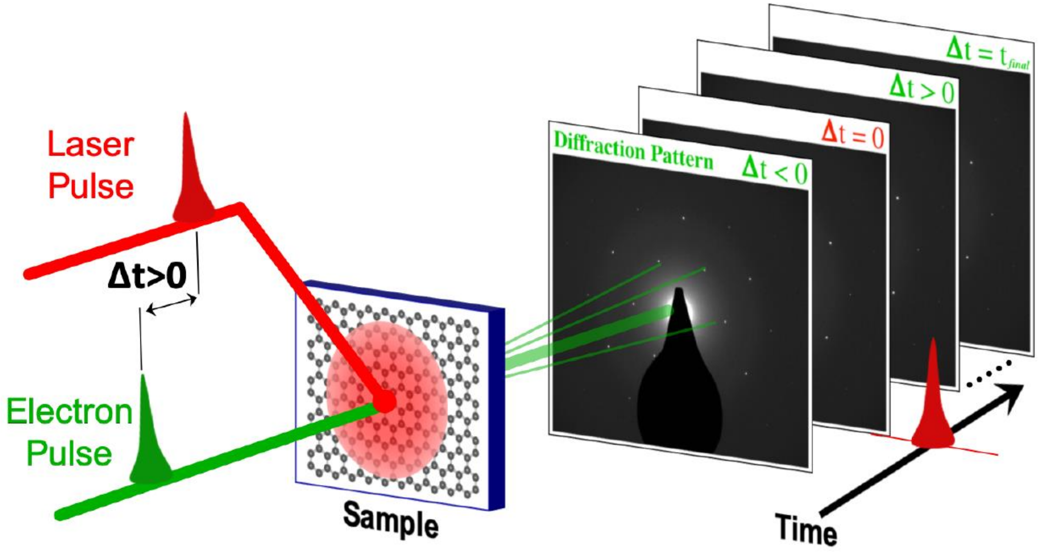


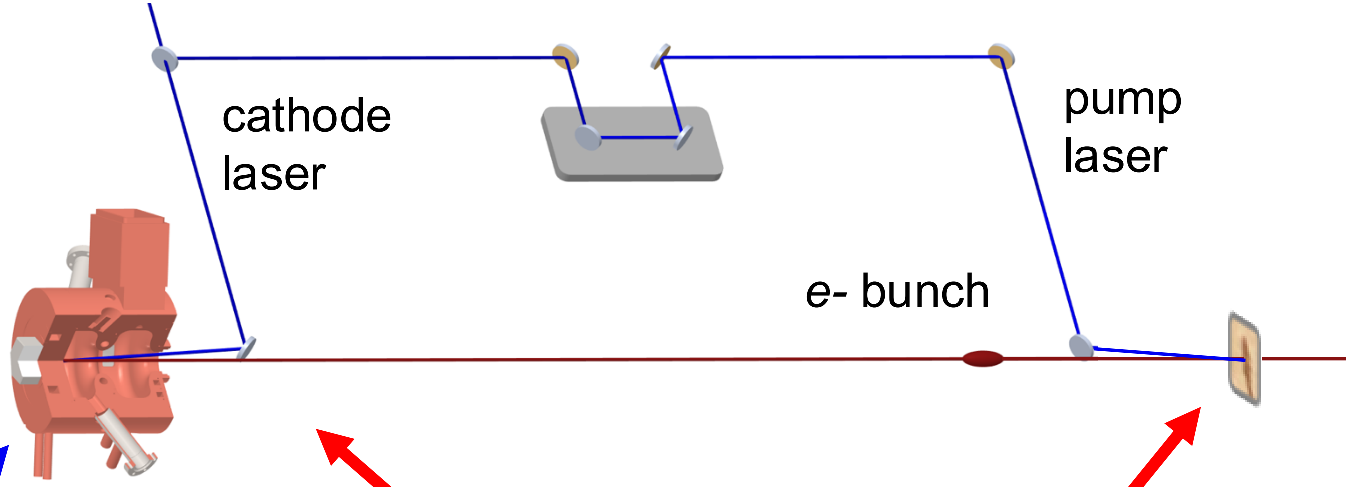
High rep-rate
UED and imaging



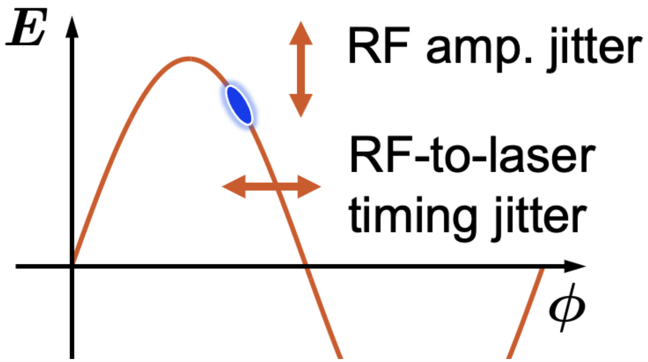
Temporal resolution and challenges

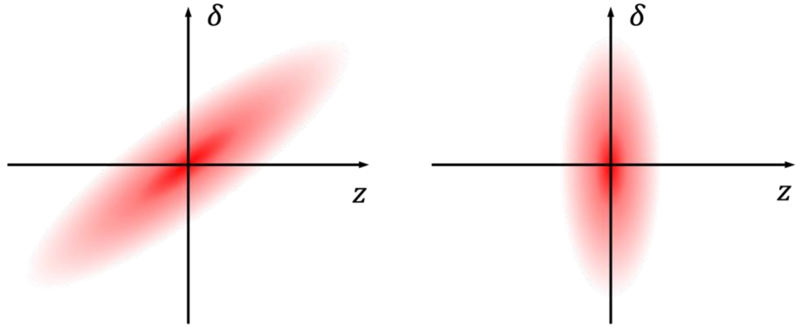
$$\tau_{\mathrm{res}} = \sqrt{\tau_{\mathrm{ph}}^2 + \tau_{\mathrm{e}}^2 + \tau_{\mathrm{TOF}}^2}$$



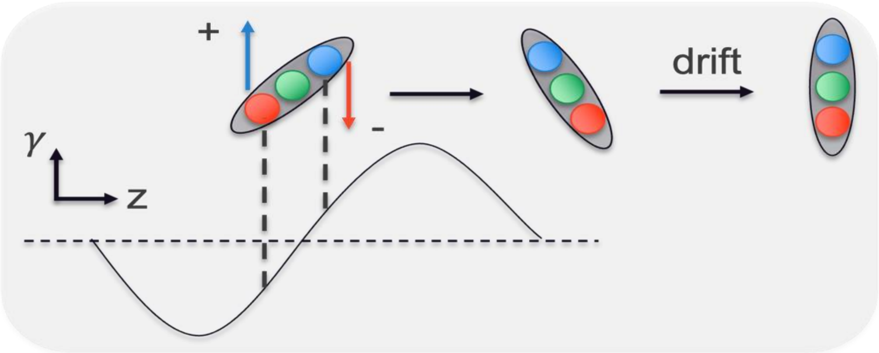


- t_0: when laser hits cathode and sample (w/ fixed delay)
- **TOF:** time of flight of *e*- from cathode to sample
- τ_{TOF}: due to RF amp. and RF phase-laser jitter

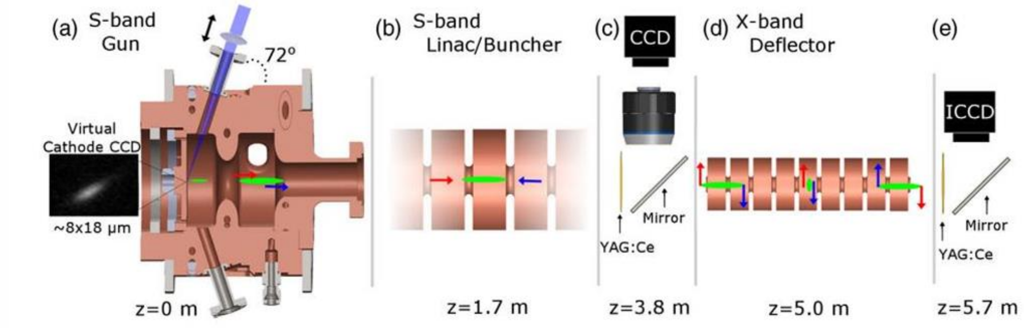




RF or THz compression

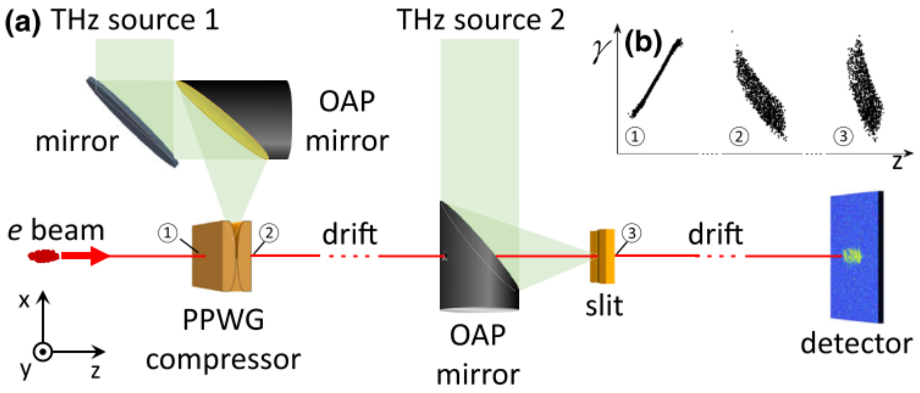


- Bunch head has higher energy
- Use an active RF or THz to **reverse the chirp**
- Bunch duration compresses during drift



- well-known 'velocity bunching' scheme
- Sub-10 fs bunch achieved
- But τ_{TOF} remain **>10s of fs**

Maxson et al., PRL **118**, 154802 (2017)

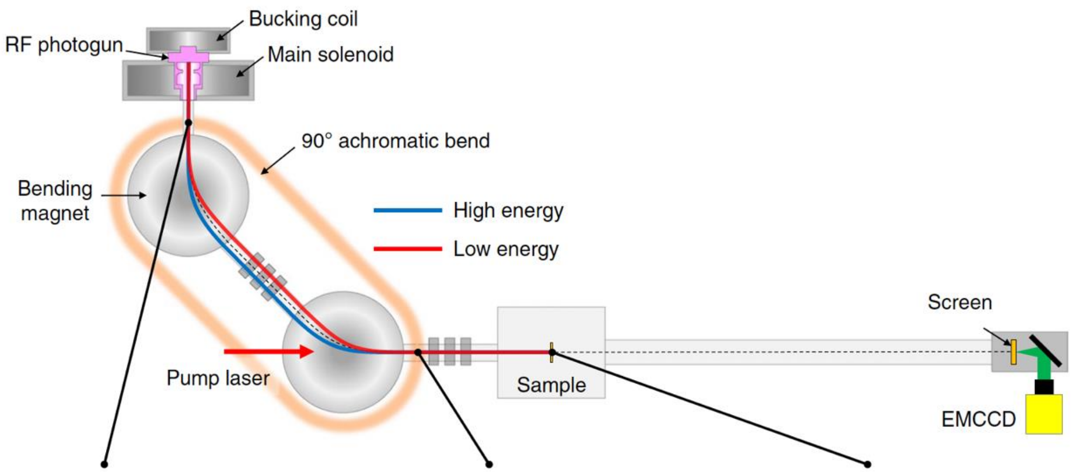


- THz intrinsically sync w/ laser
- **10s of fs τ_e and τ_{TOF}**
- Limited by small structure size, trans.-longi. coupling, THz waveforms, demand on laser etc.

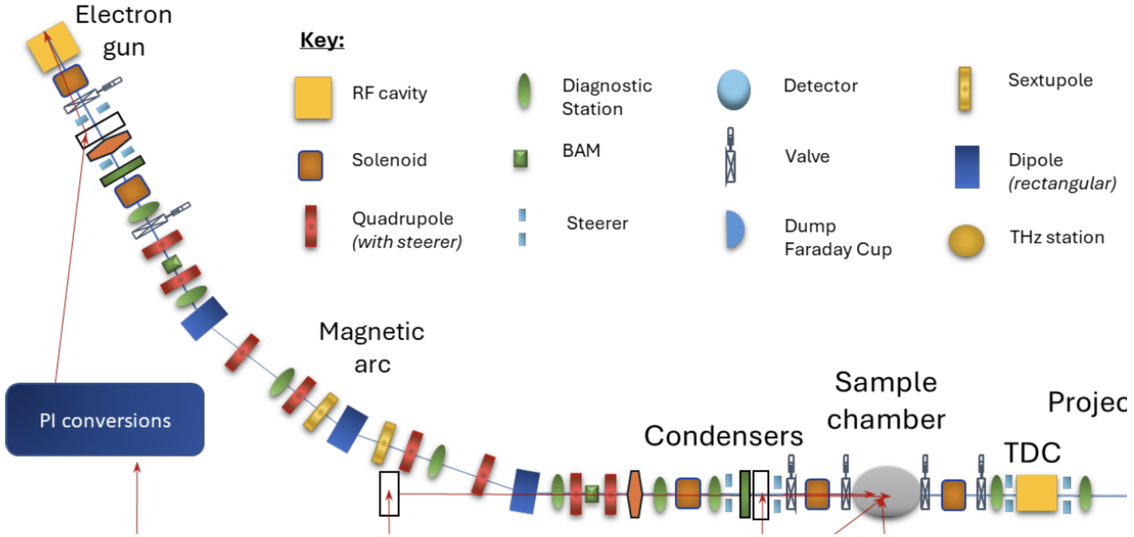
Snively et al., PRL **124**, 054801 (2020)
Zhao et al., PRL **124**, 054802 (2020)

DBA/TBA compression

- No need to reverse the chirp using RF/THz
- **Introduce DBA/TBA, common transport units, with R_{56} of opposite sign of drift sections**
- Stabilize TOF and compress τ_e
- Best measured combined precision **15-25 fs rms**
- TBA design w/ tunability to break the **10-fs barrier**

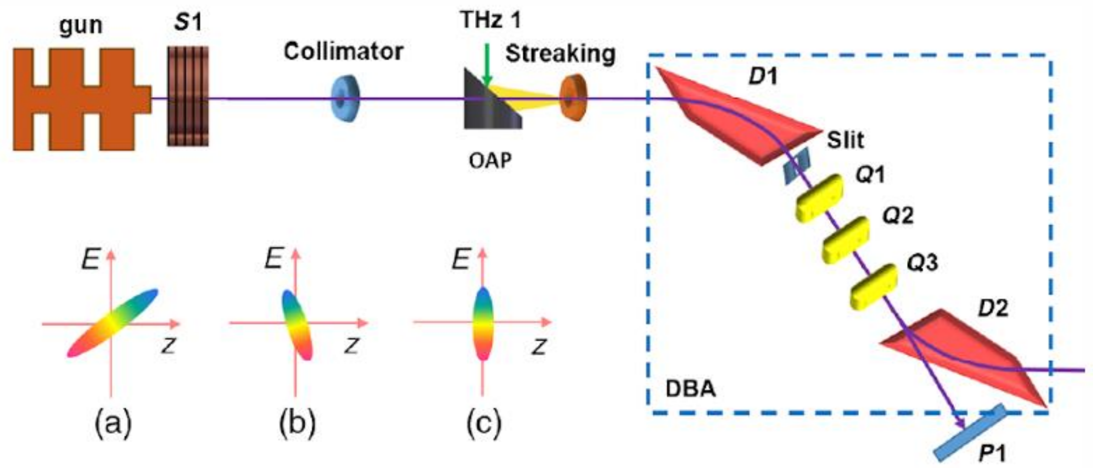


Kim et al., Nat. Photon. **14**, 245 (2020)



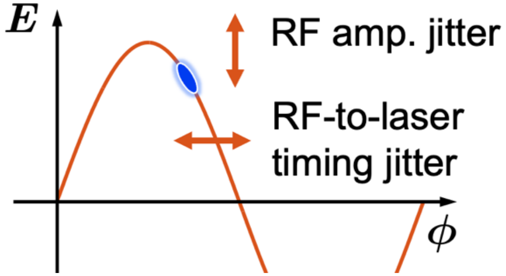
Hounsell et al., IPAC'25, TUPM021(2025)

