Outline

• Introduction: Purpose and application of collimation
  – quick examples: LHC, ILC, PSI-HIPA, E-XFEL

• Beam collimation, a multi-physics problem
  – Beam dynamics: halo diffusion & impact parameter
  – Beam dynamics: scattering & multi stage collimation
  – Beam material interaction, thermo-mechanics
  – Wakefields/Impedance

• Beam Dumps
  – Purpose of dumps for different facilities
  – Example implementations
The purpose of collimation

- remove particles beyond $n \times \sigma$ (transverse & longitudinal)
- localize losses at suited locations, provide operational tolerance for temporary “tuning” situations with high losses, avoid activation, quench, detector background [continuous loss, standard operation]
- protect machine from sudden beam loss, e.g. magnet failure [accidental loss]
- provide diagnostics by probing the beam, loss detection

Note hierarchy of apertures
In which facilities do we need collimation?

Typical use cases for collimators

- collimation in a **ring collider** with hadron beams
- collimation in **linear colliders** with highly focused electron/positron beams
- other **high intensity hadron** accelerators like cyclotrons
- applications for **single passage collimation**, i.e. for **injected** beams
- collimators and masks for **synchrotron light** in electron rings

Next slides: examples of different collimation systems
- Large Hadron Collider
- Linear Collider Final Focus Collimation
- CW High Intensity Proton Accelerator
- Post-Linac Collimation for EXFEL
Layout of LHC collimation system

Two warm cleaning insertions, 3 collimation planes
- IR3: Momentum cleaning
  1 primary (H)
  4 secondary (H)
  4 shower abs. (H,V)
- IR7: Betatron cleaning
  3 primary (H,V,S)
  11 secondary (H,V,S)
  5 shower abs. (H,V)

Local cleaning at triplets
8 tertiary (2 per IP)

Passive absorbers for warm magnets

Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 108 collimators
(100 movable).
Two jaws (4 motors) per collimator!

S. Redaelli, CollReview, 14-06-2011
CERN LHC Collimator Design

Actuation system

RF contact system

Jaw Assembly

Cooling system

Vacuum Vessel

Actuation system

[R.Losito et al]

Collimators and Dumps, M.Seidel, PSI
LHC: Collimation of High Power Loss

Example of artificial high loss test, 4TeV, no quench!
Example: International Linear Collider

final focus & collimation

Main beam dumps 17 MW each (20% margin)

Positron target and Photon dump

[2x 11km s.c. linac]

Collimators and Dumps, M.Seidel, PSI
Example Linear Collider

\[ \text{Sqrt}(\beta_{x,y}) \]

- Combination of chromatic/geometric aberration correction and collimation
- Small beam spot, high avg. Power
- Collimation to protect FF/detector

[A.Seryi et al]

Collimators and Dumps, M.Seidel, PSI
Example Post Linac Collimation EXFEL

[V.Balandin, N.Golubeva et al]

- goal: protect permanent undulator magnets from halo losses; danger of de-magnetization; avoid accidental beam impact
- 4 primary collimators plus secondaries; beam size large enough for survival of accidental impact
- Second order achromatic properties to allow certain energy bandwidth
PSI - High Power Proton Accelerator

Injector II Cyclotron
72 MeV, 160kW

Ring Cyclotron
590 MeV, 1.3MW

Cockcroft Walton
870keV, 10kW

dimensions:
120 x 220m²

UCN
Ultra-Cold Neutrons

4cm graphite target

proton therapie center
[250MeV sc. cyclotron]

SINQ
spallation source

Muon Beamlines

Collimators and Dumps, M. Seidel, PSI
**PSI-HIPA: high average load power**

Concept sketch

- 1.3MW p-beam
  - Scattered p-beam
    - $\sigma \approx 30$ mm
  - KHE2
    - $\sim 130$kW
  - KHE3
    - $\sim 30$kW
  - Collimated beam

**Aspects:**
- Fixed aperture, no adjustments
- High power density $\rightarrow$ cooling
- Protection of collimator
- High activation $\rightarrow$ shielding, handling

