# SPS PRE-BOOSTER OPTION

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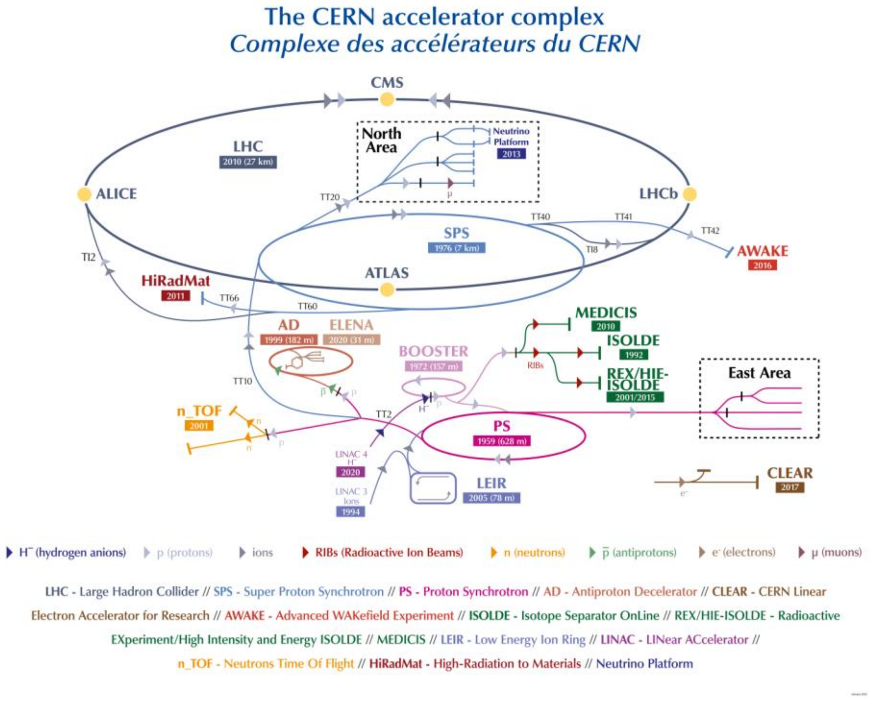
# Introduction

- The Super Proton Synchrotron (SPS, 1976) serves the North Area with slow extracted beam and as LHC injector (protons and ions)



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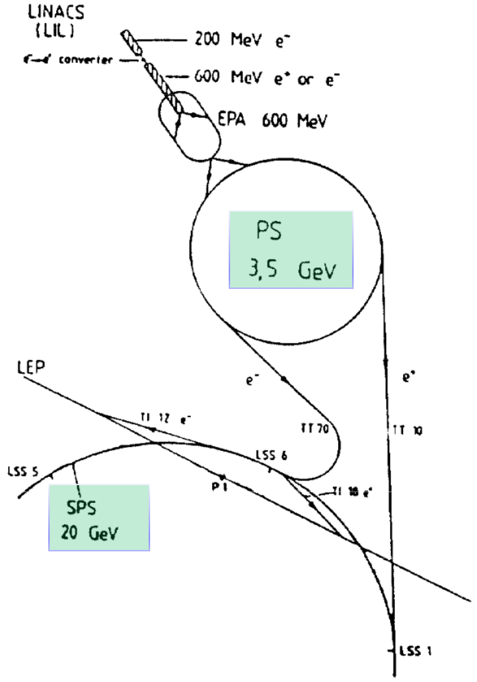


Fig. 4 Schematic layout of the transfer lines between PS, SPS and LEP

K. Cornelis, R. Schmidt, “Commissioning the SPS as LEP injector”

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- The SPS served as injector for LEP in the past (accelerating $e^+/e^-$ from 3.5 GeV to 20 GeV)
  - To achieve a precision of $\Delta I/I < 10^{-3}$ for dipoles and quadrupoles at injection, low-level **current control loops were switched between proton and lepton cycles**
  - **Synchrotron radiation** required installation of **masks both inside and outside the vacuum chamber to protect main magnets**, and **shutters for extraction septa**
  - The SPS travelling wave cavities are “directional” and could only be used for positrons – **additional 200 MHz standing wave cavities** were installed for electrons, **and a superconducting cavity at 352 MHz** for acceleration of positrons to 20 GeV

