Accelerator Physics for an ERL x-ray Source

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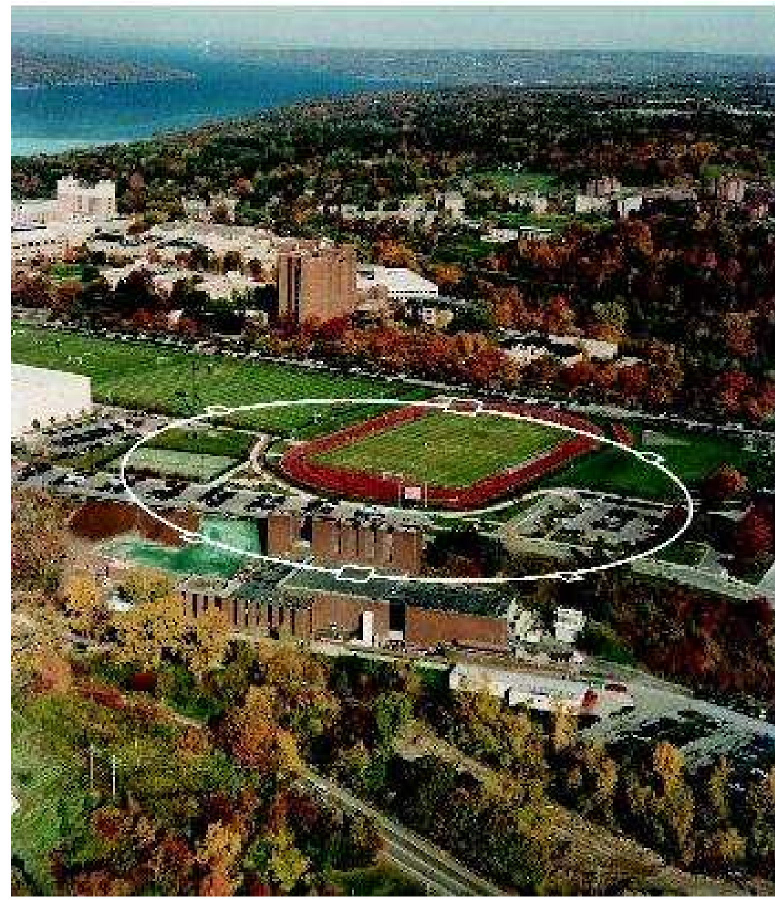
1. History of Accelerators
2. Synchrotron Radiation Sources
3. Linear Beam Dynamics
4. Emittances
5. Radiative Beam Dynamics
6. Photo Emission Guns
7. Space Charge Issues
8. Linacs
9. Accelerating cavities
10. Beam instabilities
11. SRF technology
12. Longitudinal beam dynamics
13. Wake Fields
14. Intra Beam and Gas Scattering, Shielding
15. Ions
16. CSR



Cornell's x-ray ERL

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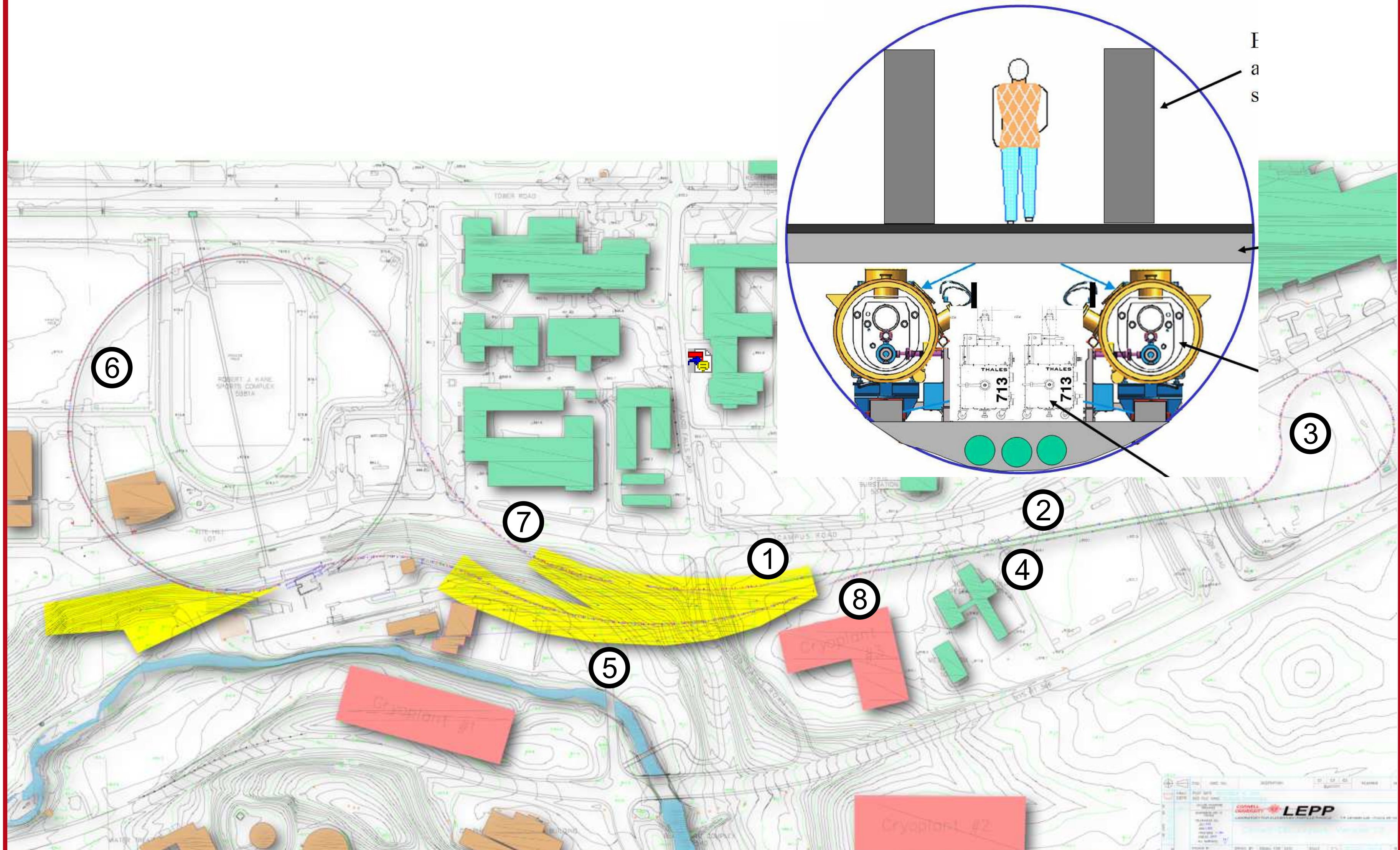

