FINE TUNING OF FCC CIRCUMFERENCE AND MULTI-BUNCH STABILITY ANALYSIS

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Outline

RF synchronization for FCC-hh and choice of circumference

FCC-ee: Offset phase optimisation for double RF

Coupled bunch instabilities (CBI) excited by high-order modes (HOMs) at calibration energy

RF synchronisation and circumference

Synchronisation principles for hadron synchrotrons

- Last update given by Linhao Z. during FCC week 2022 [talk]
- FCC-hh should be compatible with potential injectors (LHC/SPS)
- FCC-ee and FCC-hh will share the same tunnel
- For a given frequency, the circumference determines the harmonic number:

$$\frac{C_2}{C_1} = \frac{n_1}{n_2} = \frac{vT_{rev,1}}{vT_{rev,2}} = \frac{h_2}{h_1}$$

- Beam transfer is possible with a periodicity of $n_1 T_{rev,1} = n_2 T_{rev,2}$

	LHC	SPS	PS
C [m]	26658.883	6911.562	628.325
h	35640	2×4620	2×420

$$f_{RF} = 400.79 \text{ MHz}$$

$$\frac{h_{LHC}}{h_{SPS}} = \frac{27}{7} \qquad \frac{h_{SPS}}{h_{PS}} = \frac{11}{1}$$

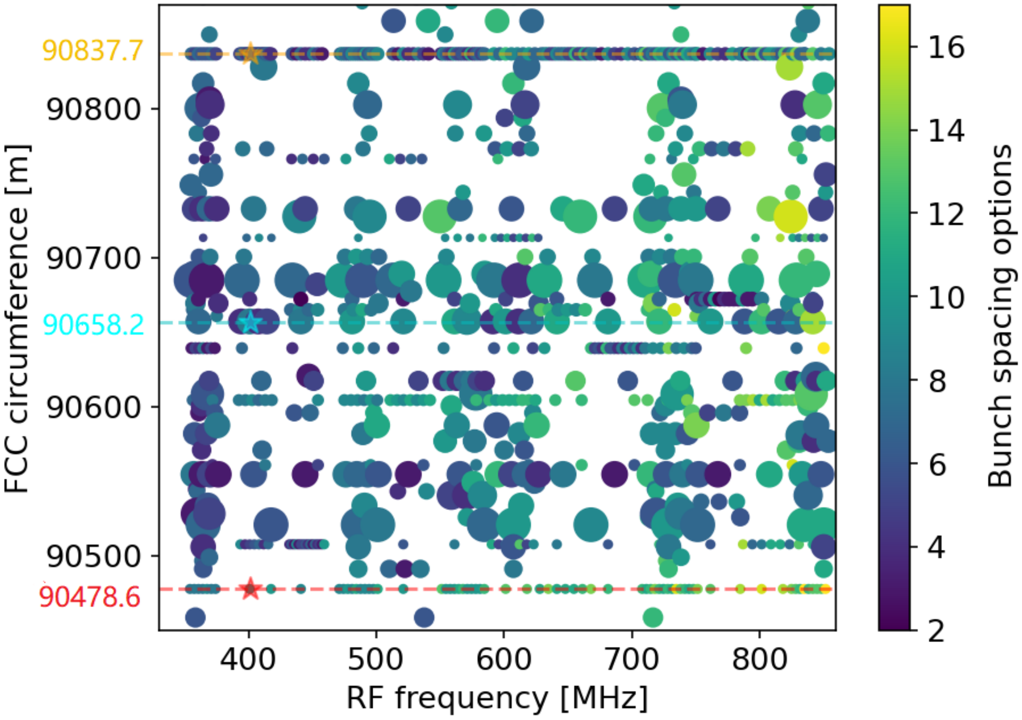
- Goal: optimize circumference based on RF synchronization

Choice of circumference for FCC-hh

8 main constraints were identified:

1. Keep SPS and/or LHC as injectors of FCC-hh (compulsory).
2. $C_{FCC} \approx 90.6$ km (geological constraints) (compulsory).
3. $f_{RF} = 400.79$ MHz (optional).
4. h_{FCC} must be divisible by 2 to allow for 4 IPs (compulsory).
5. h_{FCC} should keep a continuous bunch clock for at least 25 ns bunch spacing (compulsory).
6. h_{FCC} should provide as many bunch spacings as possible (optional).
7. Largest prime factor of h_{FCC}, h_{LHC} & h_{SPS} should be smaller than 300 (arbitrary) to allow generation of intermediate frequencies (optional).
8. Denominators in h_{FCC}/h_{LHC} and h_{FCC}/h_{SPS} should less than 300 (arbitrary) to minimise transfer times (optional).

Circumference vs RF frequency



- Color size: number of bunch spacing options
- Dot size: largest prime factor of h_{FCC}

We are looking for a horizontally well-populated line with small light-coloured dots.

Three most favorable circumference options:

h_{FCC}	C_{FCC} [m]	ΔC_{FCC} [m]	$\frac{h_{FCC}}{h_{LHC}}$	$\frac{h_{FCC}}{h_{SPS}}$	Largest prime factor	Bucket spacings	Bunch spacings [ns]	Bunch spacing options
$\mathbf{120960} = 2^7 \times 3^3 \times 5 \times 7$	90478.7	−179.5	$\frac{112}{33}$	$\frac{144}{11}$	7	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
$\mathbf{121200} = 2^4 \times 3 \times 5^2 \times 101$	90658.2	0	$\frac{1010}{297}$	$\frac{1010}{77}$	101	1, 2, 3, 4, 5, 6, 8, 10	2.5, 5, 7.5, 10, 12.5, 15, 20, 25	8
$\mathbf{121440} = 2^5 \times 3 \times 5 \times 11 \times 23$	90837.7	+179.5	$\frac{92}{27}$	$\frac{92}{7}$	23	1, 2, 3, 4, 5, 6, 8, 10	2.5, 5, 7.5, 12.5, 15, 20, 25	8

Conservative choices were deliberately made to ensure that bunch transfer and RF synchronisation would work, while allowing maximum flexibility for future parameter changes.

From [Zhang L.], to appear in ICFA BD NL#85

Parameters update

Change of circumference and luminosity optimisation lead to parameter updates.
The most relevant for RF are:

Parameter	Z	W	H	ttbar	
	Per beam	Per beam	2 beams	2 beams	2 beams
RF freq. [MHz]	400	400	400	400	800
RF voltage [MV]	79	1050	2100	2100	9200
Current [mA]	1280	135	53.4	10	10
E loss/turn SR [MV]	39.40	374	1890	10420	10420

From K. Oide (FCC Week 2023)

Stages: after the Z, W and Higgs operations, we will add 800 MHz cavities for ttbar.
We need to know which voltage satisfies beam dynamics requirements.

Optimisation of the double harmonic voltage

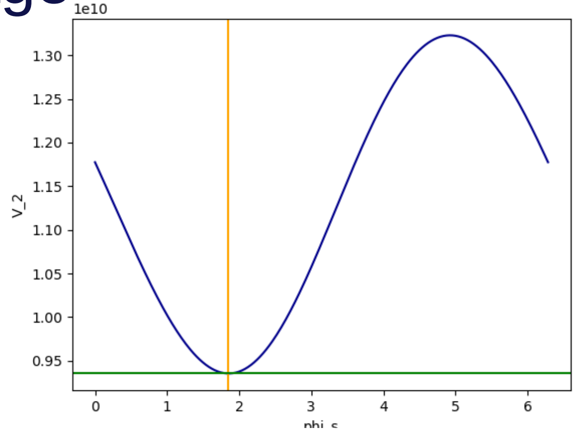
Objective: find the offset phase Φ_2 that minimises the required voltage V_{800} to compensate for an energy loss $U_0 = 10.42$ GV while satisfying

