# TAU SYSTEMS


## *STATUS OF LASER-PARTICLE ACCELERATORS AND LIGHT SOURCES & INDUSTRY PERSPECTIVE*

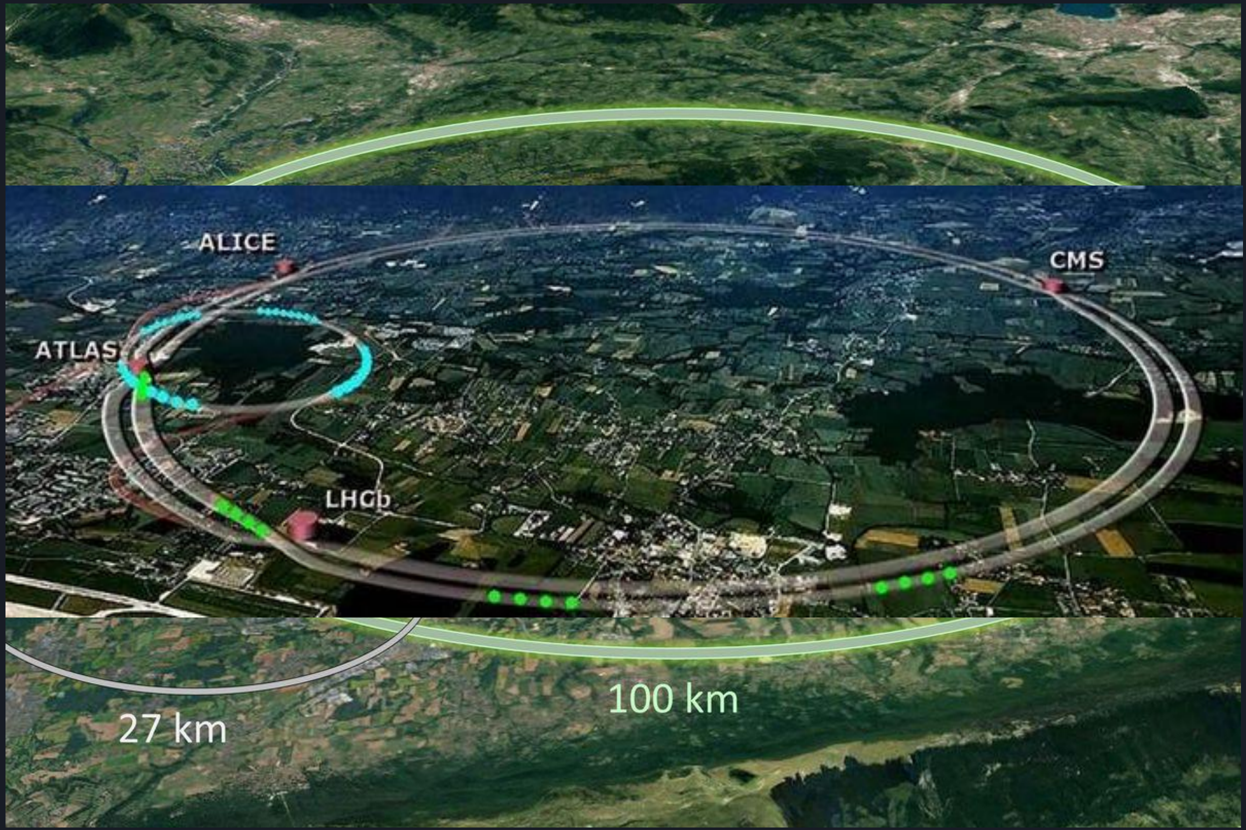
BJORN MANUEL HEGELICH

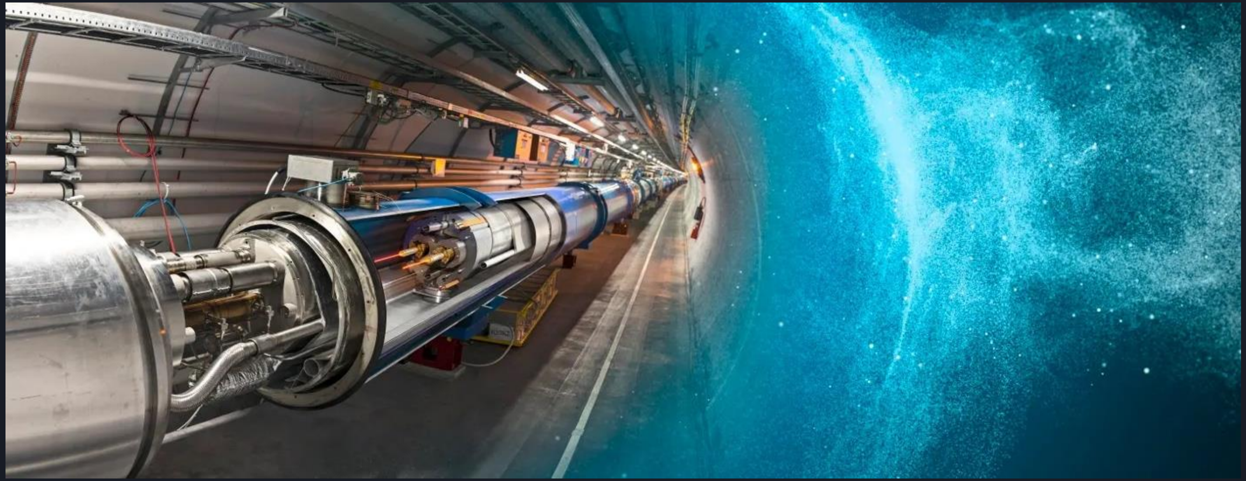
NAS MEETING
MAY 1, 2025

# ACCELERATORS - THE LARGEST MACHINES EVER BUILD

- The Large Hadron Collider at CERN has a circumference of 27km
- LHC cost ~$4.75B, CMS & ATLAS detectors ~$13B
- Annual operating cost: ~$0.5B
  - Just CERN, not accounting for member countries' science budgets
- Higgs-paper has 5,154 co-authors

## ACCELERATORS ARE DRIVERS FOR INNOVATION



# Severe innovation challenges

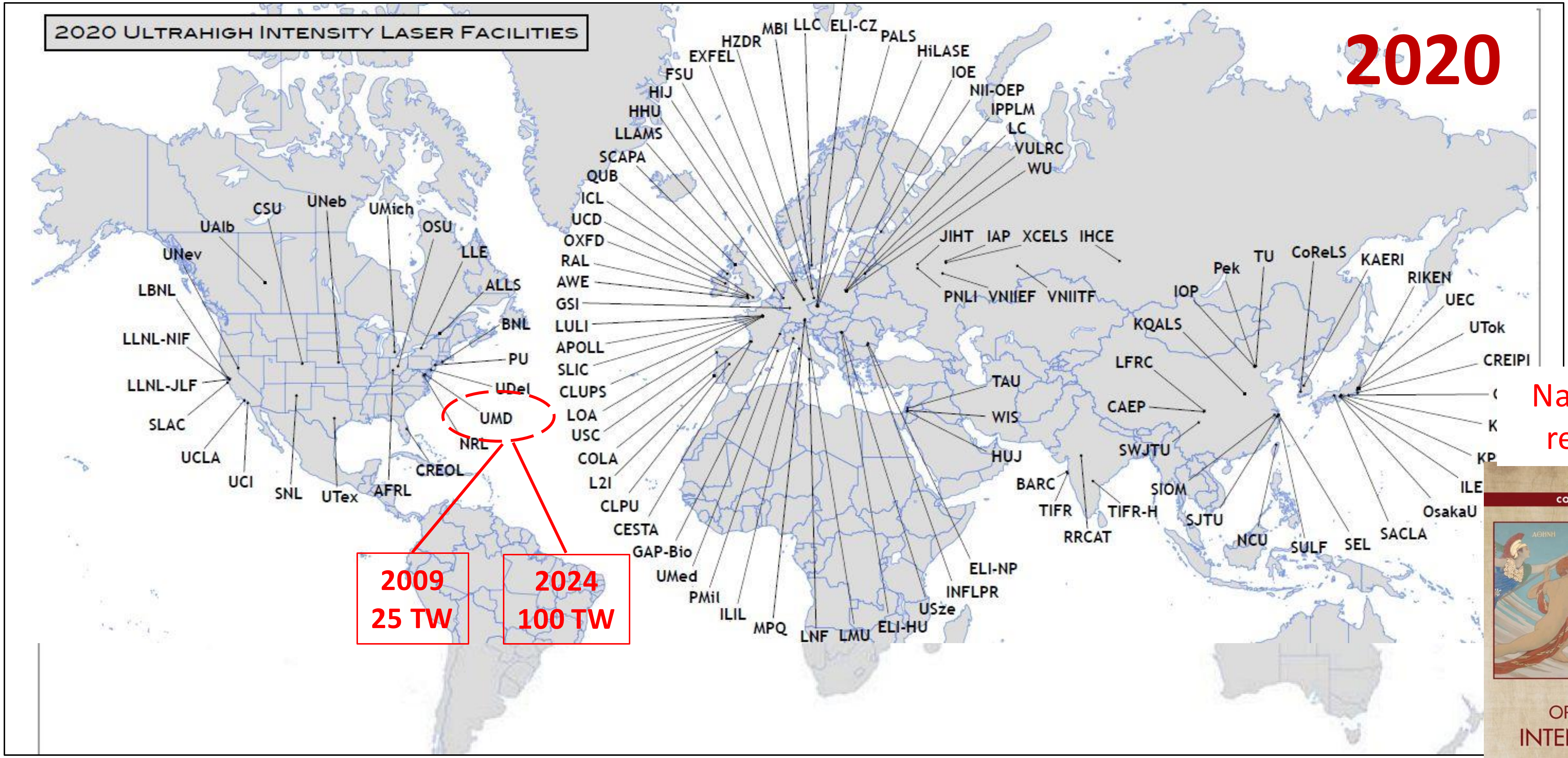
**Limited availability:** only a handful exist worldwide

**Limited time:** existing accelerators are heavily oversubscribed

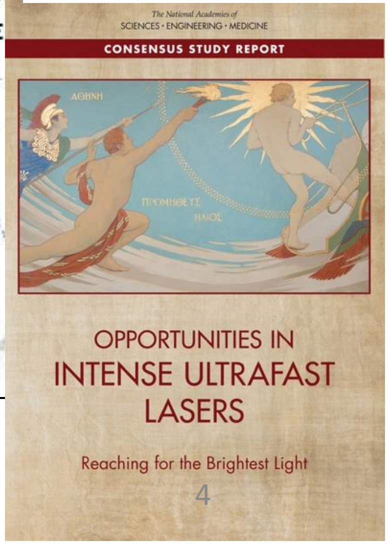
**Very expensive:** billions of dollars to build and operate

**Regulations & bureaucracy:** government funding and oversight, one-size-fits-all

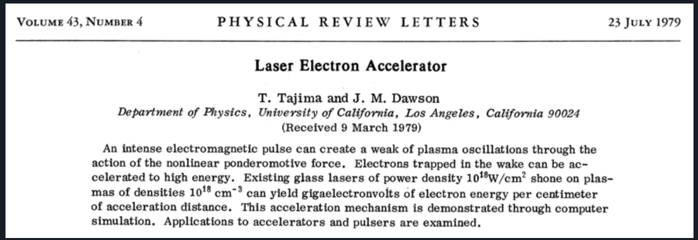
# Lasers worldwide with peak power > 10 TW




Nat. Academy report 2018



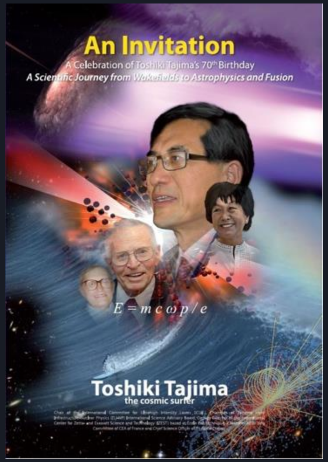
# HOW TO SHRINK A PARTICLE ACCELERATOR?

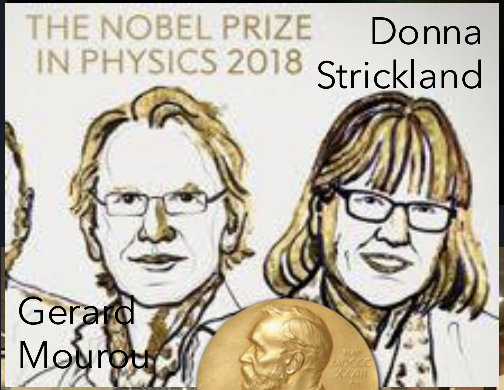

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

**Laser Electron Accelerator**

T. Tajima and J. M. Dawson
*Department of Physics, University of California, Los Angeles, California 90024*
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$W/cm$^2$ shone on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.




Conventional Accelerator:

- ~10 MV/m accelerating field
- 100 GeV energy: $\frac{100{,}000{,}000{,}000\ GeV}{10{,}000{,}000\ MeV/m} = 10{,}000\ m$
- ⇒ Acceleration length ~10 km

***Laser (Wakefield) Accelerator:***

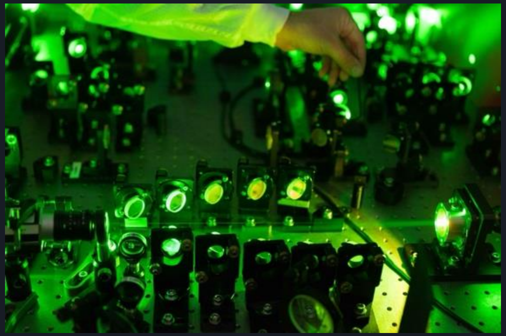
- 100,000,000,000 GV/m field
- ***Acceleration length: 1m!***

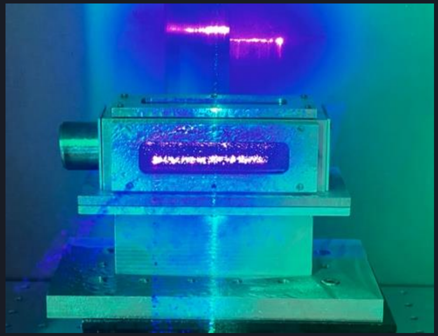
***Driven by CPA laser (Strickland & Mourou)***

# WHY ARE LASER-PLASMA ACCELERATORS SMALLER?

TODAY

TOMORROW





- Conventional accelerators use metal structures and radiofrequency electric fields to accelerate particles.
- The damage threshold of the metal limits the acceleration.
- ***A LWFA uses plasma which does not have a damage threshold.***
- Our lasers generate accelerating fields ***10,000x stronger***.
- The distance to reach the same energy can therefore be ***10,000x shorter***.

# 2

# LASER WAKEFIELD ACCELERATION: PHYSICS, STATUS, & PERFORMANCE

# LWFA PHYSICS

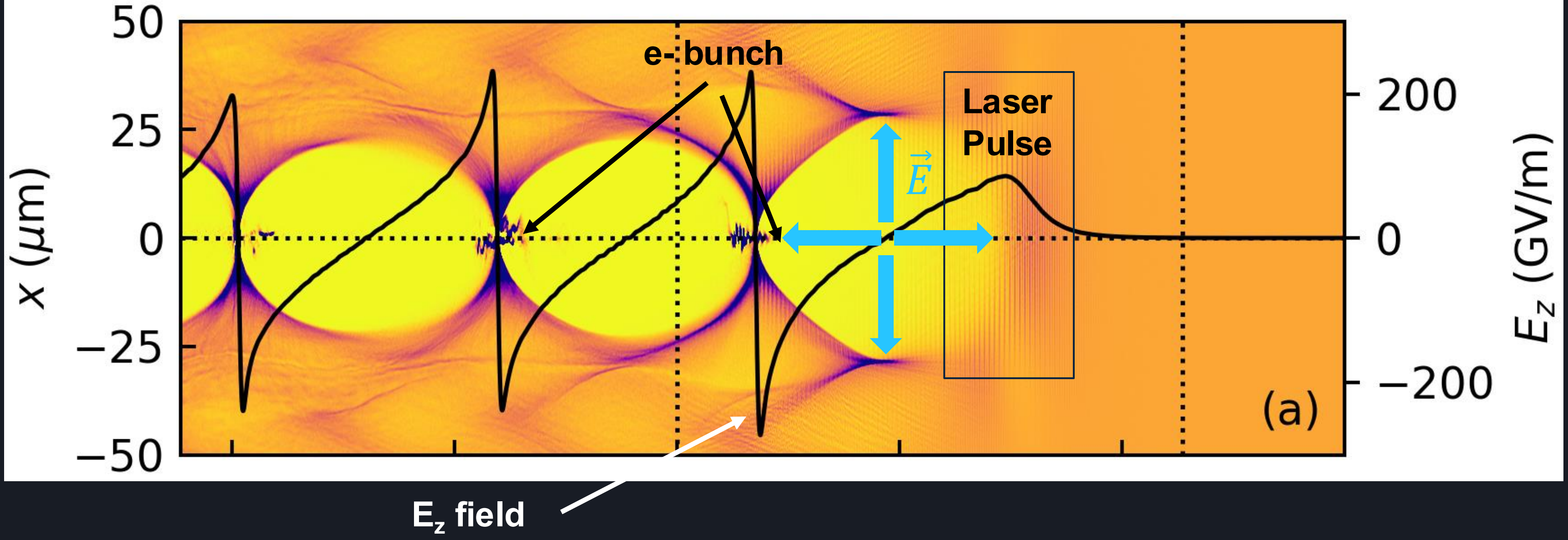
1. High power laser pulse focused at the beginning of neutral gas density profile creates a plasma and excites a plasma wave
2. Electrons crossing the back of the bubble are injected if their longitudinal velocities $\mathbf{v_e}$ are greater than the velocity $\mathbf{v_b}$ of the back of the bubble
3. Acceleration continues until electrons catch up to the middle of the bubble (de-phasing) or the bubble collapses because the laser loses energy (depletion)

**1-D linear approximation**

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{\delta n}{n_0} = c^2\nabla^2 \frac{1}{4}\left(\frac{eE_{Laser}}{mc^2\omega}\right)^2 \qquad \boldsymbol{a^2 \ll 1}$$

Plasma wave: electron density perturbation

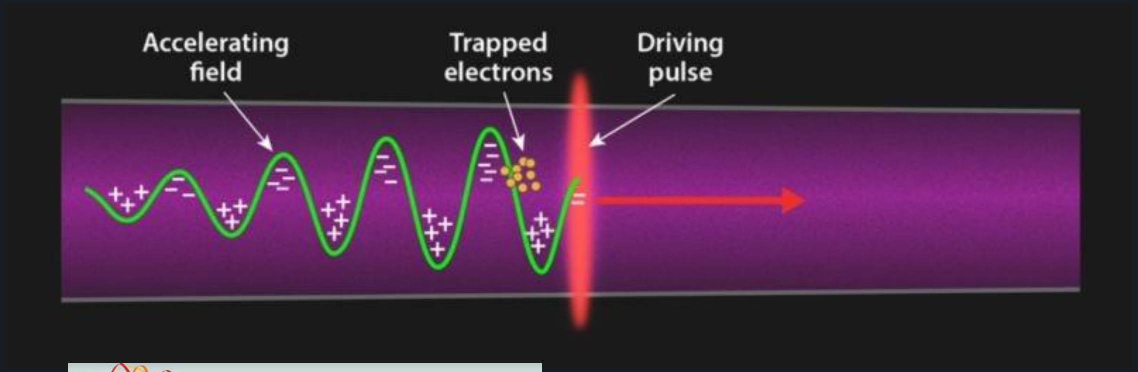
Ponderomotive force (radiation pressure)



# ADVANTAGE OF LWFA: HIGH FIELD GRADIENT

Field gradient determined by plasma density:

$$E_z \simeq \frac{m_e \omega_{pl} c}{e} \simeq 96\sqrt{\frac{n_e}{cm^3}}\,\text{V/m}$$




Plasma density determined by laser wavelength:

$$n_e \ll n_{cr} = \frac{\epsilon_0 m_e \omega_\ell^2}{e^2} \simeq 1.1 \times 10^{21}/cm^3 \left(\frac{\lambda}{\mu m}\right)^{-2}$$


nature COMMUNICATIONS

ARTICLE

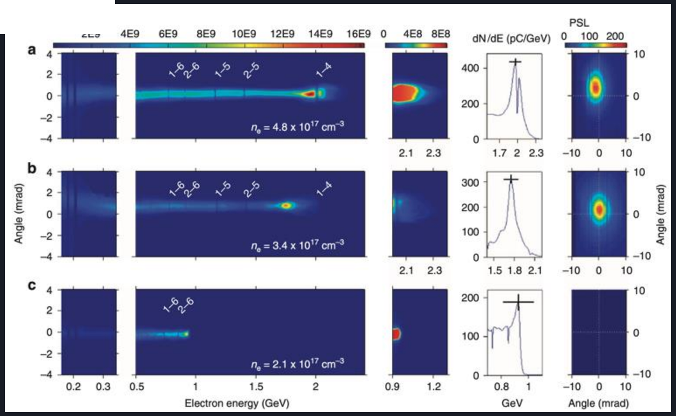
Received 2 Dec 2012 | Accepted 8 May 2013 | Published 11 Jun 2013 OPEN

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

Xiaoming Wang[1], Rafal Zgadzaj[1], Neil Fazel[1], Zhengyan Li[1], S. A. Yi[1], Xi Zhang[1], Watson Henderson[1], Y.-Y. Chang[1], R. Korzekwa[1], H.-E. Tsai[1], C.-H. Pai[1], H. Quevedo[1], G. Dyer[1], E. Gaul[1], M. Martinez[1], A. C. Bernstein[1], T. Borger[1], M. Spinks[1], M. Donovan[1], V. Khudik[1], G. Shvets[1], T. Ditmire[1] & M. C. Downer[1]

$$\frac{2\ GeV}{7\ cm} \rightarrow 29\frac{GV}{m}$$

TPW, Wang et al,
Nat. Comm., 2013




Typical operating range is $n_e \sim 10^{17} - 10^{19}/cm^3$

**Not 10s of MV/m, but 10s of GV/m**

# ADVANTAGE OF LWFAs: SHORT BUNCH LENGTH

Electron bunch length determined by plasma wavelength:

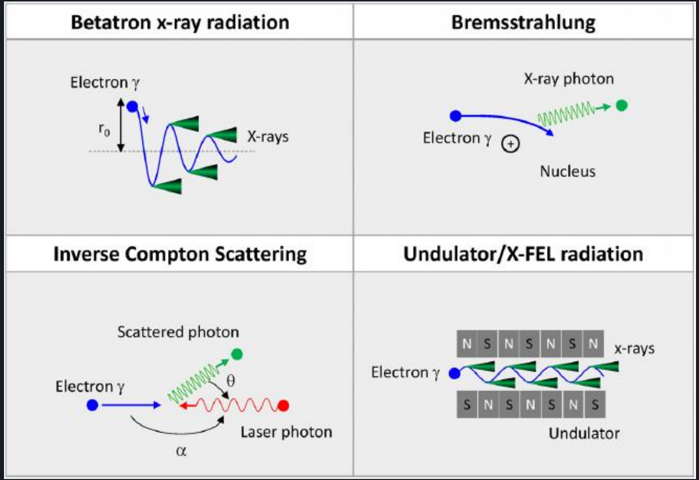
$$\Delta s < \lambda_{pl} = 2\pi \left(\frac{\epsilon_0 m_e c^2}{e^2 n_e}\right)^{\frac{1}{2}} = 33.4 \left(\frac{10^{18}/cm^3}{n_e}\right)^{\frac{1}{2}} \text{ micron}$$

With $n_e \sim 10^{17} - 10^{19}/cm^3$, typical bunch lengths are << 30 fs without compression

Actually two advantages:

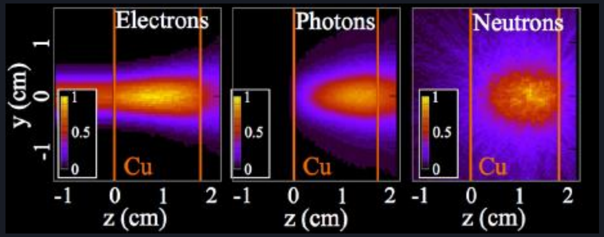
- Secondary particle beams inherit the short bunch length
- Bunch length can be traded for (slice) energy spread in a chicane for FEL operation

