Introduction to Particle Accelerators

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HEPiC Summer Week

6/30/2022

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements

SLAC

Michael Fazio
Caterina Vernieri
Mohamed Othman
Emma Snively
Xueying Lu
Valery Dolgashev
Jeff Neilson
Andy Haase
Mike Kozina
Matthias Hoffmann
Sami Tantawi

SLAC UED Team

Xijie Wang
Renkai Li
Stephen Weathersby
Xiaozhe Shen

MIT

Sam Schaub
Julian Picard
Sudheer Jawla
Rick Temkin

INFN-LNF

Bruno Spataro

UC Berkley

Samantha Lewis

Supported by:

RF Accelerator Technology Team

References

US Particle Accelerator School

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https://people.nscl.msu.edu/~lund/uspas/ap_2021/

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Outline

- Overview of Accelerator Facilities
- Major Systems and Components of Accelerator Facilities
- Future Directions

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- Major Systems and Components of Accelerator Facilities
- Future Directions

Accelerator Technology Drives Scientific Discovery

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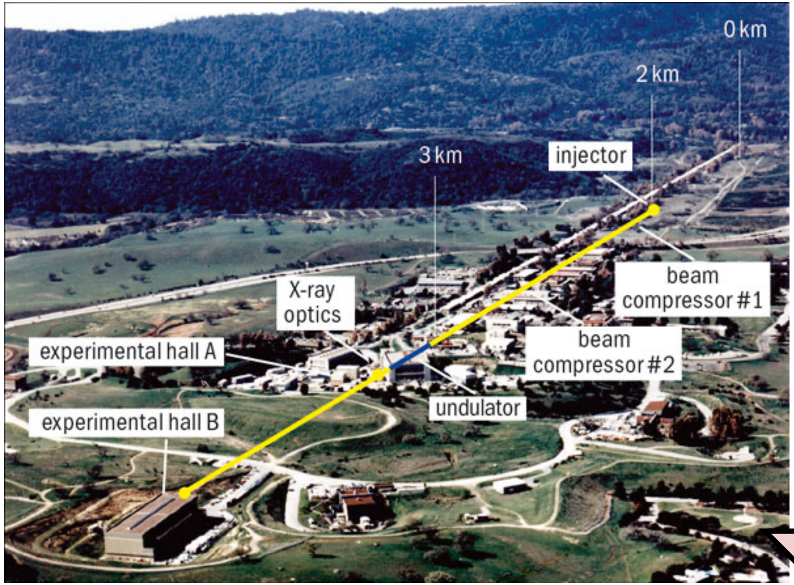
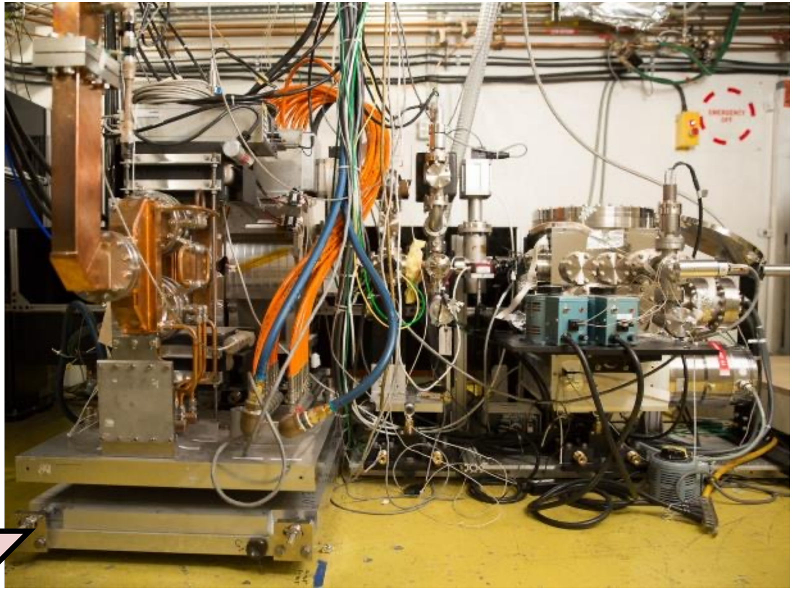
Coherent X-rays from LCLS (2009)



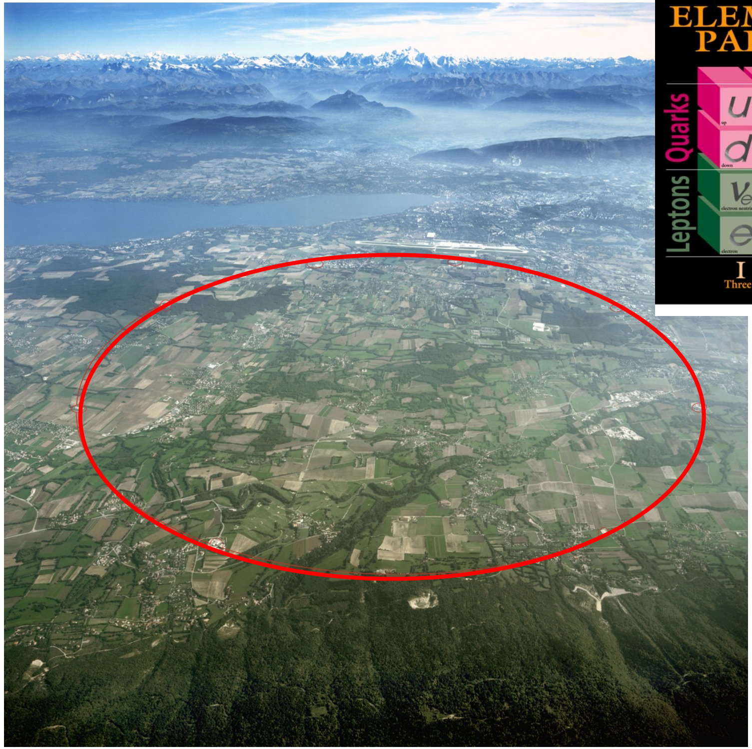
Ultrafast Electron Diffraction (2015)



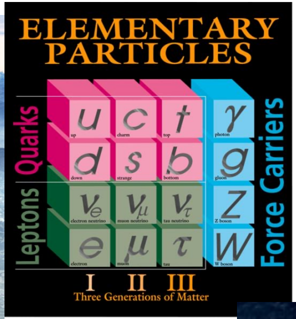
How do we develop the next generation of accelerators and what new science does this enable?

RF Accelerators have been essential instruments of scientific discoveries for decades

Experimental validation of the Standard Model of Particle Physics

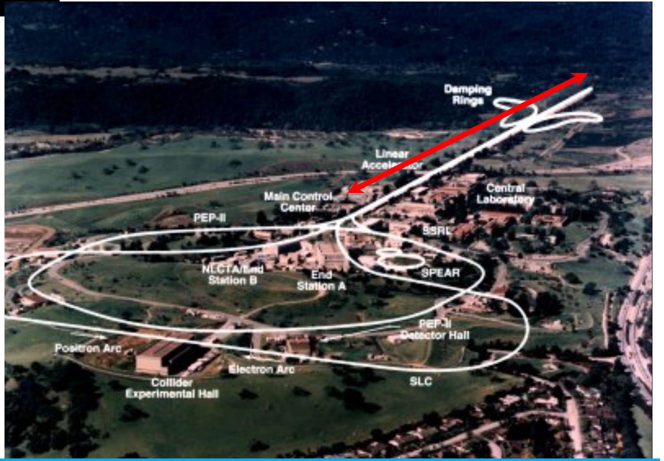


27 km LHC @ CERN



FOUR FORCES

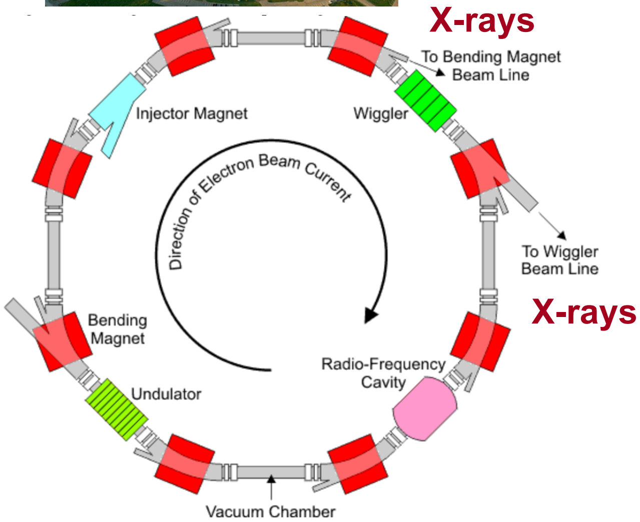
E&M
Strong
Weak
Gravity



SLAC "2 Mile" Accelerator / Collider

Accelerators have advanced other fields of science, in addition to particle physics

Particles traveling along a circular path emit synchrotron radiation

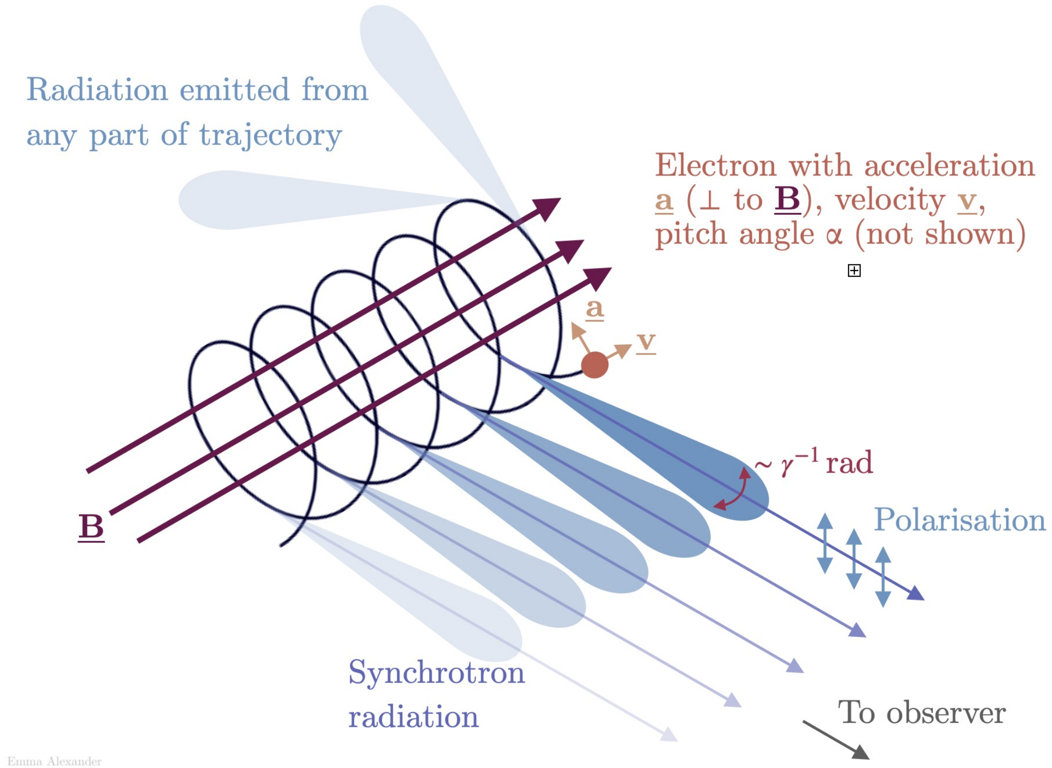


Synchrotron is a 3rd generation x-ray light source, ca. 1970s

Power radiated ~ k x $Energy^4 / R^2$

- X-rays for research in biology, chemistry, materials science
- US DOE operates 4 national synchrotron user facilities that are fully subscribed
- Stellar record of discoveries
- Radiation is incoherent and peak brightness is low. (more like a dim flashlight)

Synchrotron Radiation



$$P_\gamma = \frac{1}{6\pi\varepsilon_o}\frac{q^2 a^2}{c^3}\gamma^4$$

ε_o is the vacuum permittivity,

q is the particle charge,

a is the magnitude of the acceleration,

c is the speed of light,

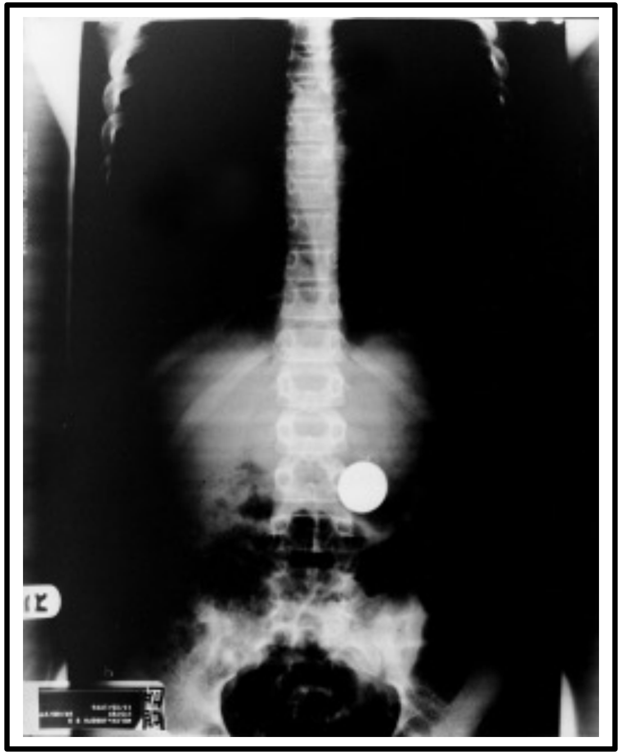
γ is the Lorentz factor.

https://en.wikipedia.org/wiki/Synchrotron_radiation

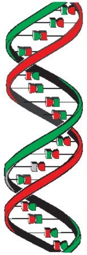
Why X-Rays and how do we push the frontier of x-ray science?

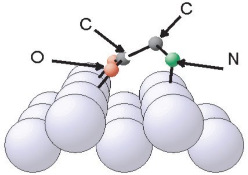
SLAC

See through matter

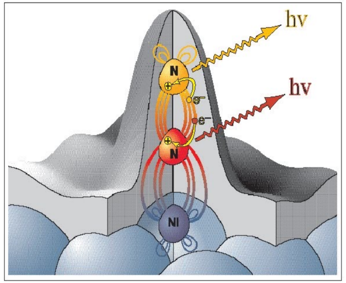


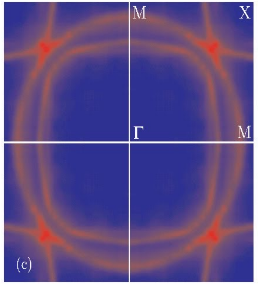
Where are the atoms?