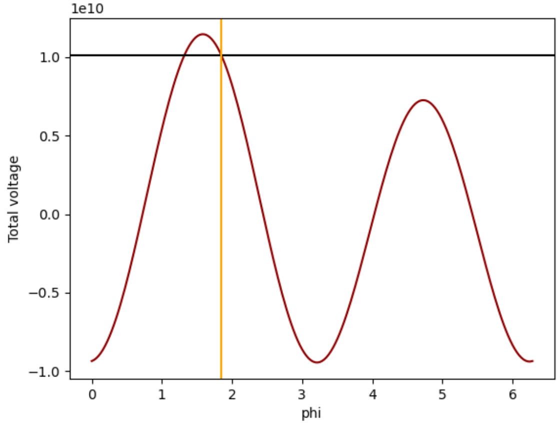
$$\begin{cases} V_{400}\sin(\phi_s) + V_{800}\sin(n\phi_s + \Phi_2) = 10.42\text{ GV} \\ \cos(\phi_s) + n\dfrac{V_{800}}{V_{400}}\cos(n\phi_s + \Phi_2) = \dfrac{Q_s^2}{C} \end{cases}$$

$$V_{800,min} = argmin_{\phi_s \in [0,2\pi]}[V_{400} f(\phi_s)]$$

$\phi_{s,min} = 1.85$ $V_{800,min} = 9.35$ GV $\Phi_2 = -1.60$

From K.Oide, FCC-ee parameter meeting, Nov. 16, 2021 [Indico]





CBI at calibration energy due to HOMs

Calibration: once a month, for each working point (W, H, ttbar) the machine will operate at Z pole (45.6 GeV) with maximum possible current to minimise calibration time.

Standard formulae for the shunt impedance threshold (only one sideband contributes) are:

$$Z_{\parallel}^{\mathrm{th}}(f) = \frac{2E_b Q_s}{e I_{b,\mathrm{DC}} \eta \tau} \frac{1}{f} \qquad Z_{\perp}^{\mathrm{th}} = \frac{E_b}{e f_{\mathrm{rev}} I_{b,\mathrm{DC}} \beta_{xy} \tau}$$

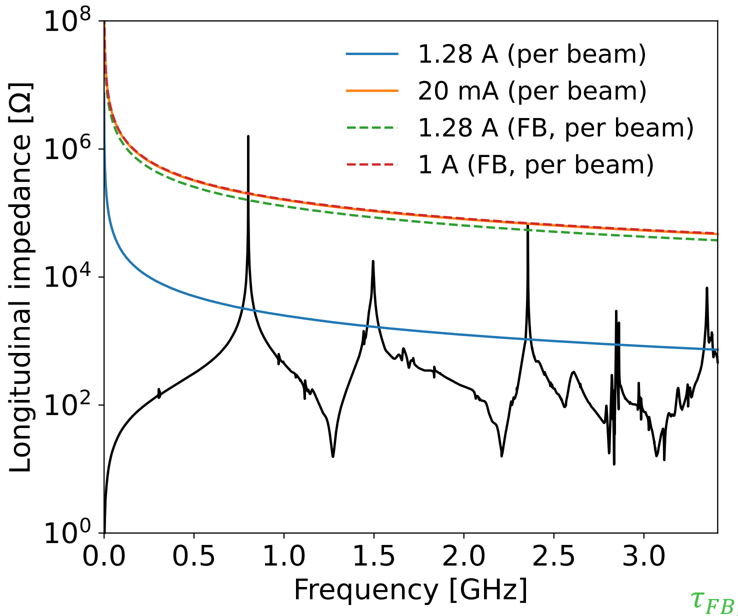
The impedance instability threshold is:

- proportional to the energy
- inversely proportional to the current

Low energy will drive coupled bunched instabilities. What is the maximum current allowed for energy calibration at each working point?

