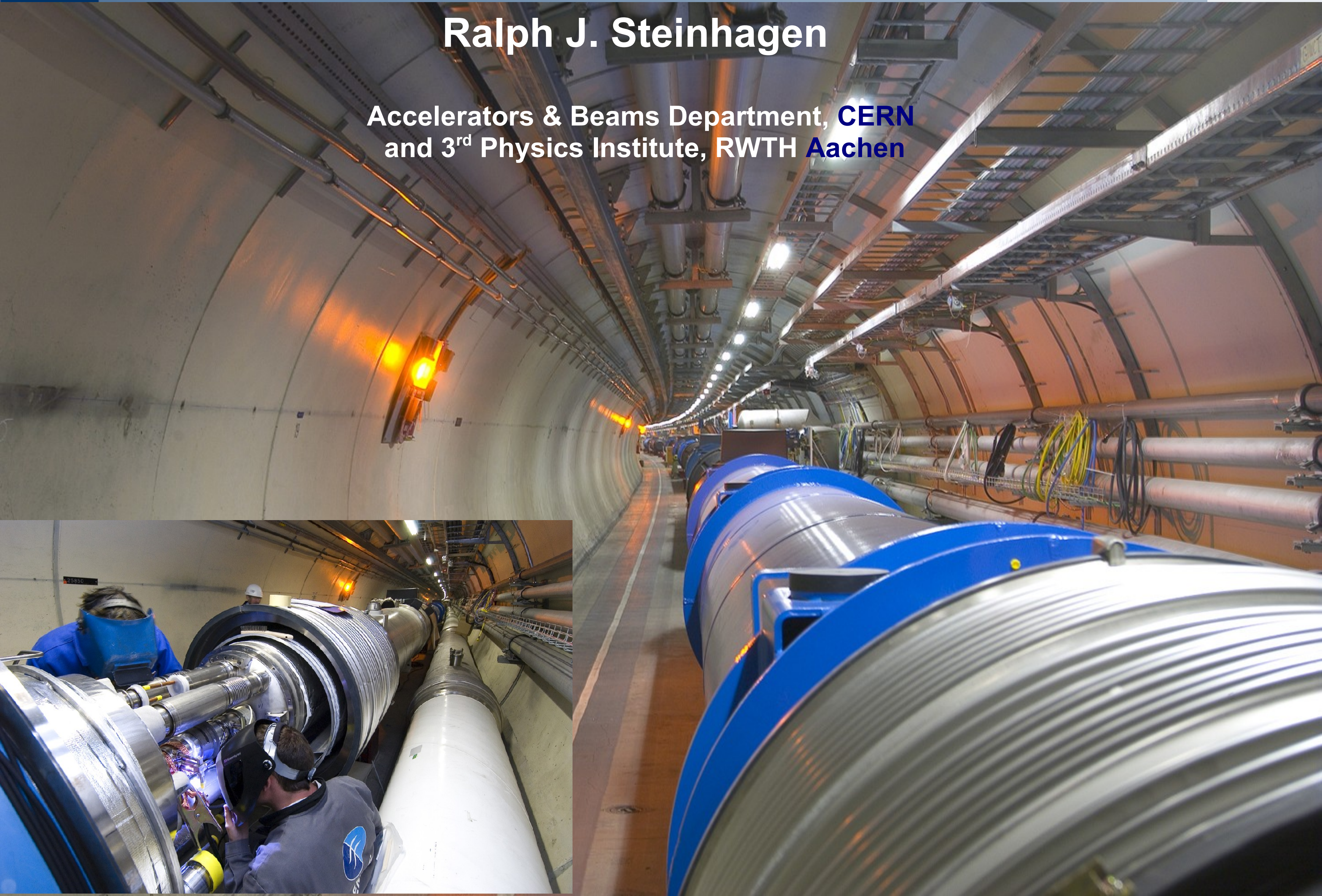
LHC Status and Beam Stabilisation



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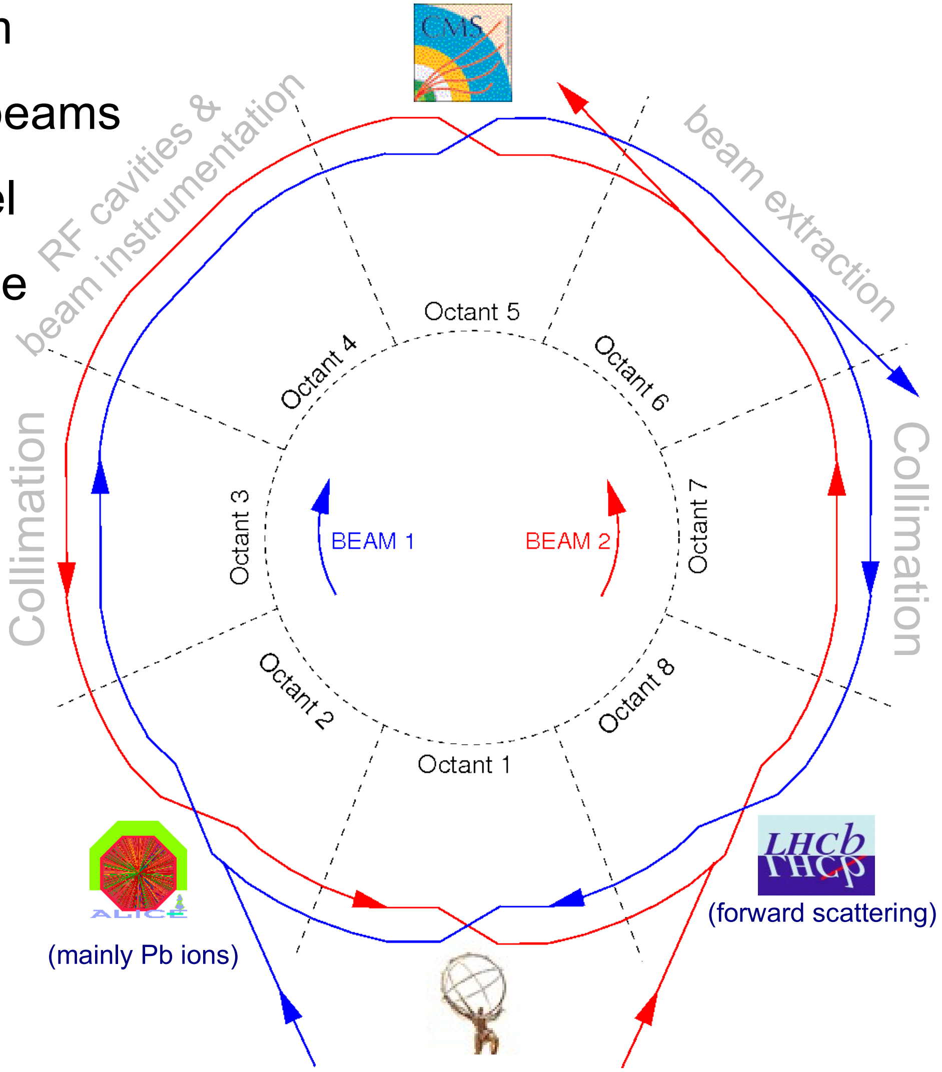
LHC = Large Hadron Collider

- 27 km circumference, depth ~ 100 m
- accelerates two positively charged beams
  → two machines in the same tunnel
  → more bunches per beam possible
- eight-fold symmetry
  - four crossing insertions
- parameters for physics
  - p-p collisions at
    - $E_{cms} = 14$ TeV   ($E_{beam} = 7$ TeV)
    - nominal $L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  - Pb-Pb:
    - $E_{cms} = 1148$ TeV
    - nominal $L = 10^{27}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



protons @ 450 GeV
injection from the SPS

LHC status

- Technical stop in 2005
  - maintenance of the machines
  - PS dipole magnets are ~ 50 years old
    - 25% of coils preventively being replaced (radiation damage)

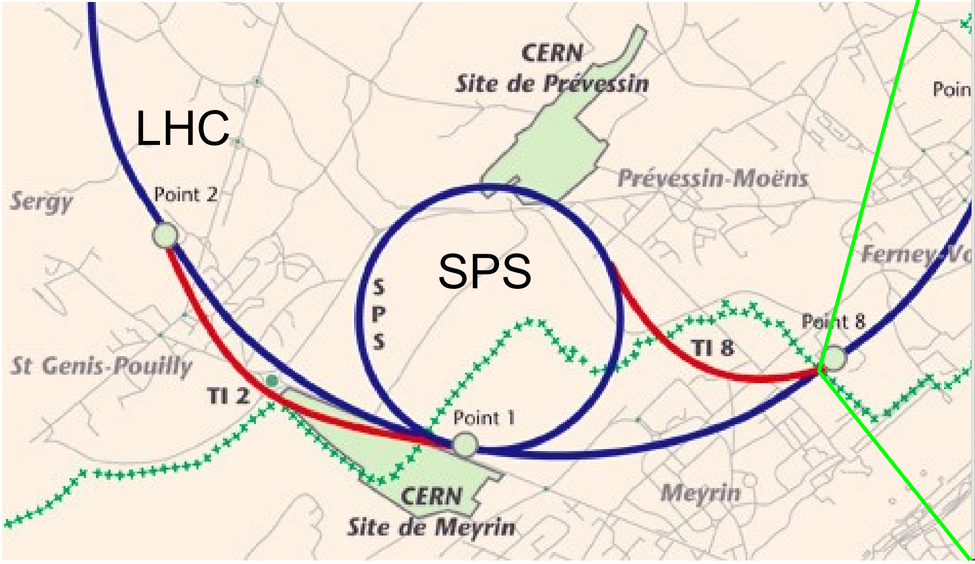
2006: All accelerator operation in CCC

- Restart of PS and SPS in 2006
  - Commissioning of CNGS beam line (CERN Neutrinos to Gran Sasso)
  - All accelerator operation will move to CERN's Common Control room