Literature

Required:
Required material will be photocopied by the instructor.

Optional:
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

Related material:
Handbook of Accelerator Physics and Engineering, Alexander Wu Chao and Maury Tigner, 2nd edition, 2002, World Scientific, ISBN: 981 02 3858 4

Particle Accelerator Physics II, Helmut Wiedemann, Springer, 2nd edition, 1999, ISBN 3 540 64504 7

Images

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 Ionenoptik, Frank Hinterberger, 1997, Springer, ISBN 3 540 61238 6

Introduction to Ultraviolet and X-Ray Free-Electron Lasers, Martin Dohlus, Peter Schmusser, Jorg Rossbach, Springer, 2008, in preparation

Various public web pages, 2003-2008

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

Different accelerators

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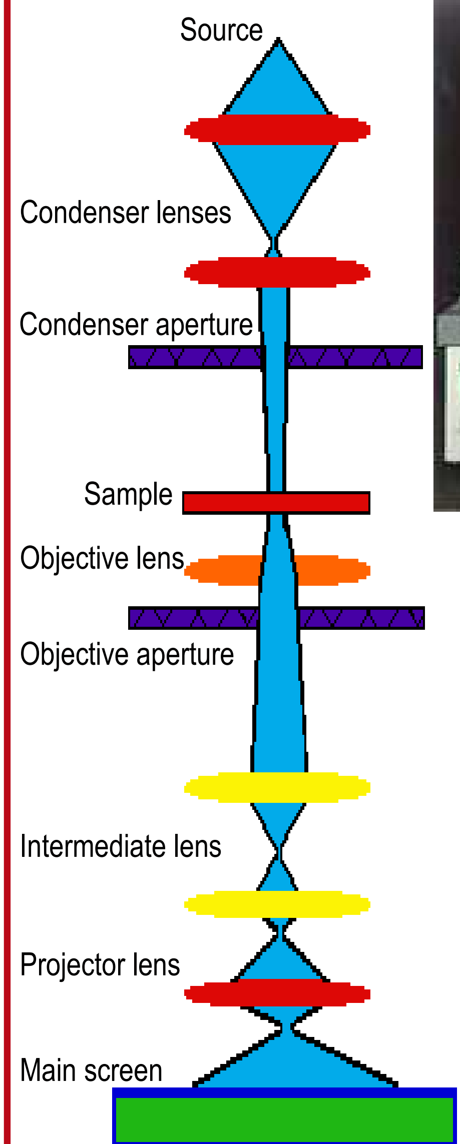
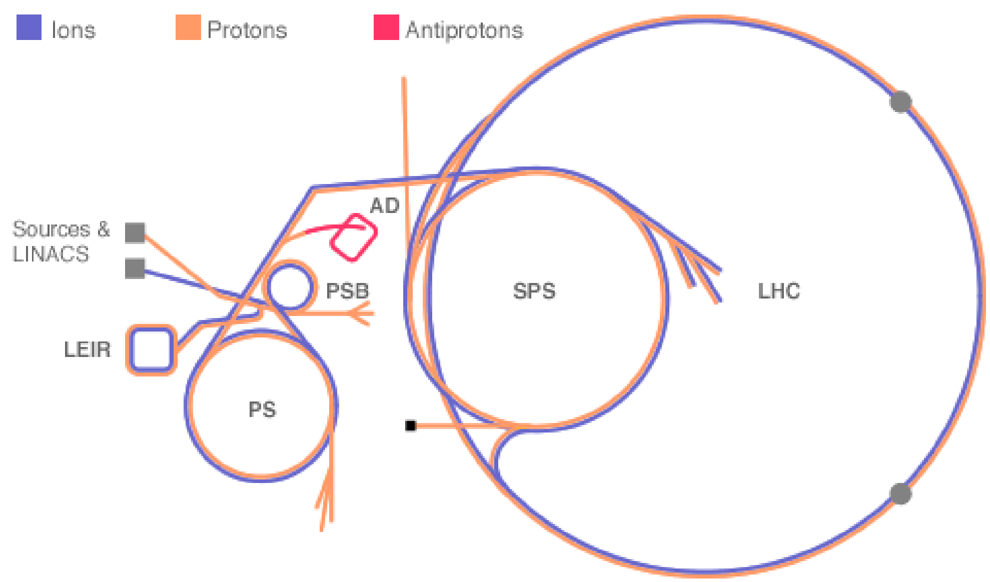




