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Particle Accelerators: Subsystems

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Subsystems

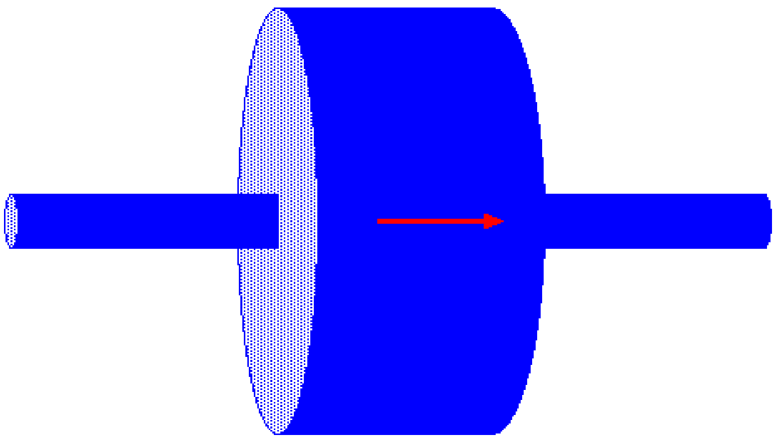
- RF system, acceleration, phase stability
- Magnets
- Vacuum
- Injection and extraction
- Collimation and beam-abort system
- Control system
- Machine- and personnel-protection

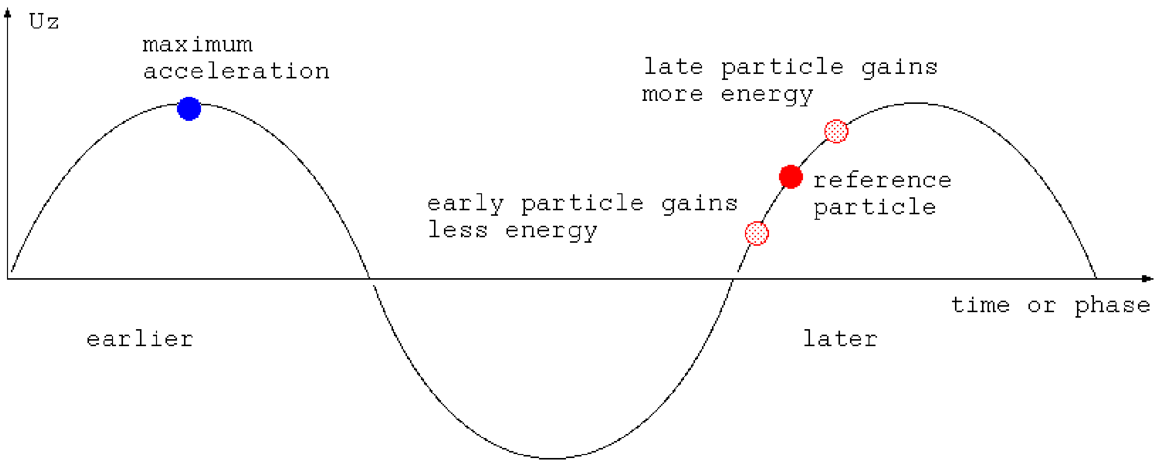
Circular accelerators: RF cavity

- Providess a rapidly oscillating longitudinal electric field

$$E_z(t) = \hat{E}_z \cos(2\pi f t)$$

- Accelerates particles that get there on time





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What happens in a cavity?

- Inside of cavity is empty → vacuum
- electromagnetic waves the travel at the speed of light
- but bounce off the walls
- and create interference patterns which are
- standing waves that have spatial patterns that depend on the wall geometry → Modes.
- Usually want modes with sinusoidally changing longitudinal electric field $E_z(t)$.

