New Acceleration Techniques

Tor Raubenheimer

ICHEP 2010

Paris, France

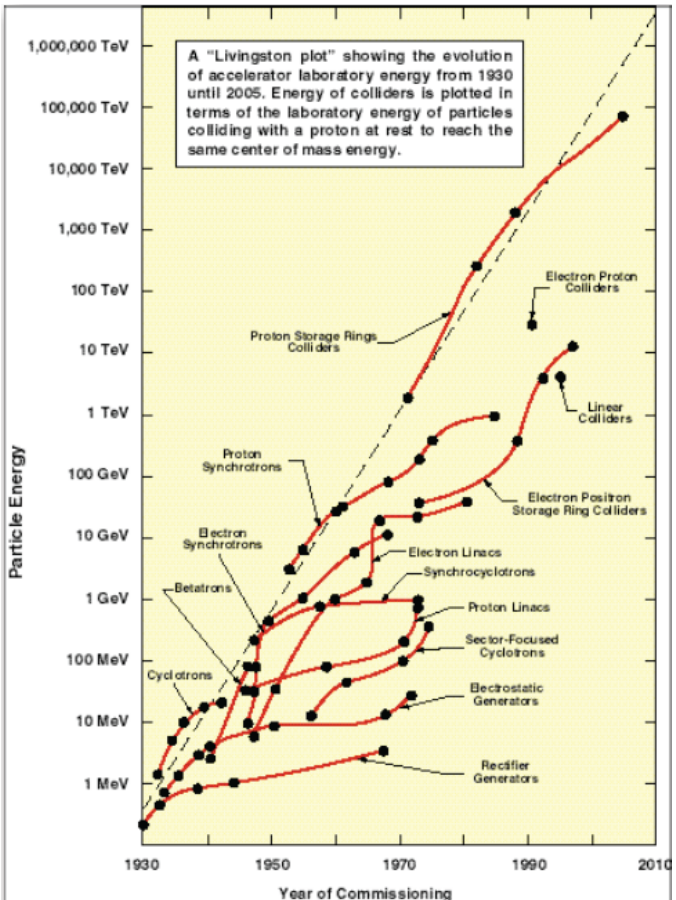
July 28th, 2010

Introduction

- Context
  - Why new accelerator techniques?
  - Challenges in accelerator research?
  - Energy frontier concepts: Lepton Colliders and LEHC
  - Intensity frontier concepts: neutrinos and flavor factories
- Advances in accelerator techniques
  - High beam power
  - High beams brightness
  - High beam energy
- Issues for the future

Why New Acceleration Techniques?

- Accelerator have been primary tool to advance HEP frontiers
  - But accelerators have continued to increase in size and cost and appear to be approaching the limit that can be supported



The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky

2-017

- Need new technologies that are aimed at cost effective solutions

- Accelerator research very broad from materials to rf to nonlinear dynamics
  - Advances come from both fundamental research and directed R&D aimed at applications

SLAC NATIONAL ACCELERATOR LABORATORY

Primary Challenges for Accelerator R&D

1. Beam power → average luminosity or brightness
   – Power (average current times energy) is frequently measured in megawatts and has both technical and physical limitations
2. Beam brightness and control → peak luminosity and radiation source brightness
   – Brightness is flux divided by 6-D phase space volume (emittance) which should be conserved after beam creation
3. Beam energy → energy reach or radiation wavelength
   – Critical problem for HEP requiring new cost-effective concepts
   – Novel concepts will enable new applications elsewhere as well

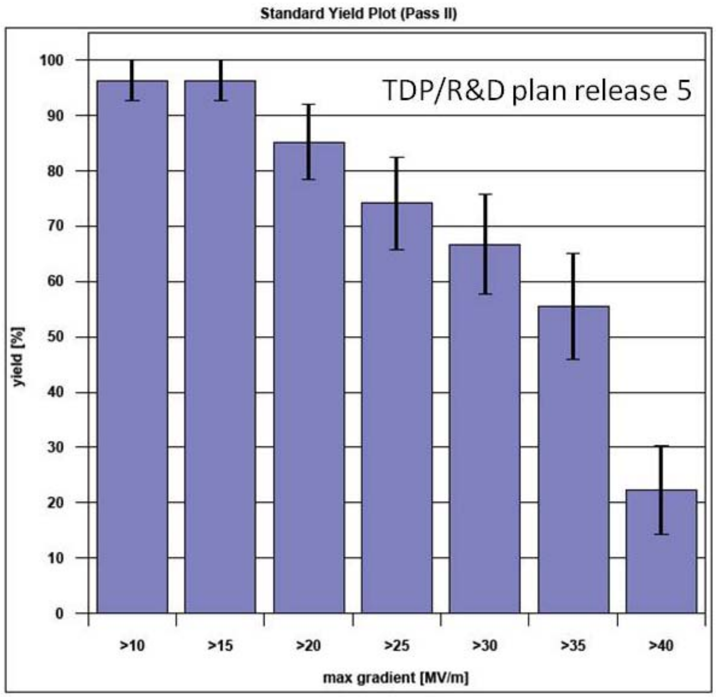
- Cost-effective approaches are needed across the field
- Paths to educate and attract more people to field

1. Beam Power Challenge

- Many critical technologies
  - Targets, collimators and dumps, materials, MPS, SCRF, …

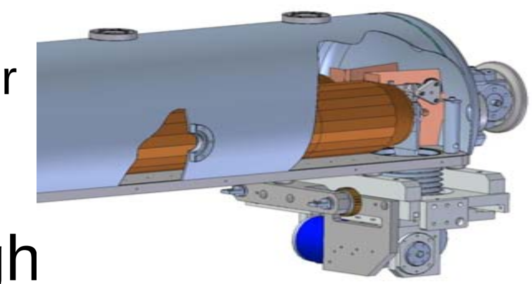
Barry Barish, Saturday session

Yield of ILC 1.3 GHz cavities



- LHC beam will be ~350 MJ
  - Beam collimation challenge!

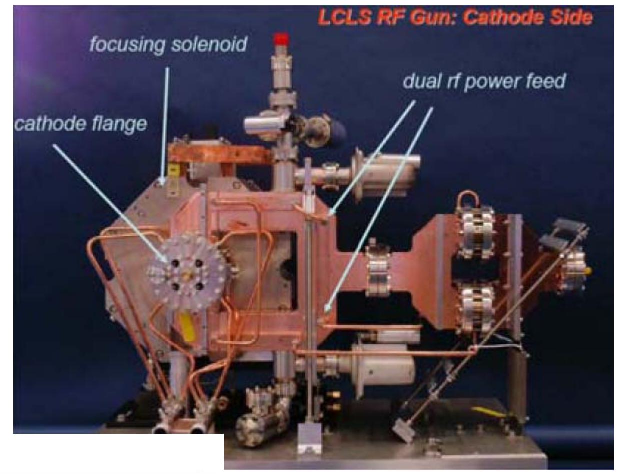
Metallic collimator to reduce $Z_{\perp}$



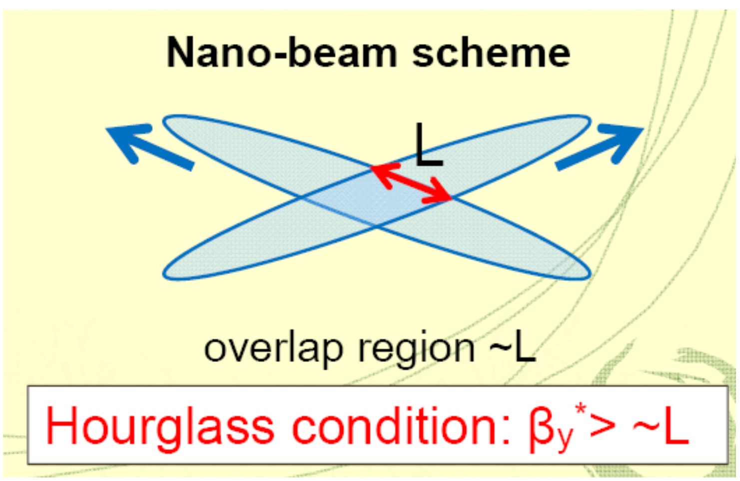
- SCRF → high power proton beams for a number of new applications:
  - Neutrino beams
  - Neutrino factory & Muon Collider
  - Accelerator Driven Systems (sub-critical reactors) and transmutation of waste

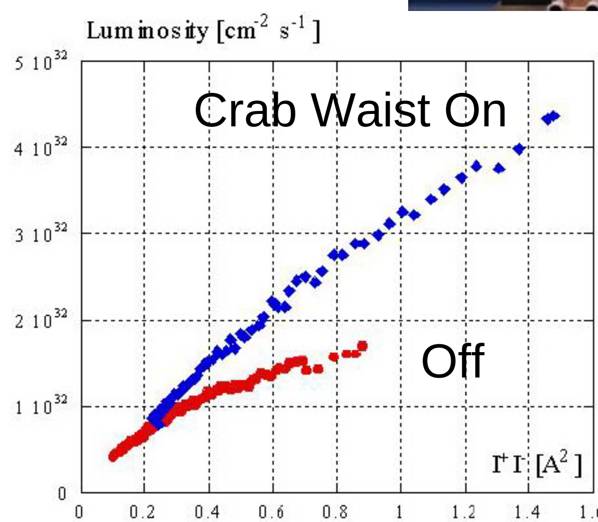
2. Beam Brightness Challenge

- Beam brightness most tightly tied to 'beam physics'
  - Some of the hot topics over the years:
    - Rf guns, final focus systems, emittance preservation, electron cloud, long-range wakefields, emittance exchange, …
- New e- guns 1000 x brighter than best storage/damping rings
  - Development pushed by FEL community
  - How can HEP benefit?