The damping time τ can be acted on to mitigate the threshold : Will synchrotron radiation suffice to suppress transverse CBI due to HOMs or is a bunch-by-bunch feedback system required?

Longitudinal and transverse CBI due to HOMs: ttbar at calibration energy

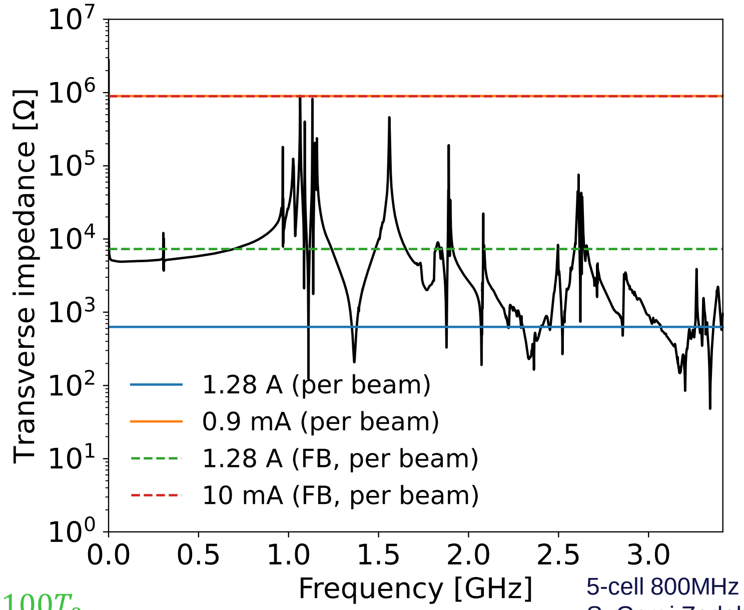


$$E_b = 45.6\ \text{GeV}$$

$$\tau = \tau_{SR}, \tau_{FB}$$

$$Z_{\parallel}^{\text{th}}(f) = \frac{2E_b Q_s}{eI_{b,\text{DC}}\eta\tau}\frac{1}{f}$$

$$Z_{\perp}^{\text{th}} = \frac{E_b}{ef_{\text{rev}}I_{b,\text{DC}}\beta_{xy}\tau}$$



5-cell 800MHz
S. Gorgi Zadeh

$$\tau_{FB,l} = \frac{2T_0}{Q_s}$$

$$\tau_{FB,t} = 100T_0$$

	τ_{SR}	τ_{FB}
I_{max}	20 mA	1 A

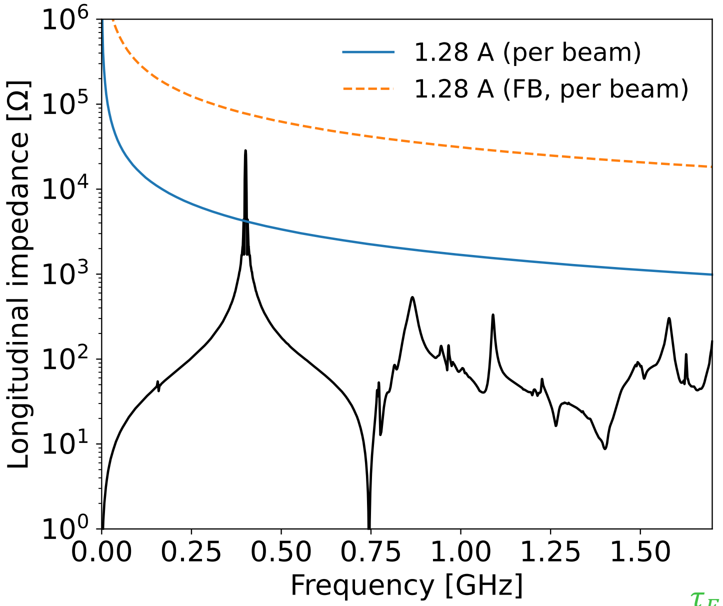
(per beam)

