First consideration of RF scheme to mitigate longitudinal instabilities in Super Proton-Proton Collider

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Sept. 24, 2019

Outline

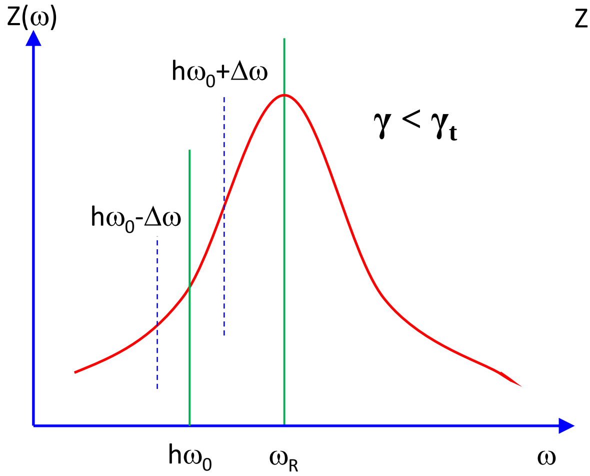
- A simple review of the main longitudinal instabilities
- RF scheme to mitigate longitudinal instability in SPS/LHC
- Introduction to SPPC
- RF scheme to mitigate longitudinal instability in SPPC
- Summary and outlook

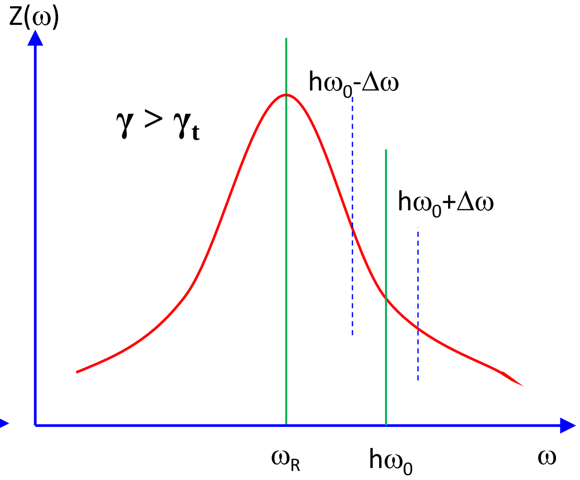
A simple review of the main longitudinal instabilities

Single bunch effects: Robinson Instability [1]

- The Robinson instability is a longitudinal instability caused by impedance of RF cavity

$$Z_m^{\parallel} = \frac{R_S}{1 + iQ\left(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right)}$$





- In essence:
  - ✓ the Robinson instability comes from the fact that the revolution frequency of an off-momentum beam is slightly different from the on-momentum revolution frequency, depending on both the slip factor and the energy deviation.

$$\frac{\Delta\omega}{\omega_0} = -\eta\frac{\Delta p}{p_0}$$

- Stable condition:
  - ✓ If $\eta>0$, above transition, Robinson damping → $h\omega_0 > \omega_R$
  - ✓ If $\eta<0$, below transition, Robinson damping → $h\omega_0 < \omega_R$

[1] Qing Qin, High Energy Circular Accelerator Physics, Chinese edition

A simple review of the main longitudinal instabilities

Single bunch effects: Longitudinal microwave instability [2]

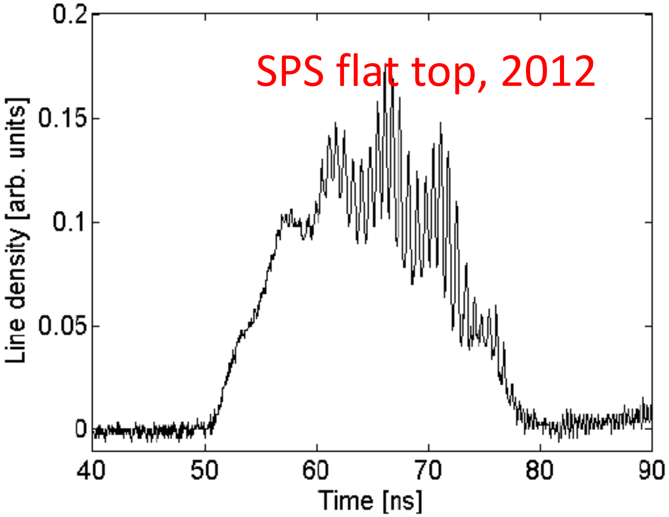
- Keil-Schnell-Boussard criterion:

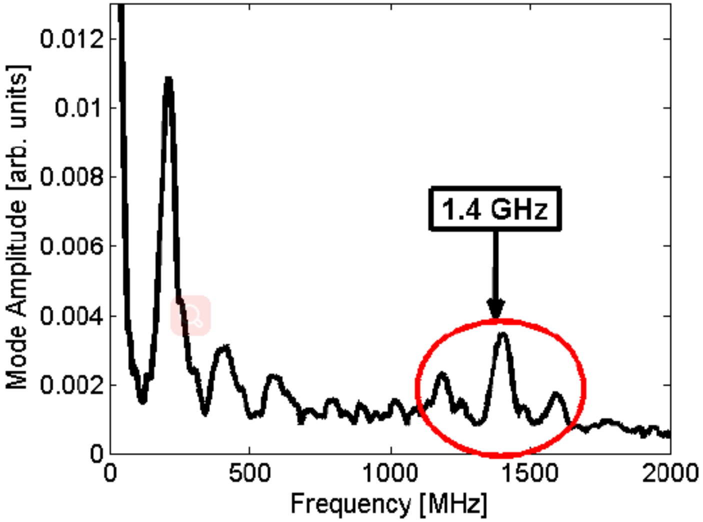
$$\left|\frac{Z_{//}}{n}\right| \le \frac{2\pi\beta^2 E\sigma_\delta^2|\eta|F}{e\hat{I}}$$

- grows usually fast;
- the bunch will split into many micro bunches and the momentum spread will increase.
- In proton accelerators the microwave instability is observed as a fast increase of the bunch length and thus of the longitudinal emittance ε_l.
- $f_r\tau >> 1$, microwave signals (100MHz~3GHz)

- Usually, longitudinal microwave instability will not be worsened for larger hadron machines.[3]

$$\left|\frac{Z_{//}}{n}\right| \propto \frac{\sigma_\delta^2\sigma_\tau}{N_b}$$





[3] K.Y. Ng, Coupling Impedances and Beam Instabilities in Accelerator Rings, US Accelerator School, 2015

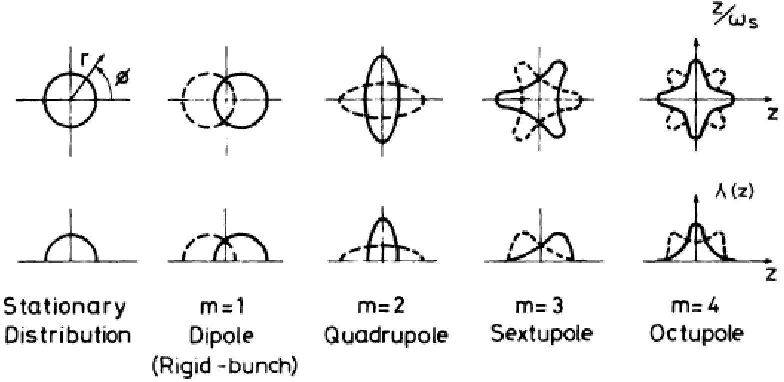
A simple review of the main longitudinal instabilities

Loss of Landau damping

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.

