INTRODUCTION TO ACCELERATORS.

Part II: Physics and engineering behind technical components

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HELMHOLTZ

DESY.

Purpose of this lecture

Get a glimpse on the (physics-heavy) "technical" side of accelerators

- Particle accelerators are composed of 100's – 1000's individual devices/components
- Every component is a field of study of its own
- Combines various physics/engineering skills
  - Particle physics, EM-field dynamics, vacuum/fluids, plasmas, …
  - Electronics, mechanical engineering, material science, …
- Accelerators are a mature technology
  BUT: still research and development on ~all components with regular paradigm shifts and new inventions

→ **lots of interesting work** in a most interdisciplinary field!

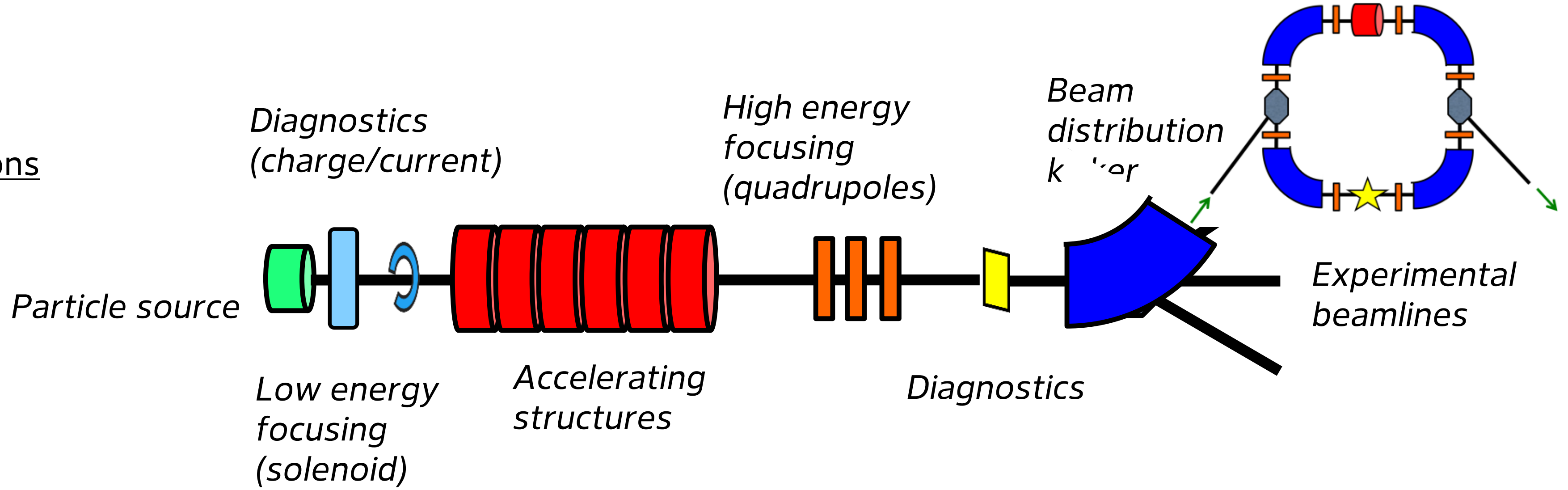
There are 10's of different types of accelerators/components, enough for weeks of lectures.

Today: introduction of concepts with some current examples from DESY and references for further reading…
Minimum take-away: Most (patented) inventions are transfers of concepts between fields/disciplines
→ Maybe you take some with you today ☺

Technical components in an accelerator

What do we roughly need to get usable particle beams?

- Particle source
  - Ions
  - Electrons
    - Photocathode investigations
  - Positrons
- Accelerating structures
  - DC
  - Radiofrequency structures
  - Radiofrequency systems
    - New e^{-} gun for "REGAE"
- Diagnostics
- Pulsed ("kicker"/"septum") magnets
  - Overview
    - Beam injection @PETRA IV
- DC magnets



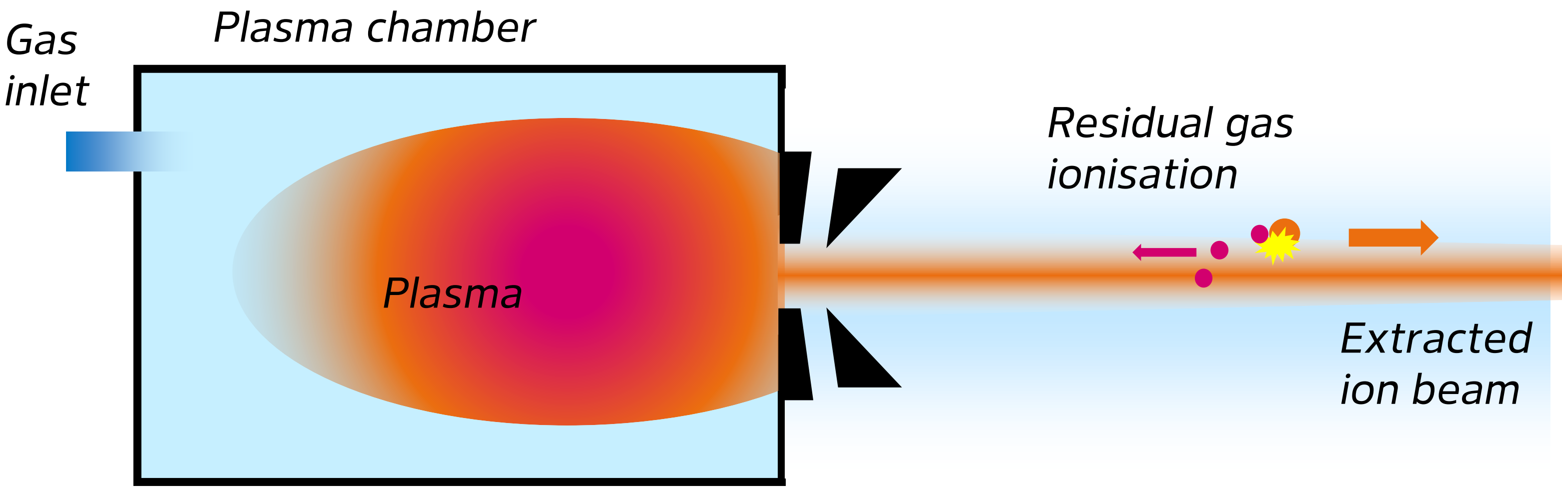
Particle sources

Ion sources

- Free ions ~ not available (in large numbers)
  - Ions & electrons form stable atoms
  - Atoms form molecules/crystals

→ Mechanism to set ions free?!

- Typically: form plasma & "suck" ions out
  → various types of plasma formation
  - Arc discharge
  - RF plasma
  - Ion trap
  - …
- Why different types?
  - Elements are gaseous / solid /conducting / insulating / radioactive…
  - Applications need high current / high charge state /…



Child-Langmuir law: $J_{CL} = \frac{4\sqrt{2}}{9}\epsilon_0\sqrt{\frac{e}{m}}\frac{V^{3/2}}{d^2}$

Particle sources

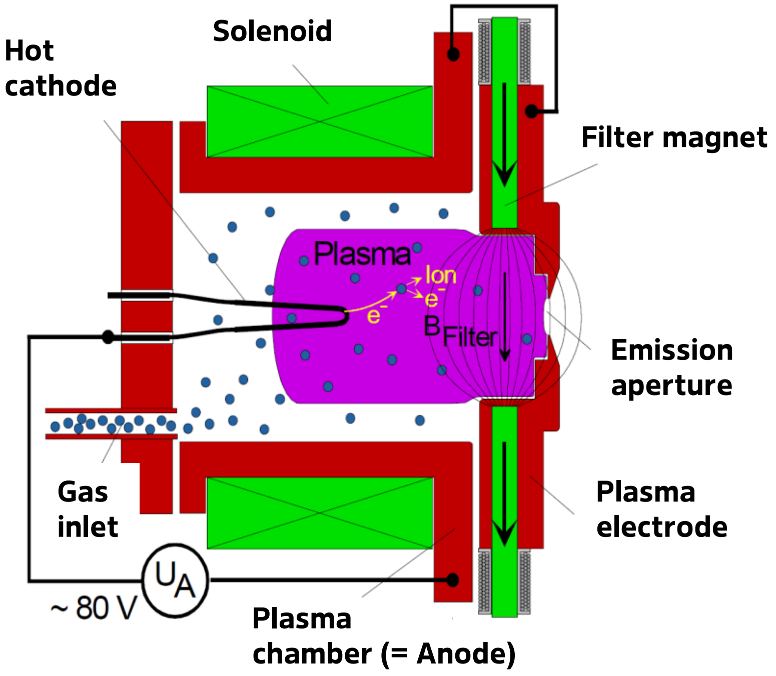
Ion sources

- B-field: electrons → cyclotron motion
  - Increase path length
    → more collisions/ionisation
- High charge states: maximise interaction time
  → trap ions & heat up electrons