- High luminosity B-factories

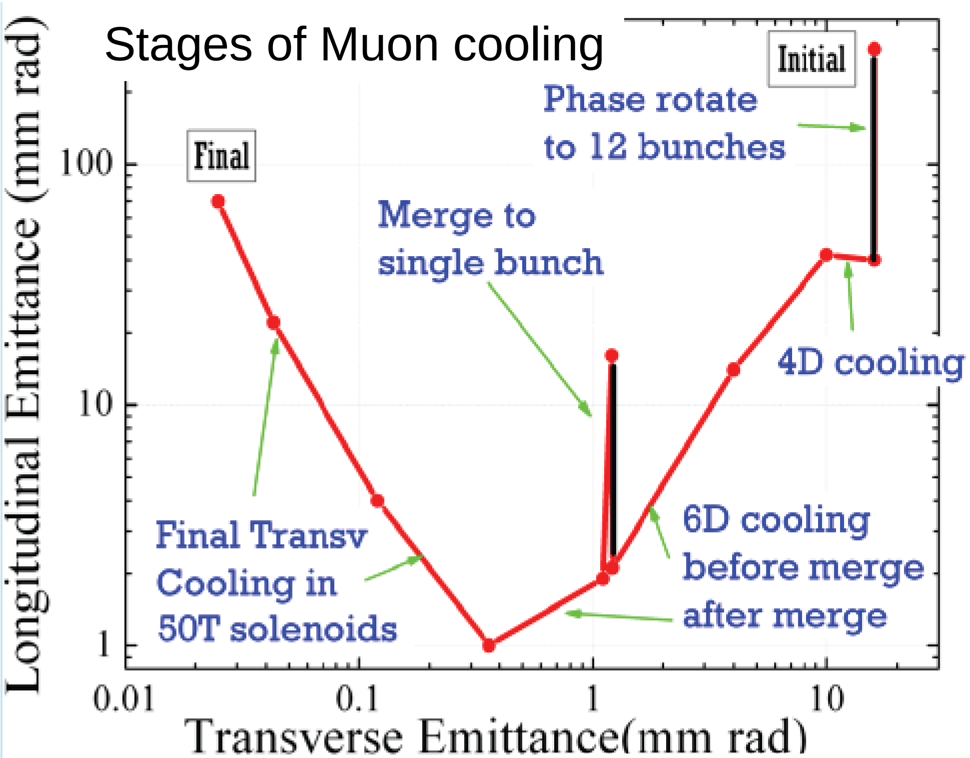




Super B-factories described in Sat. afternoon session

SLAC NATIONAL ACCELERATOR LABORATORY

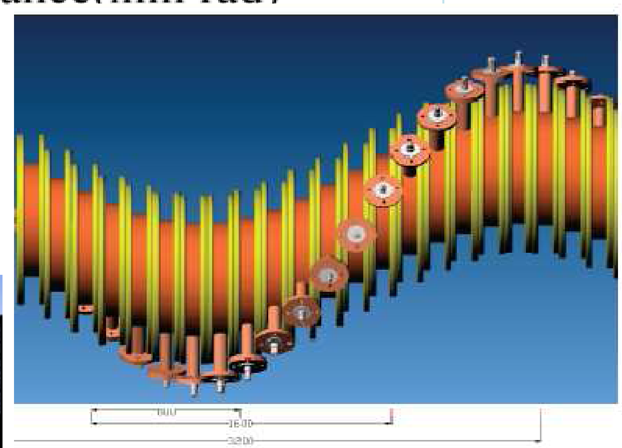
2. Muon Cooling

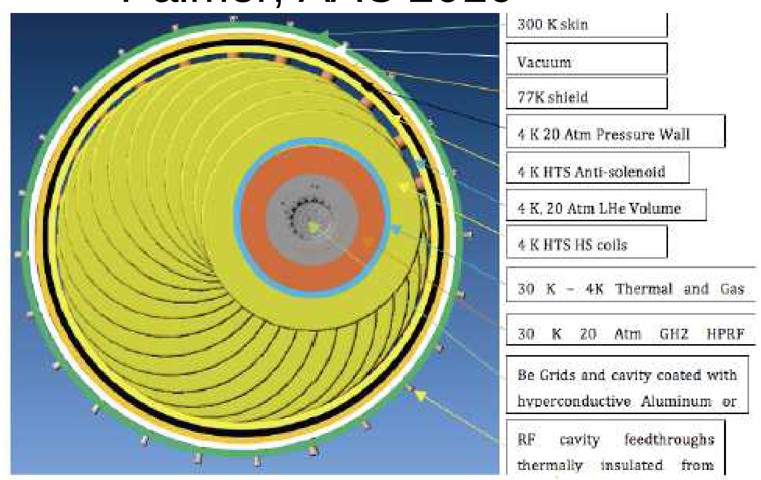


- Ionization cooling is the critical technology for muon collider
  - Requires 10^6 reduction of 6-dimensional emittance
  - Multiple concepts being studied

See Gail Hansen, Saturday pm session

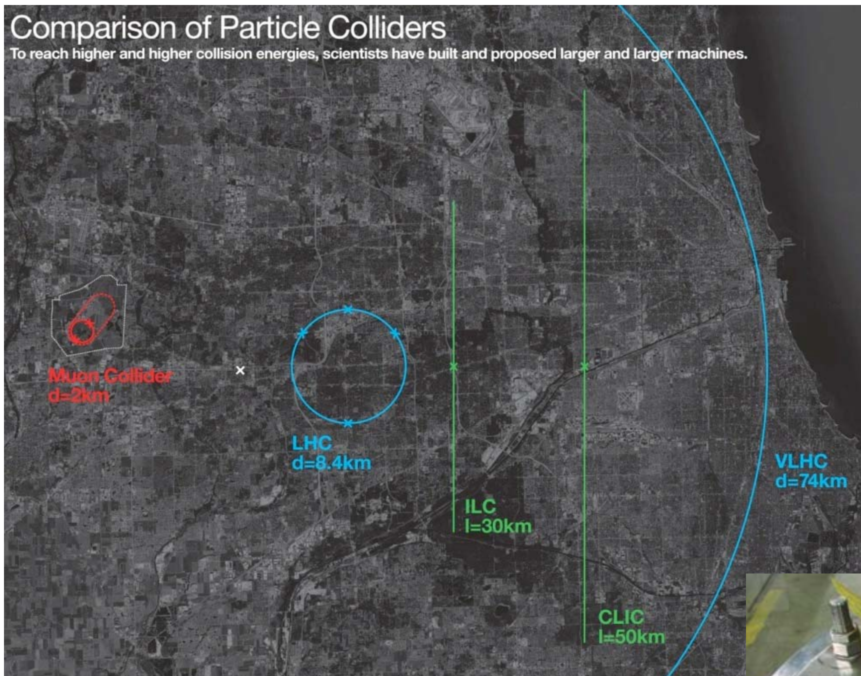
Concept for a Helical Cooling Channel
Palmer, AAC'2010





3. Beam Energy Challenge

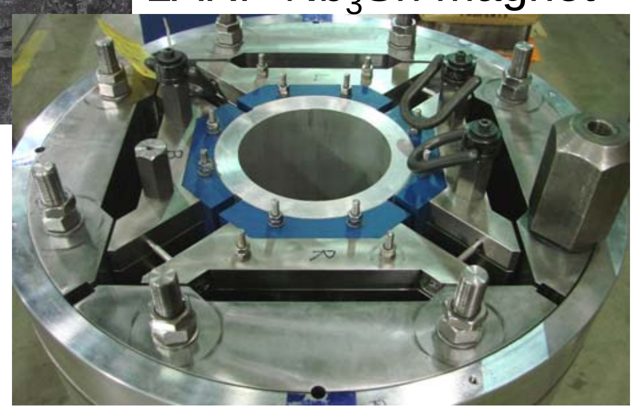
- Size of a facility is a large cost driver
  - Recirculating systems, e.g. Muon Collider vs. Linear Collider
  - High gradient acceleration and high field magnets



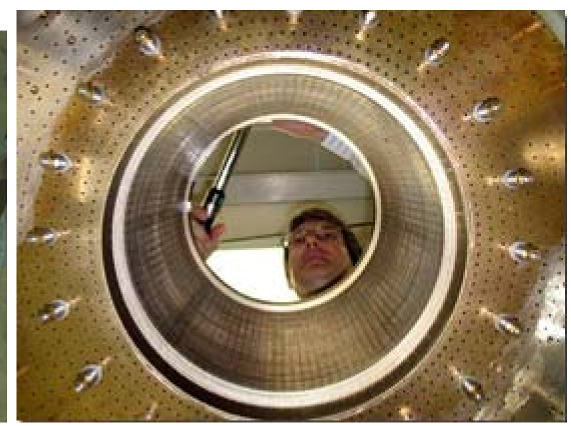
From Gail Hansen – Saturday

- High field magnets
  - Examples abound: LHC, LEHC, MC
    - 20T for LEHC and 50T for MC
  - Continuous improvement in fields relies on fundamental research and directed magnet R&D

