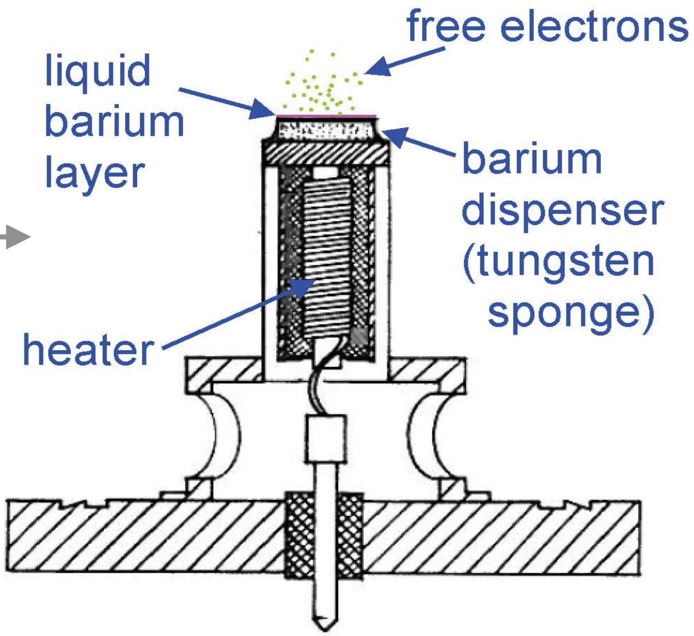
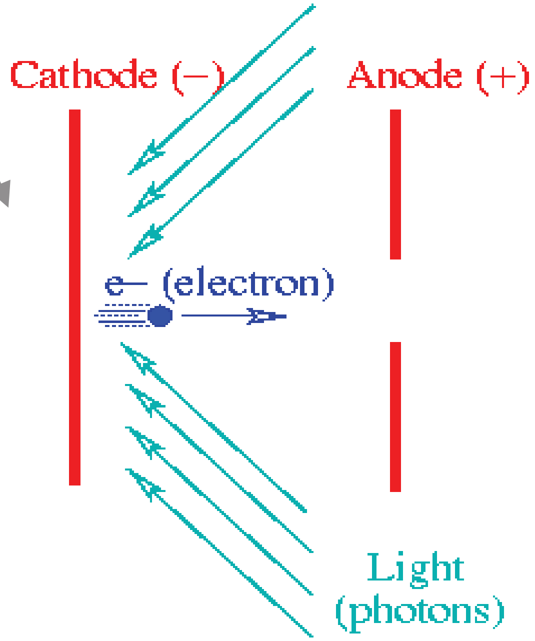
2. Accelerator basics and types

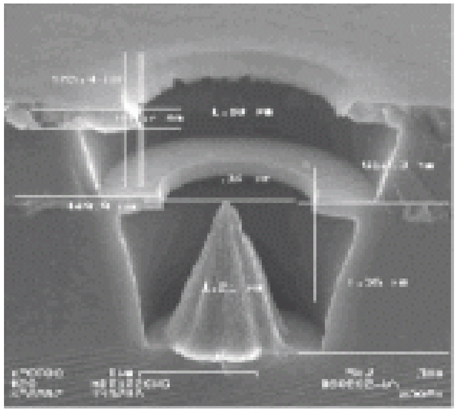
- Particle sources
- Electric and magnetic fields
- Electrostatic accelerators
  - Marx ■ Cockcroft-Walton ■ van der Graaff
- Radio-frequency acceleration
- Linear accelerators
  - Linac ■ Buncher ■ Linear collider ■ FEL
- Recirculation 1: fixed magnetic field and variable orbit
  - Recirculated linac ■ Microtron ■ Cyclotron ■ FFAG
- Recirculation 2: variable magnetic field and fixed orbit
  - Betatron ■ Synchrotron and storage ring
  - Light sources ■ Circular colliders ■ The LHC

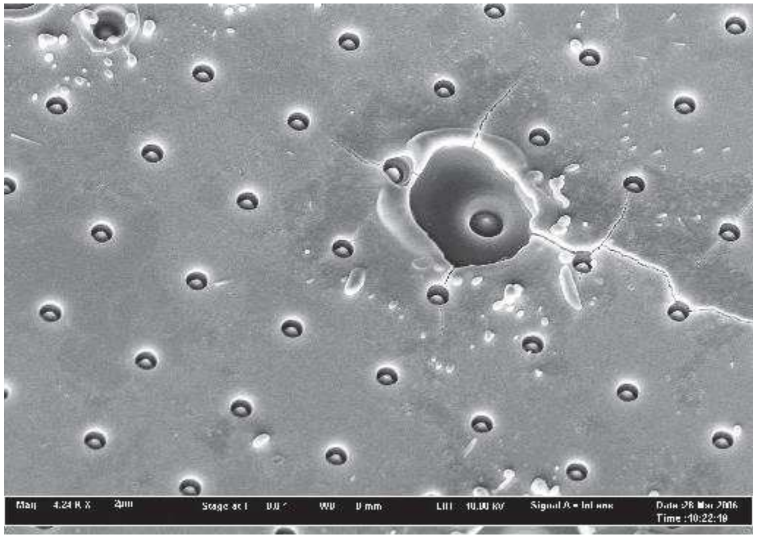
Particle sources
→ I. Electron sources

- thermionic cathode
- laser cathode (photo effect)
- field emission







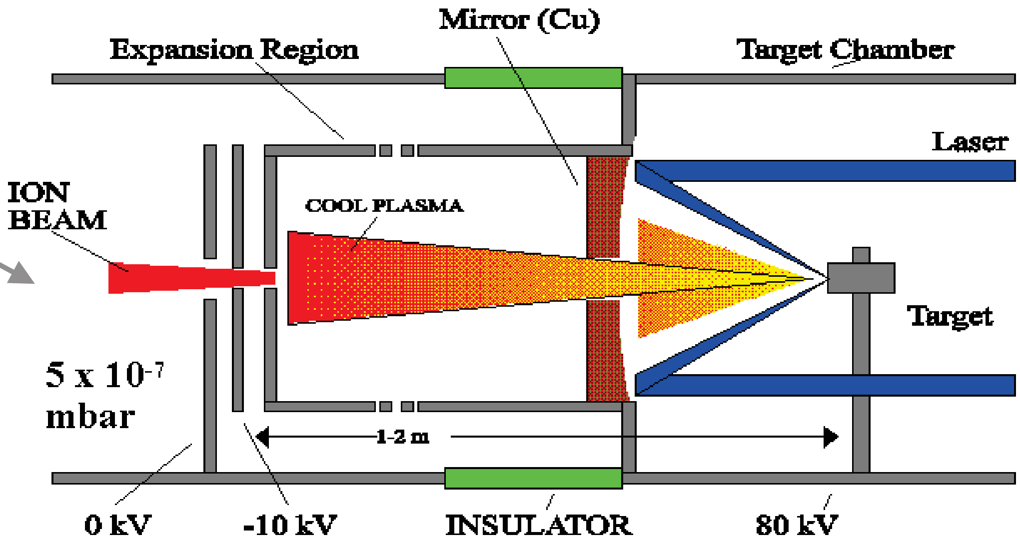


⇦ gated field emitter (MIT)

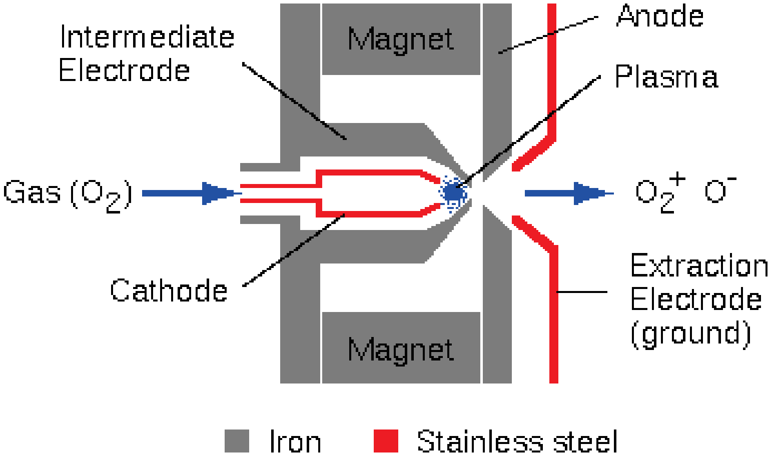
field emitter array ⇨
with a damage

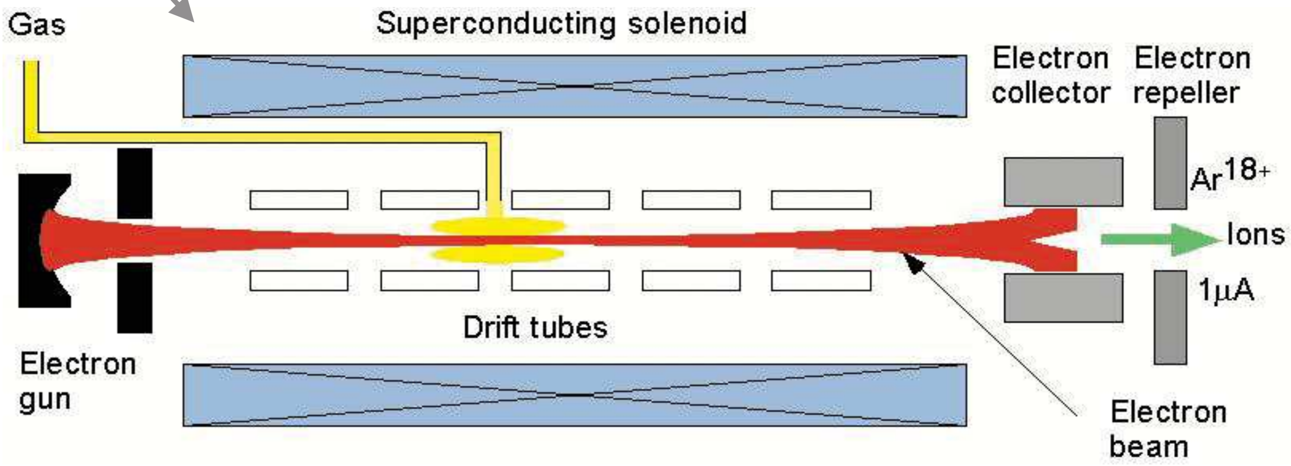
Particle sources → II. Proton [ion] sources

- plasma ion source
- laser ion source
- electron beam ion source



Duoplasmatron





Electric and magnetic fields

How to accelerate ?

Lorentz Force: $\dot{\vec{p}} = \vec{F} = q\,(\vec{v} \times \vec{B} + \vec{E}), \qquad \vec{v} = \dfrac{\vec{p}}{m}$

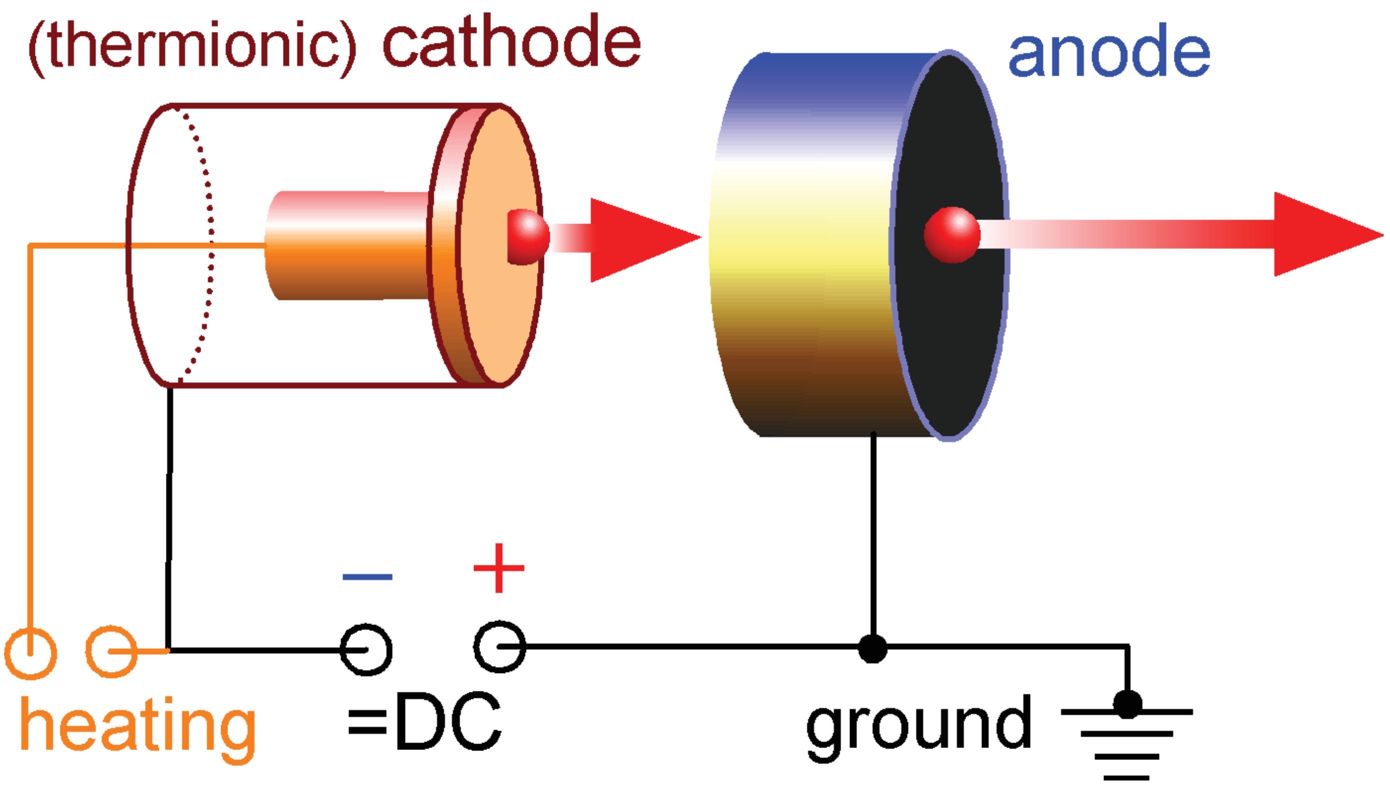
Increase of *a*bsolute momentum: $\dot{p} > 0$?

$$\dot{p} = \frac{d}{dt}\sqrt{\vec{p}\cdot\vec{p}} = \frac{\vec{p}\cdot\dot{\vec{p}}}{p} = \underbrace{\frac{q}{p}\cdot\vec{p}\cdot\underbrace{(\vec{v}\times\vec{B})}_{\perp\vec{p}}}_{=0} + \frac{q}{p}\cdot\vec{p}\cdot\vec{E}$$

$\Longrightarrow$ Only the electric field can increase absolute momentum:

$$\dot{p} = qE\,\cos\{\vec{p};\vec{E}\}$$

The most simple electron accelerator



color-TV tube: 27 kV

X-ray tube: ≈ 100 kV

What are magnetic fields good for?

$$\boxed{q\,\vec{v}\times\vec{B}=\vec{F}=\dot{\vec{p}}=m\dot{\vec{v}}\quad\text{since}\quad\dot{m}=0\ \text{(no energy gain).}}$$

assume $\vec{B}=B_z\vec{e_z} \longrightarrow \quad \dot{v}_x=\frac{q}{m}v_yB_z \quad \dot{v}_y=-\frac{q}{m}v_xB_z \quad \dot{v}_z=0$

