Longitudinal beam dynamics for the accelerator chain

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Nov. 7, 2017

OUTLINE

- Survey of LHC longitudinal dynamics
- Parameter design of SPPC longitudinal dynamics
- Preliminary consideration of longitudinal dynamics of SPPC injector chain
- Summary

LHC beam production and requirements

- LHC proton beam production:
- Source → Linac2 (Linac4) → PSB → PS → SPS → LHC
- Extraction kinetic energies or momenta: 50 MeV (160 MeV) → 1.4 GeV (2 GeV) → 25 (26) GeV/c → 450 GeV/c → 7 TeV
- The requirements from luminosity:
- the beam emittance (small aperture of SC magnet)
- the total beam intensity k_bN_b (synchrotron radiation)
- the beam-beam effect ($\propto N_b/\varepsilon_n$ → tune spread, footprint)
- the space-charge limits in the injectors

$$L = \frac{k_b N_b^2 f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}$$

transverse beam brightness ~N_b/ε_n

- Longitudinal emittance requirements:
- ✓ small at injection (small Δp/p to ease beam transport from the SPS through the two ~2.5 km long lines) (to avoid injection loss)
- ✓ larger in collision (avoid transverse emittance blow-up by Intra-beam scattering)

LHC RF considerations

- 400MHz (main) + 200MHz(capture)
- At injection into the LHC：
  - 200 MHz RF system only for capture.
  - Four cavities, 0.75 MV each, which can be pushed up to 1 MV.
  - For capture the operational total voltage at 200 MHz is 3 MV;
- After capture:
  - 400 MHz RF system adiabatically is increased up to 8 MV
  - 200 MHz RF system is decreased to zero;
  - **Acceleration only with 400 MHz.**
- On the flat top:
  - the emittance is 2.5 eVs.
  - f_{rf}=400MHz, $V_{rf(max)}$=16MV to produce ~1 ns long bunches.

LHC RF considerations

- The main RF system provides some damping of injection errors and natural Landau damping. (No longitudinal damper)
- Emittance increase during acceleration to reduce IBS growth rate but this will be in the capabilities of the RF system.
- Controlled emittance increase by excitation with band-limited noise. ($\varepsilon_s \propto \sqrt{E}$ to optimise instability threshold)
- The longitudinal emittance at top energy defined by intra-beam scattering lifetime (considering synchrotron radiation damping), RF lifetime and instability threshold considerations.
- A transverse feedback system damps transverse injection errors and stabilizes the beam against the resistive wall instability.

Survey of LHC longitudinal dynamics

LHC main beam and RF parameters

Table 6.1: The Main Beam and RF Parameters

	Unit	Injection 450 GeV	Collision 7 TeV
Bunch area (2σ)*	eVs	1.0	2.5
Bunch length (4σ)*	ns	1.71	1.06
Energy spread (2σ)*	10^{-3}	0.88	0.22
Intensity per bunch	10^{11} p	1.15	1.15
Number of bunches		2808	2808
Transverse emittance V/H	μm	3.75	3.75
Intensity per beam	A	0.582	0.582
Synchrotron radiation loss/turn	keV	-	7
Longitudinal damping time	h	-	13
Intrabeam scattering growth time - H	h	38	80
- L	h	30	61
Frequency	MHz	400.789	400.790
Harmonic number		35640	35640
RF voltage/beam	MV	8	16
Energy gain/turn (20 min. ramp)	keV	485	
RF power supplied during acceleration/ beam	kW	~275	
Synchrotron frequency	Hz	63.7	23.0
Bucket area	eVs	1.43	7.91
RF (400 MHz) component of beam current	A	0.87	1.05

* The bunch values at 450 GeV are an upper value for the situation after filamentation, ~ 100 ms after each batch injection. The bunch parameters at injection are described in the text.

controlled emitt-ance blow-up

Some formulas

- Momentum compaction factor:

$$\alpha_p = \frac{1}{\delta}\frac{\Delta C}{C} = \frac{1}{C}\oint \frac{D(s)}{\rho(s)} ds \approx \frac{\langle D\rangle}{R} \approx \frac{1}{\nu_x^2}$$

- Phase slip factor: $\eta = \alpha_p - \frac{1}{\gamma^2}$

- Synchrotron frequency:

$$f_s = \frac{\omega_0}{2\pi}\sqrt{-\frac{heV_{RF}\eta\cos\phi_s}{2\pi\beta_s^{\ 2}E}}$$

- Bucket half height:

$$\left(\frac{\Delta E}{E}\right)_{\max} = \pm\beta\sqrt{\frac{eVG(\varphi_s)}{\pi h\eta E_s}}$$

$$G(\varphi_s) = (\pi - 2\varphi_s)\sin\varphi_s - 2\cos\varphi_s$$

- Bucket area:

$$A_{\mathrm{B}} = \frac{16}{\omega_{\mathrm{RF}}}\sqrt{\frac{\beta^2 E\mathrm{eV}}{2\pi h|\eta|}}\alpha_b(\phi_s)$$

- Bunch area: $\varepsilon_{\mathrm{s}} = 4\pi\sigma_t\sigma_{\Delta E/E}E$

- Bunch length:

$$\sigma_s = RA_{\mathrm{rms}}^{1/2}\left(\frac{\omega_0}{\pi\beta^2 E}\right)^{1/2}\left(\frac{2\pi\beta^2 E|\eta|}{heV|\cos\phi_s|}\right)^{1/4}$$

- Momentum spread:

$$\sigma_\delta = A_{rms}^{1/2}\left(\frac{\omega_0}{\pi\beta^2 E}\right)^{1/2}\left(\frac{heV|\cos\phi_s|}{2\pi\beta^2 E|\eta|}\right)^{1/4}$$

- The relation between bunch length and momentum spread:

$$\sigma_z = \frac{R|\eta|}{\upsilon_s}\sigma_\delta$$

- Energy loss per turn:

$$U_0(\mathrm{KeV}) = 7.783\times10^{-12}\times\frac{E^4(\mathrm{GeV})}{\rho(\mathrm{m})}$$

- Synchrotron radiation damping time:

$$\tau_E = \frac{1}{2}\frac{T_0E_0}{U_0} \qquad \tau_x = 2\tau_E$$

The basic starting point

- According to the basic requirements for luminosity, and meanwhile taking luminosity upgrade into account.
- Besides, leaving a margin of certain parameter space for RF system to upgrade.