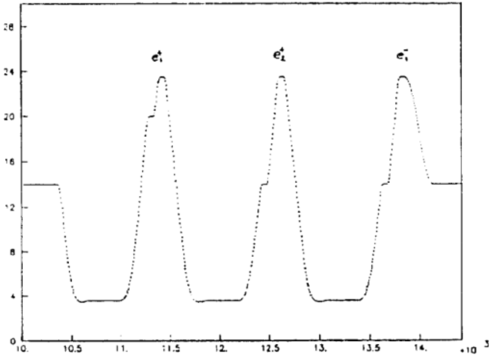


Fig. 2 The three lepton cycles

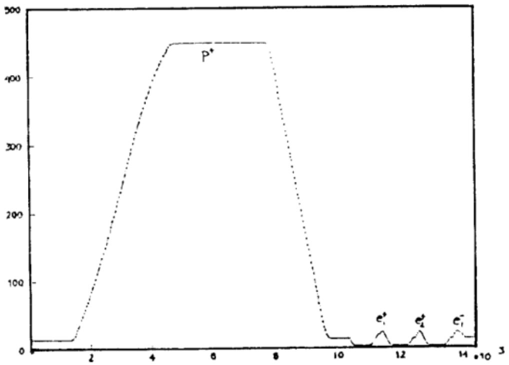
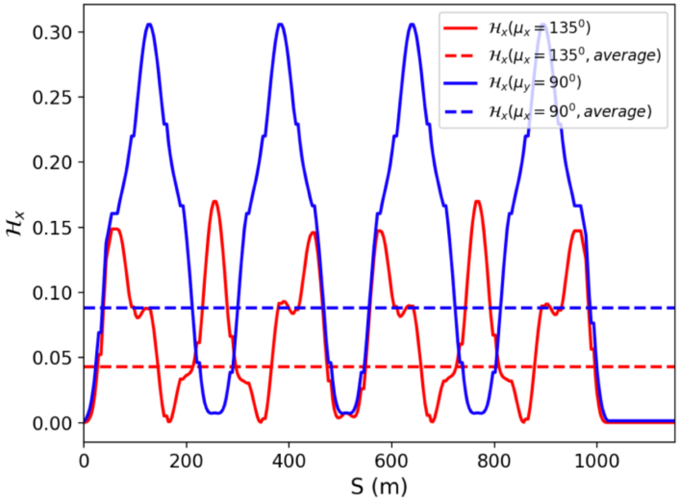


Fig. 1 The SPS supercycles with one proton and three lepton cycles

K. Cornelis, R. Schmidt, “Commissioning the SPS as LEP injector”

# Optimization of SPS optics

- The SPS consists of regular FODO cells with 6-fold symmetry (90 degree phase advance)
- **Horizontal phase advance of 135 degree optimizes horizontal emittance**
  - But still large emittance @extraction and damping time @injection (instabilities)

