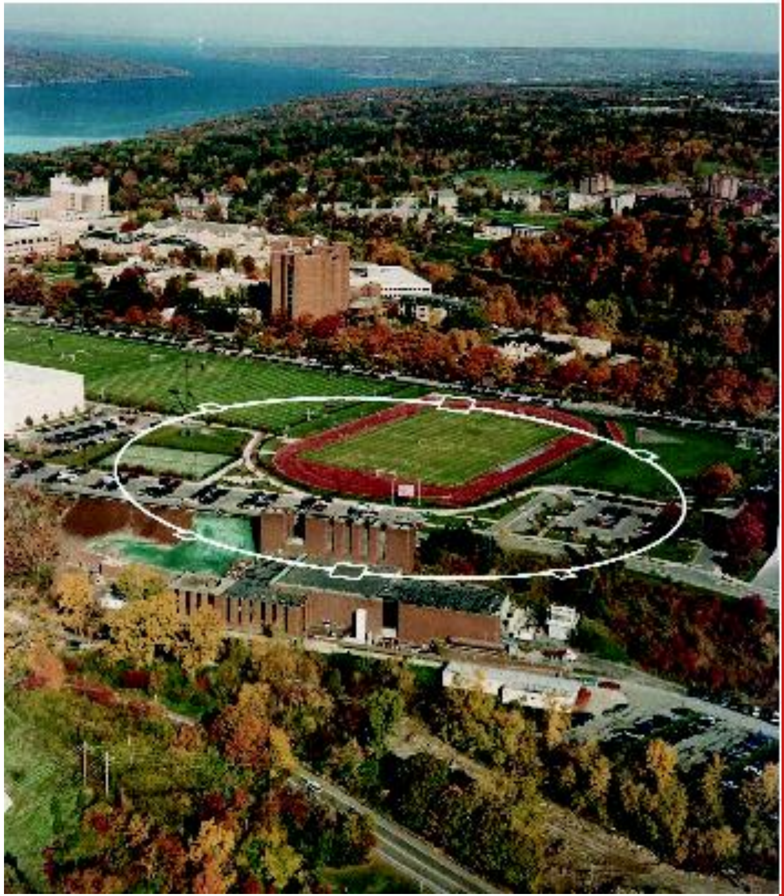
Topics in Accelerator Physics

CHESS & LEPP

Content

1. Typical Particle Accelerators
2. Linear Beam Optics in Straight Systems
3. Linear Beam Optics in Circular Systems
4. Nonlinear Beam Optics in Straight Systems
5. Nonlinear Beam Optics in Circular Systems
6. FFAs for large energy acceptance
7. RF Systems for Particle Acceleration
8. Energy Recovery Linacs (ERLs)
9. Beam Breakup Instability
10. Synchrotron Radiation from Bends, Wigglers, and Undulators



Dates: every Tuesday and Thursday 1:25 – 2:40 Room 231 Rockefeller Hall

Exceptions: One Tuesday in Fall break and one Thursday at Thanksgiving

Duration: From Thursday August 29 to Tuesday December 10, 2019

Grader: William Lou, wl528@cornell.edu, Wilson Lab, 3rd-floor grad office. Office hours by email arrangement.

Homework handout every Thursday on the class web page

Homework return in hardcopy during class one week later.

Lecture notes, homework, and homework solution will be on the class web page

https://www.classe.cornell.edu/~hoff/LECTURES/19F_7688/index.html

Grades are S/U, the final will consist of a project that is carried through 2/3 of the class, staring after about one month.

Accelerator simulation

To practice what will be learned, accelerators will be simulated with the programs Tao and BMAD. The will be run through terminal-login to a computer in the Cornell Laboratory of Accelerator-baSed Sciences and Education (CLASSE).

1) Get a classe linux account by contacting wl528@cornell.edu with cc to georg.hoffstaetter@cornell.edu
2) Open a terminal on your mac, you linux computer, or use virtual box on your PC.
3) Type 'ssh –Y netID@lnx201.lepp.cornell.edu'. This will prompt you to enter the password of your CLASSE linux account.
4) Copy an example for optics matching as a first learning tool: 'cp –r /home/wl528/nfs/lib_SL7/tao/examples/optics_matching .' (Don't miss the final period.)
5) A directory optics_matching should have appeared. Enter this directory.
6) Run Tao by '/home/wl528/nfs/lib_SL7/production/bin/tao'. If a plot pops up for you, the system works and you can use tao from now on.

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Images are taken from many sources, including:

The Physics of Particle Accelerators, Klaus Wille, Oxford University Press, 2000, ISBN: 19 850549 3

Particle Accelerator Physics I, Helmut Wiedemann, Springer, 2nd edition, 1999, ISBN 3 540 64671 x

Teilchenbeschleuniger und Ionenoptic, Frank Hinterberger, 1997, Springer, ISBN 3 540 61238 6

Introduction to Ultraviolet and X-ray Free-Electron Lasers, Martin Dohlus, Peter Schmüser, Jörg Rossbach, Springer, 2008

Various web pages, 2003 – 2017

Literature

Recommended as

Introduction

The Physics of Particle Accelerators: An Introduction, Klaus Wille, Oxford University Press

Wide selection of well explained topics

Particle Accelerator Physics, Helmut Wiedemann, Springer, (preferably 3rd edition)