	τ_{SR}	τ_{FB}
I_{max}	0.9 mA	10 mA

(per beam)

- Limit instabilities → need safety margin (a factor of 3-10) → Even lower current is required
- Transverse stability is the main concern → more aggressive FB system needs to be explored

Longitudinal and transverse CBI due to HOMs: Higgs at calibration energy



$E_b = 45.6$ GeV

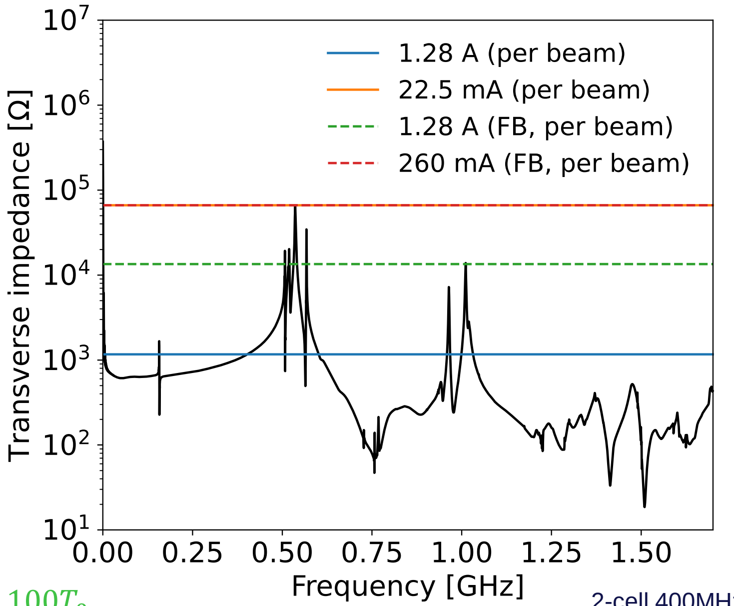
$\tau = \tau_{SR}, \tau_{FB}$

$$Z_{\parallel}^{\text{th}}(f) = \frac{2E_b Q_s}{eI_{b,\text{DC}}\eta\tau}\frac{1}{f}$$

$$Z_{\perp}^{\text{th}} = \frac{E_b}{ef_{\text{rev}}I_{b,\text{DC}}\beta_{xy}\tau}$$

$\tau_{FB,l} = \frac{2T_0}{Q_s}$

$\tau_{FB,t} = 100T_0$



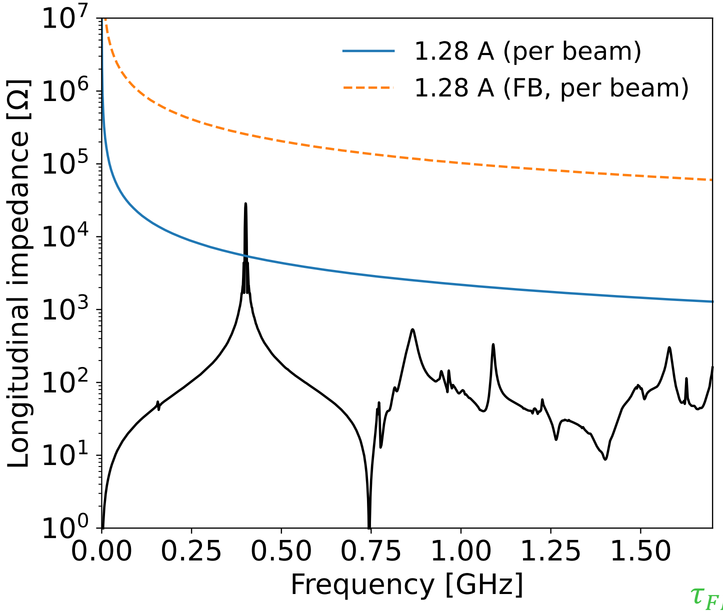
2-cell 400MHz
S. Gorgi Zadeh

	τ_{SR}	τ_{FB}	
I_{max}	nominal	nominal	(per beam)