[D.Kiselev et al]
High intensity collimator: activation after years

Dosisleistungsmessung am KHE2 im ATEC

- measured
- computed

[ Remotely controlled exchange flask ]
[ Sliding door ]
[ Support bridge ]

Collimators and Dumps, M. Seidel, PSI
Energy, power and other impressive numbers

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>FCC</th>
<th>ILC</th>
<th>EXFEL</th>
<th>PSI-HIPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam kinetic energy</td>
<td>7 TeV</td>
<td>50 TeV</td>
<td>up to 500 GeV</td>
<td>17.5 GeV</td>
<td>0.59 GeV</td>
</tr>
<tr>
<td>beam stored energy /</td>
<td>0.36 GJ</td>
<td>8.4 GJ</td>
<td>up to 13.7 MW</td>
<td>0.65 MW</td>
<td>1.4 MW</td>
</tr>
<tr>
<td>power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tolerated beam loss power</td>
<td>0.5 MW/10s</td>
<td>11 MW (!)</td>
<td>low</td>
<td>low</td>
<td>130 kW</td>
</tr>
<tr>
<td>rms beam size at collimator</td>
<td>200 µm</td>
<td>200x15 µm²</td>
<td>100 µm</td>
<td>≈ cm</td>
<td></td>
</tr>
<tr>
<td>comment</td>
<td>pioneering, impressive perf.</td>
<td>loss power is one of major issues</td>
<td></td>
<td>interchangeable apertures</td>
<td>after target, fixed aperture</td>
</tr>
</tbody>
</table>

→ high energy/power leads to tight requirements for **collimation efficiency**
→ ... and demanding requirements for **thermomechanics** and interlock systems
Physics problems of Collimation
Collimation: a multi-physics problem

a) **Beam dynamics**: impact parameters (ring), collimation hierarchy, cleaning inefficiency, betatron phases, impedance/wake fields, tolerances ...

b) **Radiation transport**: phase space of scattered beam, energy deposition, activation

c) **Thermomechanical aspects**: shock- and continuous heating, thermal stress and resulting deformations, risk of fatigue failure, choice of material/advanced materials

d) **Operational aspects**: precision positioning, control through operation cycle, efficient positioning of large numbers of collimators, handling of activated components

e) **Beam diagnostics**: monitoring of loss rate, temperatures, shock impact / damage, beam position at jaws
Collimation in rings – relation to $\beta^*$

- primary collimator typically at 5..7×rms width
- for highest luminosity the smallest possible $\beta^*$ is desired; the smaller $\beta^*$, the larger the beam size in final focus quads
  \[ \beta(s) \approx \frac{s^2}{\beta^*} \]
- In units of beam rms-width collimators must be set tighter than the aperture of the beam
  → thus direct relation between $\beta^*$ and collimator settings

Example: LHC

Collimators and Dumps, M.Seidel, PSI
Betatron Collimation in Rings - Impact Parameter

Position a collimator at certain distance to the beam, e.g. 5 rms-width of core distribution.

I) At which distance from edge will the collimator be hit by particles?
II) Most particles will be scattered after first contact (angular kick, some energy loss). How can these scattered particles be captured?

Betatron oscillations in a FODO lattice.
A particle that just passes the collimator will perform many turns before it finally hits the collimator at close distance from the edge.
To consider collimation in a hadron ring, use the distribution in action $J$

**proj. distribution in $x$:**
- Gaussian

**distribution in $J$:**
- Exponential

$$J = \frac{1}{2} \left( \gamma x^2 + 2\alpha xx' + \beta x'^2 \right)$$

Halo diffusion after collimator movement
Determining diffusion in $J$ by collimator retraction tests

HERA

$$\hat{n} \propto \frac{\Delta J}{\sqrt{Dt}}$$

$$\hat{n} \propto \left(1 - \text{erf} \left( \frac{\Delta J}{2\sqrt{Dt}} \right) \right)$$

NIM A 351, 279 (1994)

Fig. 5.5: Observed shower rates during collimator movements (upper plot). The jaw position is given on the lower plot. The time marks correspond to the following collimator movements:
1.) $\Delta x = -50 \, \mu\text{m}$; 2.) $\Delta x = -100 \, \mu\text{m}$; 3.) $\Delta x = +100 \, \mu\text{m}$; 4.) $\Delta x = -150 \, \mu\text{m}$