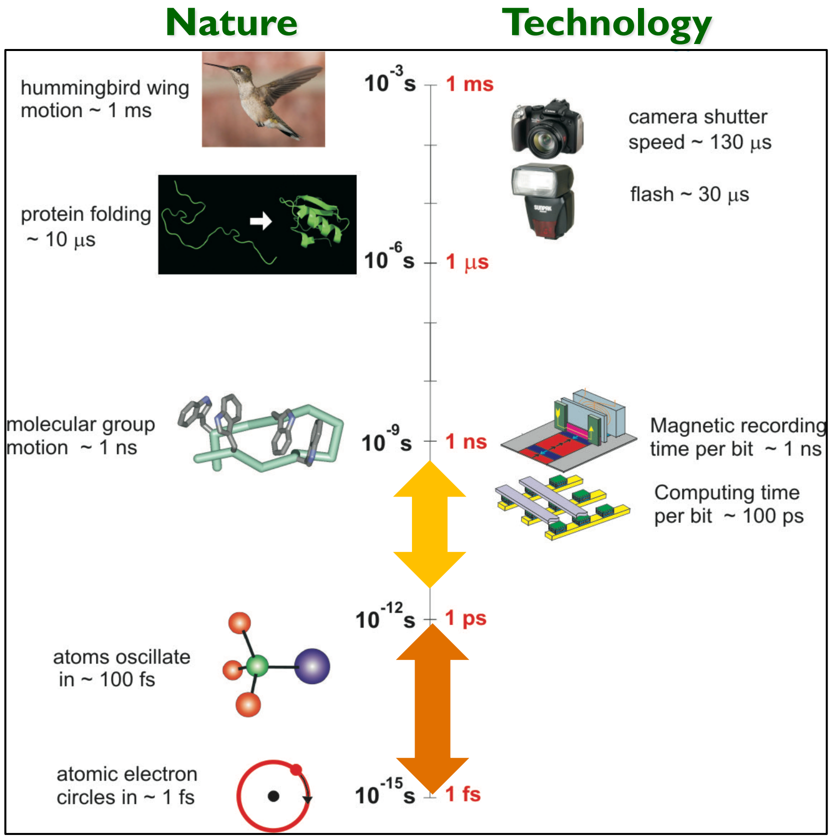


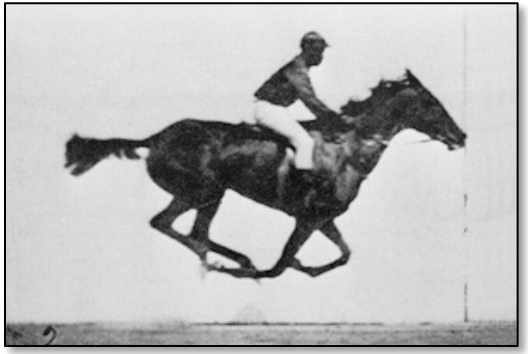
Where are the electrons?



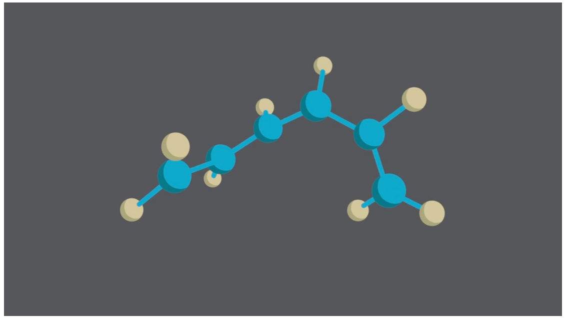


Ultra-fast and Ultra-small: The New Frontier





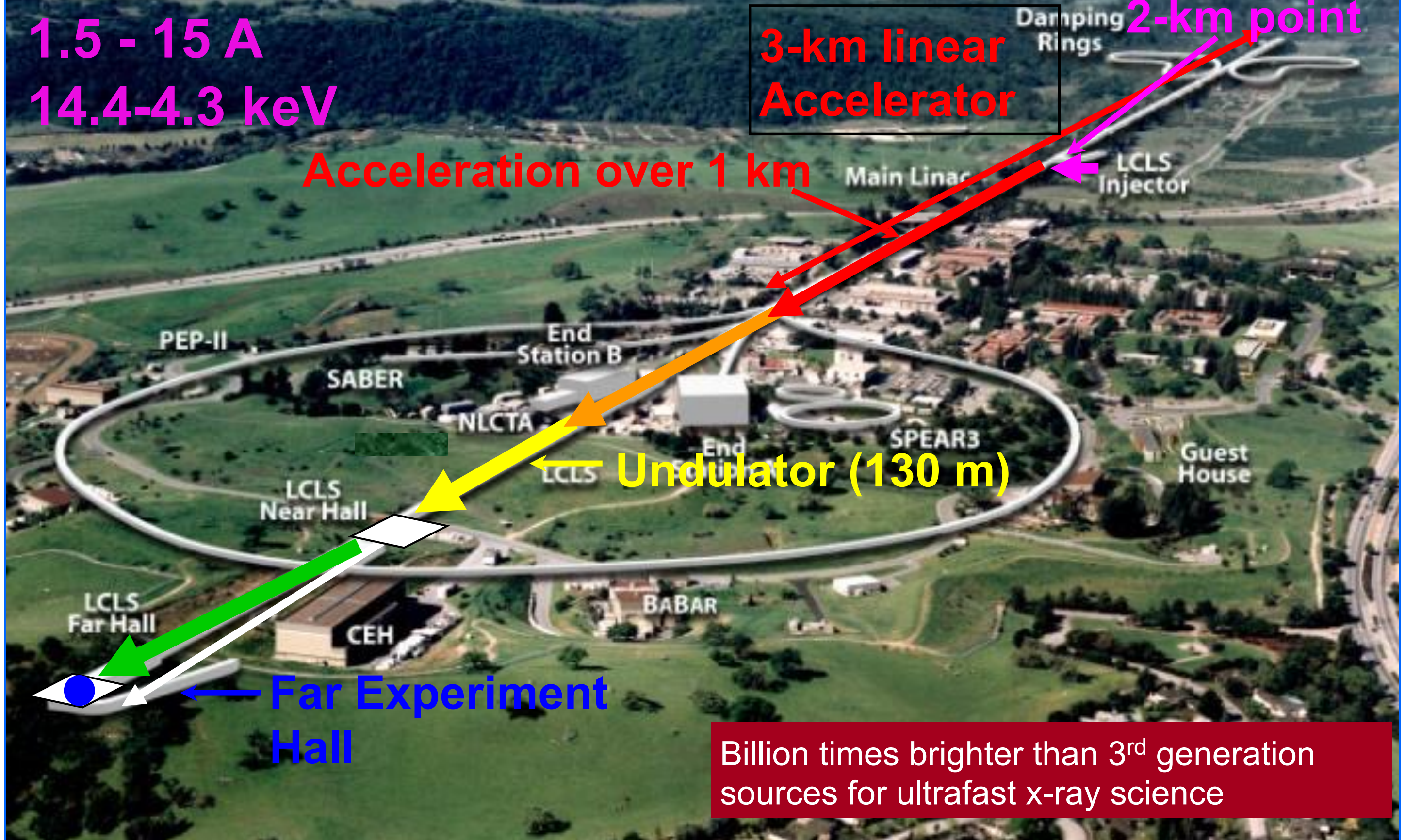
1 msec shutter speed



10-100 femtosecond shutter speed

Linac Coherent Light Source at *SLAC*

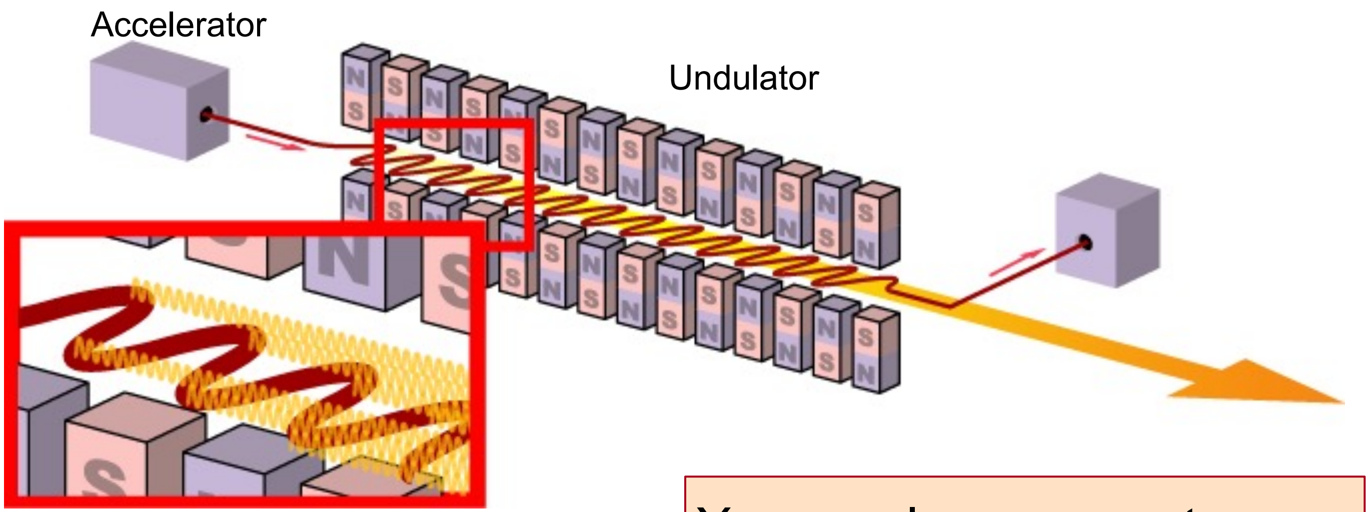
LCLS –first x-ray free-electron laser (XFEL) using last 1-km of existing 3-km linac



Billion times brighter than 3rd generation sources for ultrafast x-ray science

A Free Electron Laser is a High Energy (5-12 GeV) Electron Linac Coupled to an Undulator Magnet

SLAC

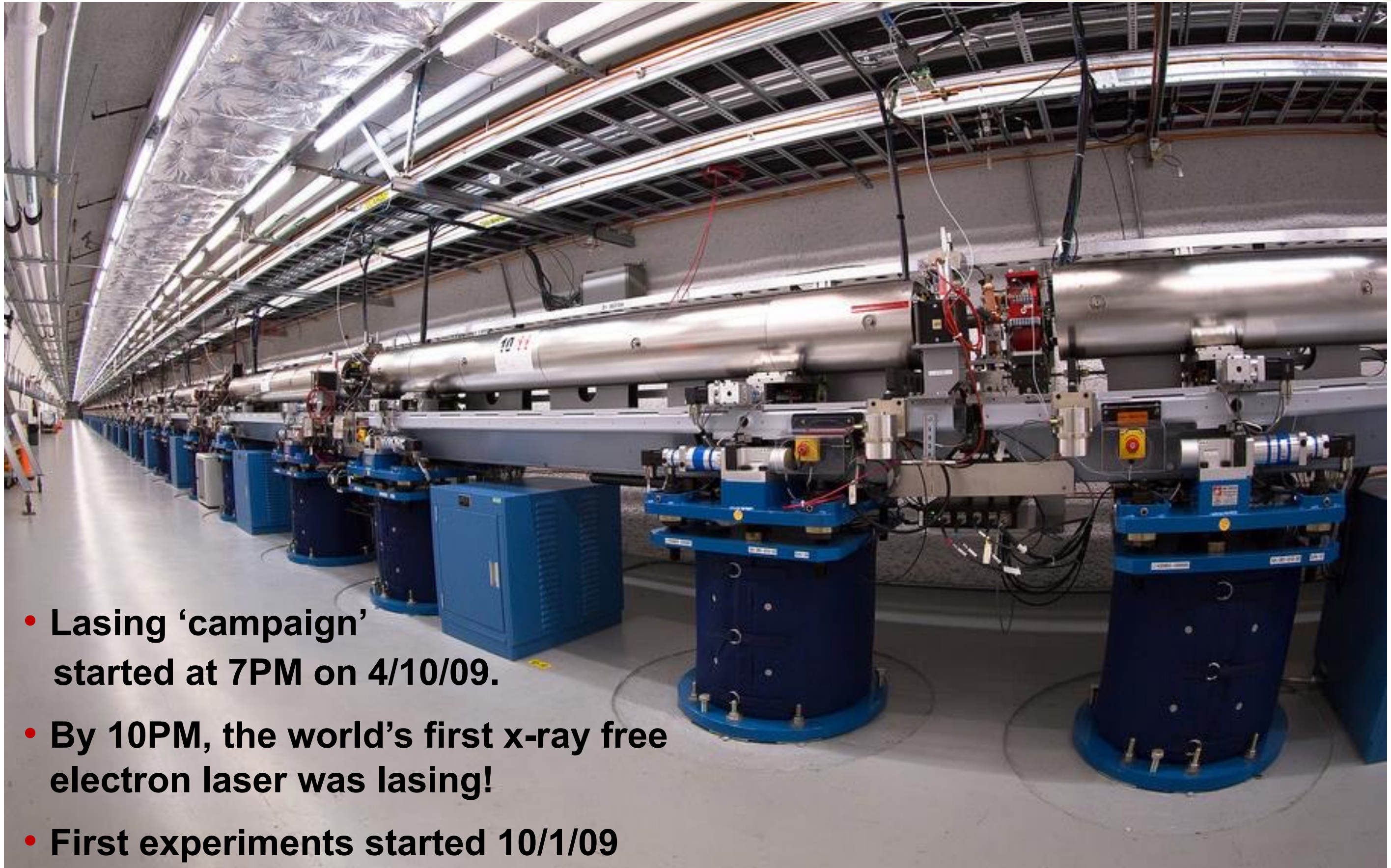


- Free relativistic electrons in bunch radiate in periodic H-field
- Amplification through electron ordering in its own radiation

X-ray pulse parameters

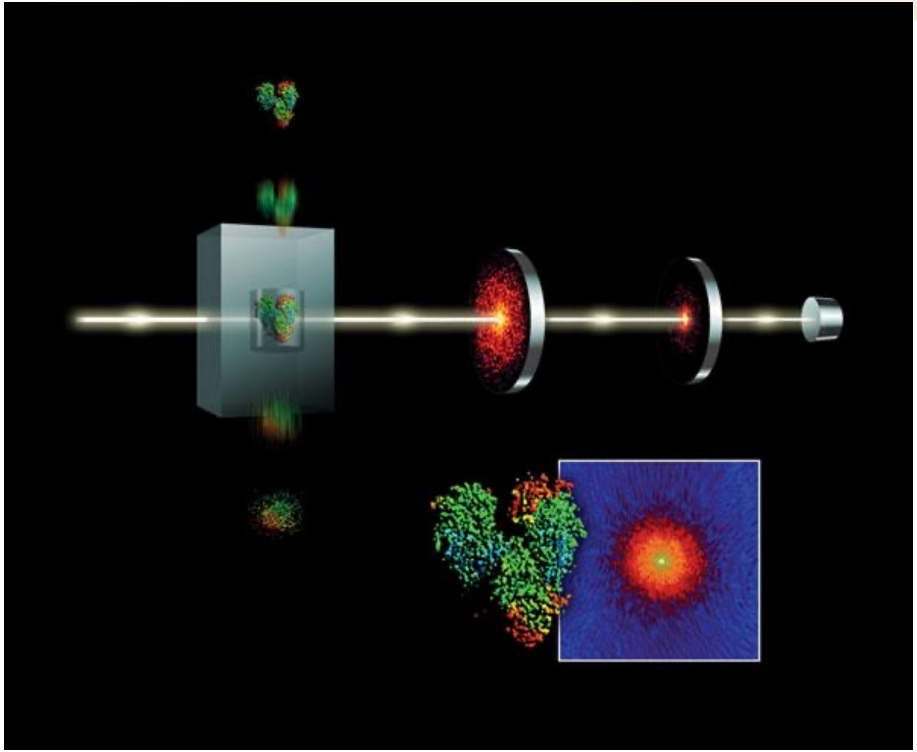
- 1-100 femtoseconds
- Tunable energy to 20 keV
- Angstrom wavelength
- 120 Hz now, 1 MHz LCLS-II

Inside View: LCLS Undulator Tunnel



- Lasing ‘campaign’ started at 7PM on 4/10/09.
- By 10PM, the world’s first x-ray free electron laser was lasing!
- First experiments started 10/1/09

How Molecular Imaging with X-rays Works

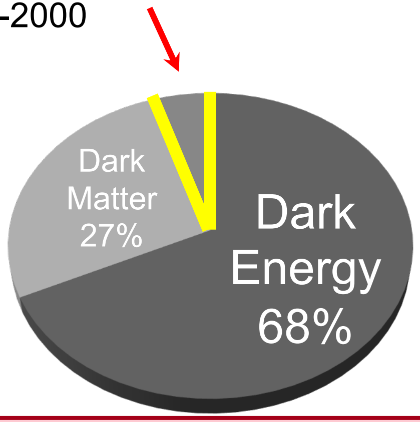


X-ray "camera" with shutter speed of 1-10 femtoseconds (10^{-15})
See atoms and electrons moving on their natural timescale to watch a chemical reaction atom by atom

So where do we go next?