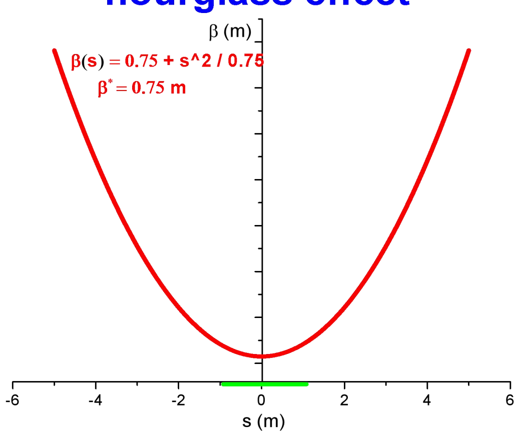
Luminosity

- Luminosity: $L = \frac{f_{rev} n_b N_b^2}{4\pi\varepsilon\beta^*} = \frac{I\gamma\xi}{e\beta^* r_p}$ (head-on)

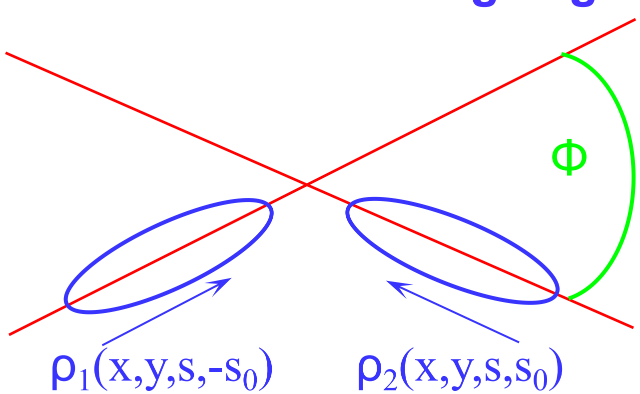
  beam current : $I = e f_{rf} n_b N_b$ beam-beam parameter : $\xi = \frac{N_b r_p}{4\pi\varepsilon_n}$

- Two effects lowering luminosity:

hourglass effect



Collisions at crossing angle



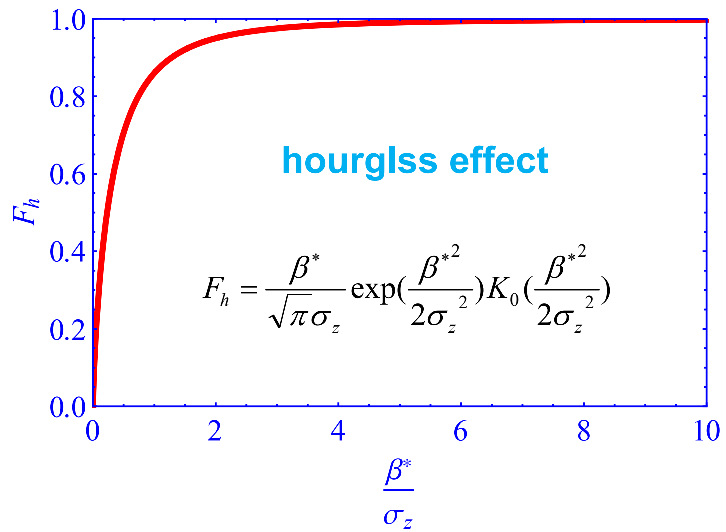
Parameter design of SPPC longitudinal dynamics

Luminosity

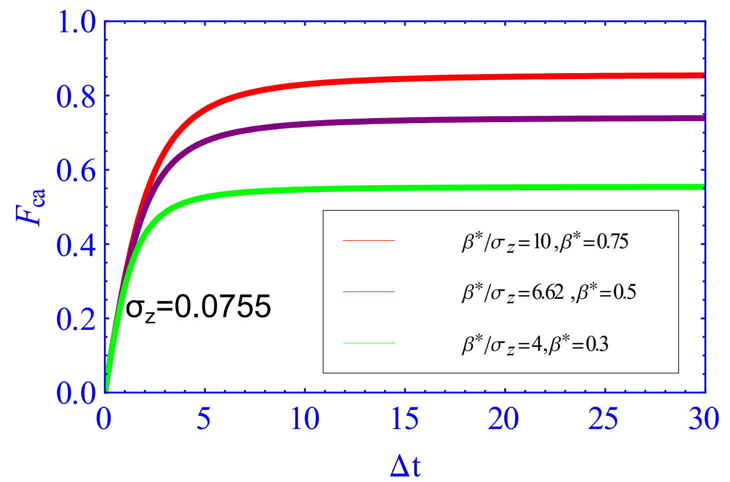
$$L = \frac{I\gamma\xi}{e\beta^* r_p} \cdot F_{ca} \cdot F_h$$

$$F_{ca} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma^*}\right)^2}} = \frac{1}{\sqrt{1+\Phi^2}}, \quad \Phi = \frac{\sigma_z\theta_c}{2\sigma^*} = 12\sqrt{\frac{\sigma_z^2}{(c\Delta t)^2} + \frac{1}{4(\beta^*/\sigma_z)^2}}$$

Φ is Piwinski Angle



- β^*/σ_z>>1, it can be neglected.



- The larger β^*/σ_z, the higher the luminosity.
- Only a little effect on luminosity by shortening bunch length.

