R&D Test Facilities are Here to Enable the Future

FAST/IOTA Collaboration Meeting

V. Yakimenko

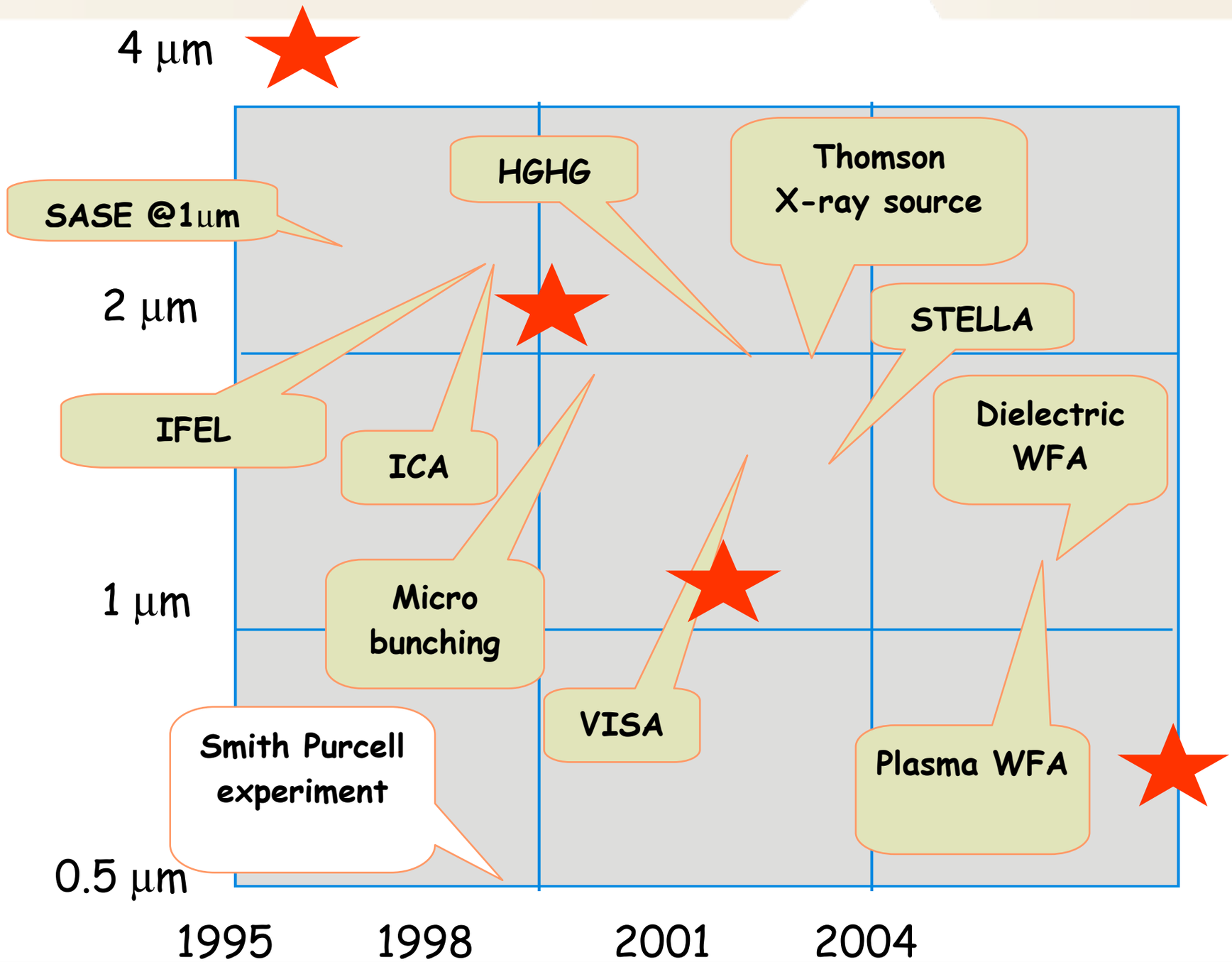
June 17, 2020

Checklist for a Successful R&D Test Facility:

- 1-2 long term R&D initiatives with high impact when successful
- The user program enabled by and demonstrating continuing progress on the above R&D initiative
- Connection to the mission of the host laboratory
- Plan for introduction of new capabilities on a regular basis
- Sustained education and training program
- Solution to manage safety and productivity of users and students
- Facility leaders that believe in mutualism

Directed Research and Diverse Programs at Beam Test Facility:
SLAC, UCLA, BNL collaboration to test 1.6 cell FEL photo injector at ATF

SLAC

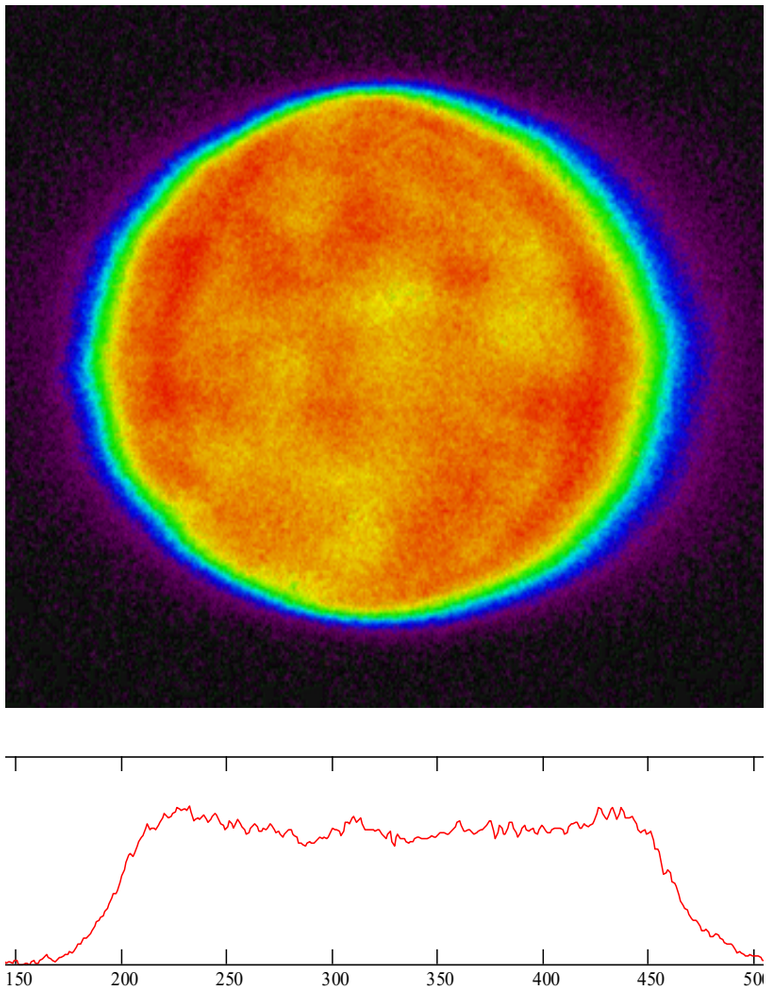


Directed program will benefit from co-existence with parallel broad user program when managed correctly

Virtual Cathode Camera (VCC) - Laser Transverse Uniformity

SLAC

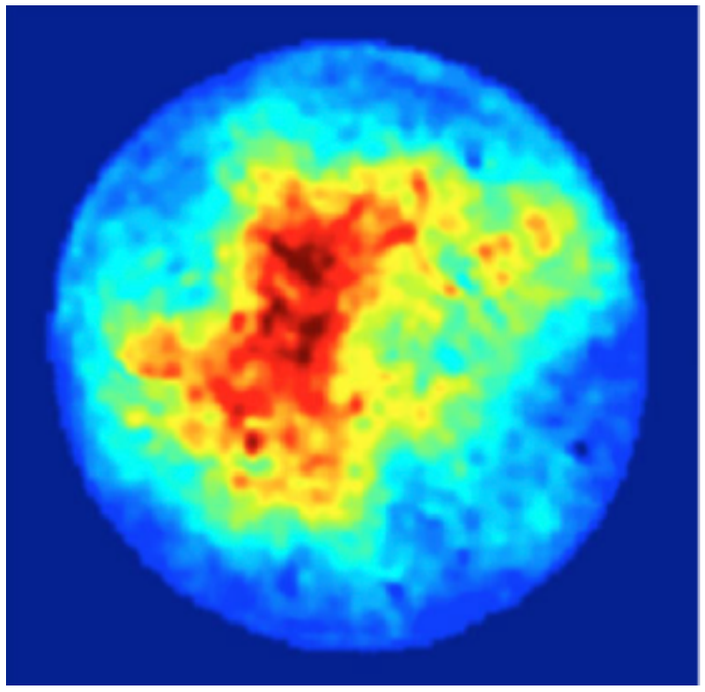
ATF 2001

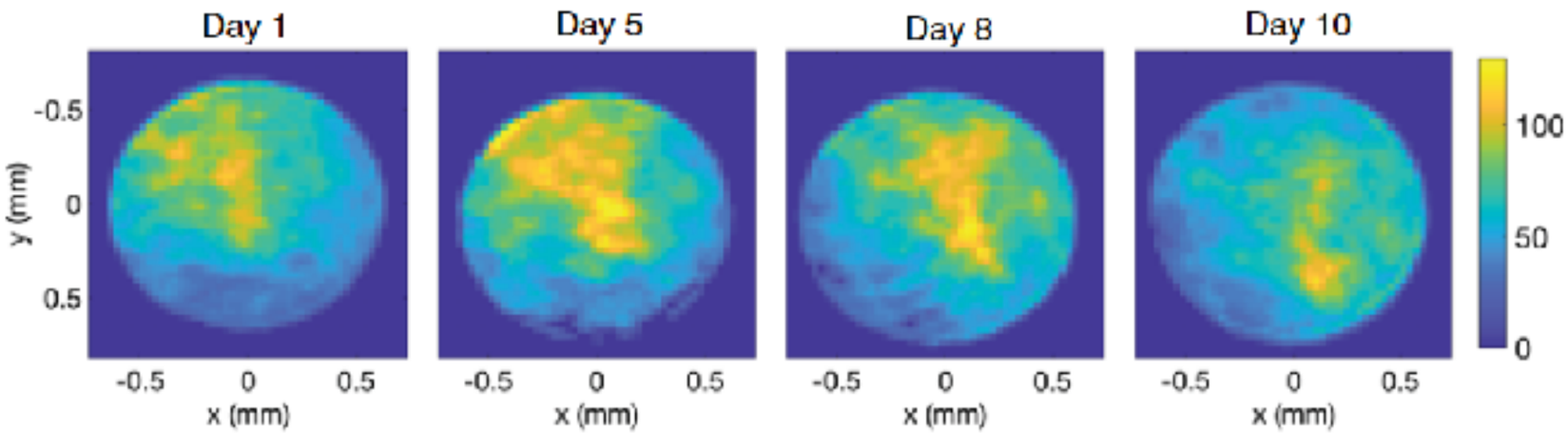


Difficult task to balance:

- what is possible
- what is required/useful
- effort required to realize
- to maintain

