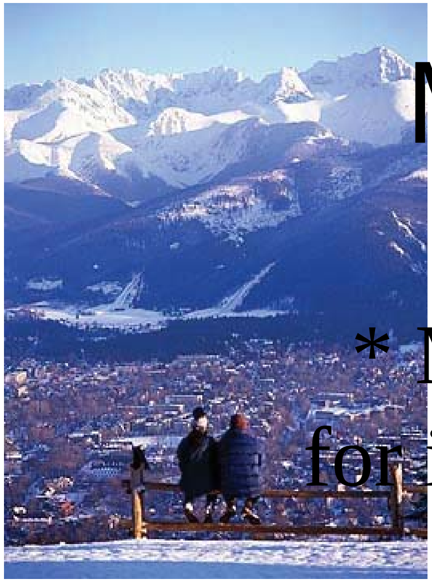
THE CERN ACCELERATOR SCHOOL



Machine apertures

* Many thanks to the organizers for inviting me to give this lecture!

What is the machine aperture? (I)
General introduction

- The aperture is defined by **the maximum amplitude** that a particle can reach while performing its oscillations **before it gets lost**.
- Apertures can be defined in the **transverse** as well as in the **longitudinal** planes:
  - Transverse → *Physical acceptance*, *dynamical aperture*
  - Longitudinal → *Rf-bucket acceptance*, *transverse momentum aperture*
- **Apertures are the main limitation of all accelerators/storage rings.**

What is the machine aperture? (II)
Some remarks!

- The apertures of an accelerator are not only defined by the vacuum chamber, but also by the electromagnetic fields which guide and accelerate the beam, confining it in its 6-dimensional phase space.

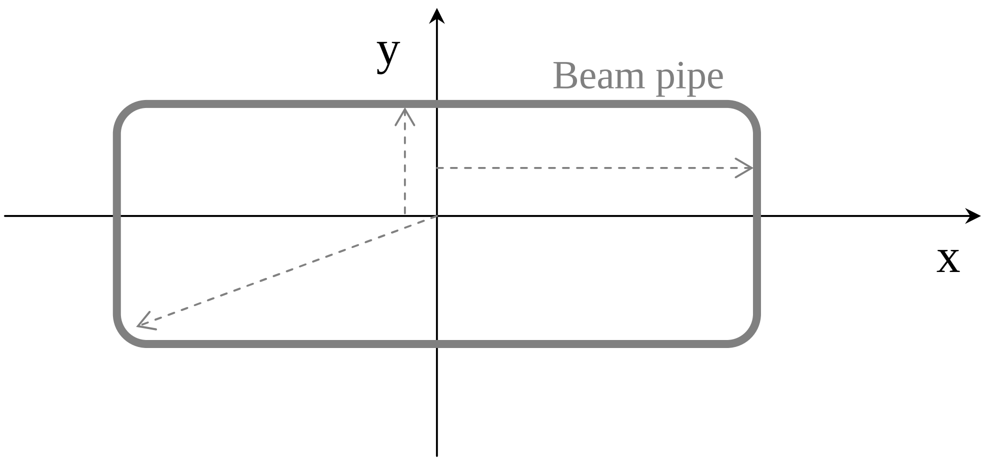
  → **Magnetic fields**: dipoles, quadrupoles, sextupoles, octupoles, IDs, IRs, lattice errors, ...

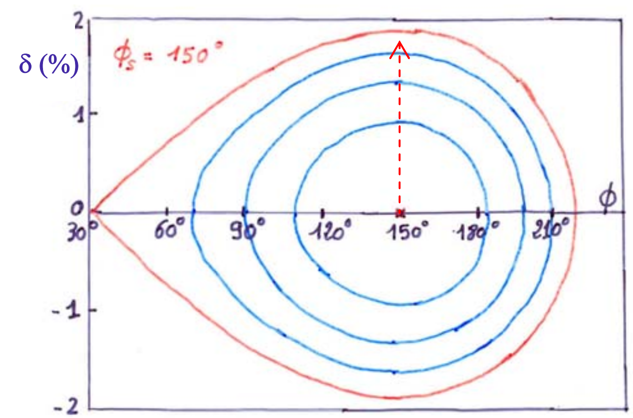
  → **Electric fields**: rf-cavities

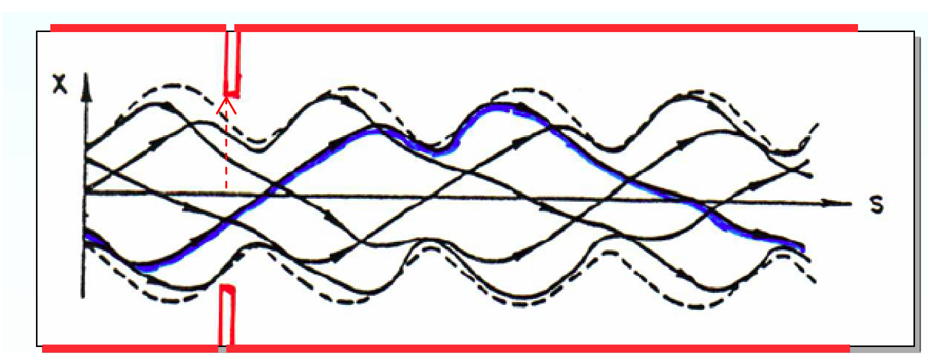
- **Nonlinearities** limit the amplitude of stable motion and can define stable areas that are smaller than the physically available space.

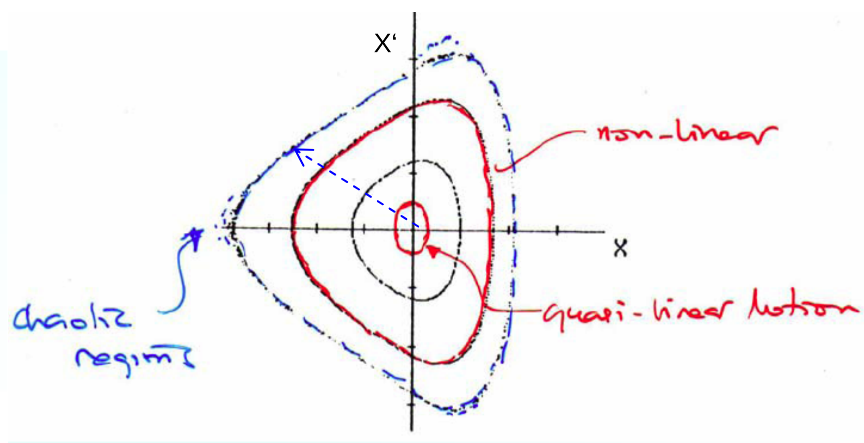
- Particles are eventually ALWAYS LOST at the chamber surface, but they may reach it due to having exceeded these dynamical limits.

What is the machine aperture? (III) Visual impact









What causes beam particles to exceed the aperture limits and be lost? (I)

- Stable beam (**slow losses**):
  - Scattering events with the residual gas molecules (*Elastic Scattering* and *Bremsstrahlung*)
  - Scattering events with particles in the same bunch (*Intra Beam Scattering* and *Touschek effect*)
  - Crossing of resonances (tune modulation) via nonlinearities, space charge, ...
  - Other events that depend on the machine type (e.g., charge exchange in ion rings, scattering between particles in different bunches in colliders, nuclear interactions, ...)

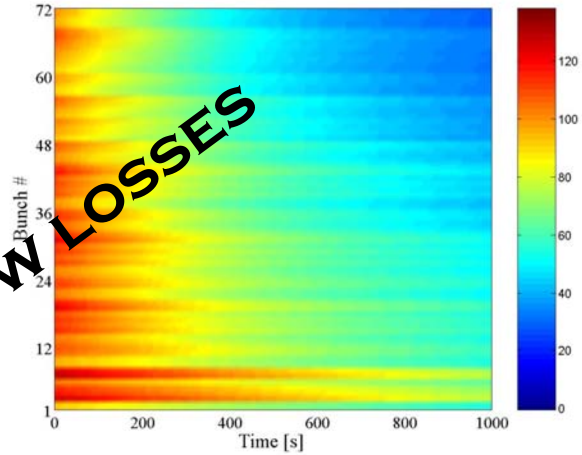
What causes beam particles to exceed the aperture limits and be lost? (II)

- Unstable beam:
  - Electromagnetic interaction of the particle beam with its wake fields (resistive wall, broad-band impedance, narrow-band impedance(s)).

    $\rightarrow$ These phenomena can be short- or long-range and they affect the beam **transversely** or **longitudinally**.
  - Electromagnetic interaction of the particle beam with particles of opposite charge that accumulate in the vacuum chamber (electron clouds and fast-ion instabilities)
- Losses due to instability are generally **very fast**. Slow instabilities can be suppressed by natural damping mechanisms (Landau, radiation) or efficiently cured with feedback systems (transverse and longitudinal dampers).

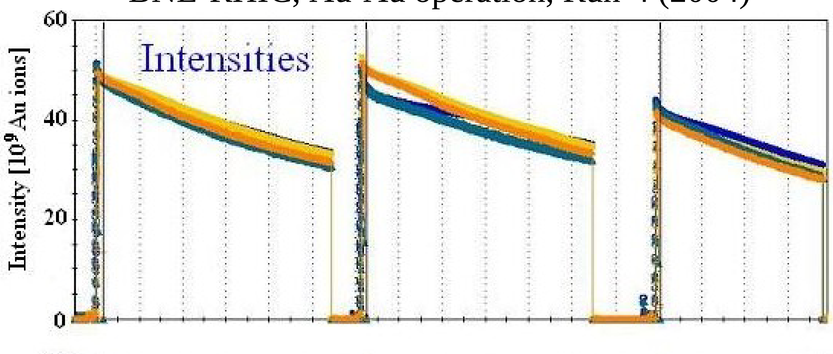
Examples of beam lifetimes (plots show measured beam intensity vs time)

CERN-SPS (I) Bunch by bunch life times with LHC beam (2004)



SLOW LOSSES

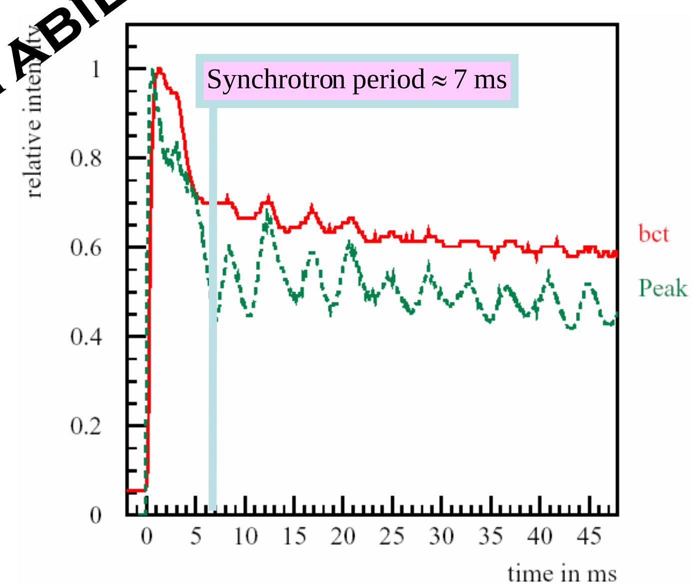
BNL-RHIC, Au-Au operation, Run-4 (2004)



16h

FAST LOSSES: INSTABILITY

CERN-SPS (II) TMC Instability (2003)



Note the different time scale on these plots!

