Injection and Extraction

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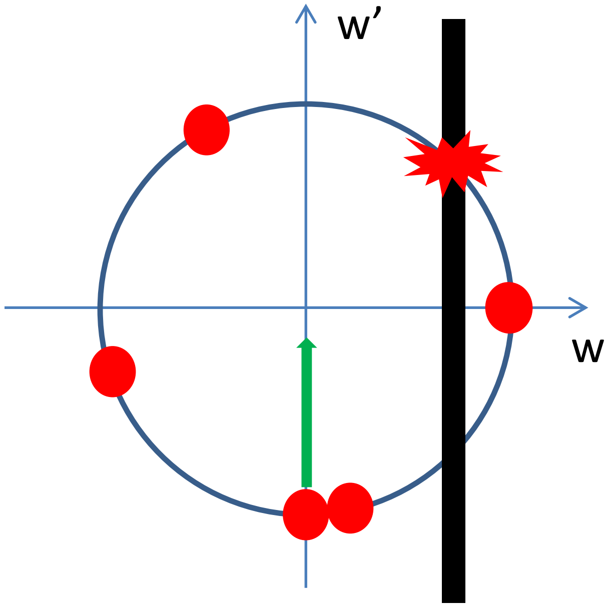
* Linear collider is not mentioned in this lecture but injection and extraction are relevant for damping rings

Basics (1)

- How to inject/extract beam into/from rings
  - Ring accelerator has a *closed orbit* (No entrance/exit)
  - *Kicker* is used to place the beam onto (or to temporarily open) the closed orbit
  - Kicker is normally not strong enough, and *Septum* is then used
  - Extraction is essentially a reversal process of injection



Basics (2)

- Kicker
  - Driven by high voltage pulse
  - $B_y \sim \mu_0 \frac{NI}{G}$ (static field approximation)

    μ_0: Permeability in vacuum

    $4\pi \times 10^{-7}$ (H/m)

    N : Conductor number of turns

    I : Current (A)

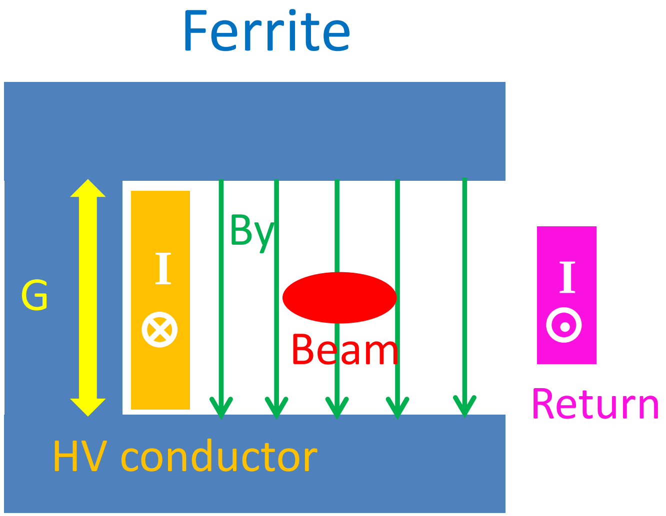
    G : Gap height (m)
  - Kick angle, $\theta \sim B_y L_k / B\rho$

    L_k : Kicker length (m)

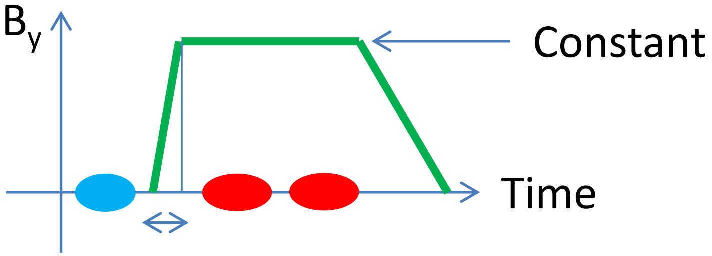
    $B\rho$: Magnetic rigidity (Tm)
    - Beam momentum

    $P(GeV) = 0.3 B\rho(Tm)$
  - For high energy beam (β~1), E-field contribution is marginal

Cross section of typical ferrite kicker



"Good kicker"



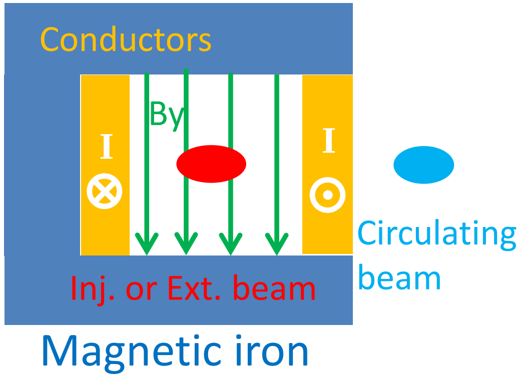
Short rise time

(Fall time is important for some cases)

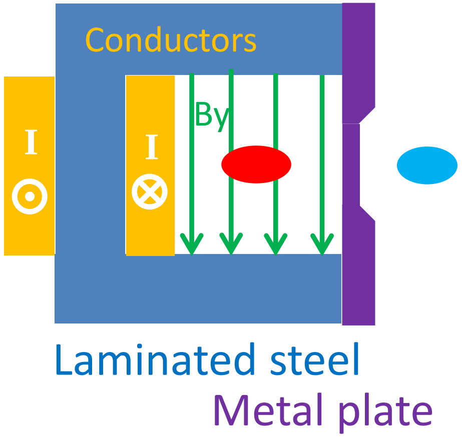
Basics (3)

- Septa
  - B-field only inside the channel
  - DC or Pulse magnet
  - The equations in the last slide are valid to evaluate approx. septum deflection angle
  - Lambertson septum
    - Ver. separation and hor. deflection and vise versa
    - Relatively strong deflection with thin septum wall

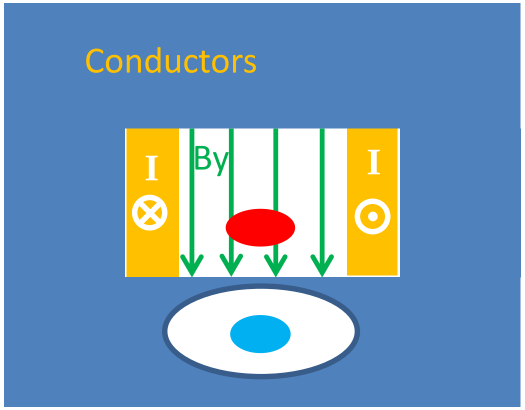
Cross section of typical DC septum



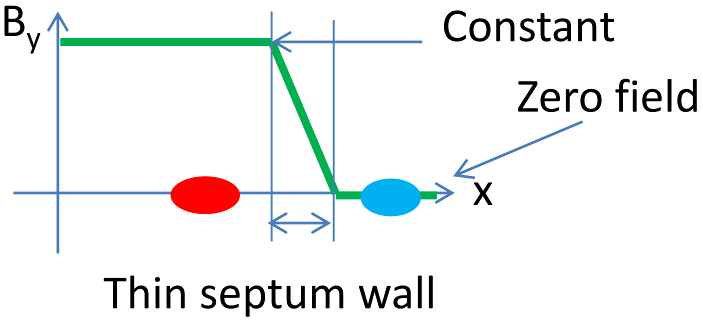
Cross section of typical pulse septum



Typical Lambertson septum



"Good septum"