In ***Particle Physics*** the frontier is electron-positron collisions > 1 TeV

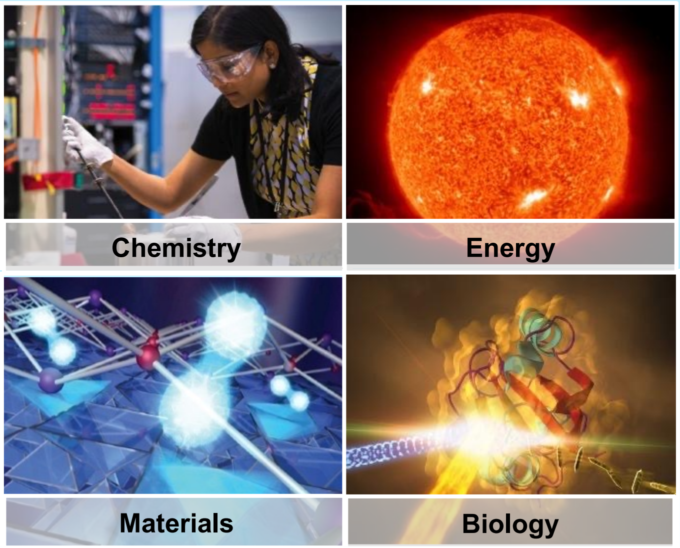
The 5% studied with particle accelerators 1960-2000



High Impact Applications for electron & ion accelerators & RF technology

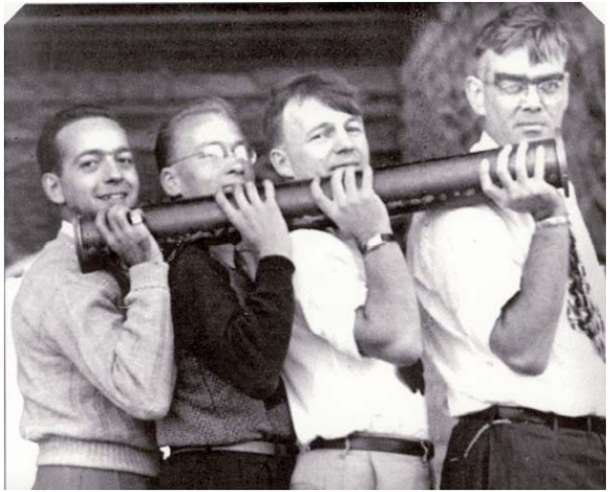
- Medicine
- Energy & environment
- Security and defense
- Communications, radar & remote sensing

In ***X-ray Science*** the next light source will be > $1 B and the beam time will likely be oversubscribed.



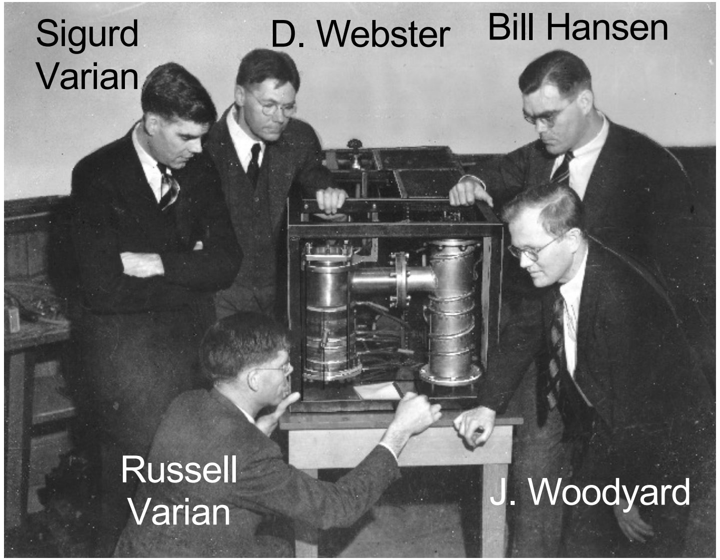
RF Accelerator Technology Got its Start With Key Technology Developments in the decades Flanking WWII

Use of RF resonant cavities for particle acceleration



First 3-foot section of MARK I electron linear accelerator at Stanford (William Hansen and three of his students) 1947.

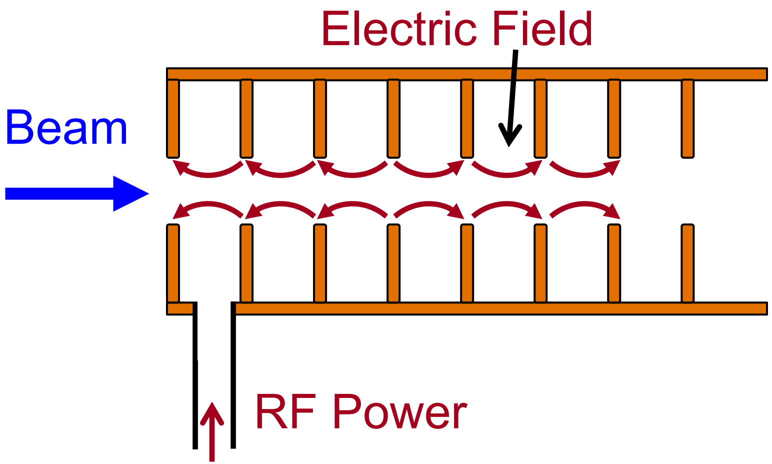
Powerful RF sources

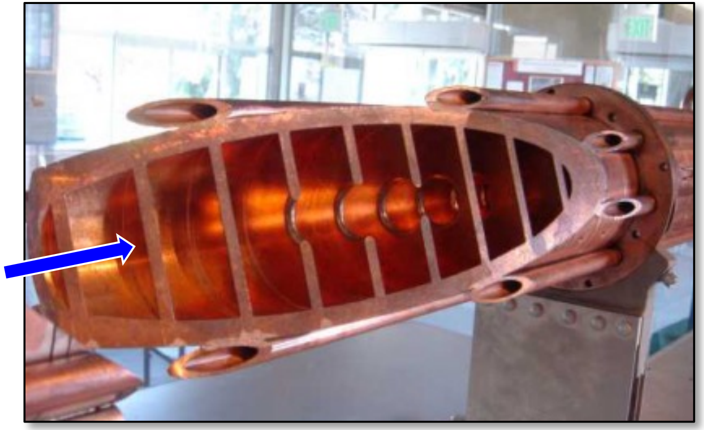


250 MHz klystron used for the U.S. Army blind landing system before World War II, Stanford University, 1939.

How an Radiofrequency Linear Accelerator Works

Disk Loaded Waveguide Structure



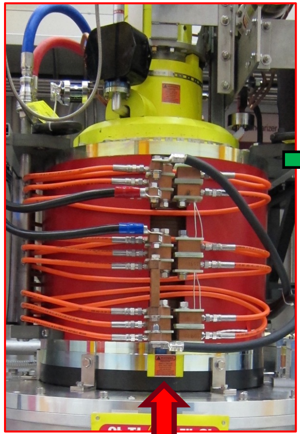


Section of the SLAC (2 Mile) accelerator structure - 2.856 GHz

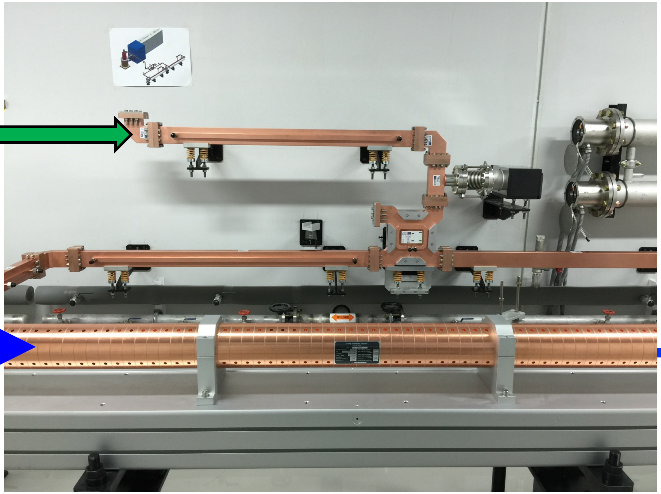
Typical gradients ~ 15-20 MeV/m

Accelerator Systems for Making Energetic Particles and Radiation

RF Power Source



Accelerator



Particle source

Particle beam:
e-, e+, p, d+, ions

Power supply/modulator

Interaction phenomena producing particles or photons- optical, γ , x-rays

Particle/Photon Radiation

Outline

- Overview of Accelerator Facilities
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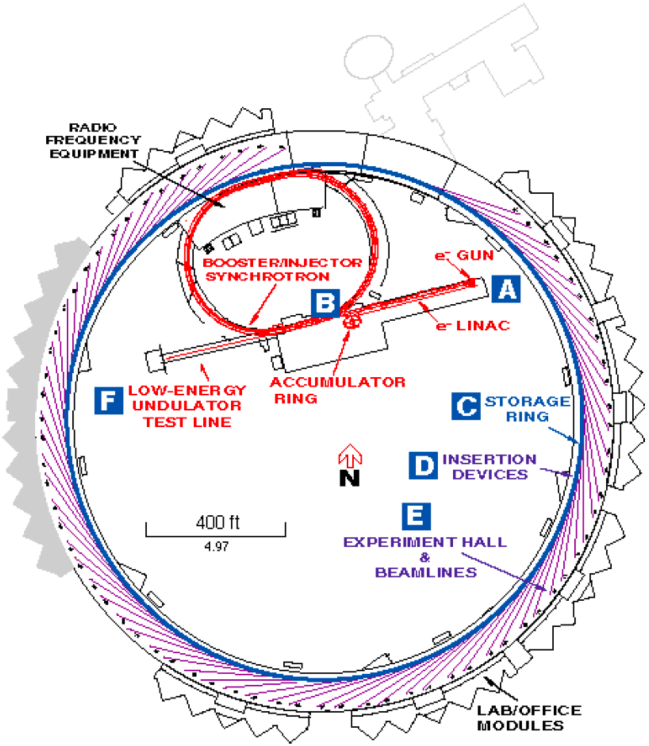
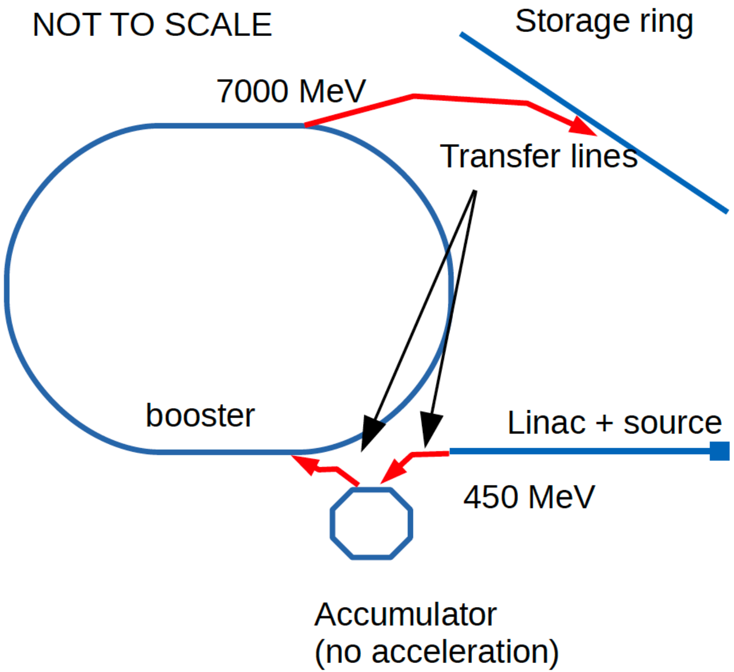
Advanced Photon Source

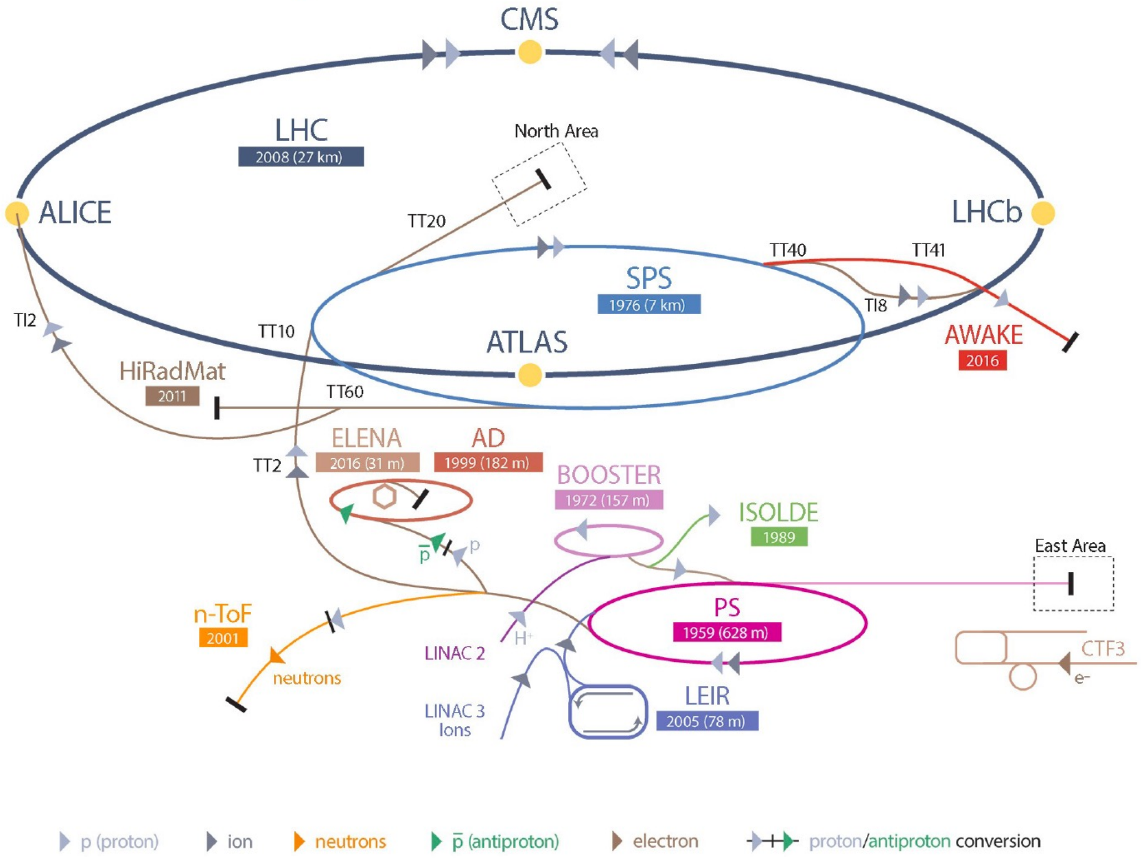
- X-ray synchrotron light sources contain many of the key components of accelerator facilities

Schematic View of the Advanced Photon Source





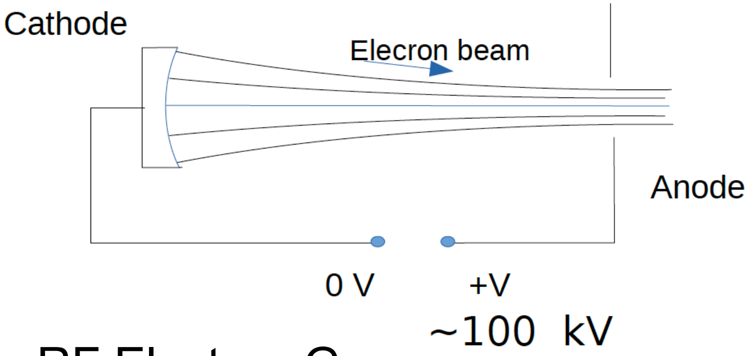
Comparison with LHC Injection



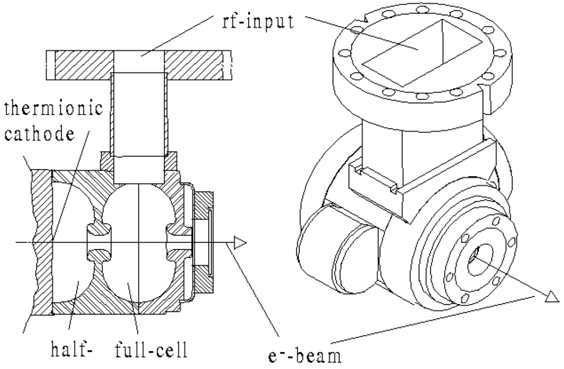
Particle (Electron) Sources

- Electrons emitted by providing enough free energy to overcome binding energy
- Thermionic, field and/or photo emission
- Need electric fields to accelerate particles away from the surface