Outline and scope of this lecture

- Physical Aperture
  - Definition
  - Measurement techniques
  - Examples in real machines
- Dynamical Aperture
  - Definition(s)
  - Use of DA concept in simulations for design purposes
  - Measurements in existing machines
- Momentum aperture
  - Definition
  - Measurement techniques and examples

→ Have an overview on the limits of a machine and the methods how to identify them!!

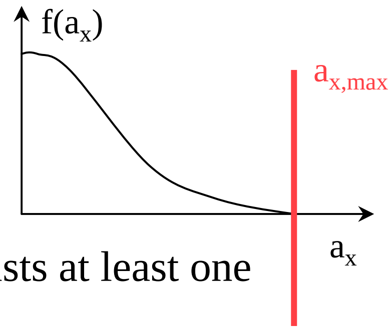
The Physical Aperture

Definition of physical aperture (H)

The **physical aperture** is defined from the particle transverse linear motion and the physical limit $x_{vac}(s)$. We start from the horizontal plane (H):

$$x(s) = \sqrt{a_x \beta_x(s)} \cdot \cos\phi_x(s) + D(s)\delta$$

$$x_{max}(s) = \sqrt{a_{x,max} \beta_x(s)} \cdot \cos\phi_x(s) + D(s)\delta$$



The **physical acceptance** $A_{x,phys}$ is the minimum $a_{x,max}$ such that there exists at least one location s_0 around the machine for which: $x_{max}(s_0)=x_{vac}(s_0)$.

→ It gives the maximum emittance that can be sustained by the machine.

$$A_{x,phys}(\delta) = \min_{s_0 \in [0,L]} \left[\frac{(x_{vac}(s_0) - D(s_0)\delta)^2}{\beta_x(s_0)} \right]$$

$$x_{phys}(\delta, s) = \sqrt{\min_{s_0 \in [0,L]} \left[\frac{(x_{vac}(s_0) - D(s_0)\delta)^2}{\beta_x(s_0)} \right] \beta_x(s)}$$

Definition of physical aperture (V,N)

→ In the vertical plane (V) these definitions are simpler, because in a perfect storage ring the vertical dispersion is zero:

$$A_{y,phys}(\delta) = \min_{s_0 \in [0,L]} \left[\frac{y_{vac}^2(s_0)}{\beta_y(s_0)} \right]$$

$$y_{phys}(s) = \sqrt{\min_{s_0 \in [0,L]} \left[\frac{y_{vac}^2(s_0)}{\beta_y(s_0)} \right] \beta_y(s)}$$

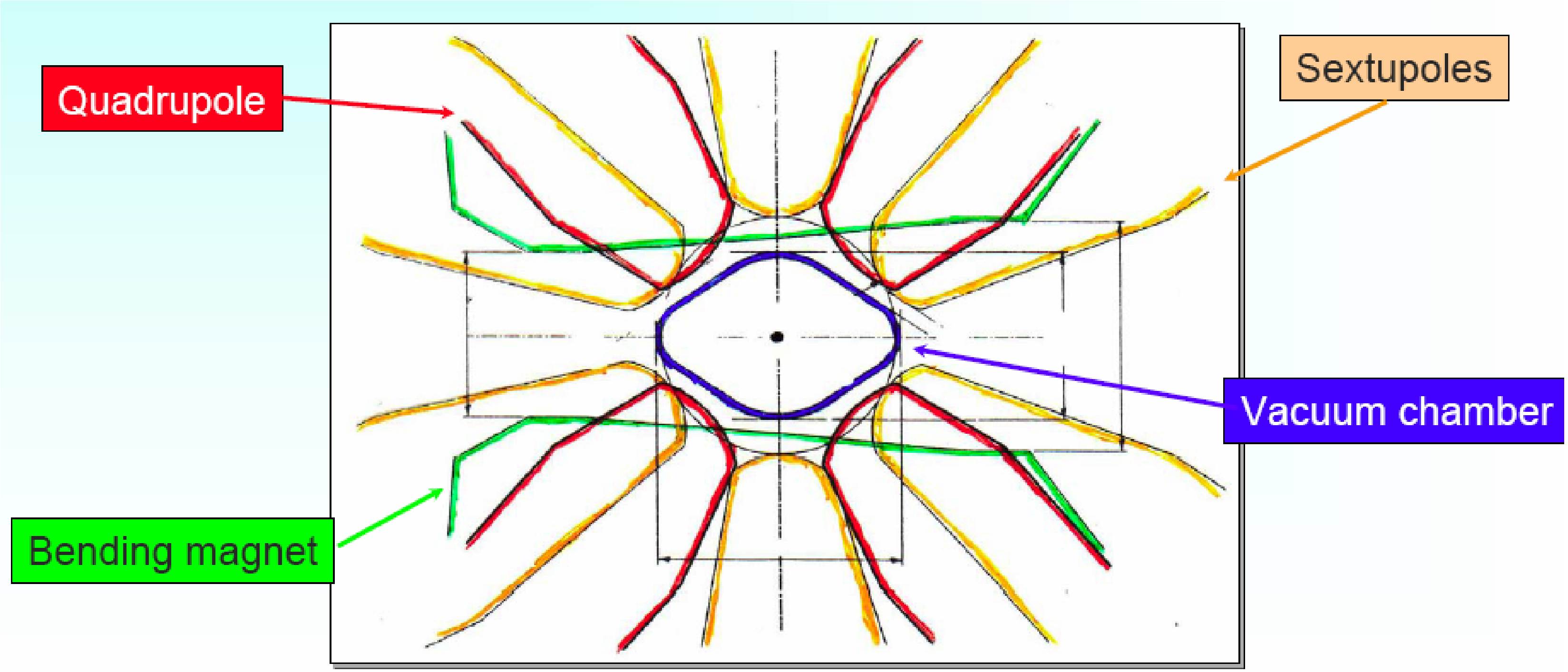
→ It is very useful to express the physical aperture as **number of sigmas with respect to a reference emittance** (i.e. the emittance of the nominal beam put into the machine)

$$N_{x,y} = \sqrt{\frac{A_{(x,y),phys}}{\epsilon_{x,y}}} \quad > N_{(x,y),design}$$

The beam vacuum chamber

What defines the hard limits $x_{vac}(s)$, $y_{vac}(s)$?

The vacuum chamber is mostly designed to stay within the magnet apertures. In field-free spaces it usually accommodates equipments for operation, vacuum, diagnostics or other applications.



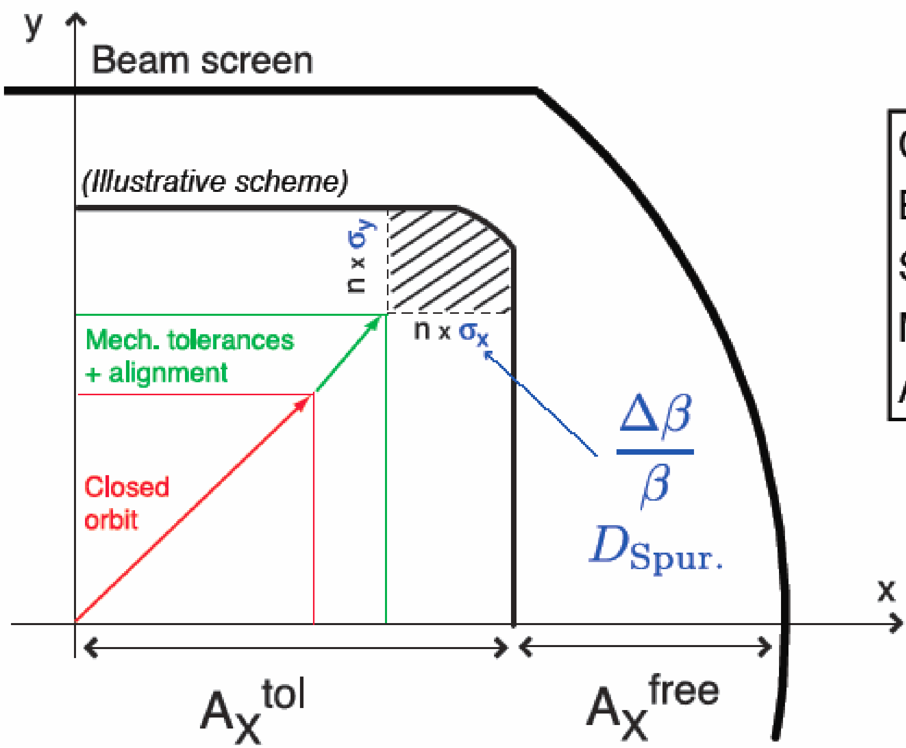
The beam vacuum chamber (II)
some additional information...

- Some designs have constant cross-section radius around the machine.

  Other designs try to match the machine optics: the chamber radius varies according to the model-predicted beta functions.
- Because of the finite conductivity of the pipe material, the chamber is seen by the beam as an impedance (resistive wall effect) and can adversely affect the beam stability.
- The **vacuum pressure** in the beam pipe is a fundamental parameter because many loss mechanisms are associated to interactions of the beam with the residual gas. It often determines the beam lifetime.
- The available space is usually smaller than the pipe geometric radius:
  - Installed equipments may limit it physically
  - Closed orbit error and alignment/mechanical tolerances to be included
  - Since the aperture is usually given in terms of number of sigmas, beta beat and spurious dispersion give a further margin

The beam vacuum chamber (III)

Example: **LHC chamber design**



Tolerance table

Closed orbit	± 4 mm
Beta-beat	± 20 %
Spurious dispersion	27% D_{nom}^{Arc}
Mechanical tolerance	1-2.5 mm
Alignment	1.0.-1.6 mm

$$A_x^{\mathrm{Available}} = \frac{\overbrace{(A_x^{\mathrm{mech}} - A_x^{\mathrm{tol}})}^{A_x^{free}}}{\sigma_x}$$

$$\sigma_i = \sqrt{\beta_i \epsilon}$$

Design criterion: $A_x^{Available} > 7$

Courtesy S. Redaelli

Based on J.B. Jeanneret, LHC-Project-Note 111

Not only vacuum chamber...

- There might be locations around the ring where the mechanical aperture is intentionally made very small:
  - **Septum sheet for injection** (H)

    Injection into a storage ring is normally done in the horizontal plane, sufficient aperture should be allowed for the procedure to be efficient
  - **Physical gap of insertion devices** in light sources (V)
  - **Collimators** (H,V,skew)

    Cut off the beam halo. It is necessary for machine protection and to avoid magnet quenches. They can be retracted.
  - **Scrapers** (H,V,skew)

    Reduce beam current in a controlled way. Remove unnecessary tails to improve beam quality. They are movable.
  - **Momentum cleaning collimators** (H)

    Remove beam particles with high energy deviation in a controlled way

Electrons/positrons

Hadrons

Physical aperture measurements

- There are several methods to determine experimentally the physical aperture of an accelerator/storage ring. We review three of them.

⇒ Controlled Emittance blow-up + Beam Profile (IPM, WS) measurement

It gives a global estimation of acceptance and is normally used for preliminary checks to exclude major obstacles rather than for detailed measurements

⇒ Calibrated Kick + Beam Current (BCT) measurement

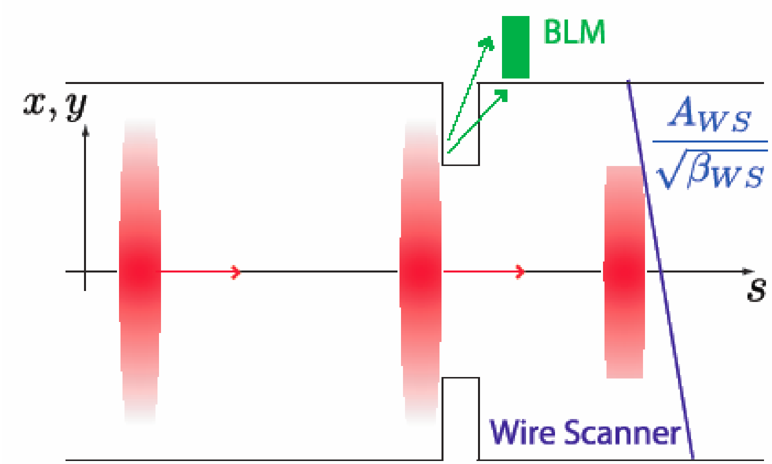
It is local and relies on the combined use of Beam Loss Monitors (BLM) or Beam Position Monitors (BPM) for the loss localization.