X-rays



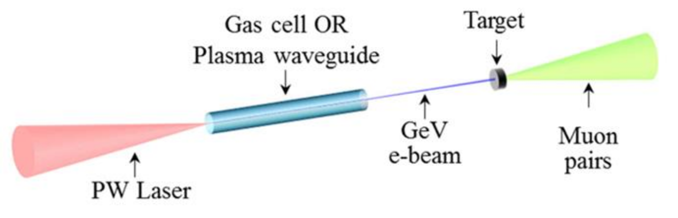

Neutrons

$e^- + N \rightarrow \gamma \rightarrow (\gamma, n)$




Muons

$\gamma + N \rightarrow N + \mu^- \mu^+$



- ENERGY
- CHARGE
- …

# 3

PARTICLE
ENERGY

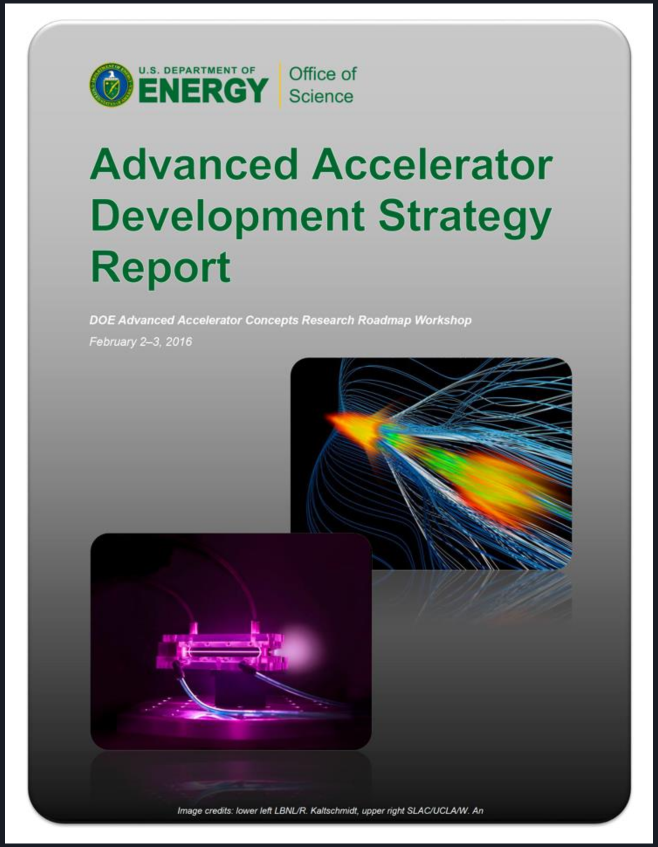
# ELECTRONS SURF A PLASMA WAVE BEHIND A LASERPULSE, LIKE WAKE-SURFERS BEHIND A BOAT

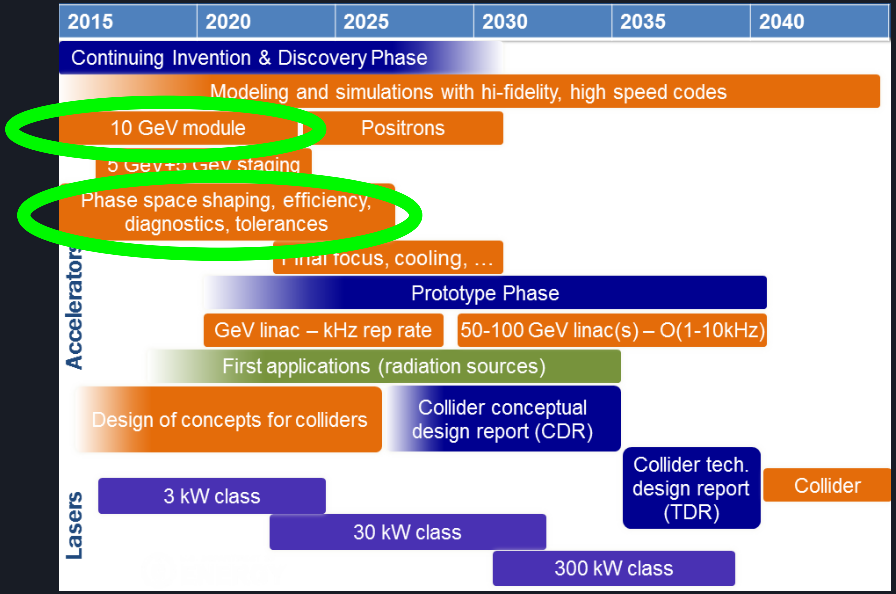
## A compact high-energy electron accelerator and ultrabright X-ray source

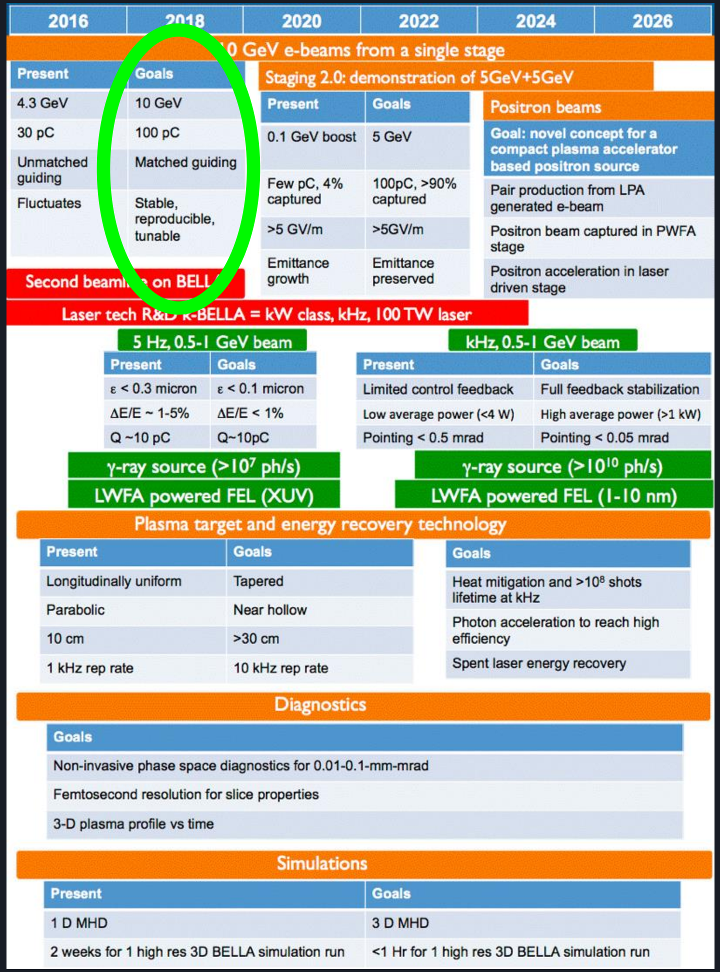
Three key components:

- Infra-red Laser: ultra-high intensity and ultra-short light pulses
- Accelerator: electrons at almost the speed of light over a few millimeters
- X-rays: electrons wiggle during acceleration, creating ultrabright X-rays

# Community Milestone: 10 GeV from a single stage



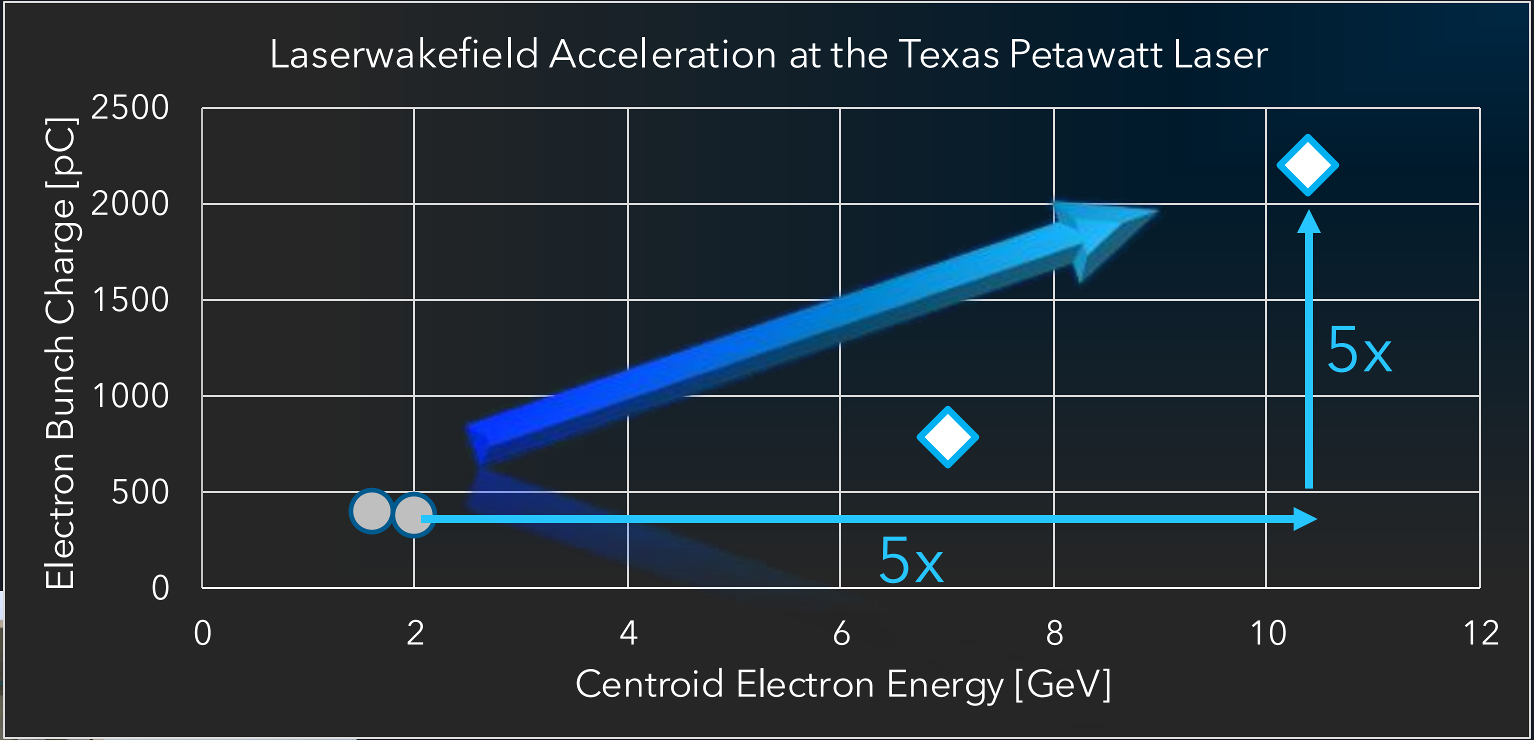
# THE TEXAS PETAWATT LASER AT UT AUSTIN

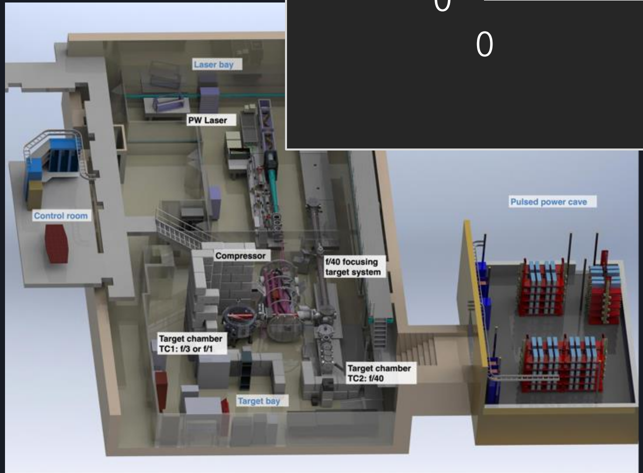
## Laser Parameters:

- 150 J
- 150 fs
- 1 shot/hr
- 2 Target Areas:
  - F/40: $2 \times 10^{18}$ W/cm$^2$
  - F/3: $10^{21}$ W/cm$^2$
  - F/1: $>3 \times 10^{22}$ W/cm$^2$


## Demonstrated Performance

- GeV electrons
- 100 MeV protons
- 600 MeV carbon
- 4.4 GeV Au
- $>10^{10}$ neutron/shot
- $>50$ MeV γ-ray beam



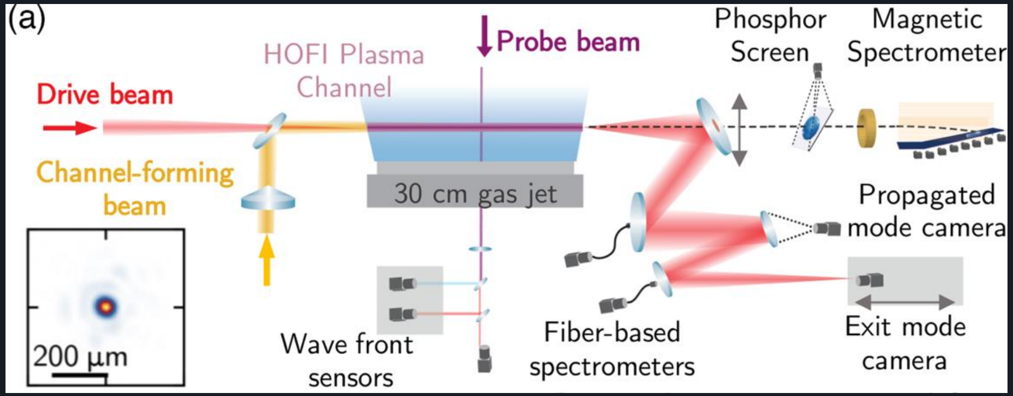



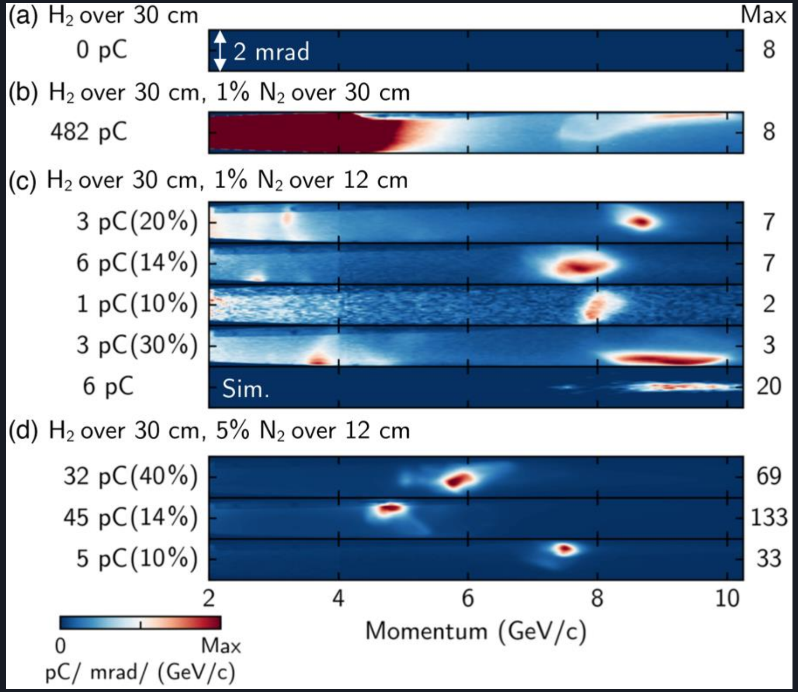


C. Aniculaesei et al., Matter Radiat. Extremes 9, 014001 (2024)

# LBNL & CSU: 9 GeV in 2024 & 2025

- 9.15 GeV, 3 pC, 30cm accel. length

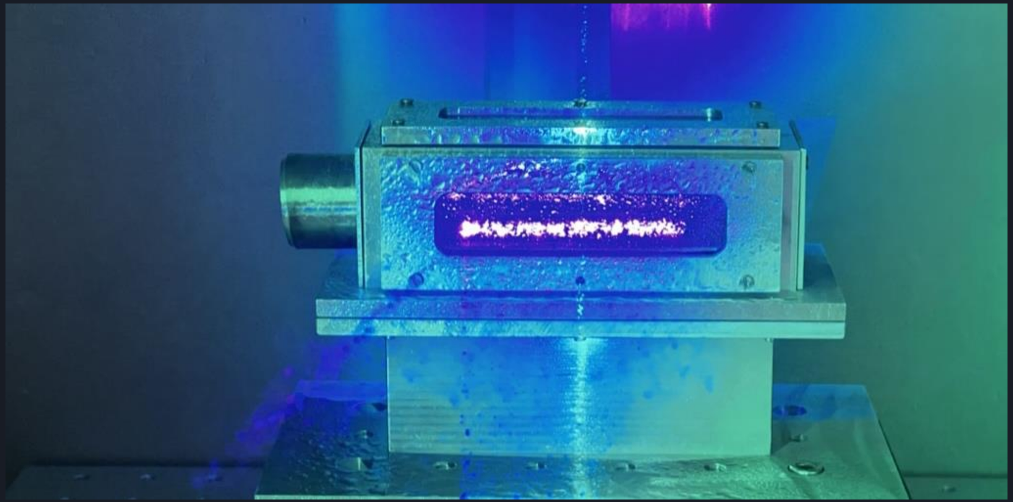


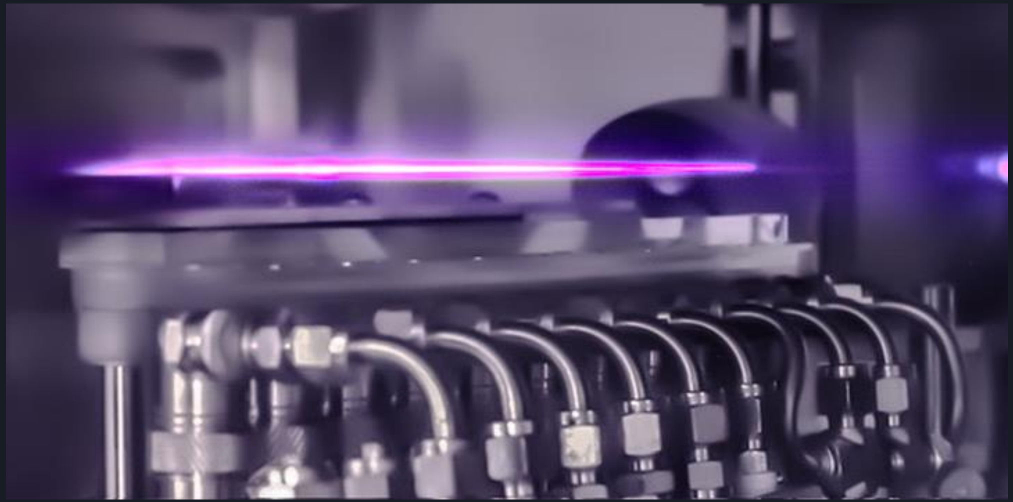




## High charge laser acceleration of electrons to 10 GeV


Ela Rockafellow [1], Jaron E. Shrock [1], Bo Miao [1], Ari Sloss [1], Manh S. Le [1], Scott W. Hancock [1], Sina Zahedpour [2], Reed C. Hollinger [2], Shoujun Wang [2], James King [2], Ping Zhang [2], Jiří Šišma [3 4], Gabriele M. Grittani [3], Roberto Versaci [3], Daniel F. Gordon [5], Gerald J. Williams [6], Brendan A. Reagan [6], Jorge J. Rocca [2 7], Howard M. Milchberg [1 8]

# LPA targets





# MULTI-GEV LPA EXPERIMENTS

10cm

| Accelerating Field | Energy | Acceleration length | Charge | Method | Facility | Year |
|---|---|---|---|---|---|---|
| [GV/m] | [GeV] | [cm] | [pC] | | | |
| 29 | 2 | 7 | 63 | Cell, SI | TPW | 2013 |
| 39 | 7.8 | 20 | 5 | Cap, HB, II | Bella | 2019 |
| 64 | 4.5 | 7 | 200 | Cell, II | CoReLS | 2019 |
| 25 | 5 | 20 | 2 | HOFI | CSU | 2022 |
| **104** | **10.4** | **10** | **340** | **Cell, nano** | **TPW** | **2023** |
| 30 | 9.15 | 30 | 3 | HOFI | Bella/UMD | 2024 |
| 30 | 9 | 30 | 10 | HOFI | CSU/UMD | 2025 |

# 3

# OTHER BEAM PARAMETERS

- EMITTANCE
- STABILITY
- …

# LWFA STATE-OF-THE ART PERFORMANCE

| Beam property | Value | Reference |
|---|---|---|
| Energy (Centroid/Peak) | 10 GeV<br><br>8 GeV | Aniculaesei et al., MRE 9, 014001 (2024)<br><br>Gonsalves et al., Phys.Rev.Lett. 122, 084801 (2019) |
| Energy spread | ~0.3% | Ke, et al. , Phys.Rev.Lett. 126, 214801 (2021) |
| Charge | ~700 nC | Shaw, et al., Sci. Rep. 11 (2021) |
| Emittance | 0.14 mm mrad | Weingartner et al. Phys. Rev. ST Accel. Beams 15, 111302 (2012) |
| Bunch duration | 1.5 fs | Lundh et al., Nat. Phys. 7, 219 (2011) |
| Repetition rate | ~1 kHz | Salehi et al., Phys.Rev.X 11, 021055 (2021)<br>Lazzarini et al., PoP (2023) |

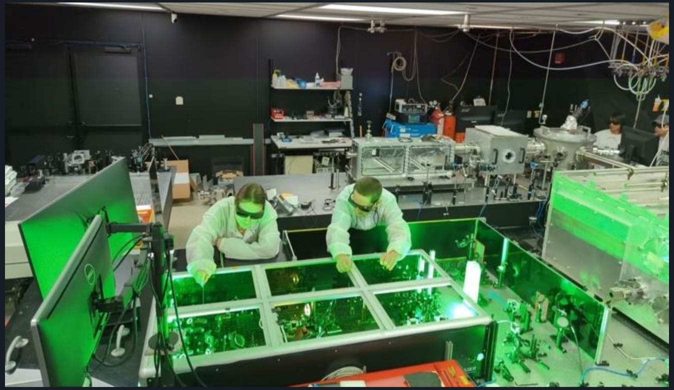
Other achievements:

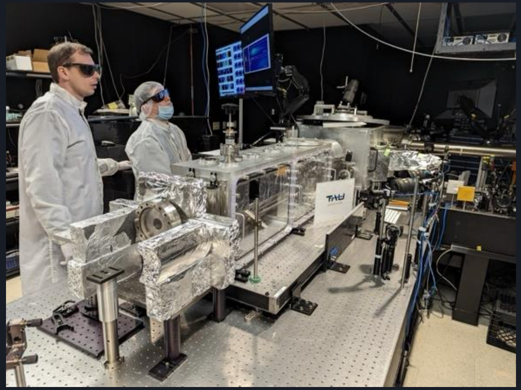
- **multi-staging:**
  Steinke et al., Nature 530, 190 (2016)
- **closed-loop optimization:**
  Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)
  Shaloo et al., Nat. Comm. 11, 6355 (2020)
- **long-term operation:**
  Maier et al., Phys. Rev. X 10, 031039 (2020)
- **LWFA/PWFA-based FEL:**
  Wang et al., Nature 595, 516 (2021);
  Pompili et a., Nature 605, 659 (2022) [Beam-driven]

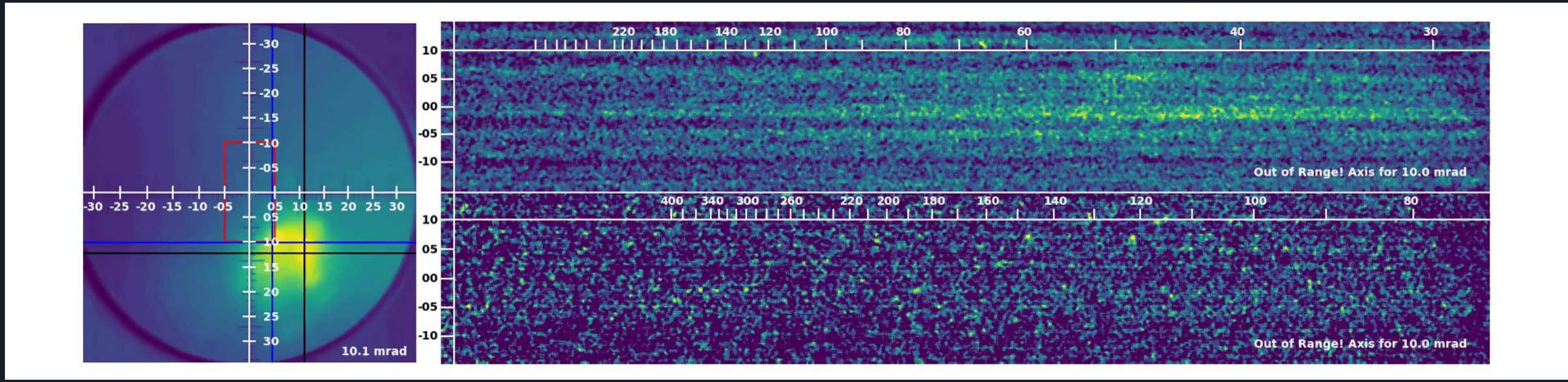
# UT$^3$ IS A 30TW CPA LASER DRIVING A 100MEV-CLASS LWFA ELECTRON ACCELERATOR

## Laser Parameters

| | |
|---|---|
| Energy on target | (1000±25) mJ |
| Pulse duration | <(31±1) fs |
| Focal spot diameter | <16μm FWHM, (F/12) |
| Focal position stability | <3.5 μm |
| Enclosed energy | >70%, first null |
| Maximum rep rate | 10 Hz |
| Wavelength | (790±20) nm |