➢ Luminosity upgrade measures:

- decreasing β^*, meanwhile shortening bunch length;
- increasing beam-beam parameter;
- increasing bunch numeber in order to increase single beam current

The requirements for SPPC longitudinal dynamics

Input parameters	Value
Circumference (km)	100
Energy (TeV)	37.5
Transition gamma γ_{tr}	99.21
Bunch intensity	1.5 x10^{11}
Number of bunches	10080
Bunch spacing (ns)	25
Bunch length during physics (m)	0.0755
RF frequency (MHz)	400

- Two constraints:
  - Intra-beam Scattering
  - Beam instability limits
- The goals:
  - How to achieve this goal of bunch length 7.55cm.
  - The variable range of bunch length for luminosity upgrade.

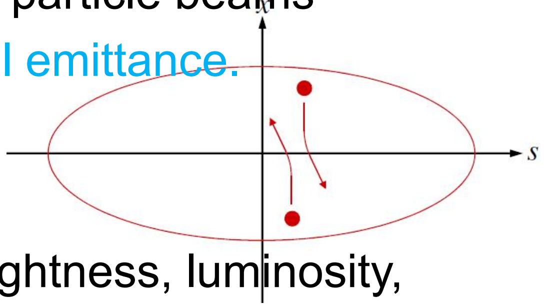
The design of longitudinal dynamics

- Determination of longitudinal emittance (IBS and beam instabilities need to be considered, pivotal issue);
- Given bunch length, we can get momentum spread;
- Determination of RF cavity voltage (f_{rf} = 400MHz)

Intra-beam Scattering (IBS)

- **Intrabeam Scattering (IBS):**
  - Multiple small-angle Coulomb scattering of charged particle beams

    ⟹ An increase in both transverse and longitudinal emittance.

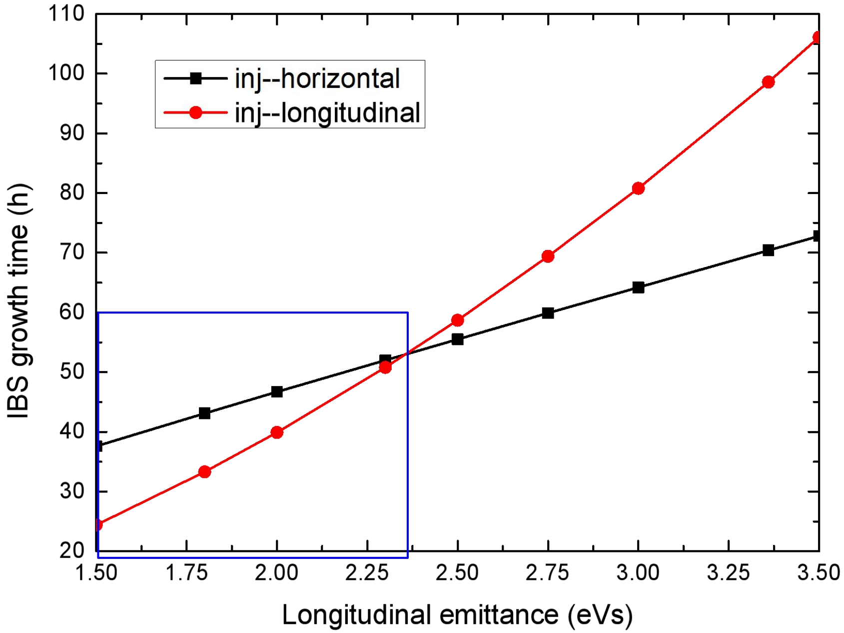


- The effects of IBS:
  - Redistribution of beam momenta
  - Beam diffusion with impact on the beam quality (Brightness, luminosity, etc)
- IBS growth rate: $\frac{1}{T_i} \propto \frac{N_b}{\gamma^4 \varepsilon_{xn}\varepsilon_{yn}\varepsilon_{sn}} f(optics, \gamma, \varepsilon_{xn}, \varepsilon_{yn}, \varepsilon_{sn})$

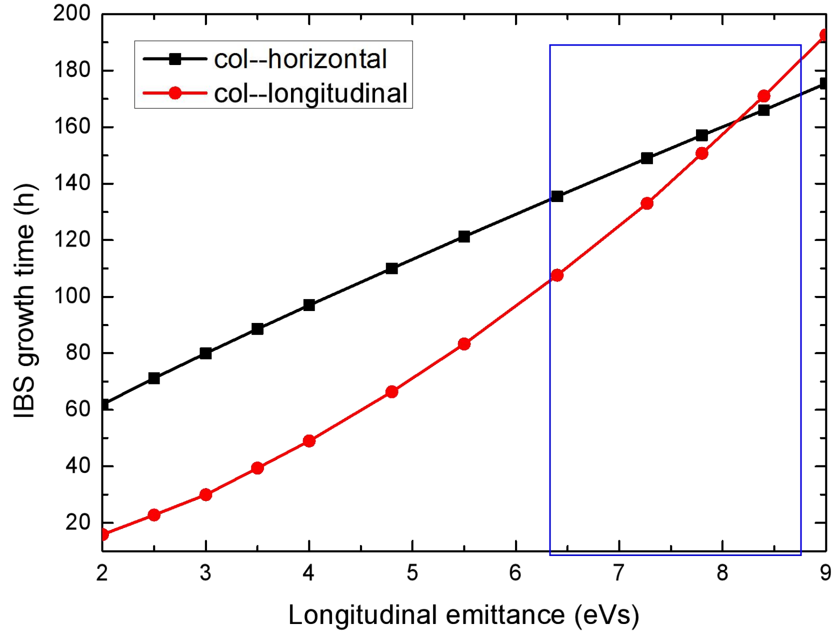
- Theoretical models and their approximations
  - Classical models of Piwinski (P) and Bjorken - Mtingwa (BM)
    - Complicated integrals averaged around the rings.
    - Depend on optics and beam properties.
  - High energy approximations **Bane, CIMP, J.Wei,** etc
    - Integrals with analytic solutions
- Tools: MADX, BETACOOL, etc