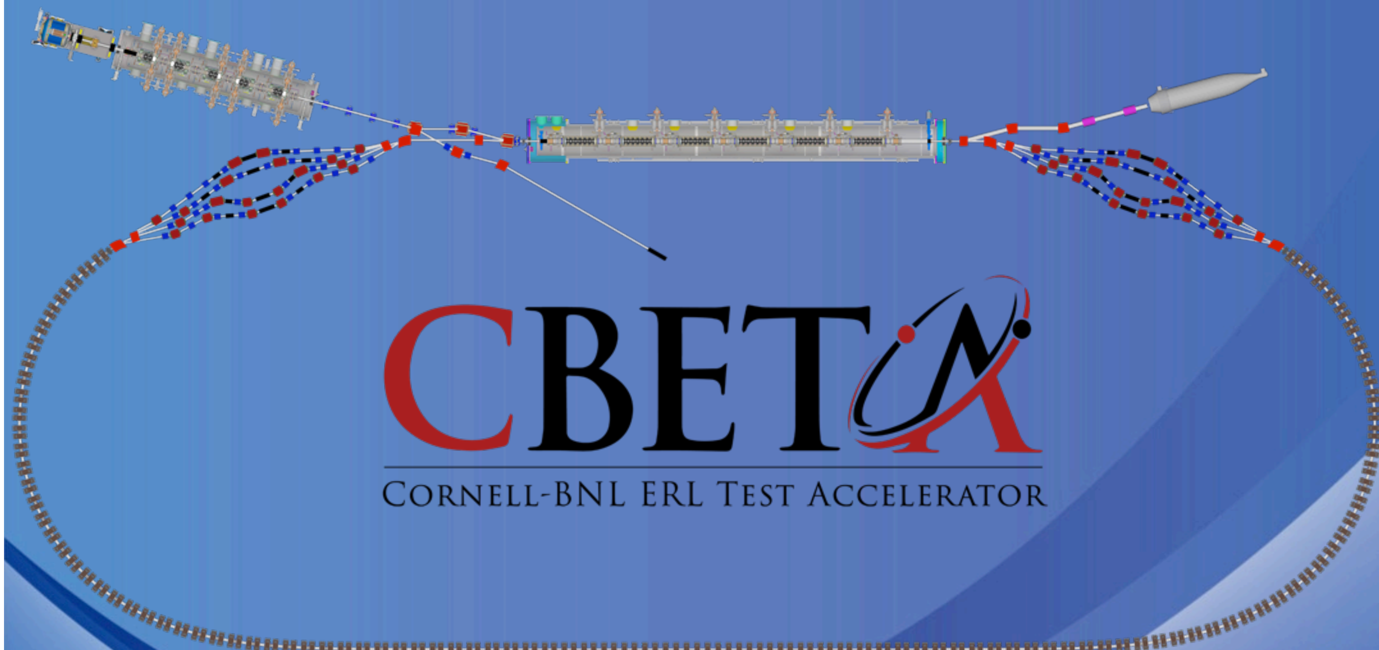
Tremendous overview, with references for derivations and explanations

Handbook of Accelerator Physics and Engineering, Alexander Wu Cao, Maury Tigner, Frank Zimmermann, Karl-Hubert Mess (preferably 2nd edition)

From a colloquium at Cornell April 2017

A new kind of particle accelerator:
The Cornell-BNL ERL Test Accelerator
for eRHIC Prototyping and Bright-Beam Applications

Georg Hoffstaetter (Cornell)



BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

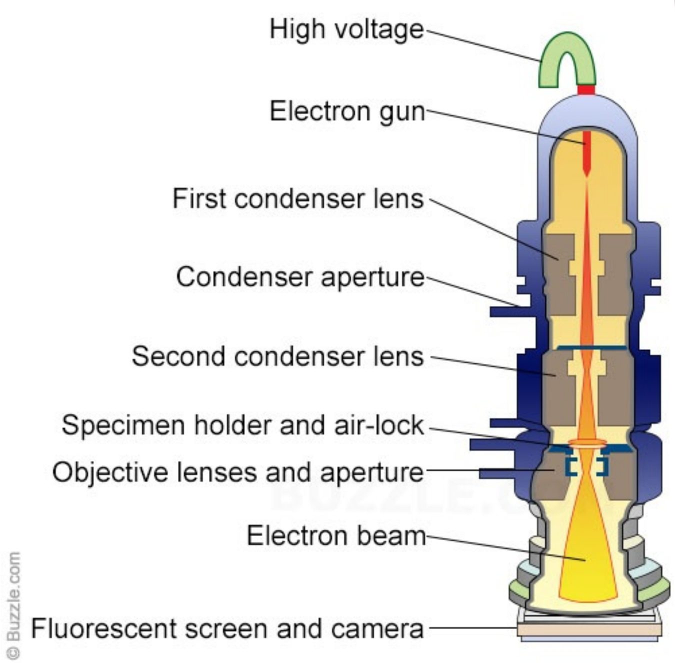
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