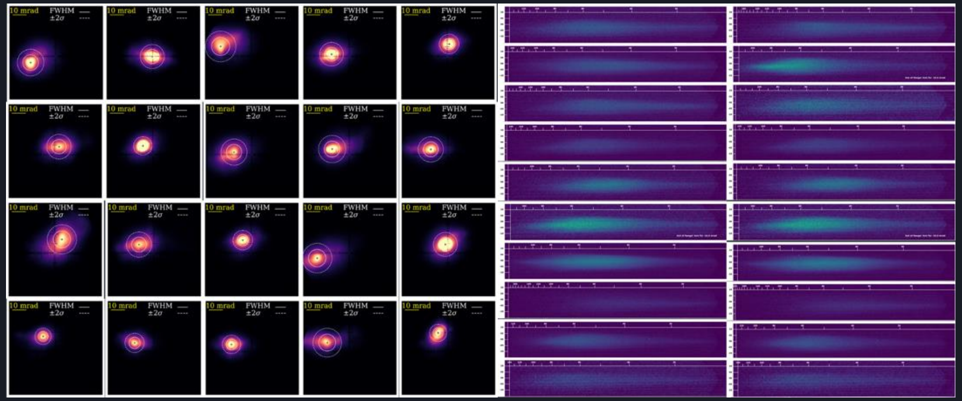




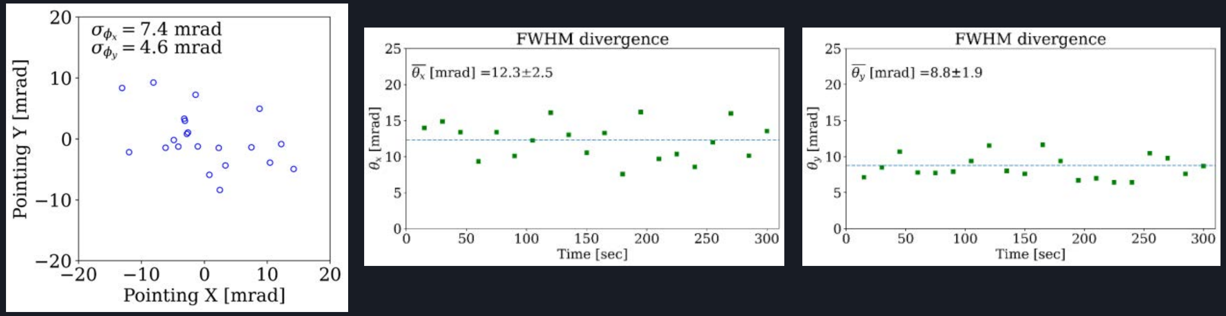

Focal position scan, Oct 19th 2023

# ACCELERATOR PERFORMANCE IMPROVED DRAMATICALLY FROM LASER UPGRADES ALONE

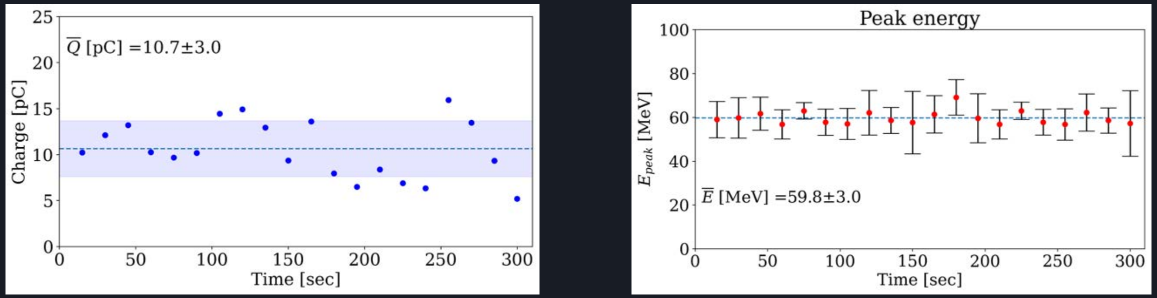
- Data from April 2024
- Laser plasma electron accelerator (LPA) with:
  - 10mrad shot-to-shot pointing stability
  - 10mrad average divergence
  - 60MeV peak bunch energy
  - 10pC single-bunch charge
  - Bunch duration 10fs



Electron bunch spatial profiles and spectra of 20 consecutive shots over 5 minutes at the UT[3] LPA




Shot-to-shot pointing (left) and divergence in horizontal (center) and vertical (right) planes of 20 consecutive shots over 5 minutes

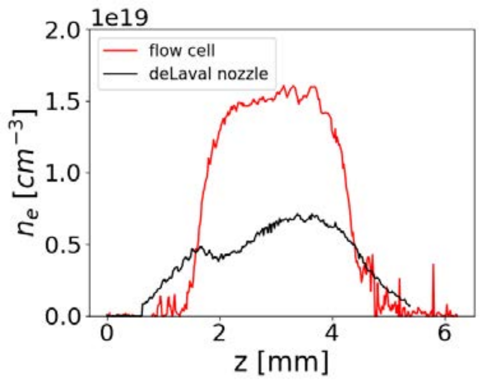



Bunch charge (left) and peak energy (right) of 20 consecutive shots over 5 minutes. Error bars in peak energy represent ±half a standard deviation of the energy distribution for each shot.

# LASER-PLASMA COUPLING WAS FURTHER OPTIMIZED YIELDING A STABLE, HIGH QUALITY ELECTRON BEAM

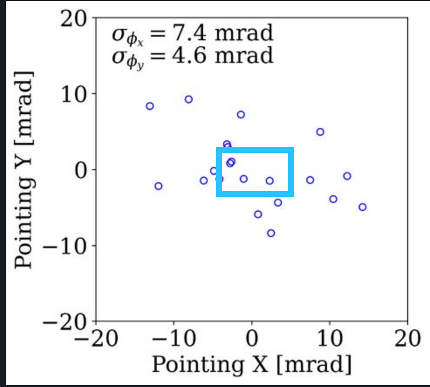
- Data from June 2024
- Laser improvements allow optimal performance at lower plasma density
- Best performance was achieved for ionization injection (1% N, 99% He) in non-uniform profile at $n_e$~7e18cm$^{-3}$ (black curve)

Measured plasma density profiles

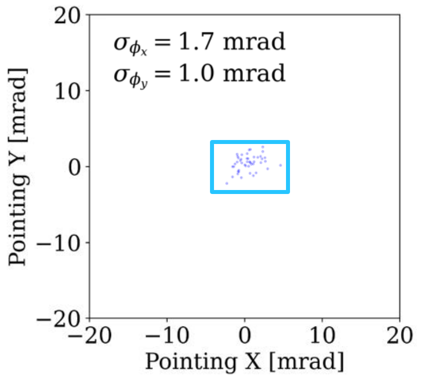


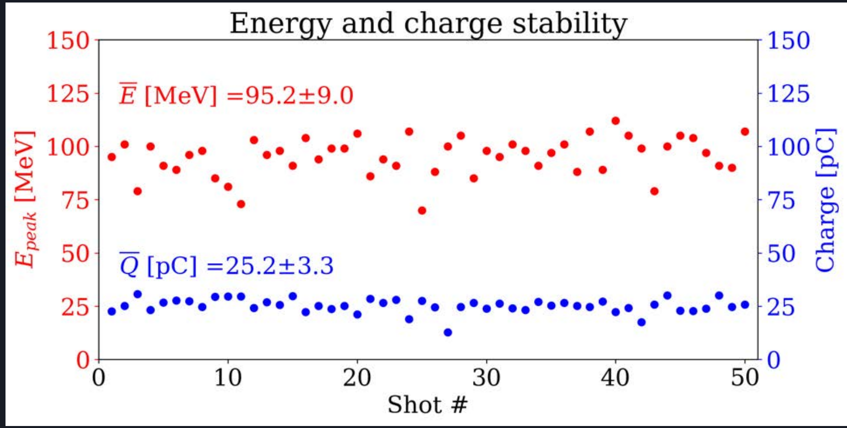

Pointing fluctuations

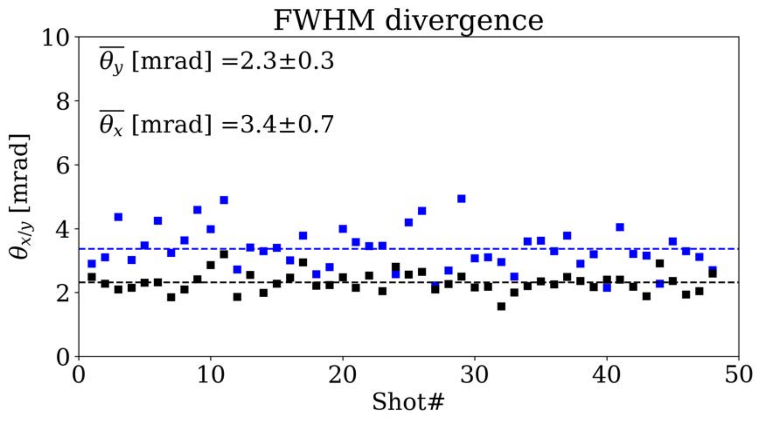
April 2024



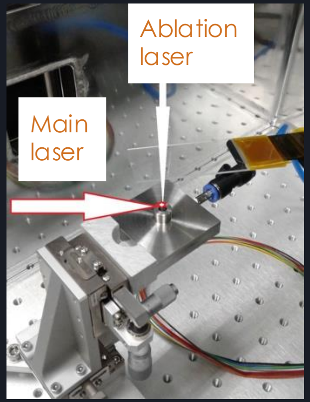

June 2024

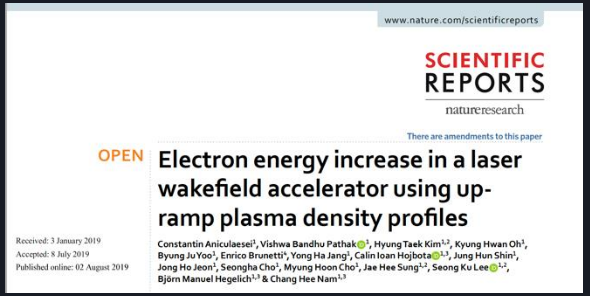


# NANOPARTICLE-ASSISTED ELECTRON INJECTION INTO A WAKEFIELD WITH A 50 TW LASER





www.nature.com/scientificreports
SCIENTIFIC REPORTS
natureresearch
There are amendments to this paper

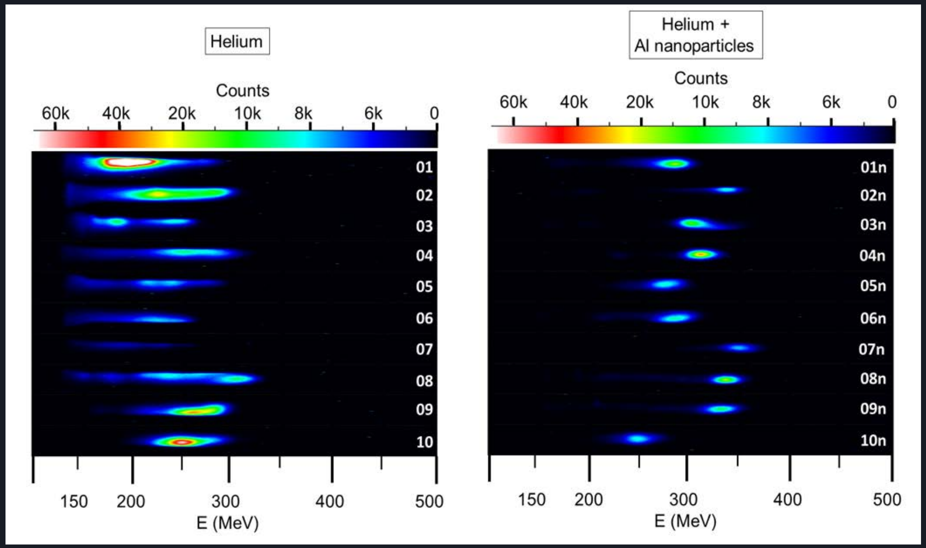
OPEN

**Electron energy increase in a laser wakefield accelerator using up-ramp plasma density profiles**

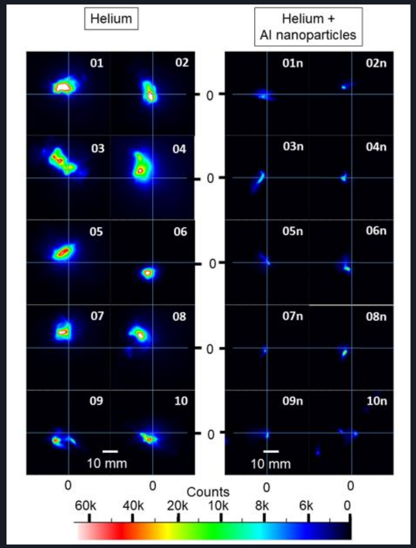
Received: 3 January 2019
Accepted: 8 July 2019
Published online: 02 August 2019

Constantin Aniculaesei[1], Vishwa Bandhu Pathak[1], Hyung Taek Kim[1,2], Kyung Hwan Oh[1], Byung Ju Yoo[1], Enrico Brunetti[4], Yong Ha Jang[1], Calin Ioan Hojbota[1,3], Jung Hun Shin[1], Jong Ho Jeon[1], Seongha Cho[1], Myung Hoon Cho[1], Jae Hee Sung[1,2], Seong Ku Lee[1,2], Björn Manuel Hegelich[1,3] & Chang Hee Nam[1,3]

no nanoparticles | with nanoparticles



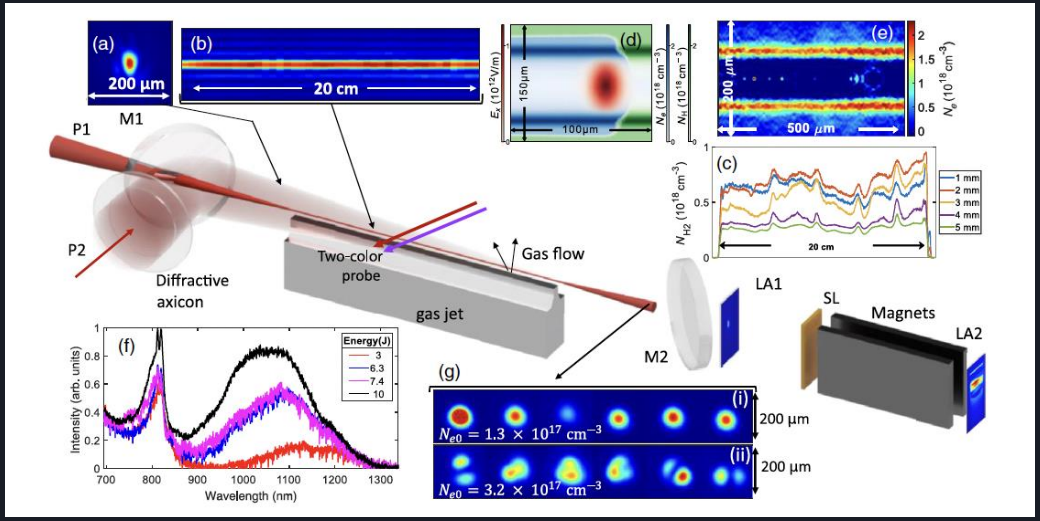

no nanoparticles | with nanoparticles

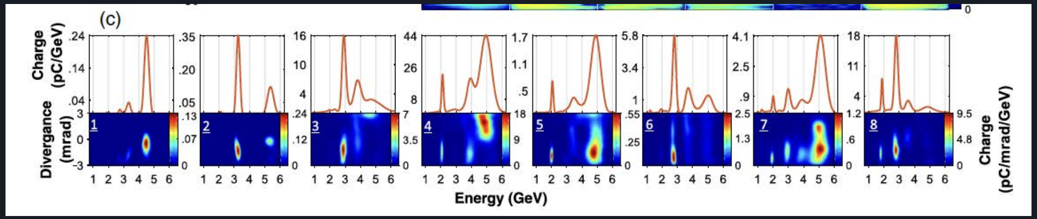



- *Electron peak energy and energy spread greatly improved*
- Electron beam divergence decreased

# ENERGY OPTIMIZED LPAs

## MIAO ET AL., PRX, 12, 031038 (2022): 5 GEV FROM A 400 TW LASER




## OUBRERIE ET AL. NATURE LSA (2022), 11:180 1.1 GEV FROM A 50 TW LASER

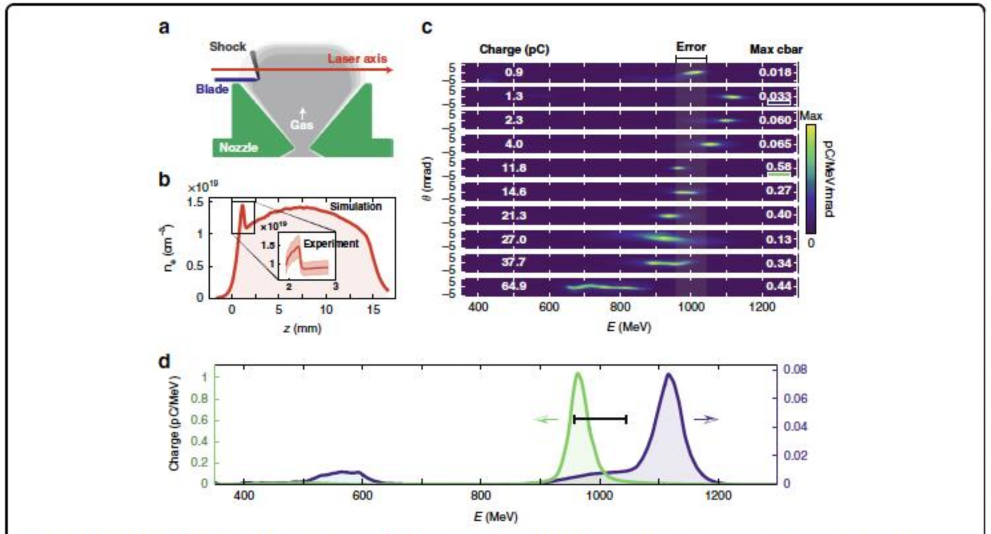


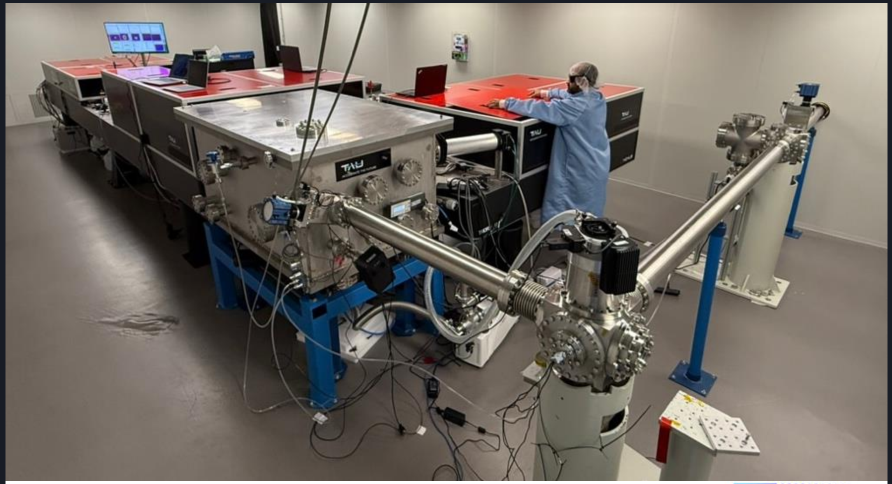

**Fig. 4 Acceleration of high-quality electron beams with density transition injection. a** Schematic view of the gas target. **b** Density profile obtained from a fluid simulation for our experimental parameters and measured density profile in the shock region (inset). **c** Ten angularly resolved electron spectra sorted by charge (charge in the peak for $d^2N/dEd\theta > 0.1(d^2N/dEd\theta)_{max}$). **d** Two examples of angularly-integrated spectra corresponding to spectra marked by blue and green lines in (**c**). The black segment indicates the uncertainty on the energy due to fluctuations of beam pointing

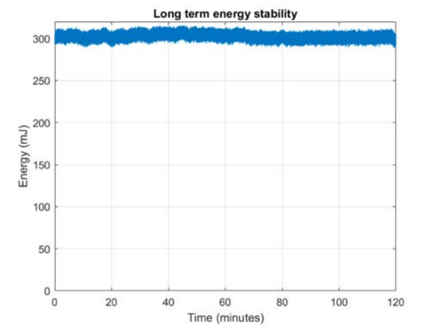
TAU

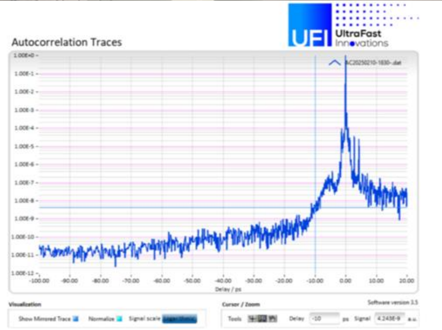
# DIFFERENT RADIATION TYPES FROM ONE FACILITY

Synchrotron beamtime requires complicated applications and long wait times. TAU Labs will offer synchrotron-like capabilities without the wait…

| Source Type | Spectrum | Shot Rate | Pulse Energy | Pulse Duration |
|---|---|---|---|---|
| Infrared | 800 ± 20 nm | 100 Hz | 1 J | 25 fs |
| Electron source | 50 - 150 MeV | | 10 - 100 pC | ~10 fs |
| X-ray source | 1 – 10 keV | | $10^9$ photons / shot<br>$10^{11}$ photons / s | ~10 fs |
| $\gamma$-ray source | 1-10 MeV | | $10^8$ photons / shot<br>$10^{10}$ photons / s | 10fs – 1ps |
| neutrons | MeV | | $10^7$ neutrons / shot<br>$10^9$ neutrons / s | ps |



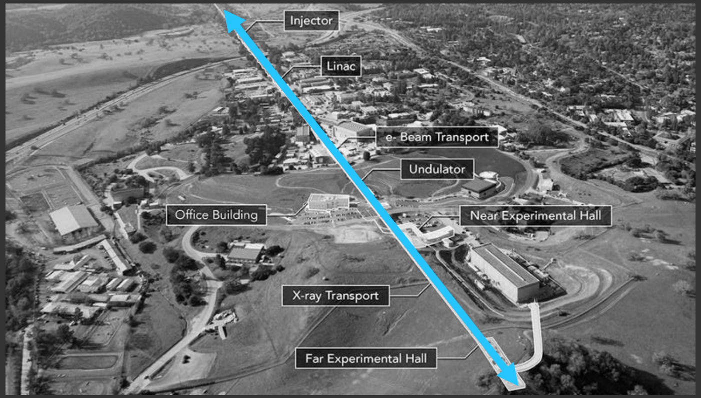



TAU

# *A laser accelerators becomes competitive at >100MeV, 100Hz*

Titanium Sapphire Laser with ≥1J pulse energy and 100Hz repetition rate

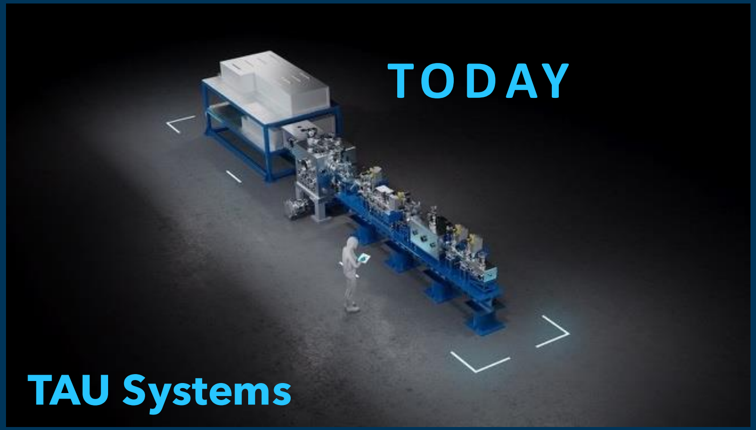


**S**tanford **L**inear **A**ccelerator **C**enter

$1B and 2 miles

**<1/100 the size**

**<1/100 the cost**




$10M and 10 meters

## *A laser accelerators becomes superior at 1GeV, 1kHz*

# CONTRIBUTORS

## BELLA Center

**Samuel Barber**, Jeroen van Tilborg, Fumika Isono, Carl Schroeder, Eric Esarey, Jens Osteroff, Cameron Geddes, Anthony Gonsalves, Kei Nakamura, **Finn Kohrell, Chris Doss, Kyle Jensen**, Curtis Berger…