Sacherer formalism [4,5]



$$g(r,\phi,t) = g_0(r,\phi) + g_1(r,\phi,t),$$

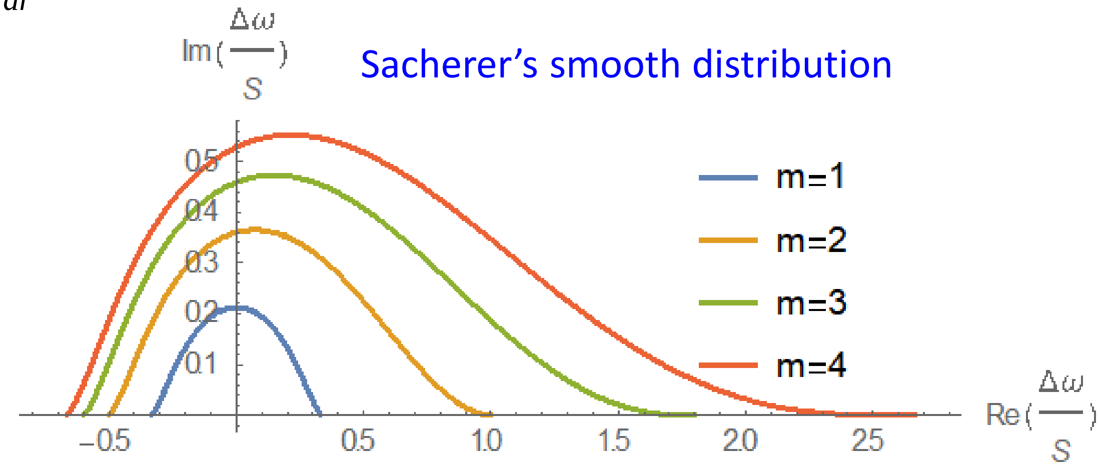
$$where\ g_1(r,\phi,t) = \sum_{m=1}^{\infty} R_m(r) e^{-im\phi} e^{-i\omega t} \qquad \omega = m\omega_s + \Delta\omega_m$$

Considering mode coupling can be neglected [6]

$$1 = \frac{\Delta\omega_m}{W_m} \int_0^{\infty} \frac{r^{2m}}{\omega - m\omega_s(r)} \frac{dg_0}{dr} dr, \qquad where\ W_m = \int_0^{\infty} r^{2m} \frac{dg_0}{dr} dr$$

$$g(r) = \frac{n+1}{\pi\hat{\tau}^2}\left(1 - \frac{r^2}{\hat{\tau}^2}\right)^n, \ 0 < r < \hat{\tau}$$

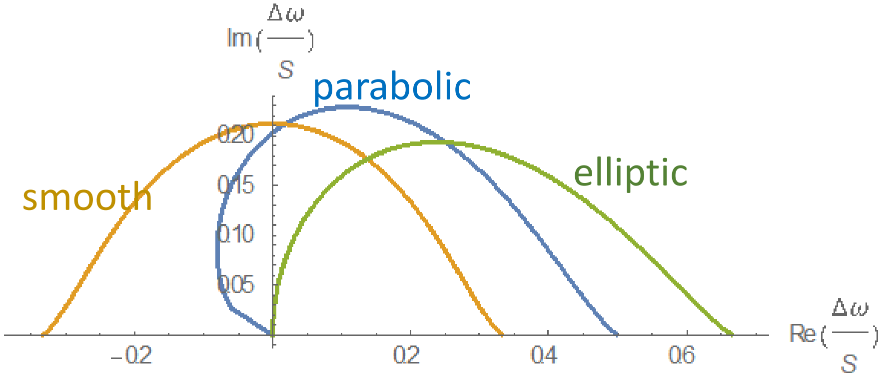
n=1/2 , elliptic distribution
n=1, parabolic distribution
n=2, smooth distribution,
n=-1/2, flat distribution


Sacherer's smooth distribution

[6] Ibon Santiago González, Loss of Longitudinal Landau Damping in the LHC Injectors,

A simple review of the main longitudinal instabilities

Loss of Landau damping

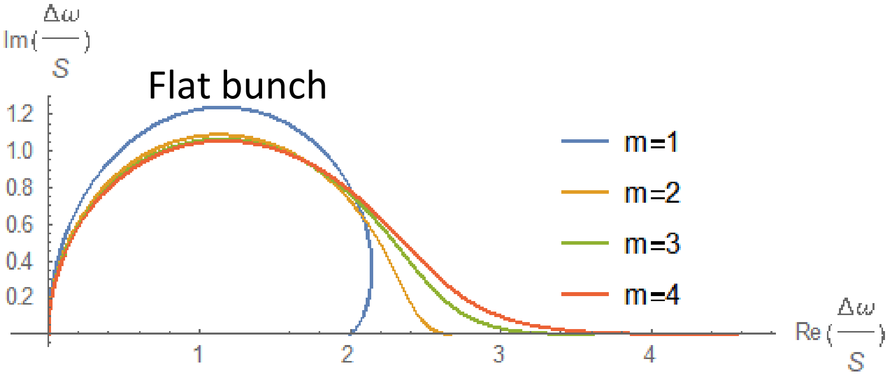


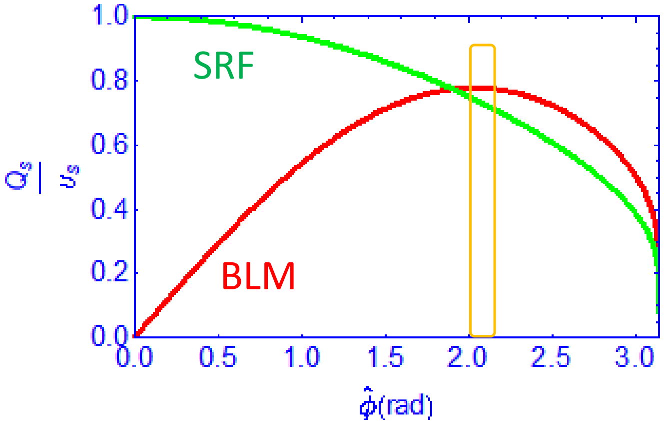
- the stable region is relevant to the distribution.
- stable boundary: S > 4Δω [4]
- Broad-band impedance: single bunch effect [7]

$$\frac{|\mathrm{Im}\,Z|}{n} < F\frac{|\eta|E}{eI_b\beta^2}\left(\frac{\Delta E}{E}\right)^2\frac{\Delta\omega_s}{\omega_s}f_0\tau$$

- Narrow-band impedance: couple bunch effect [7]

$$R_{sh} < \frac{|\eta|E}{eI_0\beta^2}\left(\frac{\Delta E}{E}\right)^2\frac{\Delta\omega_s}{\omega_s}\frac{F}{f_0\tau}G(f_r\tau)$$