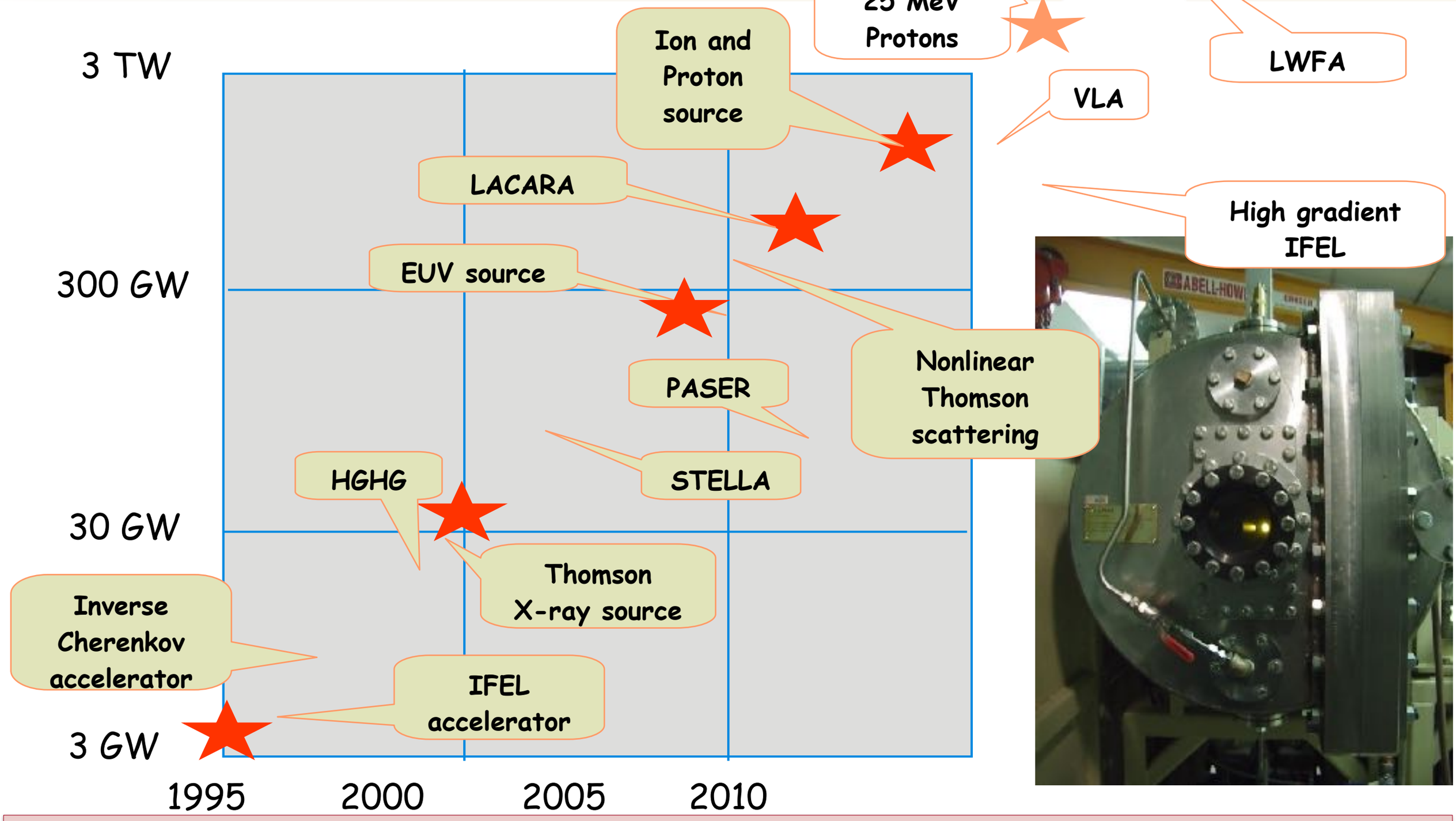
LCLS 2020





Stability and quality are critical and require discipline and not settling for less than great

ATF Terawatt CO2 Laser Story



Demands from users stimulated laser development

Inverse Free Electron Laser - Humble and Hungry

Proposed by R. Palmer

- J. Appl. Phys. 43, 3014-23 (1972).

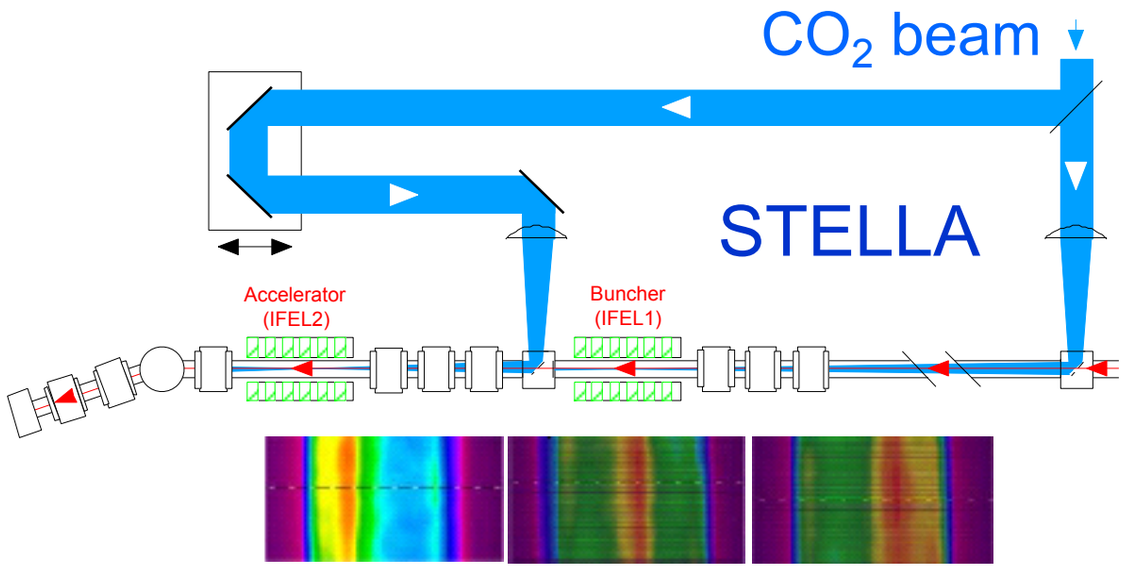
Tested at ATF as accelerator.

- PRL 77, 2690 (1996)

Used as key element in ATF experiments:

- Microbunching: PRL 80, 4418 (1998)
- STELLA, PRL 86, 4041 (2001)
- HGHG, ***Science***, 289 (2000), PRL 86, 5902 (2001)
- STELLA II, PRL 92, 54801 (2004)
- PASER, PRL 97, 134801 (2006) IFEL, ***Nat. Comm.*** 5, 4928 (2014)

First Staging of Two Laser Accelerators



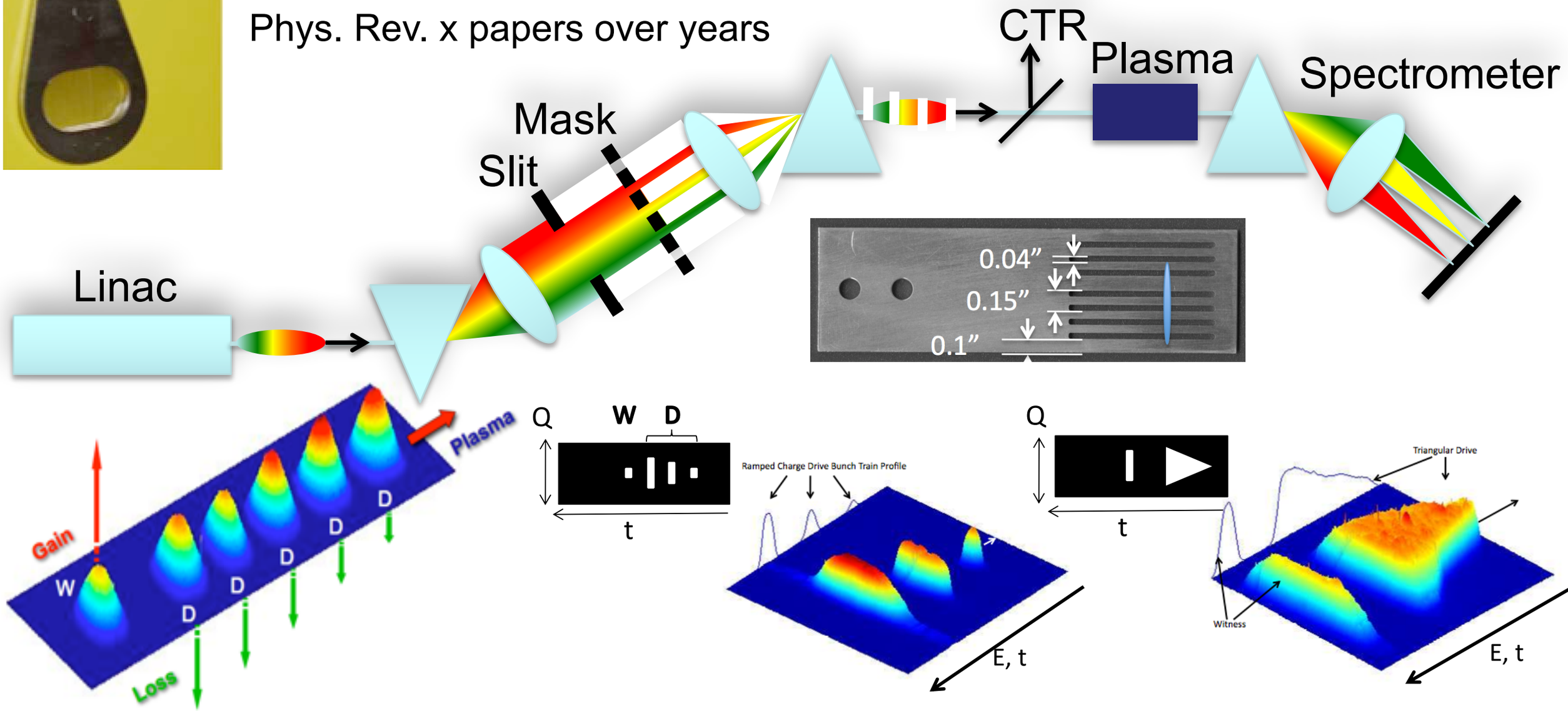
IFEL is key element to:

- Preserve emittance during compression at LCLS
- High Gain Harmonic Generation
- Optical stochastic cooling
- Short X ray beams at ALS

IFEL is a typical example of continued surprises of applicability of Advanced Accelerator R&D

