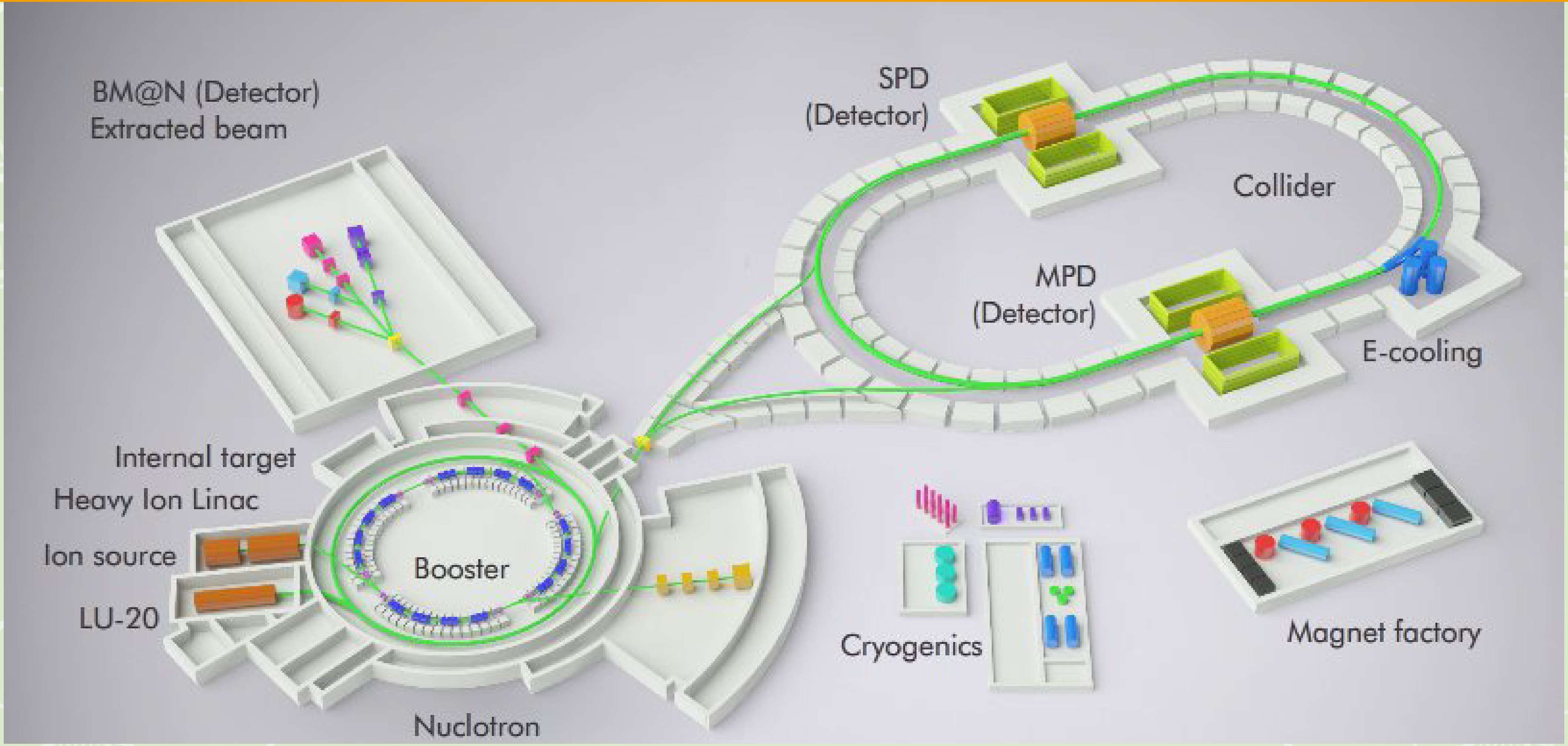
# Acceleration complex and magnet factory




M. Shandov

First Open Day of the NICA Complex, JINR, Dubna, October 31, 2018

# Introduction

## Topics

What Are Accelerators Used For?

NICA Structure

Basic Principle of Accelerators

Accelerator History

Accelerator Types

Basic Systems of Accelerators

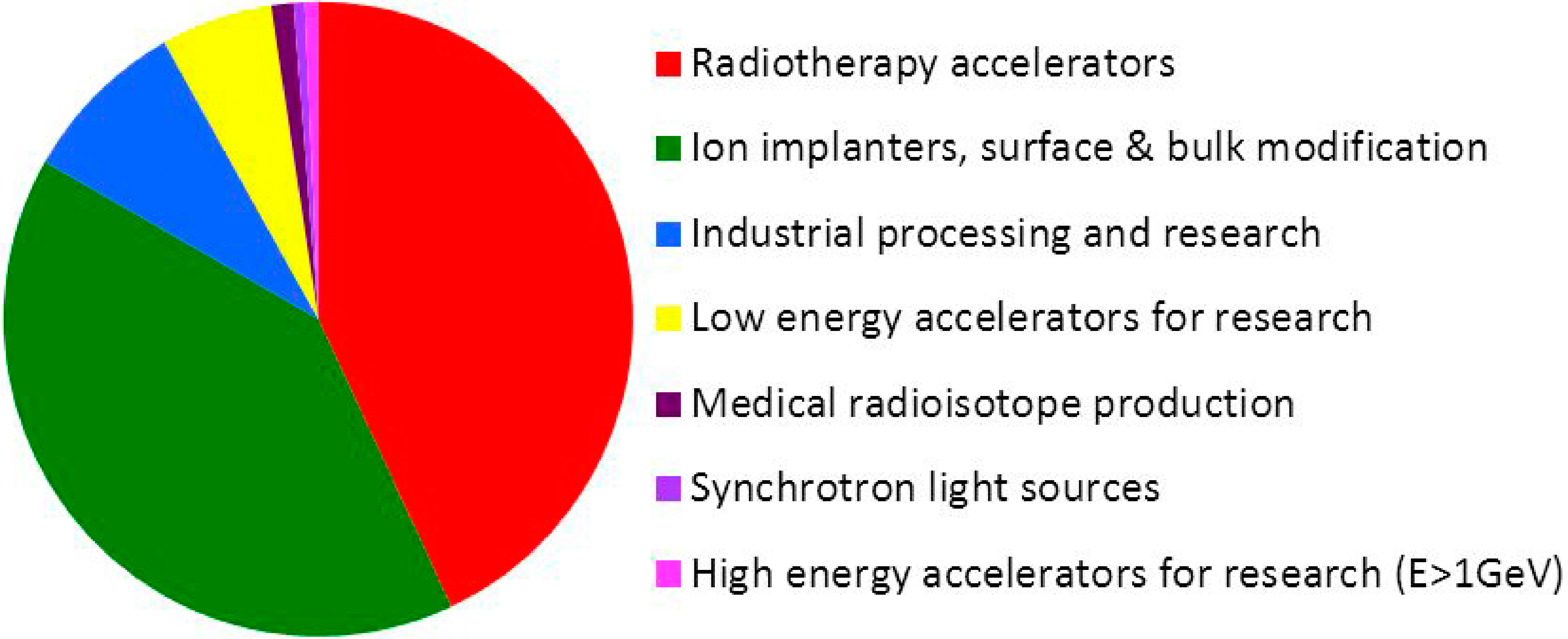
Superconductivity Magnets. Magnet Factory

Other Acceleration Methods

The Accelerator: Different Points of View

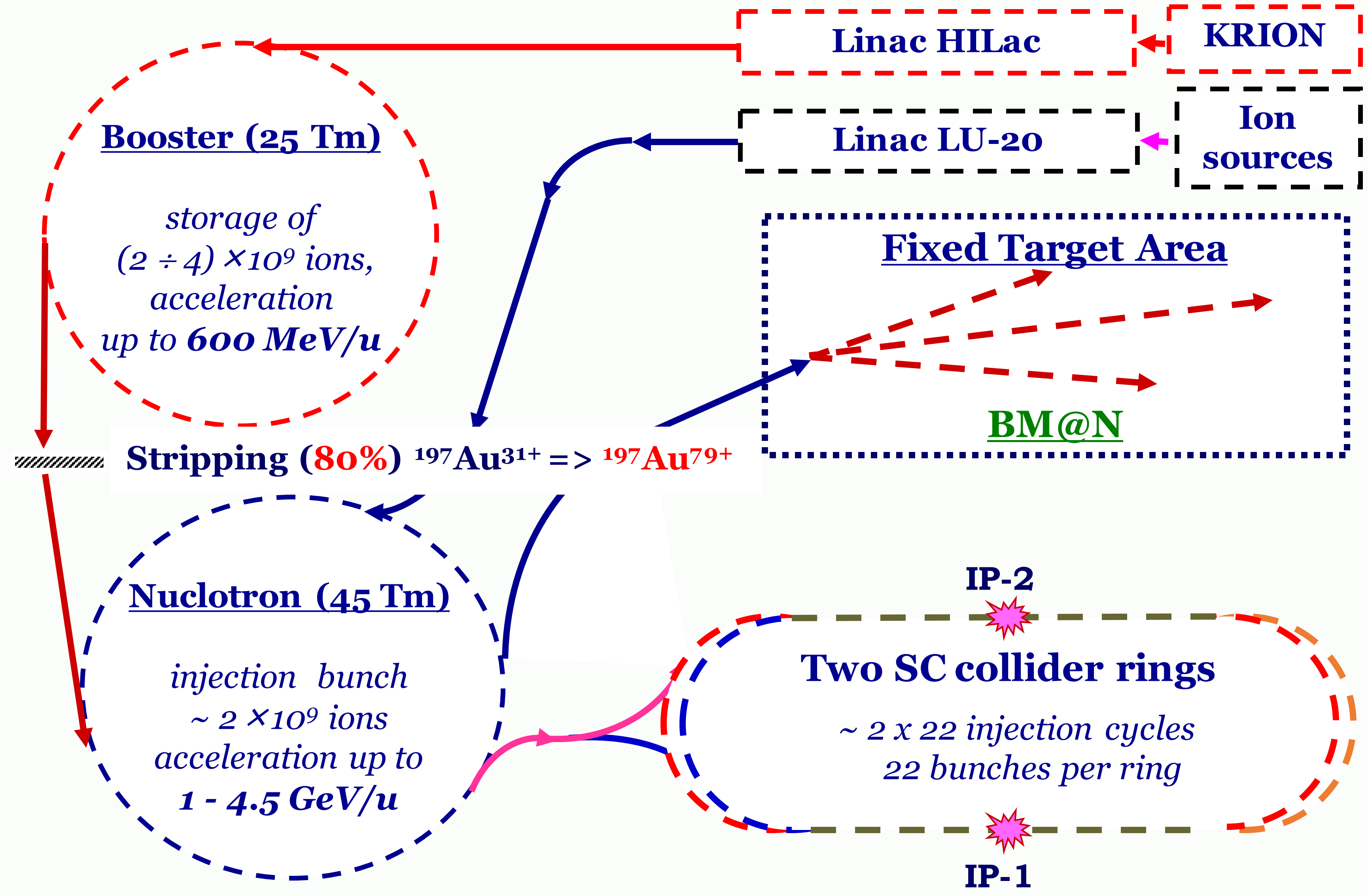
# What are accelerators used for?