➢ landau damping is lost when the derivative of synchrotron frequency is zero outside the bunch center. [8]

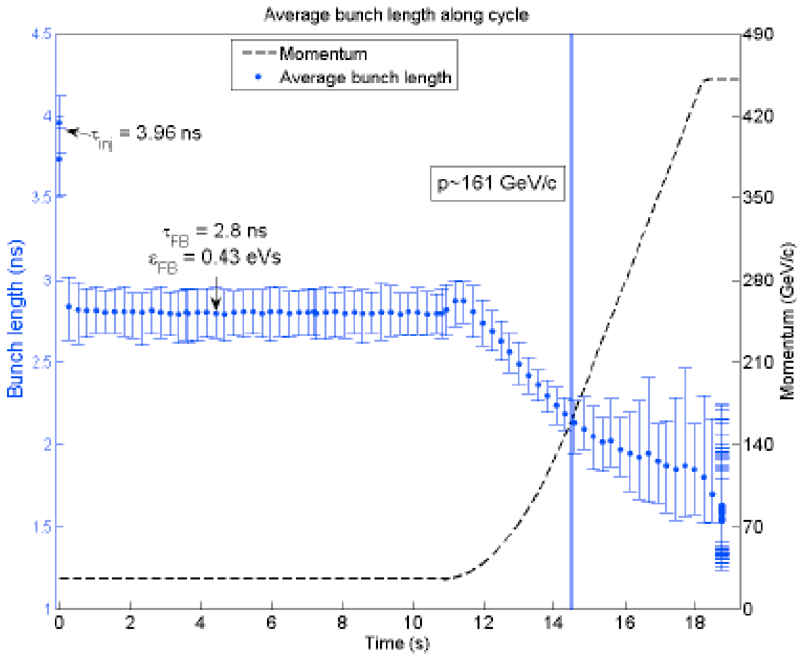
[8] E. Shaposhinikova, Bunched beam transfer matrices in single and double RF systems, CERN-SL-94-19

RF scheme to mitigate longitudinal instability in SPS/LHC

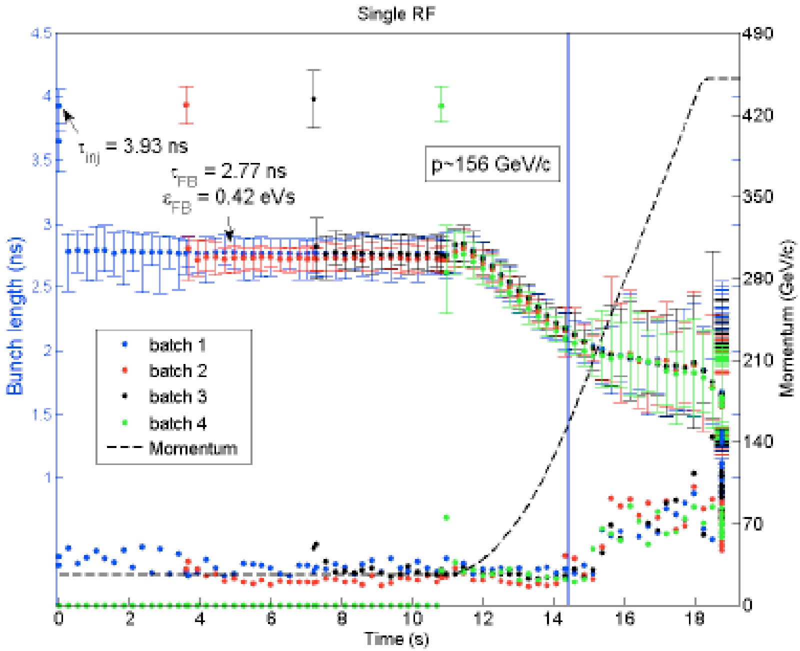
Longitudinal instabilities in the SPS [9,10]

Single RF, LHC beam with 50 ns spacing, $1.6\text{x}10^{11}$ p/b

1 batch x 36 bunches



4 batch x 36 bunches, batch gaps:250ns



- Longitudinal multi-bunch instability: very low threshold
- The instability starts almost at the same energy.

[9] E. Shaposhinikova et, 52nd ICFA Advanced Beam Dynamics Workshop HB2012

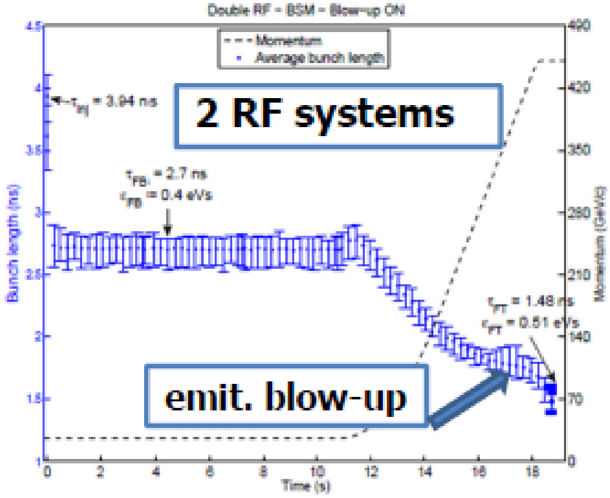
RF scheme to mitigate longitudinal instability in SPS/LHC

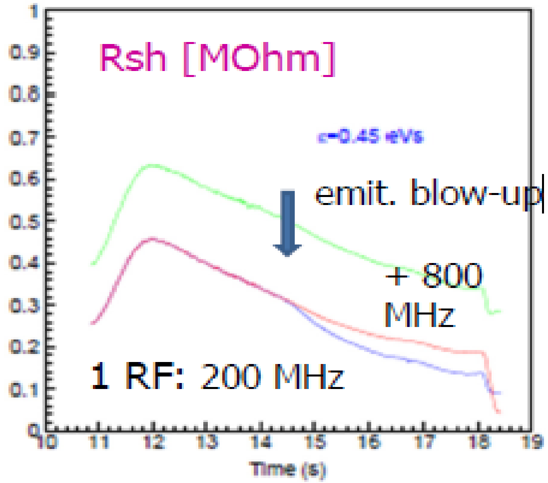
Cures to stabilize beam in the SPS [9, 10]

- Active damping: RF feedback, feed-forward, longitudinal damper;
- 4th Harmonic RF system (800MHz) in bunch-shortening mode (BSM);
- Controlled emittance blow-up;
- Optics with lower transition energy, $N_{th} \sim |\eta|$
- Impedance reduction;