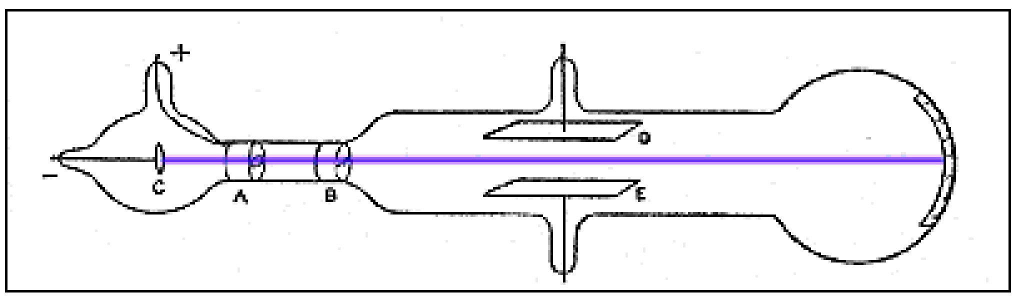
A short history of accelerators

- 1862: Maxwell theory of electromagnetism
- 1887: Hertz discovery of the electromagnetic wave
- 1886: Goldstein discovers positively charged rays (ion beams)
- 1894: Lenard extracts cathode rays (with a 2.65um Al Lenard window)
- 1897: JJ Thomson shows that cathode rays are particles since they followed the classical Lorentz force $m\vec{a} = e(\vec{E} + \vec{v} \times \vec{B})$ in an electromagnetic field
- 1926: GP Thomson shows that the electron is a wave
  (1929-1930 in Cornell, NP in 1937)

NP 1905

Philipp E.A. von Lenard

Germany 1862-1947



NP 1906

Joseph J. Thomson

UK 1856-1940

Davison-Germer Experiment

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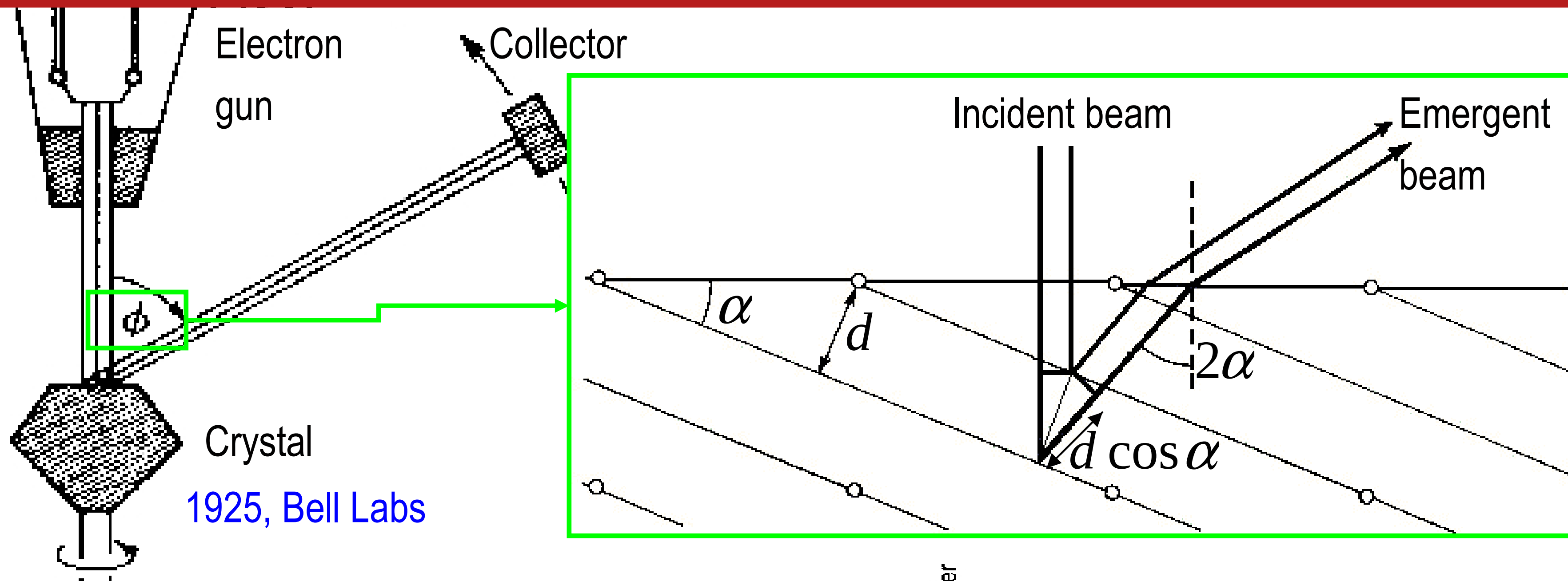
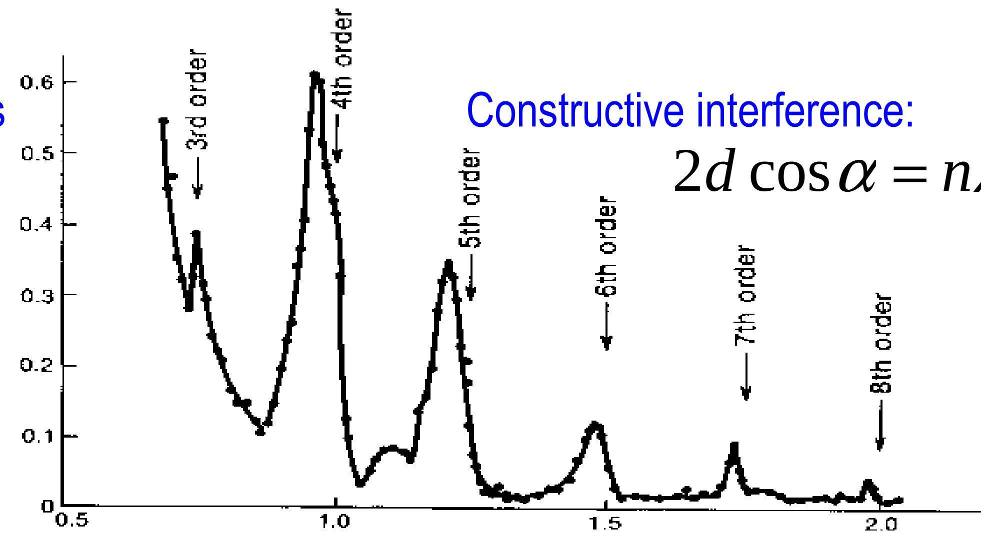


