FINAL EXAM

- Friday Morning, 9:30 a.m. - 11:30 a.m.
  - bring scratch paper, calculators
- "Open Book" -- the following are allowed:
  - class textbooks (Edwards & Syphers, plus one more if desired)
  - class handouts, labs, homeworks, ...
  - hand-written class notes

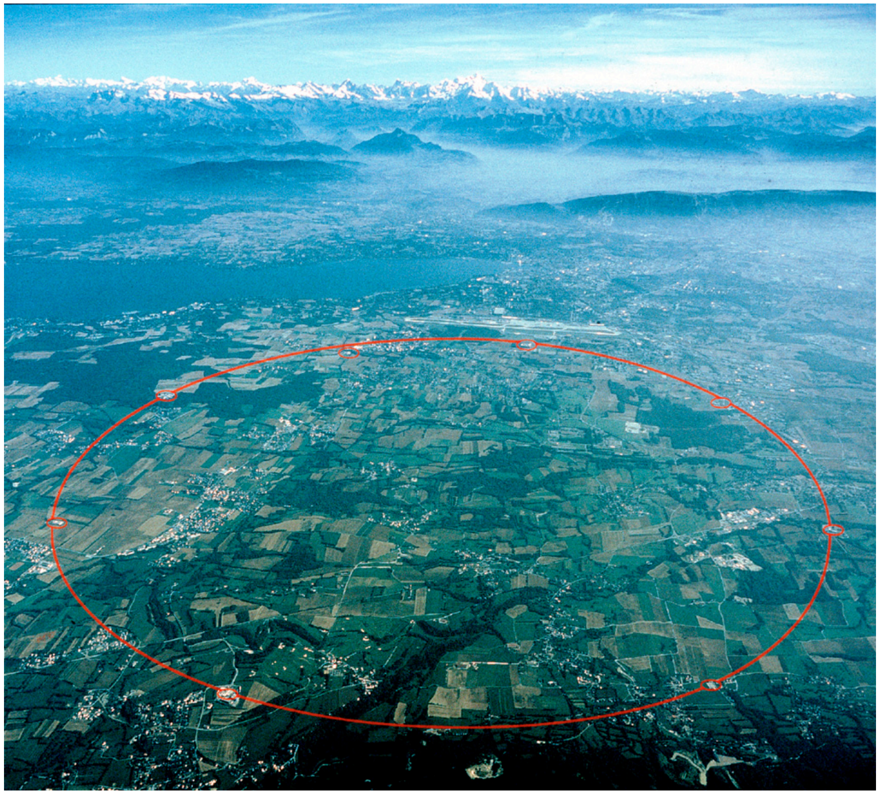
Resonance Conditions

- previously, ...   integer, half-integer
- sextupoles revisited -- third-integer
- skew fields
  - rotated quads; a_1; solenoids; tune split
- driven harmonic oscillator and tune diagram
- resonance correction/enhancement systems
  - slow resonant extraction

Issues for the Future of High Energy Accelerators

Future Hadron Colliders:

- With present RF technology, real estate vs. magnetic field is issue
- Comments on Large Hadron Collider (CERN); due out ~2008-09
  - Top Energy, 7 TeV, determined by existing (LEP) tunnel + 8-10 T magnets
  - L determined by need to compete w/ SSC -- Sigma ~ $1/M^2$, so $L \sim E^2$ --> $10^4/\mu$b/sec
  - Synch. Rad. becomes a nuisance, not an asset for luminosity
  - L pushes N pushes SR load, vacuum, stored energy, Energy Deposition in magnets, ...
  - rms beam size at collision -- ~20 microns; colliding human hairs straight on
    - note: Tevatron has 30 micron beams at collision points
  - Pushing accelerator parameters AND reliability of components



Possible Next Steps with standard RF technology --

Some ideas…

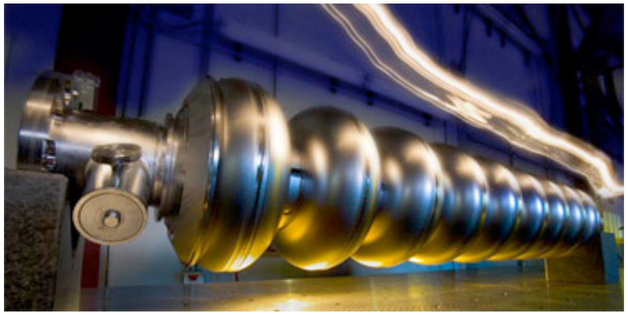
- Very Large Hadron Collider (VLHC) -- 20x20 to 100x100 TeV (pp)
- International Linear Collider -- 0.25 x 0.25 up to 0.5 x 0.5 TeV (e+e-)
- Muon Collider -- generate beams of muons, accelerate (*quickly*!) to few TeV and collide

- Snowmass 2001 -- VLHC (no) *vs*. ILC (yes); [μ-μ: *too far away*...]
  - ILC more "complementary" to LHC; natural next step
  - physics events easier to "disentangle" -- leptons vs. hadrons
  - ILC more affordable (???)