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011



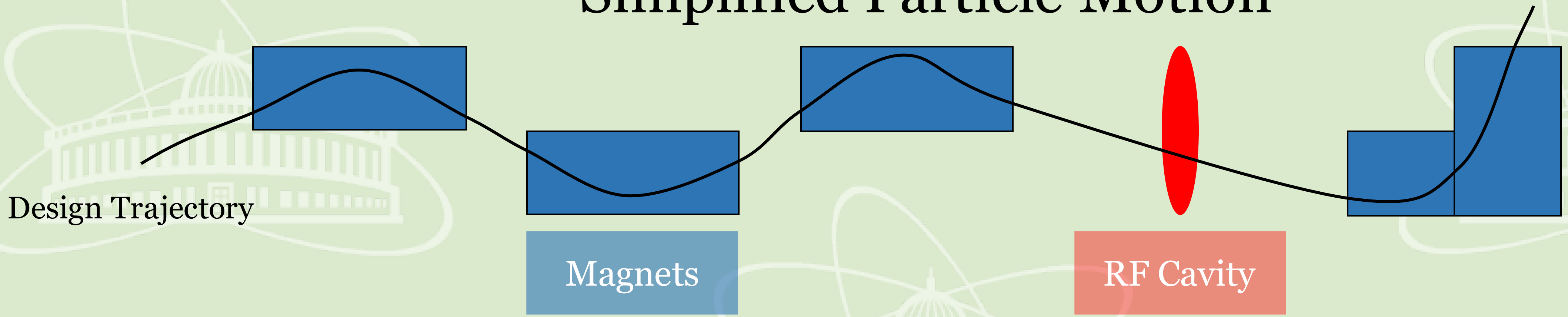

There are roughly 35,000 accelerators in the world (Above 1 MeV...)

# NICA structure



# Basic principle of accelerator

## Simplified Particle Motion

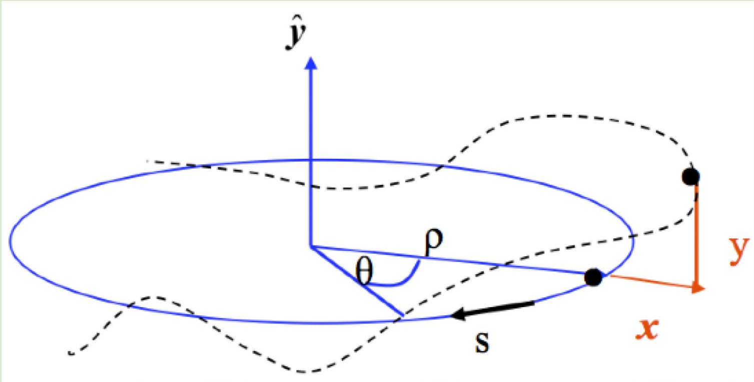



## Design trajectory

- Particle motion will be perturbatively expanded around the design trajectory or orbit
- This orbit can be over $10^{10}$ km in a storage ring

## Separation of fields: Lorentz force $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$

- Magnetic fields from static or slowly-changing magnets
    - transverse to design trajectory $\bar{x}, \bar{y}$
- Electric fields from high-frequency RF cavities
    - in the direction of design trajectory $\bar{s}$



# Convenient units

$$\Delta W = qV_0$$
$$1eV = (1.602 * 10^{-19}C)(1V) = 1.602 * 10^{-19}J$$
$$1MeV = 1.602 * 10^{-13}J$$
$$1GeV = 1.602 * 10^{-10}J$$

- How much is TeV?
  - Energy to raise 1g about 16 μm against gravity
  - Energy to power 100W light bulb 1.6 ns
- But many accelerators have $10^{10-12}$ particles
  - Beam "instantaneous power" of thousands or millions of Joules

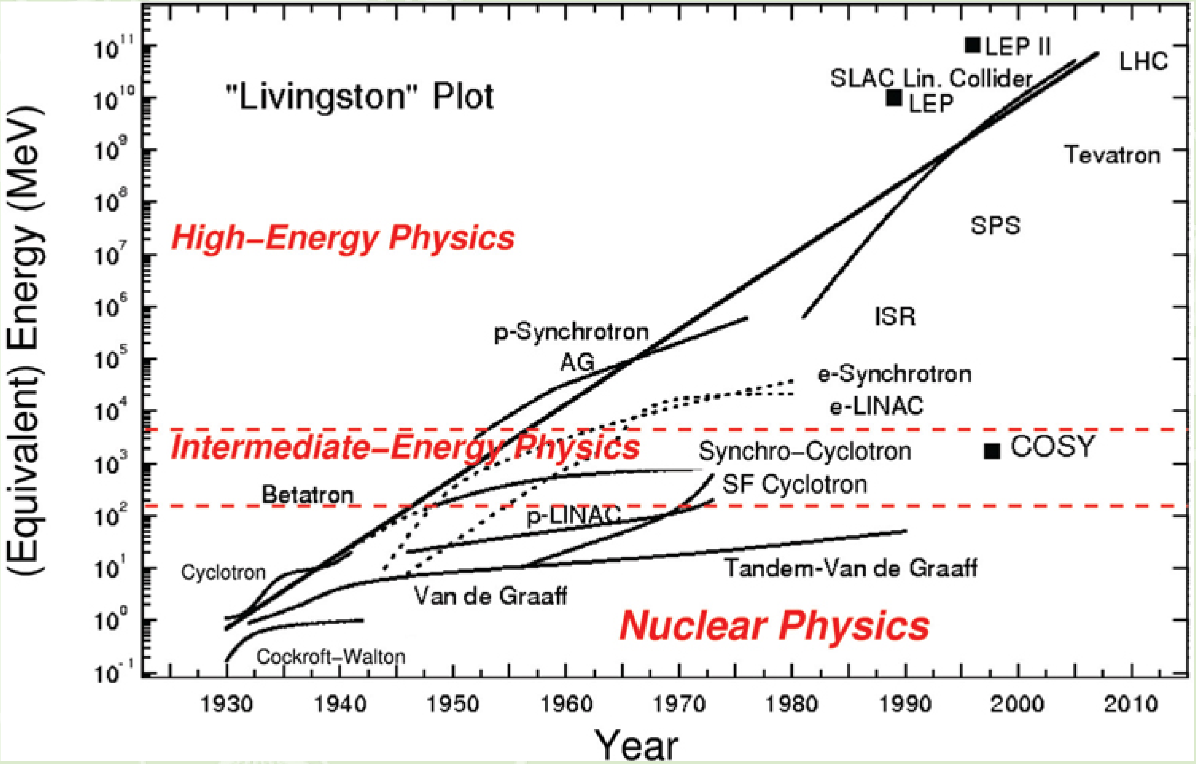
$$(1.602 * 10^{-19}J) * 10^{12} * 10^{11} = 1.602 * 10^{4}J$$

$$W = \frac{mv^2}{2} \Rightarrow m = \frac{2W}{v^2}$$

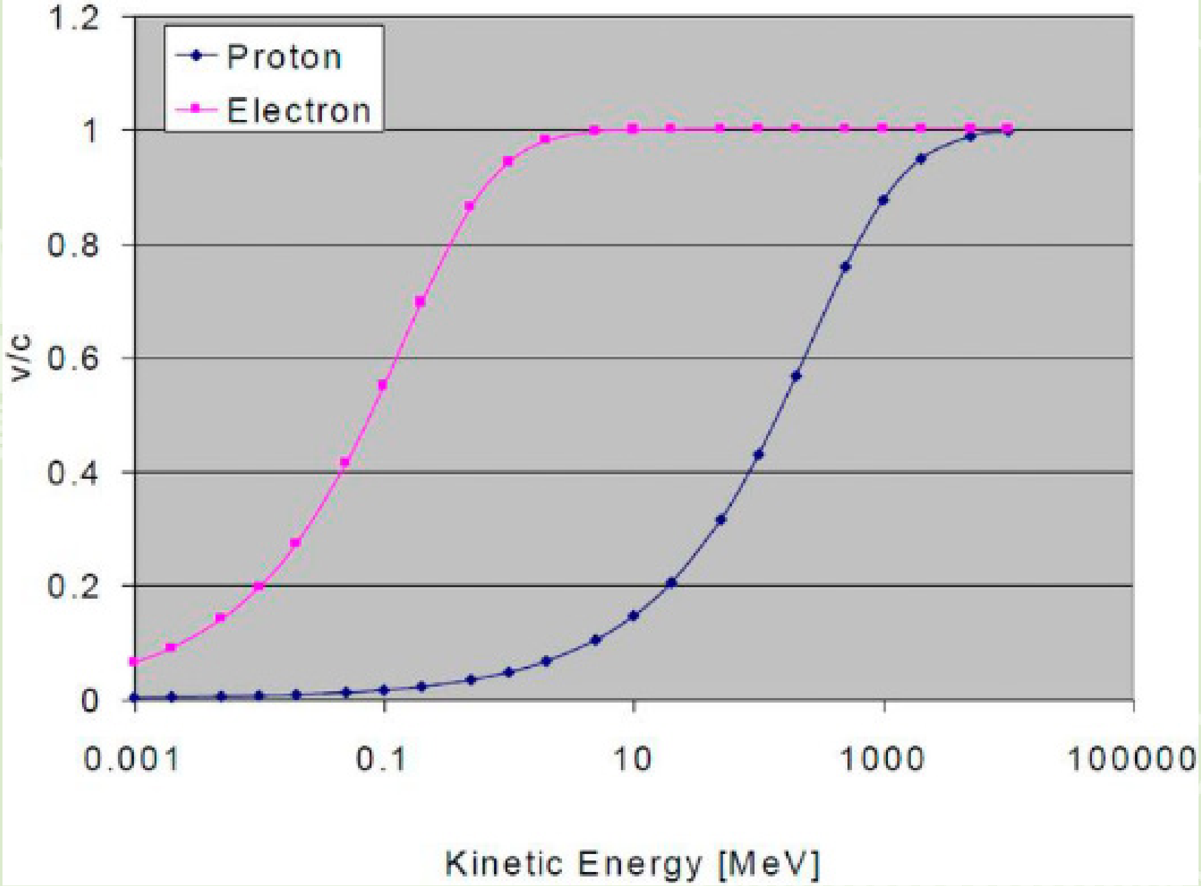
$$\frac{1.602 * 10^{-7}J * 10^{11} * 2}{(331\, {}^{m}/_{s})^2} \approx 0.292kg$$