1925, Bell Labs

Clinton Davisson
(1881-1958)
Nobel Price 1937

Reflection as a function of energy

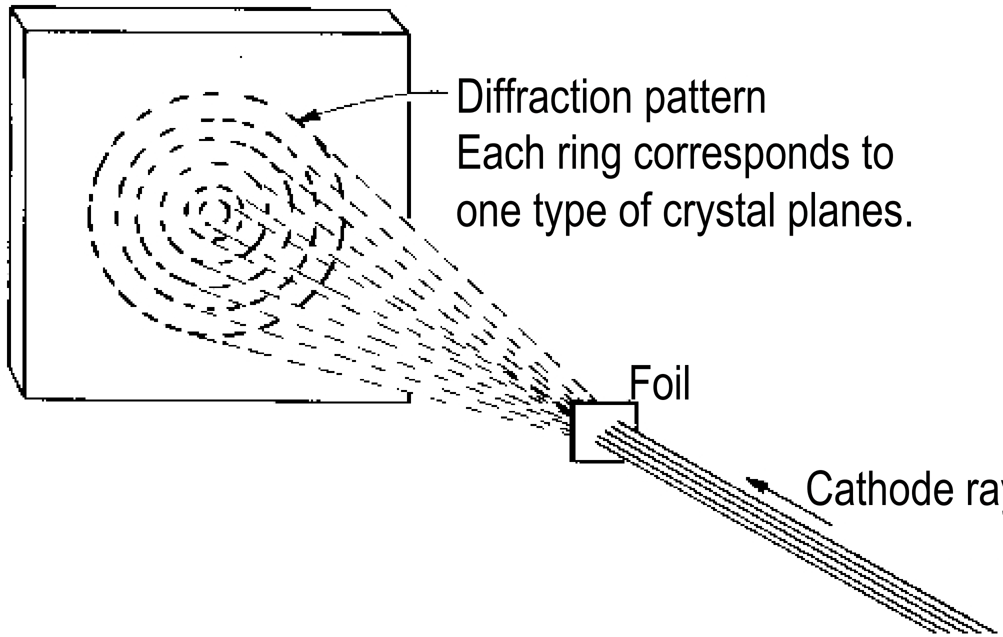


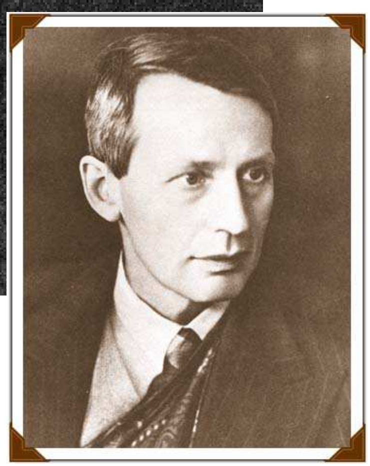
Constructive interference:

$$2d\cos\alpha = n\lambda$$

George Thomson's Experiment

In a powdered, microcrystalline substance there is always some crystal which has the correct angle for constructive interference $2d \cos \alpha = n\lambda$





George P.Thomson
(1892-1975)
1937 Nobel prize
Son of Joseph J. T.

A magnetic field can change the rings, showing the the waves are associated with the electron charge.

A short history of accelerators

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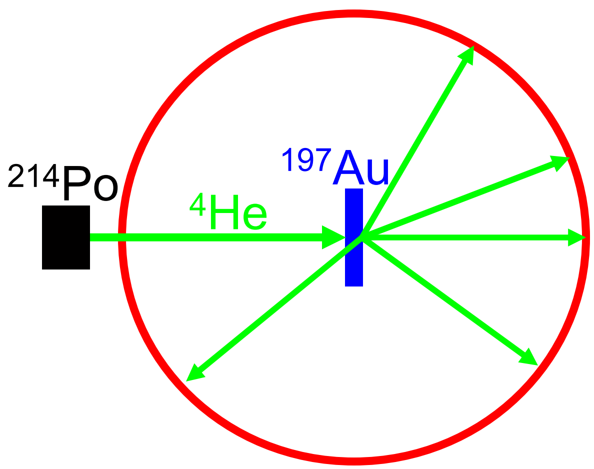
- 1911: Rutherford discovers the nucleus with 7.7MeV ^{4}He from ^{214}Po alpha decay measuring the elastic cross section of ^{197}Au + ^{4}He $\mapsto$ ^{197}Au + ^{4}He.



$$E = \frac{Z_1 e Z_2 e}{4\pi\varepsilon_0 d} = Z_1 Z_2 m_e c^2 \frac{r_e}{d},$$

$$r_e = 2.8\text{fm}, \quad m_e c^2 = 0.511\text{MeV}$$

d = smallest approach for back scattering

- 1919: Rutherford produces first nuclear reactions with natural ^{4}He
  ^{14}N + ^{4}He $\mapsto$ ^{17}O + p
- 1921: Greinacher invents the cascade generator for several 100 keV
- Rutherford is convinced that several 10 MeV are in general needed for nuclear reactions. He therefore gave up the thought of accelerating particles.