$\Longrightarrow$ $[d/dt\ldots]$ Oscillation of velocities

$$\begin{array}{rcl} v_x(t) & = & v_{xo}\cos(\omega t)+v_{yo}\sin(\omega t)\\ v_y(t) & = & v_{yo}\cos(\omega t)-v_{xo}\sin(\omega t)\\ v_z(t) & = & v_{zo}\end{array}$$

Cyclotron frequency $\omega=\frac{q}{m}B_z$

$\Longrightarrow$ Helical trajectories (closed circles for $v_{zo}=0$)

$$\begin{array}{rcl} x(t) & = & x_o+\rho\cos(\omega t-\phi)\\ y(t) & = & y_o+\rho\sin(\omega t-\phi)\\ z(t) & = & z_o+v_{zo}t\end{array}$$

Radius of curvature $\rho \;=\; \frac{m\sqrt{v_{xo}^2+v_{yo}^2}}{qB_z}$

$$\tan\phi \;=\; \frac{v_{yo}}{v_{xo}}$$

Magnetic vs. electric deflection

$$\begin{array}{llllll} \vec{B} \quad \perp \quad \vec{v} \quad \| \quad \vec{E} & \rightarrow & F = q(vB + E) & \\ v \rightarrow c & \rightarrow & F \approx q(cB + E) & [1 \text{ MeV } e^- : v = 0.86c] \end{array}$$

Technical limitations:

electric fields: $E_{\text{max}} \approx 10^7$ V/m (10 kV/mm)

magnetic fields: $B_{\text{max}} \approx 2$ T (normalconducting)/10 T (superconducting)

$\longrightarrow$ $cB_{\text{max}} \approx 100 \times E_{\text{max}}$

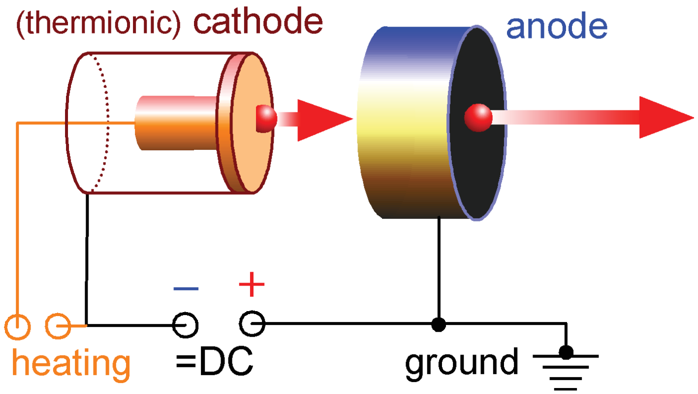
$\Longrightarrow$ Magnetic fields for deflection (bending and focussing)

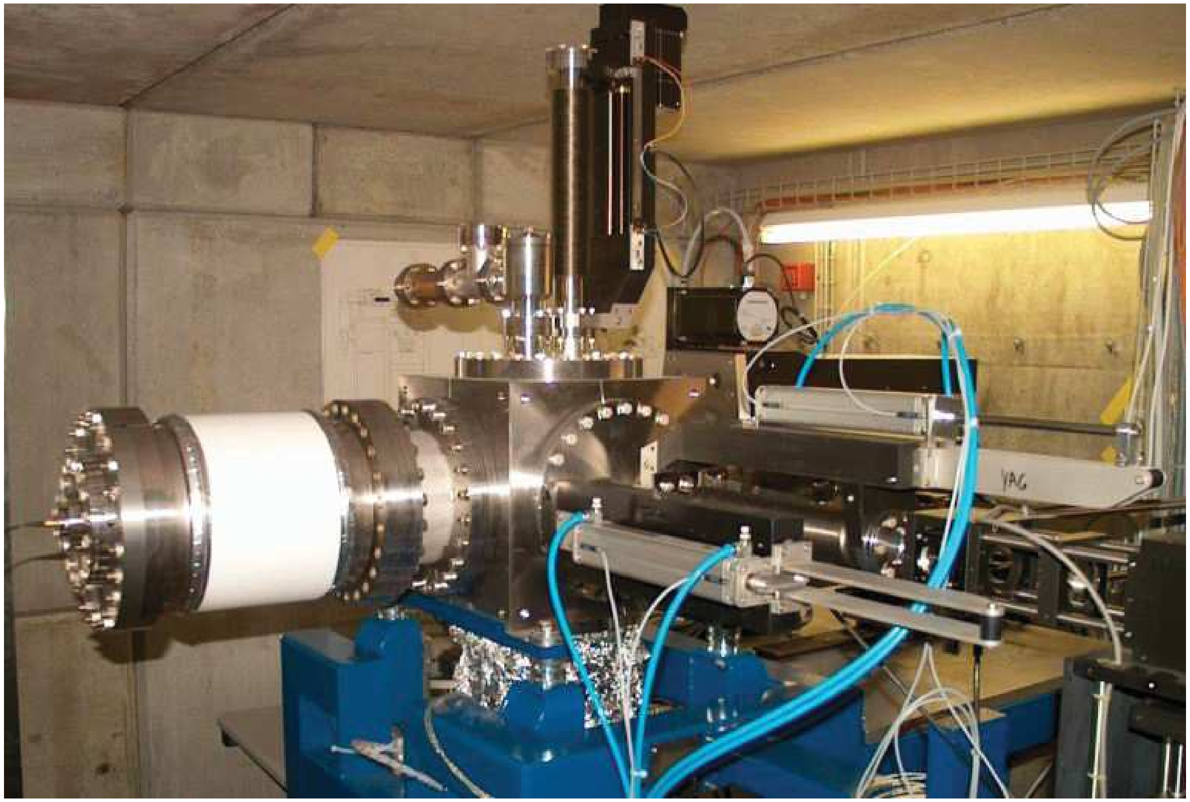
$\Longrightarrow$ Electric fields for acceleration.

(In special cases, electric fields too are used for deflection).

Electrostatic Accelerators

Cathode ray tubes (<1900) ⟶ DC ("direct current") electron guns





Example:

PSI

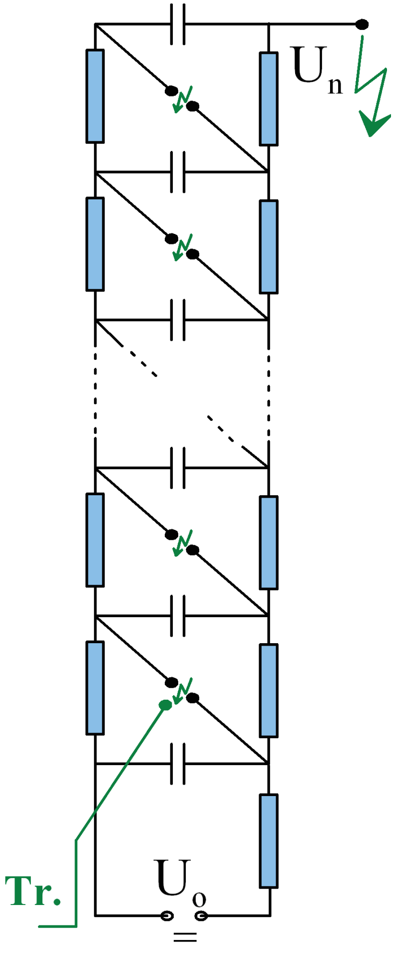
100 keV Teststand for **LEG**
("**L**ow **E**mittance **G**un")

Characterization of field emitter array type cathodes for **SwissFEL** project.

⟹ Increase voltage ! ⟹

Cascaded high voltage generators

Marx Generator (1920)



Principle

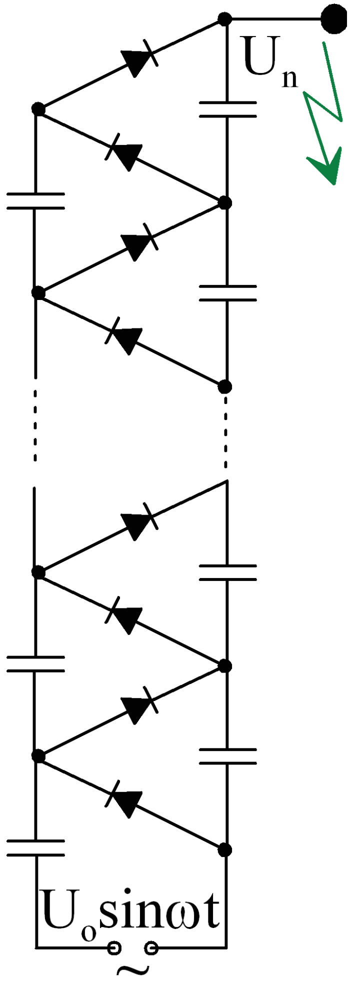
first arc trigger fires all arcs and connects capacitors in series.

$$U_n = nU_o$$

- high voltage
- high current
- short pulses
- low duty cycle

$$U_{\max} \sim 6\ \mathrm{MV}$$

Cockcroft Walton (1930)



Principle

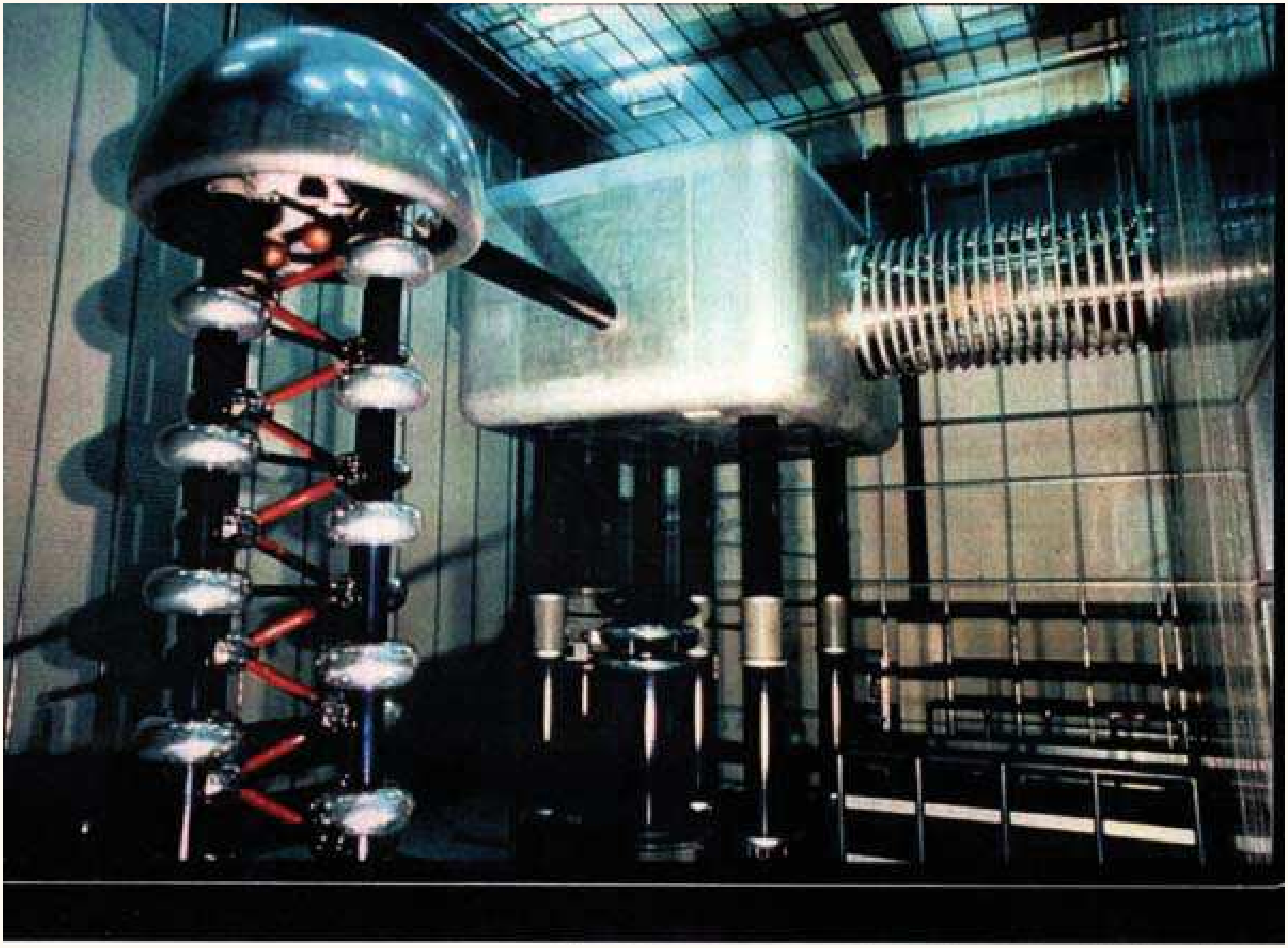
diodes shift up voltage offset on capacitor chain.

$$U_n(t) = 2nU_o + U_o \sin(\omega t)$$

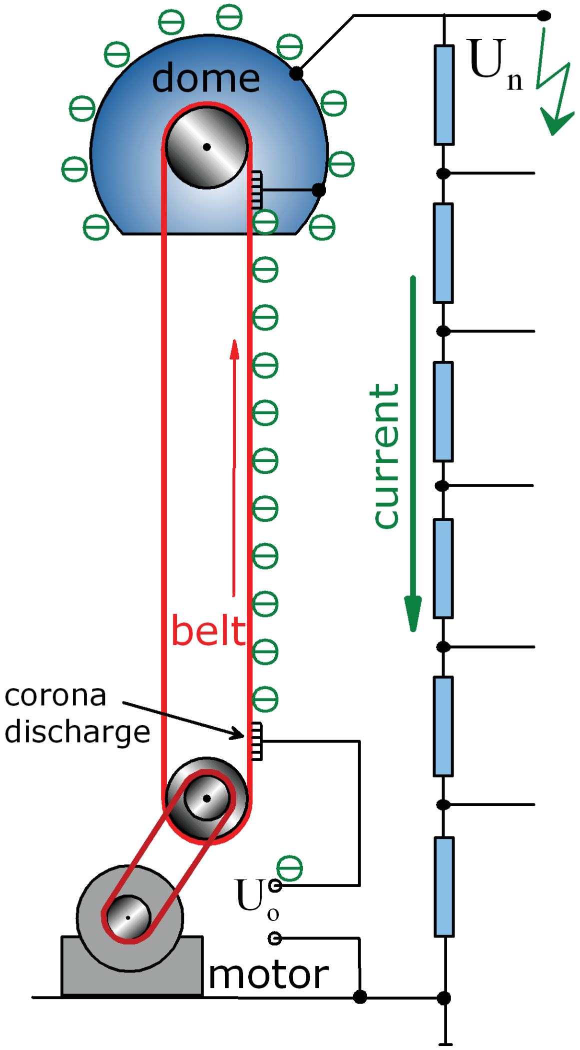
- quasi DC HV
- with AC ripple

$$U_{\max} \sim 4\ \mathrm{MV}$$

PSI Cockcroft Walton 870 keV proton source



Van der Graaff Generator (1930)

