2ND EURONU PLENARY MEETING

Review of CERN Proton Driver bunch compression studies

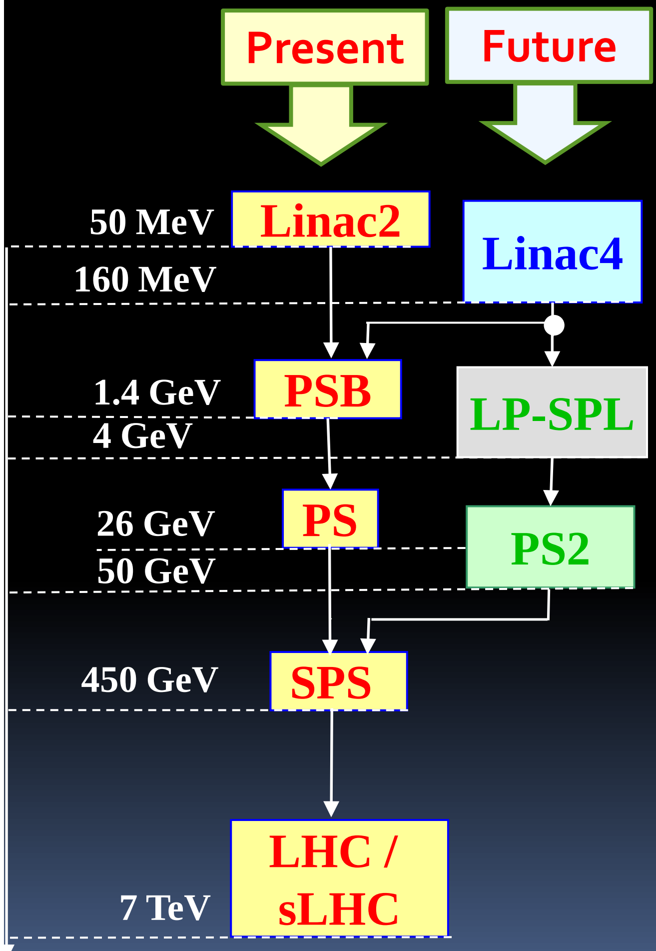
Contents

- Plans for possible future new LHC injectors (*1st scenario*)
- Plans for Linac4 plus upgrade of existing LHC injectors (*2nd scenario*)
- Potential extensions for Neutrino Factory with a high power SPL: SPL-Based Proton Driver
- Summary

CREDITS

- **Masamitsu Aiba**
  - **IDS-NF Meeting, 23 March 2009**
  - **NuFact 08, June 30 - 05 July, 2008**
  - **CERN-AB-2008-048 BI, CERN-AB-2008-060 BI**
- **Elena Benedetto**
  - **NuFact 09, July 20-25, 2009**
- **Roland Garoby**
  - **ECFA, EuCARD, NEU2012 Workshop, 1-3 October 2009, CERN, CH**
  - **EuCARD Annual Meeting, 14-16 April 2010, STFC, UK**

Plans for possible future new LHC injectors (*1st scenario*)



Not suitable for a ν-Factory

1. Reliability ↑

The present accelerators get aged and operate far beyond their initial design parameters

⇒ Interest of upgraded/new accelerators fitted to the LHC and its future needs

2. Performance ↑

- Luminosity depends upon beam brightness *N/ε**
- Brightness limited by space charge at injector low energy

⇒ Call for increase the synchrotron injection energy

ν-Factory needs LP-SPL upgrade + accumulator & compressor + target + muon accelerator & storage ring complex

$$L \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot N_b \cdot k_b \qquad \Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

N_b : number of protons/bunch

k_b : number of bunches/ring

$\varepsilon_{X,Y}$: normalized transverse emittances

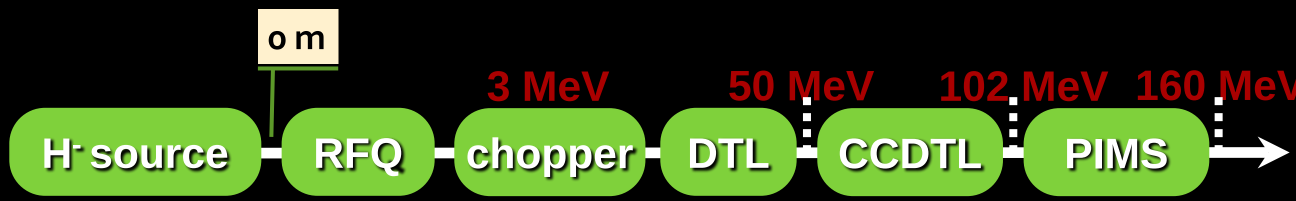
R : accelerator mean radius

LP-SPL: Low Power SPL (kinetic energy 4 GeV)

PS2: High Energy PS (~ 5 to 50 GeV at 0.3 Hz)

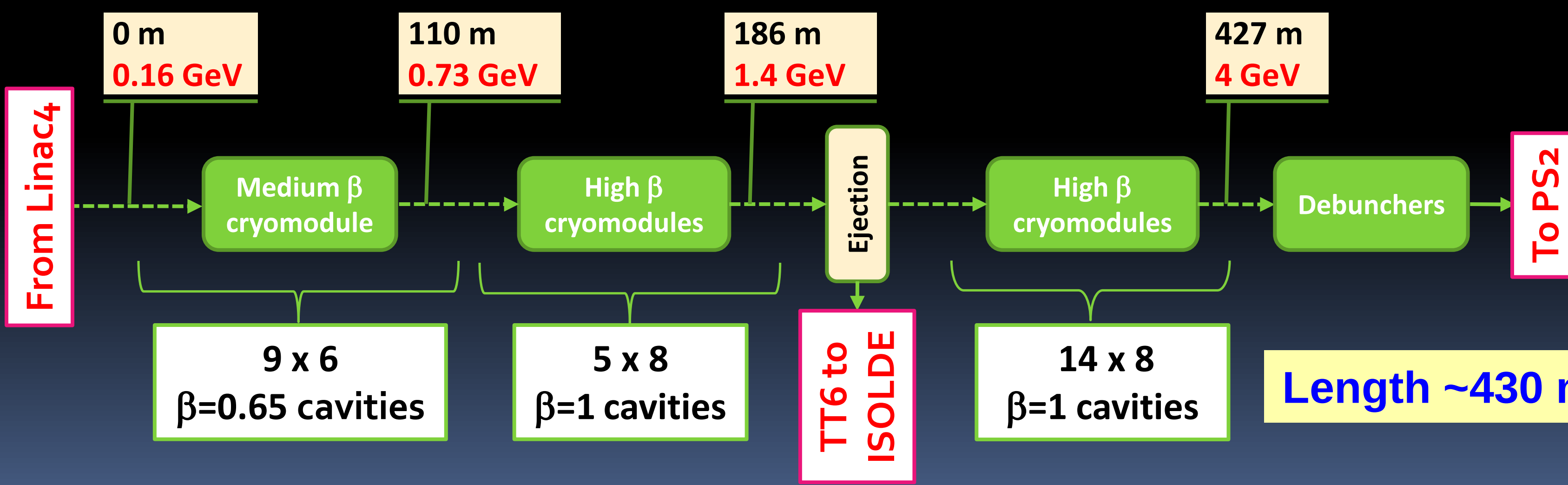
sLHC: "Super-luminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)