Loss of landau damping threshold

$$N_{th}^{LD} \propto \frac{\varepsilon_l^2 |\eta| \tau}{E_0}$$

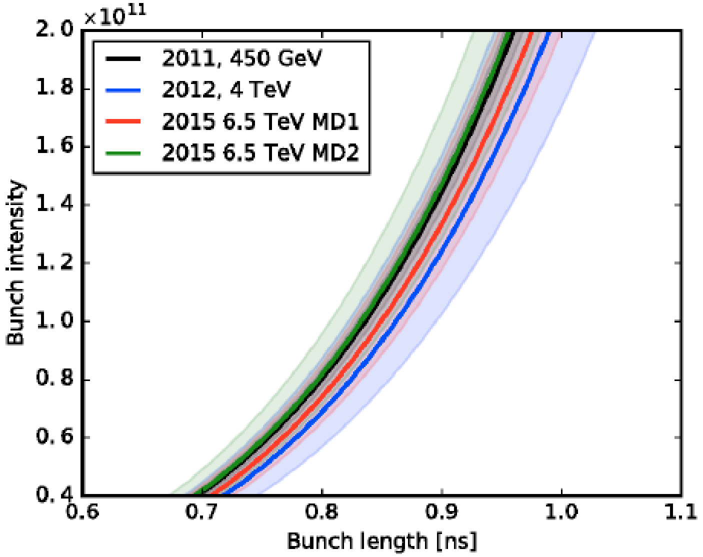




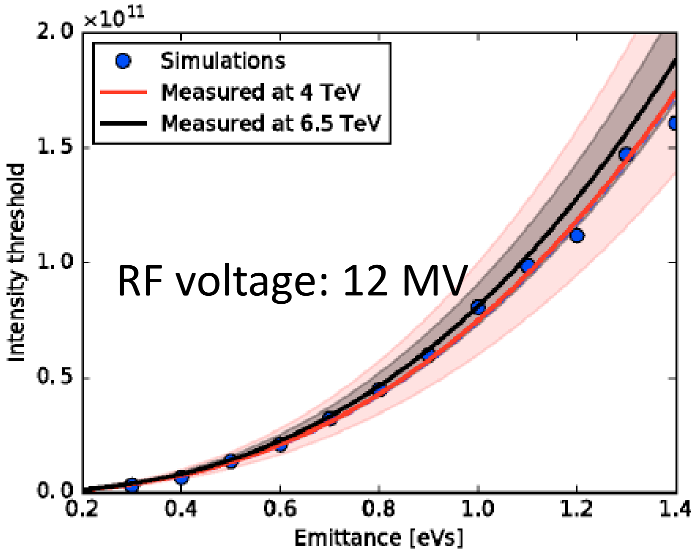
[10] T. ARGYROPOULOS, Longitudinal beam instabilities in a double RF system, CERN-Thesis-2015

RF scheme to mitigate longitudinal instability in SPS/LHC

Longitudinal instabilities in the LHC [11]



(b) Stability threshold as a function of bunch intensity and length at 12 MV



(a) 4 TeV

- Loss of Landau damping:

$$\frac{|\mathrm{Im}\,Z|}{n} < F\,\frac{|\eta|E}{eI_b\beta^2}\left(\frac{\Delta E}{E}\right)^2\frac{\Delta\omega_s}{\omega_s}\,f_0\tau$$

$$\left(\frac{|\mathrm{Im}\,Z|}{n}\right)_{th} \propto \frac{\tau^5 V}{N_b}$$ Constant energy

$$\left(\frac{|\mathrm{Im}\,Z|}{n}\right)_{th} \propto \frac{\varepsilon^{5/2}h^{7/4}}{N_b E^{5/4} V^{1/4}}$$ Energy dependence

The thresholds are in good agreement with the threshold given by loss of landau damping.

[11] Juan Federico ESTEBAN MÜLLER, Longitudinal intensity effects in the CERN Large Hadron Collider, CERN-Thesis-2016

RF scheme to mitigate longitudinal instability in SPS/LHC

RF scheme to mitigate Longitudinal instabilities in the LHC

- 400MHz (main) + 200MHz(capture) [7]
- 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;

Not installed

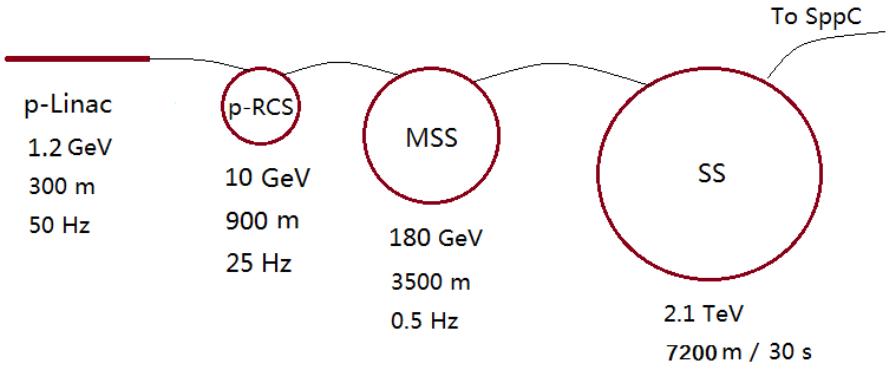
- After capture:
  - 400 MHz RF system adiabatically is increased up to 8 MV
  - 200 MHz RF system is decreased to zero;
  - **Acceleration only with 400 MHz.**
- On the flat top:
  - the emittance is 2.5 eVs.
  - f_{rf}=400MHz, $V_{rf(max)}$=16MV to produce ~1 ns long bunches.

- Cure for :
- The main RF system provides some damping of injection errors and natural Landau damping;
- Controlled emittance blowup by excitation with band-limited noise

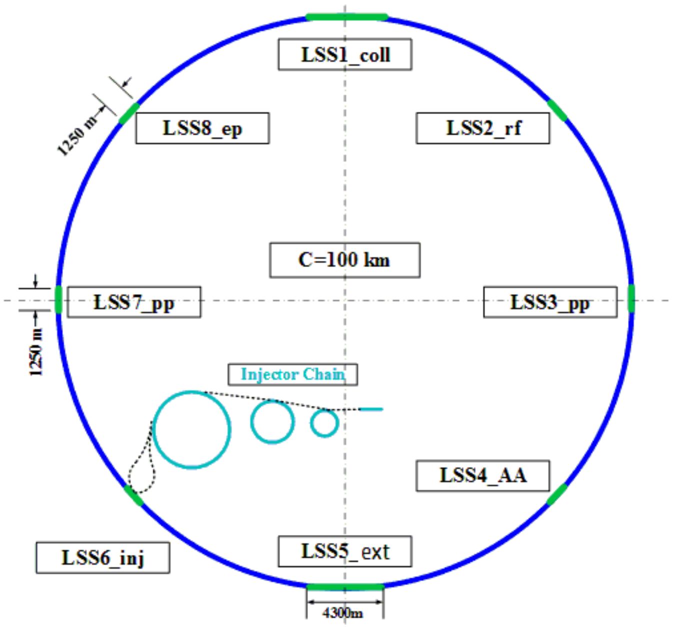
Introduction to SPPC

Layout and main parameters

main parameters	Value
Circumference (km)	100
Dipole field (T)	12
Injection energy (TeV)	2.1
Collision 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



SPPC Layout



- LSS1:collimation system (comnbine β and momentum)
- LSS5: extraction system
- LSS2: RF system
- LSS6： Injection system
- LSS3/LSS7: pp collision
- LSS4: AA collision
- LSS8: ep collision