Tunneling allows low energies

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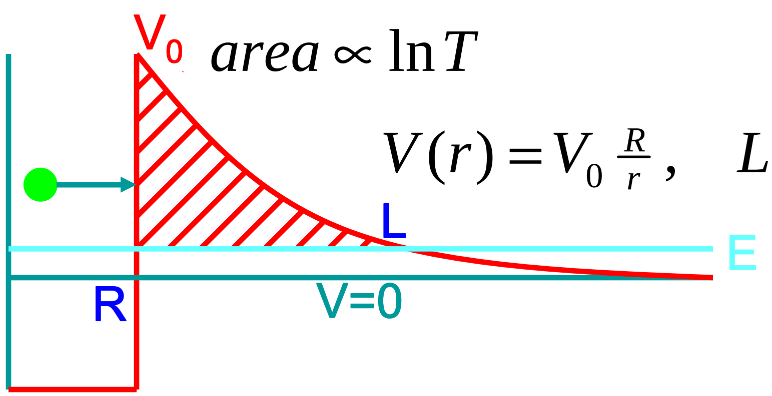
- 1928: Explanation of alpha decay by Gamov as tunneling showed that several 100keV protons might suffice for nuclear reactions

Schroedinger equation: $\frac{\partial^2}{\partial r^2}u(r)=\frac{2m}{\hbar^2}[V(r)-E]u(r)\,,\quad T=\left|\frac{u(L)}{u(0)}\right|^2$

The transmission probability T for an alpha particle traveling from the inside towards the potential well that keeps the nucleus together determines the lifetime for alpha decay.

