Optimization of FCC circumference for hh

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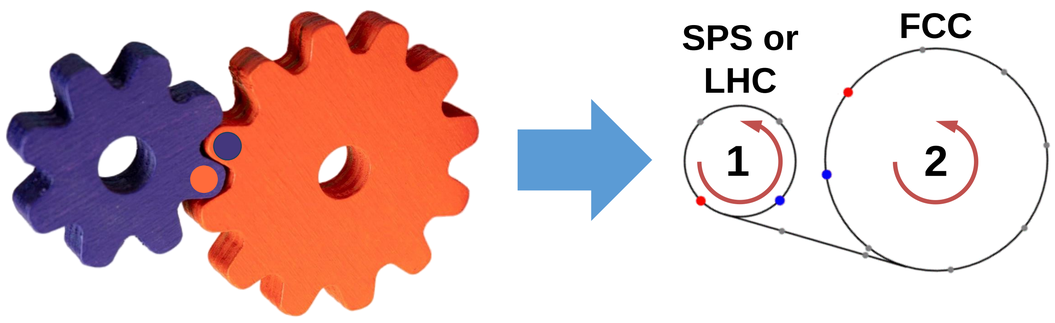
Abstract

The accelerator circumference will remain an unchangeable parameter throughout the entire life of the FCC program. A cautious choice is therefore essential to cover all present and future requirements in terms of beam transfer schemes or bunch spacing and length. The exact circumference becomes particularly important for the FCC-hh, when hadron beams will be supplied by a high-energy booster synchrotron either in the SPS or the LHC tunnel. The numerator and denominator in the rational circumference ratio between the FCC and its injector define the fundamental periodicity of possible beam transfers. The ratio of FCC and LHC for the present baseline circumference is extremely close, but not exactly 17/5. Moving it to precisely that value by shortening the tunnel by 18 m would allow hadron injections to take place every five revolutions, opening the door to, for example, RF manipulations to control the bunch length and alternative beam transfer schemes. This contribution summarizes the impact of the proposed fine tuning of the FCC circumference on RF frequencies, as well as its benefits for more flexibility at beam transfer.

Introduction

- **Transfer between circular accelerators → cogwheeling**



- **For equal RF frequencies $f_{\mathrm{RF},1} = f_{\mathrm{RF},2}$ in both synchrotrons**

→**Ratio between harmonic numbers, *h*, circumferences, *C*, and number of turns, *n*:**

$$\frac{h_1}{h_2} = \frac{C_1}{C_2} = \frac{n_2}{n_1}$$

→**Beams at identical azimuths after n_1 turns in accelerator 1, corresponding to *exactly* n_2 turns in accelerator 2**

→**Present FCC circumference baseline of 90658.2 m would allow injection only every 297 turns (90 ms, i.e. 1010 turns in LHC) or every 77 turns (23 ms, i.e. 1010 turns in SPS)**

→**Prefer small rational ratios n_2/n_1 to maximize transfer occasions**
→**Rare opportunity to optimize length for entire FCC program**

→**Change from ratio C_{FCC}/C_{LHC} = 1010/297 ≈ 3.40067 to 17/5 = 3.4**

3.40067 → **3.4 = 17/5** → C_{FCC} = 90640.2 m

Why small circumference ratios between hadron synchrotrons?

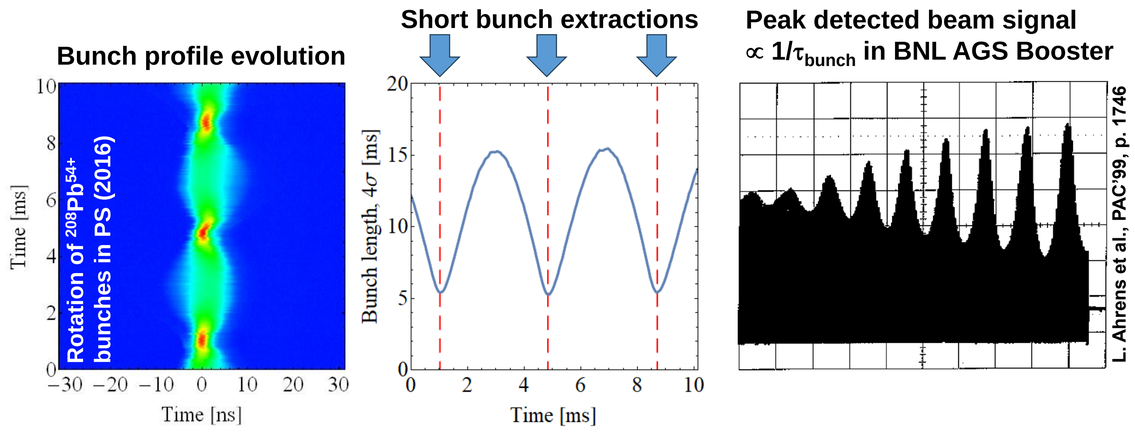
→**Almost instant transfer between HEB in LHC tunnel and FCC**

→**Required for manipulations like, e.g., bunch rotation at transfer**
- **Operational: AGS Booster → AGS, CERN PS → SPS and SPS → AWAKE, DESY PETRA → HERA, FNAL Booster → MI**
- **Planned: CERN SPS-LHC (ions), SSC HEB → Collider**

- **Multiple transfers of ~80-bunch batches**

→**Required for HEB-FCC to limit transferred beam energy**

→**Trigger ejection each half-period of synchrotron oscillation, T_S**



→**Only possible when T_S much larger than $n \cdot T_{rev}$**
→**Future exotic schemes like off-momentum or barrier-bucket stacking, etc. also very constrained**

Impact of modifying FCC circumference by ΔC = -18 m?

