A first taste of Non-Linear Beam Dynamics

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Purpose of the lecture

- Introducing aspects of non-linear dynamics
  - Effects of **nonlinear perturbations**
    - Resonances, tune shifts, dynamic aperture
  - **Mathematical tools** for modelling nonlinear dynamics
    - Power series (Taylor) maps and symplectic maps
  - **Analysis** methods
    - Normal forms, frequency map analysis

- Illustrate methods and tools for a simple example of an accelerator
  - **Storage ring**
Define the **resonance conditions** for periodic lattices

Explain significance of **symplectic maps**, and describe some of the challenges in calculating and applying symplectic maps

Outline some of the **analysis methods** that can be used to characterise nonlinear beam dynamics in periodic beamlines.
Resonances
If we include vertical as well as horizontal motion, then we find that resonances occur when the tunes satisfy

$$m_x \nu_x + m_y \nu_y = \ell$$

where $m_x$, $m_y$ and $\ell$ are integers; resonance is of order $|m_x| + |m_y|$.

Resonances up to order 5

- normal resonances ($= \text{even } m_y$)
- skew resonances ($= \text{odd } m_y$)
Resonances are associated with chaotic motion of particles in storage rings.

The number of resonance lines in tune space is infinite: any point in tune space will be close to a resonance of some order …

This observation raises two questions:

- How do we know what the real effect of any given resonance line will be?
- How can we design a storage ring to minimise the adverse effects of resonances?
Resonance cancellation by periodicity

- By imposing a **periodicity** $P$ in the lattice (i.e. building a machine from $P$ identical cells), the resonance condition becomes

$$m_x \frac{\nu_x}{P} + m_y \frac{\nu_y}{P} = l \quad \Rightarrow \quad m_x \nu_x + m_y \nu_y = P\ell$$

- i.e. the resonance condition needs to be satisfied by each cell, since for the dynamics there is no difference between passing one cell $P \times N$ turns or passing a lattice consisting of $P$ identical cells for only $N$ turns

- Resonances for which $l$ is integer $\rightarrow$ systematic

- If $l$ is NOT integer the resonance cancels $\rightarrow$ non-systematic

![Periodicity P=1](solid lines: normal resonances) ![Periodicity P=2](dashed lines: skew resonances) ![Periodicity P=3](solid lines: normal resonances)
Simple storage ring with periodicity

3 Qx = 1 resonance

\[ m_x \nu_x + m_y \nu_y = P \ell \]
3 Qx = 2 resonance

\[ m_x \nu_x + m_y \nu_y = P \ell \]
Real life example for periodicity: ALS

Advanced Light Source, design lattice periodicity: 12

Measurement of beam loss as function of tune

\[ 72 = 6 \times 12 \]

Synchrotron light beam spot

Uncorrected optics

Corrected optics

Beta beating
Before optics correction: \(~30\%\)
After optics correction: \(<1\%\)

Simulated phase space

D. Robin, C. Steier, J. Safranek, W. Decking, “Enhanced performance of the ALS through periodicity restoration of the lattice”, proc. EPAC 2000.
CERN SPS (hadron machine) has design lattice periodicity of 6

Sextupole resonances can be clearly identified although they should be suppressed by lattice periodicity

Unfortunately the SPS has no individual quadrupoles to restore optics functions distortions (and typical beta beating is only around 10-20%)
Non-linear map representation
For any dynamical variable $x_j$ the **Taylor map** up to $3^{rd}$ order can be written as

$$x_j^{\text{new}} = \sum_{k=1}^{6} R_{jk} x_k + \sum_{k=1}^{6} \sum_{l=1}^{6} T_{jkl} x_k x_l + \sum_{k=1}^{6} \sum_{l=1}^{6} \sum_{m=1}^{6} U_{jklm} x_k x_l x_m$$

**Taylor series** provide a convenient way of systematically representing **transfer maps** for **beamline components**, or sections of beamline.