DC Electron Gun

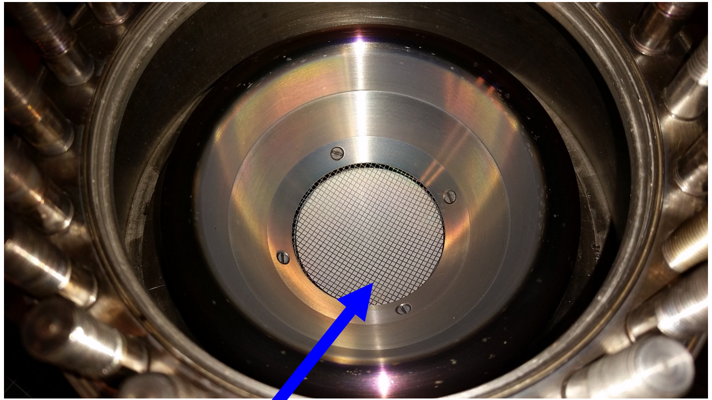


RF Electron Gun



Real Electron Guns

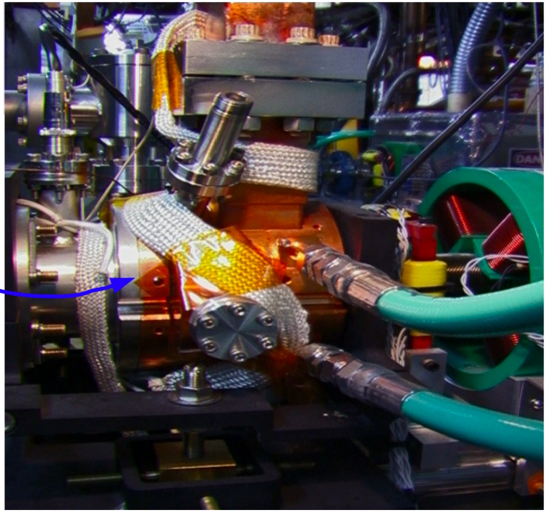
DC Electron Gun



Emitter heated to 1000 ^{o}C

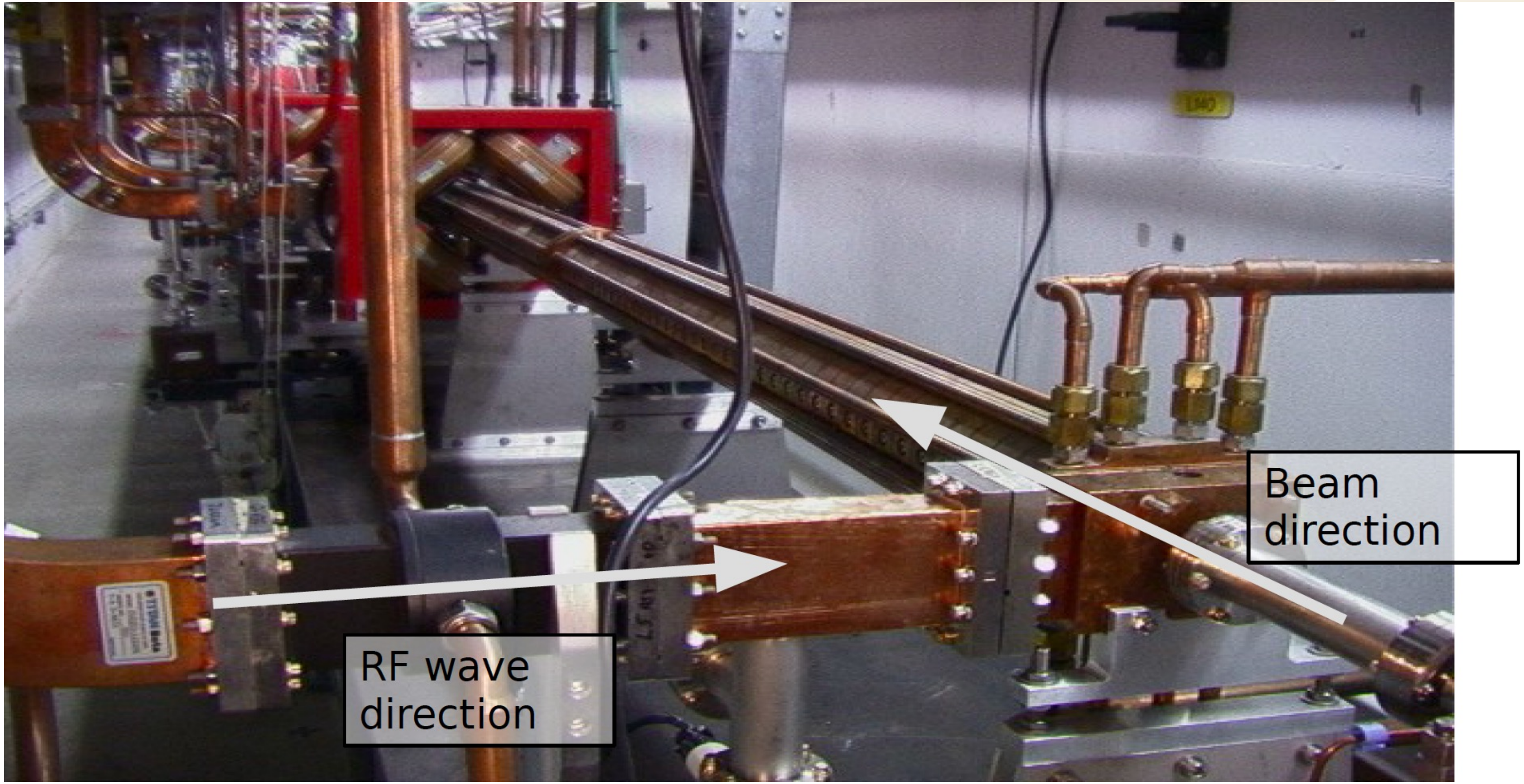
RF Electron Gun

cathode somewhere inside



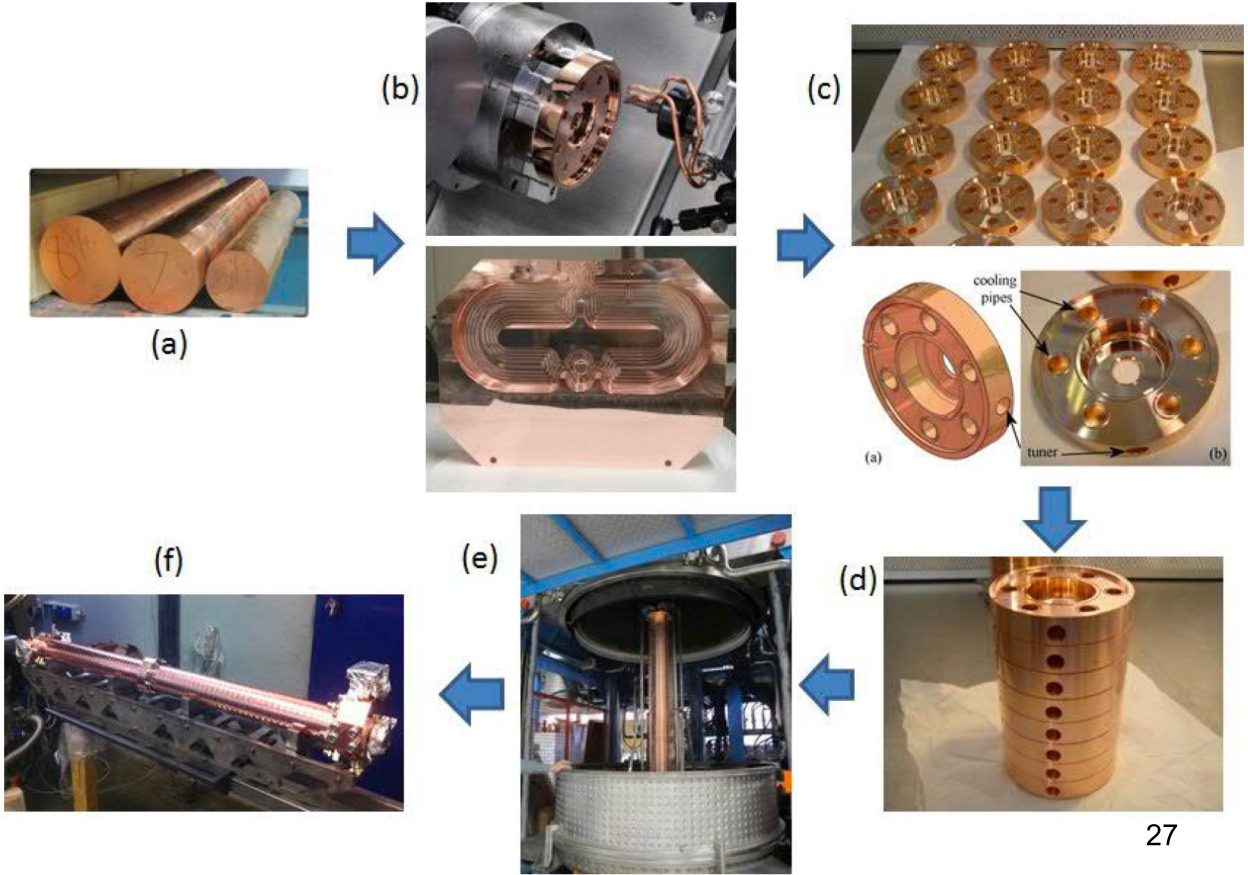
cooling hose that you see on most accelerator components

RF Linear Accelerator Increases Beam Energy



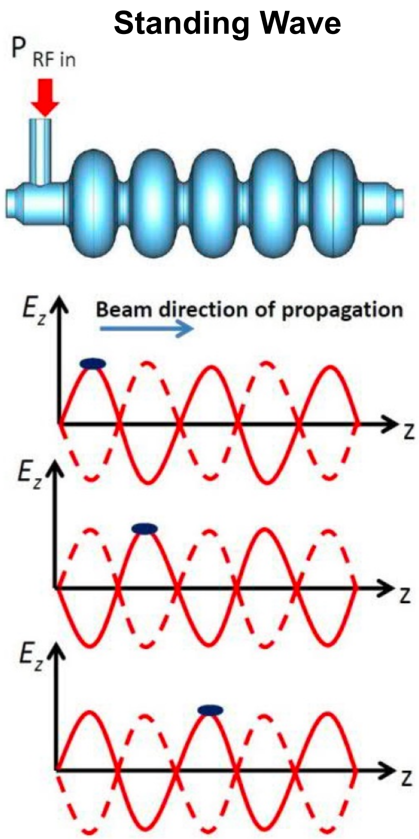
Fabrication of RF Accelerators

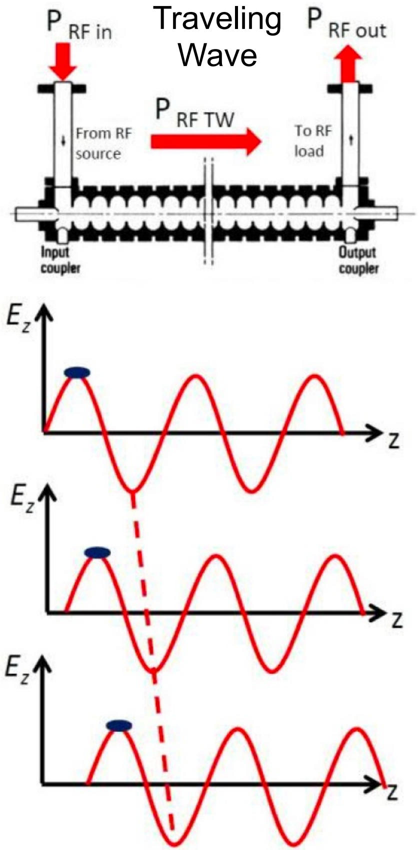
(a) OFHC forged copper; (b) realization of cells by lathes; (c) single cells machined and ready to be stacked; (d) cells piled up before brazing; (e) the structure in a vacuum or hydrogen furnace; (f) the brazed structure.



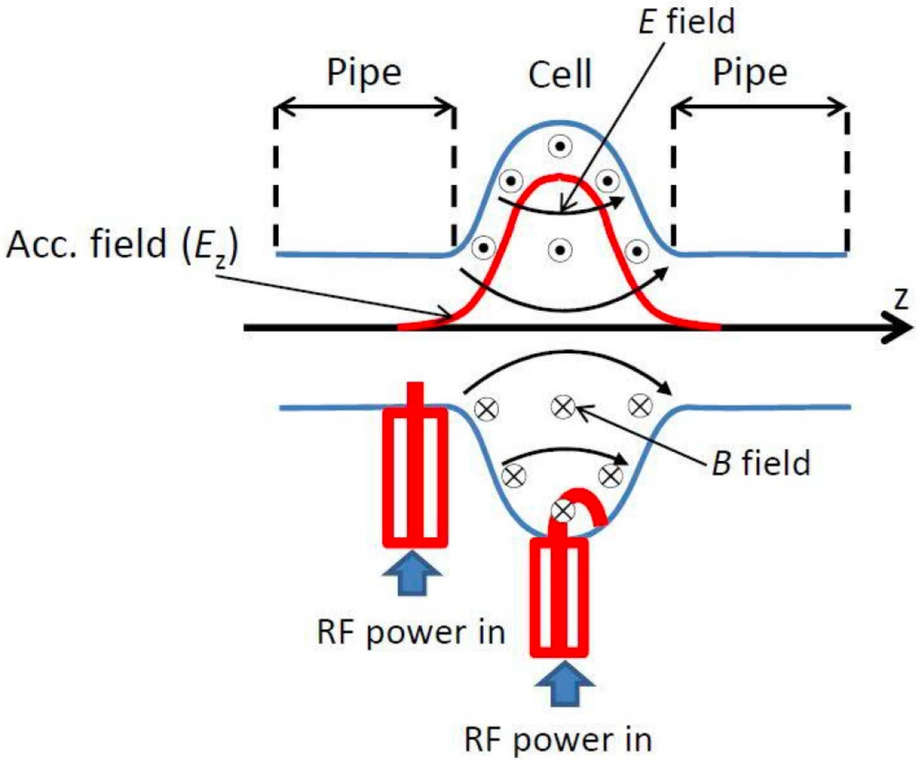
Electromagnetic Fields Used to Accelerate Particles

- Phase of electromagnetic wave needs to be controlled to match the particles velocity
- Standing Wave - fields in cavity alternate polarity in cavities and oscillate
- Traveling Wave – fields propagate with a phase velocity that matches particle velocity





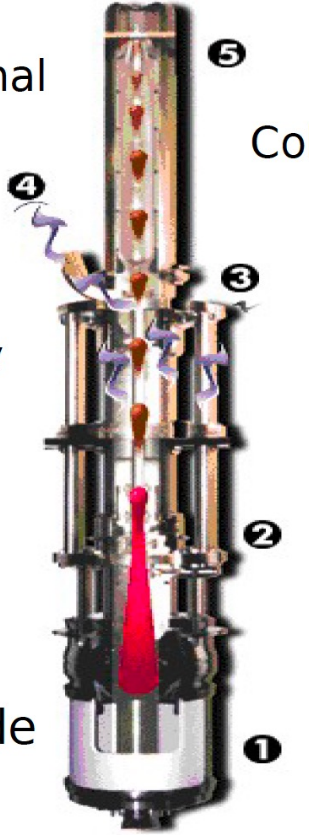
Axial Electric Field Increases Kinetic Energy



$$E_z(z,t) = E_{RF}(z)\cos\left(\underbrace{2\pi f_{RF}}_{\omega_{RF}} t + \varphi\right) = \mathrm{Real}\left[\tilde{E}_z(z)e^{j\omega_{RF}t}\right]$$