Block diagram of LINAC4



Length ~80 m

Block diagram of LP-SPL



Length ~430 m

Plans for possible future new LHC injectors

Linac 4 and LP-SPL beam characteristics

$(\beta\gamma^2)_{160MeV}/(\beta\gamma^2)_{50MeV}=2 \rightarrow$
twice brightness in PSB

PSB H^- charge exchange injection

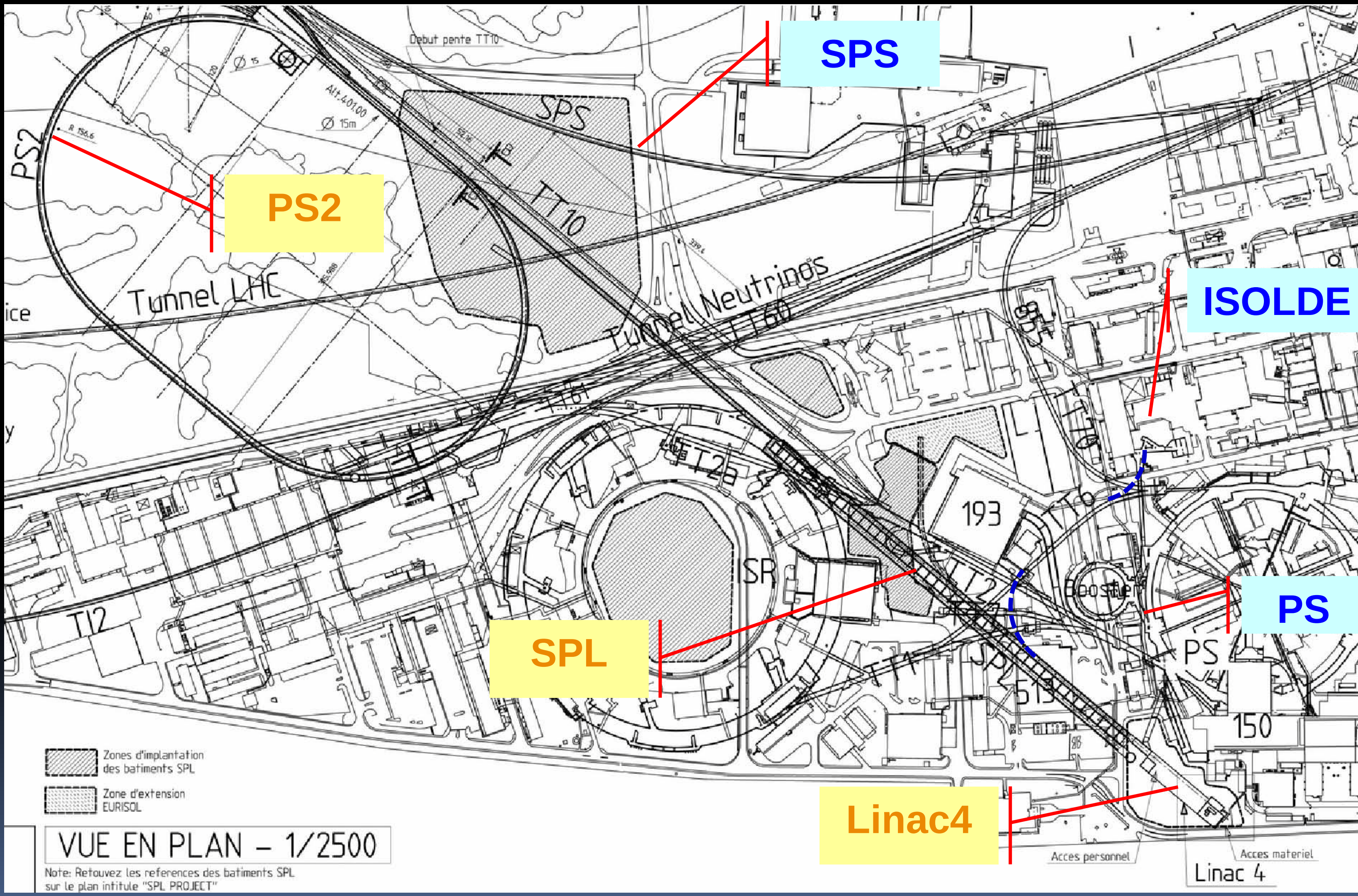
	Linac4	LP-SPL
Output kinetic energy [GeV]	0.16	4
Av. linac pulse current [mA]	40 (10^{14} H^-/pulse)	20
Pulsing rate [Hz]	2	2
Beam pulse duration [ms]	1.2	0.9
Beam power [MW]	0.0051	0.14

50 Hz max. pulsing rate for RF structures →
- ❑ Power supplies and electronics well-proportioned for PSB and LP-SPL
- ❑ structures and klystrons compatible with HP-SPL