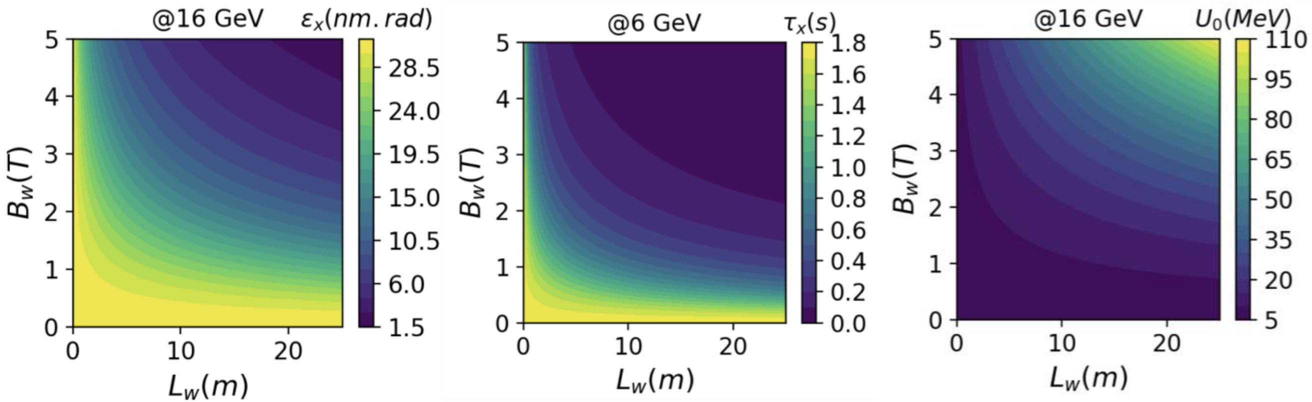



| SPS Parameters * <br> *phase advance is close to $135^0$ | | Requirements |
|---|---|---|
| SPS Bending radius [m] | 741.63 | |
| SPS injection energy [GeV] | 6 | |
| SPS extraction energy [GeV] | 16 | |
| Dipole length | 6.26 | |
| Bending field @ injection [Gauss] | 269.811 | |
| Bending field @ extraction [Gauss] | 899.3703 | |
| Emittance @ injection [m.rad] | $4.8\times10^{-9}$ | |
| Emittance @ extraction [nm.rad] | 34 | 5 |
| Energy Loss / turn @ injection [MeV] | 0.154 | |
| Energy Loss / turn @ extraction [MeV] | 7.8 | |
| Transverse Damping time @ injection [s] | 1.79 | 0.1 |
| Natural chromaticity h/v | -72/-40 | |
| Energy acceptance at @ injection | 1% | |

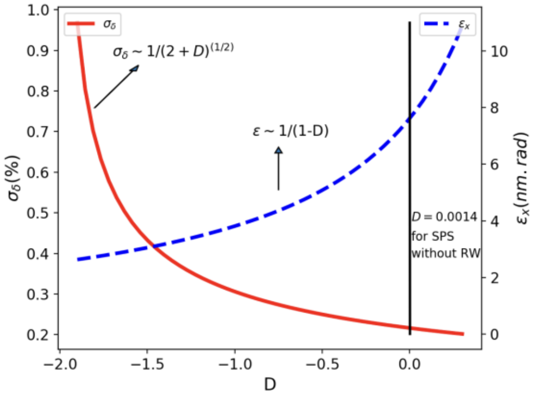
# Installation of damping and Robinson wigglers

- **Smaller horizontal emittance at extraction** and damping time at injection can be achieved with a **wiggler of length 23 m and 3.5 T peak field**
- Energy loss per turn is however very large (>60 MeV)
- Damping wigglers also needed to mitigate coherent instabilities, in addition to feedback
- **Robinson wiggler studied** to further reduce horizontal emittance (but larger energy spread)