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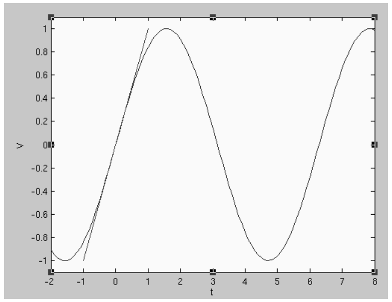
Phase Stability



- Higher energy particle “lies further out” and have a longer way to go (use *dt = ΔT*) $dt = \alpha\,\delta$
- Higher energy particles travel faster $dt = -1/\gamma^2\,\delta$
- Summary: $dt/dn = (\alpha - 1/\gamma^2)\,\delta$ (change of arrival time per turn)
- Energy change in accelerating RF-cavity: $$\frac{d\delta}{dn} = \pm\frac{\omega_{RF}V}{E}t$$

$$\frac{d^2\delta}{dn^2} = \pm\frac{\omega_{RF}V}{E}\frac{dt}{dn} = \pm\frac{\omega_{RF}V}{E}\left(\alpha - \frac{1}{\gamma^2}\right)\delta$$

- Stable Harmonic oscillator, if negative sign chosen → phase RF properly
- Synchrotron oscillations. What happens at transition, $\alpha = 1/\gamma^2$?

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Linac: Waveguides

- Maxwell's equation govern

$$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}\ , \qquad \vec{\nabla} \cdot \vec{B} = 0\ ,$$
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}\ , \qquad \vec{\nabla} \cdot \vec{D} = \rho$$

$$\vec{D} = \varepsilon\varepsilon_0 \vec{E} \quad \text{and} \quad \vec{B} = \mu\mu_0 \vec{H}$$

- Boundary conditions determine permissible solutions, usually called modes
- On perfectly conducting boundaries, the parallel electric field and the perpendicular magnetic fields are zero.

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Acceleration and RF-plumbing

- We need to feed energy to the particles, but
  - particles have a velocity < c
  - phase velocity of e&m waves is larger than c
- Need to slow down the waves
- The RF-power is transported to and alongside the beam by wave-guides
- To start with we will look at waveguides

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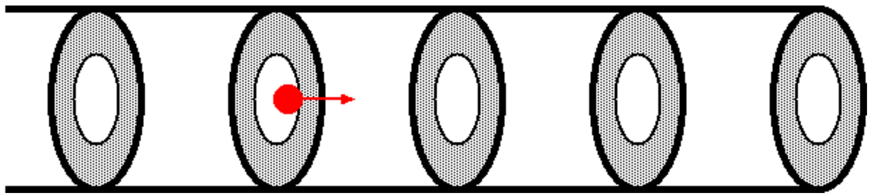
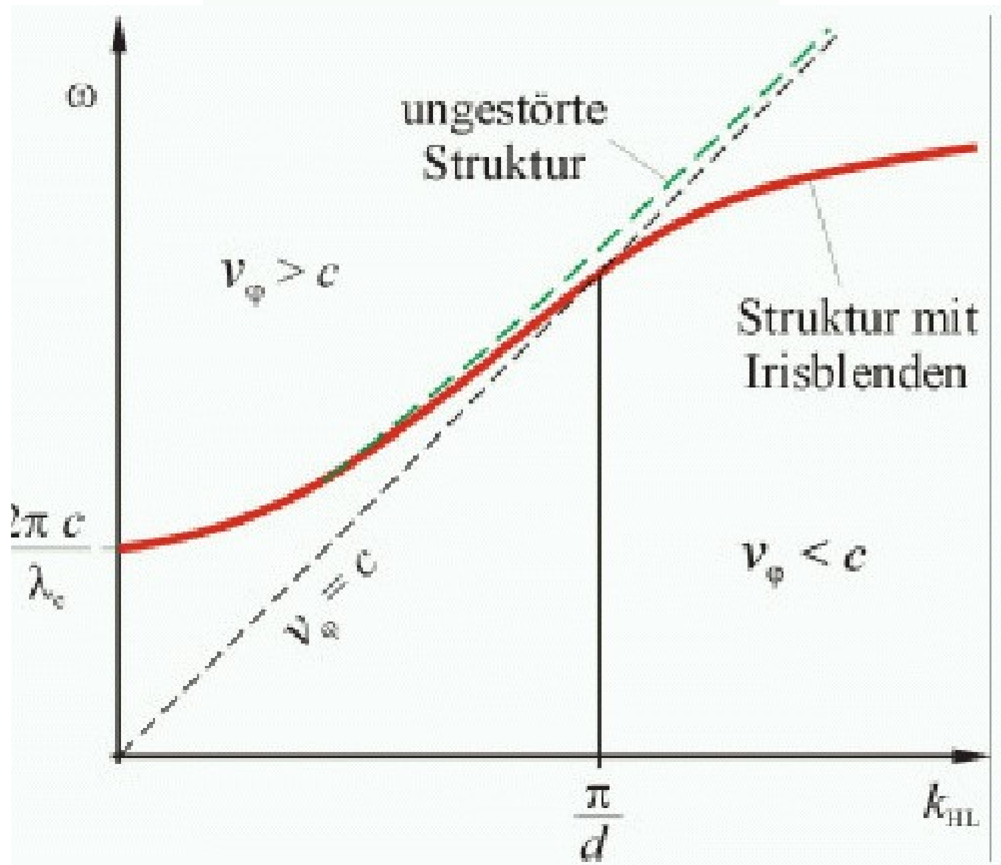
How to slow modes down