Intra-beam Scattering (IBS)

Injection



Collision



- At injection, longitudinal emittance between 1.5 eVs and 2.5 eVs may be a good choice; (injection time 840s)
- In collision, longitudinal emittance between 6 eVs and 9 eVs may be a good choice; (time during physics 14.2h)

Beam instability limits

- Two instability bottlenecks:
  - Loss of Landau damping
  - Transverse mode coupling instability (TMCI)

Loss of Landau damping

- Landau damping of the instability can come from the spread in the synchrotron frequency due to the nonlinearity of the synchrotron force in the bunch.
- The coherent tune shift induced by the broad-band impedance for a longitudinal mode of order n can be approximate to

$$\Delta Q_n^L \approx \frac{|n|}{|n|+1}\frac{Q_s I_b}{3h\, V_{rf}}\left(\frac{2\pi R}{L}\right)^3 \mathrm{Im}\left(\frac{Z_L}{n}\right)_{eff}$$

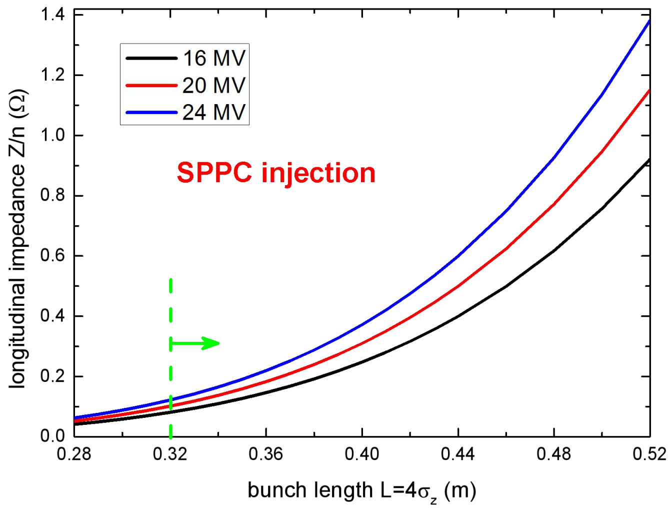
- The synchrotron tune spread $\Delta Q_s = (\pi^2/16)(hL/2\pi R)^2 Q_s$

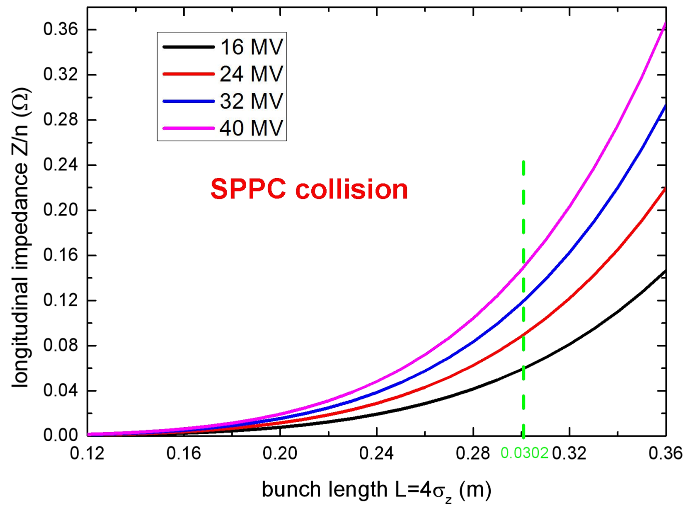
Requiring $\Delta Q_L \le \frac{1}{4}\Delta Q_s$ → $\frac{|\mathrm{Im}\, Z_{//}|}{n} \le \frac{3\pi^2}{64}\frac{h^3 V_{rf}}{I_b}\left(\frac{L}{2\pi R}\right)^5$ $L = 4\sigma_s$

the impedance threshold

Parameter design of SPPC longitudinal dynamics

Beam instability limits





$\sigma_z \geq 8$ cm, $Z/n \geq 0.1\Omega$

$\sigma_z = 7.55$ cm, Vrf ≥ 32MV ➡ $Z/n \geq 0.1\Omega$

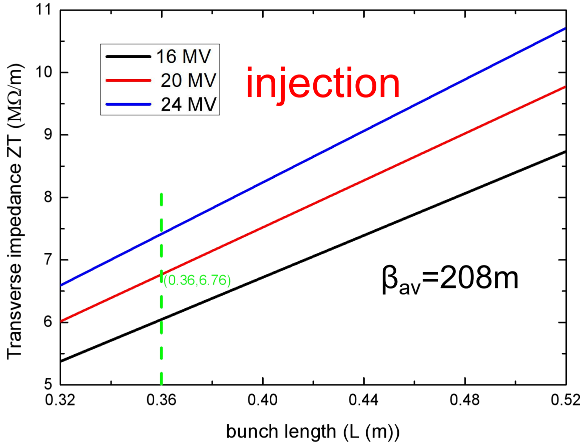
Shorter bunch length (luminosity upgrade)
➡ smaller longitudinal impedance.

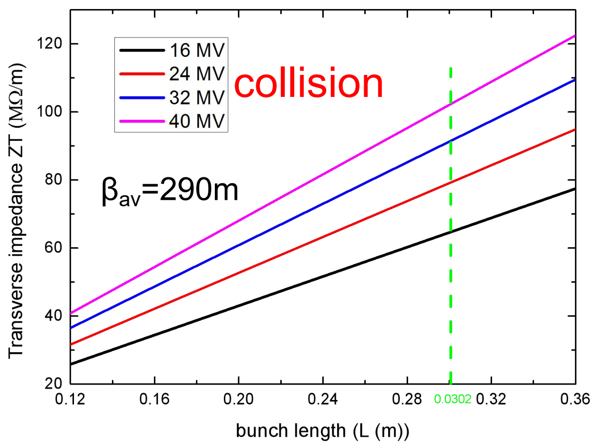
Longitudinal impedance of less than 0.1Ω needs to be studied !