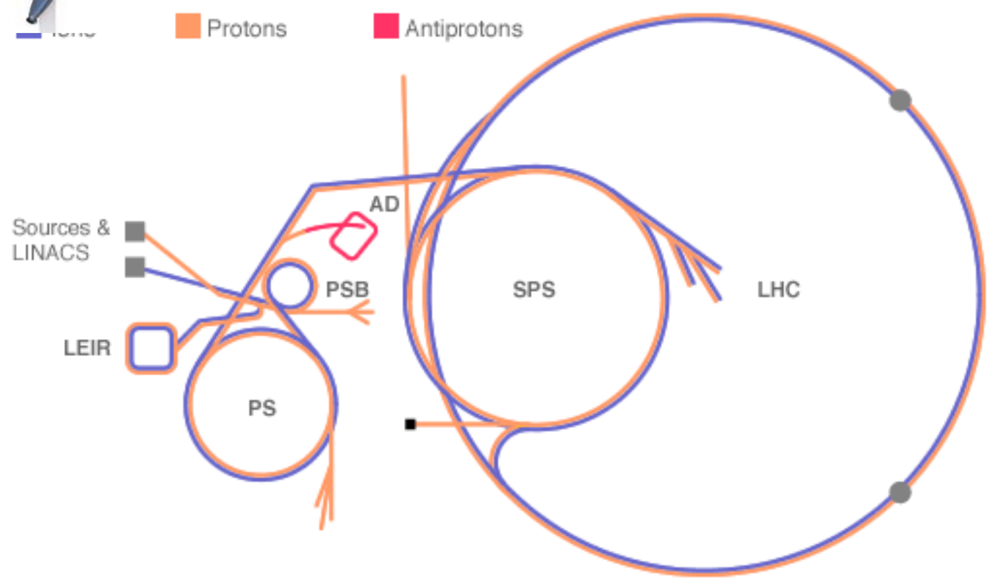
What is accelerator physics

Accelerator Physics has applications in particle accelerators for high energy physics or for x-ray science, in spectrometers, in electron microscopes, and in lithographic devices. These instruments have become so complex that an empirical approach to properties of the particle beams is by no means sufficient and a detailed theoretical understanding is necessary. This course will introduce into theoretical aspects of charged particle beams and into the technology used for their acceleration.

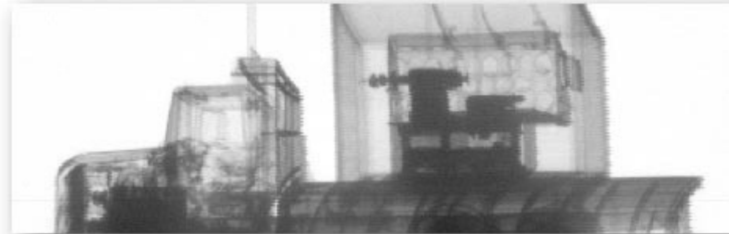
- Physics of beams
- Physics of non-neutral plasmas
- Physics of involved in the technology:
  - Superconductivity in magnets and radiofrequency (RF) devices
  - Surface physics in particle sources, vacuum technology, RF devices
  - Material science in collimators, beam dumps, superconducting materials

Particle accelerators, large and small

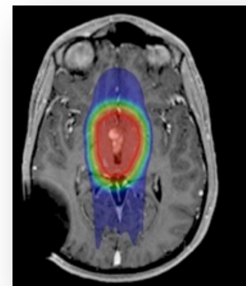




Why accelerator physics ?

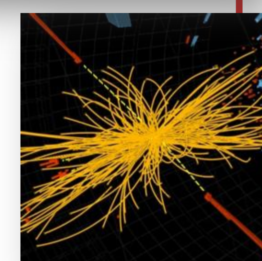


- Industry
  - Food & product safety
  - Contraband detection
  - Semiconductor fabrication
  - Bridge safety



- Medicine
  - Tumor detection and treatment.

~30,000 industrial and medical accelerators are in use, with annual sales of $3.5 B and 10% growth per year.



- Research
  - X ray sources and colliders for nuclear & particle physics
  - Electron microscopes

Since 1943, a Nobel Prize in **Physics** has been awarded to research benefiting from accelerators every 3 years.

Since 1997, the same has been true of **Chemistry**.

Accelerator physics at Cornell

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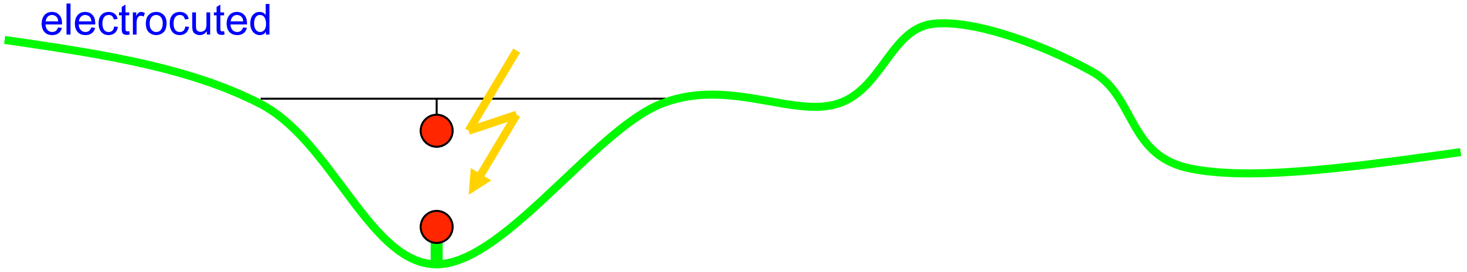
- 1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted



- 1934: Livingston builds the first Cyclotron away from Berkely (2MeV protons) at Cornell (in room B54)
- 1949: Wilson et al. at Cornell are first to store beam in a synchtotron (later 300MeV, magnet of 80 Tons)
- 1954: Wilson et al. build first synchrotron with strong focusing for 1.1MeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1979: 5GeV electron positron collider CESR (designed for 8GeV)
- Currently:

CESR operation and optimization for the CLEO experiment

CESR operation and optimization for CHESS

ERL prototyping facility (ERL e-source and injector linac)

Construction of the worlds first multi-turn SRF ERL - CBETA

Accelerator simulations, damping ring studies with CESR

Accelerator history at Cornell

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Cornell accelerators:

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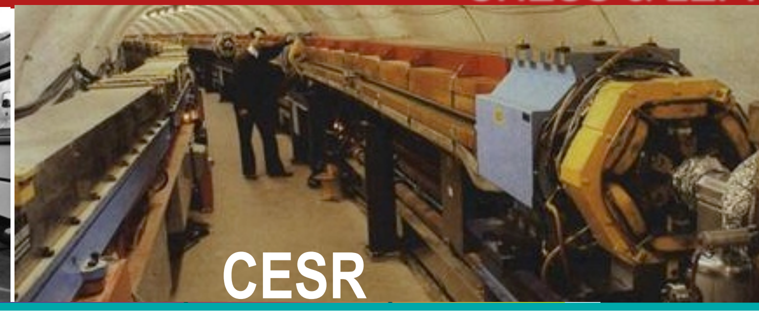


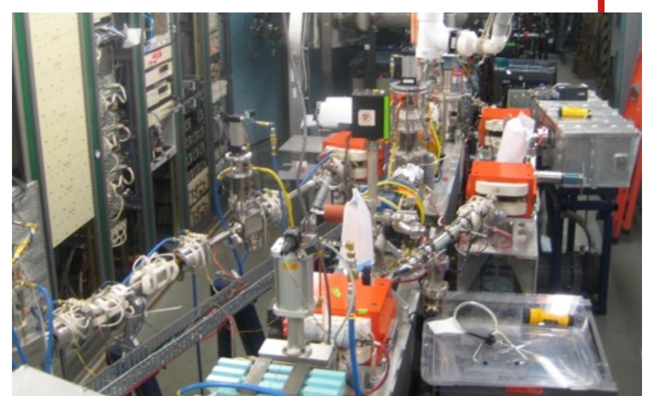
1930 1940 1950 1960 1970 1980 1990 2000 2010 2015

Cornell is a world leader in accelerators

Superconducting acceleration.

Bright electron sources. World record high current, low emittance.

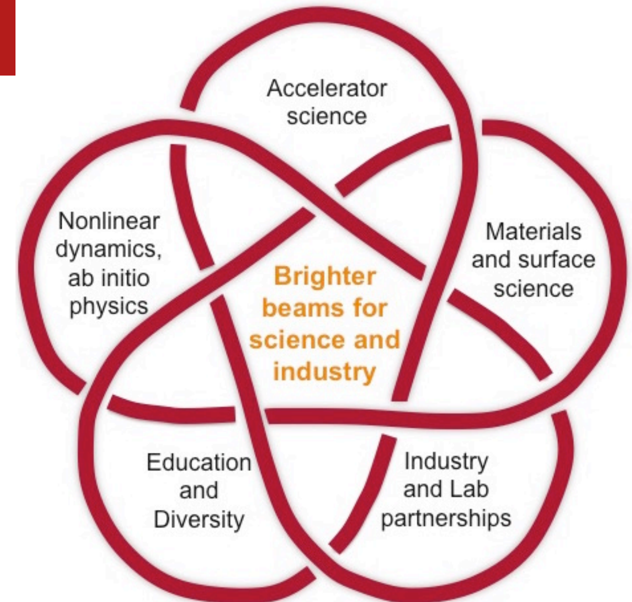
Energy Recovery Linacs. The new accelerator paradigm.



Cornell's academic program in accelerator science is the strongest in the U.S.

Most faculty, most PhD's, most high-impact accomplishments.

Center of Bright Beams (CBB)



CBB Vision:

Better particle beams for applications ranging from giant colliders to table top electron microscopes enabling new opportunities for science and industry.

CBB Mission:

Transform the reach of electron beams by increasing their brightness x100 and reducing the cost and size of key enabling technologies.

Transfer the best of these technologies to national labs and industry.

Cornell University
UF University of Florida
The University of Chicago
UCLA
University of Toronto
BYU
University of Maryland
Chicago State University
Morehouse College
Clark Atlanta University
Fermilab
Berkeley Lab
TRIUMF