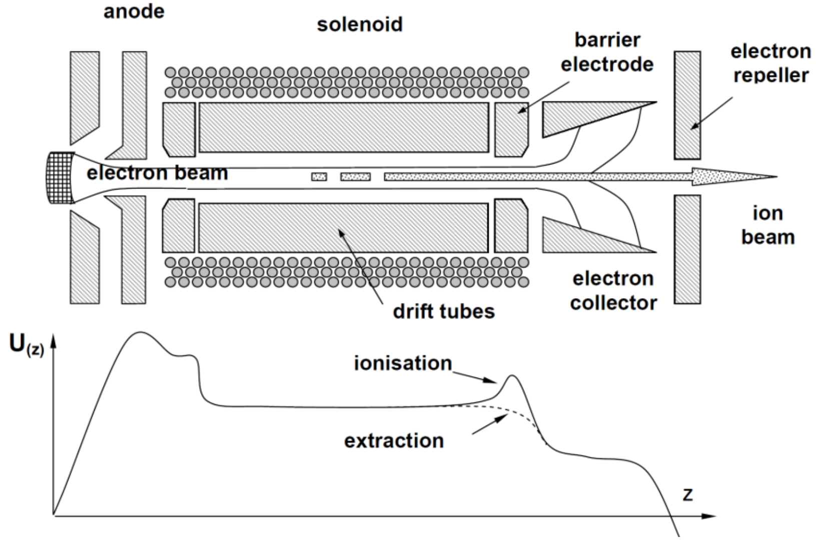
- Beam extraction
  - Extraction electrodes
  - Low energy beam transport (LEBT)
    → matching beam into accelerator

- Special case: negative ions!
  - Several applications
    - Inject into circulating bunch (DESY III)
    - Neutral beam into fusion plasma
  - Ions attach e^- in plasma
  - Opposite extraction polarity → separate electrons

Image Credit: O. Kester



Volume ion source



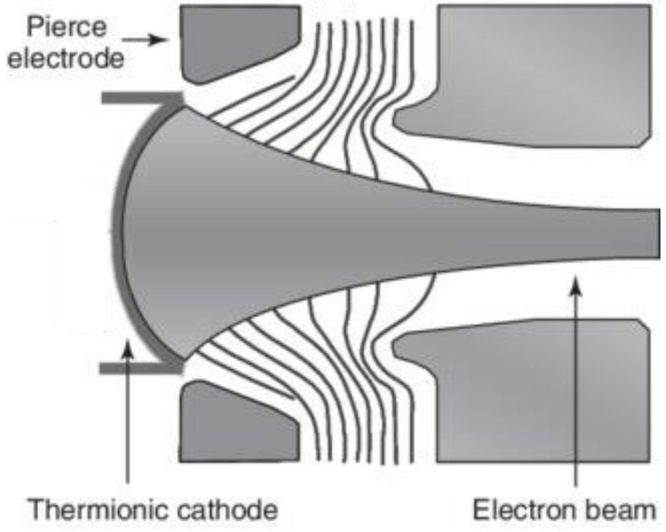
Electron beam ion source (EBIS)

Particle sources

Electron sources

- Free electrons ~ not available
  - Ions & electrons form stable atoms

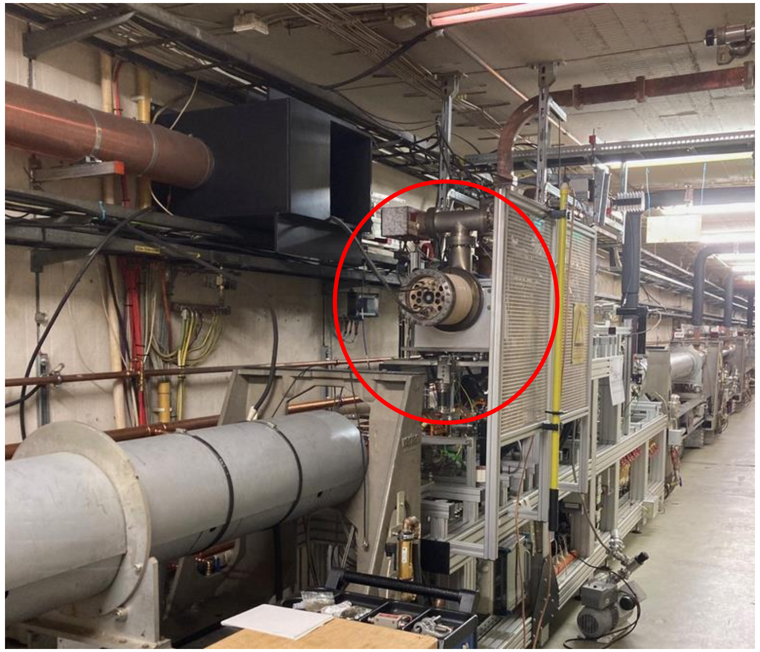
→ Mechanism to set electrons free?!
  - (Collisional ionisation)
  - (Field ionisation)
  - Thermal ionisation
  - Photoionisation



Richardson's law: $J = AT^2 e^{-\frac{W_e}{k_B T}}$

- Thermionic guns
  - Workhorse in most synchrotron light sources
  - Emission ~ T > 1000 K

- Source requirements/parameters
  - Bunch charge
  - Bunch length
  - Beam quality (i.e., particle density/uniformity)
  - Longevity!



LINAC II electron gun

Particle sources

Electron sources – photoelectron guns

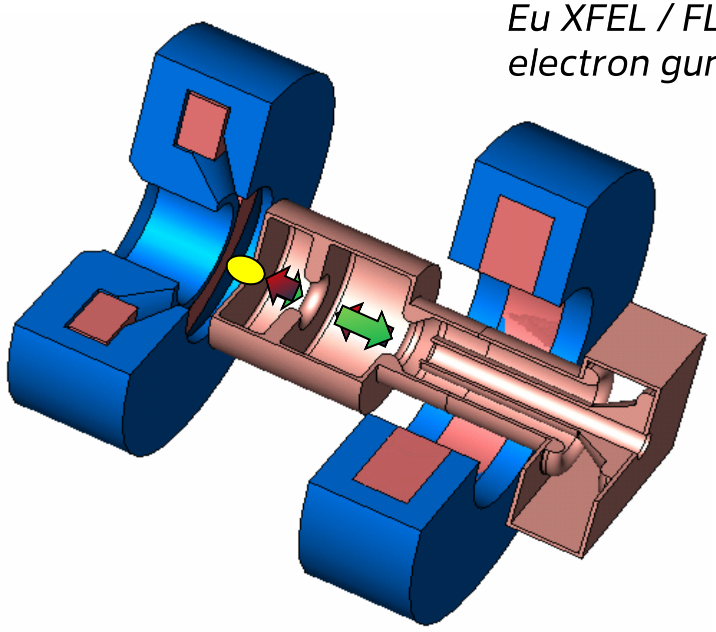
- Electrons for “precision“ applications
  - High electron density → good beam quality
  - Wide charge range
  - Short bunches possible (~ps – ns)
  - Spin polarised beams possible

  → Free-electron lasers, linear colliders, …

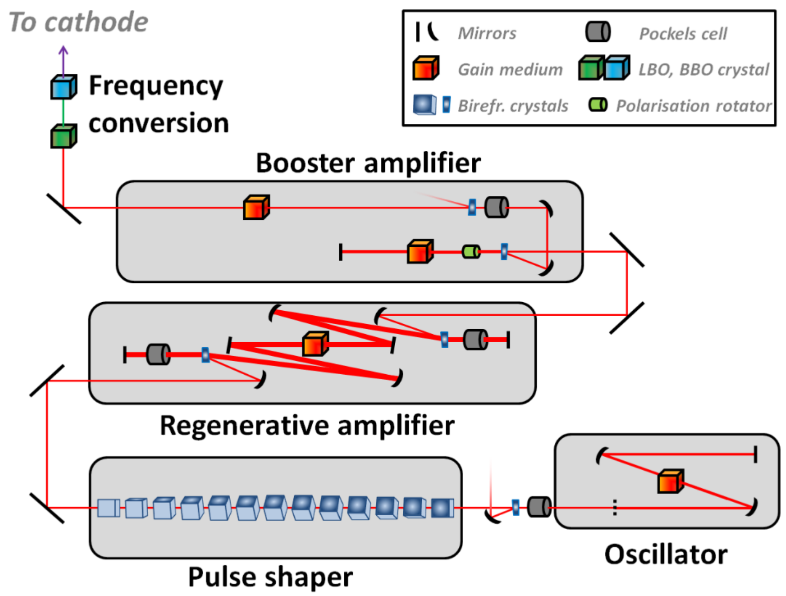
- Photocathode in accelerating field
  - Direct acceleration
  - Reduce space charge effects quickly