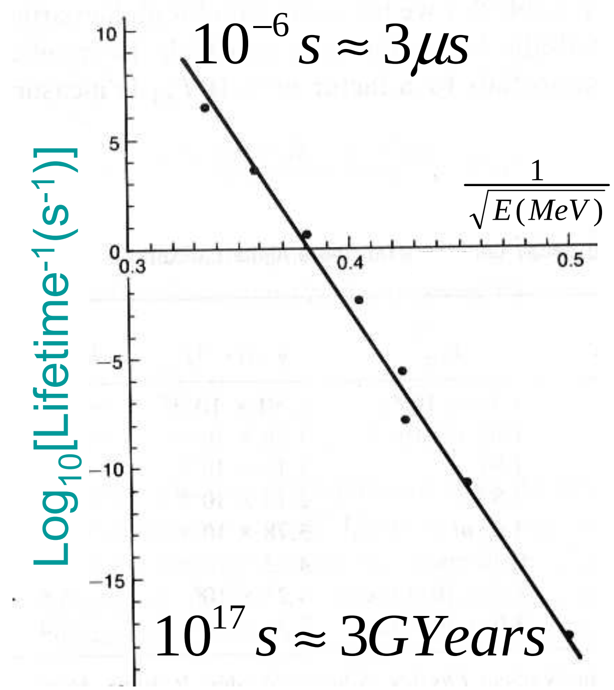
$area \propto \ln T$



$V(r)=V_0\frac{R}{r}\,,\quad L=\frac{V_0}{E}R$

$$T\approx\exp[-2\int_R^L\frac{\sqrt{2m[V(r)-E]}}{\hbar}dr]$$

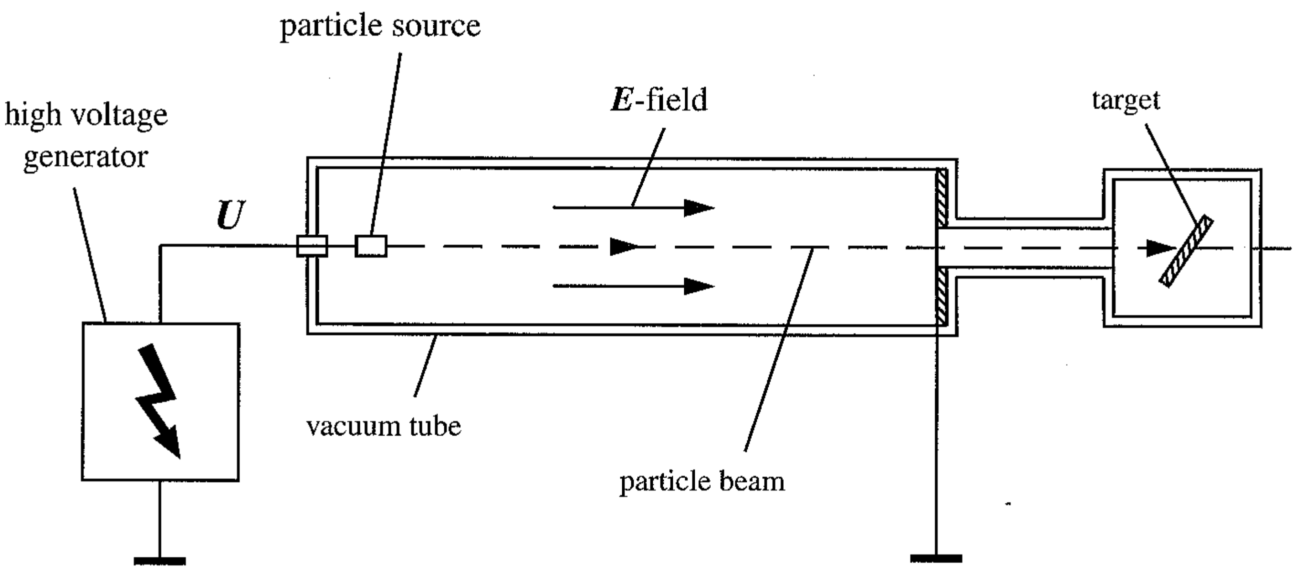
$$\ln T\approx A-\frac{C}{\sqrt{E}}$$



Three historic lines of accelerators

Direct Voltage Accelerators

Resonant Accelerators   Transformer Accelerator



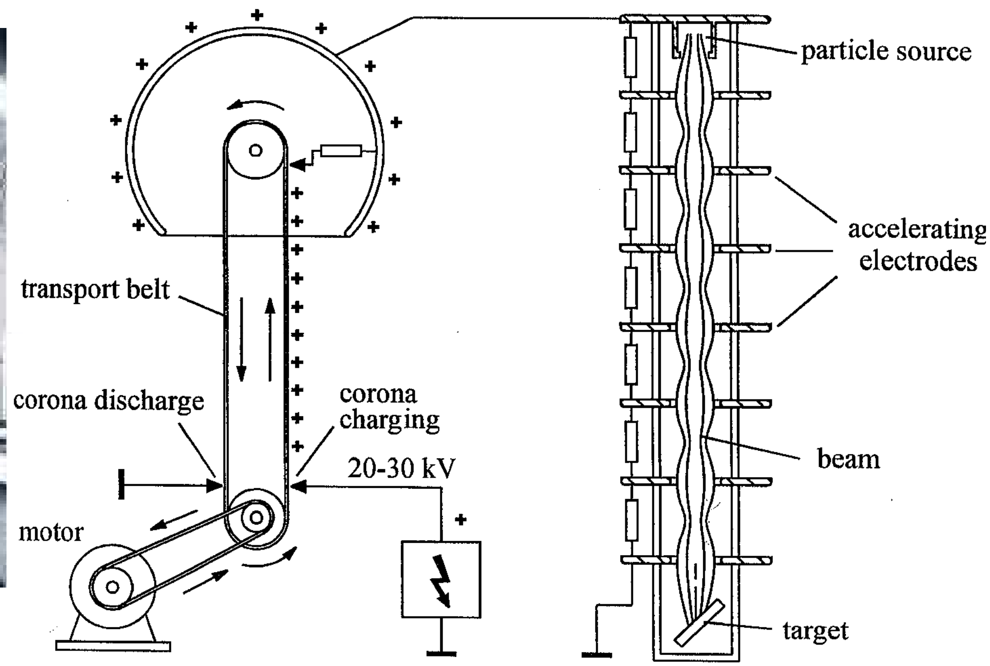
Voltage 1MV
Charge Ze
Energy Z MeV

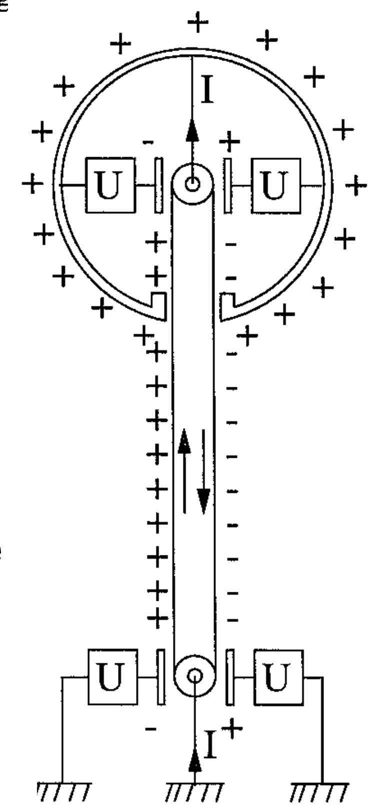
The energy limit is given by the maximum possible voltage. At the limiting voltage, electrons and ions are accelerated to such large energies that they hit the surface and produce new ions. An avalanche of charge carries causes a large current and therefore a breakdown of the voltage.