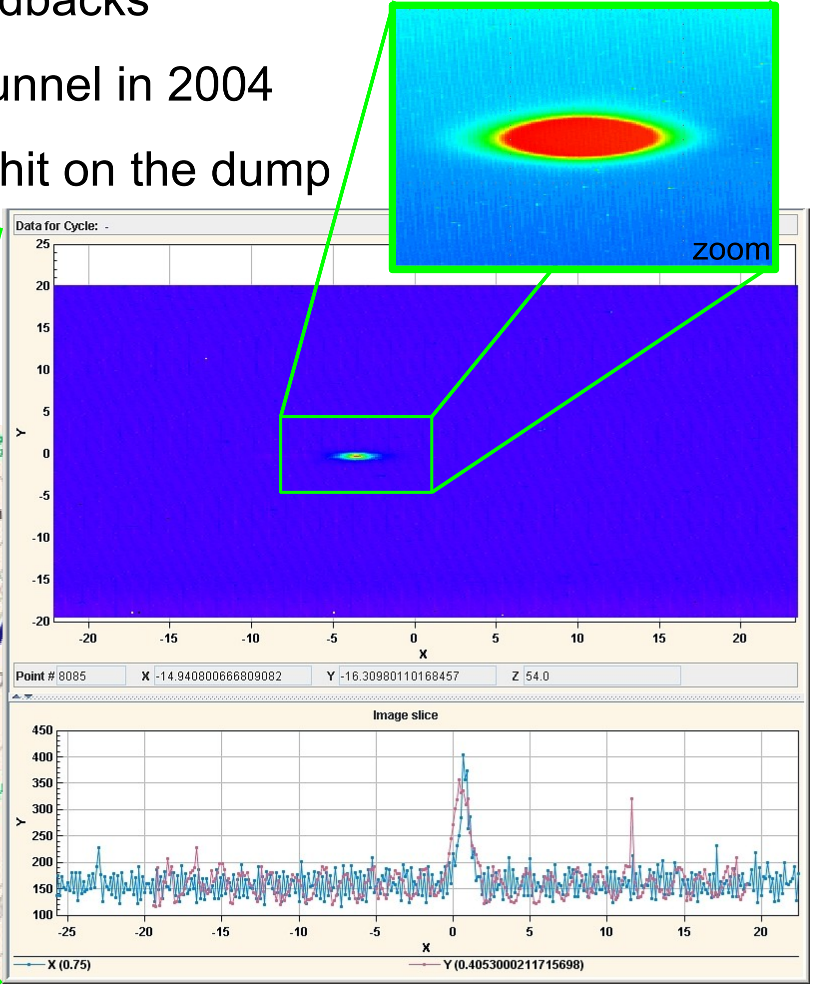
    (CCC, on the Prevessin site. includes: Linacs, Booster, PS, SPS, TS, cryogenics ... (and later LHC) operation)
- Installation schedule
  - LHC cryogenics and magnets installation in time
    - Status in August 2005: 1000/1650 main magnets arrived
  - Hardware commissioning started for some systems
  - Beam commissioning followed by physics program expected in 2007

Status of LHC Injectors

- injectors can produce beam with nominal parameters (emittance, intensity)
- successful tests of:
  - LHC style beam diagnostics and feedbacks
  - TI8 transfer lines down to the LHC tunnel in 2004
    - first extraction → first controlled hit on the dump (only 300 m away from LHC



Beam profile @ dump



Data for Cycle: -

Point # 8085 X -14.940800666809082 Y -16.30980110168457 Z 54.0

Image slice

X (0.75)

Y (0.4053000211715698)

General LHC Parameters

- compared to other present and previous colliders

		Hadron machines		Lepton machines	
		LHC	Tevatron 2a	LEP	KEKB
Energy	[GeV]	7000 x 7000	980 x 980	105 x 105	8 x 3.5
Luminosity	[cm-2 s-1]	1e34	1e32	1e32	1.4e34
σ_x x σ_y @ IR	[µm x µm]	17 x 17	30 x 30	200 x 2	77 x 2
Circumference	[km]	26.7	6.3	26.7	3.0
Number of bunches		2808	36	4	1294*
Bunch spacing	[ns]	25	396	22e3	~8*
Particles pb	[1e10]	12	30/8	50	6/2
Max. stored energy	[MJ]	350	1.6	0.04	0.1

- main challenges for the LHC:
  - beam energy and magnet technology (control of field errors)
  - control of particle loss in superconducting environment
  - control of instabilities and dynamic effects

    (electron cloud, beam-beam, decay/snapback, orbit, final focus squeeze, dynamic aperture, ...)

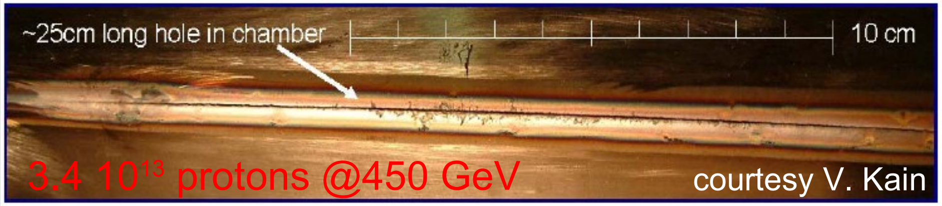
(*KEKB inital design: ~5000 bunches with 7 ns spacing, actual values limited by e-cloud)

Maximum LHC Energy of 7 TeV

- For hadrons synchrotron light emission does not limit maximum beam energy
  (LHC: proton synchrotron light loss @7 TeV ~ 7 keV per turn)
- Maximum beam energy given by max. main dipole strength (first order)
- LHC: E_{beam} = 7 TeV: B_{max} = 8.33 Tesla → superconducting magnets
  - Energy loss into magnet is inevitable in an accelerator environment
  - Loss of superconducting state if particle loss exceeds limits
    (minimum quench energy E_{MQE}, loss density N_{loss}, time scale @7 TeV: 10 – 20 ms)

$$E_{MQE} < 30 \text{ mJ/cm}^{-3} \text{ resp. } N_{loss} < 10^{8} \text{ protons/m}$$

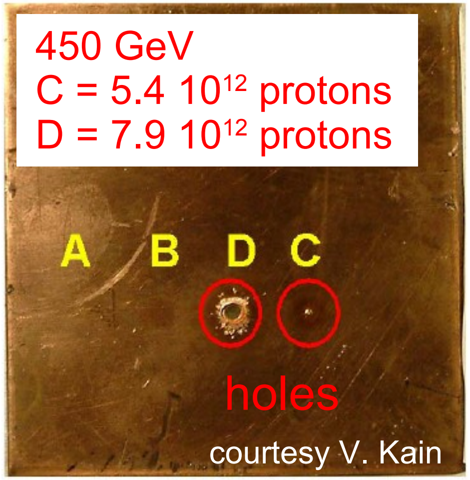
  - nominal LHC: E_{stored} = 350 MJ/beam resp. N_{total} ~ 3 10^{14} protons
  - sufficient to quench all magnets and/or to cause serious damage



25 cm long hole in the vacuum pipe of QTRF in TT40

Controlled damage tests:
2 mm Cu plate
after ~5 cm of material
(Zn, Cu, INCONEL, 316L "sandwich")

details see: Chamonix XIV: "Damage levels - Comparison of Experiment and simulation" and PAC'05



Superconducting main dipole magnets @ 8.33 T

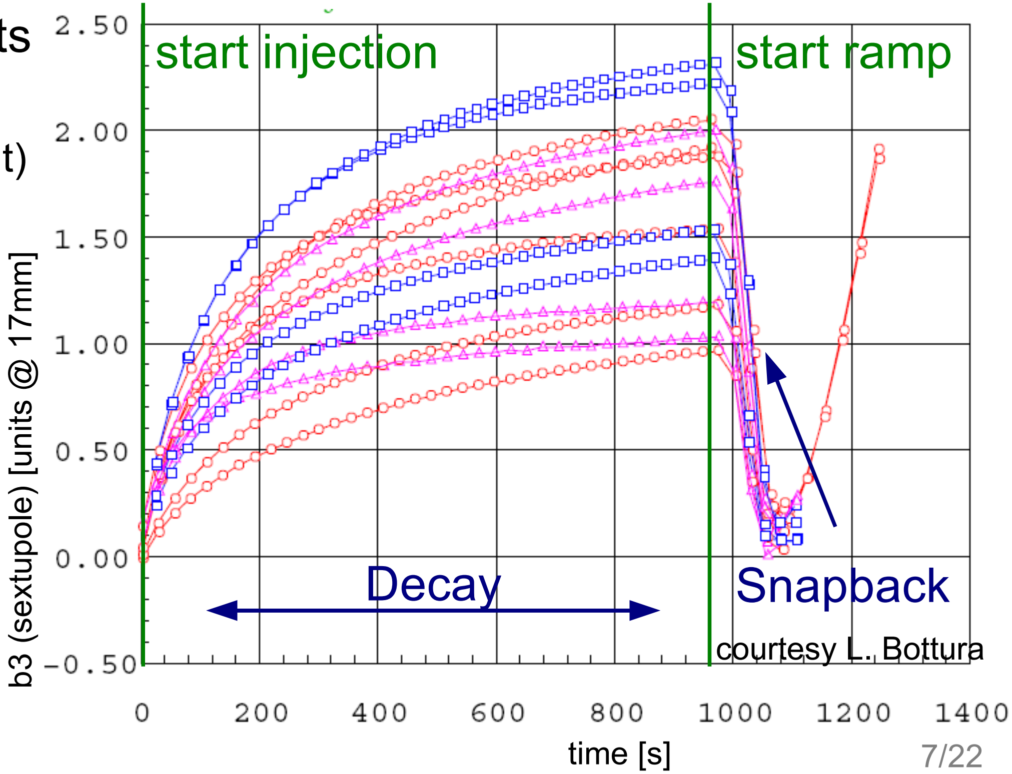
- normal conducting magnets: field quality mainly given by pole shape quality

  (iron saturates above ~2 T)
- Field stability of superconducting magnets given by coil design, its mechanical stability and powering
  - main dipole magnet have non-negligible higher multipole momenta
    - Main source for optic mismatch
    - Intend to measure all magnets @1.6 K
  - dynamic multipole components
    - Decay & Snapback

      (main dipole magnets dominant)

→ requires active control

- Fill-to-fill feed-forwards
- Feedbacks

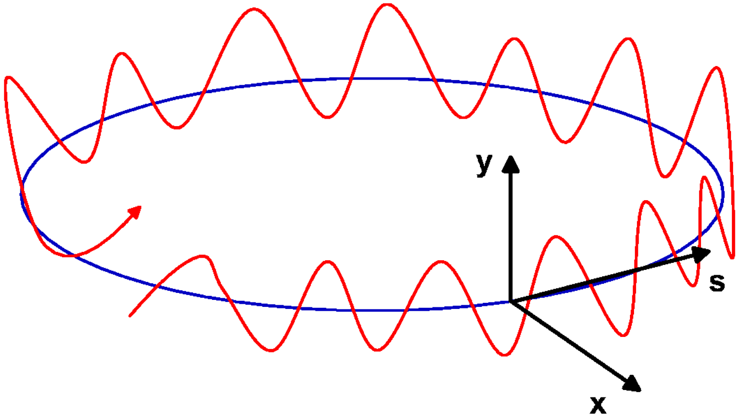


courtesy L. Bottura

Accelerator Fundamentals

- Charged particle perform transverse betatron oscillations in an circular accelerator with circumference C (x = (x,y), q charge, p momentum)
- Hill's equation (1st order only):

$$\frac{d^2 x(s)}{ds^2} \pm k(s)\,x(s) = 0$$



- k(s) quadrupole gradient
  (focusing in one de-focusing in the other plane → ”±”)
- periodic solution k(s)=k(s+C):

