Introduction to accelerators

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Acronyms

- RF – radiofrequency
- MW – microwave
- HV – high voltage
- SC – superconducting

Links

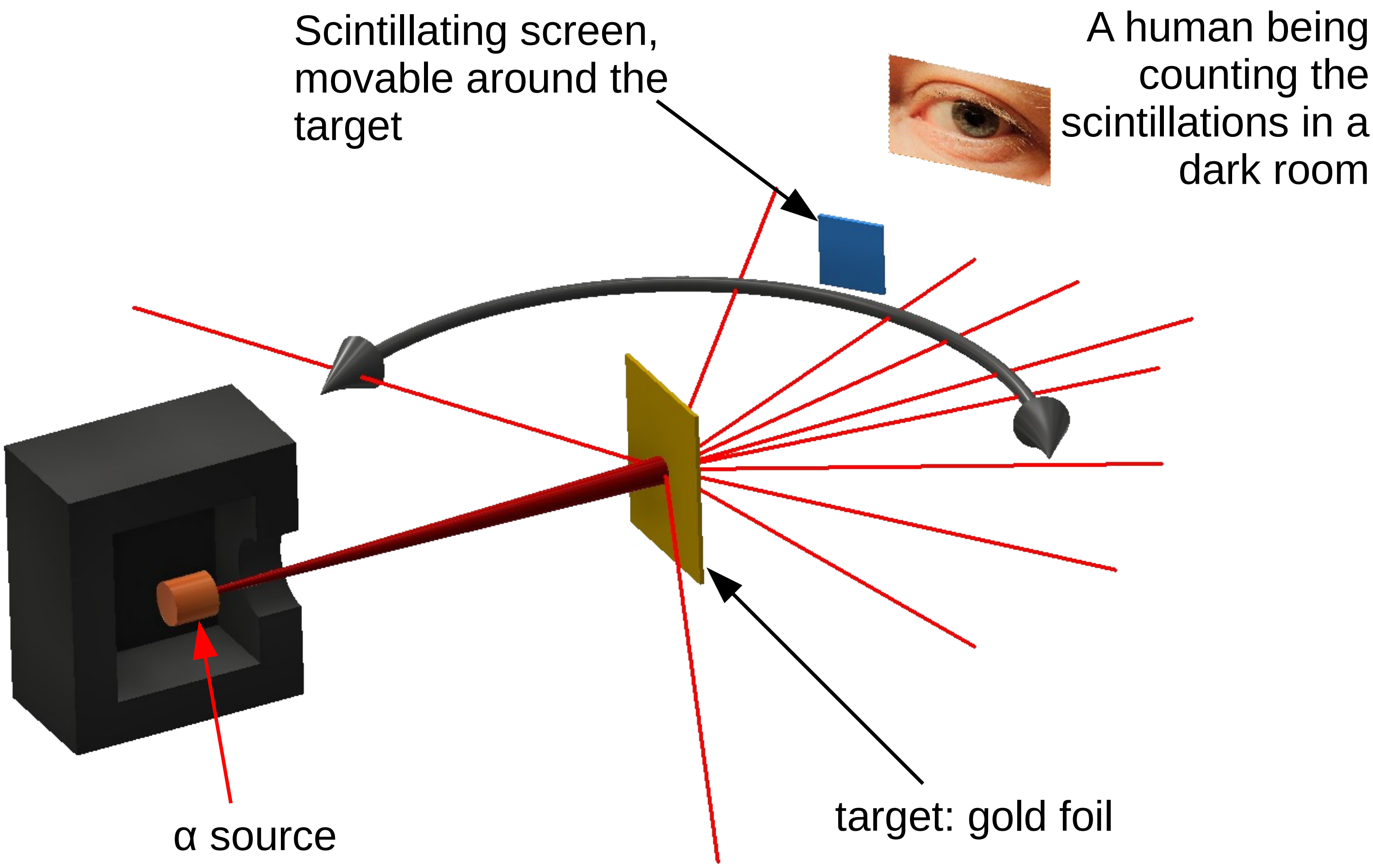
- http://indico.cern.ch/event/532397/timetable/ (CERN Accelerator School 2016, Budapest, videorecordings!)

TODO

- Introduce luminosity

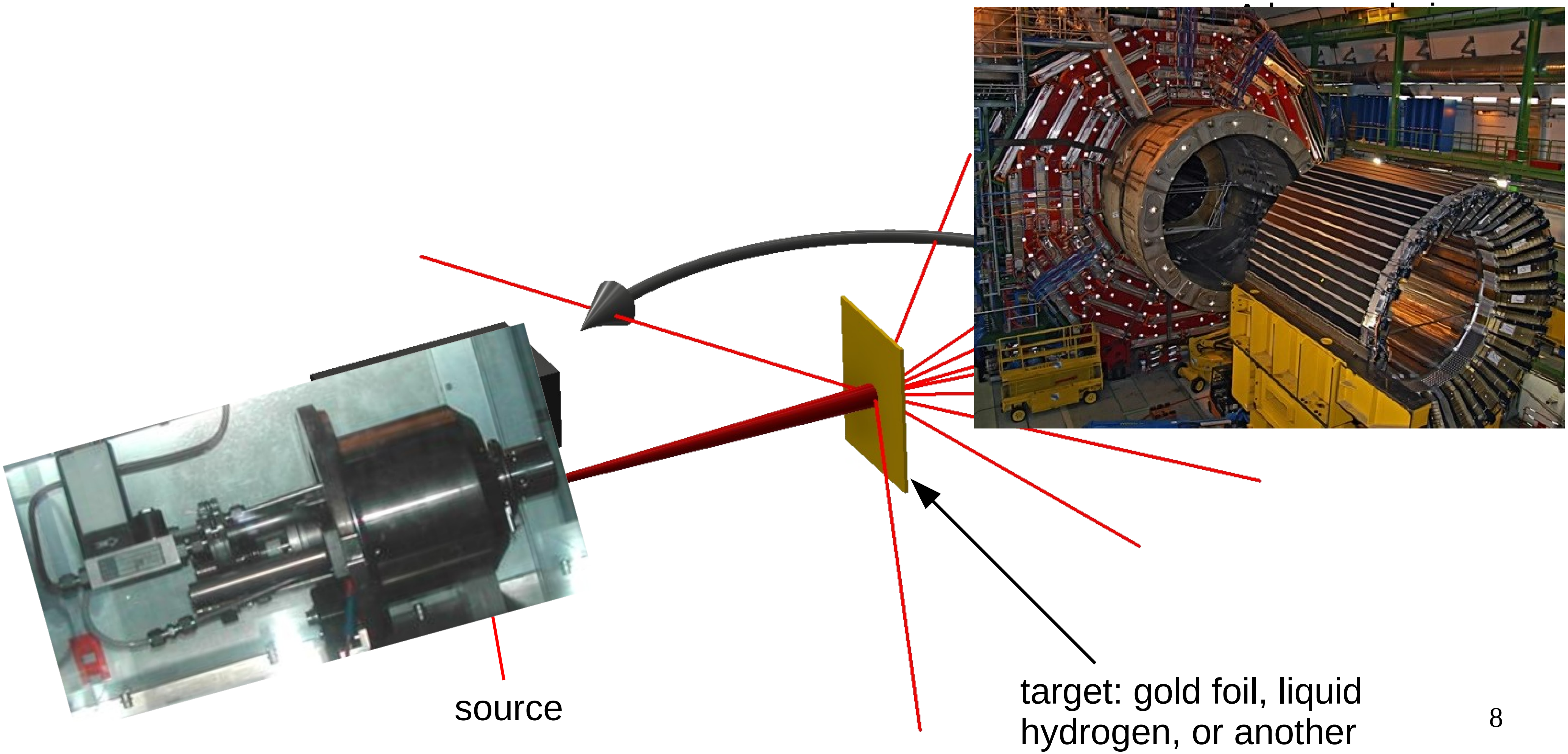
The beginning...

- Rutherford experiment (1908-1913): radioactive (α) radon source – “natural accelerator” (outcome: discovery of the nucleus)



The beginning...

We are repeating the bloody same experiment ever since...



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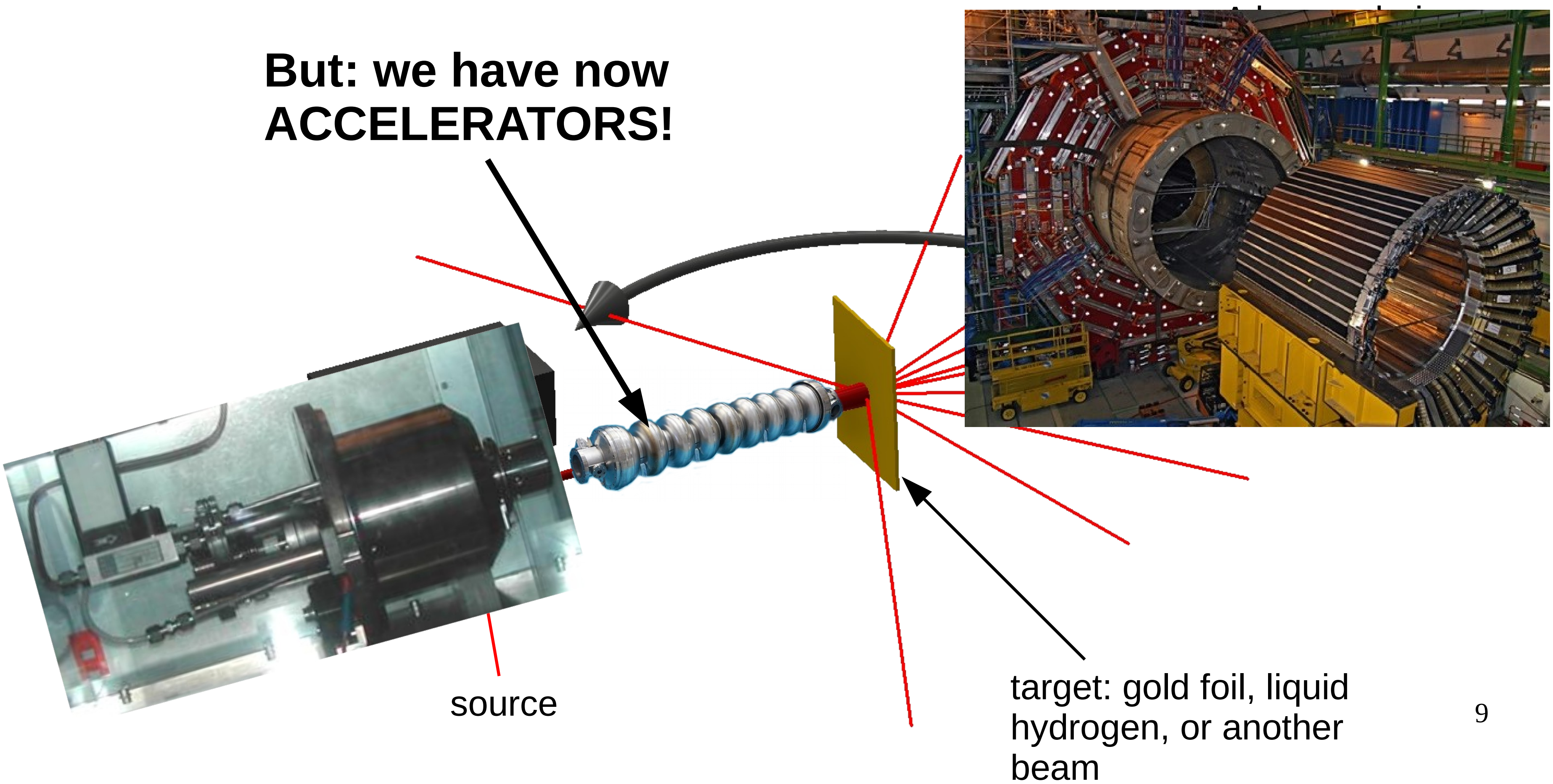


The beginning...

- Rutherford (1927): *“What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accomodated in a reasonably sized room and operated by a few kilowatts of power. We require too an exhausted tube capable of withstanding this voltage. [...] I see no reason why such a requirement cannot be made practicable by the use of oil or air under high pressure, but these are problems for the future”*

Particle sources

Particle sources: classification

- Primary beams: produced directly
  - Protons
  - Electrons
  - Ions
    - positive
    - negative

  } constituents of ordinary matter

- Secondary beams: produced by another beam hitting a target
  - Pions
  - Muons
  - Antiprotons
  - Positrons

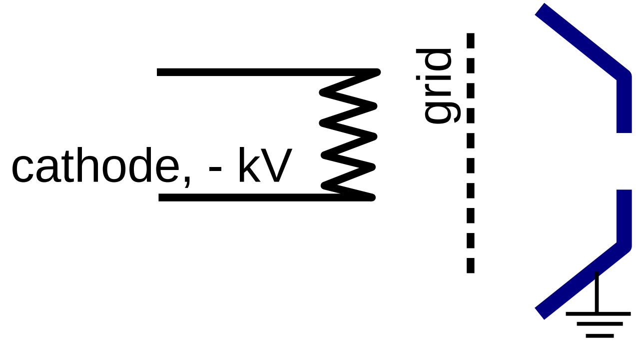
Electron sources

- Electrons must receive sufficient energy to overcome the work function
  - Temperature (heated or thermic cathodes)
  - Laser (photocathodes)

Electron sources: thermic cathodes

- Current: number of electrons above work function

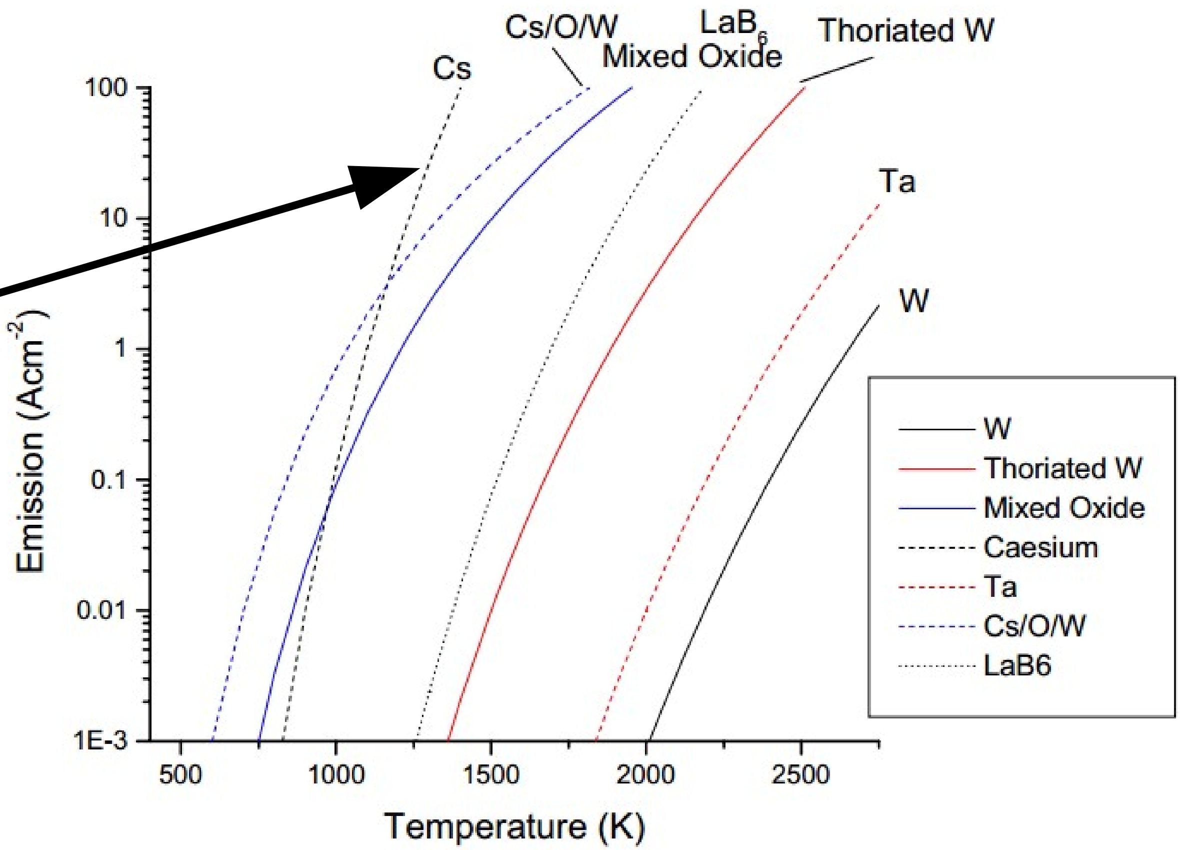
$$J = A\,T^2 \exp\left(\frac{-e\Phi_{work}}{kT}\right)$$



time structure of electron beam can be manipulated by voltage on the grid

- Good cathode materials:
  - Survives high temperatures
  - Low work function

(Cs melts above 300K, curve is for info only)



- Old televisions used this technique
(CRT–cathode ray tube)

Electron sources: photocathodes

- Same principle like photomultiplier: photon with energy above work function $E=h\nu > \Phi_{work}$, can liberate an electron
- Surplus energy above work function goes to kinetic energy
- **Quantum efficiency (Q_e)**: average # of electrons for 1 photon.
- Metals: work function in UV. Reflection → low Q_e (copper: ~10^{-4})
- Semiconductors are better
- Fast, short and well timed laser pulses can deliver a bunch train with required microstructure (needed for RF acceleration, see later)

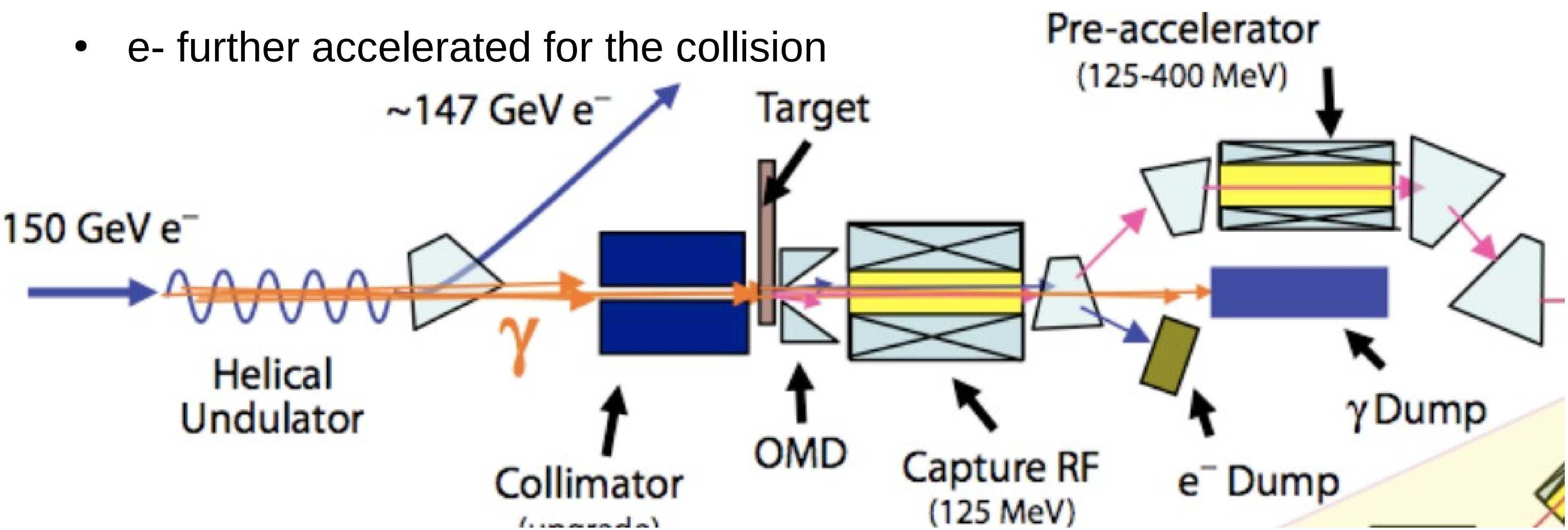
	Q_e [%]	λ [nm]
Cu	0.01	267
K_2CsSb	29	590
Cs_2Te	12.4	~350
GaAs:Cs	17	225

Electron sources in general

- Electrons have small (negligible) kinetic energy
- Initially accelerated by the static or RF field of carefully designed electrodes (puller or extraction electrode)
- Child-Langmuir limit: electron cloud at the surface of the cathode shields the puller electrode's field, this limits achievable current.

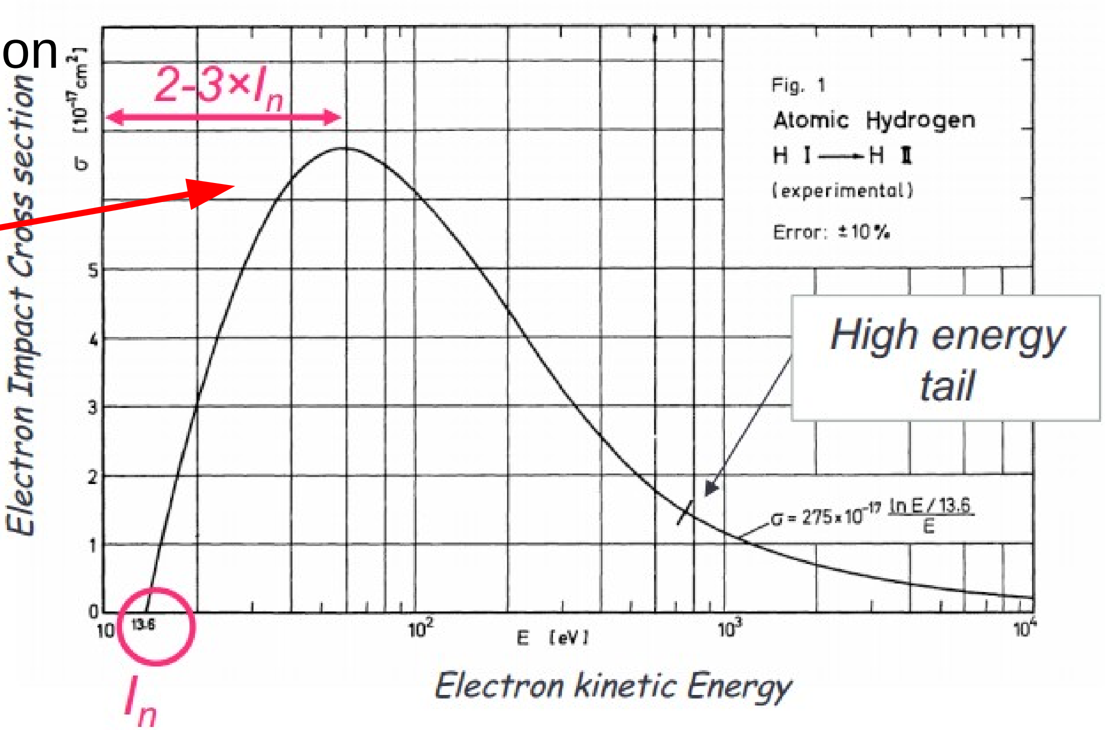
Positron-sources (secondary beam)

- Standard solution:
  - intensive electron-beam (few GeV – 20 GeV) on target. Positron intensity ~ total energy of e- beam
  - thick, large-Z target. (production- or conversion-target). Beam energy is converted into electromagnetic shower: e+/e- particles + others
- ILC (International Linear Collider – planned) [250+250 GeV]
  - Main electron beam at 150 GeV passes an undulator
  - produces 30 MeV-es photons (like in a Free Electron Laser)
  - Photons hitting a thin production target: $e^{\pm}$ pair production
  - e- further accelerated for the collision



Ion sources

- Ionization of a low-pressure gas - plasma
- Typically electrons used for ionization
- Electrons must have:
  $E_{kin} > I_n$ (ionization energy)
  optimum: $E_{kin} \sim$ 2-3 x I_n
- Phenomena in a plasma:
  - Electron impact ionization:
    $e^- + A^{n+} \rightarrow A^{(n+1)+} + 2e^-$
  - Charge exchange:
    $A^{n+} + B^0 \rightarrow A^{(n-1)+} + B^+$
  - Elastic collisions



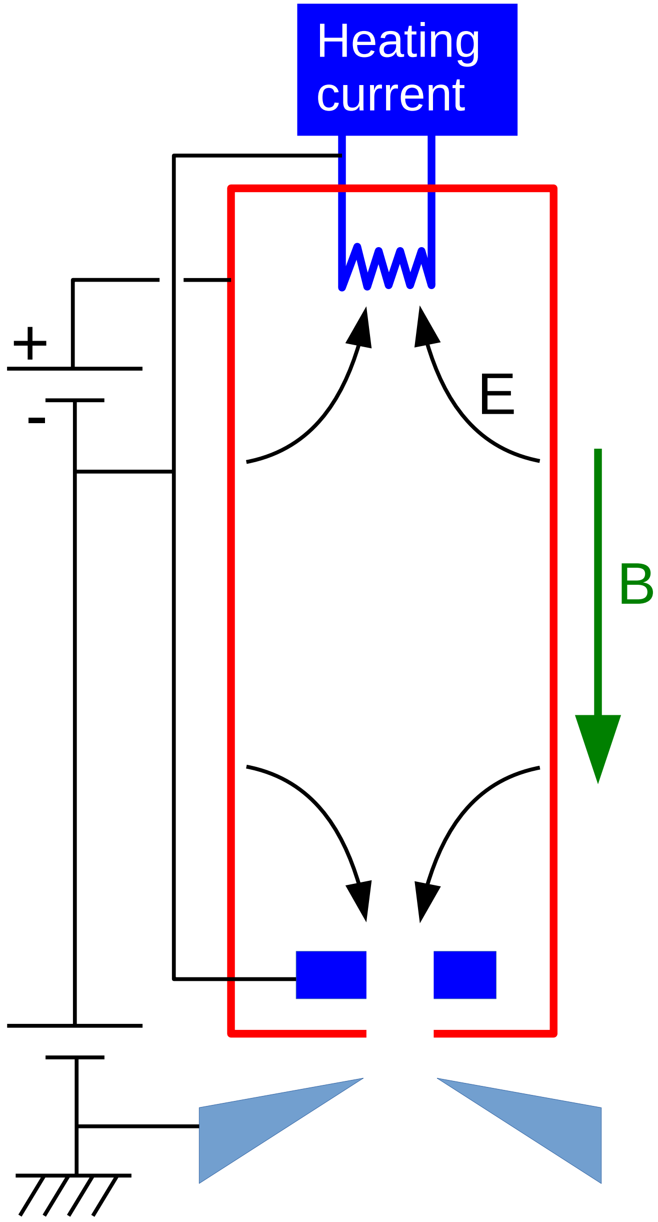
- Plasma needs to be confined for long term with stable parameters
- Need several collisions for multiply ionized ions – keeping for long time

Electrons can come from:

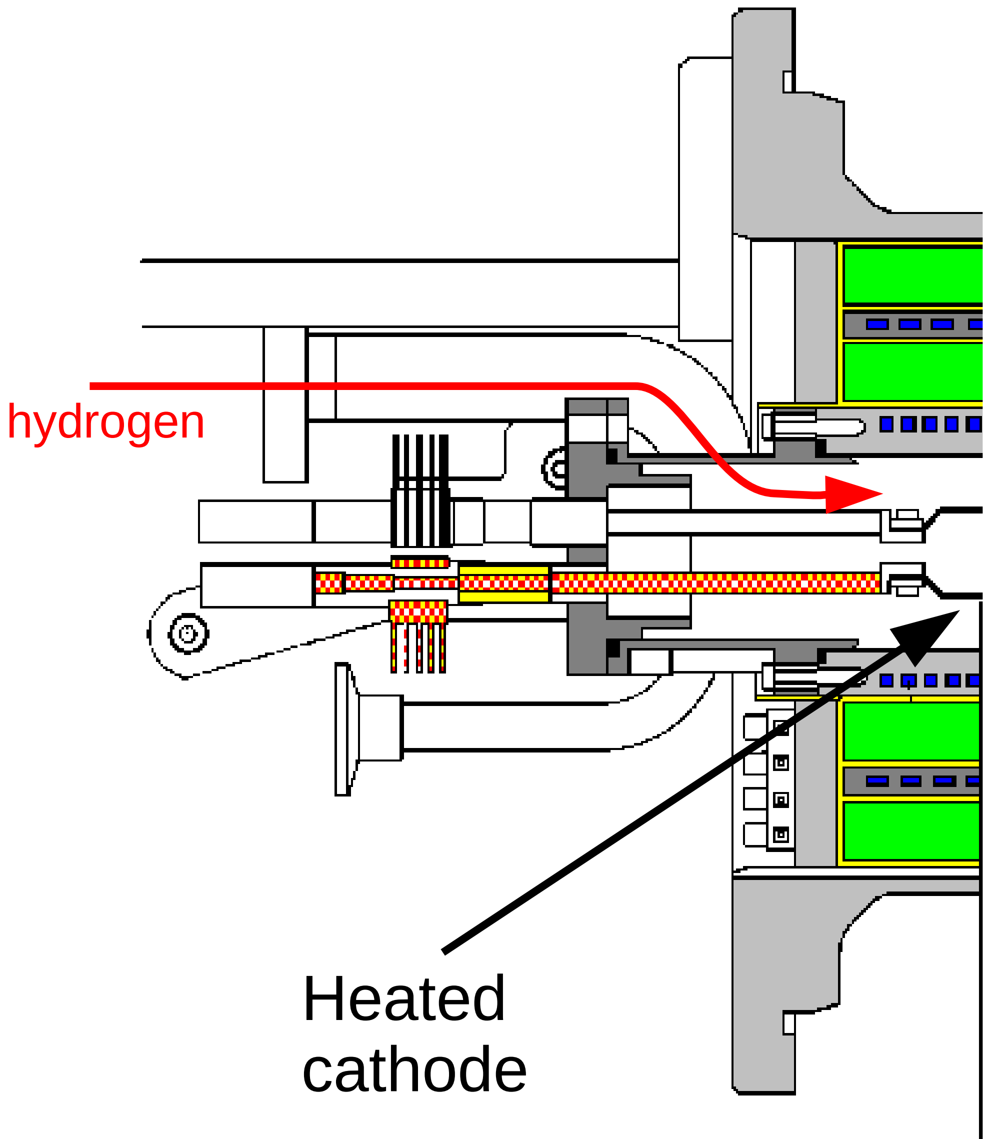
- External source – electron gun
- From the plasma itself