**Effect of damping wigglers**




**Effect of Robinson wiggler**



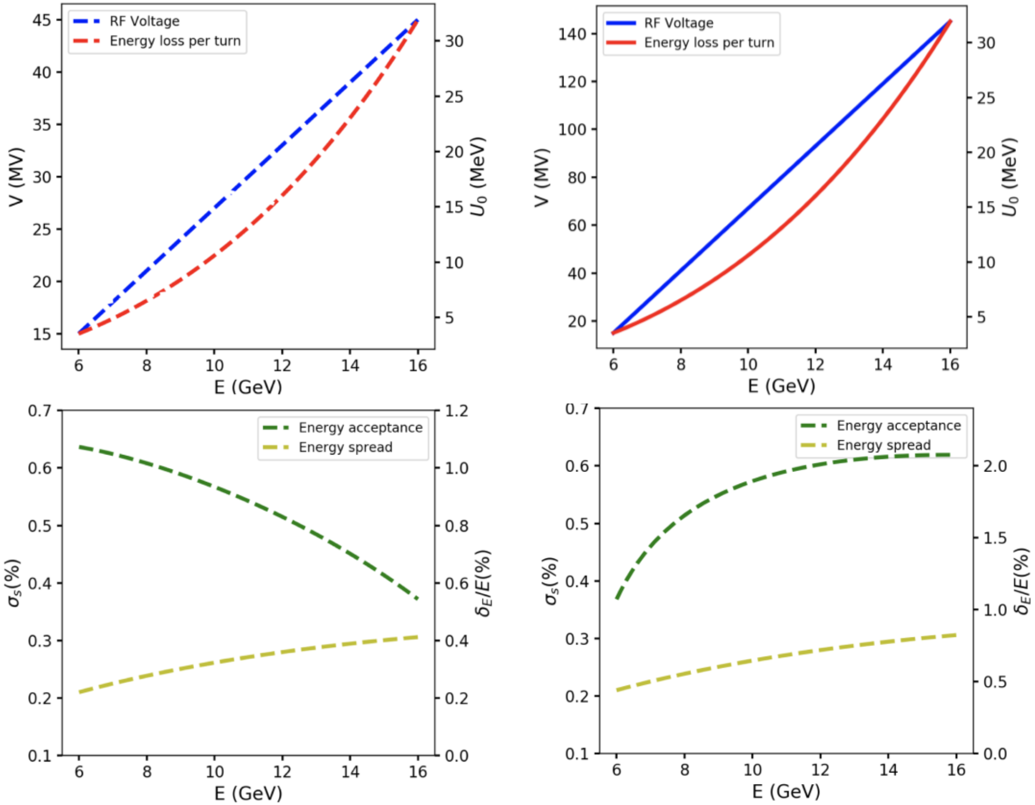
# Extraction energy considerations

- The CDR extraction energy is 20 GeV
- As this however leads to a very large energy loss per turn, **different extraction energy options were investigated**
- **The 16 GeV option provides a reasonable energy spread, energy loss per turn and emittance**

| | 20 GeV option | | | | 18 GeV option | | | | 16 GeV option | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | @ injection | | @ extraction | | @ injection | | @ extraction | | @ injection | | @ extraction | |
| | w/ wiggler | w/o wiggler | w/ wiggler | w/o wiggler | w/ wiggler | w/o wiggler | w/ wiggler | w/o wiggler | w/ wiggler | w/o wiggler | w/ wiggler | w/o wiggler |
| **Horizontal emittance* (nm.rad)** | **1.03** | 4.88 | **5.92** | 54.25 | **0.95** | 4.88 | **5.60** | 43.9 | 0.73 | 4.88 | 5.64 | 34.7 |
| **Energy loss per turn (MeV)** | **9.96** | 0.15 | **128.0** | 19.09 | **6.97** | 0.15 | **73.9** | 12.5 | 3.49 | 0.15 | 31.5 | 7.82 |
| **Damping time** (s)** | **0.012** | 1.79 | **0.003** | 0.048 | **0.01** | 1.79 | **0.005** | 0.06 | 0.03 | 1.79 | 0.01 | 0.09 |
| **Energy spread*** (%)** | **%0.3** | %0.01 | **%0.60** | %0.06 | **%0.35** | %0.01 | **%0.5** | %0.05 | %0.3 | %0.01 | %0.38 | %0.05 |
| **RF Voltage (MV)** | **35** | | **160** | | **30** | | **90** | | 25 | | 45 | |
| **Damping wiggler B[T] / L [m]** | 6 / 12.15 | | | | 5 / 12.15 | | | | 3.5 / 12.15 | | | |
| **Robinson wiggler B[T] / L [m]** | 0.5 / 12 | | | | 0.5 / 12 | | | | 0.5 / 6 | | | |