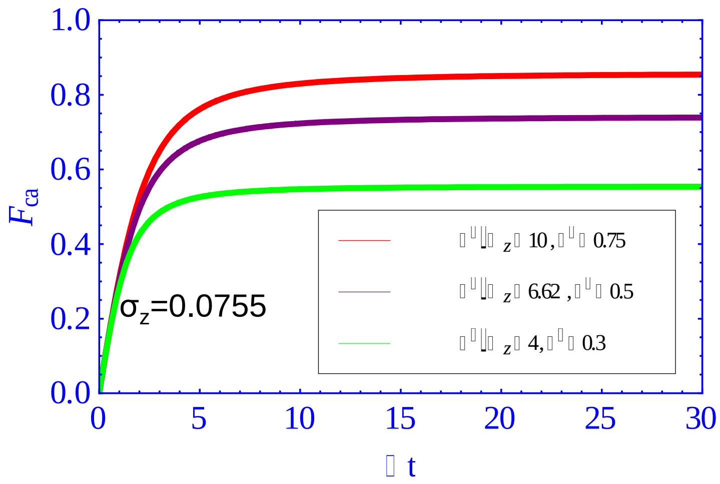
Introduction to SPPC

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 : Piwinski Angle



- 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

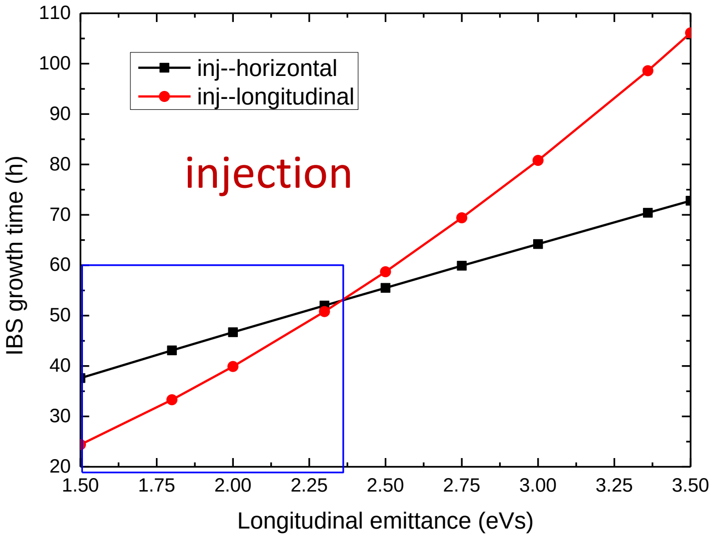
- Two constraints:
  - Intra-beam Scattering
  - Beam instability limits

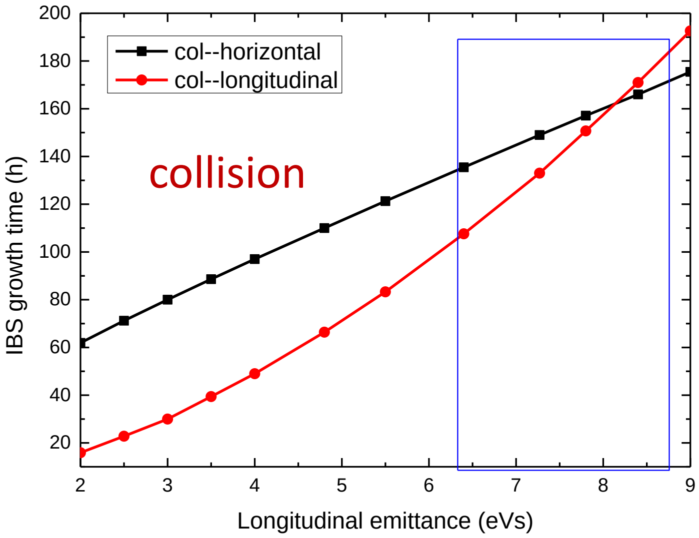
- The goals:
  - achieve this goal of bunch length 7.55cm.
  - The variable range of bunch length for luminosity upgrade

Introduction to SPPC

Intra-beam Scattering (IBS)

- Multiple small-angle Coulomb scattering of charged particle beams





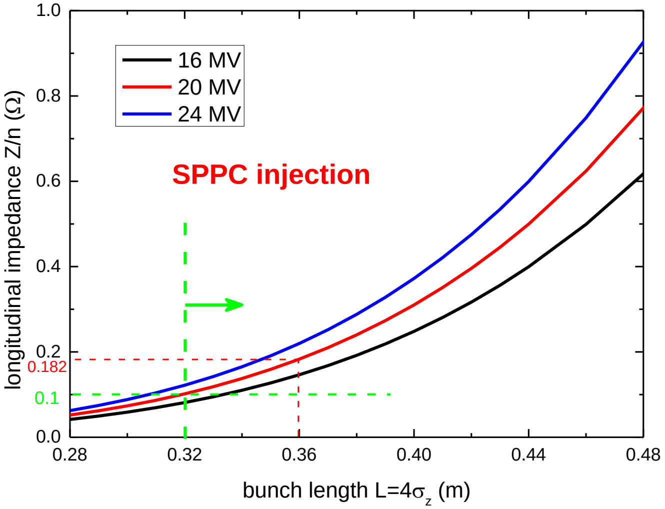
- At injection, longitudinal emittance between 1.5 eVs and 2.5 eVs may be a good choice; (injection time 840s)
- In collision, longitudinal emittance between 6 eVs and 9 eVs may be a good choice; (time during physics 14.2h)

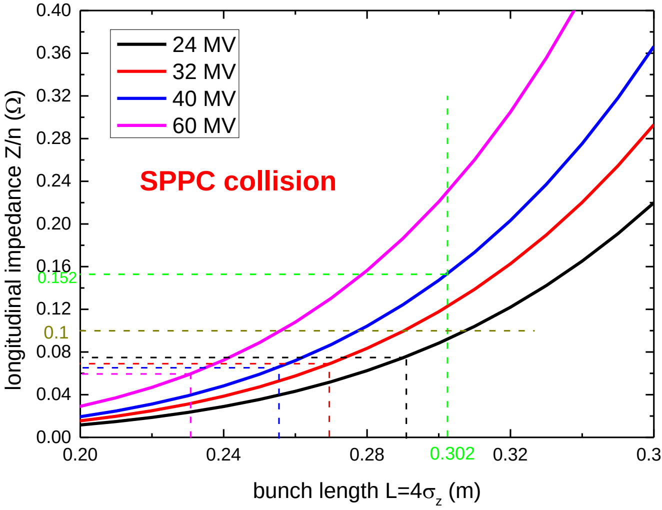
- Using controlled emittance blowup, IBS maybe not a serious matter.