## Tau Systems

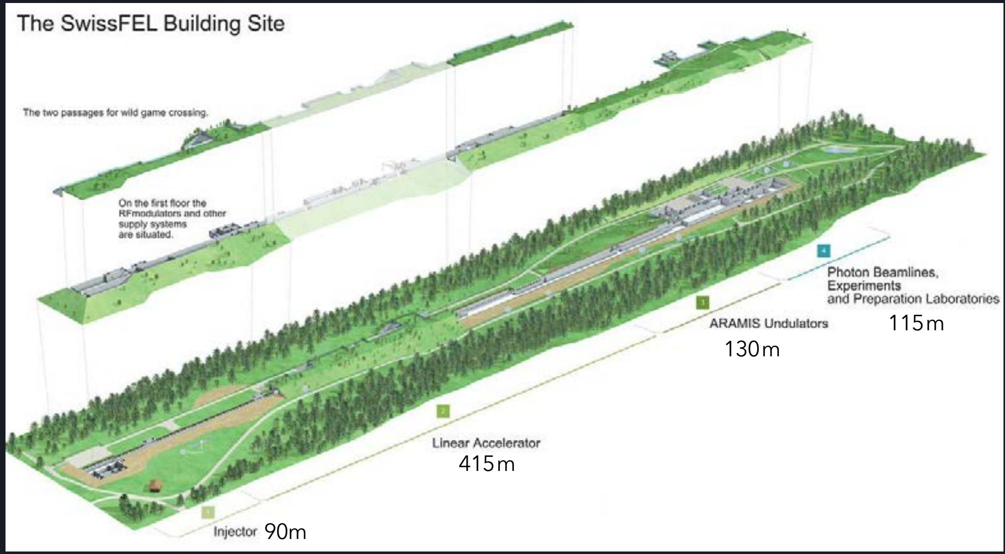
Stephen Milton, Guillaume Plateau, Reinier van Mourik, Dung Phan, …

# 5

# COMPACT LWFA-DRIVEN FREE-ELECTRON LASERS (LFEL)

# SwissFEL X-ray Free Electron Lasers

SwissFEL had "The goal of building a compact and not all too costly Free Electron Laser"




Length: ~0.75 km

Cost: >$300M*

Power Consumption: 3.8 MW

Electron Energy: 2.5 – 6.5 GeV

X-ray photon energy: ~0.26 – 12.7 keV

Wavelength: 0.1nm – 7nm

Repetition Rate: 100Hz

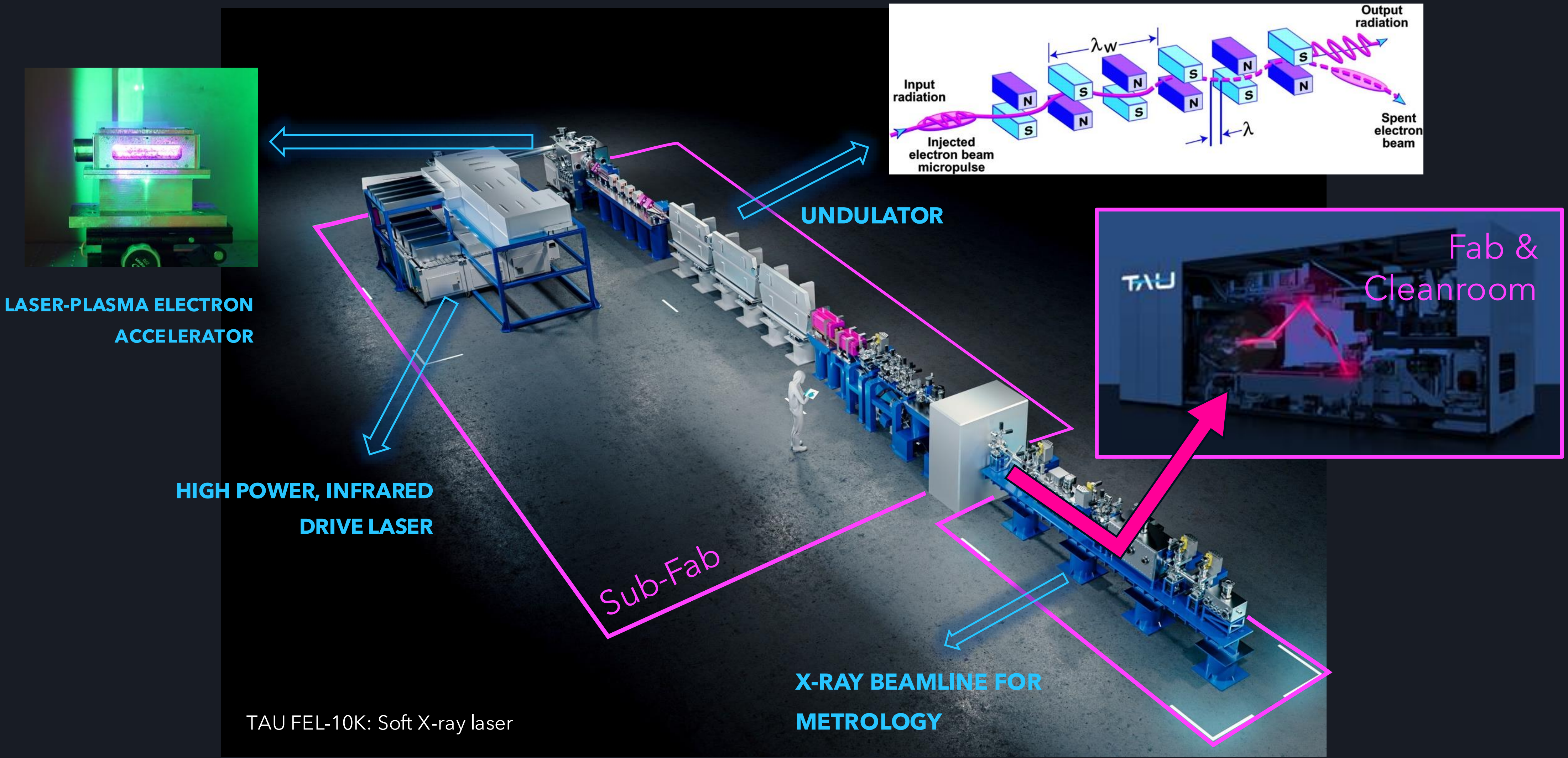
Peak Brilliance: $1.3 \times 10^{33}$ ph/s $mm^2$ $mrad^2$ 0.1% BW

**Accelerator parameters**

- Electron energy: 2.5 – 6.5 GeV
- Electron bunch charge: 10 – 200 pC
- Repetition rate: 100Hz
- Length: 505m
- <Acceleration gradient>: 11.5 MV/m

- RF-gun 100 MV/m
- S-band injector 20MV/m
- C-band main linac 28 MV/m

# TAU'S ULTIMATE LIGHT SOURCE IS A *COMPACT* EUV/X-RAY FREE ELECTRON LASER

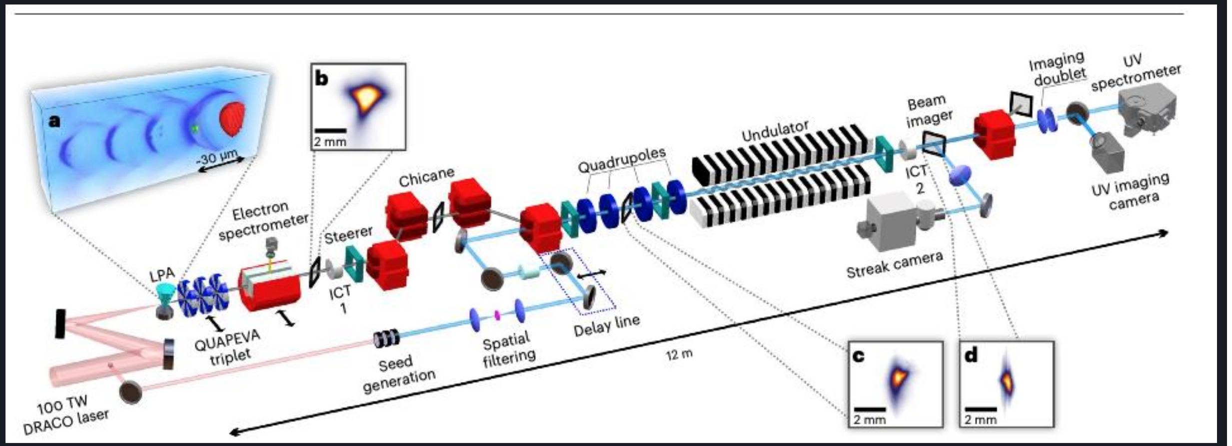


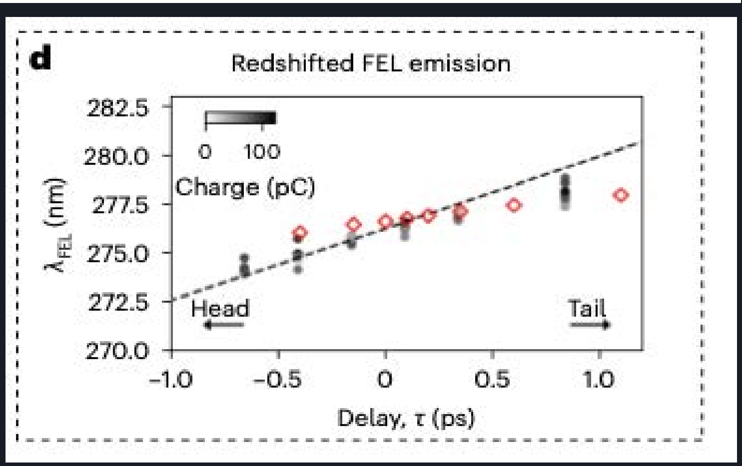

TAU FEL-10K: Soft X-ray laser

# MATURITY DEMONSTRATED BY FEL OPERATION

LWFA Systems have now been constructed for a purpose other than accelerator research.

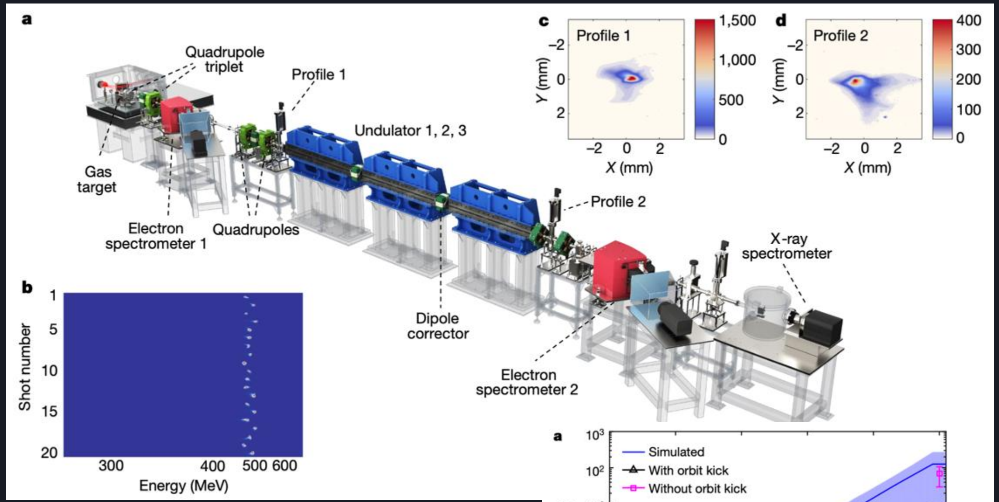
## Dresden-Rossendorf

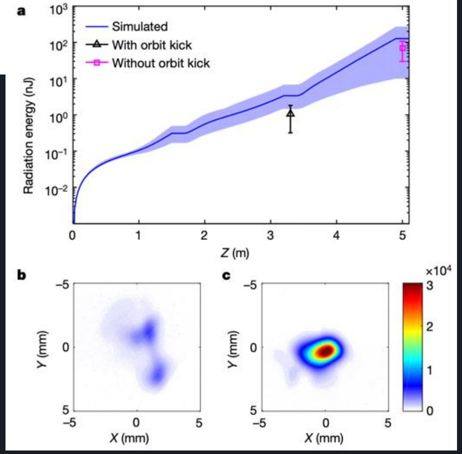



Labat, et al., "Seeded free-electronlaser driven by a compact laser plasma accelerator", Nature Photonics **150-156** (2023).

## Shanghai Institute of Optics and Fine Mechanics



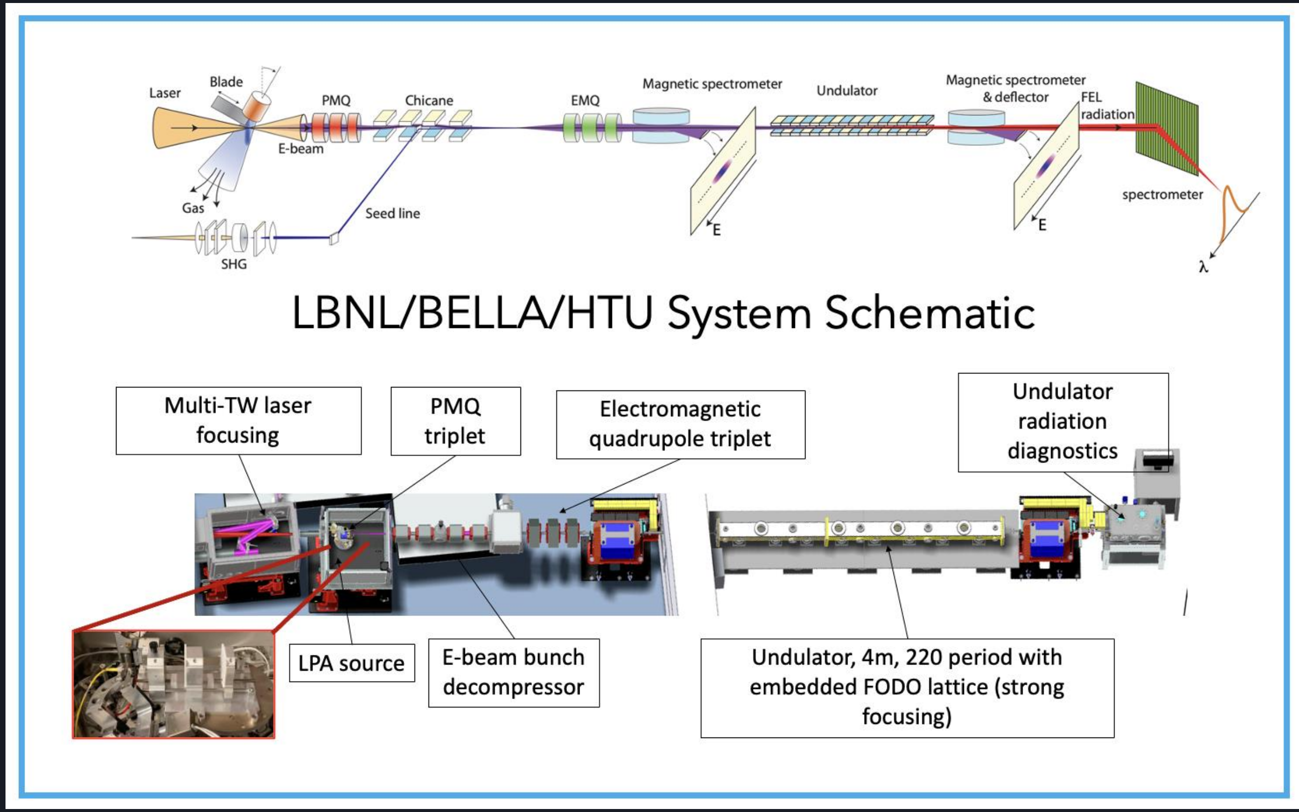



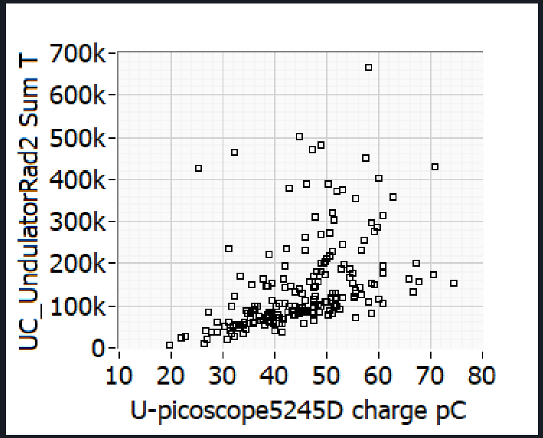

Wang, et al., "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator", Nature **595** (2021)

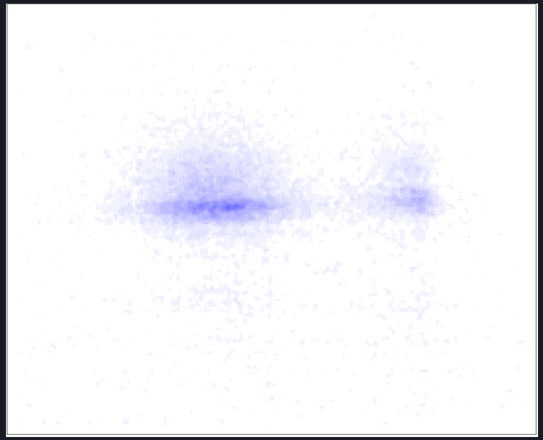
Gain measured at 27 nm

# INITIAL RESULTS

## FEL system at the BELLA Center LBNL



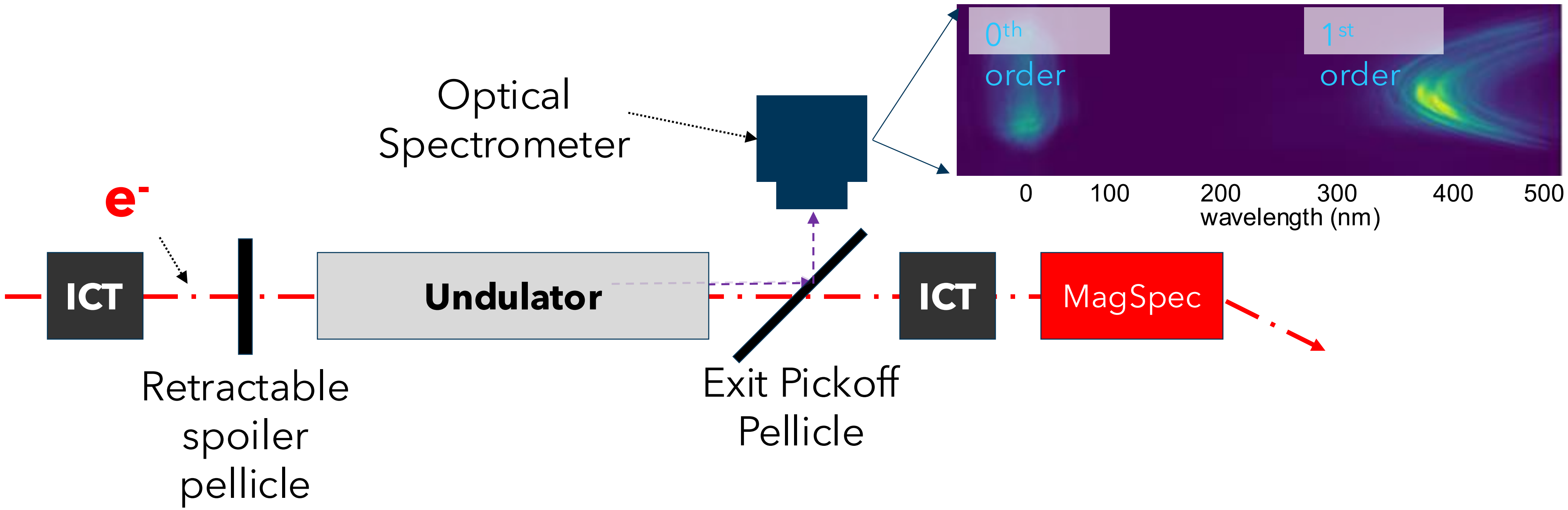




The LBNL component of this work was supported by the U.S. Department of Energy (DOE), Office of Science, the Office of Basic Energy Sciences, and the Office of High Energy Physics, under Contract No. DE-AC02-05CH11231

This work was made possible through Collaborative Research and Development Agreement (CRADA) between TAU Systems Inc. and Lawrence Berkeley National Laboratory (LBNL).