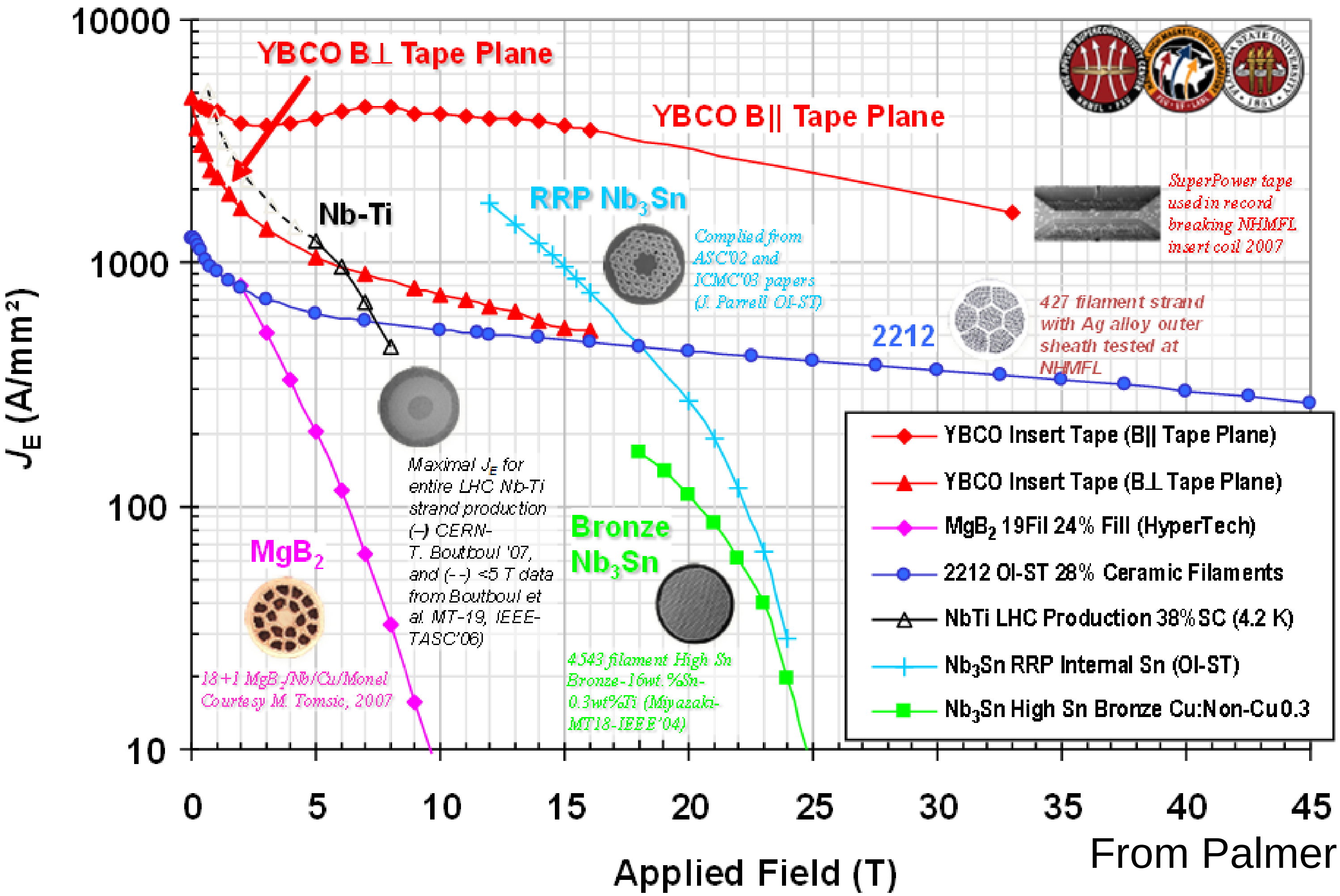
LARP Nb_3Sn magnet



35T Bitter magnet



Superconducting Wire



From Palmer, AAC'2010

High Gradient Acceleration

- High gradient acceleration requires high peak power and structures that can sustain high fields
  - Beams and lasers can be generated with high peak power
  - Dielectrics and plasmas can withstand high fields

- Many paths towards high gradient acceleration
  - RF source driven metallic structures
  - Beam-driven metallic structures

    } ~100 MV/m
  - Laser-driven dielectric structures
  - Beam-driven dielectric structures

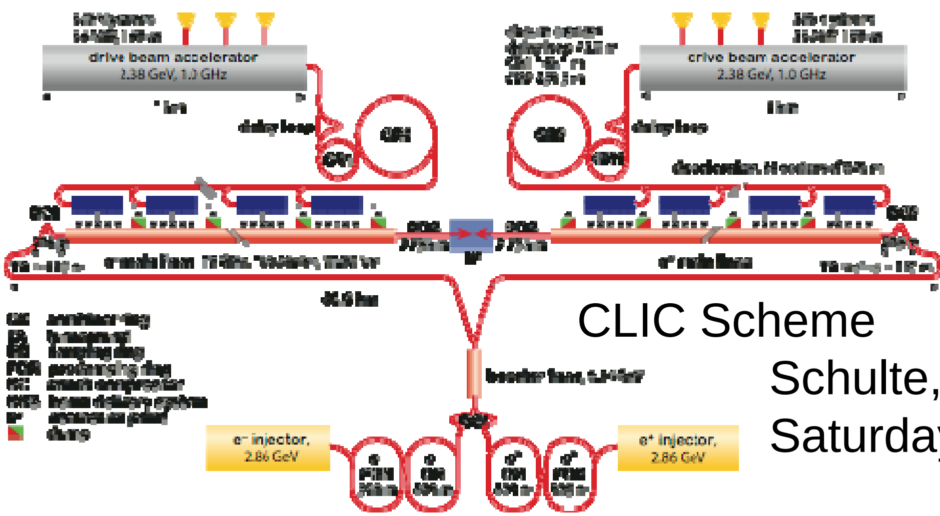
    } ~1 GV/m
  - Laser-driven plasmas
  - Beam-driven plasmas

    } ~10 GV/m

SLAC NATIONAL ACCELERATOR LABORATORY

Beam-Driven vs Discrete Source

- Beam-driven accelerators could be cost effective for large installations
  - Electron beams couple better to structures than lasers or rf
  - Use highly efficient rf→beam transfer to generate drive beam
  - Electron beams easier to manipulate than rf
  - Consolidate main power sources

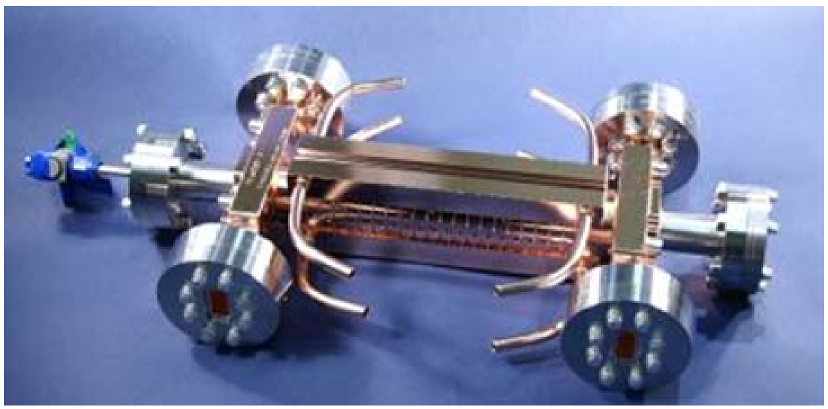


CLIC Scheme
Schulte,
Saturday

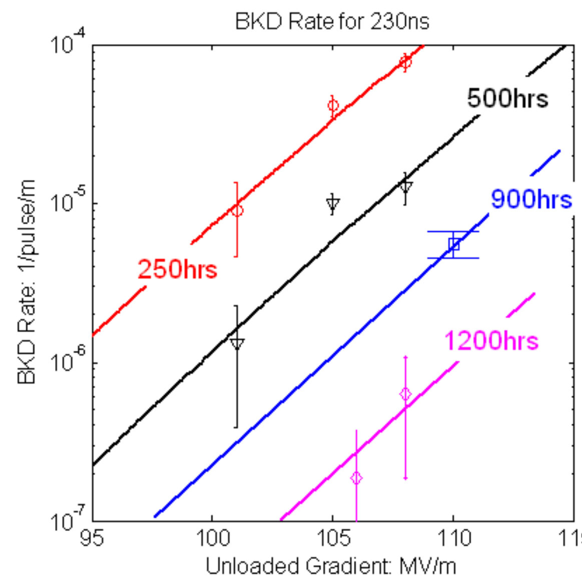
- Not appropriate for compact installations
- Complicated power handling
- Little experience with large systems and difficult to demonstrate in advance

High Gradient RF Acceleration

- Extensive R&D on breakdown limitations in microwave structures
  - US High Gradient Collaboration
  - CERN and Japan