→**Harmonic number h_{LHC} = 35640 (f_{RF} = 400.8 MHz) in LHC would correspond to h_{FCC} = 121176 = $2^3 \cdot 3^4 \cdot 11 \cdot 17$ in FCC**
→**Not suitable for 25 ns bunch spacing nor particularly flexible**
→**Change RF frequency for FCC-ee and later for FCC-hh**

- **Bunch spacings → harmonic number multiple of $2^4 \cdot 3 \cdot 5 = 240$**
- **Include also 17 as an integer factor → $m \cdot 240 \cdot 17 = 4080$**

→**Closest to h_{FCC} = 121176 is h_{FCC} = 122400 = $30 \cdot 4080 = 2^5 \cdot 3^2 \cdot 5^2 \cdot 17$**

→***Proposed* RF frequency for FCC-ee: f_{RF} = 404.8 MHz**

- **SPS (or successor) likely required as (pre-)injector for protons**

→**Harmonic number must include factor 27 = 3^3**
→ **$m \cdot 27 \cdot 4080 = 36720$ → RF frequency multiple of 121.5 MHz**

→***Proposed* RF frequencies FCC-hh: f_{RF} = 364.4,(485.8, 607.3) MHz**

Large scale accelerator facilities worldwide

Accelerator	Circumference [m]	Ratio	Remark
TRISTAN Acc. Ring	377.26	-	
TRISTAN	3018.08	8	Initial proton option
AGS	807.10475	-	
RHIC	**3833.845**	19/4	Evolution of ISABELLE, CBA
FNAL Booster	474.2	-	
FNAL MI/Recycler	3319.419	7	
FNAL MR/Tevatron	6283	53/28 (MI), 53/4 (Booster)	Originally NAL MR length
PETRA	2304	-	Initially for leptons only
HERA	6336	11/4	
IHEP Protvino U-70	1483.699	-	
IHEP Protvino UNK	20771.786	14	Tunnel completed
SPS	6911.562	-	
LEP/LHC	**26658.883**	27/7	
SSC HEB (1994)	**10800**	-	Adapted for cogging
SSC collider	87120	121/15	23 km tunnel constructed

→ **Often multiple iterations made before settling to a final circumference**
→ **Small rational ratios of circumferences allow flexible transfer every few turns**
→ **Conservatively chosen tunnel lengths**
→ **Detailed studies for LEP circumference**

Summary

h_{FCC}	C_{FCC} [m]	ΔC_{FCC} [m]	$\frac{h_{FCC}}{h_{LHC}}$	$\frac{h_{FCC}}{h_{SPS}}$	f_{RF} [MHz]	Bucket spacings	Bunch spacings [ns]	Bunch spacing options	
120960 = $2^7 \times 3^3 \times 5 \times 7$	90478.6	−179.5	$\frac{112}{33}$	$\frac{144}{11}$	400.8	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25	10	→ -180 m (too far)
110160 = $2^4 \times 3^4 \times 5 \times 17$	90640.2	−17.95	$\frac{17}{5}$	$\frac{459}{35}$	364.4	1, 2, 3, 4, 5, 6, 8, 9, 10, (12)	2.7, 5.5, 8.2, 11, 13.7, 16.5, 22, 24.7, 27.4	9	→ Proposal FCC-hh
121176 = $2^3 \times 3^4 \times 11 \times 17$					400.8	1, 2, 3, 4, 6, 9, (11, 12)	2.5, 5, 7.5, 10, 15, 22.5, (27.4, 29.9)	6	
122400 = $2^5 \times 3^2 \times 5^2 \times 17$					404.8	1, 2, 3, 4, 5, 6, 8, 9, 10, 12	2.5, 5, 7.5, 10, 12.5, 15, 20,22.5, 25	9	→ Proposal FCC-ee
146880 = $2^6 \times 3^3 \times 5 \times 17$					485.8		2.1, 4.1, 6.2, 8.2, 10.3, 12.4, 16.5, 18.5, 20.6, 24.7	10	
183600 = $2^4 \times 3^3 \times 5^2 \times 17$					607.3	1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15	1.7, 3.3, 4.9, 6.6, 8.2, 9.9, 13.2, 14.8, 16.5, 19.8, 24.7	11	
121200 = $2^4 \times 3 \times 5^2 \times 101$	90658.2	0	$\frac{1010}{297}$	$\frac{1010}{77}$	400.8	1, 2, 3, 4, 5, 6, 8, 10	2.5, 5, 7.5, 10, 12.5, 15, 20, 25	8	→ Baseline
121440 = $2^5 \times 3 \times 5 \times 11 \times 23$	90837.7	+179.5	$\frac{92}{27}$	$\frac{92}{7}$	400.8	1, 2, 3, 4, 5, 6, 8, 10	2.5, 5, 7.5, 12.5, 15, 20, 25	8	→ +180 m (too far)

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