Xu & England, arXiv:2408.00936

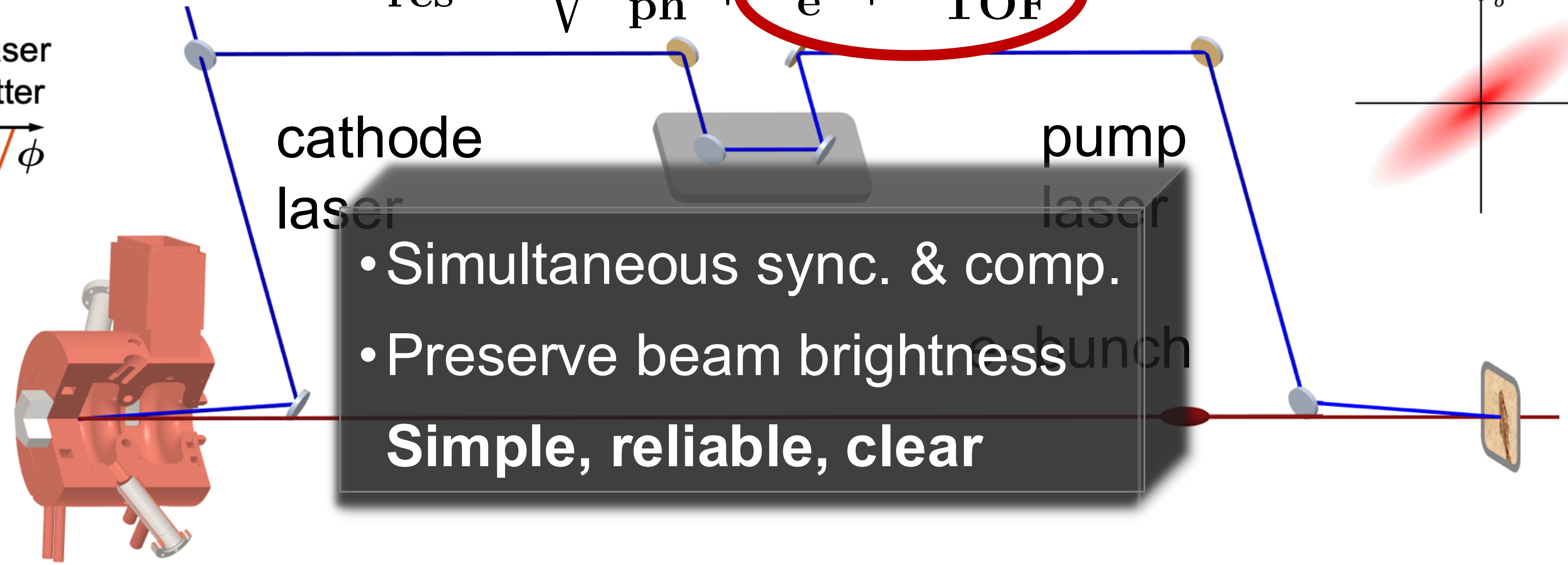


Qi et al., PRL **124**, 134803 (2020)

Criteria and challenges for temporal control

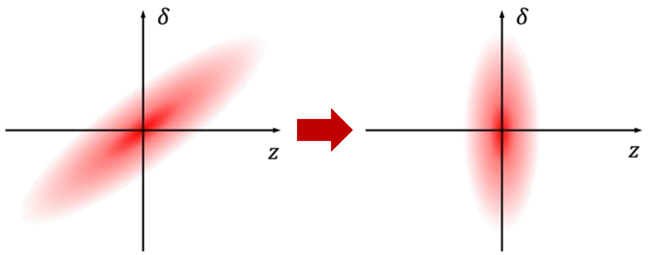


$$\tau_{\mathrm{res}} = \sqrt{\tau_{\mathrm{ph}}^2 + \tau_{\mathrm{e}}^2 + \tau_{\mathrm{TOF}}^2}$$



- Simultaneous sync. & comp.
- Preserve beam brightness

Simple, reliable, clear



$$R_{56} = \frac{\delta z}{\delta p/p}$$

Fix cathode-target TOF

- $\delta\gamma$ inevitable, try make $R_{56} \to 0$
- **RF phase-to-laser jitter still causes TOF jitter**

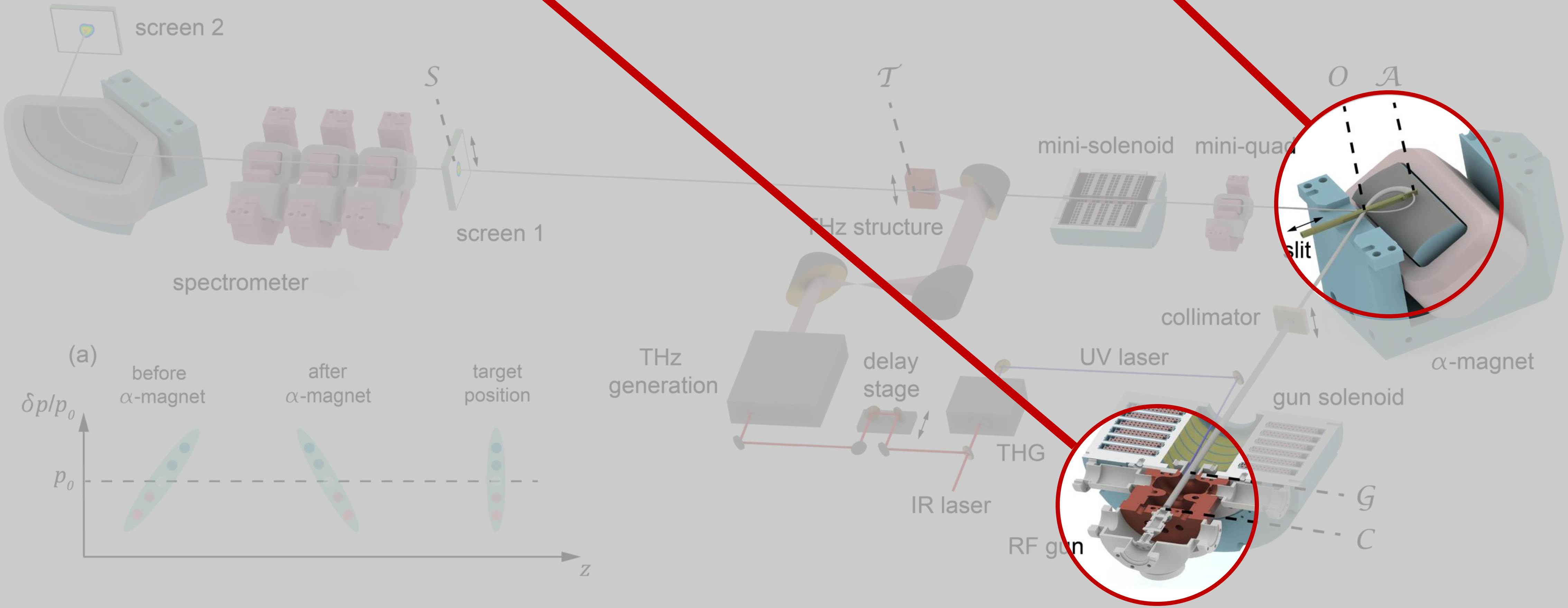
Compress bunch duration

- Rotate LPS w/o affecting centroid TOF (no ‘active’ EM fields)

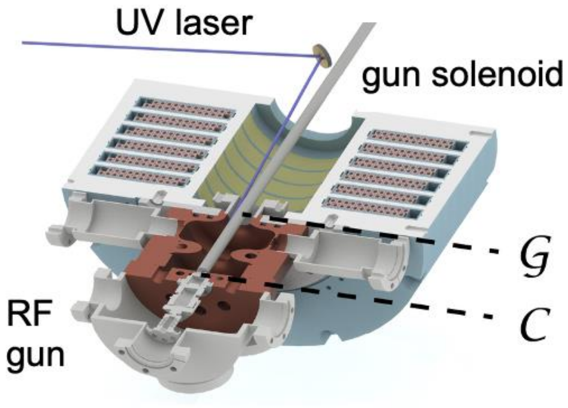
a new method for few-fs control

Low-jitter photoinjector

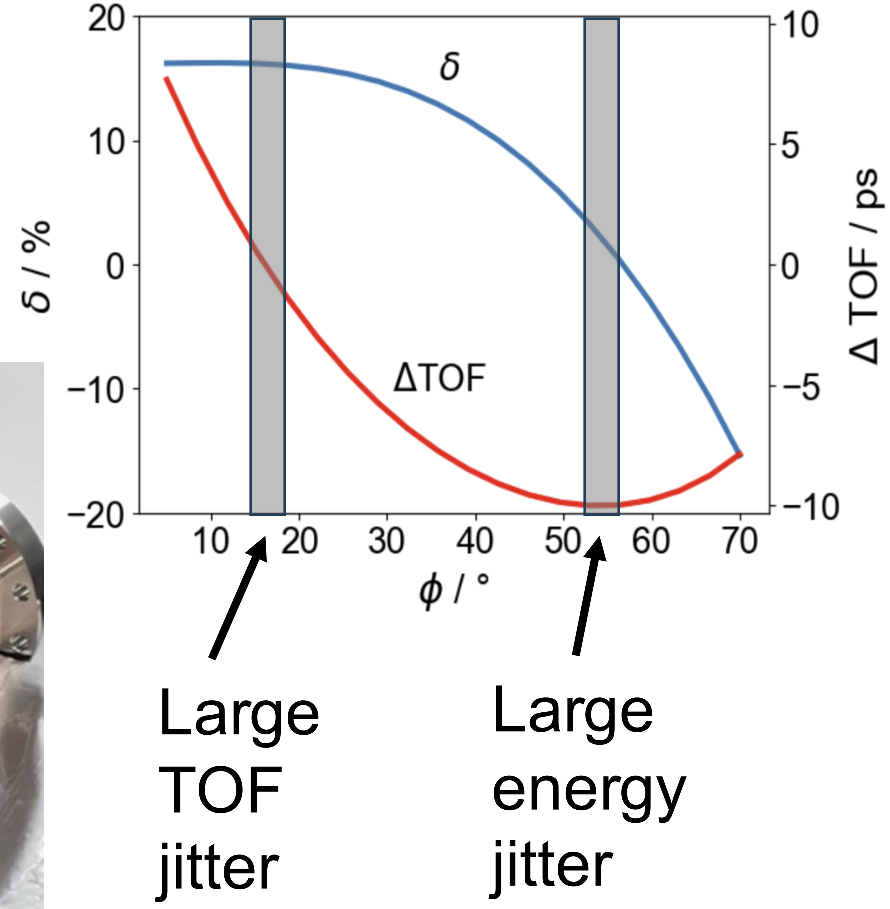
High-gradient α-magnet



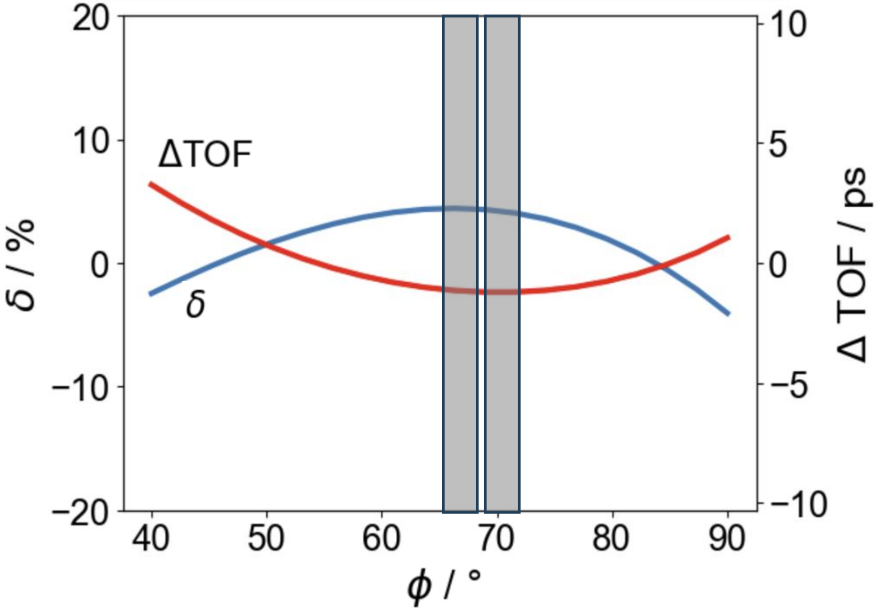
Low-jitter photoinjector



Conventional gun (1.6 cell)



New geometry (1.4 cell)

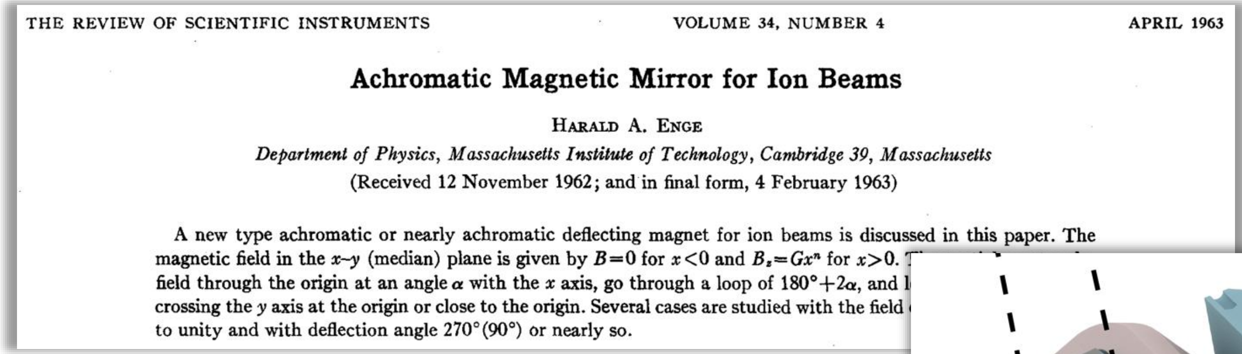


- Much less impact from $\Delta\phi$
- ΔRF amp. → Δmomentum, ΔTOF

Δmomentum ↕ ΔTOF: R_{56}

What is an α-magnet?

Harald Enge, proposed in 1963


THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 34, NUMBER 4 APRIL 1963

Achromatic Magnetic Mirror for Ion Beams

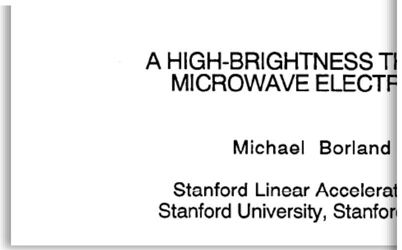
HARALD A. ENGE

Department of Physics, Massachusetts Institute of Technology, Cambridge 39, Massachusetts

(Received 12 November 1962; and in final form, 4 February 1963)

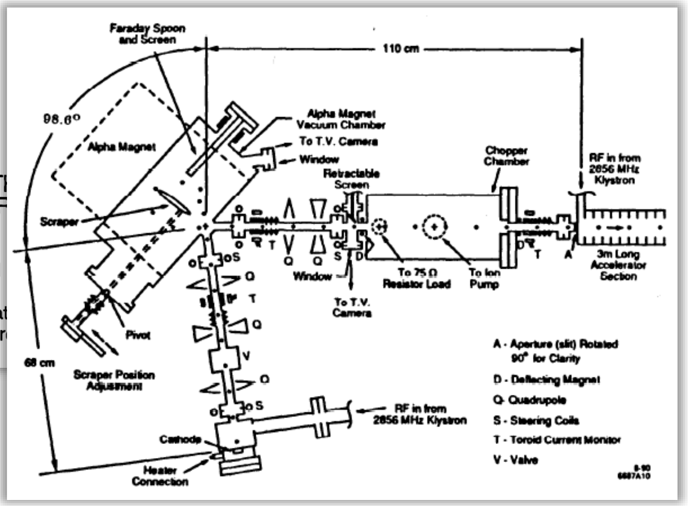
A new type achromatic or nearly achromatic deflecting magnet for ion beams is discussed in this paper. The magnetic field in the x–y (median) plane is given by $B=0$ for $x<0$ and $B_z=Gx^n$ for $x>0$. T… field through the origin at an angle α with the x axis, go through a loop of $180°+2\alpha$, and l… crossing the y axis at the origin or close to the origin. Several cases are studied with the field … to unity and with deflection angle 270° (90°) or nearly so.