Cornell's synchroton and storage ring

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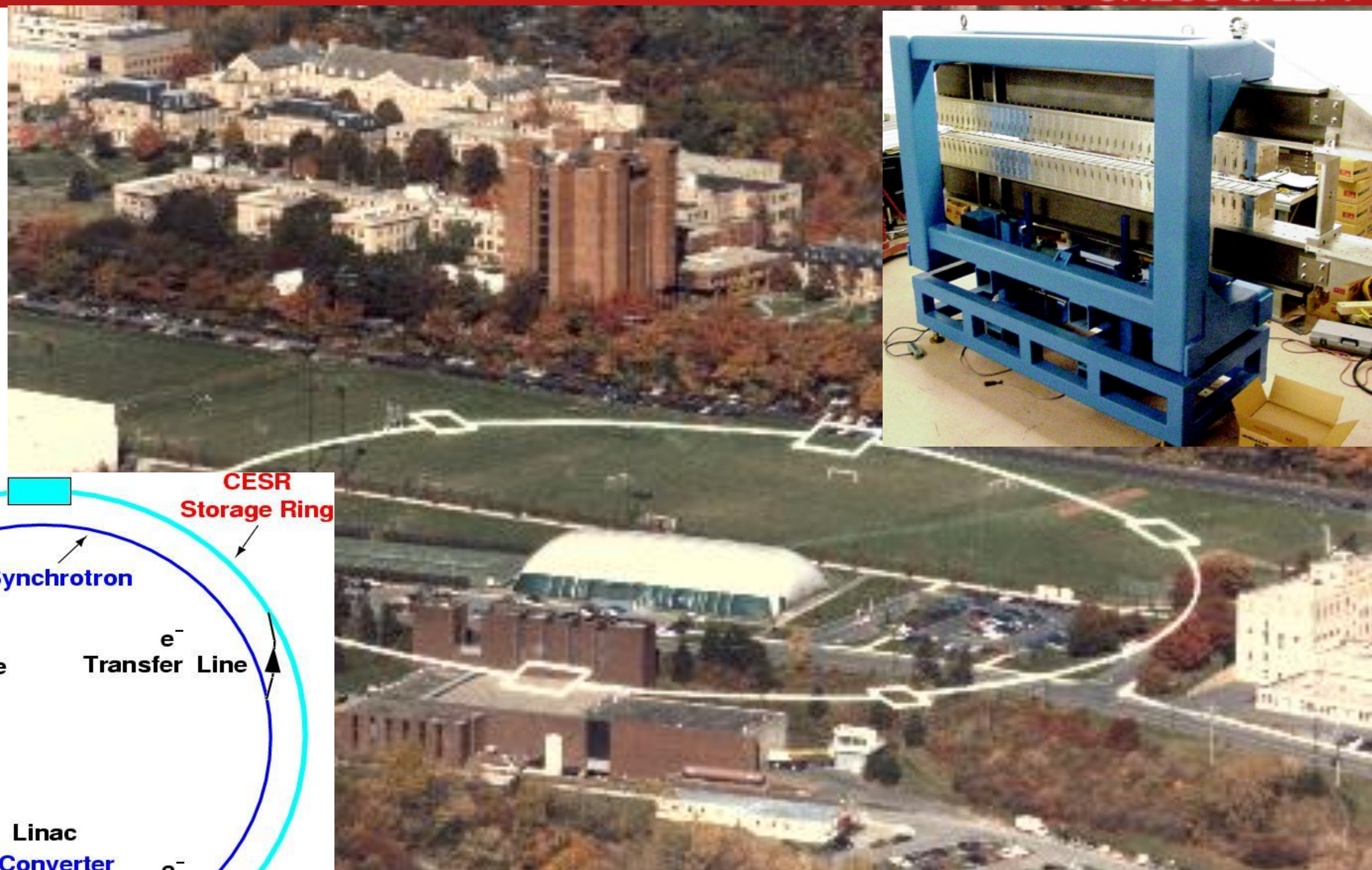

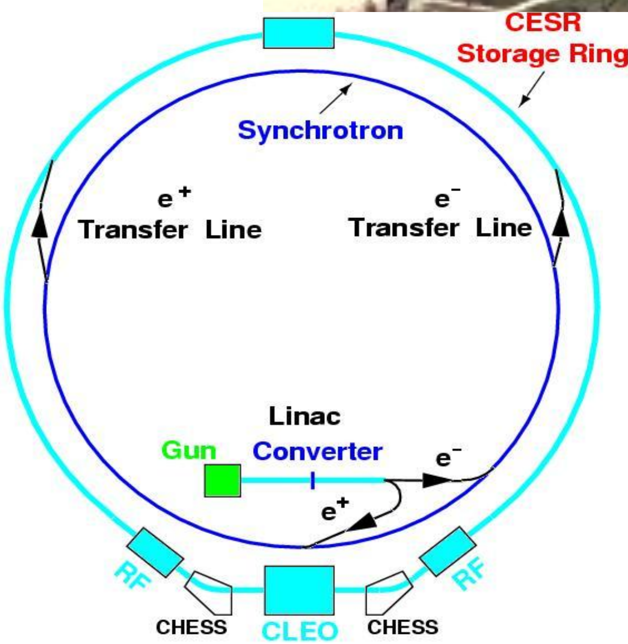

An early construction and NSF project

Tunnel digging
(as of 1966)

… out

The largest single NSF investment at up to date at the time.

Cornell's long tradition of tunnels

Tunnel digging
(as of 1830s)

At Ithaca falls, constructed by Ezra Cornell.

The cyclotron frequency

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Dee

Condition: Non-relativistic particles.

Therefore not for electrons.

- The synchrocyclotron:

  Acceleration of bunches with decreasing

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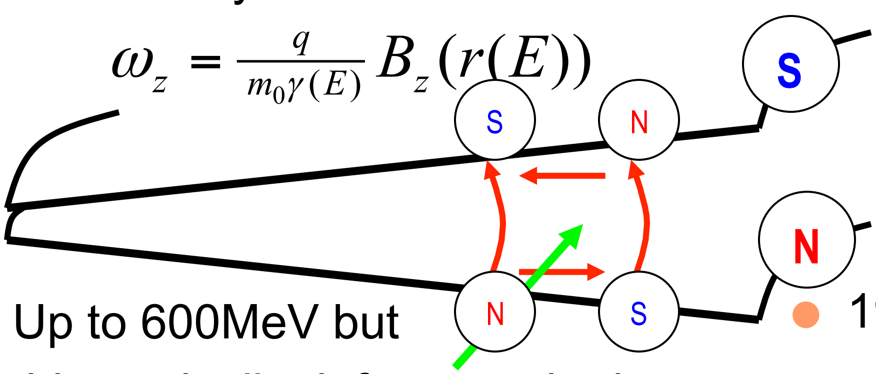
- The isocyclotron with constant

$$\omega_z = \frac{q}{m_0\gamma(E)} B_z(r(E))$$



Up to 600MeV but

this vertically defocuses the beam

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- 1938: Thomas proposes strong (transverse) focusing for a cyclotron