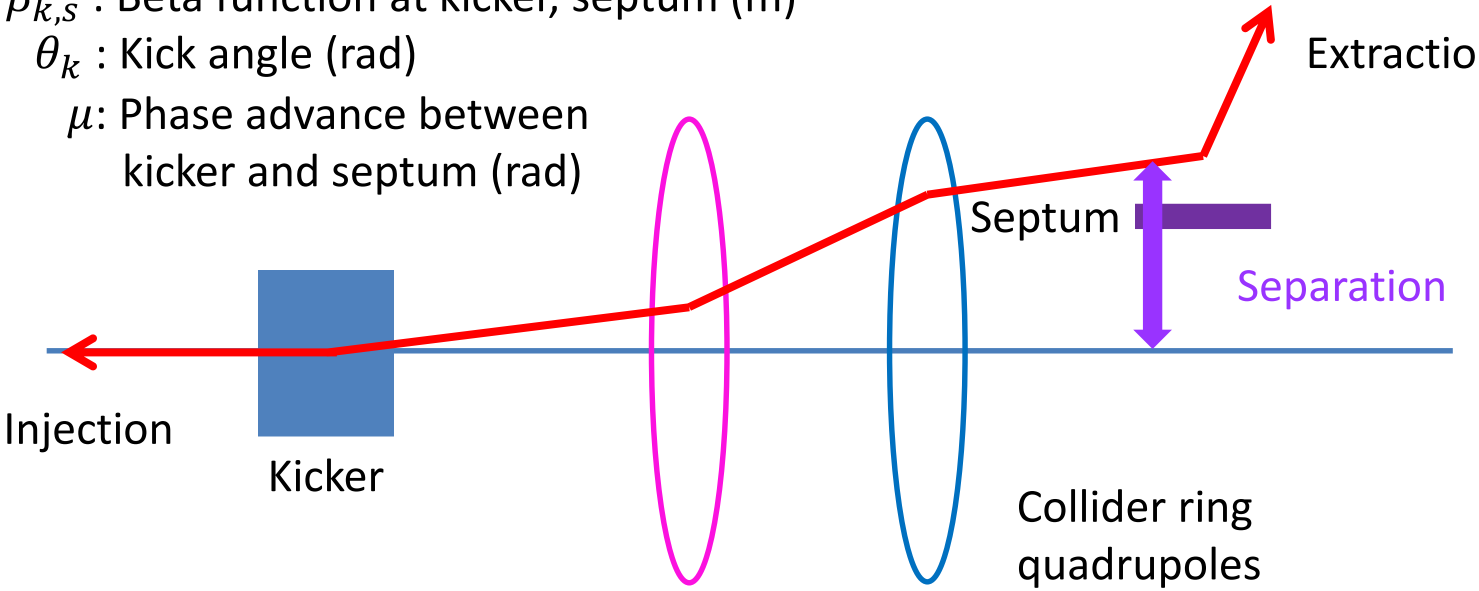


See more in the lecture by M. Paraliev, 'Kicker and Septa' on 5th March

Basics (4)

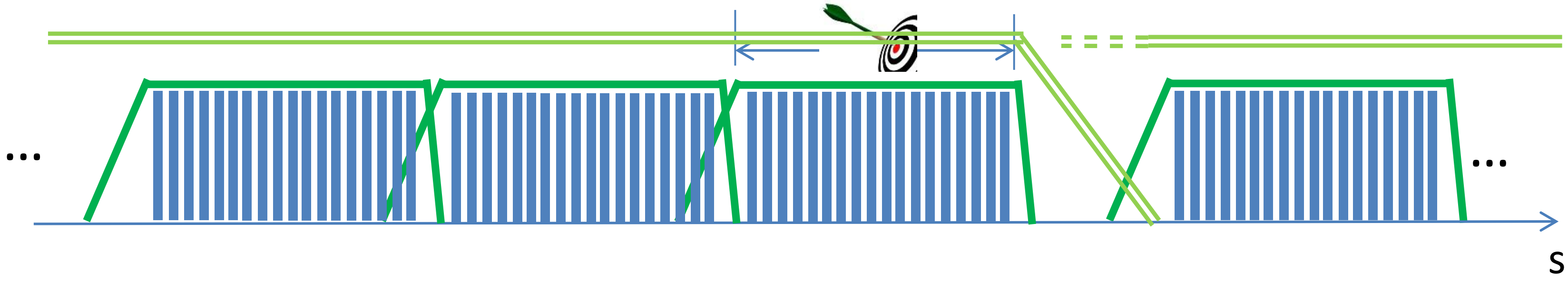
- Kicker strength, septum thickness and *separation*
  - Between kicker and septum, injection/extraction orbit is determined by the kicker’s kick angle and collider ring optics: Separation $= \sqrt{\beta_k \beta_s}\,|\theta_k \sin\mu|$

$\beta_{k,s}$: Beta function at kicker, septum (m)
θ_k : Kick angle (rad)
μ: Phase advance between kicker and septum (rad)



Basics (5)

- Filling pattern
  - Injection
    - In hadron colliders, several injections to fill the collider ring, normally not at one go; Much shorter booster circumference (for instance, SPS and LHC)
    - Not all the rf buckets are filled because of finite kicker rise time → *Gaps* in filling pattern
    - In lepton colliders, gap is not necessary (see later slides)
  - Extraction
    - One relatively long gap (aka *abort gap)* is required, for both hadron and lepton colliders, because of extraction kicker rise time



Injection and extraction in future circular colliders

- Future collider’s beam features
  - High energy to explore the energy frontier, and high beam current to achieve the luminosity goal

    →Large energy stored by the beam
  - Small beam emittance to enhance the luminosity

    →High energy density
- (Fundamental) Requirements
  - Minimising beam losses due to injection and extraction

    → Highly stable and reliable injection/extraction system, taking into account fault cases
  - Emittance preservation during injection for hadron colliders
  - Top-up injection due to short beam lifetime for lepton colliders
  - Emergency/Intentional extraction (aka. *Beam dump/abort*)

Hadron collider inj. & ext.

- LHC as an example in the following slides

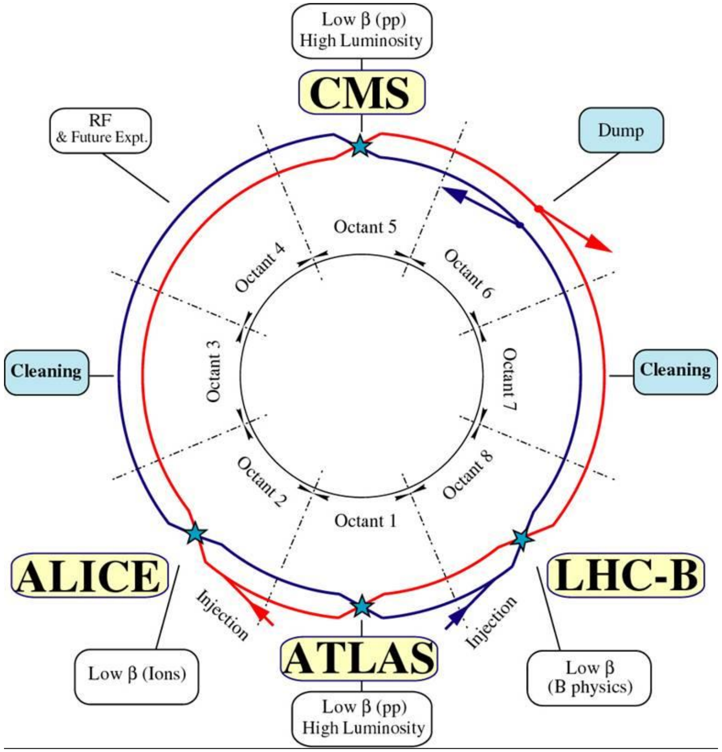


Image from https://lhc-machine-outreach.web.cern.ch/

Hadron collider injection (1)

- LHC injection [2]
  - Injection system integrated into IR2/8 matching section
  - Lambertson septum, 12 mrad hor. bend with 5 magnet
  - Kickers, 0.85 mrad ver. kick with 4 modules, rise time <~1 μs
  - Diagnostics: 5 screens (per beam), ICT, BPMs and BLMs
  - LHC full injection (two beams with >2000 bunches per beam) takes about 20 min

