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Synchronisation and RF

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Y. Dutheil, B. Goddard, F. Velotti

Laser-bunch synchronisation

- Laser frequency must be at an harmonic of the revolution frequency and of the bunch pattern
  - The SPS RF system is at ~200MHz, or $f_{RF} = h \times f_{rev}$ with h=4620 and f_{rev}~23kHz
  - With the SPS filling patterns, the laser at ~40Mhz can interact with every bunch

$$f_{laser} = \frac{h}{5} \times f_{rev} = 924 \times f_{rev}$$

- Finding the resonance involves changing the beam energy, which may change the revolution frequency
- The initial synchronization between the laser and the RF system needs to be considered

Revolution frequency with energy changes

- 3 ways to change the ion bunch energy, with different effects
  - Constant frequency
  - Constant optics
  - Constant field

- In accelerator physics we routinely use deferential relations to quickly understand and quantify changes of revolution frequency f_{rev}, average beam radius R, momentum p and dipole field B.

Case of Constant Frequency

Here we constrain the revolution frequency to be fix by maintaining the RF frequency, note that $f_{RF} = h\, f_{rev}$ and the laser cavity frequency is $f_{cav}=h/5\, f_{rev}$

$$\frac{dB}{B} = \gamma_t^2 \frac{df_{rev}}{f_{rev}} + \frac{\gamma^2 - \gamma_t^2}{\gamma^2} \frac{dp}{p}$$

That equation does not contains the average beam radius as it is constrained by the other 3 quantities. Furthermore we fix a constant frequency so df=0 and the first term vanishes.

We consider a relative change in momentum of $\frac{dp}{p} = 10^{-3}$ and with the PoP numbers we get a relative change in field of $\frac{dB}{B} = 0.945 \times 10^{-3}$.

Case of constant optics

Here we aim at preserving the beam trajectory while changing field and frequency synchronously. The equation used here links p, f_{rev} and R

$$\frac{dp}{p} = \gamma^2 \frac{df_{rev}}{f_{rev}} + \gamma^2 \frac{dR}{R} \quad \text{or} \quad \frac{df_{rev}}{f_{rev}} = \frac{1}{\gamma^2}\frac{dp}{p} - \frac{dR}{R}$$

But as we consider the field is changed synchronously we have dR=0 and the second term disappears.

We consider a relative change in momentum of $\frac{dp}{p} = 10^{-3}$ and with the PoP numbers we get a relative change in the revolution freqeuncy of $\frac{df}{f} = 1.07 \times 10^{-7}$ or in absolute df= 0.00466 Hz.

However we are most interested in the cavity length L_{cav} and its frequency f_{cav}

$$f_{cav} = \frac{h}{5} f_{rev} \quad \text{and} \quad L_{cav} = \frac{5}{2} \frac{c}{h * f_{rev}}$$

Which gives a freqeuncy of around 40.1 MHz and a length of 3.74 m

Also we ca write the differential relation of the cavity length to f_{rev}

$$dL_{cav} = -\frac{5}{2} \frac{c}{h} \frac{1}{f_{rev}^2} df_{rev}$$

and using the numbers discussed above we get $dL_{cav} = -0.402$ um

As one could expect this number is quite small. The reason is that the beam is already very relativistic and the frequency change is only cause here by the change in the speed of the particle, which is minimal. Also it is negative since we increased the speed.

Constant field case

Now that we have discussed the constant frequency and constant optics case we we look at the constant field case. In this case the machine fields are kept constant while the frequency is moved to induce a change in momentum. The deferential relation linking the field B, the revolution frequency and the momentum is

$$\frac{dB}{B} = \gamma_t^2 \frac{df}{f} + \frac{\gamma^2 - \gamma_t^2}{\gamma^2} \frac{dp}{p}$$

As we fix the field dB=0 and the relation becomes

$$\frac{df}{f} = \frac{\gamma_t^2 - \gamma^2}{\gamma^2 * \gamma_t^2} \frac{dp}{p} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}\right) \frac{dp}{p} = \eta \frac{dp}{p}$$

We consider a relative change in momentum of $\frac{dp}{p} = 10^{-3}$ and with the PoP numbers we get a relative change in the revolution freqeuncy of $\frac{df}{f} = -1.83 \times 10^{-6}$ or in absolute df= -0.0795 Hz.

But again, we are most interested in the cavity length variation. With the numbers above it is $dL_{cav} =$ 6.86 um

The variation in cavity length is much larger here. This is because with a fixed field the trajectory, and average beam radius, are changed. This has a strong effect on the path length and revolution frequency. It is positive because the path length increases with the momentum increase.

Summary

- Primary frequency tuning system of the laser uses piezo-electric crystals and conventionally give a tuning range in the order of nanometers.
  - Constant optics and constant field cases require much larger tuning ranges
  - Fixed frequency, by definition, does not need the laser to change frequency but changes the position of the beam at the IR due to non-zero dispersion. However that can be compensated as we foresee the integration of BPMs inside the laser cavity

- Synchronisation of the SPS RF and bunches with the laser system
  - An initial scan will be required as such system cannot be absolute
  - A system very similar to the one used by AWAKE (fixed frequency) could be used see details https://indico.cern.ch/event/802131/contributions/3346480/

Thank you