⇒ (Sliding) Orbit Bump + Beam Current (BCT) measurement

It is local and can be used to scan the machine in small rings (like light sources) or to identify known bottle-necks in large rings.

∗ Reference: „LHC Aperture Measurements at Injection Energy“, S. Redaelli in 11th Meeting of the LHC Commissioning Working Group

Emittance blow-up + profile scan



Normalized coordinates around CO

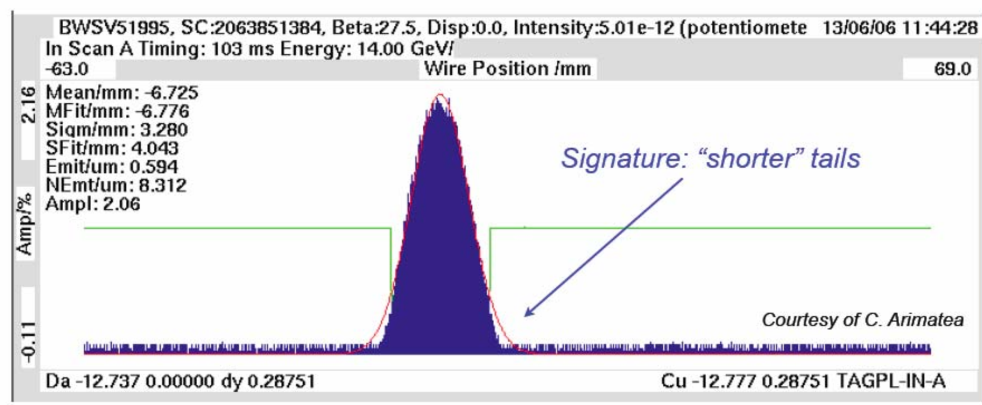
- Blow-up the emittance (transverse noise) until you touch the aperture
- Measurements of scraped beam profile give the machine acceptance
- Get local aperture bottleneck if you know the loss location

Example: SPS experiment

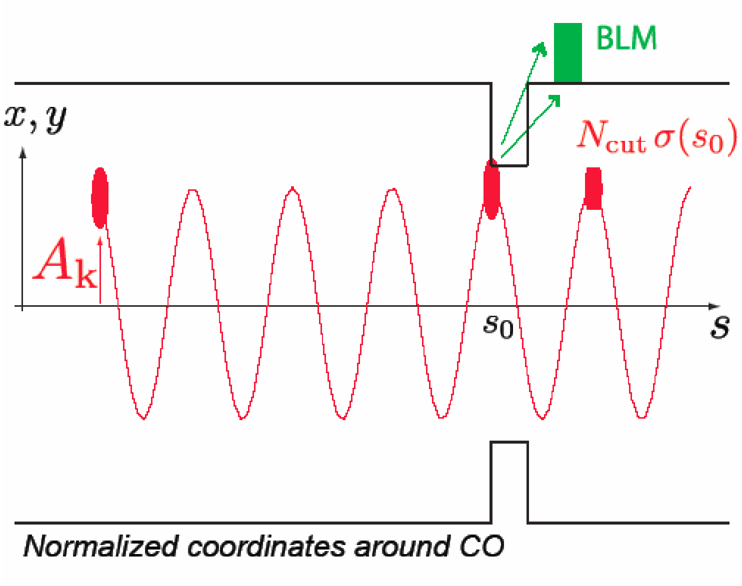
The aperture can be inferred from **the cut in the transverse distribution**.

→ The method relies on the sensitivity of the profile monitor

→ Better with IPM than WS



Kick + Beam Current Measurement

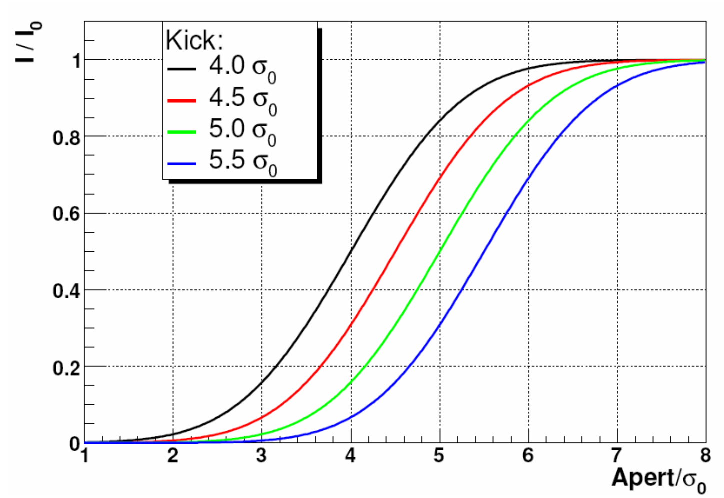


1. Kick the beam until you lose a significant fraction of particles (usually large kick needed)
2. If not previously known, localize the loss location s_0 by means of **BLMs** or from the difference between two consecutive BPM sum signals
3. Use beam current signal and calibration curves (based on some assumption on the beam transverse distribution), to determine the aperture

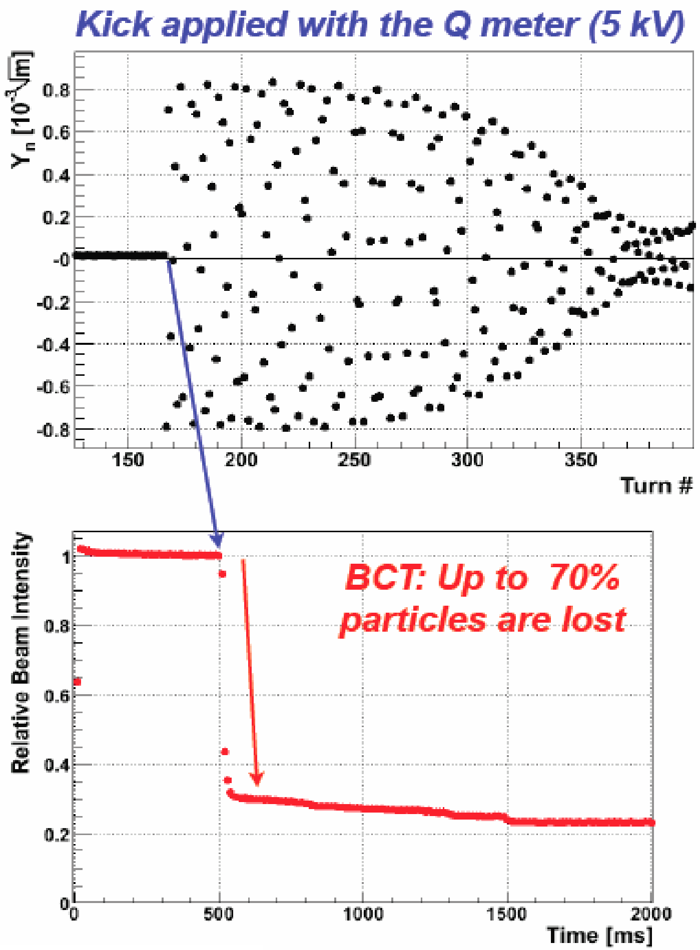
$$A_{mech}(s_0) = A_{kick} + N_{cut}(I/I_0) \cdot \sigma(s_0)$$

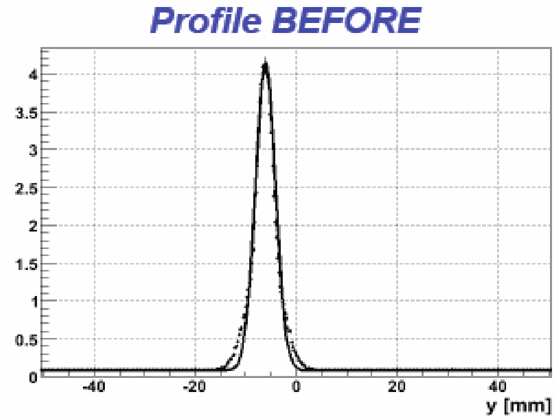
Example of **calibration curves** (Courtesy F. Roncarolo):

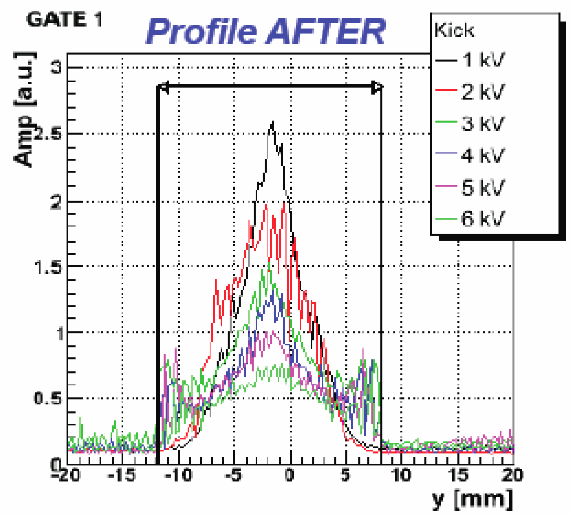
Assuming a **Gaussian distribution**, they associate expected apertures to relative beam losses for a given kick amplitude



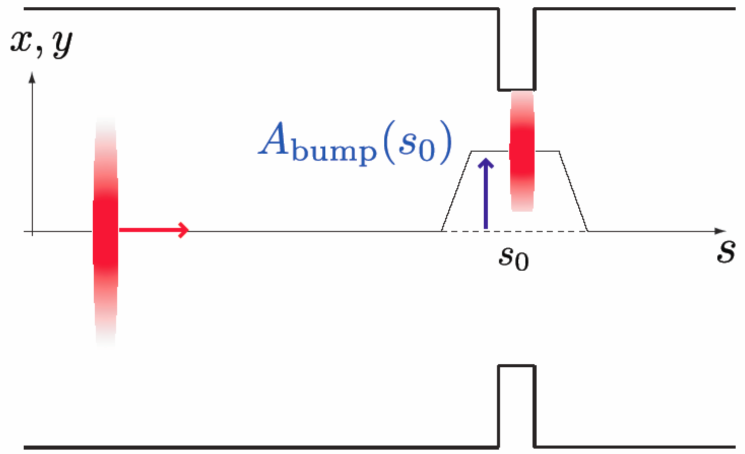
SPS measurements in July 2006 (performed by F. Roncarolo, S. Redaelli, analysis by F. Roncarolo)







Orbit bump + Beam Current Meas.