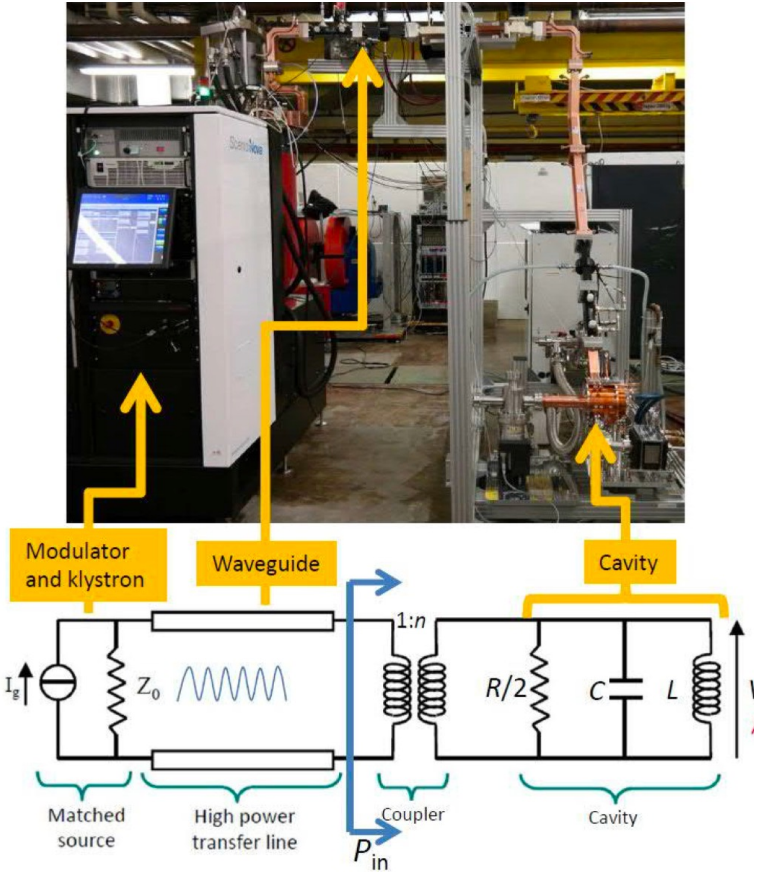
$$V_{acc} = \left|\int_{cavity} \tilde{E}_z(z)e^{j\omega_{RF}\frac{z}{v}}dz\right|$$

RF Sources Power the Accelerator

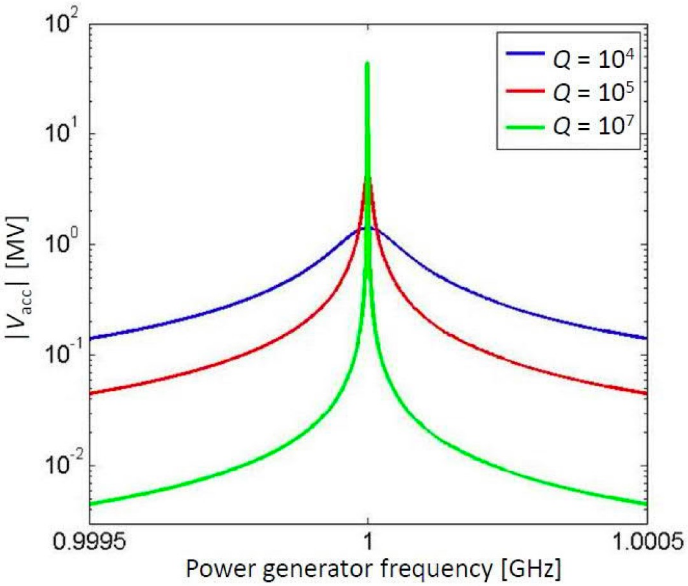


RF Source (Klystron)

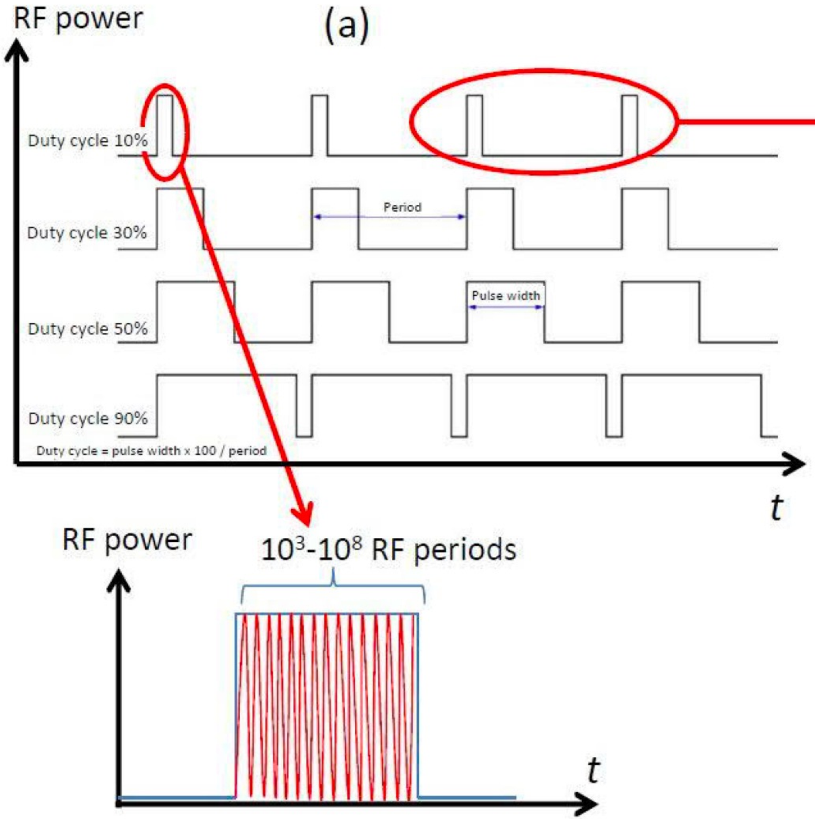
Circuit Model for Powering Accelerators

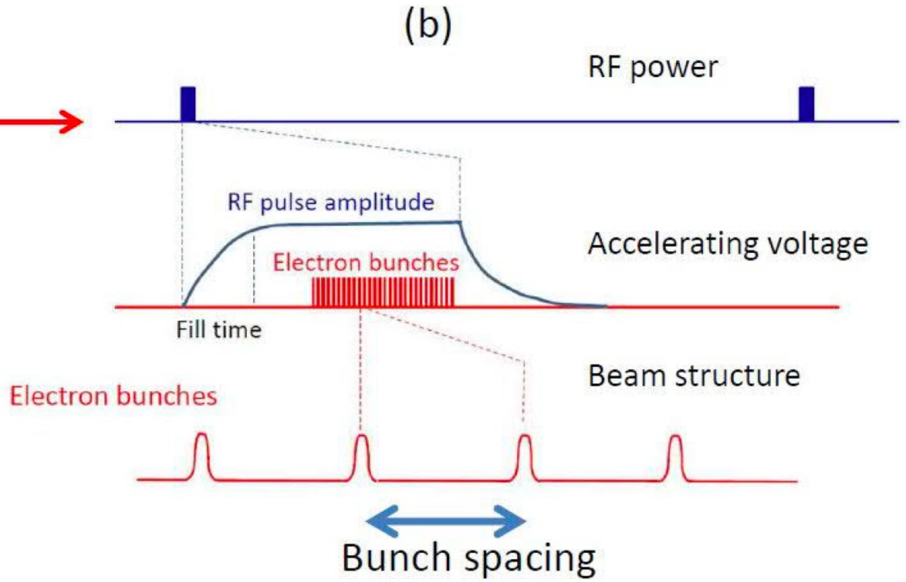


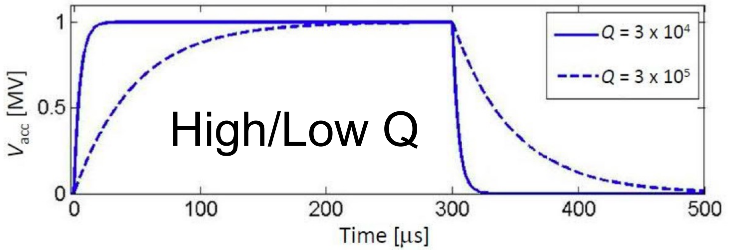
- High quality factor increases energy gain for fixed power



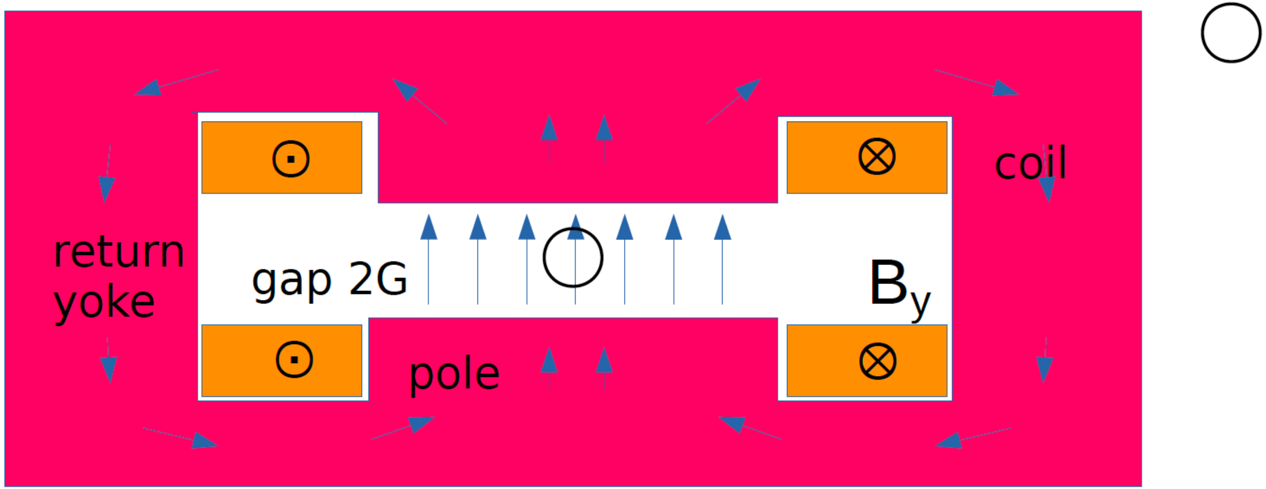
RF and Beam Pulse Structure







Magnets Guide and Transport the Beam

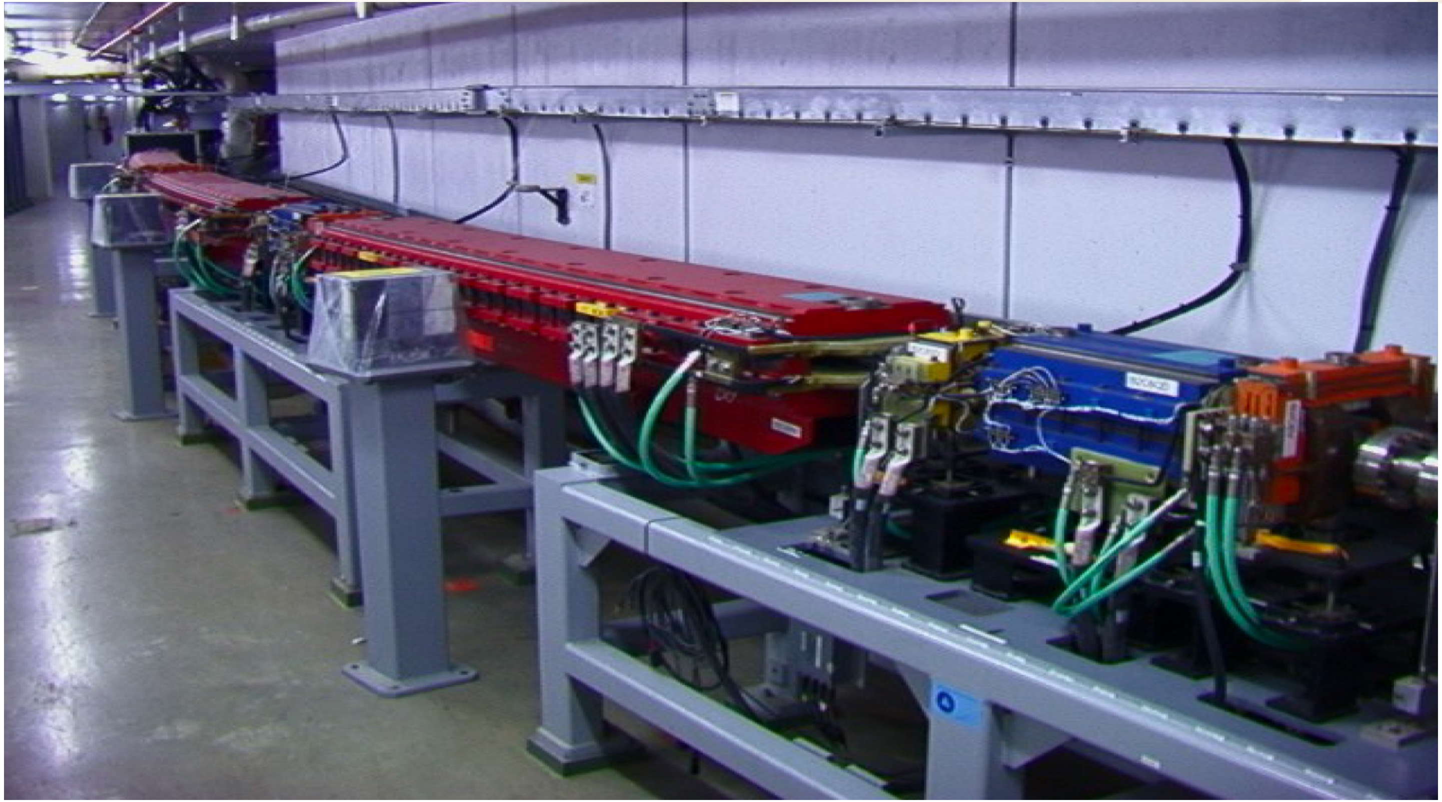


Beam-pipe in center of symmetry of magnet aperture

$$B_y[T] = \frac{0.4\pi}{10^4} \frac{I[A-turn]}{G[cm]}$$

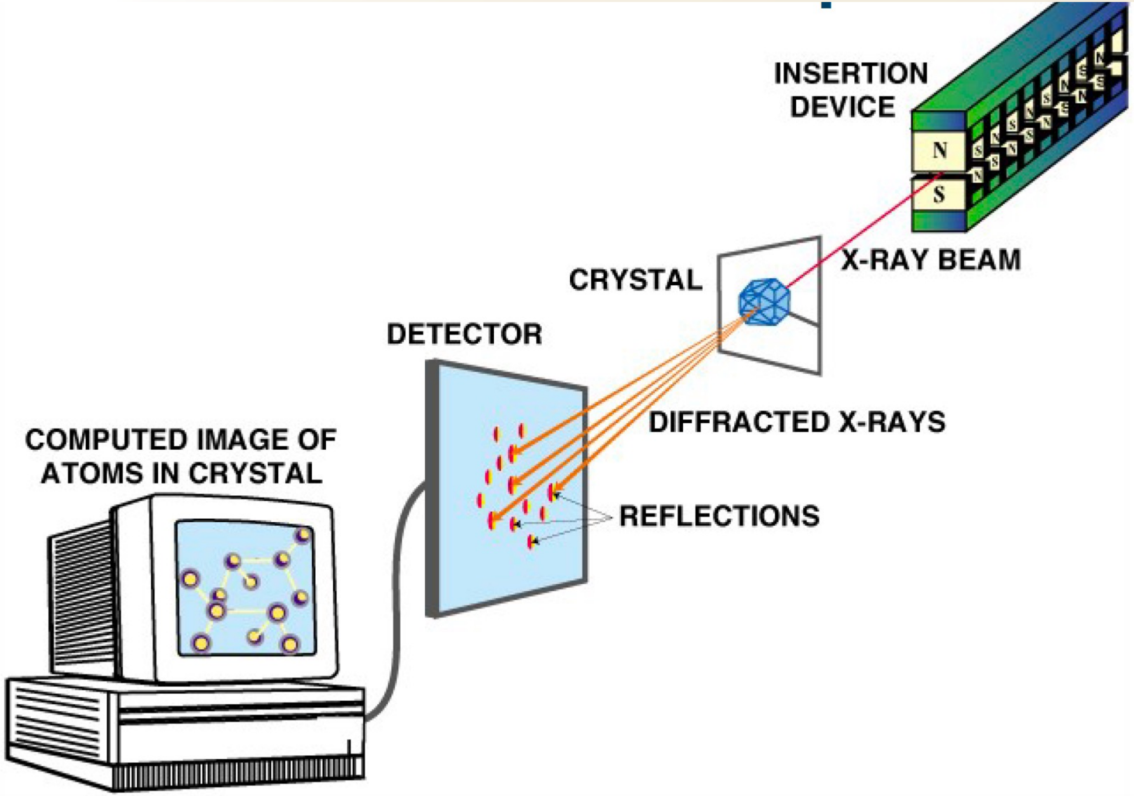
$$\frac{1}{\rho[m]} = 0.3 \frac{B_y[T]}{\beta E[GeV]}$$