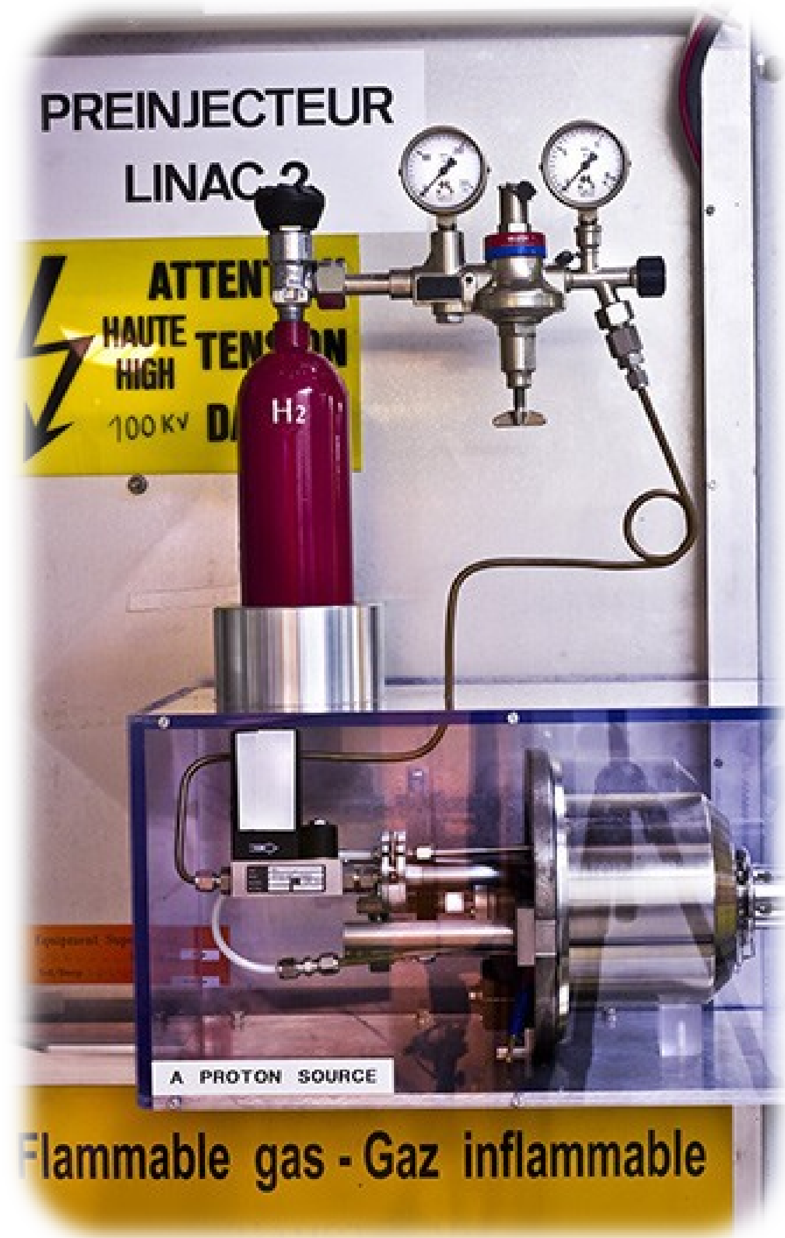
Penning ionization gauge (PIG) ion source

- Heated cathode provides electrons
- Penning trap: electrons confined by B field in the transverse, E field in the longitudinal direction
  - cf Penning vacuum gauge
- Electrons gain energy from E field, and ionize the low-pressure gas
- Gas pressure typically 10^{-3} – 1 mbar:
  - If pressure too large, electrons collide before gaining sufficient energy
  - If pressure too low, not enough output current
- Whole unit on positive voltage. Ions extracted by grounded puller/extraction electrodes



Duoplasmatron





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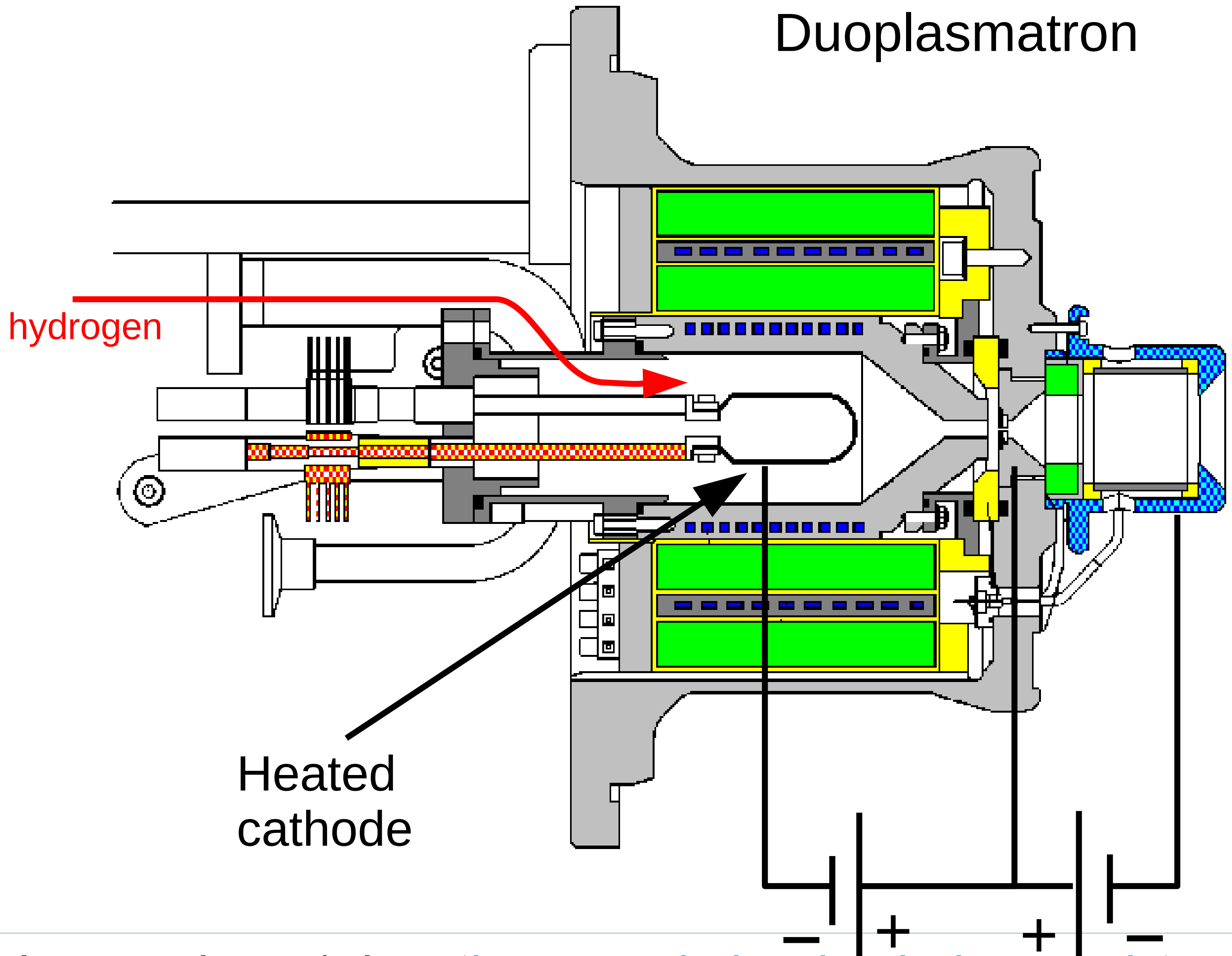

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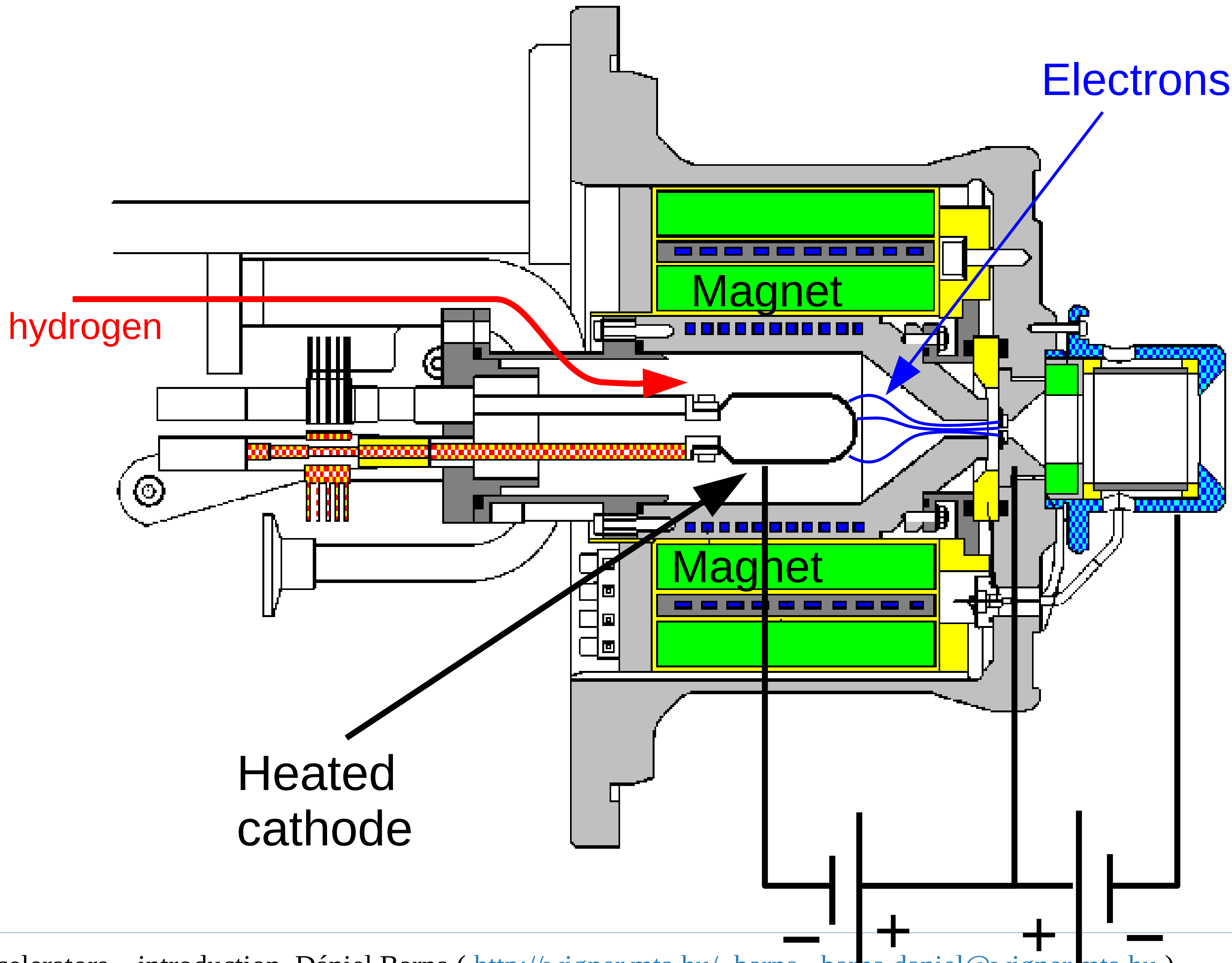

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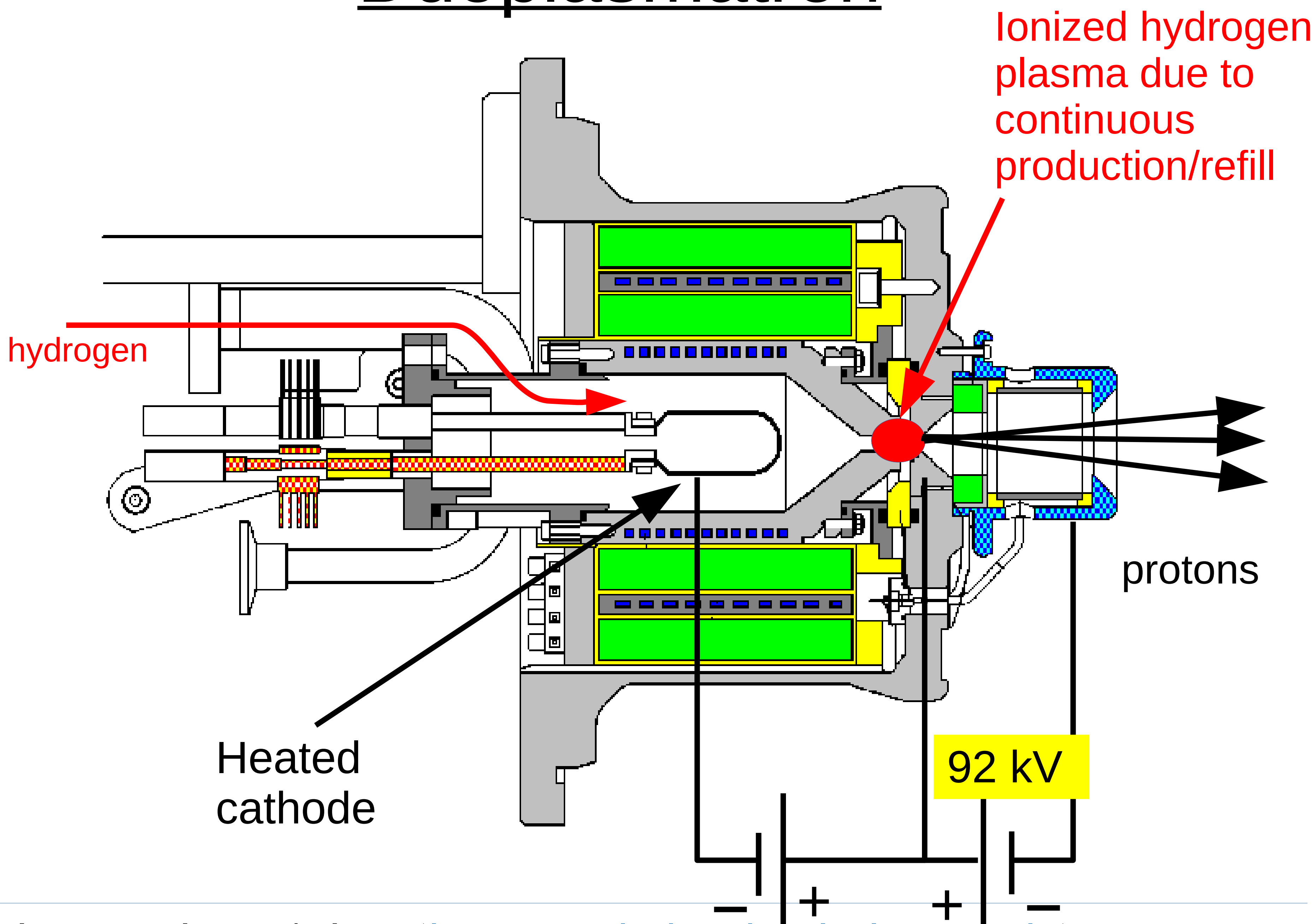
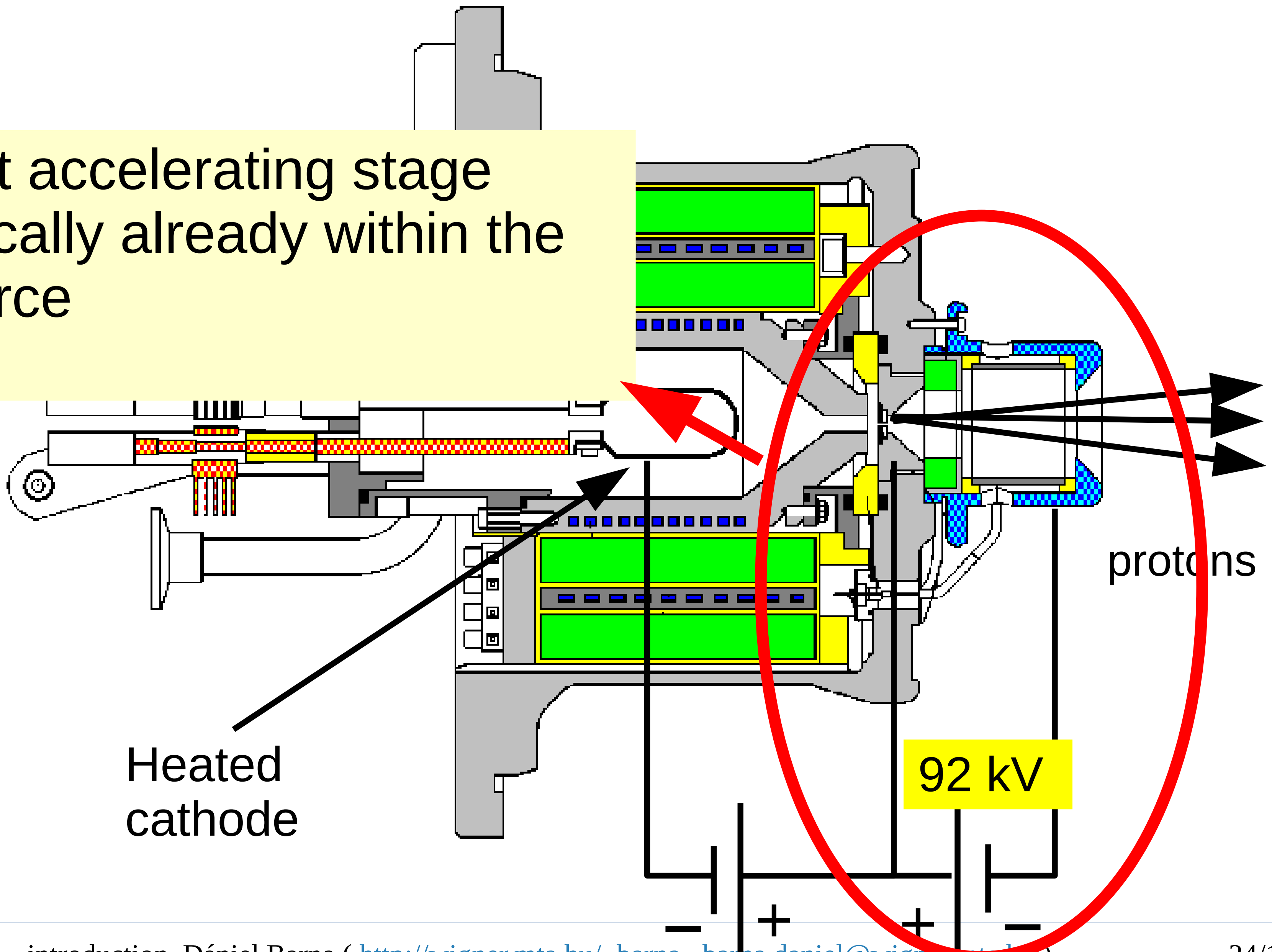


Duoplasmatron

- First accelerating stage typically already within the source



Electron Cyclotron Resonance Ion Source (ECRIS)

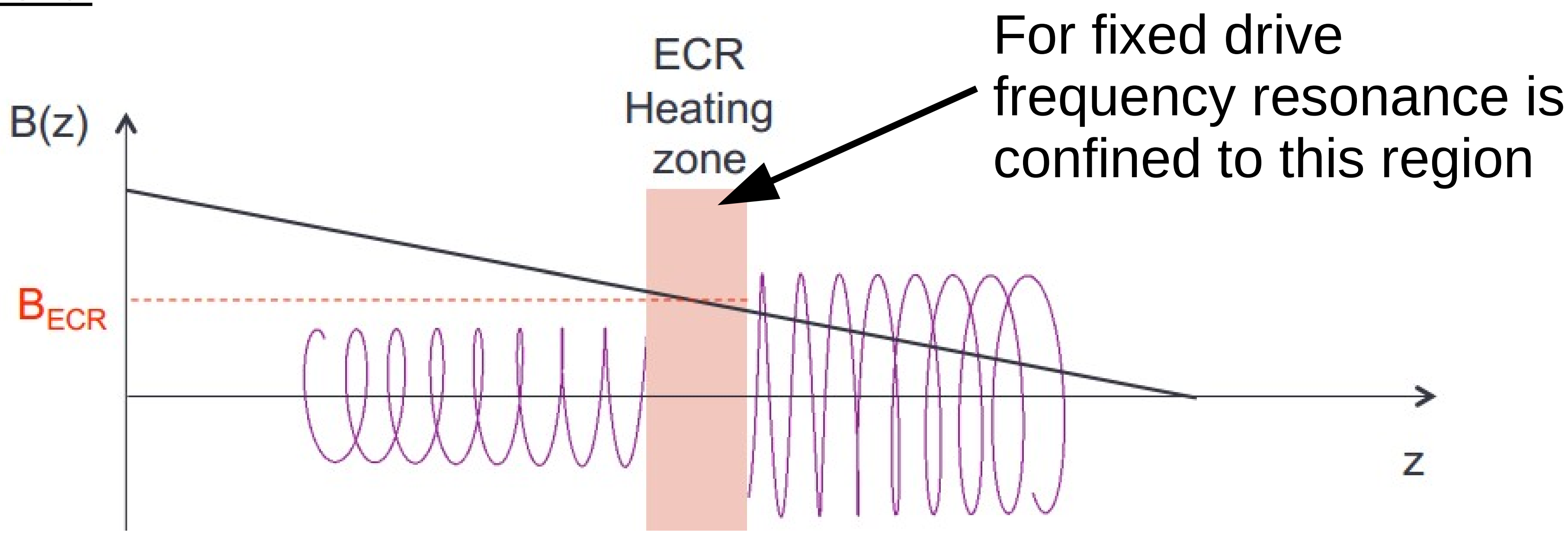
- More: http://cas.web.cern.ch/cas/Slovakia-2012/Lectures/ThuillierI.pdf
- **Electron cyclotron resonance**:
  - In B field the (nonrelativistic) revolution frequency of electrons (cyclotron frequency) is constant:

$$\omega = \frac{qB}{m} \qquad f = \frac{qB}{2\pi m}$$

  - Typically in the MW regime:
    f=28 GHz (B=1T); f=2.8 GHz (B=0.1T)
  - Resonance: E field with same frequency will excite cyclotron motion, electrons gain energy for ionization

Electron Cyclotron Resonance Ion Source (ECRIS)

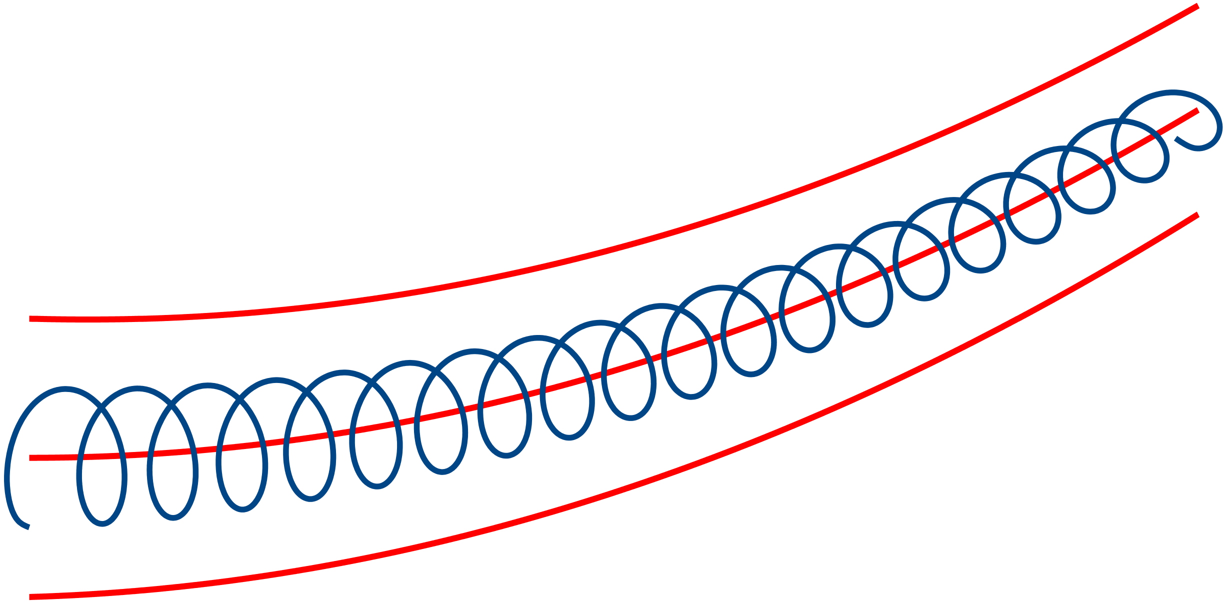
- **Electron cyclotron resonance in inhomogeneous B field**:



- Size of ECR zone correlates with gradient of B
- In ECRIS, the ECR zone is typically a confined surface

Electron Cyclotron Resonance Ion Source (ECRIS)

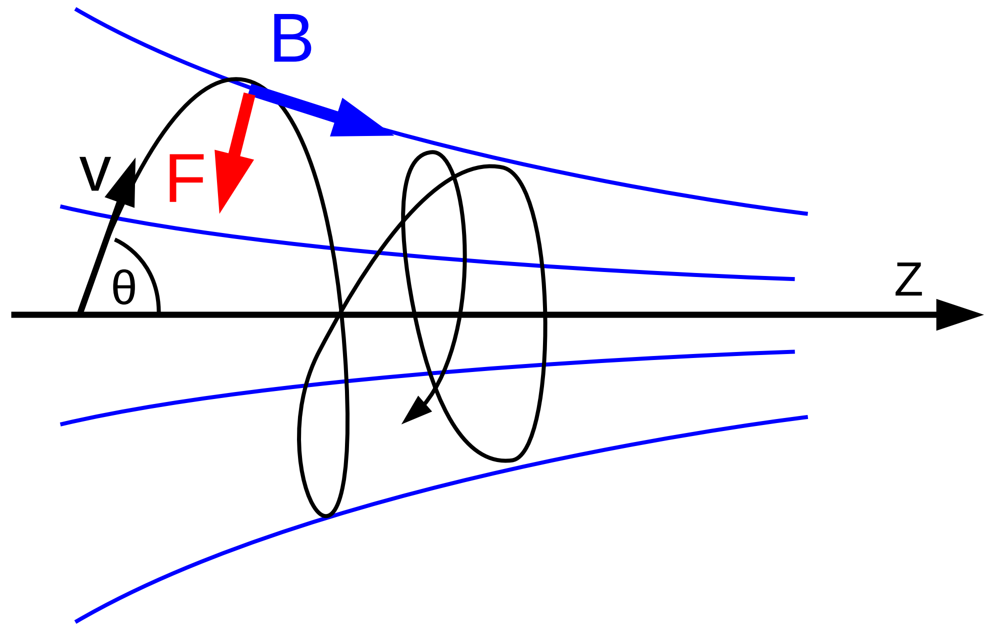
- **Charged particles in a magnetic field**
  - E_{kin}=const, since $\vec{F}=q\,\vec{v}\times\vec{B} \quad \perp \quad \vec{v}$
  - Low-energy particles spiral around induction lines
    - if their energy << inhomogeneity of field
    - more specifically if: $\delta B/B \ll 1$ over one cyclotron turn



Electron Cyclotron Resonance Ion Source (ECRIS)

Magnetic mirror, magnetic bottle

- Stronger magnetic field → converging induction lines
- Force has z component
- If angle is over a threshold $\theta > \theta_{min}$ (depending on B), particle bounces back