- Look at Linear Collider ...

Same limiting factors ...

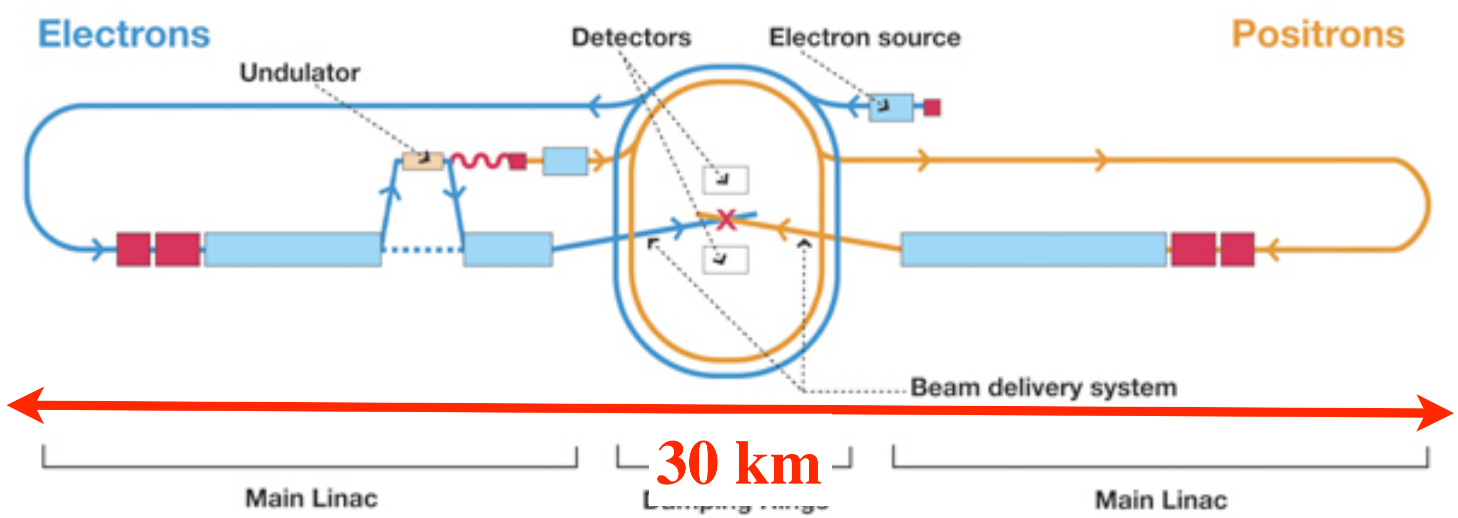
- superconducting technology -- accel. cavities this time, not magnets
- high accelerating gradient (>30 MeV/m)



- Synchrotron Radiation
  - effects obvious in e+e-; hence, the **L** in ILC
  - real estate vs. electric field strength
- have discussed stored energy in LHC; *beam power* issue in linac
- energy deposition at Interaction Points; backgrounds
- small apertures --> alignment tolerances (micron scale)
- requires very small beam sizes at collision point -- nm scale
  - damping rings -- S.R. put to good use
  - emittance exchange -- eliminate need for damping rings?

ILC Conceptual Layout

- Use (part of) Main Linac to accelerate beams for positron production
- Use Damping Rings to generate small beams at low energy (~10 GeV) *via* Synch. Radiation -- makes flat beams, longer bunches than desired
- Beams travel length of tunnel, turn around (bunch compression) and enter Main Linacs
- Exit Main Linacs with E~250 GeV; deliver to Experiments