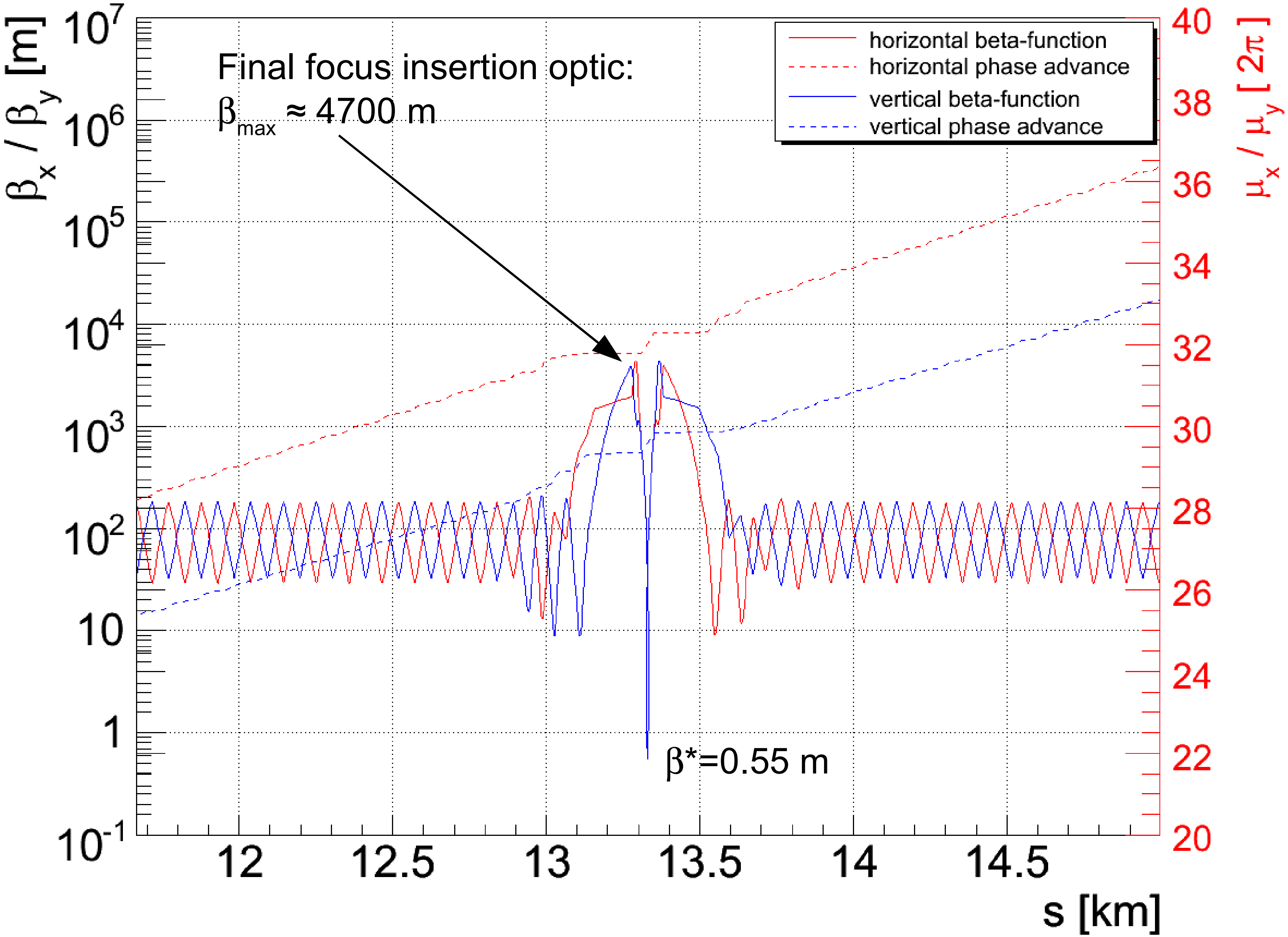
  (only numerically solvable)

$$x(s) = \sqrt{\epsilon\,\beta(s)} \cdot \cos(\mu(s) + \phi)$$

  - Beta-function β(s) defined by location and strength k(s) of quadrupoles
    - Beta-function β(s) and phase advance μ(s)

      (constants: emittance: ε and initial phase: ϕ)
    - beam size: $\sigma(s) = \sqrt{\frac{\epsilon\,\beta(s)}{\gamma_{rel}}}$
    - tune Q = number of oscillations per turn: $Q = \frac{\mu(C)}{2\pi}$

Example: LHC Optics around IR5 (CMS)



Luminosity: $dN_{event}/dt = L\,\sigma_{process}$

- Storage ring design:

$$L = \frac{N^2 k\, f_{rev}}{4\pi\,\sigma_x \sigma_y} \cdot e^{-\frac{1}{4}\left[\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2\right]} \cdot F_{crossing} \cdot F_{hour\ glass} \cdot \ldots$$

	LHC	Tevatron
– *N*: number of particles per bunch,	N_{pilot}=5 10^9, $N_{nominal}$= 12 10^{10}	N_p=30 10^{10}
– *k*: total number of bunches,	*k* = 1 ... 2808	k = 36
– σ_x, σ_y: hor./vert. r.m.s. beam size in IR	$\sigma_x=\sigma_y$ ~ 17 μm	$\sigma_x=\sigma_y$~30 μm
– f_{rev}: revolution frequency,	f_{rev}= 11.2 kHz (fixed)	f_{rev}= 47.7 kHz
– Δ_x, Δ_y: hor./vert. beam separation in IR		
– $F_{crossing}$, $F_{hourglass}$: numerical form factors,	$F_{cross.}$(285 μrad)~0.8 1- $F_{hourgl.}$~ 0.4%	$F_{cross.}$(0)=1 1- $F_{hourgl.}$~ 38%

correct for the effect of the crossing angle and *"hourglass"* effect (strong final focus)

- LHC luminosity example:
  - 1 pilot/beam: ~ 10^{28} cm^{-2} s^{-1}
  - 1 nominal bunch/beam: ~ $5\cdot10^{30}$ cm^{-2} s^{-1}
  - nominal beam: ~ 10^{34} cm^{-2} s^{-1}

LHC Luminosity Basics

- general luminosity optimisation rules:

$$L=\frac{N^2 k\, f_{rev}}{4\pi\,\sigma_x\sigma_y}\cdot e^{-\frac{1}{4}\left[\left(\frac{\Delta x}{\sigma_x}\right)^2+\left(\frac{\Delta y}{\sigma_y}\right)^2\right]}\cdot F_{crossing}\cdot F_{hour\ glass}\cdot\ldots$$

  - decrease beam sizes σ_x, σ_y in interaction region (IR)
    - stronger final focus → $F_{\text{h-glass}}$ ↓↓ (or σ_t ↓ but N↓& ΔE↑)
    - smaller emittance (negl. sync-rad.)
  - increase total beam intensity $I=Nk_{bunch}$
    - more bunches k_{bunch} → $F_{crossing}$ ↓↓
    - more intensity per bunch N → $F_{crossing}$ ↓↓
  - minimise beam separation Δx, Δy
    - luminosity feedback in IRs

LHC Luminosity Optimisation – Beam Intensity

$$L = \frac{\boxed{N^2 k} f_{rev}}{4\pi \sigma_x \sigma_y}$$

- *increase total beam intensity $I = N k_{bunch}$*
  - *higher radiation level/dose (lifetimes of devices)*
  - *N*: number of charges per bunch,
  - limited by: LHC: Tevatron
    - max. acceptable pileup N_{cross} of events per crossing
      - LHC nominal: $N_{cross} \sim 20$ $N_{cross} \sim 6$
        (eg. 2N → $N_{cross} = 80$)
      - Phase$_0$ Luminosity upgrade: $N_{cross} \sim 50$
        (β^*: 0.55→0.5 m & N_{bunch} 1.15 → 1.7 10^{11})
    - injector capability
  - k_{bunch}: total number of bunches, (25 ns bunch spacing) (396 ns)

    limited by:
    - detector (tracker) speed, speed of beam diagnostics
    - radio frequency system, more bunches/smaller spacing:
      - » requires high power klystrons and cavities (costs)
    - electron cloud and multiple bunch instabilities

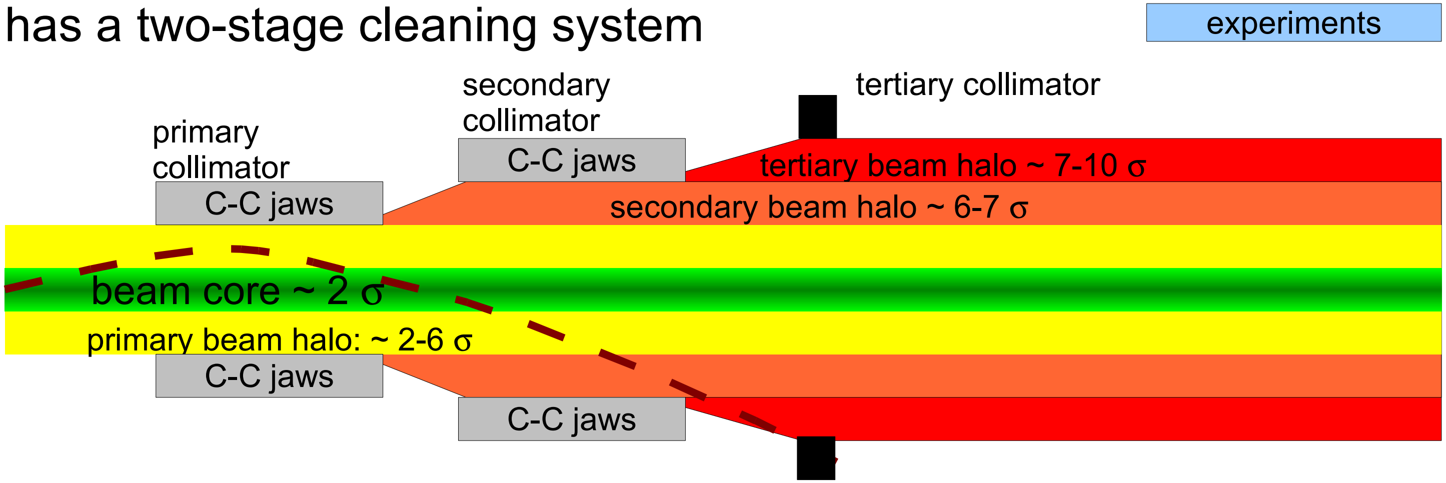
E-cloud not critical for Tevatron

Total Beam Intensity: Collimation and Protection

- LHC:
  - Total beam intensity (performance) is limited by the capability to control particle losses into the superconducting aperture
  - Two system:
    - Collimation System (IR3 & IR7) http://lhc-collimation.web.cern.ch
      - captures slow particle losses, preventing quenches
      - more than background optimisation for the experiments
    - Machine Protection System (all LHC): http://lhc-mpwg.web.cern.ch
      - prevents damage to the machine due to accidental beam losses
      - ultra-reliable, failsafe system
      - SIL3 safety, one critical failures every ~ 10^3 - 10^4 years (continuous mode, SIL=Safety-Integrity-Level)
  - Collimation/Protection System required during all operational phases
    - unprecedented in other machines

Total Beam Intensity: Collimation and Protection

- LHC has a two-stage cleaning system



- primary beam halo (BH_1) created by
  - beam-beam, intra beam scattering, electron cloud, noise, ...

experiments

(nominal parameters)

- primary collimator: absorbs BH_1/creates BH_2
- secondary collimator: absorbs BH_2/creates BH_3
- tertiary collimator (absorber)
  - insertion quadrupole quench protection
  - and protection against accidental beam loss
  - (possible use for background minimisation)