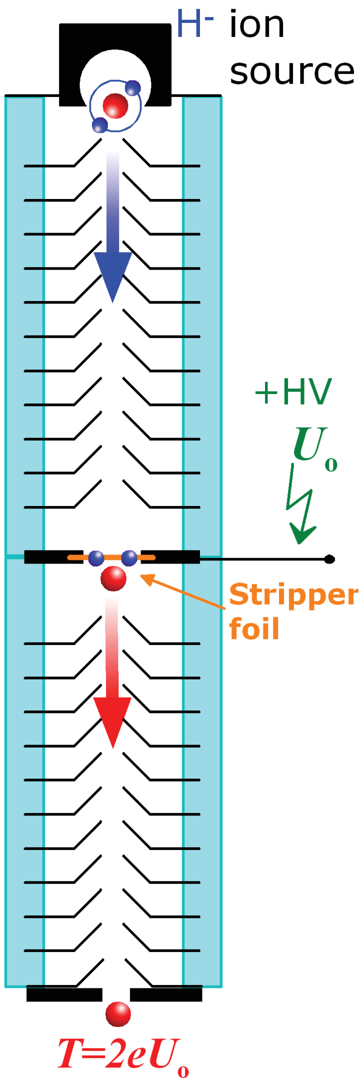


Principle

corona discharge sprays charge on belt.
charge is accumulated on high voltage dome.
current through resistor chain stabilizes voltage.
accelerator: resistor column = beam tube

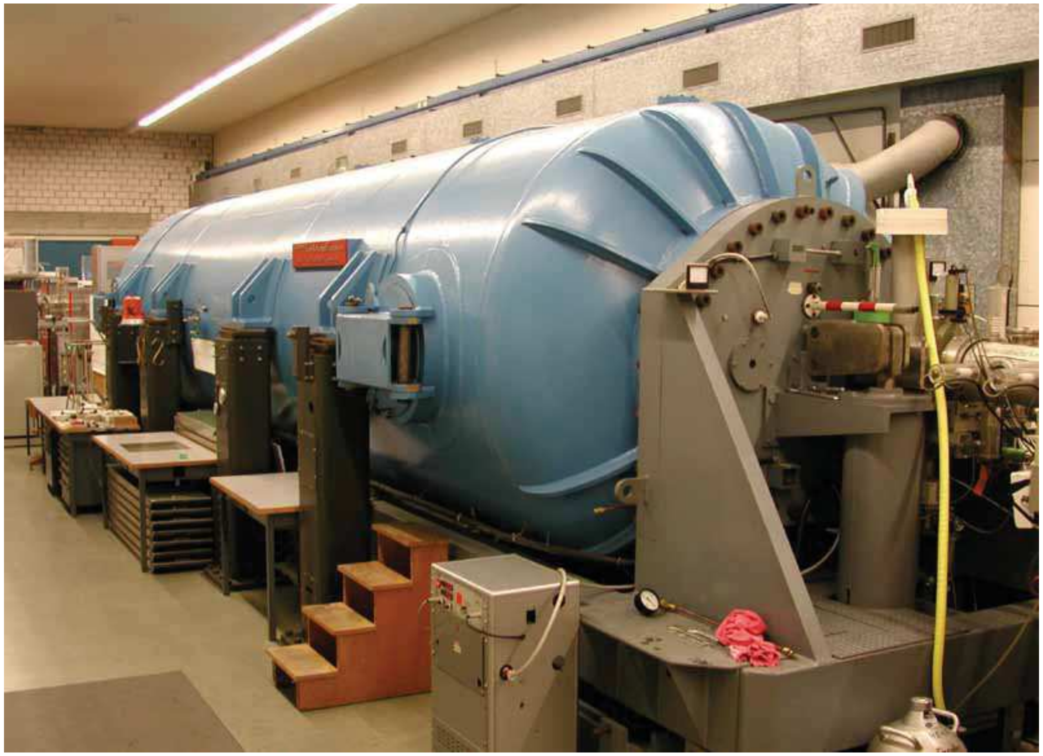
$$U_{\mathrm{max}} \sim 10\ \mathrm{MV}$$

Tandem van der Graaff



Principle

inversion of ion charge by stripper foil $\Longrightarrow$ double ($H^- \rightarrow H^+$) or multiple (ions) energy.



6 MV ion tandem van der Graaff at ETHZ

Voltage limitations

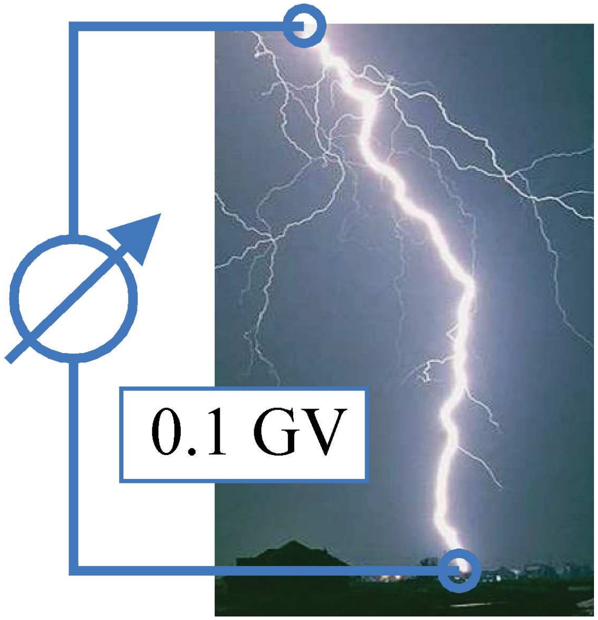
Maximum DC voltage $U \sim 10\ \mathrm{MV}$

technical limitations: discharge, insulation etc.

$\Longrightarrow$ maximum particle [kinetic] energy $T = qU < 10\ \mathrm{MeV}$

for protons and electrons ($q = \pm e$).

(multiply charged ions: $|q/e| > 1 \longrightarrow$ some 10 MeV)



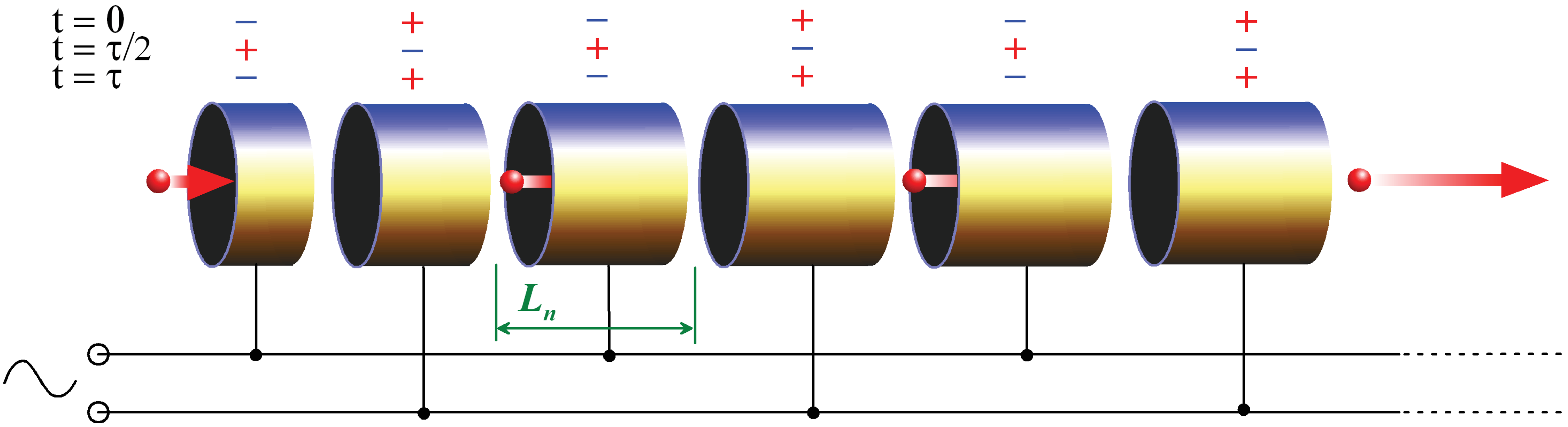
PP requirements

$W^{\pm}, Z, H^{\circ}$ production: $> 100\ \mathrm{GeV}$

how to accelerate further ?

Radio-frequency (RF) acceleration

AC/RF acceleration (*Ising* 1925, *Wideröe* 1928)
RF (”*R*adio *F*requency”) = high frequency AC (“*A*lternating *C*urrent”): MHz ... GHz



Drift tube length ($v \ll c$): $L_n = \frac{\tau}{2} v = \frac{\tau}{2}\sqrt{\frac{2T}{m_o}} = \frac{\tau}{2}\sqrt{\frac{2nqU_o \sin\phi}{m_o}}$

$$U = U_o \sin(\omega t + \phi) \quad \longrightarrow \quad T = nqU_o[\sin\phi]$$ ***basically unlimited!***

Phase ϕ: maximum acceleration for $\phi = \frac{\pi}{2}$, ***but . . .***

Phase focussing

Kinetic energy gain for *synchronous particle* ($\hat{t} = 0$)

$$\hat{T} \;\rightarrow\; \hat{T} + qU_o \sin\phi$$

Consider particles arriving too early ($t < 0$) or too late ($t > 0$):

$$T \;\rightarrow\; T + qU_o \sin(\phi + \omega t) \approx T + qU_o \sin\phi + \omega q U_o \cos\phi \cdot t; \qquad |t| \ll \tau$$

$0 < \phi < \pi/2 \quad \rightarrow \quad$ acceleration **and** $\cos\phi > 0$:

late particles get more energy $\longrightarrow$ faster; catch up with synchronous particle
early particles get less energy $\longrightarrow$ slower; wait for synchronous particle

---

$\Longrightarrow$ Stability – within some interval $[t_{\rm min}, t_{\rm max}]$ $=$ the *bucket*

$\Longrightarrow$ *Bunched beam*:

In RF accelerators, the beam is not continuous but distributed on separate *bunches*.
Temporal spacing $\tau = 2\pi/\omega$, longitudinal spacing $v\tau \xrightarrow{v\rightarrow c} \lambda_{\rm rf}$.

Phase focussing: a simple tracking

sub-relativistic linac: cell length adjusted to reference particle velocity $\hat{v}$:

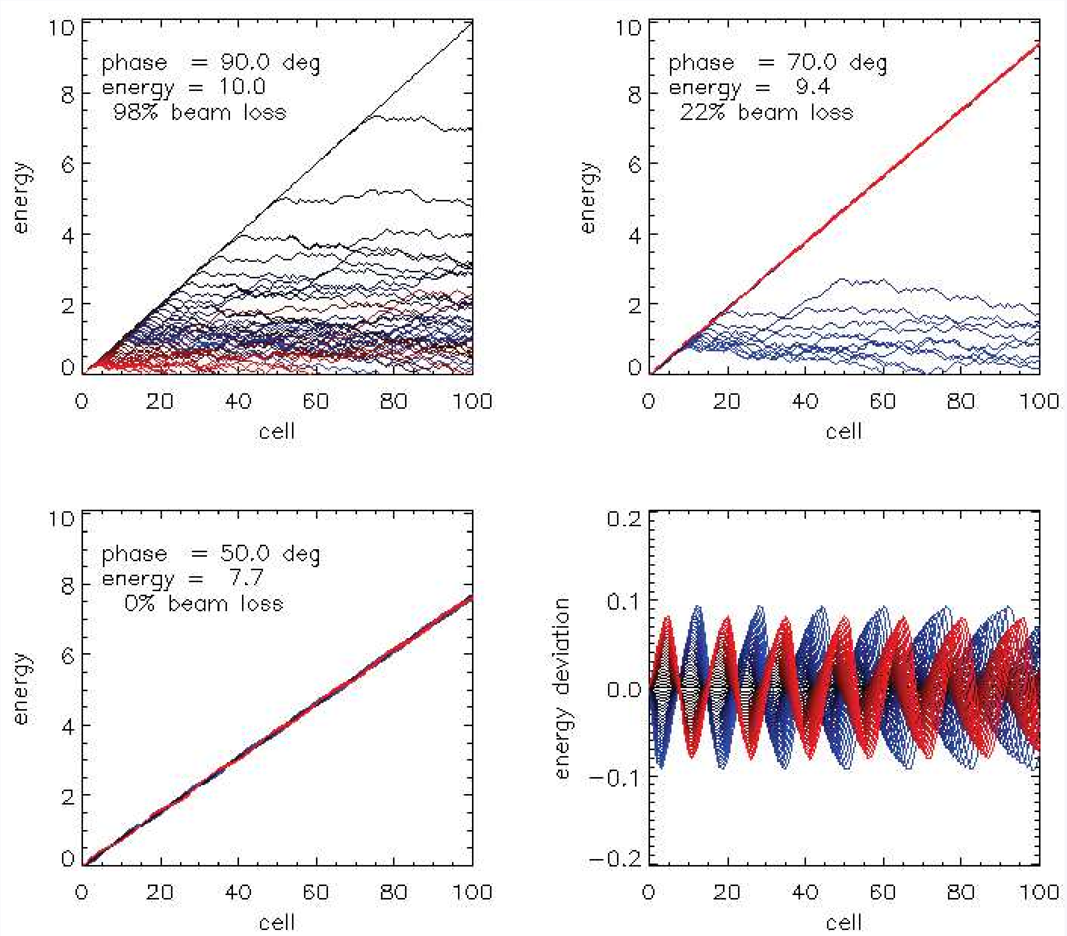
$$L_n = \frac{\tau}{2}\hat{v}_n,\ \hat{v}_n = \sqrt{\frac{2\hat{T}_n}{m_o}},\ \hat{T}_n = nU_o \sin\phi.$$

Tracking recursion:

$$T_n = T_{n-1} + U_o \sin(\phi + \omega t_{n-1})$$
$$v_n = \sqrt{2T_n/m_o}$$
$$t_n = t_{n-1} + L_n(\hat{v}_n - v_n)$$

Parameters:
$U_o = 0.1,\ \tau = 1,\ m_o = 1$

Starting conditions:
$t_o = (-0.1 \ldots +0.1)\tau$

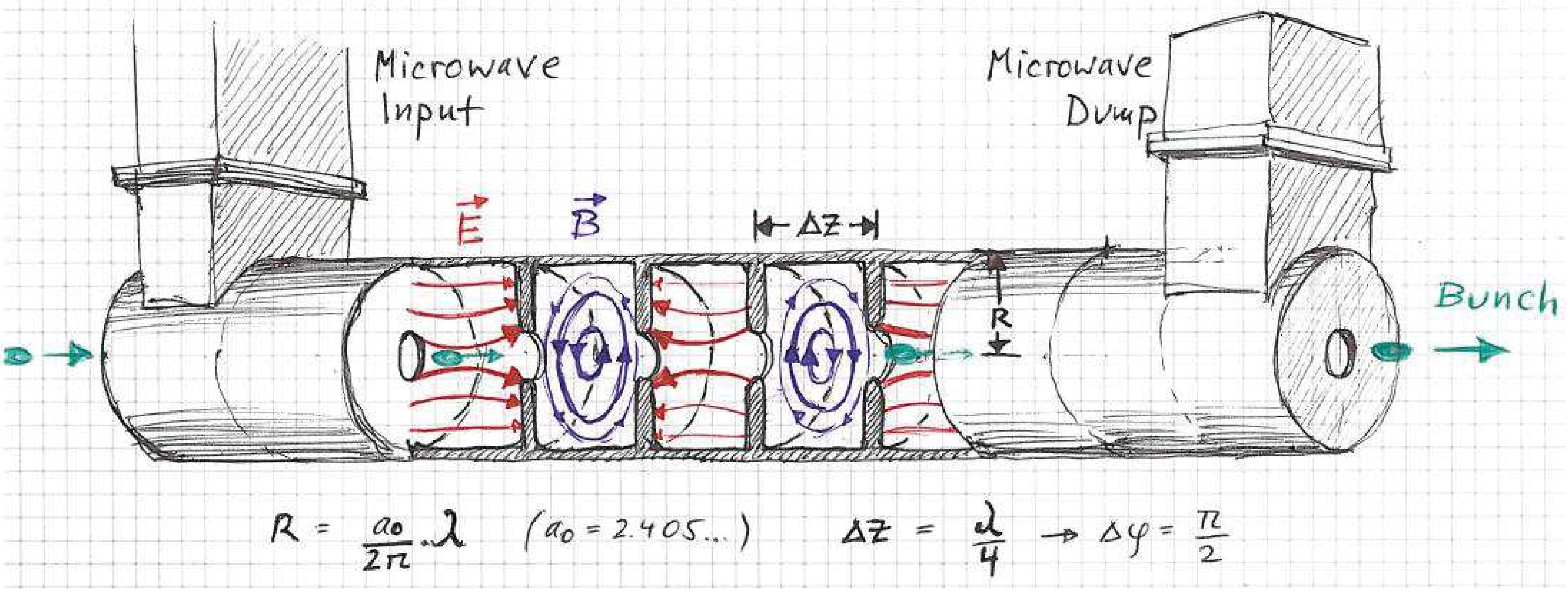


Phase $\phi \to \pi/2$: maximum energy but small bucket: large beam loss

Lower phase, larger bucket: particles perform stable oscillations during acceleration.