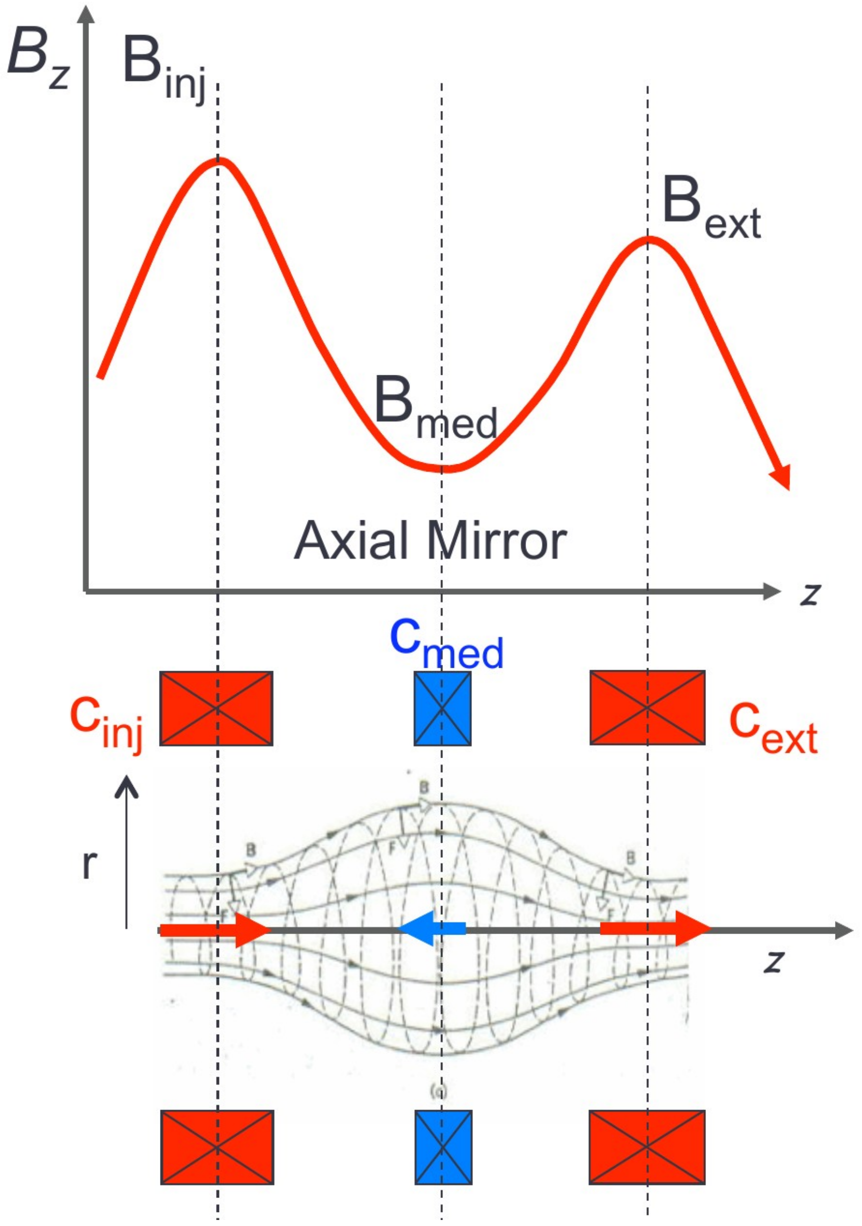


- $\theta < \theta_{min}$ - “loss cone”, particles escape the bottle. Collisions always refill this zone.
- Loss cone is used to outcouple the ions

Electron Cyclotron Resonance Ion Source (ECRIS)

Trapping along the z axis: using a magnetic bottle

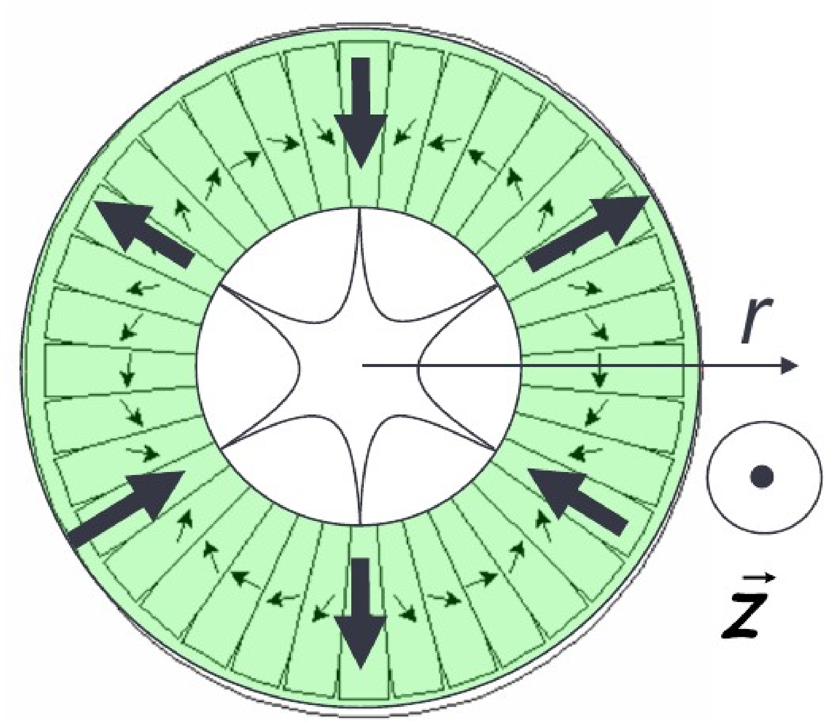
Confines both electrons and ions



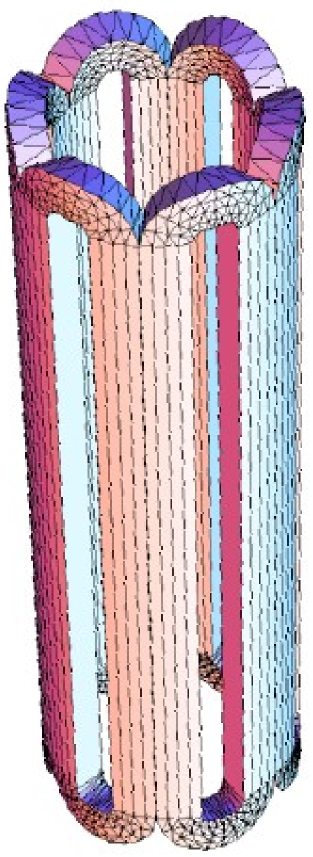
Electron Cyclotron Resonance Ion Source (ECRIS)

Trapping radially: sextupole field

Using permanent magnets… or electromagnets



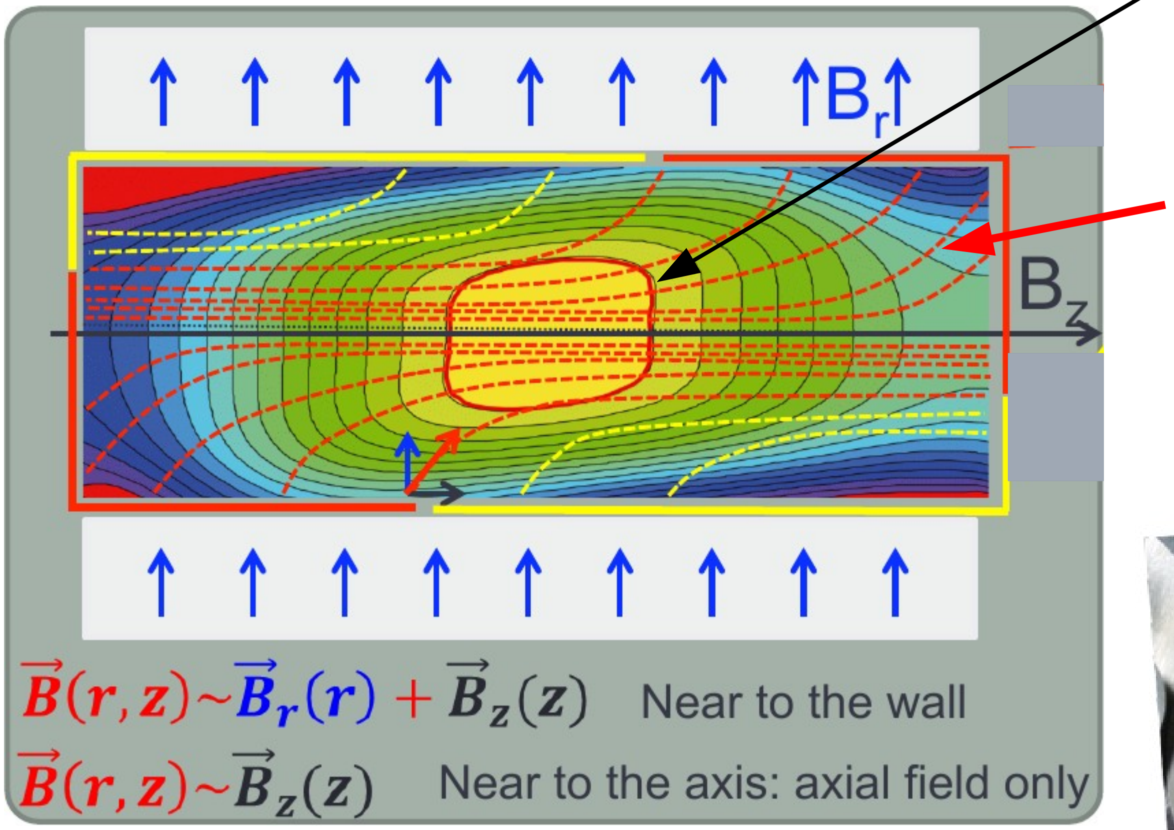
(HallBach Hexapole
With 36 permanent magnets
30° rotation/magnet)



Electron Cyclotron Resonance Ion Source (ECRIS)

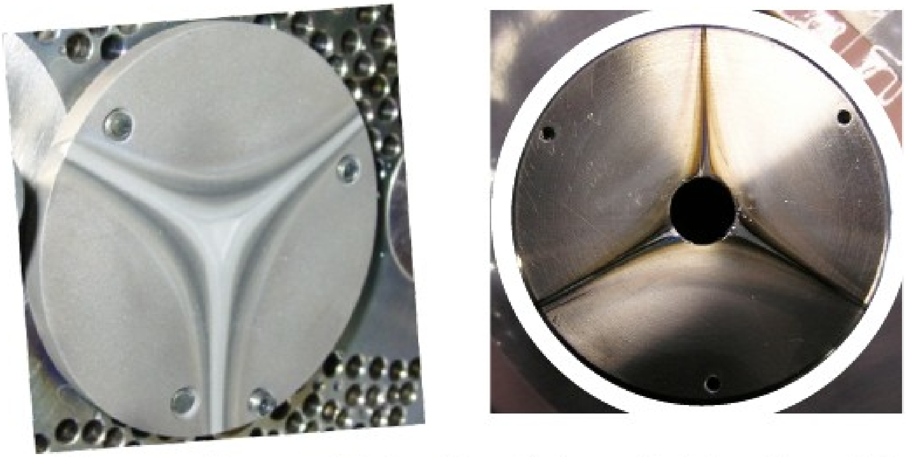
Resulting magnetic field is not easy to understand

Color: |B|



Source: Thuillieri CAS lecture

Resonance surface. Electrons following red induction lines passing through this surface gain energy from MW field and ionize on their path



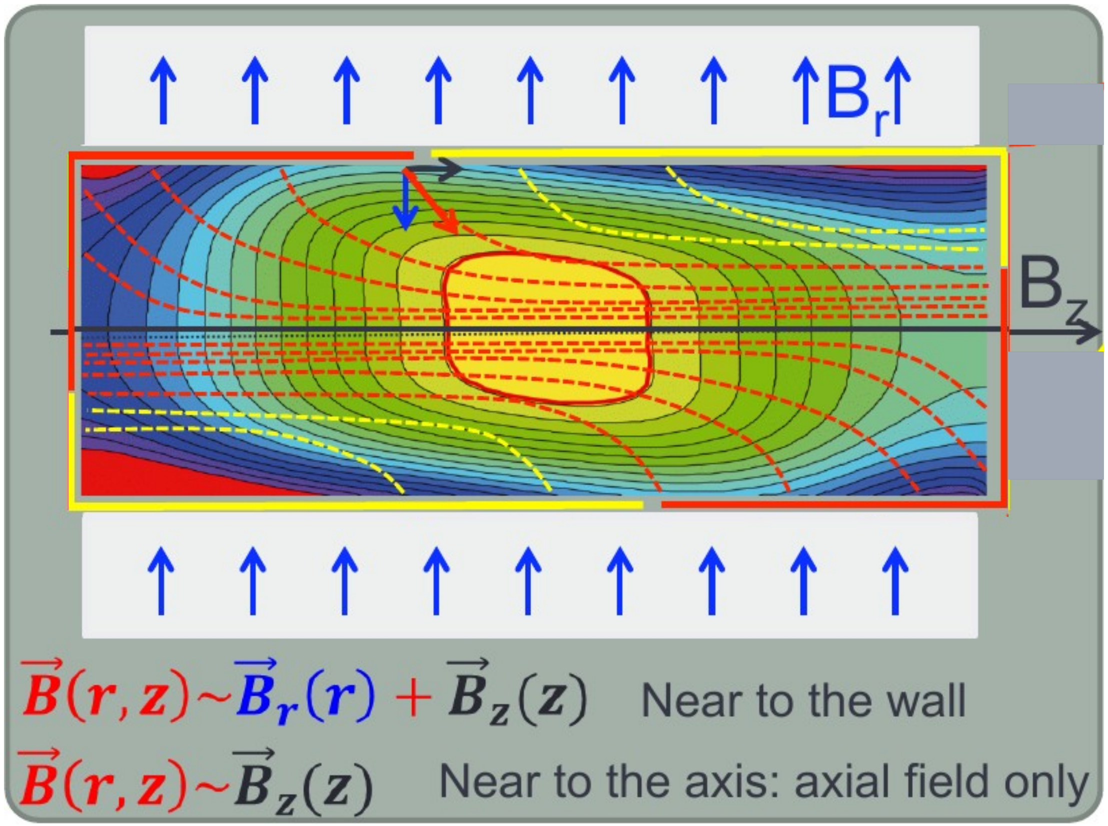
Plasma shape at injection (L) and Extraction (R)

Electron Cyclotron Resonance Ion Source (ECRIS)

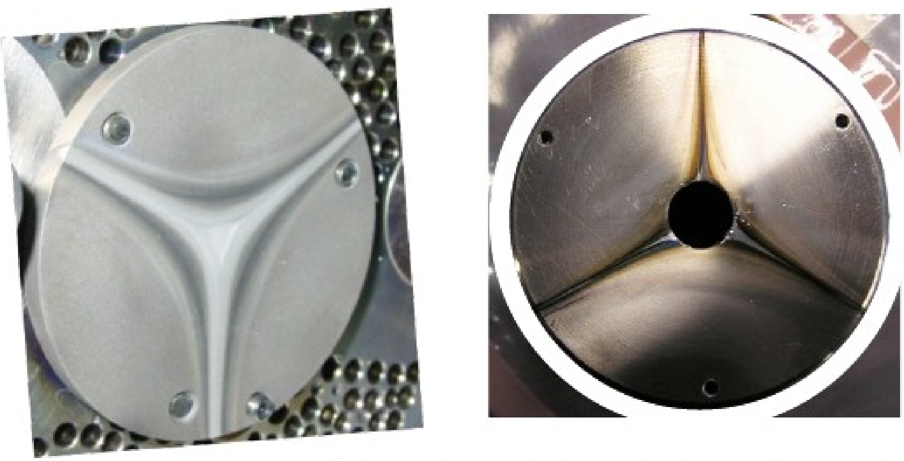
Resulting magnetic field is not easy to understand

Rotated by 60° around z axis

Color: |B|



Forrás: Thuillieri CAS előadás



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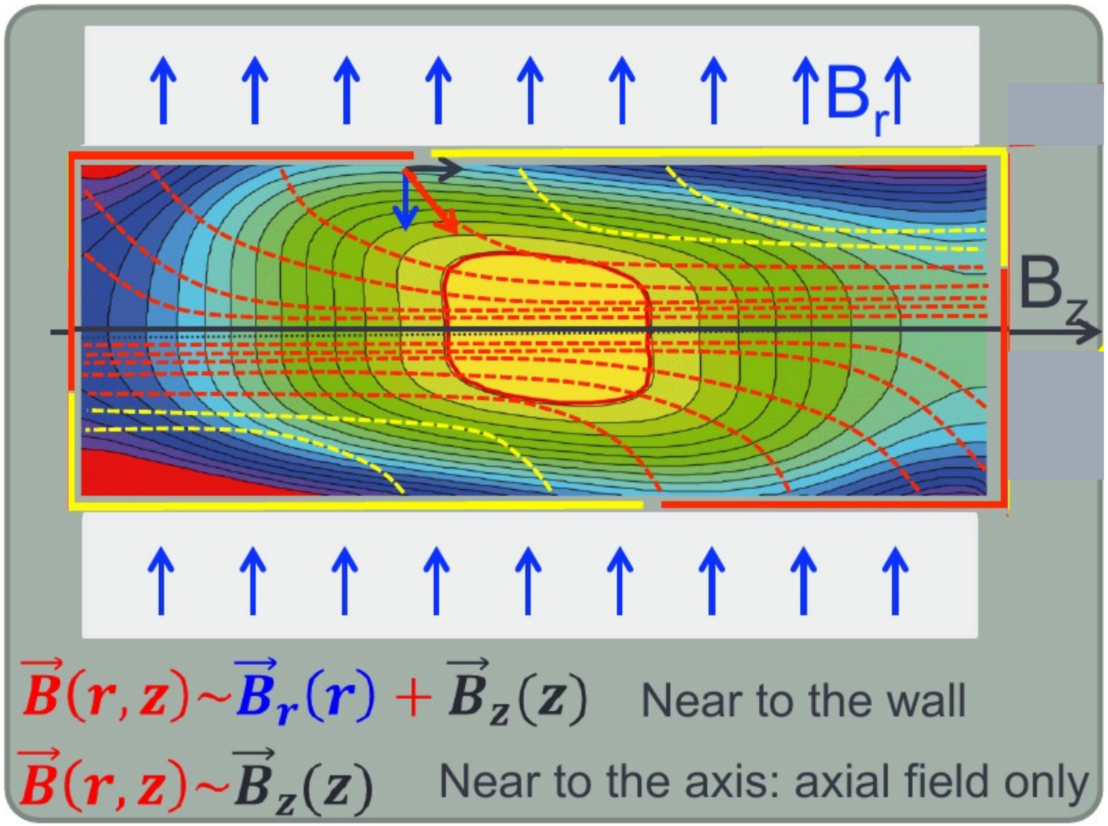

Question: on the |B|=const resonance surface, why is the induction line density non-constant, whereas |B| is?

Forrás: Thuillieri CAS előadás

Plasma shape at injection (L) and Extraction (R)

Pion beam

- Secondary beam
- For example a proton beam hitting a target

Muon beam

- From the decay of a pion beam in a straight beampipe

Charged particles in electromagnetic fields

Electromagnetic force:

$$F = q\,E + \underbrace{q \cdot v \times B}_{\perp v\text{, does not make work}}$$

- Acceleration:
  - **Electric field (always!!!)**
  - **But:** electric field can be produced by induction: $\nabla \times E = \frac{-\partial B}{\partial t}$
    and not only by charges: $\nabla \cdot E = \rho / \epsilon_0$
- Bending, focusing (i.e. transverse manipulation):
  - Magnetic field: proportional to velocity → automatically increases with energy, without increasing B.
    (we still need to increase B if we need same orbit:
    F = m·a = m · v²/R,   B*R=p/q   )
    Always use B at high energies
  - Electric field
    - Useful at low energies (E_{kin}~100 keV): 1-10 kV for beam manipulation
    - Simple electrodes, cheap voltage sources
    - Electrostatic beamlines typically used for atomic physics experiments, radioactive beams, etc
    - The RFQ (see later) also uses electric field

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  - Electric field

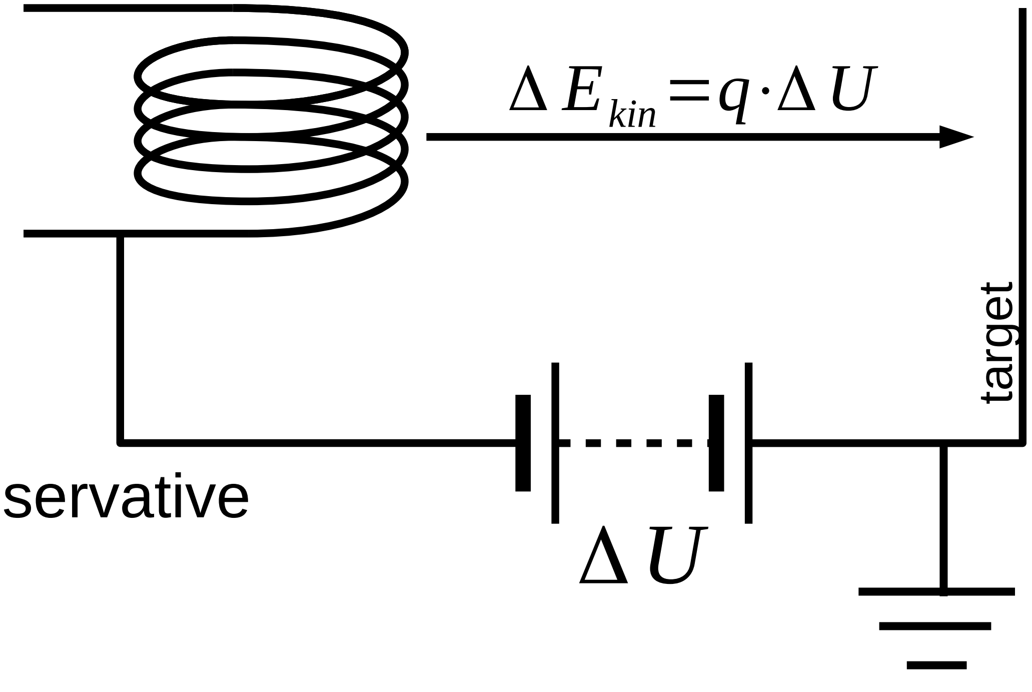
At **high energies** (v=c): 1 Tesla ↔ 300 MV/m

- Magnets for bending, focusing
- Electric field for acceleration

Electrostatic acceleration

Electrostatic acceleration

- Target or source at high voltage (MV), other one typically grounded (exception: tandem...)



- Single-pass (can not reuse same electric field by guiding the beam through it again), since electro**static** field is conservative

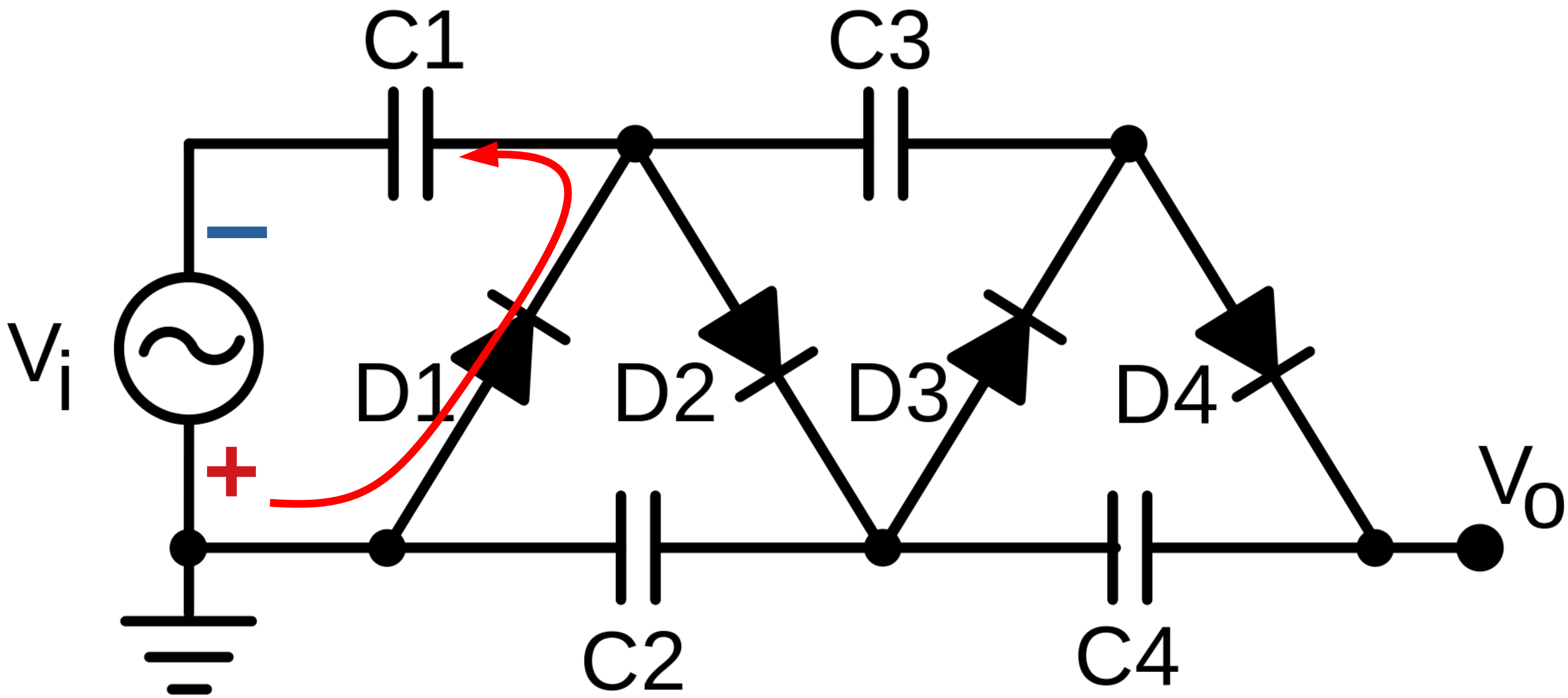
$$\oint E \, \mathrm{d}s = 0$$

- HV generators
  - Cockroft-Walton (~MeV)
  - Van de Graaff (~10 MeV)

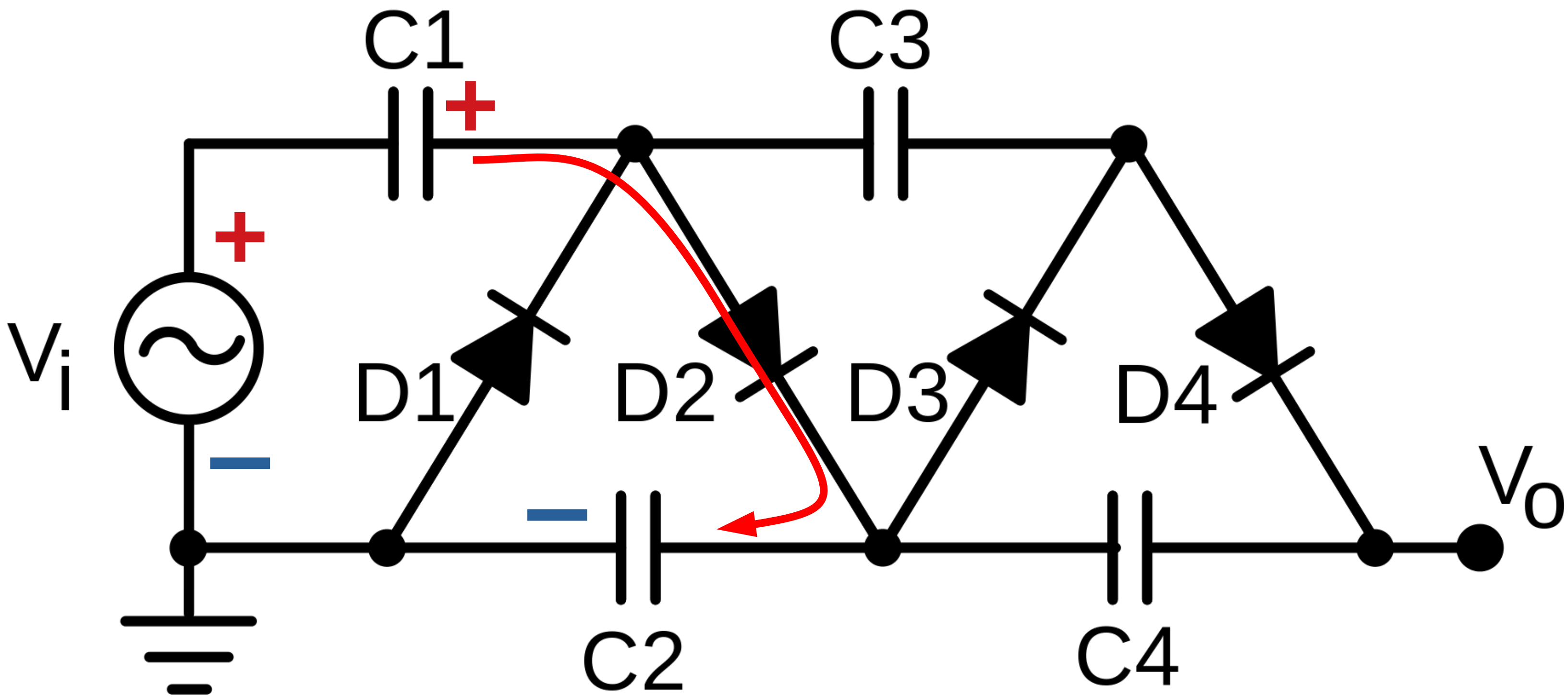
- Limit: electric breakdown, sparking, size of insulation