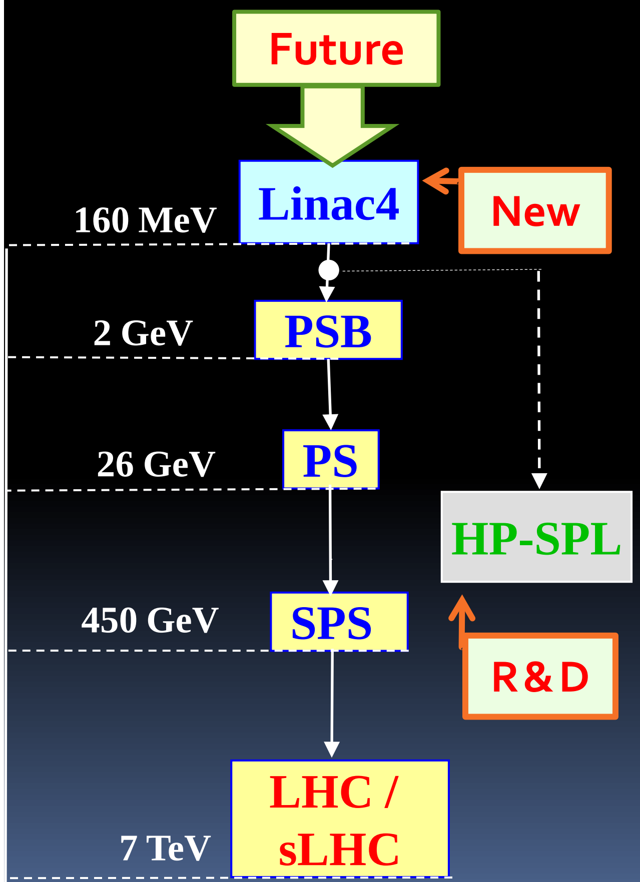
2nd EuroNu Plenary Meeting

Site layout

Plans for possible future new LHC injectors



Plans for Linac4 plus upgrade of existing LHC injectors (*2nd scenario*)



- New 160 MeV Linac4 (under construction)
- Increase the energy the PSB output energy to ~2 GeV
- Upgrade the PS for 2 GeV injection
- Upgrade the PS and SPS to accelerate and operate beam with higher brightness and longitudinal density
- R&D for a high power SPL
- Maintain potential for Neutrinos physics programme

LP-SPL & PS2 not needed anymore

HP-SPL: High Power SPL (kinetic energy 5 GeV)
sLHC: "Super-luminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)

Potential extensions for neutrino factory

HP-SPL beam characteristics

Twice more beam current requires twice more klystrons…

	HP-SPL option 1	HP-SPL option 2
Output kinetic energy [GeV]	4 or 5 [a]	4 or 5 [a]
Av. linac pulse current [mA]	20	40 [b]
Pulsing rate [Hz]	50	50
Beam pulse duration [ms]	0.9	1.2 [b]
Beam power [MW]	2.25 MW (2.5 GeV) or 4.5 MW (5 GeV)	5 MW (2.5 GeV) and 4 MW (5 GeV)

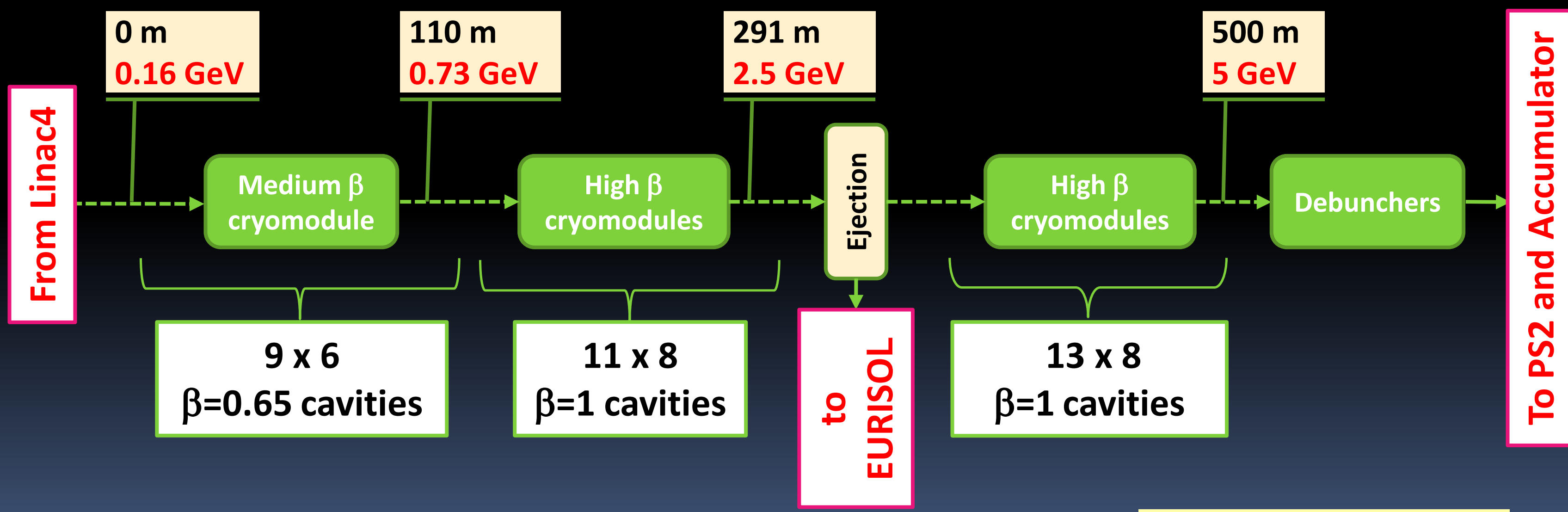
[a] needed for a ν-factory, [b] needed for 2 users of high beam power or for 5 MW at 2.5 GeV

Faster pulsing rate necessitate more supplies, cooling …

Block diagram of HP-SPL

- Upgrade of infrastructure (cooling water, electricity, cryogenics etc.)
- Replacement of klystron power supplies,
- Addition of 5 high β cryomodules to accelerate up to 5 GeV (for ν-Factory)