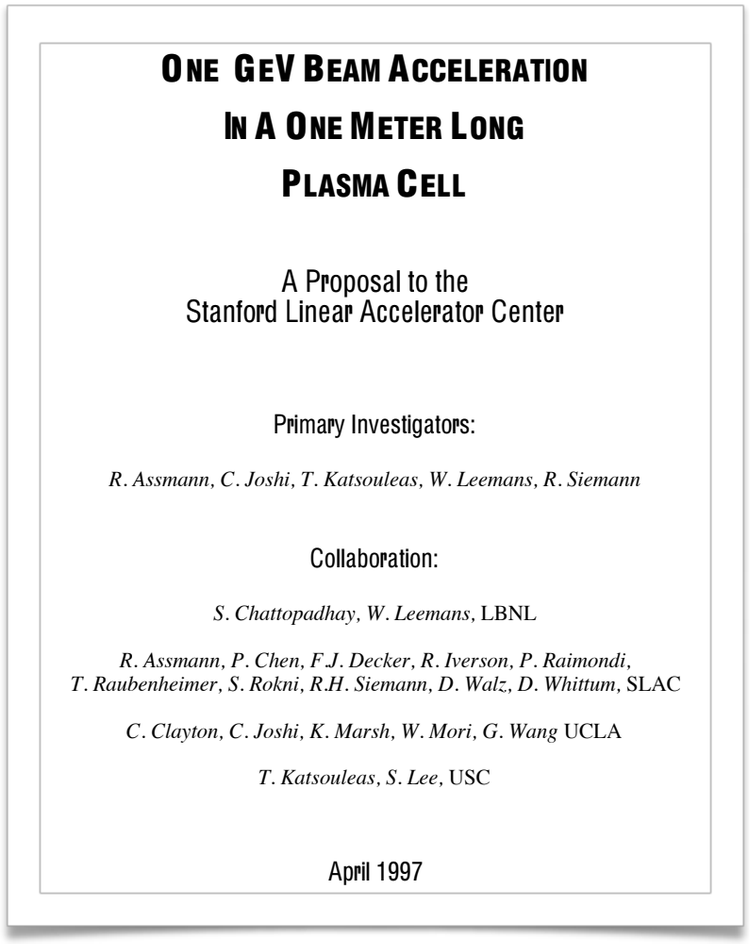
Introduction of New Capabilities on a Regular Basis is Critical for Reinvigoration of Science Program

It took ~1 week to successfully implement beam slicing technique at ATF: user request, manufacturing, installation, measurements. It became a major part of the science program (Plasma and Dielectric Wakefield accelerations) with ~12 Phys. Rev. x papers over years



New capabilities are critical to long term relevance

Directed Research and Diverse User Programs: PWFA at FFTB, FACET, FACET-II



ONE GEV BEAM ACCELERATION IN A ONE METER LONG PLASMA CELL

A Proposal to the
Stanford Linear Accelerator Center

Primary Investigators:

R. Assmann, C. Joshi, T. Katsouleas, W. Leemans, R. Siemann

Collaboration:

S. Chattopadhay, W. Leemans, LBNL

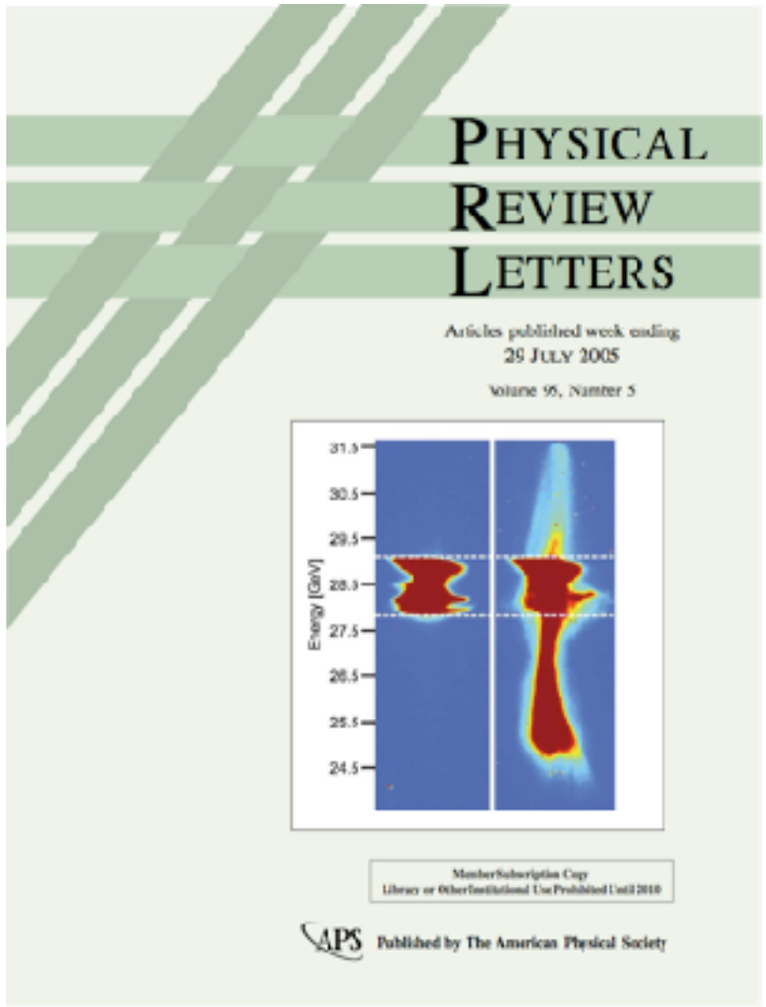
R. Assmann, P. Chen, F.J. Decker, R. Iverson, P. Raimondi, T. Raubenheimer, S. Rokni, R.H. Siemann, D. Walz, D. Whittum, SLAC

C. Clayton, C. Joshi, K. Marsh, W. Mori, G. Wang UCLA

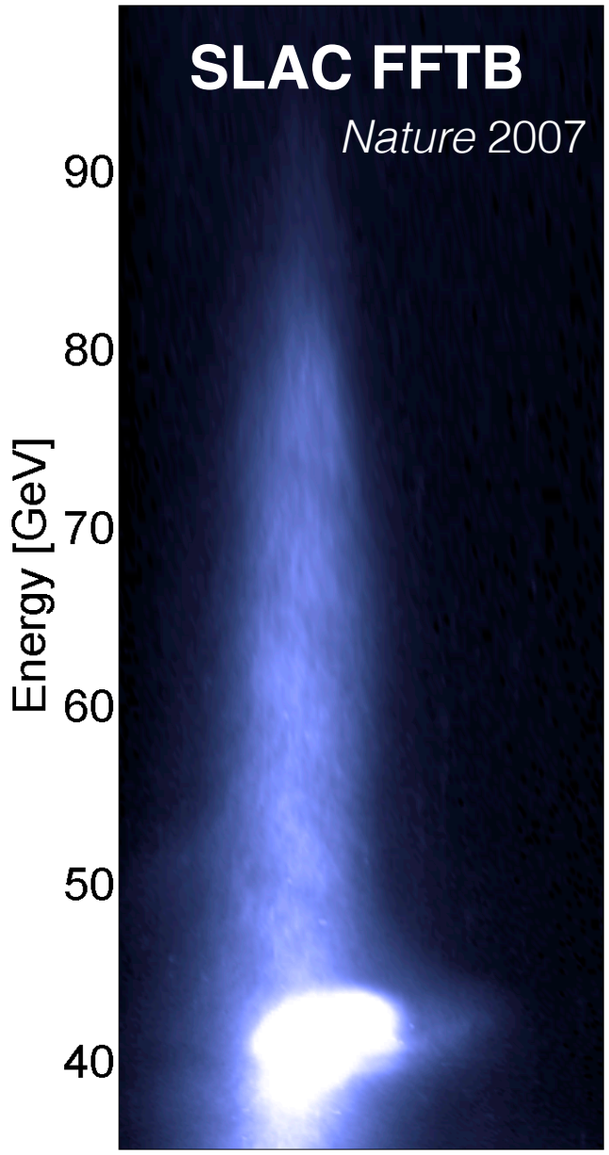
T. Katsouleas, S. Lee, USC

April 1997

1997:
Proposal for 1 GeV PWFA



2004:
Clear energy gain



43 GeV
Energy Gain

It is important for facility to have backbone science program

Directed Research and Diverse User Programs: PWFA at FFTB, FACET, FACET-II

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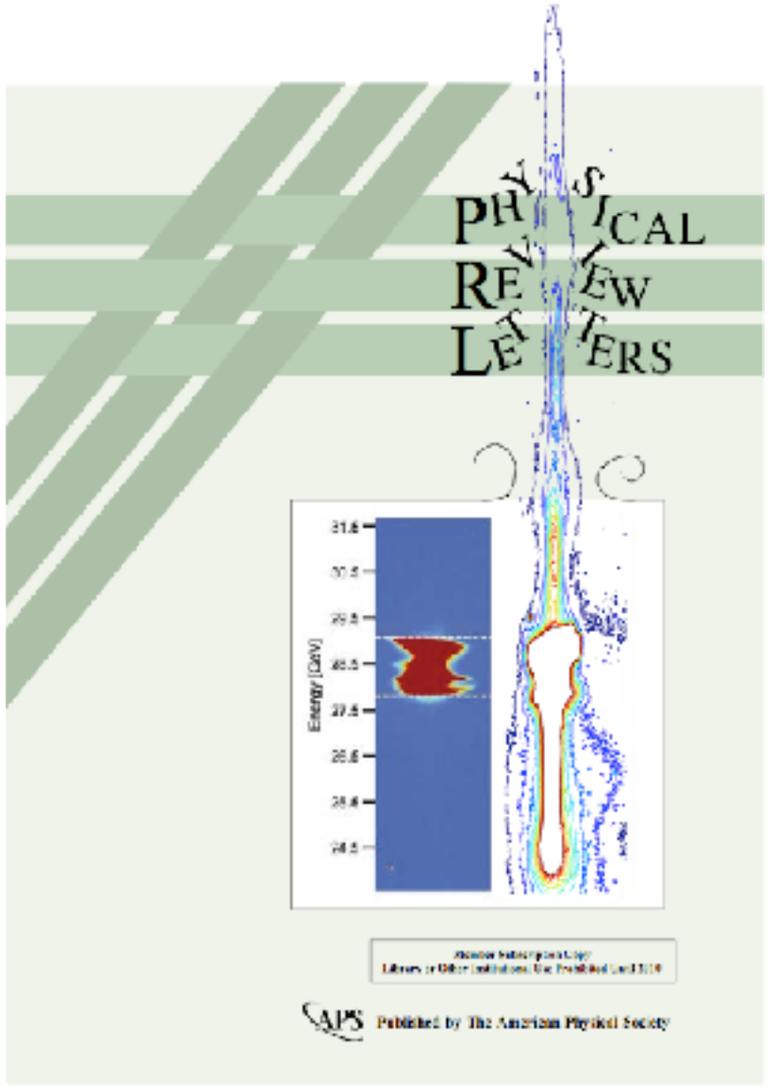
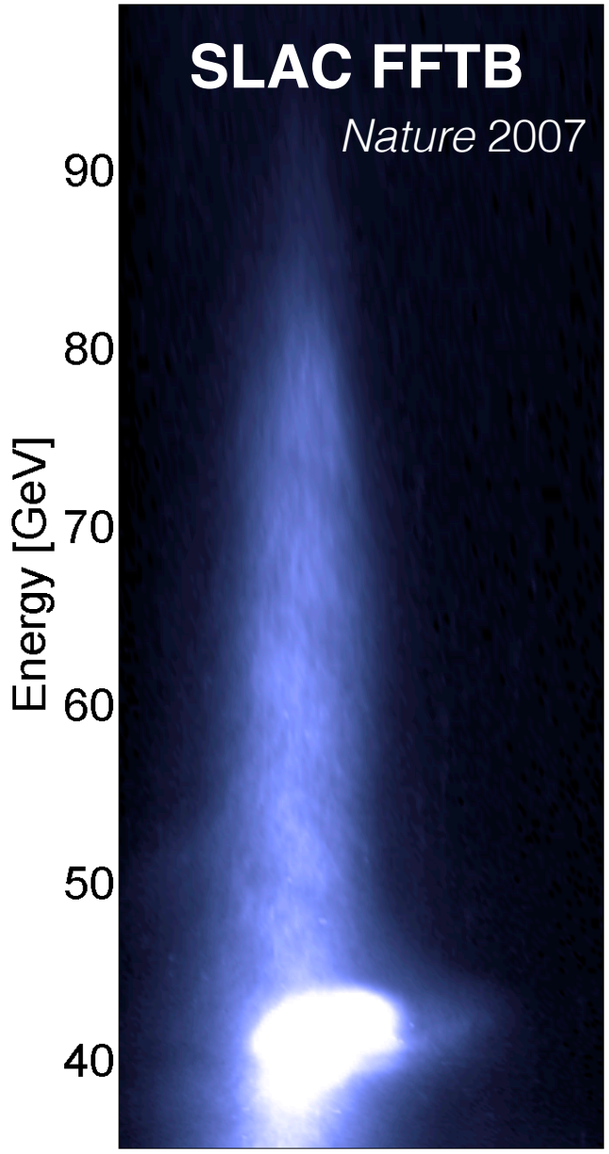