- In order to Landau damp longitudinal coupled-bunch instability, a large spread in synchrotron frequency inside the bunch is required.
- **One way: install a higher harmonic cavity (800MHz RF cavity needs to be studied)**

Beam instability limits

- Transverse mode coupling instability (TMCI)
- This instability arises when the relative tune shift of two adjacent head-tail modes equals the synchrotron tune.
- The corresponding impedance threshold : $\mathrm{Im}(Z_T)_{eff} \leq 2\frac{E}{e}\frac{Q_s}{I_b\beta_{av}}\frac{L}{R}$





$\sigma_z \geq 8$ cm, $V_{rf} \geq 20$MV ➡ $Z_T \geq 6$ MΩ/m

$\sigma_z = 7.55$ cm, Vrf ≥ 32MV ➡ $Z_T \geq 80$ MΩ/m

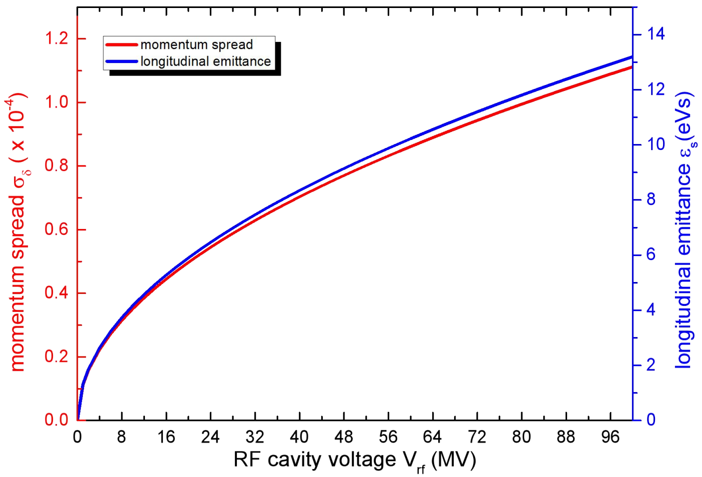
Shorter bunch length (luminosity upgrade) ➡ more stringent requirement for transverse impedance.

Tansverse impedance of less than 60MΩ/m needs to be studied !

Parameter design of SPPC longitudinal dynamics

The relation of longitudinal emittance, momentum spread and bunch length

- Momentum spread and bunch area vary with RF Voltage:

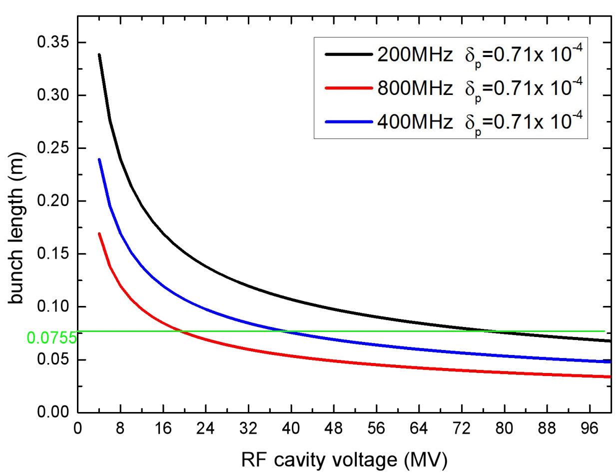


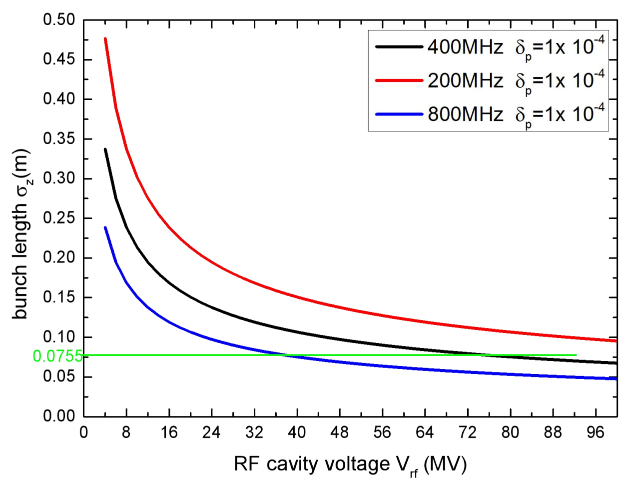
- **bunch length: σz=7.55cm**
- **RF frequency: 400MH**

$$\sigma_\delta \propto \sqrt{V_{rf}}$$

$$\varepsilon_s = 4\pi\sigma_t\sigma_{\Delta E/E}E$$

- Bunch length varies with RF voltage:





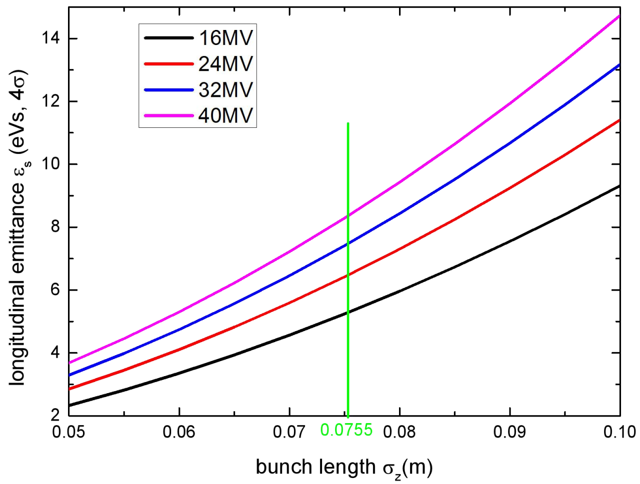
$$\sigma_z \propto \frac{1}{\sqrt{V_{rf}}}$$