RF scheme to mitigate longitudinal instability in SPPC

Loss of Landau damping at 400 MHz

- Loss of Landau damping: $$\frac{\left|\mathrm{Im}\,Z_{//}\right|}{n} \le \frac{3\pi^2}{64}\frac{h^3 V_{rf}}{I_b}\left(\frac{L}{2\pi R}\right)^5$$





$\sigma_z \ge 8$ cm, $(Z/n)_{th} \ge 0.1\Omega$

easy to bunch-receiving from SS

$\sigma_z = 7.55$ cm, $V_{rf} \ge 32$MV $(Z/n)_{th} \ge 0.1\Omega$

Shorter bunch length (luminosity upgrade) smaller longitudinal impedance.

- Injection: $\sigma_z = 9$ cm, 0.182 Ω @20 MV; Collision: $\sigma_z = 7.55$ cm, 0.152 Ω @40 MV
- **Longitudinal reactive impedance less than 0.15 Ω needs to be studied! [LHC~0.1 Ω]**

RF scheme to mitigate longitudinal instability in SPPC

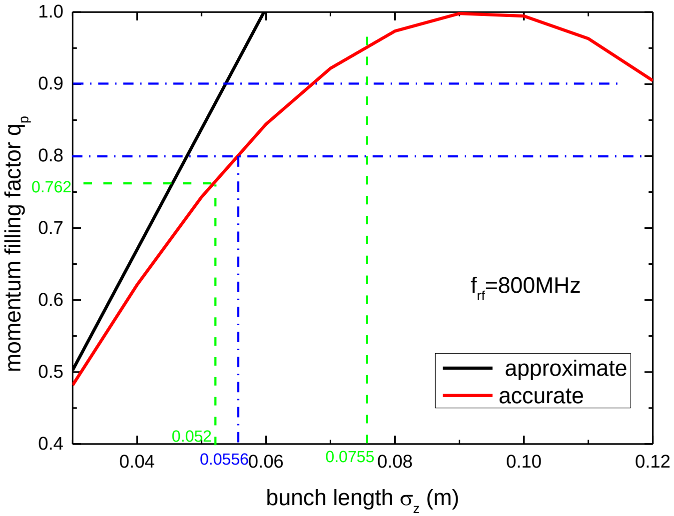
RF schemes to mitigate longitudinal instability in SPPC

- In order to enhance Landau damping, a large spread in synchrotron frequency inside the bunch is required.

Ways of mitigation

① **use a higher harmonic cavity (800MHz RF cavity needs to be studied)**
② **Dual harmonic RF system**
③ **Controlled emittance blow-up**

① 800 MHz RF system



- 7.55 cm @ 800 MHz, $q_p > 0.9$, i.e. significant beam loss. So the rms. bunch length will have to be reduced if using 800 MHz RF cavity.
- $q_p \leq 0.8$ --> $\sigma_z \leq 5.56$ cm;
- the goal bunch length is set as σ_z =5.2 cm, then q_p=76.2%;
- Correspondingly: ε_s=6.4eVs, V_{RF}=52MV, $\sigma_\delta=0.79\times10^{-4}$

The corresponding impedance threshold

$$\left|\frac{\mathrm{Im}\,Z_{//}}{n}\right|_{800} \Big/ \left|\frac{\mathrm{Im}\,Z_{//}}{n}\right|_{400} = \left(h^3 V_{rf} L^5\right)_{800} \Big/ \left(h^3 V_{rf} L^5\right)_{400} \approx 1.6 \Rightarrow \left|\frac{\mathrm{Im}\,Z_{//}}{n}\right|_{800} = 0.243\Omega$$

RF scheme to mitigate longitudinal instability in SPPC

② Dual harmonic RF system (400MHz+800MHz)

- Applied RF voltage is: $V(\phi)=V_0(t)\left[\sin\phi+k\sin(n\phi+\phi_2)\right]$
- in (ϕ, $\Delta E/\omega_0$) phase space, the Hamiltonian is

$$H=\frac{h\omega_0^2\eta}{2\beta^2E}W^2+\frac{eV_0}{2\pi}U(\phi)$$

$$\frac{dW}{dt}=-\frac{\partial H}{\partial\phi}=\frac{e}{2\pi}[V(\phi)-V(\phi_s)]$$

$$\frac{d\phi}{dt}=\frac{\partial H}{\partial W}=\frac{h\omega_0^2\eta}{\beta^2E}W$$

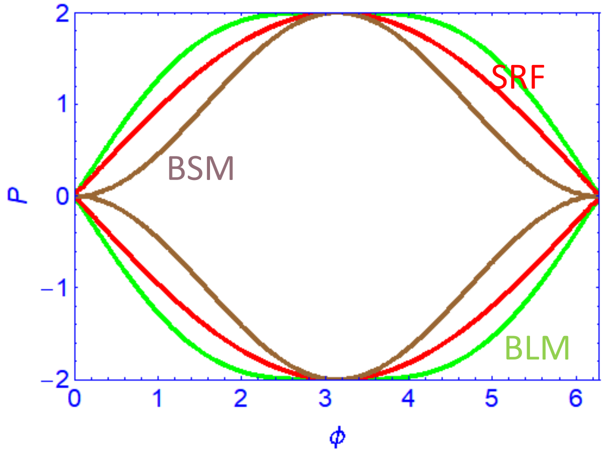
$$W=\frac{\Delta E}{\omega_0}$$

- The potential well is

$$U(\phi)=-\frac{1}{V_0}\int_{\phi_s}^{\phi}\left[V(\phi)-V(\phi_s)\right]d\phi=(\cos\phi-\cos\phi_s)+\frac{k}{n}\left[\cos(n\phi+\phi_2)-\cos(n\phi_s+\phi_2)\right]+(\phi-\phi_s)\left[\sin\phi_s+k\sin(n\phi_s+\phi_2)\right]$$

- In normalised phase space $(\phi,\ P=-h|\eta|/\nu_s\delta)$, the Hamiltonian is

$$H=-\frac{1}{2}\nu_sP^2+\nu_sU(\phi)\qquad \nu_s=\sqrt{\frac{heV_0|\eta|}{2\pi\beta^2E}}$$

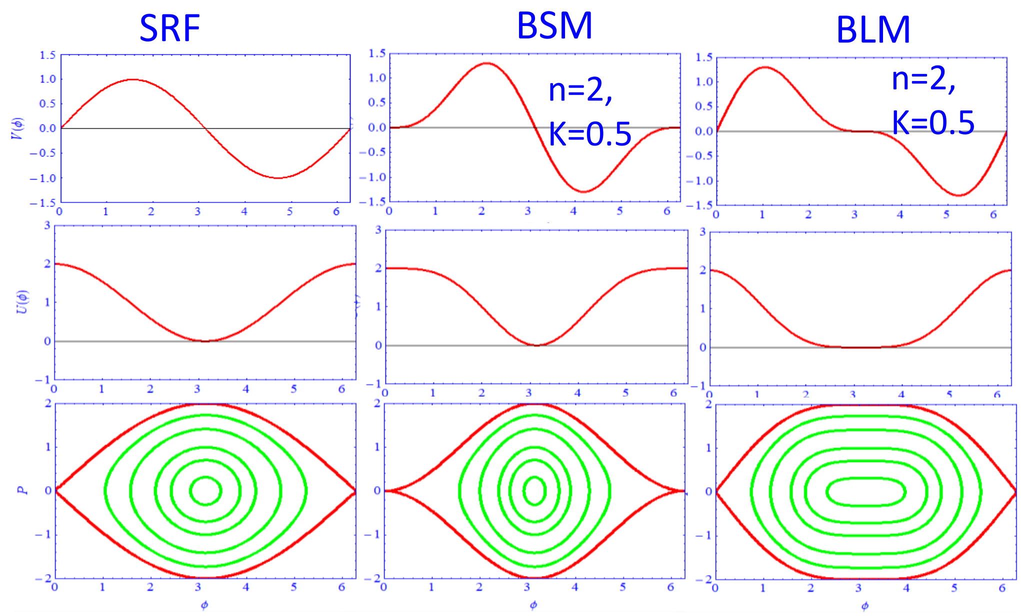


- ➢ Bunch lengthening mode (BLM):
  n=2, k=0.5, ϕ_2=0, for $\eta>0$
- ➢ Bunch shortening mode (BSM):
  n=2, k=0.5, $\phi_2=\pi$, for $\eta>0$