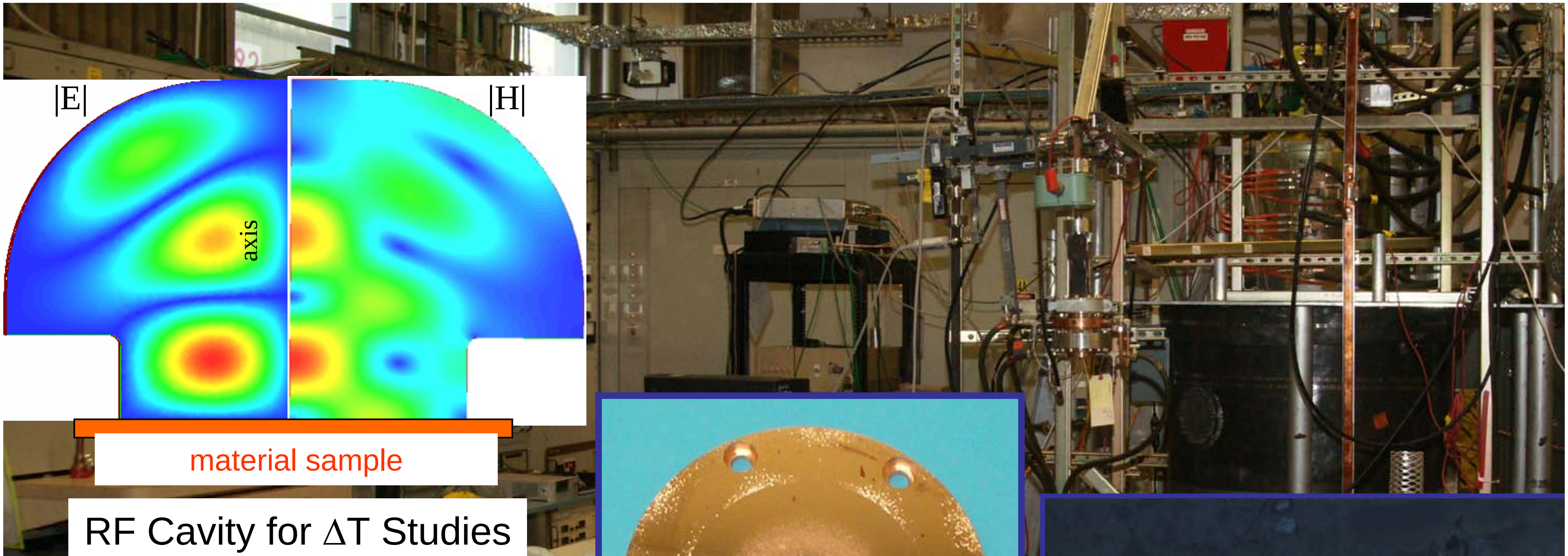


RF BKD Rate Gradient Dependence for 230ns Pulse at Different Conditioning Time



- In the last few years:
  - X-band gradients have gone from ~50 MV/m loaded to demonstrations of ~150 MV/m loaded with ~100 MV/m expected
  - C-band rf unit is operating at 35 MV/m; 8 GeV XFEL almost finished

Accelerator Materials



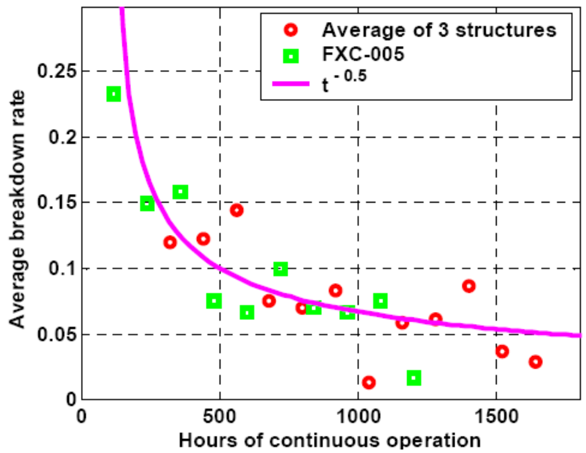
RF Cavity for ΔT Studies

Investigating Cu and Cu-alloys
Mo, Ti, …

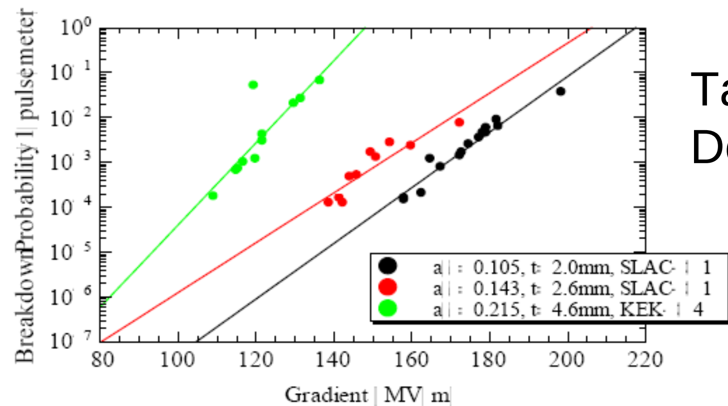
Intergranular fractures 500X

Understanding Cu Breakdown Limits

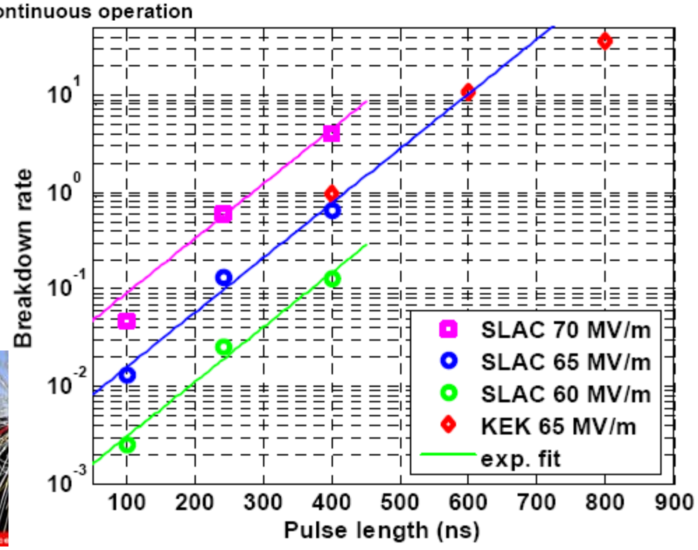
- Combination of analytic modeling, simulation and experiments have made great progress in understanding
  - Still not at ‘Standard Model’ status but many advances since 2000’s

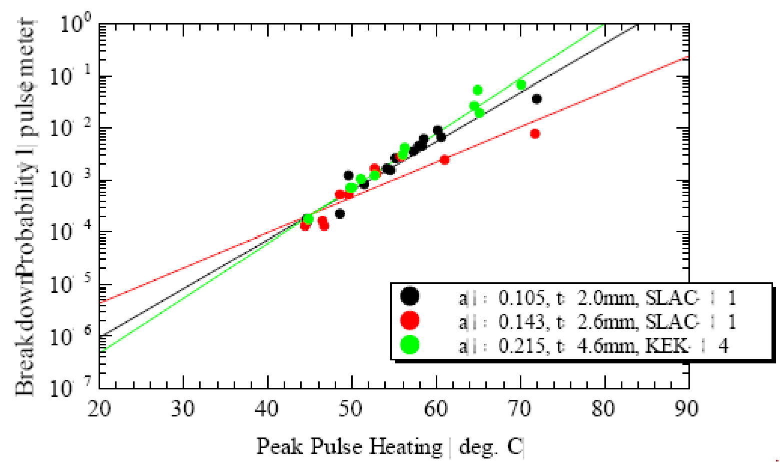


Doebert & Adolphsen



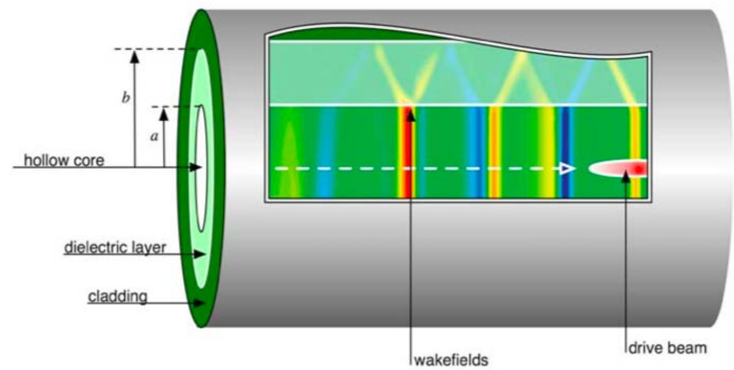
Tantawi & Dolgashev



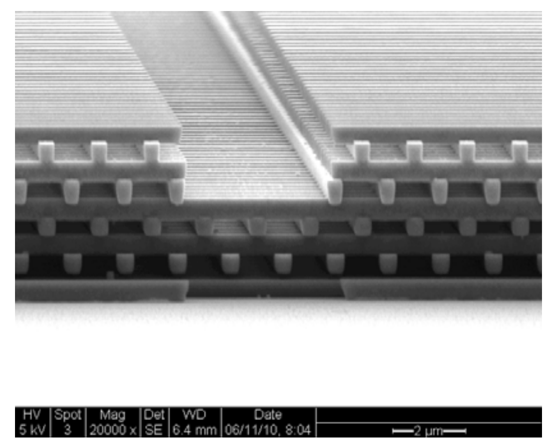


Dielectric Structures

- Unlike Cu, dielectric structures have higher breakdown limits approaching 1 GV/m at THz frequencies
  - Extensive damage measurements to characterize materials
  - Structures can be either laser driven or beam driven (wakefield)
- Beam-driven structures
  - Frequencies are in GHz regime and dimensions are cm-level
  - Higher gradients than metallic structures but more difficult wakes