2005:
Energy Gain > 10GeV!



43 GeV
Energy Gain

It is important for facility to have EXCITING backbone science program

FACET: A National User Facility Based on High-Energy Beams and their Interaction with Plasmas and Lasers

Timeline:

- Construction, Commissioning (2008-2011)
- Experimental program (2012-2016)

A National User Facility:

- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

✓Mono-energetic e- acceleration

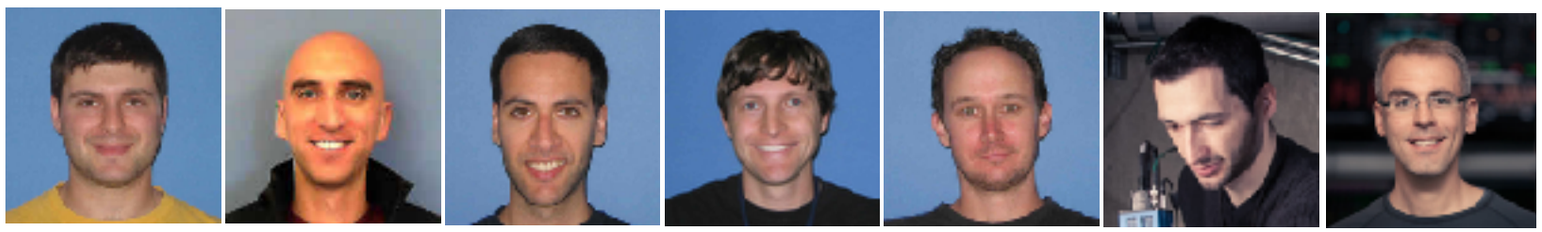
✓High efficiency e⁻ acceleration (***Nature* 515**, Nov. 2014)

✓First high-gradient e⁺ PWFA (***Nature* 524**, Aug. 2015)

✓Demonstrate required emittance, energy spread (***Nature Physics***, Aug. 2019)

Program Developed Next Generation Leaders

Including 4 faculty appointments at the end of FACET



"…is not how many followers you have, but how many leaders you create."
Mahatma Gandhi

E210 international team: >20 Professors, Post-docs, PhD-Students from 6 universities in 4 countries (UCLA, Strathclyde, Hamburg, Austin, Oslo, Boulder) + industry (RadiaBeam + Tech-X + Radiasoft) + SLAC FACET & linac team

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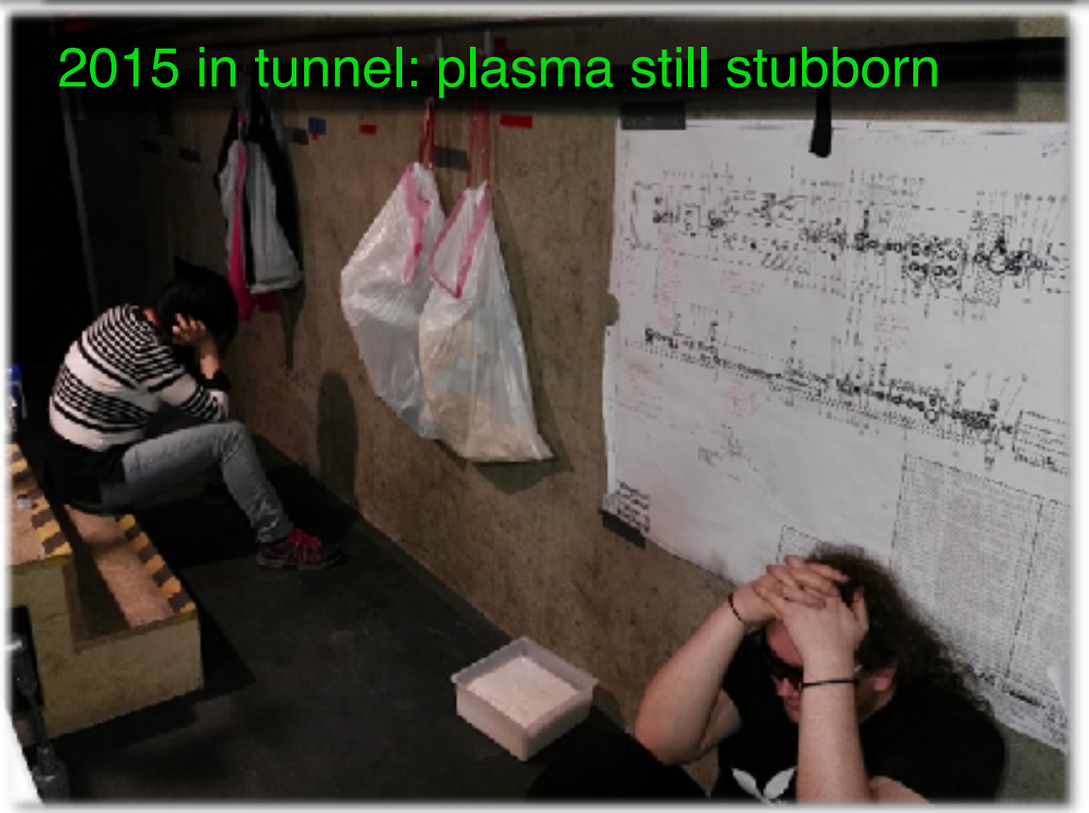
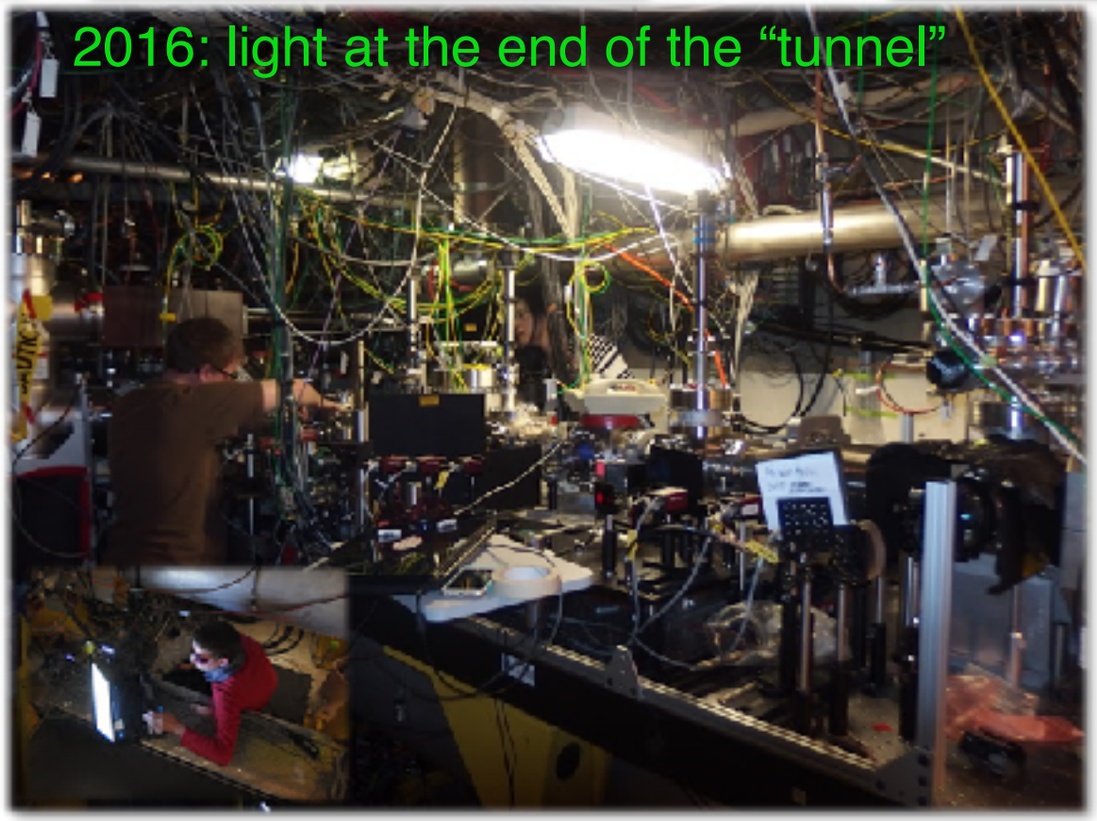
2013 at SAREC – cautiously optimistic


2015 in tunnel: plasma still stubborn


2016: light at the end of the “tunnel”


Success..


..at last!