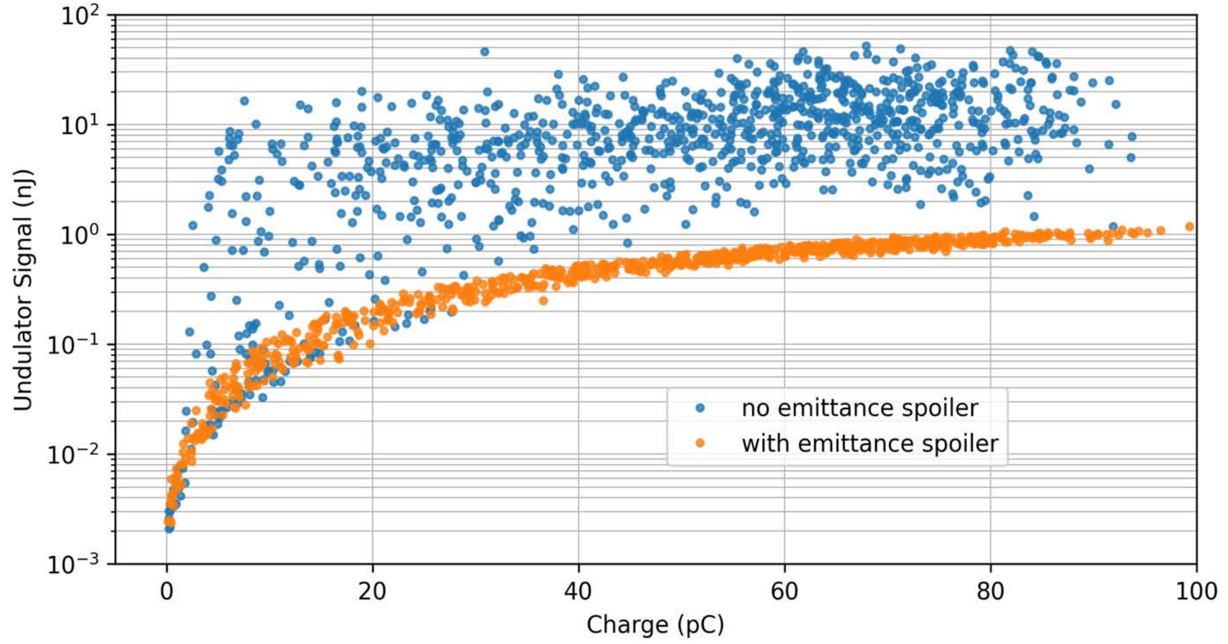
# DIAGNOSTIC SETUP FOR UNDULATOR RADIATION CHARACTERIZATION




- Setup allows radiation characterization at multiple points along 4 meter undulator
- Retractable pellicle enables emittance spoiling without loss of charge for confirming microbunching instability

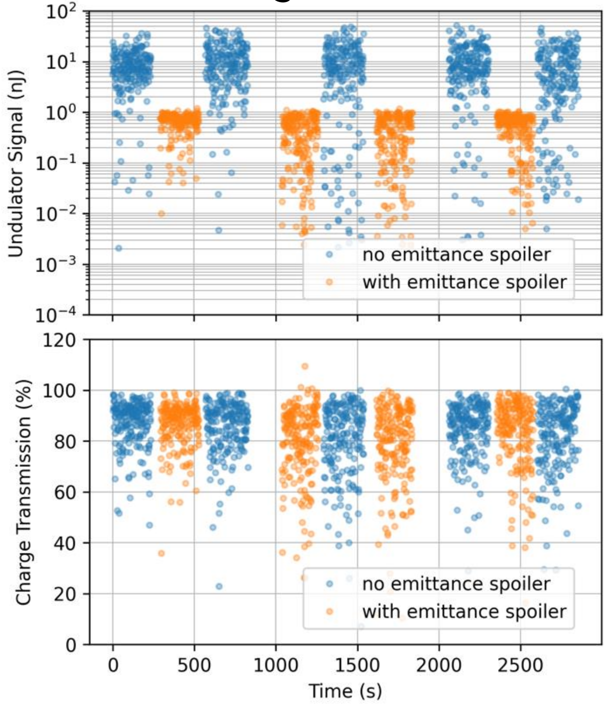
# RADIATION MEASUREMENTS WITH/WITHOUT EMITTANCE SPOILER REVEAL CLEAR EVIDENCE OF FEL GAIN

**Undulator radiation signal vs charge for 1000 consecutive shots**



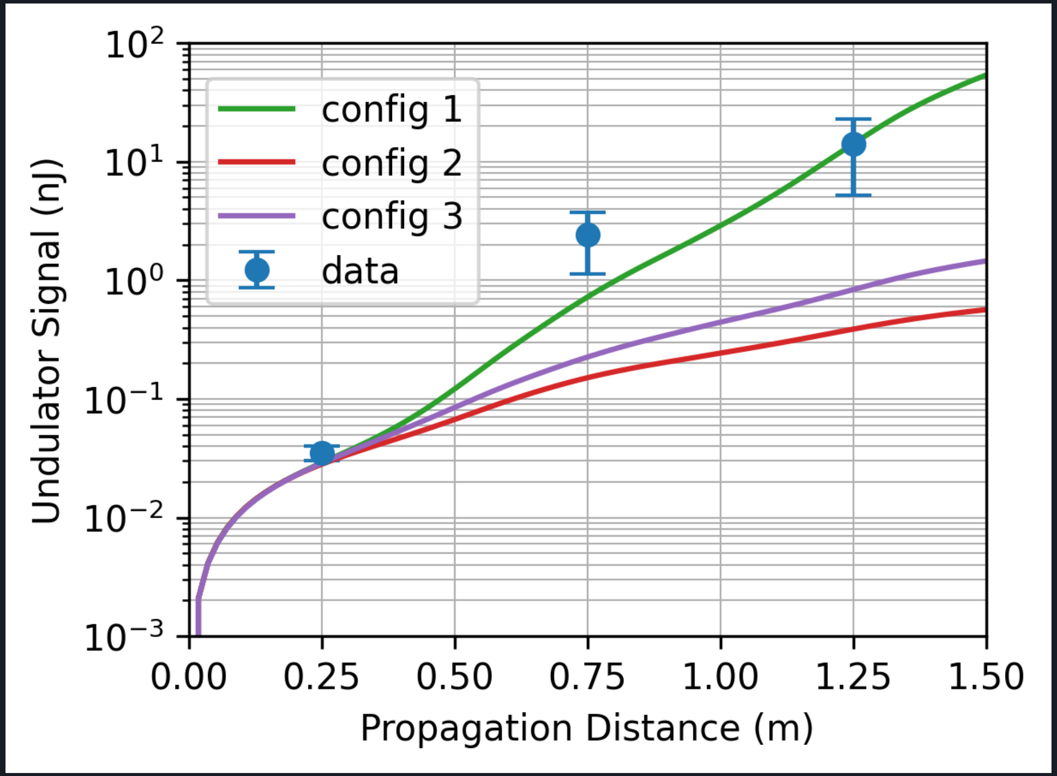

- Optimized transverse focusing and alignment using radiation signal at the end of the 4 meter undulator
- **Gain over incoherent undulator radiation on >90% of shots**
- Ratio FEL to incoherent: ~200-300x (max), 50-100x (average)

**Undulator radiation signal measured over 1 hour**




- Stable operation of FEL with data acquisition over hours of beamtime
- Emittance spoiler has no impact on charge transmission (bottom)

# COMPARING MEASUREMENTS TO GENESIS SIMULATIONS CAN PROVIDE INFORMATION ON DIFFICULT TO MEASURE BEAM PARAMETERS



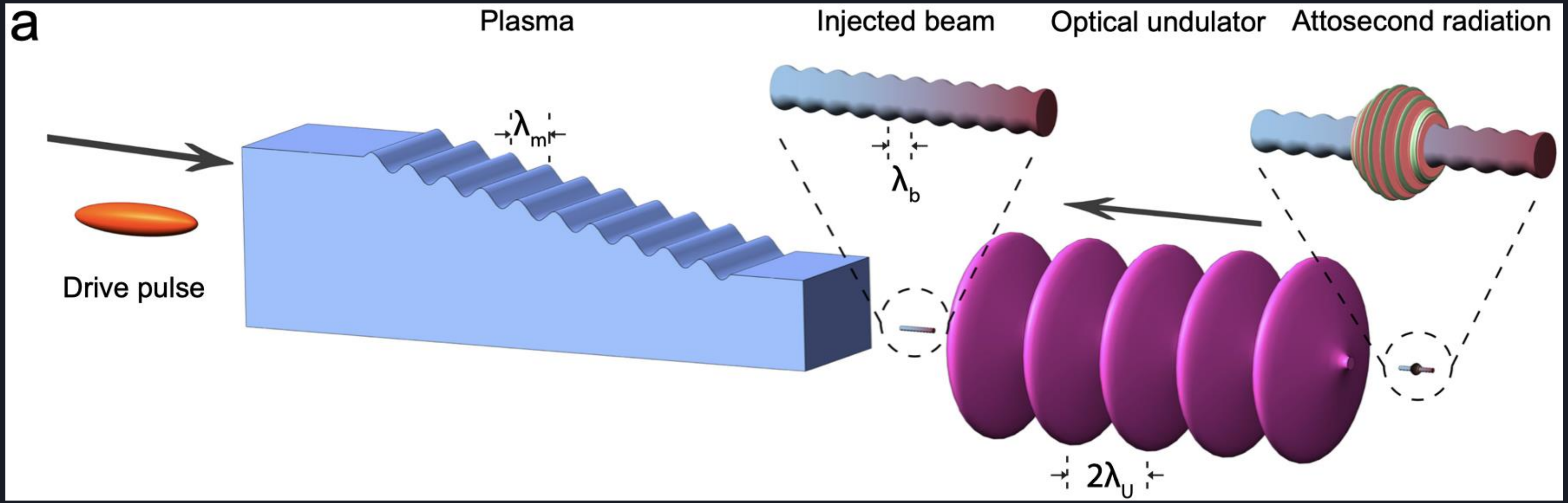

Direct comparison of measurements to Genesis simulations for 3 different configurations. 20 time dependent simulations performed for each configuration

- **Measured values:** 100 MeV, 90 pC, 5% rms energy spread, $R_{56}$ = 200 $\mu$m , post chicane current = ~1kA, $\beta_{x,y}$ = 50 cm
- **Unknown quantities:** Slice emittance and slice energy spread
- Simulation shows excellent agreement with data for sub 0.5 um slice emittance and sub 0.5% slice energy spread

| | $\varepsilon_{x,y}$ [$\mu$m] | slice energy spread [%] |
|---|---|---|
| Config 1 | 0.25 | 0.4 |
| Config 2 | 0.75 | 0.4 |
| Config 3 | 0.25 | 0.7 |

# Generate a pre-bunched but chirped train of electron microbunches and collide them against an Optical Undulator (laser pulse)

Chan Joshi[3]




Electron energy reduced to <50 MeV from few GeV

Modulated density ramps help Electron injection in the wake

The injected bunches are spaced Few nm apart.

Electrons collide with an intense laser pulse that acts as an undulator

$$\gamma_{r1} = \sqrt{\frac{\lambda_U}{2\lambda_b}\left(1+\frac{K^2}{2}\right)} \approx 75 \text{ (38.3 MeV)}$$

MWIR laser undulator with K=3.5
Self filtering of the electrons that are injected periodically in the wake

X.L. Xu et.al. Nature Comm. 20122
X.L. Xu et. al. Nature Photonics Submitted

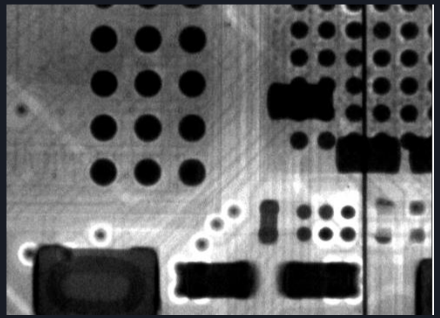
Work at FACET and ZEUS/ATF/UT-A - UR?

# 6

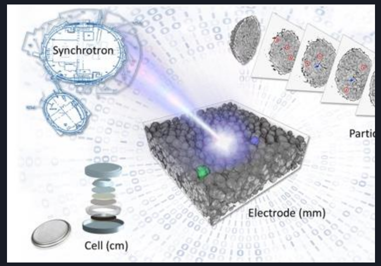
# OTHER APPLICATIONS

## Radiation testing of space bound electronics (SEET and Total Dose)

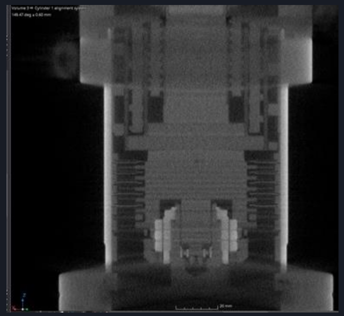
## High resolution 3D imaging of semiconductors and batteries



## Energy Materials Ultrafast Charge Transfer

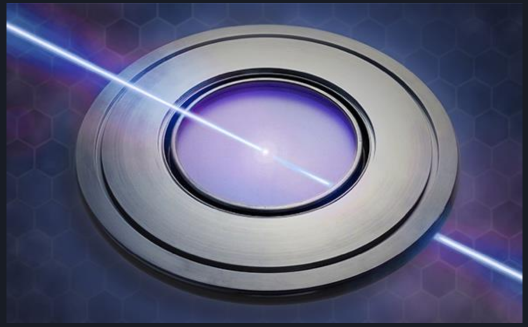



## Industrial radiography of large, high density objects

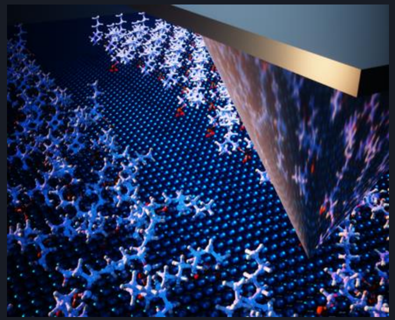


## Medical Diagnostics and Therapeutics R&D (XACT, VHEET)

## Laser induced damage testing at high intensity and in vacuum



## Clean Energy Tech Nanoengineering



TAU

# SPACE RADIATION TESTING – SINGLE EVENT EFFECTS

**ADVANCED SOURCES FOR SINGLE-EVENT EFFECTS TESTING (ASSERT)**

**CURRENTLY, SINGLE EVENT EFFECTS TESTING DONE WITH HEAVY IONS**

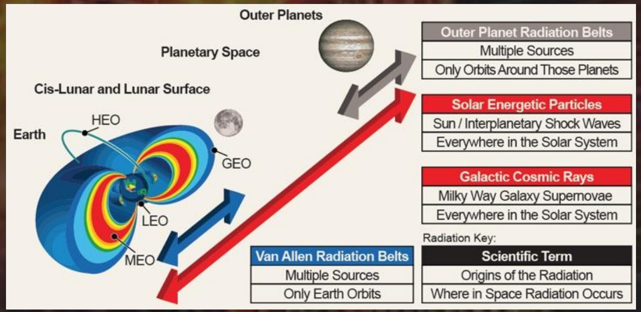
**MAIN PARAMETERS**

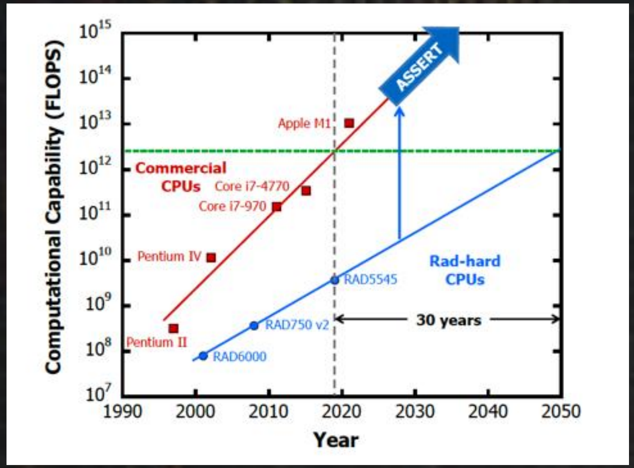
- **Species: H – Bi**
- **Energy [MeV/n]: 0.1 - 100**
- **LET [MeV/(mg/cm2)]: 0.01 - 100**
- **Range in Si [mm]: 0.001 – 1**

**ASSERT GOAL:**

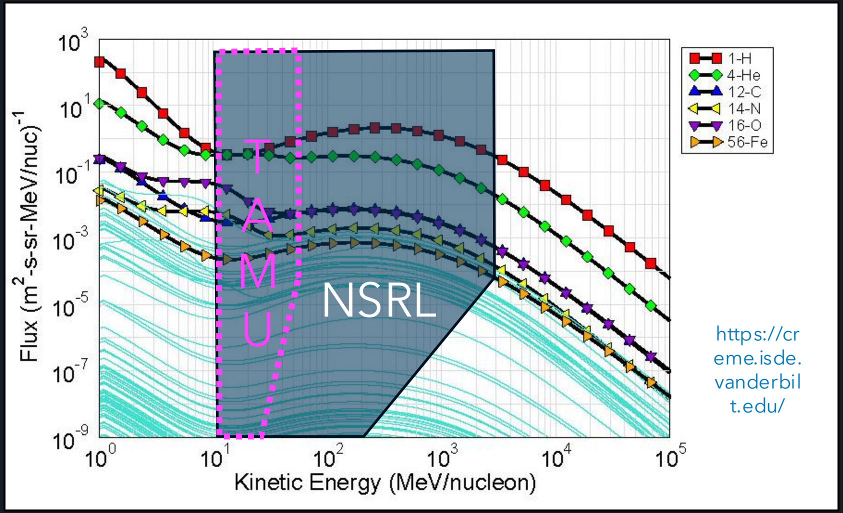
**5mm / 100 MeV-cm2 / mg**

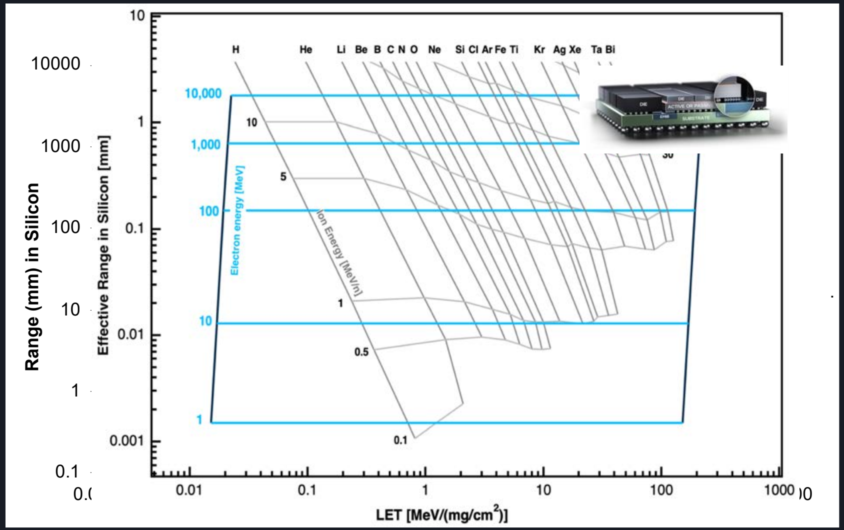
- Current SEE infrastructure is fragile and oversubscribed
- Only three main facilities:
  - BNL NSRL
  - LBNL
  - TAMU
- Heavy ions can achieve high LET or long range in Si, *but not both!*
- Capacity *and* capability gaps for testing 3D chips



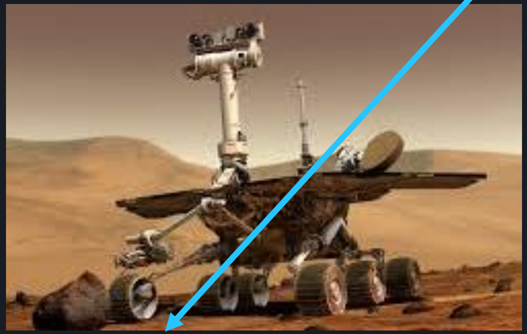



# Space radiation testing on Earth



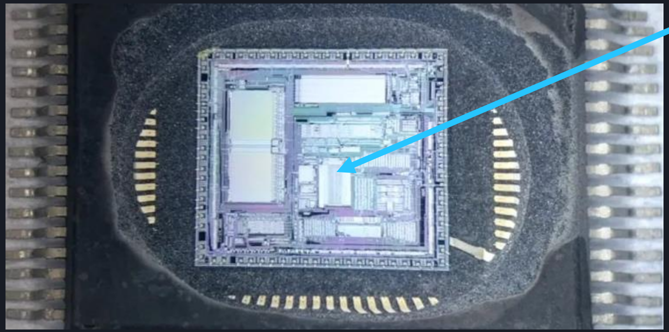







heavy ion
10 GeV/u

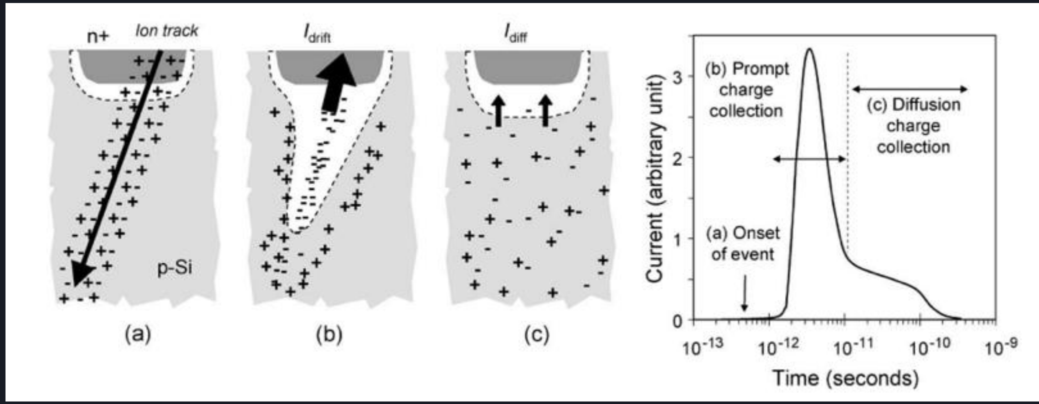

heavy ion
1 GeV/u

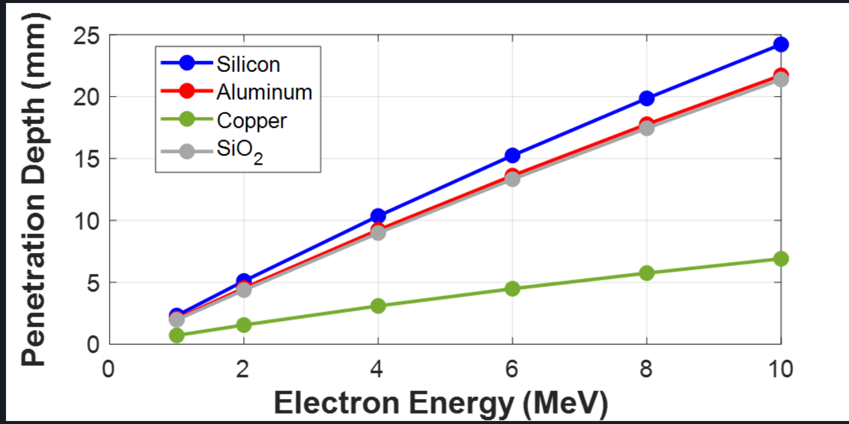


heavy ion
10 MeV/u

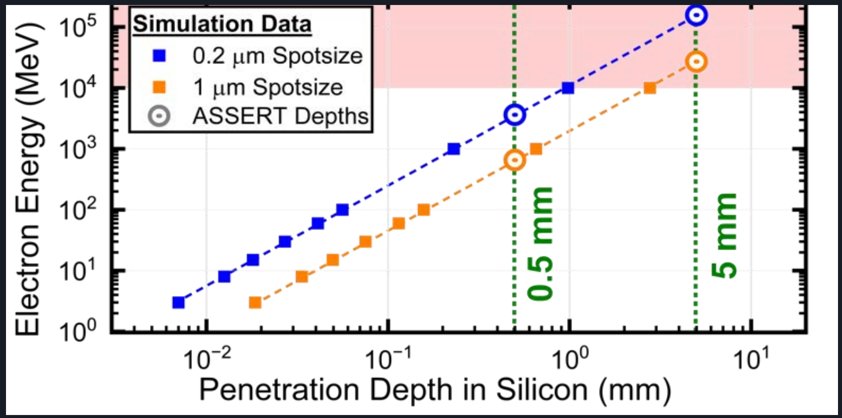
# eSEE*-CONCEPT: A PULSED ELECTRON PACKET CAN EMULATE HEAVY ION SINGLE EVENT EFFECT

