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
- External experiments, like CNGS

Transfer (in, out, and between machines) is important!
Injection and Extraction

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

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

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

\[ L = \frac{\mu_0 w l}{g} \]  (magnet length l)

\[ \frac{dI}{dt} = \frac{V}{L} \]

Typically 3kA in 1μs rise time
Magnetic septum

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

Typically I 5-25kA

Septum coil

Return coil

Soft Iron Laminated yoke

B=0

Yoke
Electrostatic septum

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

\[ E = \frac{V}{g} \]

- Typically \( V = 200\text{kV} \)
- \( E = 100\text{kV/cm} \)
Normalised phase space

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

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

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

\[
\bar{X}' = \sqrt{\frac{1}{\beta_s}} \cdot \alpha_s x + \sqrt{\beta_s} x'
\]
Normalised phase space

\[ \varepsilon = \gamma \cdot x^2 + 2\alpha \cdot x \cdot x' + \beta \cdot x'^2 \]

\[ \varepsilon = \bar{X}^2 + \bar{X'}^2 \]
Injection

- Inject one or more bunches into a synchrotron, in one or more turns
- Elements involved:
  - Transfer line
  - Bumper magnet
  - Septum magnet
  - Fast kicker magnet
  - Synchrotron (receiving machine)
Single-turn injection

- Septum deflects the beam onto the closed orbit at the centre of the kicker
- Kicker compensates for the remaining angle
Single-turn injection

Example system – injection into the LHC at 450 GeV/c
Single-turn injection – normalised phase space

Large deflection by septum

\[ \theta_{\text{septum}} \]
Single-turn injection

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

Kicker deflection places beam on central orbit

$\theta_{\text{kicker}}$
Injection errors

Angle errors $\Delta \theta_{s,k}$

Measured Displacements $\delta_{1,2}$

phase $\mu$

$\delta_1 = \Delta \theta_s \sqrt{(\beta_s \beta_1)} \sin (\mu_1 - \mu_s) + \Delta \theta_k \sqrt{(\beta_k \beta_1)} \sin (\mu_1 - \mu_k)$

$\approx \Delta \theta_k \sqrt{(\beta_k \beta_1)}$

$\delta_2 = \Delta \theta_s \sqrt{(\beta_s \beta_2)} \sin (\mu_2 - \mu_s) + \Delta \theta_k \sqrt{(\beta_k \beta_2)} \sin (\mu_2 - \mu_k)$

$\approx - \Delta \theta_s \sqrt{(\beta_s \beta_2)}$
Injection oscillations

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.

\[ \text{Diagram showing beam oscillations around central orbit.} \]
Injection oscillations

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

For imperfect injection the beam oscillates around the central orbit.
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.
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation
Filamentation

Eventually phase space is effectively filled \(\Rightarrow\) emittance increase
Emittance blow-up

• Any residual transverse oscillation will lead to an emittance blow-up through filamentation

• Transverse damper systems used to damp injection oscillations
  – Bunch position pick-up linked to a kicker

• Possible that injection trajectory is well corrected, but there is still an emittance blow-up
  – Optical mismatch
Optical Mismatch at Injection

Particles oscillate with conserved C-S invariant: $a = \gamma x^2 + 2\alpha xx' + \beta x'^2$
Optical Mismatch at Injection

Filamentation fills larger ellipse with same shape as matched ellipse

Treatment of this effect in lecture tomorrow
Multi-turn injection

- For hadrons the beam density at injection is either limited by space charge effects or by the injector (heavy ions...)
- We cannot increase charge density, so we fill the horizontal phase space to increase injected intensity.
  - Acceptance of receiving machine larger than delivered beam emittance
- Elements used
  - Septum
  - Fast beam bumpers, made out of 3 or 4 dipoles, to create a local beam bump
Multi-turn injection for hadrons

- Bump amplitude varies with time
- Inject a new bunch at each turn
- Phase-space painting
Multi-turn injection for hadrons

- Example: fractional tune $Q_h = 0.25$
  - Beam rotates $\pi/2$ per turn in phase space

- On each turn
  - Inject a new batch
  - Reduce the bump amplitude
Multi-turn injection for hadrons

Turn 1

Septum
Multi-turn injection for hadrons

Turn 2

1

2

$X'$

$X$
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 4
Multi-turn injection for hadrons

Turn 5

Diagram showing multi-turn injection with labeled sections and coordinates.
Multi-turn injection for hadrons

Turn 6
Multi-turn injection for hadrons

Turn 7
Multi-turn injection for hadrons

Turn 8
Multi-turn injection for hadrons

Turn 9
Multi-turn injection for hadrons

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

Turn 13

The diagram shows a view of a circular accelerator with labeled sections. The injection point is marked with a red square, and the turns are numbered around the circumference.
Multi-turn injection for hadrons
Multi-turn injection for hadrons

Turn 15
Multi-turn injection for hadrons

• Requirements:
  – To control the tune $Q_h$ accurately
  – To control the bump accurately
  – A very thin septum

• In order to:
  – Minimise losses
  – Fill the horizontal phase space most efficiently
  – Reduce phase space dilution
Charge exchange H- injection
Charge exchange H- injection

- Possible to “beat” Liouville’s theorem, which says that emittance is conserved….
- Paint uniform transverse phase space density by modifying the beam bump and steering injected beam
- Foil thickness calculated to double-strip most ions (99%)
  - 50 MeV - 50 $\mu$g.cm-2
  - 800 MeV - 200 $\mu$g.cm-2 (~1$\mu$m of C)
- Carbon or Aluminium foils can be used – very fragile!
- Bump reduced during injection to paint phase space, and to zero after injection, to avoid excessive foil heating and unnecessary beam blow up
Charge exchange H- injection

Circulating beam on axis after painting

Beam envelope at end of painting

Support for foil

Stripping foil
Lepton injection

• Single-turn injection can be used as for hadrons; however, *lepton motion is damped* (different with respect to proton or ion injection).