- Physics/engineering challenges
  - Source material properties/production
  - Laser physics/engineering
  - Integration into vacuum/acceleration structure

    → Mechanical design, EM field dynamics



Eu XFEL / FLASH electron gun

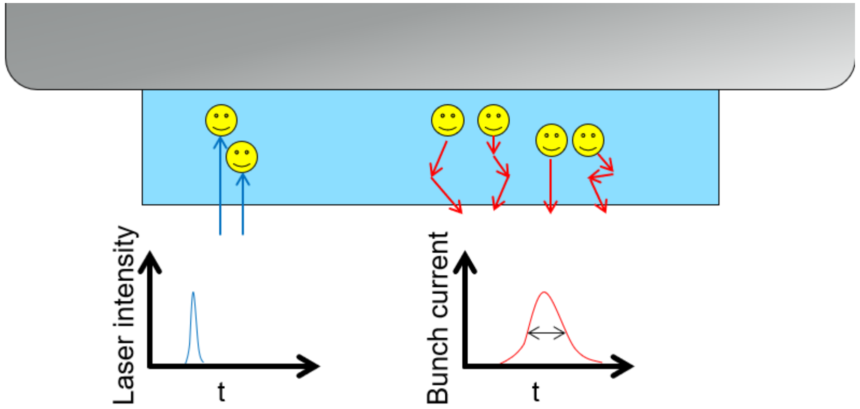


PITZ photoinjector laser system

Particle sources

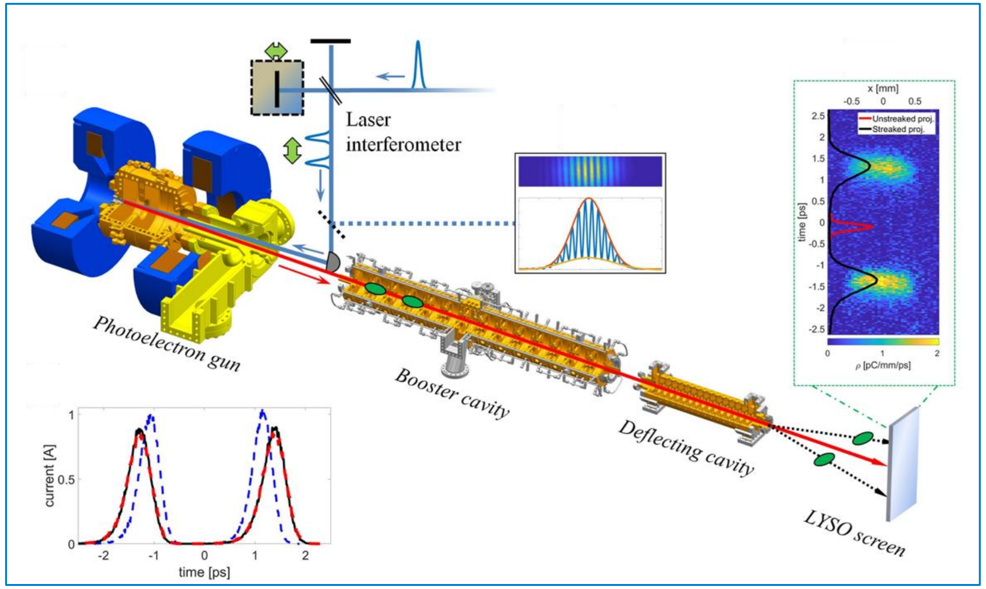
Photoelectron guns – measuring minimum possible bunch length

- Electrons ionised by UV photon on photocathode
- Immediate acceleration by E-field
- BUT: bunch length ~fs – ps!
  → every path difference changes extraction timing

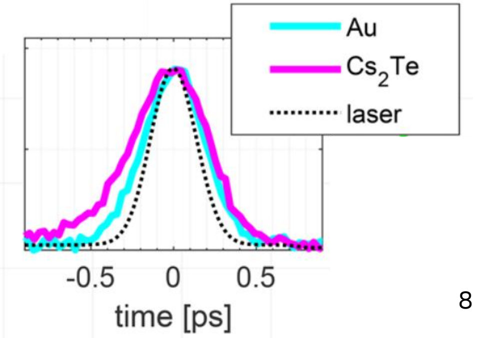


- Variation of extraction timing = minimum bunch length

- How to measure this:
  - Measure length of laser pulse
  - Produce 2 bunches with known delay
  - Measure beam time profile
    → distance gives reference for time basis
    → compare bunch shape w/ laser pulse shape



- Result for FLASH/European XFEL: ~180fs in Cs_2Te cathode



G. Loisch *et al.*, Appl. Phys. Lett. **120**, 104102 (2022)

Particle sources

Secondary particle sources – Positrons

- Free positrons ~ not available
  - No stable positrons around

→ Mechanism to create free positrons????!!!!

  - Pair production!

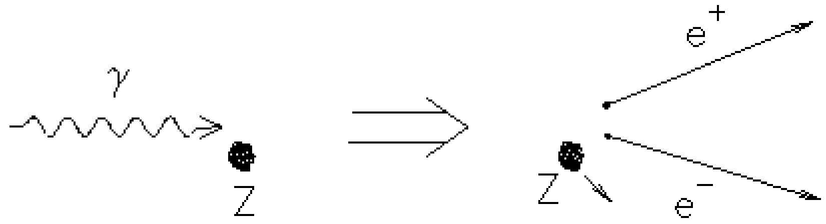
- How to produce pairs (in large numbers)
  - Need gamma photon & nearby heavy particle

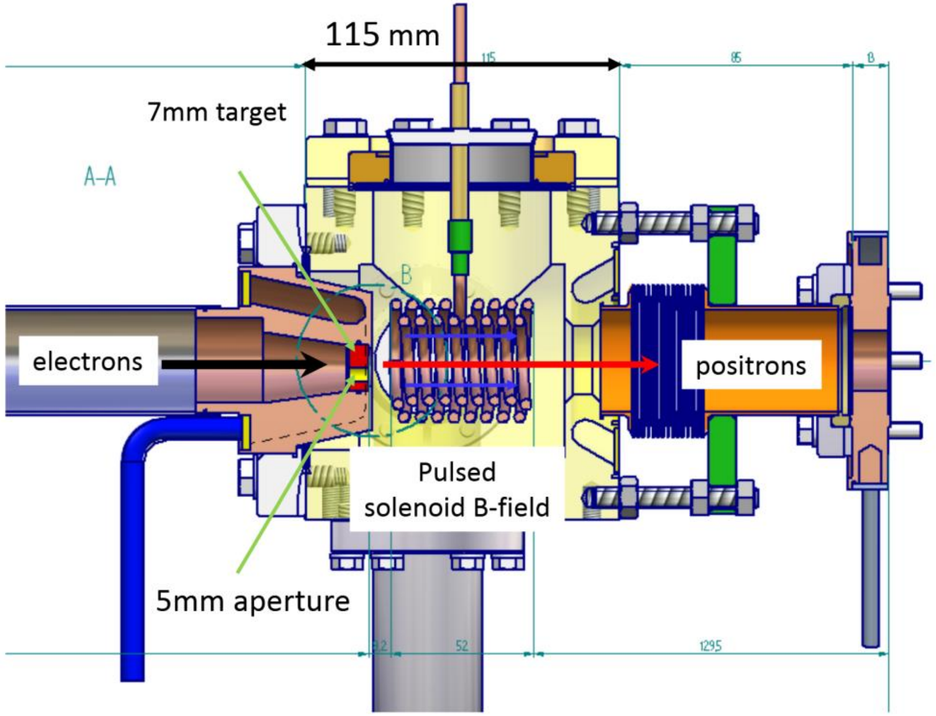
    (e.g. atomic nucleus; → momentum & energy conservation)

  - Particle beam stopping in heavy metal
    - Bremsstrahlung gamma photons
    - Pair production in same target

  - Gamma photons into metal
    - Produce gamma photons separately
    - Shoot photons onto metal target

Image Credit: Wikipedia





DESY's LINAC II positron source (retired)

Accelerating structures

DC acceleration

- First accelerators used DC voltage
  - Most basic setup
  - Only high voltage that was available
  - Allows DC beam
- Different ways to produce high voltage
  - Van-de-Graaf generator
  - Cockcroft-Walton voltage cascade
- Basic issue: electrical breakdown!
  - DC voltage > MV hard to insulate
- Extension of DC accelerators: Tandem acc.
  - Change charge of particles at high voltage potential → accelerate to ground by same amount!
  - Additional feat: source & experiment on ground…