Single-event "soft error" in a P-N junction





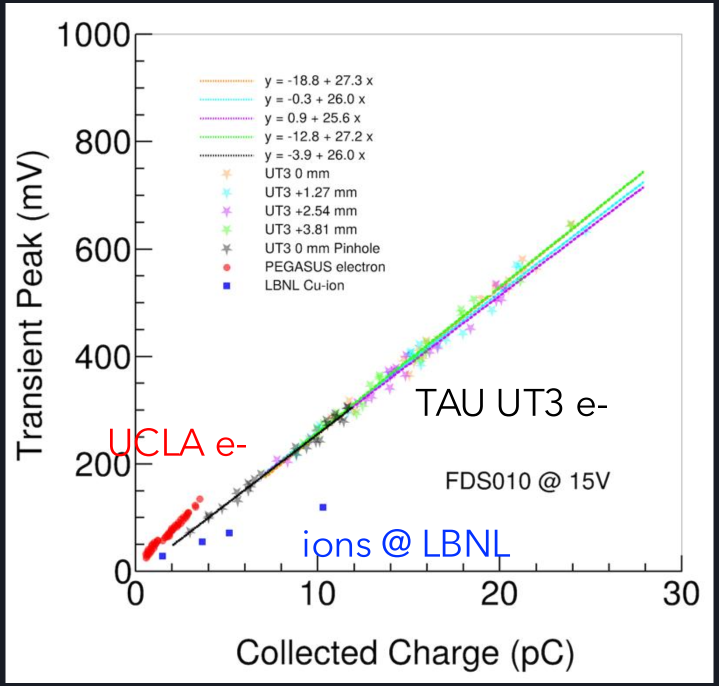


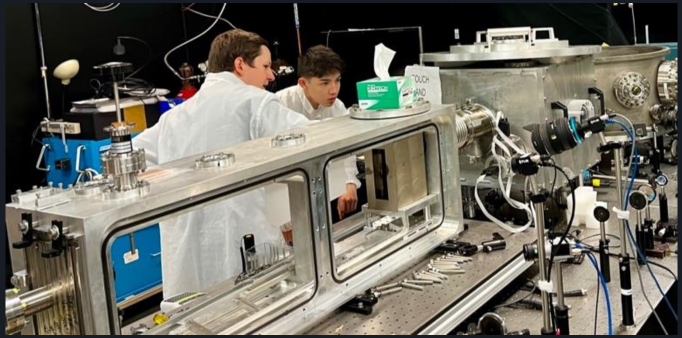

* Concept originally conceive by Greg Allen and Harald Schone

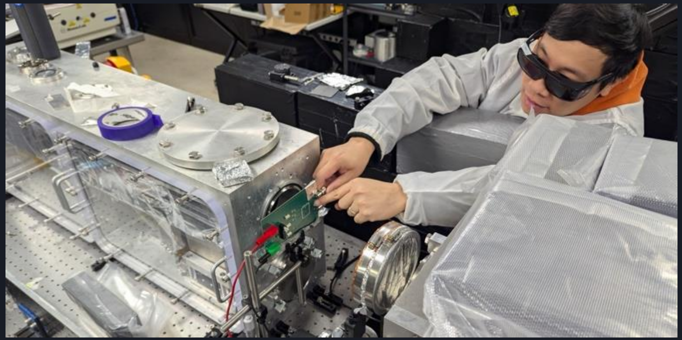


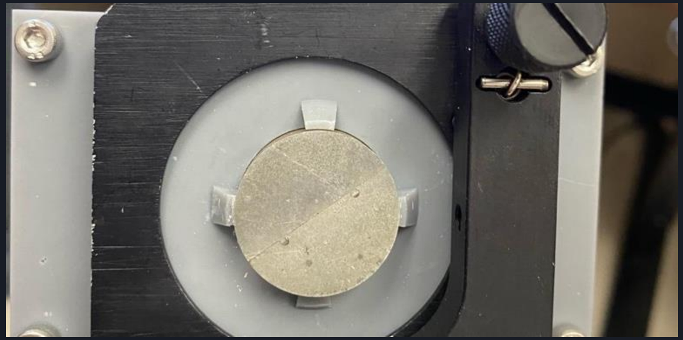
DOI:10.1109/TDMR.2005.853449

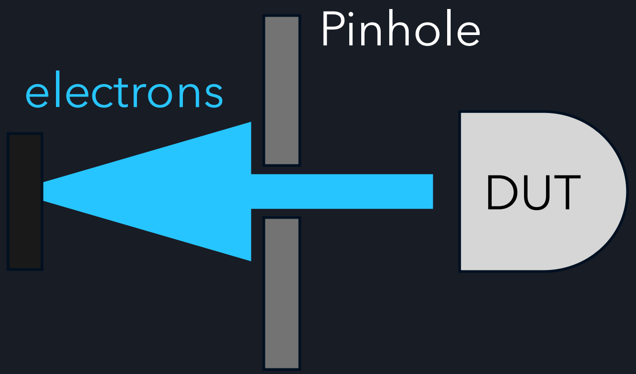
# FIRST MEASUREMENTS AT UT3 WITH 100 MEV ELECTRONS CONFIRM UCLA RESULTS

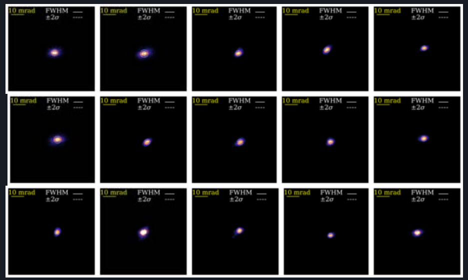








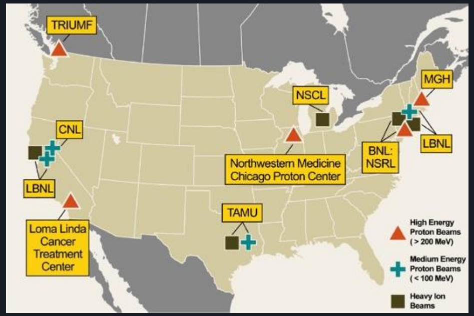



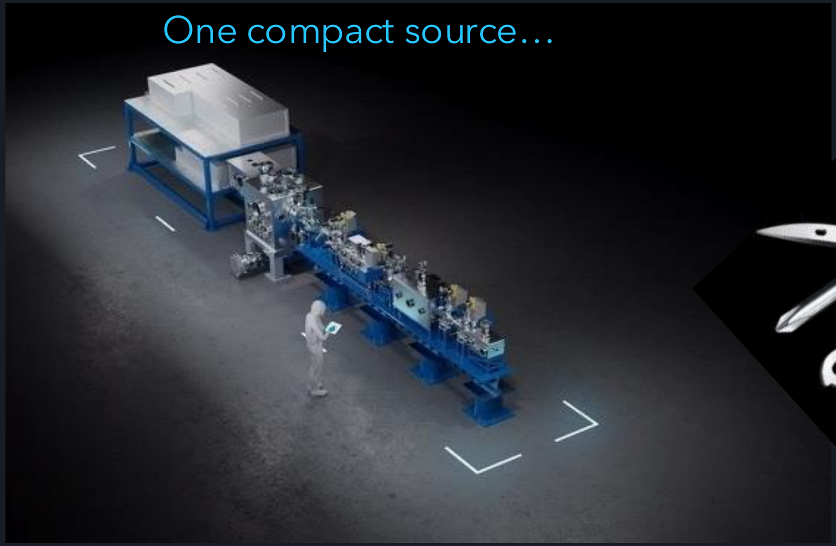
Laser-accelerated electron beams

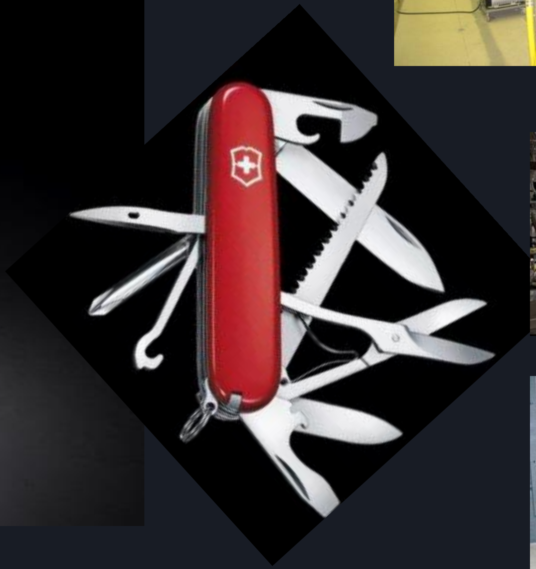
# TAU-RAD – THE SWISS ARMY KNIFE OF RADIATION TESTING

**MULTI-PURPOSE RADIATION TESTING FACILITY:**

- **HEAVY ION EQUIVALENT (E-SEE)**
- **GAMMA TID**
- **X-RAYS**
- **ELECTRONS**
- **NEUTRONS**
- **LASER**



Single event effects

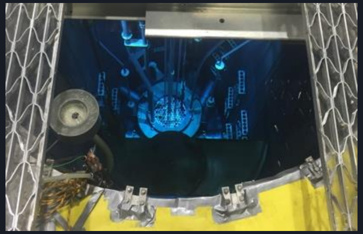
Dose rate

Total ionizing dose

Multiple test types at one facility:

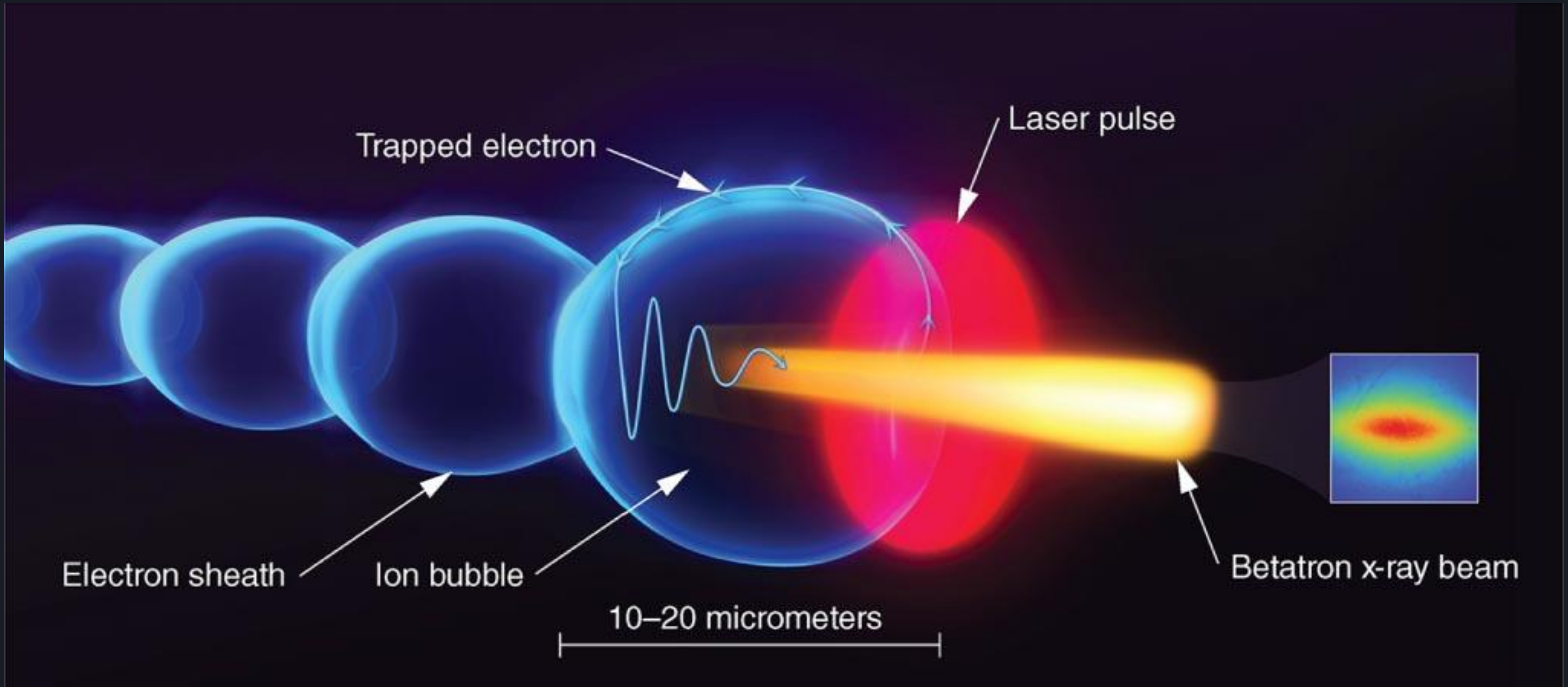
- Single event effects (Heavy ions)
- Total Ionizing Dose (Gammas)
- Dose rate (Gammas, electrons)
- Displacement Damage Dose (Neutrons)

No need to travel around the country for different tests!



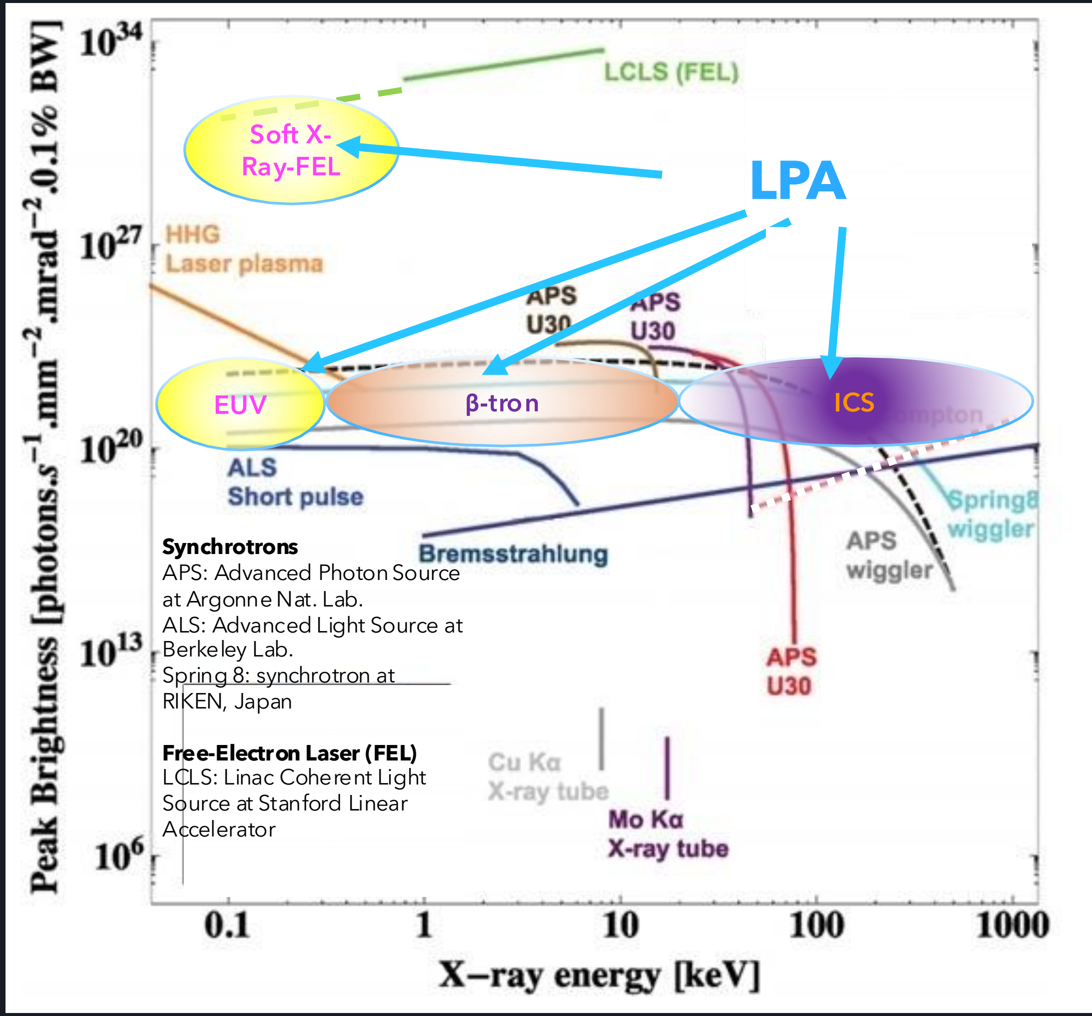
Displacement damage dose

# TAU ACCELERATOR EMITS X-RAYS A BILLION TIMES BRIGHTER THAN CONVENTIONAL X-RAY MACHINES




## LASER-DRIVEN BETATRON RADIATION

# LWFA-BASED SECONDARY SOURCES SPAN THE FULL RANGE OF PHOTON ENERGIES.



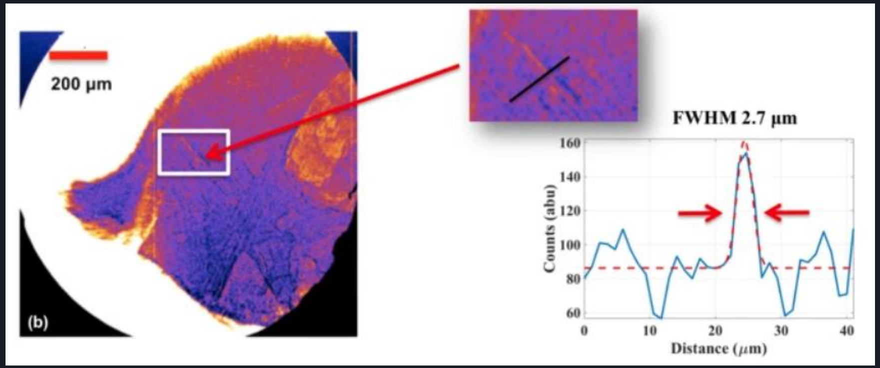

TAU's compact X-ray sources:

- High X-ray energy: 100s keV
- High peak brightness: >$10^{20}$ photons.$s^{-1}$.$mm^{-2}$.$mrad^{-2}$.0.1% BW
- Very small source size for high imaging resolution: ~1 µm
- Ultrashort pulses: less than 25 fs

Synchrotron performance in a lab or a fab.

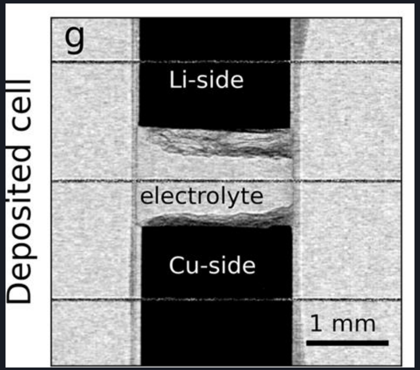
# BETATRON RADIATION APPLICATIONS

Imaging microstructures in materials



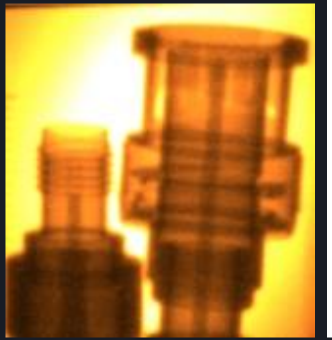

A.E. Hussein et al., Sci. Rep. 9, 3249 (2019)

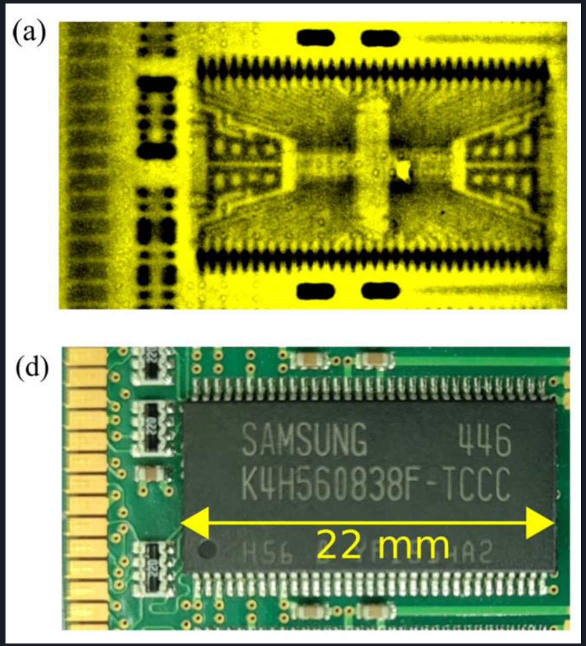
Battery cell imaging




A. Doherty et al., Comm. Phys. 6, 288 (2023)

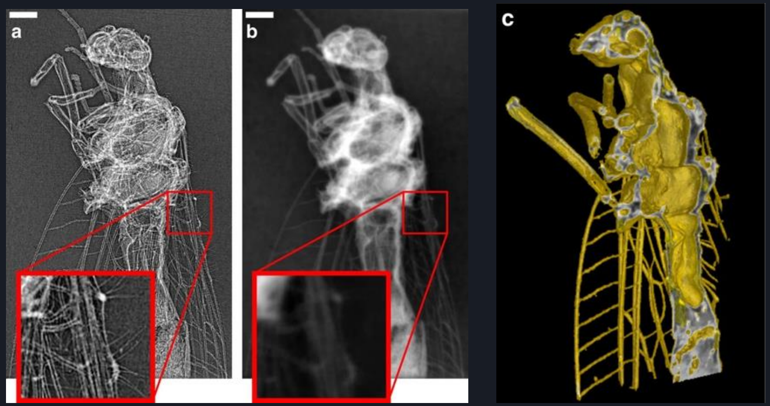
Industrial NDT for microchips and additive manufacturing





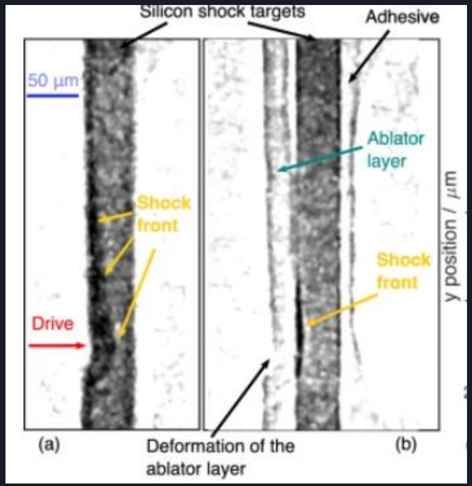

C.I. Hojbota et al., Eur. Phys. Journal A 59 (10), 247 (2023)

Radiography and tomography in biology



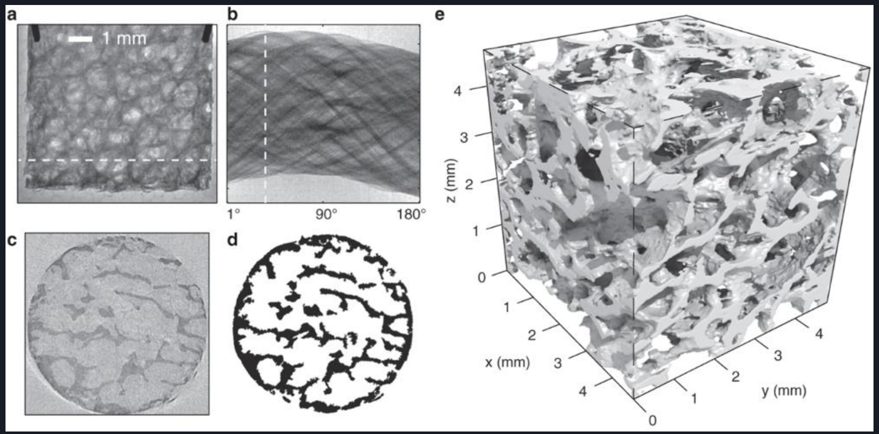

J. Wenz, Nature Communications 6, 7568 (2015)

Ultrafast shocks




J.C. Wood et al., Sci. Rep. 8, 11010 (2018)

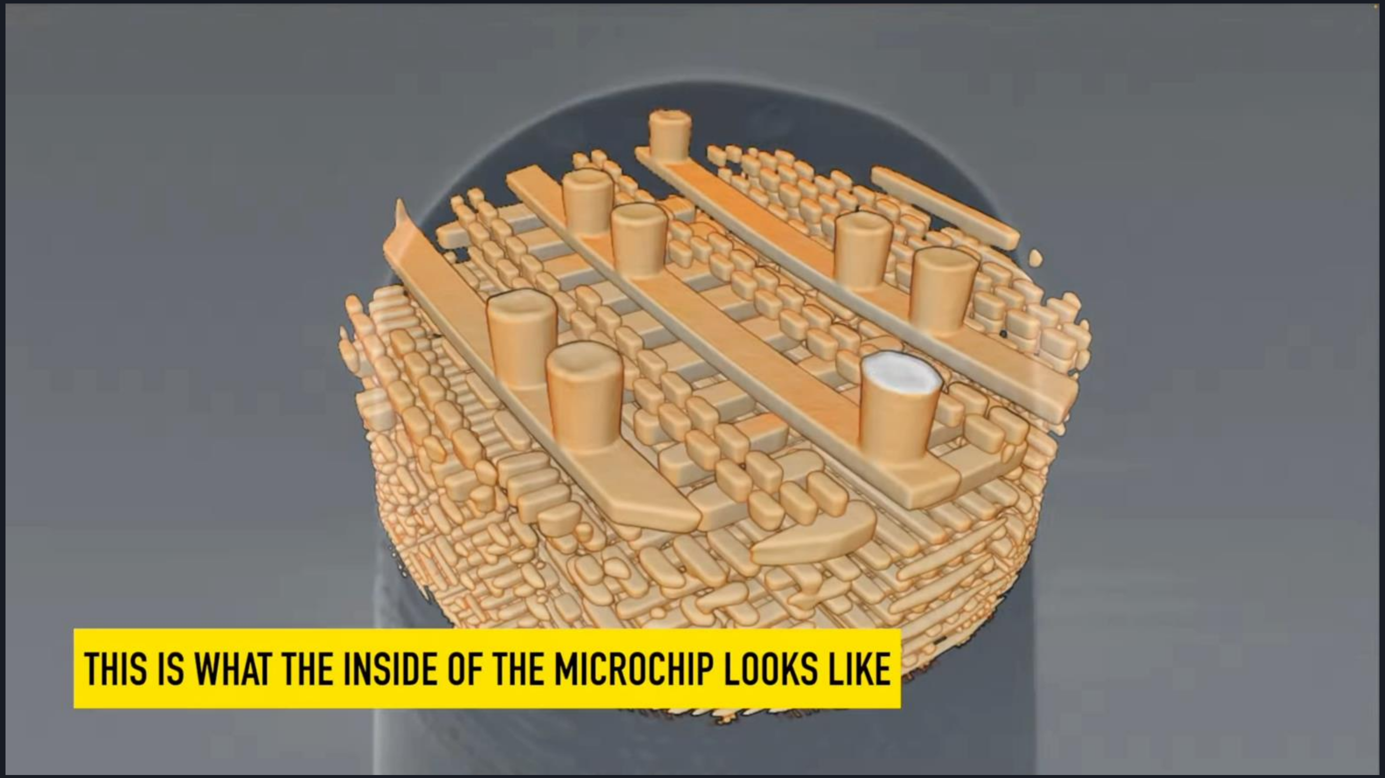
Bone tomography




J.Cole et al., Sci. Rep. 5, 13244 (2015)

# LPA CAN ENABLE NANOMETER RESOLUTION IN FAB

Synchrotron Light Source (SLS) at Paul Scherer Institute, Switzerland




Today: only at synchrotron

- World record resolution: 4nm
- Full day of measuring time

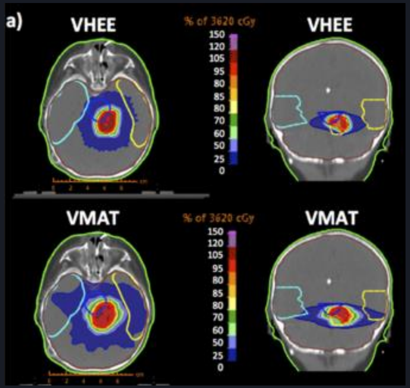
Tomorrow: in-fab

Emil Schueler, Ph.D, DABR

Department of Radiation Physics, Division of Radiation Oncology

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center

# VHEE: VERY HIGH ELECTRON ENERGY CANCER THERAPY




## VHEE HAS BETTER CONFORMITY AND PRECISE DOSE DELIVERY

VHEEs have a much sharper penumbra than X-rays, reducing damage to healthy tissue. They are also insensitive to density changes for improved beam conformity.