FY15 FACET Run – 15 Experiments

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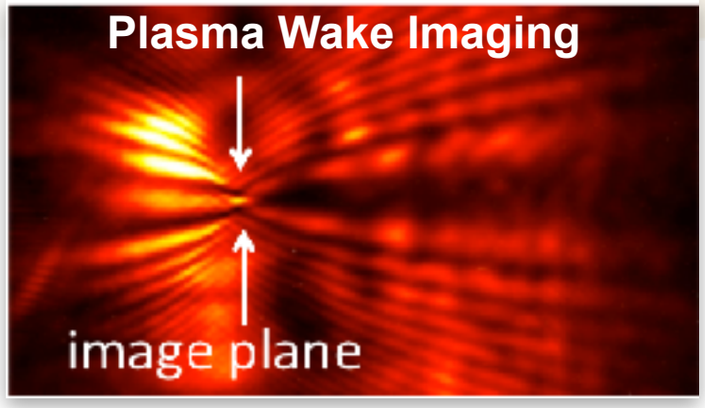
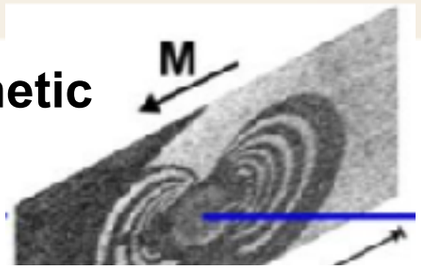
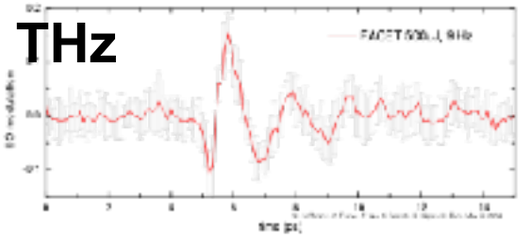
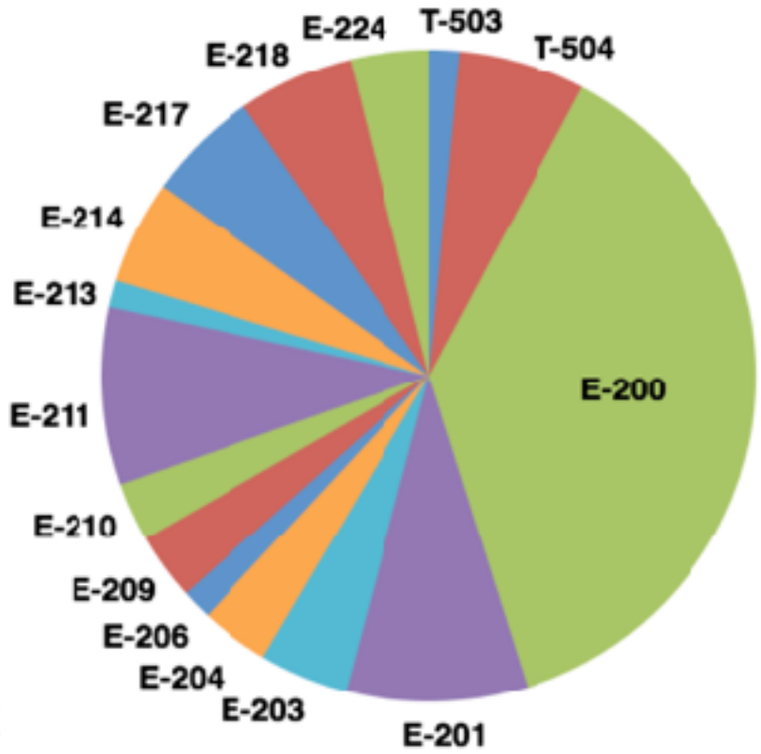
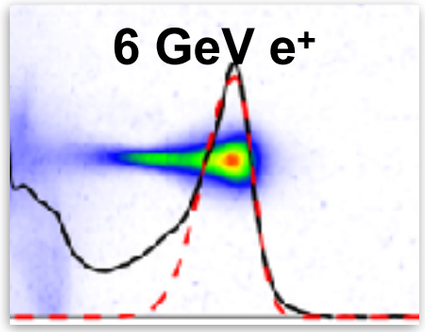


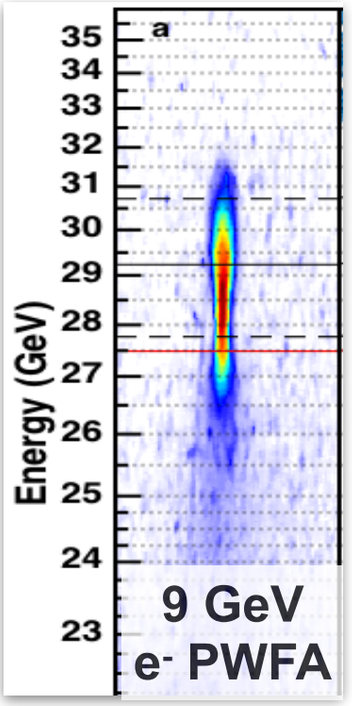
Ultrafast Magnetic Switching

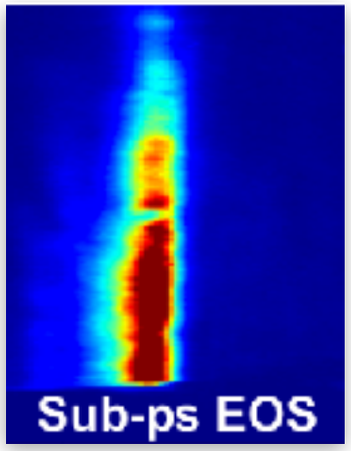




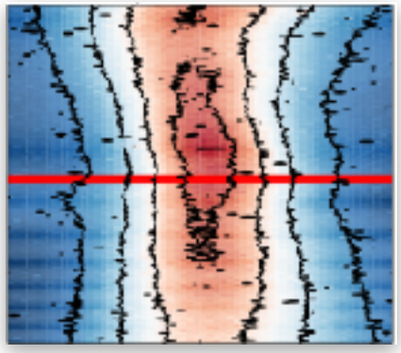


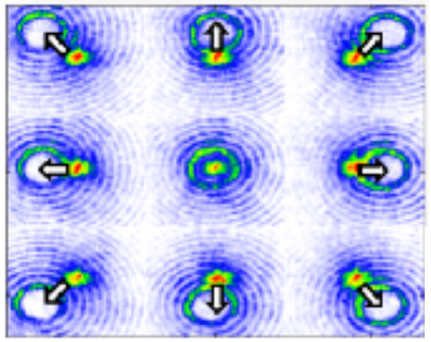






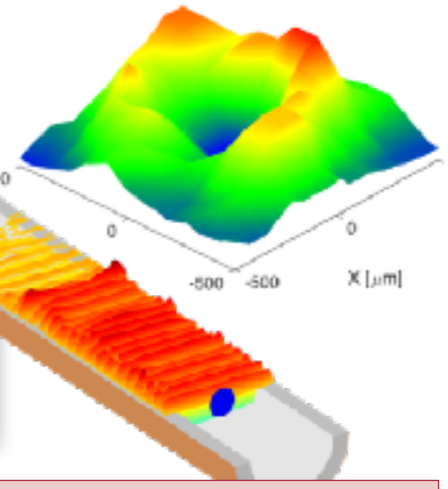
Ionization Injection

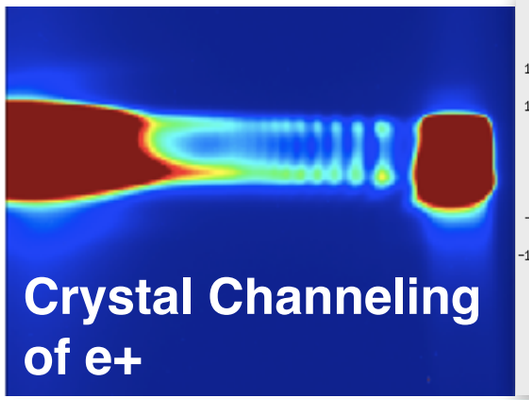


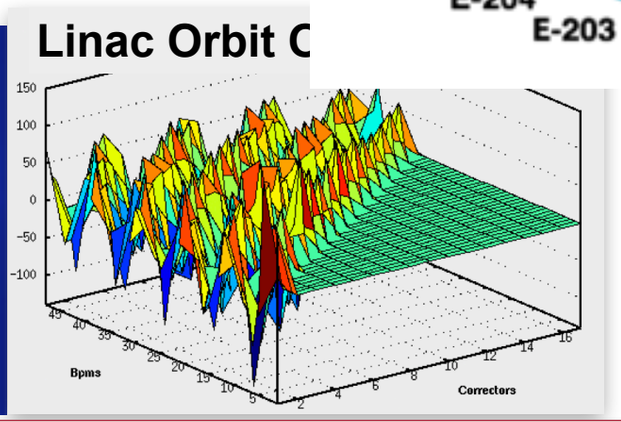


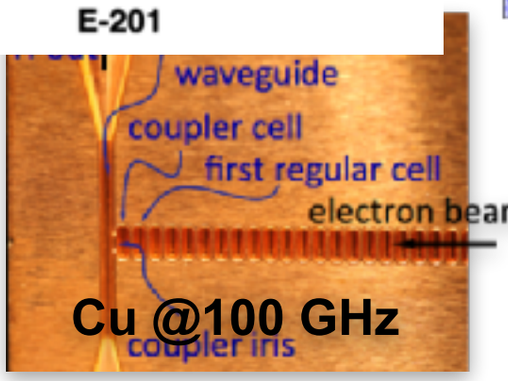
Dielectric WFA

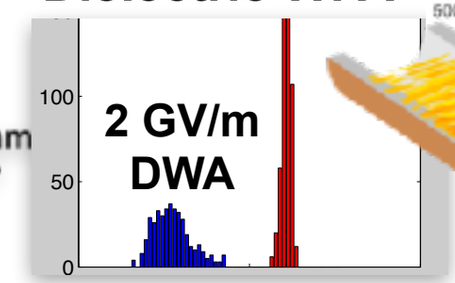
Hollow Channel Plasmas











Diverse science program offers students opportunities to collaborate, learn new exciting subjects, exposure and chance to shine

IOTA / FAST: Excellent Schedule for New Capabilities

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IOTA: novel, unique, exciting, relevant R&D program

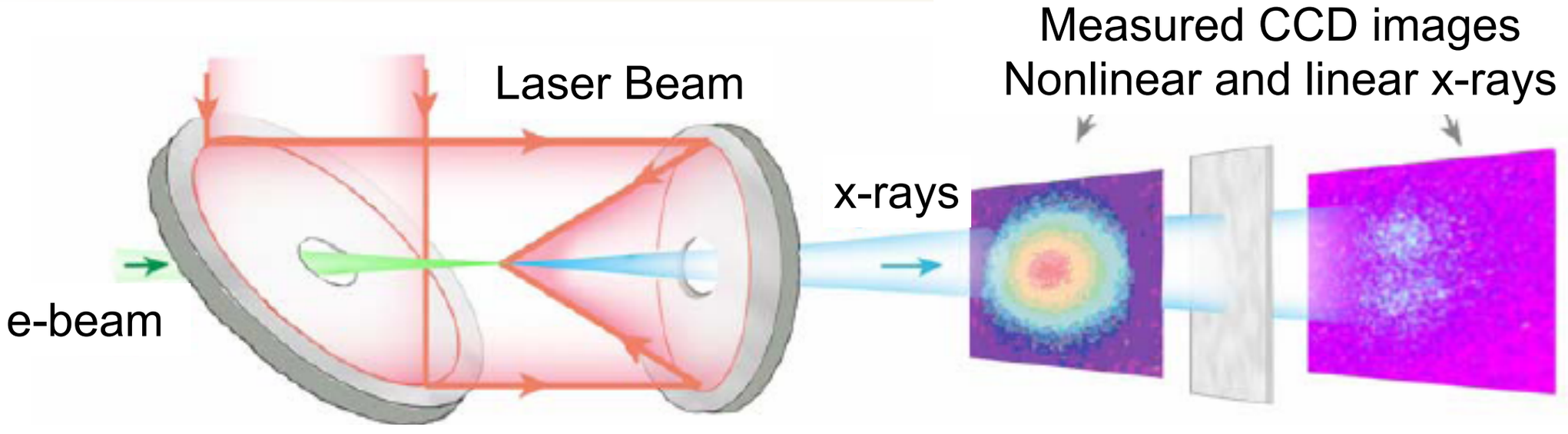
- Nonlinear Integrable Optics
- Optical Stochastic Cooling
- Space-charge Compensation
- Single electron QED
- Hands on education on ring physics