Linear accelerator (``Linac'')

Electromagnetic wave travelling through *disk loaded* wave guide:



phase velocity of wave $\overset{!}{=}$ particle velocity

cell radius R given by frequency (first zero of radial Bessel function)

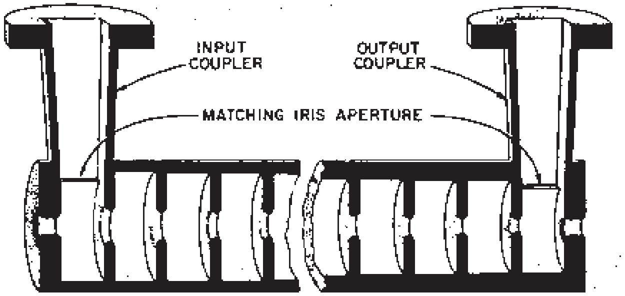
cell length Δz determines phase velocity: phase advance per cell

disk iris: aperture for wave and beam propagation

Accelerating structures

Drift tube linacs

- for $v \ll c$ (protons, ions)
- frequency ~ 100 MHz
- gradient $1 \ldots 10$ MV/m



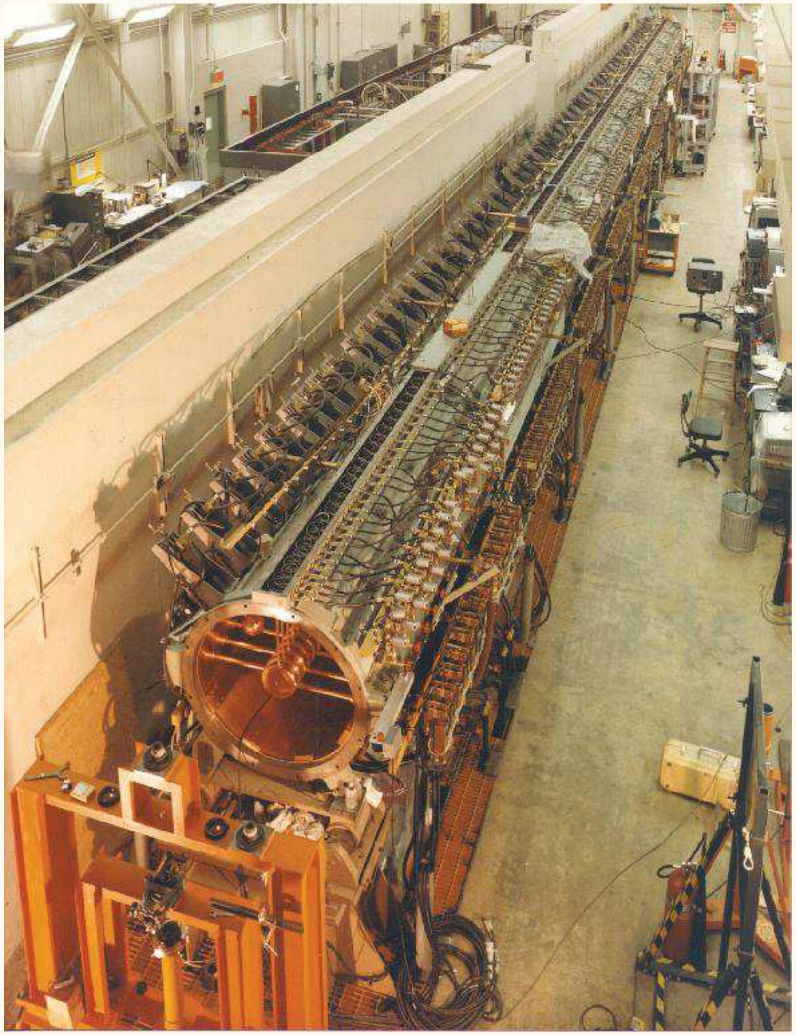
Travelling wave linac

- for $v \approx c$ (electrons)
- frequency ~ 3 GHz
- pulsed (few μs, $10 \ldots 100$ Hz repetition)
- gradient $10 \ldots 50$ MV/m

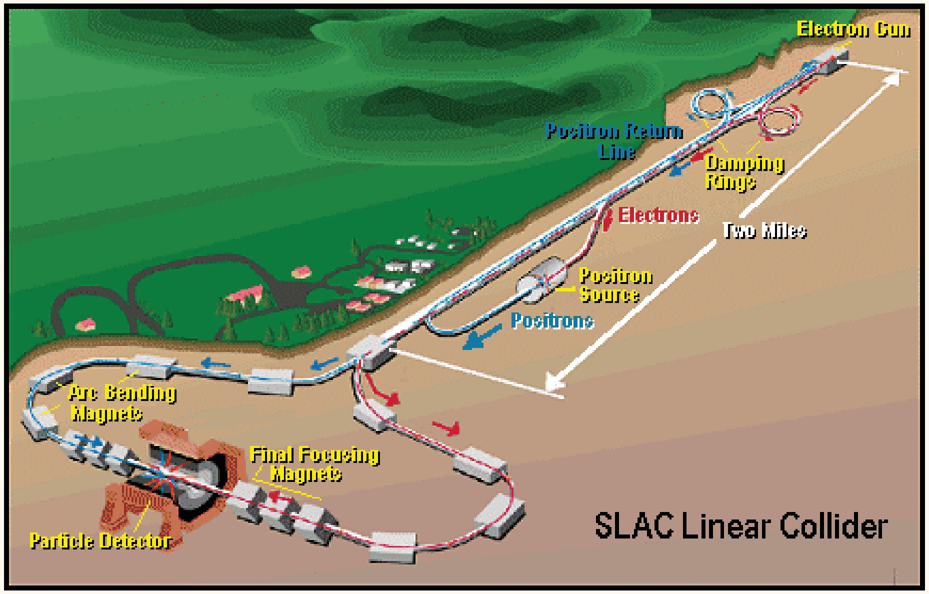
Standing wave structures / RF cavities

- continuous operation possible:
  $\longrightarrow$ circular machines
- frequency ~ 100 MHz $\ldots 3$ GHz
- gradients ~ 1 MV/m

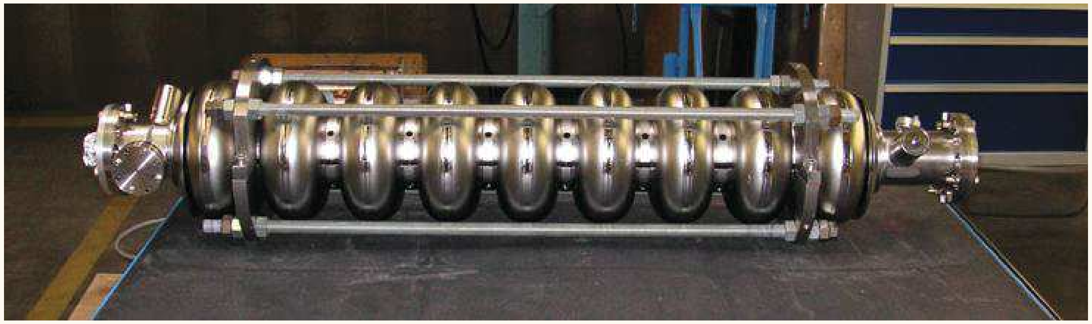
Linacs



Argonne National Lab 50 MeV proton linac of drift tube type



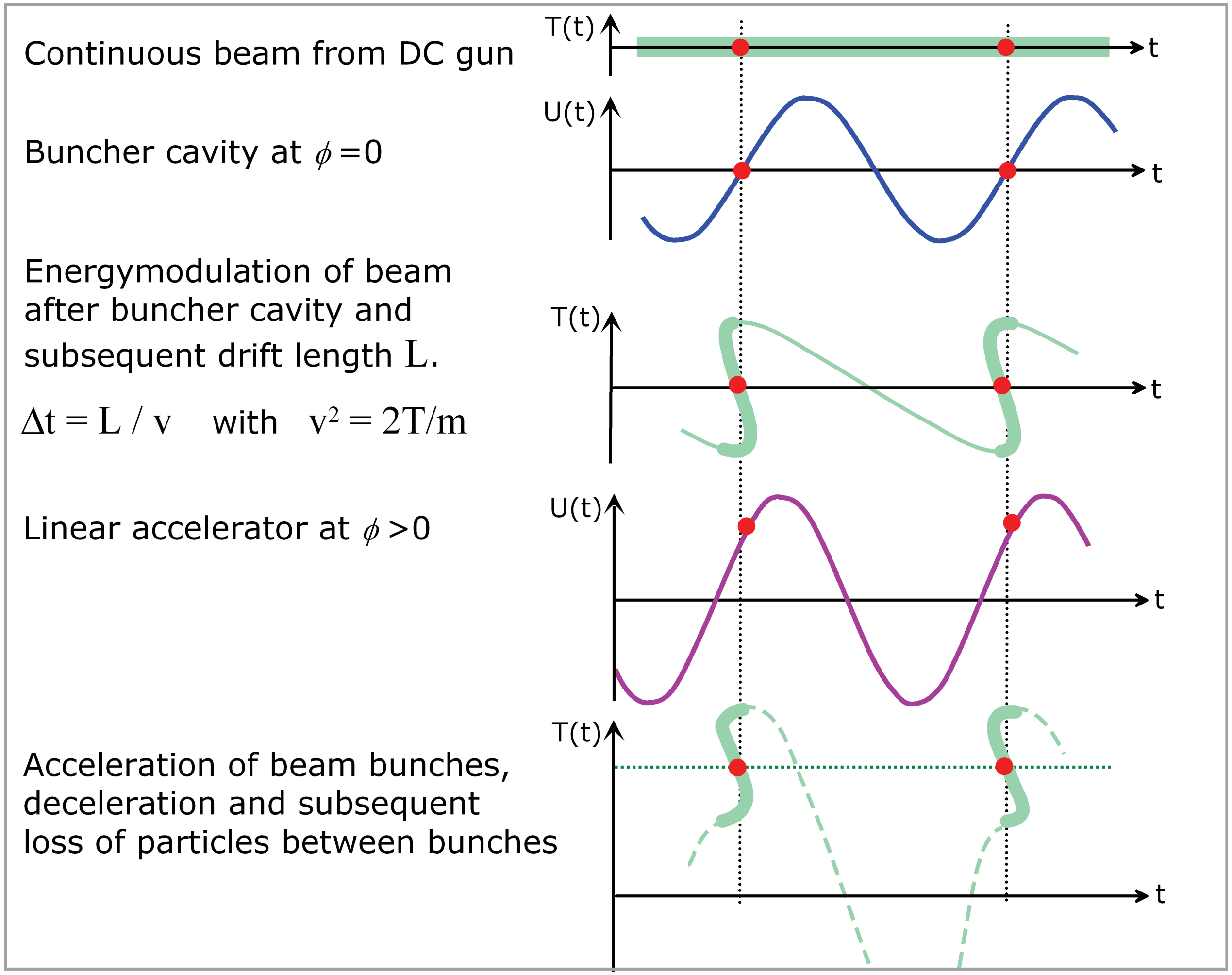
Stanford 100 GeV electron/positron linac collider **SLC**



Superconducing linac structure from Accel company

Bunching

Buncher: short linac or cavity at $\phi \approx 0 \quad \rightarrow \quad \Delta T = qU \sin(\omega \Delta t) \approx \omega q U \Delta t$



Continuous beam from DC gun

Buncher cavity at $\phi = 0$

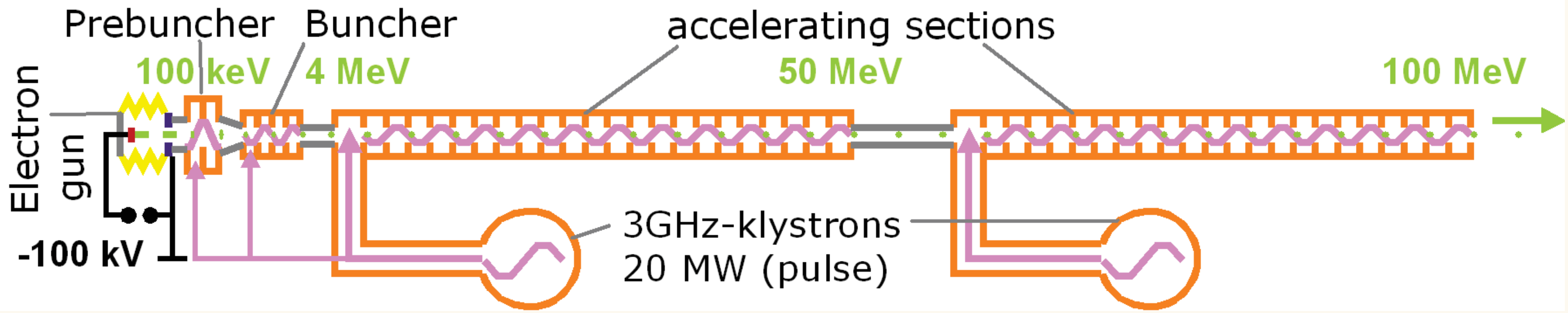
Energymodulation of beam after buncher cavity and subsequent drift length L.