Cockroft-Walton accelerator

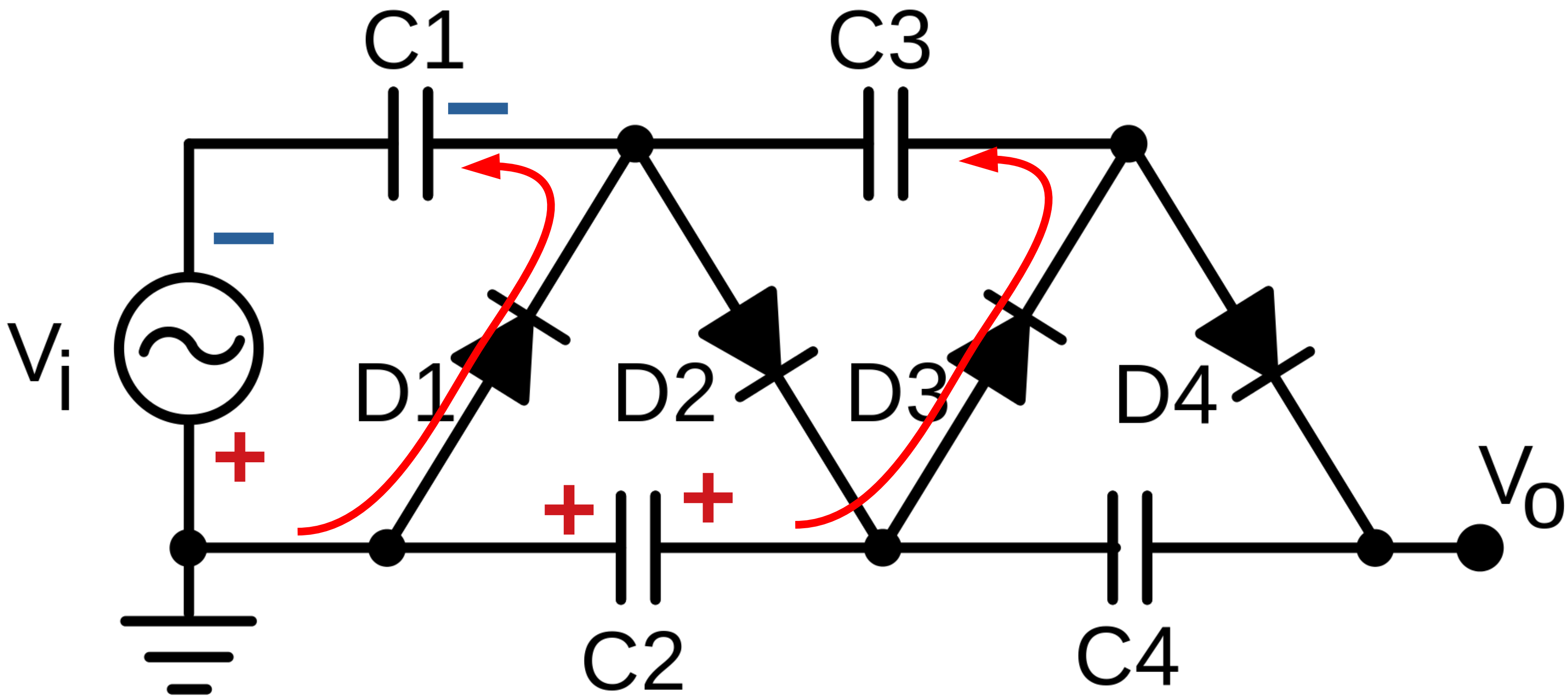
Cockroft-Walton accelerator



Cockroft-Walton accelerator



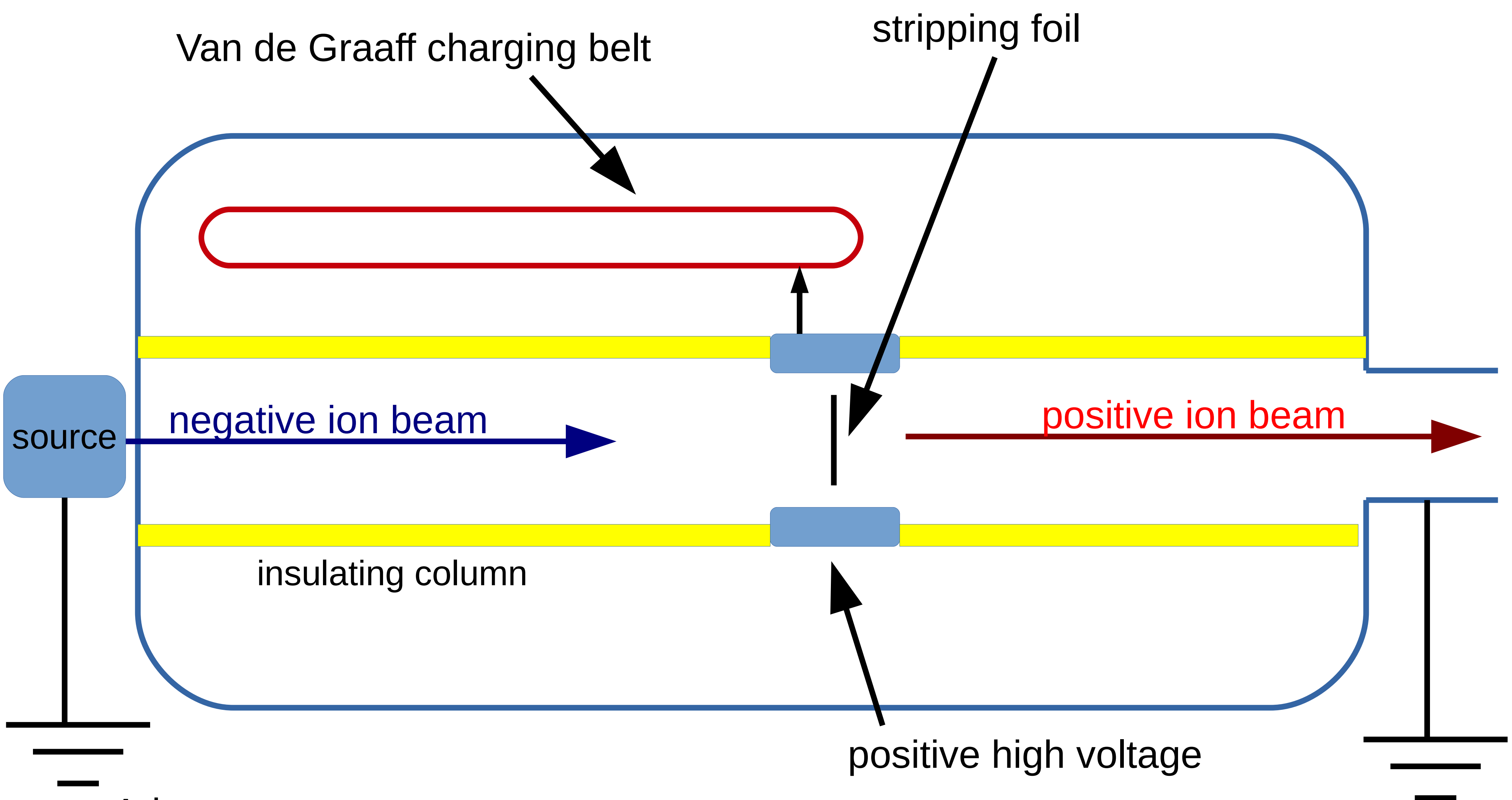
Cockroft-Walton accelerator



Van de Graaff accelerator

Often times vertical (unlike this) to avoid gravitational load on long insulating column

Tandem Van de Graaff



Advantages:

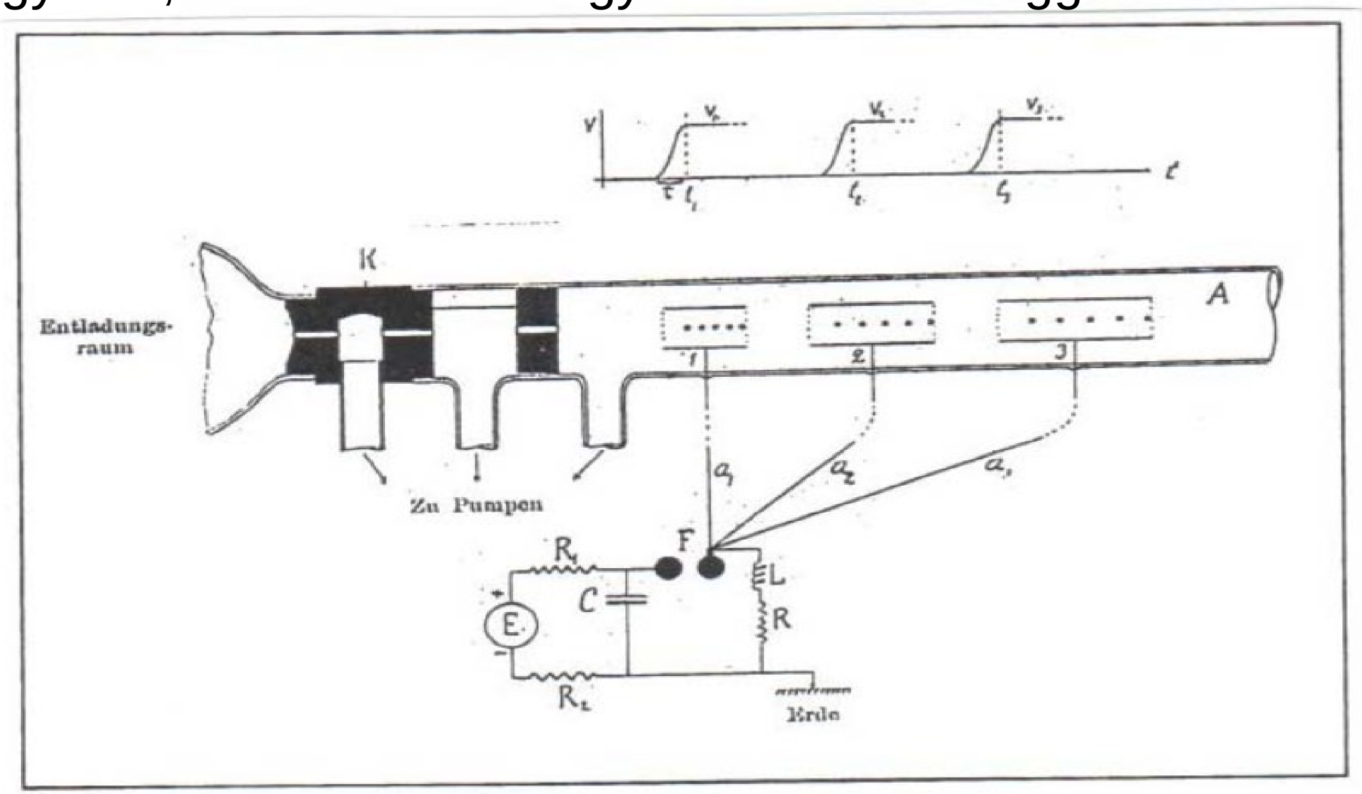
- Double output energy for same high voltage
- Source and target can be grounded

Changing electromagnetic fields:
1) Linear accelerators (LINAC)

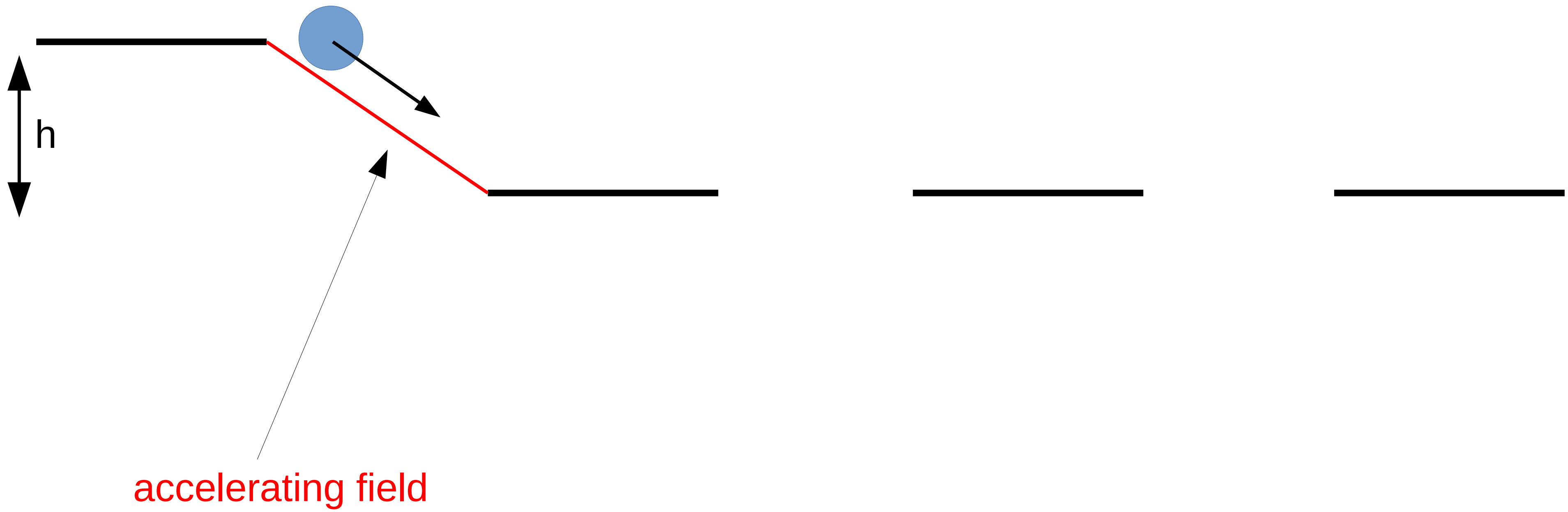
Pulsed drift tube linac

Ising, 1924 – koncepció

- Nem szükséges, hogy a teljes gyorsító tér egyidőben rendelkezésre álljon (átütés veszélye...), elég épp ott, ahol a részecske van (az elektromos tér gyorsít, nem a “potenciál”...)
- (Váltakozó EM térben nincs definiálva a potenciál!)
- Egyetlen fokozat helyett sok kisebb fokozat
- Jól időzített pulzusokkal (amíg a részecske a csövön belül van)
- csövek közötti rés gyorsít, csövek hossza egyre nő a sebességgel



Pulsed drift tube linac



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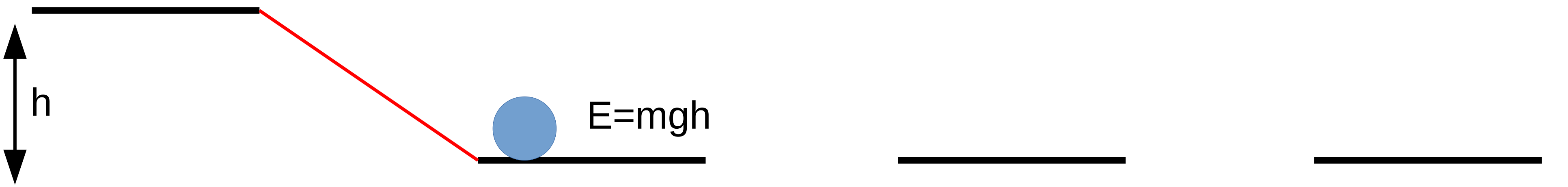

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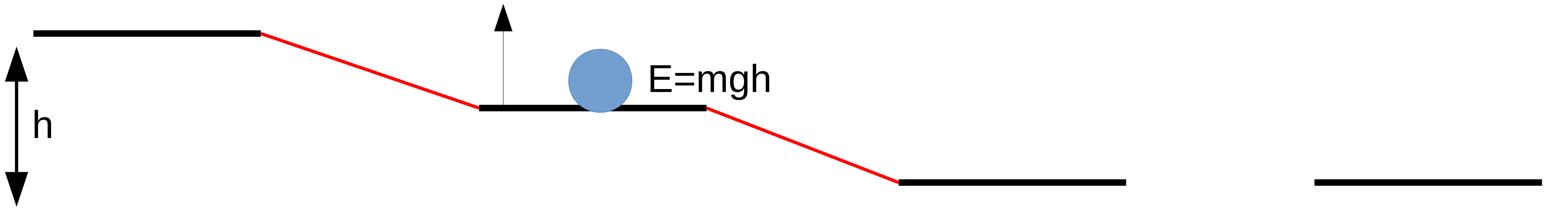

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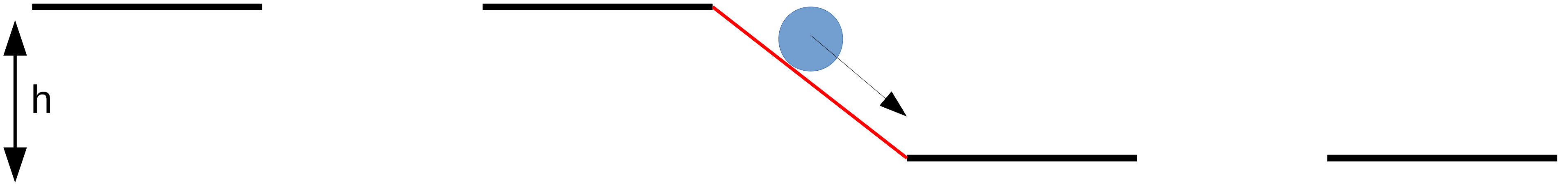

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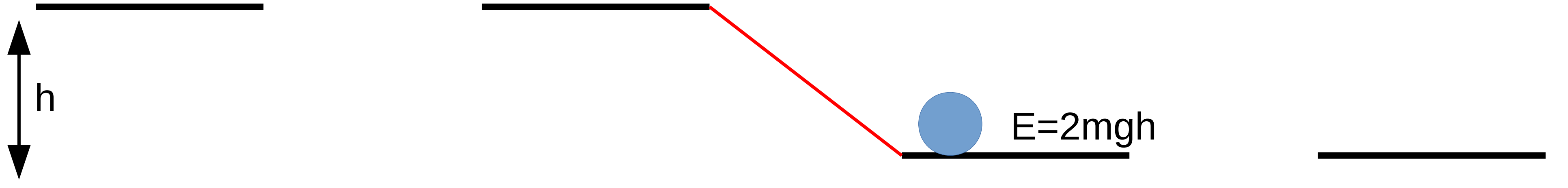

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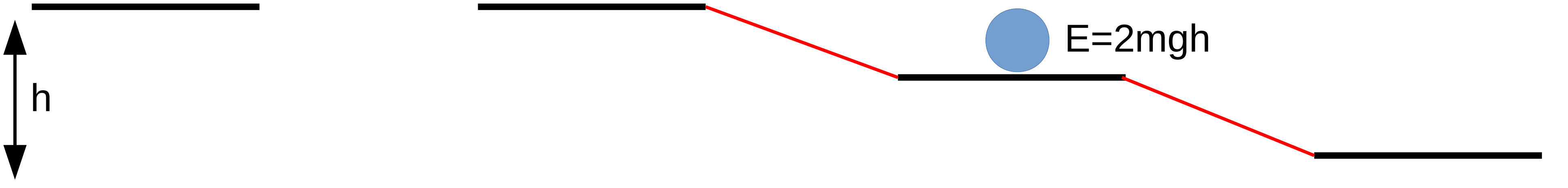

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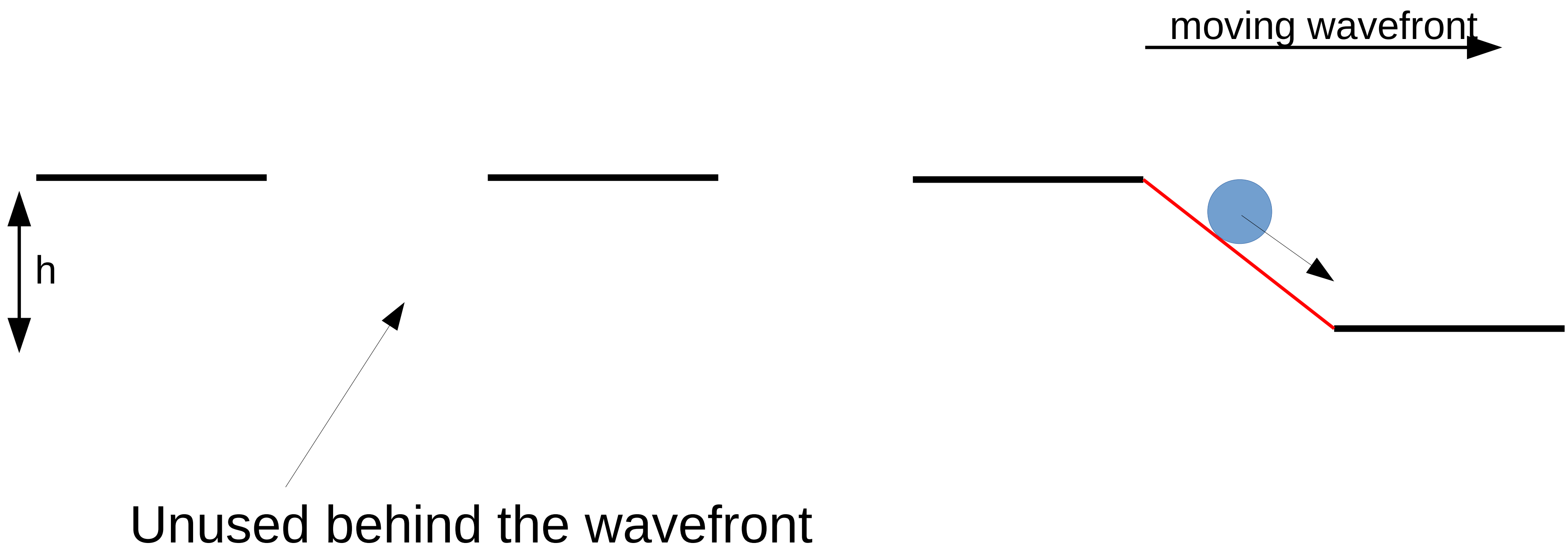
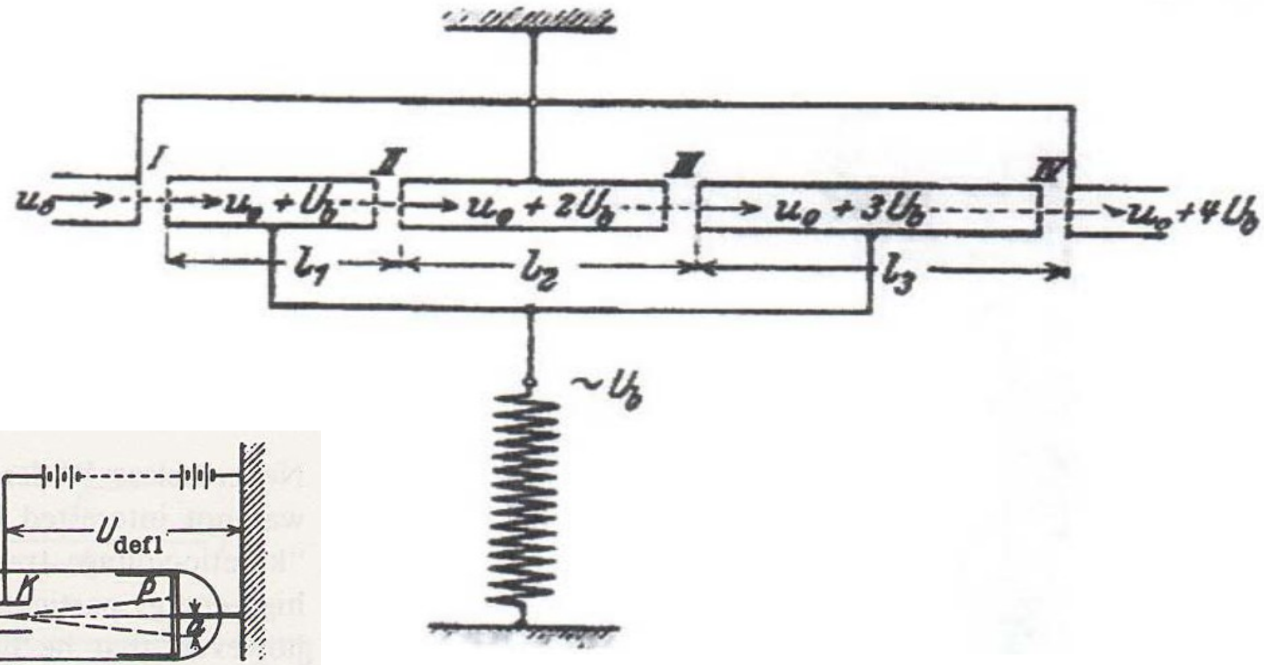
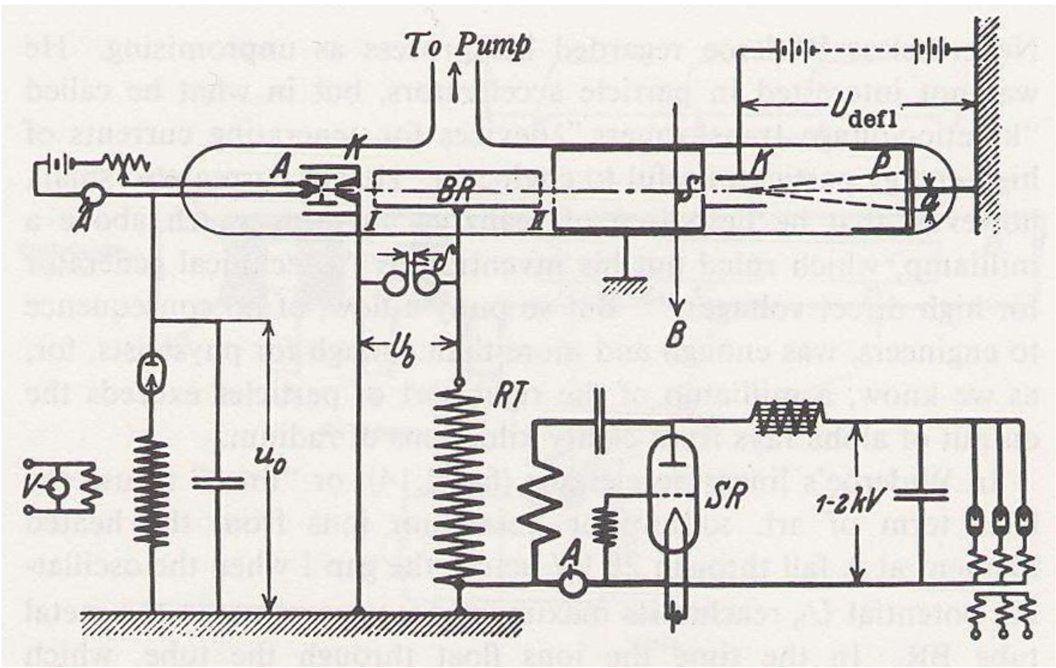


Wideröe RF linac

Wideröe (1928):

Use RF instead of timed pulses!
RF changes 180^0 while particle reaches next gap

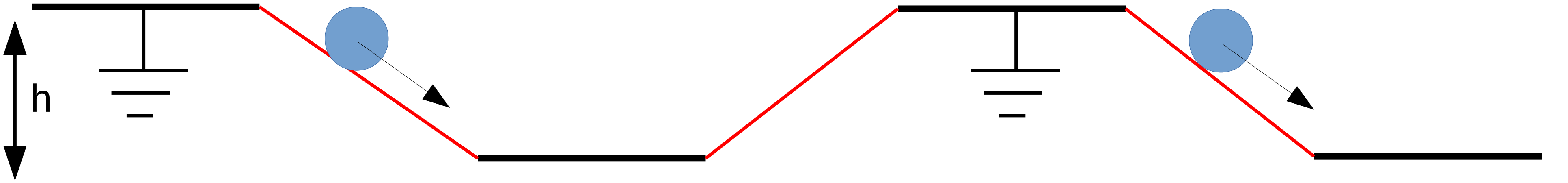




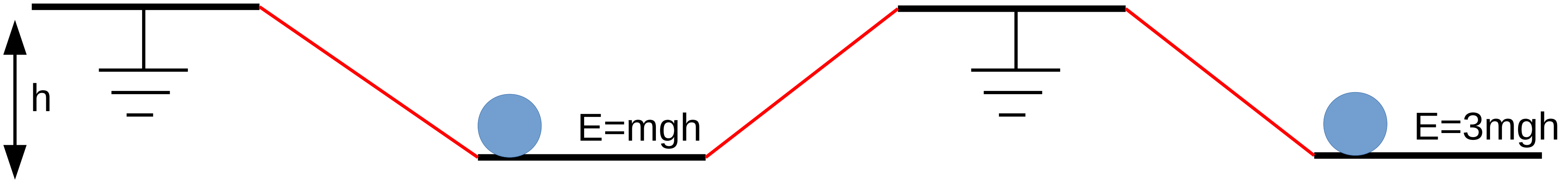
- PhD thesis: construction of a 3 tubes (2 gaps) accelerator 2 x 25=50 keV

- Limitations
  - Before world war 2: only low RF frequency available → need long drift tubes ($L = v/f_{RF}$)
  - WW2 radar R&D: high RF frequencies → open drift tubes radiate as antennas

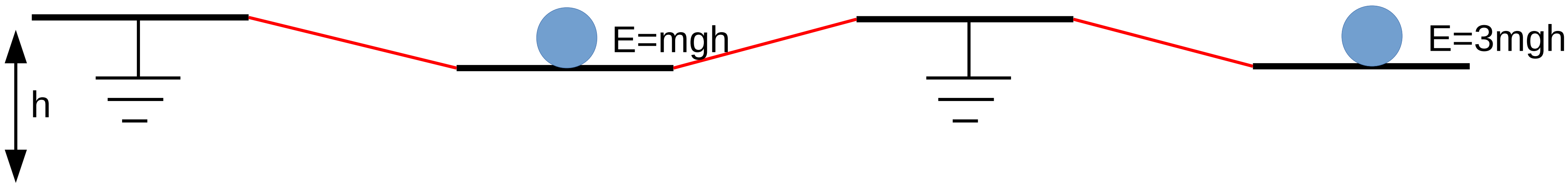
RF linac



RF linac



RF linac



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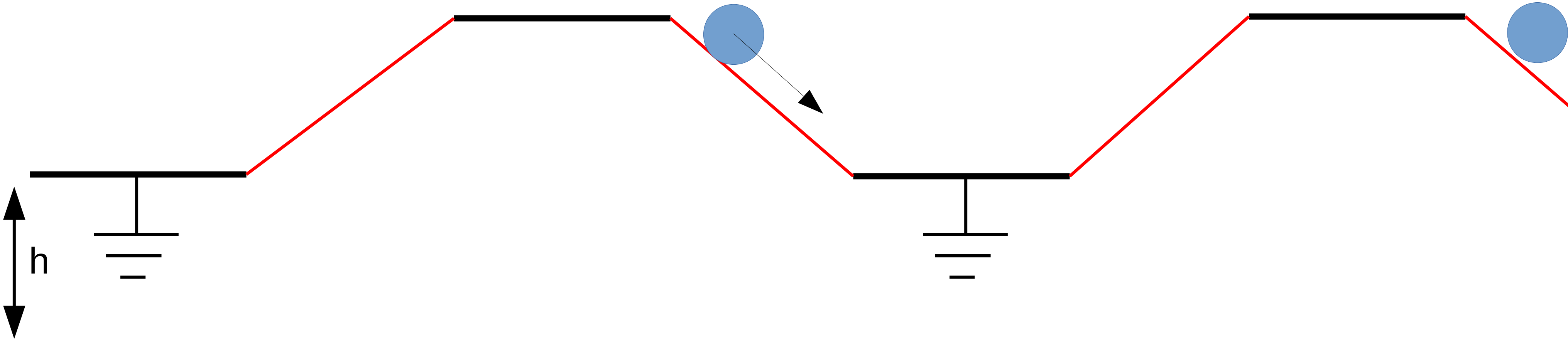
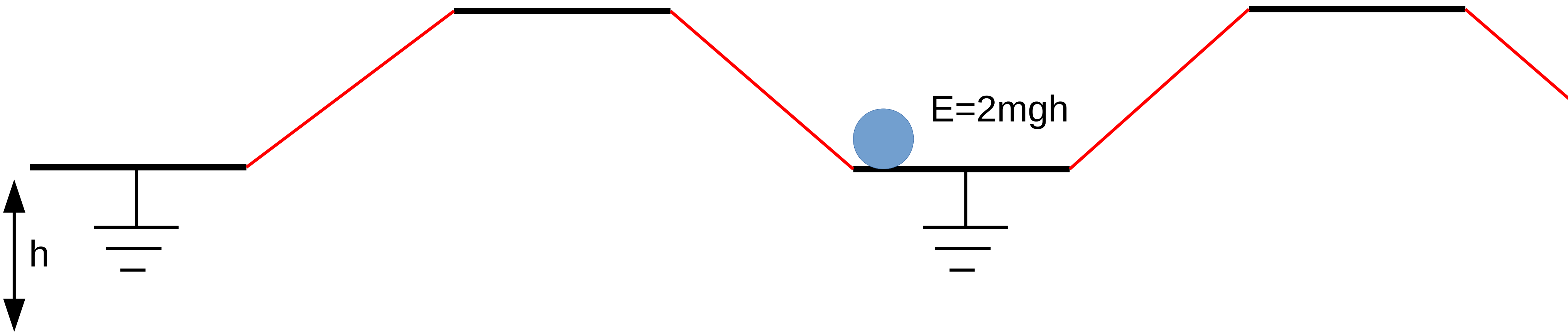


Standing wave!