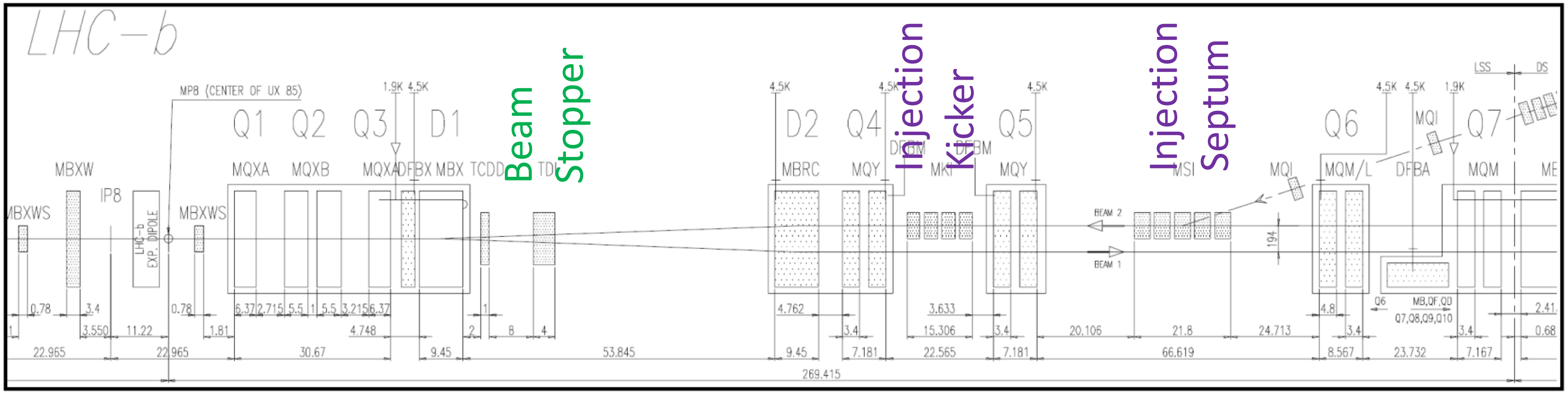
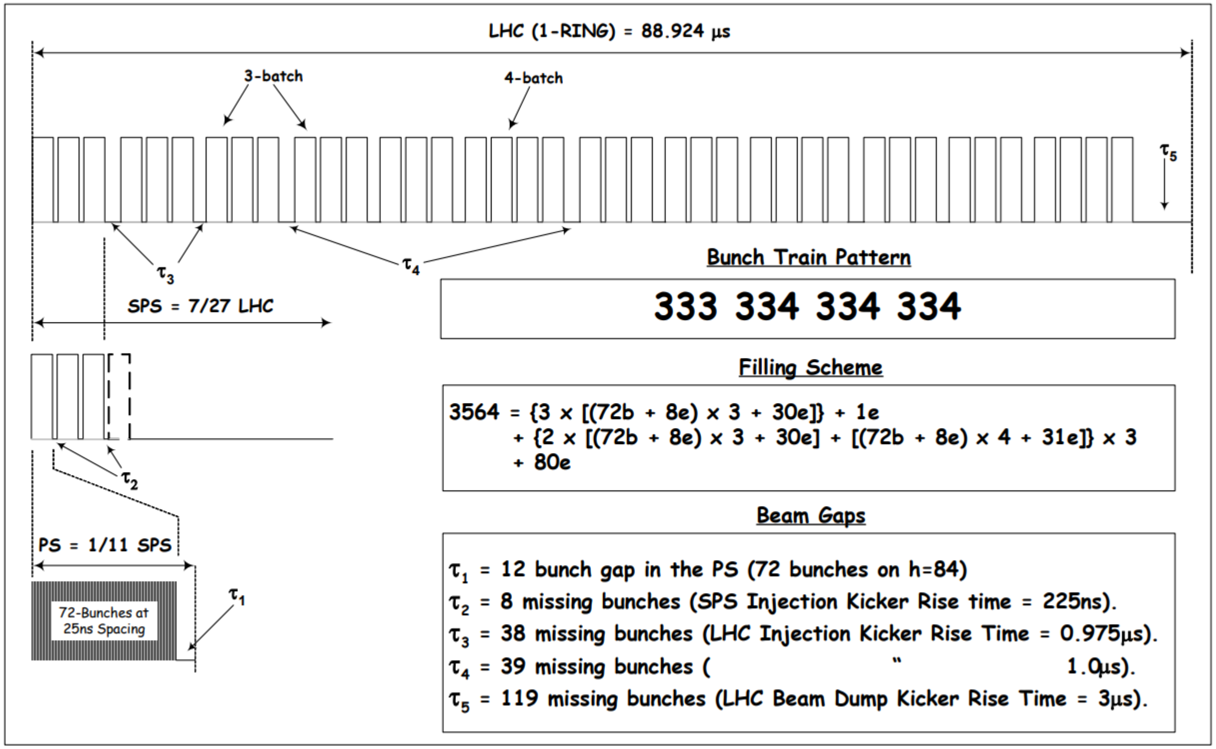


Figure taken from [1]

Hadron collider injection (2)

- Typical LHC filling pattern



Bunch Train Pattern

333 334 334 334

Filling Scheme

$3564 = \{3 \times [(72b + 8e) \times 3 + 30e]\} + 1e$
$+ \{2 \times [(72b + 8e) \times 3 + 30e] + [(72b + 8e) \times 4 + 31e]\} \times 3$
$+ 80e$

Beam Gaps

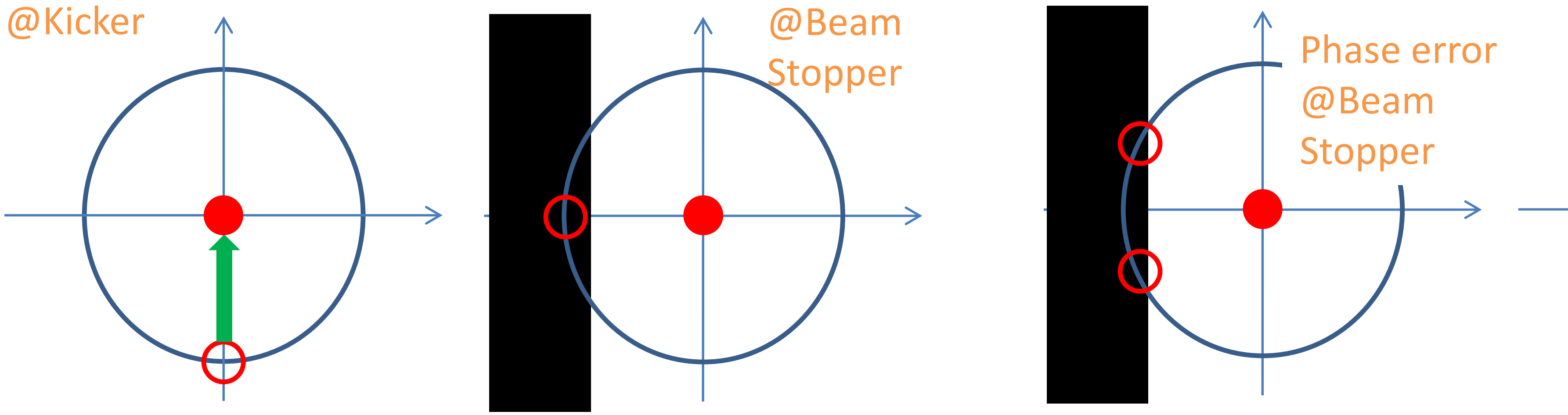
τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975μs).
τ_4 = 39 missing bunches (" 1.0μs).
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3μs).

Figure taken from [3]

Hadron collider injection (3)

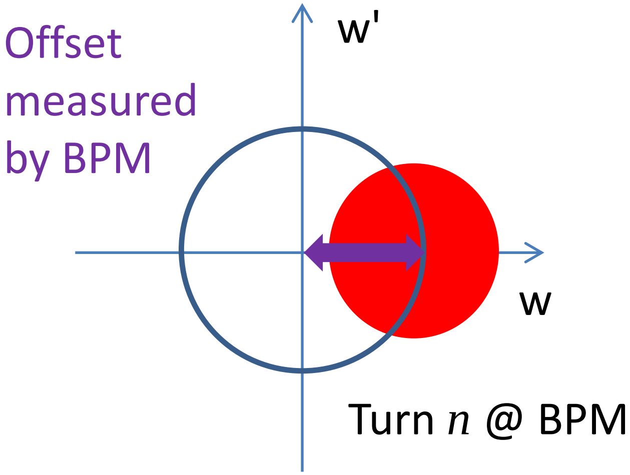
- Possible failure/error and protection
  - Beam stopper at a betatron phase advance of 90 deg from kicker, absorbing miskicked beams
  - Beam stopper is inserted only during the injection (connected to interlock system)
  - Collimators located at further downstream (n×180 +/-20 deg from Beam stopper) to cope with possible error in phase advance between the kicker and beam stopper

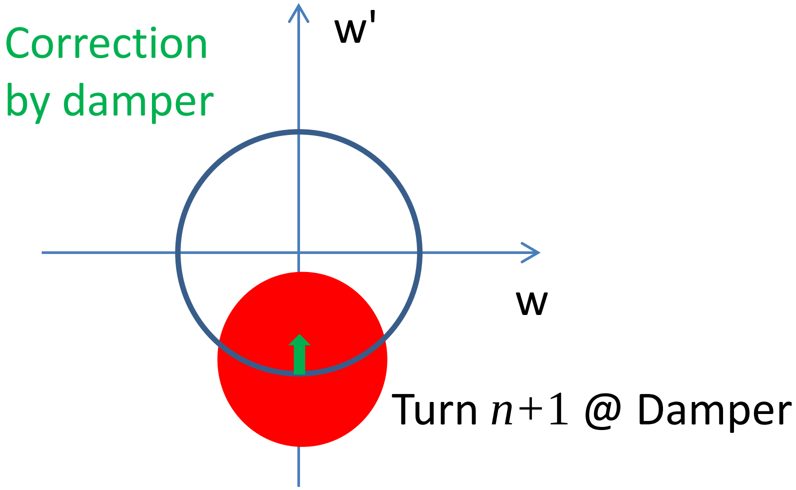
Injection beam in phase space (normalised coordinate)