1. An orbit bump is created at a location where we want to measure/test the aperture
2. The bump amplitude is changed until the aperture is touched and beam loss is observed. The beam can also be kicked while keeping the bump constant.
3. Use beam current signal and calibration curves (based on some assumption on the beam transverse distribution), to determine the aperture

$$A_{mech}(s_0) = A_{bump} + A_{kick} + N_{cut}(I/I_0) \cdot \sigma(s_0)$$

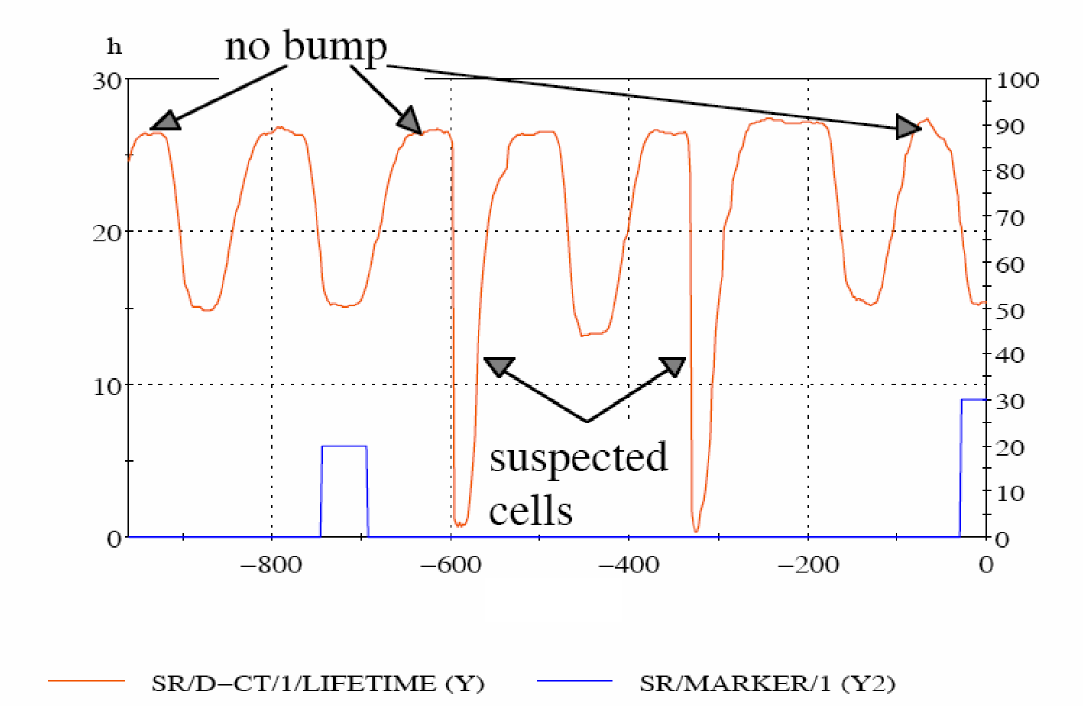
- This method can be used to identify known bottlenecks in a large ring,

  $\Rightarrow$ in the SPS the deformation of a Ti foil was believed to limit the aperture. Check by creating an orbit bump at the suspected location (G. Arduini, F. Roncarolo)

- Sliding bump + kick + lifetime measurements can be used to map a small machine

  $\Rightarrow$ at the ESRF this was used a troubleshooting method to localize obstacles like broken rf-fingers (A. Ropert)

Example of measurement at ESRF



The orbit bump and kick amplitudes are chosen so that the lifetime is at the limit of dropping in a reference cell (where there is certainly no obstacle).

When the bump is slided to test a cell with obstacle, the beam lifetime drops!

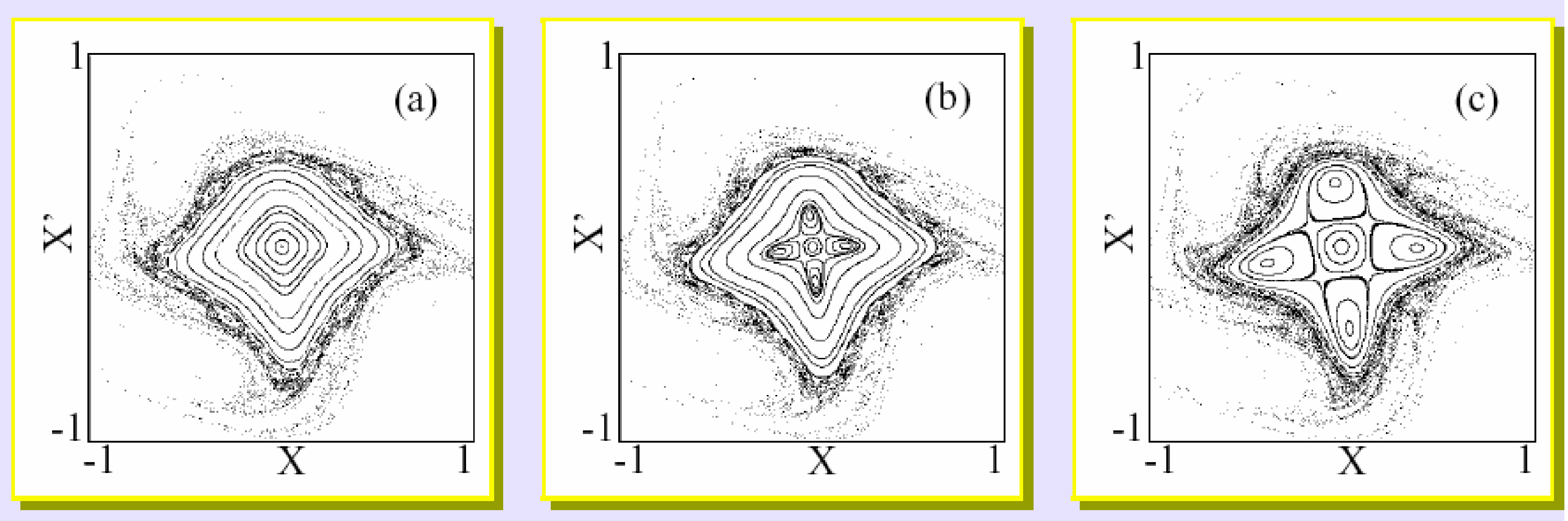
From „Dynamic Aperture Studies at ESRF“, A. Ropert, EPAC‘98

The Dynamic Aperture

Definition of dynamic aperture
Preamble

- **The particle motion in an accelerator would be linear if the lattice were made of perfect dipoles and quadrupoles! Linear motion would be dynamically unbounded.**
- In reality, there are several **sources of nonlinearity** along the beam path:
  - Dipoles and quads are not perfect ⇒ **Multipolar field errors** (fringe fields, large amplitudes, ...)
  - **Sextupoles** are necessary for chromaticity correction (necessary in machines above transition, possibly required for lifetime issues below transition)
  - **Octupoles** are used some times to enhance Landau damping against coherent instabilities (and/or to correct the detuning with amplitude)
  - **Insertion devices** in light sources
  - **Beam-beam** interaction in colliders
  - **Space charge, electron clouds** (typically for high intensities)
- **Nonlinearities are responsible for detuning with amplitude and momentum and thus for a reduction of the stable area available to the beam**

Definition of dynamic aperture
Phase space



Example: CERN-PS with nonlinearities (sextupoles & octupoles) with three different working points: (a) 0.252 (b) 0.249 (c) 0.245

With increasing initial amplitudes, the motion progressively becomes:
linear → nonlinear (with or without islands) → chaotic → unstable

„**Multiturn Extraction using Island Capture**“, **M. Giovannozzi, E. Métral, *et al.***

Definitions of dynamic aperture
An interesting collection...

- „Unlike the physical aperture, the dynamic aperture separating stable (within a given number of turns) and unstable trajectories is not a hard boundary. Rather there exist high diffusion zones where the particles can diffuse to large transverse amplitudes.“

  C. Steier *et al*., Phys. Rev. E, 65, 056506

- „The radius of the largest circle inscribed inside the domain of initial conditions in (x,y) space observed to be stable after 10^5 turns, i.e. about 10 secs of LHC time“

  LHC papers and design reports

- „The maximum stable initial transverse amplitude in the presence of nonlinearities, before the onset of chaotic motion. Stability needs to be checked over few hundreds of turns.“

  C. J. Bocchetta, ELETTRA, CAS-„Synchrotron Radiation and Free Electron Lasers“, Brunnen, July 2003

- „The maximum initial betatron amplitude below which no particle loss takes place within a time interval of interest“

  W. Fischer *et al*., Phys. Rev. E, 55, No. 3, March 1997

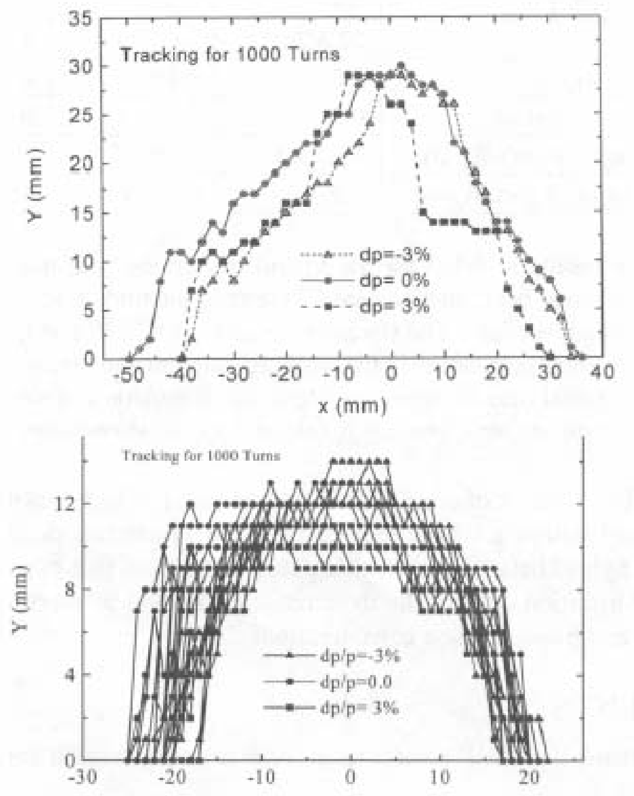
Some D.A. useful information

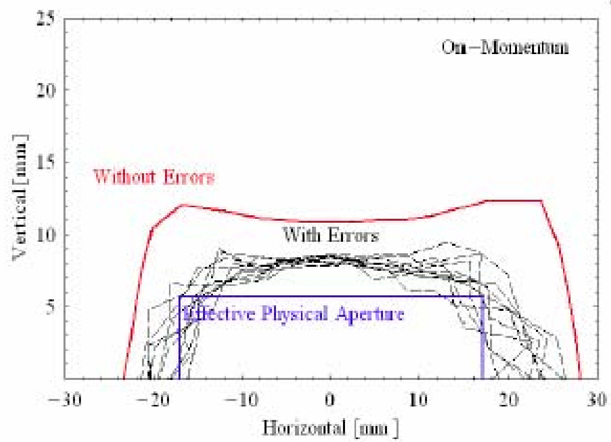
- D.A. studies are very important in the **design of a machine**. They are usually carried out via **tracking** with all the predicted sources of nonlinearities:
  - **Lepton machines** → Few hundreds of turns enough due to radiation damping
  - **Hadron machines** → Hundreds of thousands of turns needed to establish long-term stability
- The ideal machine design always requires **a dynamic aperture larger than its physical aperture**
- The dynamic aperture is generally required to be large, but it can be some times **purposely reduced for extraction**:
  - **Slow extraction** is based on D.A. reduction through tune or nonlinearity strength variation. Particles can slowly move to the large amplitudes and eventually leave the beam pipe through an extraction septum
  - **Multi-turn extraction through island capture in phase space**
- D.A. can be improved by using more sextupoles (→ **harmonic sextupoles**) or octupoles to cancel the effect of the chromaticity sextupoles

D.A. studies with particle tracking

- Maximization of D.A. ⇔ Nonlinear lattice optimization, an essential part of lattice design!
- **D.A. is determined by running numerical tracking of a number of particles over a high number of turns for different sets of nonlinearities. The purpose is to check their survival over the given time.**
  - Tracking is accurate and works for strong and weak nonlinearities
  - Drawbacks: it may give little theoretical insight into nonlinear motion and is usually slow and computer intensive (requires massive simulation campaigns)
  - Several codes exist: MAD-X, SIXTRACK, MICROMAP, TRACY, SAD, DIMAD, MERLIN, PCT...
- Standard nonlinearities used in tracking simulations can be controlled in number, position and strength (like the harmonic sextupoles and the octupoles) or come out of field quality studies (field and multipolar errors) and have generally both systematic and random components.
- A large D.A. for off-momentum particles is also important to guarantee a good lifetime to the beam. Requires reliable off-momentum tracking.