The Van de Graaff Accelerator

- 1930: van de Graaff builds the first 1.5MV high voltage generator

Van de Graaff

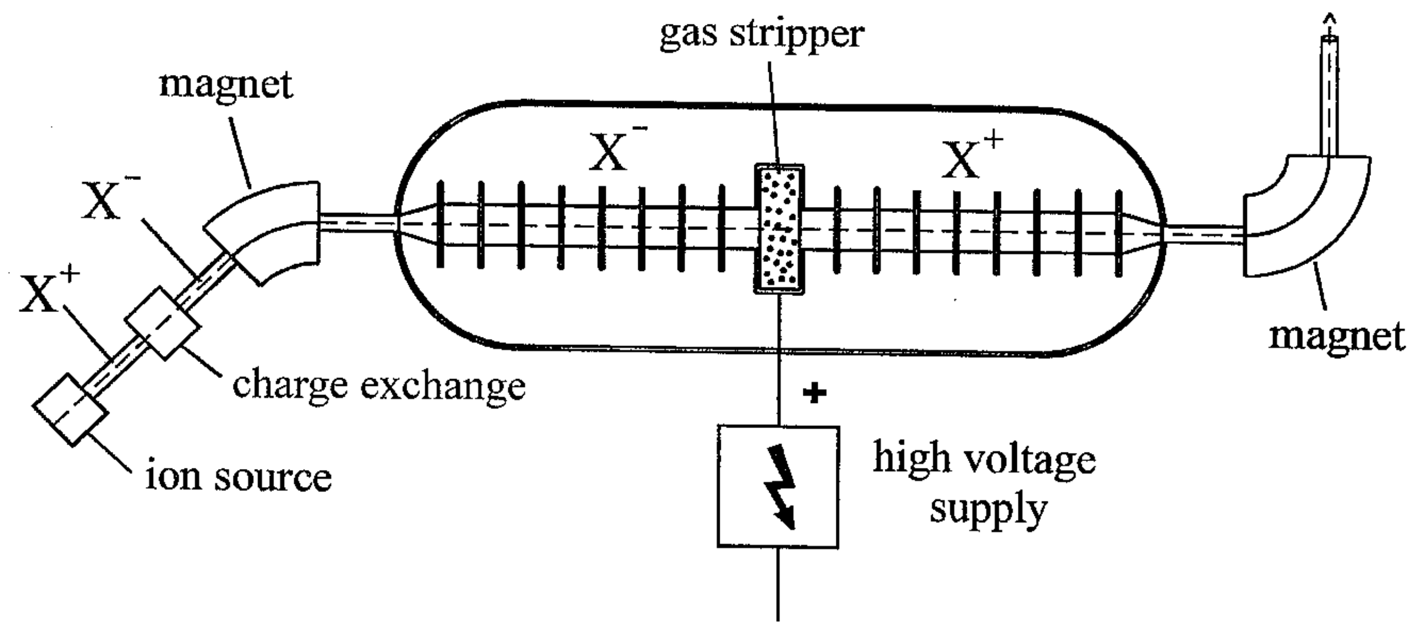




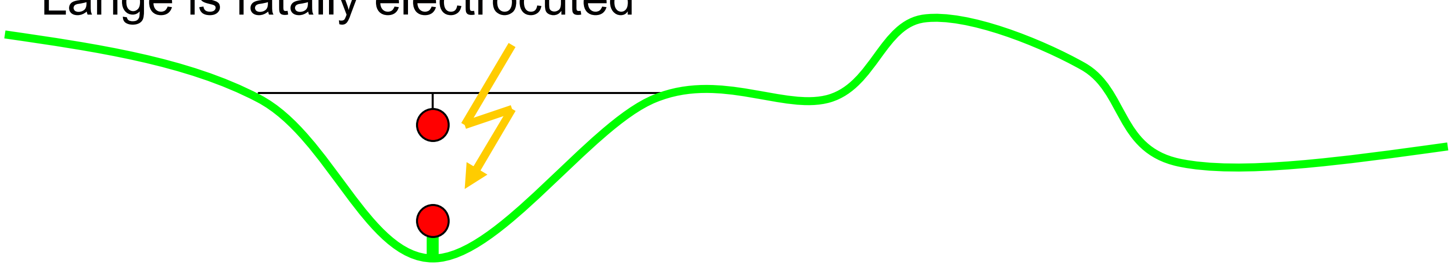
- Today Peletrons (with chains) or Laddertron (with stripes) that are charged by influence are commercially available.
- Used as injectors, for electron cooling, for medical and technical n-source via $d + t \mapsto n + \alpha$
- Up to 17.5 MV with insulating gas (1MPa SF_6)

The Tandem Accelerator

- Two Van de Graaffs, one + one –
- The Tandem Van de Graaff, highest energy 35MeV



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



The Cockcroft-Walton Accelerator

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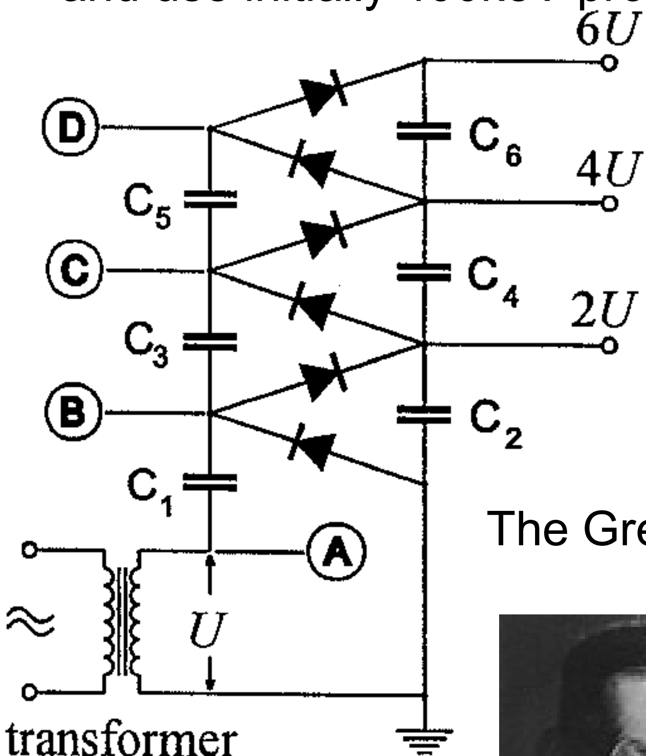
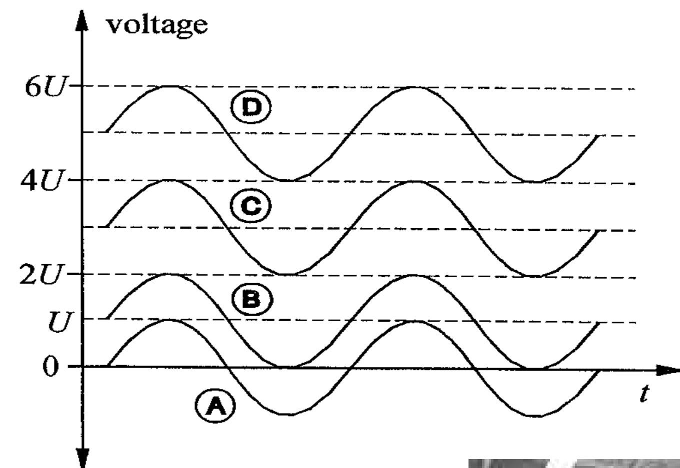
1932: Cockcroft and Walton 1932: 700keV cascate generator (planed for 800keV) and use initially 400keV protons for $^{7}Li + p \mapsto {}^{4}He + {}^{4}He$ and $^{7}Li + p \mapsto {}^{7}Be + n$