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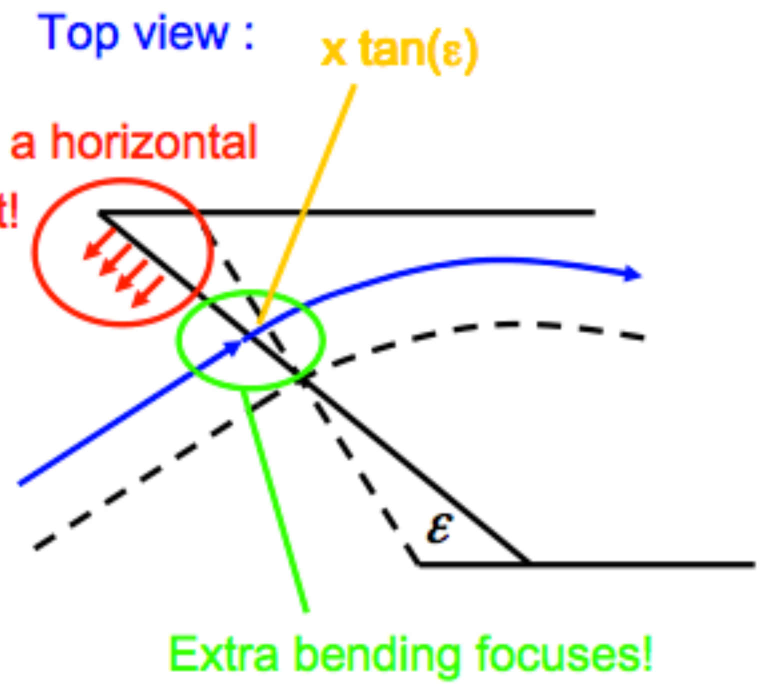
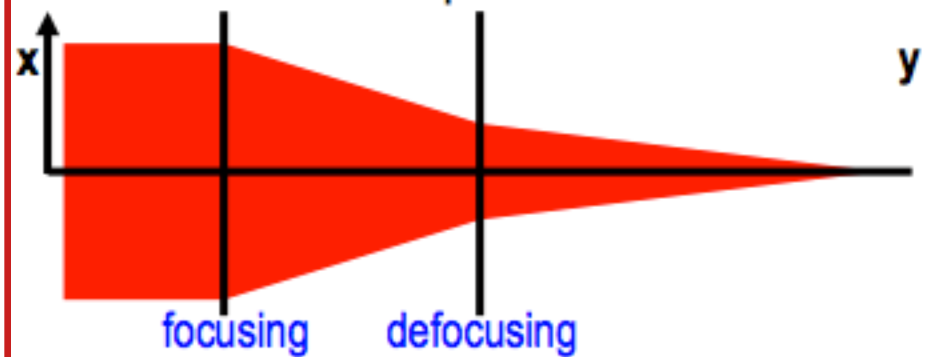
Horizontal focusing with $\Delta x' = -x\frac{\tan(\varepsilon)}{\rho}$

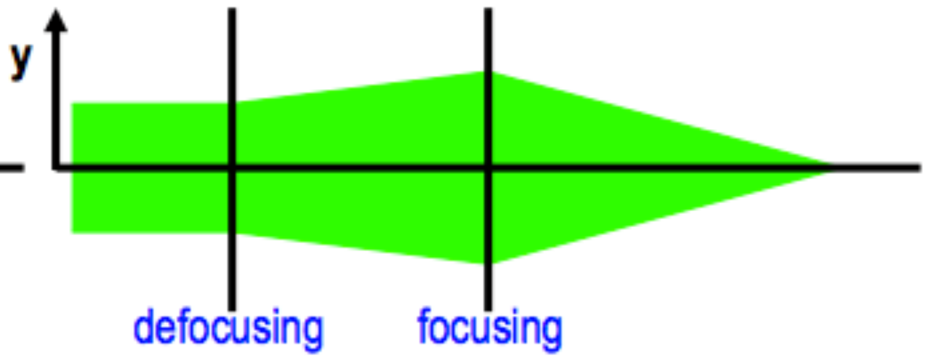


The longitudinal field above the enter plain defocuses, turns out to: $\Delta y' = y\frac{\tan(\varepsilon)}{\rho}$

Quadrupole effect: focusing in x and defocusing in y or defocusing in x and focusing in y.