Cockcroft-Walton cascade generator

1928

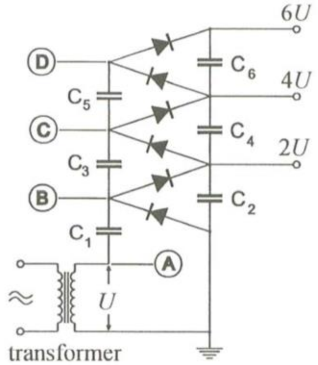
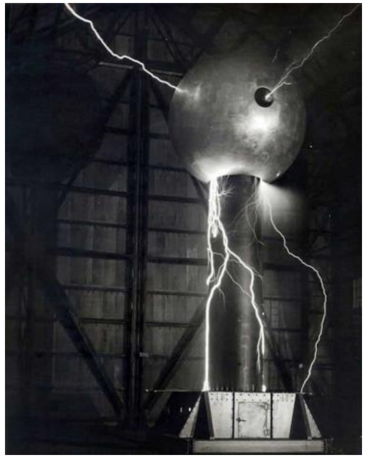


Image Credit: K. Wille

Van de Graaff accelerator

1930



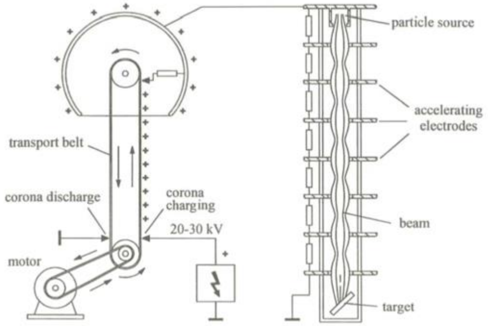
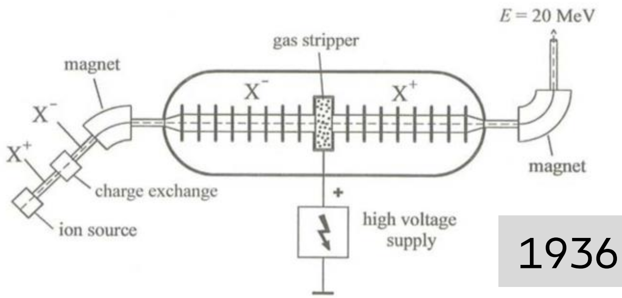


Image Credit: K. Wille

Tandem Van de Graaff accelerator



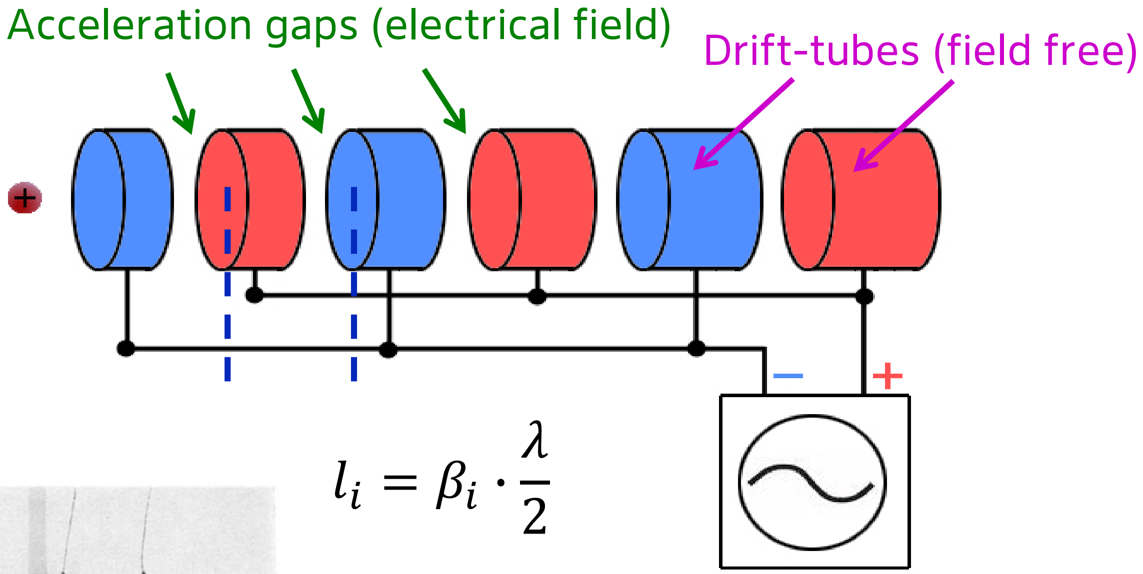
1936

Image Credit: K. Wille

Accelerating structures

AC / Radiofrequency (RF) acceleration

- Proposed by Gustaf Ising & first realised by Rolf Widerøe (1928)
  - Use several tube electrodes & connect to AC voltage → deceleration shielded; acceleration in every gap
  - Basic principle still used today
- Main issues:
  - Tube length too large at high velocity
  - electrodes = antenna at > ~10 MHz
- Solution?
  - Resonant cavities → no RF radiation
  - Tank = resonant circuit
  - Frequencies ~10 MHz – ~20 GHz
- Prinicpal distinction:
  - Low-β (v<<c ; ions at low energy)
  - High-β (v~c ; e⁻ & ions at high energy)



$$l_i = \beta_i \cdot \frac{\lambda}{2}$$

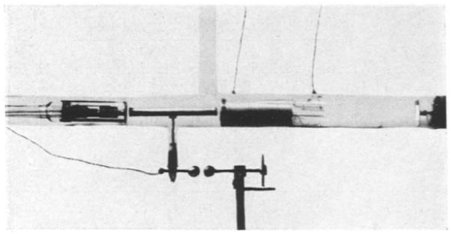


Bild 6. Die Versuchsröhre.

Image Credit: R. Widerøe, *Archiv fuer Elektrotechnik*, **28**, 387-406 (1928)

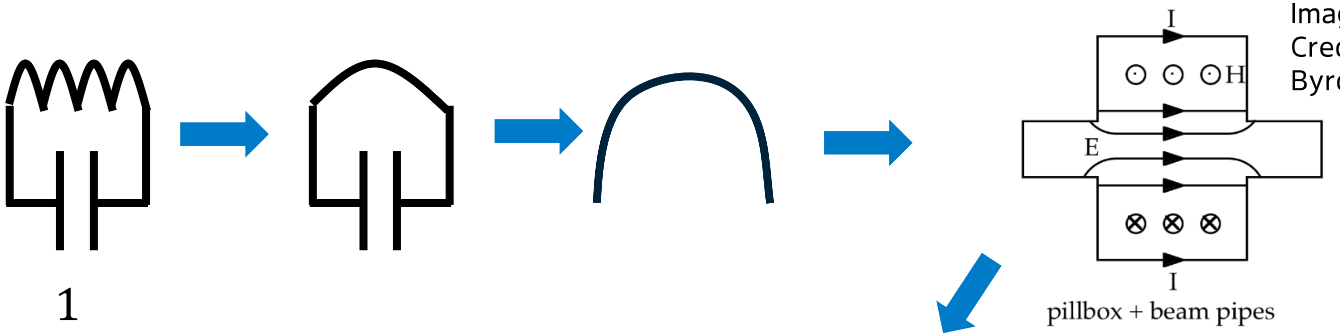
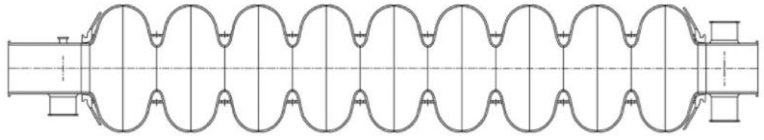