Because electrons are charged particles, they can be focused and steered for precise control over the dose deposition.

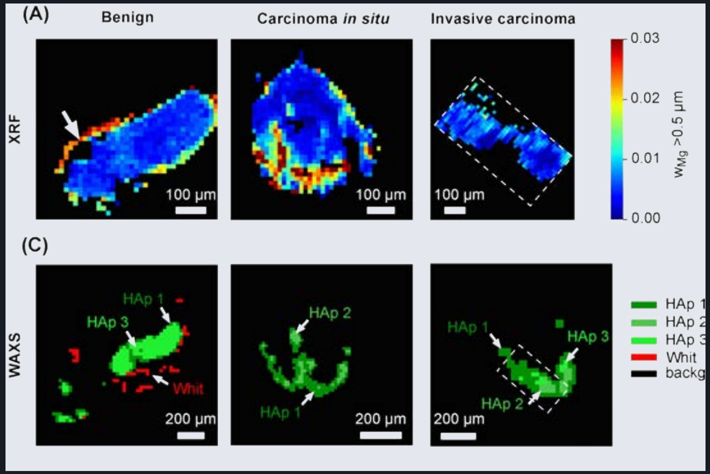
New Proton Therapy Center at MD Anderson

160,000 sq.ft. → 1,600 sq.ft

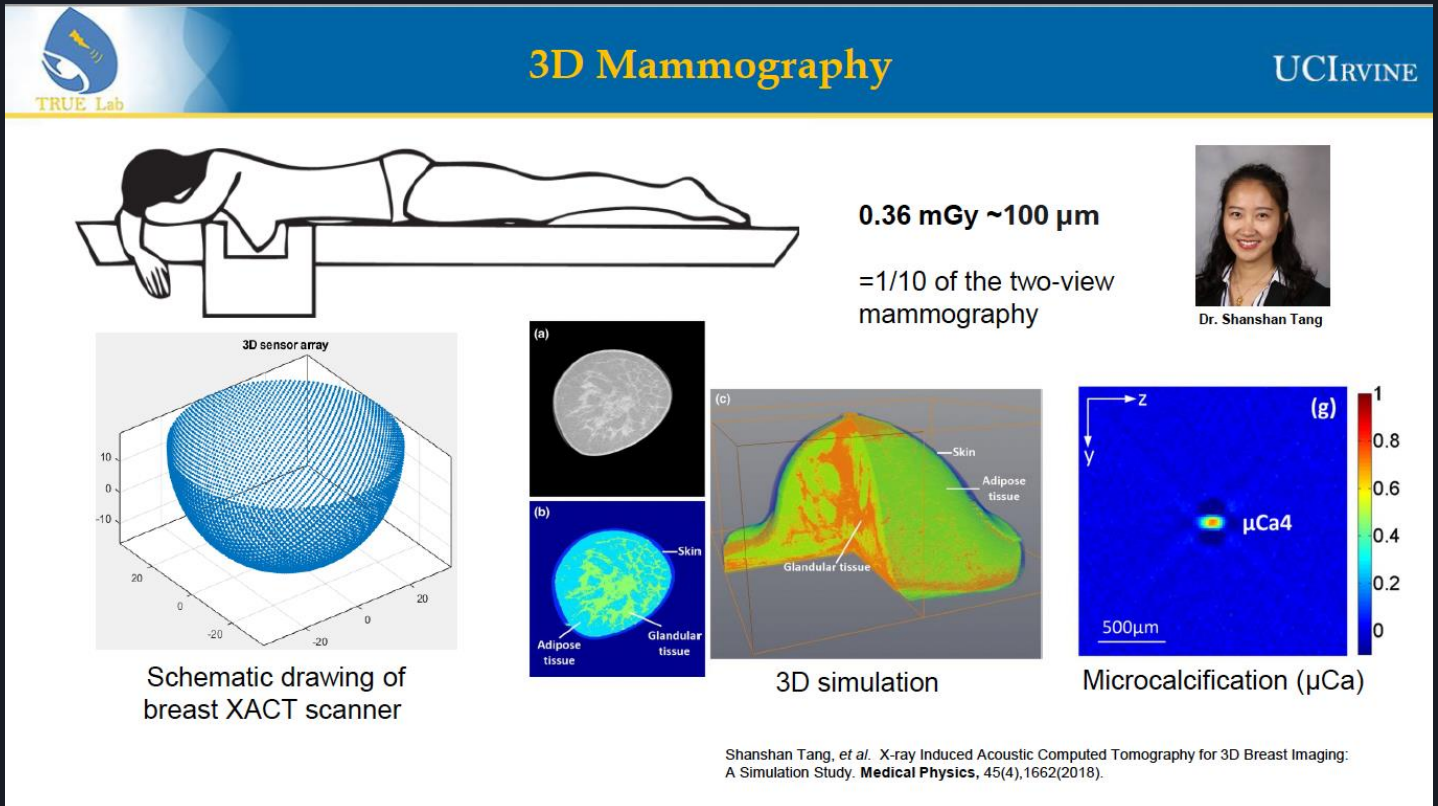
~$200M → ~$20M

1/100 the size
1/10 the cost


# X-RAY ACCOUSTIC TOMOGRAPHIC IMAGING (XACT)




https://www.psi.ch/en/lsb/scientific-highlights/whitlockite-in-mammary-microcalcifications-is-not-associated-with-breast

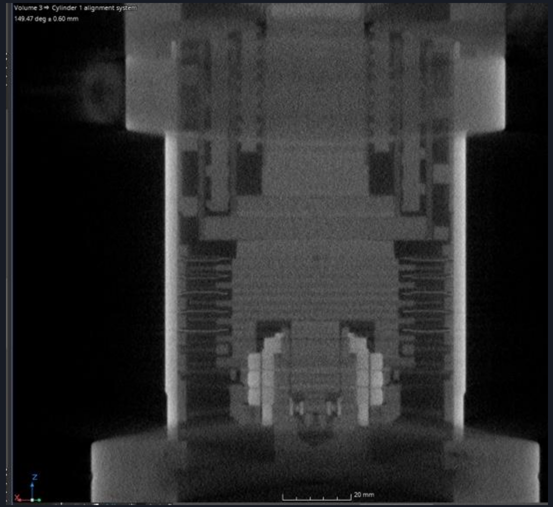


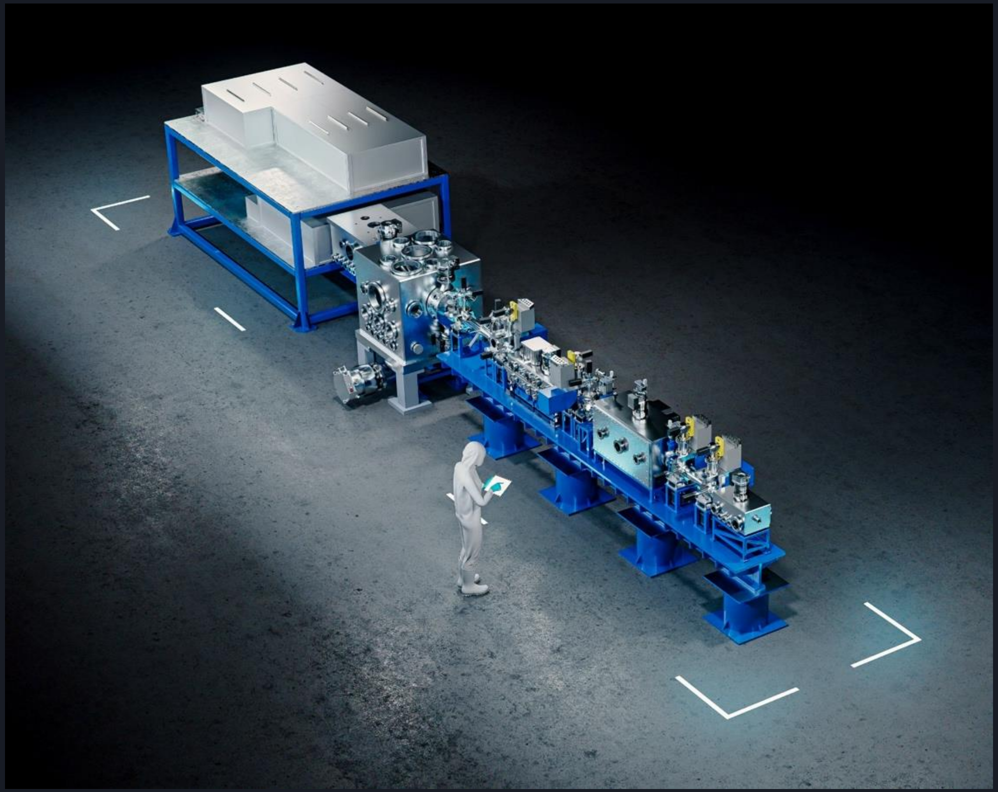

XACT:

- 3D images with 100x less radiation dose
- => makes routine scans possible
- Real time monitoring of radiaton dose delivery when combined with VHEE therapy

# TAU-100 CAN DRIVE A 100-HZ, MEV GAMMA SOURCE FOR NON-DESTRUCTIVE TESTING OF INDUSTRIAL OBJECTS

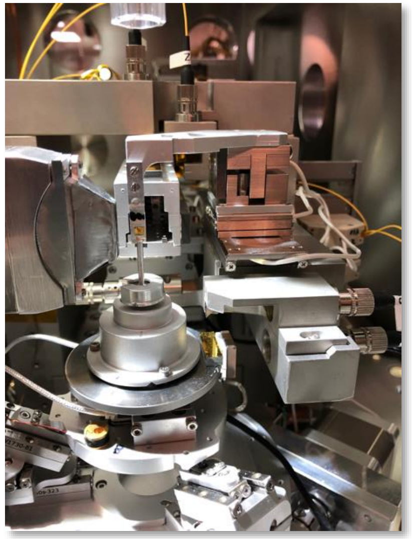
- With collaborators at Los Alamos National Laboratory, we have developed the simple solid source to TRL 4
- Tau Systems has a laser driver capable of matching LANL performance at 10x higher repetition rate (100 Hz)
- Full CT scans possible in <20s of laser operation



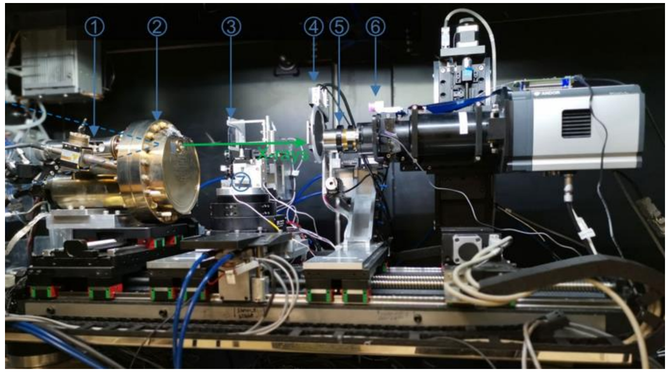
# An integrated multi-modal experimental approach for energy science

Prof. Y. Liu
UT, Cockrell School of Engineering

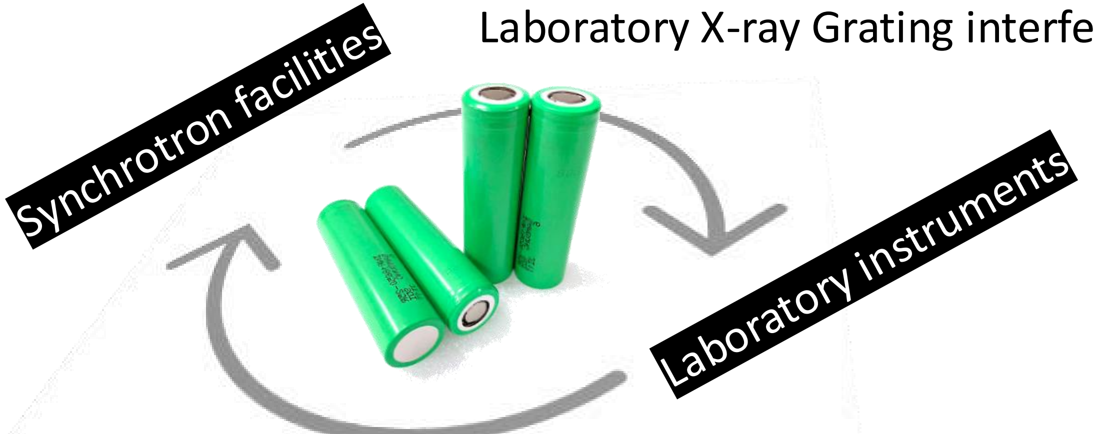


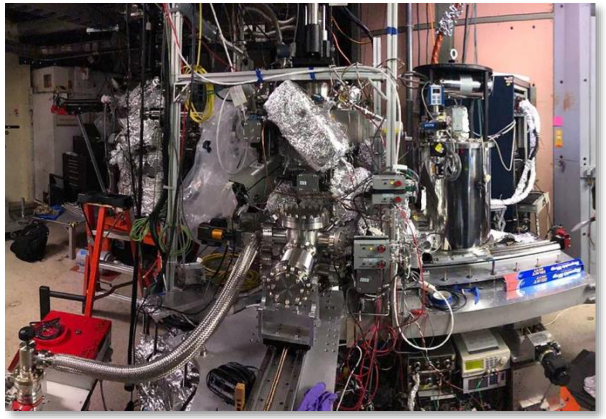
Hard X-ray nano probe

Soft X-ray nano probe



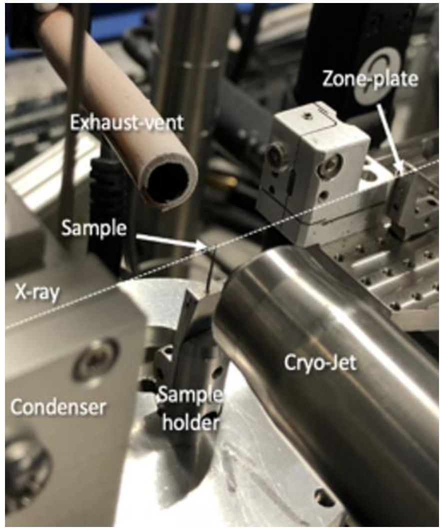

Laboratory X-ray Grating interferometry

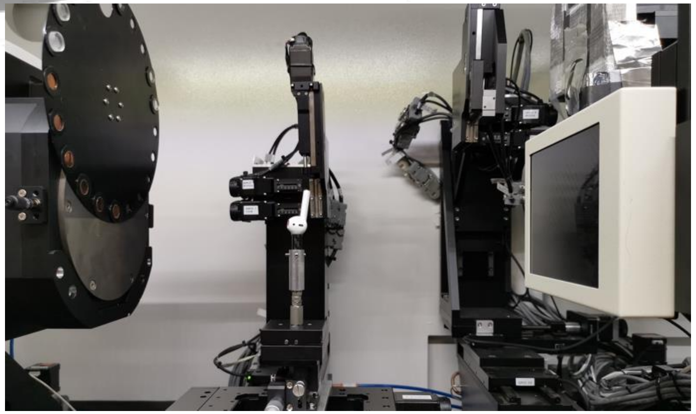


Soft X-ray spectroscopy - RIXS

X-ray nano-CT

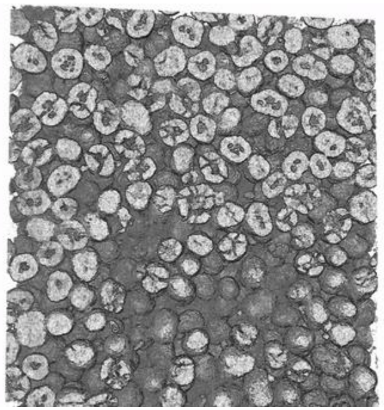


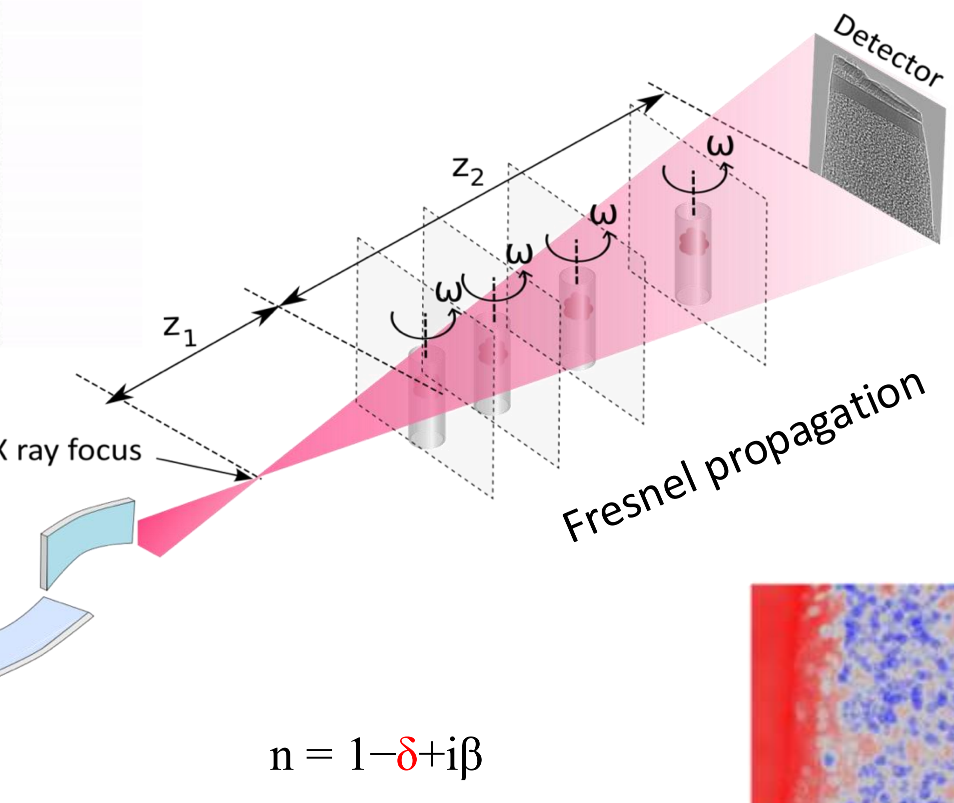
X-ray micro-CT

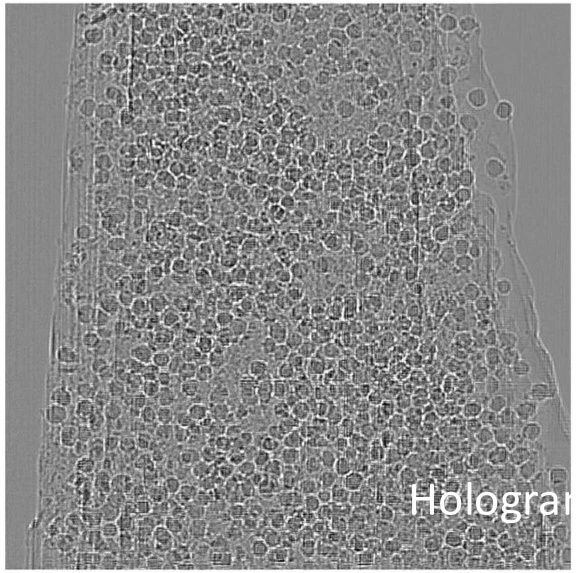
# Phase contrast imaging: quantitative phase retrieval offers improved image quality

Prof. Y. Liu
UT, Cockrell School of Engineering



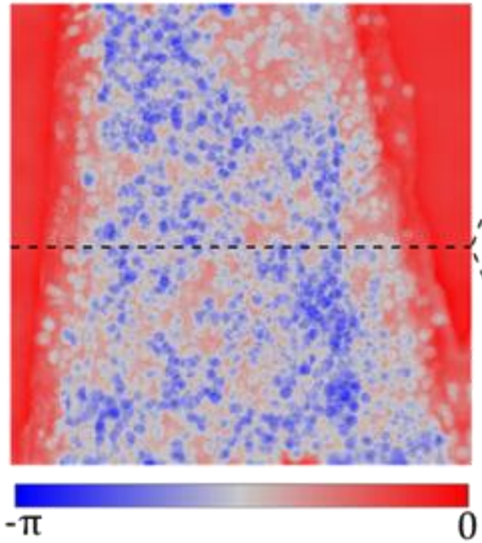
3D visualization



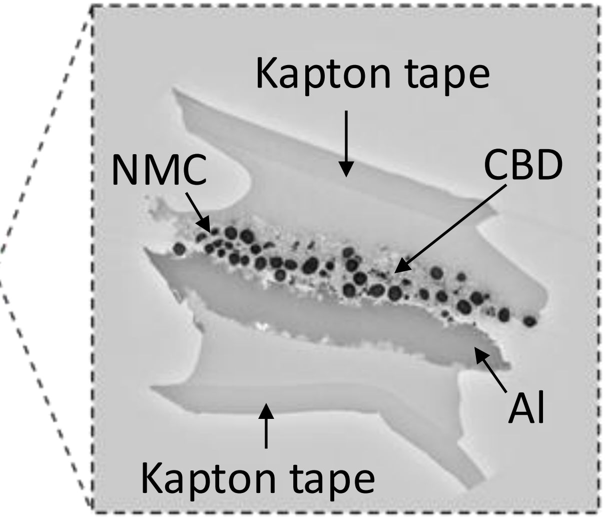




$$n = 1 - \delta + i\beta$$

$\delta$ is often several orders of magnitude higher than $\beta$




Phase map

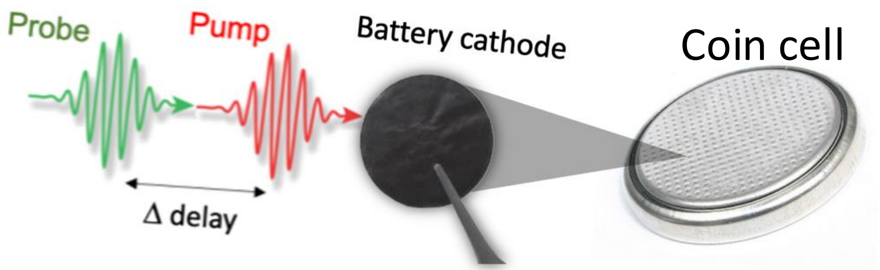


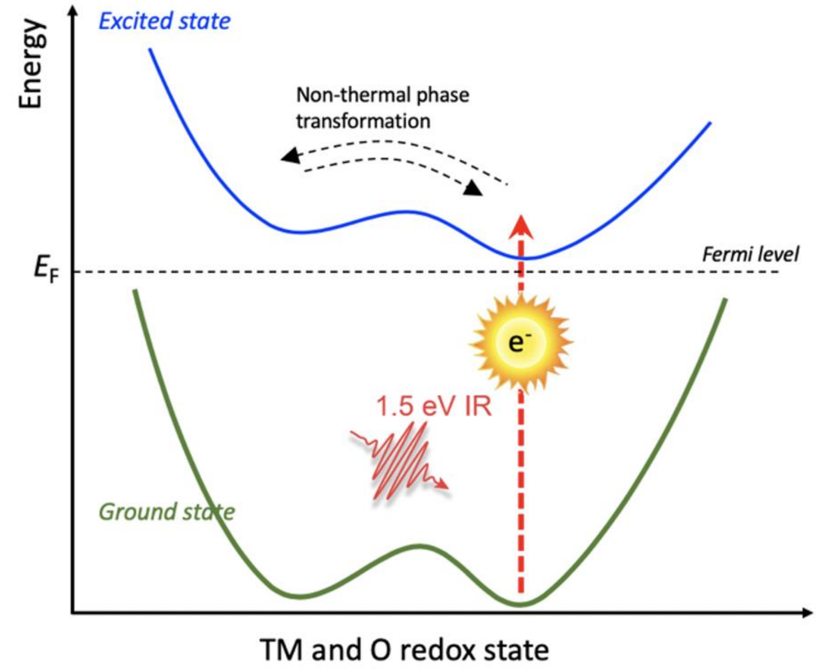

Virtual slice

Cloetens et al., Appl Phys Lett. 75, 2912–2914 (1999)
Yang, Liu* et al., Adv. Energy Mater. 1900674 (2019)