Michael Borland's PhD Thesis, 1991

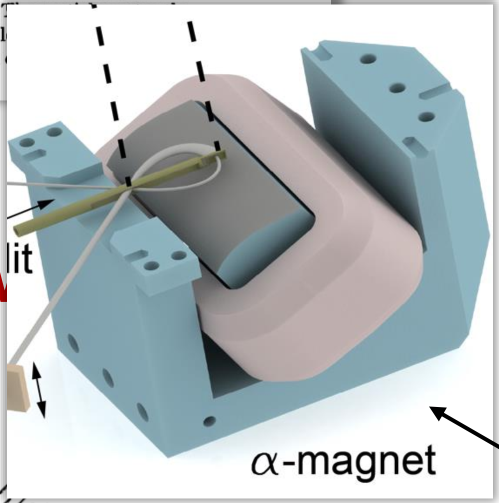

A HIGH-BRIGHTNESS T…
MICROWAVE ELECTR…

Michael Borland

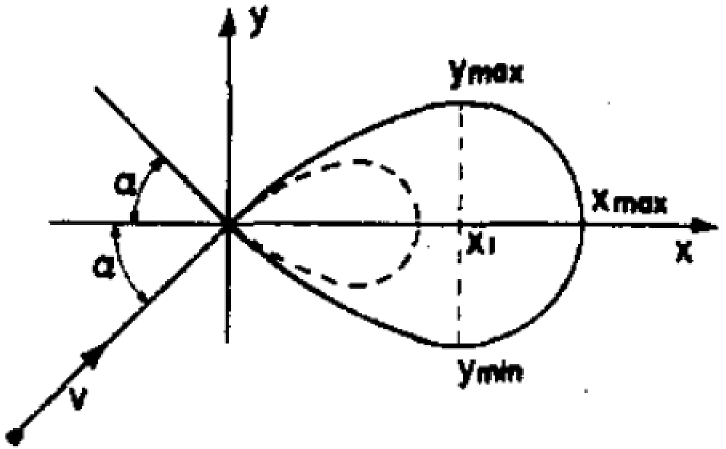
Stanford Linear Accelerat…
Stanford University, Stanfor…



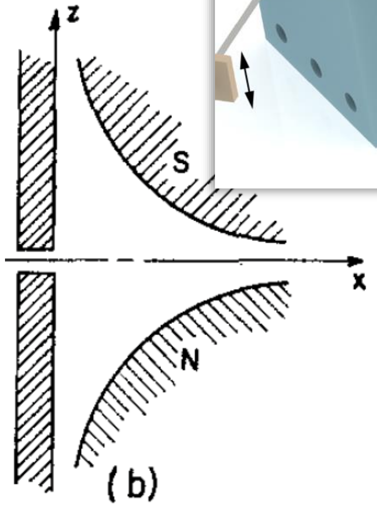
SSRL injector



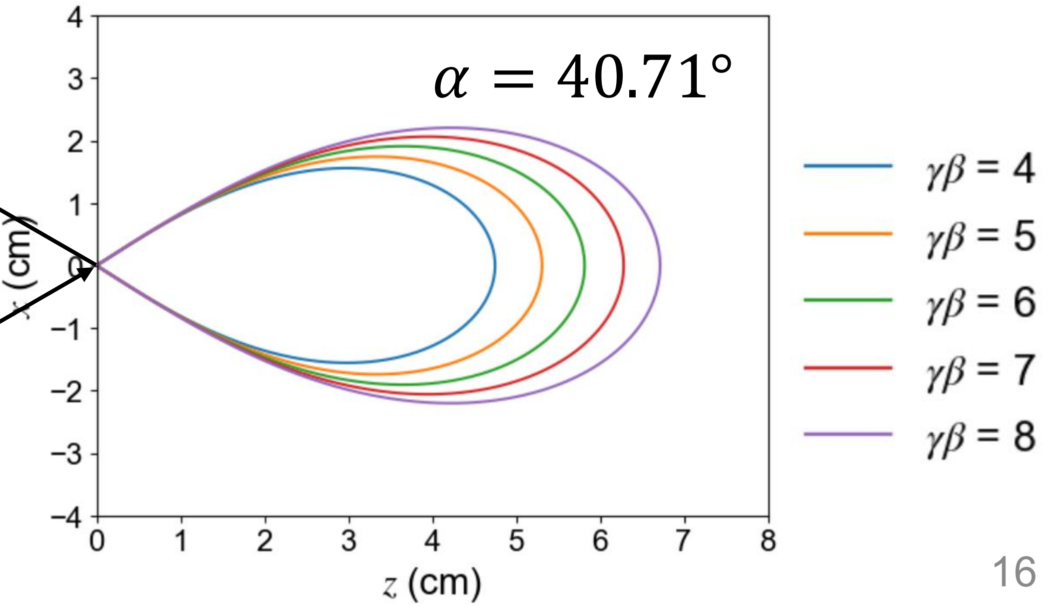
Top view



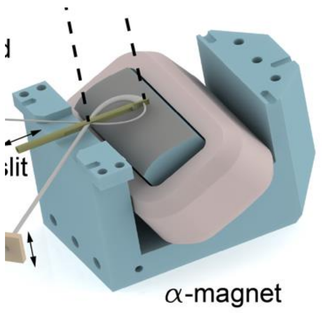
Side view

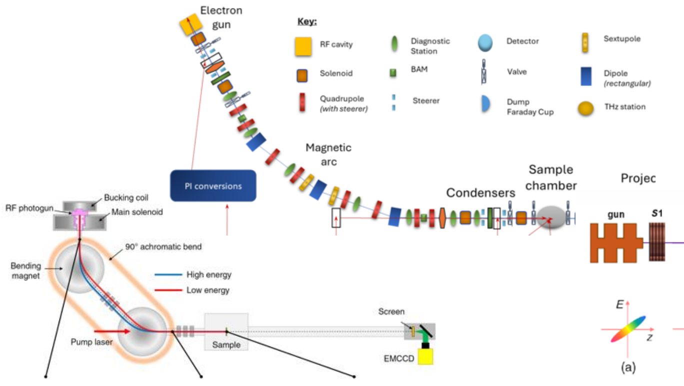


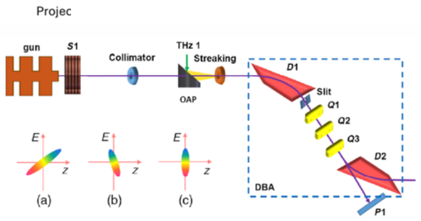
GPT tracking results



α-magnet and DBA/TBA comparison







No. of elements	1	5-10+
R_{56} tunability	Yes	DBA no, TBA yes
T_{566}	$-R_{56}/4$, low few cm	~m w/o pole face or sextupole
Path length	0.1-0.2 m	meter scale
Beam energy	**<few MeV**	**Very broad**

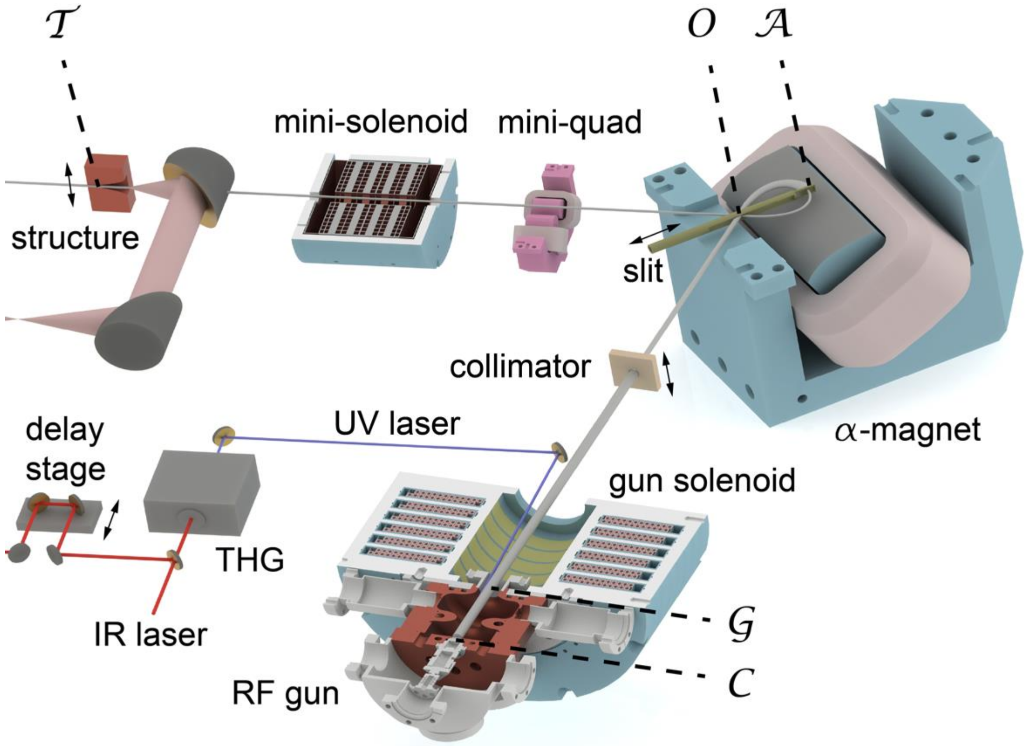
α-magnet put into new use

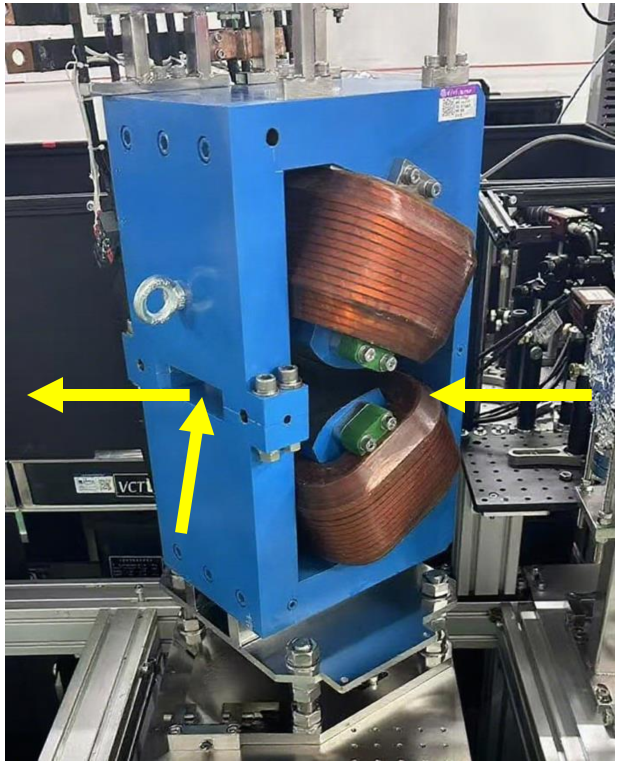
Drift section $R_{56}^{\mathrm{drift}} = L/\gamma^2$ **(~ 4 cm for $\gamma \approx 7$ and $L \approx 2$ m)**

α-magnet $R_{56}^{\alpha}(\mathrm{cm}) = -9.6\sqrt{\gamma\beta/g(\mathrm{T/m})}$ **(~ -7 cm for $\gamma \approx 7$ and $g \approx 12$ T/m)**

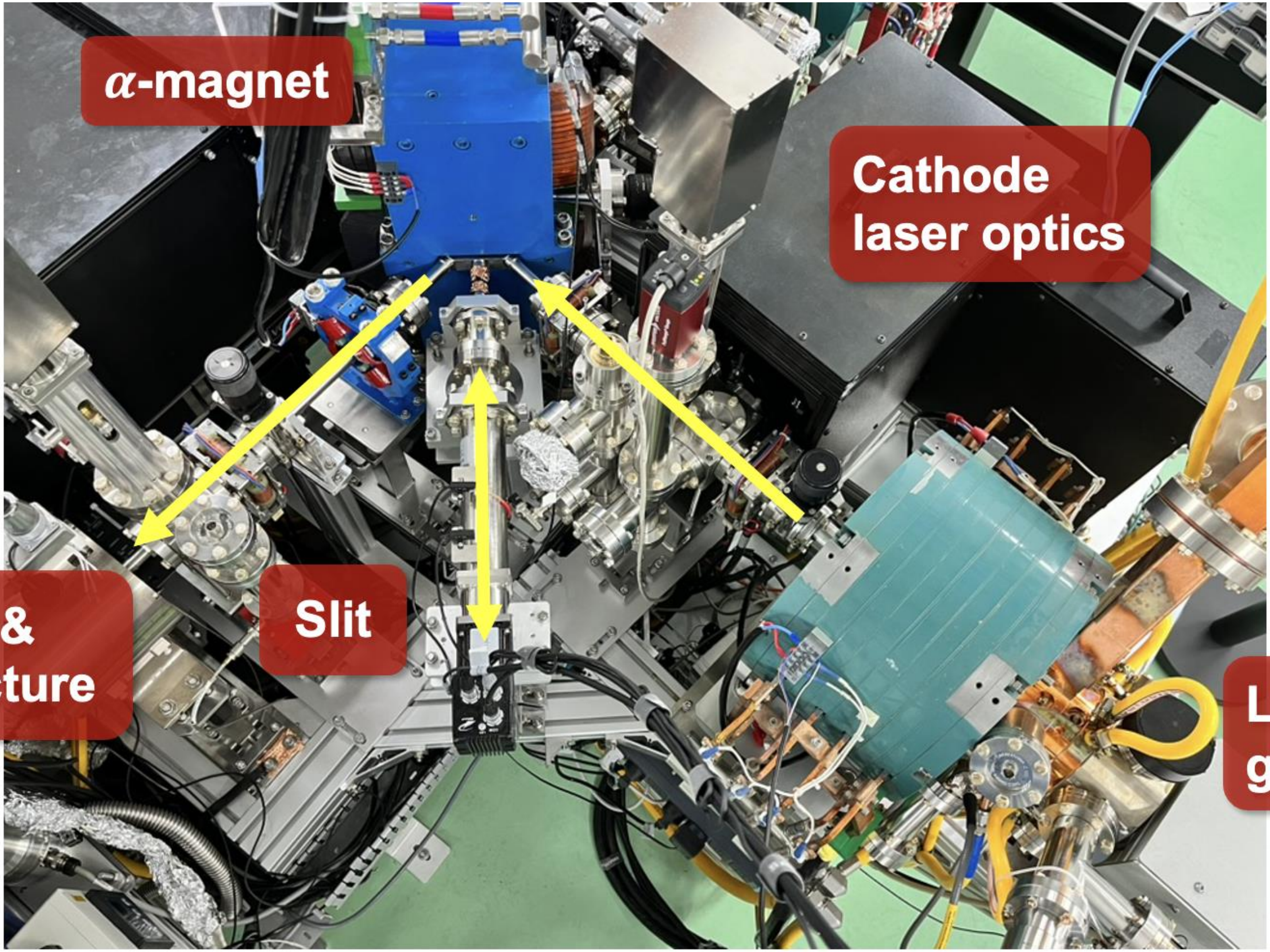
$$R_{56}^{\mathrm{gun}} + R_{56}^{\mathcal{GO}} + R_{56}^{\alpha} + R_{56}^{\mathcal{OT}} \to 0$$