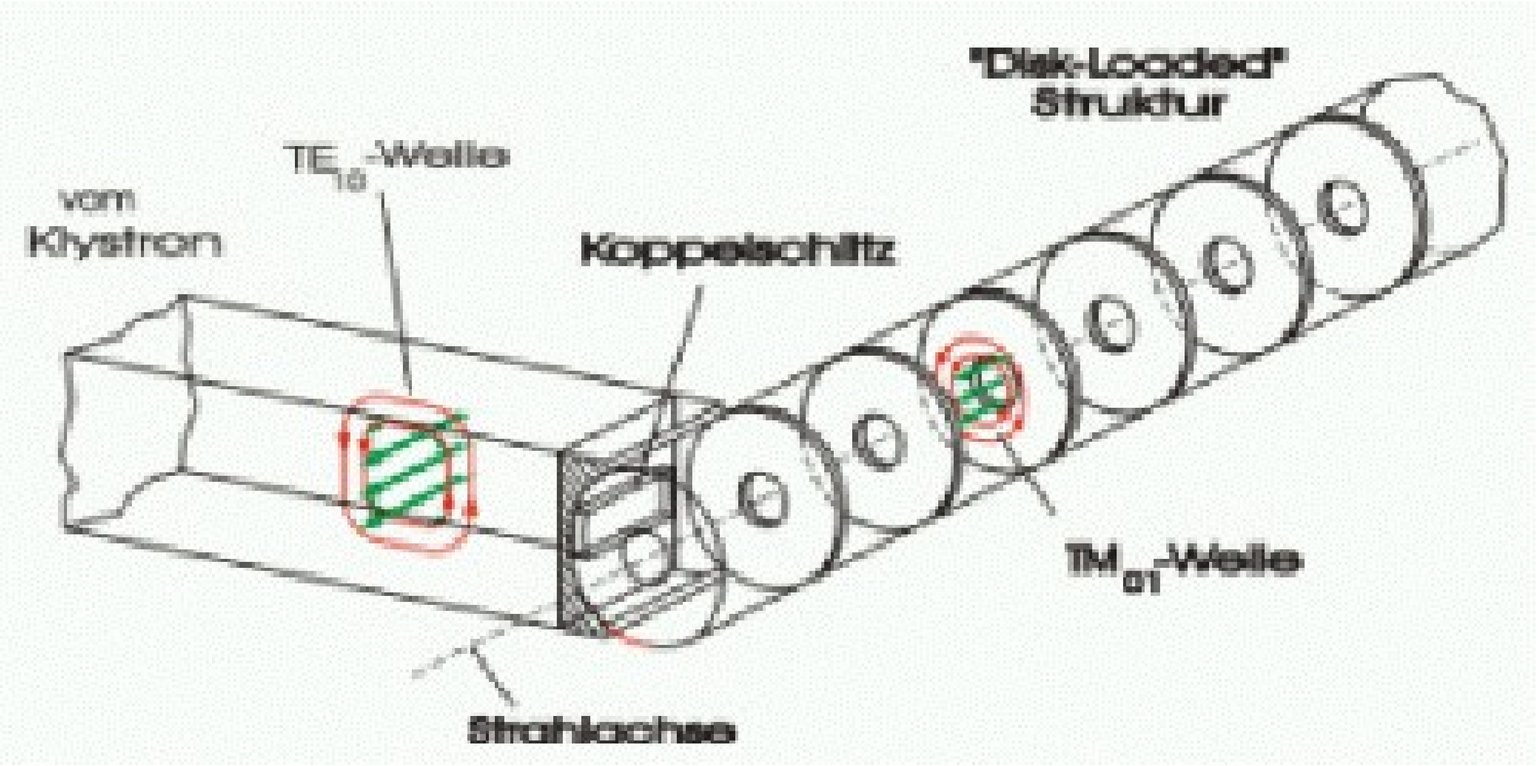
$$\omega = c\sqrt{\beta^2 + k_c^2}$$



from K. Wille's lecture slides

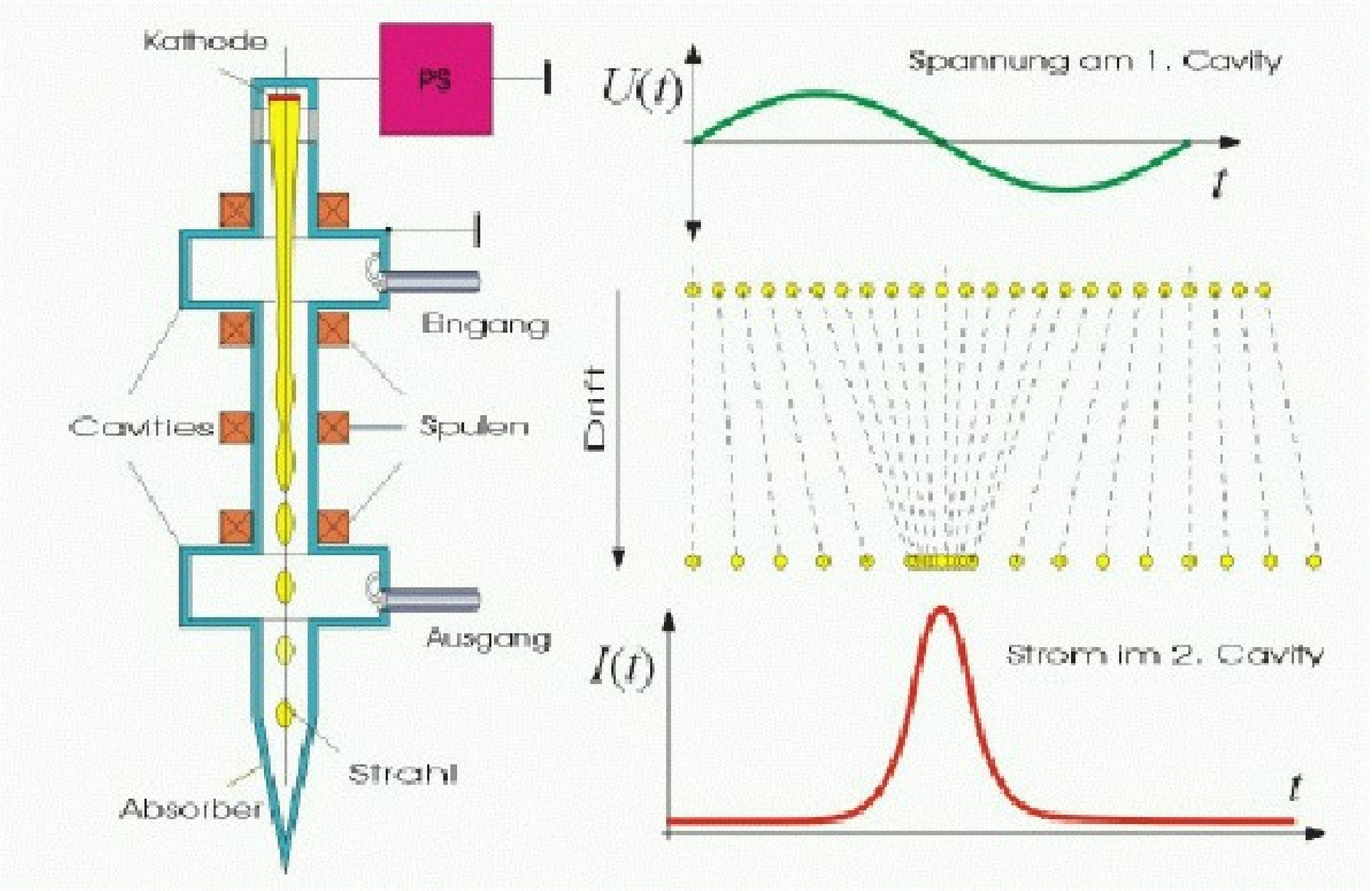
- Add washer disks
- Similar to what happens to quasi-free electrons in a periodic (crystal) lattice
- Intuitive picture: The disks behave like capacitors that need to be charged and discharged and that takes a little time.