# Energy acceptance and RF voltage

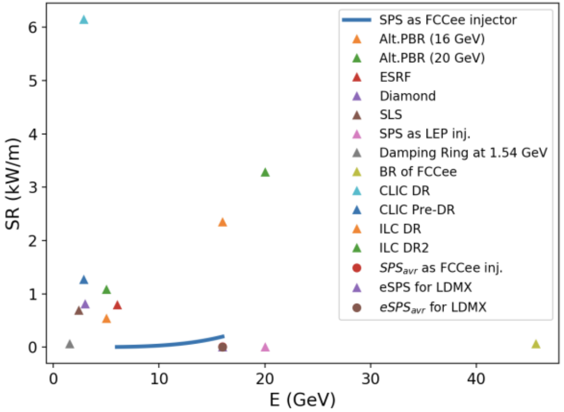
- At 16 GeV extraction the minimum RF voltage increases up to 45 MV
  - **δE/E=0.55% for $\sigma_s$=0.3%**
    **→ this is probably too optimistic**
  - **Updated RF voltage requirement to 140 MV at 16 GeV with wigglers**
- **Option without wiggler** (at least at flat top) **seems more interesting** due to significantly smaller RF voltage required (basically what was done for LEP) – **to be further studied with booster compatibility**



# Synchrotron radiation power

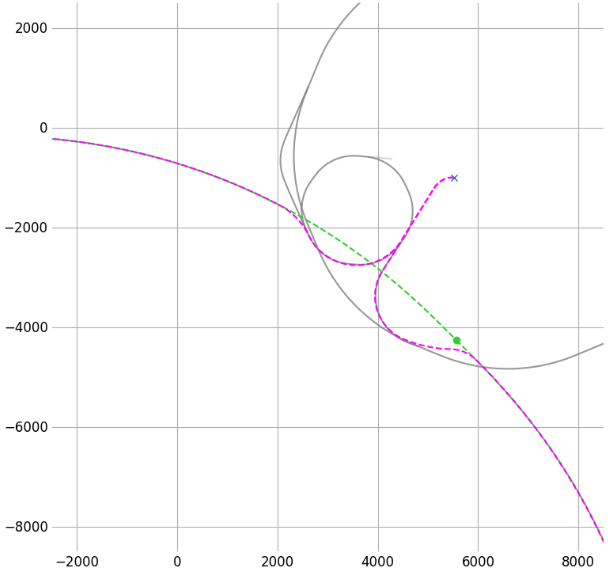
- **The present SPS machine layout cannot sustain the SR power**
- **Need absorbers and possibly a new vacuum system with cooled chambers**
  - During LEP times had masks in front of magnets and movable shutters to protect proton septa
  - **Ongoing studies by vacuum experts** – to be seen if a solution can be found that does not require replacing the entire vacuum system (vacuum chambers are integral part of SPS bending magnets, coils are in the median plane of the magnets), but would also need significantly improved vacuum levels to avoid fast ion instabilities
  - **Special absorbers for wiggler magnets** also to be implemented

| Parameters | SPS for LEP | SPS for FCC |
|---|---|---|
| Extraction energy [GeV] | 20 | 16 |
| SR - dipole magnets only (W/m) | 1.85 | 198 |
| Averaged SR- dipole magnets only (W/m) | 0.024 | 8.1 |
| SR - dipole and damping wiggler (W/m) | - | 809 |
| Averaged SR - dipole and damping wiggler (W/m) | - | 107 |
| Beam current (mA) | 0.45 | 160 |