RF linac

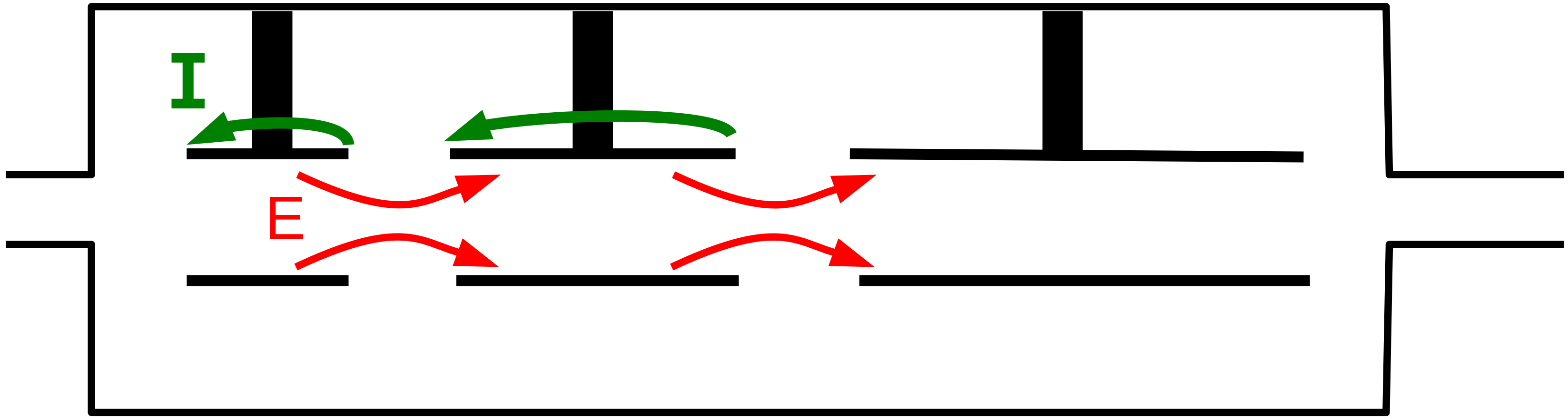


Standing wave!

http://wigner.mta.hu/~barna/content/Lectures/Illustration of RF acceleration principle.webm

Alvarez linac

- Alvarez (1946)
  - Grounded electrodes of Wideröe connected to other RF pole
  - Accelerating structure can be transformed into a closed resonator cavity
  - EM standing wave within a closed resonator
  - Resonator → no radiative losses



Alvarez linac

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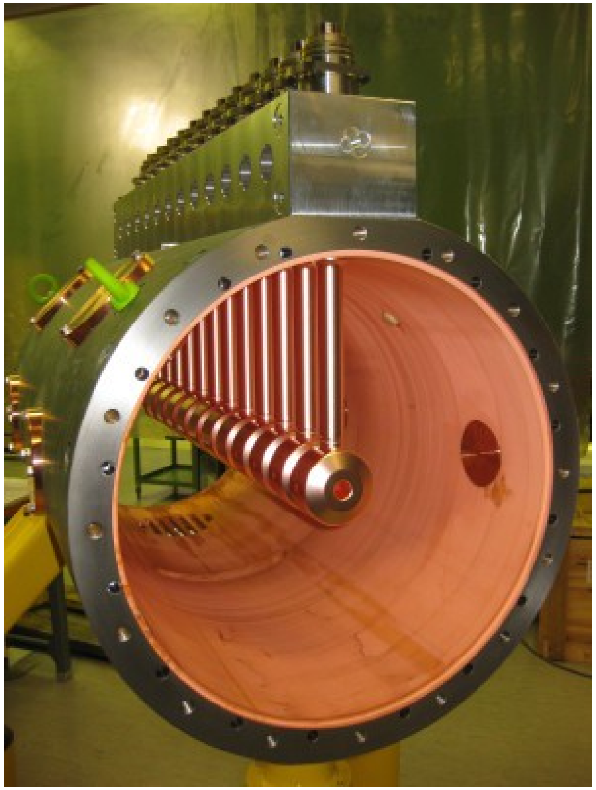
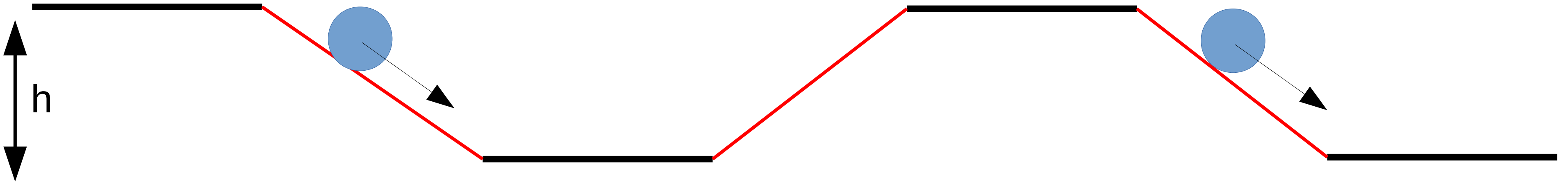


CERN Linac4 – 50 MeV

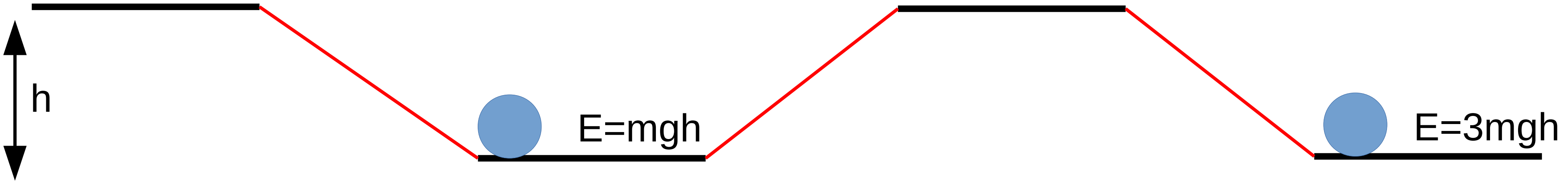
Lawrence Berkeley National Lab (LBNL), 1957

- Can be individual accelerators...
- … or injectors into rings

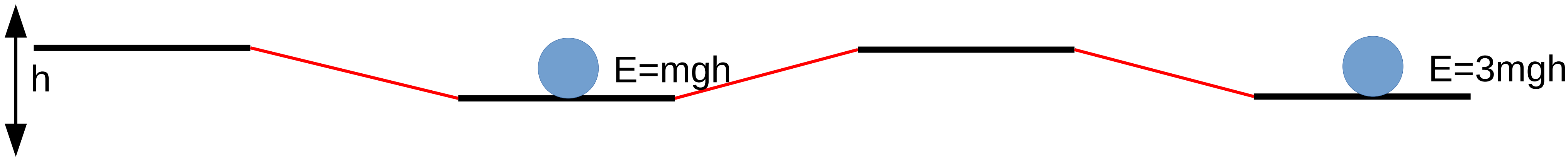
Alvarez linac



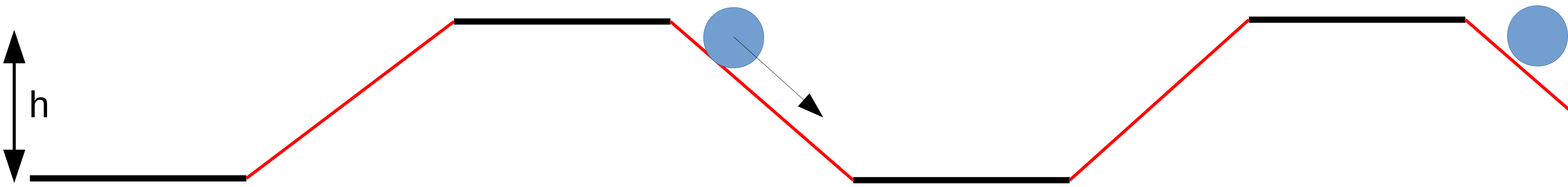
Alvarez linac



Alvarez linac

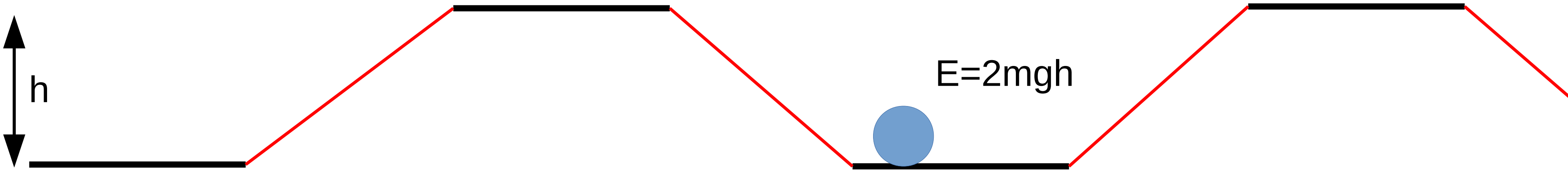


Alvarez linac



Standing wave!

Alvarez linac



Standing wave!

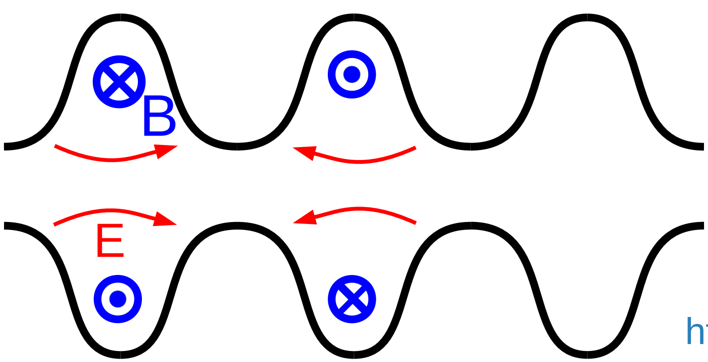
http://wigner.mta.hu/~barna/content/Lectures/Illustration of RF acceleration principle.webm

Alvarez linac

CERN Linac2 (protons, 50 MeV)

Tesla cavity

- Normalconducting (e.g. LEP initially)
- Superconducting (LEP upgrade, LHC, etc)



π-mode: (E-field with 180° phase diff. in neighbouring cells)

https://wigner.mta.hu/~barna/content/Lectures/Tesla cavity illustration.webm

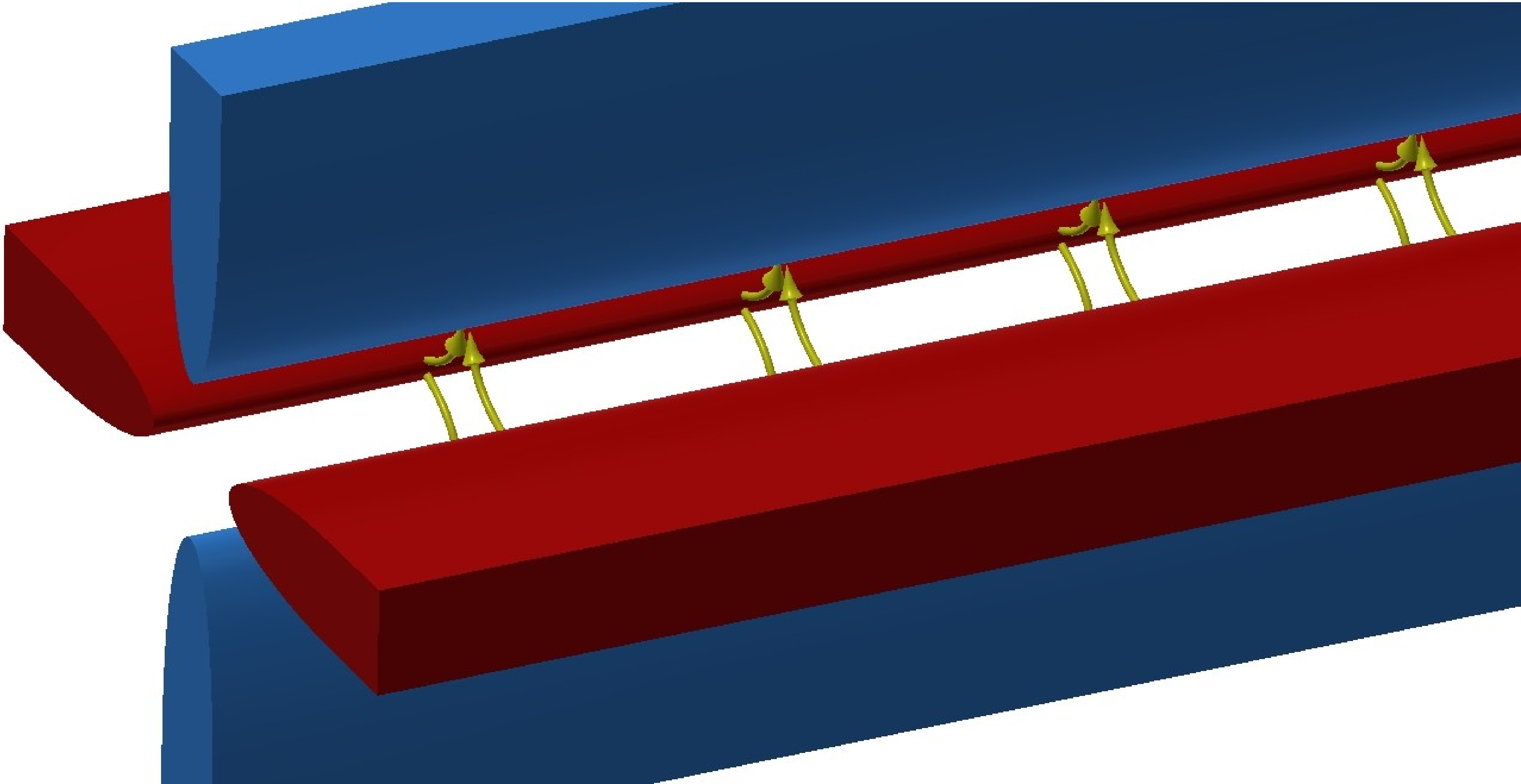
RadioFrequency Quadrupole (RFQ)

- Kapchinskij, Teplyakov (1970)
- First operational RFQ: 1974, input: 100 keV output: 620 keV (50% eff)
- Western countries learn about it only in 1977(!) (cold war times...)
  1980: Los Alamos, 100 --> 640 keV, 90%
- Invented later than the other components reviewed so far, but it is used at an intermediate stage at lower energies:
  typical intermediate component **between ion source and drift-tube linac**.
  Increases transport/capture efficiency (adiabatic bunching – see later)
- Combined machine for 3 functions
  1) Focusing
  2) Acceleration
  3) Bunching
- Uses only E field for all functions
- Delivers bunched DC beam (i.e. continuous output with a microstructure = RF)

RadioFrequency Quadrupole (RFQ)

1) Focusing (by the electric field!)

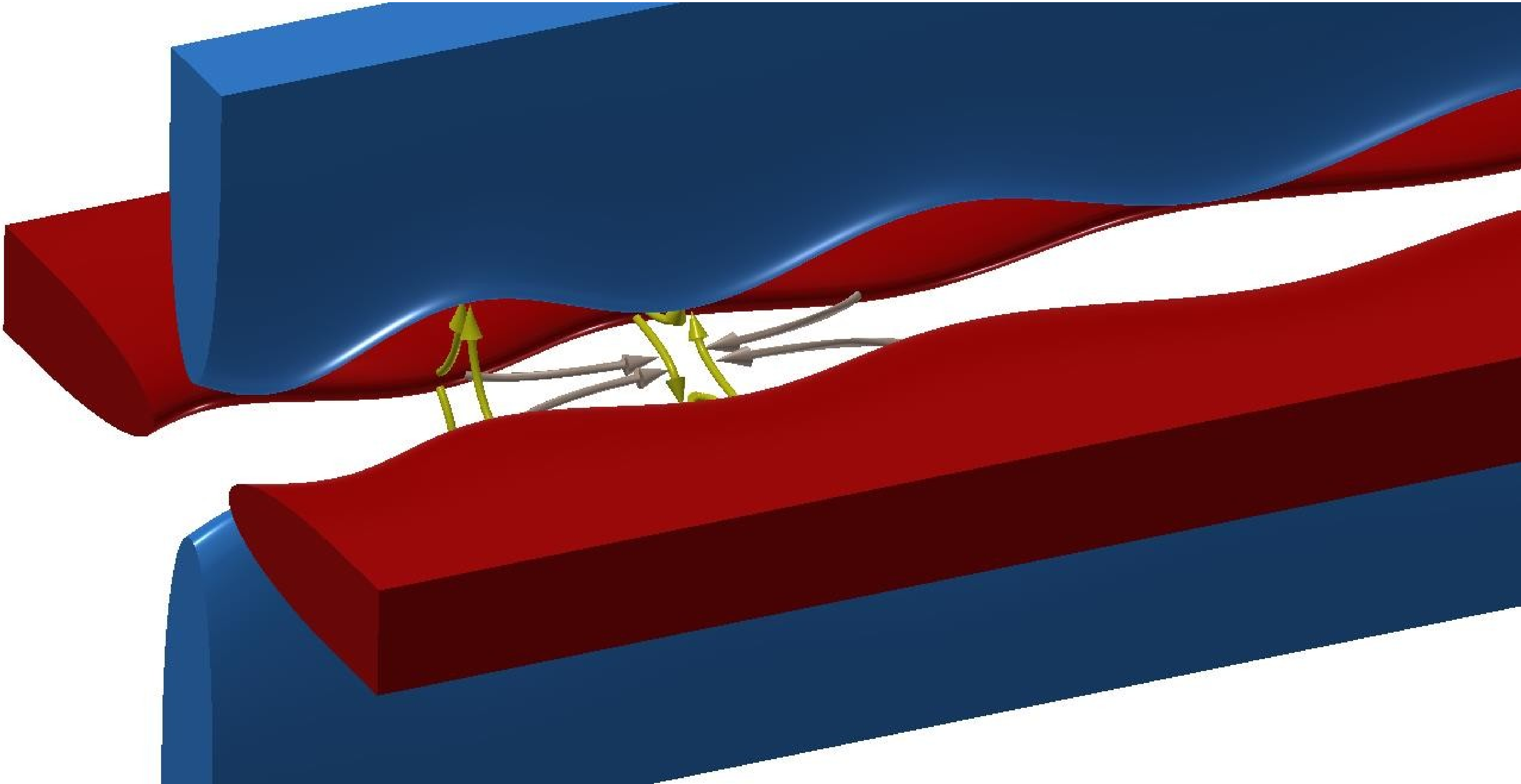
- Transverse quadrupole electric field focuses in one plane, defocuses in other
- If this alternates in time: net focusing in both planes (← ponderomotive force) (cf. Paul trap, AGS/strong focusing) – ask now rather than at the exam!



RadioFrequency Quadrupole (RFQ)

2) Acceleration

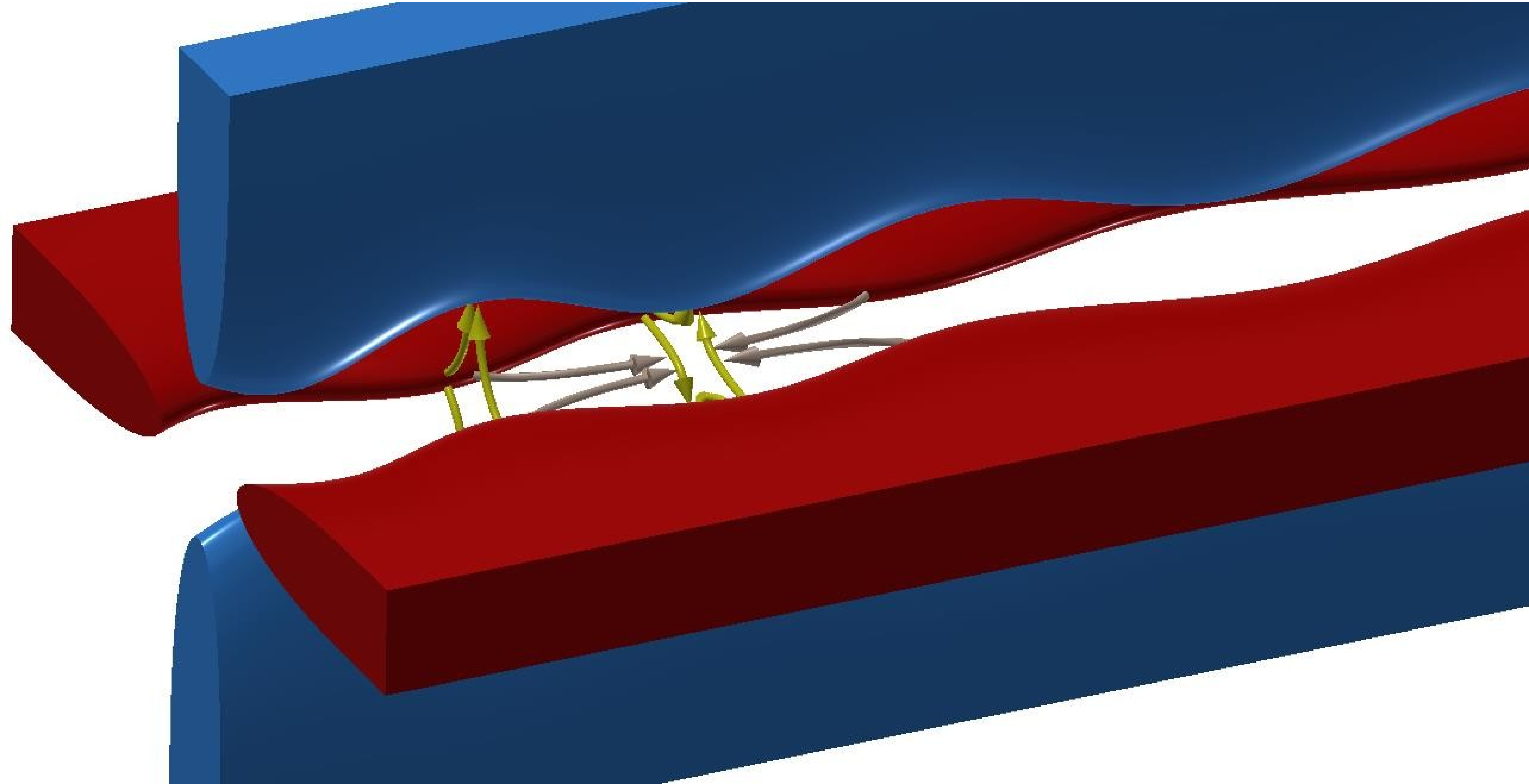
- Longitudinal electrode shape modulation (180⁰ diff between x/y electrodes)
- Alternating longitudinal **electric** field component, accelerates only particles at correct phase



RadioFrequency Quadrupole (RFQ)

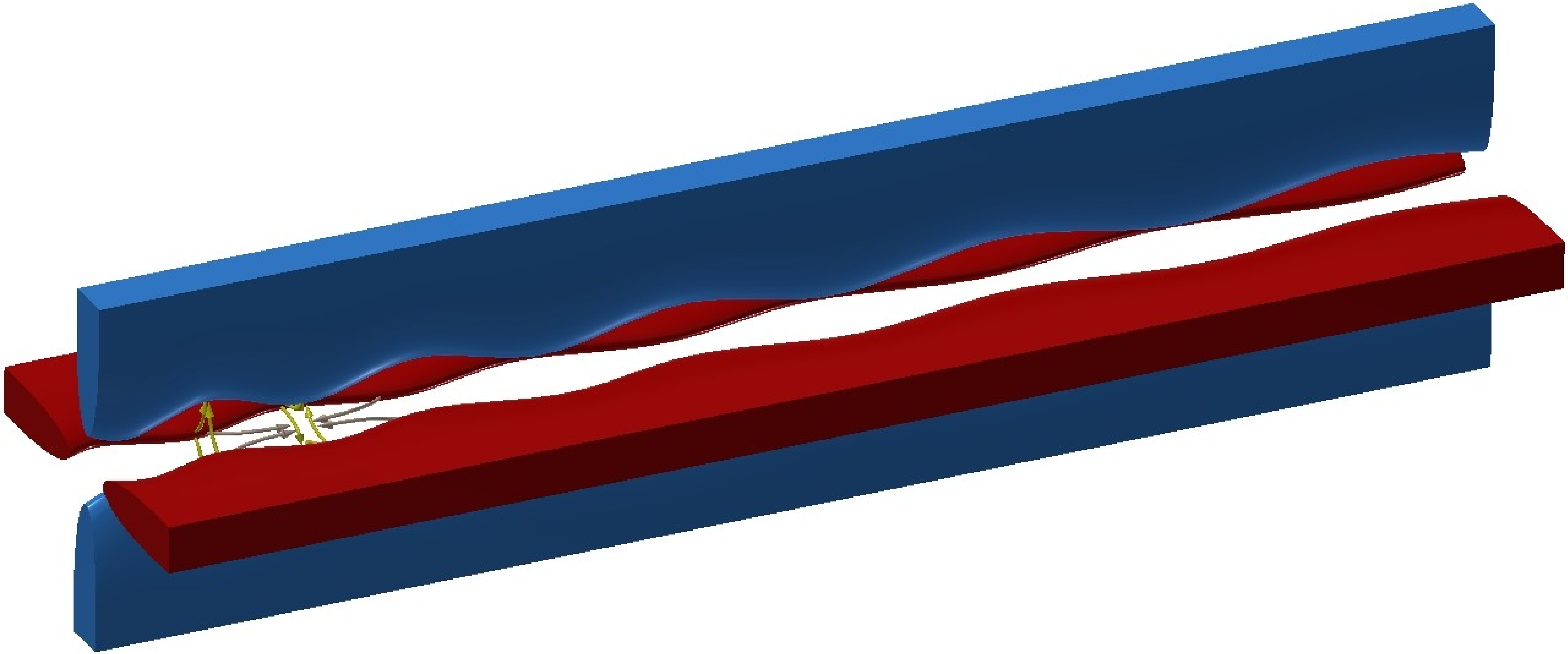
3) Bunching

- Accelerates only in correct phase
- Bunches the particles “adiabatically”:
- Electrode modulation “slowly” developing from input to output