The **main drawback** of Taylor series is that in general, transfer maps can only be represented exactly by series with an **infinite number of terms**.

In practice, we have to **truncate** a **Taylor map** at some order, and we then lose certain desirable properties of the map. In particular, a **truncated map** will be usually **non-symplectic**.
Symplectic maps

- Consider two sets of canonical variables $\vec{x}_i$, $\vec{x}_f$, which represent the evolution of the system between two points in phase space.

- A map $\mathcal{M} : \vec{x}_i \mapsto \vec{x}_f$ describes the transformation from one set to the other.

- This map is **symplectic**, i.e. it **conserves phase space volumes** when it is applied, if

\[
J^T S J = S
\]

**Symplecticity condition**

where

\[
J_{mn} \equiv \frac{\partial x_{m,f}}{\partial x_{n,i}} \quad S = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix}
\]

**Jacobian matrix** of the map, antisymmetric matrix with block diagonals.

... this is Liouville’s theorem, and is a property of charged particles moving in electromagnetic fields, in the absence of radiation.
The effect of **losing symplecticity** becomes apparent if we compare phase space portraits constructed using symplectic (below, left) and non-symplectic (below, right) transfer maps.

Modelling a storage ring using non-symplectic maps can lead to an inaccurate estimate of the dynamic aperture and the beam lifetime.
There are a number of ways of representing transfer maps to ensure symplecticity. These include:

- Taylor maps can be specially constructed to retain symplecticity with a certain (finite) number of terms. Taylor maps are explicit: once the coefficients have been calculated, the map can be applied simply by substitution of values for the dynamical variables.
- Lie transformations provide a symplectic finite representation for infinite Taylor series, and are useful for analytical studies.

**Symplectic Taylor maps** with a finite number of terms can be constructed for multipole magnets of any order using the “kick” approximation.
Symplectic integration

- Consider a sextupole with equations of motion:
  \[
  \frac{dx}{ds} = p_x, \quad \frac{dp_x}{ds} = -\frac{1}{2}k_2x^2
  \]

- Exact solutions using some elementary functions do not exist

- By splitting integration into three steps, it is possible to write an explicit and symplectic approximate solution

  \[
  \begin{align*}
  0 & \leq s < L/2 : \\
  s & = L/2 : \\
  L/2 & < s \leq L :
  \end{align*}
  \]
  \[
  \begin{align*}
  x_1 & = x_0 + \frac{L}{2}p_{x0}, & p_{x1} & = p_{x0}, \\
  x_2 & = x_1, & p_{x2} & = p_{x1} - \frac{1}{2}k_2Lx_1^2, \\
  x_3 & = x_2 + \frac{L}{2}p_{x2}, & p_{x3} & = p_{x2}
  \end{align*}
  \]

- This is an example of a symplectic integrator known as a “drift–kick–drift” approximation
Analytical methods for nonlinear dynamics
There are two approaches widely used in accelerator physics: **perturbation theory** and **normal form** analysis.

- In both these techniques, the goal is to construct a quantity that is **invariant** under application of the single-turn transfer map. In both cases the mathematics is unfortunately complicated and fairly cumbersome …

In the case of a **single sextupole** in a storage ring, we find from **normal form analysis** the following expression for the betatron action as a function of the betatron phase (angle variable):

\[
J_x \approx I_0 - \frac{k2L}{8} (2\beta_x I_0)^{3/2} \frac{\cos(3\mu_x/2 + 2\phi_x) + \cos(\mu_x/2)}{\sin(3\mu_x/2)} + O(I_0^2)
\]

where \(I_0\) is a constant (an invariant of the motion), \(\phi_x\) is the angle variable, and \(\mu_x\) is the phase advance per cell. The second term becomes **very large** when \(\mu_x\) is close to **third integer**.