Feeding power into structures



- from K. Wille's lecture notes

Klystrons



- Amplify low RF voltage to MW power levels

Super- vs normal-conducting RF

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- Oscillating E&M fields at high frequency penetrate into the wall (skin-depth)
  - and cause losses due to resistivity
- Not a problem if short pulses or low power
  - CLIC (short pulses, ns) or proton storage ring
    - → **normal conducting** RF structures
- Big problem if large RF power is needed
  - to compensate synchrotron losses (LEP)
  - make long (ms) pulses (ILC, XFEL)
    - → **super-conducting** RF structures

Magnets

- Dipoles, Quadrupoles and Multipoles
  - bending, focussing and correction of chromaticity and non-linear effects
- Iron dominated magnets define field through the pole geometry and 'pump fluxlines' into the iron with coils (or permanent magnets).
  - Limited in field because iron saturates below 2 T
- In super-conducting magnets the field is defined by the coil geometry
  - much higher fields can be reached (8.3 T *DC* in LHC)

Vacuum

- Accelerated particles interact with atoms of the residual gas (just like an internal target)
  - Energy loss by ionization
  - Transverse scattering by Rutherford scattering
- This affects the
  - Beam quality, e.g. emittances
  - Lifetime
  - Instabilies
- Better make sure there is low pressure in accelerators ($10^{-6} \rightarrow 10^{-11}$ torr ~ 1atm/10^{14})

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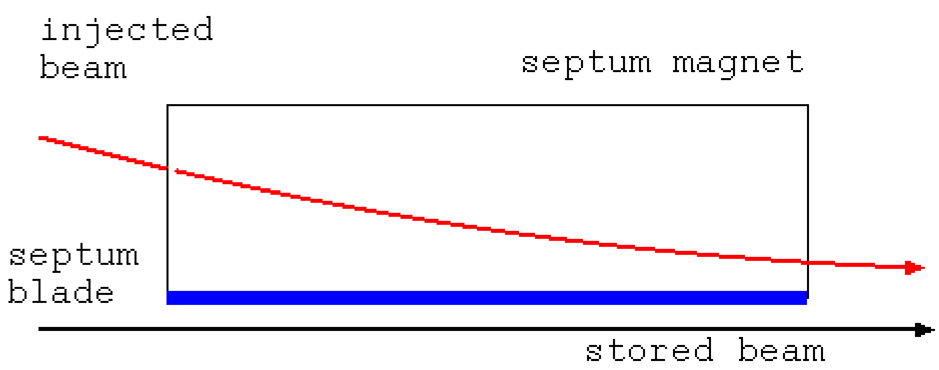
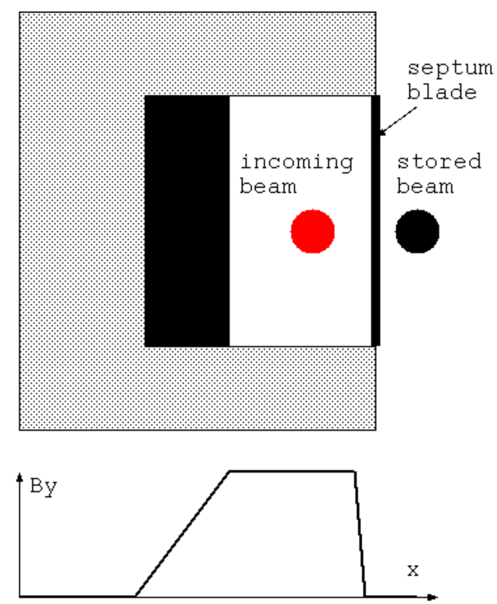
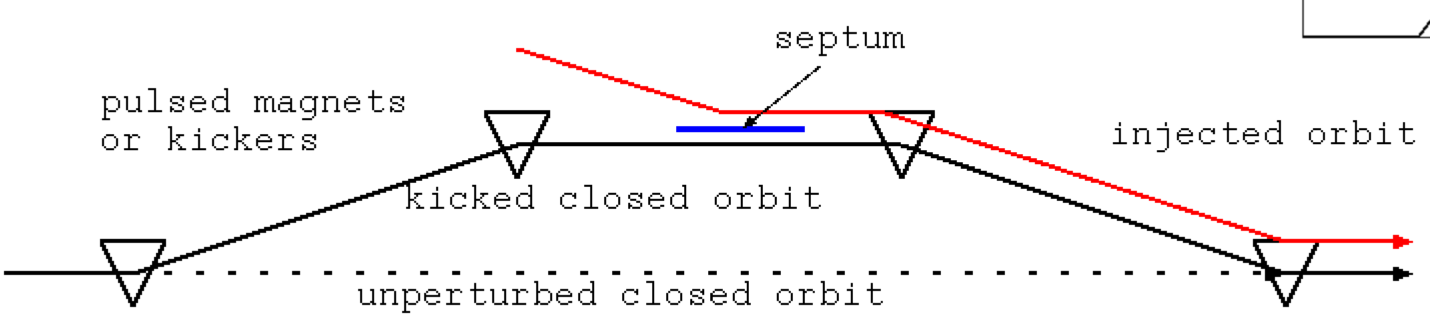
Injection and Extraction