Need $g > 10\ \mathrm{T/m}$ for TOF stabilization



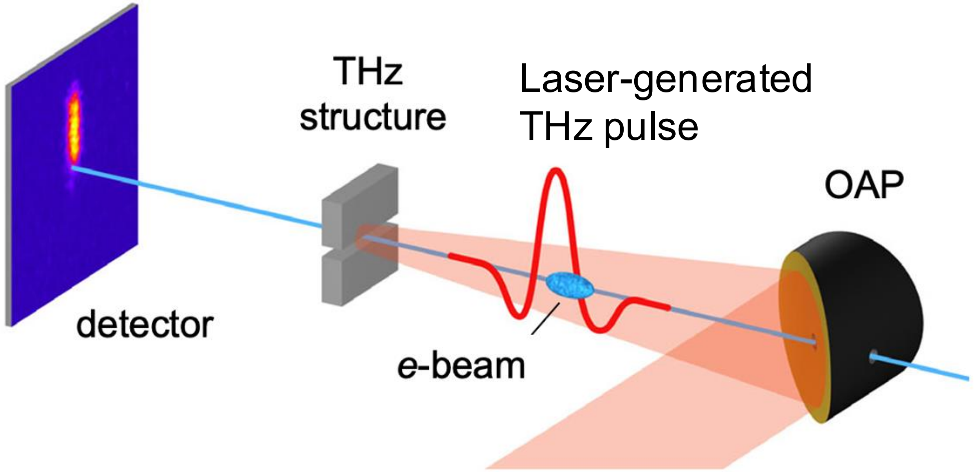


- Designed and constructed to **15 T/m**, versus previous typical ~5 T/m or lower level
- Allow straight trajectory from another gun

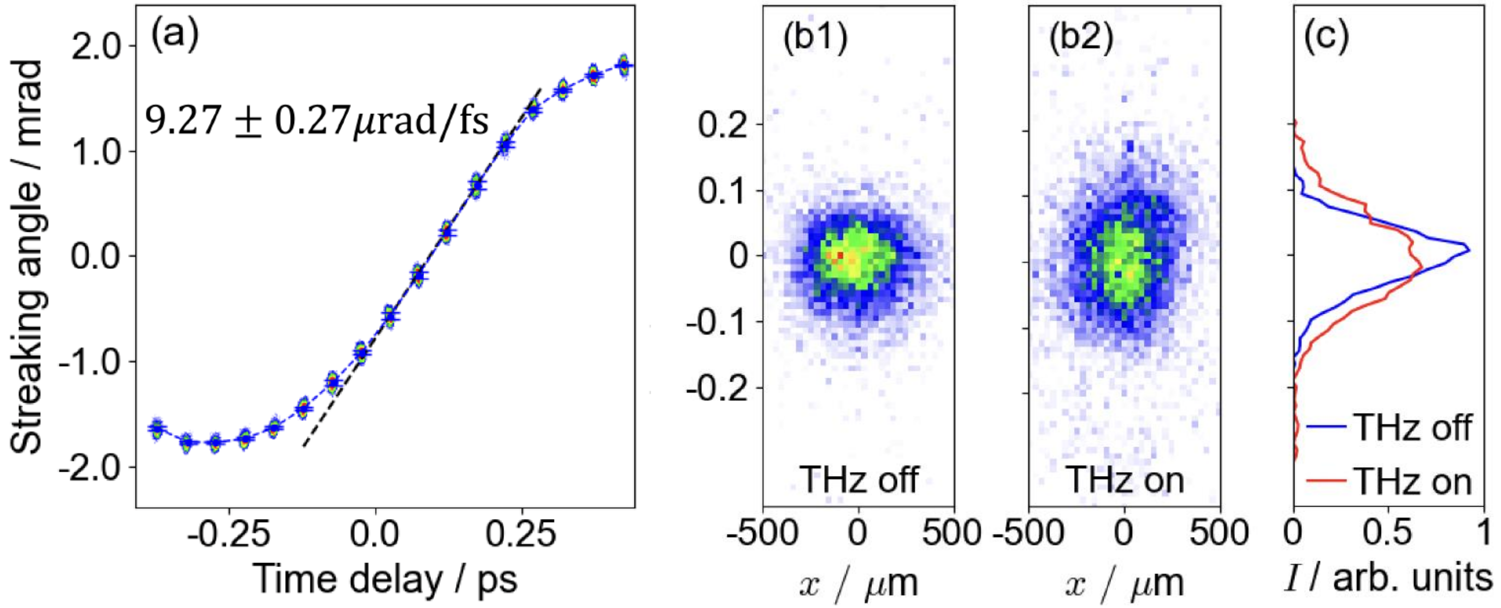


7e-11/2e-10 Torr

THz streaking



R. K. Li et al., PRAB **22**, 012803 (2019)



- Strong linearly polarized THz generated by and intrinsically synchronized with ultrafast lasers
- Map temporal distribution into transverse profile
- Measure bunch duration and **relative-to-laser** timing jitter

TOF resolution

$$\frac{\text{pointing jitter}}{\text{streaking strength}}$$

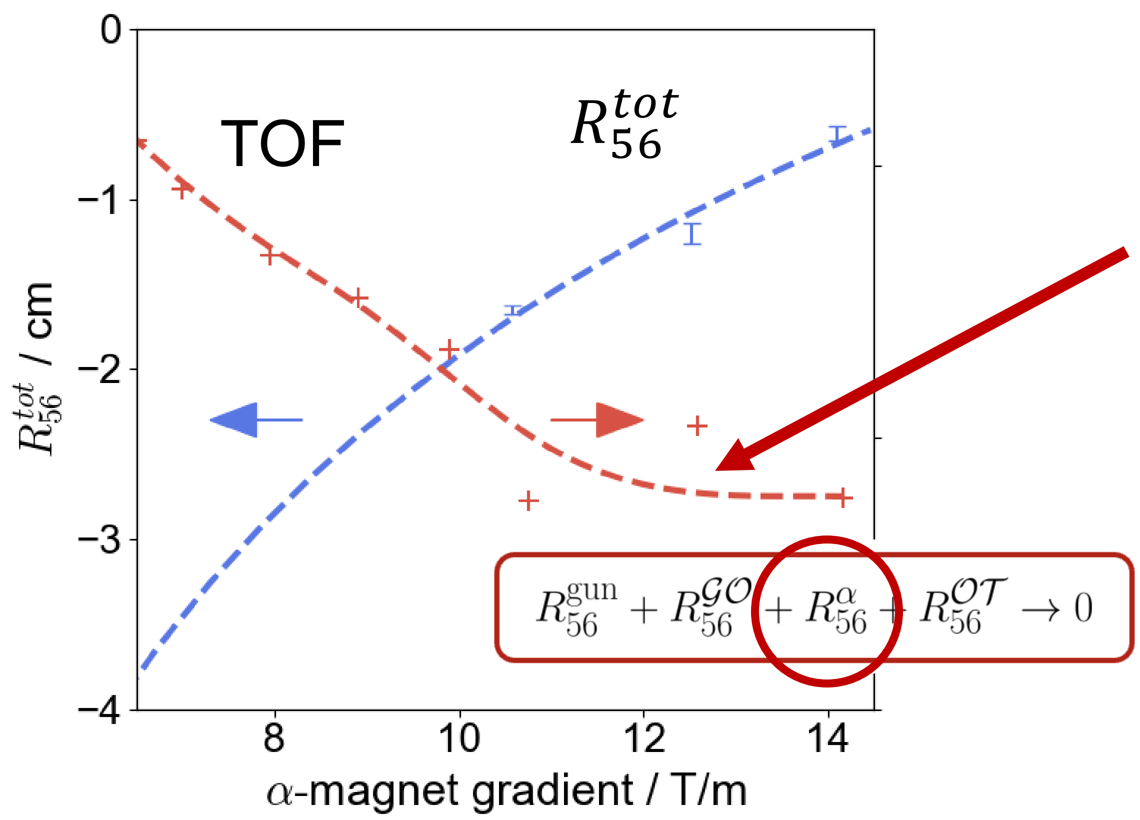
0.51 fs rms

Bunch duration resolution

when beam size differ from unstreaked beam size by 3σ

2.55 fs rms

TOF control and measurement

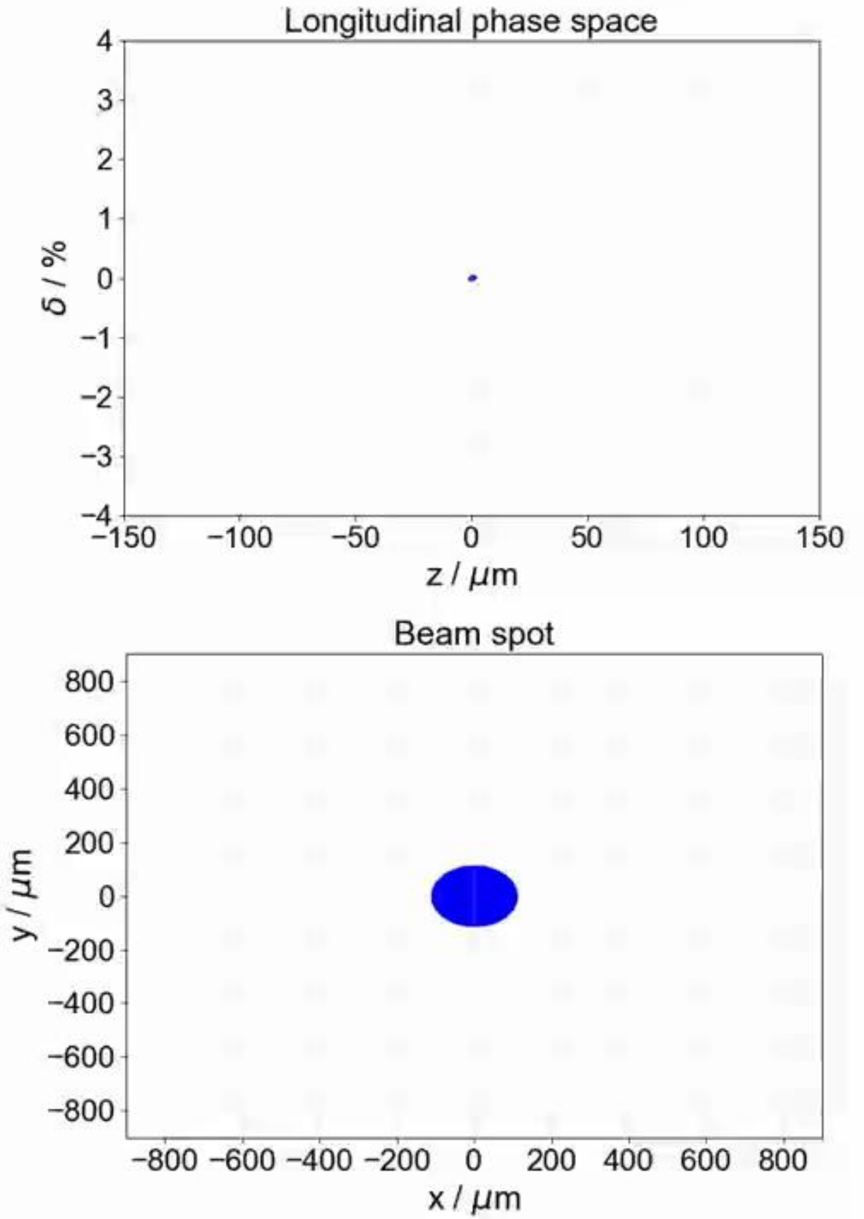


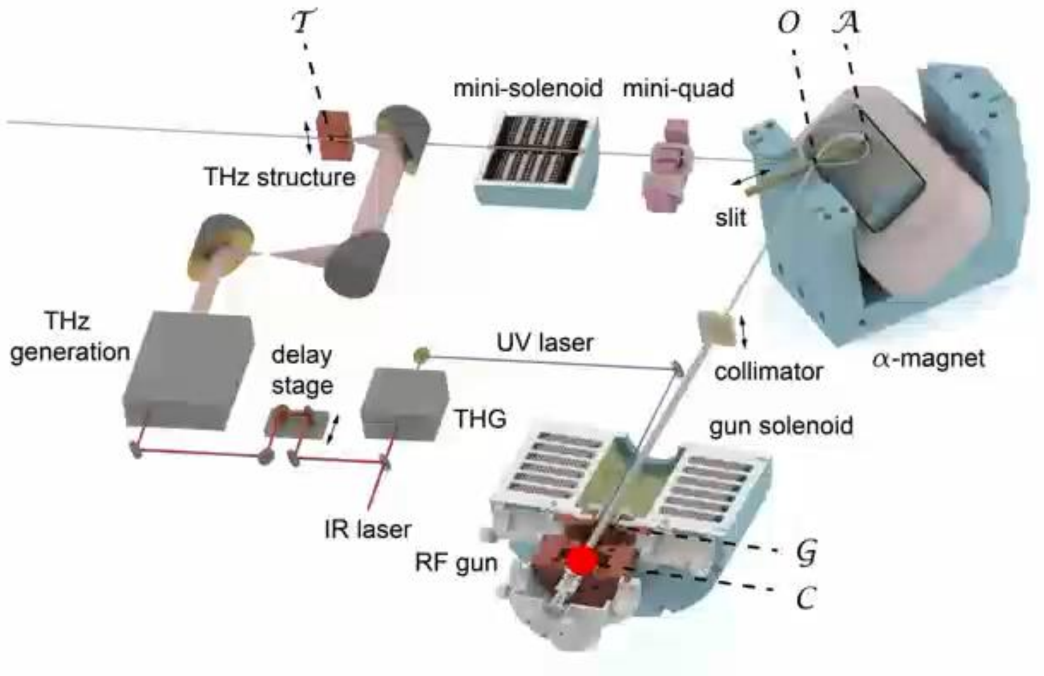
- Increase α-magnet gradient, tune R_{56}^{tot} toward 0 from negatives
- Tunability, high-gradient is needed

TOF levels off at around 4 fs rms for $|R_{56}^{tot}| < 2$ cm or $g > \sim 11$ T/m

- **~fs** contributions from vibrations of optics and laser pointing, including THz waveforms
- $R_{56}^{tot} = -1.67$ cm and $\frac{\delta\gamma}{\gamma} = 2.6 \times 10^{-5}$ contributes **1.4 fs rms**
- $dS_\alpha(cm) = -9.6\sqrt{\gamma\beta/g(cm)}\frac{\delta B}{B}$ by 10 ppm magnetic field variation yields **2.6 fs rms**