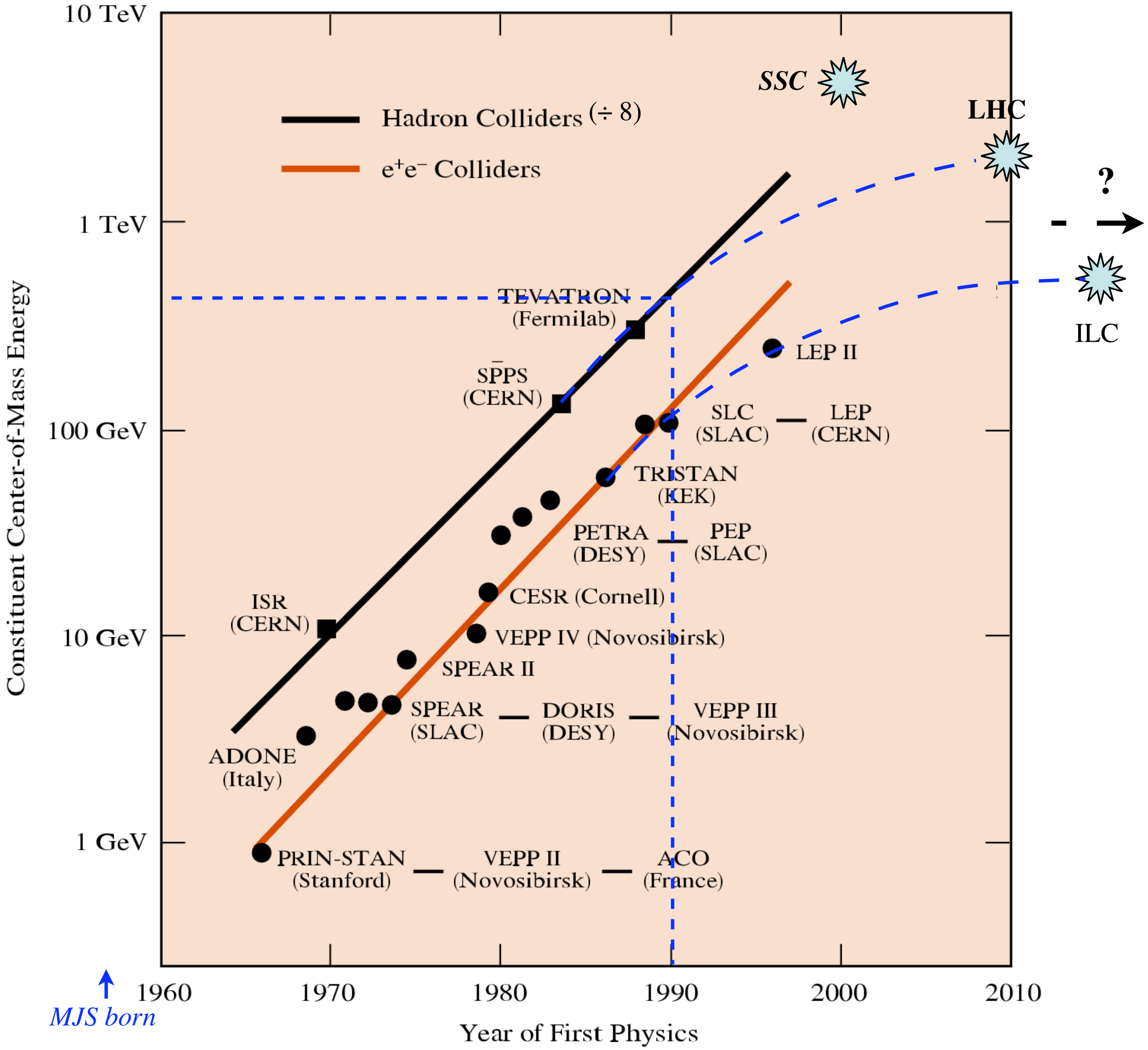
Linear Collider

- Real Estate: to date, ~30 MeV/m ----> 250 GeV = ~8 km *each linac*
- upgrade paths
  - laser straight vs. follow the earth's curvature
  - note: asymptotic energy limit: “curved” ---> synch. rad.
  - --> acceleration ends when energy loss = energy gain: E_{max} ~ 10 TeV
- CLIC (CERN) -- proposal to use particle beams to generate power for very high gradient structures
  - toward 150 MV/m with "warm" structures at 30 GHz
- Note -- luminosity of linear collider: throwing away beam power
  - need to look toward “energy recovery” in future accelerators

The Livingston Curve

- In attempt to compare e^- & p, look at C-of-M view of *constituents*
- seeing a new roll-off happening
- driven by budgets, if constrained to present technology
- thus, need *new* technologies to make affordable...

from W. Panofsky. *Beam Line* (SLAC) 1997



About time for new approach(es)?