# Energy evolution

The types of machines are distinguished by the velocity of particles that are accelerated and by the mass of particles accelerated

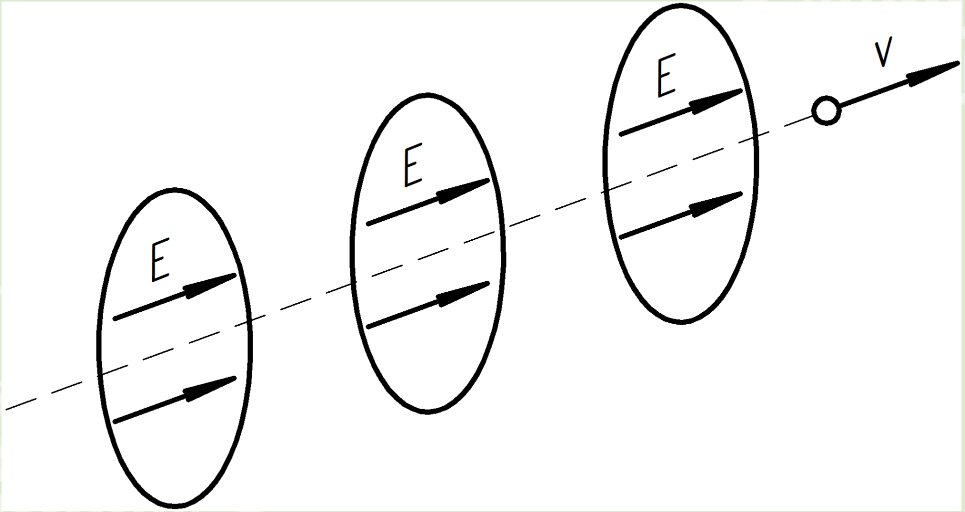



“Livingston” plot

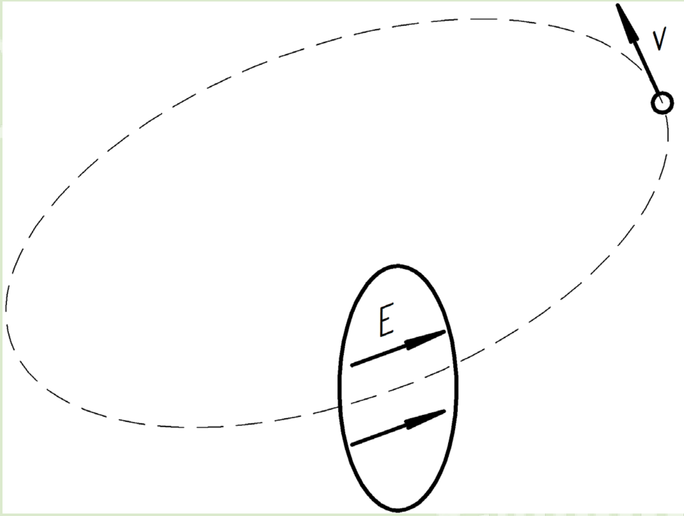


# From electrostatic to RF acceleration

- What about putting on AC voltage?
  - Attach consecutive electrodes to opposite polarities of ACV generator
  - Electric fields between successive electrodes vary sinusoidally
  - Consecutive electrodes are 180 degrees out of phase (π mode)
- At the right drive frequency, particles are accelerated in each gap
  - While polarity change occurs, particles are shielded in drift tubes
  - To stay in phase with the RF, drift tube length or RF frequency must increase at higher energies



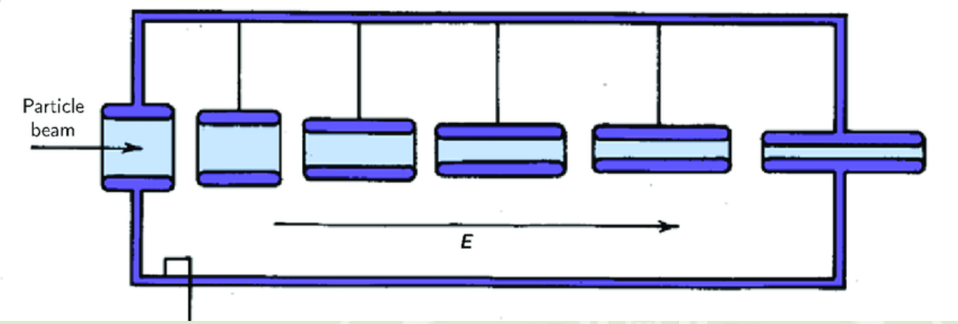

Linear accelerators



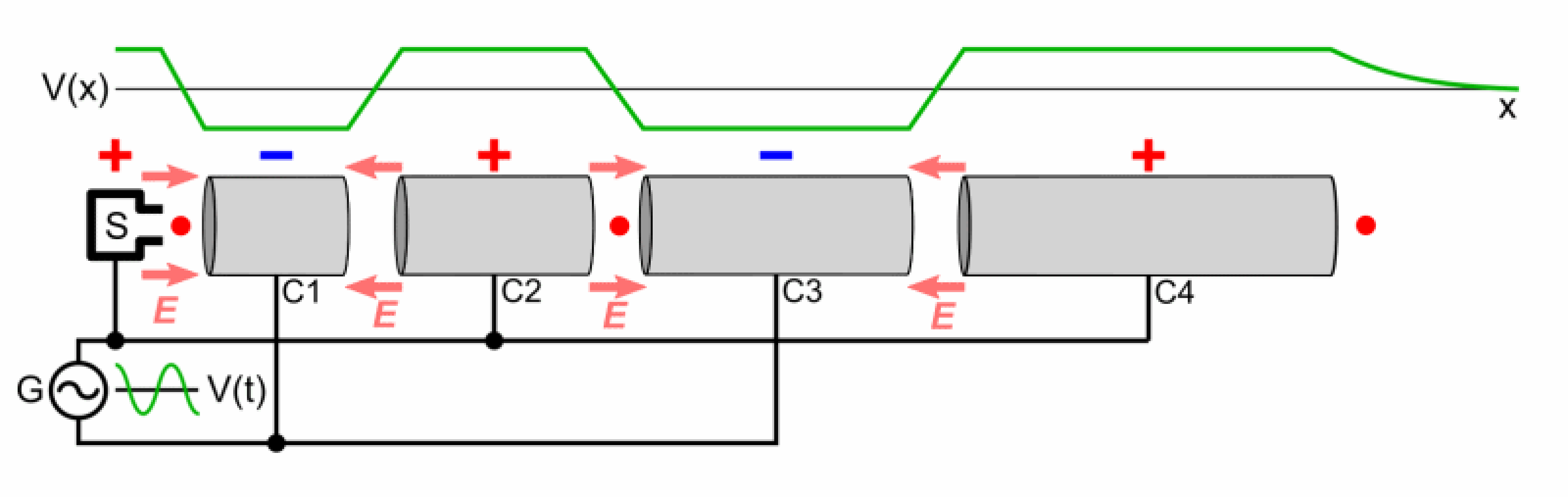

Circular accelerators

# Resonant Linac structure

- Wideroe linac: π mode
- Alvarez linac: 2π mode
- Need to minimize the excess RF power (heating)
  - Make drift tubes/gaps resonant to RF frequency
  - In 2π mode, currents in walls separating two subsequent cavities cancel; tubes are passive

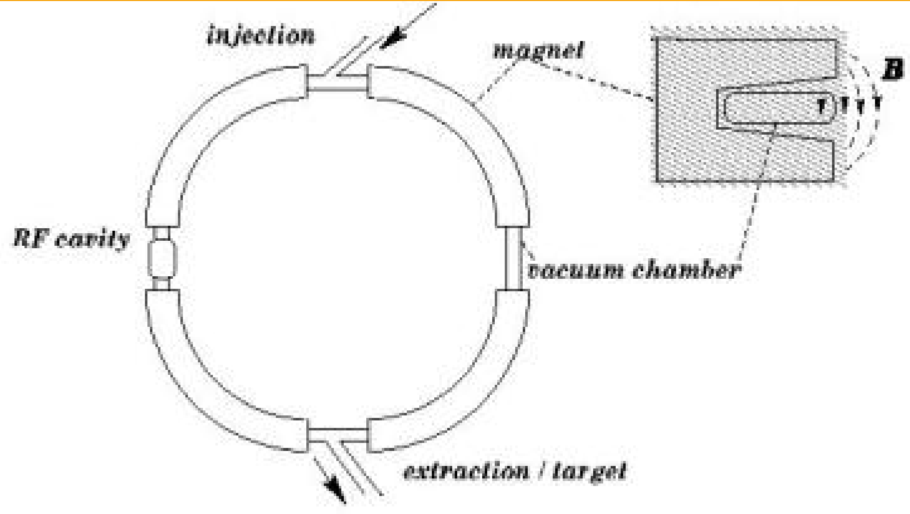



Alvarez structure




Wideroe structure

# The synchrotron




- In synchrotrons, the particles are accelerated along a closed, circular orbit and the magnetic field which bends the particles increases with time so that a constant orbit is maintained during acceleration
- The synchrotron concept was proposed for the first time in 1943 by the Australian physicist Mark Oliphant
- Uniform circular motion is maintained via centripetal acceleration:

$$\frac{mv^2}{\rho} = qvB \Rightarrow B\rho = \frac{p}{q} \Rightarrow \rho = \frac{1}{q}\left(\frac{p}{B}\right), p = \beta\gamma m_0 c$$

- For a proton synchrotron, the injected beam is not yet relativistic, so the RF accelerating frequency both ramp with particle velocity ($\beta$) and particle momentum ($p$) too:

$$f_{rev} = {}^{\beta c}/_{2\pi\rho}\,; f_{rf} = 2\pi h f_{rev} = {}^{h\beta}/_{\rho}\,, h \equiv harmonic\ number$$

- For an electron synchrotron, the injected beam is already relativistic, so only the magnetic field changes with beam energy

