Injection, extraction and transfer

• Introductory slides:
  – Kickers, septa and normalised phase-space

• 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 and resonant multi-turn (fast) extraction
  – Resonant multi-turn (slow) extraction

Matthew Fraser, CERN (TE-ABT-BTP)
based on lectures by Brennan Goddard

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 facilities and experiments:
  – e.g. ISOLDE, HIRADMAT, AWAKE...

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

Kicker magnet

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

$B = \mu_0 I / g$
$L \text{[per unit length]} = \mu_0 w / g$
$\frac{dI}{dt} = V / L$
Typically 3 kA in 1 µs rise time

Magnetic septum

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

Typically ~10x more deflection given by magnetic septa, compared to kickers

$B_0 = \mu_0 I / g$
Typically I 5 - 25 kA
Electrostatic septum

- DC electrostatic device with very thin 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 \((x, x', s)\) to normalised co-ordinates \((\vec{X}, \vec{X}', \mu)\) where the independent variable becomes the phase advance \(\mu\):

\[
\begin{bmatrix}
\vec{X} \\
\vec{X}'
\end{bmatrix} =
N
\begin{bmatrix}
x \\
x'
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{\beta(s)} & 0 \\
\alpha(s) & \beta(s)
\end{bmatrix}
\begin{bmatrix}
x \\
x'
\end{bmatrix}
\]

**Real phase space**

- \( x(s) = \sqrt{\frac{E}{\beta(s)}} \cos[\mu(s) + \mu_0] \)
- \( \mu(s) = \int_0^s \frac{d\alpha}{\beta(\sigma)} \)

**Normalised phase space**

- Area = \( \pi \epsilon \)
- \( \epsilon = \vec{X}^2 + \vec{X}'^2 \)

**Single-turn injection – same plane**

- Injected beam

- Septum magnet

- Circulating beam

- Kicker magnet

- 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

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Single-turn injection

Normalised phase space at centre of idealised septum

\[ \theta \text{septum} \]

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Single-turn injection

\( \mu/2 \) phase advance to kicker location

\[ \theta \text{kicker} \]

---

Single-turn injection

Normalised phase space at centre of idealised septum

\[ \theta \text{septum} \]

---

Single-turn injection

Normalised phase space at centre of idealised kicker

Kicker deflection places beam on central orbit:

\[ \theta \text{kicker} \]
For imperfect injection the beam oscillates around the central orbit, e.g. kick error, Δ:

After 1 turn...

After 2 turns...

After 3 turns etc...

\[ \theta_{\text{kicker}} - \Delta \]
Injection oscillations

- Betatron oscillations with respect to the Closed Orbit:

Injection errors

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

Measured Displacements $\delta_{1,2}$

\[ \delta_1 = \Delta \theta_s \sqrt{\beta_s \beta_1} \sin (\mu_1 - \mu_s) + \Delta \theta_k \sqrt{\beta_k \beta_1} \sin (\mu_1 - \mu_k) \]
\[ \approx \Delta \theta_k \sqrt{\beta_k \beta_1} \]
\[ \delta_2 = \Delta \theta_s \sqrt{\beta_s \beta_2} \sin (\mu_2 - \mu_s) + \Delta \theta_k \sqrt{\beta_k \beta_2} \sin (\mu_2 - \mu_k) \]
\[ \approx -\Delta \theta_k \sqrt{\beta_k \beta_2} \]

Filamentation

- Non-linear effects (e.g. higher-order field components) 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
  - Chromaticity coupled with a non-zero momentum spread at injection can also cause filamentation, often termed chromatic decoherence
  - “Transverse damper” systems are used to damp injection oscillations - bunch position measured by a pick-up, which is linked to a kicker
Filamentation

Animation not included in full on this handout: see slides on Indico website!
Filamentation

- Residual transverse oscillations lead to an effective emittance blow-up through filamentation:

Blow-up from steering error

- Consider a collection of particles with max. amplitudes $A$
- The beam can be injected with an error in angle and position.
- For an injection error $\Delta a$, in units of $\sigma = \sqrt{\beta \epsilon}$, the mis-injected beam is offset in normalised phase space by an amplitude $L = \Delta a \sqrt{\epsilon}$

Any given point on the matched ellipse is randomised over all phases after filamentation due to the steering error

For a general particle distribution, where $A_i$ denotes amplitude in normalised phase of particle $i$:

\[ \epsilon_{\text{matched}} = \frac{A^2}{2} \]