- A_{BLM}/A_{single}~1.1478, A_{BSM}/A_{single}~0.7854;
- The bucket height keeps the same.

RF scheme to mitigate longitudinal instability in SPPC

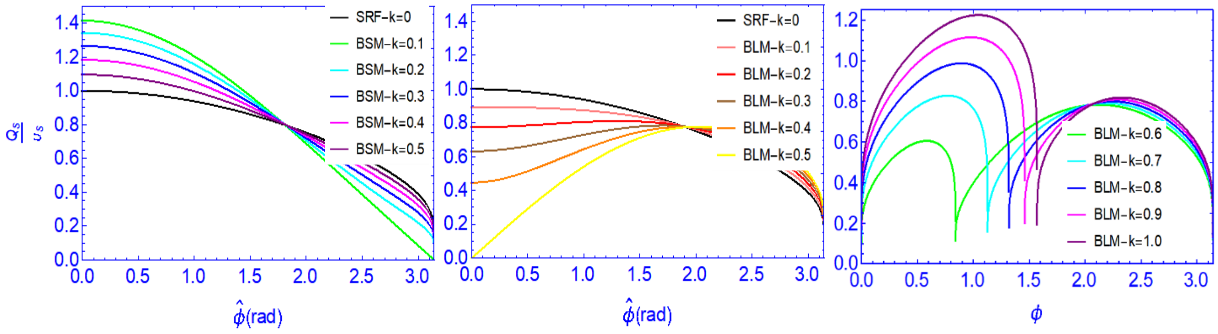
② Dual harmonic RF system (400MHz+800MHz)



The BLM is used much more often, because for the same voltage and harmonic ratios it gives :

- larger bucket area;
- smaller peak line density reduced space charge effects.
- larger synchrotron frequency spread.

➢ Synchrotron frequency distribution: n=2

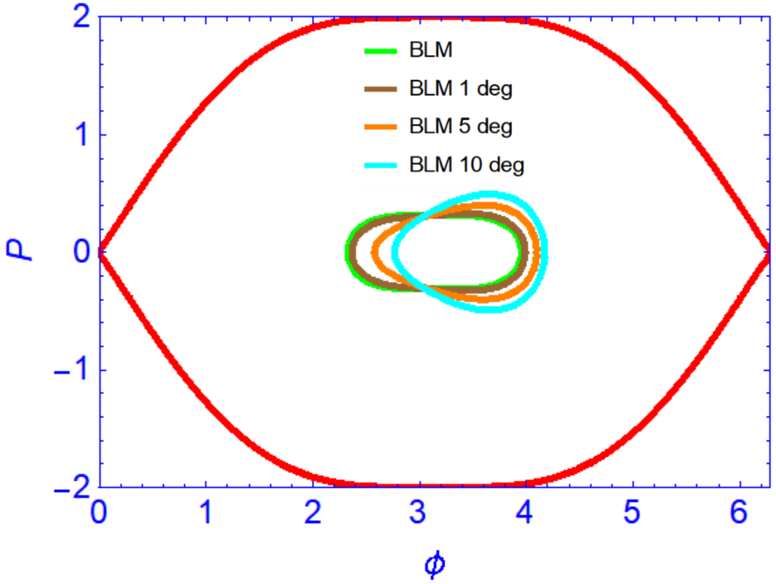


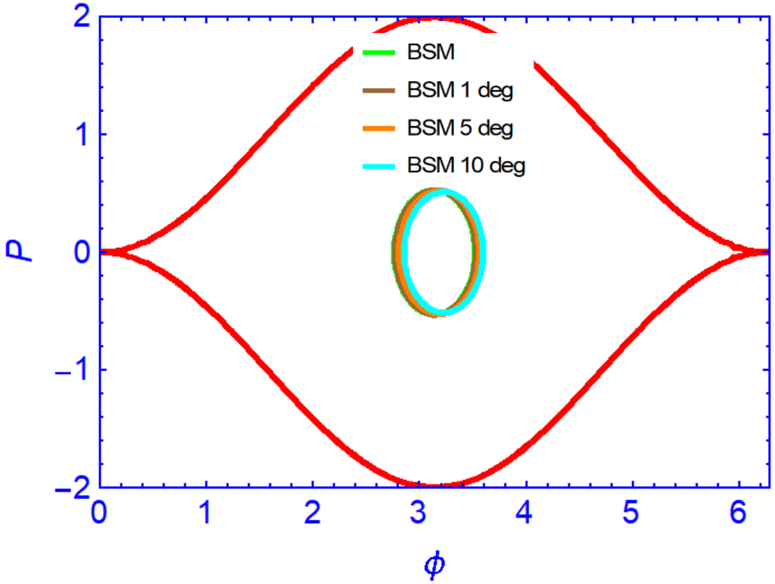
- In BL-mode region $\omega_s'(\phi)=0$ exists for n=2 and~ k>0.2 → loss of Landau damping
- <Qs> is smaller for BLM, bad for TMCI($\propto$ Qs).

RF scheme to mitigate longitudinal instability in SPPC

② Dual harmonic RF system (400MHz+800MHz)

➢ The effect of relative phase shift error





- BLM is extremely sensitive to the relative phase error between two rf system;
- BSM seems more reasonable.

RF scheme to mitigate longitudinal instability in SPPC

③ Controlled emittance blowup

(1) Band limited RF phase noise: [12-14]

- injected into the main RF system through phase Loop;
- the choices of excitation noise spectrum:

$$0.85\Omega_{s0} \leq \Omega \leq 1.1\Omega_{s0}$$

- Steady state between resonance and diffusion
- Example: LHC, SPS, PSB

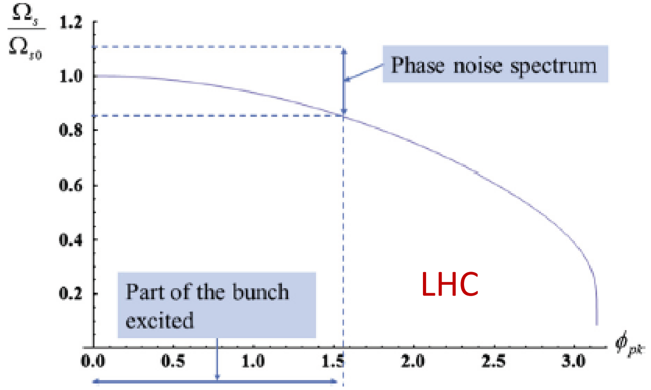


Fig. 2. Ω_s/Ω_{s0} as a function of the maximum phase deviation in radians. Stationary bucket.