# The largest weak-focusing synchrotrons

The Synchrophasotron

1957-2003, VBLHEP, JINR, USSR, 10 GeV, 36000 tons

The Bevatron

1954-2009, LBNL, USA, 6.3 GeV, 10000 tons

# Two serious problems

## These machines were getting way too big

- Magnets were grater than 10,000 tons
- Apertures scale linearly with machine size, energy (length/circumference scales linearly with energy at fixed field strength too…)

## Fixed target energy scaling is painful

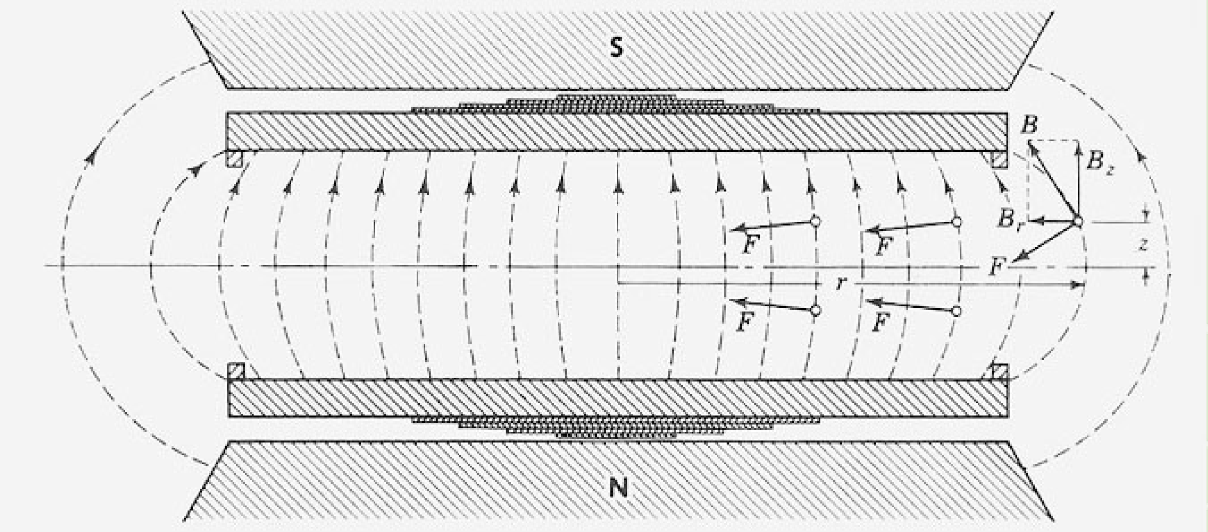
- Available CM energy only scales with $\sqrt{E_{beam}}$

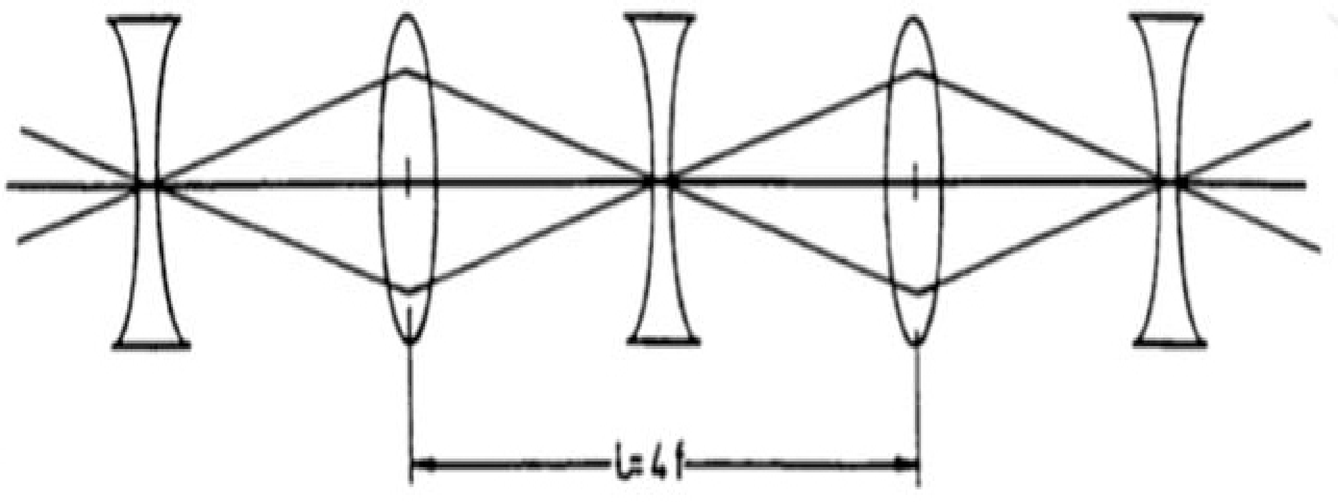
## Accelerator size grew with the square of desired CM energy

- Something had to be done!!!

**Strong Focusing (1952) and Colliders (1958-62 ish) to the rescue!!!**

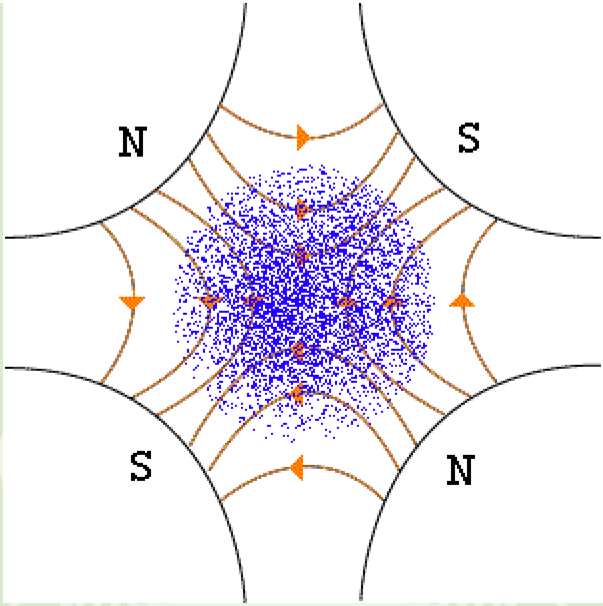
# Beam focusing




Weak focusing

Strong focusing




- Suppose two particles start the acceleration process. One has exactly the correct energy, position and angle, so that it is properly accelerated. The accompanying particle has slightly different starting parameters. Some way of ensuring that non-perfect particles are also accelerated was needed

# Fixed target vs. colliders



**Fixed target**

$$E_{cm} \approx \sqrt{2E_1(m_{02}c^2)}$$

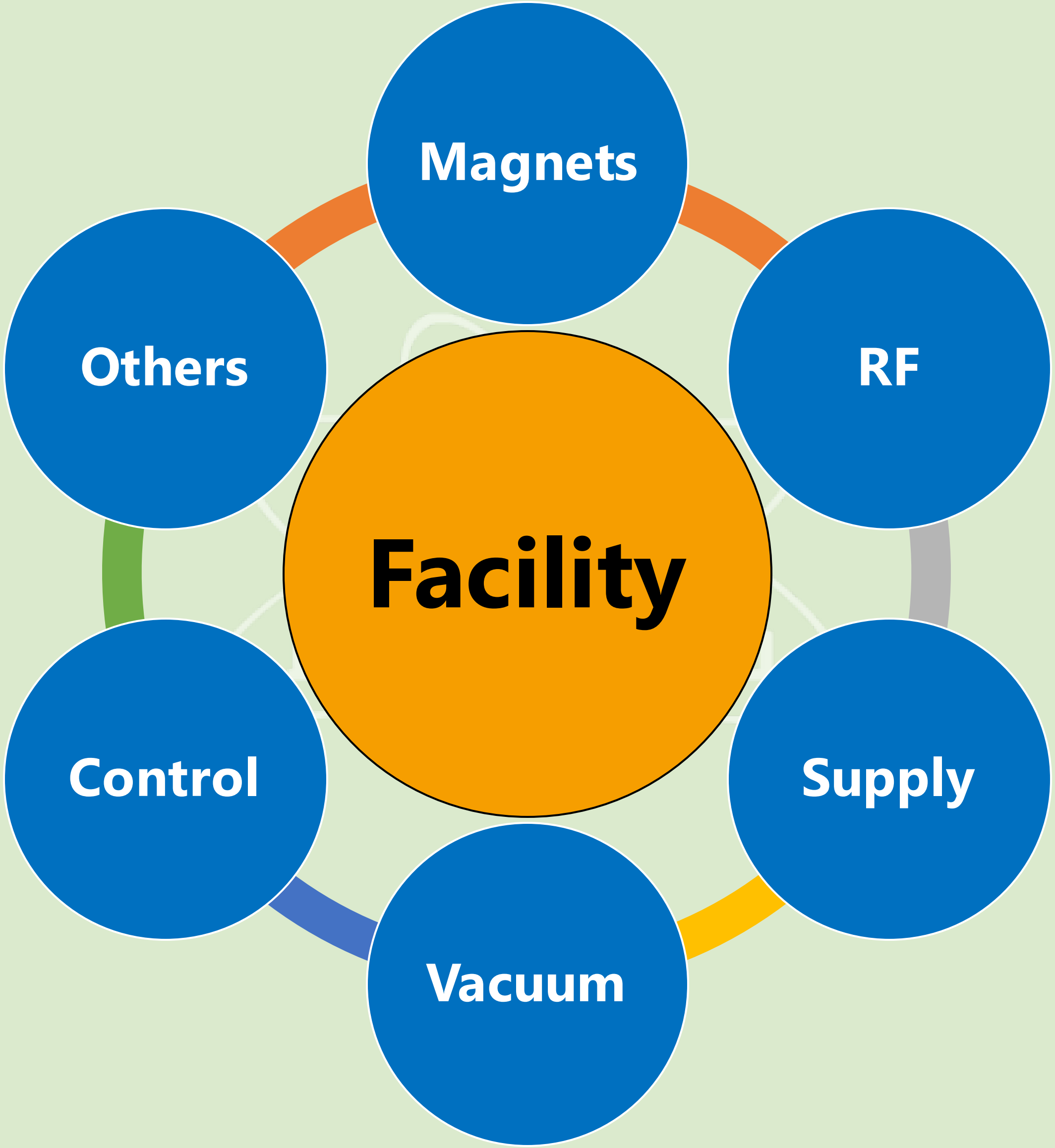
Much of the energy is lost in the target and only partial results in usable secondary particles