Transverse fields defocus in one plane if they focus in the other plane.
But two successive elements, one focusing the other defocusing,
can focus in both planes:

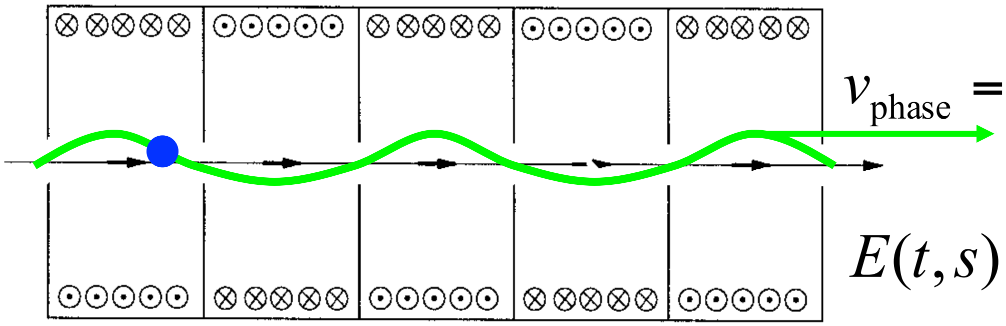




Accelerating cavities

- 1933: J.W. Beams uses resonant cavities for acceleration

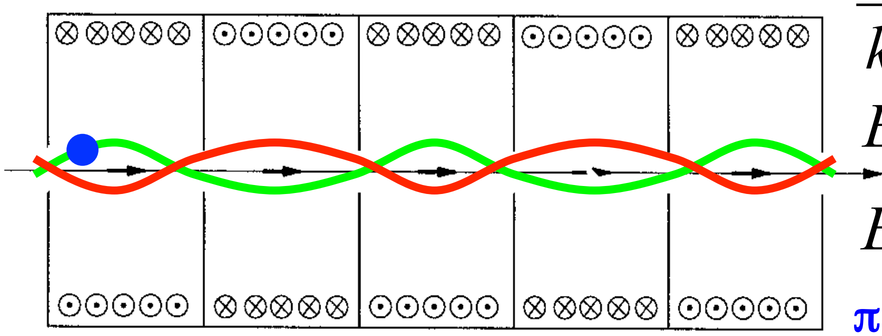
Traveling wave cavity:



$$v_{\text{phase}} = \frac{\omega}{k} = v_{\text{particle}}$$ Here v=c for electrons

$$E(t,s) \approx E_{\max} \sin(\omega t - ks)$$

Standing wave cavity:



$$\frac{\omega}{k} = v_{\text{particle}}$$

$$E(t,s) \approx E_{\max} \sin(\omega t)\sin(ks)$$

$$E(\tfrac{s}{v_{\text{particle}}}, s) \approx E_{\max} \sin^2(ks)$$

π or the 1/2βλ mode

Transit factor (for this example): $\langle E \rangle = \frac{1}{\lambda_{RF}} \int_0^{\lambda_{RF}} E(\tfrac{s}{v_{\text{particle}}}, s)\, ds \approx \tfrac{1}{2} E_{\max}$

The Synchrotron

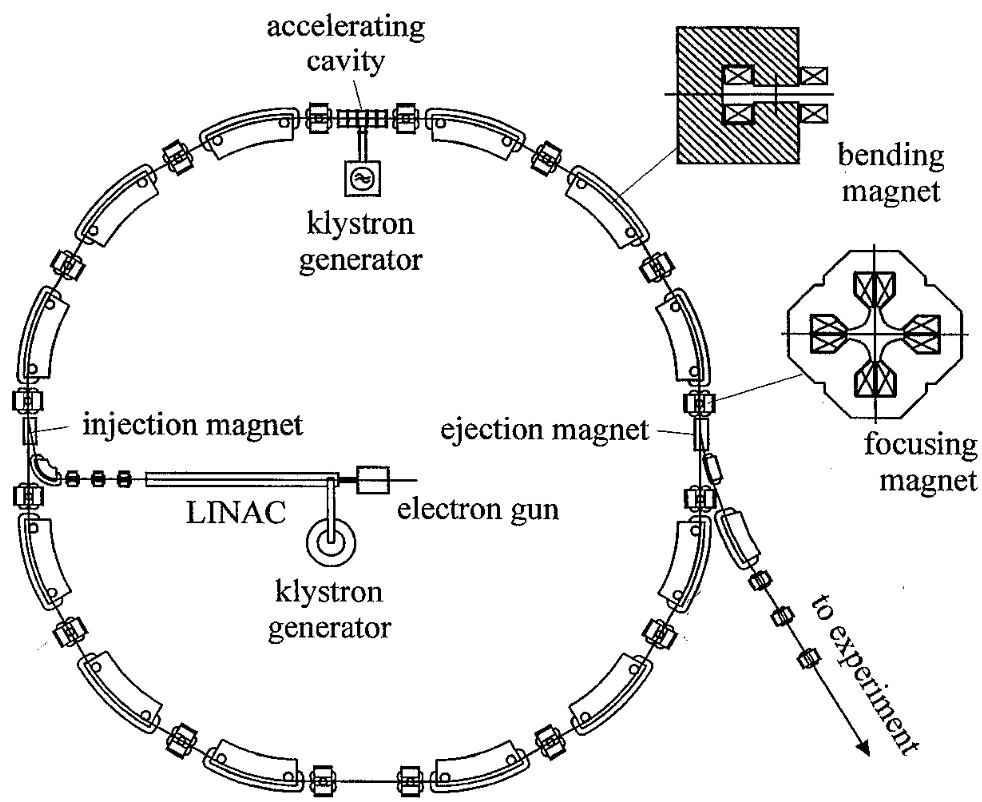
- 1945: Veksler (UDSSR) and McMillan (USA) invent the synchrotron
- 1946: Goward and Barnes build the first synchrotron (using a betatron magnet)
- 1949: Wilson et al. at Cornell are first to store beam in a synchrotron (later 300MeV, magnet of 80 Tons)
- 1949: McMillan builds a 320MeV electron synchrotron