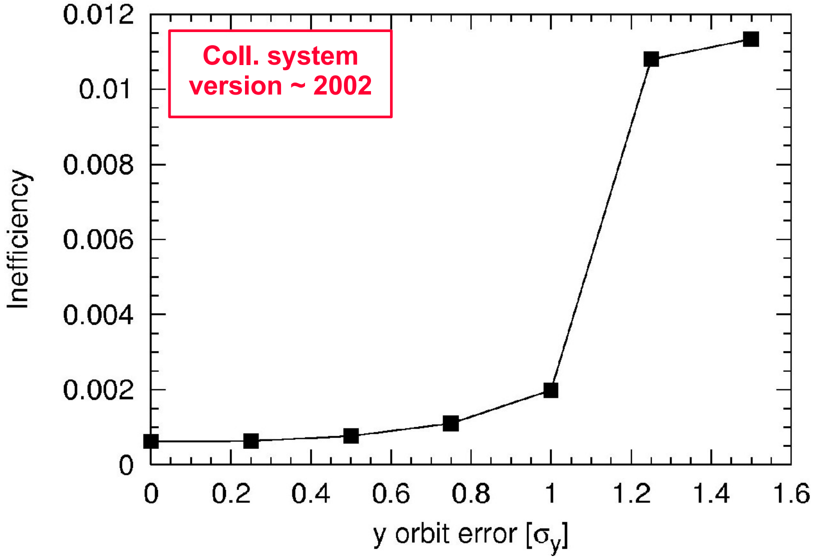
Collimation performance

- LHC beam intensity requires low collimation inefficiency on the ~10^{-3} level)

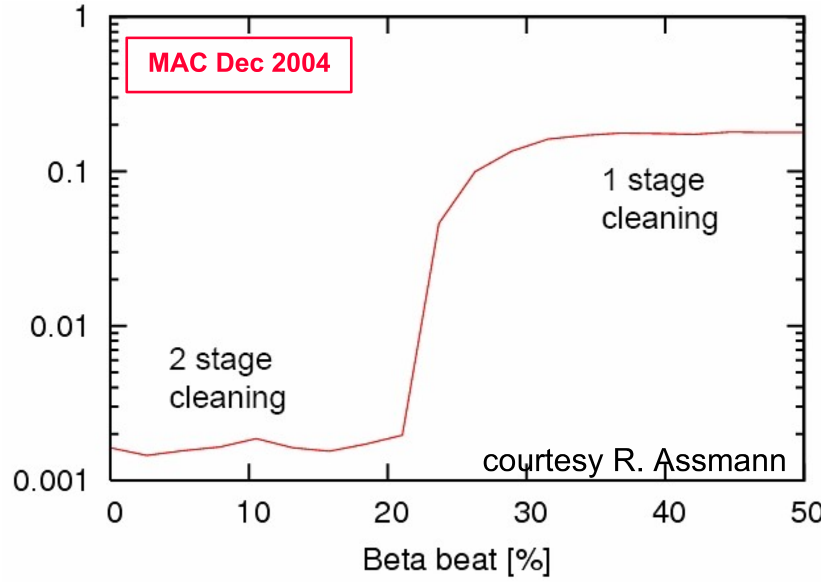
$$Inefficiency = \frac{number \quad of \quad escaping \quad protons}{number \quad of \quad impacting \quad protons}$$

- critically depends on the orbit and beam size stability
  - control beta-beat better than 20%
  - tight orbit stability requirement of σ/3 (~ 70 μm @ coll. jaws)

Collimation inefficiency vs. position error



Collimation inefficiency vs. β-beat (β^*=0.55 m)



courtesy R. Assmann

Stability and Luminosity?

- Obtained from machine parameters:

$$L=\frac{N^2 k\, f_{rev}}{4\pi\,\sigma_x\sigma_y}\cdot e^{-\frac{1}{4}\left[\left(\frac{\Delta x}{\sigma_x}\right)^2+\left(\frac{\Delta y}{\sigma_y}\right)^2\right]}\cdot F_{crossing}\cdot F_{hour\ glass}\cdot\ldots$$

  - Either: Neutron flux calorimeter (at θ=0) and "Van der Meer" scan (variation of Δx, Δy)
  - Or: measurement of ε and β_0: $\sigma(s)=\sqrt{\frac{\epsilon\,\beta(s)}{\gamma_{rel}}}$ → σ_x, σ_y
  - Fast bunch current transformer: → N
  - Error (both dominated by systematics): ~ 5 – 10%

- Optical Theorem and total p-p cross-section: $\sigma_{total}=4\pi\,Im\left[f_{el}(-t=0)\right]$
  - Measure for $10^{-3} < t=(p\theta)^2 < 10$ GeV² and extrapolate to 0

    (5 μrad < θ < 500 μrad or 8.3 < |η| <12.9)

- ΔL/L ≈1% → Δt/t ≈1% → Δθ/θ ≈ Δx/x ≈ $5\cdot 10^{-3}$ $t=(p\,\theta)^2\sim\frac{p^2}{\beta_0}\cdot x^2$
  - → absolute beam position stability at roman pot (x_{min}~ 1mm) < 5 μm!!
  - Understanding of systematics and alignment play an important role

Stability Requirements and Perturbation Sources

- ... numerous requirements on the beam orbit stability
  - Global: 0.2-0.5 mm (r.m.s.)
  - Local: < 70 μm

    (Collimation < 70 μm, Totem: < 5 μm)

    (Orbit stability is not an issue at Tevatron)

- Three important classes of beam perturbation:
  - Environmental: < 15 μm/s, ~500 μm/fill
  - Machine Inherent: < 25 μm/s, ~ 30 mm! (max)

    (largest contribution due to β^* squeeze)
  - Machine failures: < 15 μm/s, ~2.7 mm (max)

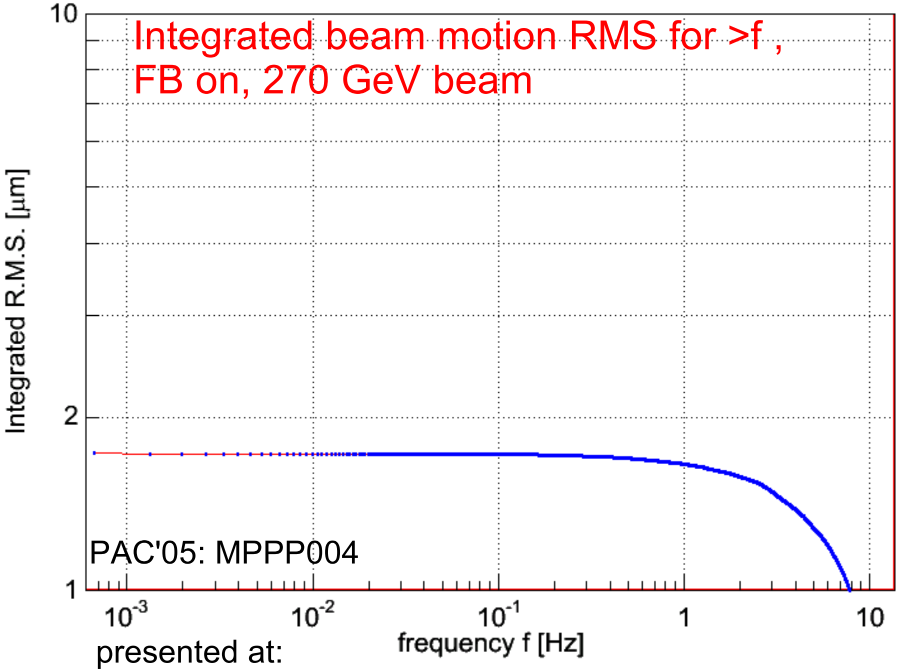
    (failure of COD power converter)

- Exceptionally for hadron collider:
  - LHC beam positions have to be stabilised during all operational phases
  - Global orbit feedback @ 25 Hz (50 Hz) with ~1 Hz effective bandwidth
    - Involves more than 3000 active elements (robustness is an issue).

LHC Orbit Feedback Tests

- LHC Orbit Feedback Prototype successfully tested at the SPS in 2004
  - 6 LHC bunch-by-bunch based beam position monitor System
  - achieved <u>relative</u> orbit stability down to 2 µm over several hours (~ 1/20 σ)
    - Relative stability fine for machine (collimation, protection ....)
    - However, BPM systematic offsets are dominant for absolute measurements
  - Stability limited by BPM noise/quality

- The Tests give confidence that:
  - baseline architecture works
  - beam can be stabilised better than 50 µm at the collimator jaws



presented at:
"3^{rd} Int. Workshop on Beam Orbit Stabilization 2004", Grindelwald, Switzerland

Integrated Luminosity

- Integrated Luminosity L_{int}

$$L_{int} = \iint_0^T L(s, \epsilon, \ldots, t)\, dt$$

1st order: $$\langle L \rangle \approx L_0 \cdot \tau \cdot \frac{1 - e^{\frac{-t_r}{\tau}}}{t_r + t_p}$$

  - run time $t_r \approx 10$ hours ("free" parameter)
  - preparation time t_p
    - LHC magnet cycle
    - LHC injectors,
    - LHC detectors
    - ...
  - beam lifetime τ
    - tune
    - tune spread
    - ...
    - (numerical aperture)
    - electron cloud

Optimisation of stops between LHC fills

- Recipes to win the SUSY/Higgs Grandprix
  - optimise the machine (τ, tp)
- LHC is a joint team effort!

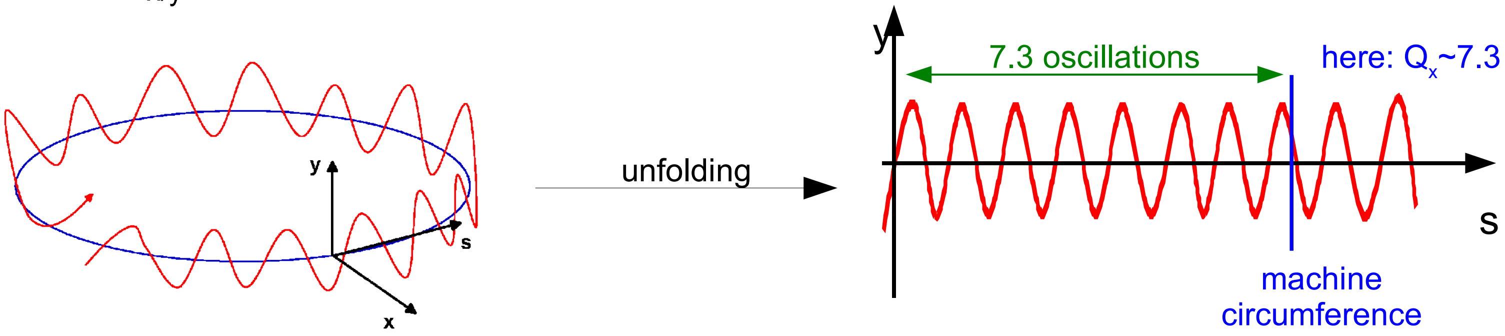
Conclusions

- SPS is ready to inject protons with nominal parameters into the LHC
- LHC accelerator has numerous challenges
  - beam energy and superconducting magnet technology (control of field errors)
  - control of beam losses into the superconducting aperture (collimation, machine protection)
  - control of accelerator and optics parameters
- Numerous machine parameter that control beam lifetime
  - orbit, tune, tune spread, dynamic aperture, electron cloud, ...
- Many systems depend on the beam stability and BPM system
  - Detector for physics, collimation, measurement of optics ....
- LHC Real-time Orbit Feedback system was tested at the SPS
  - Relative stability < 2 μm over several hours @ 270 GeV in the SPS
  - Beam stability < 50 μm seem to be reasonable for LHC Collimation
  - Issues: systematics, long-term quality of BPM data, reliability and robustness against failures