- **Momentum spread less than 1x10⁻⁴ will be a good choice !**

Parameter design of SPPC longitudinal dynamics

The relation of longitudinal emittance, momentum spread and bunch length

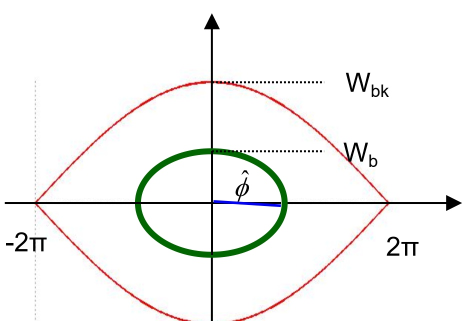
- Under different RF voltages, the relation between longitudinal emittance and bunch length is



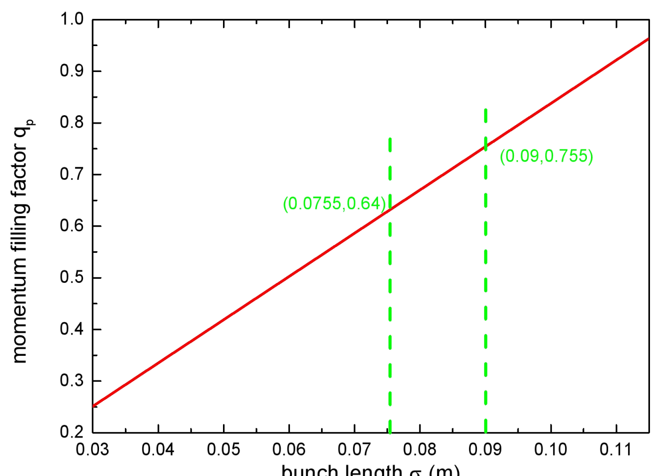
$$\varepsilon_s = 4\pi\sigma_{\Delta E/E}\sigma_z\frac{E}{v} = 4\pi\beta\sigma_\delta\sigma_z\frac{E}{c}$$

$$= 4\pi\beta\frac{\upsilon_s}{R|\eta|}\sigma_z^2\frac{E}{c} \qquad \propto \sigma_z^2$$

- Filling factor in momentum



$$W = 2\pi\frac{\Delta E}{\omega_0}$$



$$q_p = \frac{2\delta_p}{\left(\frac{\Delta p}{p}\right)_{\max}} \Rightarrow q_p = \frac{h}{R}\sigma_z$$ (small amplitude)

$$W_b = W_{bk}\sin\frac{\hat{\phi}}{2} \Rightarrow q_p = \frac{W_b}{W_{bk}} = \sin\frac{\hat{\phi}}{2}$$ (accurate)

Parameter design of SPPC longitudinal dynamics

SPPC longitudinal dynamics parameters

			LHC		HE-LHC	SPPC	
1			LHC		HE-LHC	SPPC	
2			Injection	Collision	Collision	injection	collision1
3	Proton energy	[GeV]	450	7000	16500	2100	37500
4	Relativistic gamma		480.61	7461.52	17586.52	2239.16	39968.09
5	Relativistic beta		1.00	1.00	1.00	1.00	1.00
6	Bending radius	[m]	2803.95	2803.95	2803.95	10415.4	10415.4
7	Number of particles per bunch	10^{11}	1.15	1.15	1.30	1.50	1.50
8	Number of bunches		2808	2808	1404	10080	10080
9	Longitudinal emittance(4σ)	[eVs]	1	2.5	4	2	8.4
10	Transverse normalized emittance	[μm rad]	3.5	3.75	2.59	2.4	2.4
11	Circulating beam current	[A]	0.582	0.582	0.329	0.727	0.727
12	Stored energy per beam	[MJ]	23.3	362	482.5	508.7	9083.3
13	Momentum compaction	10^{-4}	3.225	3.225	3.225	1.016	1.016
14	Slip factor η	10^{-4}	3.182	3.225	3.225	1.014	1.016
15	Gamma transition γ_{tr}		55.68	55.68	55.68	99.21	99.21
16	Ring circumference	[m]	26658.883	26658.883	26658.883	1.00E+05	1.00E+05
17	Revoluntion frequency	[kHz]	11.245	11.245	11.245	3.00	3.00
18	RF frequency	[MHz]	400.8	400.8	400.8	400.0	400.0
19	Bunch filling factor		0.788	0.788	0.788	0.756	0.756
20	Bunch seperation	ns	25	25	25	25	25
21	Harmonic number		35640	35640	35640	133333	133333
22	Synchrotron phase	rad	π	3.1412	3.1352	π	3.1046
23	Total RF voltage	[MV]	8	16	32	20	40
24	Synchrotron frequency	[Hz]	63.7	23.0	21.2	13.6	4.55
25	Bucket area	[eVs]	1.43	7.91	17.18	4.48	26.73
26	Bucket half height(ΔE/E)	$[10^{-3}]$	1.00	0.36	0.33	0.67	0.22
27	RMS bunch length	[cm]	11.24	7.55	6.48	9.00	7.55
28	Full bunch length(4σ)	[ns]	1.50	1.01	0.86	1.20	1.01
29	Momentum spread σ_δ	10^{-4}	4.72	1.13	0.89	2.53	0.71
30	Energy loss per turn U_0	[keV]	1.15E-04	6.67	205.78	0.01	1477.88
31	Longitudinal damping time τ_ε	[h]	48524.46	12.97	0.99	6680.90	1.17
32	Intrabeam scattering growth time-H	[h]	38	80		46.7	166
33	Intrabeam scattering growth time-L	[h]	30	61		39.9	171

- longitudinal emittance:
- 2 eVs(inj.) 8.4eVs (col.)
- Bunch length:
- 9.0 cm(inj.) 7.55 cm(col.)
- Momentum spread($x10^{-4}$):
- 2.53(inj.) 0.71(col.)
- RF voltage:
- 20MV(inj.) 40MV(col.)