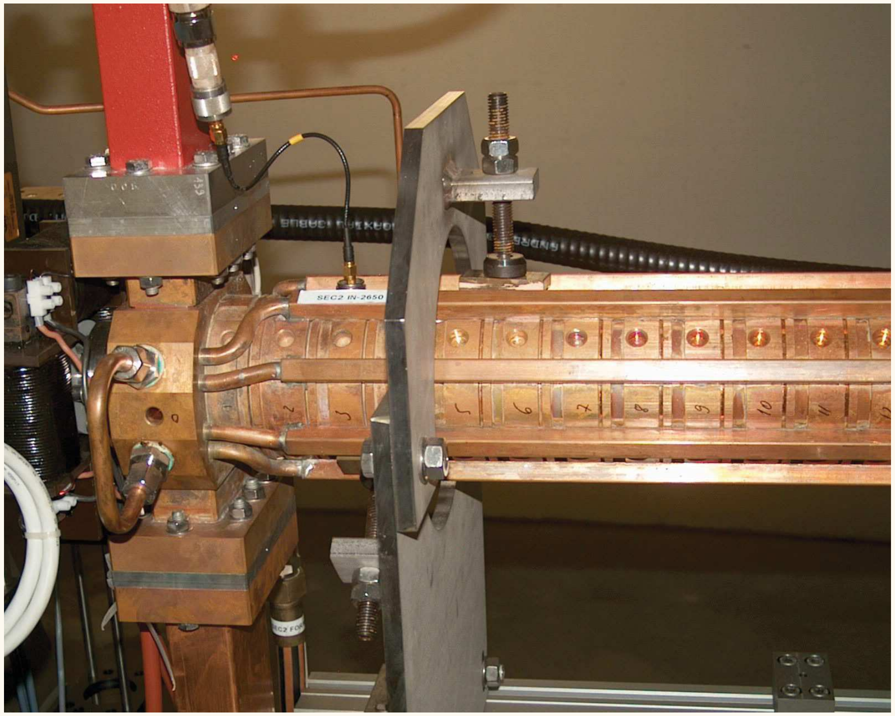
$\Delta t = L / v$ with $v^2 = 2T/m$

Linear accelerator at $\phi > 0$

Acceleration of beam bunches, deceleration and subsequent loss of particles between bunches

SLS 100 MeV electron linac





Linear colliders

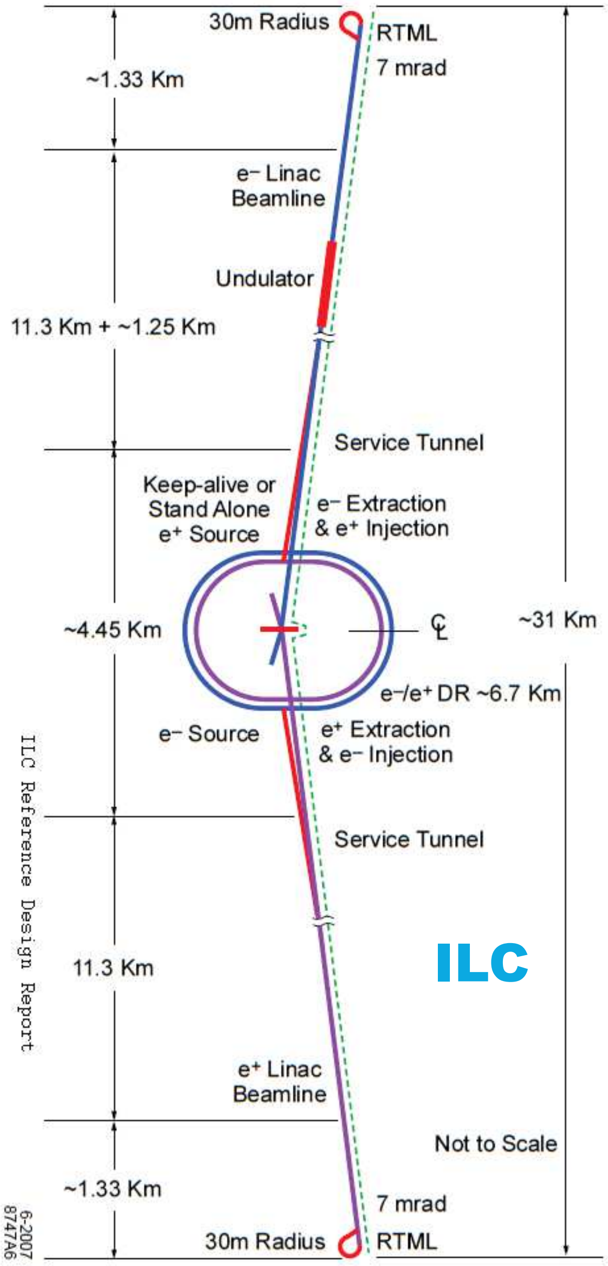
why ?

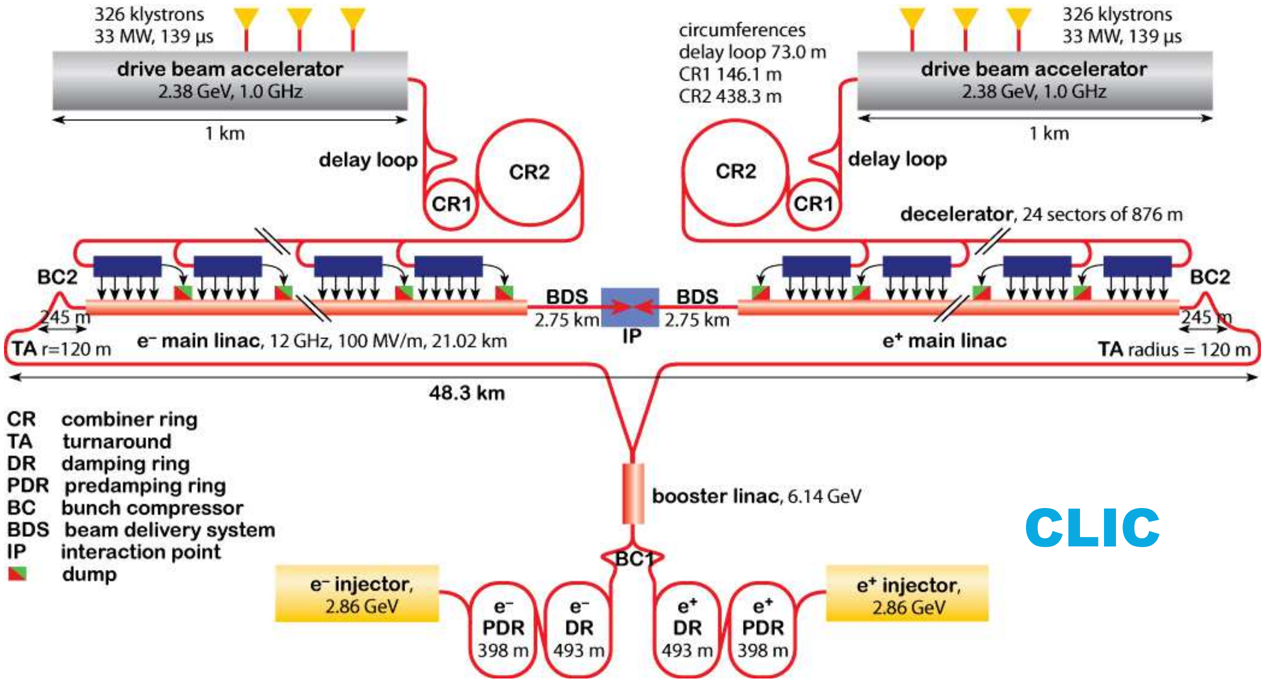
- e^+e^- collisions complementary to pp (**LHC**)
- energy limited for circular e^+e^- colliders (**LEP**)

⇨ **ILC** (International Linear Collider): $E_{cm} = 500$ GeV, 31 km

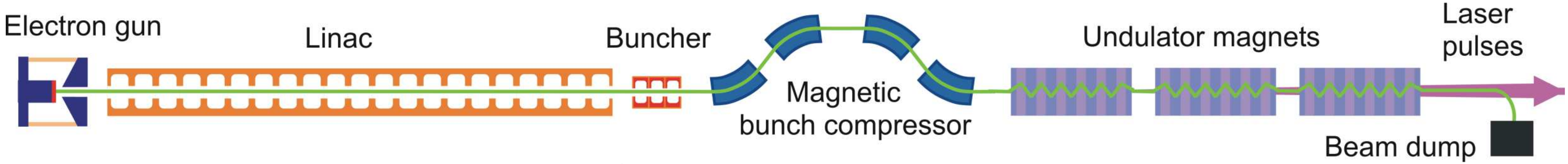
⇨ **CLIC** (Compact LInear Collider): $E_{cm} = 3$ TeV, < 50 km

Costs become main design criterion.





Free electron laser



prepare electron beam of *very high phase space density*:

low transverse emittances, very short pulse, low energy spread

⇨ coherent emission of light and self amplification (⇨ ch.6)

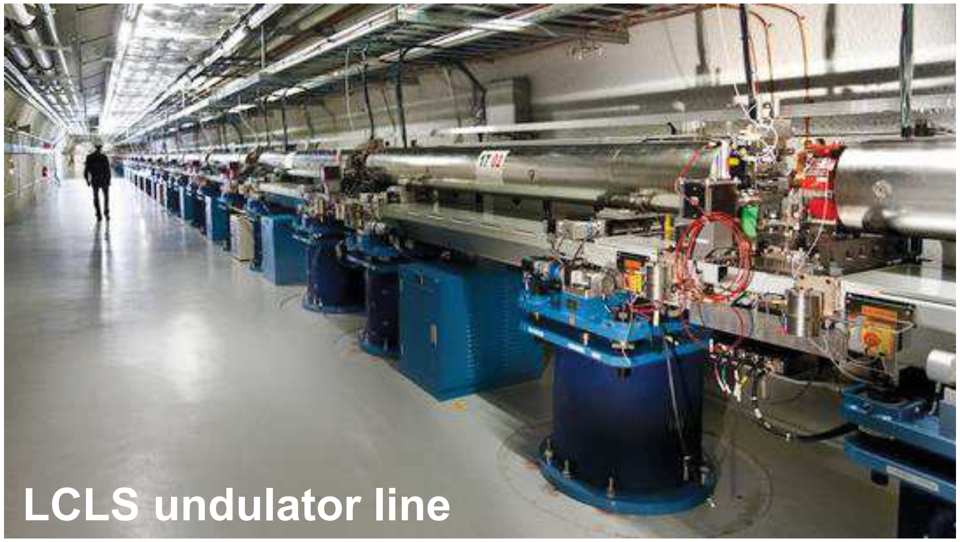
1 Å X-ray pulses: pulse length < 100 fs, power > 10 GW

In operation:

LCLS (SLAC/USA),
FLASH (DESY/DE)
SACLA (RIKEN/JP)

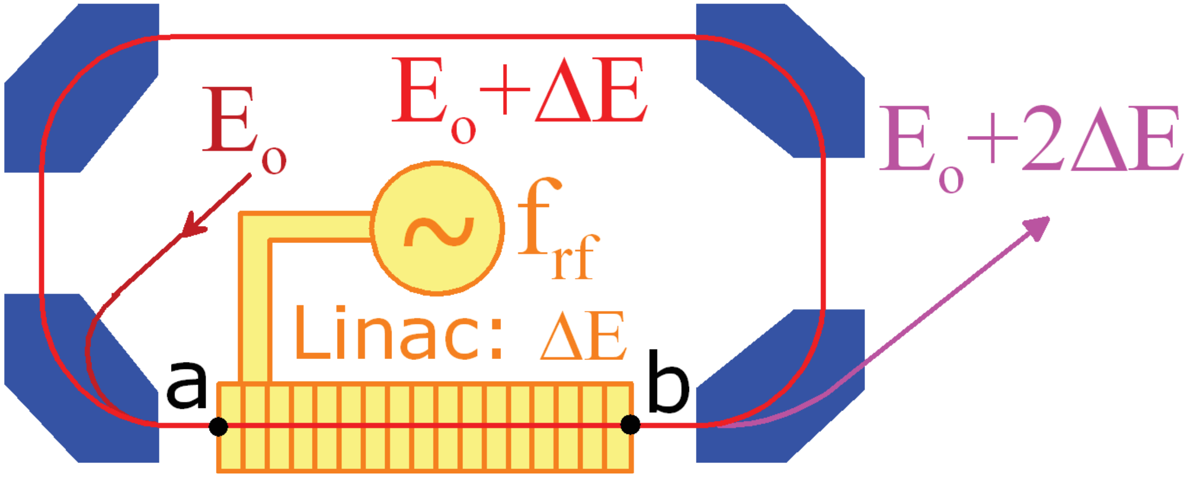
Under construction:

XFEL (DESY/EU)
SwissFEL (PSI/CH)



⇨ Linac development is common **PP** and **MR** interest

Recirculated Linacs



Economic re-use of linac

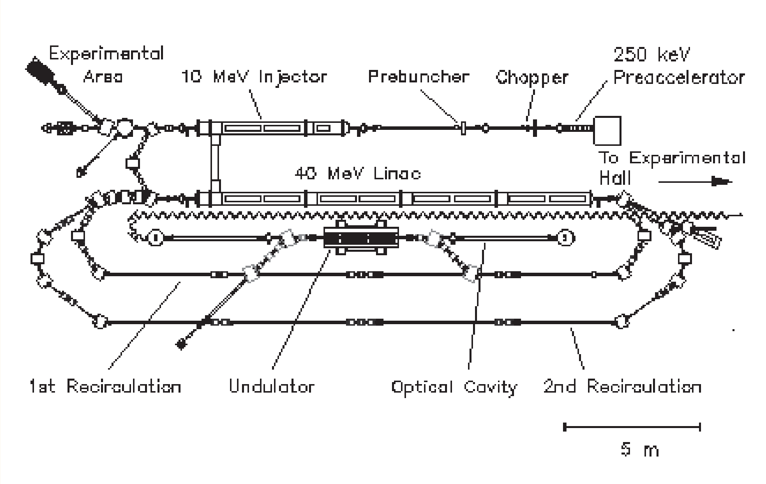
Constraints:

time of flight for recirculation track $\Delta t_{a\rightarrow a} \overset{!}{=} n\tau_{\mathrm{rf}} \quad n \in N$

linac pulse $>$ total travel time $\Delta T_{a\rightarrow a\rightarrow b}$
$\longrightarrow$ or *c.w.* (“continuous wave”) operation.