Bending Magnets in the APS Ring

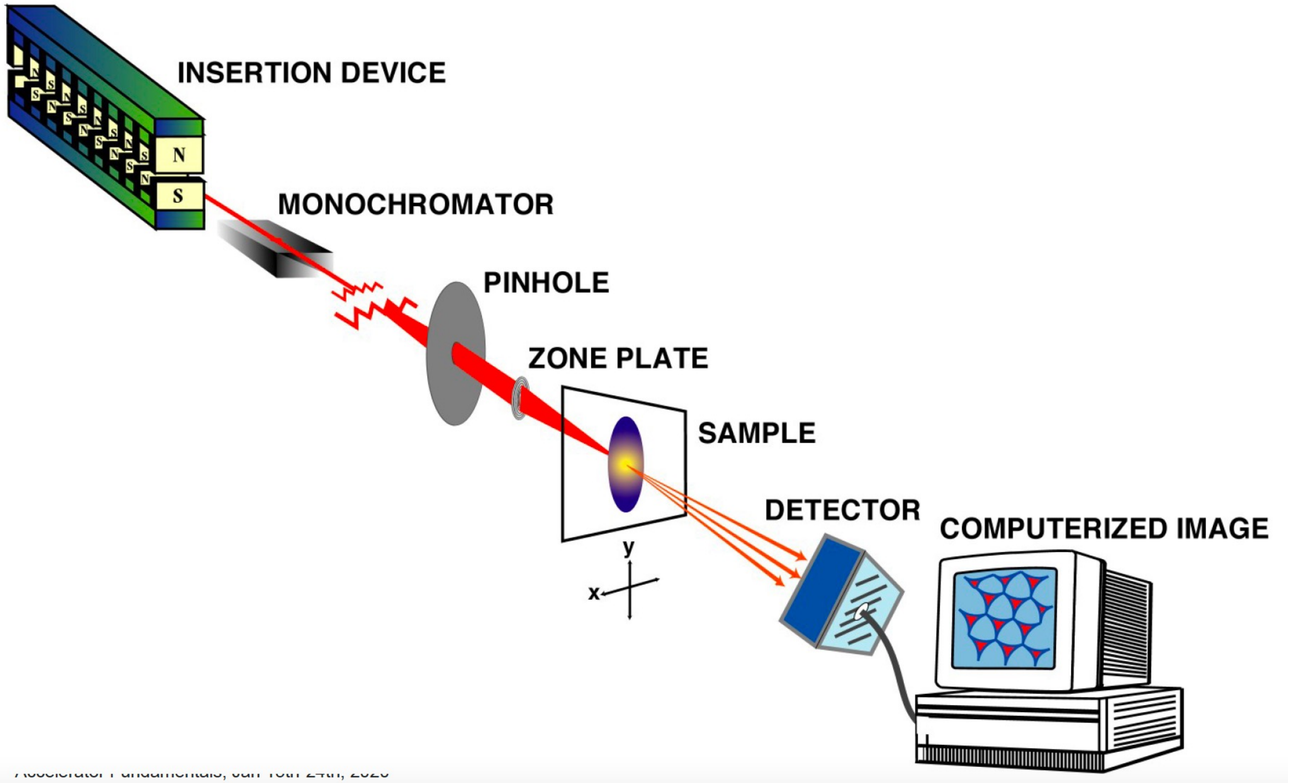


APS Magnets Awaiting Installation

Applications Side – X-ray Diffraction

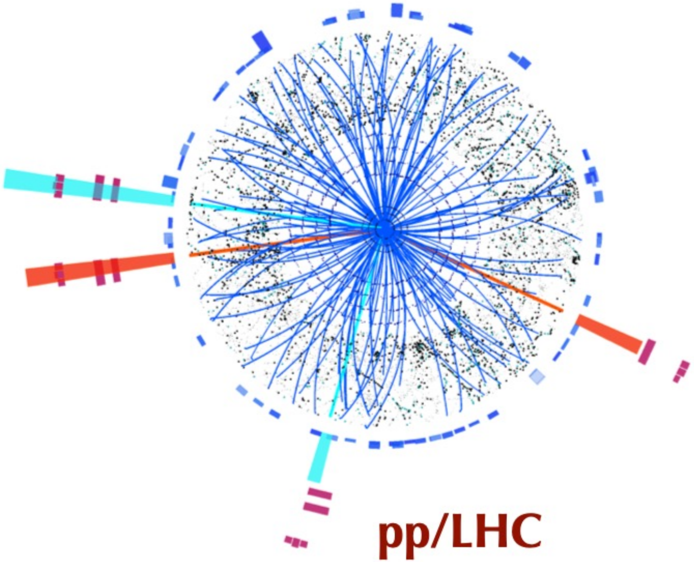


Applications Side – X-ray Imaging

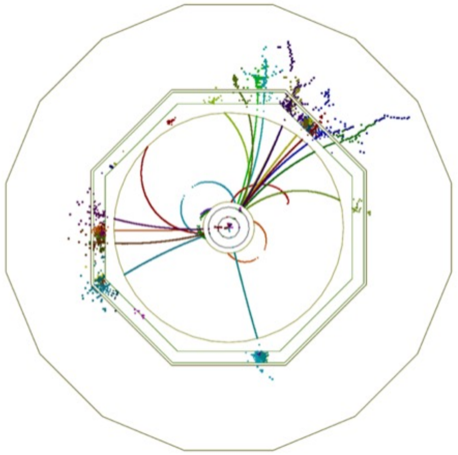


Applications Side – Colliders

- HEP community is pushing for e+e- collider to study the Higgs
- Initial state well defined & polarization ⟹ High-precision measurements
- Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and trigger-less readout



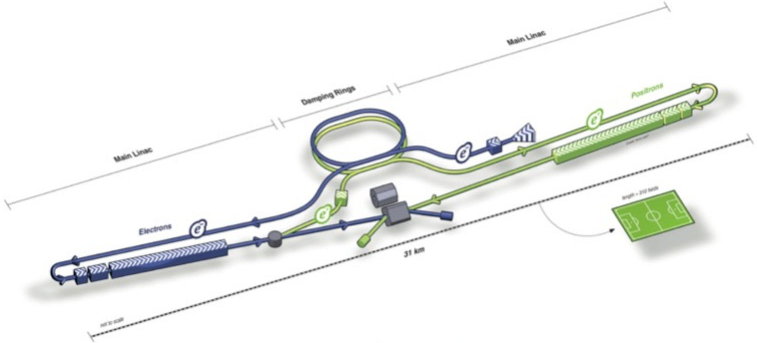
pp/LHC

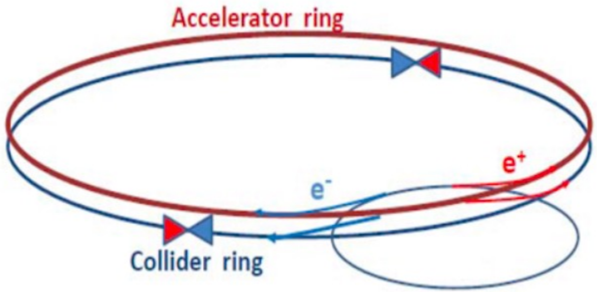


e^+e^-

Linear vs. Circular

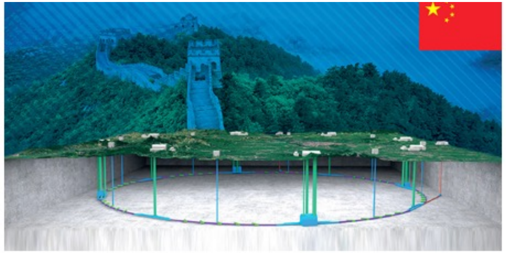
- **Linear** e^+e^- colliders: ILC, C^3, CLIC
  - Reach higher energies (~ TeV), and can use
  - Relatively low radiation
  - Collisions in bunch trains
- **Circular** e^+e^- colliders: FCC-ee, CEPC
  - Highest luminosity collider at Z/WW/Zh
    - limited by synchrotron radiation above 350– 400 C
  - Beam continues to circulate after collision





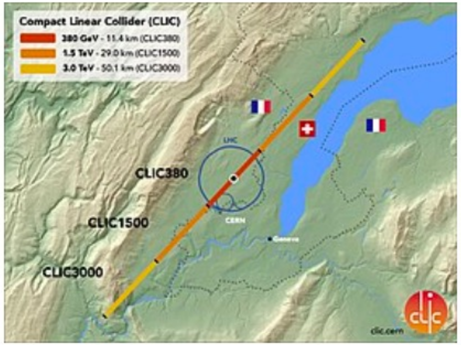
Collider Proposals….

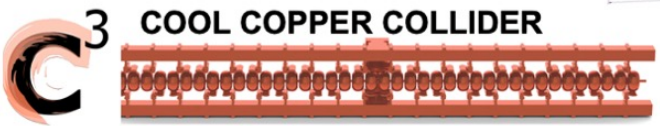
250/500 GeV



CEPC 240 GeV

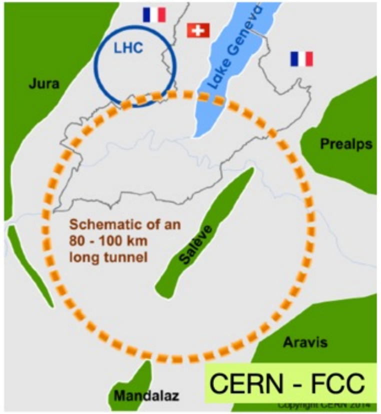
CLIC 380/1500/3000 GeV





250/550 GeV

… > TeV



FCC-ee

240/365 GeV

Outline

- Overview of Accelerator Facilities
- Major Systems and Components of Accelerator Facilities
- Future Directions

Next Generation Accelerators in Pursuit of Compactness, Efficiency and Performance

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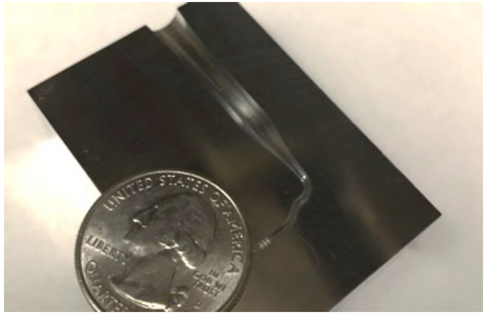
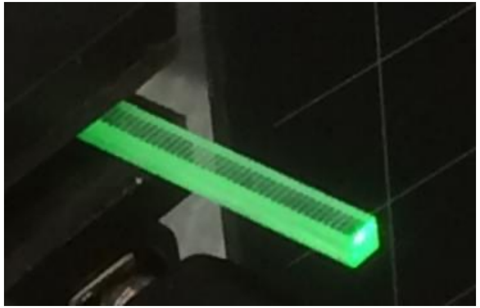
S-band Accelerators 30 MeV/m		mm-Wave/THz Accelerators GeV/m

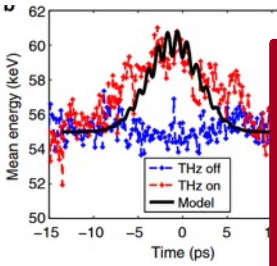


Klystron Source 10s MW, μs, ~3 GHz		mm-Wave/THz Sources MW, ns, ~0.3 THz



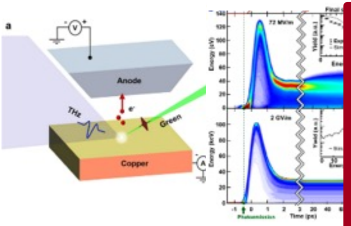
Rapid Development of THz Accelerator Technology

Acceleration



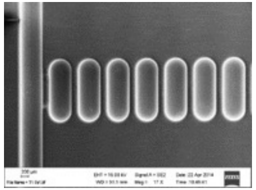
Nature Comm. 6 (2015):

Photoinjectors



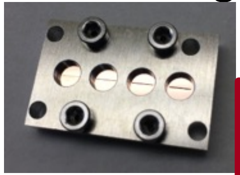
Huang, W. R., et al., *Nature Scientific Rep.* 5 (2015).

Beam-Driven GV/m Fields



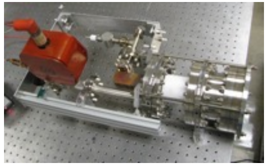
M. Dal Forno, et al., *PRAB* 19 (2016): 051302.

Deflectors and <1 fs Timing

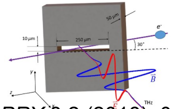


afast O
2017)

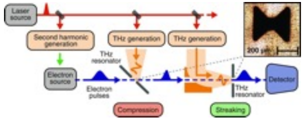
Toward Externally Driven GeV/m Accel.



Growing International Community:



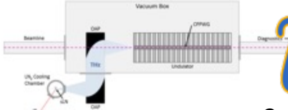
Zhao, et al. *PRX* 8.2 (2018): 021061.



Kealhofer, et al. *Science* 352.6284 (2016)

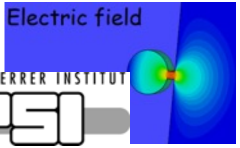
The Cockcroft Institute of Accelerator Science and Technology

Healy, et al., *UCMMT, 2017*



Curry, et al. *arXiv 1708.06385* (2017).