**Collider**

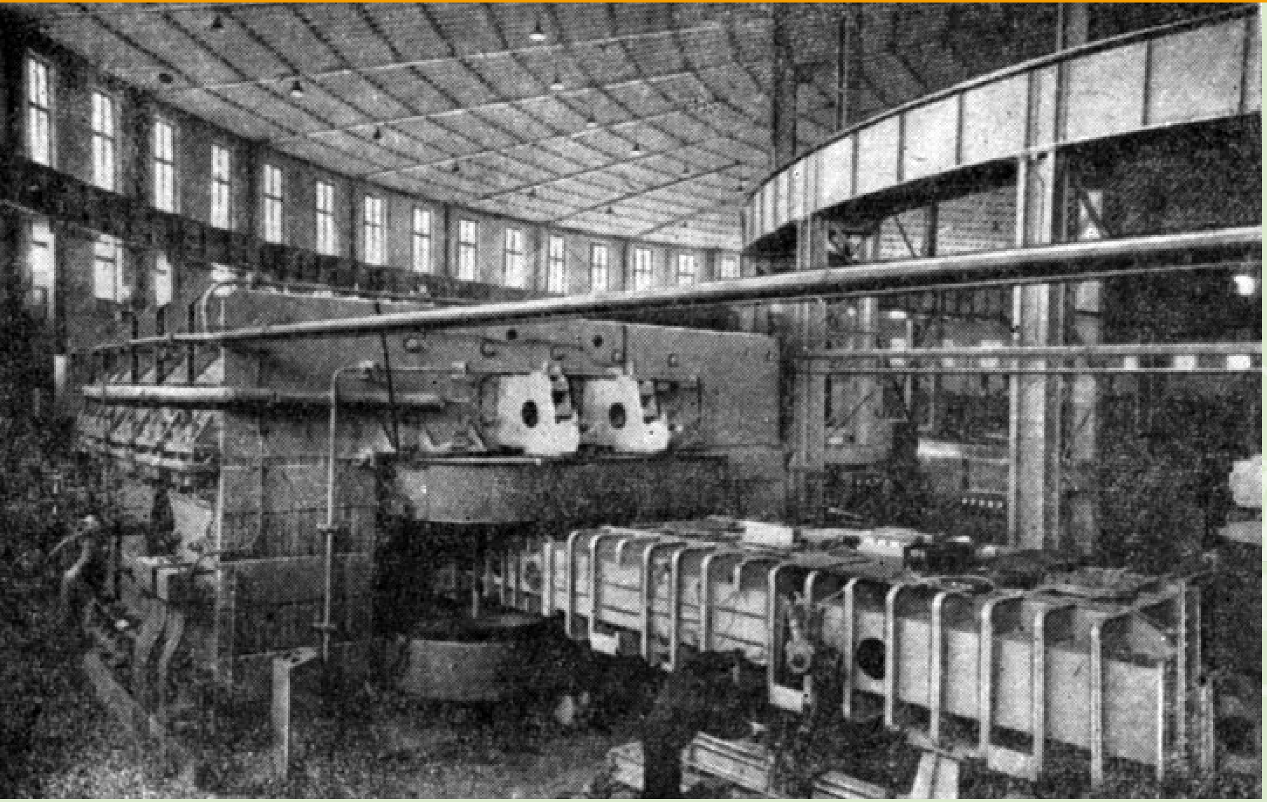
$$E_{cm} \approx 2\sqrt{E_1 E_2} \approx 2E \; if \; E_1 = E_2$$

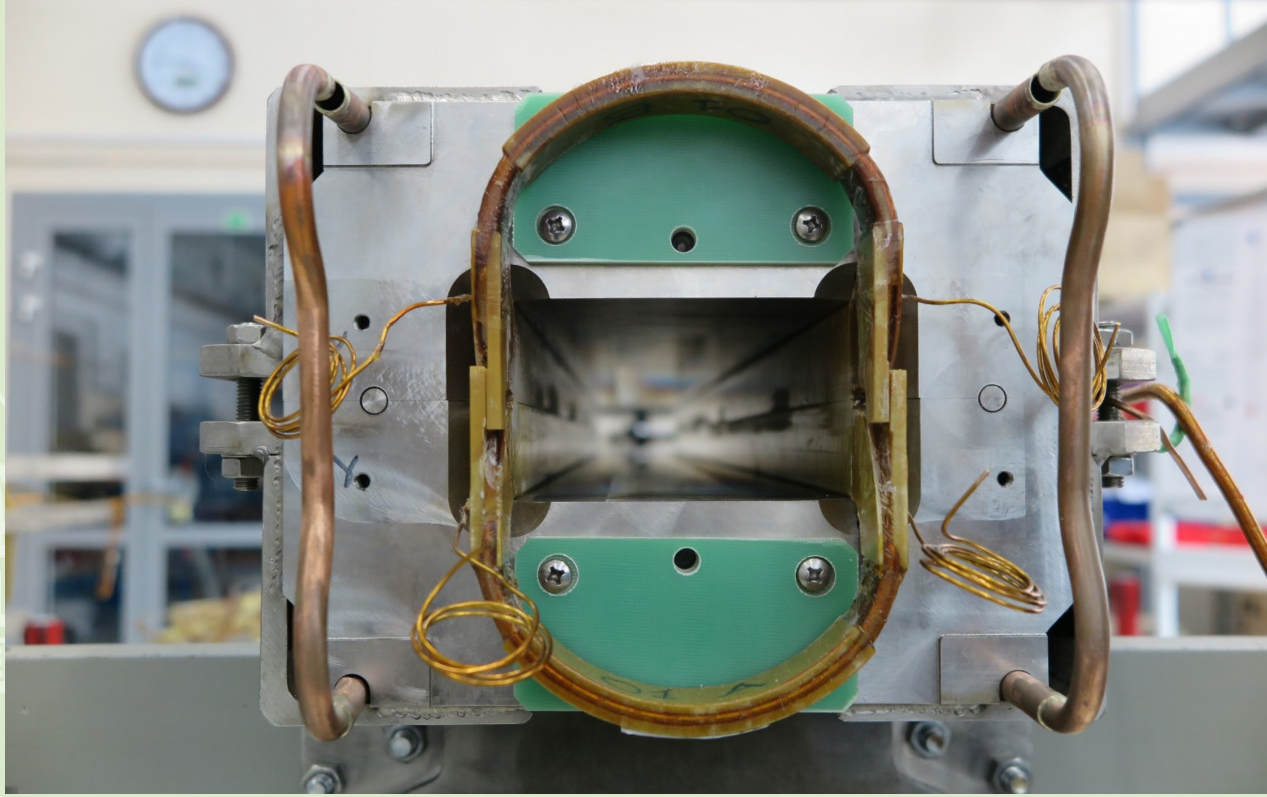
All energy will be available for particle production

# Accelerator systems



# Why superconductivity?

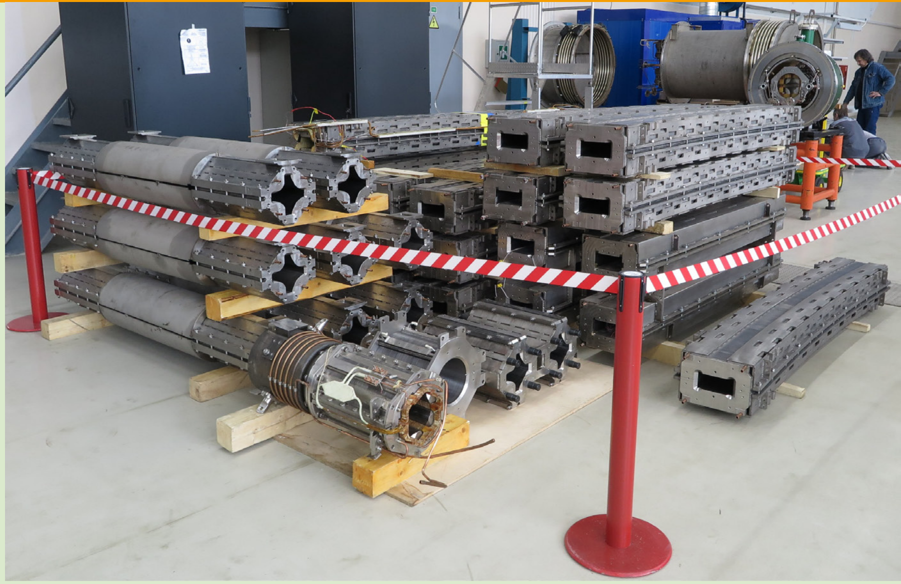




Abolish Ohm's law

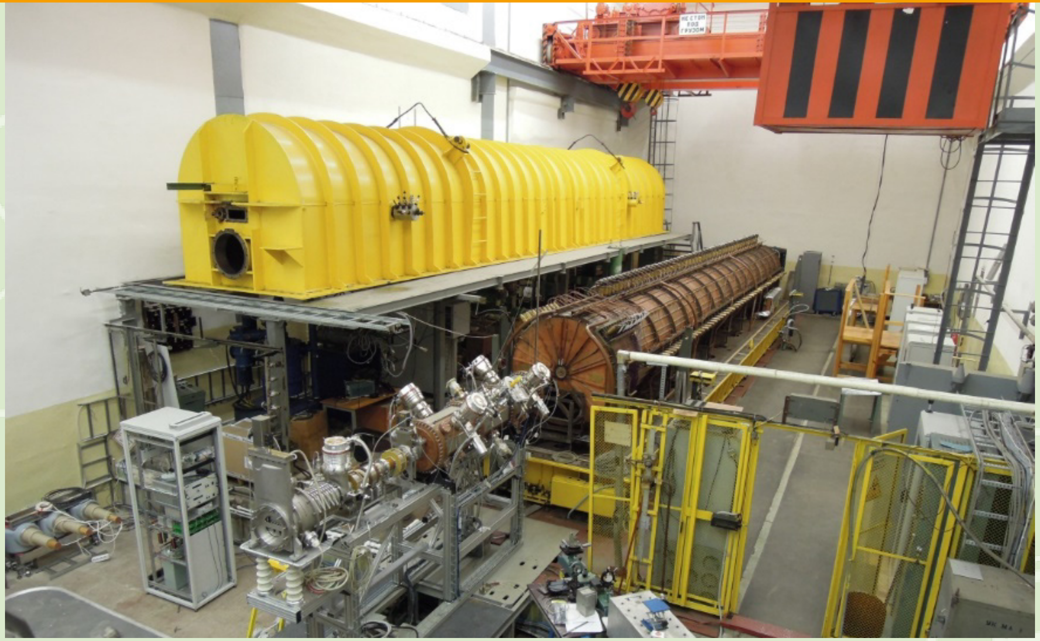
- no power consumption (although need refrigeration power); high current density; ampere turns are cheap
- lower running cost; energy savings; smaller, lighter, cheaper magnets; reduced capital cost; higher magnetic fields economically feasible ⇒ new research possibilities; etc.