The cartesian variables can be expressed in terms of the action–angle variables:

\[
x = \sqrt{2\beta_x J_x} \cos \phi_x,
\]

\[
p_x = -\sqrt{2J_x/\beta_x}(\sin \phi_x + \alpha_x \cos \phi_x)
\]
Normal form for sextupole

$$\mu_x = 0.28 \times 2\pi$$
Normal form for sextupole

\[ \mu_x = 0.30 \times 2\pi \]
Normal form for sextupole

\[ \mu_x = 0.315 \times 2\pi \]
Close inspection of the plots on the previous slides reveals another effect, in addition to the obvious distortion of the phase space ellipses: the **phase advance** per turn (i.e. the tune) **varies** with increasing **betatron amplitude**.

Normal form analysis (and perturbation theory) can be used to obtain **estimates** for the **tune shift** with amplitude.

In the case of a sextupole, the **tune shift** is **higher-order** in the sextupole strength.

An octupole, however, does have a **tune shift** with amplitude in **first-order** of the octupole strength, given by:

\[
\nu_x = \nu_{x0} + \frac{k_3 L \beta_x^2}{16\pi} J_x + O(J_x^2)
\]
The tune shift with amplitude becomes obvious if we track a small number of turns (30) in a lattice with a **single octupole**.

\[ \mu_x = 0.330 \times 2\pi \]

\[ \mu_x = 0.336 \times 2\pi \]
Resonant islands of 4th order resonance

- Simulation of simple storage ring with a **single octupole** close to 4th order resonance
- **Detuning with amplitude** (linear in action)
- Particles in the stable islands have a tune **locked** to the resonance

![Diagram showing resonant islands and tune evolution](image-url)
Resonant islands of 3\textsuperscript{rd} order resonance

- Simulation of simple storage ring with a \textbf{sextupole} and an \textbf{octupole} close to 3\textsuperscript{rd} order resonance
- The \textbf{amplitude detuning} induced by the octupole can create \textbf{stable islands} even for the 3\textsuperscript{rd} order resonance (recall the phase-space plot for the case of a single sextupole)
Impact of resonances on stability

- Perturbation theory and normal form analysis depend on the existence of constants of motion in the presence of nonlinear perturbations.

- The fact that constants of motion can exist in the presence of nonlinear perturbations is a consequence of the Kolmogorov–Arnold–Moser (KAM) theorem.
  - The KAM theorem expresses the general conditions for the existence of constants of motion in nonlinear Hamiltonian systems. Under small perturbations, quasi-periodic phase space trajectories exist.

- Resonances do not necessarily result in loss of stable motion.
  - Resonances will typically tend to drive the amplitudes of particles with a particular tune to large amplitudes.
  - For sufficiently large tune-shift with amplitude, there can be a stable region at amplitudes larger than that at which the resonance occurs (see the example of the octupole in the previous slide).
Onset of chaos and loss of stability

- The overlap of two resonances is associated with a transition from regular to chaotic motion

- The Chirikov criterion describes the parameter range over which the particle motion becomes chaotic
  - It is a geometric criterion of the resonance overlap based on the size of resonance islands
Arnold diffusion

- We have shown phase space portraits for motion in one degree of freedom. In those cases, instability occurred when the oscillation amplitude exceeded a certain value. Chaotic motion can occur also for smaller amplitudes.

- In multiple degrees of freedom, a new phenomenon occurs: **Arnold diffusion**. There can be regions of phase space where invariant tori exist at large amplitudes compared to regions of chaotic motion.