- Many smaller magnets instead of one large magnet
- Only one acceleration section is needed, with

$$R = \frac{p(t)}{qB(R,t)} = \text{const.}$$

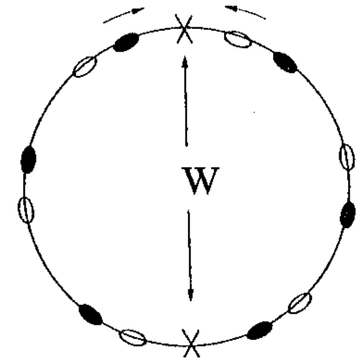
$$\omega = 2\pi \frac{v_{\text{particle}}}{L} n$$

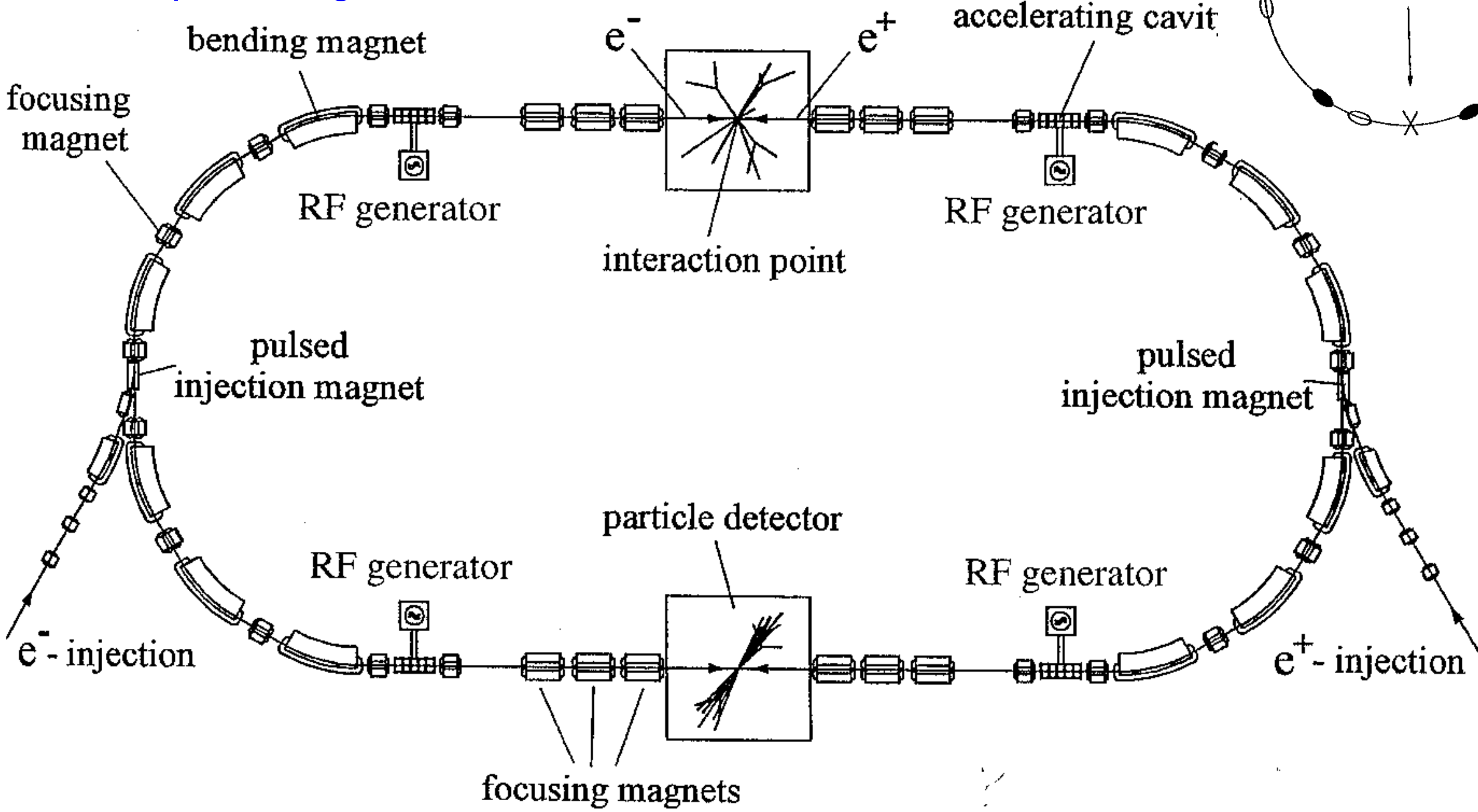
for an integer n called the harmonic number



Ellements of a Collider

- Saving one beam while injection another
- Avoiding collisions outside the detectors.
- Compensating the forces between e^+ and e^- beams





Storage Rings

To avoid the loss of collision time during filling of a synchrotron, the beams in colliders must be stored for many millions of turns.

Challenges:

- Required vacuum of pressure below 10^{-7} Pa = 10^{-9} mbar, 3 orders of magnitude below that of other accelerators.
- Fields must be stable for a long time, often for hours.
- Field errors must be small, since their effect can add up over millions of turns.
- Even though a storage ring does not accelerate, it needs acceleration sections for phase focusing and to compensate energy loss due to the emission of radiation.