Image Credit: J. Byrd

$$f = \frac{1}{\sqrt{LC}}$$

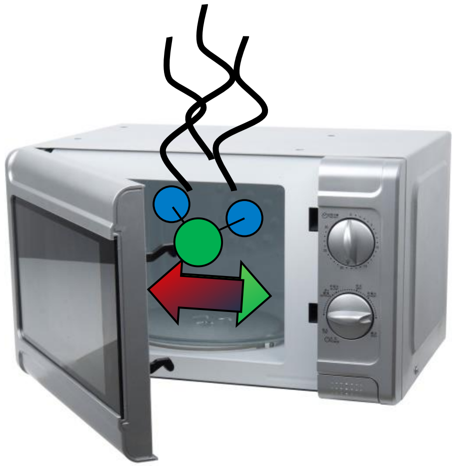


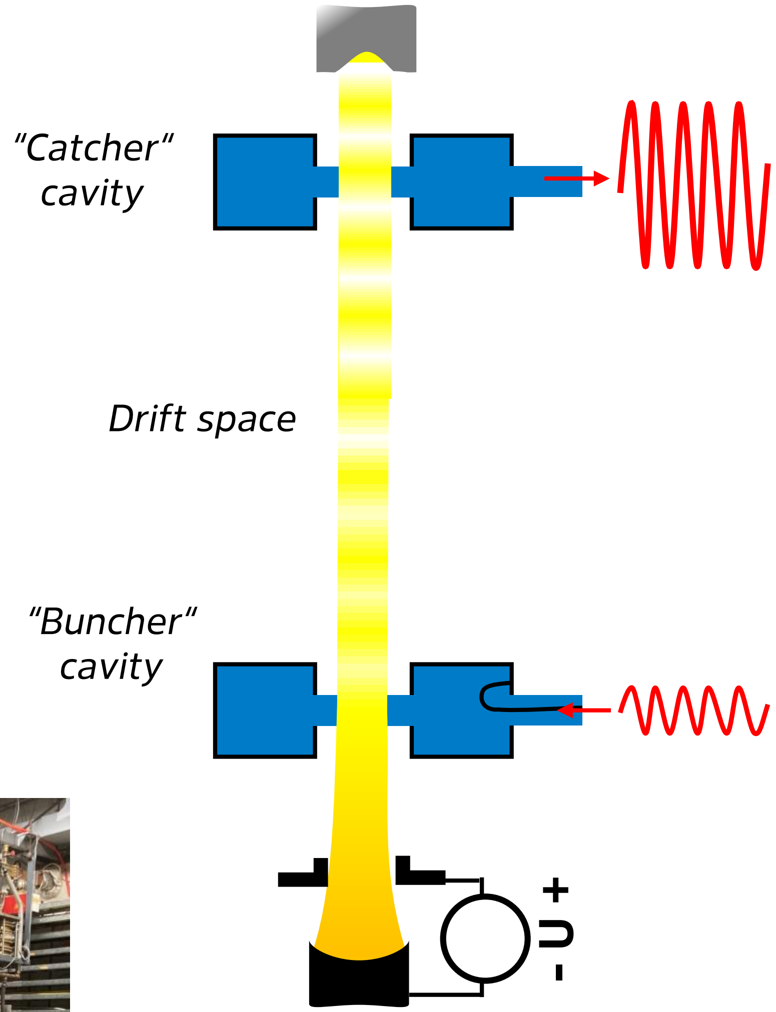
1.3 GHz superconducting TESLA cavity

Accelerating structures

Radiofrequency (RF) sources

- Need source for high power RF!
- First device: magnetron
  - Still in use today (industry, microwave ovens!)
  - Issue: RF created in device → no synchronisation
- Need RF amplifier (small signal distribution & amplification for accelerating structures)
- Continuous wave (CW) amplifiers (ring accelerators!)
  - Tube amplifiers (similar to old radios, just bigger…)
  - Solid state amplifiers
- BUT: Higher RF power → more acceleration > 100's kW → need pulsed operation
- Pulsed RF amplifier
  - "Klystron" → developed in WW2 for radar
  - Converts ~DC voltage into RF
  - Klystron powered by high voltage modulator
  - < ~150MW pulsed RF power



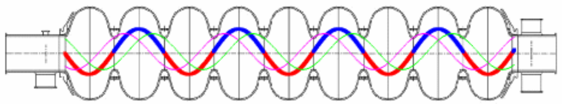


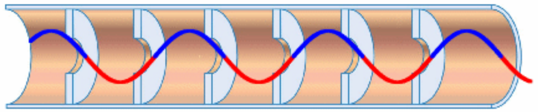
Klystron schematic

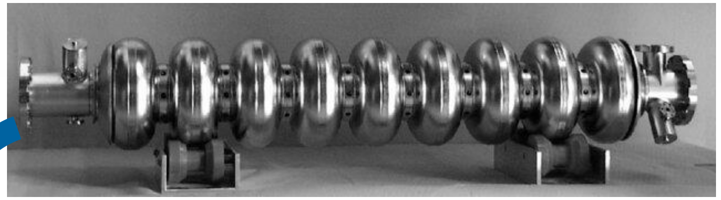
LINAC II RF station

Accelerating structures

AC / Radiofrequency (RF) acceleration







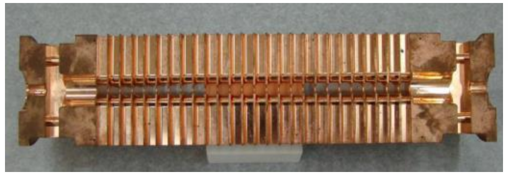
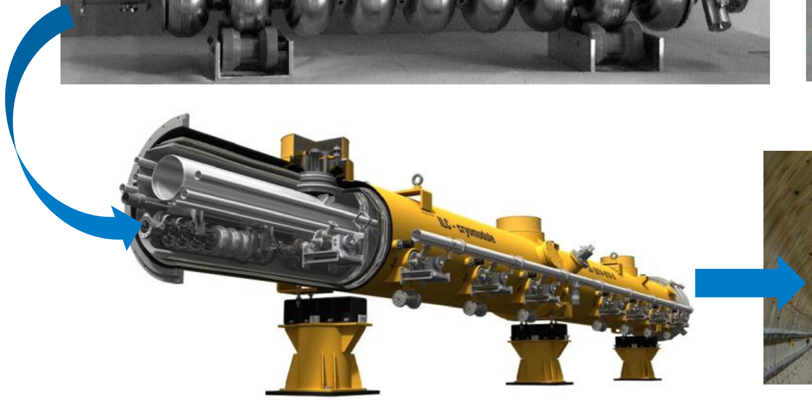


Image Credit: W. Wuensch, CERN



- High-β~no change of velocity → periodic structures
- Two types of structure
  - Standing wave
  - Traveling wave

- Number of bunches per second?
  - Many → long RF pulse → standing wave
  - Few → short RF pulse → ~traveling wave

- Acceleration: RF power transfer to beam
  - Efficiency depends on structure & beam
  - Rest: heat dissipation in structure
    → "Quality factor" = oscillations before 1/e damping

- Material choice
  - Normal conducting (~Cu): $T_{RF} << 1\%$
  - Superconducting (~Nb): $T_{RF} \geq \sim 1\%$

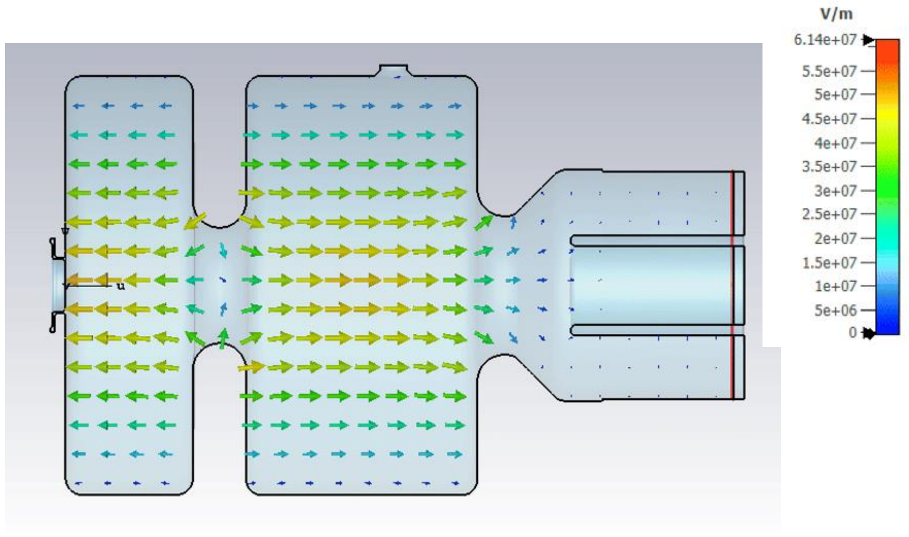
Accelerating structures

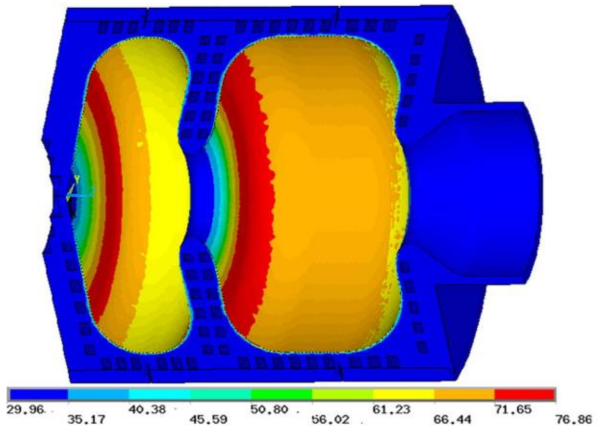
Current development: high repetition rate electron gun (for REGAE)

- REGAE: ultrafast electron microscope (bunch length ~ fs)
- Data taking speed ~ bunches/second
  → more RF pulses per second → faster data (today: ≤ 50 Hz)

- Current development: electron gun for 1000 Hz
- Challenges:
  - Heating!
    → RF pulses as short as possible
    → minimum pulse length ~ "resonance" quality of cavity
    → trade-off: resonance (i.e. acceleration/power) vs. filling time

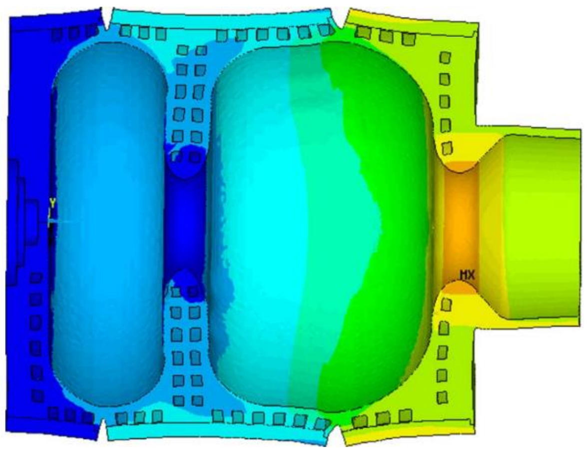
- Typical simulation codes: CST, Comsol, Ansys
- Iterations between:
  - EM simulation
  - Beam dynamics
  - Thermo-mechanical sim.