Hadron collider injection (4)

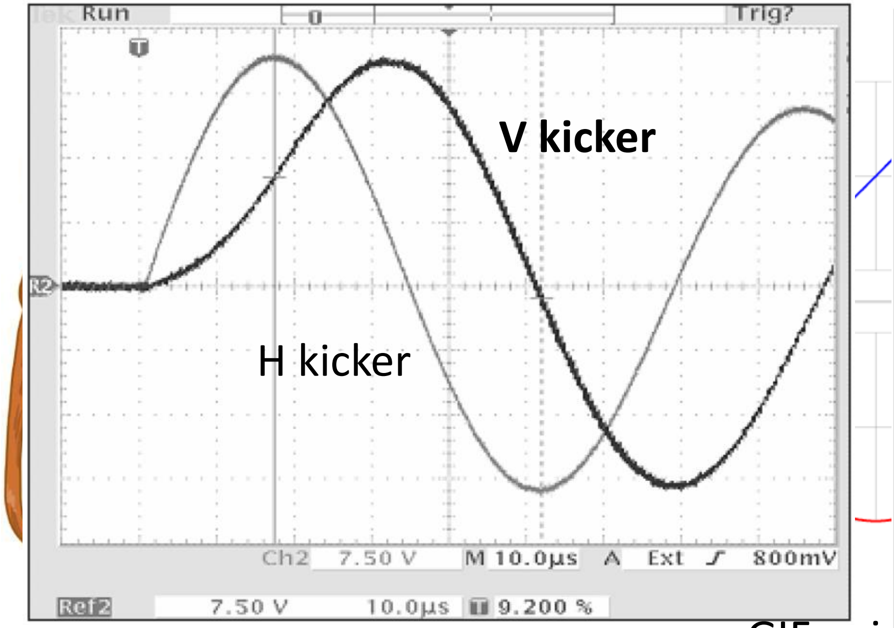
- Emittance preservation [4]
  (Remember the lecture by H. Schmickler last Friday)
  - Source of injection beam betatron oscillation
    - Injection beam angle and position offsets, constant over bunches
    - Ripple in SPS extraction and LHC injection kicker pulse flat top, varying bunch by bunch
  - *Transverse damper*, 0.5 μrad kick at 450 GeV, bunch-by-bunch capable with some limitation on the kick strength, is used to damp the injection beam oscillations
  - Damping time (~4 ms) is not fully negligible relative to filamentation time (~67 ms). These numbers set the requirement on the SPS and LHC kickers to ±0.5% to limit the emittance growth to <2.5% specification
  - Quadrupolar mismatch can be controlled through injection beamline quad tunings

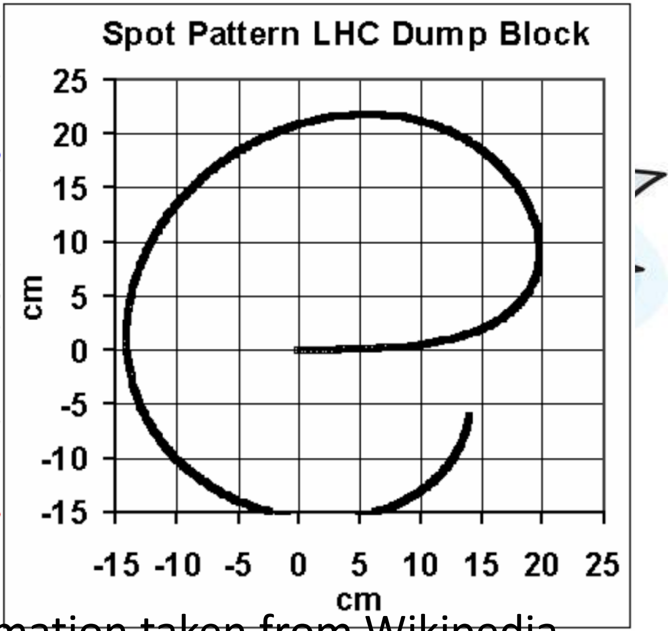




Hadron collider extraction (1)

- Extraction with Kicker+Septum+"Dilution kicker"
  - Enormous energy stored in the beam, >300 MJ at 7 TeV
  - It is necessary to reduce the energy deposit density on the beam dump block, otherwise the beam dump is damaged
  - Dilution kicker = a series of horizontal and vertical kickers, excited by sinusoidal wave with 90 deg phase difference in H and V (sin and cos)





GIF animation taken from Wikipedia

Figures taken from [1]

Hadron collider extraction (2)

- LHC beam extraction
  - Extraction system is installed into IR6 for both Beam 1 and 2
  - Kicker: 0.27 mrad hor. kick with 15 modules, 3 μs rise time
  - Lambertson septum: 2.4 mrad ver. Bend, 15 magnets
  - Dilution kicker: ±0.14 mrad kicks in H/V
  - Beam dump assembly at 750 m from Septum (Contained in an inert gas filled vessel to avoid fire)
  - Absorbers in front of septum and Q4 to protect these components in case of failure

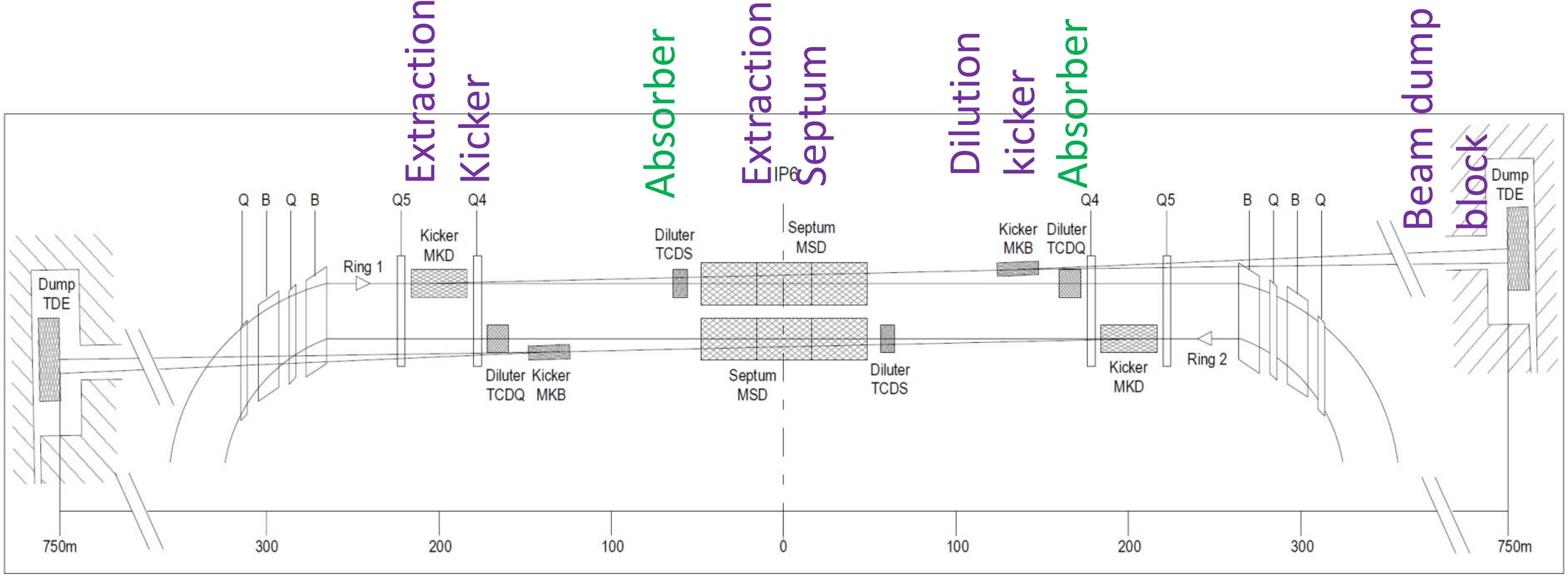


Figure taken from [1]

Hadron collider extraction (3)