- Laser-driven structures
  - Use lasers to excite structures similar to
  - microwave accelerators but with 10,000x smaller wavelengths

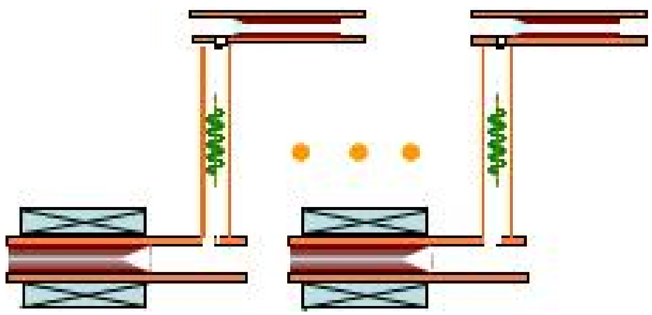


See Colby, Saturday am session

Concept of Beam-Driven Dielectric Linac

3GeV module (15m)

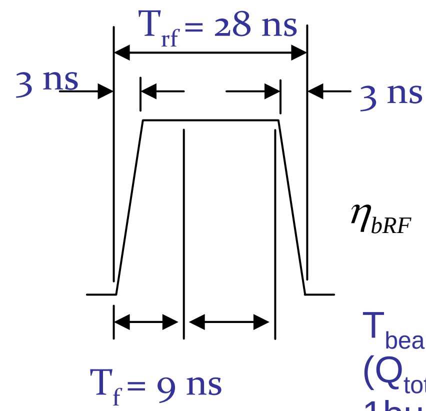
(38 DWPE & 38 DLA→ fill factor=76%)



1.33 GW output/Dielectric PETS;
5% rf transportation loss;
E_{load} = 267 MV/m (I_b=6.5A);

Drive beam becomes 80MeV, main beam gain 3GeV

W. Gai, Argonne National Lab



Competitive rf-beam efficiency for the short pulse TBA

$$\eta_{bRF} = \frac{I_{beam} E_{load} L_s}{P_{rf}} \times \frac{T_{beam}}{T_{rf}} = 26\%$$

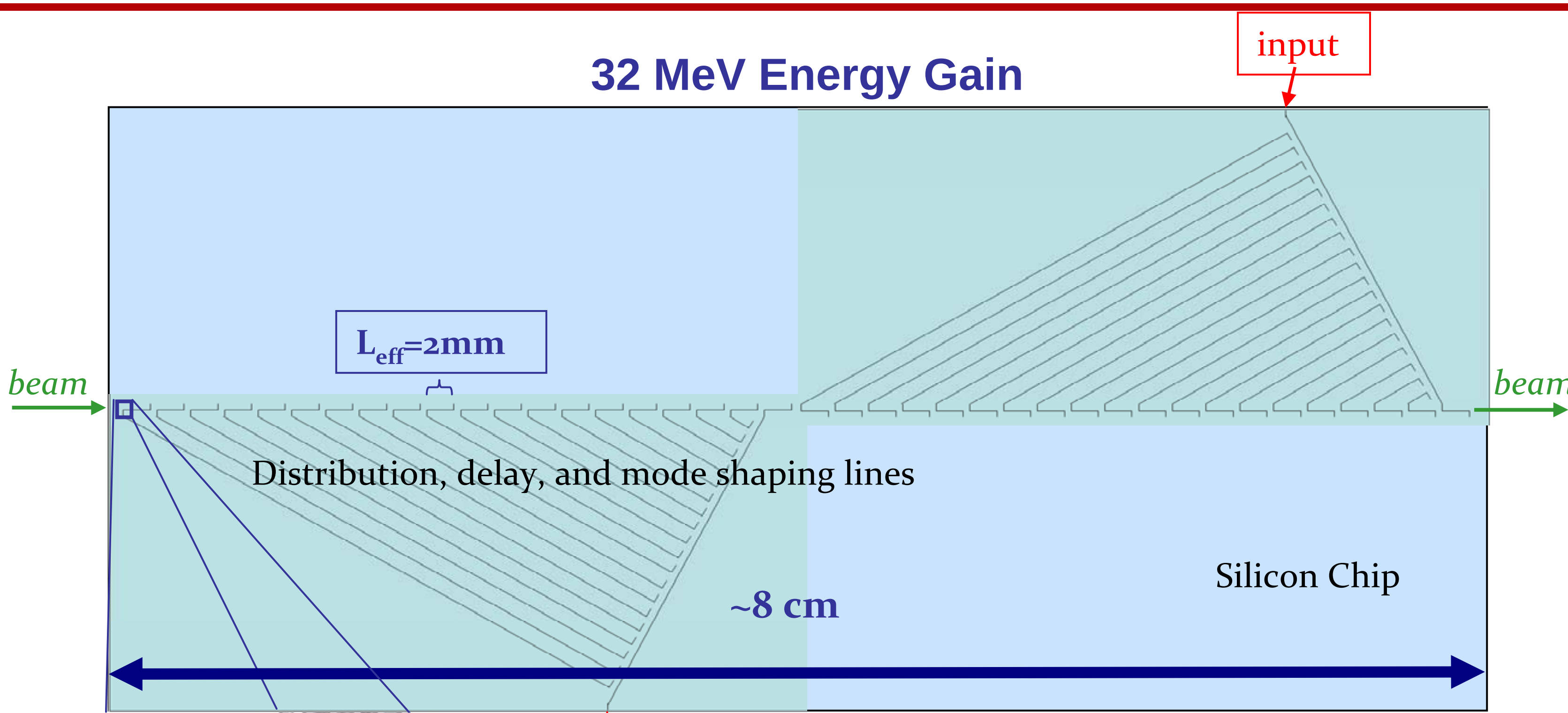
T_{beam}= 16 ns = 416 rf cycles (26 GHz)
(Q_{total}= 208 nC)
1bunch / 2 rf periods, 0.5nC / bunch

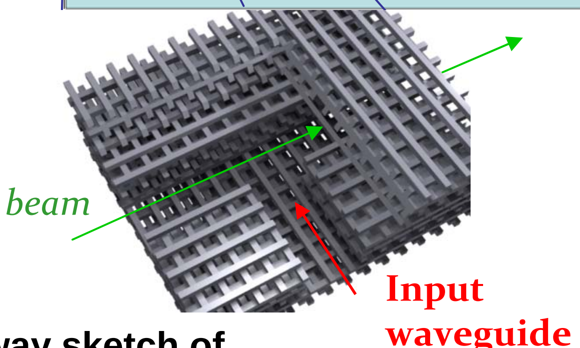
	AWA Short Pulse (1.5TeV,e+)
Average drive beam current	80 mA
Average drive beam power	68.8 MW
Average rf power to main linac	60MW
Average main beam current	10.4 uA
Average main beam power	15.6 MW

SLAC NATIONAL ACCELERATOR LABORATORY

Laser-Driven Dielectric Accelerator
(Accelerator-on-a-chip)

32 MeV Energy Gain



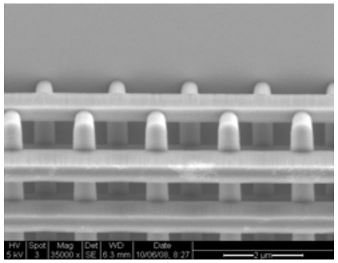


Cutaway sketch of coupler region

Image courtesy of B. Cowan, Tech-X.

Fiber coupled input

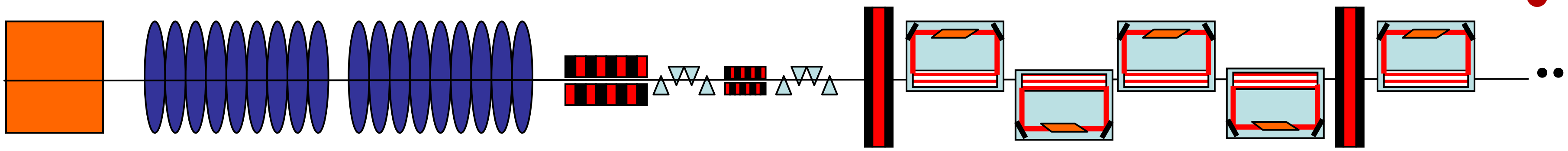
λ=2 μm
20 μJ/pulse
1 ps laser pulse



4-layer Structure Fabrication (completed at SNF)

Image courtesy of C. McGuinness, Stanford.