# Magnet factory



November 28, 2016

# Linear accelerators



LU-20

| q/A | 0.5 | 0.3 |
|---|---|---|
| Injection energy, keV/u | 61.8 | 103 |
| Output energy, MeV/u | 5 | |
| Transmission, % | ~75 | ~50 |
| Frequency, MHz | 145.2 | |
| Operating mode | $2\beta\lambda$ | |

| q/A | 6.25 ($Au^{32+}$) |
|---|---|
| Injection energy, keV/u | 17 |
| Output energy, MeV/u | 3.2 |
| Transmission, % | ≥80 |
| Frequency, MHz | 100.625 |

HILac

# Synchrotrons

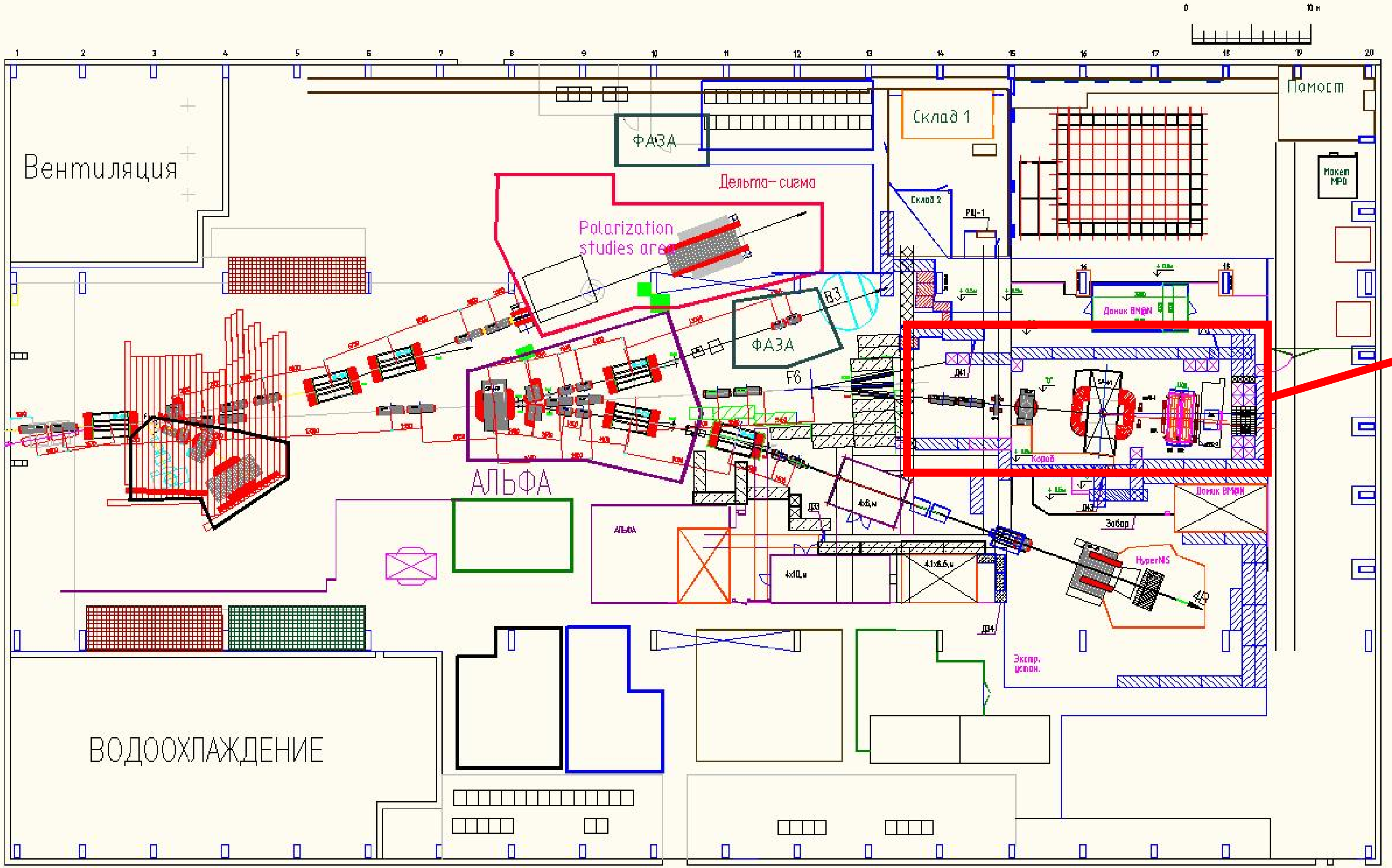
Booster

| The arc lattice | DFO, cells |
| --- | --- |
| Magnet rigidity, T/m | 25 |
| Circumference, m | 211.2 |
| Output energy, $Au^{31+}$, MeV/u | 600 |
| Momentum dispersion, Δp/p | ± 0.010 |
| Intensity, ions | $2\text{-}4 \cdot 10^9$ |

| The arc lattice | FODO, cells |
| --- | --- |
| Magnet rigidity, T/m | 45 |
| Circumference, m | 251.5 |
| Output energy, $Au^{79+}$, GeV/u | 4.5 |
| Momentum dispersion, Δp/p | ± 0.010 |
| Intensity, ions | $2 \cdot 10^9$ |

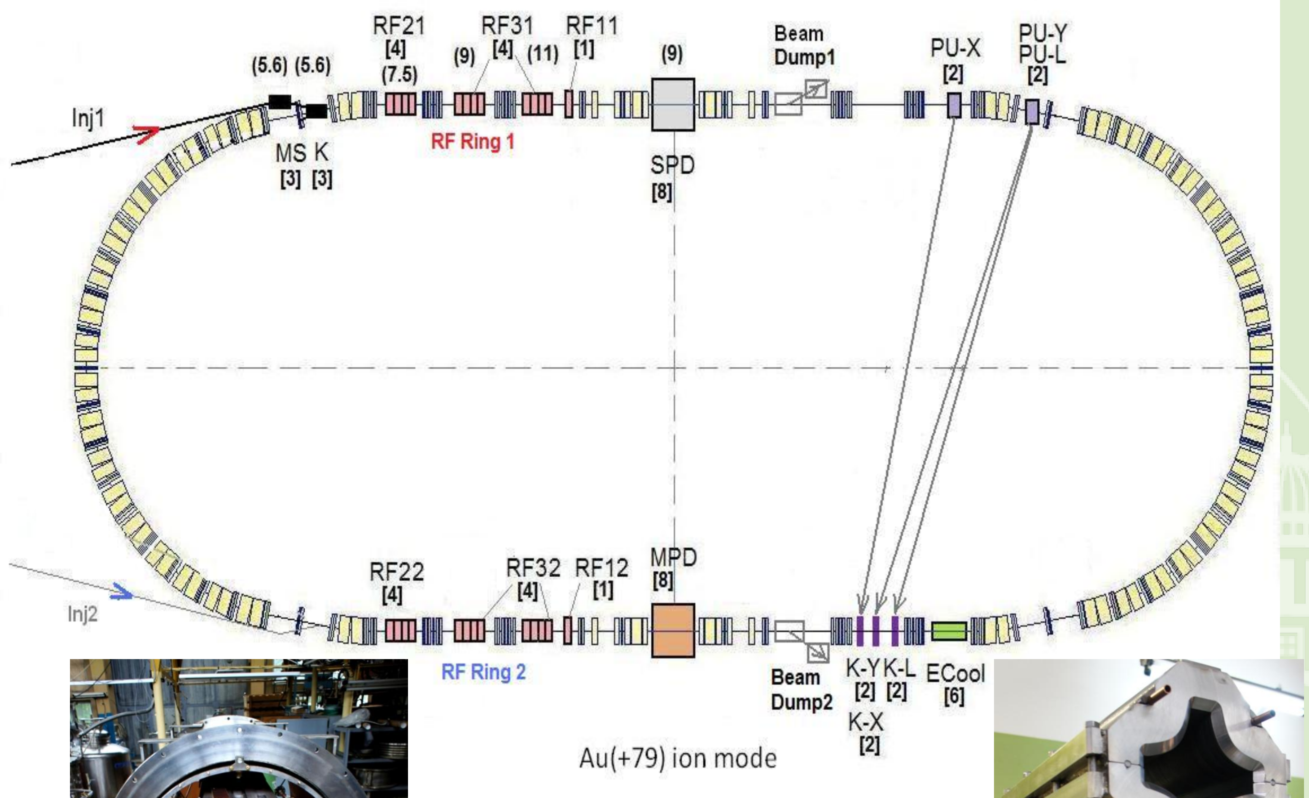
Nuclotron

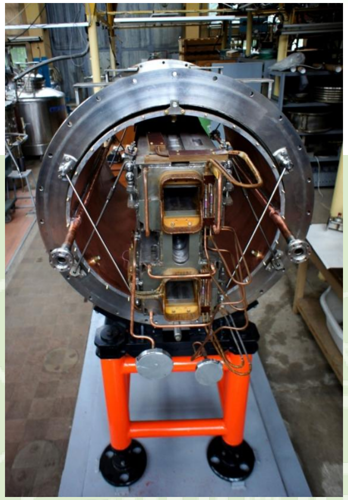
# Fixed targets hall



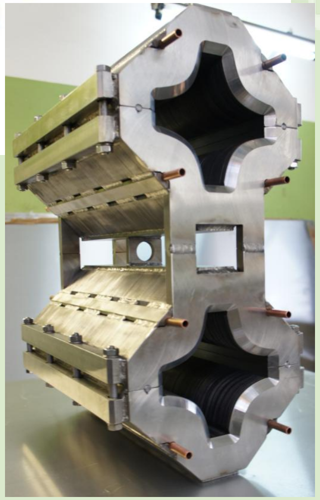

**BM@N**

# The storage ring



Lattice



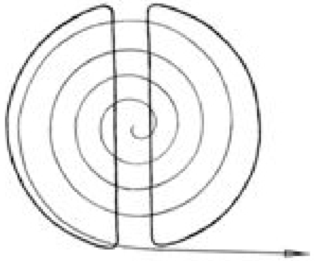
| Circumference, m | 503.04 | | |
|---|---|---|---|
| The arc lattice | FODO, cells | | |
| Number of bunches | 22 | | |
| Momentum dispersion, Δp/p | ± 0.010 | | |
| Ion energy, $Au^{79+}$,GeV/u | 1 | 3 | 4.5 |
| Luminosity, $cm^{-2} \cdot s^{-1}$ | $0.6 \cdot 10^{25}$ | $1 \cdot 10^{27}$ | $1 \cdot 10^{27}$ |
| IBS growth time IBS, s | 160 | 460 | 1800 |

# Other acceleration methods

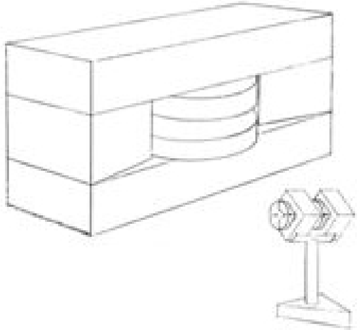
- Isochronous cyclotrons
- Accelerator-based light and neutron sources
- Accelerator-driven subcritical reactor
- Wakefield
- Others (lasers, dielectric wall acceleration, etc.)