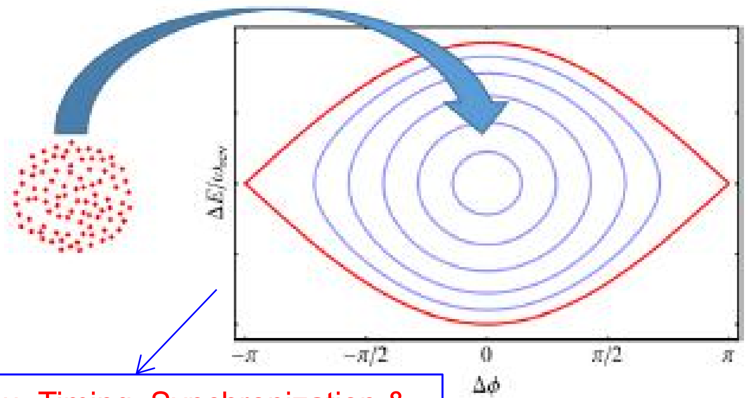
Possible problems faced in injectors

- Matching between injector chain;
- Space charge effect at low energy;
- Beam instability (Which instability dominate)
- IBS (may not important, but still to calculate);
- Beam loading in the RF cavity......
- Need special study for p-RCS;

Matching between injector chain

- How to transfer beam from accelerator A to B?
- Accelerator A → Accelerator B

Matched bunch-to-bucket transfer



H. Damerau. Timing, Synchronization & Longitudinal Aspects, CAS 2017.

Synchrotron phase is π at injection and extraction of each injectors; i.e. extraction will happen at flat top of each injector;

- More stable;
- Time structure preserved;

➢ Other considerations:

- Longitudinal emittance is conserved during transfer to the next;
- Longitudinal emittance may blow up during acceleration at each ring, but keep constant as far as possible;

Parameter design of SS

			SS	
1				
2			Injection	Extraction
3	Proton energy	[GeV]	180	2100
4	Relativistic gamma		192.84	2239.16
5	Relativistic beta		1.00	1.00
6	Ring circumference	[m]	7200	7200
7	Beam rigidity	[Tm]	603.5	7008.0
8	Dipole fied	[T]	0.71	8.26
9	Bending radius	[m]	848.42	848.42
10	Dipole filling factor		0.74	
11	Repetition period	[s]	30	
12	Fillings per cycle		2	
13	Number of particles per bunch	10^{11}	1.5	1.5
14	Number of bunches		672	672
15	Bunch spacing	[ns]	25	25
16	Accummulated particles	10^{14}	1.01	1.01
17	Revolution frequency	[kHz]	41.7	41.7
18	Revolution period	[μs]	24.0	24.0
19	Circulating beam current	[A]	0.67	0.67
20	Stored energy	[MJ]	2.9	33.9
21	Longitudinal emittance(4σ)	[eVs]	1.0	2.0
22	Gamma transtion		25.65	25.65
23	Momentum compaction factor	10^{-3}	1.52	1.52
24	Slipping factor	10^{-3}	1.49	1.52
25	RF frequency	[MHz]	200	200
26	Harmonic number		4800	4800
27	Ramping up time	[s]	12	
28	Total RF voltage	[MV]	6	8
29	Synchrotron phase	rad	π	π
30	Synchrotron frequency	[Hz]	256.92	87.63
31	Bucket area	[eVs]	6.24	24.38
32	Bucket half height(ΔE/E)	[10^{-3}]	1.72	0.58
33	RMS bunch length	[cm]	19.18	13.72
34	Full bunch length(4σ)	[ns]	2.56	1.83
35	Momentum spread σ_δ	10^{-3}	0.69	0.17
36	Intrabeam scattering growth time-H	[h]	0.86	253
37	Intrabeam scattering growth time-L	[h]	4.97	87

- Controlled emittance blow-up
- Note: the bunch length is 1.83ns at extraction of SS, but 1.2ns(SPPC inj. @400MHz), so **200MHz RF cavity is needed for SPPC capture.**
- IBS growth time is enough.

Parameter design of MSS

injection into SPPC

		MSS	
		Injection	Extraction
Proton energy	[GeV]	10	180
Relativistic gamma		11.66	192.84
Relativistic beta		1.00	1.00
Ring circumference	[m]	3478.24	3478.24
Beam rigidity	[Tm]	36.4	603.5
Dipole fied	[T]	0.10	1.699
Bending radius	[m]	355.23	355.23
Dipole filling factor		0.75	
Repetition rate	[Hz]	0.5	
Fillings per cycle		3	
Number of particles per bunch	10^{11}	1.5	1.5
Number of bunches		336	336
Bunch spacing	[ns]	25	25
Accummulated particles	10^{14}	0.50	0.50
Revolution frequency	[kHz]	86.3	86.3
Revolution period	[µs]	11.6	11.6
Average beam current	[µA]	4.04	4.04
Beam power	[MW]	0.04	0.73
Transverse normalized emittance	[µm rad]	2.4	2.4
Longitudinal emittance(4σ)	[eVs]	0.5	1.0
Gamma transtion		87.36i	87.36i
Momentum compaction factor	10^{-4}	-1.31	-1.31
Slipping factor	10^{-4}	-74.89	-1.58
RF frequency	[MHz]	40.02	40.02
Harmonic number		464	464
Ramping up time	[s]	0.8	
Total RF voltage	[MV]	3	5
Synchrotron phase	rad	0	0
Synchrotron frequency	[Hz]	3513.20	155.22
Bucket area	[eVs]	2.36	88.97
Bucket half height(ΔE/E)	[10^{-3}]	2.34	4.91
RMS bunch length	[cm]	110.22	25.38
Full bunch length(4σ)	[ns]	14.70	3.38
Momentum spread σ_δ	10^{-3}	1.08	0.52
Intrabeam scattering growth time-H	[s]	167	146
Intrabeam scattering growth time-L	[s]	2001	1093