Valentino et al

LHC

(a)Inward collimator jaw movement
Halo Diffusion and Impact Parameters

The impact parameter (distance from edge) will be affected by:

• Choice of betatron tune
• Nature of amplitude growth (e.g. characterized by diffusion coefficient)
• Slow oscillation mechanisms: betatron coupling, synchrotron oscillations

[for detailed considerations see COLLI_HERA]

1µm impact parameter is a typical value => small!

Simulation HERA-p 920GeV

simplified linear growth:
away from resonant tunes the maximum impact parameter approaches a „typical“ value

more realistic diffusion growth:
numerical simulation including slow oscillations
Scattering at Primary Collimator

→most particles will be scattered due to misalignment
best possible alignment and flatness help to maximize
the travel length in material and the scattering angle

1) In a ring, other than in a linac, due to the small
impact parameter scattering always leads to an
increase in action (secondaries can stay in shadow)

2) In general (α≠0) alignment angle of jaw depends
on amplitude
Two Stage Collimation

Scattered particles from the primary are absorbed at two secondary collimators; also tertiary collimators are possible.

Optimum phase advances are around 30 and 150 degree.

Secondaries should stay in the shadow of primaries (tolerances!), while the natural aperture should stay in the shadow of all collimators.
Momentum Collimation

- install collimators at positions with large dispersion function
- always a combination of transverse and longitudinal amplitude

\[ x(s) = \sqrt{2J_x \beta_x(s)} \cos(\varphi(s) - \varphi_0) + D_x(s) \times \frac{\Delta p}{p} \]

- Collimator hierarchy is still o.k. if: \[ \frac{|D_p|}{\sqrt{\beta_p}} \geq \frac{|D_s|}{\sqrt{\beta_s}} \]

Betatron part

Momentum part
choose location with large \( D_x \) for momentum primary collimator
Collimator Wakefields

- Collimator material positioned close to beam
- **geometric** and **resistive wakefields** act back on the beam
- In Ring: contribute to Impedance (multi bunch/turn), onset of instabilities
- In Linac: kick acts back on beam, disturbs beam shape, increases energy spread
Example: geometric and resistive wakefields measured in SLAC Linac

Method: high quality electron beam passes collimator gap at varying position, determine angular kick from difference orbits; done for copper and graphite

Parameters: gap=3.8mm, $\sigma_y=50\mu$m, 1.2GeV

result for graphite jaw: $w_\perp = 3\pm0.3$ V/pC/mm
or in practical units: $\theta = 8.2\pm0.7$ µrad/mm → agrees to theory within 20%
Positioning of collimators close to the beam is critical!
serious cutting into the beam would result in excessive loss, unwanted beam dump, even jaw damage or quench → care needed!
But - conservative probing of beam with many jaws costs much luminosity → automation, refinement, jaw BPMs

Example DESY-HERA, 1994
automatic alignment of two primaries (x,y) and 4 secondaries using loss rates and edge detection
CERN: Jaws with integrated BPM´s

- drastically reduced setup time
- higher setup precision → tighter settings acceptable → smaller $\beta^*$
  → Higher Luminosity

 Courtesy O. Aberle, A. Bertarelli, F. Carra, A. Dallocchio, L. Gentini et al.
beam material interaction and heating for collimators and dumps
Collimators & Dumps: Thermomechanics

Beam deposits thermal energy

I) Instantaneous heating $\rightarrow$ shock, stress, fatigue failure?

II) Equilibrium heating $\rightarrow$ cooling, melting?

