Injection and extraction

- Kickers and septa
- Injection methods
  - Single-turn hadron injection
  - Injection errors, filamentation and blow-up
  - Multi-turn hadron injection
  - Charge-exchange H- injection
  - Lepton injection
- Extraction methods
  - Single-turn (fast) extraction
  - Non-resonant multi-turn extraction
  - Resonant multi-turn (slow) extraction

Brennan Goddard (presented by Wolfgang Bartmann)
CERN
Injection, extraction and transfer

• An accelerator has limited dynamic range.
• Chain of stages needed to reach high energy
• Periodic re-filling of storage rings, like LHC

Beam transfer (into, out of, and between machines) is necessary.
Kicker magnet

Pulsed magnet with very fast rise time (100ns – few μs)

\[
B = \frac{\mu_0 I}{g}
\]
\[
L = \frac{\mu_0 w l}{g} \quad \text{(magnet length l)}
\]
\[
dI/dt = \frac{V}{L}
\]

Typically 3 kA in 1 μs rise time
Magnetic septum

Pulsed or DC magnet with thin (2-20mm) septum between zero field and high field region

\[
B = \frac{\mu_0 I}{g}
\]

Typically \( I \approx 5-25 \text{ kA} \)

\( B_0 \) is the magnetic field strength at the septum.
Electrostatic septum

DC electrostatic device with very thin (~0.1mm) septum between zero field and high field region

High voltage electrode

Hollow earth electrode

Thin wire or foil (~0.1 mm)

E = V / g
Typically V = 200 kV
E = 100 kV/cm

High Voltage Electrode

Septum wires

Hollow earth electrode
Normalised phase space

• Transform real transverse coordinates $x, x'$ by

$$\begin{bmatrix} \bar{X} \\ \bar{X}' \end{bmatrix} = N \cdot \begin{bmatrix} x \\ x' \end{bmatrix} = \sqrt{\frac{1}{\beta_s}} \cdot \begin{bmatrix} 1 & 0 \\ \alpha_s & \beta_s \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \end{bmatrix}$$

$$\bar{X} = \frac{1}{\sqrt{\beta_s}} \cdot x$$

$$\bar{X}' = \sqrt{\frac{1}{\beta_s}} \cdot \alpha_s x + \sqrt{\beta_s} x'$$
\[ \varepsilon = \gamma \cdot x^2 + 2\alpha \cdot x \cdot x' + \beta \cdot x'^2 \]

\[ \varepsilon = \overline{X}^2 + \overline{X'}^2 \]
• Septum deflects the beam onto the closed orbit at the centre of the kicker
• Kicker compensates for the remaining angle
• Septum and kicker either side of D quad to minimise kicker strength
Single-turn injection

Normalised phase space at centre of idealised septum

Large deflection by septum
Single-turn injection

$\pi/2$ phase advance to kicker location
Single-turn injection

Normalised phase space at centre of idealised kicker

Kicker deflection places beam on central orbit
For imperfect injection the beam oscillates around the central orbit. 1

kicker $\theta$ error
Injection oscillations

For imperfect injection the beam oscillates around the central orbit.
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For imperfect injection the beam oscillates around the central orbit.
Injection oscillations

- Betatron oscillations with respect to the Closed Orbit

Transfer line to LHC (first turn)
Filamentation

- Non-linear effects (e.g. magnetic field multipoles) present which introduce amplitude dependent effects into particle motion.
- Over many turns, a phase-space oscillation is transformed into an emittance increase.
- So any residual transverse oscillation will lead to an emittance blow-up through filamentation
  - “Transverse damper” systems used to damp injection oscillations - bunch position measured by a pick-up, which is linked to a kicker
Filamentation
Filamentation
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Filamentation
Damping of injection oscillations

- Residual transverse oscillations lead to an emittance blow-up through filamentation.
- “Transverse damper” systems used to damp injection oscillations - bunch position measured by a pick-up, which is linked to a kicker.
- Damper measures offset of bunch on one turn, then kicks the bunch on a subsequent turn to reduce the oscillation amplitude.
Optical Mismatch at Injection