Reserve Slides

LHC Tune

- Tune $Q_{x/y}$ = number of h/v oscillations per turn



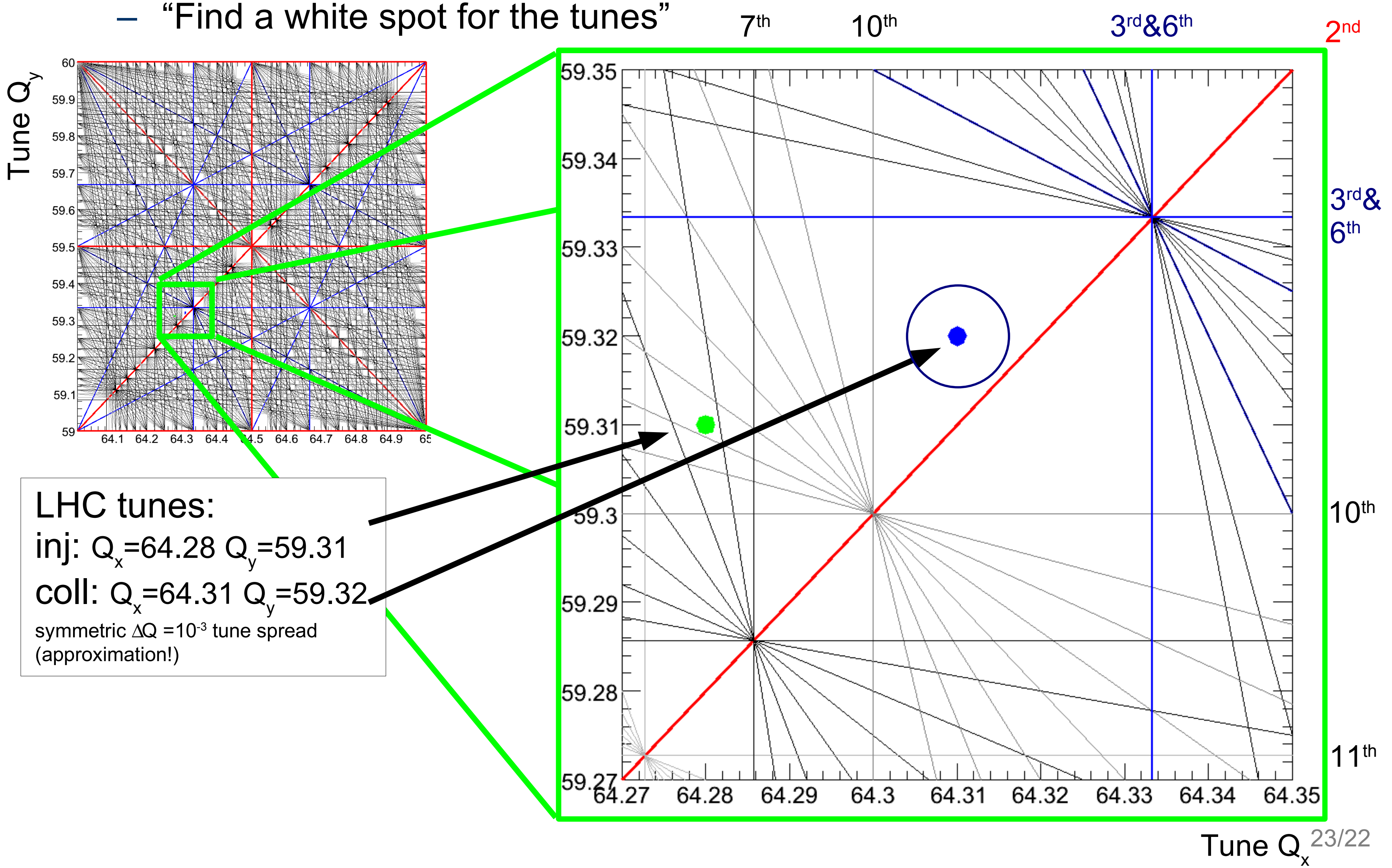
- magnet errors are part of the real (experimental physicists) world
  - e.g. dipole magnet and Q=n (n integer, no synchrotron damping for protons!):
    - field error accumulates and beam (orbit) growths linearly → beam lost ☹
- more general: particle are excited resonantly (order O) and lost if (m,n,p integer)

$$m\,Q_x + n\,Q_y = p \qquad \text{and} \qquad O = |m| + |n|$$

- avoid resonances up to O < 12th order
  - LHC injection: $Q_x=64.28$ and $Q_y=59.31$
  - LHC collision: $Q_x=64.31$ and $Q_y=59.32$

12th order tune diagram

- 1st + 2nd order resonances (red), 3rd order resonance (blue)
  - "Find a white spot for the tunes"



LHC tunes:

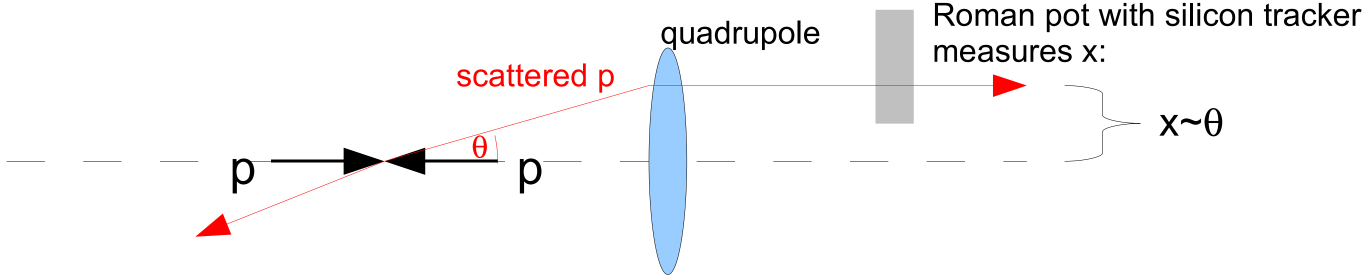
inj: Q_x=64.28 Q_y=59.31

coll: Q_x=64.31 Q_y=59.32

symmetric $\Delta Q = 10^{-3}$ tune spread (approximation!)

p Luminosity using Optical Theorem

- Special parallel to point focusing machine optic ($\beta_0 \approx 1600$ m)



  - Roman Pots move close to the beam halo (~ 10σ) and measure dN/dt down to:

$$t_{min} = (p\,\theta_{min})^2 \sim \frac{p^2}{\beta_0 \beta_d} \cdot x_{min}^2$$

  - Requires good knowledge on
    - Beta-functions β_0 at IP and β_d at detector
    - Beam momentum p
    - minimum distance of roman pot x_{min} w.r.t. beam centre
  - Desired: $\Delta L/L \approx 1\% \rightarrow \Delta t/t \approx 1\% \rightarrow \Delta\theta/\theta \approx \Delta x/x \approx 5\cdot 10^{-3}$
    - → absolute beam position stability at roman pot (x_{min}~ 1mm) < 5 μm!!
    - Understanding of systematics and alignment play an important role

LHC Luminosity Optimisation – Beam Size

- decrease beam sizes $\sigma(s)$ in interaction region (γ_{rel}=E/m, $\beta(s)$ optics function)

$$\sigma(s)=\sqrt{\frac{\epsilon\,\beta(s)}{\gamma_{rel}}}$$

LHC: pilot: $\varepsilon \sim 1.0$ μm rad
nom.: $\varepsilon \sim 3.8$ μm rad
Tevatron (p): $\varepsilon \sim 3.3$ μm rad

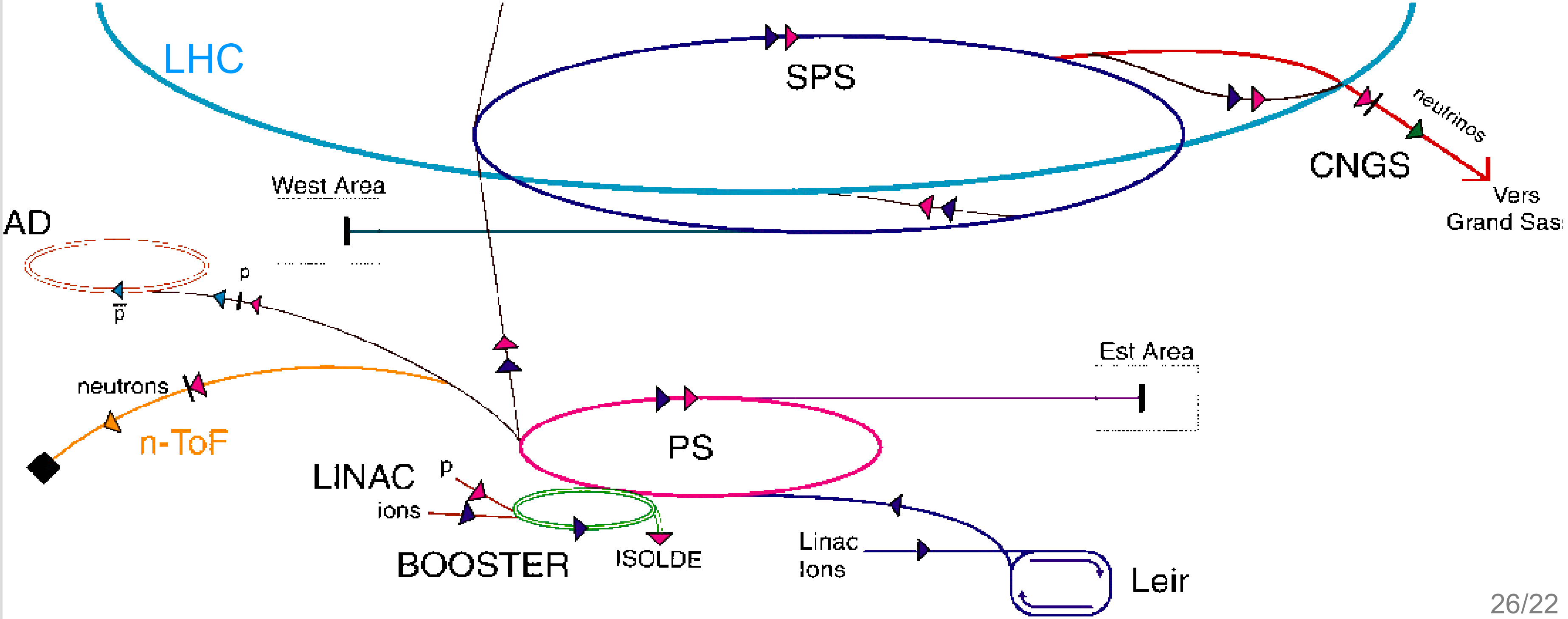
- either: β^* ↓↓ = 'final focus', limited by
  - final focus quadrupole aperture (and peak field strength)
  - large β_{max}: more sensitive to field errors and failures (effects scale with β)
  - "hour glass" effect, once $\beta^* \sim$ bunch length σ_s

    (transverse bunch tails larger than waist)
- or: emittance ε↓↓, ~ *"temperature"* of the bunches