- Extraction system must be always ready
  - During the acceleration, kickers and septa power supplies should follow the varying beam energy
- Fail-safe design
  - Whenever something wrong detected in the extraction system, the beam is extracted before the situation gets worse
  - RF system failure, magnet quench, etc. trigger immediately beam dump
  - Asynchronous dump: when one of 15 kickers faultily triggered, all the others are immediately triggered
  - Extraction can be accomplished with a missing kicker out of 15 kickers
- High reliability is ensured with
  - Surveillance: checking the devices continuously
  - Redundancy: important parts of the system are doubled
  - Post checks: checking if the system worked properly after extraction

  - Diagnostics: about 3000 beam loss monitors are installed

Hadron collider extraction (4)

- Asynchronous dump…

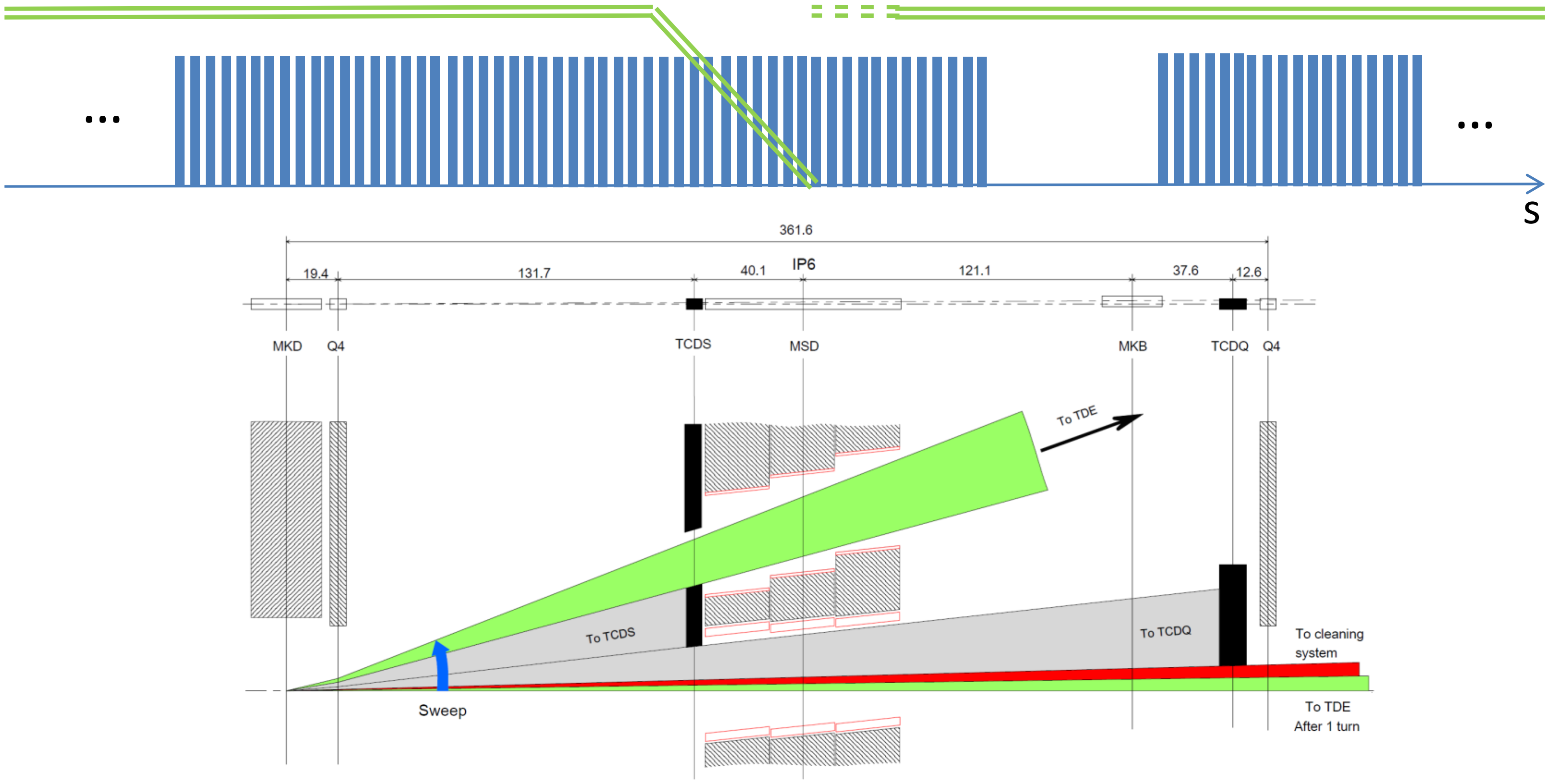
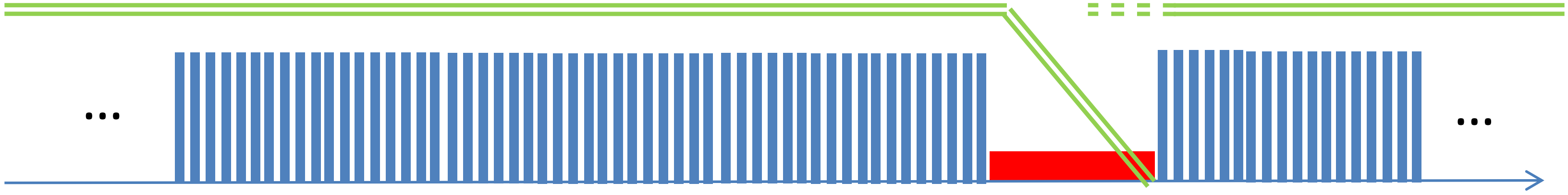


Figure taken from [1]

Hadron collider extraction (5)

- Abort gap cleaning [5,6]
  - Particles leaking from rf buckets drift into the abort gap
  - These particles are not conducted into the extraction septum channel since they are deflected with the rising edge of the extraction kicker (similarly to asynchronous damp)
  - Cleaning using transverse damper system (LHC)
    - Transverse damper is used conversely to excite betatron oscillation, bringing the particles to ring collimators
    - Damper is excited at the betatron frequency
    - Sweeping in the excitation frequency to increase the cleaning efficiency, taking into account (higher order) chromaticity and amplitude dependent tune
    - Cleaning at the flat bottom after injection, and at flat top when AG population becomes high (5×10^9 at 6.5 TeV, 10% of Q4 quench level)



Hadron collider extraction (6)

- Gap cleaning in operation

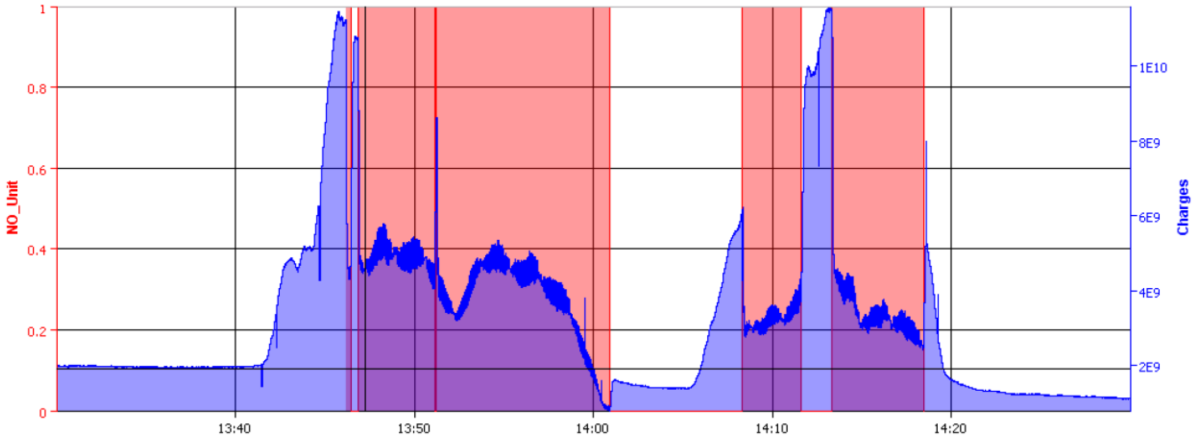


Figure 1: Example of abort gap cleaning showing on the left axis (red) cleaning on/off, right axis (blue) the abort gap population.

Figure taken from [5]

From LHC to FCC-hh

- Injection [7]
  - Energy stored in an injection bunch train is limited to a few MJ for machine protection reasons both in LHC and FCC-hh
  - Number of bunches per injection will be significantly smaller in FCC-hh due to higher injection energy: 450 GeV vs. ~3 TeV (?)
  - Many injections required, resulting in many gaps
  - Shorter injection kicker rise time is then specified to achieve reasonable filling factor, <~300 ns (?)