- Can also have an emittance blow-up through optical mismatch
- Individual particles oscillate with conserved CS invariant:
  \[ a_x = \gamma x^2 + 2\alpha xx' + \beta x'^2 \]
Optical Mismatch at Injection

- Filamentation fills larger ellipse with same shape as matched ellipse
Multi-turn injection

• For hadrons the beam density at injection can be limited either by space charge effects or by the injector capacity

• If we cannot increase charge density, we can sometimes fill the horizontal phase space to increase overall injected intensity.
  – Condition that the acceptance of receiving machine is larger than the delivered beam emittance
Multi-turn injection for hadrons

- No kicker
- Bump amplitude decreases and inject a new bunch at each turn
- Phase-space “painting”
Multi-turn injection for hadrons

Example: CERN PSB injection, fractional tune $Q_h = 0.25$

Beam rotates $\pi/2$ per turn in phase space

Turn 1

On each turn inject a new batch and reduce the bump amplitude
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 3

\[ \begin{align*}
X' & \rightarrow \\
X & \rightarrow
\end{align*} \]
Multi-turn injection for hadrons

Turn 4

\[ X \]
\[ X' \]
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 6
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 8
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 10
Multi-turn injection for hadrons
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 13

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$\bar{X}' \begin{array}{c} Y \end{array}$ $X$
Multi-turn injection for hadrons
In reality filamentation occurs to produce a quasi-uniform beam
For multturn injection over $n$ turns, injected beam ellipse is deliberately mismatched to circulating beam ellipse to reduce losses.
Charge exchange H- injection

- Multiturn injection is essential to accumulate high intensity
- Disadvantages inherent in using an injection septum
  - Width of several mm reduces aperture
  - Beam losses from circulating beam hitting septum
  - Limits number of injected turns to 10-20
- Charge-exchange injection provides elegant alternative
  - Possible to fully “deploy” Liouville’s theorem, which says that emittance is conserved.…
  - Convert H- to p+ using a thin stripping foil, allowing injection into the same phase space area
Charge exchange H- injection

Start of injection process

H- beam

Stripping foil

Circulating p+

Displace orbit

Injection chicane dipoles
Charge exchange H- injection

End of injection process

- H- beam
- Stripping foil
- Circulating p+
- Injection chicane
- p+
Charge exchange H- injection

- Paint uniform transverse phase space density by modifying closed orbit bump and steering injected beam
- Foil thickness calculated to double-strip most ions (>99%)
  - 50 MeV - 50 µg.cm-2
  - 800 MeV - 200 µg.cm-2 (~1 µm of C!)
- Carbon foils generally used – very fragile
- Injection chicane reduced or switched off after injection, to avoid excessive foil heating and beam blow up
H- injection - painting

Note injection into same phase space area as circulating beam

~100 turns
Lepton injection

- Single-turn injection can be used as for hadrons; however, lepton motion is strongly damped (different with respect to proton or ion injection).
  - Synchrotron radiation
- Can use transverse or longitudinal damping:
  - Transverse - Betatron accumulation
  - Longitudinal - Synchrotron accumulation
Betatron lepton injection

- Beam is injected with an angle with respect to the closed orbit
- Injected beam performs *damped* betatron oscillations about the closed orbit
Injected bunch performs **damped** betatron oscillations

In LEP at 20 GeV, the damping time was about 6’000 turns (0.6 seconds)
• Beam injected parallel to circulating beam, onto dispersion orbit of a particle having the same momentum offset $\Delta p/p$.

• Injected beam makes damped *synchrotron oscillations* at $Q_s$ but does not perform betatron oscillations.
Double batch injection possible.