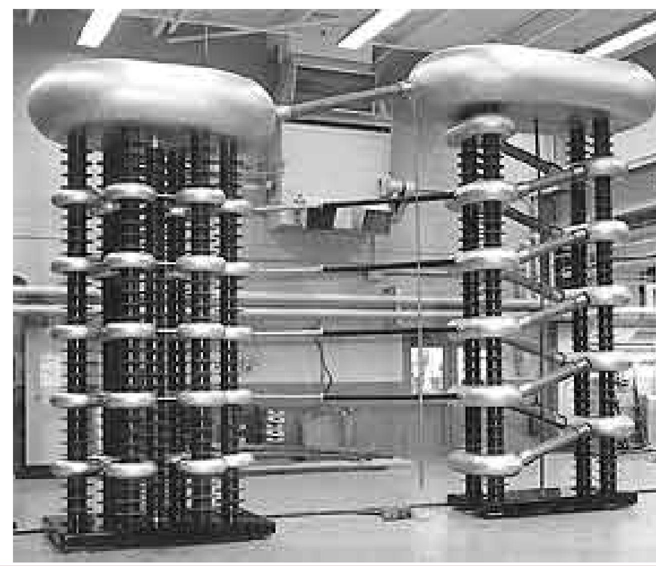
The Greinacker circuit

Up to 4MeV, 1A

NP 1951

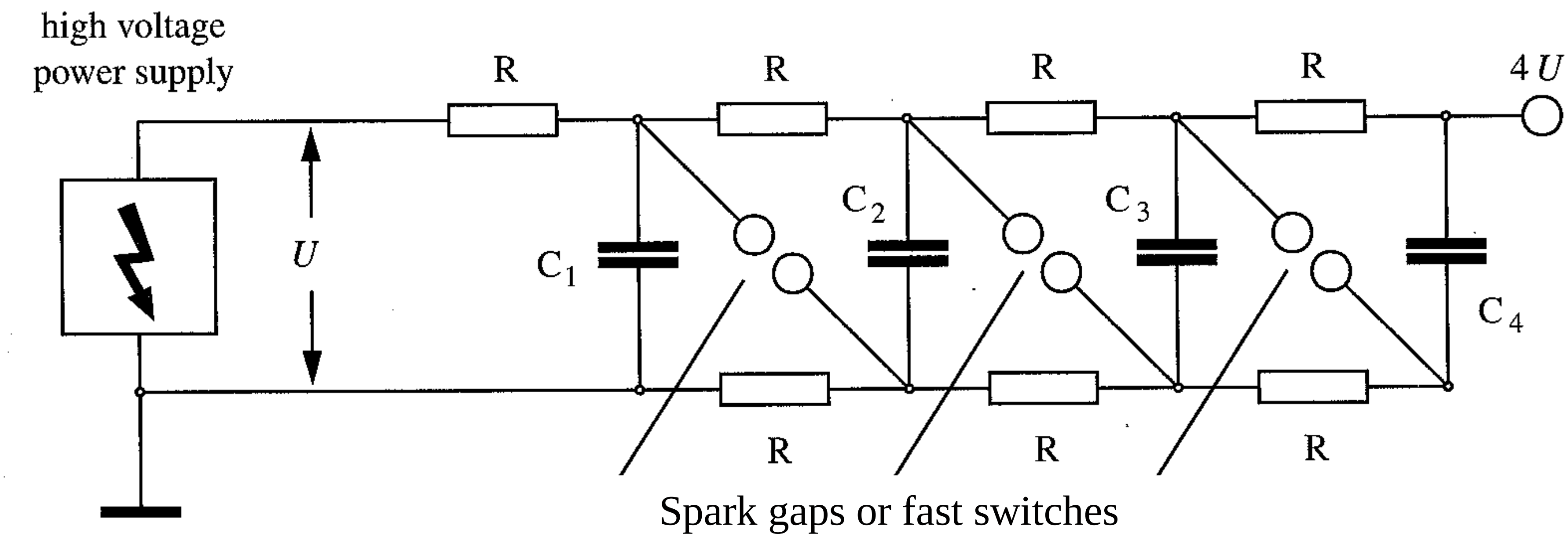
Sir John D Cockcrof

Ernest T S Walton



The Marx Generator

- 1932: Marx Generator achieves 6MV at General Electrics



After capacitors of around 2uF are filled to about 20kV, the spark gaps or switches close as fast as 40ns, allowing up to 500kA.

Today:
The Z-machine (Physics Today July 2003) for z-pinch initial confinement fusion has 40TW for 100ns from 36 Marx generators