Concept of Laser-Driven Dielectric Linac



CW Injector

Warm rf gun   Cold Preaccelerator   Optical Buncher

433 MHz x 6E03 e^-/macropulse (145 μpulse/macropulse)

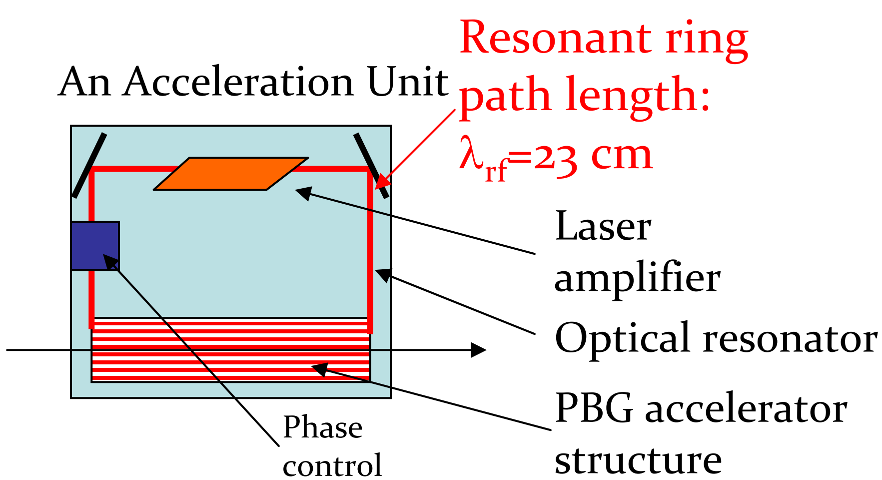
ε_N~10^{-10} m (but note Q/ε_N << 1 nC/μm)

Laser Accelerator

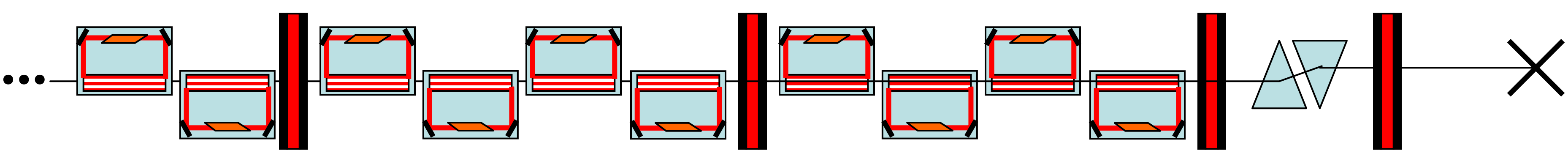
λ=2-4 μ, G~1 GeV/m

Photonic Band Gap Fiber structures embedded in optical resonant rings

Permanent Magnet Quads (B'~2.5 kT/m)

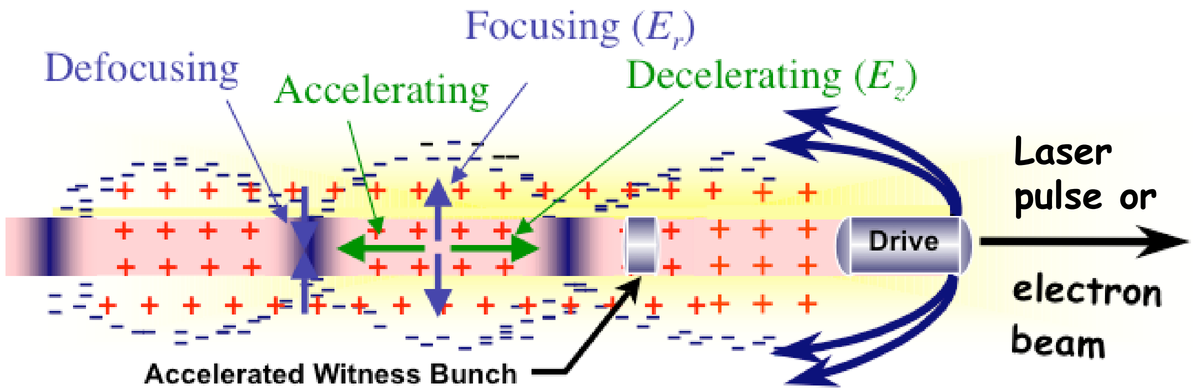


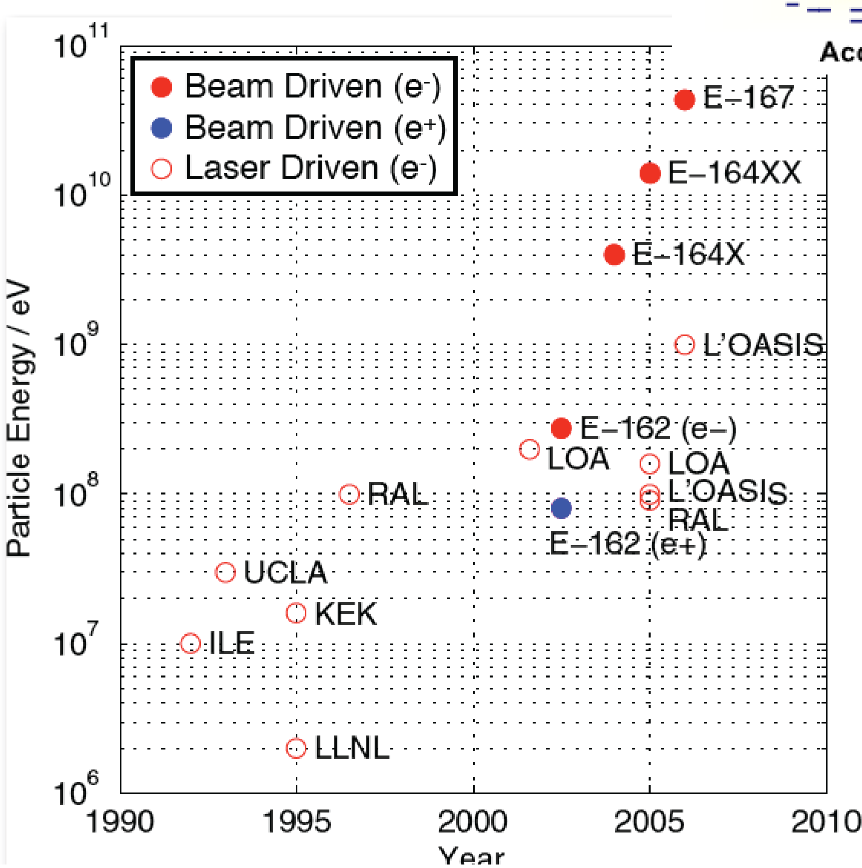
- DLA concept benefits from commercial laser and semiconductor industries
  - 100 MHz lasers with μJ per pulse
  - Potential cost break using lithographic techniques
  - Challenge is nm-level tolerances

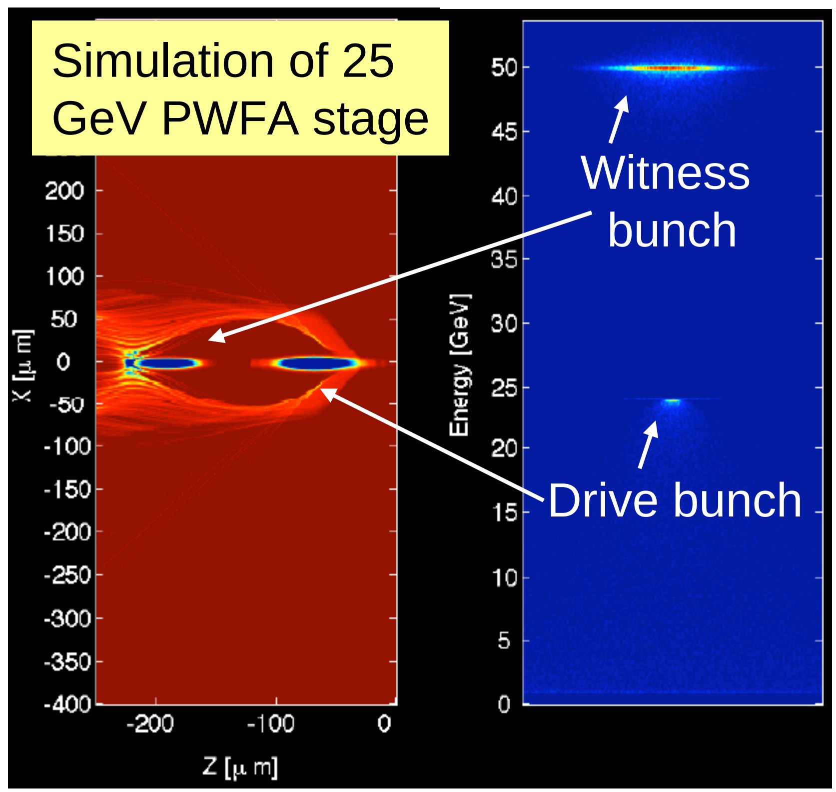


Plasma Acceleration
(Beam-driven or Laser-driven)

- 50 GV/m demonstrated
  - Potential use for linear colliders and radiation sources