PAUL SCHERRER INSTITUT



M. Dehler, HG2017

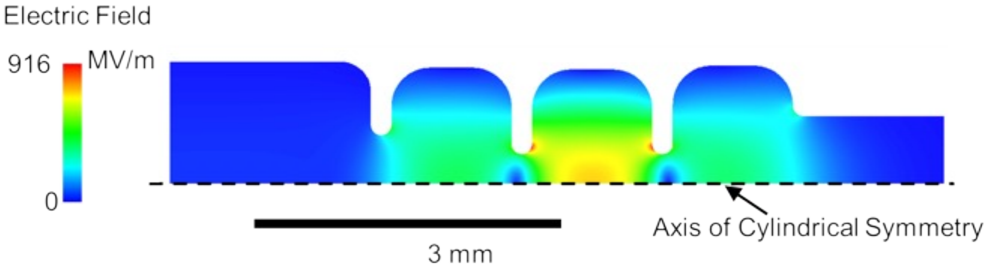
INFN

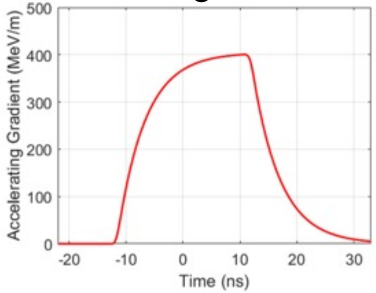
Impacting Diverse Areas of Accelerator Technology:

- Precision Diagnostics and Beam Manipulation - <fs resolution
- Ultrafast Electron Diffraction - 100 fC, <10 fs
- X-ray Generation – few to 10s pC, low emittance
- High Current, High Luminosity >>10s pC, bunch trains

What is the Real Scaling in Frequency for Breakdown Physics?

- Demonstrate realizable THz accelerating structure
- Power with stand-alone RF source – Experimental test underway at MIT with 1 MW gyrotron oscillator
- Direct comparison w/ X-band breakdown studies



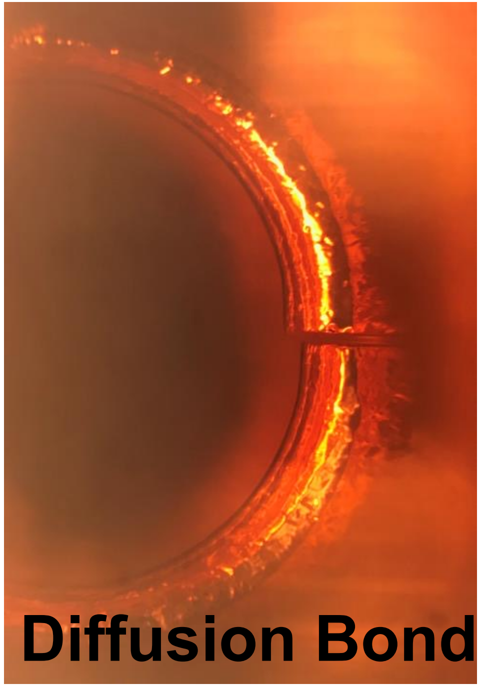


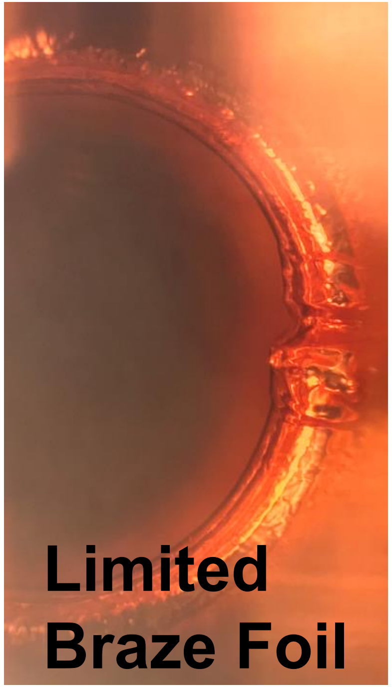
Need to Develop High-Power High-Frequency Sources for Practical Applications

Comparison of Assembly Techniques

SLAC

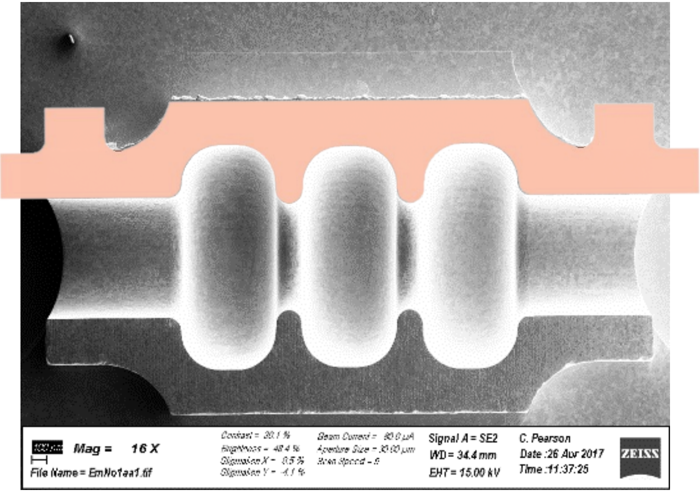
- Assembly from halves makes RF performance insensitive to defects
- Local features significantly different

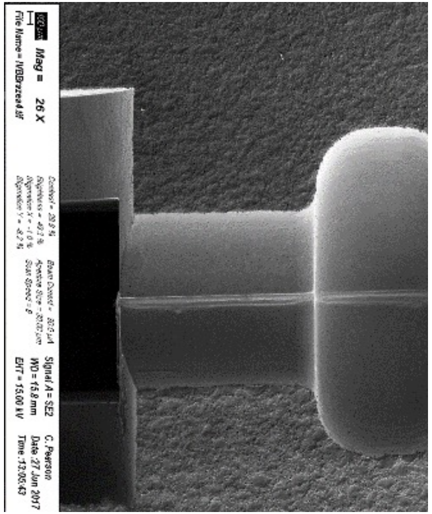


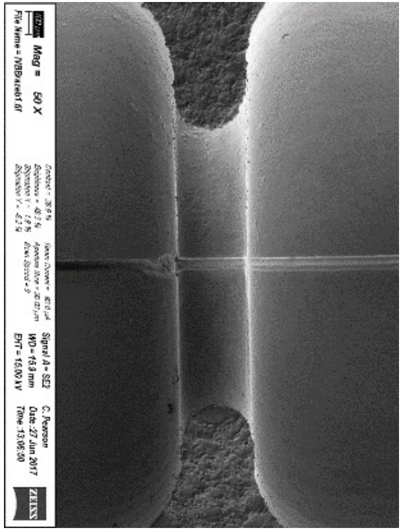


Details of Isolated + Limited Brazed Assembly

- New techniques and approaches needed for fabrication
- Successfully adapted split-cell approach to mm-Wave/THz range
- Braze foil tailored to cavity shape to control volume





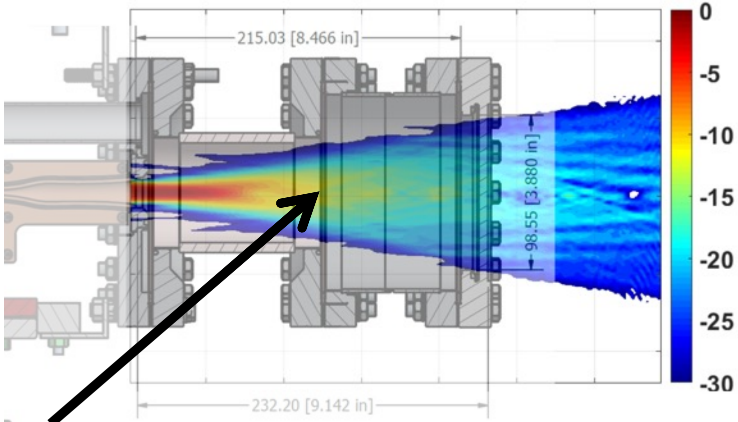


Efficient Excitation of THz Accelerating Structures

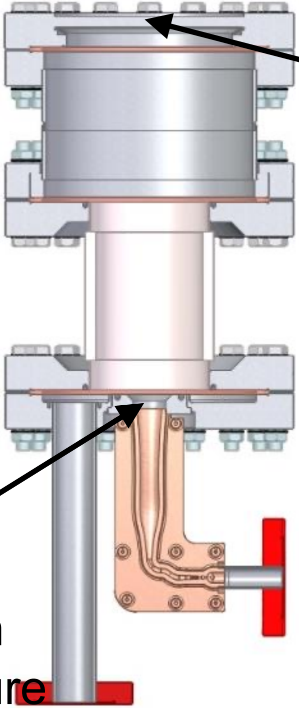
SLAC

Schaub, Jawla

- Avoid lossy waveguides with quasi-optical transport and couplers

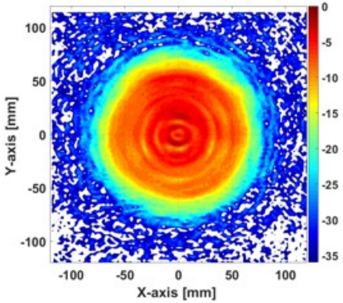


Measured/back-propagated field in the cut plane of the assembly

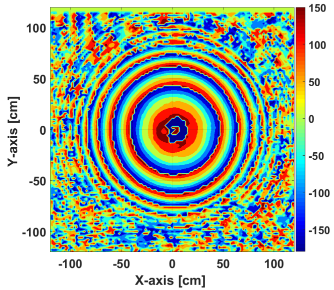


Free-space Gaussian beam coupled to structure

Measured Amplitude



Measured Phase

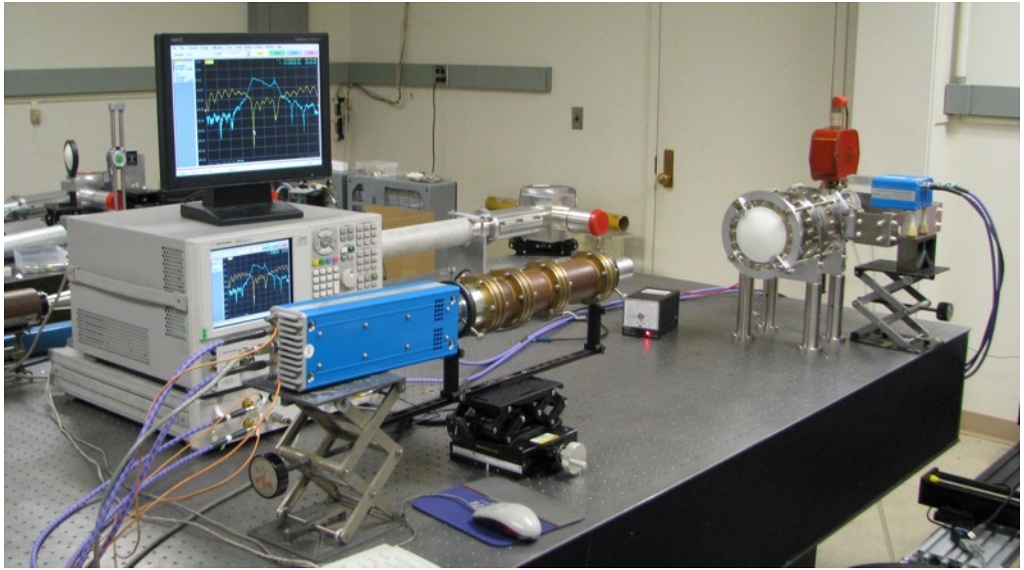


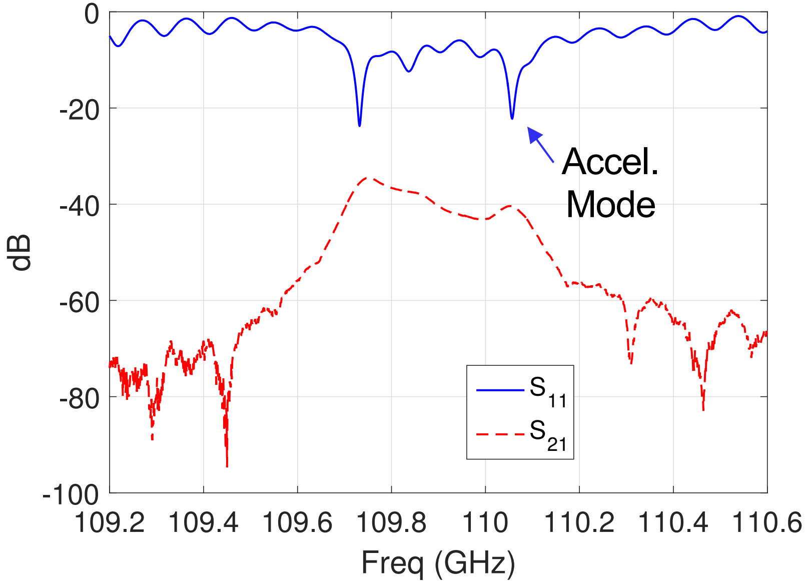
Versatile Topology Compatible with New Structures and Different Frequencies

Results from Quasi-Optical Transport Test

Schaub, Jawla

- Gaussian beam launcher used to test excitation
- Matches design - π-mode 110.1 GHz, S_{11}≈-25 dB, S_{21}≈-40 dB



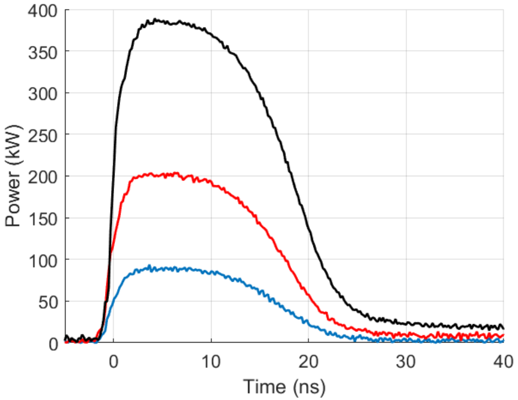


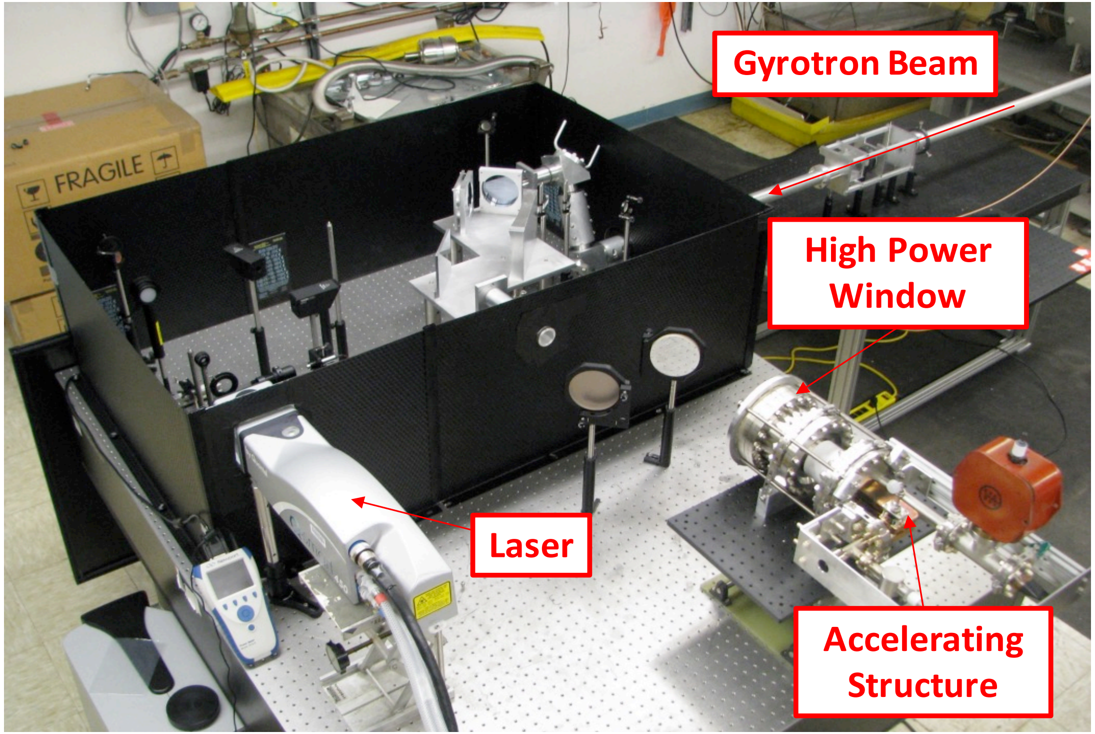
First Quasi-Optical Coupling into Narrow-Band Accelerating Structure