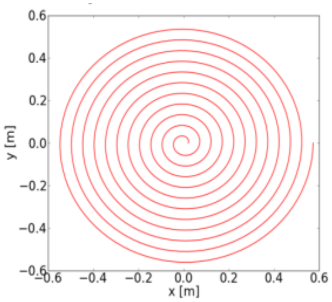


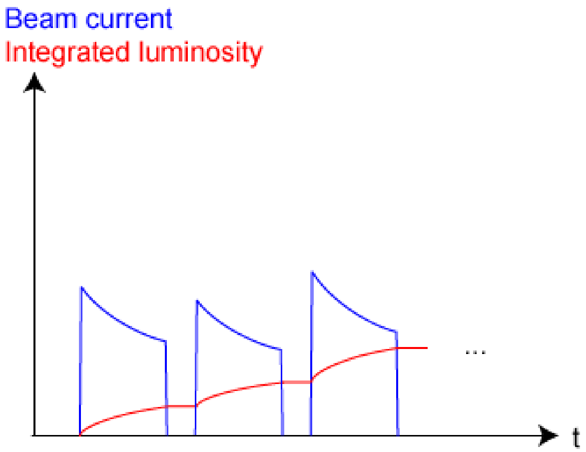
Figure taken from [8]

- Extraction [8]
  - Energy stored in the beam is 8.5 GJ at flat top !
  - One of kicker design concept under study is:
    - Using a large number of kickers ~300
    - Accidental triggering in one of kicker results in only a small betatron oscillation
    - Asynchronous damp is then necessary only when multiple mis-triggering happens
  - Due to the very high beam energy, superconducting septum is considered
  - More dilution on the beam dump as shown in the figure
  - Sacrificial absorbers…

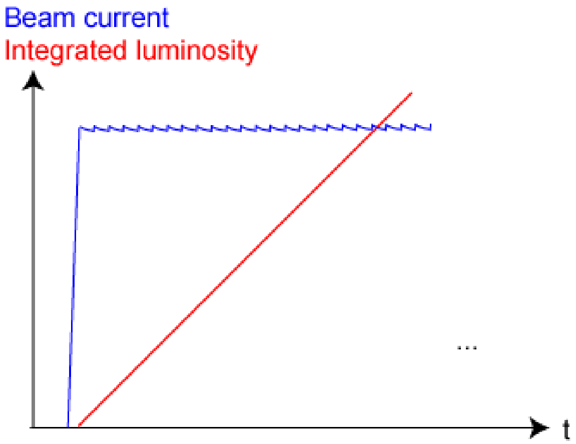
Lepton collider injection (1)

- *Top-up injection*
  - Injecting electrons/positrons atop of circulating beam to compensate for the beam current decrease during collision
  - Maximising the integrated luminosity
  - Stabilising the machine with constant heat load due to synchrotron radiation

Early time operation mode

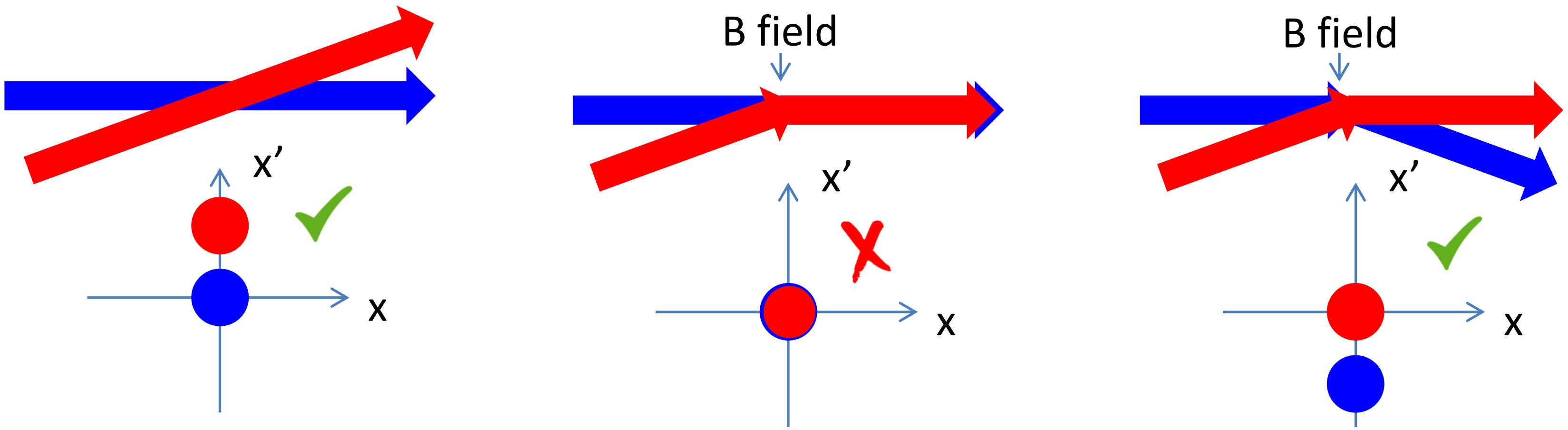


Top-up operation



Lepton collider injection (2)

- Liouville's theorem (for accelerator physics)
  - "Under the influence of conservative forces the density of the particles in phase space stays constant" (Sentence from [9])
  - This is true for charged particles moving in magnetic field
  - For beam injection into rings, injection beam particles cannot overlap *in phase space* with the stored beam particles at the time of injection

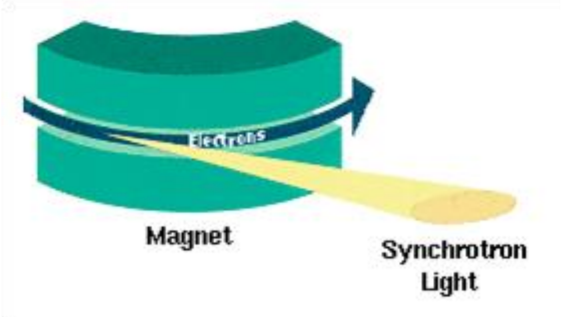


Top-up injection cannot continue as the entire phase space will be filled with particles!?

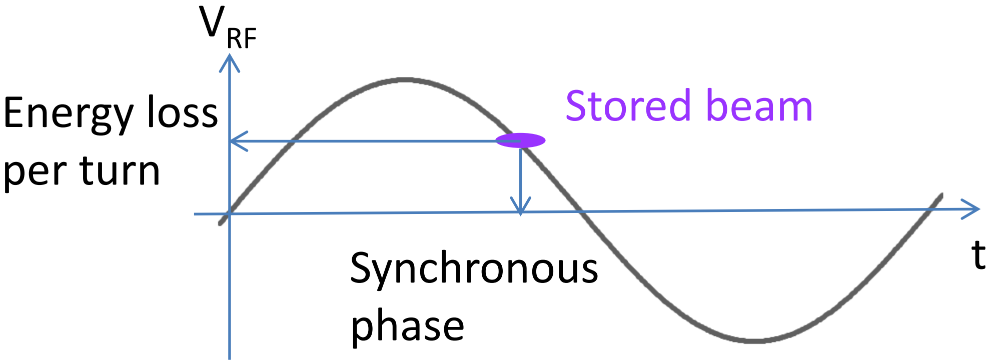
Lepton collider injection (3)

- Synchrotron radiation (SR) damping [9]
  - Photon emission when charged particle is *accelerated*
    - Bending field gives a transverse acceleration
    - Emission due to longitudinal acceleration is normally marginal
  - Particle energy loss $\propto \gamma^4/\rho$ (with transverse acceleration)
    - With γ and ρ being Lorentz factor and curvature radius
    - Can be significant for $e^{+/-}$ while marginal for hadrons
    - Makes system non-conservative
  - Energy loss is recovered by RF turn by turn

SR [Figure taken from Wikipedia]



Energy recovery by RF



V_{RF}

Energy loss per turn

Stored beam

Synchronous phase

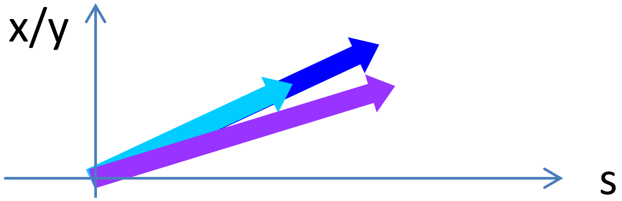
t

Lepton collider injection (4)