  (volume in phase space that is occupied by the particles)
  - Protons:
    - synchrotron radiation negligible - no damping as for leptons!
    - "active cooling" inefficient (esp. at high energies)
  - produce low emittance ("cold") proton bunches at the source

“Protons have a memory!” – Emittance Preservation

- Gradual acceleration: p source → LINAC2 → PSB → PS → SPS → LHC
- low emittance needs careful treatment already in injectors
- Low emittance proton source
- avoid emittance blow-up
  - Inject at higher energy (space charge critical)
  - minimise resonances and optimised acceleration (e.g. across the transition energy)

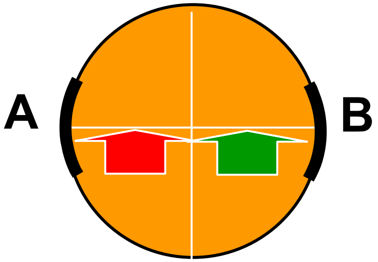


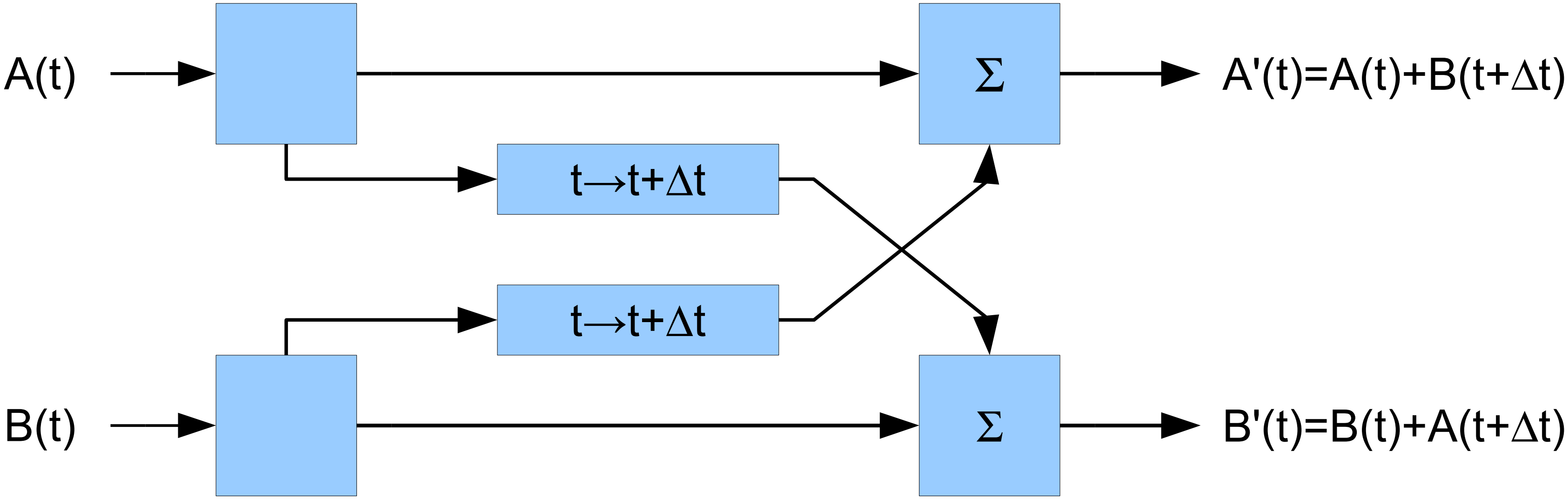
Tune Stability

- Required tune precision: $\Delta Q < 10^{-3}$
- Expected tune spread: $\Delta Q \sim 10^{-2}$ (mainly beam-beam induced)
  - mostly predictable and/or reproducible from one run to another
- 1st day: compensation with dedicated 'trim quadrupoles'
  - standard measurement procedure:
    - "kick" = excite the beam and find the (fractional) tune peak in the Fourier spectrum of the beam position monitors' trajectory data
    - drawback:
      - emittance blow-up (kick puts energy into the bunch)
      - potentially dangerous with full nominal beam (oscillating bunches may hit the aperture/collimator jaws)
- later: LHC Tune Feedback, once emittance blow-up free tune measurements are operational

Wide-Band-Time-Normaliser Principle I/II

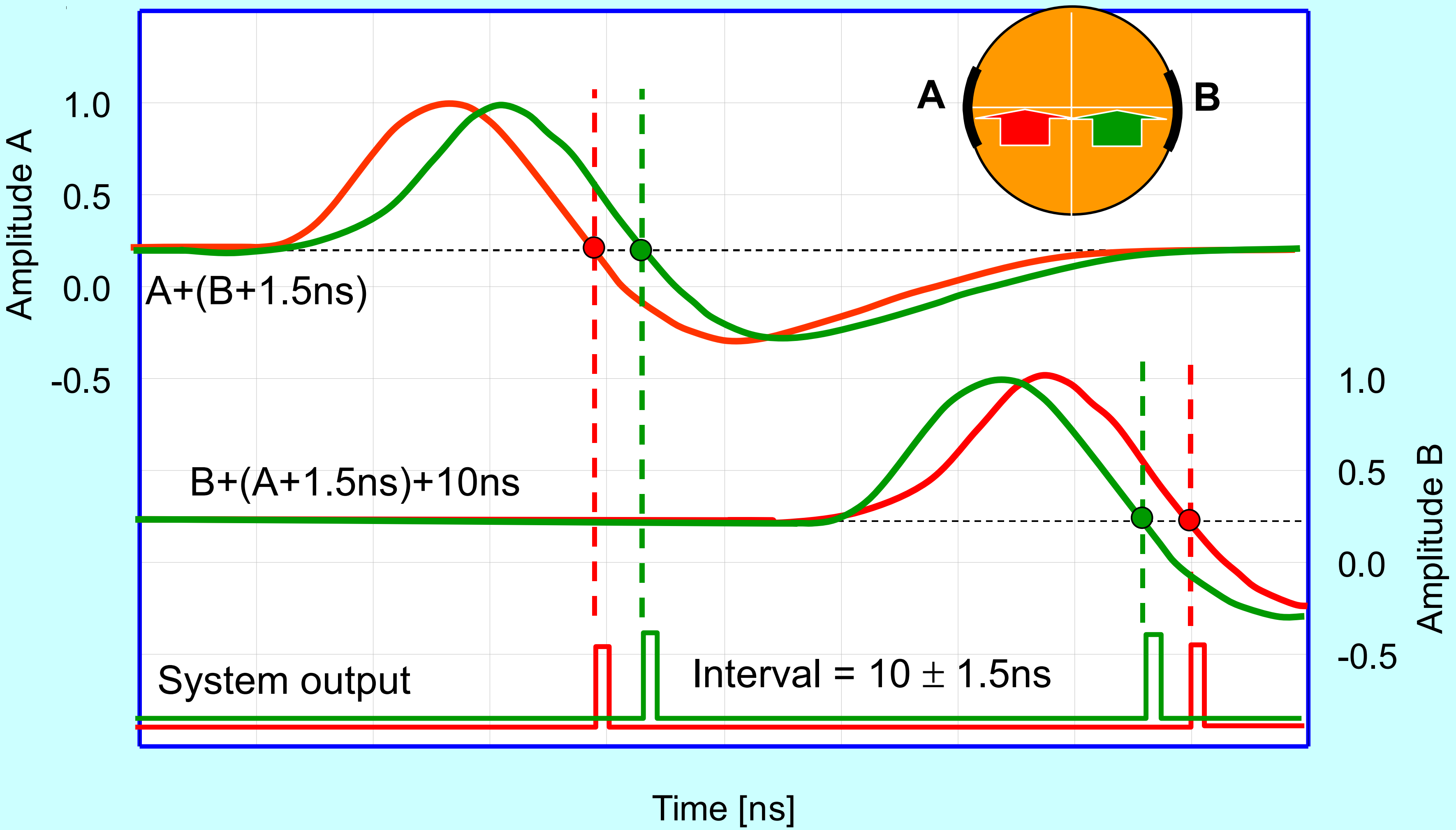
- Beam position monitor button signal A(t) and B(t) which are derrivatives of the bunch image on the vacuum chamber (gauss distributed)





- For more details:
  - D. Cocq, “The Wide Band Normaliser - A New Circuit to Measure Transverse Bunch Position in Accelerators and Colliders”, NIMA 416, Elsevier, 1998

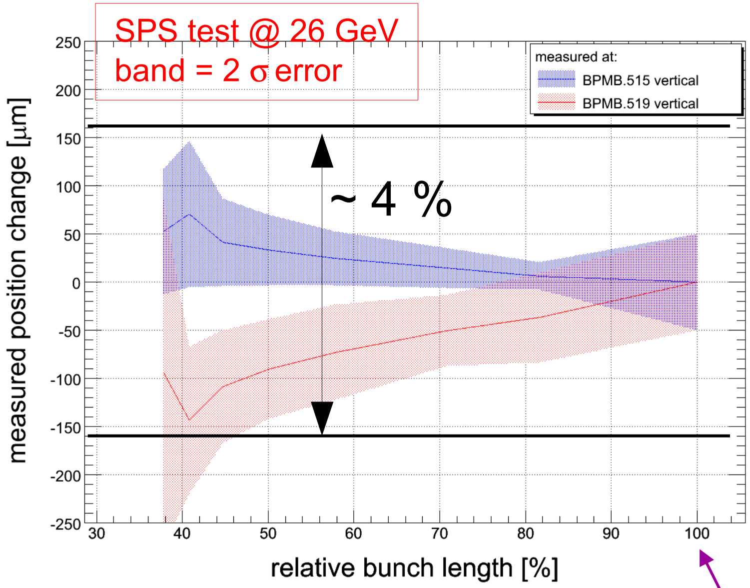
Wide-Band-Time-Normaliser Principle II/II



Beam Position Monitor Systematics

- BPMs are based on a wide-band-time-normaliser circuit
  - Linear within 1% w.r.t. BPM half aperture over large range of beam parameter
  - Small remaining dependence on:
    - bunch intensity (relatively small)
    - bunch length (more dominant in the SPS, monitors are LHC optimised)

Remaining BPM dependence on bunch length:

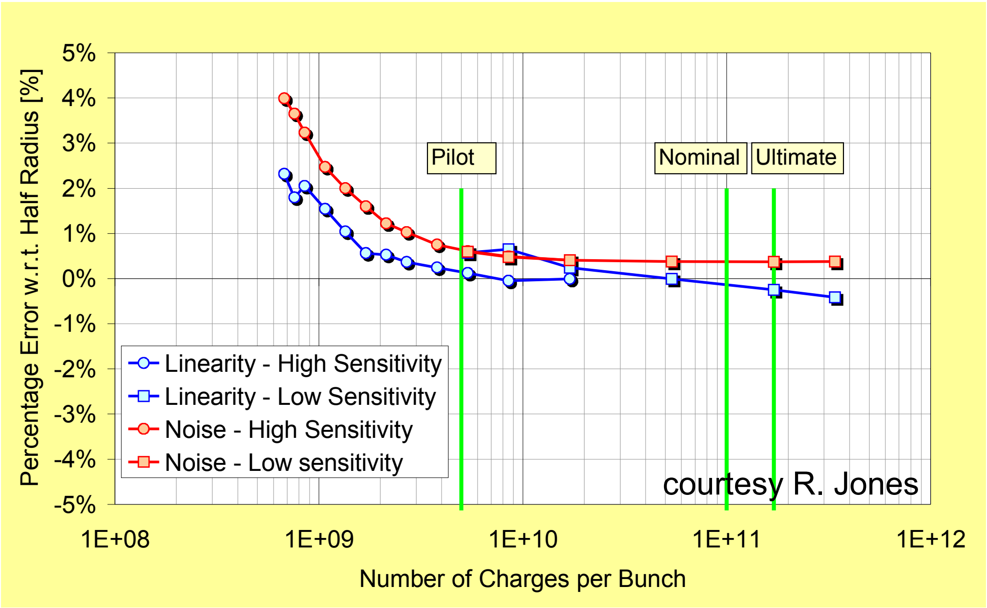


SPS test @ 26 GeV
band = 2 σ error

LHC: reduced dependence on bunch length for nominal bunches σ_t~1 ns, going to keep σ_t constant