# The cyclotron: different points of view

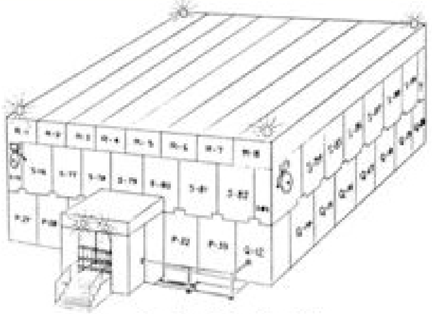




*… the inventor*

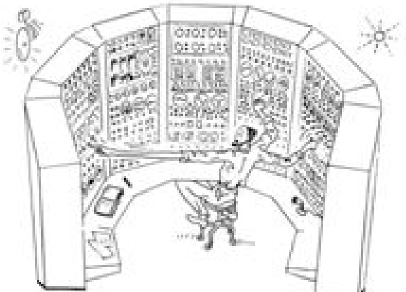


*… the mechanical engineer*



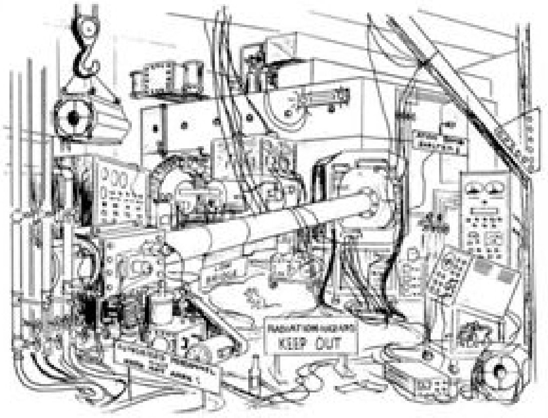
*… the health physicist*

*… the experimental physicist*

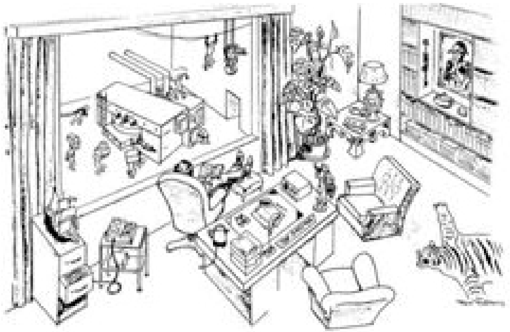


*… the operator*

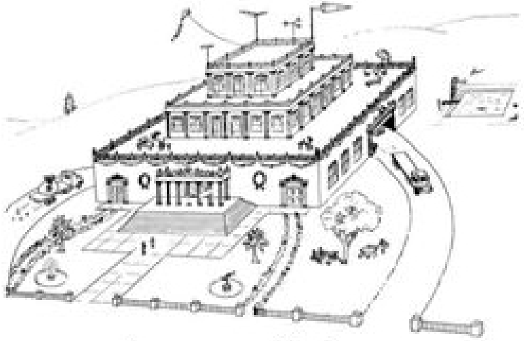
From LBNL Image Library Collection
by Dave Judd and Ronn MacKenzie



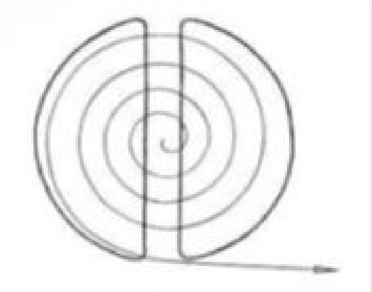

*… the visitor*



*… the laboratory director*



*… the governmental funding agency*



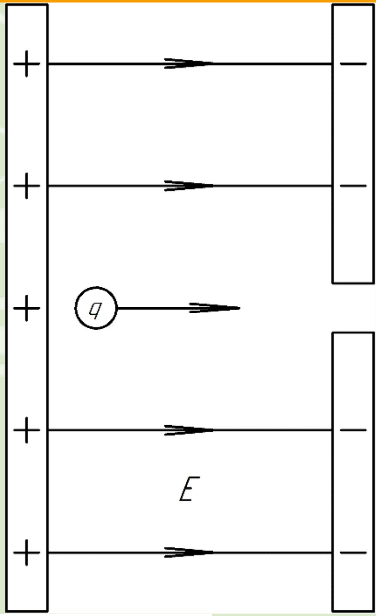
*… the student*

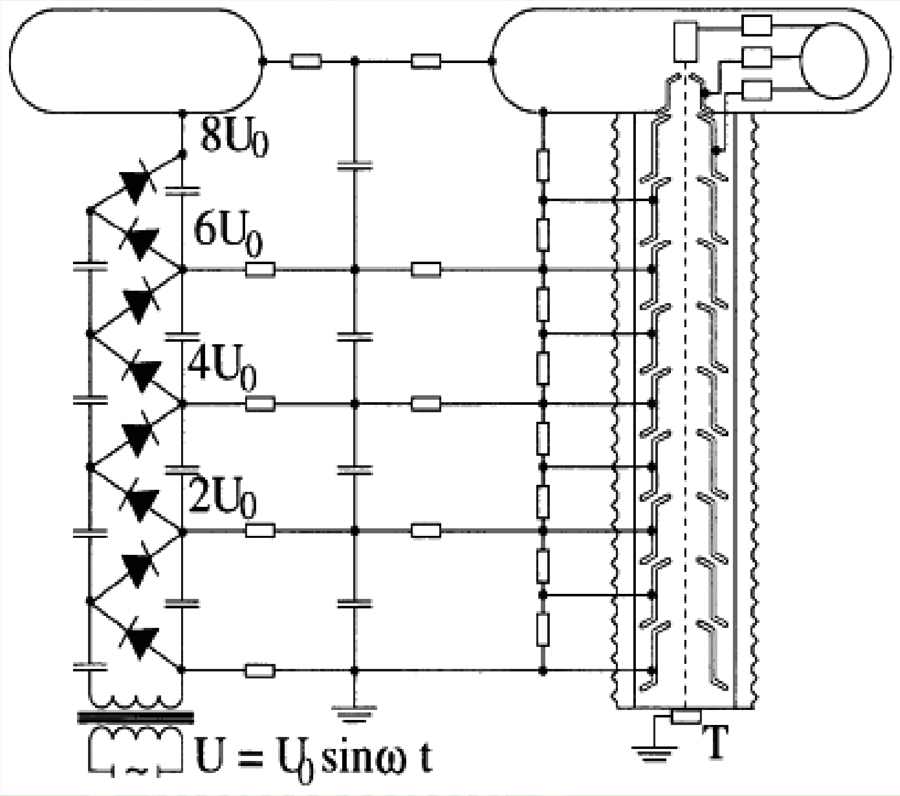
# THANK YOU FOR ATTENTION !!!

# EXTRA SLIDES

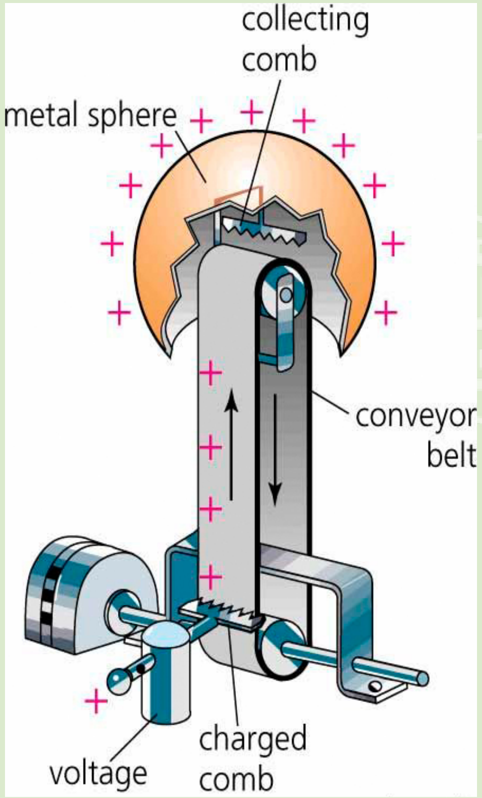
# Potential-drop accelerators

- These accelerators use static, DC, potential difference between two conductors to impart a kinetic energy: $\Delta W = qV_0$
- The highest voltage achieved is 25 MV
- It is difficult to establish and maintain a static DC field of 20+ MV