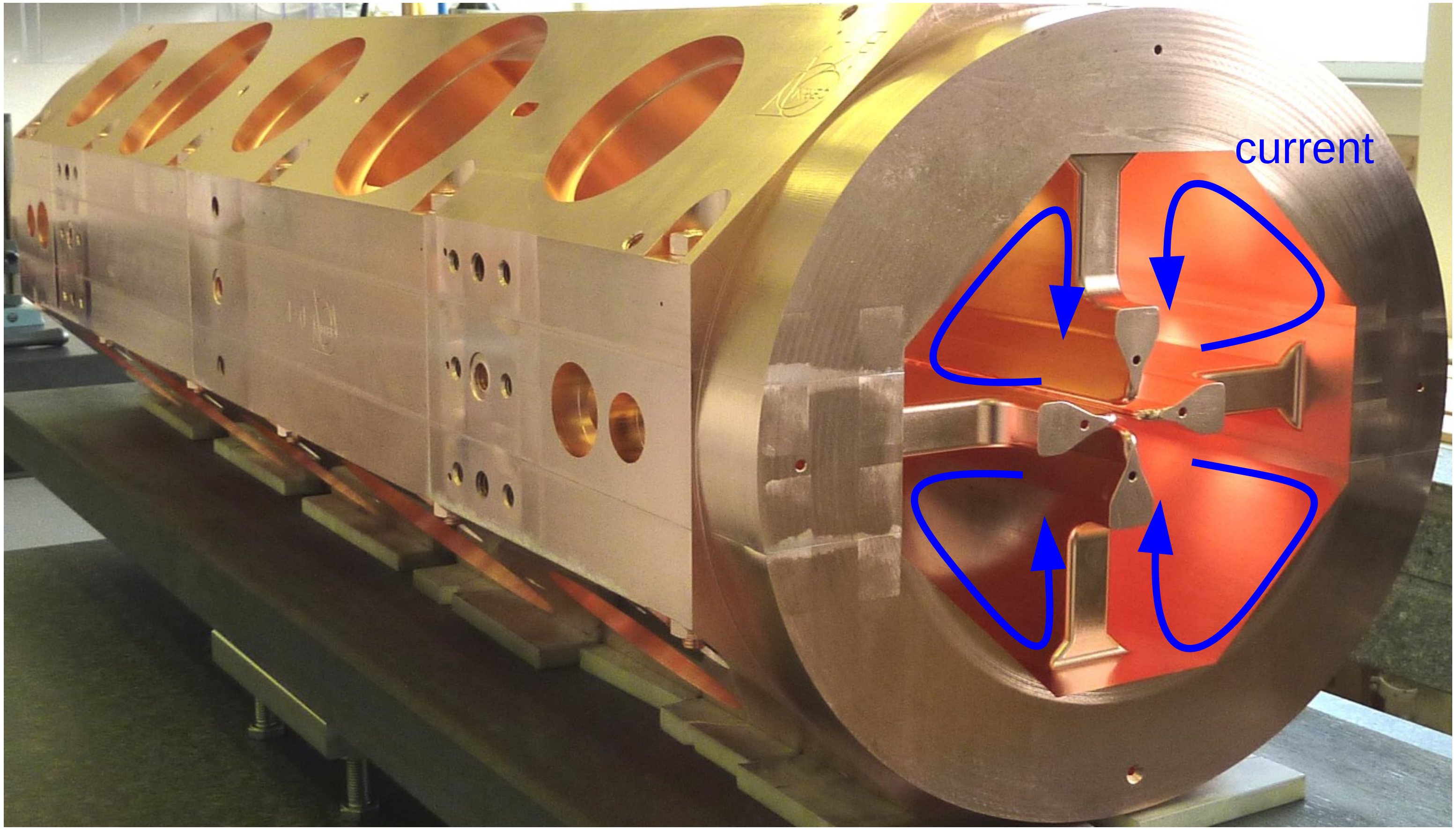
RadioFrequency Quadrupole (RFQ)

- Wavelength of electrode modulation changing in accordance with velocity of particles
- Manufactured by CNC (Computer Numerical Control) machines
- Electrode shape "adiabatically" changing from input to output ("slowly" captures the particles into bunches)

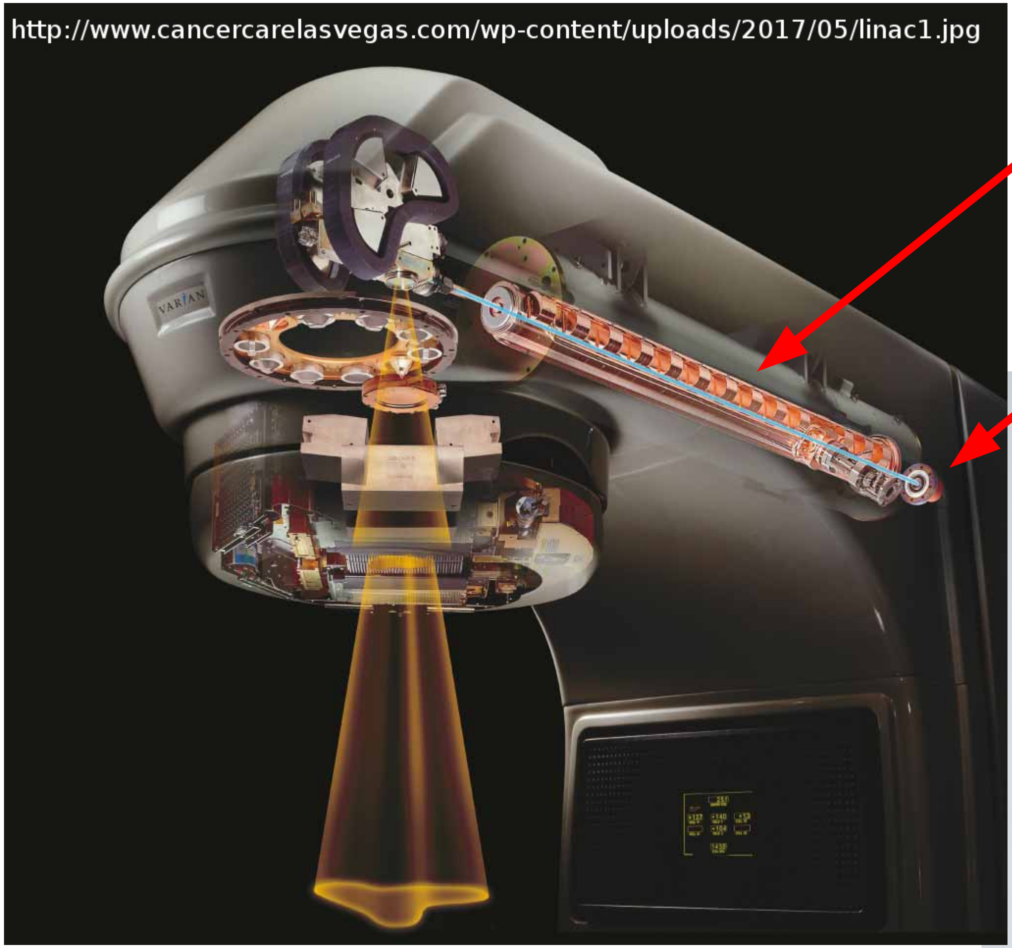


RadioFrequency Quadrupole (RFQ)

- RFQ for LINAC4 (CERN – being commissioned):
  - protons
  - output energy: 3 MeV
  - 3 m length
  - Closed resonator
  - 78 kV between pole tips



Linacs in our life



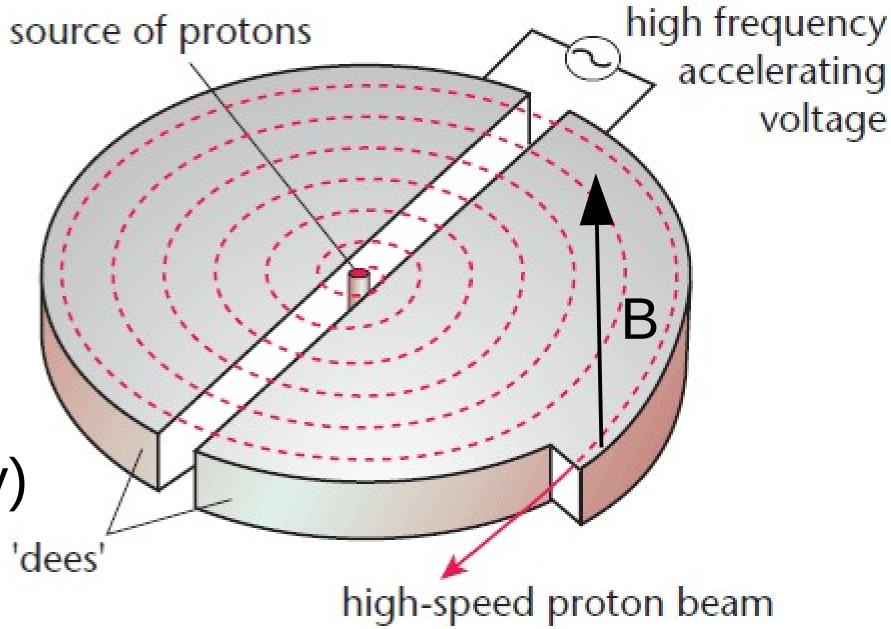
Linear electron accelerator

Electron gun

Changing electromagnetic fields: 2) accelerator rings

“Let’s reuse the same accelerating structure several times by guiding the beam back to it using magnets”

Cyclotron



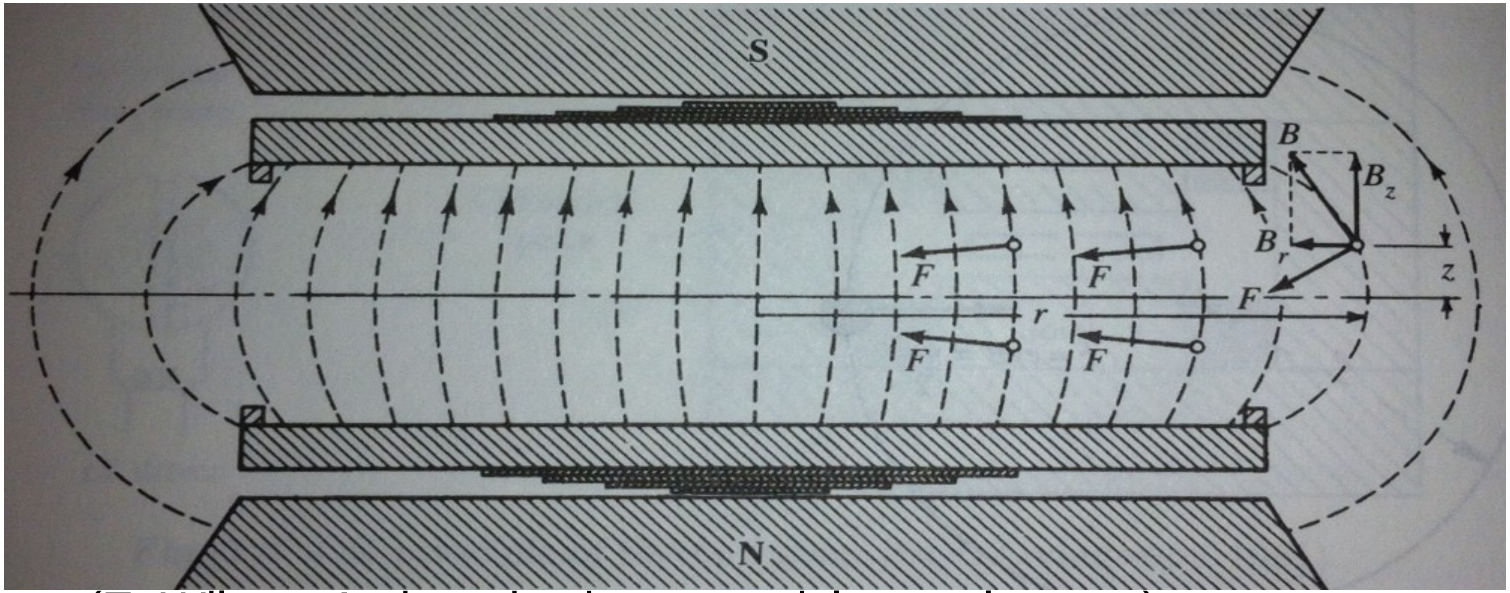
- Lawrence & Livingston (1931)
- Particle orbit is a circle in a constant field. Cyclotron radius increases proportionally to momentum: $B \cdot R = p/q$
- In the **nonrelativistic** regime: revolution frequency (cyclotron frequency) is energy-independent:

$$f_{cyc} = \frac{v}{2\pi R} = \frac{v}{2\pi} \cdot \frac{qB}{p} = \frac{qB}{2\pi} \frac{v}{p} = \frac{qB}{2\pi} \frac{1}{m}$$

- Cyclotron resonance: frequency of E-field between two D electrodes equals cyclotron frequency: $f_{RF} = f_{cyc}$
- In this case: E accelerates at each passage through gap
- DC (continuous) beam, with a microstructure matching the RF

Cyclotron

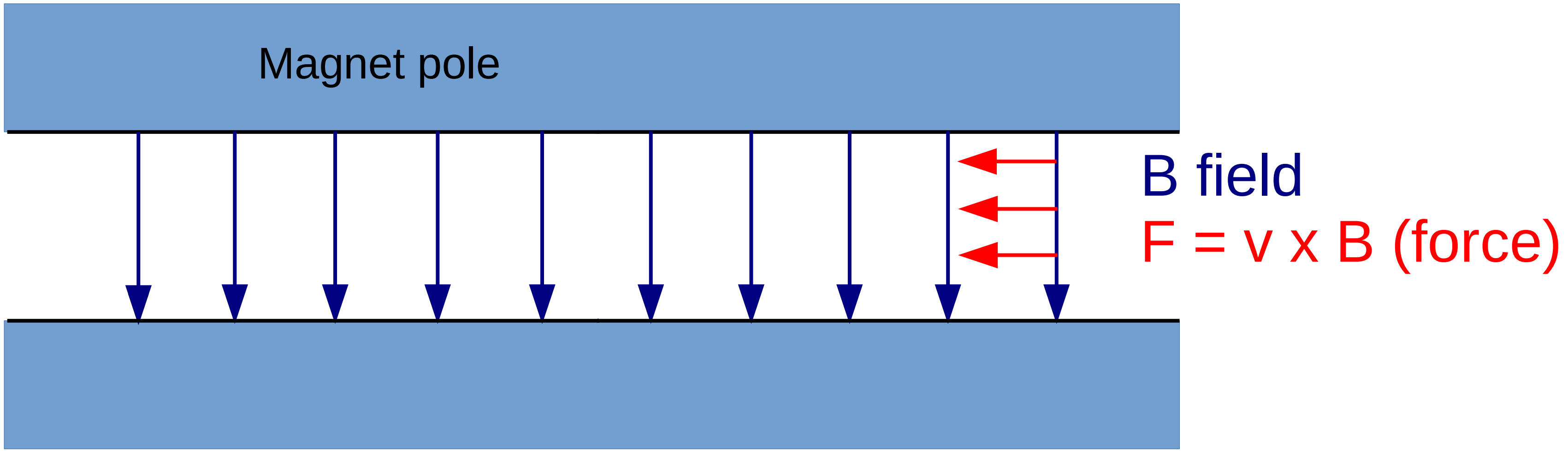
- How can it be that particles are not lost over a lot of cycles, even though they are not parallel?
- McMillan: played with the magnetic field (using pole shims) → suddenly the output current increased



(E. Wilson: An introduction to particle accelerators)

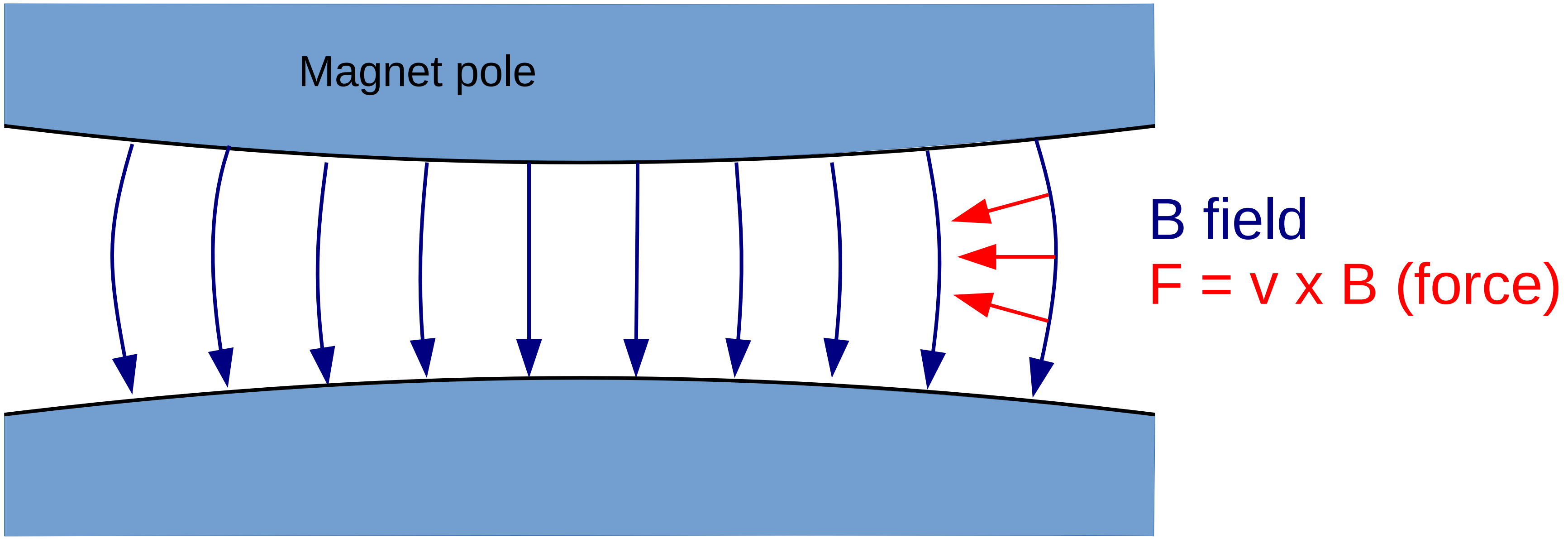
- Horizontal B komponent → vertical focusing or defocusing
- Focusing if B has the right curvature ↔ decreases outwards
  If B increses outwards → defocusing
- Horizontal focusing might get messed up if B decreases too fast outwards (see later: weak focusing)

Weak focusing – preliminary



- At iron-air boundary, B field in air is perpendicular to iron surface (homework: why? hint: μ_r ~ 3-4000 for iron)
- The larger the gap between the poles, the weaker the field

Weak focusing – preliminary



- At iron-air boundary, B field in air is perpendicular to iron surface (homework: why? hint: μ_r ~ 3-4000 for iron)
- The larger the gap between the poles, the weaker the field

The “good field” (focusing in the vertical direction) must decrease with increasing radius!

Cyclotron: relativistic limit

$$f_{cyc} = \frac{v}{2\pi R} = \frac{qB}{2\pi} \cdot \frac{v}{p}$$

Substitute cyclotron radius: R = qB/p

Cyclotron: relativistic limit

$$f_{cyc} = \frac{v}{2\pi R} = \frac{qB}{2\pi} \cdot \frac{v}{p} = \frac{q\,B}{2\pi} \cdot \frac{1}{m}$$

Classic formula: p=mv, therefore v/p=1/m and f_{cyc} = const

Cyclotron: relativistic limit

$$f_{cyc} = \frac{v}{2\pi R} = \frac{qB}{2\pi} \cdot \frac{v}{p} = \frac{q\,B}{2\pi} \cdot \frac{1}{m}$$

Classic formula: p=mv, therefore v/p=1/m and f_{cyc} = const

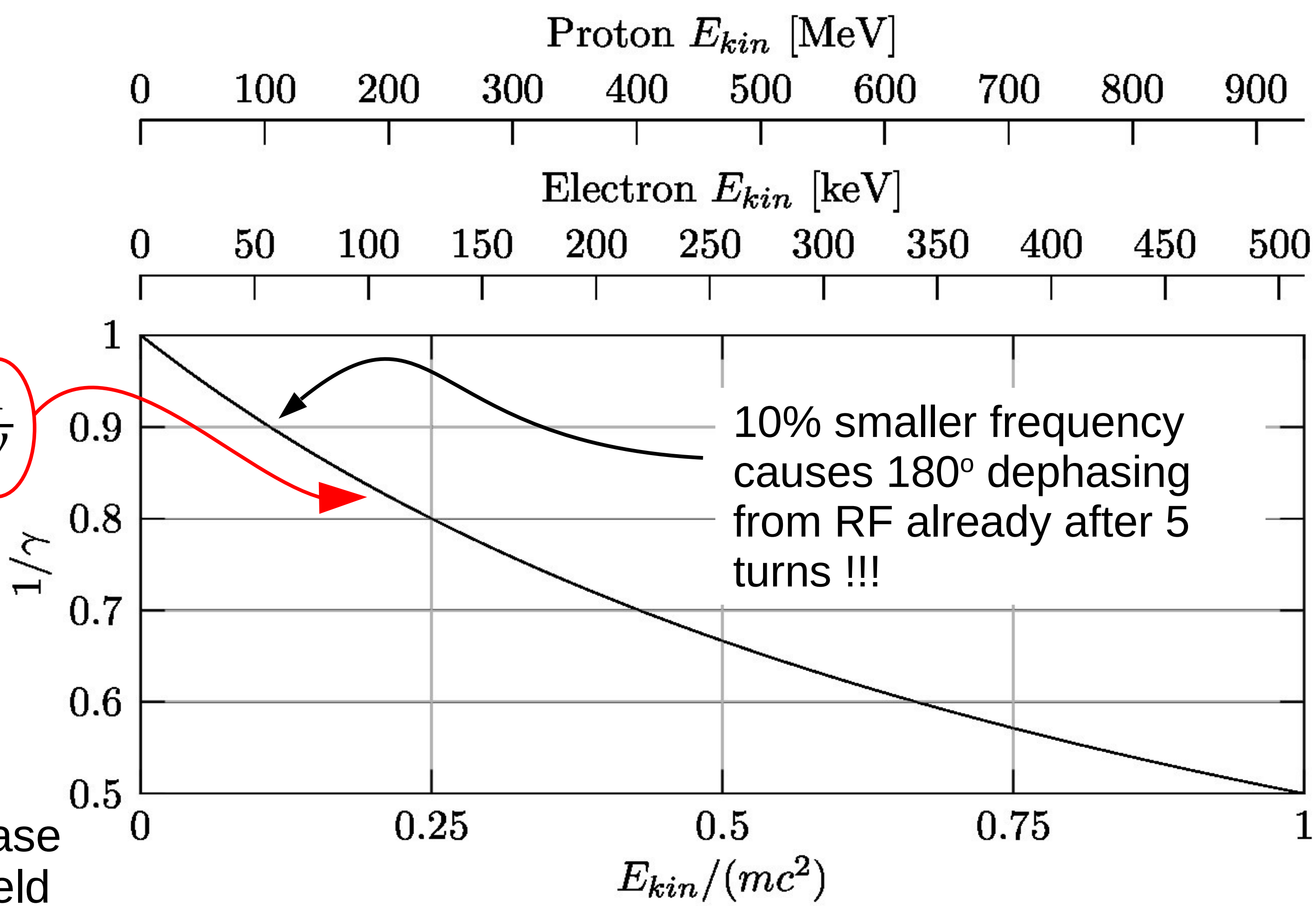
- Relativistic formula (homework!): momentum (and proportionally R) increases, but velocity saturates to c

$$p = \frac{mv}{\sqrt{1 - v^2/c^2}} = \gamma m v$$

$$\frac{v}{p} = \frac{1}{\gamma m}$$

$$f_{cyc} = \frac{qB}{2\pi m} \frac{1}{\gamma} = f_{cyc}^{class} \frac{1}{\gamma}$$

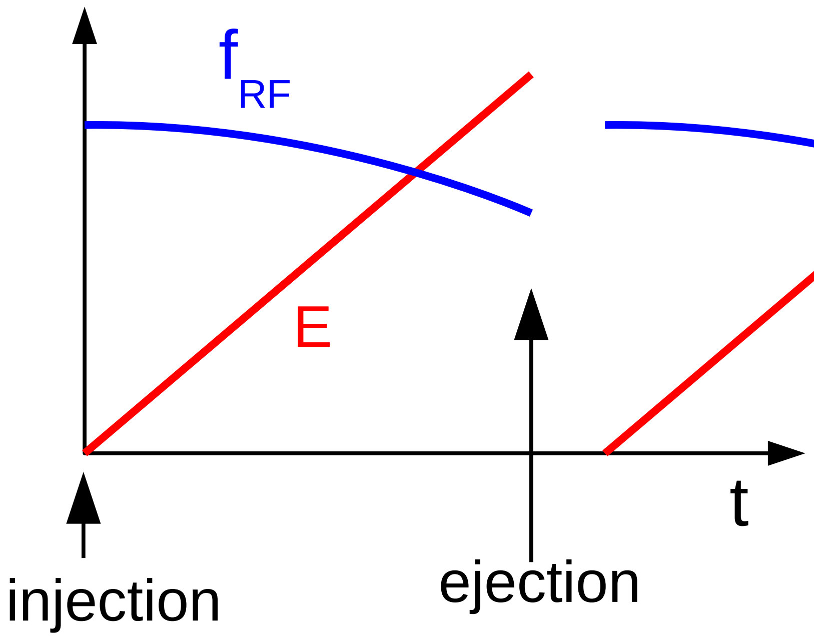
- Few% deviation already for few-10 MeV protons



- Particles get out-of-phase with accelerating RF field

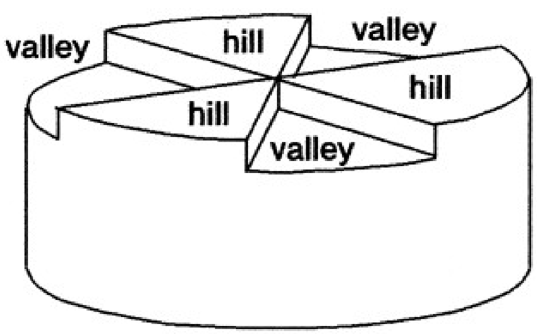
Cyclotron: overcoming the relativistic limit #1

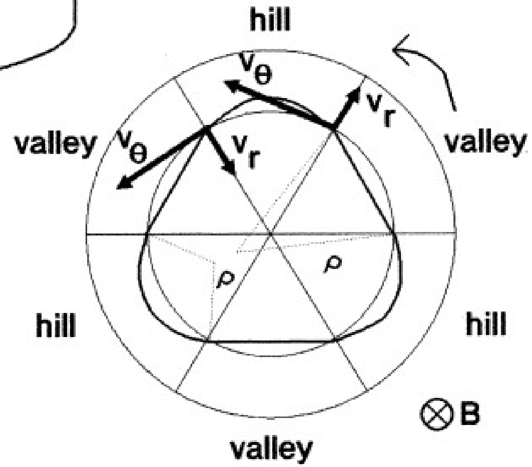
- **Synchro-cyclotron**: RF frequench (f_{RF}) decreasing in sync. with increasing energy
- Cyclic (non-DC) operation. Delivers particle bunches

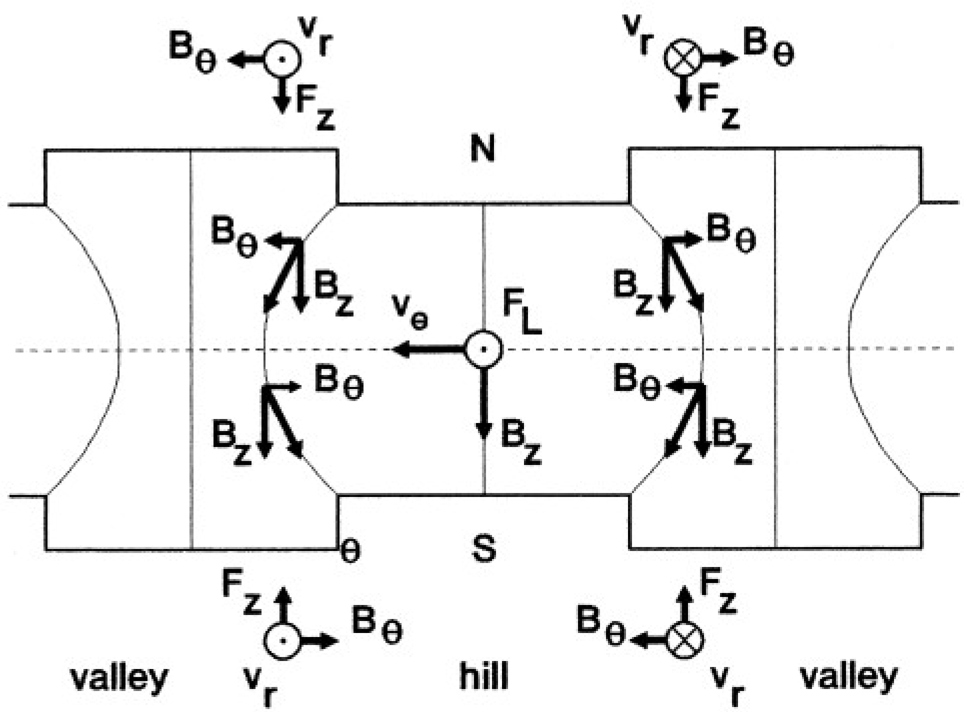


Cyclotron: overcoming the relativistic limit #2

- **Isochronous cyclotron** = **azymuthally varying field (AVF)** cyclotron ≈ sector-focused cyclotron
- **B increasing with R** (in order not to allow the orbit radius to grow proportionally to momentum → to keep the revolution frequency constant).
- Problem: B increasing with R → defocusing vertically
- Solution: (~edge focusing – orbit entering the magnet non-perpendicularly!)