Examples of D.A. tracking simulations



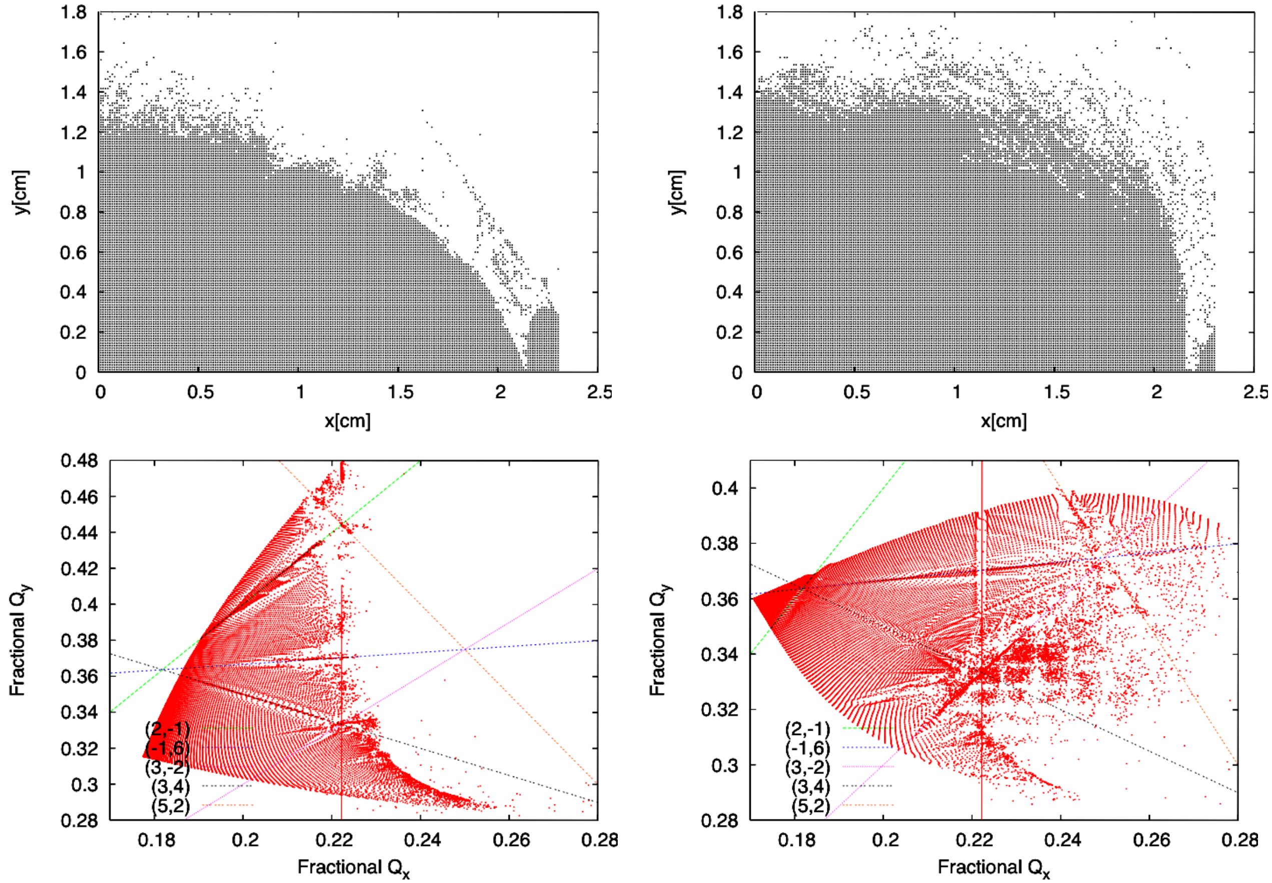


DIAMOND, Dynamic aperture including misalignments, field errors and systematic and random multipole errors and random field errors.

SSRF, Dynamic aperture without and with systematic and random multipole errors and random field errors.

„Optimization of modern light source lattices“, S. L. Smith, in EPAC‘02, Paris

Examples of D.A. tracking simulations

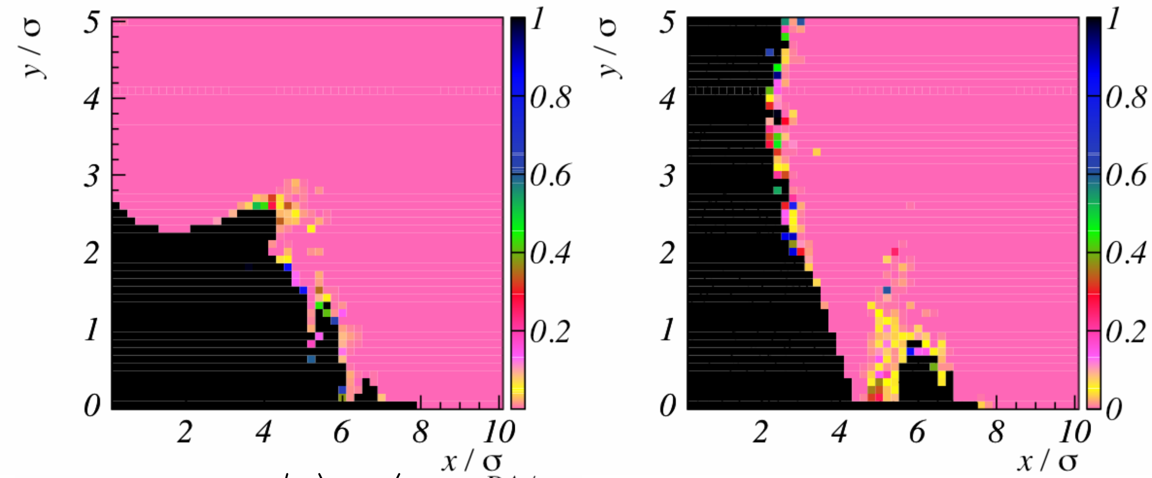


Change of **ALBA** working point brings a clear improvement of vertical D.A.

Frequency maps show the area occupied by the beam in the tune plane and thus which resonance lines are crossed by particles.

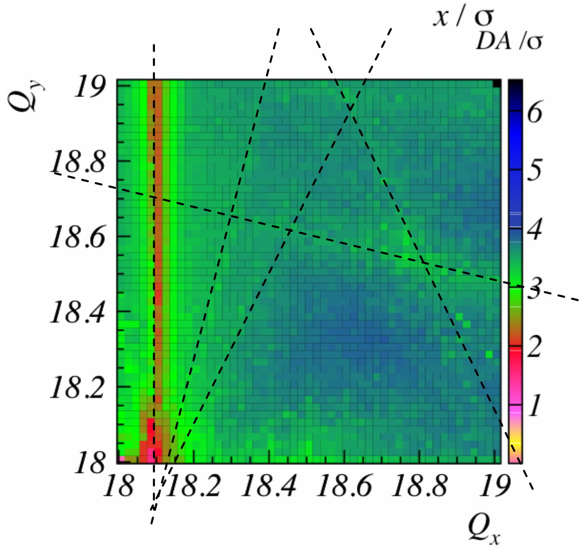
„Dynamic Aperture study for ALBA“, R. Tomás, M. Muñoz, CELLS-Barcelona

Examples of D.A. tracking simulations



GSI-SIS18: D.A. is calculated through tracking with (right) and without (left) **space charge**. The space charge detuning stabilizes a large area in the *y*-plane but reduces the D.A. in the *x*-plane

Palette → percent of surviving beam over 10^5 turns



GSI-SIS100 for the **FAIR Project**

D.A. si calculated over 10^4 turns with magnet powering at 640A. It is shown on the tune plane. Some resonance lines can be more or less clearly identified in spite of the short tracking time. The shift from the nominal position is due to nonlinearity detuning.

Courtesy G. Franchetti, Studies on GSI-SIS18 and FAIR project

Examples of D.A. tracking simulations

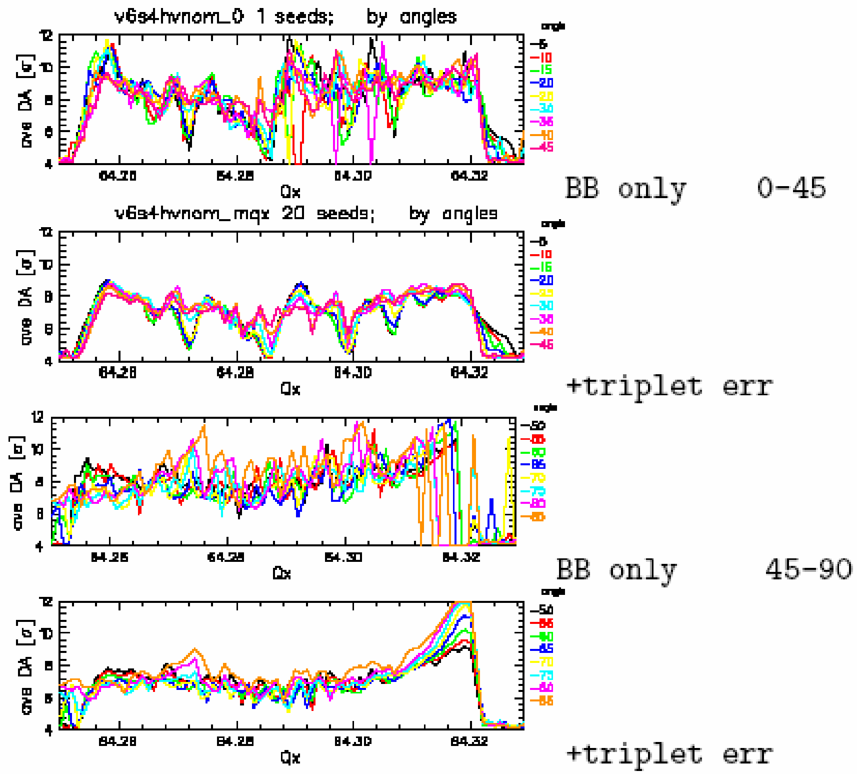
LHC design at the forefront of D.A. tracking: Techniques to make use of large distributed computing facilities allow for denser parameter scans of D.A. Besides, the number of ‚seeds‘ (i.e. possible realizations of multipolar error components around the machine) and the number of turns can be increased.

→ A large campaign to investigate **the effect of head-on and long-range beam-beam collisions on the LHC D.A. for different optical configurations and machine imperfections** is being performed with the **LHC@HOME** project, which uses 60000 hosts for distributed computing.