	τ_{SR}	τ_{FB}	
I_{max}	22.5 mA	260 mA	(per beam)

- Limit instabilities → need safety margin (a factor of 3-10) → even lower current required
- Transverse stability is the main concern → more aggressive FB systems need to be explored
- Due to lower impedance, maximum current larger than for ttbar

Longitudinal and transverse CBI due to HOMs: W at calibration energy



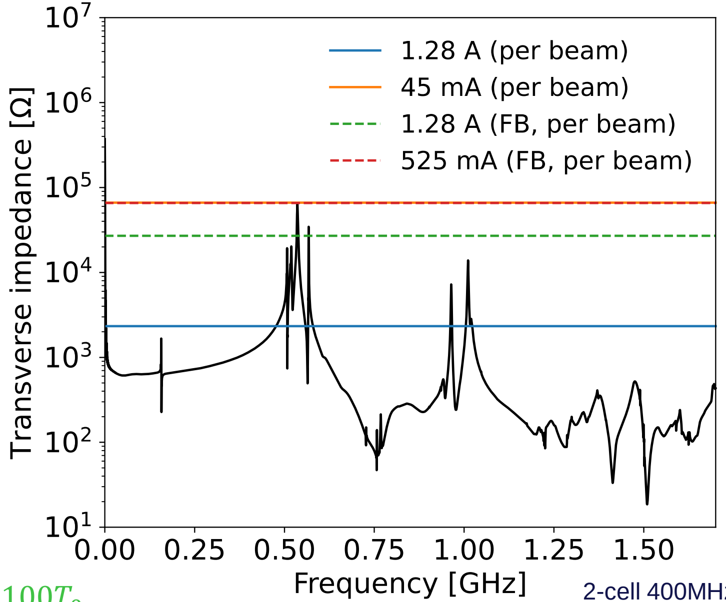
$$E_b = 45.6\ \text{GeV}$$

$$\tau = \tau_{SR}, \tau_{FB}$$

$$Z_{\parallel}^{\text{th}}(f) = \frac{2E_b Q_s}{eI_{b,\text{DC}}\eta\tau}\frac{1}{f}$$

$$Z_{\perp}^{\text{th}} = \frac{E_b}{ef_{\text{rev}}I_{b,\text{DC}}\beta_{xy}\tau}$$

$$\tau_{FB,l} = \frac{2T_0}{Q_s} \qquad \tau_{FB,t} = 100T_0$$



2-cell 400MHz
S. Gorgi Zadeh

	τ_{SR}	τ_{FB}
I_{max}	nominal	nominal

(per beam)

	τ_{SR}	τ_{FB}
I_{max}	45 mA	525 mA

(per beam)

- Limit instabilities → need safety margin (a factor of 3-10)
- Higher current allowed due to less cavities

Summary

- FCC circumference further reduced from 2022, current design $C_{FCC} = 90658.154$ m
- Following the collider parameters update, the 800 MHz RF voltage was optimised
- At calibration energy (Z mode 45.6 GV), the maximum current allowed are (without margin):

Longitudinal

I_{max}	τ_{SR}	τ_{FB}
$ttbar$	20 mA	1 A
$Higgs$	nominal	nominal
W	nominal	nominal

Transverse

I_{max}	τ_{SR}	τ_{FB}
$ttbar$	0.9 mA	10 mA
$Higgs$	22.5 mA	260 mA
W	45 mA	525 mA

- Feasibility of more aggressive feedback should be explored
- Maximum current might be further reduced after analysis of:
  - Stability limits due to fundamental mode impedance
  - RF power limits due to beam loading
  - Higher-order modes power losses

Thank you
for your attention.

Additional Slides

2 cell vs 5 cell impedance dominance

Impedance largely dominated by 5-cell 800 MHz (red curve) vs 2-cell 400 MHz (black curve)