- Radiation damping in transverse plane (Betatron oscillation)
  - Longitudinal and transverse momenta loss due to SR while only longitudinal acceleration with RF
- Radiation damping in longitudinal plane (Synchrotron oscillation)
  - Energy loss due to SR is proportional to $(1+\delta)^3$, where δ is the fractional energy deviation ($\Delta E/E$)

SR damping, transverse

Initial Emission Acceleration

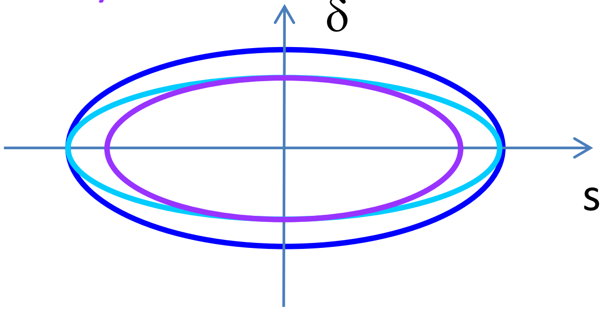


(Arrow = Particle momentum)

SR damping, longitudinal

Initial Emission+Acceleration

Synchrotron oscillations

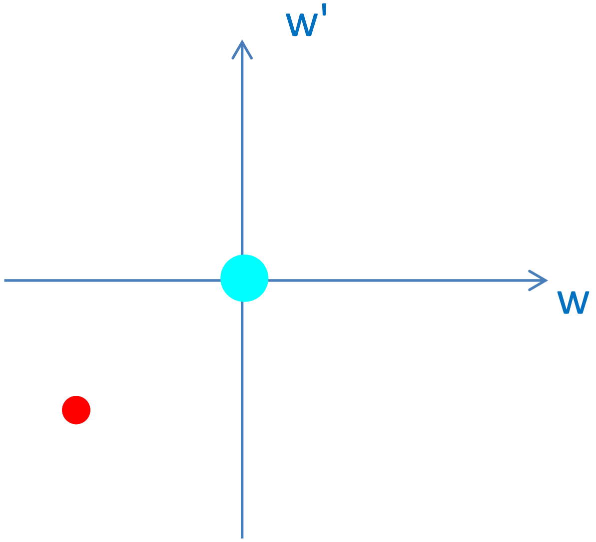


(Area of ellipse = Longitudinal emittance)

Note: Emittance will not be zero because the synchrotron radiation excites betatron and synchrotron oscillation at the same time. Equilibrium emittances are determined such that the damping and excitations cancel each other.

Lepton collider injection (5)

- Injection process (to be repeated!)

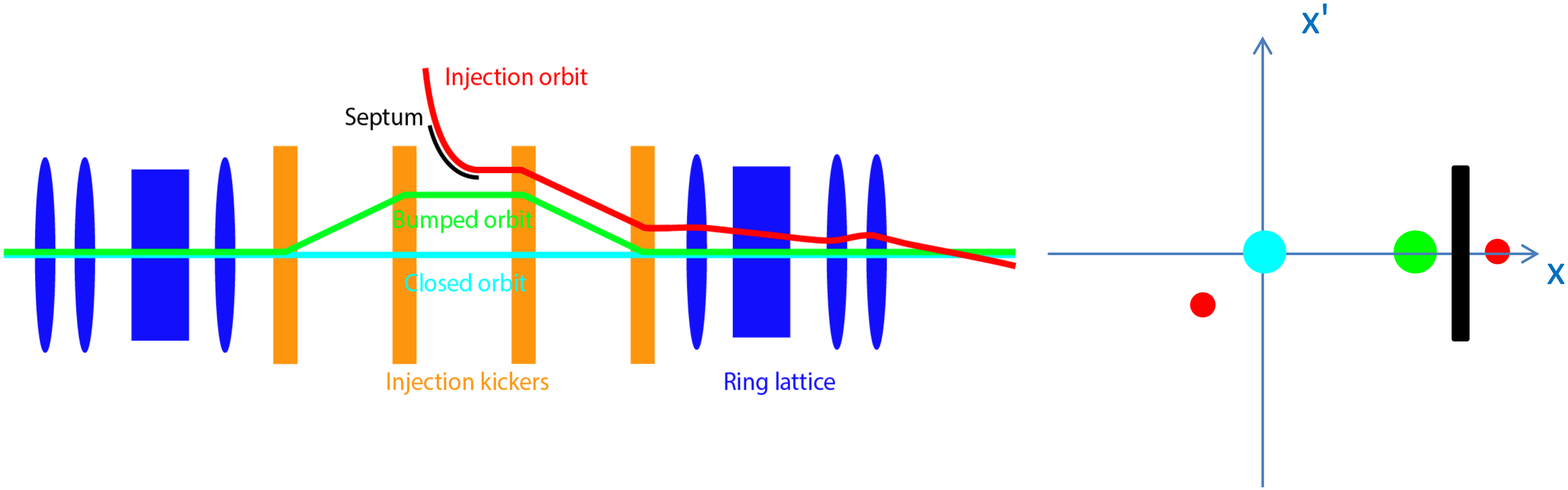


Thanks to SR damping, top-up injection can continue unlimitedly!

Note: The initial injection errors, namely mismatch and centroid offset, are to be “forgotten” in e$^{+/-}$ machines, while they have to be minimised in hadron machines.

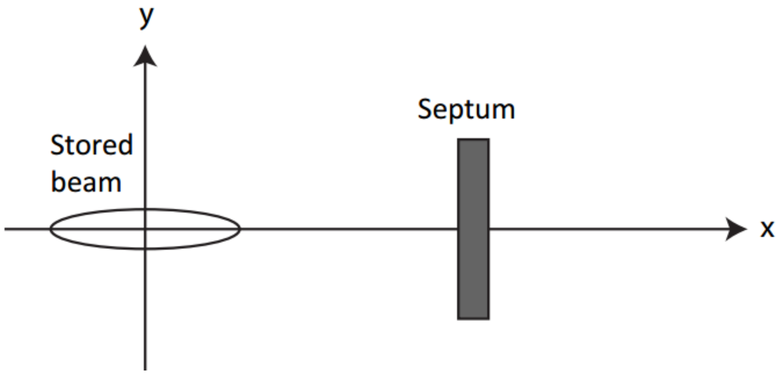
Lepton collider injection (6)

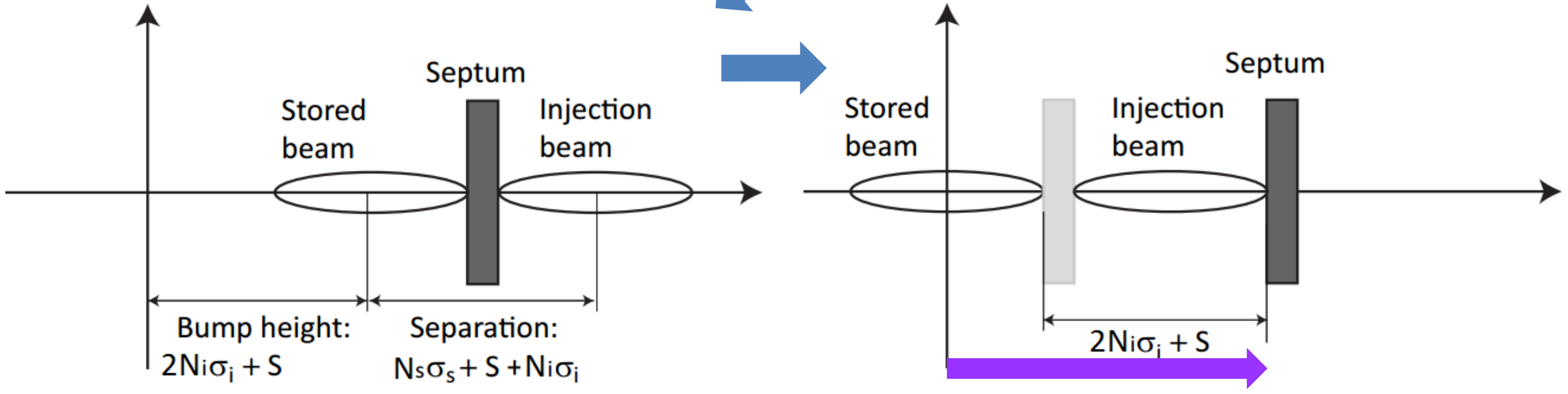
- Conventional top-up injection scheme
  - Widely used in lepton colliders and light sources
  - Septum + Kicker bump (a series of kickers)
  - Gap for the kicker rise time is *not required* in top-up injection (Gaps may still be required to avoid ion instabilities)