Laser-Triggered Semiconductor Switch for Pulse Shaping

- Short tunable pulse lengths few-100s nanoseconds at MIT
- Quasi-optical coupling also demonstrated on high power setup

Measured Pulse After Switch

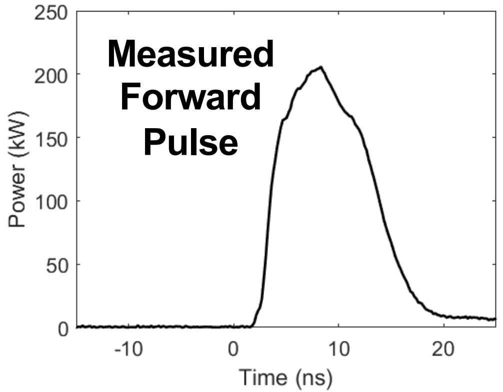




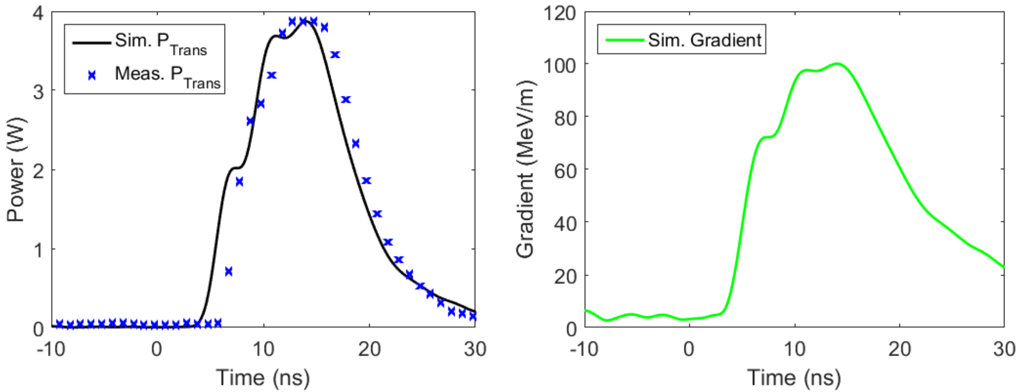
Picard, Schaub

High-Power Testing of 110 GHz Accelerating Structures

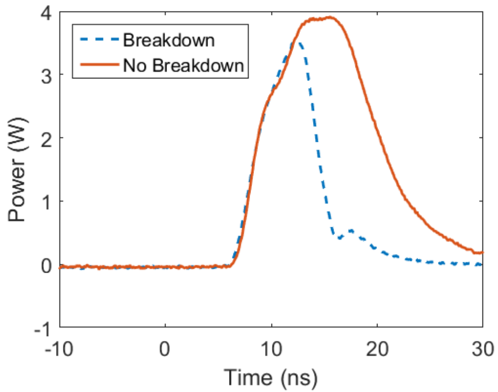
- **Achieved 110 MeV/m Gradient (<25k pulses)**
  → Power Available for 100s MeV/m
- Breakdowns observed after power increased and rapidly process away
- Improving transport, coupling, diagnostics



Transmitted Pulse and Gradient



Impact of Breakdown on Transmitted Pulse

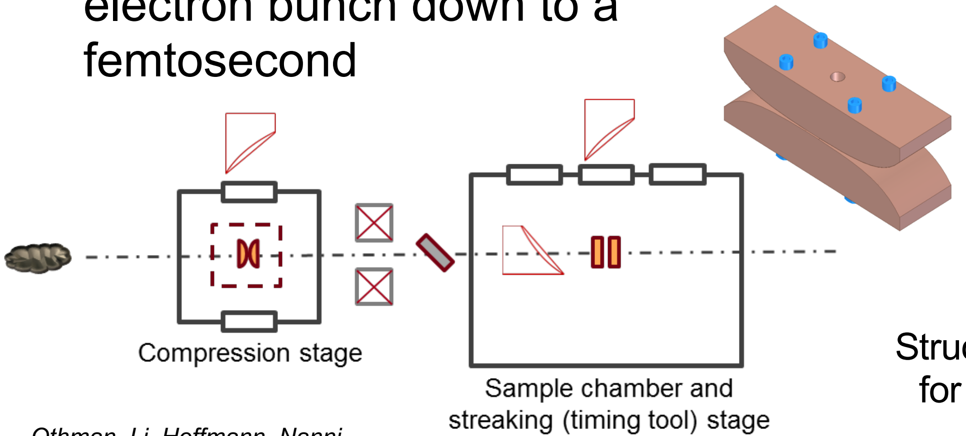


Exploring New Frontiers of THz Acceleration with Laser-Driven THz Sources

SLAC

Single-Cycle THz Source Experiments

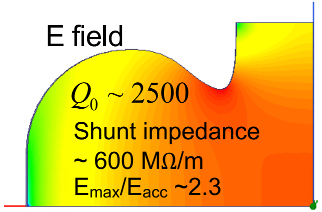
- Experimental stepping stone
- Successfully demonstrated <fs streaking diagnostic at SLAC UED
- Pursuing structures to demonstrate compression of electron bunch down to a femtosecond

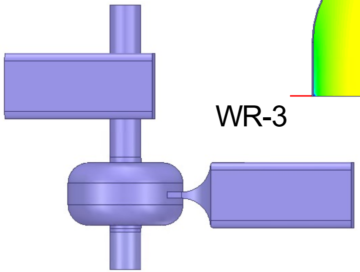


Othman, Li, Hoffmann, Nanni

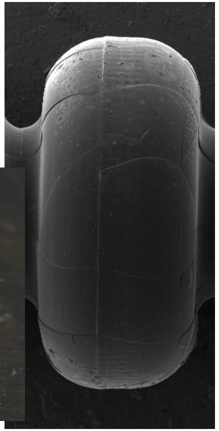
Narrow-Band THz Source Experiments

- Developing structure for test with 100 ps 100 kW source (w/ Minamide RIKEN)





3D Printing Accelerating Structures at 300 GHz for Electro-Forming

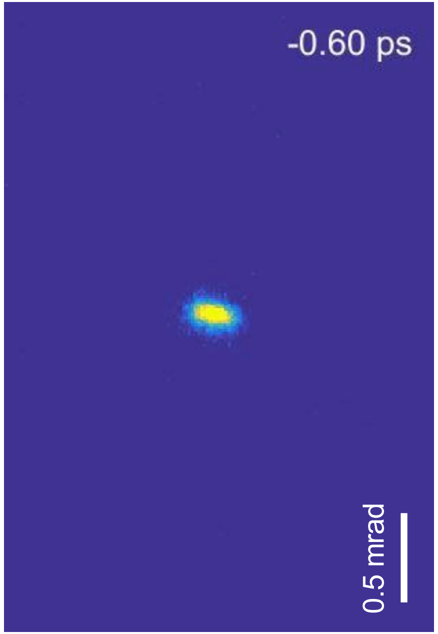


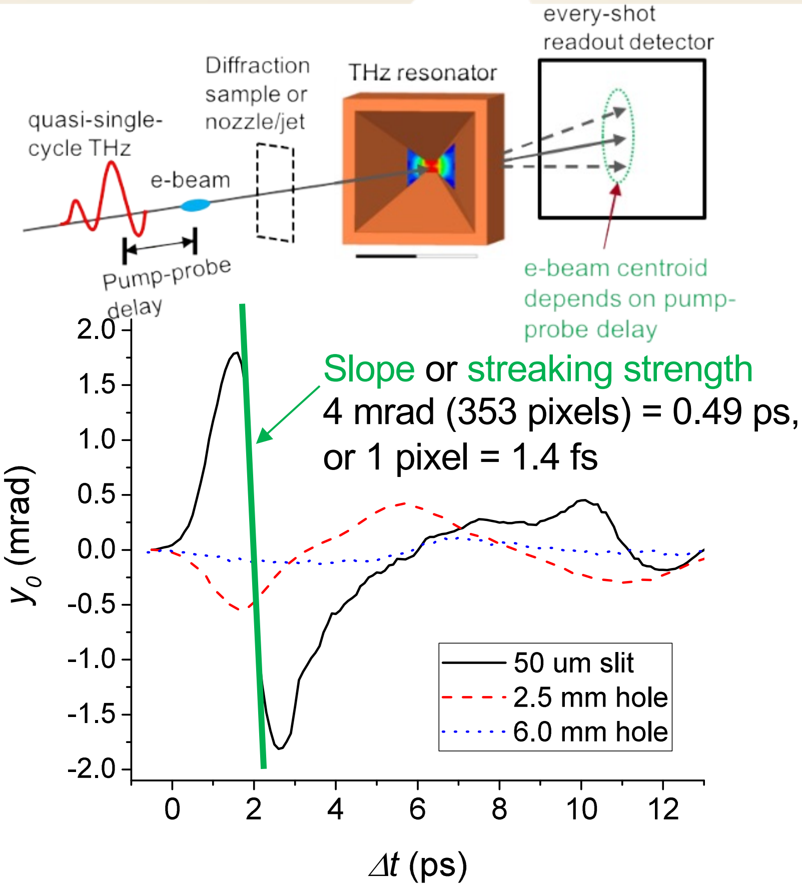
THz streaking of femtosecond electron beams

SLAC

- Characterize timing jitter and bunch length
- Develop a timing tool for UED
- THz manipulation/ acceleration of fs ϵ-beams

3.1 MeV electrons, 50 um gap, 100 um thick slit



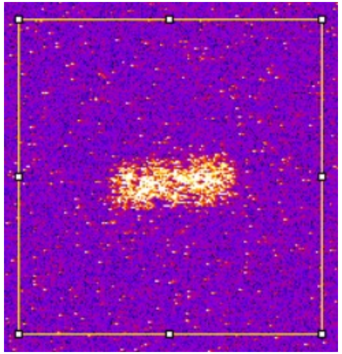


R.K. Li et al., arXiv:1805.01979 (2018)

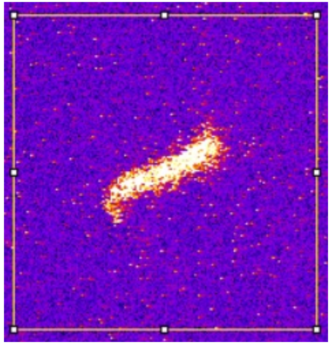
THz Compression Experiment in Progress – *Very Preliminary Results*

- Observing 3X compression and timing jitter reduction
- Stable performance demonstrated
    - **Bunch length ~ 19 ± 5 fs RMS**
    - **Jitter ~ 12 fs**

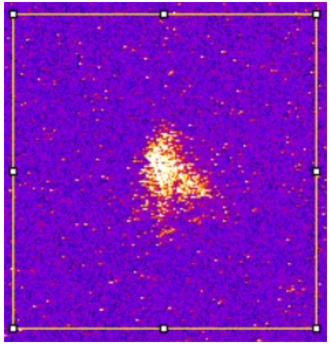
Compressor off

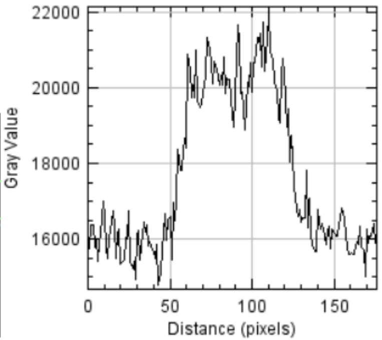


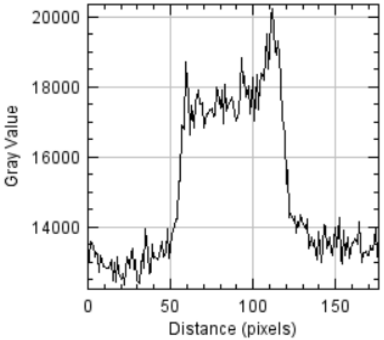
Elongated

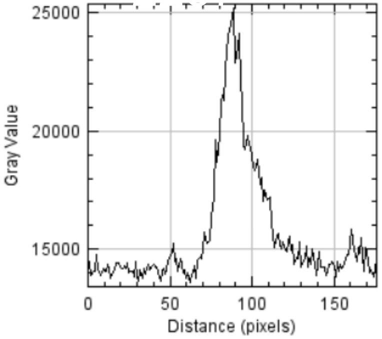


Compressed

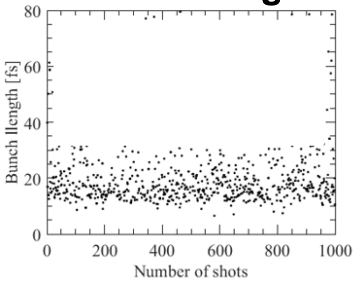




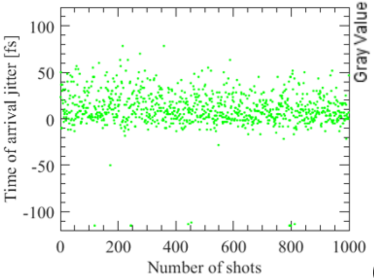




Bunch Length



Time of Arrival

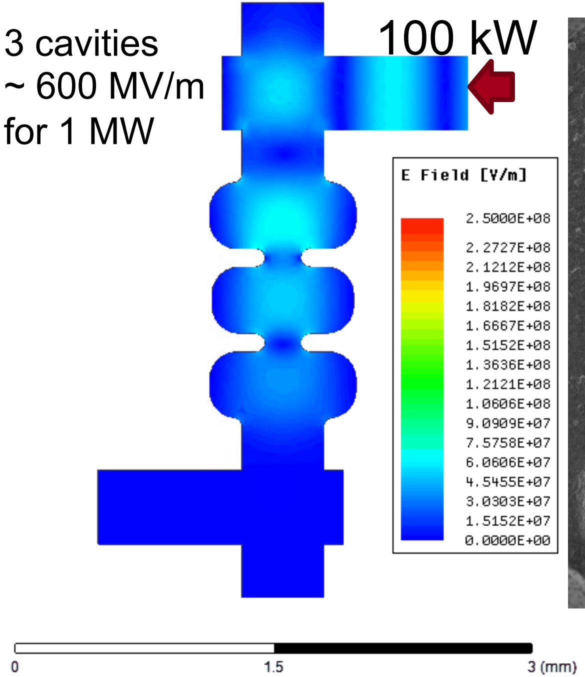


Othman, Snively, Li, Hoffmann, SLAC UED Team

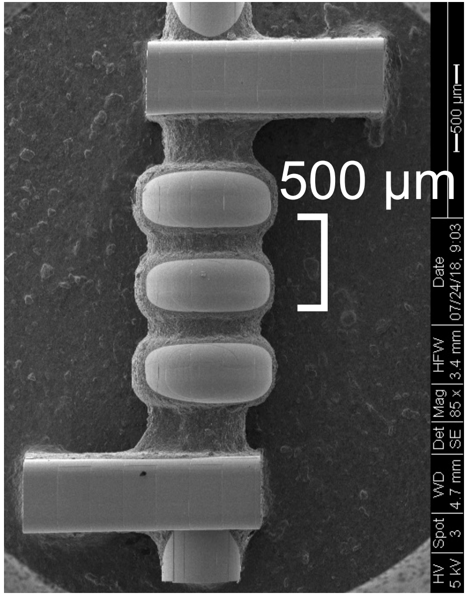
Bridging the Gap Between Single-Cycle and Quasi-CW Excitation for Optimized High-Field Performance

- Laser-driven THz sources can produce high power pulses on 100s ps timescale
- Pursuing pulse-compression of electron-beam sources for very efficient nanosecond pulses
  - 3 cavities
  - ~ 600 MV/m for 1 MW
- Nanosecond time scale preserves high-shunt impedance of structures

Single-cell 300 GHz structure



3D printed prototype



Conclusions

- Accelerators are powerful tools for scientific discovery
- A great variety of parameters are achievable – species, power, wavelength, repetition rate
- Technology is evolving rapidly to enable new capabilities
- Opportunity to work closely with detector community in developing new / improved systems
- Questions?