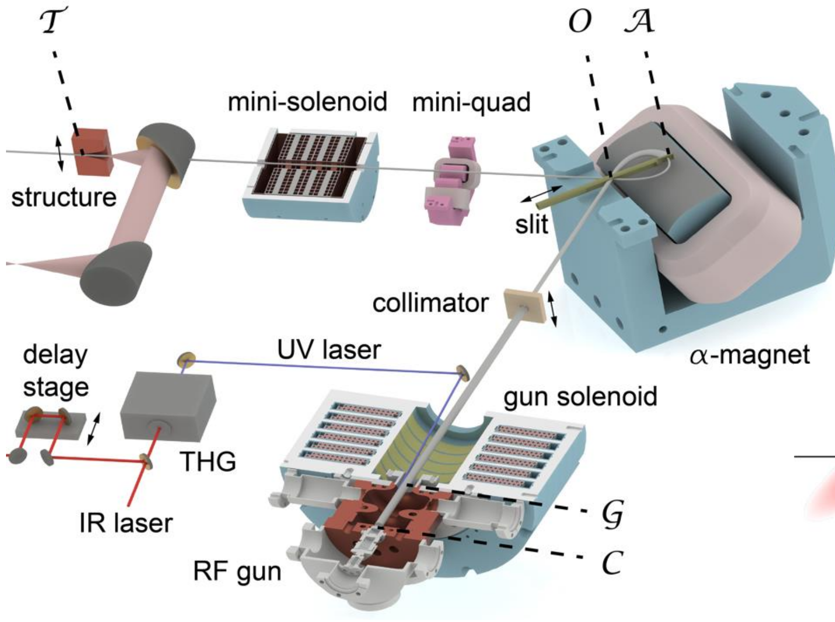
Phase space evolution



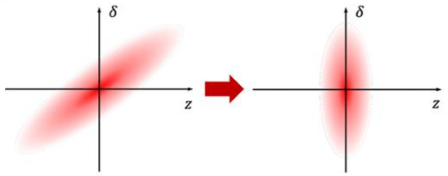


Courtesy of Yining Yang

Compression and chirp control

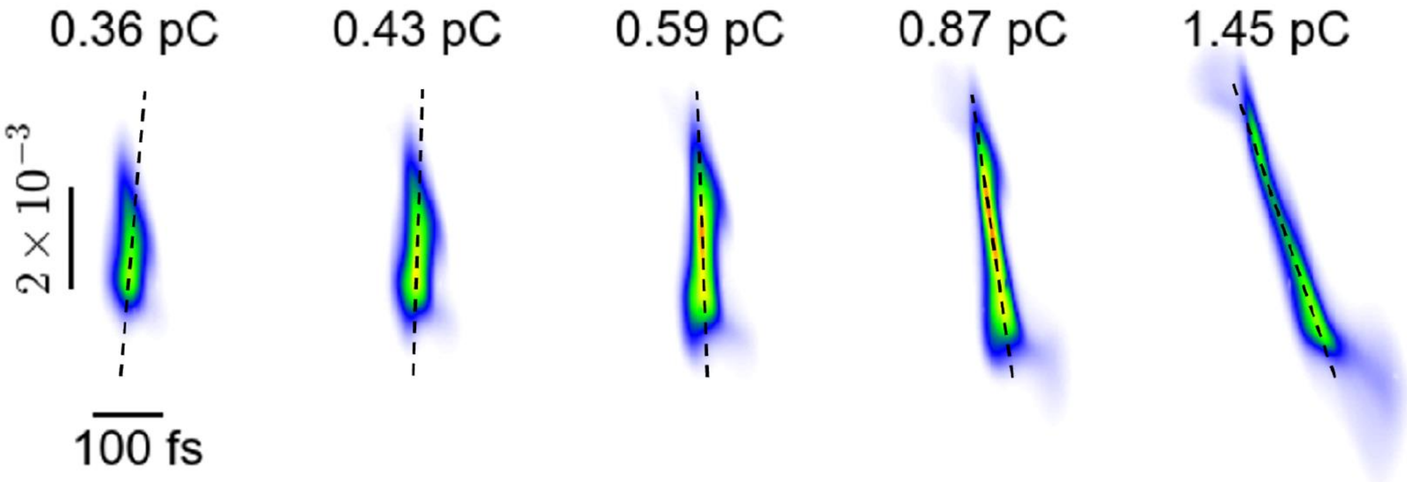


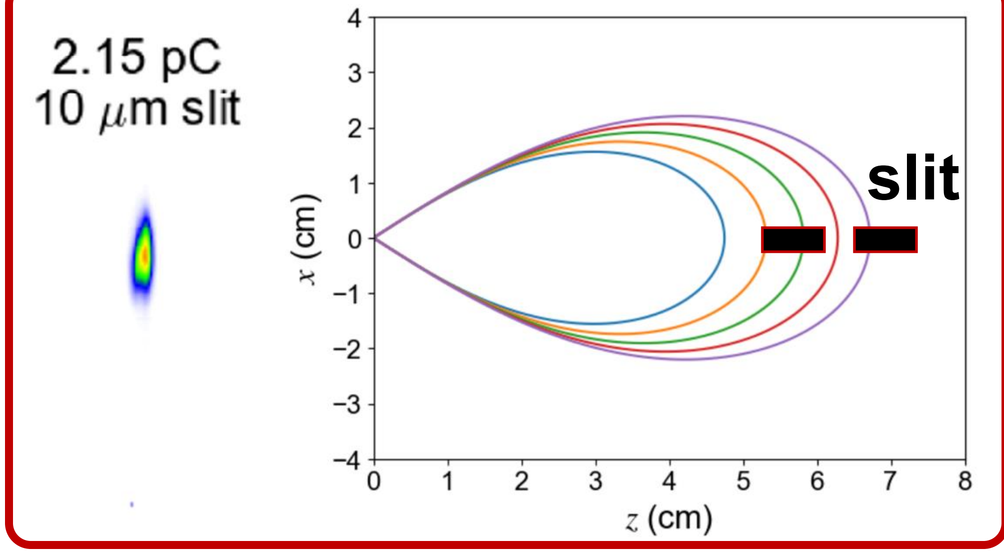
- First optimize TOF, which fixes α-magnet
- Then tune electron bunch charge density to control the bunch chirp h^{O}, so that



$$1 + h^{\mathcal{O}}(R_{56}^{\alpha} + R_{56}^{\mathcal{OT}}) = 0$$

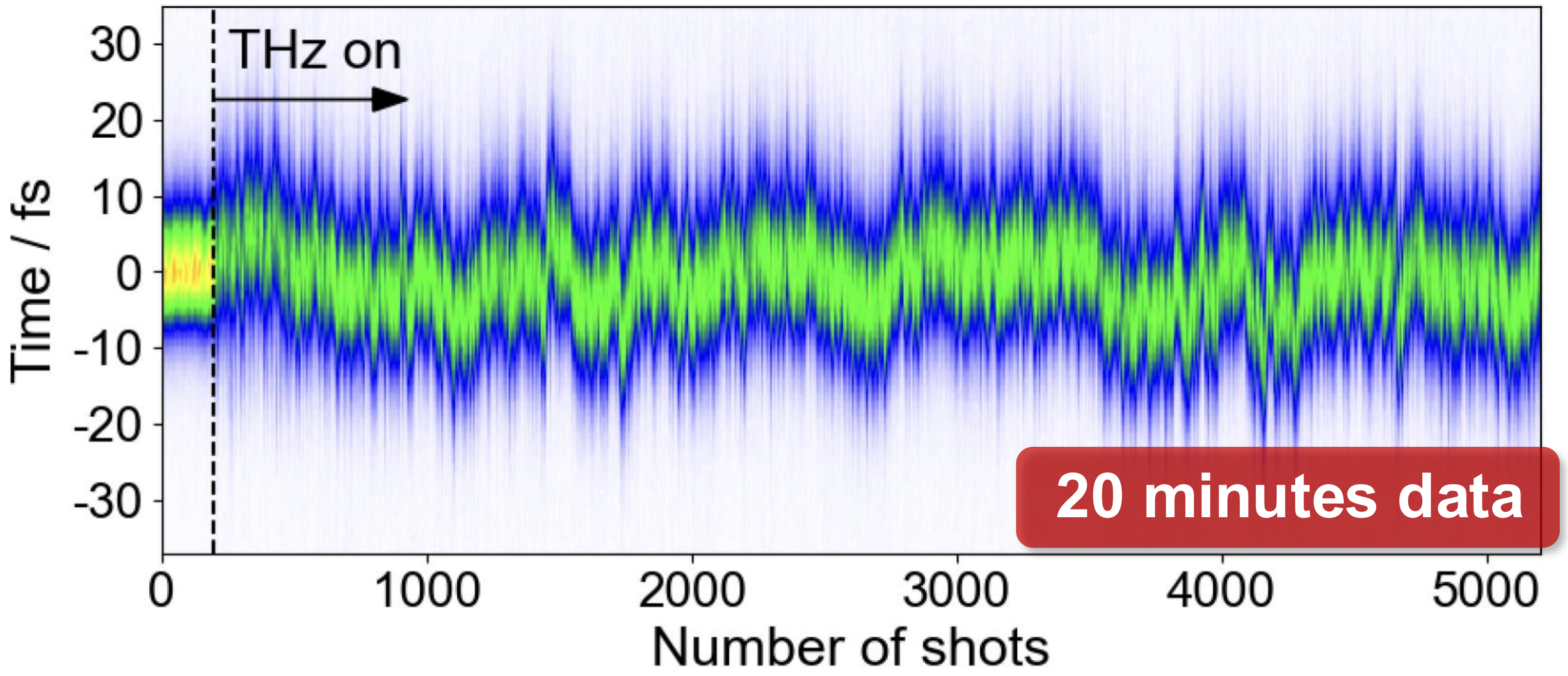
Precise phase-space selection





Robust, sub-5 fs control

- **Simple, clear, compact, reliable**
- **Minimal number of elements**
- **Emittance preserved for high brightness**



Y. Yang et al., arXiv:2508.03946

Bunch duraiton

3.47 ± 0.33 fs rms

TOF-to-laser jitter

4.34 fs rms

Bunch charge

1.6 fC

5D brightness $B_{5D} = 2I/\epsilon_n^2$

7.1×10^{15} A/(m rad)^2

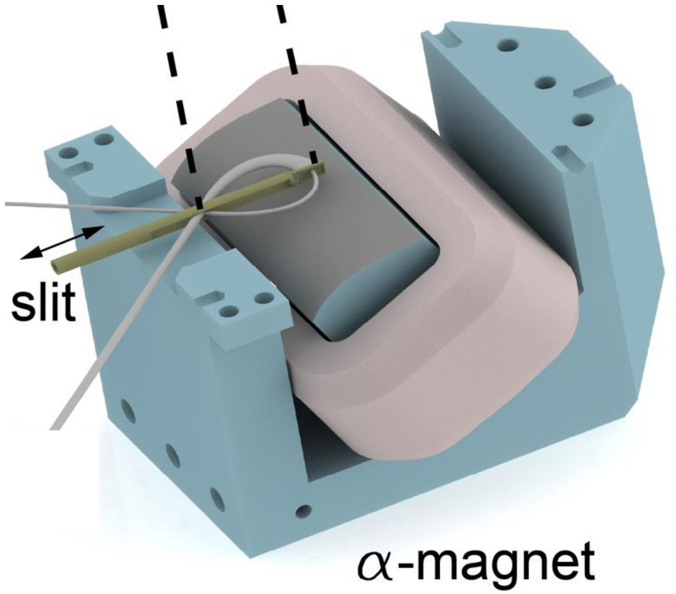
Energy spread

$(5.7 \pm 0.37) \times 10^{-4}$

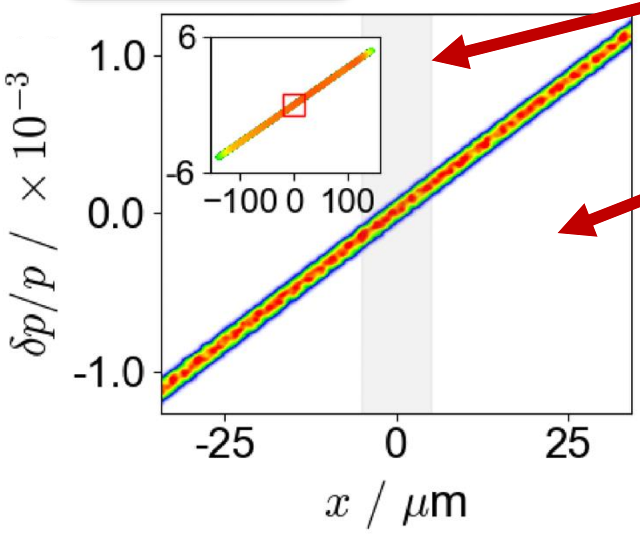
Momentum jitter

2.6×10^{-5}

For UED experiments



x - $\delta p/p$

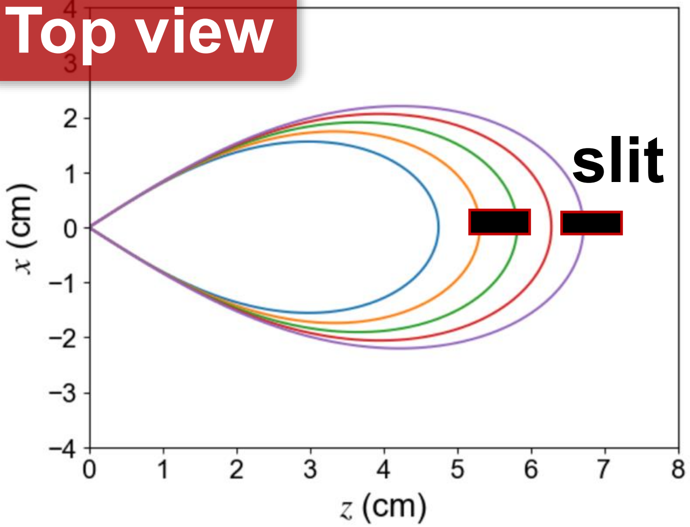


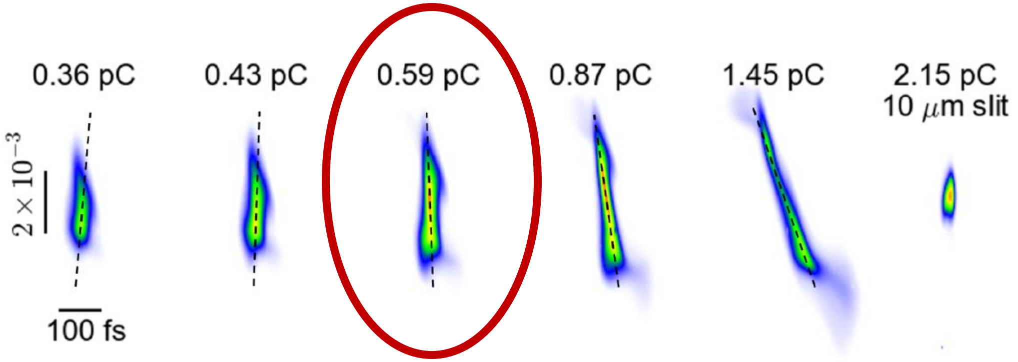
w/ slit, sub-5 fs and mid-10^{-4} $\delta p/p$

w/o slit

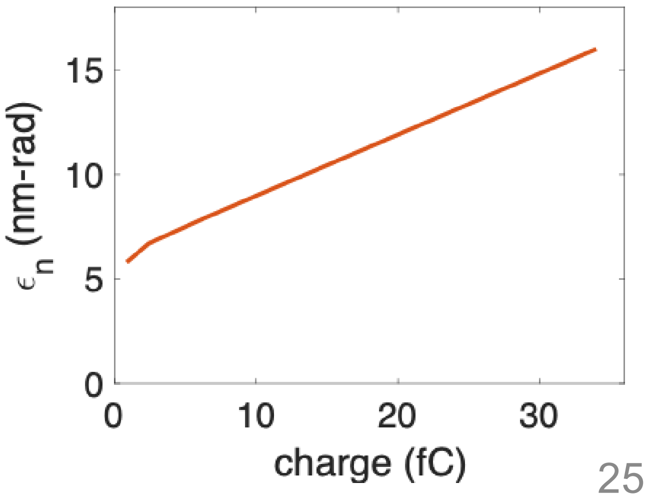
- **~10 fs**
- **<mid-10^{-3} $\delta p/p$**
- **higher charge (~1 fC to >10 fC)**
- **low emittance (~7 to 15 nm-rad)**