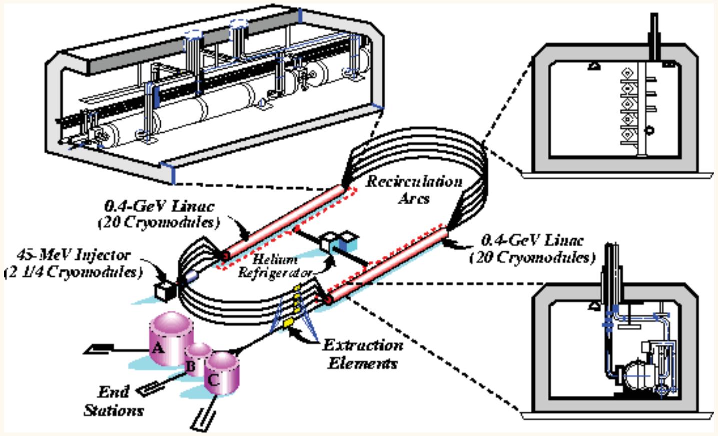
S-DALINAC (Darmstadt, D)

$130\,\mathrm{MeV}\ 2\times$ recirculated s.c. linac for free electron laser and nuclear physics



CEBAF (“**C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility”)

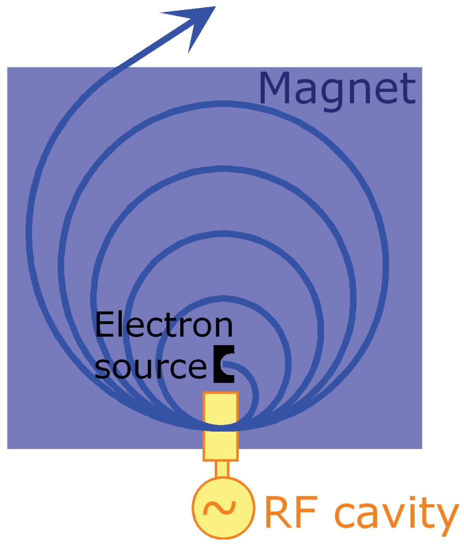
$6\,\mathrm{GeV}\ 5\times$ recirculated double s.c. linac for nuclear physics (Newport News, USA)



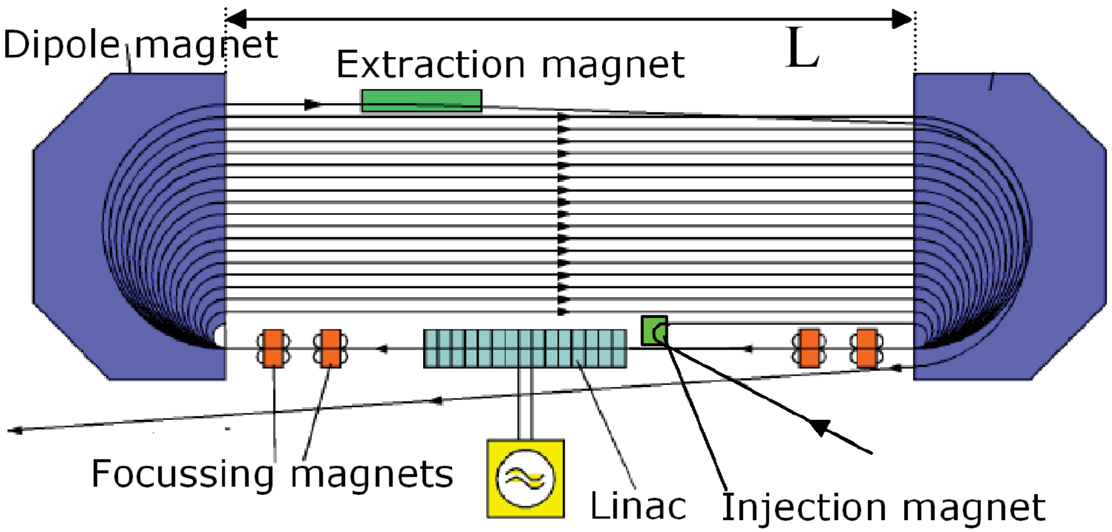
The Microtron / racetrack microtron

Electrons only!

$(\beta \to 1)$



Original microtron



Racetrack microtron

Time of flight for track k $\quad t_k = \frac{2\pi R_k + 2L}{c} \quad$ (R_k bending radius)

Lorentz force $\frac{mv^2}{R} = evB \quad \xrightarrow{v\approx c} \quad R_k = \frac{m_o \gamma_k c}{eB} = \frac{E_k}{eBc} \quad \longrightarrow \quad t_k = \frac{2\pi E_k}{eBc^2} + \frac{2L}{c}$

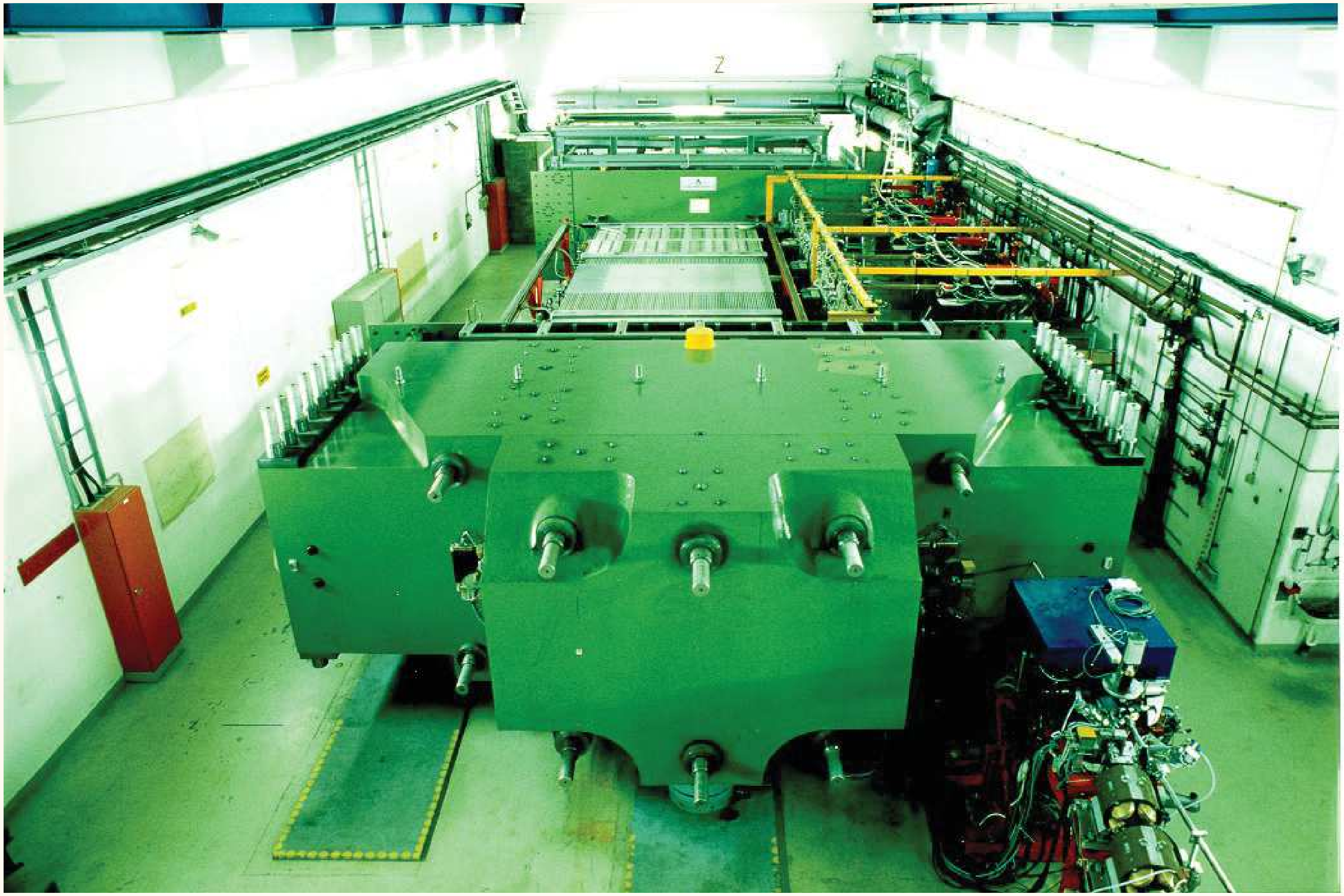
Time difference from one turn to next: $\Delta t = t_{k+1} - t_k = \frac{2\pi}{eBc^2} \underbrace{(E_{k+1} - E_k)}_{=\Delta E_\text{linac}} \overset{!}{=} n\tau_\text{rf}$

Microtron condition: $\quad \Delta E/e\ [\mathrm{MeV}] \times f_\mathrm{rf}\ [\mathrm{GHz}] = 14.3\ n\, B\ [\mathrm{T}]$

MAMI ("**MA**inz **MI**crotron") (Mainz, D)

Cascade of 3 racetrack microtrons and 1 double sided microtron:

$3.5\ \mathrm{MeV} \longrightarrow 14\ \mathrm{MeV} \longrightarrow 180\ \mathrm{MeV} \longrightarrow 850\ \mathrm{MeV} \longrightarrow 1.5\ \mathrm{GeV}$

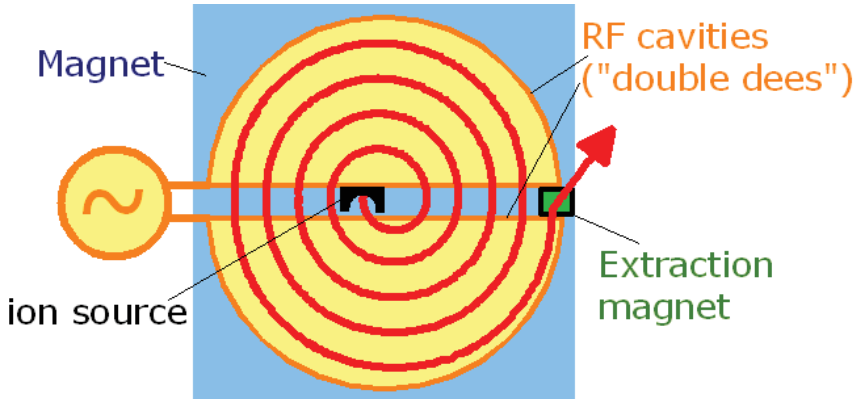


MAMI-RTM3 (850 MeV): $n = 1,\ f_{\mathrm{rf}} = 2.5\ \mathrm{GHz},\ B = 1.3\ \mathrm{T},\ \Delta E = 7.5\ \mathrm{MeV}$

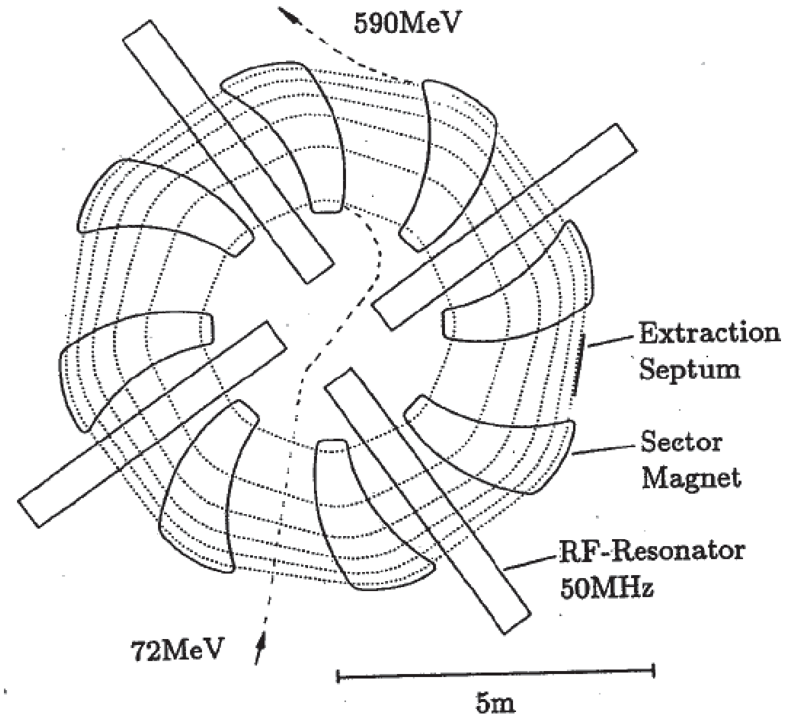
The Cyclotron (Lawrence/Livingston 1932)

protons and ions only!

$(\beta \ll 1)$



Original cyclotron



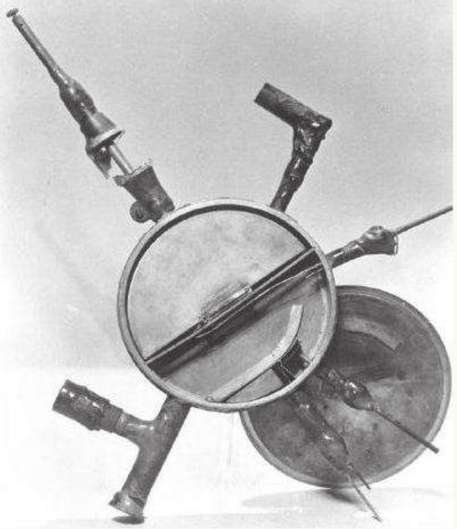
Sector cyclotron (PSI)

Lorentz force: $\frac{m_o v^2}{R} = evB \quad \longrightarrow$ recirculation time $\quad t = \frac{2\pi R}{v} = \frac{2\pi m_o}{eB}$

t no function of energy (for $\beta \ll 1$) $\quad \longrightarrow \quad$ *isochronous machine*

cyclotron frequency $\quad \omega_c = \frac{2\pi}{t} = \frac{e}{m_o}B$

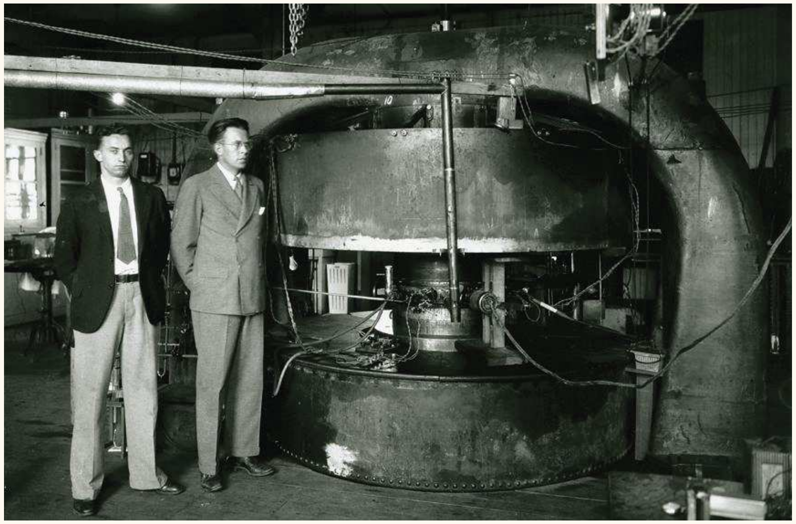
Constraint: $\omega_{\mathrm{rf}} \overset{!}{=} n\omega_c$

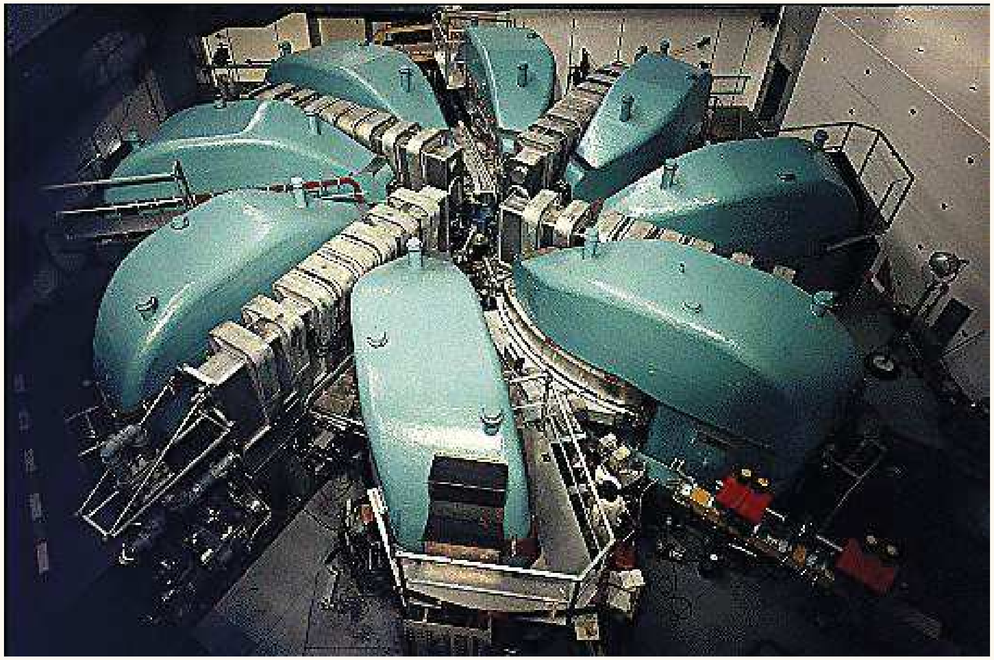


Cyclotrons

$\leftarrow$
Lawrence's first 80 keV cyclotron from 1932 (≈ 15 cm diameter)

$\rightarrow$
Livingston and Lawrence at the 70 cm cyclotron, Berkeley





PSI

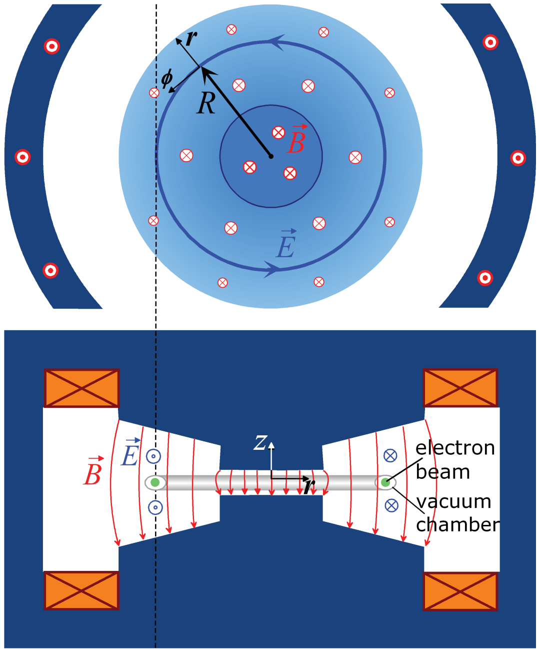
590 MeV proton cyclotron

cw operation at 2 mA proton current
$\Longrightarrow$ > 1 MW proton beam power!

world's most powerful accelerator!