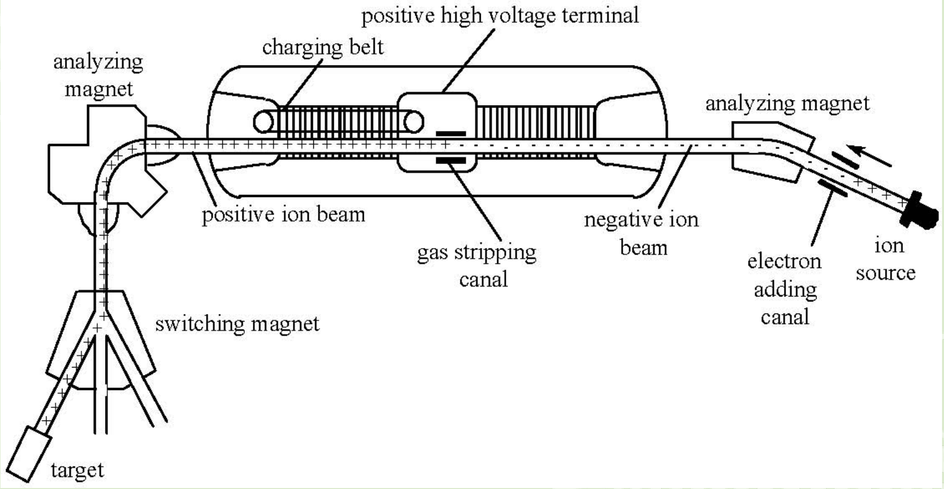



Cockcroft- Walton generator




Van de Graaff generator




Tandem Van de Graaff

# The cyclotron

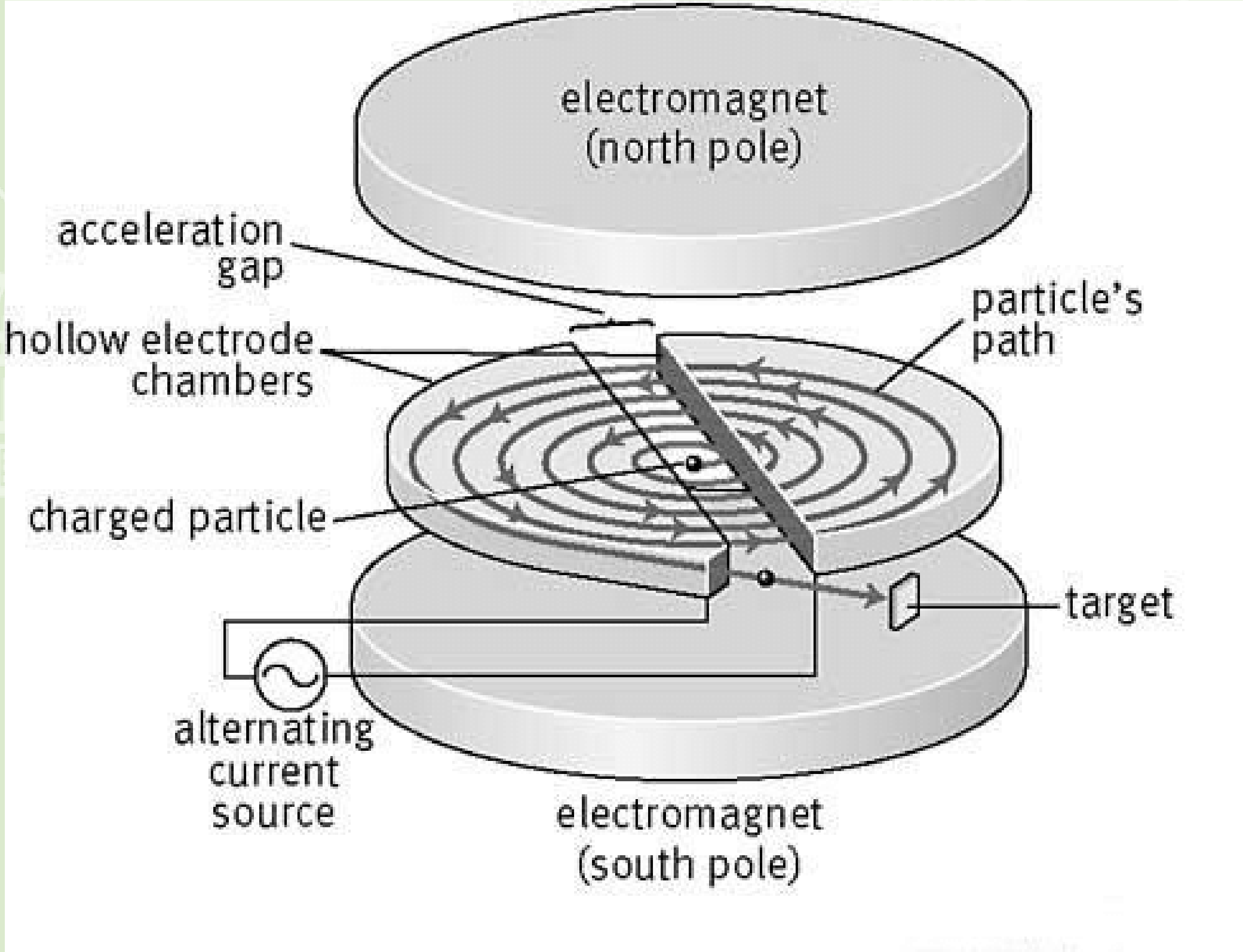
- Lawrence applied Wideroe's idea in a new form. Nobel prize, 1939
- Uniform circular motion is maintained via centripetal acceleration:

$$\frac{mv^2}{r} = qvB \Rightarrow r = \frac{mv}{qB}$$

- The revolution period and frequency are do not depend on particle velocity:

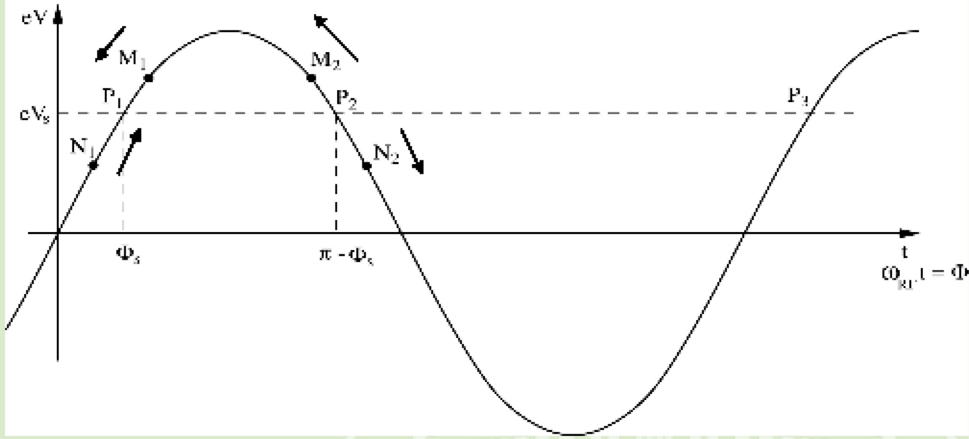
$$T = \frac{2\pi m}{qB}; f = \frac{qB}{m}$$

- The particle is in synchronism with the time-varying electrical field
- Cyclotrons can accelerate proton energies up to 20-30 MeV.
- The situation becomes more complicated at higher energies due to the increase in relativistic mass (get out of synchronism)



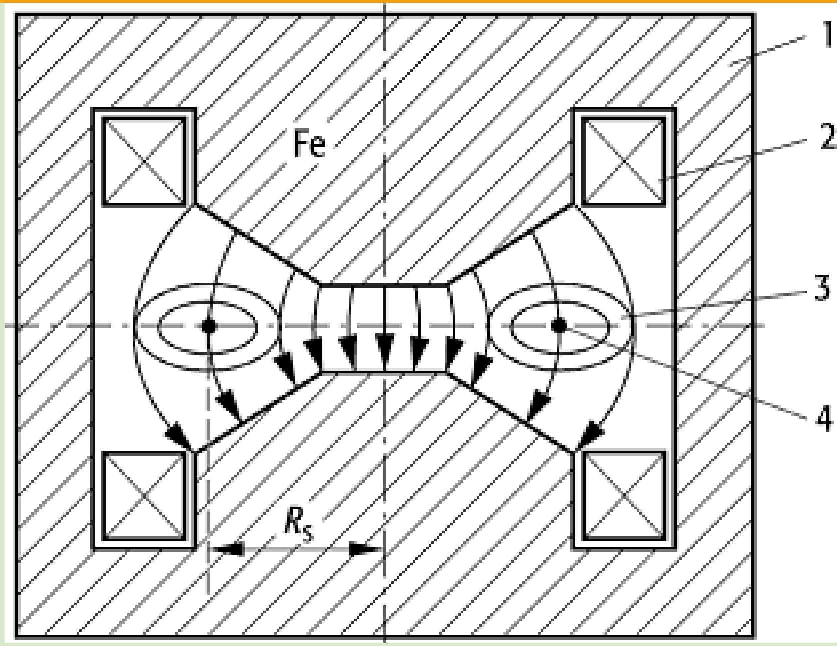
# The synchro-cyclotron

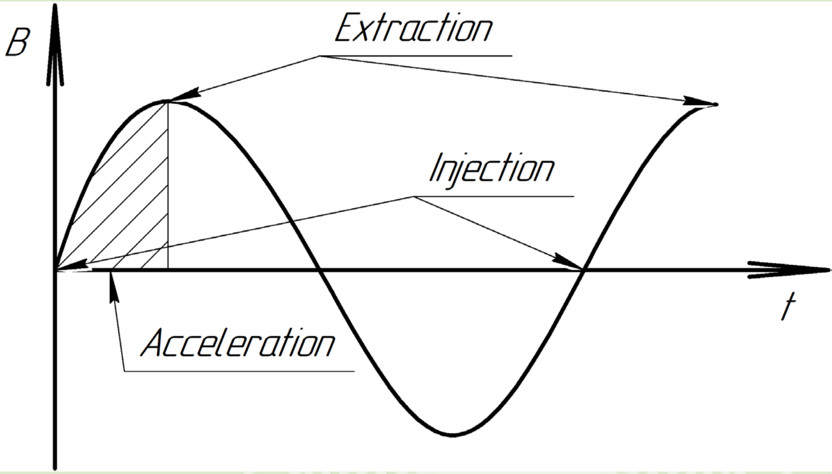
- Veksler and McMillan showed, independently, that by adjusting the frequency of the applied voltage to the decreasing frequency of the rotating protons, it was possible to accelerate the protons to several hundred MeV (the synchro-cyclotron can only accelerate a single “bunch” of particles)
- By design there is a synchronous phase $\Phi_s$ that gains just enough energy to hit phase $\Phi_s$ in the next gap
- $P_{1,2}$ are fixed points: they “ride the wave” exactly in phase
- If increased energy means increased velocity (below transition)
  - $M_1$, $N_1$ will move towards P1 (local stability) => phase stability
  - $M_2$, $N_2$ will move away from P2 (local instability)
- Vice versa for above transition



# The betatron

- Electrons (beta particles) are accelerated by rotational electric field generated by induction from time-varying magnetic field (Faraday's law)
- Beam accelerate half the time!
- Wideroe's betatron condition: $|B(t)| = \frac{1}{2}\langle|B(t)|\rangle + |B_0|$
- Early proofs of stability: weak focusing and betatron motion
- Betatrons produced electrons up to 300+ MeV
  - Early materials and medical research
  - Also produced medical hard X-rays and gamma rays
- Betatrons have their challenges
  - Linear aperture scaling
  - Large stored energy/impedance
  - Synchrotron radiation losses
  - Quarter duty cycle
  - Ramping magnetic field quality



# The microtron

- Microtrons are like cyclotrons
  - but each revolution electrons “slip” by integer # of RF cycles
  - Trades off large # of revs for minimal RF generation cost
  - Bends must have very large momentum aperture