- For storage rings, this means that trajectories with (initially) small amplitudes can be unstable, even if trajectories with much larger amplitudes are stable.
Numerical methods: Dynamic aperture (DA) and Frequency map analysis (FMA)
The most direct way to evaluate the nonlinear dynamics performance of a ring is the computation of **Dynamic Aperture** (short: DA), which is the **boundary of the stable region in co-ordinate space**

- Need a **symplectic tracking code** to follow particle trajectories (a lot of initial conditions) for a number of turns until particles start getting lost → this boundary defines the **Dynamic aperture**

- Dynamic aperture plots show the maximum initial values of stable trajectories in x-y coordinate space

**DA simulations for CLIC damping rings**
LHC design was based on a large campaign of systematic DA simulations (including margin for stability)

- The goal is to allow significant margin in the design – the measured dynamic aperture is often smaller than the predicted dynamic aperture

- A few years after LHC started operating, a measurement of the DA was performed (kicking the beam to large amplitudes)

- Very good agreement between tracking simulations and measurements in the machine

E. Mclean, PhD thesis, 2014
Frequency Map Analysis (FMA)

- Frequency Map Analysis (FMA) is a numerical method pioneered by J. Laskar for putting in evidence the chaotic motion in Solar Systems.

- FMA relies on precise tune determination using the **Numerical Analysis of Fundamental Frequencies (NAFF)** algorithm.
  - When a quasi-periodic function \( f(t) = q(t) + ip(t) \) in the complex domain is given numerically, it is possible to recover a quasi-periodic approximation:

\[
f'(t) = \sum_{k=1}^{N} a'_k e^{i\omega'_k t}
\]

  - in a very precise way over a finite time span, **several orders of magnitude more precisely** than simple Fourier techniques!
Building the FMA from simulations

- Choose coordinates \((x_i, y_i)\) with \(p_x=p_y=0\)
- Numerically integrate the particle trajectories through the lattice for sufficient number of turns (“tracking”)
- Precisely compute \(Q_x\) and \(Q_y\) after a sufficient number of turns
- Plot them in the tune diagram
Frequency Map (example for ALS)

- Computing the tunes $v_x$ and $v_y$ for 2 consecutive intervals through NAFF, allows plotting the **tune variation with a color code in configuration space** $x$-$y$ (left) and **tune space** $v_x$-$v_y$ (right)
  - **small tune diffusion** corresponds to **regular motion**
  - **Large tune diffusion** is associated with **chaotic motion**, it occurs at the dynamic aperture of the machine
  - **Resonances appear as distorted lines in frequency space** (or curves in initial configuration space) → allows to determine which part of the configuration space is affected by which resonances

J. Laskar, “Frequency map analysis and particle accelerators”, PAC 2003
Frequency Map for LHC in collision

Large tune footprint and DA reduction due to “long range beam-beam” forces (electromagnetic field from the other beam in the interaction region)

DA clearly improved when compensating long range beam-beam with a wire

S. Fartoukh et al., PRSTAB, 2015
Experimental frequency maps

- **Frequency analysis of turn-by-turn data** of beam oscillations produced by a fast kicker magnet and recorded on a Beam Position Monitor

- **Reproduced in tracking simulations using the non-linear model of the ALS storage ring**

D. Robin, C. Steier, J. Laskar, and L. Nadolski, PRL 2000
Conclusions and Summary
Nonlinear dynamics appear in a wide variety of accelerator systems, including single-pass systems (such as bunch compressors) and multi-turn systems (such as storage rings).

It is possible to model nonlinear dynamics in a given component or section of beamline by representing the transfer map as a power series.

Conservation of phase space volumes is an important feature of the beam dynamics in many systems. To conserve phase space volumes, transfer maps must be symplectic.

In general, (truncated) power series maps are not symplectic.

To construct a symplectic transfer map, the equations of motion in a given accelerator component must be solved using a symplectic integrator (e.g. the “drift–kick–drift” approximation for a multipole magnet).
Common features of nonlinear dynamics in accelerators include phase space distortion, tune shifts with amplitude, resonances, and chaotic particle trajectories at large amplitudes (dynamic aperture limits).

Analytical methods such as perturbation theory and normal form analysis can be used to estimate the impact of nonlinear perturbations in terms of quantities such as resonance strengths and tune shifts with amplitude.

Frequency map analysis (FMA) provides a useful numerical tool for characterising tune shifts and resonance strengths from tracking data.

This can give some insight into limitations and ways for optimizing the dynamic aperture (DA).