- Studies long underway on plasma, wakefield, laser acceleration processes; very encouraging recent results! (that I'm familiar with...)

- SLAC, E-167 collab. plasma wakefield result
  - 28 GeV particles from 90 cm plasma column
- LBNL laser wakefield result
  - 1 GeV *beam* from 3.3 cm discharge waveguide

- Each seeing effects of field gradients of ~ 30 GeV/m

(30,000 MeV/m!!)

SLAC Collab. Result

SLAC-PUB-12164
October 2006

Energy Measurements of Trapped Electrons from a Plasma Wakefield Accelerator

Neil Kirby[1], David Auerbach[2], Melissa Berry[1], Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Devon Johnson[2], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1], and Miaomiao Zhou[2]

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[2]*University of California at Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095, USA*

[3]*University of Southern California, Los Angeles, CA 90089, USA*

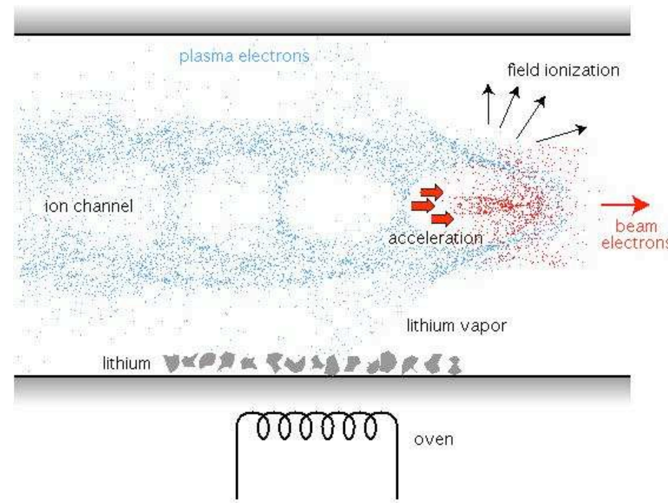
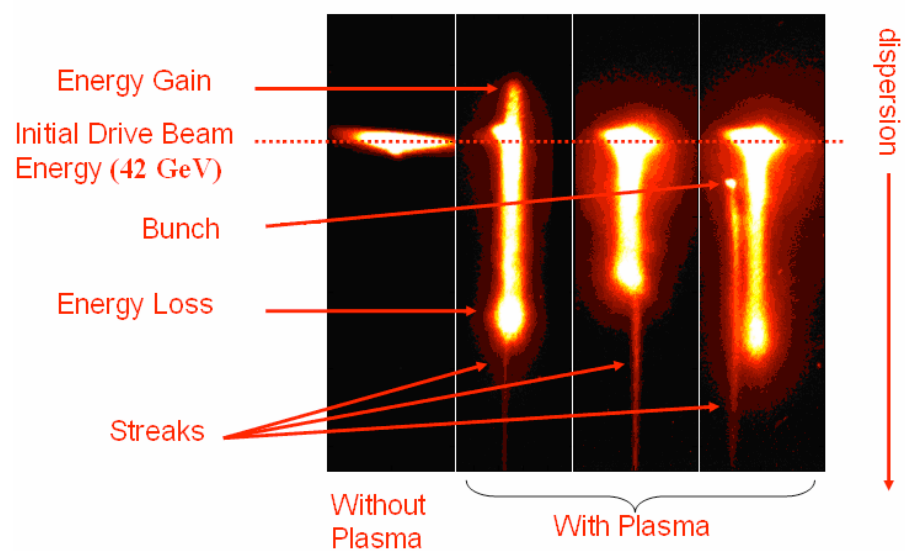


FIGURE 1. An illustration of a plasma wakefield accelerator.



Energy gain of ~ **10-30 GeV** in ~0.85 m observed

LBNL Result

RESEARCH NEWS
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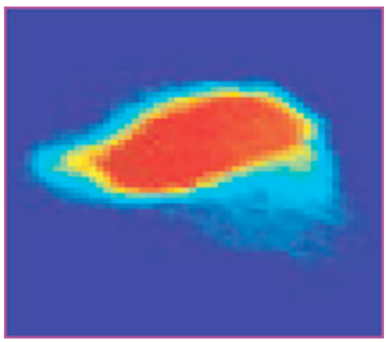
September 25, 2006 news releases | receive our news releases by email | science@berkeley lab

From Zero to a Billion Electron Volts in 3.3 Centimeters

Highest Energies Yet From Laser Wakefield Acceleration

Contact: Paul Preuss, (510) 486-6249, paul_preuss@lbl.gov

BERKELEY, CA — In a precedent-shattering demonstration of the potential of laser-wakefield acceleration, scientists at the Department of Energy's Lawrence Berkeley National Laboratory, working with colleagues at the University of Oxford, have accelerated electron beams to energies exceeding a billion electron volts (1 GeV) in a distance of just 3.3 centimeters. The researchers report their results in the October issue of *Nature Physics*.