τ = 4 ns

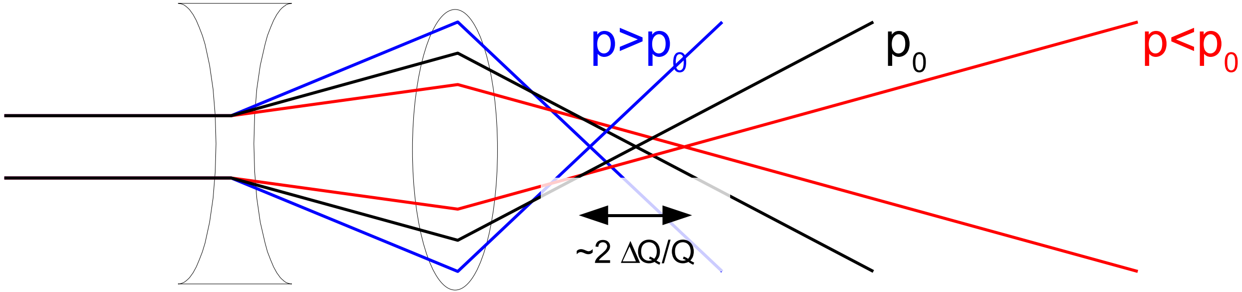
Remaining BPM dependence on bunch intensity:



courtesy R. Jones

Beam Chromaticity

- similar to light optics: chromatic error



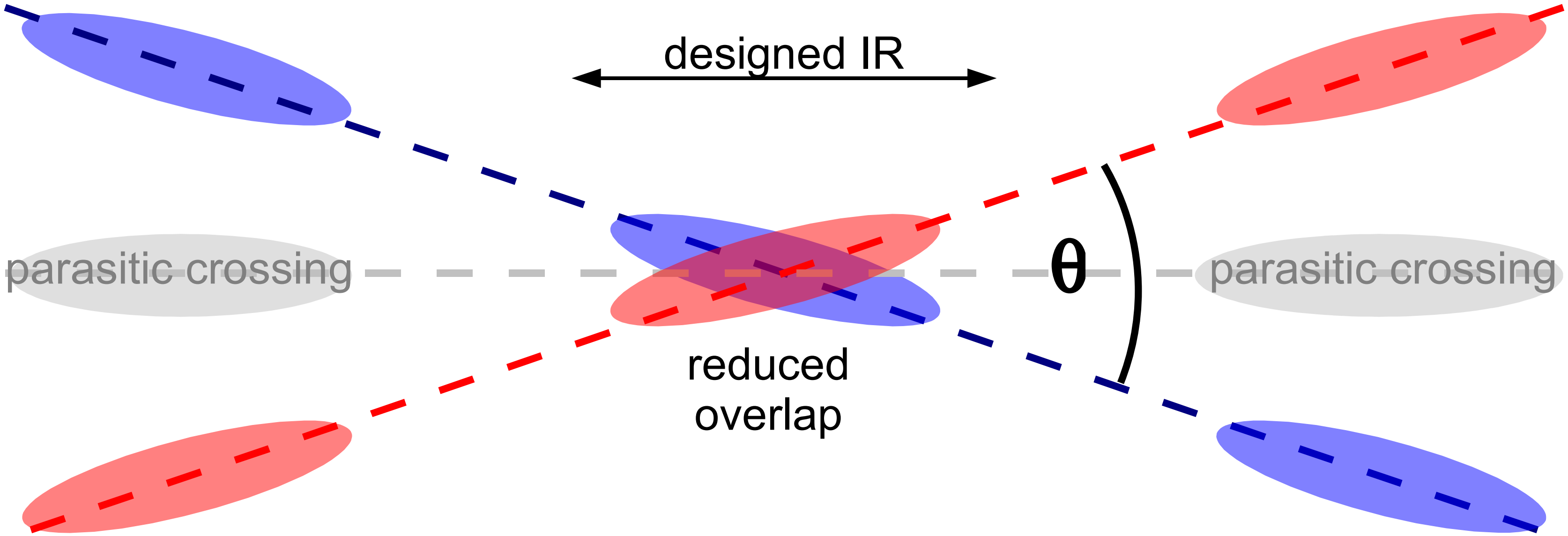
- Tune spread ΔQ/Q due to momentum spread Δp/p:

$$\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$$

  - ξ: 'chromaticity'
  - intrinsic to every quadrupole in the machine
  - increases beam footprint in tune diagram and causes resonances for off-momentum particles (target: ξ = +1 - 2)
- Decay and Snapback changes cromaticity up to 100 units
- Compensated by sextupole and higher multipole magnets

Luminosity: Effect of Crossing Angle

- Small bunch spacing:
  - crossing angle θ to avoid additional parasitic crossings
    - CMS: 25 ns spacing and θ=0: ~ 7 additional interaction regions
    - reduced overlap of bunches
  - “crab cavities” compensate this effect (e.g. KEKB):
    - rotate the bunches before and after the IR
      (required kick voltage KEKB ~1.44 MV@ β=100m, LHC: 144 MV @ β=2000m)



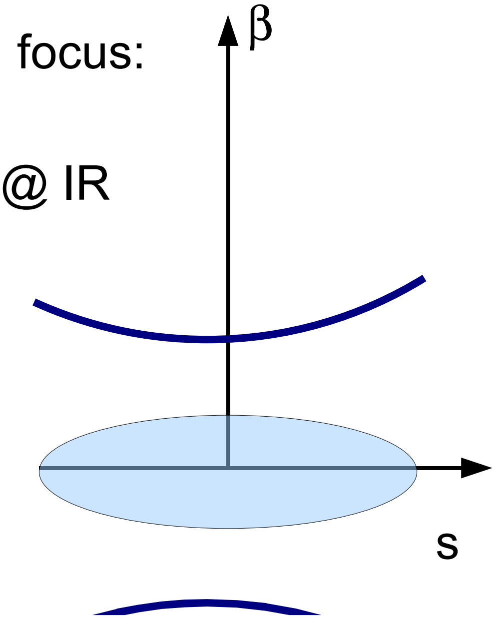
Luminosity: Hour Glass Effect

- Small beam sizes $\sigma(s)$ IR limited by final focus beta-function β_0. (LHC: β_0 = 0.55 m)
  - max possible beta function around the detector
    - large β_{max}: more sensitive to field errors and failures (many effects scale with β)
    - max available final focus quadrupole gradient
  - 'hour glass' effect if β^* similar to bunch length σ_s:

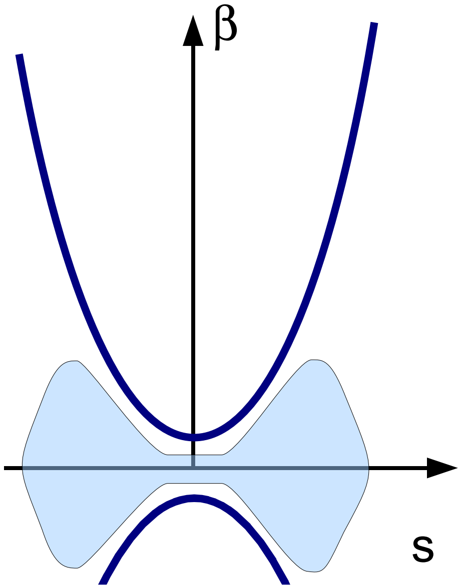
$$\sigma(s)=\sqrt{\frac{\epsilon\beta(s)}{\gamma_{rel}}}$$

$$\beta(s)=\beta_0\left(1+\left(\frac{s}{\beta_0}\right)^2\right)$$

Weak final focus:
$\beta_0 > \sigma_s$
σ_s ~ const @ IR



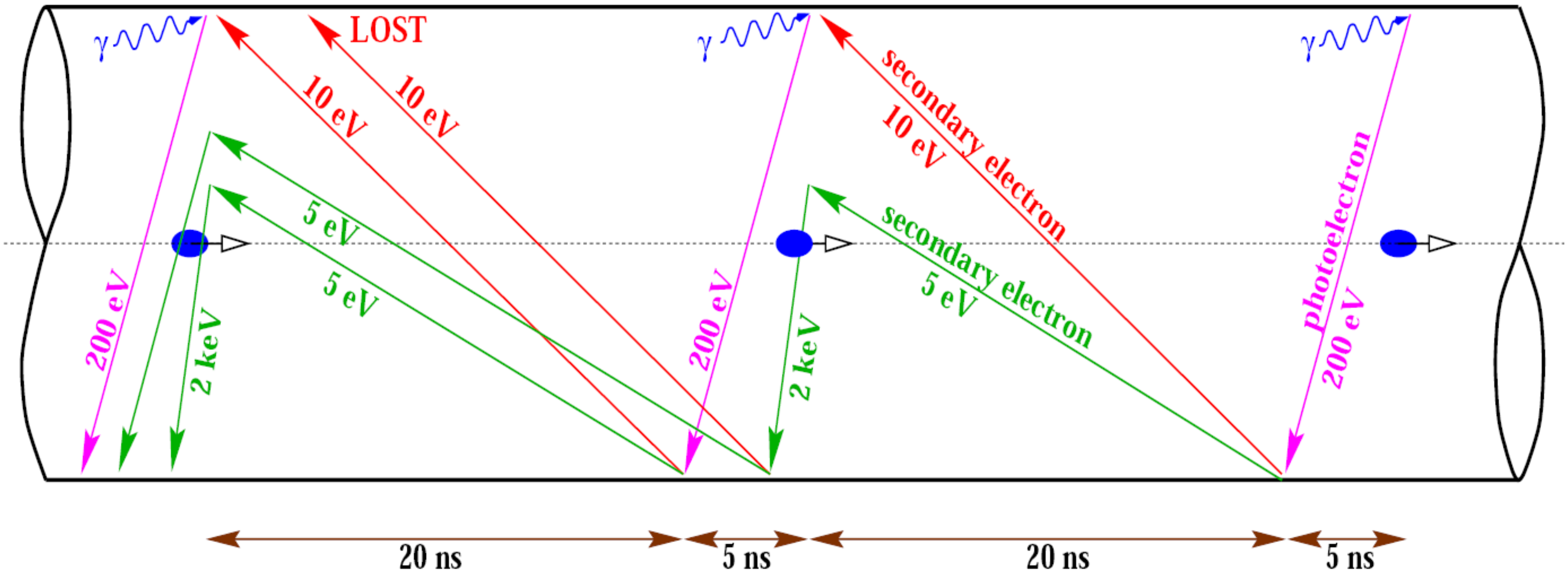
Strong final focus:
$\beta_0 < \sigma_s$
$\sigma_s = \sigma_s(s)$



counteract with shorter bunches:
protons: decrease ε_s while keeping $\varepsilon_{x/y}$ constant or decreasing ... (not trivial)