Heating in a gun cavity

Image Credit: Ilker Ilgün & Valentin Paramonov



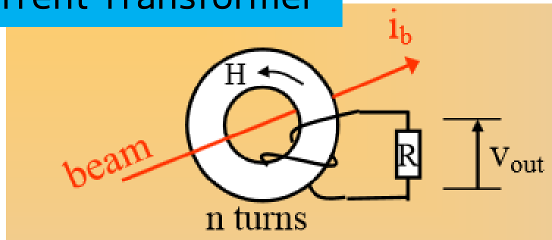
Mechanical stress in a gun cavity

Diagnostics

How to “see” your beam; some basic concepts…

- Particles are not “visible”
- What do we need to know?
  - How many particles are there? → bunch charge
    - *Faraday-Cup* (destructive)
    - *Current transformer / mirror current monitor* (non-destructive)
  - Where are they? → bunch position
    - *Scintillator screen* (destructive)
    - *Beam position monitor* (non-destructive)
  - How big is the bunch? → transverse size
    - *Scintillator screen*
    - *Wire scanner (…)*
  - How long is the bunch? → longitudinal size
    - *Measure current signal (~>ns)*
    - *Complex…. (TDS, CSR, …)*
  - How is the bunch quality? → size & divergence
    - *Measure size & size after drift…*

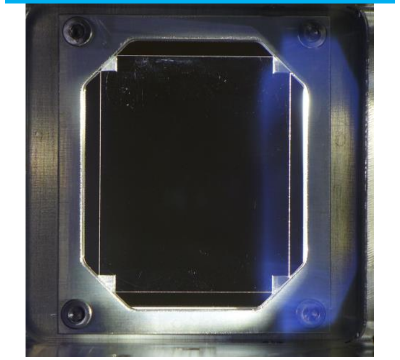
Current Transformer



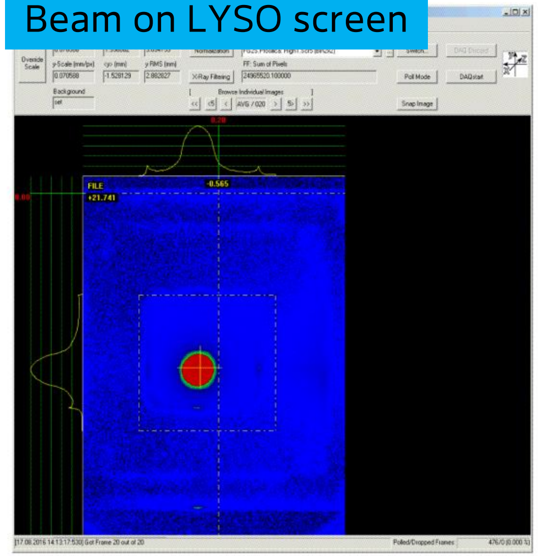
Faraday Cup

YAG scintillator coated on Al

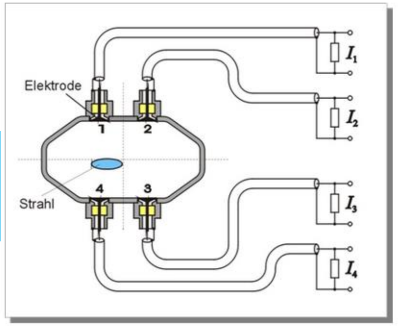
LYSO scintillator



Beam on LYSO screen



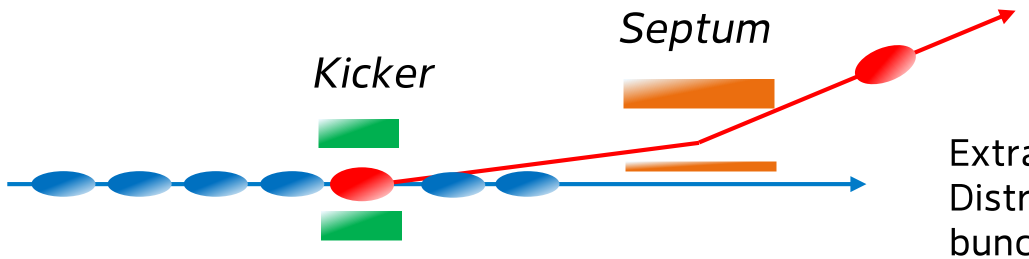
Beam Position Monitor (BPM)



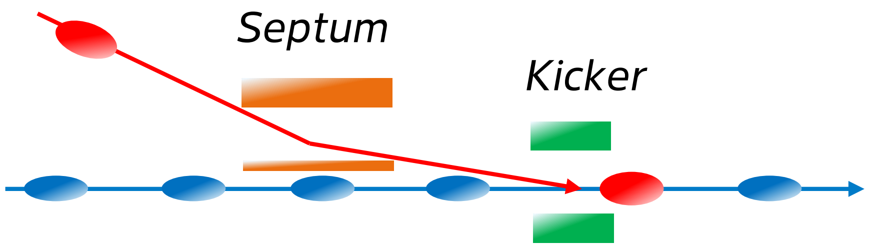
Pulsed magnets

"Kick" bunches into the right direction

- Why a pulsed magnet?
  - Train of bunches → multiple experiments
  - Ring full of bunches → get additional bunch in
- Two types of pulsed magnets
  - "Kicker": one beam pipe, FAST pulses (<ns – >µs)
    → fast/small kick
  - "Septum": two beam pipes VERY close, slower pulse (> µs)
    → beams as close/parallel as possible
- Typical challenges/tasks:
  - High voltage electronics (kV, kA → MW! , ns-µs)
  - EM field simulations (eddy currents, parasitic inductance/capacitance, …)
  - Material science (EM material properties in MHz – GHz)

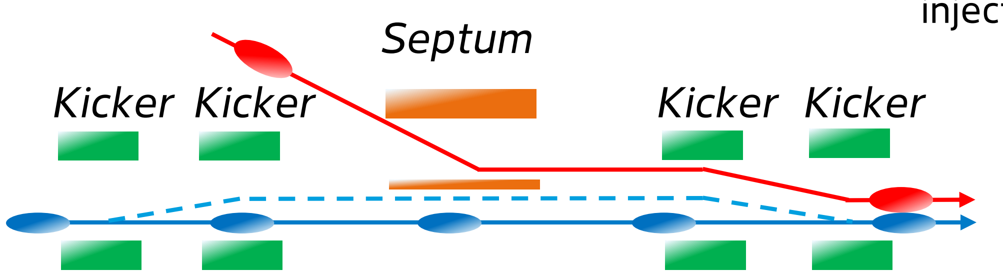


Extraction/ Distribution of bunches



"On-axis" injection into ring

"Off-axis" injection into ring



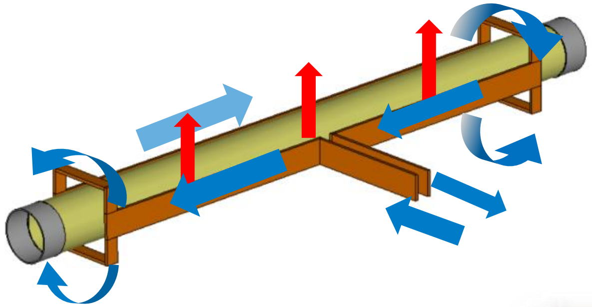
Pulsed magnets

"Kick" bunches into the right direction

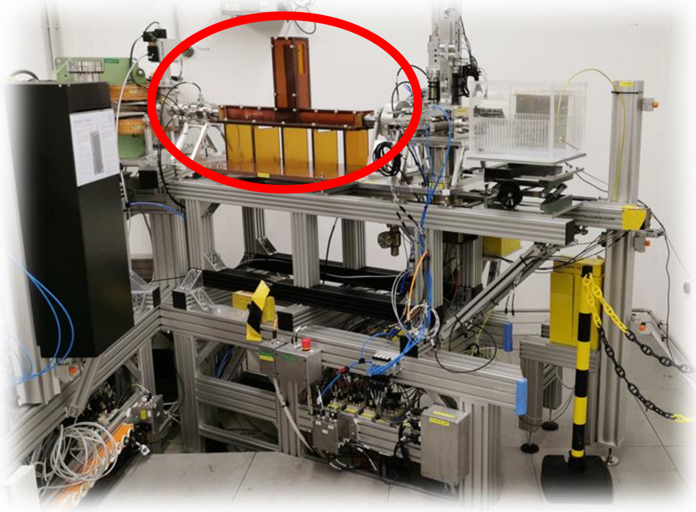
- Various types of kickers
  - Single/few loop magnet
  - "Transmission line kicker"
    → coil with capacitances → compensate inductivity
  - Stripline kicker
    → 2 beam-parallel electrodes → E & B fields → ~coaxial cable