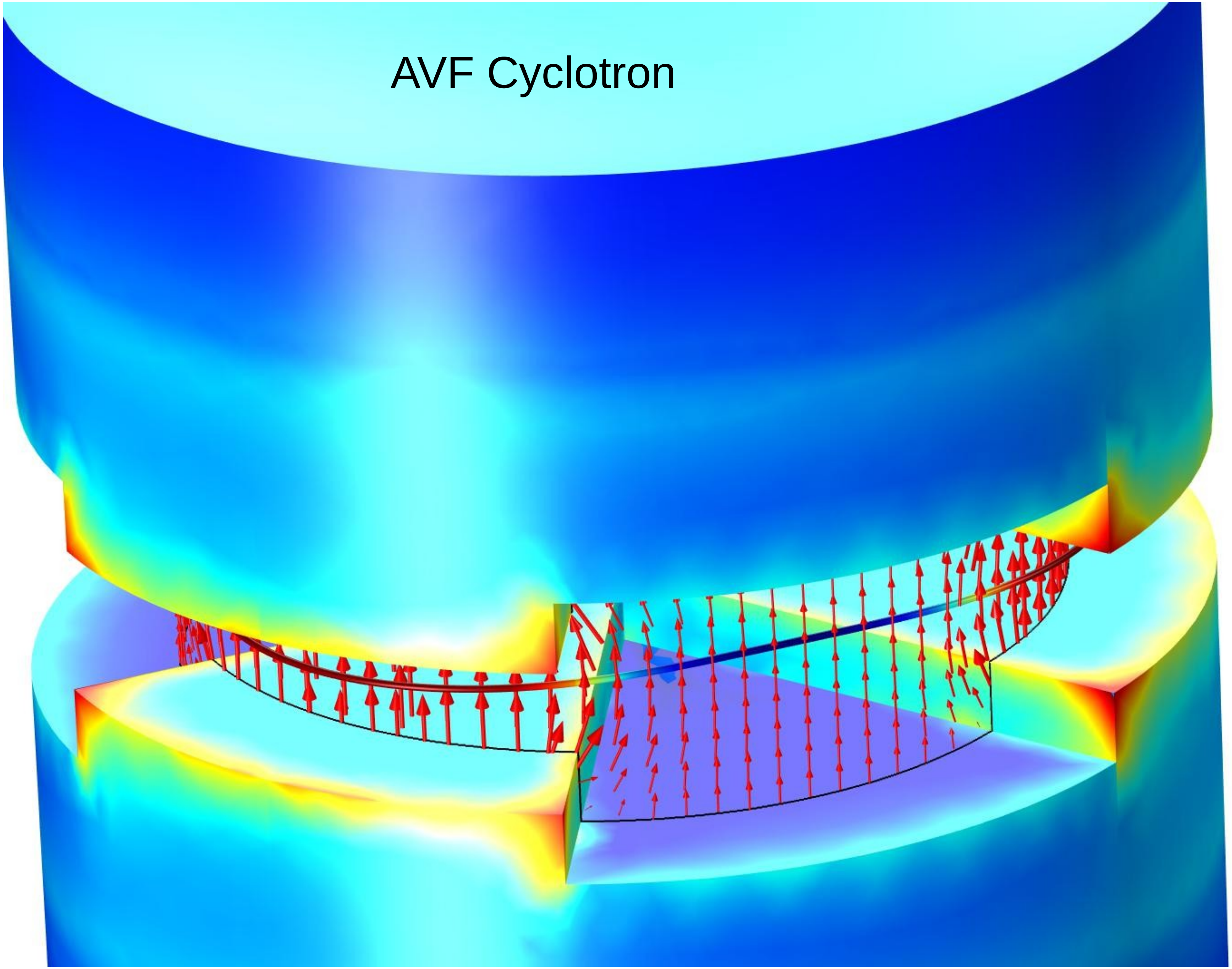






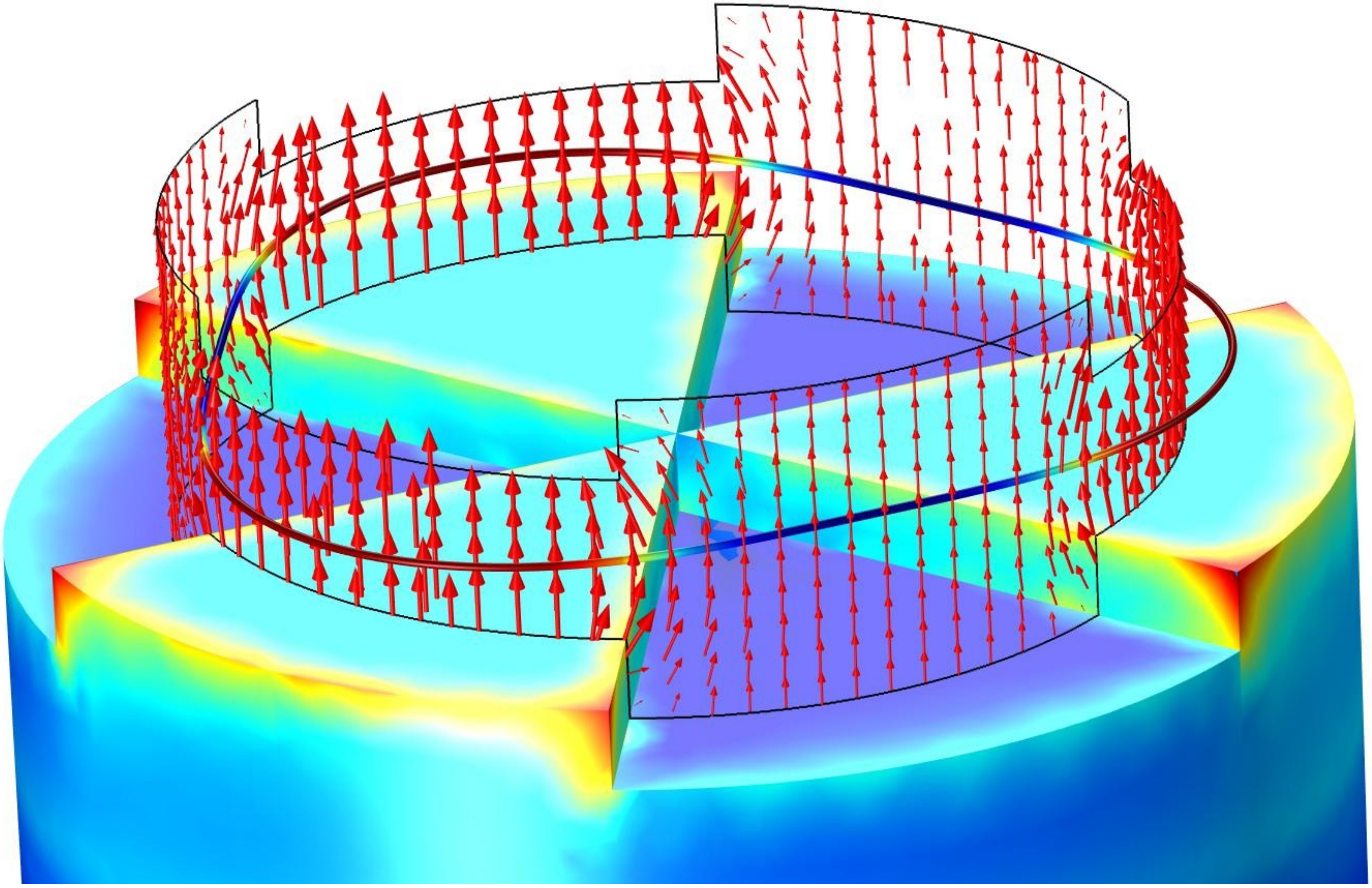
Illusztrációk: K. Strijckmans, Computerized Medical Imaging and Graphics 25 (2001) 69

Cyclotron: overcoming the relativistic limit #2



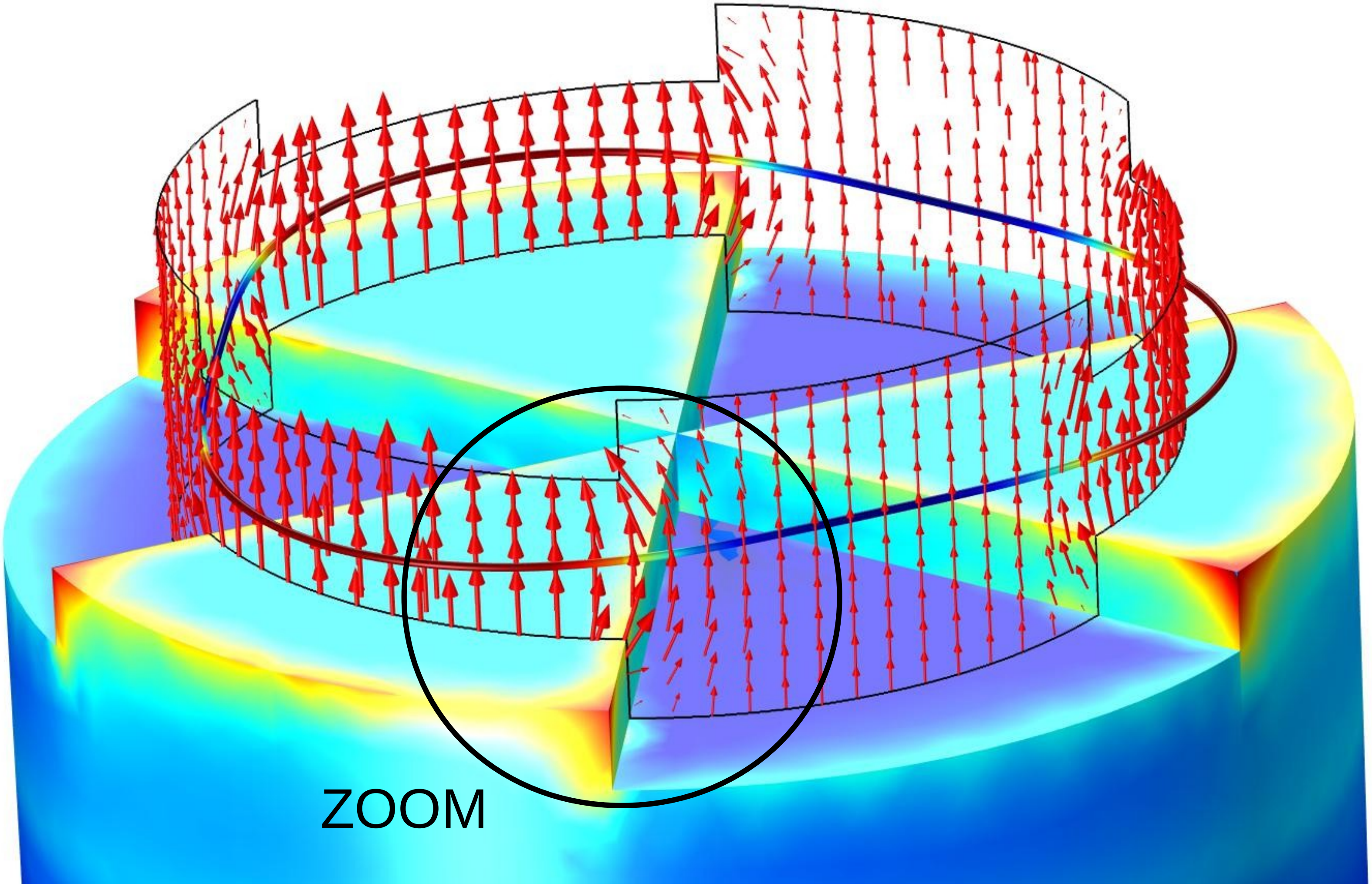
Cyclotron: overcoming the relativistic limit #2

AVF Cyclotron

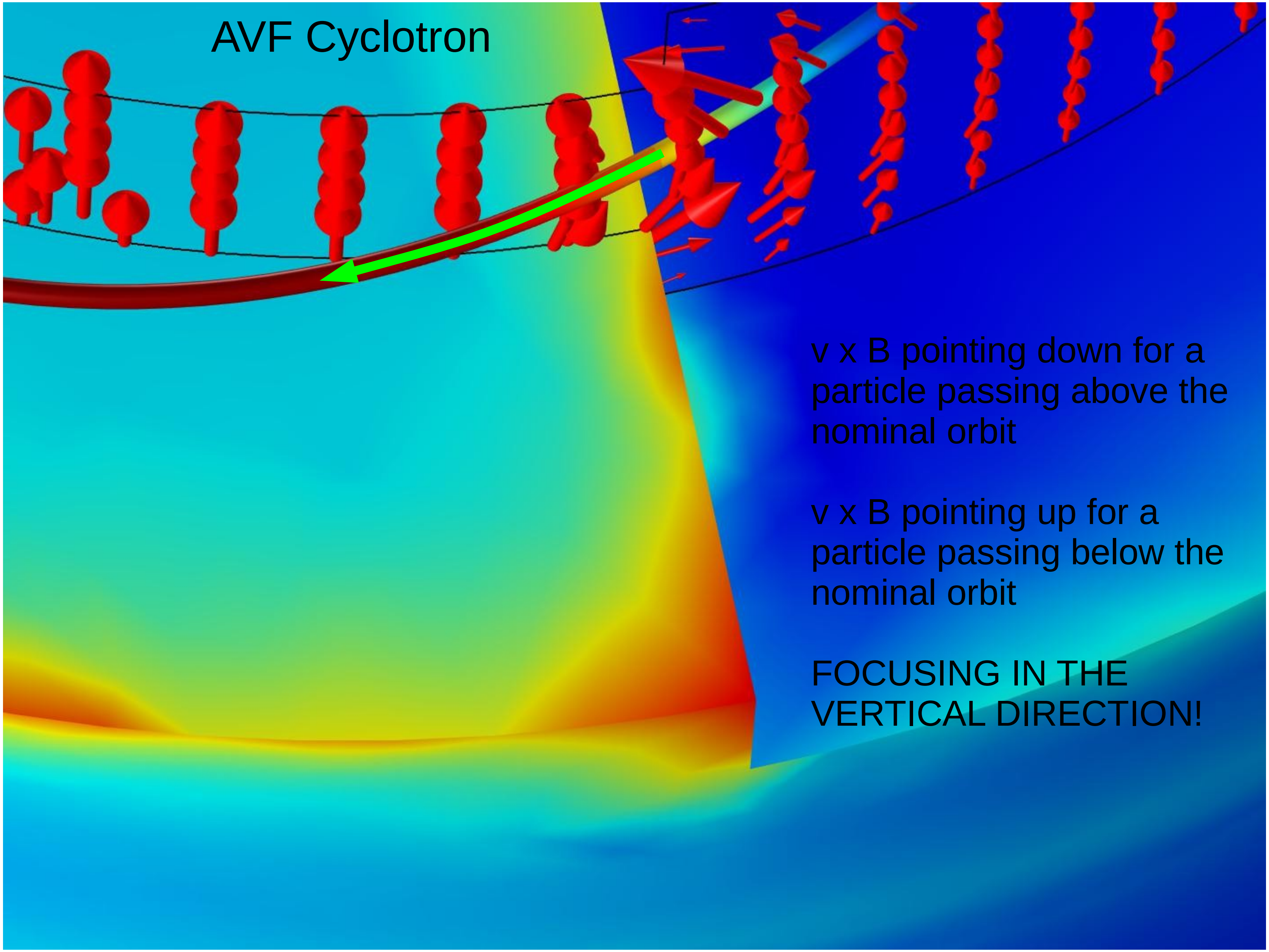


Cyclotron: overcoming the relativistic limit #2

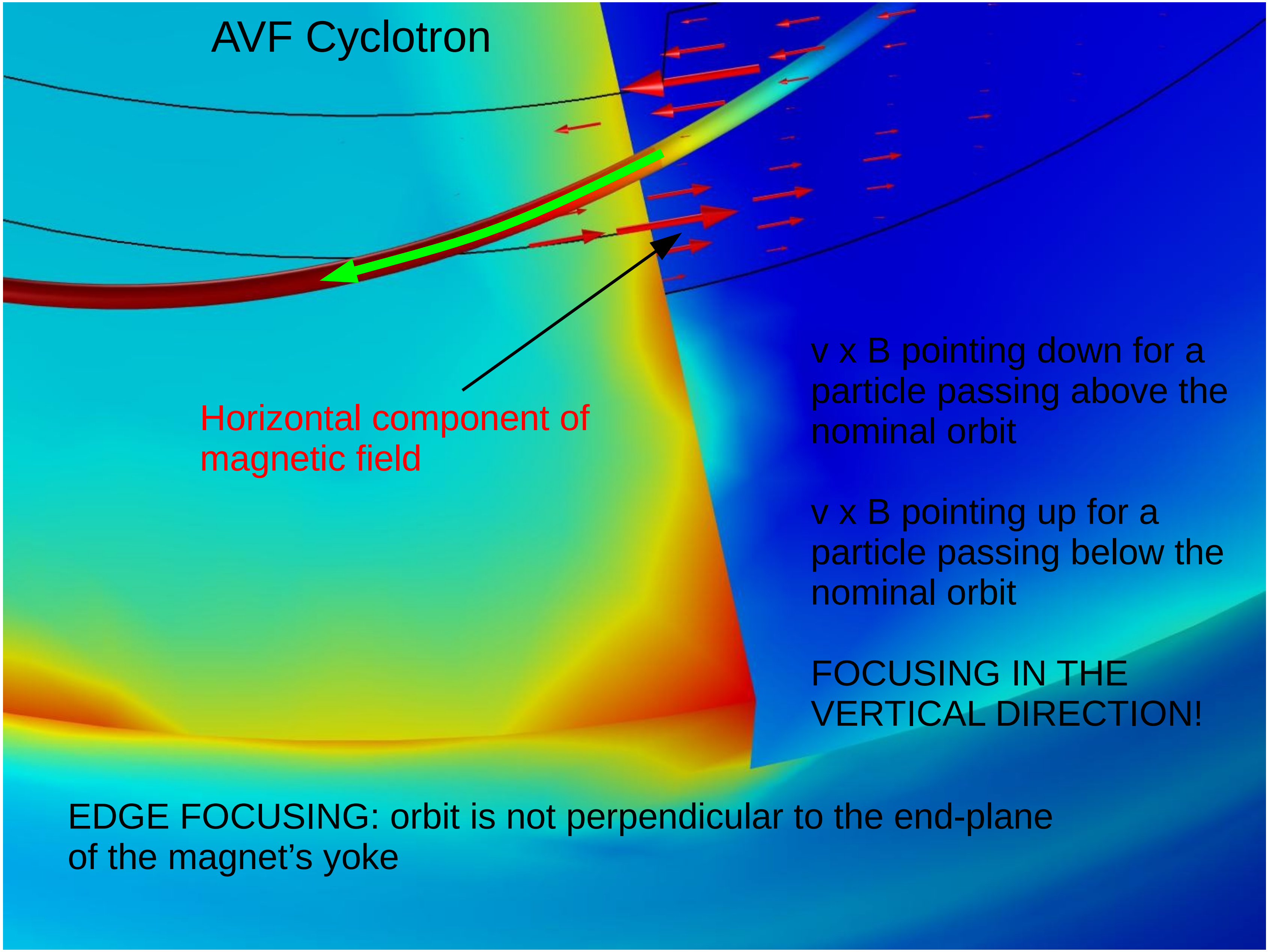
AVF Cyclotron



Cyclotron: overcoming the relativistic limit #2



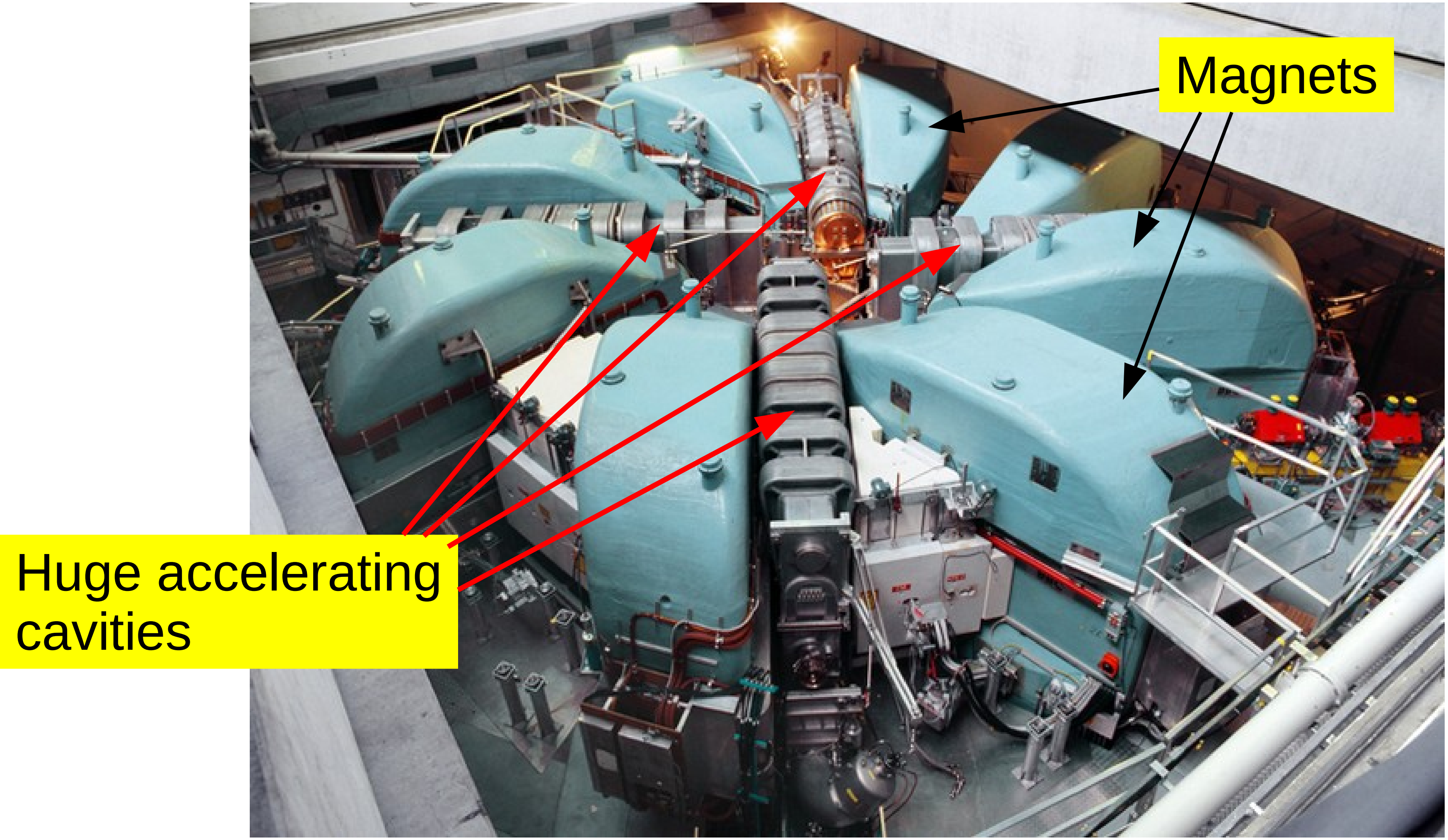
Cyclotron: overcoming the relativistic limit #2



Sector focused cyclotron (PSI)

Extreme case of AVF: Magnets in discrete sectors, with interleving gps.
Advantages:

- Easier access to the vacuum system
- Accelerating cavities can be placed between the magnets



Cyclotrons today

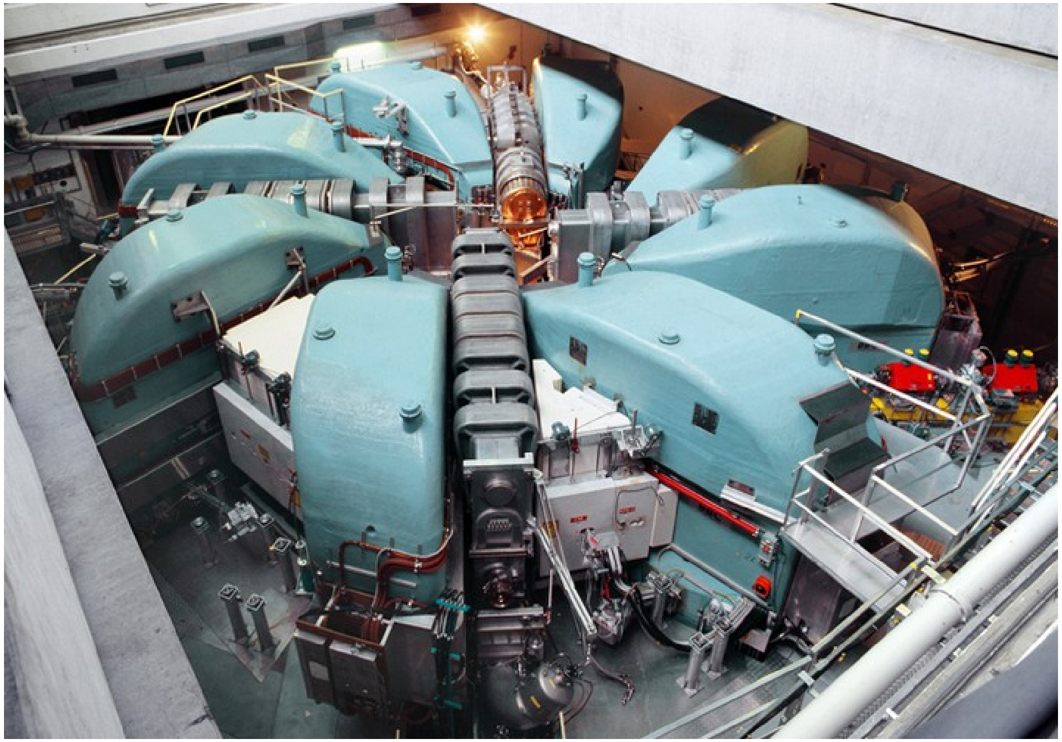
- ~650 cyclotrons in operation
- Production of radioisotopes
- Proton therapy
- Nuclear research

Proton Therapy Center - Prague

Commercial,
turn-key systems

Cyclotrons today: PSI (Paul Scherrer Institute, Switzerland)

- Cockroft-Walton (870 keV) → small cyclotron (72 MeV) → large cyclotron (590 MeV)
- diameter: 15 m. Proton current: 2.2 mA (!!!)
  1g hydrogen in 1.5 years!
  most intense proton beam
- secondary π/μ beams
- neutron spallation source



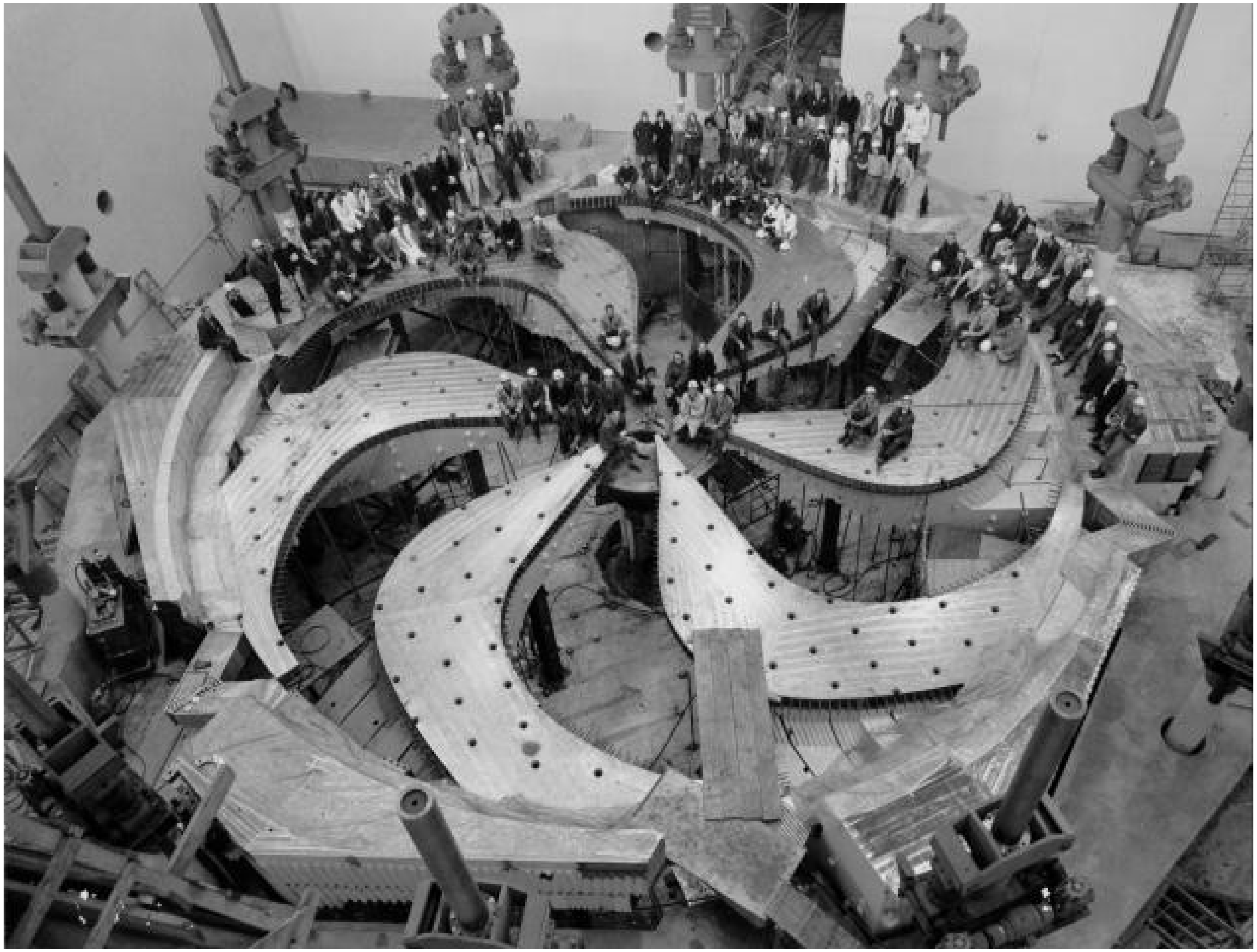
Also @ PSI:
- 250 MeV SC cyclotron (proton therapy)