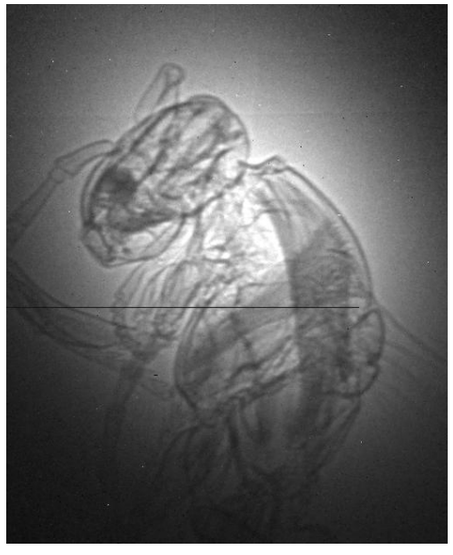
FAST: high power beam (ILC train beam format)

- Beam test (beam quality and stability)
- Compton source (via laser enhancement cavity)
  - ILC beam format offers potentially exciting opportunity for movies with MeV gamma rays and nanoseconds frame rate
    - Many exciting R&D opportunities: detector, Laser, etc.

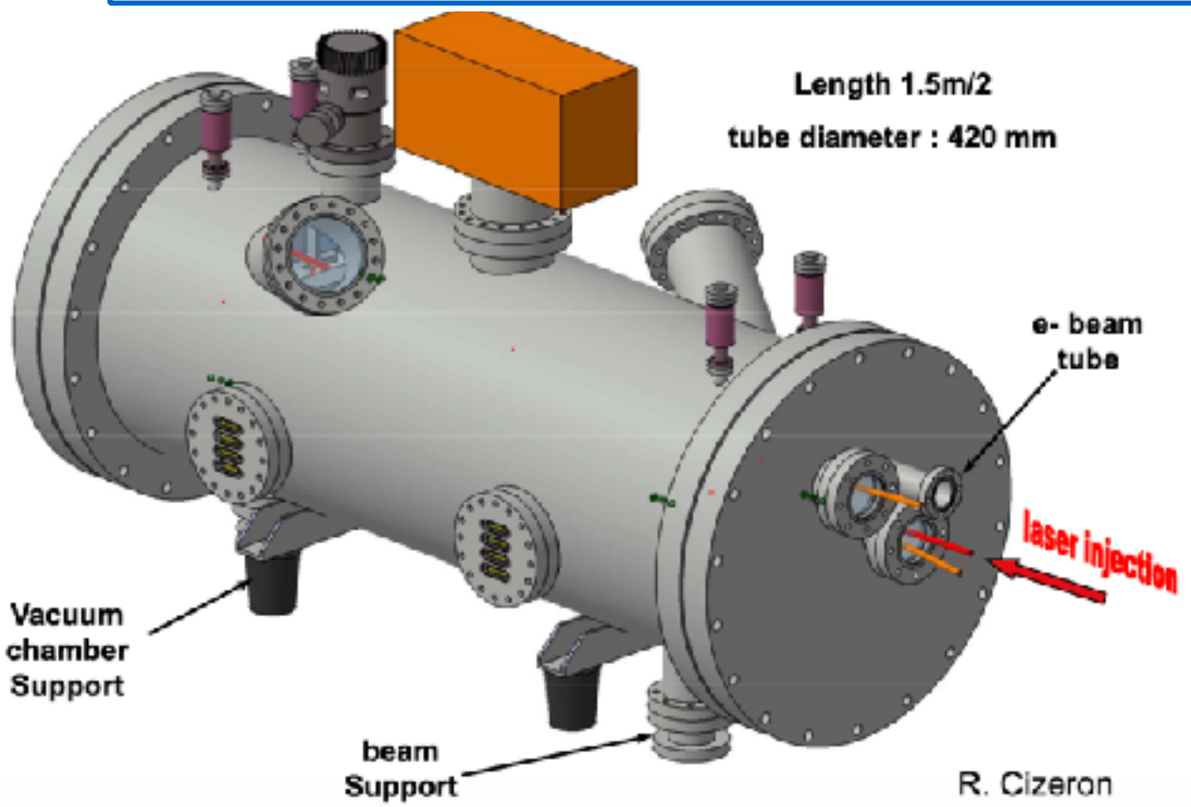
Important to define backbone for FAST - broad user proposals will follow

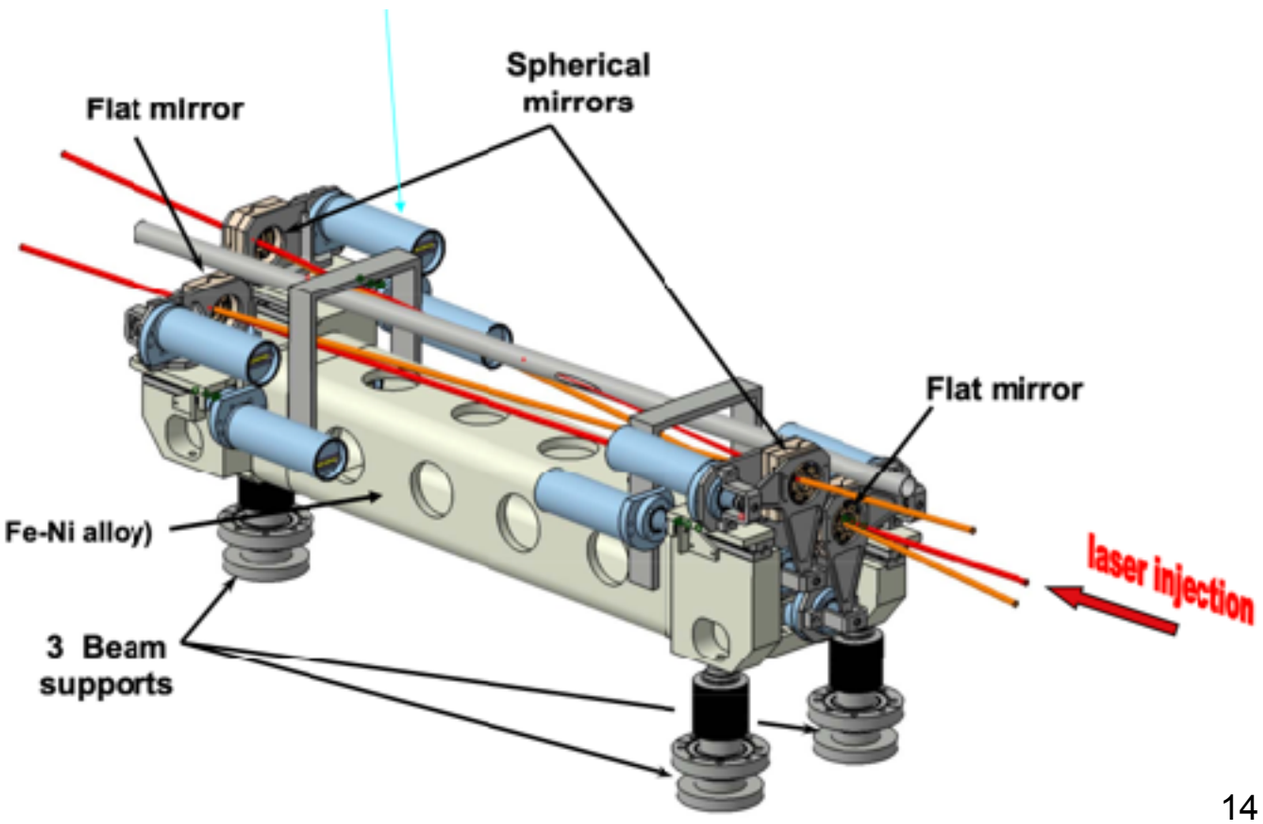
Compton Based Source at BNL/ATF and KEK/ATF





Very High Enhancement ~ 20000 - 100000 Small spot size ~ 10 micron
Sophisticated cavity structure with 4 mirrors (Complementary R/D in LAL and KEK)





R&D Test Facility VS. Lab Construction Project

Different mentality:

- Time to study problem VS. concentrating on a solution
- Longer timeline VS. well defined project schedule
- Role of scientists are different (research vs support)
- Staff retention (accepting training role)

It is difficult, often impossible to predict beneficiary of the research, yet HEP is paying for it

Students:

- excellent opportunities to train students
- will make mistakes, facility will be scrutinized more when students are involved
- trained students likely work outside of HEP

Strategy to preserve facility during difficult budget times is important

Long-term perspective and planning is critical

It's hard to make progress when the data just keep confirming the theories we have, rather than pointing toward new ones