Small Bunch Spacing & Electron Cloud Effect I/II

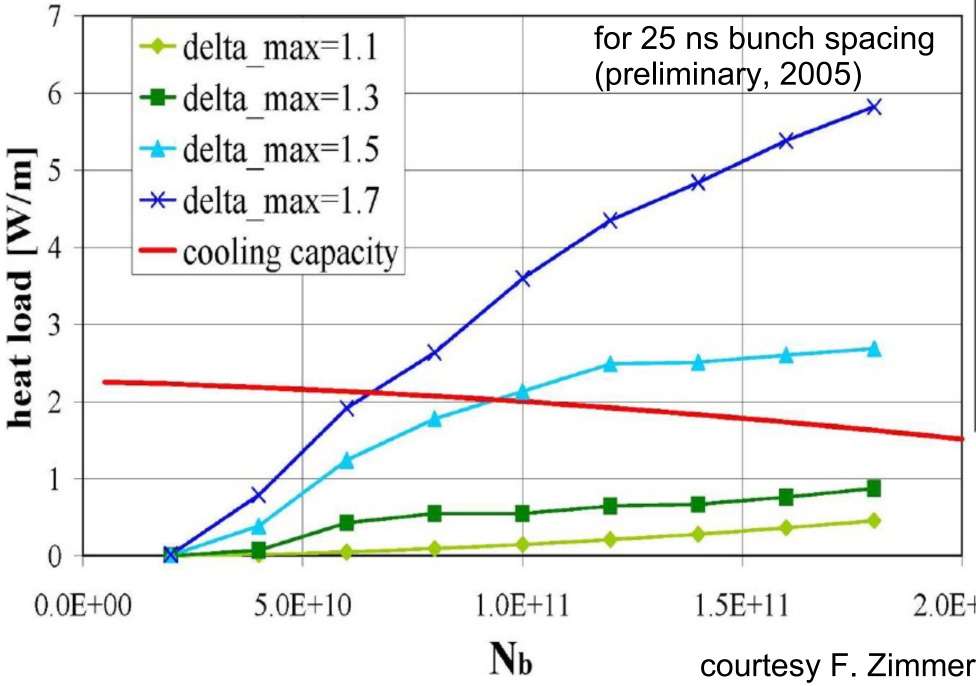
- -> Mechanism of multi-pacting:
  - synchrotron light liberates electrons from the chamber wall
  - electrons are accelerated by the beam
  - hit vacuum chamber and generate more electrons
- electron cloud causes instabilities and heat loss into the cryogenic environment



courtesy F. Ruggiero

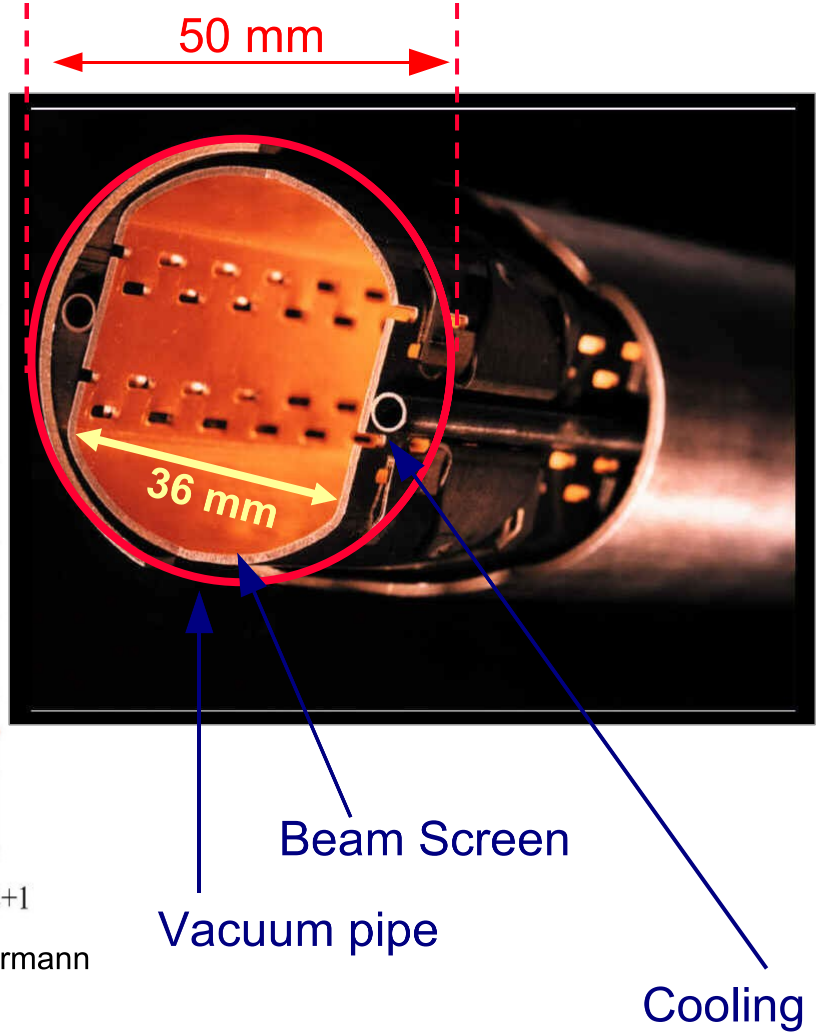
Small Bunch Spacing & Electron Cloud Effect II/II

- Additional 'beam screen' inside vacuum pipe
- heat load on the beam screen increases
  - with number of particles per bunch
  - with reducing bunch spacing

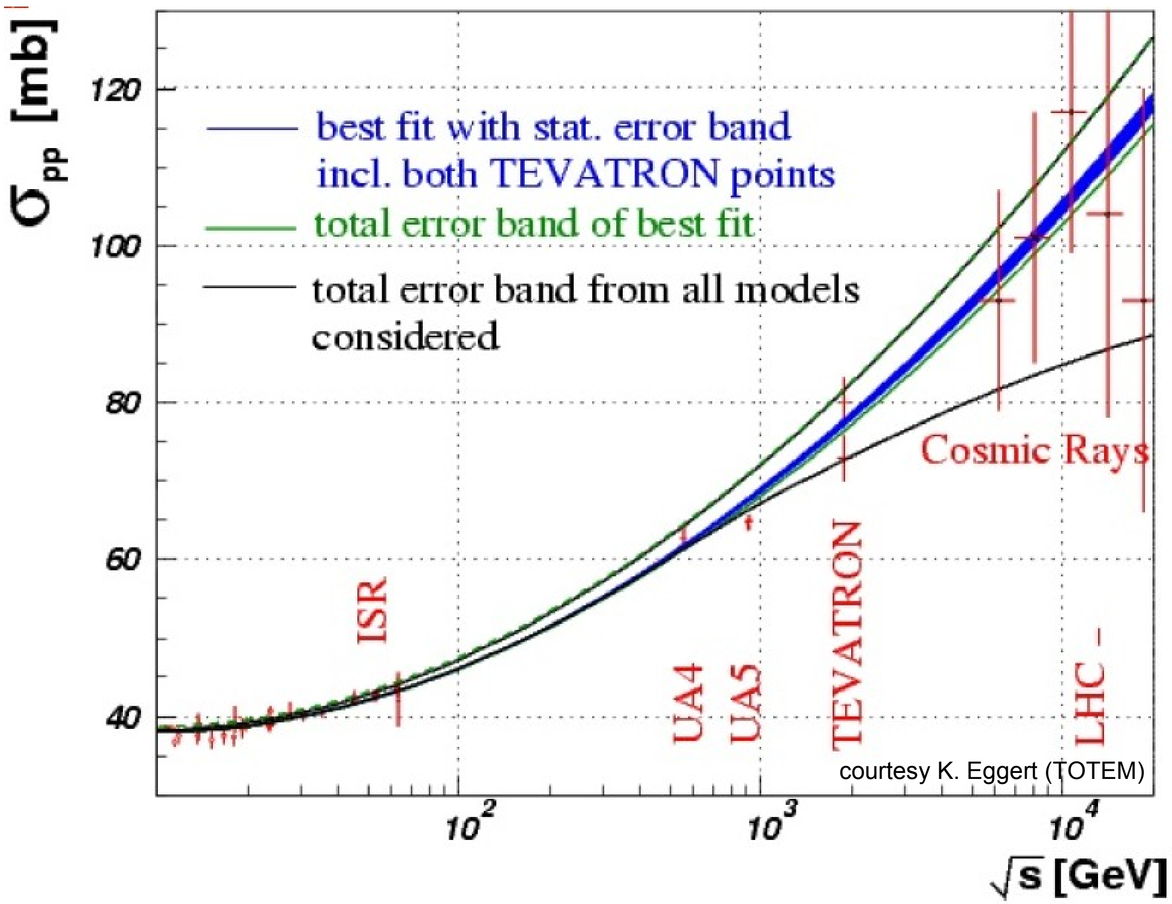


courtesy F. Zimmermann

delta_max: secondary electron yield property of the screen



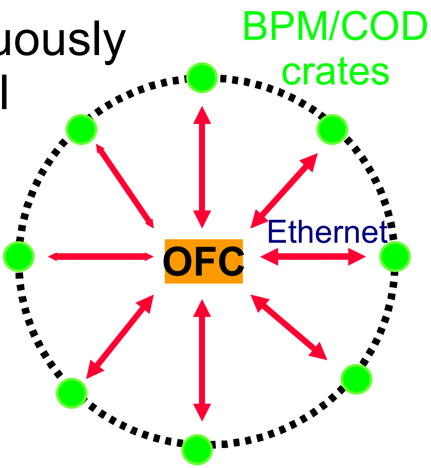
Total p-p Cross Section



courtesy K. Eggert (TOTEM)

LHC $\sigma_{tot} = 111.5 \pm 1.2 \, {}^{+4.1}_{-2.1}$ mb

LHC orbit feedback system



- Small perturbations around the reference orbit will be continuously compensated using beam-based alignment through a central global orbit feedback system. The system consists of:
  - 1056 beam position monitors (BPM)
    - Measure in both planes: > 2112 readings!
  - One Central Orbit Feedback Controller (OFC)
    - Gathers all BPM measurements, computes and sends currents through Ethernet to the PC-Gateways to move beam to its reference position:
      - 🔴 high numerical and network load on controller front-end computer
      - 🟢 rough machine model sufficient for steering
      - 🟢 flexible
      - 🟢 easier to commission and debug
  - 530 correction dipole magnets (CODs)/plane
    - Bandwidth (for small signals): $f_{bw} \approx$ 1-2 Hz (defines total feedback limit)
- Involves more than 3000 active elements!
  - feedback robustness is important for availability of the accelerator
  - Designed to be insensitivity to noise, errors, machine optic uncertainties