# Power converter modifications

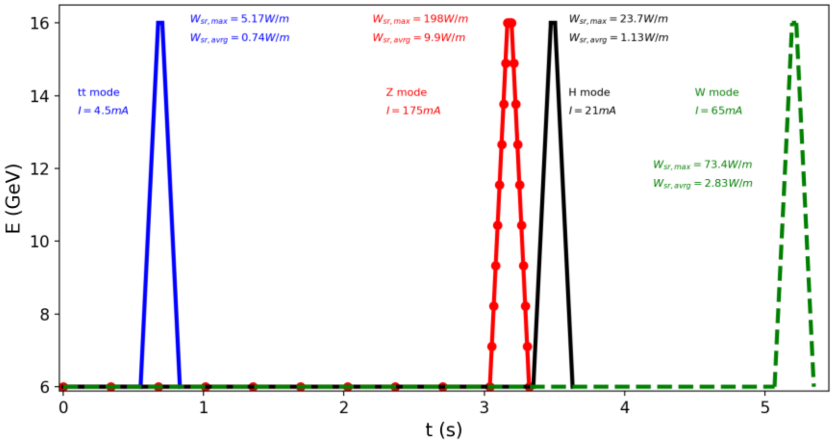
- **SPS mains** (Thyristor based) are **not able to operate at the low current needed for leptons**
  - **During LEP times**, there were **bleeders** installed on the mains to create an offset in current
  - In order to achieve the required precision on the regulation, **additional DCCTs and power converter regulation** electronics were installed with a system to switch between proton and lepton operation
  - **All these systems have been decommissioned** and are not available any longer.
- As FCCee injector, **a similar system of bleeders and additional regulation electronics would be needed**
  - This **could even allow for bipolar operation for electrons/positrons in the same direction of the ring** (e.g. injection in BA4, extraction in BA4 and BA6)




W. Bartmann

# Filling time studies

- **Ramping of SPS magnets from 6 GeV to 16 GeV is relatively fast** (~0.125 s)
- Long accumulation time (e.g. 3 s for Z mode) to fill the ring, **acceleration time is ~negligible**
  - **Similar filling time as for HE-Linac option**, details to be worked out for latest parameter set
- **During Z mode operation, not much machine time left for protons**
  - High duty factor (>76%) for leptons and continuous top-up