SPL [160 MeV → 4 (5?) GeV] with ejection at intermediate energy



Length ~500 m

ν-factory: SPL-Based Proton Driver

Potential extensions for neutrino factory

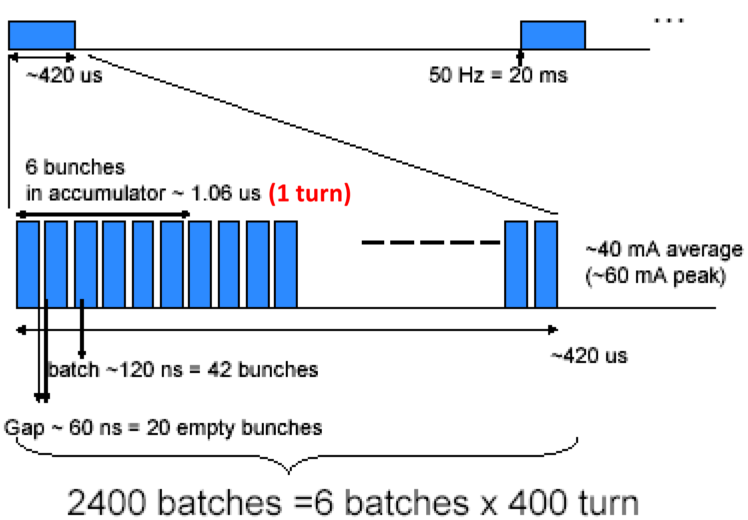
Parameters	Accumulator (6-bunches)	Accumulator (3 & 1-bunches)
Circumference [m]	318.5	185.8
Nb. of accumulation turns	400	640/1920
Nb. of bunches	6	3 / 1
Nb. of protons per bunch	1.67×10^{13}	3.34×10^{13}/ 10^{14}
Gamma transition (γ_t)	6.33	
Slip factor ($\eta= \gamma_t^{-2}- \gamma^{-2}$)	~0* (isochronous ring no RF system)	

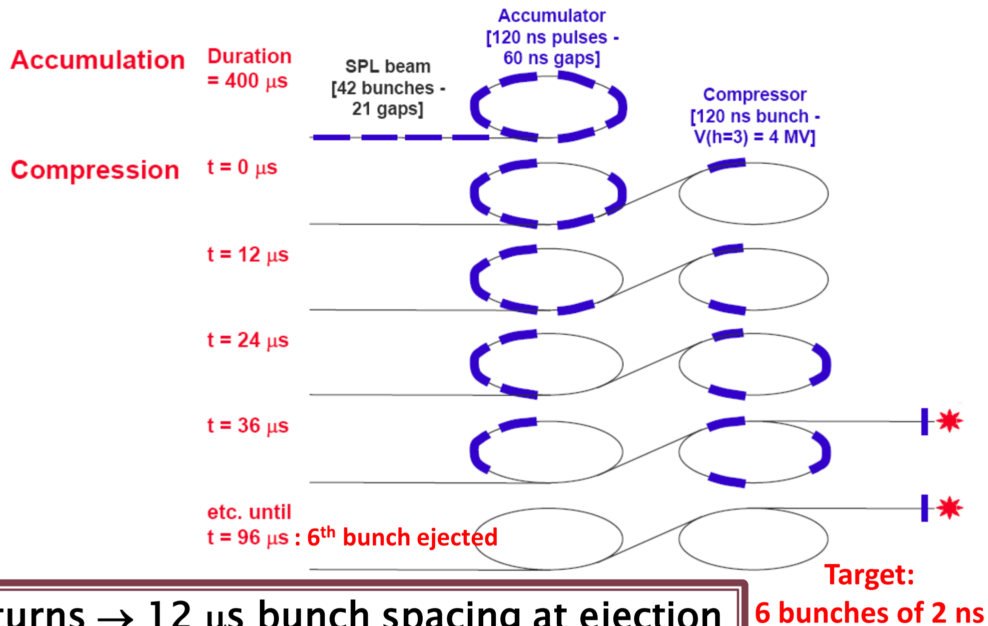
Parameters	Compressor ("6-bunches")	Compressor (3 &1-bunches)
Circumference [m]	314.2	200.0
Nb. of compression turns	36	86
Nb. of bunches	3	3 / 1
Nb. of protons per bunch	1.67×10^{13}	3.34×10^{13} / 10^{14}
RF voltage on h=3 [MV]	4	1.7
Gamma transition (γ_t)	2.3	2.83
Slip factor ($\eta= \gamma_t^{-2}- \gamma^{-2}$)	0.16**	0.10**

* To "freeze" the bunches longitudinally during accumulation so that no RF cavities are needed
** Large slip factor to do the phase rotation rapidly to fulfill the total burst duration requirement

Bunch generation for a ν-factory

- A ν-Factory Proton Driver must deliver a 4 MW beam power at 5-15 GeV, in 1-6 ns rms bunches (~2 ns) spaced by ~16 ms onto a production target, at a 50 Hz repetition rate.
- Chopped SPL beam is accumulated in a few long bunches (120 ns) via H^- injection.
- Accumulator is Isochronous to maintain the SPL beam time structure, no RF to minimize the impedance.
- Singly bunch transfer to the compressor → bunch rotation → ejection to the target.





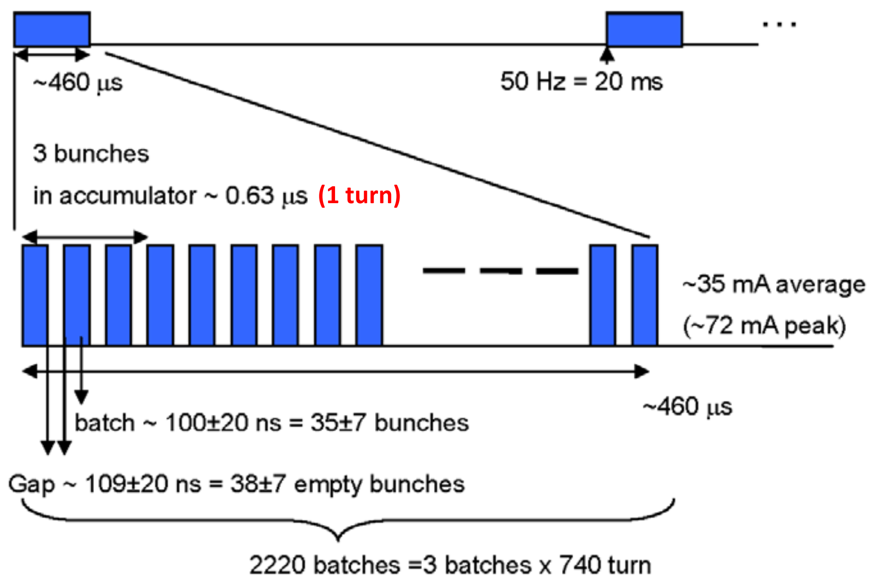
Bunch rotation 36 turns → 12 μs bunch spacing at ejection