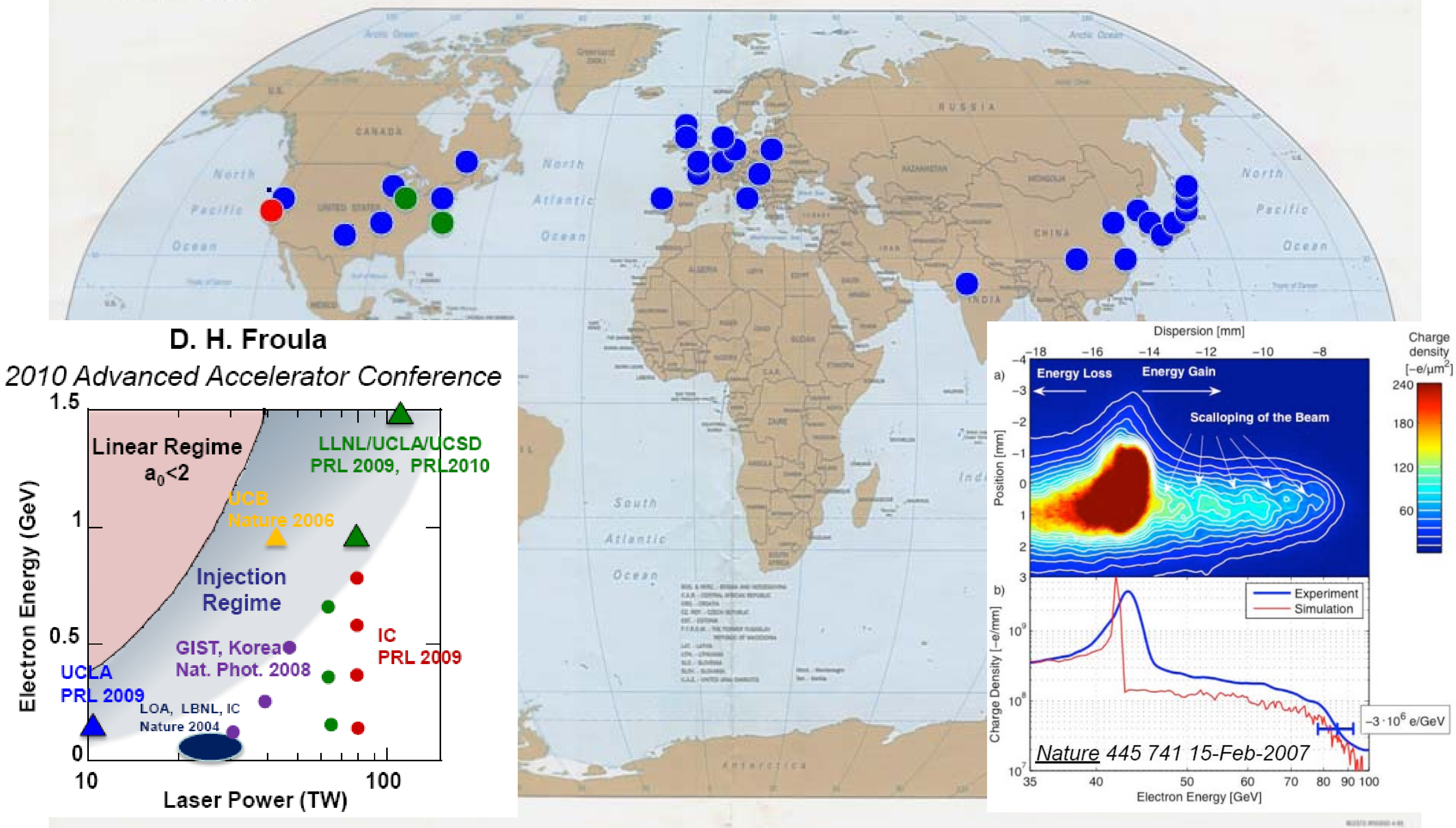






World-Wide Interest in Plasma Acc.

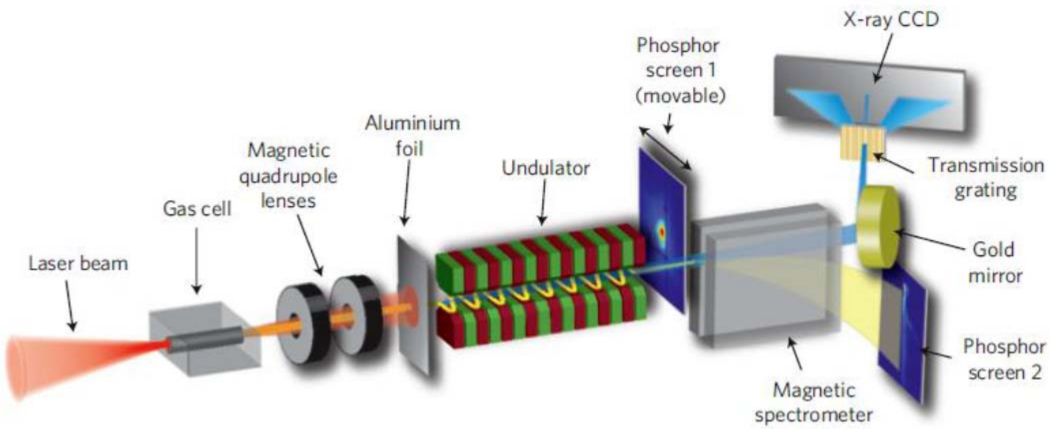
Plasma Acceleration on the Globe, T. Katsuoleas



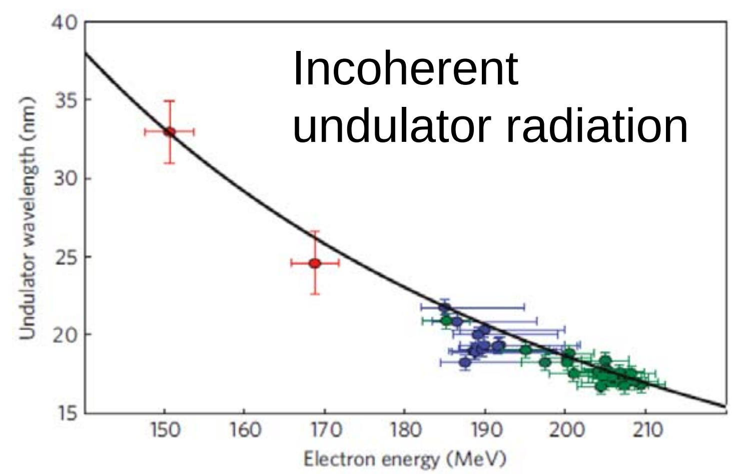
● Laser Wake Expts ● Electron Wake Expts ● e-/e+ Wake Expts

Compact Plasma Accelerators

- Plasma accelerators have many potential applications
  - Experiments at MPQ, Oxford Univ., Univ. of Edinburgh, JAERI aimed at generating a compact laser plasma-based FEL
    - Working on beam quality, stability, etc
  - Many other labs around the world have similar goals



Laser-driven soft-X-ray undulator source
Fuchs et al, Nature Physics (2009)