Top view





Slit width scan



Temporal resolution

Robust ~10 fs temporal control of full bunch

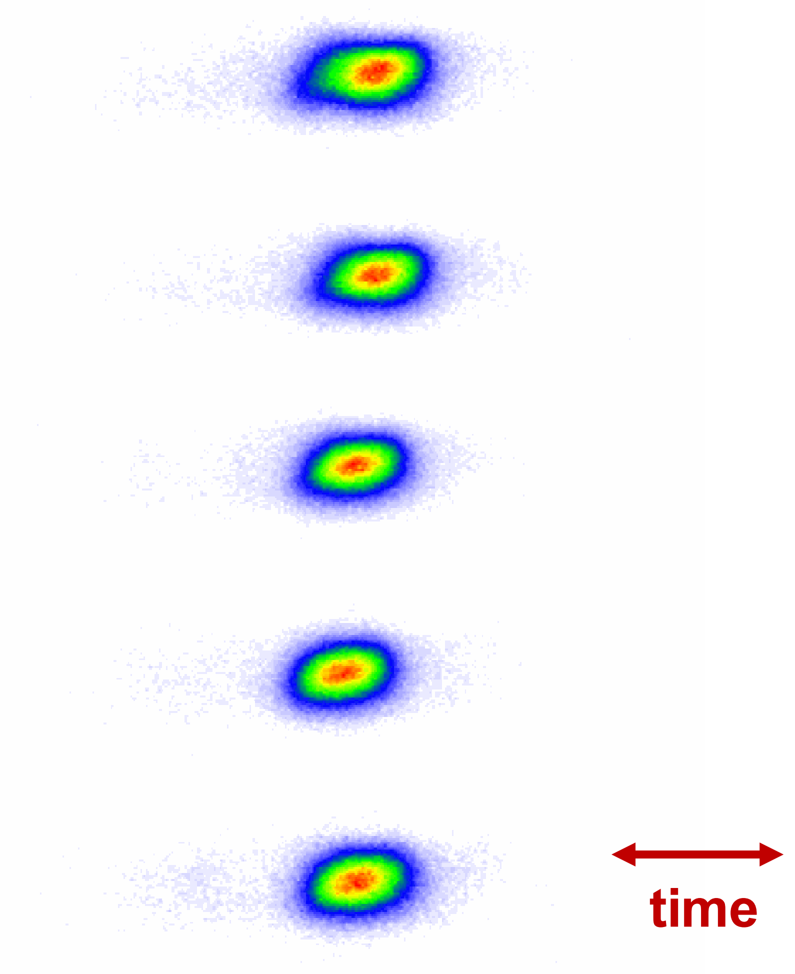
$Q = 482$ fC

$Q = 420$ fC

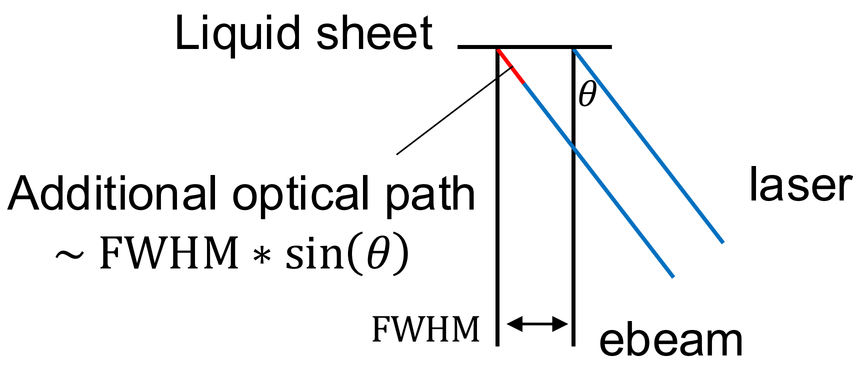
$Q = 309$ fC

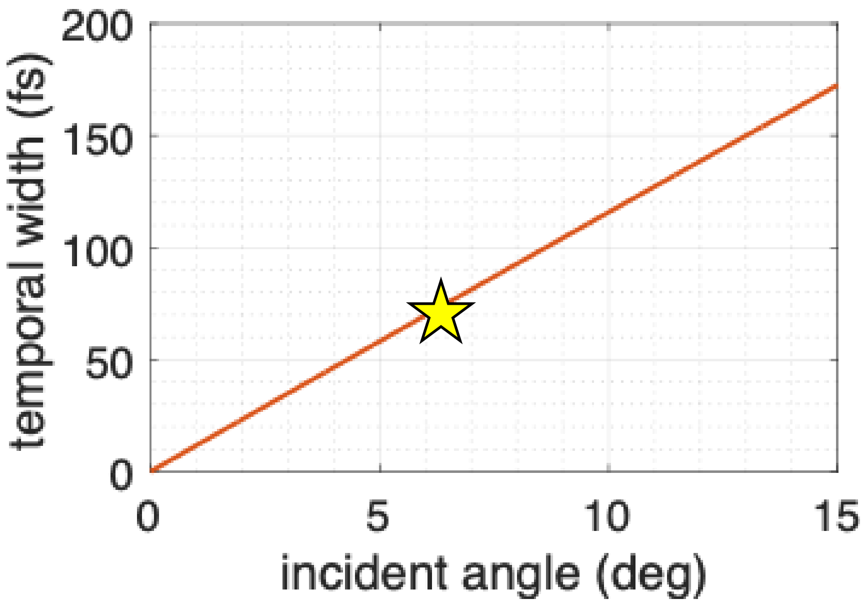
$Q = 250$ fC

$Q = 192$ fC



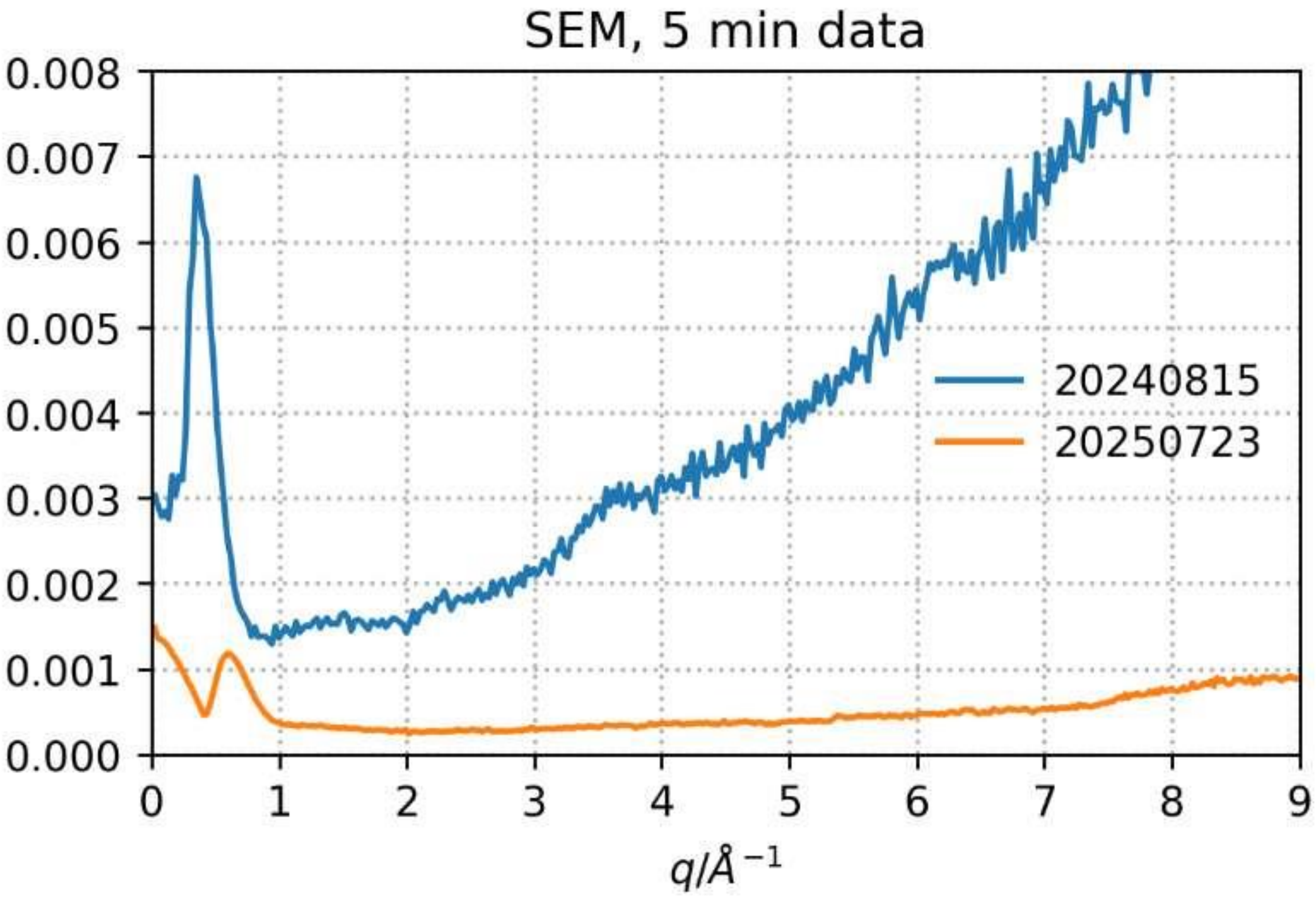
Looking for fast processes, now dealing with pump laser (40 fs FWHM) geometry





Bunch charge and SNR

Liquid-phase data comparison 2024 vs 2025



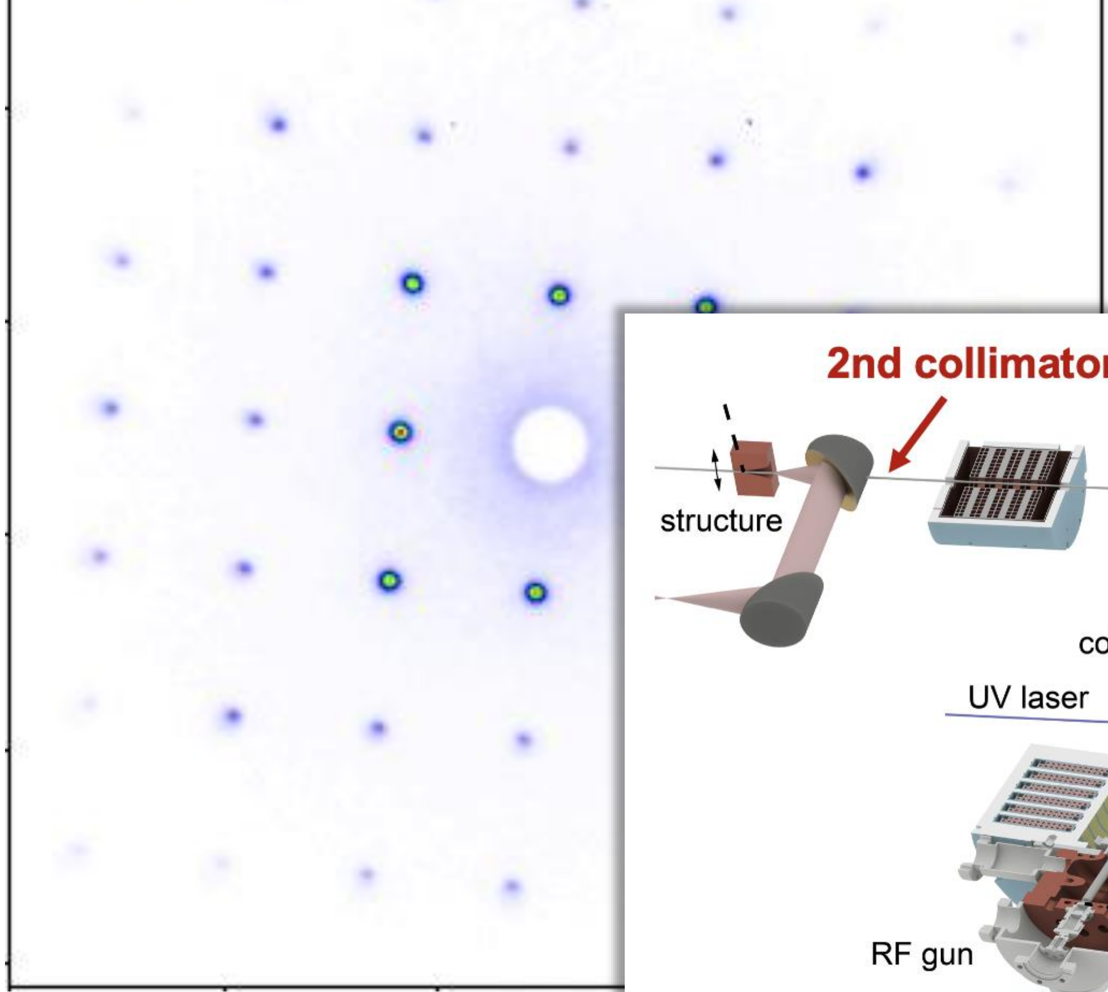
SEM: standard error of mean

- ~5-10 times imporvement of SEM over the q-range
- Confirmed > ~10 times increase in probe charge