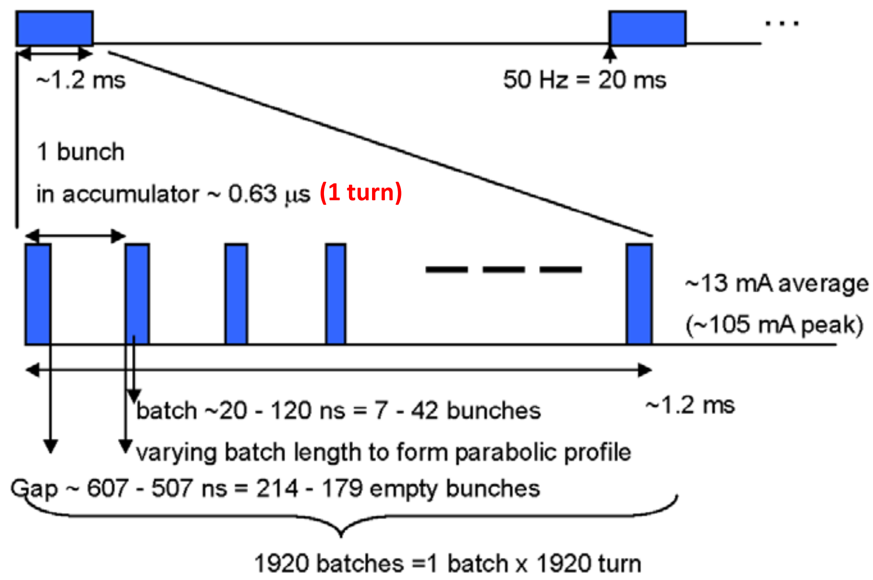
6 bunches accumulation-compression scheme

Bunch generation for a ν-factory

Nb. of accumuled bunches	6	3	1
Peak/mean current [mA]	60/40	72/35	105/13
Pulse duration [μs]	400	460	1200

SPL beam for accumulation



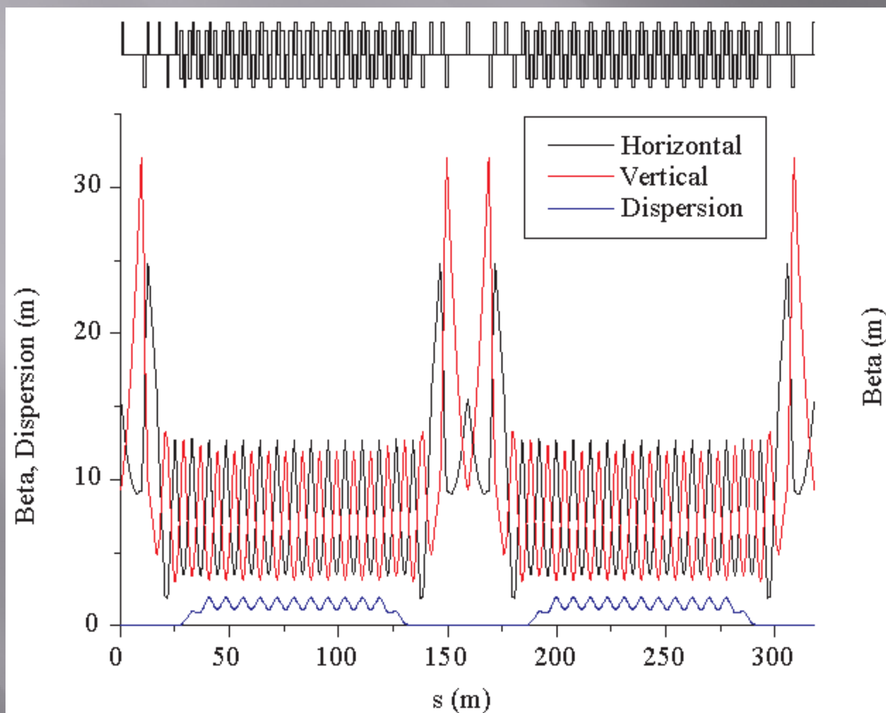


3- bunches accumulation **1- bunch accumulation**

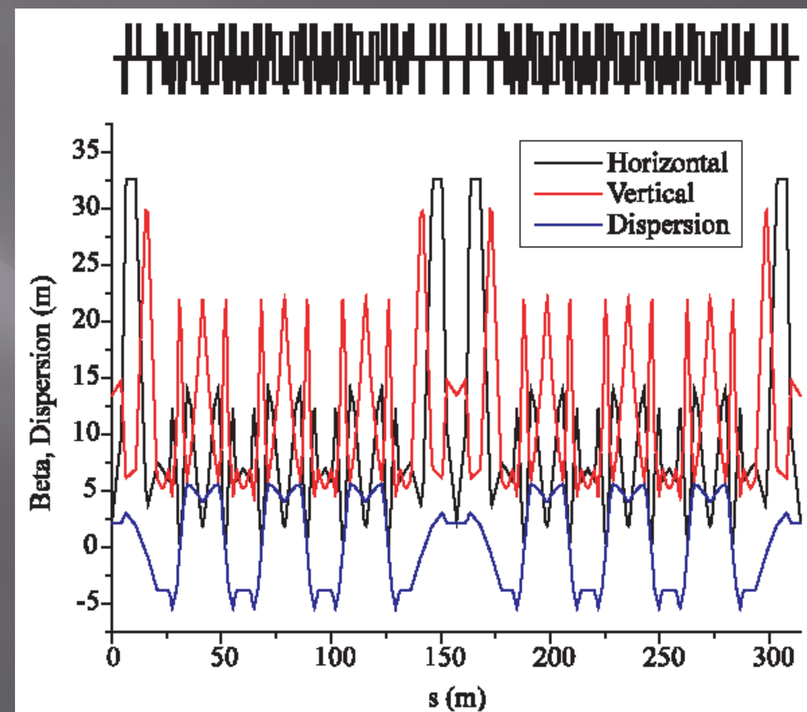
Accumulator and compressor lattices

Potential extensions for neutrino factory

Isochronous accumulator conserve the energy spread during accumulation (ring with barrier rf cavities was also investigated) → important to the bunch length compression



Accumulator lattice with insertion section (normal conducting magnets) (Q_x=7.77, Q_y=7.67, γ_t=6.33)