Some sample results of beam-beam tracking:

- o Preparation of the optics model with MAD-X, tracking done with SixTrack.
- o **20 seeds, 10^6 turns, 17 phase space angles**
- o Different crossing schemes tested (here HV-Nom), and tune split 0.01
- o Beam-beam only or beam-beam plus triplet errors (dominant at top energy)

⇒ **D.A. plotted as a function of Q_x**



W. Herr, D. Kaltchev, E. McIntosh, F. Schmidt, LHC-Project-Report 927

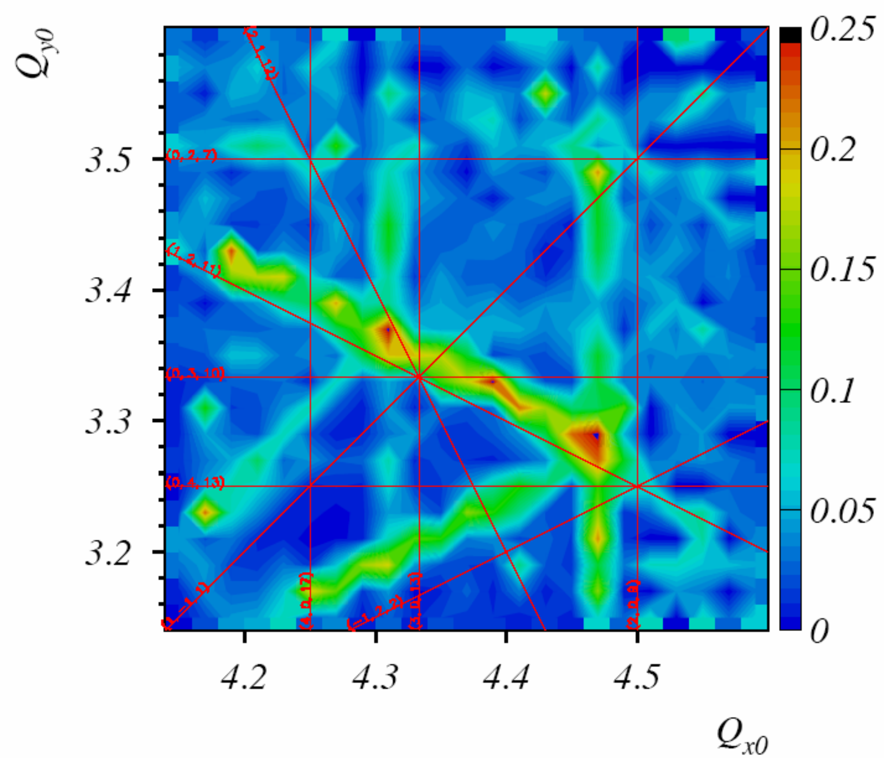
D.A. Measurements: Principles

- D.A. experiments have been carried out in many machines:
  - In some cases it was necessary **to enhance the strength of nonlinearities** to see an effect (e.g. at the SPS)

    → W. Fischer *et al*., Phys Rev. E, 55, No. 3, 1997
  - Some times the multipole errors were enough to see D.A. effects **under normal operating conditions** (especially for machine with superconducting magnets, like at HERA)

    → O. Brüning, *et al*., DESY Report No. HERA 95-05
- Measurements of **beam loss or lifetime scanning the tune plane** give a feel of D.A. as a function of the working point of a machine
- Similar to the techniques discussed for physical aperture measurements, also detailed D.A. measurements can be carried out by
  - Kicking the beam to different amplitudes and observing when the lifetime drops
  - Blowing up the beam emittance by transverse noise or by applying several small dipole kicks, and observing when a cut in the transverse distribution is seen.
- In some experiments an additional tune modulation was applied to the beam to measure D.A. when sweeping a region of the tune plane.

Examples of D.A. Measurements

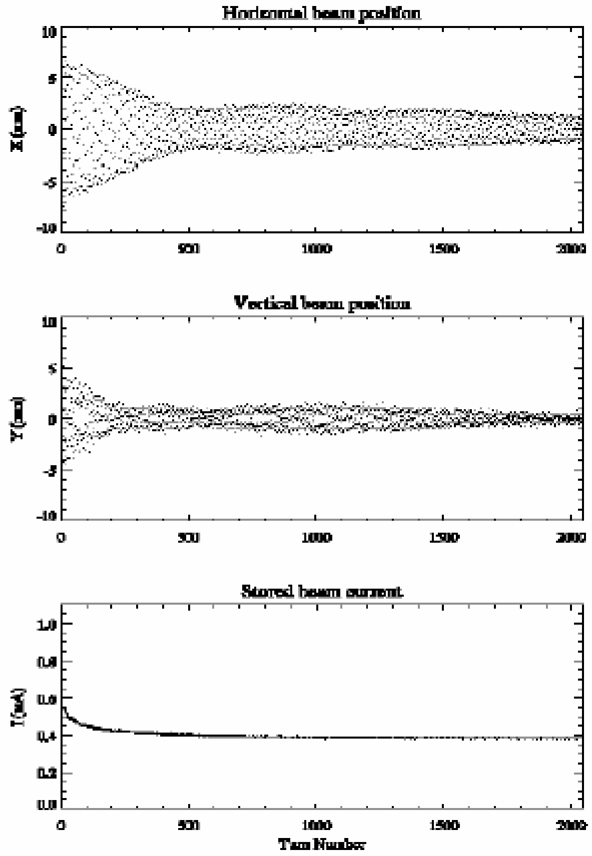


GSI-SIS18: Dangerous resonances in normal operation are identified through a loss scan in the tune plane.

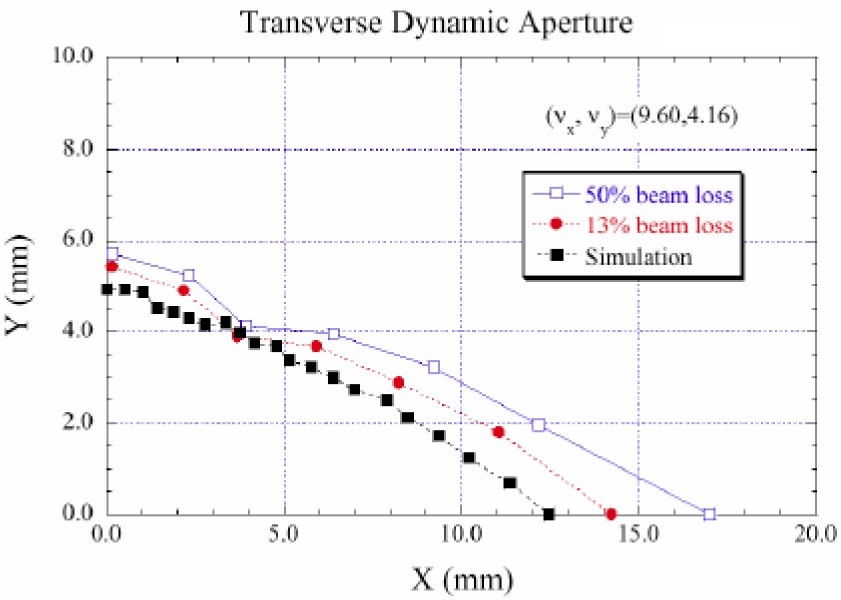
→ palette: initial beam loss rate, $\Delta I(t)/I_0$

G. Franchetti, G. Rumolo, T. Hoffmann, P. Schütt, A. Franchi, GSI-Acc-Note-2005-02-001

Examples of D.A. Measurements

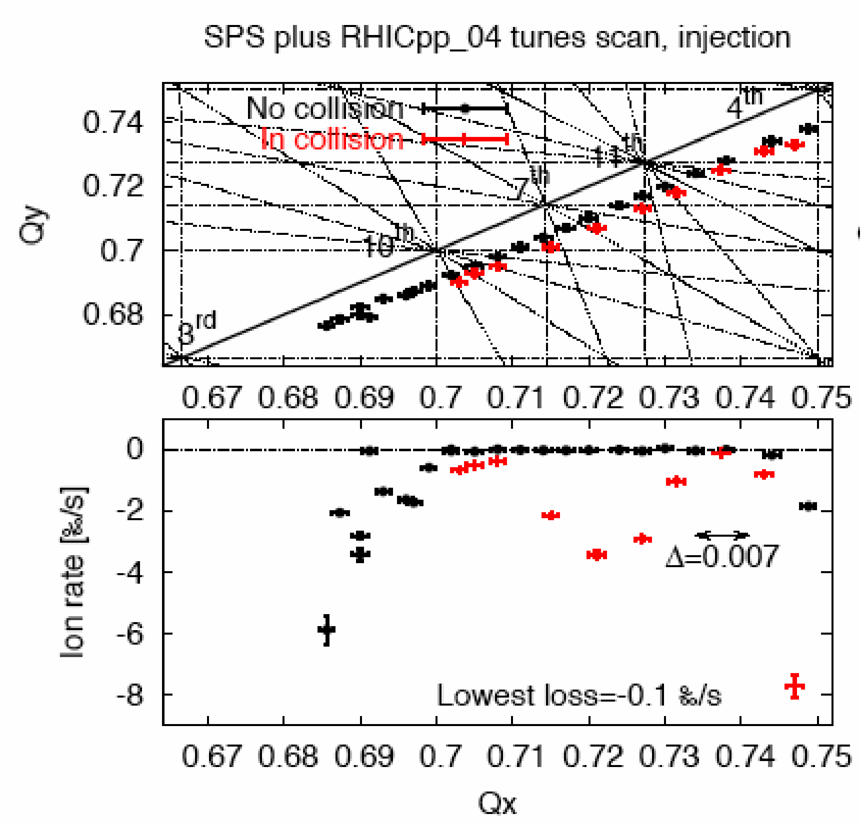


Kick then measure on fast position monitors and loss rates



Photon Factory EPAC'00 **Y.Kobayashi and K. Haga**

Examples of D.A. Measurements



BNL-RHIC: SPS and RHICpp_04 working points are scanned with and withut collisions (degradation of the D.A. due to beam-beam effect). Experimental study done at injection energy

„Quest for a new working point in RHIC“, R. Tomás, 2004

The Momentum Aperture

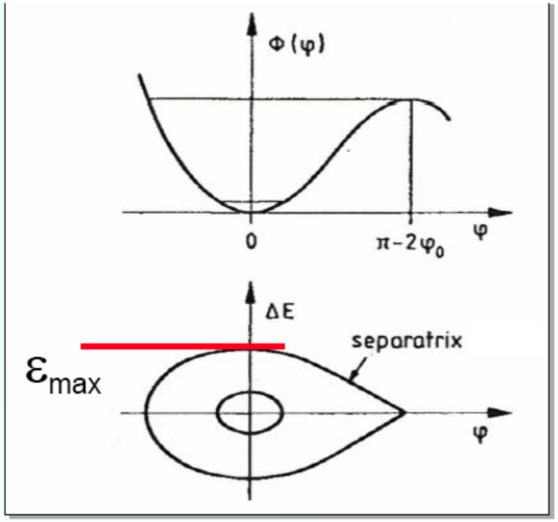
Definition of momentum aperture
Rf-acceptance

- In the longitudinal plane the **acceptance** is determined by the rf system and is a function of the rf voltage and the magnetic lattice through the slip factor.
  → **The rf acceptance is constant along the lattice!**
- A **large acceptance is needed in the longitudinal plane** to accommodate particles that suffer large momentum changes because of bremsstrahlung and/or Touschek effect and guarantee a good beam lifetime.

Particles are trapped in the potential well of the rf field and their motion is therein bounded. Their momentum deviation must not exceed:

$$\epsilon_{rf} = \pm \left[\frac{2U_0}{\pi|\eta|hE_0} \sqrt{\left(\frac{V_{rf}}{U_0}\right)^2 - 1} - \arccos\left(\frac{U_0}{V_{rf}}\right) \right]^{1/2}$$

The **separatrix** is the limit (in phase space) of stable motion!