Driver for **SINQ**
(Swiss Spallation Neutron Source)

The Betatron (Kerst 1940)



Kerst at his betatron.

$\Longleftarrow$ Recirculation $\Longrightarrow$

fixed B-field, variable radius	variable B-field, fixed radius
microtron and *cyclotron*	*betatron* and *synchrotron*

The Betatron: $\mathrm{rot}\vec{E} = -\dot{\vec{B}}$ (Maxwell)

B-field varies in radius and time: $\vec{B} = B(r,t)\vec{e}_z$

Stokes: $\oint \vec{E}(t)\cdot\vec{e}_\phi\, ds = -\int\int \dot{\vec{B}}(r,t)\cdot\vec{e}_z\, r dr d\phi$

$$2\pi R E(t) = -\langle\dot{\vec{B}}(t)\rangle\pi R^2 \rightarrow E = E_\phi = -\tfrac{1}{2}R\langle\dot{B}\rangle$$

Lorentz force bends: $mv = p = eRB_{(r=R)}$

Electric force accelerates: $\dot{p} = F = eE = \tfrac{1}{2}eR\langle\dot{B}\rangle$

$\Longrightarrow$ Betatron equation:

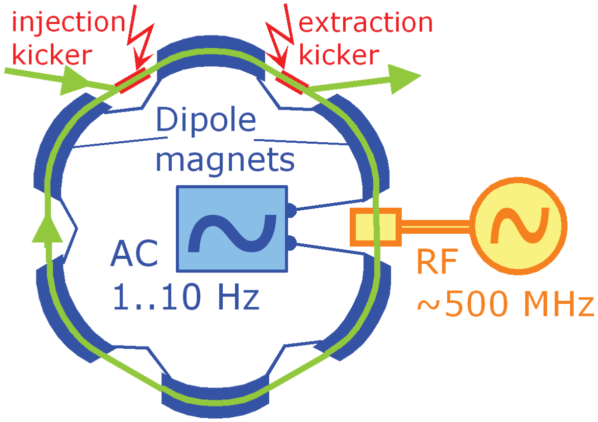
$\boxed{\dot{B} = \tfrac{1}{2}\langle\dot{B}\rangle}$ or $\boxed{B(t) = \tfrac{1}{2}\langle B(r,t)\rangle + B_o}$

acceleration on a circle of constant R (given by B_o)

[gradient $\frac{dB(r)}{dr}|_R$ provides vertical focussing]

inductive acceleration without RF!

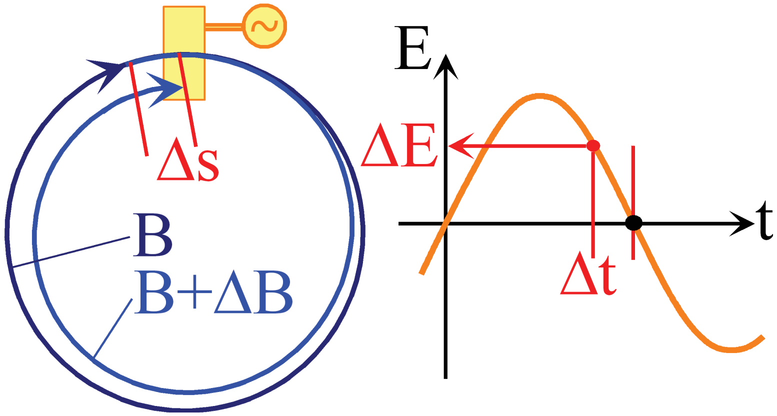
The Synchrotron (Veksler, McMillan 1945)



$$\frac{mv^2}{R} = qvB \quad \longrightarrow \quad p = qRB \quad \longrightarrow \quad p(t) = qRB(t)$$

Momentum follows magnet field variation due to RF phase focussing:

- inject beam into ring at B_o with momentum $p_o = qRB_o$
- increase B-field $\quad \longrightarrow \quad B + \Delta B$
- bending radius shrinks by $\Delta R < 0$
- path becomes shorter by $2\pi\Delta R$
- particles arrive earlier by $\Delta t = \frac{2\pi}{\beta c}\Delta R < 0$
- RF cavity: $U(\Delta t) = qU_o \sin(\omega \Delta t + \phi) > 0$
  for $\Delta t < 0$ if $\phi \approx \pi$
- acceleration by $\Delta p = \beta q U(\Delta t)$

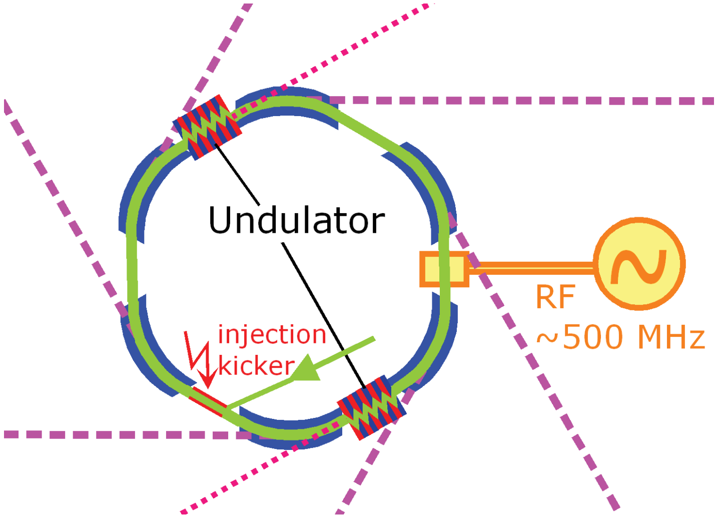


$\Longrightarrow$ self-synchronisation of $p(t)$ with $B(t)$!

Constraints: $\phi \approx \pi$ and $2\pi R = n\beta\lambda_{\mathrm{rf}}$

- extract beam at $B_{\max}$ with momentum $p_{\max} = qRB_{\max}$

The storage ring



storage ring = synchrotron
at constant energy (momentum)

accumulate and store beam for long time (hours)
⟶ synchrotron photon source ⟶

$\Delta E = qU_o \sin\phi - \Delta E_{\text{loss}} = 0.$

only*) for compensation of losses due to synchrotron radiation, wake fields etc.

*) Electron storage ring: radiated power:

$$P\ [\mathrm{W}] = 88.5 \frac{(E\ [\mathrm{GeV}])^4 \times I\ [\mathrm{mA}]}{R\ [\mathrm{m}]}$$

E = beam energy
I = beam current
R = radius of path in dipoles

e.g. **LEP** ("**L**arge **E**lectron **P**ositron collider"):

Beam energy $E = 100\ \mathrm{GeV}$, beam current $I \approx 2 \times 5\ \mathrm{mA}$

$B = 0.11\ \mathrm{T} \ \rightarrow R = 3\ \mathrm{km}$; $\approx 70\%$ magnet filling $\rightarrow$ circumference $27\ \mathrm{km}$!

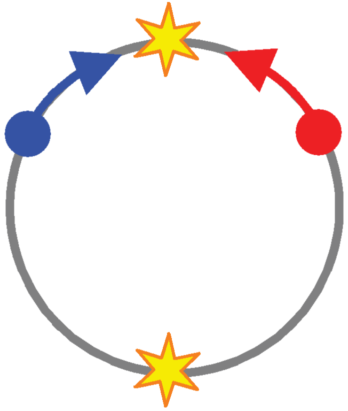
Synchrotron radiation power $\approx 30\ \mathrm{MW}$, requires $> 60\ \mathrm{MW}$ electric.

⟹ upper energy limit for electron rings. No problem with protons ⟶ **LHC**

Circular collider

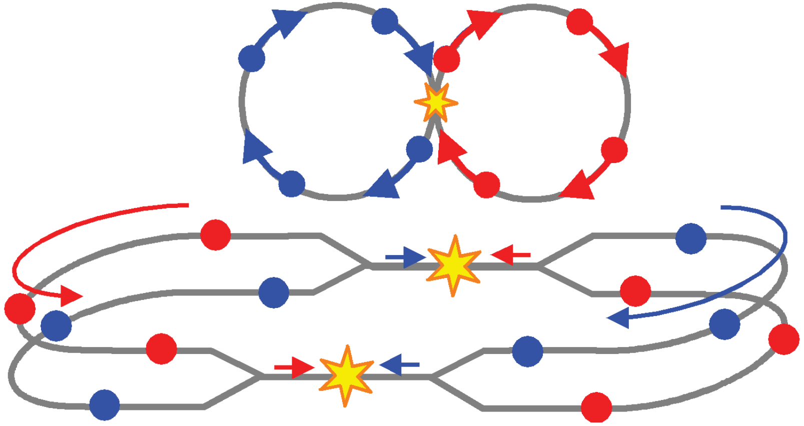
circular collider = one or two storage rings
with opposite beams of particles $\bullet \leftrightarrow \bullet$ and energies E, E

single ring



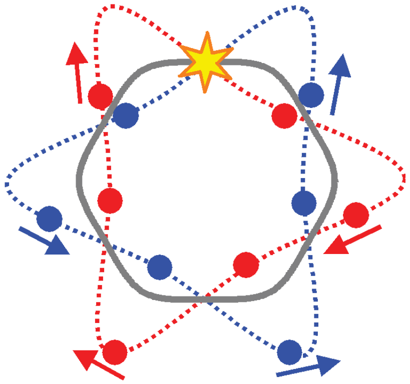
$2n$ interaction points
$2 \times n$ bunches
$\bullet = \bar{\bullet}$ $E = E$

double rings



1 or $2n$ IPs, $> 2n$ bunches
avoid parasitic collisions
or close encounteres
allows $\bullet \neq \bar{\bullet}$ $E \neq E$

"brezel" scheme



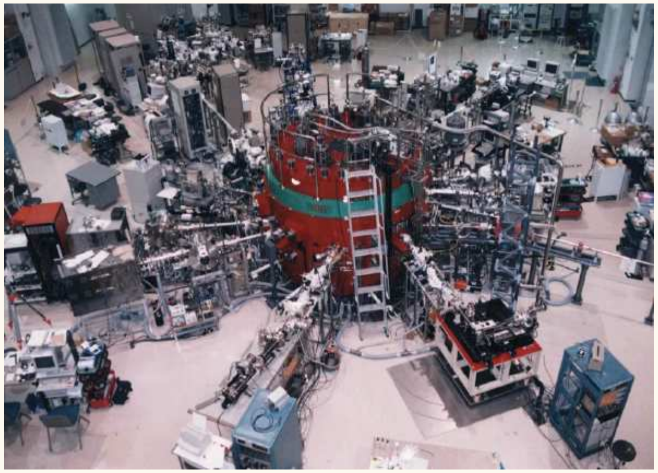
1 or few IPs
orbit oscillations to avoid
parasitic collisions.
$\bullet = \bar{\bullet}$ $E = E$

Synchrotrons

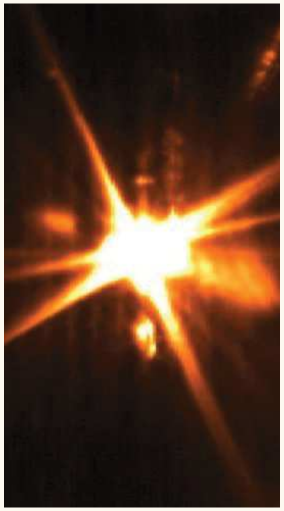
- Pure synchrotrons: [accumulation], acceleration and extraction
  - ▷ booster synchrotrons to fill storage rings: **SPS→LHC**.
  - ▷ beam on target for experiments (pulsed): **SPS→CNGS**.
- Damping rings: accumulation, damping and extraction
  - ▷ damping rings for linear colliders: **SLC**, **ILC**.
- Storage rings: accumulation, [acceleration], damping and storage
  - ▷ antiproton accumulator: **AD**, **AA** at CERN.
  - ▷ light sources: store beam and *use* radiation: **AURORA**, **SLS**, **ESRF**.
- Circular colliders: accumulation, [acceleration], storage and collision
  - ▷ classic single ring **AdA** or double ring **VEP-1**.
  - ▷ high energy frontier: **LEP** $e^+ \leftrightarrow e^-$, **LHC** $p \leftrightarrow p$.
  - ▷ particle factories: **DAΦNE**, **KEK-B**, **LEP**.
  - ▷ special: **HERA** $e^- \leftrightarrow p$, **RHIC** $\mathrm{Au}^+ \leftrightarrow \mathrm{Au}^+$, muon colliders $\mu^+ \leftrightarrow \mu^-$.