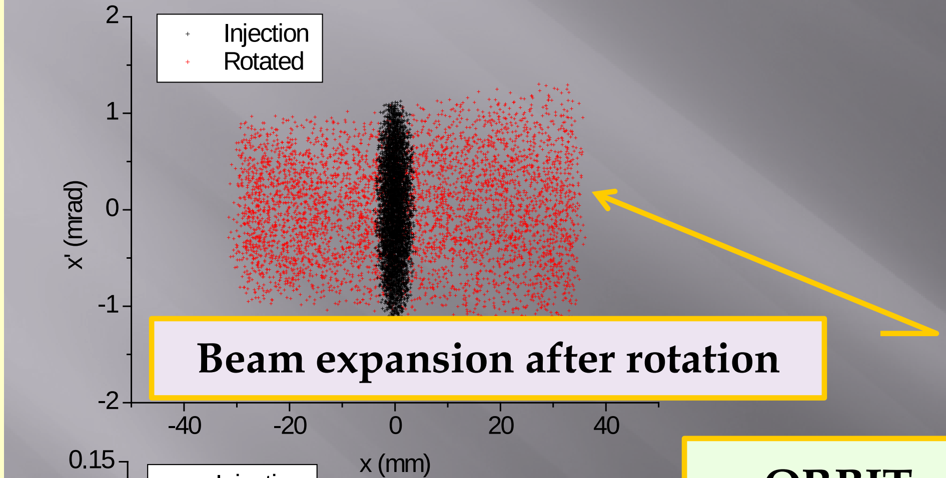
Compressor lattice with negative (superconducting) bending magnets (Q_x=10.79, Q_y=5.77, γ_t=2.3)

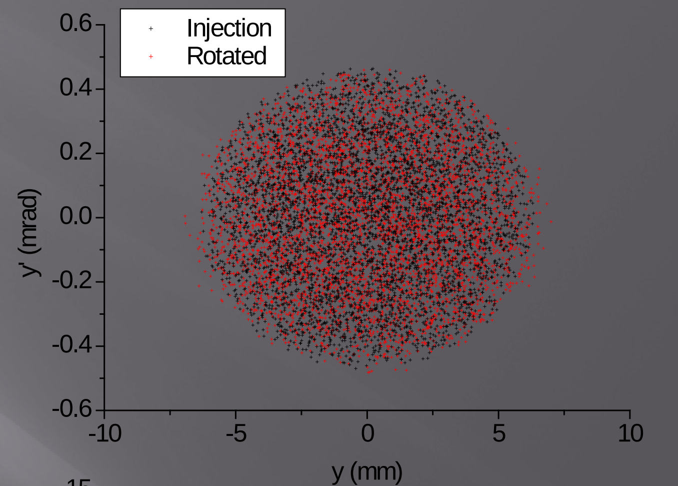
Accumulator and compressor lattices for the 6-bunches scheme

Compressor bunch rotation

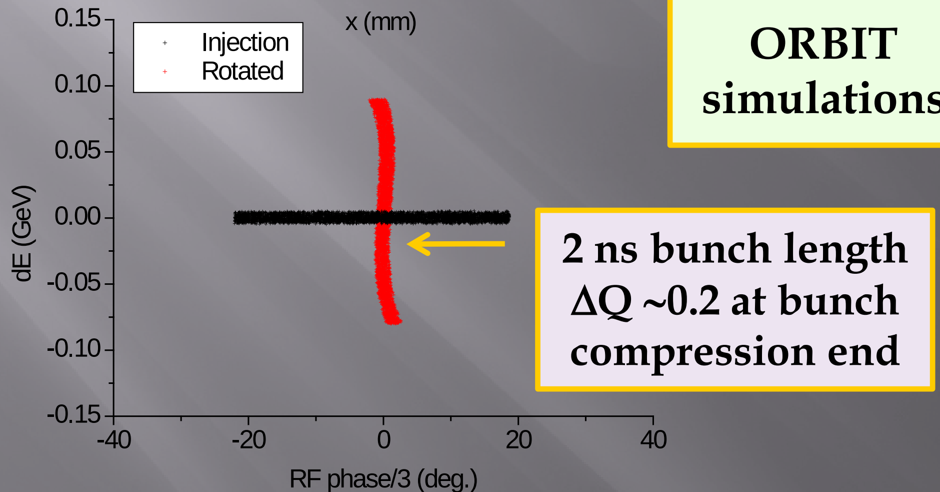
- 3μm (rms physical) transverse emittances satisfy needs for foil heating, aperture, space charge and beam size on target

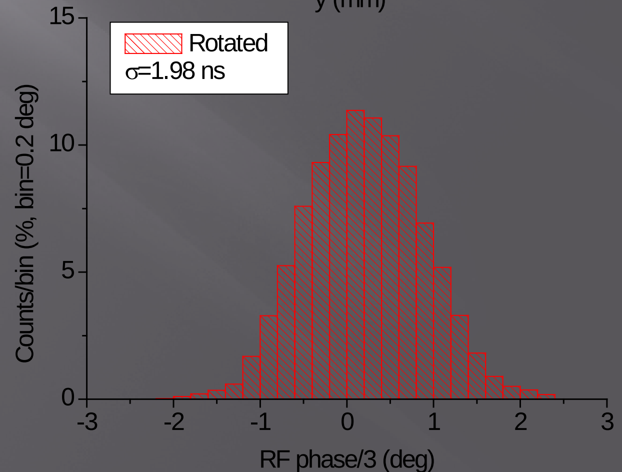
Potential extensions for neutrino factory





ORBIT simulations





phase plane plots before and after bunch rotation

Accumulator impedance

Contributions

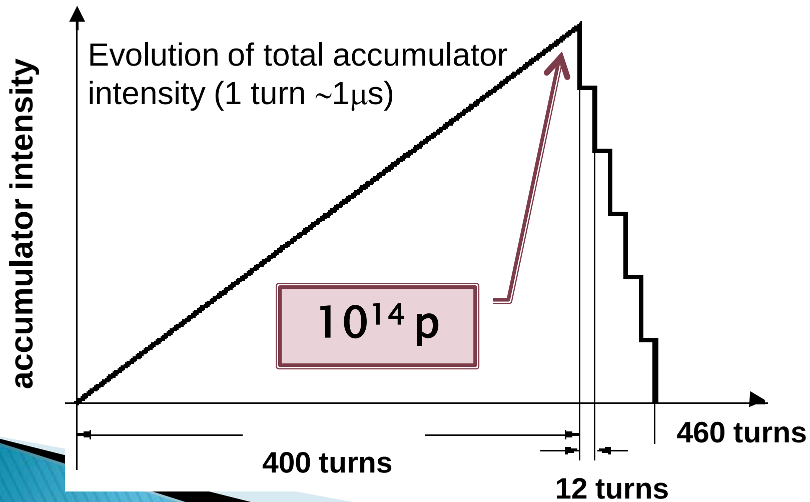
Transverse plane:

- **Resistive wall:** beam pipe resistivity
- **Narrow-band resonators:** not relevant since no RF cavities in the accumulator
- **Broad-Band resonator:** beam-pipe discontinuities
- **Electron cloud**: not an issue as no major electron build-up anticipated

Longitudinal plane:

- **Narrow-band resonators:** not relevant since no RF cavities
- **Broad-Band resonator:** kickers and other discontinuities

Mainly single-bunch instabilities (since narrow-band neglected)



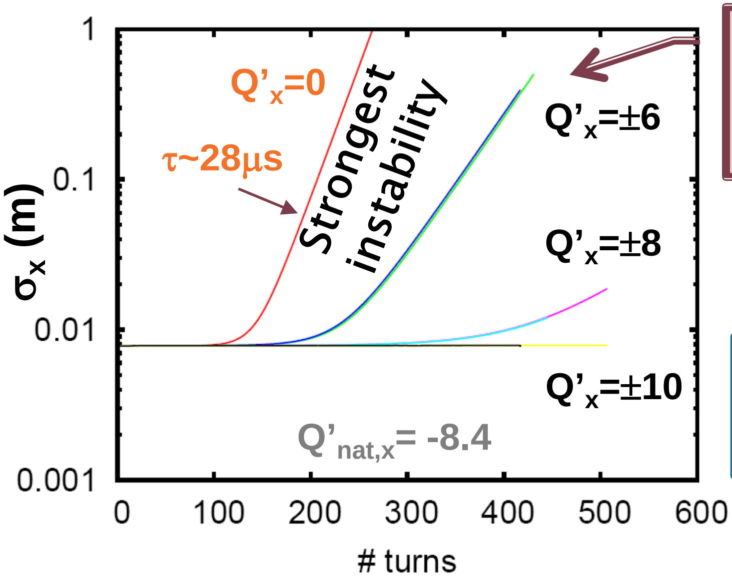
PESSIMISTIC analysis:

Full intensity assumed over the whole storage time whereas:

- **accumulation takes place over 400 μs → the intensity growths from 0 to10^{14} protons**
- **bunch transfer to compressor lasts 60 μs**
- **bunch rotation and extraction process in the compressor lasts 96 μs (5×12 turns to empty the accumulator + 3×12 turns to complete rotation of the remaining bunch and ejection)**

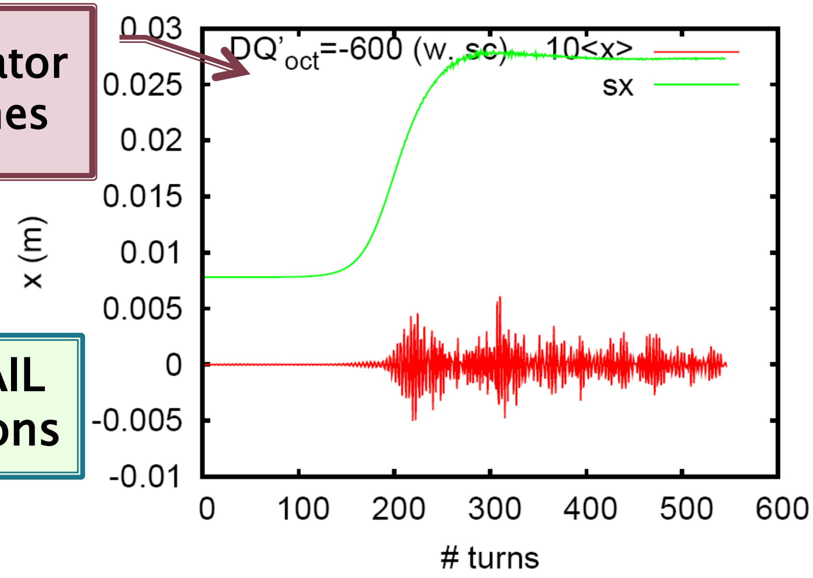
Transverse Broad-Band Impedance

Can be cured by introducing a quantity of tune spread



Accumulator 6–bunches

HEADTAIL simulations



Horiz. beam size vs turns for various chromaticities (BB resonator : 1MΩ/m, Q_R=1, f_R=1GHz)

Horiz. beam size and position vs with **octupoles**

BBI cured with sextupoles (by chromaticity)

- **Positive/negative values of Q' are OK (η~0)**
- **Need chromaticity |Q'|>10 tu cure the instability $\rightarrow \Delta Q_{rms}$~0.01 for $(\Delta p/p)_{rms}$~10^{-3}**

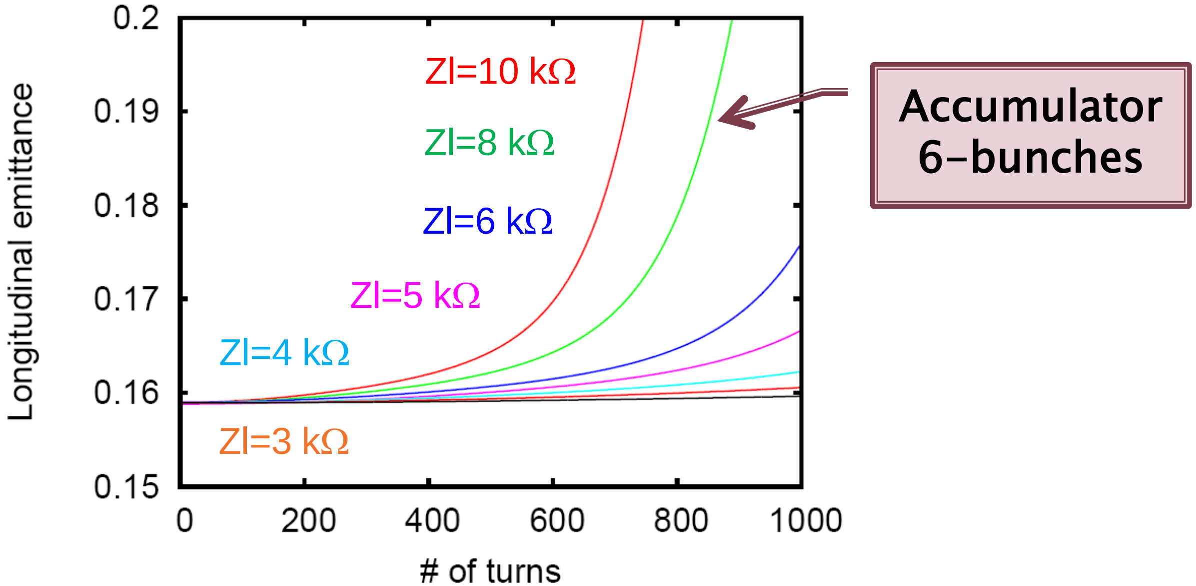
BBI cured with octupoles (detuning vs amplitude)