Longitudinal damping time in LEP was ~ 3’000 turns (2 x faster than transverse)
Synchrotron lepton injection in LEP

Synchrotron lepton injection in LEP gave improved background for LEP experiments due to small orbit offsets in zero dispersion straight sections.
Injection - summary

• Several different techniques
  – Single-turn injection for hadrons
    • Boxcar stacking: transfer between machines in accelerator chain
    • Angle / position errors ⇒ injection oscillations
    • Optics errors ⇒ betatron mismatch oscillations
    • Oscillations ⇒ filamentation ⇒ emittance increase
  – Multi-turn injection for hadrons
    • Phase space painting to increase intensity
    • H- injection allows injection into same phase space area
  – Lepton injection: take advantage of damping
    • Less concerned about injection precision and matching
Extraction

• Different extraction techniques exist, depending on requirements
  – **Fast extraction**: \( \leq 1 \) turn
  – **Non-resonant multi-turn extraction**: few turns
  – **Resonant multi-turn extraction**: many thousands of turns
  – **Resonant low-loss multi-turn extraction**: few turns

• Usually higher energy than injection \( \Rightarrow \) stronger elements (\( \int B \cdot dl \))
  – At high energies many kicker and septum modules may be required
  – To reduce kicker and septum strength, beam can be moved near to septum by closed orbit bump
Fast single turn extraction

- Whole beam kicked into septum gap and extracted.

- Kicker deflects the entire beam into the septum in a single turn
- Septum deflects the beam entire into the transfer line
- Most efficient (lowest deflection angles required) for $\pi/2$ phase advance between kicker and septum
Fast single turn extraction

- For transfer of beams between accelerators in an injector chain.
- For secondary particle production (e.g. neutrinos)
- Septum deflection may be in the other plane to the kicker deflection.
- Losses from transverse scraping or from particles in extraction gap.

![Graph showing particles in SPS extraction kicker rise- and fall-time gaps.](graph.png)
Some filling schemes require a beam to be injected in several turns to a larger machine…

And very commonly Fixed Target physics experiments and medical accelerators often need a quasi-continuous flux of particles…

Multi-turn extraction…

– Non-Resonant multi-turn ejection (few turns) for filling e.g. PS to SPS at CERN for high intensity proton beams (>2.5 $10^{13}$ protons)

– Resonant extraction (ms to hours) for experiments
Non-resonant multi-turn extraction

Beam bumped to septum; part of beam ‘shaved’ off each turn.

- Fast bumper deflects the whole beam onto the septum
- Beam extracted in a few turns, with the machine tune rotating the beam
- Intrinsically a high-loss process – thin septum essential
Non-resonant multi-turn extraction

- Example system: CERN PS to SPS Fixed-Target ‘continuous transfer’.
  - Accelerate beam in PS to 14 GeV/c
  - Empty PS machine (2.1 μs long) in 5 turns into SPS
  - Do it again
  - Fill SPS machine (23 μs long)
  - Quasi-continuous beam in SPS (2 x 1 μs gaps)
  - Total intensity per PS extraction ≈ 3 × 10^{13} p+
  - Total intensity in SPS ≈ 5 × 10^{13} p+
Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer

$Q_h = 0.25$

Bump vs. turn
Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer – 5\textsuperscript{th} turn

\(Q_h = 0.25\)
Non-resonant multi-turn extraction

- CERN PS to SPS: 5-turn continuous transfer
  - Losses impose thin (ES) septum… second septum needed
  - Still about 15% of beam lost in PS-SPS CT
  - Difficult to get equal intensities per turn
  - Different trajectories for each turn
  - Different emittances for each turn
Resonant multi-turn extraction

Non-linear fields excite resonances which drive the beam slowly across the septum.