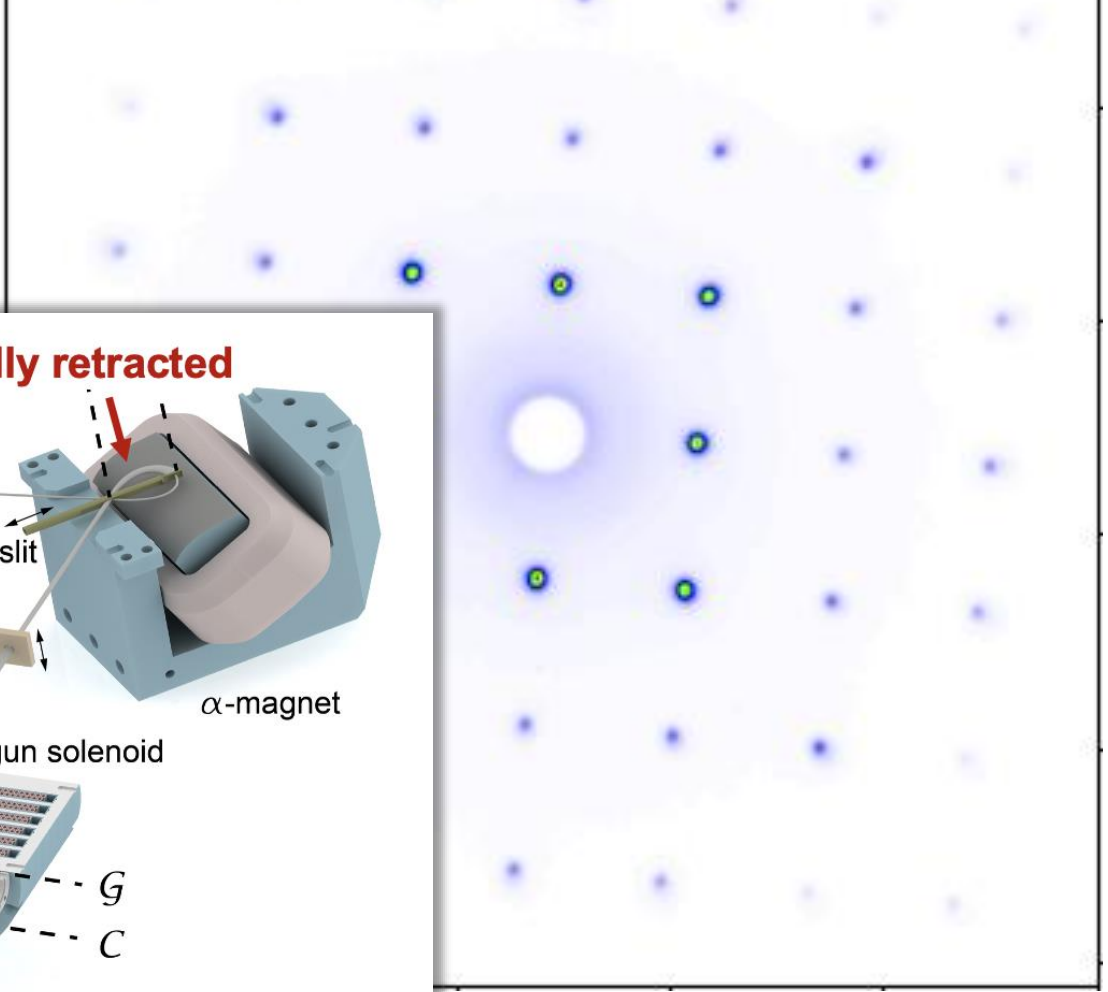
Courtesy of K. K. Chen and J. Yang

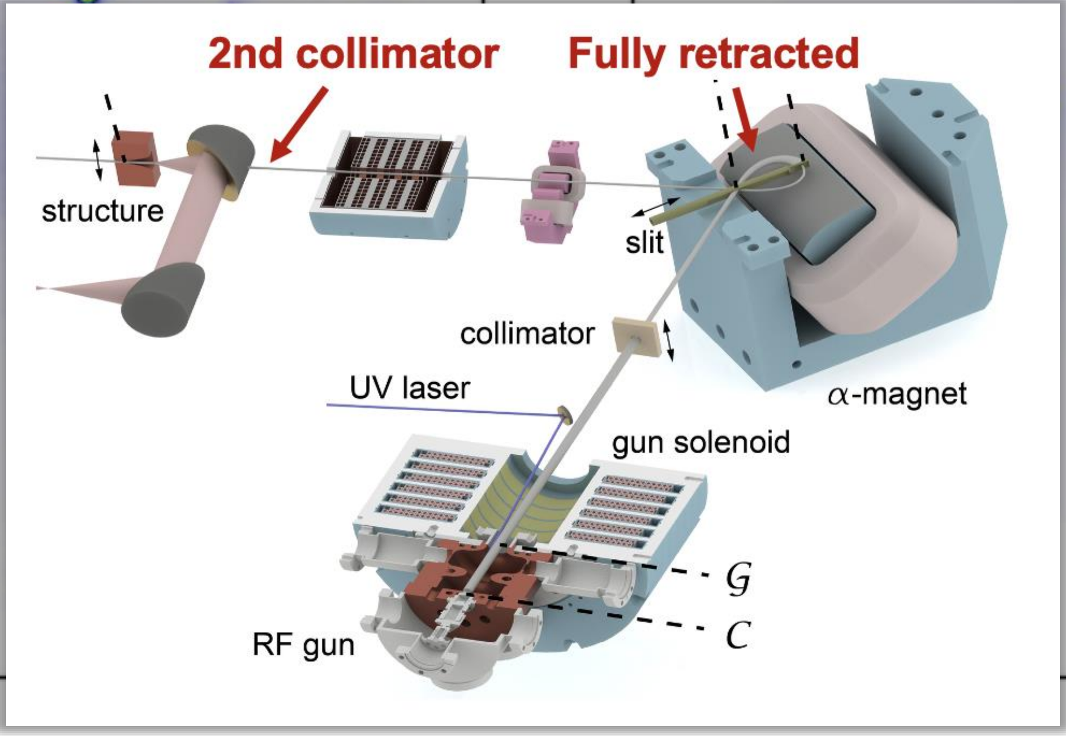
Dark current

Single image

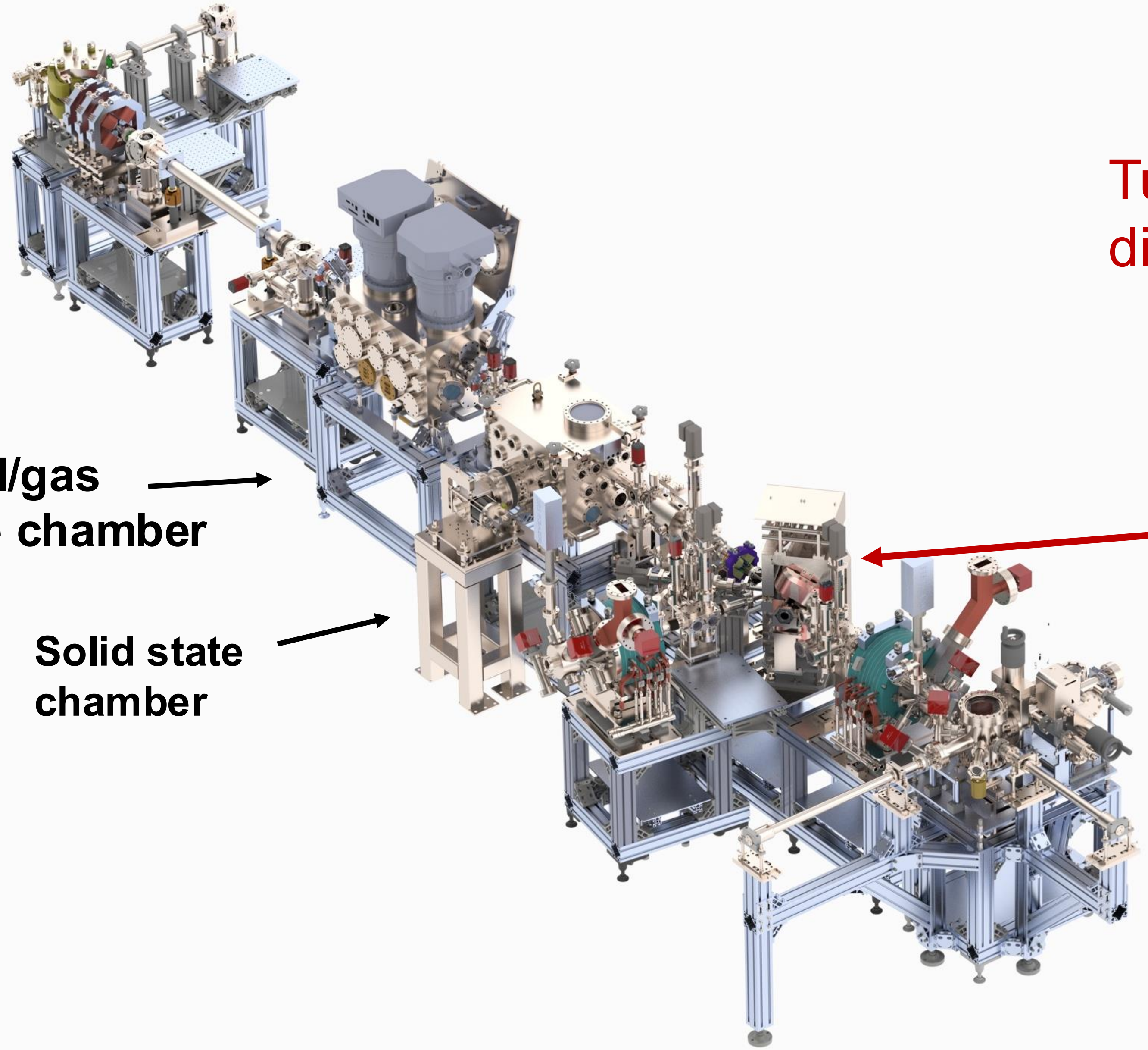


30 images averaged

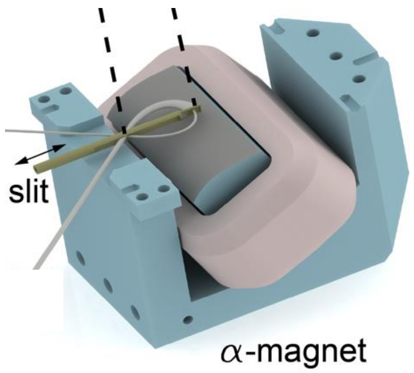




Flexibility for UED exps



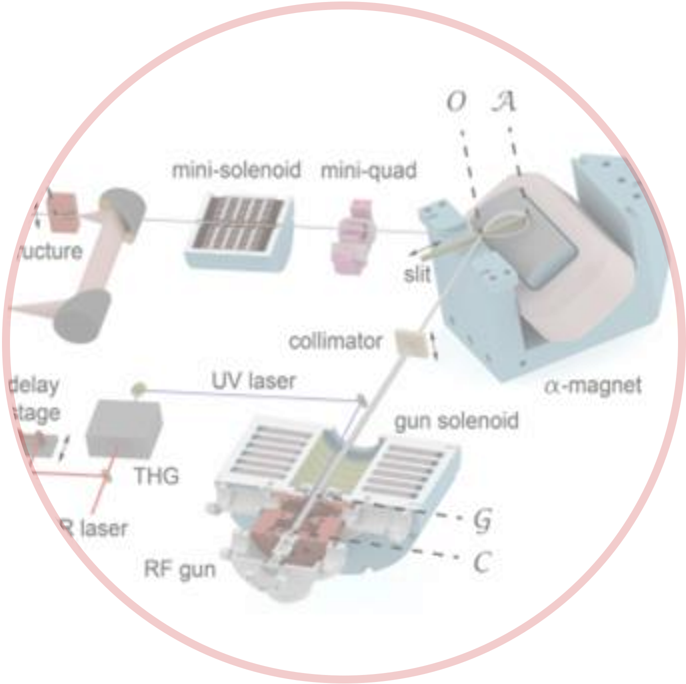
Tune the α-magnet for different chamber locations



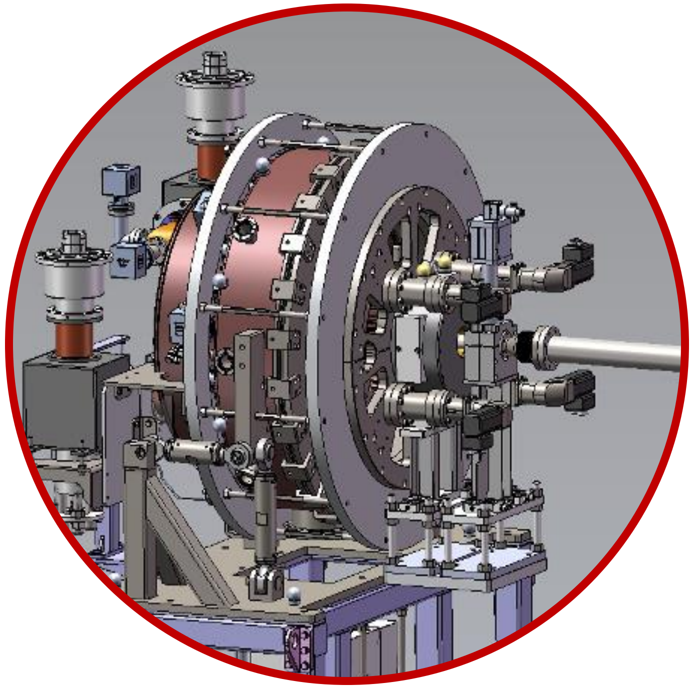
Outline

FORTRESS
stable & flexible

~5-fs
temporal control



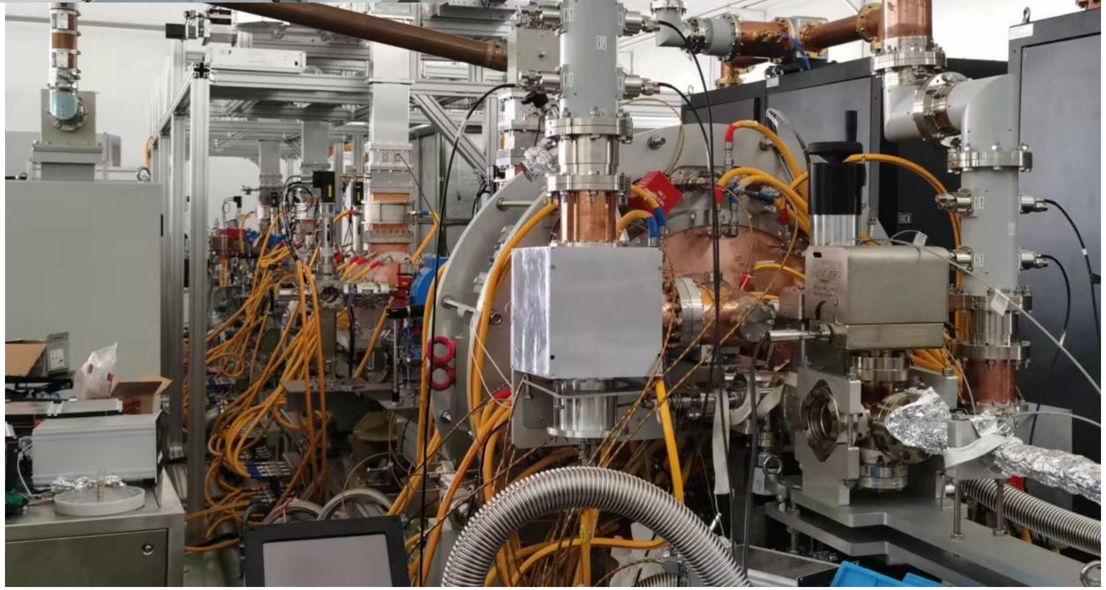
High rep-rate
UED and imaging



VHF gun

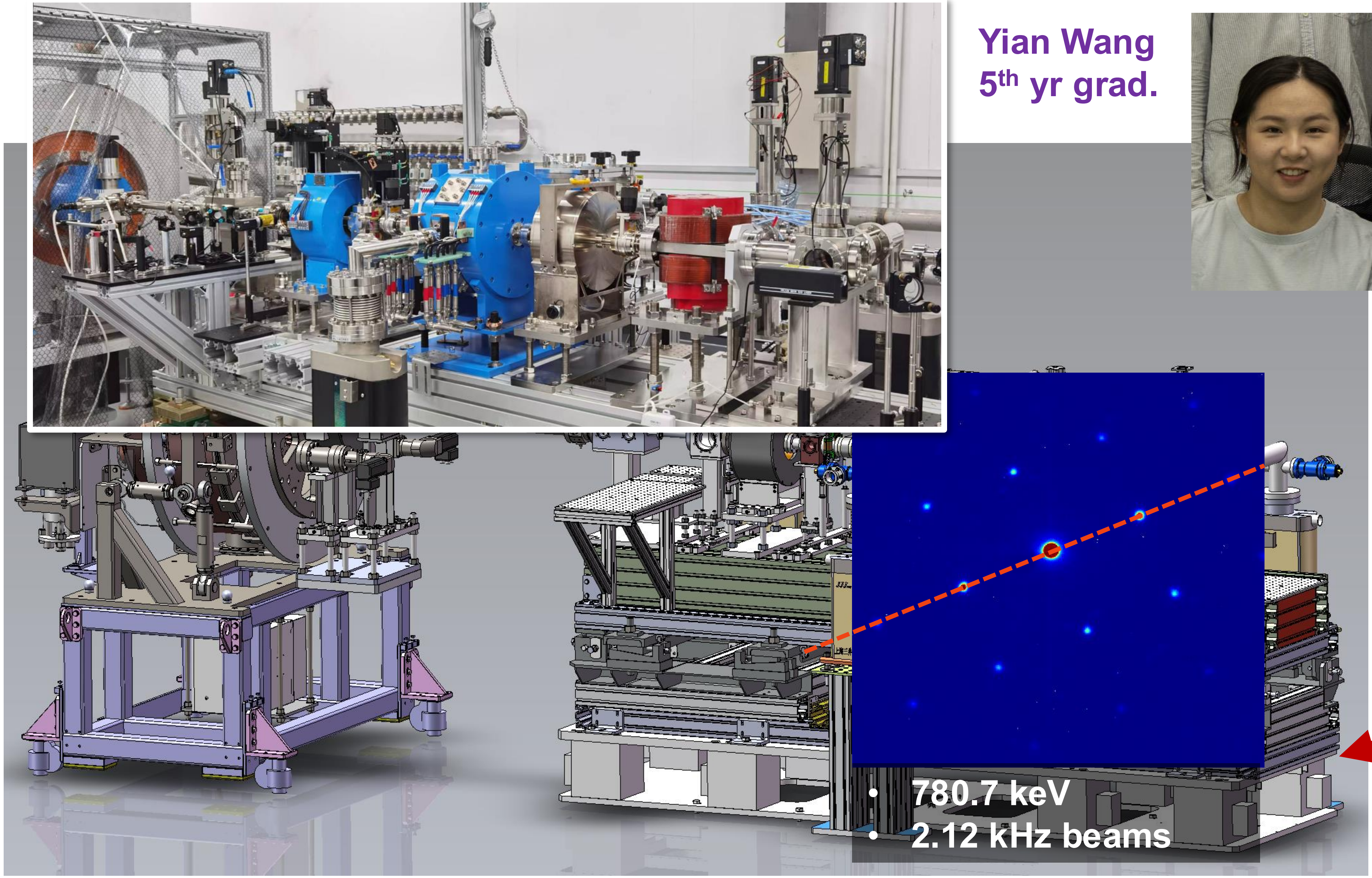
- VHF gun design pioneered at APEX and motivated by CW XFEL application
- 5 guns fabricated and commissioned since 2019 (Chuanxiang Tang, Yingchao Du, Lianmin Zheng, etc.)
- Test beamline repurposed for UES R&D and experiments

Key parameters	Values
Gun gradient	27 MV/m @ 75 kW
Gun voltage	780 kV
rf amp. stability	1.1×10^{-4}
rf phase stability	0.015 deg
Dark current	10 - 380 nA
Vacuum	Mid 10^{-8} Pa @ 75 kW CW



Test beamline: VHF gun + 400 kV CW buncher + 30 MeV 10 Hz linac

CW beam control and characterization



- 780.7 keV
- 2.12 kHz beams

Yian Wang
5th yr grad.