(2) adding a phase-modulated high frequency RF to the main RF. [15-16]

- The high-frequency phase-modulated voltage :

$$V_H = \hat{V}_H \sin(h_H \omega_R t + \alpha \sin \omega_M t + \theta_H)$$

- RF phase-modulated higher harmonic rf system drive bunch near resonant island and cause the bunch density redistribution.
- Example: PS;

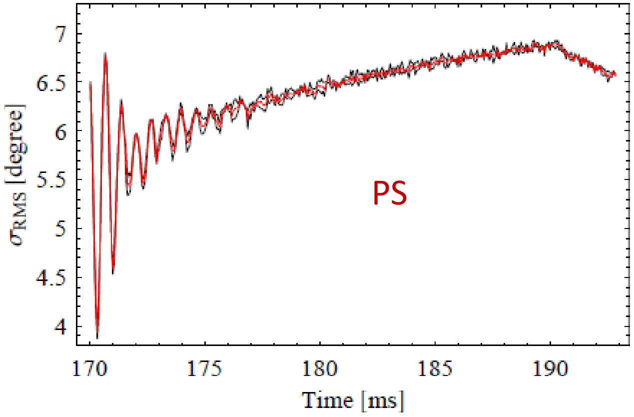


Figure 4: Measured RMS bunch length along the BU with $V_b = 28\,\mathrm{kV}$ at 200 MHz, $f_{\mathrm{mod}} = 10\,\mathrm{kHz}$, $\Delta\phi = 3.1$ rad; black lines: individual cycle, red line: average over several cycles.

Comparison and Summary

Comparison among 400MHz, 800MHz, 400+800MHz

800 MHz

Advantage:

- h increase → the frequency spread increase → instability improve;
- shorter bunch → luminosity increased by 7%.

Disadvantage:

- both the bucket area and bucket height are reduced → beam loss

400 MHz +800 MHz

BLM

Advantage:

- larger bucket area;
- smaller peak line density reduced space charge effects.
- larger synchrotron frequency spread.

Disadvantage:

- $\omega_s'(\phi)=0$ exists which cause loss of Landau damping
- average synchrotron tune reduced
- extremely sensitive to the relative phase error between two rf system

BSM

Advantage:

- the average synchrotron tune and tune spread are increased.

Disadvantage:

- the bucket area is reduced to some extent and momentum filling factor increased, but bunch length is shorter

More attractive

Outlook

Other questions need to be considered

- Synchrotron radiation
  - Energy loss per turn U0~1.48MeV,
  - Longitudinal damping time: $\tau_\varepsilon \sim 1.17\text{h}$ (physics running 14.2 h)
- The choice of controlled emittance growth
  - Like LHC or SPS, band-limited phase noise?
- Transverse Mode Coupling Instability (TMCI) [17]

$$(\beta_{av} Z_T)_{th} \propto \frac{E}{I_b} Q_s \tau$$

- No impedance model
  - macroparticle tracking cannot proceed.

Reference

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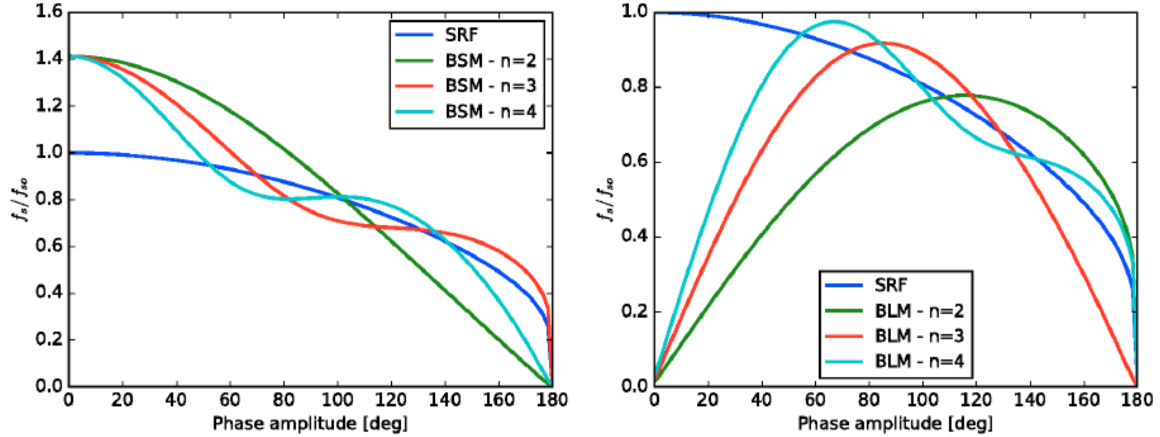
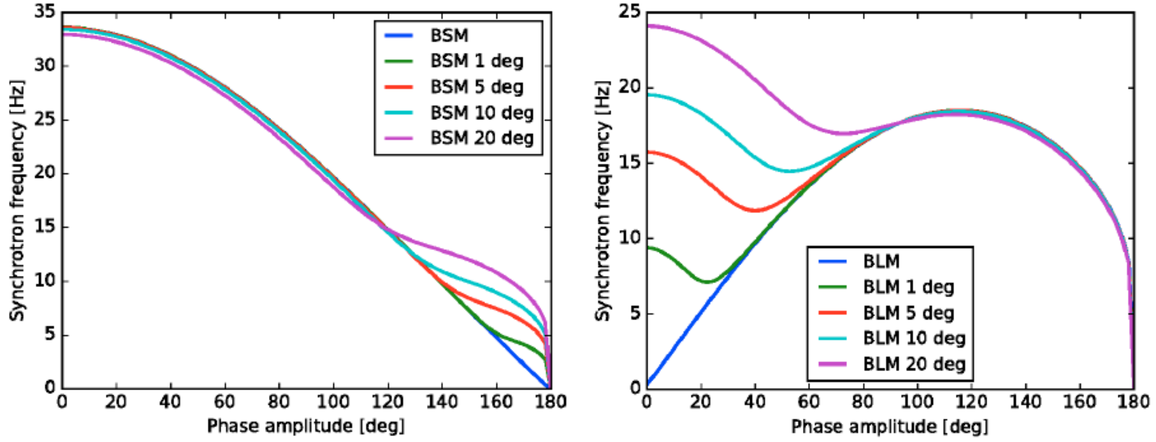
Thanks for your attention!

RF scheme to mitigate longitudinal instability in SPPC



(a) BSM (b) BLM



(a) BSM (b) BLM

$$q_p = \frac{2\sigma_\delta}{\left(\frac{\Delta p}{p}\right)_{\max}} \approx \frac{h}{R}\sigma_z$$

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