| Accelerator | FCCee-Z | | FCCee-W | | FCCee-H | | FCCee-tt | |
|---|---|---|---|---|---|---|---|---|
| Type of filling | Full | Top-up | Full | Top-up | Full | Top-up | Full | Top-up |
| Energy [GeV] | 45.6 | | 80 | | 120 | | 182.5 | |
| luminosity Lifetime [min] | 68 | 68 | 59 | 59 | 38 | 38 | 47 | 47 |
| τinj [sec] | 122 | 122 | 44 | 44 | 31 | 31 | 32 | 32 |
| Linac bunches | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| Linac Repetition rate [Hz] | 200 | 200 | 100 | 100 | 100 | 100 | 100 | 100 |
| linac RF freq [MHz] | | | | 2800 | | | | |
| Linac Bunch population [10^10] | 2.12625 | 1.063125 | 0.9375 | 0.5625 | 0.9375 | 0.5625 | 1.375 | 0.825 |
| SPS circumference | | | | 6911.503838 | | | | |
| SPS bunch spacing [MHz] | | | | 400 | | | | |
| Harmonic number | | | | 9221 | | | | |
| SPS bunches/injection | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| SPS Bunch population [10^10] | 2.12625 | 1.063125 | 0.9375 | 0.5625 | 0.9375 | 0.5625 | 1.375 | 0.825 |
| SPS Damping time @ 6 GeV [s] (without wigglers) | | | 1.787560963 | | | | | |
| SPS Damping time @ 20 GeV [s] | | | 0.048264146 | | | | | |
| Number of linac injections | 594.2857143 | 594.2857143 | 500 | 500 | 328 | 328 | 48 | 48 |
| Number of SPS extractions | 14 | 14 | 2 | 2 | 1 | 1 | 1 | 1 |
| SPS supercycle duty factor | 0.76 | 0.76 | 0.49 | 0.49 | 0.23 | 0.23 | 0.05 | 0.05 |
| SPS Number of bunches | 1188.571429 | 1188.571429 | 1000 | 1000 | 328 | 328 | 48 | 48 |
| SPS current [mA] | 175.39 | 87.70 | 65.06 | 39.04 | 21.34 | 12.80 | 4.58 | 2.75 |
| SPS injection time [s] | 3.071428571 | 3.071428571 | 5.1 | 5.1 | 3.38 | 3.38 | 0.58 | 0.58 |
| SPS ramp time [s] | | | | 0.125 | | | | |
| SPS Cycle length [s] | 3.321428571 | 3.321428571 | 5.35 | 5.35 | 3.63 | 3.63 | 0.83 | 0.83 |
| Maximum SPS bunch spacing [ns] | 17.5 | 17.5 | 22.5 | 22.5 | 67.5 | 67.5 | 477.5 | 477.5 |
| BR Number of bunches | 16640 | 16640 | 2000 | 2000 | 328 | 328 | 48 | 48 |
| BR Bunch population [10^11] | 0.212625 | 0.1063125 | 0.09375 | 0.05625 | 0.09375 | 0.05625 | 0.1375 | 0.0825 |
| BR cycle time [s] | 47.94 | 47.94 | 13 | 13 | 6.93 | 6.93 | 5.6925 | 5.6925 |
| Booster ramp time | 0.37 | 0.37 | 0.8 | 0.8 | 1.3 | 1.3 | 2.08125 | 2.08125 |
| number of cycles per species | 10 | 1 | 20 | 1 | 20 | 1 | 20 | 1 |
| Transfer efficiency | | | | 0.8 | | | | |
| Number of injections/collider bucket | 10 | 1 | 20 | 1 | 20 | 1 | 20 | 1 |
| Total number of bunches | 16640 | 16640 | 2000 | 2000 | 328 | 328 | 48 | 48 |
| bunch spacing [nsec] | | | | | | | | |
| Filling time (both species) [sec] | 958.8 | 95.88 | 520 | 26 | 277.2 | 13.86 | 227.7 | 11.385 |
| | | | | | | | | |
| required FCCee bunch population [10^11] | 1.701 | 0.08505 | 1.5 | 0.045 | 1.5 | 0.045 | 2.2 | 0.066 |

# Other points

- Aperture
  - Studies indicate **Dynamic Aperture is OK** (but errors not included yet) even for off axis injection
  - Acceptable emittance in horizontal and vertical planes are 15 and 60 nm.rad respectively assuming 0.3% rms energy spread of the incoming beam
- Injection schemes
  - **ON-axis injection**: short pulse kicker (10-20 ns) **is possible with high repetition rate** (100-200 Hz) according to PSI kicker specialist
  - **OFF-axis injection: seems also feasible**
- Extraction
  - Fast extraction channels in BA4 and BA6 are available from protons – maybe could be re-used
- Collective effects
  - Studies for various collective effects highlight **potential limitation from TMCI**
  - **SPS vacuum needs to be considerably improved to cope with fast ion instability** even with radiation damping and feedback system

# Conclusions

- **Ongoing work to consolidate the option of using the SPS as FCCee pre-booster** for cost comparison to HE-Linac option at mid-term review
- We consider the **16 GeV extraction energy** as **most interesting**
- **High synchrotron radiation power** and required **vacuum levels are challenging** – ongoing work by vacuum experts
- Installation of **damping wigglers** (and Robinson wiggler) **might be required** – ongoing studies by booster colleagues if larger horizontal emittance could be accepted
- **Additional RF system would be required** – with very high voltage at extraction when using wiggler magnets
- **Modification of power converters for bi-polar operation seems feasible**
- **Collective effects to be further studied** (in particular the fast ion instabilities and TMCI)
- **Filling time compatible with collider request** (at least for latest parameter set)