Definition of momentum aperture
Transverse momentum acceptance

A particle on axis that suffers a **large angle collision or bremsstrahlung** at the ring location s_0, and its momentum deviation changes to δ_0, moves on a different closed orbit and starts executing oscillations around it with invariant (ellipse area):

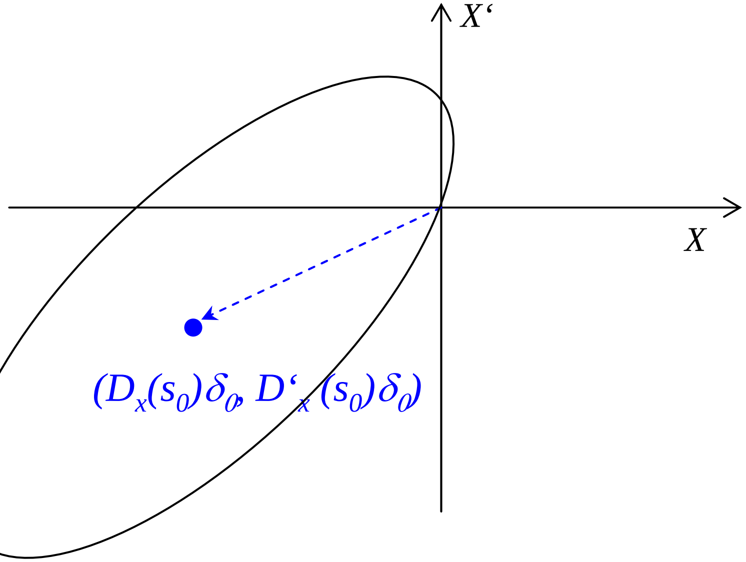
$$\mathrm{H}(s_0)\delta_0^2 = \left[\gamma_x(s_0)D_x^2(s_0) + 2\alpha_x(s_0)D_x(s_0)D_x'(s_0) + \beta_x(s_0)D_x'^2(s_0)\right]\cdot\delta_0^2$$

which translates into an induced betatron amplitude:

$$\sqrt{\beta_x(s)\mathrm{H}(s_0)}\delta_0$$

and consequently a maximum acquired horizontal displacement:

$$x_{max}(s) = \left[\sqrt{\beta_x(s)\mathrm{H}(s_0)} + D_x(s)\right]\delta_0$$



Definition of momentum aperture

Momentum aperture

The **transverse momentum acceptance** is defined as **the minimum momentum deviation** such that there exists at least one location s_1 along the ring where the particle hits the horizontal aperture, $x_{max}(s_1)=\min[x_{phys}(s_1),x_{dyn}(s_1)]$

$$\epsilon_{trans} = \min_{s_1\in[0,L]}\left[\frac{\min(x_{phys}(s_1),x_{dyn}(s_1))}{D_x(s_1)+\sqrt{\mathrm{H}(s_0)\beta_x(s_1)}}\right]$$

The **overall momentum aperture** is the smaller of the rf-momentum acceptance and the transverse momentum acceptance

$$\epsilon_{max} = \min\left[\epsilon_{rf},\epsilon_{trans}\right]$$

Definition of momentum aperture

What happens if... ?

$$\epsilon_{max} = \min\left[\epsilon_{rf}, \epsilon_{trans}\right]$$

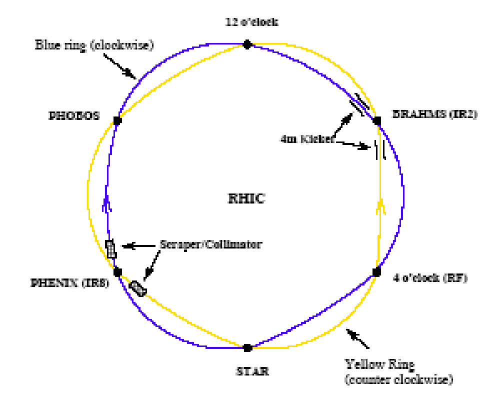
- If $\varepsilon_{rf} > \varepsilon_{trans}$ particles cannot get outside the rf-bucket because they would already be horizontally lost at highly dispersive locations before reaching the separatrix.
- If $\varepsilon_{rf} < \varepsilon_{trans}$ particles can in principle occupy all the bucket and move to however large synchrotron amplitudes within its limits.When they cross the separatrix and leave the bucket:
  - In lepton machines, they are usually lost after few turns because they get out of synchronism with the energy loss compensation and quickly reach the transverse momentum aperture limit. But they could also get back or be trapped in another bucket thanks to radiation damping.

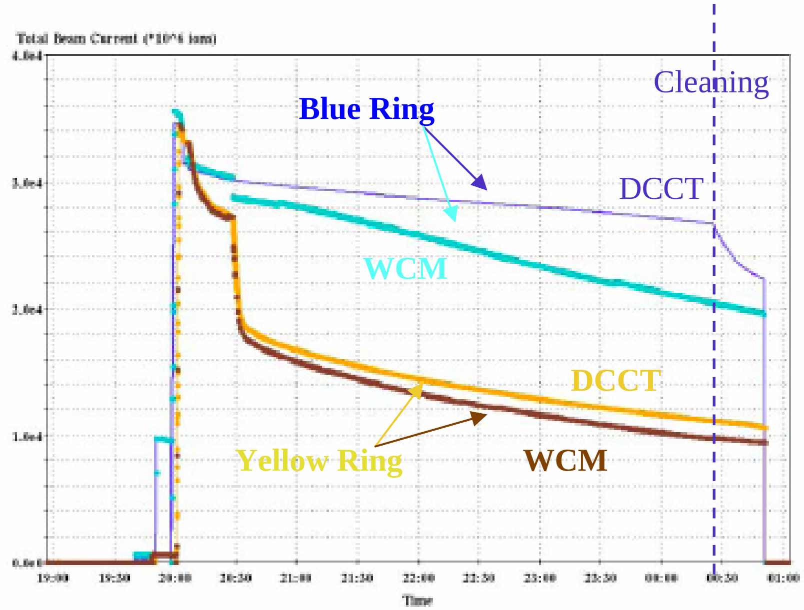
    → However, Touschek effect usually determines lifetime in light sources
  - In hadron machines, they are also lost if they leave the bucket during the accelerating ramp. They might stay in the machine and be seen as a „debunched beam“ background if the bucket is stationary (proton/ion storage rings or synchrotrons at flat top/bottom)

Momentum aperture

We can observe its effects

- $\varepsilon_{rf} < \varepsilon_{trans}$ $\Rightarrow$ In RHIC for example ions scattered out of the bucket because of IBS, keep staying in the machine as a „debunched beam“ and cause background in the IRs
- It can be seen looking at the difference between average (**DCCT**) and peak (**WCM**) current signals.
- It can be removed through a gap cleaning procedure, which uses fast transverse kickers and collimators (applied in the last 30 minutes in the Blue Ring in the fill shown).



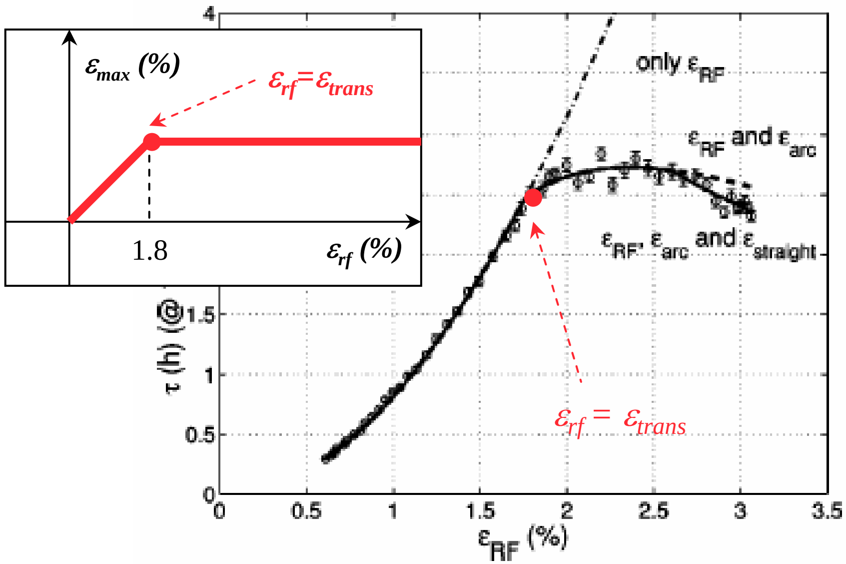


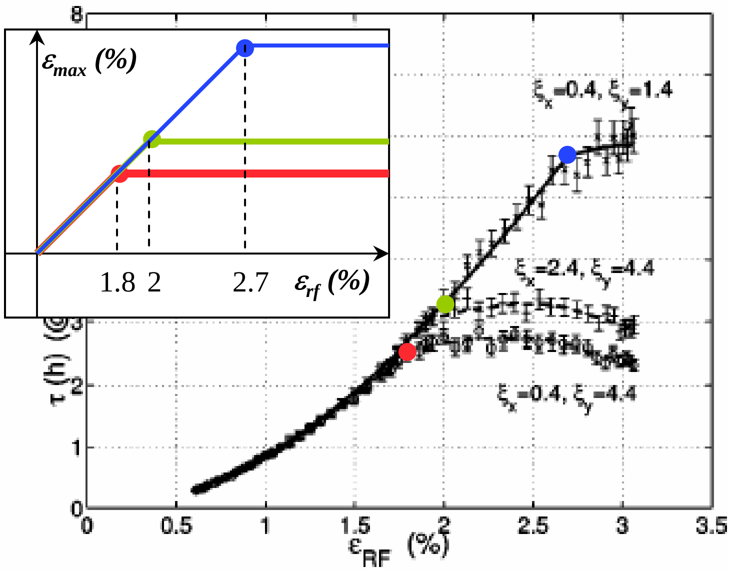
„Abort Gap Cleaning in RHIC“ A. Drees *et al.*, EPAC‘02, Paris

Momentum aperture

Lifetime measurements at the ALS

- An easy way to study whether the momentum aperture of a ring is solely determined by the rf-momentum aperture or whether it is also limited by other apertures, is **to vary the rf voltage and measure the lifetime**. It was applied at the **LBNL-ASL**
- The momentum aperture of the ring is the rf-momentum aperture as long as the calculated Touschek lifetime corresponds to the measured one.
- High chromaticity causes a reduction of the momentum aperture due to reduction of the dynamic aperture caused by the sextupoles for chromaticity overcompensation





C. Steier, *et al.*, Phys. Rev. E, 65, 056506

Momentum aperture

Advanced concepts - Periodic Resonance Crossing

- Chromaticity can also cause a reduction of momentum aperture through a more subtle mechanism.....
- The mechanism is called **periodic resonance crossing**:
  - When performing synchrotron oscillations, particles detune and move to the large amplitudes due to crossing a resonance which traps them in islands.
  - These particles go out of the dynamic aperture and are eventually lost.
- Chromaticity causes a cut in the synchrotron phase space. Particles whose synchrotron amplitudes are large enough get lost, even if they have not reached yet the transverse momentum aperture
- This phenomenon can be driven not only by chromaticity, but by whatever transverse tune modulation mechanism associated to the longitudinal oscillations.
- Space charge and electron cloud are good candidates.

⇒ **Periodic crossing of resonances is a different mechanism for particle loss that can set a lower limitation to the momentum aperture**

Thanks to all those who were patient enough to provide me with examples and plots for this lecture and/or critically went through its contents several times and came up with corrections, comments, suggestions, ...