Example: TESLA Test Facility, 1.5mm electron beam, 800MeV, 10Hz, Titanium
Instantaneous vs. equilibrium heating

Thermal diffusion coefficient relates time and length scales:

\[ D_{th} = \frac{\lambda}{c\rho} = \frac{\langle \Delta x^2 \rangle}{\Delta t} \]

\[ \Rightarrow \Delta x = \sqrt{D_{th} \Delta t} \]

\[ \lambda = \text{th. conductance} \]
\[ c = \text{heat capacity} \]
\[ \rho = \text{density} \]
Edge Cooling and Equilibrium Temperature

Static heat diffusion equation for long cylinder

\[ \lambda \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} T(r) + q(r) = 0, \quad q(r) \propto \frac{2 \sigma^2}{\pi (r^2 + 2 \sigma^2)^2} \]

Temperature: logarithmic dependence on beamsize:

\[ \Delta T_{eq} \propto I_{beam} \frac{1}{\lambda} \frac{dE}{dz} \ln \left( \frac{b}{\sigma} \right) \]

Solution also correct for half cylinder with half beam

Summary on continuous heating:

- weak dependence on beam size (logarithmic)
- relevant material parameters:
  \[ \frac{dE}{dz} \downarrow, \lambda \uparrow, T_{\text{melt}} \uparrow, \alpha \downarrow, E \downarrow, \sigma_{0.2} \uparrow \]

[HEAT, STRESS]
Numerical Calculations

use finite element codes like ANSYS, COMSOL to solve diffusion equation, extend to stress calculations → most accurate method, but less understanding of the nature of problem ...

Example: PSI-HIPA: collimator II, III behind target

beam elliptic opening: 80 mm

569°C at 3 mA
405°C at 2.15 mA
380°C at 2 mA

(max. acceptable: ca. 405°C)
**Instantaneous Heating**

→ stress may have dynamic peaks from superposition of shock waves or resonances, otherwise *same as for equilibrium case*
→ particularly problematic: cavitation shock waves in liquids, e.g. Mercury

\[ \Delta T_{\text{inst}} \propto \frac{Q_{\text{train}}}{\sigma_r^2} \frac{1}{c} \frac{dE}{dz} \]

quadratic dependence on beam size

**Summary instantaneous heating:**
- Strong dependence on beam size (quadratic)
- Relevant material parameters: \( \frac{dE}{dz} \downarrow, c \uparrow, \alpha \downarrow, E \downarrow, \sigma_{0.2} \uparrow \)
combining instantaneous and equilibrium heating

Often operation requires intermediate regime with average and superimposed pulsed heating; e.g. at elevated temperatures material strength is reduced

→ Ultimately a simulation code, ANSYS or similar, should be used to obtain precise results. However, the presented analytical approaches allow rough estimates and qualitative understanding.

Goodman diagram after D.Walz/SLAC
Stress limits are to be taken at elevated temperatures
Estimating energy loss for protons and ions

Is all delivered by simulation codes, for estimates use Minimum of Bethe-Bloch Formula:

Often just normalized value tabulated

<table>
<thead>
<tr>
<th>material</th>
<th>((dE/dx)_{\text{min}}) [MeV/cm]</th>
<th>((dE/dx)_{\text{min}}/\rho) [MeV cm²/g]</th>
<th>(\rho) [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.8</td>
<td>1.74</td>
<td>2.2</td>
</tr>
<tr>
<td>Cu</td>
<td>12.5</td>
<td>1.40</td>
<td>8.96</td>
</tr>
<tr>
<td>W</td>
<td>22.2</td>
<td>1.15</td>
<td>19.3</td>
</tr>
</tbody>
</table>

\(\theta_{\text{rms}} \approx \frac{13.6 \text{MeV}}{\beta c \rho} \sqrt{\frac{\Delta x}{X_0}}\)

→ for electron induced losses include Bremsstrahlung (Berger-Seltzer formula)
Next: advanced collimation
LHC collimators: advanced designs utilizing specialized materials

- Materials of the jaws are the **critical component** because of the tough requirements (robustness, geometrical stability, electrical conductivity, radiation resistance ...)
- New advanced materials being investigated for HL-LHC

TCPP /TCSP (LHC and HL-LHC)  
2D Carbon-Carbon

TDIS (HL-LHC)  
Graphite-Al-CuCrZn

TCSPM (HL-HLC)  
MoGr

TCTPM (HL-HLC)  
CuCD

TCTP (LHC and HL-LHC)  
Tungsten Heavy Alloy (95 W - 3.5 Ni - 1.5 Cu)