- Septum magnets
  - Electrostatic (ions)
  - DC "Lambertson"
  - <u>Eddy current shielded</u>

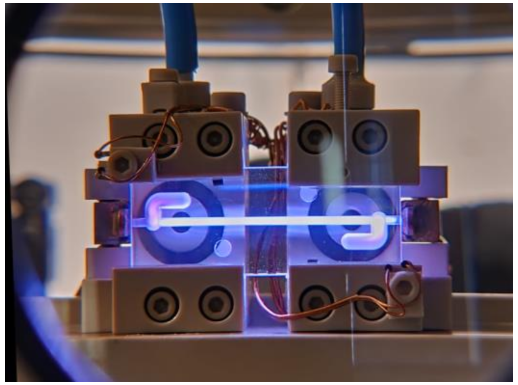
- New pulsed HV components: Plasma cells!
  - New acceleration method: plasma wakefield acceleration
  - Sometimes plasma created by electrical discharge
    → pulsed high voltage like kickers

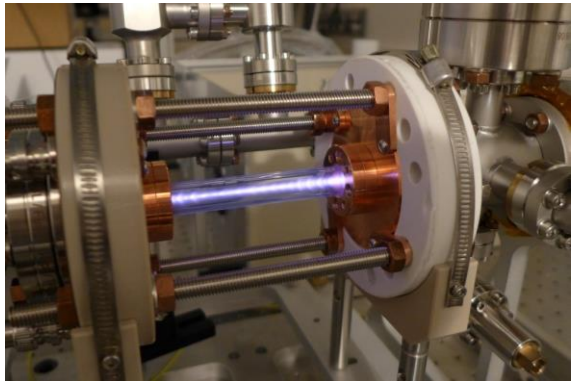


Single loop kicker



Discharge plasma cells





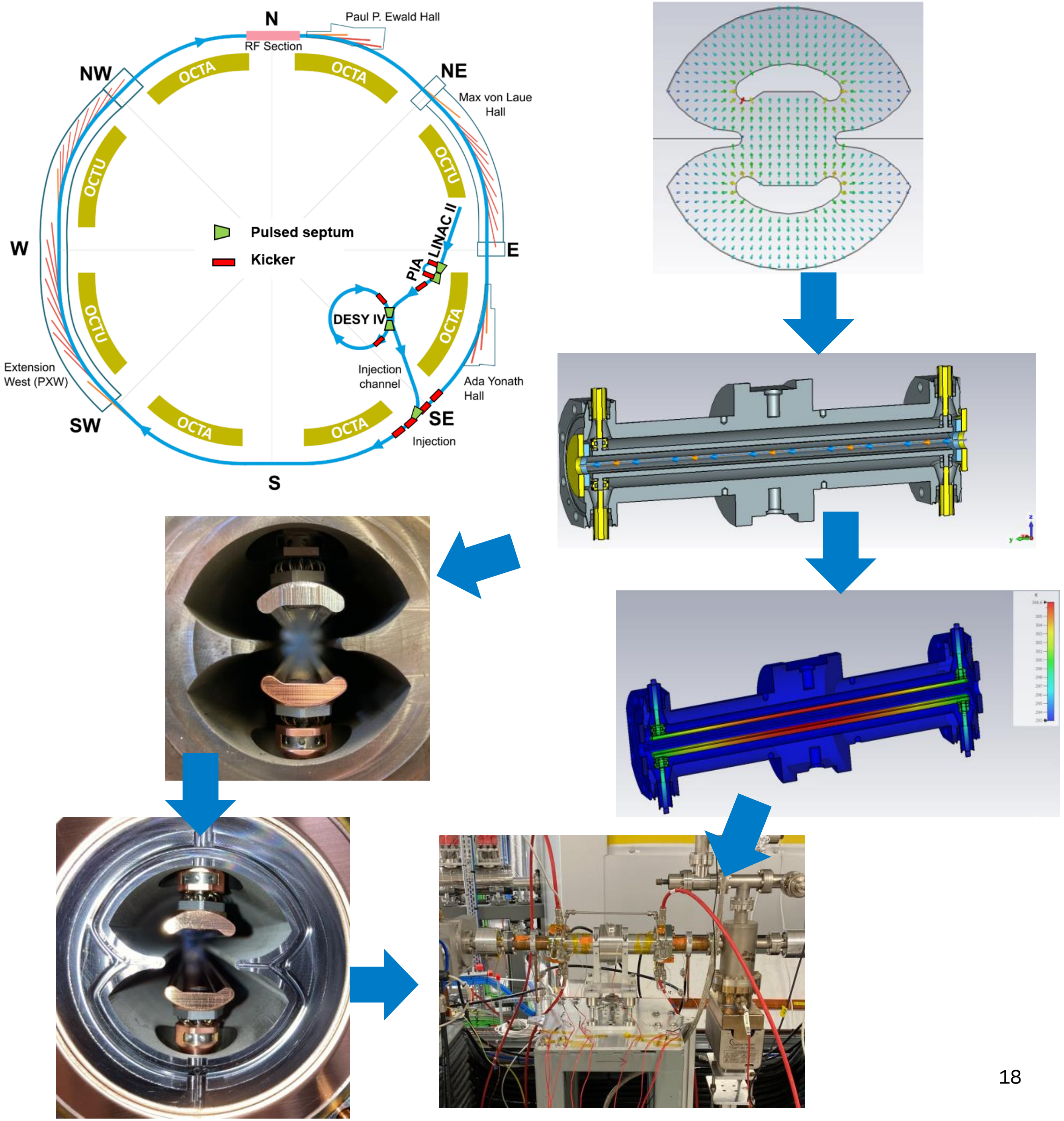
Pulsed magnets

PETRA IV storage ring injection devices

- PETRA IV: upcoming upgrade of PETRA lightsource
- 3 rings need injection (&extraction)
  - PIA (accumulator ring)
  - DESY (energy booster synchrotron)
  - PETRA (synchrotron radiation storage ring)

- Very demanding PETRA injection kickers
  - Kick only 1 bunch on injection
    → kicker pulse length ~4ns
  - Kick voltage ~15kV
  - Additional challenge: beam mirror currents heat kicker

- Extensive development & prototype programme
  - Simulations (EM, thermal & mechanical)
  - Prototype manufacturing
  - Testing at MAX IV accelerator (Lund, SE)



Pulsed magnets

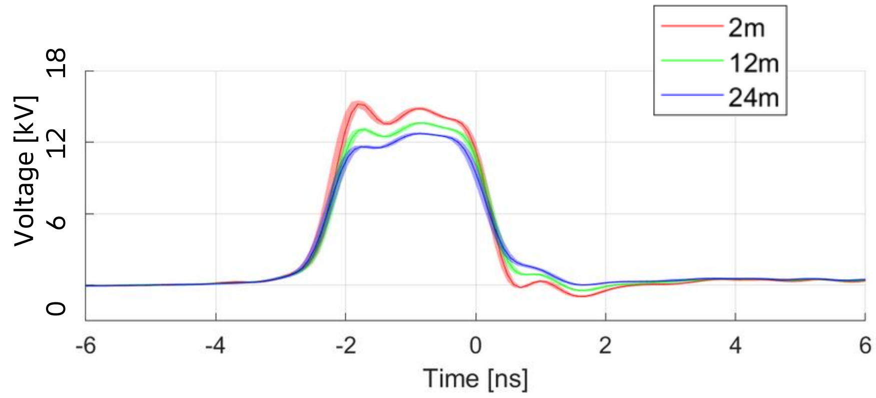
PETRA IV storage ring injection devices

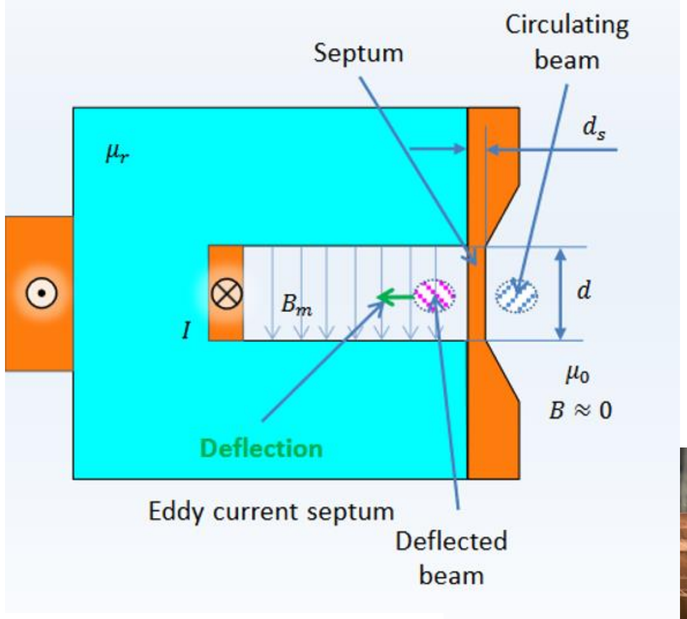
- High voltage pulse electronics
  - < ns rise time, < 15 kV VERY challenging
  - HV switch rise times > ~ns
    → special diodes (difficult ~ export controlled)