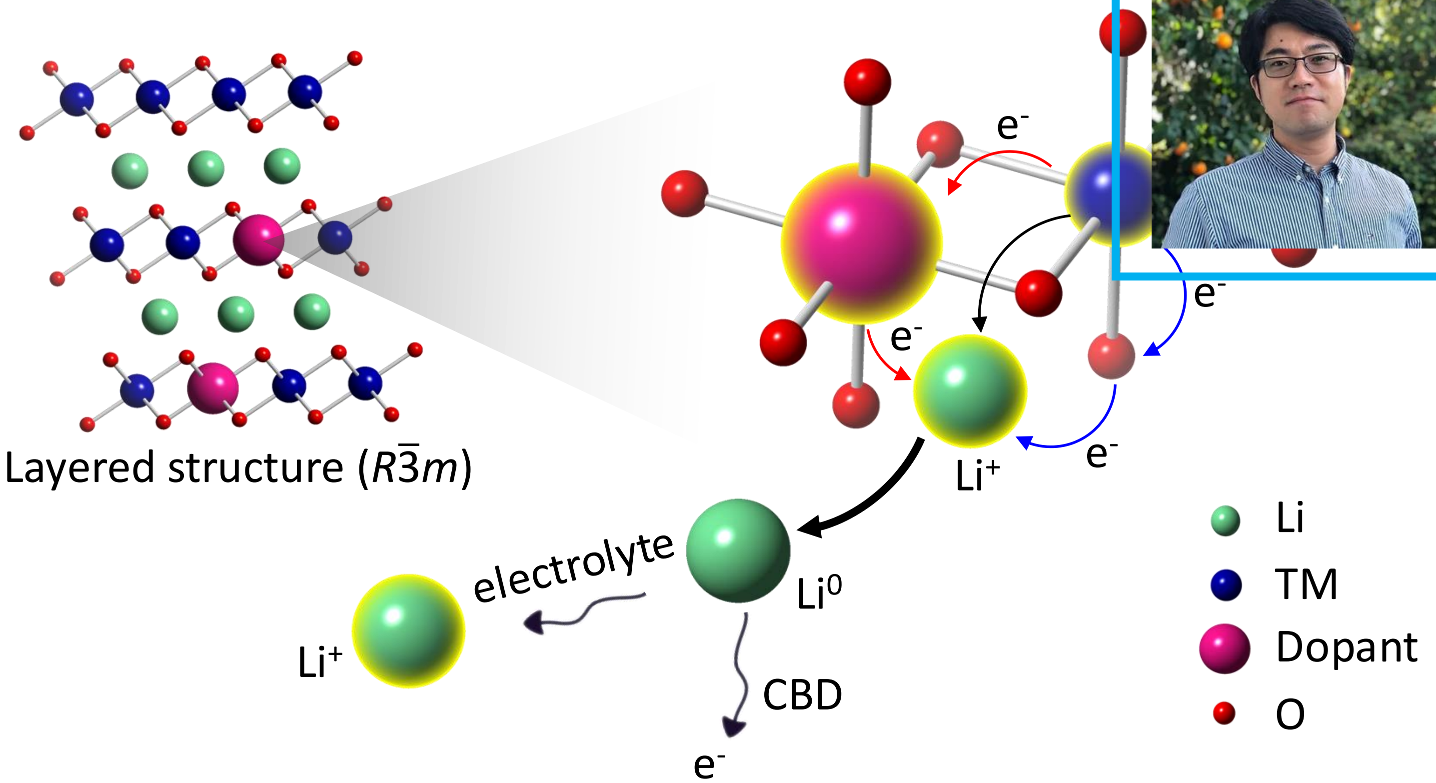
# Electrochemical redox dynamics near and far from equilibrium

Prof. Y. Liu
UT, Cockrell School of Engineering




**Hypothesis:** ultra-fast sequential charge transfer



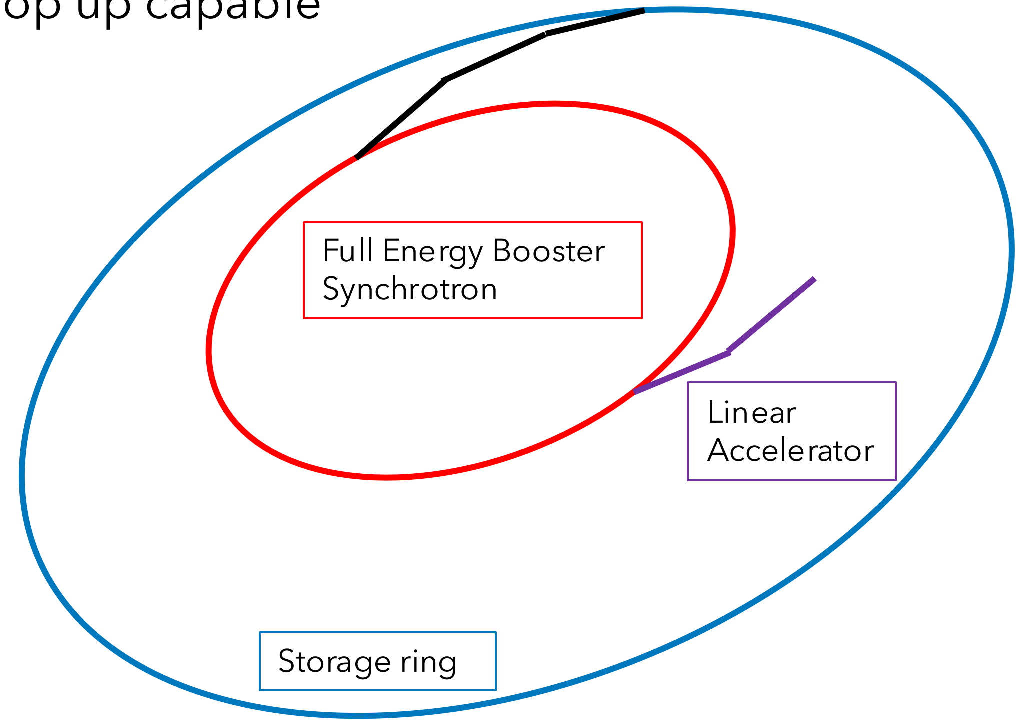

- Laser pulse knocks away some electrons, mimicking an ultrafast charging pulse.
- Dynamic charge transfer results in the charge neutrality at equilibrium.
- A non-classical insight on the dopant's role

# 7

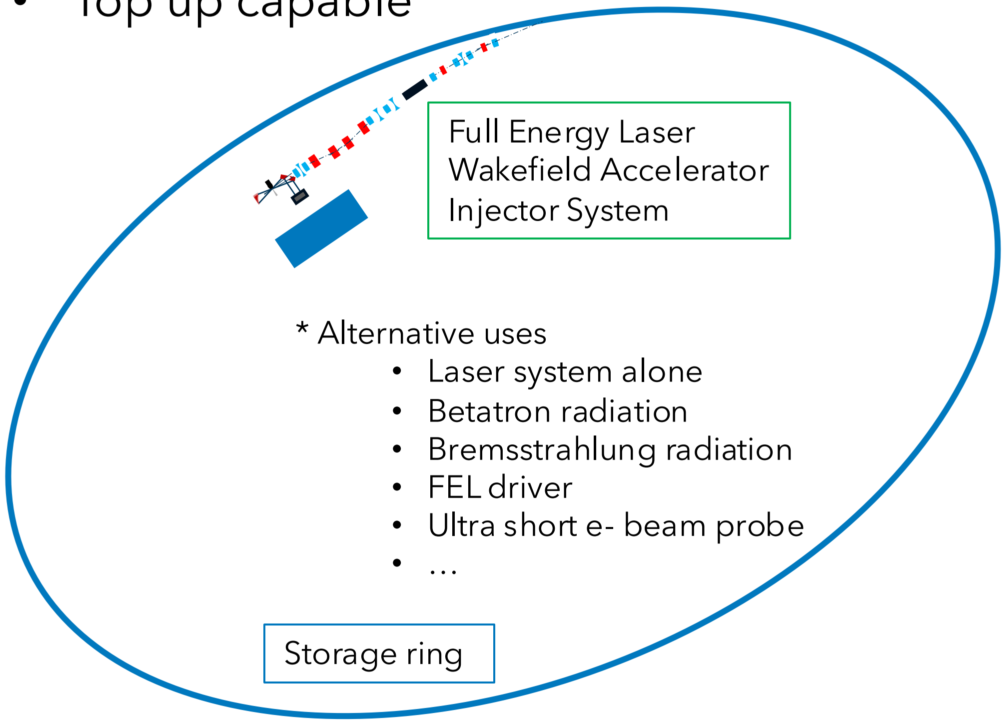
# FUTURE ACCELERATOR & LIGHTSOURCE FACILITIES

# Quick Comparison: Laser Wakefield Accelerator-Based, Full-Energy Injector for a Storage Ring vs. Traditional Linac/Booster Injector System

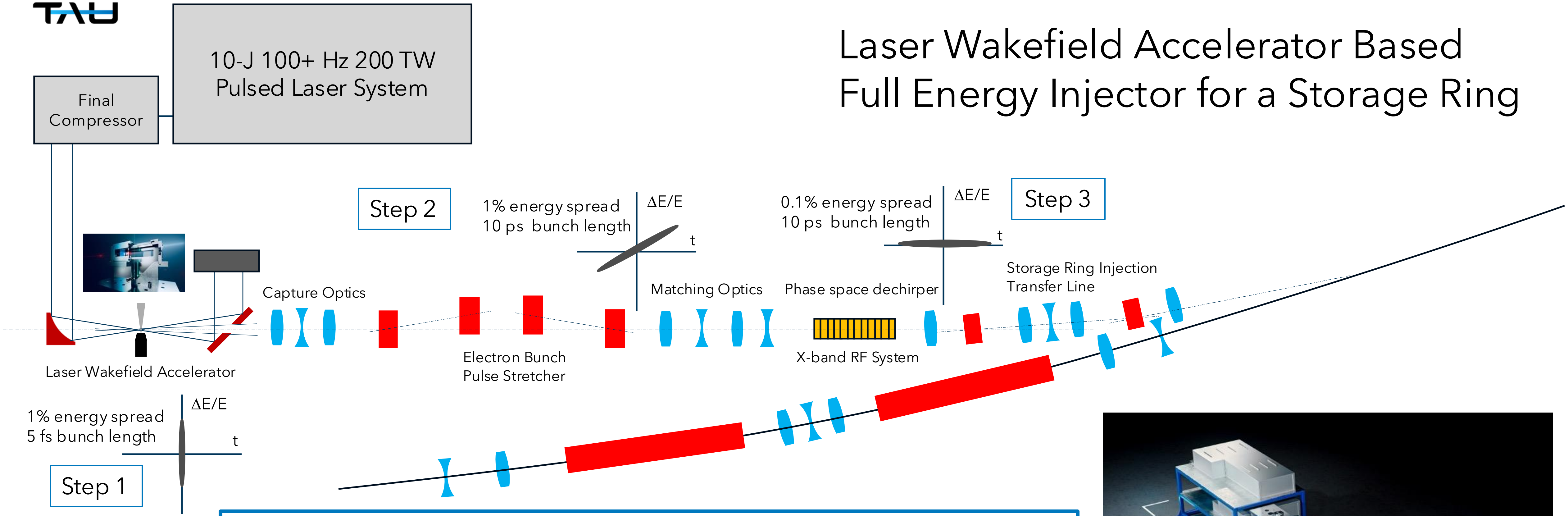
- Mature
- Long pulse only
- Rep rate limited by the synchrotron (few Hz)
- High-power consumption during operations
- Single Purpose
- Sizable
- Full energy injection
- Top up capable



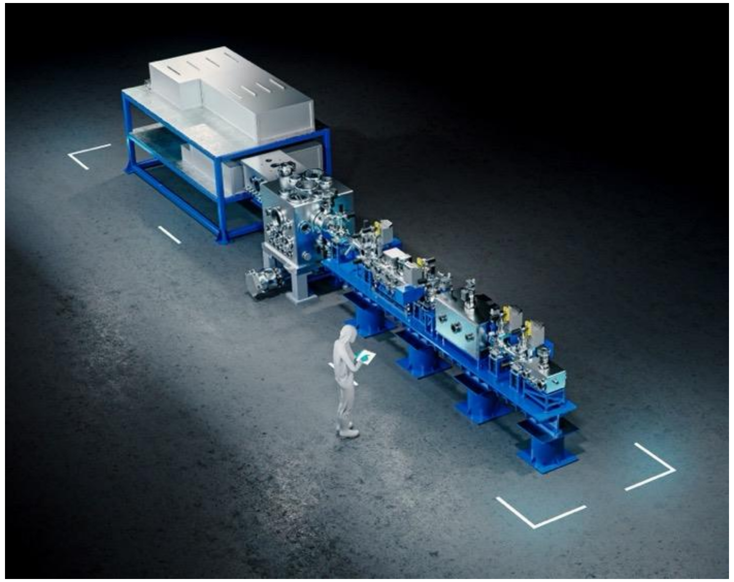

- Untried
- Short and long bunches available
- 100+ Hz rep rate
- Relatively efficient power consumer
- Alternative uses*
- Relatively compact
- Full energy injection
- Top up capable



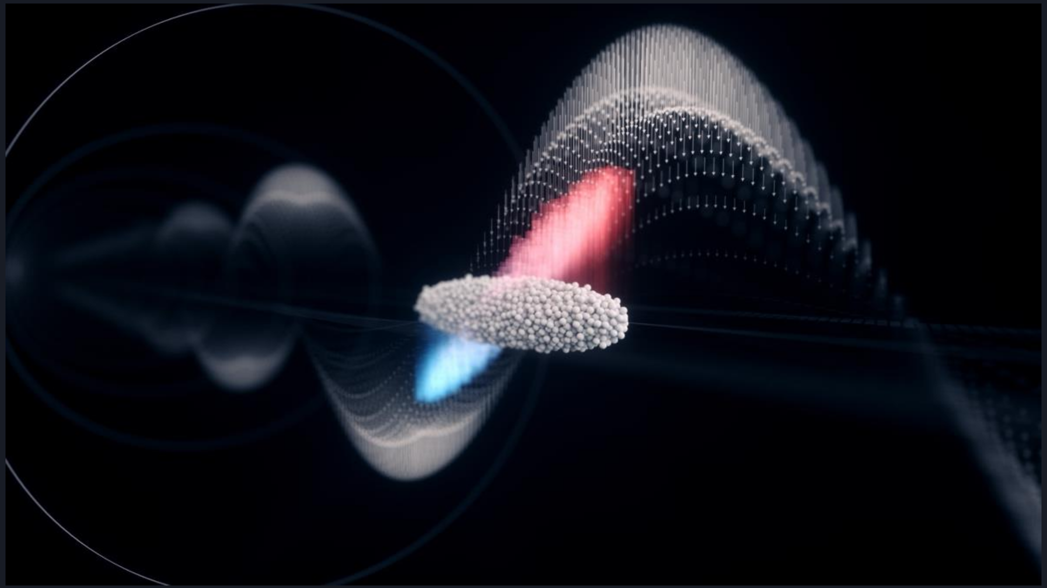
# Laser Wakefield Accelerator Based Full Energy Injector for a Storage Ring

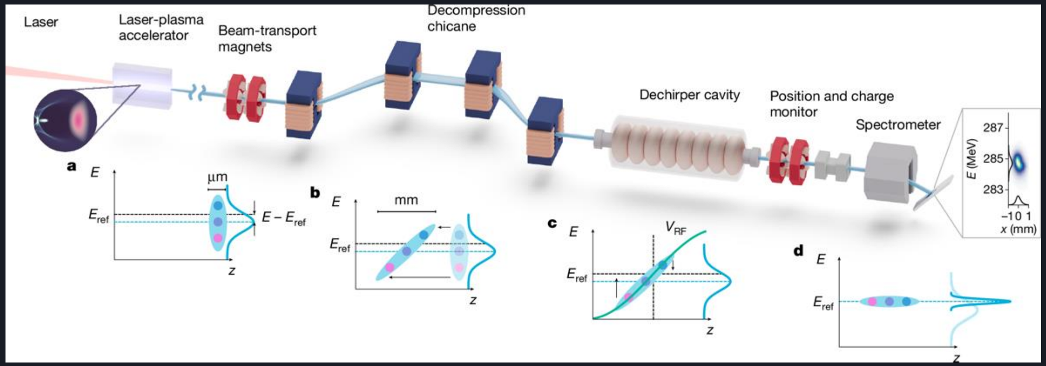


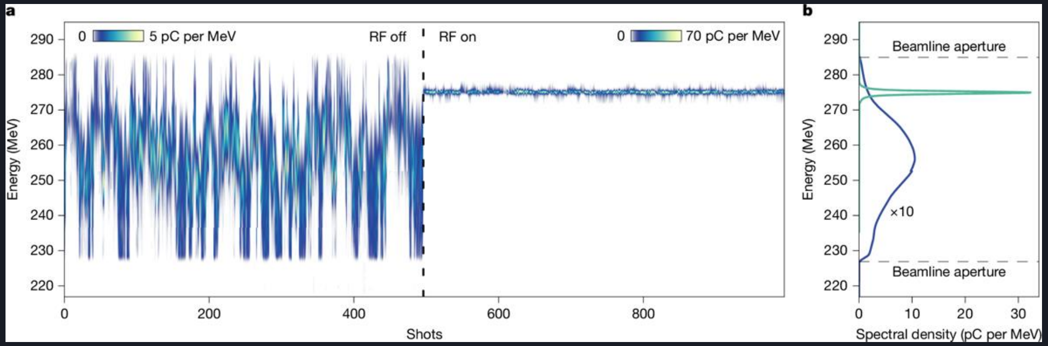

- Step 1: Generate full energy (1.3 GeV) beam with the laser wakefield accelerator.
- Step 2: Stretch the electron bunch
- Step 3: Remove the energy/time chirp
- Result
  - Low energy spread beam phase-space matched for injection into the storage ring.



# CHICANE BUNCH COMPRESSION OF AN LPA PULSE – DESY/LUX





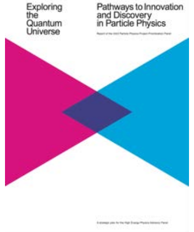

## Active energy compression of a laser-plasma electron beam

P. Winkler, M. Trunk, L. Hübner, A. Martinez de la Ossa, S. Jalas, M. Kirchen, I. Agapov, S. A. Antipov, R. Brinkmann, T. Eichner, A. Ferran Pousa, T. Hülsenbusch, G. Palmer, M. Schnepp, K. Schubert, M. Thévenet, P. A. Walker, C. Werle, W. P. Leemans & A. R. Maier

*Nature* **640**, 907–910 (2025) | Cite this article

# Plasma accelerators are a promising path to the next frontiers of particle physics

## Next physics scale anticipated at 10 TeV for electrons or muons, 100 TeV for protons




- No technology ready for this challenge

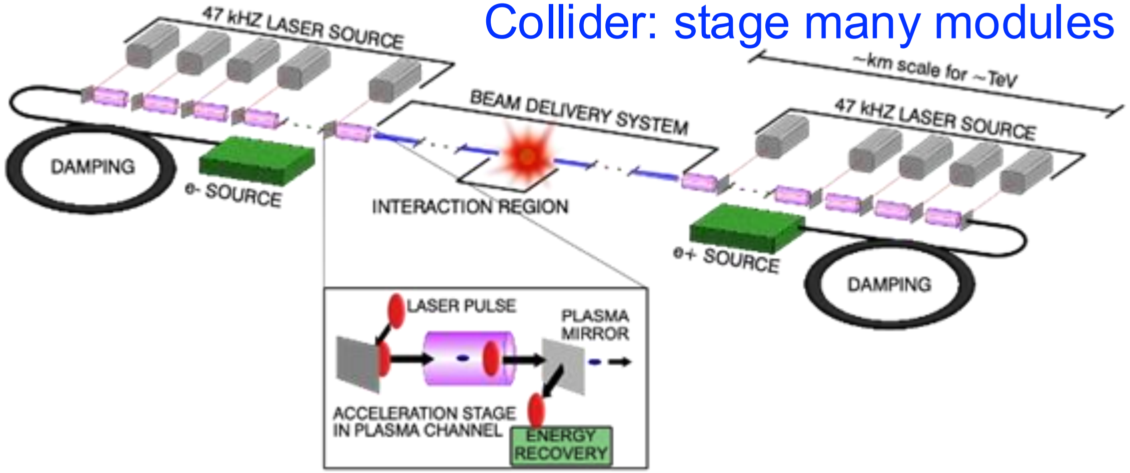
## Proton path could use a 90km tunnel – FCC

## Muon path could reduce ring size (cooling needed)

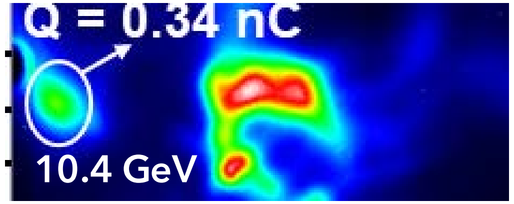
## Plasma path: potential size and cost savings

- 10 GeV/m – smaller footprint & carbon load
- Bright beam generation – reduce/improve cooling
- Strong focusing, short beams – improve lumi/power
- Strong progress: high gradient, quality, collider concepts
- Potential to combine small footprint, high efficiency

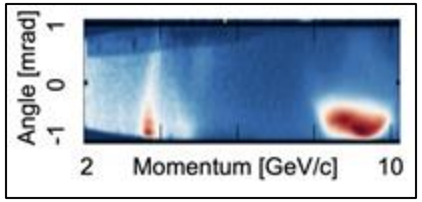
## Collider: stage many modules




## Module needs >10 GeV




10 GeV, 300pC in 10 cm

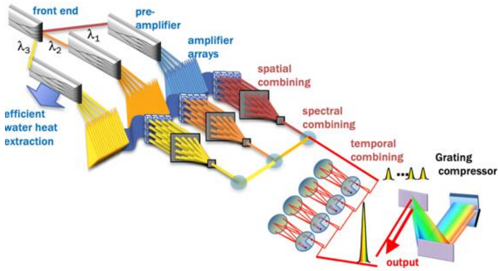



10 GeV, 3pC in 30 cm


1. C. Aniculaesei et al., Matter Radiat. Extremes 9, 014001 (2024)
2. A. Picksley, et al. Phys. Rev. Lett. 133, 255001
3. E. Rockafella, et al., NIM A, 29 April 2025, 170586


## Module needs multi-kHz, multi-J drive lasers

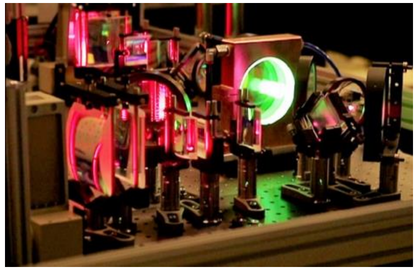
Coherently coupled fibers




BERKELEY LAB kBELLA


W.-Z. Chang et al., Optics Express (2013)
T. Zhou et al. *Optics Express* (2015)
Q. Du et al. *Optics Express* (2021)
M. Whittlesey et al, SPIE Photonics West (2022)


Big Aperture Thulium



TAU CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE


I. Tamer et al., Optics Letters (2021)
S. Rostami et al, Optcis Letters (2019)
A. Fregosi et al, High Pow. Laser Science (2025)
I. Tamer et al, SPIE Photonics West (2022)


Rad testing with S-LPA: 1,000 µm
X-ray imaging with S-LPA

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