Concept of Laser-Driven Plasma Linac

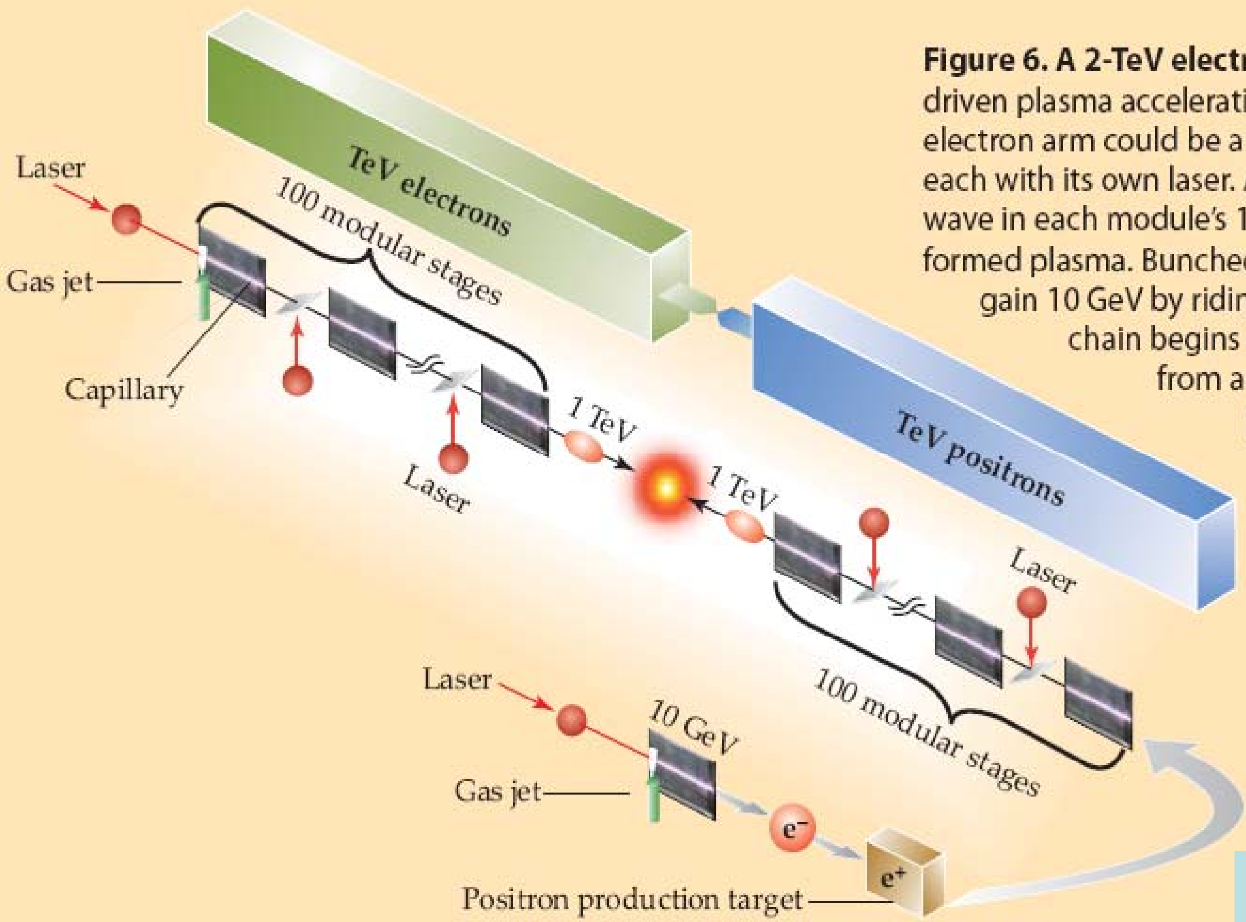
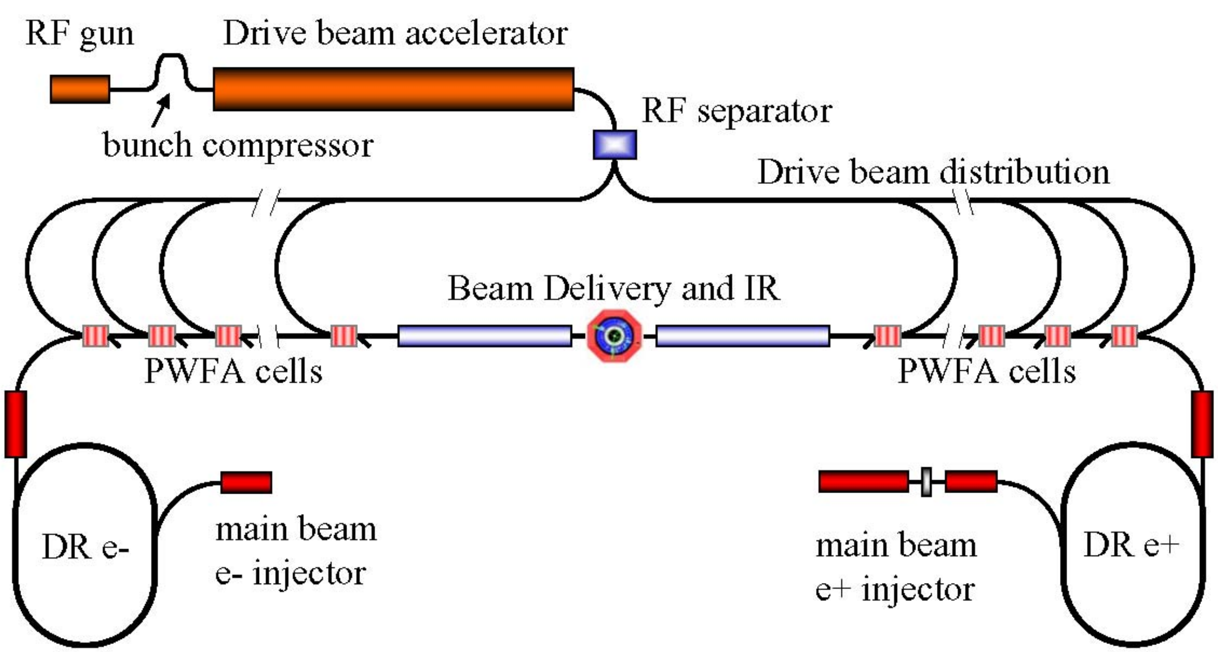


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, et al., Physics Today, March 2009

Concept of Beam-Driven Plasma Linac

- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes good use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance pres.
    - Positrons
  - Allows study of cost-scales for further optimization of R&D



SLAC NATIONAL ACCELERATOR LABORATORY

Challenges for Plasma-based Colliders

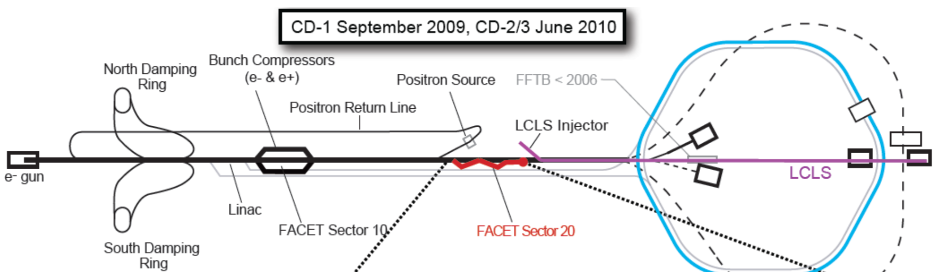
- Luminosity drives many issues:
  - High beam power (20 MW) → efficient ac-to-beam conversion
  - Well defined cms energy → small energy spread
  - Small IP spot sizes → small energy spread and small $\Delta\varepsilon$
- These translate into requirements on the plasma acc.
  - High beam loading of e+ and e- (for efficiency)
  - Acceleration with small energy spread
  - Preservation of small transverse emittances – maybe flat beams
  - Bunch repetition rates of 10's of kHz
  - Highly efficient power sources
  - Acceleration of positrons

NATIONAL ACCELERATOR LABORATORY

Plasma-based Linear Colliders

- DOE OHEP has funded two new plasma accelerator test facilities: FACET and BELLA
  - Both are aimed at linear collider relevant parameters:
    - ~1nC per bunch, many GeV energy gain, small emittance beams
  - Will address next generation challenges: emittance preservation, small energy spreads, stability and efficiency

FACET Test Facility



Nominal
FACET Beam Parameters

Energy	23 GeV
Charge	3 nC
Sigma z	14 µm
Sigma r	10 µm
Peak Current	22 kAmps
Species	e^- & e^+

Beam Parameters Driven by Science Needs

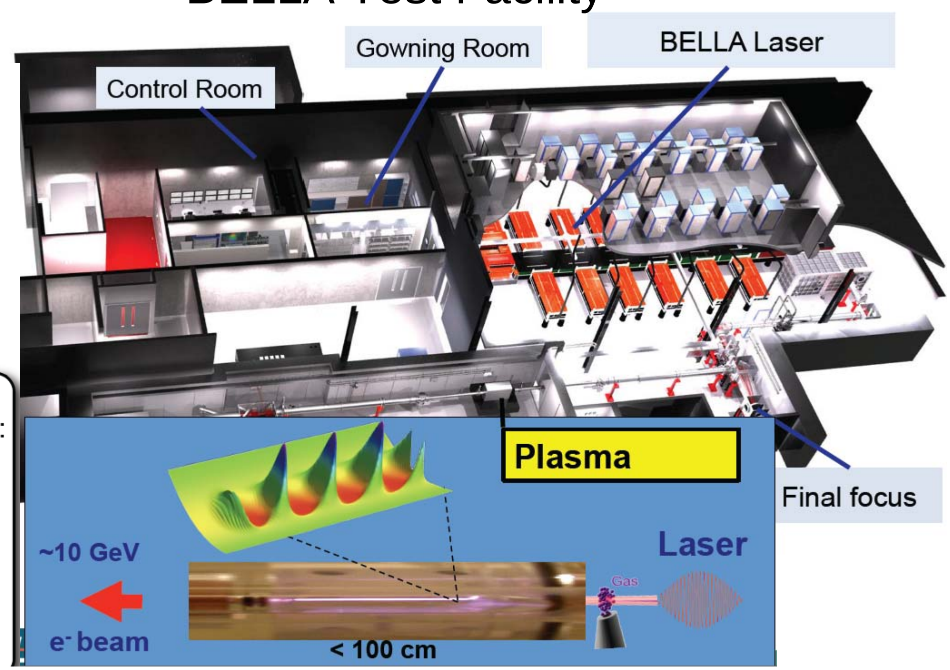
Delivered to 100m area with three distinct functions:

1. Chicane for final stage of bunch compression
2. Final Focus for small spots at the IP
3. Experimental Area(s)

Advantageous location:

- Preserves e+ capability
- No bypass lines or interference with LCLS
- Linac setup virtually identical to SPPS/FFTB

BELLA Test Facility



Accelerator Research & Development

- Timescales for accelerator development are long
  - Need to maintain pipeline of new ideas
  - Test facilities and infrastructure are critical to enable R&D
  - Requires support for both fundamental and directed (project) R&D
- Large-scale projects tend to be conservative
  - Likely will require many systems-level demonstrations
  - Important to understand timescales and costs both for the R&D as well as the demonstrations
- Important to consider early applications
  - Provides funding while allowing consideration of operational issues while demonstrating technology

Success: C-band rf Technology

- C-band technology development began in mid-1990's
  - Motivated by linear collider application
- Proceeded as independent research until 2002
  - Started development for Spring-8 XFEL
  - Industrialization proceeded rapidly
- Now installed 8 GeV C-band 35 MV/m linac
  - Commissioning fall of 2010