G. Arduini, M. C. Bellachioma, G. Bellodi, D. Brandt, H. Burkhardt, A. D'Elia, W. Fischer, G. Franchetti, A. Franchi, W. Herr, P. R. Jarnhus, F. Le Pimpec, A. Mostacci, E. Métral, B. Muratori, Y. Papaphilippou, T. Pieloni, S. Redaelli, F. Roncarolo, R. Tomás, F. Zimmermann

What causes beam particles to exceed the aperture limits and be lost? (II)

- Stable beam (**slow losses**), cont'd:
  - Some of these mechanisms (***elastic scattering, IBS, resonance crossing***) are usually associated to a slow diffusion of beam particles toward the large betatron amplitudes (beam halo), where problems could be even enhanced by the nonlinear magnetic fields.
  - Other mechanisms (***bremsstrahlung, Touschek, charge exchange, nuclear interactions***) are mainly responsible for abrupt changes of the particle momentum or charge. Particles that suffer these events (and remain within the machine rf-defined longitudinal acceptance) end up performing large betatron oscillations around dispersive orbits.

Definition of physical aperture (V)

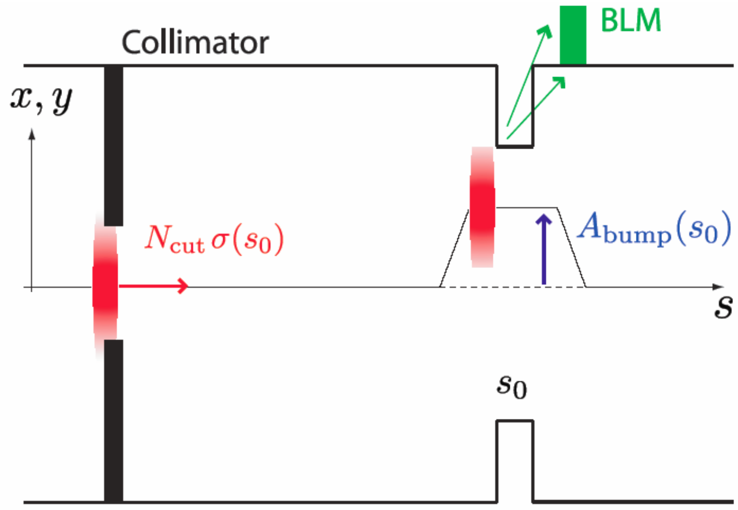
In the vertical plane (V) these definitions are similar. It is actually simpler, because in a perfect storage ring the vertical dispersion is zero, and therefore the terms with dispersion disappear and all the definitions become independent of the energy deviation δ.

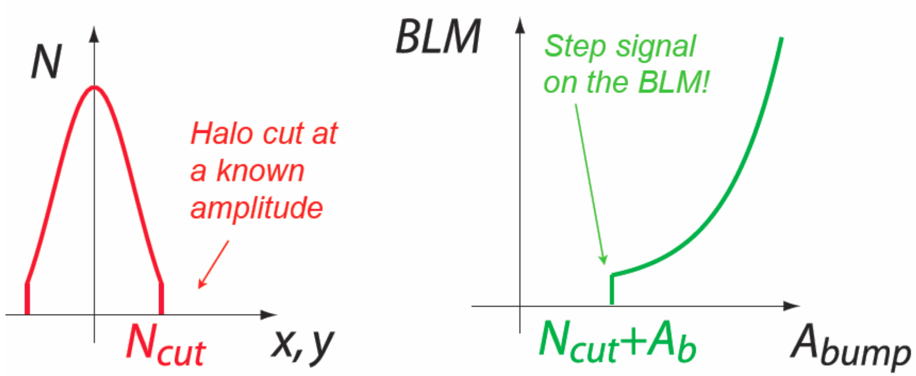
$$y(s) = \sqrt{a_y \beta_y(s)} \cos \phi_y(s) \qquad y_{max}(s) = \sqrt{a_{y,max} \beta_y(s)} \cos \phi_y(s)$$

$$A_{y,phys}(\delta) = \min_{s_0 \in [0,L]} \left[\frac{y_{vac}^2(s_0)}{\beta_y(s_0)} \right]$$

$$y_{phys}(s) = \sqrt{\min_{s_0 \in [0,L]} \left[\frac{y_{vac}^2(s_0)}{\beta_y(s_0)} \right] \beta_y(s)}$$

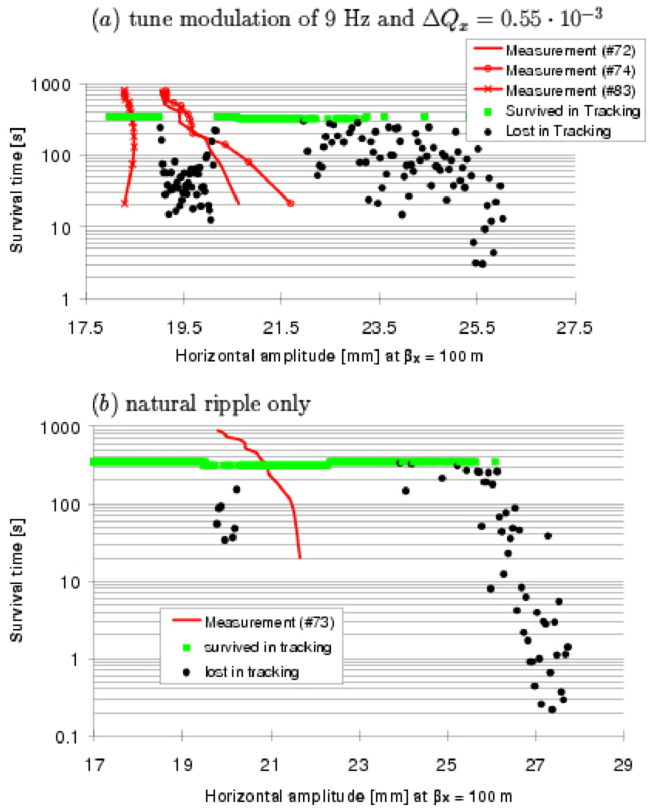
Orbit bump + Beam Loss Measurement

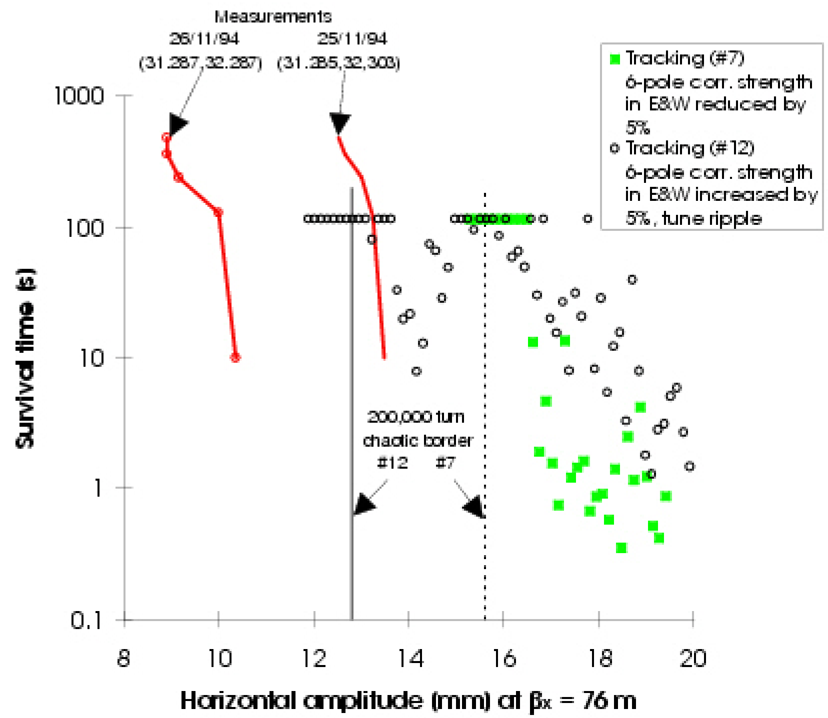




1. An orbit bump is created at a location where we want to measure/test the aperture. Upstream from the orbit bump the beam is collimated and reduced down to a known size
2. The bump amplitude is changed until the aperture is touched and **beam loss** is observed. The beam can also be kicked while keeping the bump constant.
3. While the bump and/or kick amplitude is changed, the **BLM signal** jumps from 0 to a finite value.
4. The discontinuity in the **BLM signal** is the indicator that the aperture has been touched.

Examples of D.A. Measurements





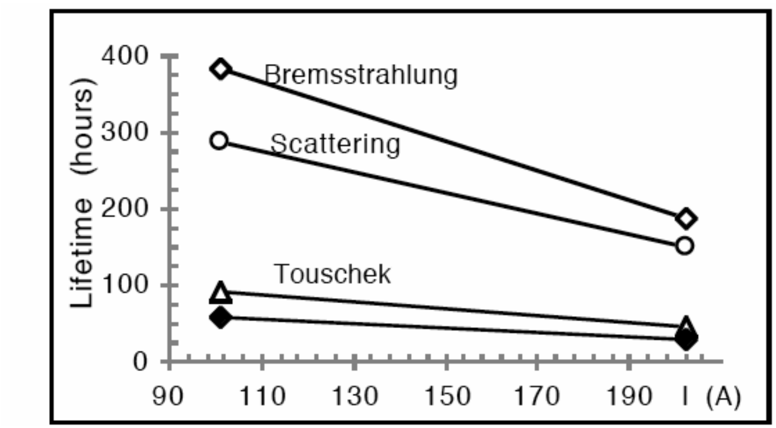
CERN-SPS (left):D.A. experiment and simulations, with enhanced nonlinearities and with or w/o tune modulation. Nonlinearities were controlled → good agreement between simulation and experiment

DESY-HERA (right): D.A. experiment and simulations with nonlinearities from persistent currents at injection. Not controlled nonlinearities → the agreement between simulations and experiment is not very good

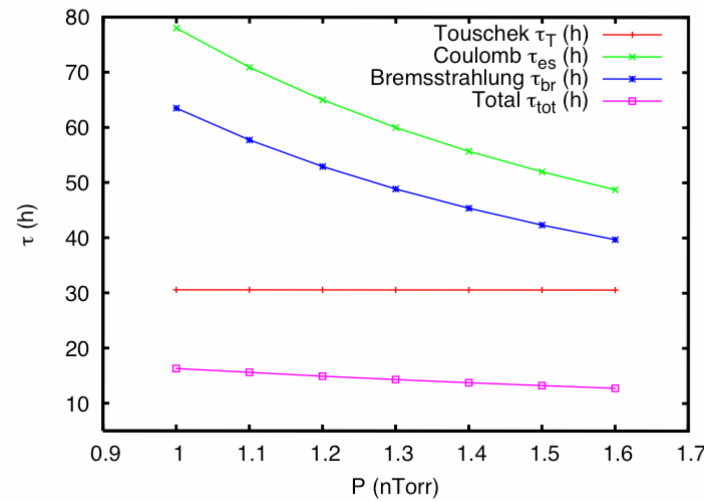
Courtesy: W. Fischer, BNL

Momentum aperture
It determines beam lifetime

- $\varepsilon_{rf} < \varepsilon_{trans}$ ⇒ In well designed light sources the limit comes from the rf. ε_{rf} is usually around 2% for existing machines. Targets are up to 4 - 5% for new machines
- With the present values of rf acceptance, the beam lifetime is generally dominated by the Touschek effect



ESRF - Lifetime as a function of beam current



ALBA - Lifetime as a function of vacuum pressure

„Litetime issues in ESRF“ A. Ropert, EPAC‘02, Paris; G. Rumolo, M. Muñoz, AAD-SR-BD-AN-0072