After filamentation:

\[ \epsilon_{\text{dilated}} = \epsilon_{\text{matched}} + \frac{L^2}{2} \]

See appendix for derivation

A numerical example…

- Consider an offset $\Delta a = 0.5 \sigma$ for injected beam:

\[ L = \Delta a \sqrt{\epsilon_{\text{matched}}} \]

\[ \epsilon_{\text{dilated}} = \epsilon_{\text{matched}} + \frac{L^2}{2} \]

\[ = \epsilon_{\text{matched}} \left[ 1 + \frac{\Delta a^2}{2} \right] \]

\[ = \epsilon_{\text{matched}} [1.125] \]

- For nominal LHC beam:

…allowed growth through LHC cycle ~10 %
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.
  - If the acceptance of the receiving machine is larger than the delivered beam emittance we can accumulate intensity.

Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$

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

- On each turn inject a new batch and reduce the bump amplitude.

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Charge exchange H- injection

- Multi-turn 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:
    - Typically 30 – 40 % for the CERN PSB injection at 50 MeV
  - Limits number of injected turns to 10 - 20
- Charge-exchange injection provides elegant alternative
  - Possible to “cheat” 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

End of injection process with painting

- 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
- Longitudinal phase space can also be painted turn-by-turn:
  - Variation of the injected beam energy turn-by-turn (linac voltage scaled)
  - Chopper system in linac to match length of injected batch to bucket
H- injection - painting

Note injection into same phase space area as circulating beam

≈100 turns

Betatron lepton injection

Injected beam

Septum magnet

Circulating beam

Closed orbit bumpers or kickers

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

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
    - see Electron Beam Dynamics lectures by L. Rivkin
- Can use transverse or longitudinal damping:
  - Transverse - Betatron accumulation
  - Longitudinal - Synchrotron accumulation

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

- Injected beam: $p = p_0 + \Delta p$
- Septum magnet
- Bumped circulating beam: $x_s = D_x \Delta p / p_0$
- Closed orbit bumpers or kickers

- 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

Longitudinal damping time in LEP was ~3'000 turns (2x faster than transverse)

Injection - summary

- Several different techniques using kickers, septa and bumpers:
  - Single-turn injection for hadrons
    - Boxcar stacking: transfer between machines in accelerator chain
    - Angle / position errors ⇒ injection oscillations
    - Uncorrected errors ⇒ 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

Optimized Horizontal First Turn Trajectory for Synchrotron Injection of Positrons into LEP.
Extraction

- Different extraction techniques exist, depending on requirements
  - Fast extraction: ≤ 1 turn
  - Non-resonant multi-turn extraction: few turns
  - Resonant low-loss multi-turn extraction: few turns
  - Resonant multi-turn extraction: many thousands of turns
- Usually higher energy than injection → stronger elements (∫B.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

- For transfer of beams between accelerators in an injector chain
- For secondary particle production (e.g. neutrinos, radioactive beams)
- Septum deflection may be in the other plane to the kicker deflection
  - Lambertson septum to be discussed tomorrow…
- Losses from transverse scraping or from particles in extraction gap:
  - Fast extraction from SPS to CNGS:

Multi-turn extraction

- 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

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 a high-loss process: thin septum essential
• Often combine thin electrostatic septa with magnetic septa

Fast closed orbit bumpers

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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 \( \approx 3 \times 10^{13} \) p+
– Total intensity in SPS \( \approx 5 \times 10^{13} \) p+

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Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer – 3rd turn

$Q_h = 0.25$

Bump vs. turn

septum

1 2 3 4 5

Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer – 4th turn

$Q_h = 0.25$

Bump vs. turn

septum

1 2 3 4 5

Non-resonant multi-turn extraction

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

$Q_h = 0.25$

Bump vs. turn

septum

1 2 3 4 5

Non-resonant multi-turn extraction

- CERN PS to SPS: 5-turn continuous transfer
  - Losses impose thin (ES) septum…
  - ...a second magnetic septum is 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 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) with the help of transverse excitation (using damper)
  - Variation of field strengths to separate the islands in phase space

- Several big advantages:
  - Losses reduced significantly (no particles at the septum in transverse plane)
  - Phase space matching improved with respect to existing non-resonant multi-turn extraction - ‘beamlets’ have similar emittance and optical parameters

Resonant multi-turn extraction

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

- Slow bumpers move the beam near the septum
- Tune adjusted close to nth order betatron resonance
- Multipole magnets excited to define stable area in phase space, size depends on $\Delta Q = Q - Q_r$