TCLD (LHC and HL-LHC)  
Tungsten Heavy Alloy (95 W - 3.5 Ni - 1.5 Cu)
Hollow Electron Beam Lens for LHC

[B. Brüning, Diego Perini et al, Chamonix Performance Workshop 2018]
Hollow Electron Beam Lens - Concept

Electron gun 3-5Ax10-15kV

Modulator

Main SC solenoid 4-6 T

Bending SC solenoids ~3T

∫ Integrated field of 0.18 Tm

Gun solenoid 0.2-3T

P-beam

Collector

6.4 – 6.5 m

[A. Rossi et al, HL-LHC annual meeting 2017 in Madrid]
Next: Beam Dumps
Beam Dumps

**Purpose of beam dumps:**
- Stop the beam safely within a defined volume
- Confine secondary activation

**Challenges:**
- Shock heating
- Average heat load
- Reliability, No false dumps for storage rings
- Activation, Handling, Safety
- Cooling power, Hydrolysis
LHC Dump with beam dilution

- the **ONLY** element in the LHC that can withstand the impact of the full 7 TeV beam!
- the dumped beam must be painted to keep the peak energy densities at a tolerable level!

[courtesy: CERN/LHC team]
Electron-Beam Dump

- material composite with increasing density along z
- $E_{\text{inst}} = 13\text{kJ}$ per bunchtrain (shock heating)
- $P_{\text{avg}} = 130\text{kW}$

[Flash/DESY Hamburg, Maslov, Schmitz et al.]
Beam Rotation/Rastering of CW beam

- Distribution of deposited energy over larger volume
- Reduction of peak load vs average volume load

Example: **circular rotation of CW Gaussian beam**

Varying beam size and rotation radius to keep outer radius fixed

Note: log scale

\[
q(r) = \frac{q_0}{2\pi \sigma^2} \exp \left( -\frac{r^2 + r_0^2}{2\sigma^2} \right) I_0 \left( \frac{rr_0}{\sigma^2} \right)
\]

- \(r_0\) = rotation radius
- \(\sigma = s\) = beam rms size
- \(I_0\) = Bessel Function
ILC Beam dumps

Conceptual Design of Main Beam Dump

Design for $E_{CM} = 1$ TeV

500 GeV $\times 2.79$ nC $\times 2450$ bunches $\times 4$ Hz:

$13.7$ MW

20% margin $\rightarrow$ $17$ MW


- Cylindrical Water Container ($\phi 1.8$ m $\times 11$ m: 28 m$^3$).
- Vortex flow
- Suppress the water boiling: 10 bar $\rightarrow$ boiling threshold 180 °C

238 J/cm$^3$, Z=180 cm, 155 °C

2820 bunches/pulse

Specific issues:
- Small beam size
- High avg. power
- Window(!)
- $^3$H, $^7$Be in water
- Hydrolysis ($O_2 H_2$)

[courtesy N.Terunuma, KEK]

[ILC-DUMP]
Vacuum tightness is ensured by a seamless 316L tube — **no welds inside the shielding**

- 3.5 m **Graphite**, 40 cm **Cupro-Chrome-Zirconium** (CuCrZr) and 40 cm **Inermet** (Tungsten)

[courtesy: F.Bordry et al, FCC week 2017]
Collimation systems remove large amplitude particles from the beam and localize these unwanted losses; Collimation systems protect sensitive components from mis-steered beams and excessive losses.

Optimizing a collimation system is a multi-physics problem, including:

- Beam dynamics, wakefields, cleaning efficiency
- Numerical simulations from particle tracking to finite element calculations
- Heating, mechanical stress and radiation damage
- Operational aspects

Beam dumps are designed to accept the full beam, allowing safe abort of circulating beam or continuous abort of CW beam.

Depending on parameters, electrons vs. hadrons, CW vs. pulsed, beam power and size, varying designs are required for collimators and dumps.
Collimators and Dumps – some References

[LHC-COLLI] O.Büning (ed) et al, **The LHC Design Report**:  
Beam Cleaning and Collimation, p467 (2004)  