• Can use transverse or longitudinal damping:
  – Transverse - Betatron accumulation
  – Longitudinal - Synchrotron accumulation
Betatron lepton injection

- Beam injected with an angle with respect to the closed orbit
- Injected beam performs damped betatron oscillations about the closed orbit
Betatron lepton injection

Injected bunch performs damped betatron oscillations

In LEP at 20 GeV, the damping time was about 6’000 turns (0.6 seconds)
Synchrotron lepton injection

- 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.
Synchrotron lepton injection

Double batch injection possible….

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

Small orbit with Synchrotron Injection in zero dispersion straight sections gave improved background for LEP experiments

P. Collier
Injection - summary

- Kickers, septa and bumpers elements used
- Single-turn injection for Boxcar stacking: transfer between machines in accelerator chain
- Angle / position errors $\Rightarrow$ injection oscillations
- Uncorrected oscillations $\Rightarrow$ filamentation $\Rightarrow$ emittance increase
- Multi-turn injection for hadrons: phase space painting
- H- injection allows injection into same phase space area
- Lepton injection: take advantage of damping
Extraction

- To reduce kicker and septum strength, beam moved near to septum by closed orbit bump

- **Fast extraction**: ≤1 turn
  - Whole beam kicked into septum gap and extracted.

- **Non-resonant multi-turn extraction**: few turns
  - Beam kicked to septum; part of beam ‘shaved’ off each turn.

- **Resonant multi-turn extraction**: many thousands of turns
  - Non-linear fields excite resonances which drive the beam slowly across the septum.

- **Resonant low—loss multi-turn extraction**: few turns
  - Non-linear fields used to trap ‘bunchlets’ in stable island. Beam then kicked across septum and extracted in a few turns.
Fast single turn extraction

- 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 neutrino production.
  – If septa used only for this purpose, they can be pulsed - few 10 ms.
• Septum deflection may be in the other plane to the kicker deflection.
• At high energies many kicker and septum modules may be required
Fast single turn extraction

- View at the septum entrance. Here the clearances are the smallest.
- For high energies / intensities, machine protection becomes an issue.
Fast single turn extraction
Example system - fast extraction from LHC at 7TeV/c (for beam dump)

- Horizontal kicker (0.3 mrad) deflects beam into septum
- Vertical septum (2.4 mrad) deflects onto beam dump
- Two systems – one for each beam
Multi-turn extraction

- Some filling schemes require a beam to be injected in several turns to a larger machine...
- And, Fixed Target physics experiments often need a 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

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

Just before extraction....

Turn N

$Q_h = 0.25$
Non-resonant multi-turn extraction

Fast closed orbit bump moves part of the beam across the septum

Turn $N+1$

$Q_h = 0.25$

Extracted beam
Non-resonant multi-turn extraction

The beam rotates across the septum....

Turn N+2

$Q_h = 0.25$

Extracted beam
Non-resonant multi-turn extraction

…and the last part is extracted on the final turn.

Turn N+3

$Q_h = 0.25$

Extracted beam

$I$ vs. turn
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

1 2 3 4 5

septum
Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer – 5th 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

- Slow bumpers move the beam near the septum
- Horizontal tune adjusted closed 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

- 3rd order resonances – Lecture from O.B.
  - 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 \( Q_n \) to the 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
Third-order resonant extraction

- Dedicated sextupole magnets produce a triangular stable area in phase space
- $\Delta Q$ decreasing – phase space distortion for largest amplitudes
Third-order resonant extraction

Septum wire
Third-order resonant extraction

Septum wire
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
Third-order resonant extraction

- $\Delta Q$ 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

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

Septum wire
Third-order resonant extraction

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

System example – SPS slow extraction at 450 GeV/c. 
~3 x 10^{13} p+ extracted in a 2 second long spill (100,000 turns)
Second-order resonant extraction

- 2nd and 4th order resonances – Lecture from O.B.
  - Octupole fields distort the regular phase space particle trajectories.
  - Stable area defined, delimited by two unstable Fixed Points.
  - Beam tune brought across a 2nd order resonance (Q→0.5)
  - Particle amplitudes quickly grow and beam is extracted in a few hundred turns.
Second-order resonant extraction

Amplitude growth much faster than 3\textsuperscript{rd} order resonance – much 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
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
Resonant low-loss multi-turn extraction

• 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

• Being implemented in CERN PS – SPS
  – High intensity beam for neutrino experiment in SPS / Gran Sasso would produce too many losses with present CT
  – Only possibility to increase extracted beam intensity
Extraction - summary

- Kickers, septa and bumpers elements used.
- 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 ⇒ slowly drive particles into resonance ⇒ long spill over many thousand turns.
- Resonant low-loss multi-turn extraction: create stable islands in phase space: slice off over a few turns.