Beam physics and technologies on

- **100 pm emittance**
- **$<10^{-4}$ energy spread**
- **10s nm beam size**
- ***Cs/Cc* aberrations**
- ***e-e* scattering**

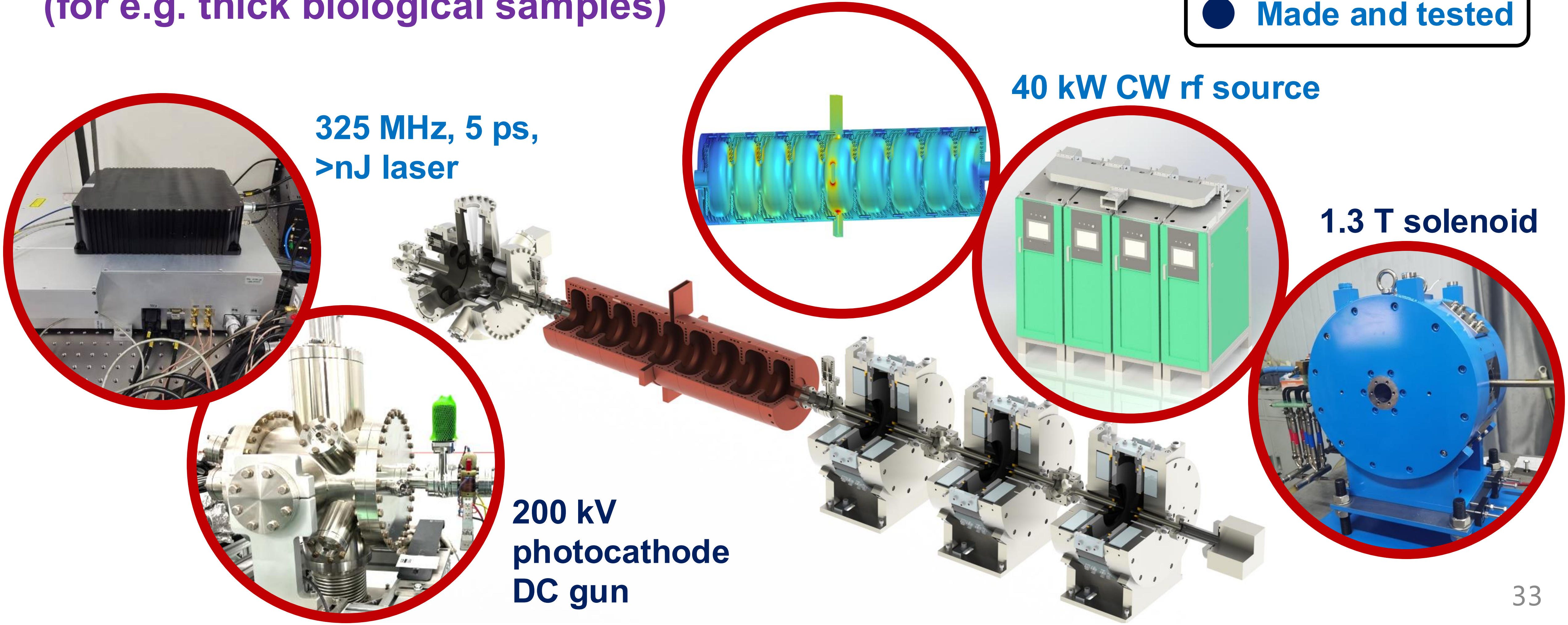
Active Vibration Cancellation

Tsinghua University

DC + CW NC RF MeV TEM

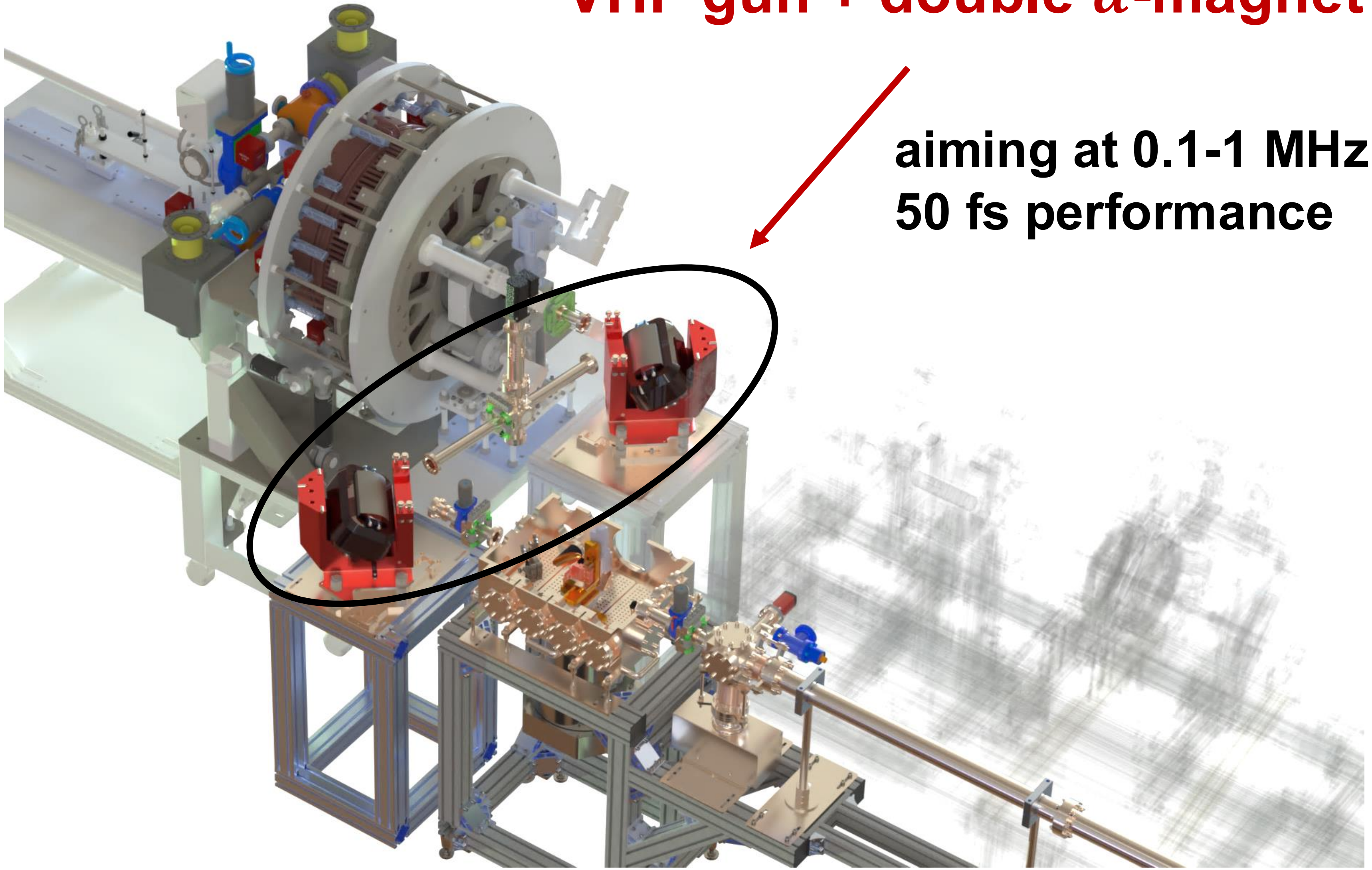
High spatiotemporal resolution MeV EM

(for e.g. thick biological samples)



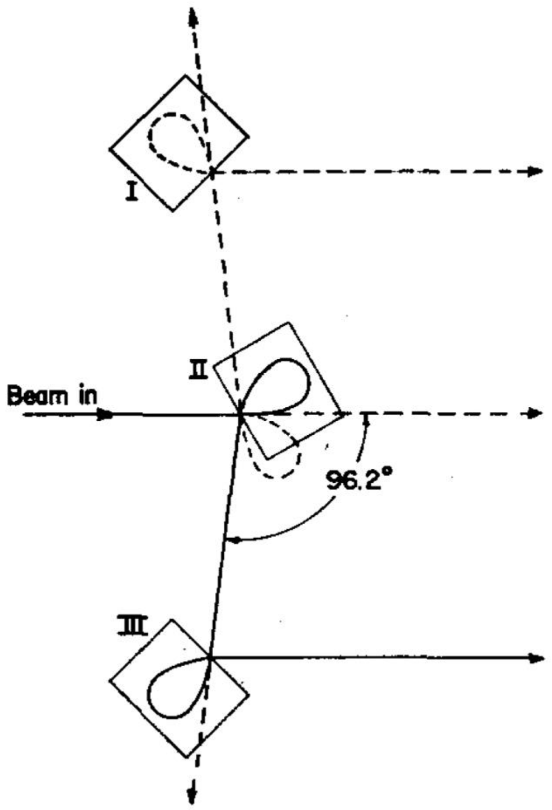
High rep-rate MeV UED

VHF gun + double α-magnet



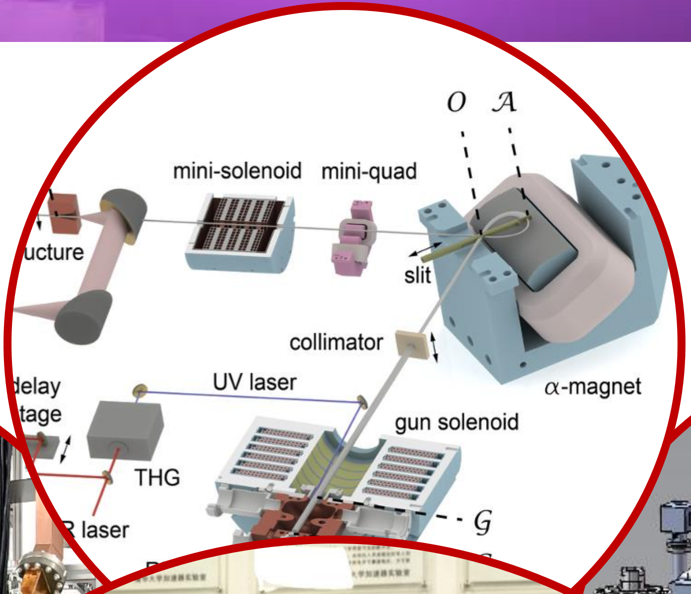
aiming at 0.1-1 MHz,
50 fs performance

Harald Enge, 1963



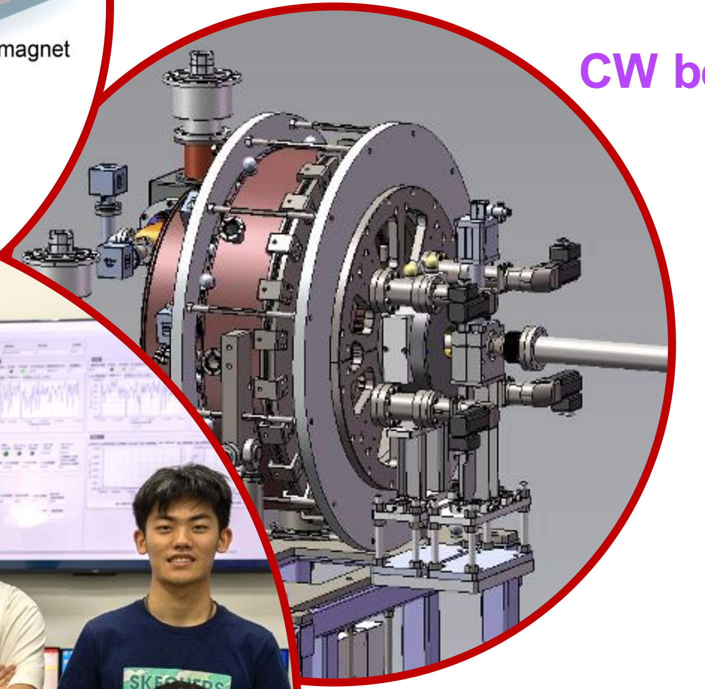
Summary and outlook

- ***Brighter, faster beams for UED***
- ***Higher resolutions for discoveries***
- ***Benefits other facilities and geneal beam physics and technology***



Sub-5 fs control, toward sub-fs

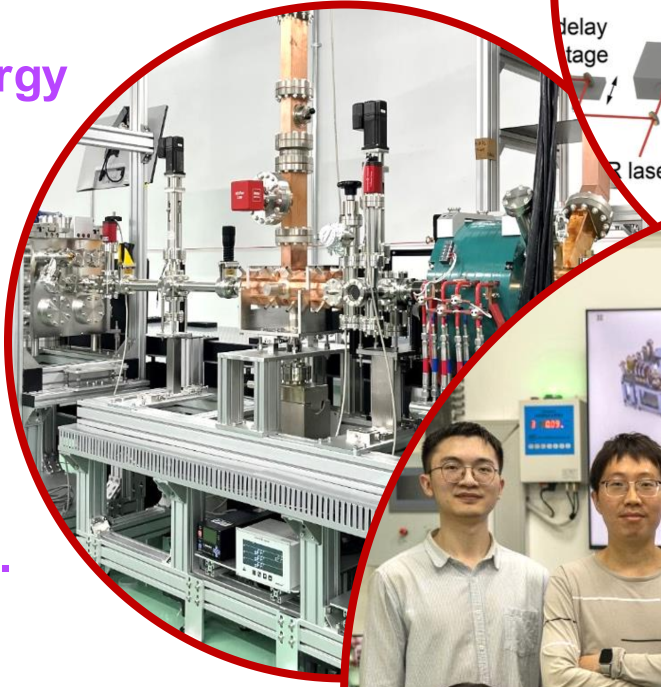
CW beam

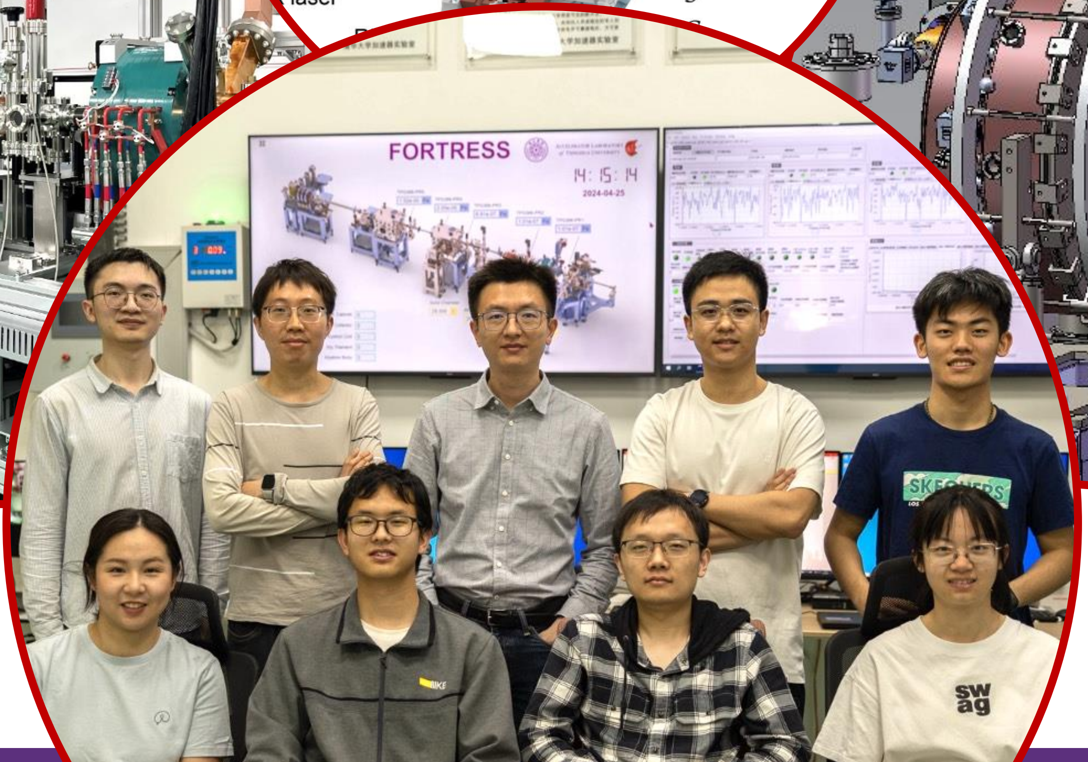


Low 10^{-5} energy stability

Source & beam shaping R&D

Advanced control & diag.





Thank you!