80MHz RFcavity is needed

beam application

		MSS	
		Injection	Extraction
Proton energy	[GeV]	10	180
Relativistic gamma		11.66	192.84
Relativistic beta		1.00	1.00
Ring circumference	[m]	3478.24	3478.24
Beam rigidity	[Tm]	36.4	603.5
Dipole fied	[T]	0.10	1.699
Bending radius	[m]	355.23	355.23
Dipole filling factor		0.75	
Repetition rate	[Hz]	0.5	
Fillings per cycle		3	
Number of particles per bunch	10^{11}	7.59	7.59
Number of bunches		336	336
Bunch spacing	[ns]	25	25
Accummulated particles	10^{14}	2.55	2.55
Revolution frequency	[kHz]	86.3	86.3
Revolution period	[µs]	11.6	11.6
Average beam current	[µA]	20.43	20.43
Beam power	[MW]	0.20	3.68
Transverse normalized emittance	[µm rad]	20.4	20.4
Longitudinal emittance(4σ)	[eVs]	0.5	1.0
Gamma transtion		87.36i	87.36i
Momentum compaction factor	10^{-4}	-1.31	-1.31
Slipping factor	10^{-4}	-74.89	-1.58
RF frequency	[MHz]	40.02	40.02
Harmonic number		464	464
Ramping up time	[s]	0.8	
Total RF voltage	[MV]	3	5
Synchrotron phase	rad	0	0
Synchrotron frequency	[Hz]	3513.20	155.22
Bucket area	[eVs]	2.36	88.97
Bucket half height(ΔE/E)	[10^{-3}]	2.34	4.91
RMS bunch length	[cm]	110.22	25.38
Full bunch length(4σ)	[ns]	14.70	3.38
Momentum spread σ_δ	10^{-3}	1.08	0.52
Intrabeam scattering growth time-H	[s]	4366	2746
Intrabeam scattering growth time-L	[s]	1359	2612

Summary

- The longitudinal dynamics parameters of SPPC have been given to achieve the required bunch length and stability.
- Based on the beam instability, a shorter bunch length will set a more stringent requirement for impedance. Longitudinal impedance of less than 0.1Ω and transverse impedance of less than 60MΩ/m need to be studied.
- Preliminary parameters design of SS and MSS have been given taking matching between injectors and IBS into considerasion.

Next to do

- Longitudinal dynamics of injector chain considering space charge and beam instability;
- Special study for p-RCS is needed;
- Longitudinal dynamics during acceleration;

Thanks for your attention !

Back up

SPS and PS requirements

- SPS
- the SPS is an “old” machine and is not optimised as an LHC injector.
- The intensity the SPS can be accelerated (at most 4 PS pulses) (Why does SPS ring have this limitation???)
- The momentum spread acceptance of the PS-SPS line (TT2, TT10) is about ±0.2% in Δp/p, while the total bunch length has to be below 4 ns to fit into the buckets of the SPS 200 MHz accelerating system, implying a longitudinal emittance of 0.35 eVs per PS bunch.
- the longitudinal emittance will be increased from 0.35 to 1 eVs during SPS acceleration, there is little margin for transverse emittance blow-up in this machine.
- The main challenges for PS complex:
- the unprecedented transverse beam brightness ($\sim N_b/\varepsilon_n$)
- the production of a bunch train with the LHC spacing of 25 ns before extraction from PS (25GeV)
- Space charge issues in PS and PSB

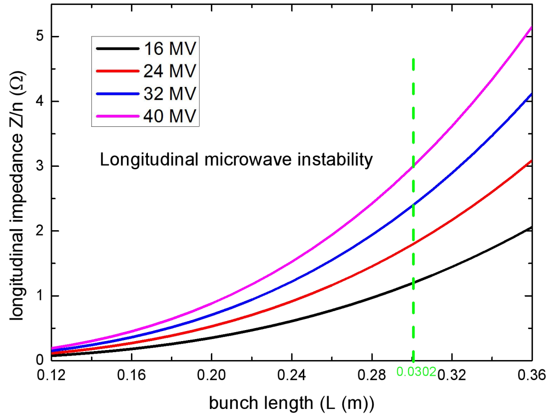
$$\Delta Q \propto -\frac{N}{\left(\beta\gamma^2\right)_{rel}\varepsilon_n}$$

Beam instability limits

- Longitudinal microwave instability
- The microwave instability is induced by the resistive part of the coupling impedance. It produce a fast increase of the mαnentum spread when the bunch intensity goes beyond a threshold value and splits a bunch into many mini-bunches.
- Keil-schnell-Boussard criterion:

$$\left|\frac{Z_{//}}{n}\right| \le \frac{\sqrt{2\pi}\eta(\frac{E}{e})(\frac{\sigma_z}{R})(\frac{\sigma_E}{E})^2}{I_b}$$

$$\left|\frac{Z_{//}}{n}\right| \le \frac{3}{2}\frac{hV_{rf}}{I_b}\left(\frac{L}{2\pi R}\right)^3$$



$$\begin{cases} \sigma_z = \dfrac{R|\eta|}{\upsilon_s}\sigma_\delta \\ \upsilon_s = \sqrt{-\dfrac{heV_{RF}\eta\cos\phi_s}{2\pi\beta_s^{\ 2}E}} \\ R = \dfrac{C_{ring}}{2\pi} \\ h = \dfrac{f_{rf}}{f_0} = \dfrac{f_{rf}\cdot C_{ring}}{\beta_s c} \end{cases} \Rightarrow \sigma_z = \sigma_\delta\sqrt{\frac{C_{ring}\cdot|\eta|\cdot E_s c\beta_s^3}{2\pi e\cdot V_{rf} f_{rf}\cdot|\cos\phi_s|}}$$