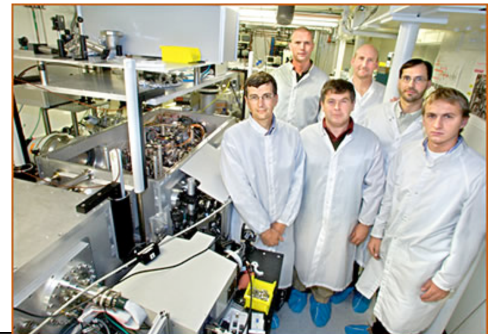


Billion-electron-volt, high-quality electron beams have been produced with laser wakefield acceleration in recent experiments by Berkeley Lab's LOASIS group, in collaboration with scientists from Oxford University.

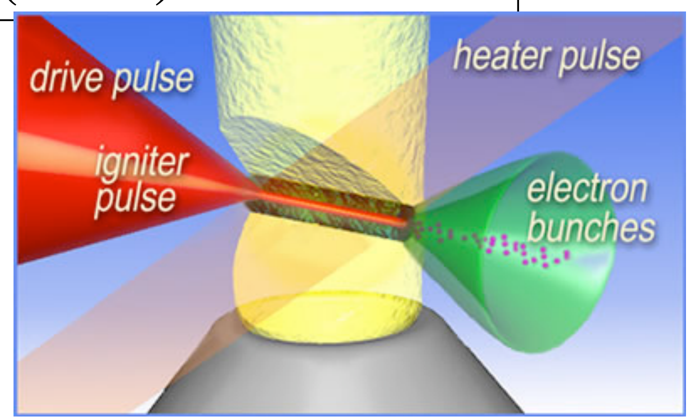
By comparison, SLAC, the Stanford Linear Accelerator Center, boosts electrons to 50 GeV over a distance of two miles (3.2 kilometers) with radiofrequency cavities whose accelerating electric fields are limited to about 20 million volts per meter.

The electric field of a plasma wave driven by a laser pulse can reach 100 *billion* volts per meter, however, which has made it possible for the Berkeley Lab group and their Oxford collaborators to achieve a 50th of SLAC's beam energy in just one-100,000th of SLAC's length.

This is only the first step, says Wim Leemans of Berkeley Lab's Accelerator and Fusion Research Division (AFRD). "Billion-electron-volt beams from laser-wakefield accelerators open the way to very compact high-energy experiments and superbright free-electron lasers."



- **30 GeV/m**, compared to 30 *M*eV/m in present ILC cavity design
- ... and, *small* momentum spread (2-5%) as well



Time for new approach(es)

- Great progress in this discipline
- SLAC, E-167 collab. plasma wakefield result -- 28 GeV/m, +/- 100%
- LBNL laser wakefield result -- 30 GeV/m, +/- 2.5%; 0.03 nC bunch
- $e^{+/-}$ colliders expect > ~2nC bunches; so, need work on bunch charge, but progress is being made. Will we see practical systems in not-too-distant future?

- other approaches on the horizon...
- with any of these, when apply to HEP, will begin to be limited by limitations in available power --> energy recovery
  - no one wants to use more than a single power plant to power the accelerator!
- exciting field right now...

Summary

- "RF" accelerators have dominated in HEP past 75 years
  - note: many other applications, not just “high energy”
- Higher Energy hadron/ion RF accelerators still feasible; magnet technology is driver; circular accelerators still an option.
  - however real estate and $$$ BIG issues
- Higher Energy lepton RF accelerators also feasible; high gradient electric fields drive this; require linear accelerators
  - ... AND real estate ... AND $$$
  - more limited in energy reach, due to S.R.
- 20 TeV SSC was “too expensive”; 7 TeV LHC coming up, but also tough on budget; ILC cost estimate unfolding -- prohibitive?
- time is ripe for a new breakthrough technology; though will take time to mature, perhaps beginning to see it emerge...

THANKS!

- Review Session: 1:30