Lepton collider injection (7)

- Parameters to be considered
  - Stored and injection rms beam sizes: σ_s, σ_i
  - Septum thickness: S
  - Clearances in units of beam size: N_s, N_i





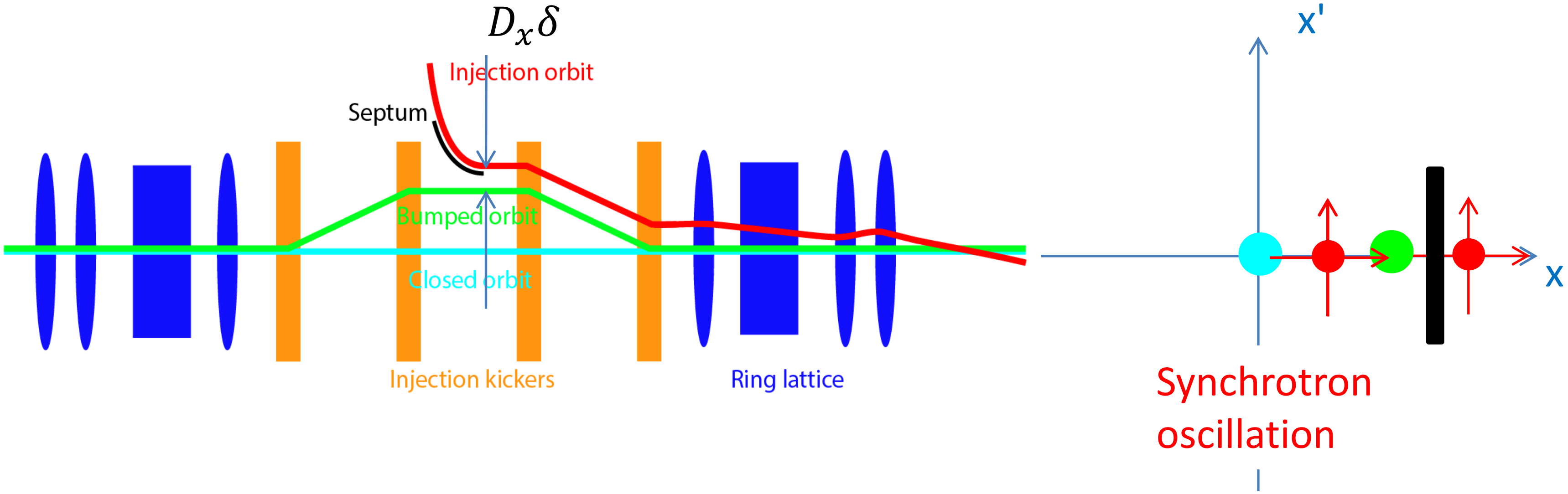
* Bump height is the minimum value required

Ring aperture required: $N_s\sigma_s+2N_i\sigma_i+S$

Lepton collider injection (8)

- Synchrotron phase space injection [10] with off-energy injection beam
  - Hardware: Septum + Kicker bump
  - Finite dispersion at septum
  - By adjusting the injection beam energy and orbit, the injection beam can be situated onto the off-energy closed orbit

Off-energy closed orbit is represented as $D_x(s)\delta$, where $\delta = \frac{\Delta P}{P} \sim \frac{\Delta E}{E}$



Lepton collider injection (9)

- Synchrotron phase space injection at LEP
  - Unwanted radiation dose to the physics detector during injection was reduced; Zero dispersion at detectors
  - Higher injection efficiency than normal conventional injection was realised

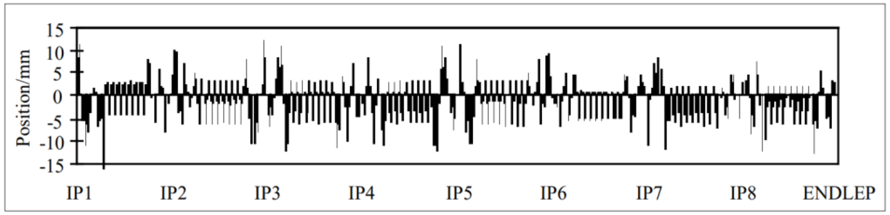


Figure 3: Optimized Horizontal First Turn Trajectory for Betatron Injection of Positrons into LEP.

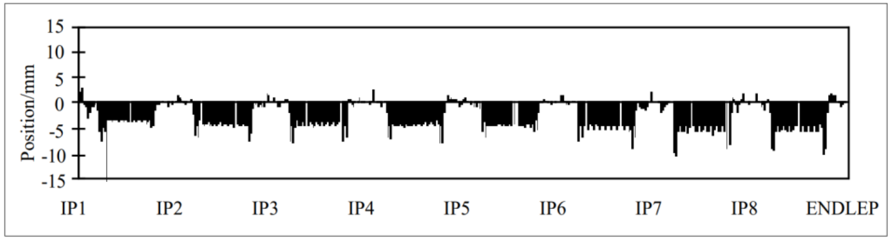
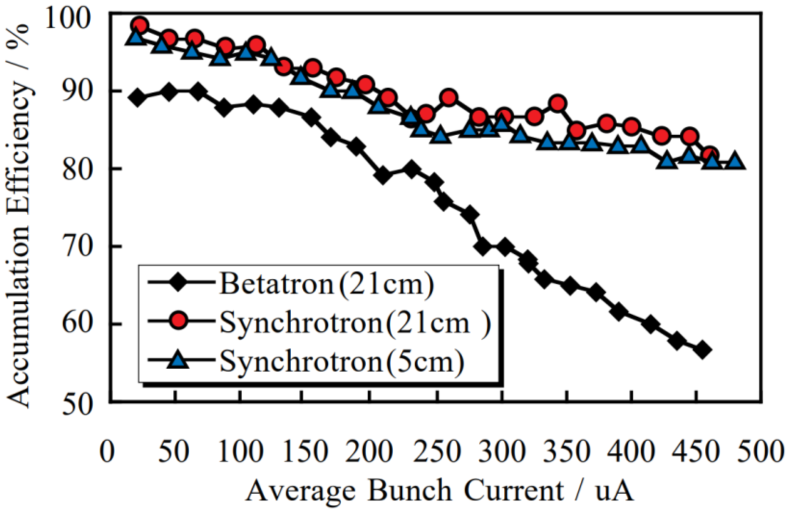


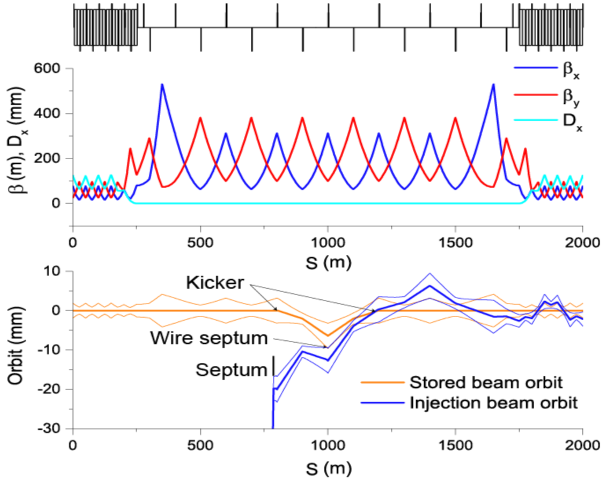
Figure 4 : Optimized Horizontal First Turn Trajectory for Synchrotron Injection of Positrons with ΔP/P at -0.6%



Figures taken from [9]

FCC-ee injection and extraction

- Injection
  - Main difficulty is injecting into limited dynamic aperture due to strongly squeezed β*
  - Conventional injection (on- and off-energy) and multipole kicker injection [11] schemes are investigated and promising [12]
  - One of possible designs:
    - Conventional injection scheme
    - Bump with two kickers with some quads in-between, enhancing bump height
    - FODO optics with ~400 m beta function
    - Wire septum is considered here. Can be normal septum with larger β function
    - Modest kicker and septum specifications



- Extraction
  - Energy stored in the beam is ~20 MJ in Z operation mode (Beam energy of 45.6 GeV)
  - 20 MJ is “not much” compared to LHC/FCC-hh but well above damage threshold, requiring a careful beam dump design

Some references

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In these lectures:

- H. Schmickler, “Emittance preservation in hadron machines”
- M. Paraliev, “Kickers and septa”
- N. Mokhov, “Machine protection concepts”
- M. Seidel, “Collimators, dumps and masks”

Thank you for your attention!

Question?