- Slow bumpers move the beam near the septum
- Tune adjusted close to \( n^{th} \) order betatron resonance
- Multipole magnets excited to define stable area in phase space, size depends on \( \Delta Q = Q - Q_r \)
Resonant multi-turn extraction

- 3\textsuperscript{rd} order resonances
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

\[
R_{fp}^{1/2} \propto \Delta Q \cdot \frac{1}{k_2}
\]

- Sextupoles families arranged to produce suitable phase space orientation of the stable triangle at thin electrostatic septum
- Stable area can be reduced by increasing the sextupole strength, or (easier) by approaching machine tune $Q_h$ to resonant 1/3 integer tune
- Reducing $\Delta Q$ with main machine quadrupoles can be augmented with a ‘servo’ quadrupole, which can modulate $\Delta Q$ in a servo loop, acting on a measurement of the spill intensity
Third-order resonant extraction

- Particles distributed on emittance contours
- $\Delta Q$ large – no phase space distortion
• Dedicated sextupole magnets produce a triangular stable area in phase space
• $\Delta Q$ decreasing – phase space distortion for largest amplitudes
Third-order resonant extraction
Third-order resonant extraction
Third-order resonant extraction
Third-order resonant extraction

- $\Delta Q$ small enough that largest amplitude particles are close to the separatrices
- Fixed points locations discernable at extremities of phase space triangle
• $\Delta Q$ now small enough that largest amplitude particles are unstable
• Unstable particles follow separatrix branches as they increase in amplitude
Third-order resonant extraction

- Stable phase area shrinks as $\Delta Q$ gets smaller
Third-order resonant extraction

- Separatrix position in phase space shifts as the stable area shrinks
Third-order resonant extraction

As the stable area shrinks, the beam intensity drops since particles are being continuously extracted.
Third-order resonant extraction
Third-order resonant extraction

\[ \bar{X}' \]

\[ \bar{X} \]

Septum wire
Third-order resonant extraction
Third-order resonant extraction

As $\Delta Q$ approaches zero, the particles with very small amplitude are extracted.
Third-order resonant extraction

Example – SPS slow extraction at 450 GeV/c.
~3 x 10^{13} p+ extracted in a 2-4 second long spill (~200,000 turns)

Intensity vs time:
~10^8 p+ extracted per turn
Second-order resonant extraction

- An extraction can also be made over a few hundred turns
- 2\textsuperscript{nd} and 4\textsuperscript{th} order resonances
  - Octupole fields distort the regular phase space particle trajectories.
  - Stable area defined, delimited by two unstable Fixed Points.
  - Beam tune brought across a 2\textsuperscript{nd} order resonance (Q\rightarrow0.5)
  - Particle amplitudes quickly grow and beam is extracted in a few hundred turns.
Resonant extraction separatrices

• Amplitude growth for 2\textsuperscript{nd} order resonance much faster than 3\textsuperscript{rd} – shorter spill
• Used where intense pulses are required on target – e.g. neutrino production
Resonant low-loss multi-turn extraction

- Adiabatic capture of beam in stable “islands”
  - Use non-linear fields (sextupoles and octupoles) to create islands of stability in phase space
  - A slow (adiabatic) tune variation to cross a resonance and to drive particles into the islands (capture)
  - Variation of field strengths to separate the islands in phase space

- Several big advantages
  - Losses reduced virtually to zero (no particles at the septum)
  - Phase space matching improved with respect to existing non-resonant multi-turn extraction - all ‘beamlets’ have same emittance and optical parameters
Resonant low-loss multi-turn extraction

a. Unperturbed beam

b. Increasing non-linear fields

c. Beam captured in stable islands

d. Islands separated and beam bumped across septum – extracted in 5 turns

 Courtesy M. Giovannozzi
Several different techniques:

- Single-turn fast extraction:
  - for Boxcar stacking (transfer between machines in accelerator chain), beam abort

- Non-resonant multi-turn extraction
  - slice beam into equal parts for transfer between machine over a few turns.

- Resonant multi-turn extraction
  - create stable area in phase space $\Rightarrow$ slowly drive particles into resonance $\Rightarrow$ long spill over many thousand turns.

- Resonant low-loss multi-turn extraction
  - create stable islands in phase space: slice off over a few turns.