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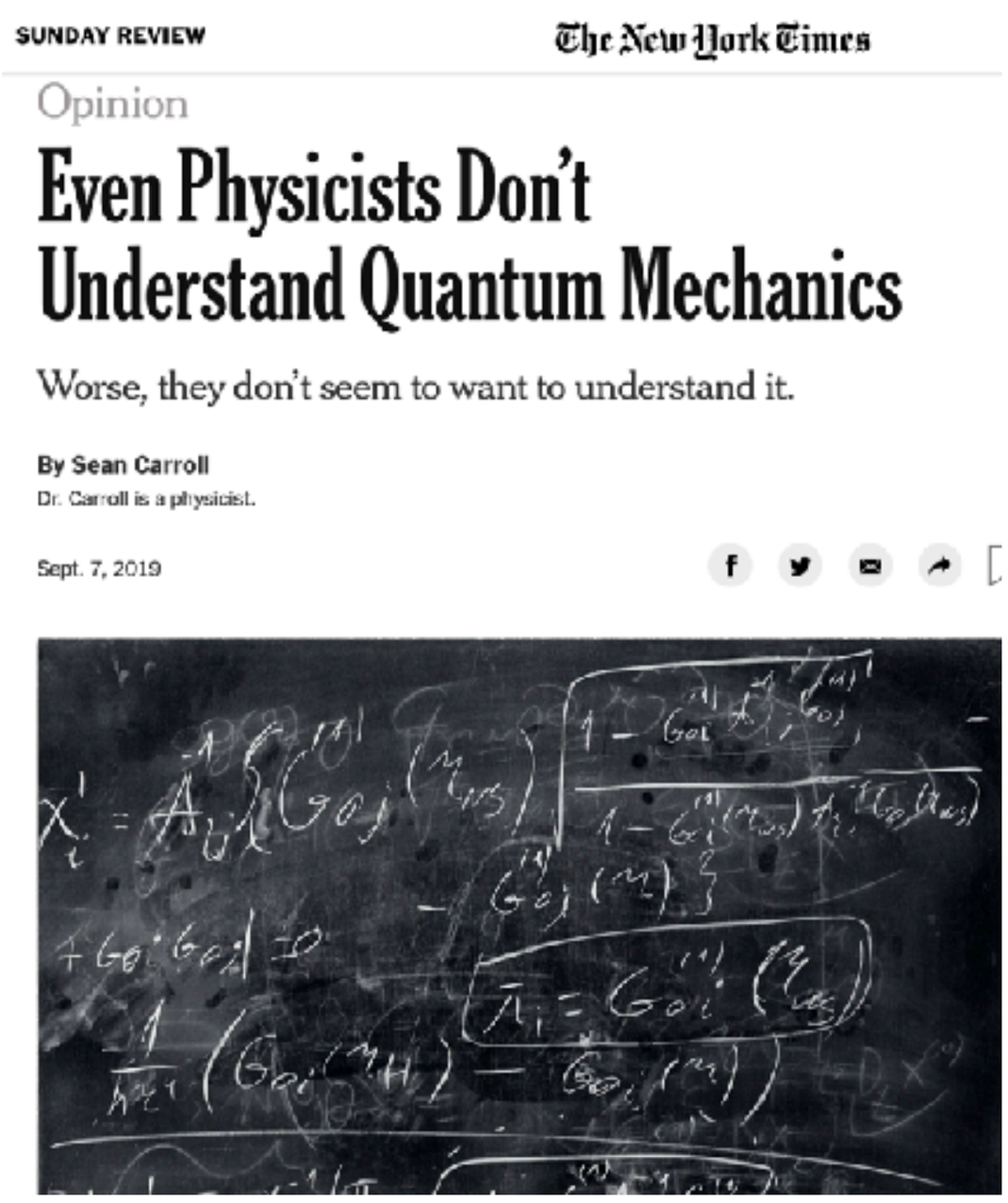


SUNDAY REVIEW

The New York Times

Opinion

Even Physicists Don't Understand Quantum Mechanics

Worse, they don't seem to want to understand it.

By Sean Carroll

Dr. Carroll is a physicist.

Sept. 7, 2019

"Our best attempts to understand fundamental physics have reached something of an impasse, stymied by a paucity of surprising new experimental results. "

"Scientists can *use* quantum mechanics with perfect confidence. But it's a black box."

"…quantum mechanics, … , seems to require separate rules for how quantum objects behave when we're not looking at them, and how they behave when they are being observed…"

"…what is the wave function? Is it a complete and comprehensive representation of the world? Or does the wave function have no direct connection with reality at all…"

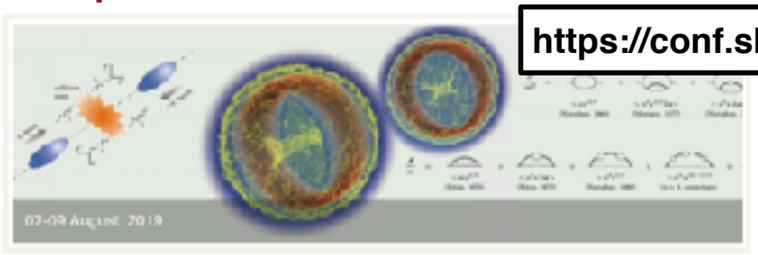
"Until physicists definitively answer these questions, they can't really be said to understand quantum mechanics — thus Feynman's lament."

Who is responsible for developing enabling capabilities for new science?

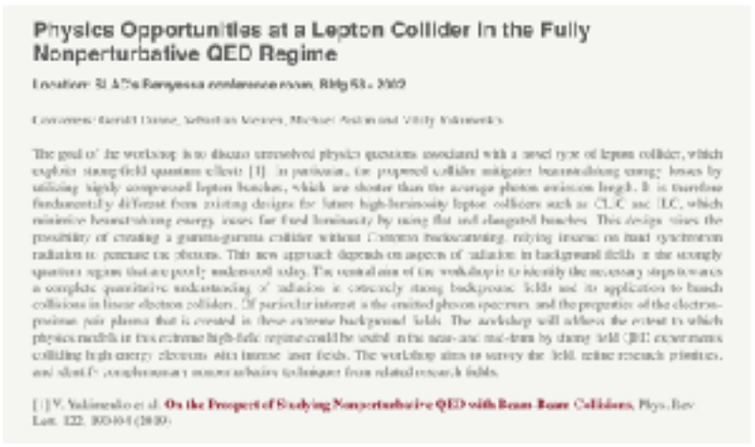
Developing Program Enabled by New Collider Concept with Ultra Short Bunches

SLAC

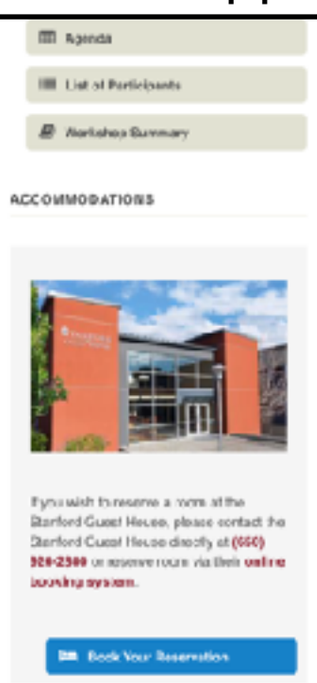
Workshop on Physics Opportunities in a novel regime of colliding lepton beams in the presence of extreme fields

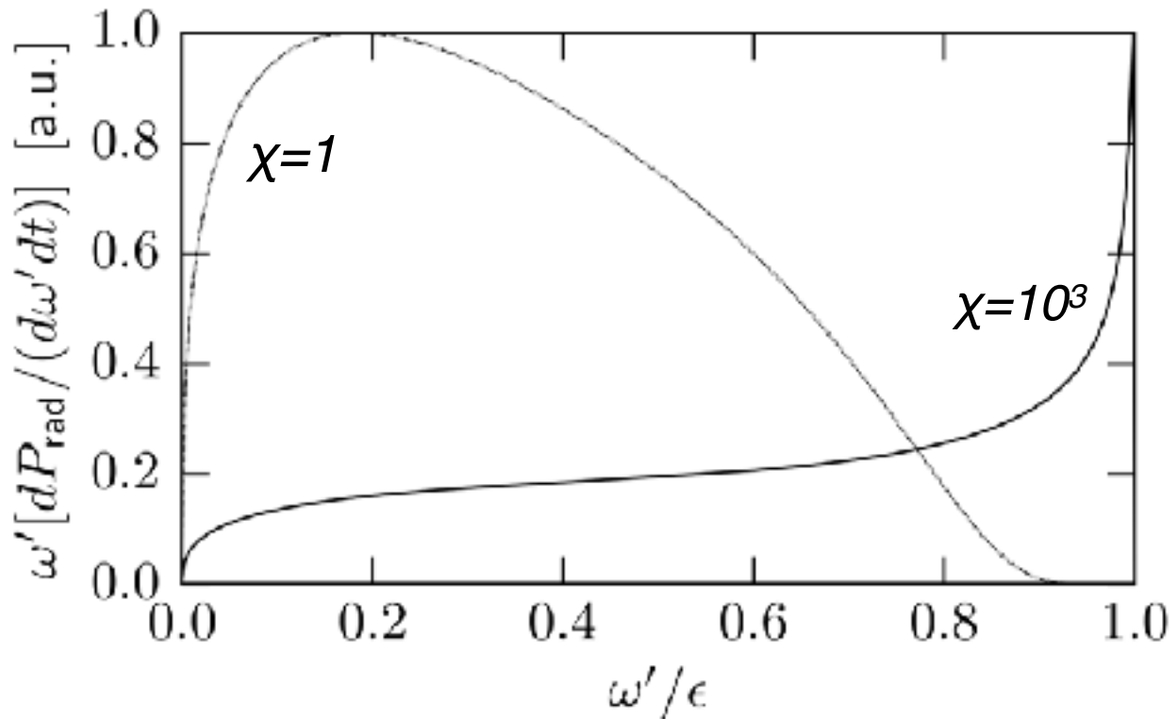


https://conf.slac.stanford.edu/npqed-2019/



Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime





R. Blankenbecler, S. D. Drell., Phys. Rev. Lett. 61, 2324 (1988)
V. Yakimenko, et.al. Phys. Rev. Lett. 122, 190404 (2019)

5 LOIs to Snowmass process:

- Particle Colliders with Ultra-Short Bunches to ***Energy frontier***
- Understanding the Fully Non-Perturbative Strong-Field Regime of QED to ***Theory frontier***
- Probing QED Cascades and Pair Plasmas in Laboratory Experiments to ***Cosmic Frontier***
- Short-Bunch Paradigm Laserless γγ Collider to **Energy *Frontier***
- Beam Physics to Enable Short-Bunch Paradigm to ***Accelerator frontier***

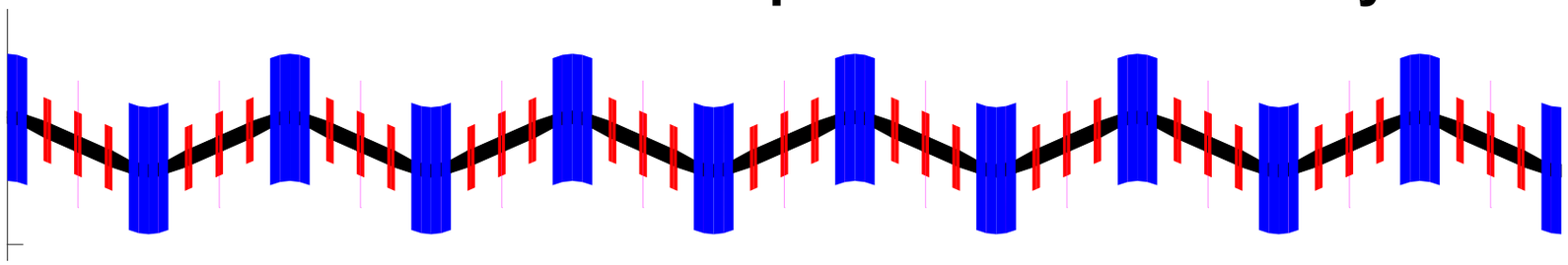
What are we doing differently to expect different outcome?