Synchrotron light sources

AURORA 0.65 GeV, π m

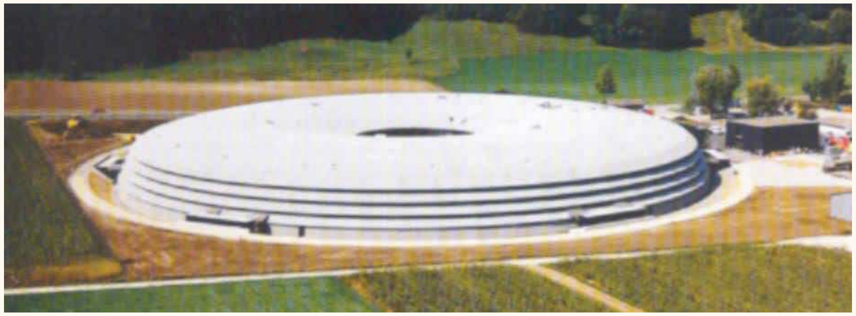


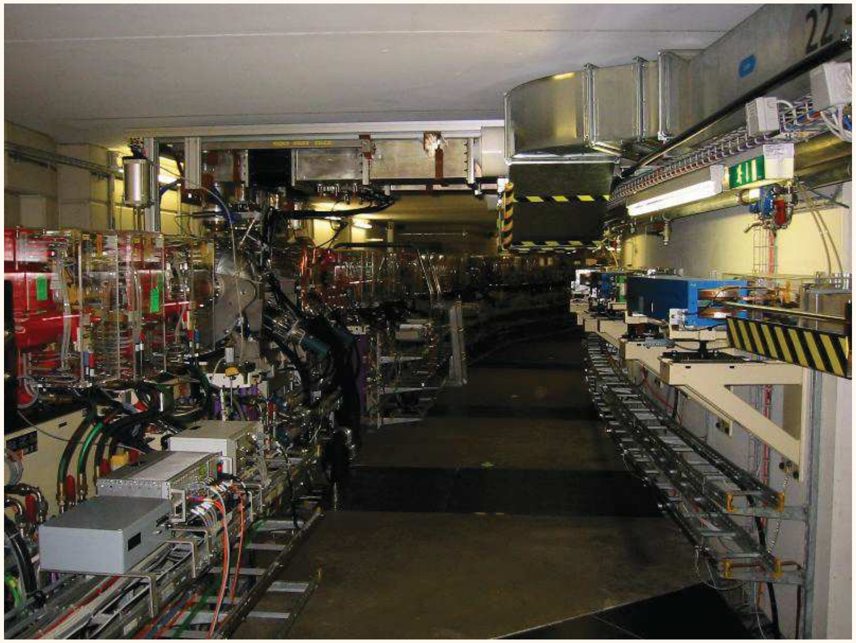
SPRING-8 8 GeV, 1436 m



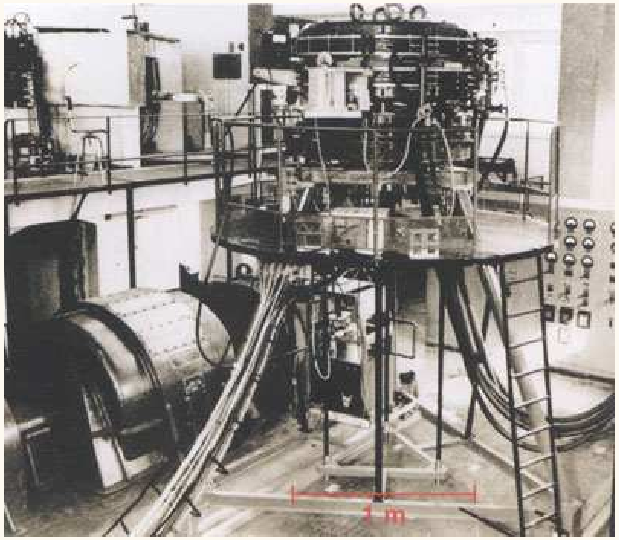
first synchrotron light from the **SLS**, 15.12.2000

SLS 2.4 GeV, 288 m





Circular colliders



← **AdA**
Frascati, 1962
First e^+e^- collisions

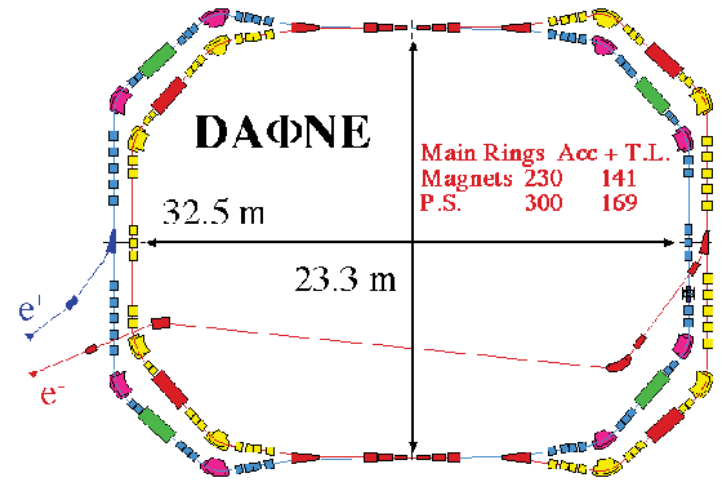
VEP-1 →
Novosibirsk, 1964
First double ring collider
e^-e^-

Tevatron
(FNAL, USA)
$2\times\ 1\ \ \mathrm{TeV}\ p\bar{p}$
↙

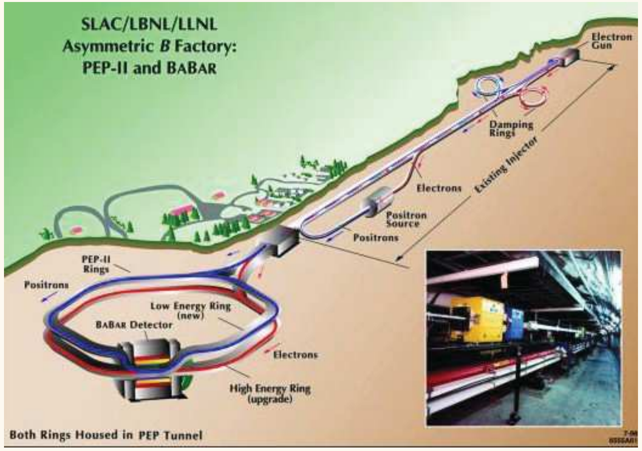
† **SSC** (Texas, USA)
$2\times\ 20\ \ \mathrm{TeV}\ p\bar{p}$
87 km circumference
1988 approval
1989 construction start
1993 cancelled

Particle factories

Particle factory = collider for maximum luminosity at fixed energy.

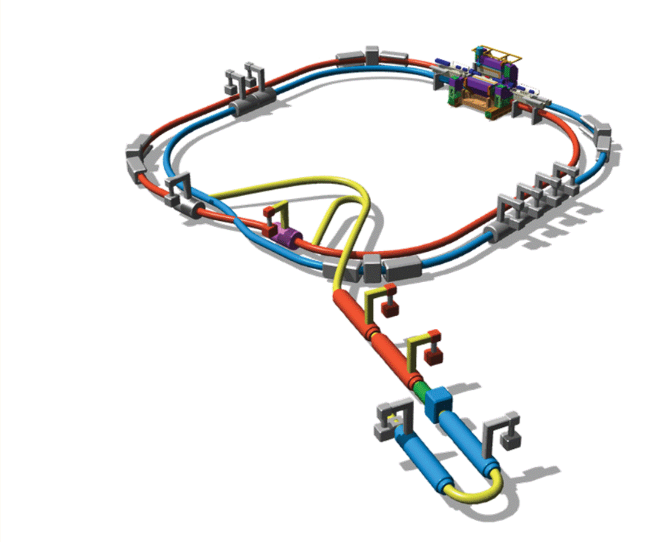


DAΦNE (Frascati, Italy). $2\times510\ \mathrm{MeV}\ e^+e^-$.

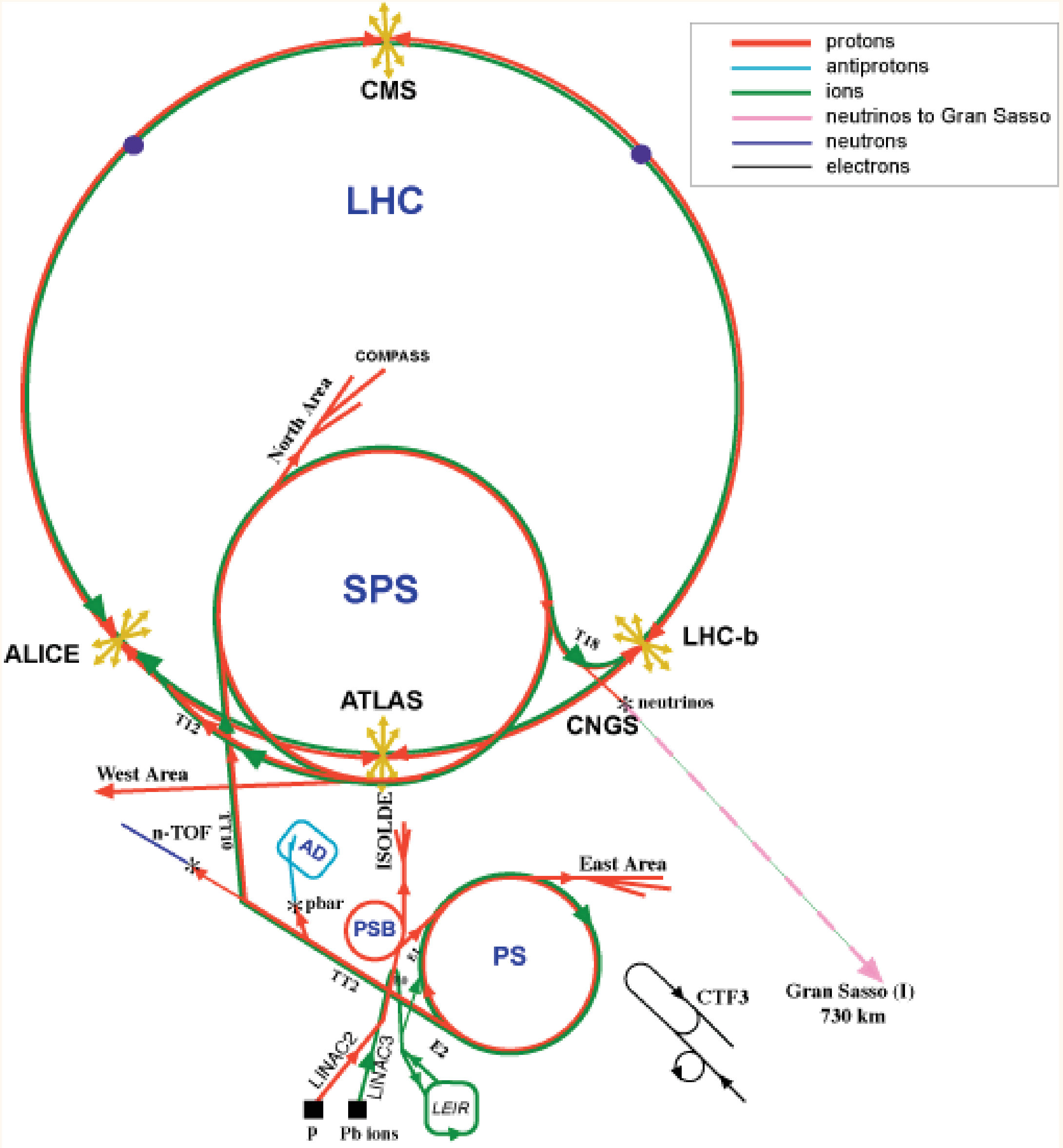


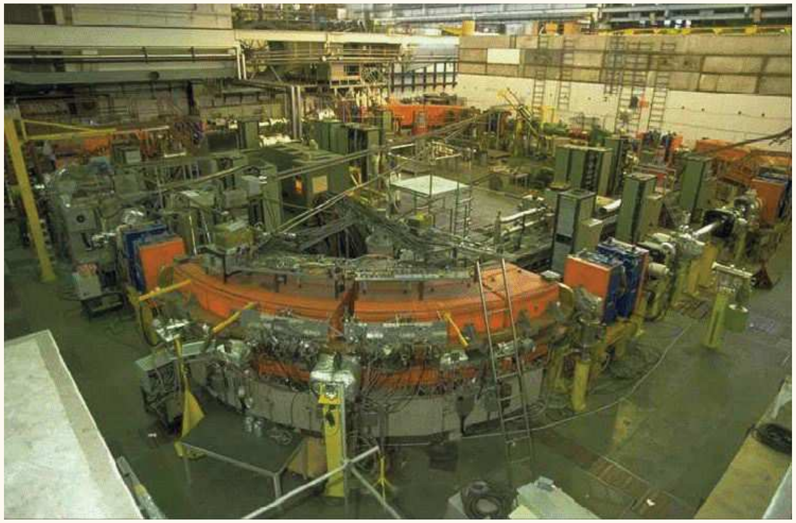
PEP-B (SLAC, USA), 9 $\mathrm{GeV}\ e^-$ ↔ 3.1 $\mathrm{GeV}\ e^+$.

KEK-B (Tsukuba, Japan), 8 $\mathrm{GeV}\ e^-$ ↔ 3.5 $\mathrm{GeV}\ e^+$.



CERN accelerators



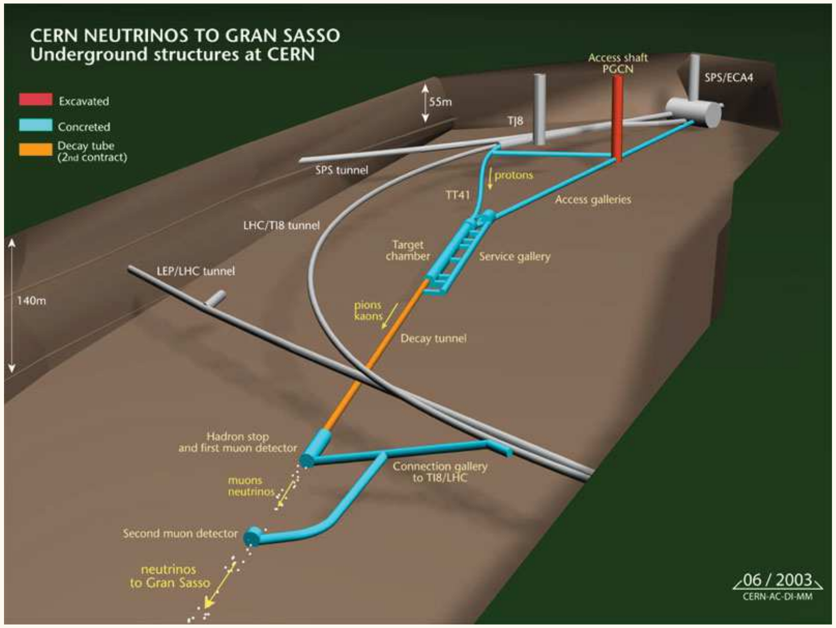


previous slide:
right/top: **LEP**/**LHC** aerial view
right/bottom: **LEIR** ("**L**ow **E**nergy **I**on **R**ing")

LEP "Z-factory" (1989-2000) copper cavities →

SPS tunnel ↘

CNGS ("**C**ern **N**eutrinos to **G**ran **S**asso")
↓ Experiment at the **SPS**



LHC the Large Hadron Collider

synchrotron & storage ring

$26'658.883$ m circumference.

1232 superconducting dipole magnets:
current 12 kA, temperature 1.9 K

Operating cycle:

1. Injection & accumulation ($\sim$minutes)
   450 GeV protons from **SPS**
2. Acceleration (≈ 15 minutes)
   $E = 450 \rightarrow 7000$ GeV
   $B = 0.535 \rightarrow 8.33$ Tesla
3. Collider operation: $\mathbf{p} \Longrightarrow \star \Longleftarrow \mathbf{p}$
   Data acquisition ($\sim$ hours)
4. Deceleration $\Longrightarrow$ 1.

First operation August 2008 $\Longrightarrow$ accident!

Restart Nov.2009 at 3500 GeV.

Shutdown 2013–2014 for consolidation.

Restart 2015 at 6500 GeV