- 3rd order resonances – see lectures by Y. Papaphilippou
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

  $$R_{fp}^{1/2} \propto \Delta Q \frac{1}{k_2}$$

  - Sextupole magnets 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...
    - Fixing the sextupole strength and scanning the machine tune $Q_r$ (and therefore the resonance) through the tune spread of the beam
    - Large tune spread created with RF gymnastics (large momentum spread) and large chromaticity

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**Third-order resonant extraction**

- Particles distributed on emittance contours
- \( \Delta Q \) large – no phase space distortion

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**Third-order resonant extraction**

- \( \Delta Q \) small enough that largest amplitude particle trajectories are unstable
- Unstable particles follow separatrix branches as they increase in amplitude

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**Third-order resonant extraction**

- Sextupole magnets produce a triangular stable area in phase space
- \( \Delta Q \) decreasing – phase space distortion for largest amplitudes

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**Third-order resonant extraction**

- As the stable area shrinks, the circulating beam intensity drops since particles are being continuously extracted

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As the stable area shrinks, the circulating beam intensity drops since particles are being continuously extracted.

On resonance, sextupole kicks add-up driving particles over septum:
- Distance travelled in these final three turns is termed the "spiral step," $\Delta X_{ES}$
- Extraction bump trimmed in the machine to adjust the spiral step

$$\Delta X_{ES} \propto k^2 X_{ES}^2 \cos \theta$$

$\Delta p / p \propto -\Delta Q$

RF gymnastics before extraction:

Slow extraction channel: SPS

$\Delta \phi = \pi$ for small $\Delta p$

$\Delta \phi = -\pi$ for large $\Delta p$

Schottky measurement during spill, courtesy of T. Bohl.
Slow extracted spill quality

- The slow-extraction is a resonant process and it amplifies the smallest imperfections in the machine:
  - e.g. spill intensity variations can be explained by ripples in the current of the quads (mains: \( n \times 50 \text{ Hz} \)) at the level of a few ppm!
  - Injection of \( n \times 50 \text{ Hz} \) signals in counter-phase on dedicated quads can be used to compensate

- A recent example of a spill at SPS to the North Area with large \( n \times 50 \text{ Hz} \) components and another noise source at 10 Hz

Resonant extraction separatrices

- Amplitude growth for 2nd order resonance much faster than 3rd – shorter spills (\( \text{milliseconds vs. seconds} \))
- Used where intense pulses are required on target – e.g. neutrino production

Second-order resonant extraction

- An extraction can also be made over a few hundred turns
- 2nd and 4th 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 2nd order resonance (\( Q \rightarrow 0.5 \))
  - Particle amplitudes quickly grow and beam is extracted in a few hundred turns

Extraction - summary

- 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 low-loss multi-turn extraction
    - create stable islands in phase space: slice off 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.

Thank you for your attention
Appendix

Blow-up from steering error

• So we plug in the new coordinates:

\[ \Delta x_{\text{error}}^2 = \bar{x}_{\text{error}}^2 + \bar{x}_{\text{error}}'^2 \]

\[ = (\bar{x}_0 + L \cos \theta)^2 + (\bar{x}_0' + L \sin \theta)^2 \]

\[ = \bar{x}_0^2 + \bar{x}_0'^2 + 2L(\bar{x}_0 \cos \theta + \bar{x}_0' \sin \theta) + L^2 \]

\[ \cos^2 \theta + \sin^2 \theta = 1 \]

• Taking the average over distribution:

\[ \langle \Delta x_{\text{error}}^2 \rangle = \langle A_i^2 \rangle + 2L\langle \bar{x}_0 \cos \theta \rangle + \langle \bar{x}_0' \sin \theta \rangle + L^2 \]

\[ = 2A_{\text{matched}}^2 + L^2 \]

• Giving the diluted emittance as:

\[ \epsilon_{\text{diluted}} = \epsilon_{\text{matched}} + \frac{L^2}{2} \]

\[ = \epsilon_{\text{matched}} \left[ 1 + \frac{\Delta a^2}{2} \right] \]

Effect of steering error on a given particle

For a general particle distribution, where \( A_i \) denotes amplitude in normalised phase of particle \( i \):

\[ A_i^2 = \bar{x}_{0i}^2 + \bar{x}_{0i}'^2 \]

The emittance of the distribution is:

\[ \epsilon_{\text{matched}} = \langle A_i^2 \rangle / 2 \]