- **Beam size is growing until it stops when detuning is effective**
- **Q''_{xx}~1200 (-2000) required to cure instability $\rightarrow \Delta Q_{rms}$~0.006 (for σ_x~10 mm)**

Longitudinal Broad-Band Impedance

Major contribution from the injection and ejection kickers (since no RF)

1. **Isochronous ring**
   - **No RF cavities → negligible narrow-band impedance, beam frozen longitudinally**
2. **Broad-Band impedance → microwave instability**
3. **If only η_0=0 considered: the instability threshold is zero and the rise time is infinity**



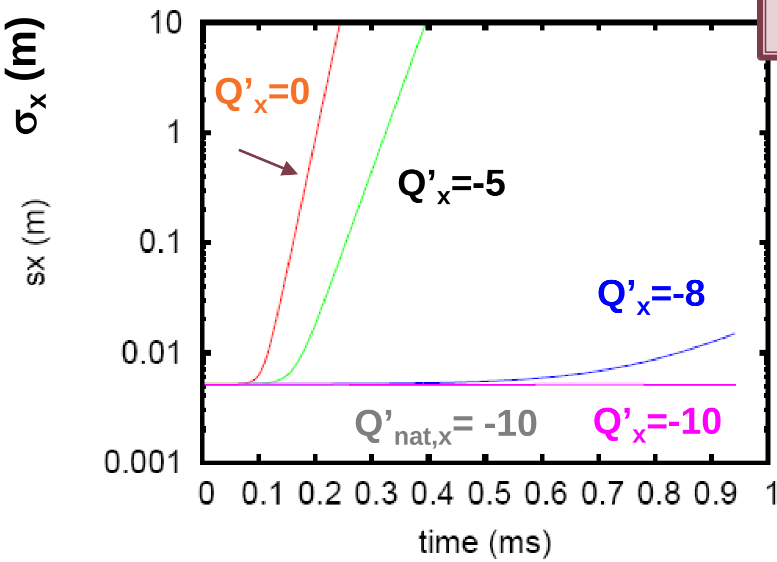
Longitudinal emittance (eVs) vs turns for various values of broad-band resonator (Q_R=1, f_R=1GHz)

Z_l < 5 kΩ → Z_l/n < 5 Ω: a few Ω easily reached in recent machines

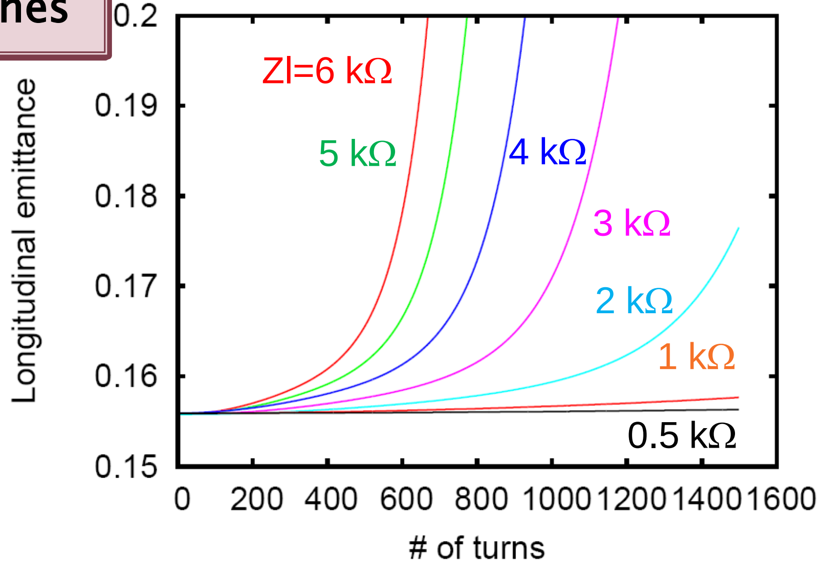
Transverse/Longitudinal Broad Band Impedances

Can be cured by introducing a quantity of tune spread

Accumulator 3-bunches



Horiz. beam size vs time for various chromaticities (BB resonator : 1MΩ/m, Q_R=1, f_R=1GHz)



Longitudinal emittance (eVs) vs turns for various values of broad-band resonator (Q_R=1, f_R=1GHz)

Transverse Broad-Band Instability: cured by natural chromaticity

Longitudinal Broad-Band Instability :

- **Maximum allowed impedance is Z_l = 2 kΩ → $(Z_l/n)_{max}$~3.2 Ω: which is a acceptable value**

Conclusion on accumulator and compressor instability studies

- **6/3-bunch accumulator options is/seems feasible and under control**
  - **Space charge okay → it guided in definition of emittance and bunch length & shape in the accumulator design**
- **Accumulator impedance**
  - narrow-band component negligible   no RF-cavities
  - resistive wall not an issue   long rise-time compared to accumulation time
  - e-cloud not an issue → flat and long bunch, no multipacting
  - longitudinal BB → $Z_l/n < 5\ \Omega$ + error-bar (f_R) (~few Ohm easily achieved in modern machines)
  - transverse BB okay → fast rising instability damped by by chromaticity ($|\xi|$~1.3) and/or amplitude-detuning induced by octupoles
    - need ΔQ ~ 0.02 → okay for tune footprint/resonance
    - assumed R_t=1MW/m → scaling laws with higher value of BB impedance
- **6/3-bunch compressor option should be feasible → beam stored for only ~ 11% of the accumulator storage time**
  - **Space charge okay** → ΔQ ~ 0.2 at the end of bunch compression, horizontal beam expansion reduces space charge

Potential extensions for neutrino factory

Summary

Progress towards future pulsed proton drivers at CERN made:

☞ **1st scenario (early scenario)**

- **New LHC injectors (Linac4, LP-SPL, PS2) and SPS consolidation**

☞ **2nd scenario (substitute scenario)**

- **Linac4 with consolidation (refurbishing) of existing LHC injectors (PSB, PS, SPS)**
- **High Power SPL R&D**

☞ **SPL-based proton driver including**

- **High Power SPL**
- **Proton drivers accumulator and compressor rings**