Cyclotrons today: PSI (Paul Scherrer Institute, Switzerland)

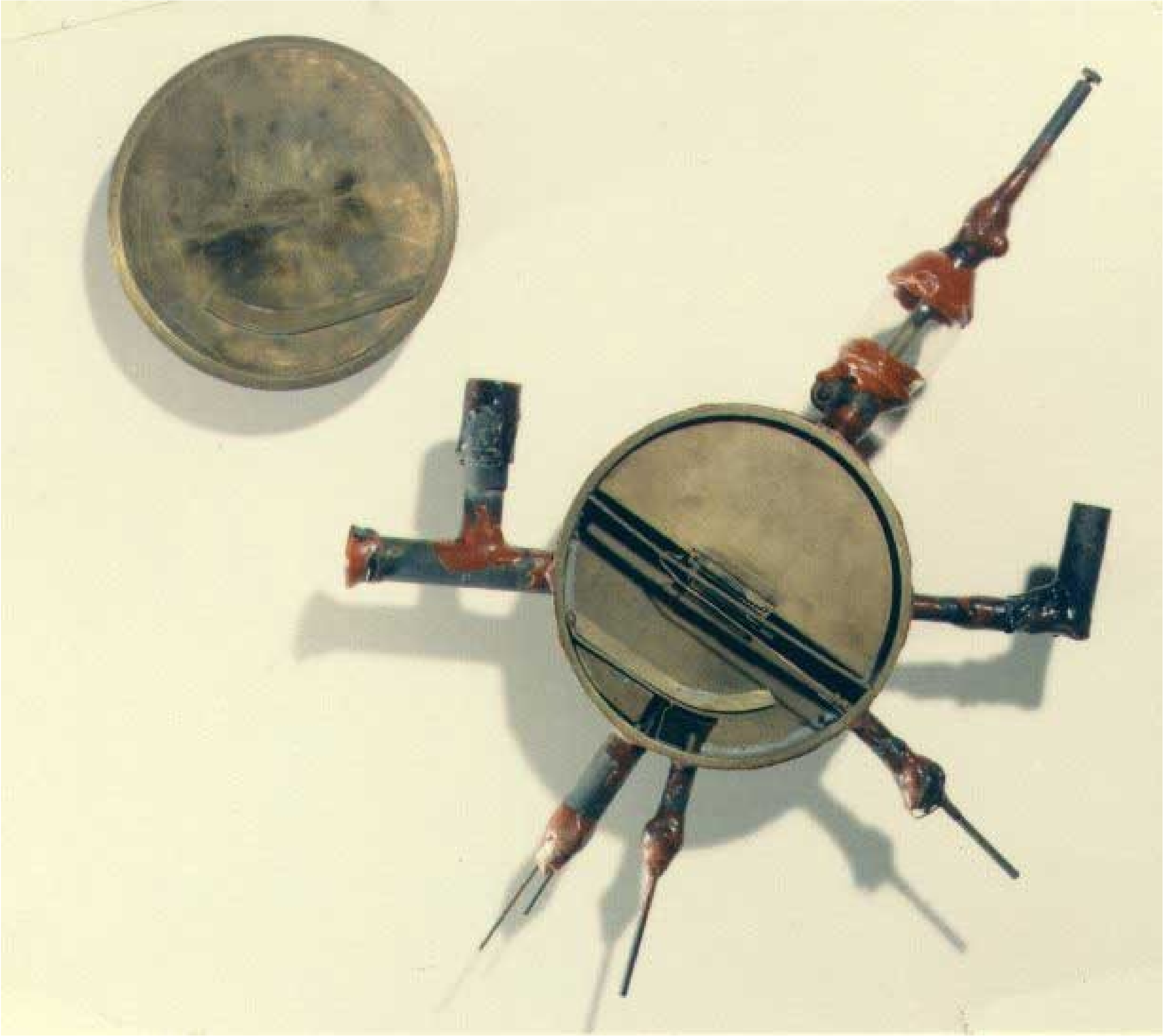
- COMET
- proton therapy
- Superconducting → compact
- 250 MeV

Cyclotrons today: TRIUMF (Canada)

- Maximum energy: 520 MeV (proton). Intensity: <400 μA (~140 μA)
- Diameter: 18 m. Weight of magnet: 4400 tons

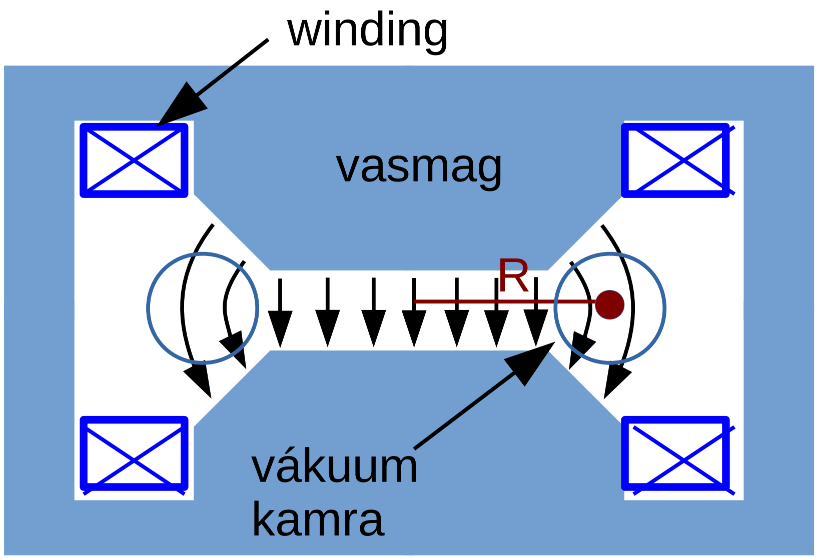


Cyclotron



Lawrence ~1931.
~12 cm diameter, 80 keV

Betatron



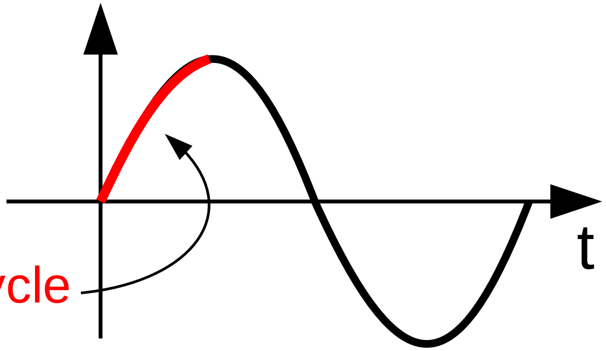
- ~ transformer: primary: winding. secondary: electron beam
- Original idea: Rolf Widerøe
  Realization: Donald Kerst
  (1940, 2.3 MeV)
- Electrons move on a **fixed** orbit!
- Bending field B_{guide} is the same as the accelerating field

$$\oint E\,ds = 2R\pi E = \int \frac{\partial B}{\partial t} dA = R^2 \pi \dot{B}_{av} \quad \rightarrow \quad E = \frac{1}{2}\dot{B}_{av} R$$

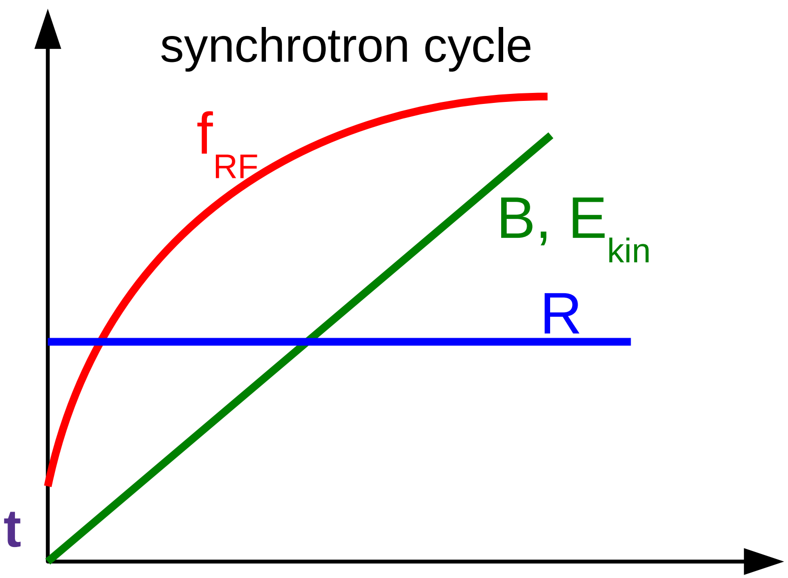
$$\dot{p} = eE = \frac{1}{2} e \dot{B}_{av} R \quad \rightarrow \quad p = \frac{1}{2} e B_{av} R = e B_{guide} R$$

$$B_{guide} = \frac{1}{2} B_{av} \quad \text{'betatron principle'}$$

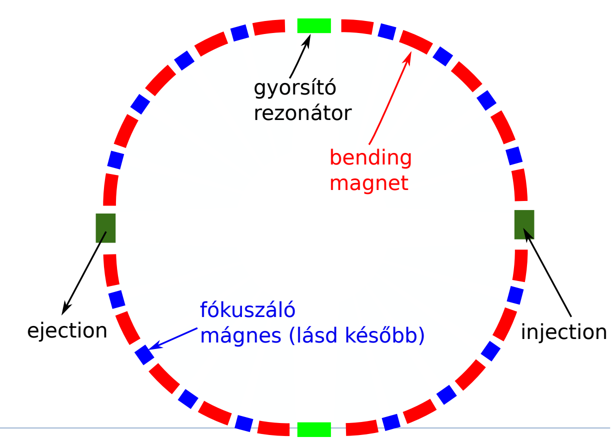
- Max energy: ~300 MeV (275 ton mgnet)
- Pulsed operation: AC current, accelerates during 1/4 cycle
- **Weak focusing** (see later)



Synchrotron – accelerator/storage ring



- 3 basic ideas:
  - Acceleration in the gap of a resonator cavity (~gap, cyclotron)
  - Frequency changing with time – (increases in this case, was decreasing for synchro-cyclotron)
  - Magnetic field increasing with time, in order to keep the **radius of orbit constant** (~betatron)
- Orbit is constant! →
  - We need B field only at the fixed orbit. Can build large accelerators, in contrast to previous principles where B had to cover huge area
    - Cyclotrons: B must cover changing orbit
    - Magnetron: need to cover area encircled by beam (induction):. $\oint \frac{\partial B}{\partial t} dA$
- Cyclic operation (not DC): injection + acceleration + ejection



Advantages of collider rings

- One accelerating cavity in the whole ring, “reused” at every turn
- Two beams colliding head-on: center-of-mass energy much larger than in fixed-target experiments
- Particles missing a collision get a second chance in the next turn.

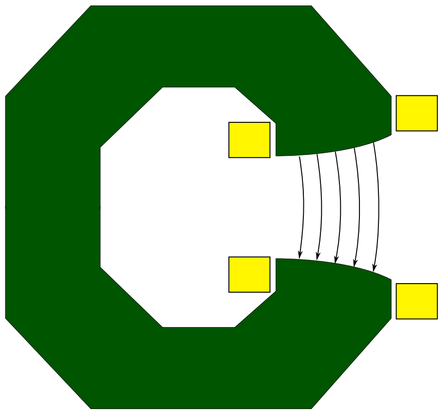
Synchrotrons – the beginning

- First proposal: Mark Oliphant, 1943 Oakridge (US). Memo to the Directorate of Atomic Energy (UK, classified document)
  A key principle (phase stability) is now known yet.
- Phase stability – even though particles have a finite velocity spread, they remain in sync with the accelerating RF field even after a loooot of turns.
  V.I. Veksler (Moszkva, 1944), E.M. McMillan (Berkeley, 1945) – see later
- McMillan proposed the construction of a synchrotron
- First working synchrotron: General Electric Co. 1946; 70 MeV electrons
  Glass vacuum tube – the first machine to produce visible synchrotron radiation
- First proton synchrotron:
  Cosmotron, 3 GeV
  (Brookhaven Nat. Lab, 1952)
  weak focusing – see later

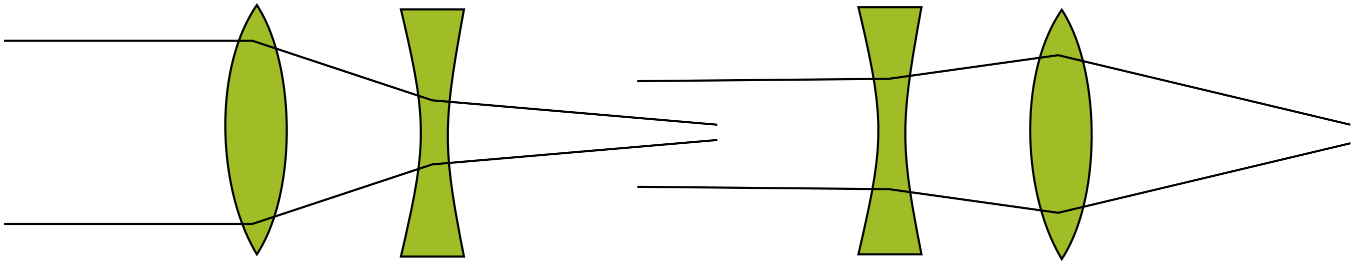
- Weak focusing → **large beamsize, large aperture, large and expensive vacuum pipes and magnets**
  Cosmotron: 20x30 cm; Bevatron (6.2 GeV): 30 cm x 1.2 m (!)

Synchrotrons – strong focusing

- Cosmotron: iron yoke saturated at large fields → distortion of the field pattern. This could lead to the **destruction of the conditions for weak focusing** (n became > 1).



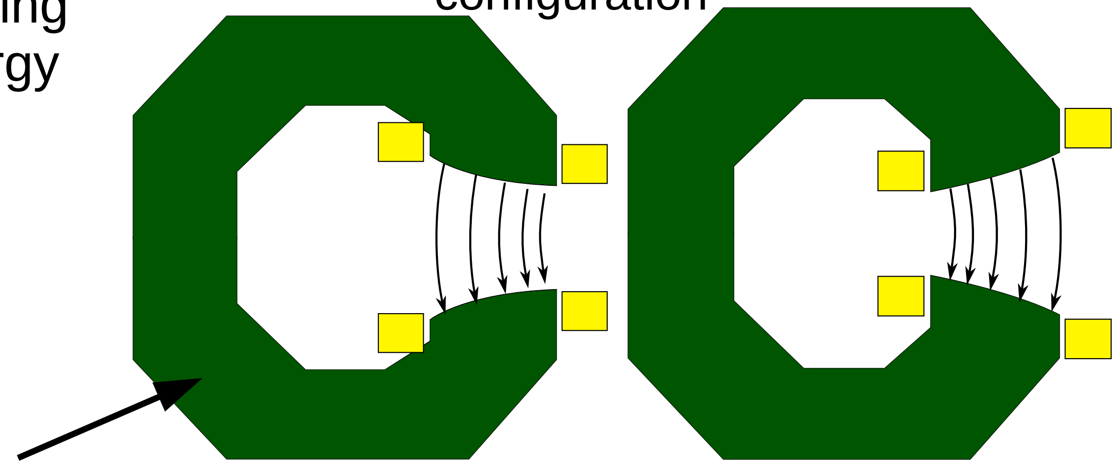
- E.D.Courant, S. Livingston, H.S.Snyder: compensate this by turning some magnets 180°, giving negative n-values, bringing the average back to 0<n<1
- Discovery: **alternating pattern can lead to much stronger net focusing in both planes simultaneously**!!
- Individual magnets do not need to focus in both planes simultaneously! **They focus in one plane, and defocus in the other plane**
- Optical analogy: net focusing with proper conditions



Synchrotrons – strong focusing

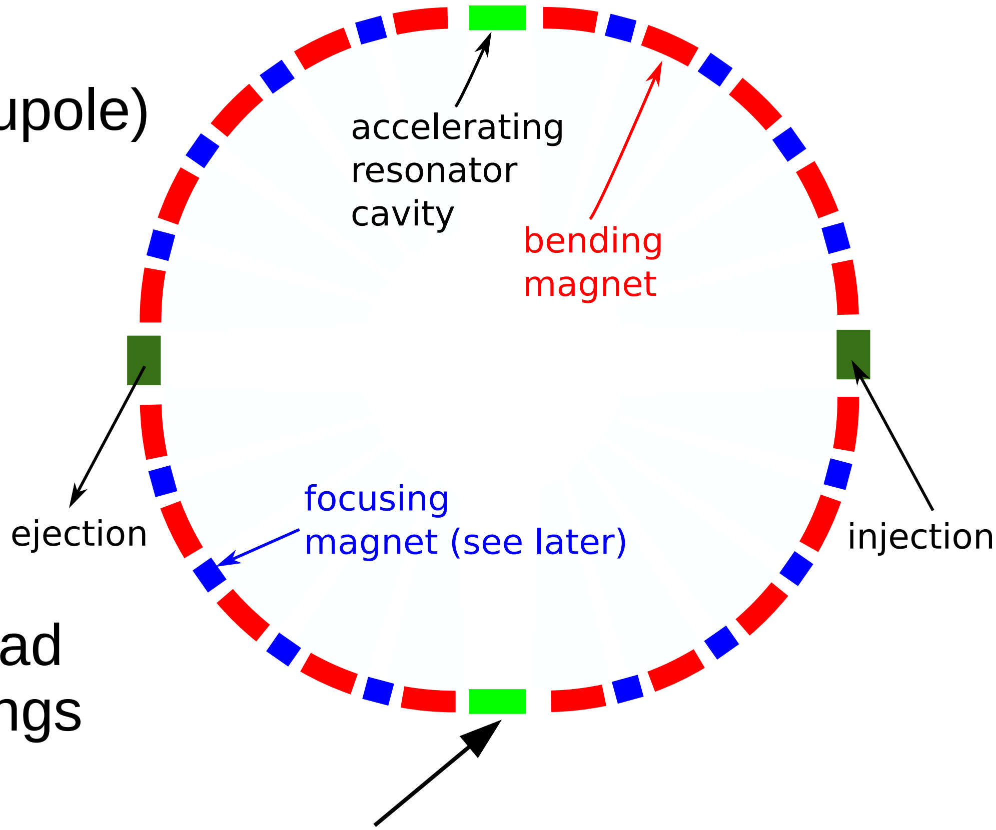
- Strong focusing gives **much smaller beamsize!**
- No need for huge vacuum pipes and magnets
- Beam can be focused to a smaller spot (higher luminosity!)
- 10 GeV proton synchrotron being planned @ CERN. Visit to BNL at the time of discovering AG (strong) focusing – old idea dropped:
  - 1959: CERN Proton Synchrotron (PS) 25 GeV, first strong focusing synchrotron, world record energy for a short time
  - 1960: BNL AGS (Alternating Gradient Synchrotron) 33 GeV
  - Both used **combined function magnets** (the same magnet creating the bending dipoleand focusing quadrupole field)
  - Very similar: cooperation & competition

Alternating gradient configuration



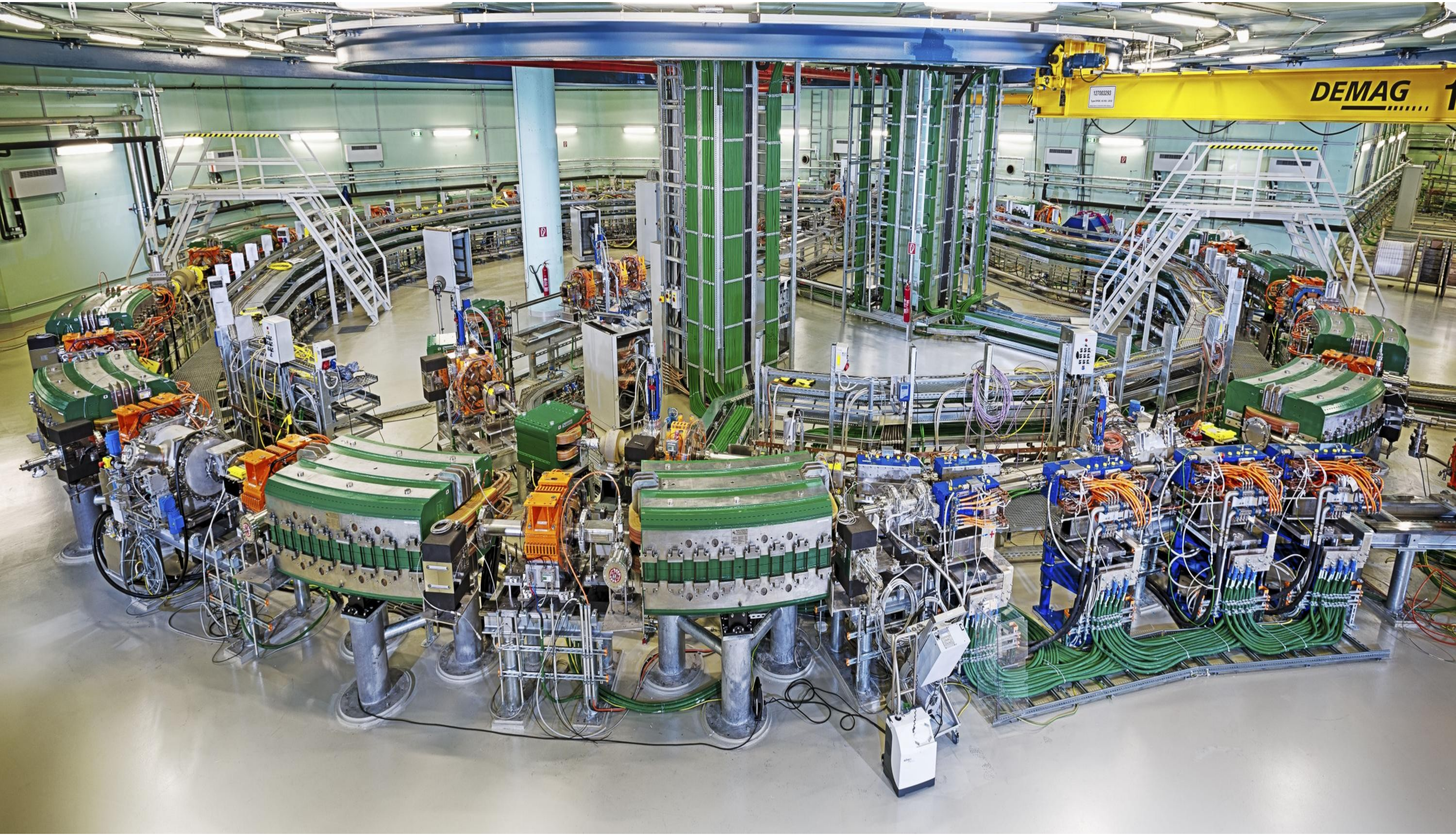
Synchrotron

- Modern synchrotrons: bending (dipole) and focusing (quadrupole) by separate magnets
- Straight (focusing, quads) and bent (dipoles) sections alternating
- + extra corrector magnets (e.g. sextupole)
- Periodic structure:
    - Largest period: the full ring
    - Repeating sectors (4 in the figure)
    - Periodic structure within a section: (FODO = focus-drift-defocus-drift)
- Synchrotrons are the most widespread for high energy physics (all CERN rings for example)



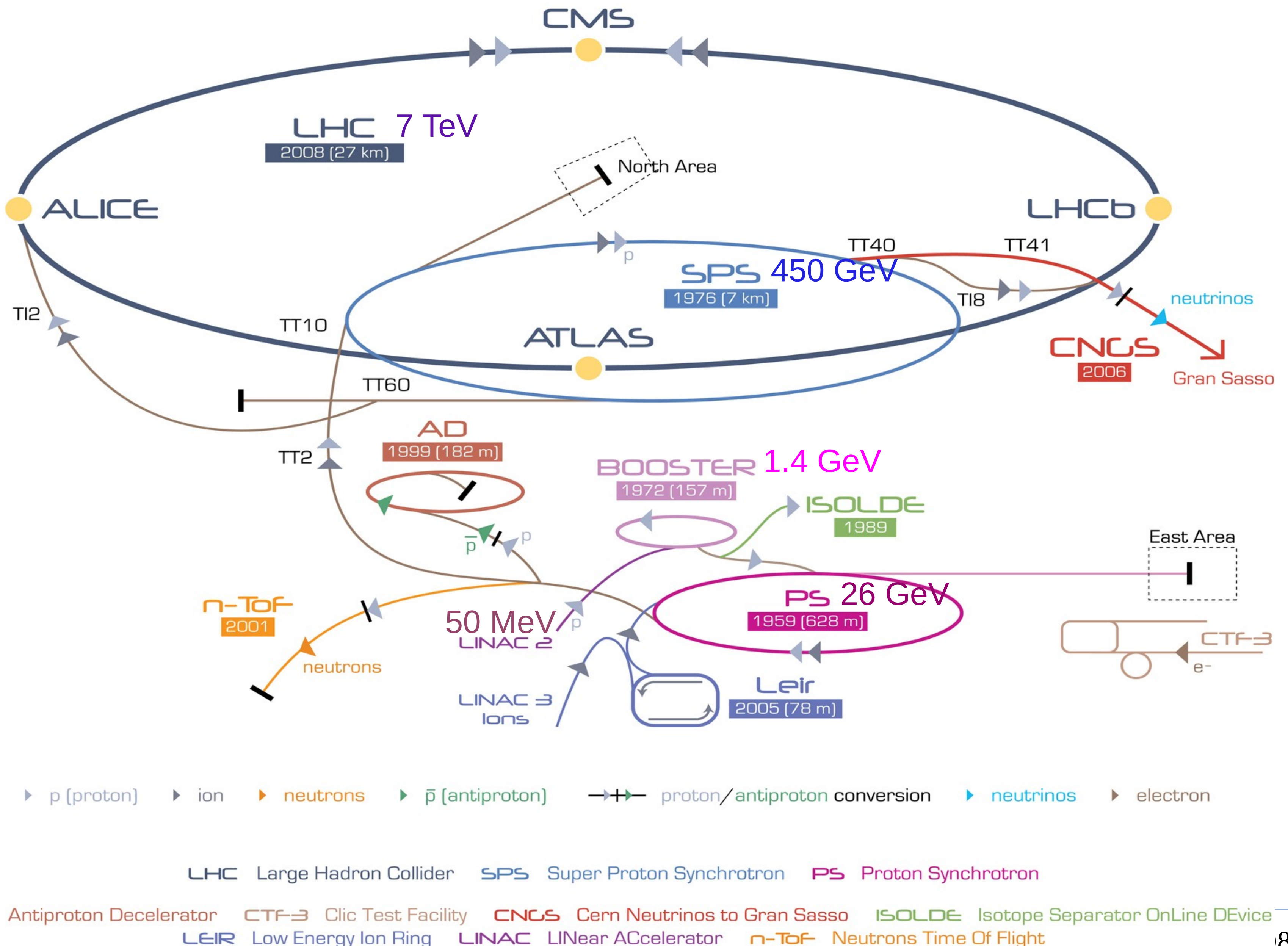
“Insertion”
LHC: “Long Straight Section (LSS)”

A medical synchrotron: Medaustron, Wiener Neustadt, Austria



Synchrotron – the accelerator of the present

- Synchrotrons have a finite energy span → hierarchy of rings with increasing energy



CERN proton-accelerator hierarchy (near past)

- Duoplasmatron ion forrás: 92 keV - electrostatic acceleration
- RFQ: 750 keV
- Alvarez drift-tube linac: 50 MeV
- PS Booster: 1.4 GeV
- PS: 26 GeV
- SPS: 450 GeV
- LHC: 7 TeV

(RFQ and Alvarez drift-tube linac: LINAC2)

(PS Booster, PS, SPS, LHC: Synchrotrons)

CERN proton-accelerator hierarchy (near future)

- H- ion source: 45 keV - electrostatic acceleration
- RFQ: 3 MeV
- Alvarez drift-tube linac: 50 MeV
- Cell-coupled drift tube linac: 102 MeV
- Pi-mode structure: 160 MeV
- PS Booster: 2 GeV (LIU: LHC Injector Upgrade)
- PS: 26 GeV
- SPS: 450 GeV
- LHC: 7 TeV

LINAC4 (RFQ through Pi-mode structure)

Synchrotrons (PS Booster through LHC)

The future (at least towards high energies)

- HL-LHC (High-luminosity LHC) – first priority @ CERN, goal: reach 10x luminosity in LHC by 2020 (serious hardware upgrade)
- FCC (Future Circular Collider) study: develop a conceptual design for the next generation collider ring @ CERN
  - 1) >350+350 GeV e+e- collider (FCC-ee)
  - 2) 50+50 TeV pp collider (FCC-hh)
  - CERN's current accelerators as injector chain
  - 80-100 km ring
- CLIC – Compact Linear Collider (CERN). 3 TeV center-of-mass energy, e+e- collider. Energy transfer: "Drive beam" → Normalconducting RF cavity → colliding beams
- ILC – International Linear Collider. Superconducting resonator technology, 500+500 GeV e+e-. (Japan?)
- China (?) - Higgs factory, 52 km 250+250 GeV electron-positron collider, and later proton-proton collider