- Constant fields cannot be used, because they kick the beam out again on the second turn







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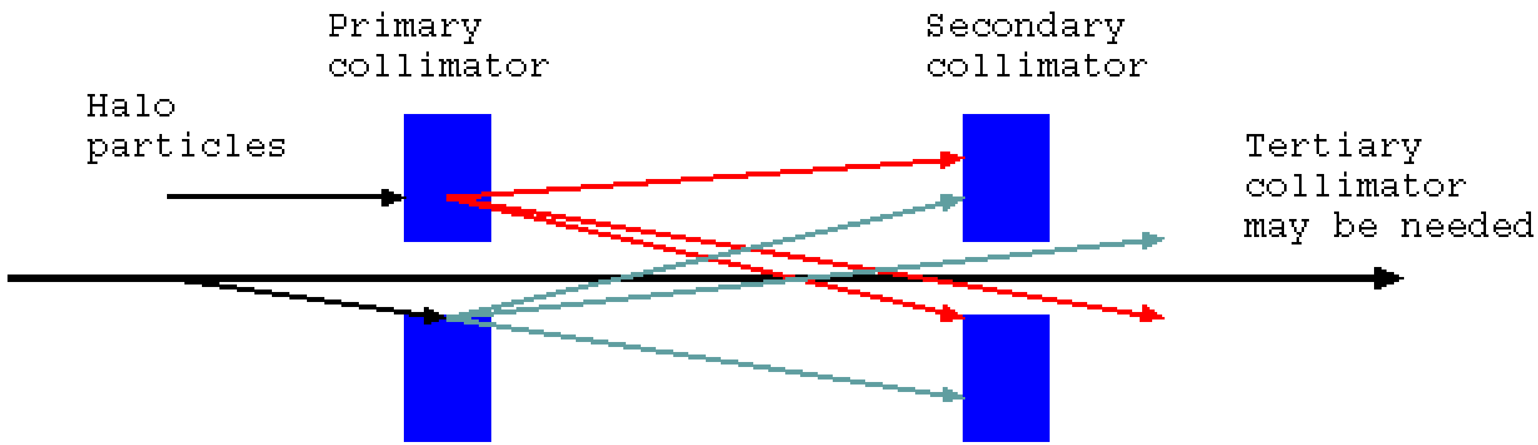
Collimation 1

- Beam particles diffuse to the tails
  - and reach the limit of stable motion
- They therefore might
  - create background for the experiments
  - damage sensitive equipment
  - might quench superconduction magnets
- better take the particles out in a controlled way
  - Collimation system
  - often two-stage to pick up scatters from first collimator.