Simulations by G. White

Developing Case for Demonstration Facility to Study Extreme Compression

SLAC

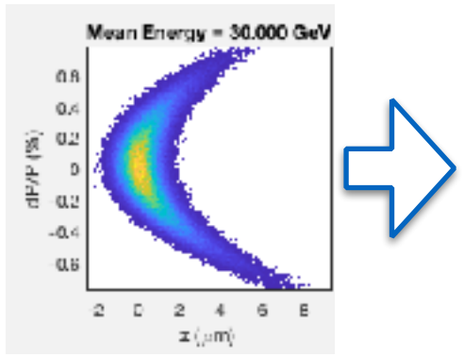
Studies of Final Bunch Compressor and Focus System

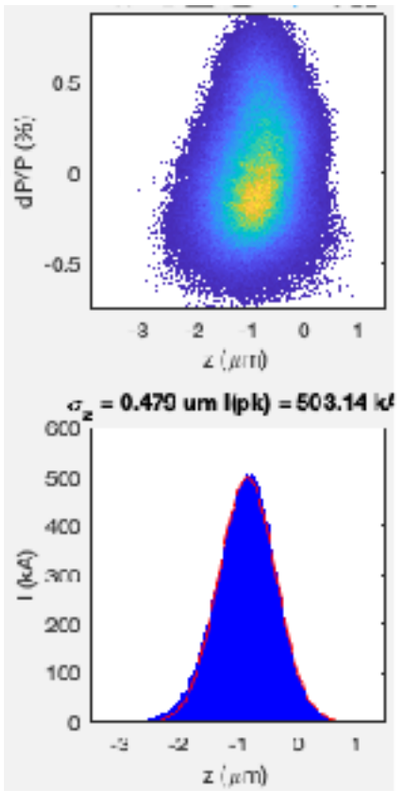


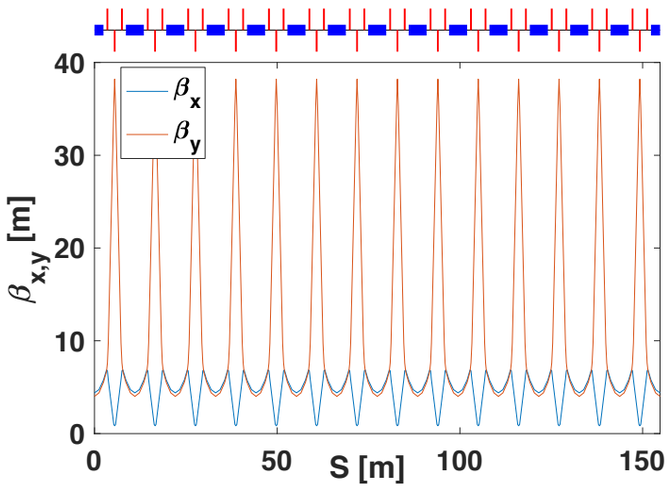
- 14X dogleg cells (150m)
  - 2 sextupoles per cell for CSR kick correction
- ISR emittance growth <10%

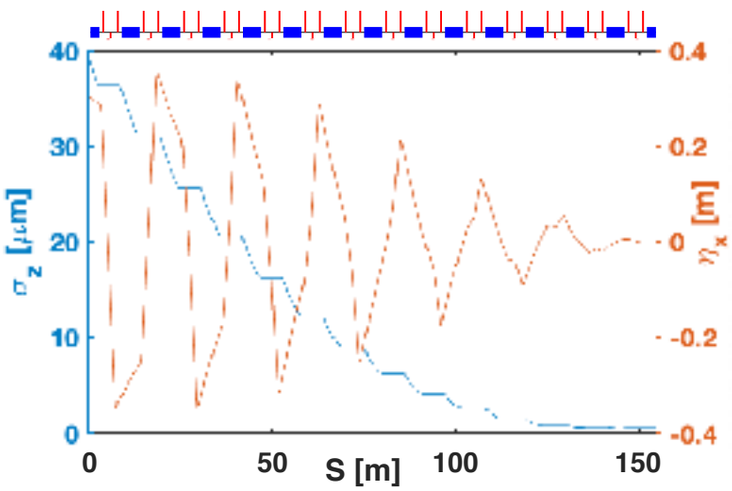
30GeV lattice for high-R56, high energy direct CSR compensation?

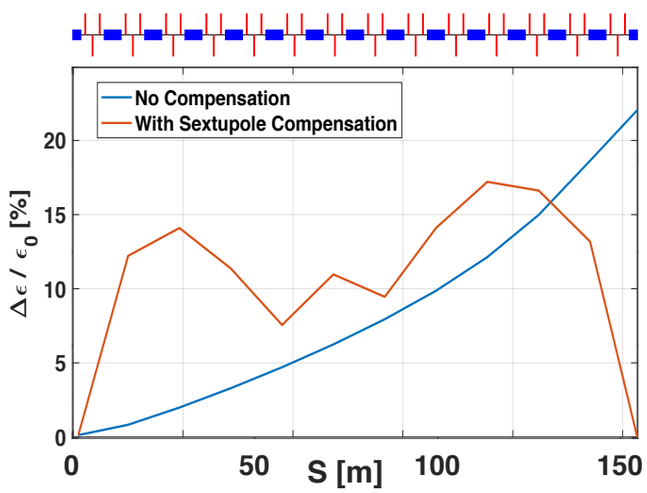
- Approach is to order various effects (chirp modification due to CSR, and due to SC, nonlinearities of the wakes, etc.) are treated iteratively as perturbations
- Utilize ML/AI for general optimization











Next steps: verify CSR cancelation with realistic bunch shapes using established 1D CSR; extend to 3D CSR; 3D CSR benchmarking and experimental validation at FACET-II

Short Bunches to Enable Qualitatively New Physics

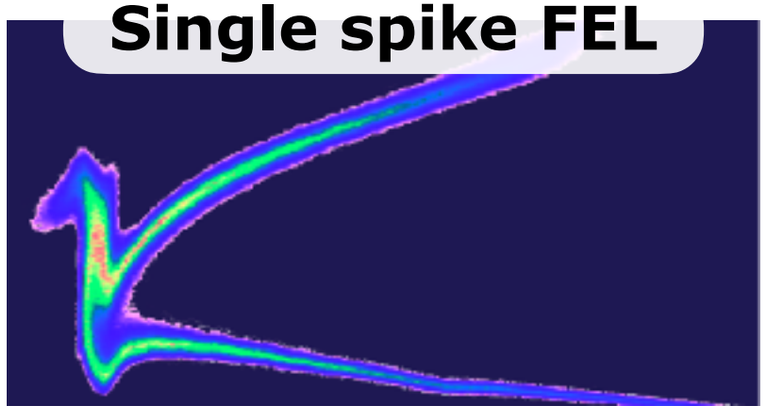
SLAC

HEP collider with low beam power

Short bunches -> beamstrahlung suppressed -> round beams at IP -> ≳100x reduction in beam & wall power / backgrounds / activation / cost $\sigma_z \sim 1\ \mu m @ 1\ TeV$

R. Blankenbecler, S. Drell, PRD 36, 277 (1987)

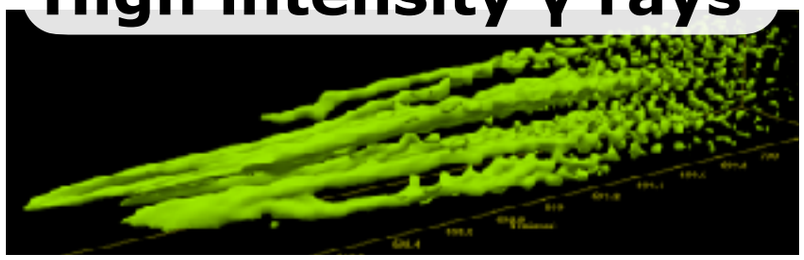
Single spike FEL



X-ray pulse has single spike when radiation emitted by the electrons in beam tail, travels to beam head in time shorter than few gain times $\sigma_z \sim 0.1\ \mu m @ 10\ GeV$

R. Bonifacio et al. PRL 73, 70 (1994)

High intensity γ rays

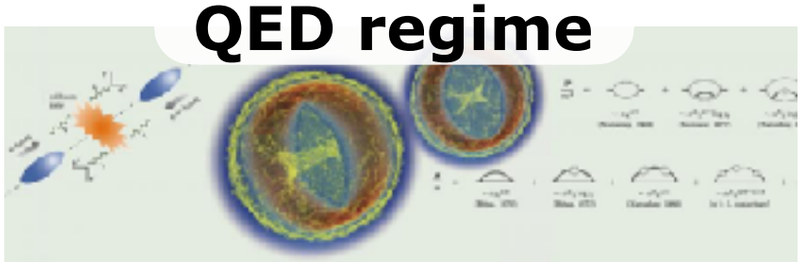


• Counter-streaming beam and plasma electrons result in instability and form self-generated beam filaments and EM fields.

•Trajectories of the beam electrons are bent in these fields and synchrotron radiation is emitted $\sigma_z \sim 0.5\ \mu m @ 10\ GeV$

A. Benedetti et al. Nature Photon. 12, 319 (2018)

Fully non-perturbative QED regime



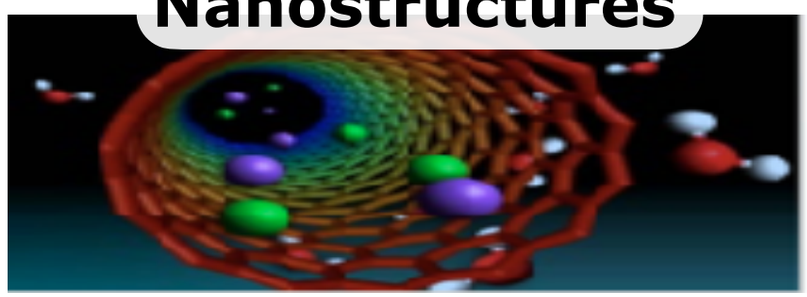
Key challenge: radiative energy loss in field transition (if $\chi \approx 1$) prevents reaching $\chi \gg 1,\ \alpha\chi^{2/3} > 1$

Radiation probability: $W \sim \alpha\chi^{2/3}\dfrac{\sigma_z/\gamma}{\lambda\!\!\!^{-}_c} < 1$

$\sigma_z \sim 0.1\ \mu m @ 100\ GeV$

V. Yakimenko, et.al. PRL 122, 190404 (2019)

TV/m in Crystals and Nanostructures



Acceleration in solid-state plasma of crystals or nanostructures has promise of ultra-high accelerating gradients 1-10 TeV/m, continuous focusing and small emittances

$\sigma_z \sim 0.3\ \mu m @ 10\ GeV$

T. Tajima, et.al. PRL 59,1440 (1987)

Beam Physics Advancement

The research problems associated with generation and acceleration of extremely short and intense beams are fundamental and difficult, requiring sustained in-depth efforts and acceptance of greater uncertainty of the outcome.

Antagonism to Commensalism to Mutualism

Antagonism is an association between organisms in which one benefits at the expense of the other.

Commensalism is a long-term biological interaction in which members of one species gain benefits while those of the other species neither benefit nor are harmed

Mutualism is an interaction between two organisms, where each individual derives a fitness benefit.

Concluding Remarks:

- Science is ultimate meritocracy
- Politics:
  - making your competitors look bad, “saying smart things vs doing it”, etc.
  - https://history.fnal.gov/testimony.html
- Important to listen to critics - Efficiency PWFA paper
- Transparency ensures discipline, correct priorities and long term relevance
- Promoting collaboration is a more difficult yet more productive and sustainable approach

People who say it cannot be done should not interrupt those who are doing it
George Bernard Shaw