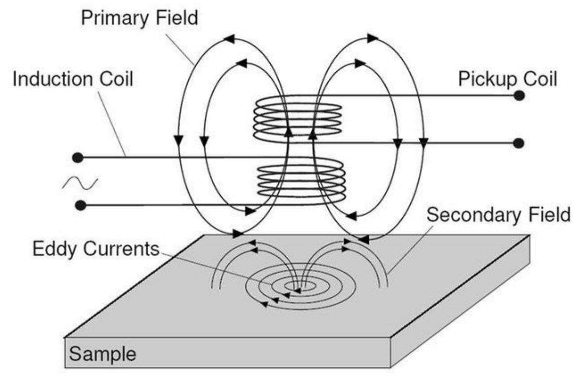
- Thin eddy current septum
  - Septum shield 1mm thick
  - Low leakage field (disturbance of circulating beam)
  - Extensive material tests
    - Cu
    - μ-metal
    - …

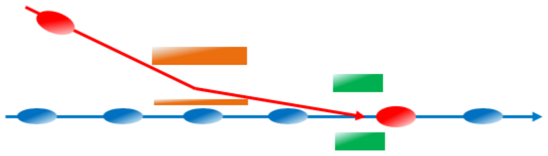
- Final task: series production!
  - ~20 kickers have to be manufactured
  - Requires some logistics & planning…

15kV ns-pulse, transmission cable length test









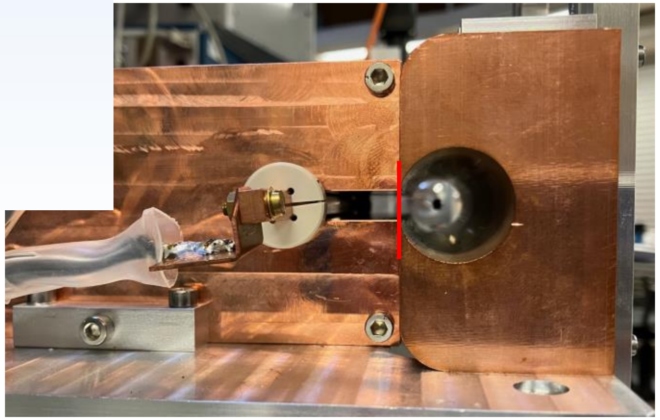


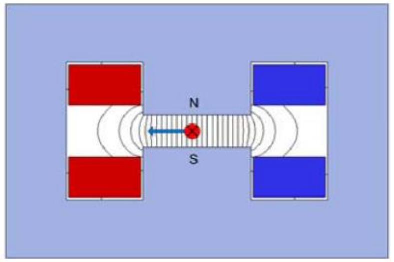
Image Credit: CERN Acc. School Magnets Proc. CERN-2010-004

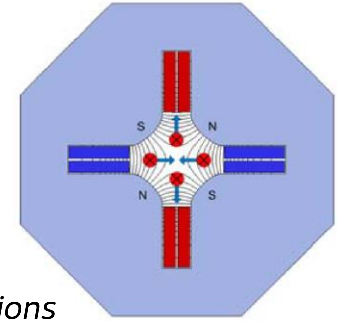
DC magnets

Static & slowly ramped magnets

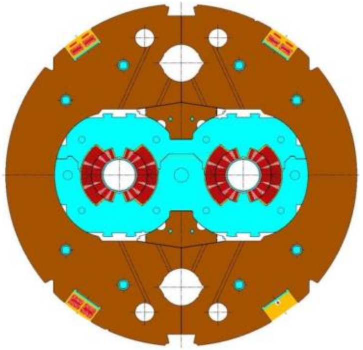
- Magnets for bending & focusing of beam
- Main component in ring
- Normal conducting (NC)
  - Current in wound conductor
  - Field guiding / shaping with ~iron "yoke"
  - Field ≤ ~2 T (~saturation of iron)
- Superconducting (SC)
  - Field >> 2 T
  - No yoke → no guiding → field ~conductor shape

- Typical tasks/challenges
  - Magnetic field simulation
  - Mechanical design (cooling, conductor bending, yoke manufacturing,..)
  - Material science (superconductors, magnetic materials, ..)
  - Cryogenics

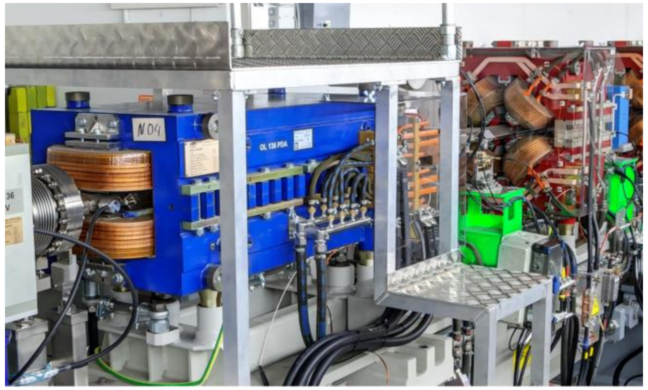




NC Dipole/Quadrupole cross-sections

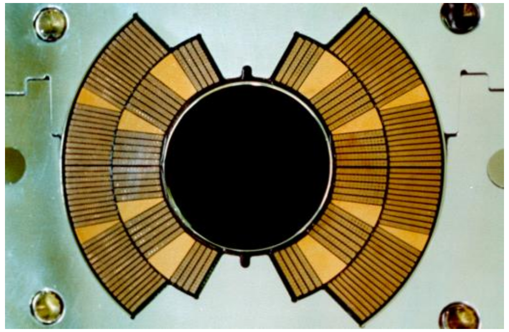


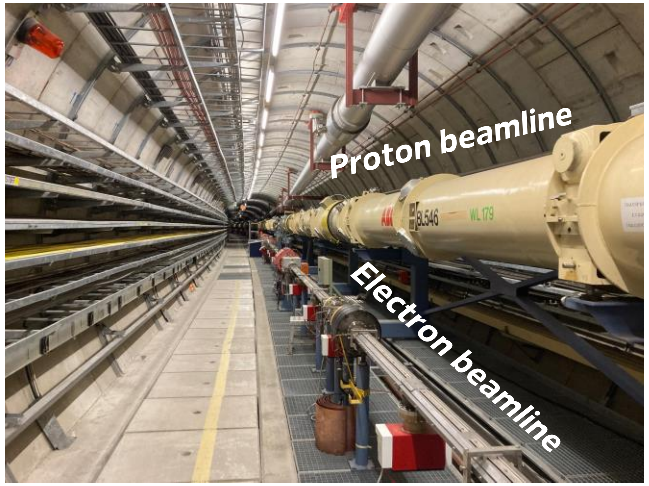
SC LHC dipole cross-section



NC PETRA III magnets

Rutherford cable





HERA tunnel at DESY

Summary

… & final remarks

- Physical/Technical components make accelerators!
- ~every (scientific) accelerator is unique
  → custom-made components
- Ever higher demands → lots of RnD!

- Accelerator technology is
  - Interesting,
  - Inter-disciplinary,
  - Never(!?)-ending,
  - Teamwork,
  - Fun!

- Questions/comments/… : Now or contact us any time!

Thank you very much!

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Further reading:

Handbook of Accelerator Physics and Engineering
Editors: A. W. Chao, K. H. Mess, M. Tigner
ISBN: 978-9-814-41584-2

RF Linear Accelerators
Author: T. P. Wangler
ISBN: 978-3-527-40680-7

CERN Accelerator School – Ion Sources - Proceedings
Senec (Slovakia), 2012;
Editor: R.Bailey
CERN-2013-007

CERN Accelerator School – Magnets - Proceedings
Bruges (Belgium), 2010;
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CERN-2010-004

SLAC: Fabricating the Linear Accelerator
Youtube
SLAC National Accelerator Laboratory
https://www.youtube.com/watch?v=oMgMNlgkqIY&ab