Collimation 2



- Collimator jaws are moved close to the beam to intercept large amplitude particles
- Large beta-function for betatron cleaning
- Large dispersion and small beta-function for momentum cleaning

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Beam-abort system

- If the energy in the stored beam is large enough it might damage
  - the accelerator and the detector
- and needs to be directed to a beam dump in a controlled way
- Kicker magnets and septum magnet to extract
  - need gap in bunch train to ramp up kicker fields
- Beam dump to handle the entire beam energy
  - water or graphite, heavily shielded with concrete

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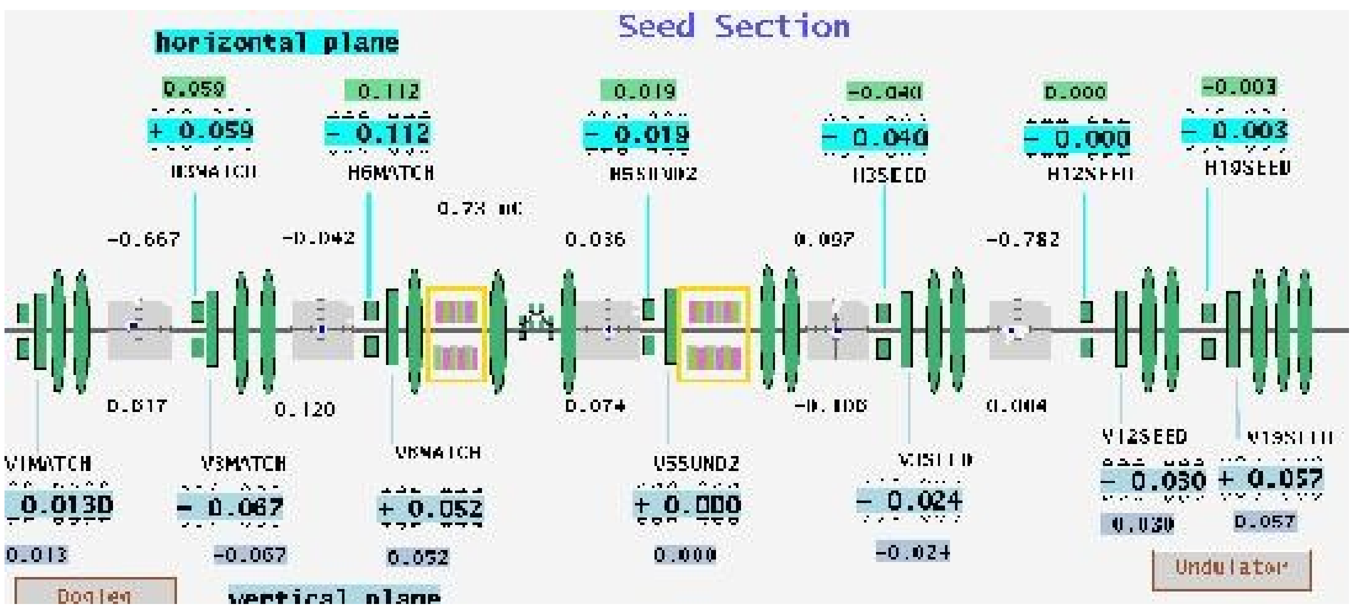
Control system

- The enormous number of devices needs to be controlled (LHC: several thousand magnets)
- and read out: BPM, screens, DCCT, …
- Normally layered: Device, VME, Workstation



Orbit control in FLASH at DESY

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Machine and personnel protection

- Normally there is a large number of interlocks
- for the accelerator: prevent e.g. beam to be parked in valves. Compare beam in/out of a section
- for personnell: prevent access to regions with a high hazard level
  - ionizing radiation
  - electrical, gas, choking hazards
  - keybanks, searching

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Summary

- Glimpsed at a number of subsystems:
  - RF acceleration
  - Magnets and Vacuum
  - Injection and Extraction
  - Collimation and Beam abort
  - Control and MPS, PPS
- Did not and will not at all touch in these lectures
  - Instabilities, beam-target, beam-beam and other limitations, particle sources, dynamical aperture, other fun theoretical aspects, and much more…