FCC circumference constraints from the injectors and the RF system

Linhao Zhang, Heiko Damerau, Ivan Karpov

31/05/2022

FCC week 2022

30 May – 03 June, Paris, France

Outline

- Introduction
- Starting point
- Baseline FCC-hh harmonic @ 400 MHz
- Alternative FCC-hh harmonic @ 500 MHz
- Summary

Introduction

Synchronization principle for **hadron** synchrotrons

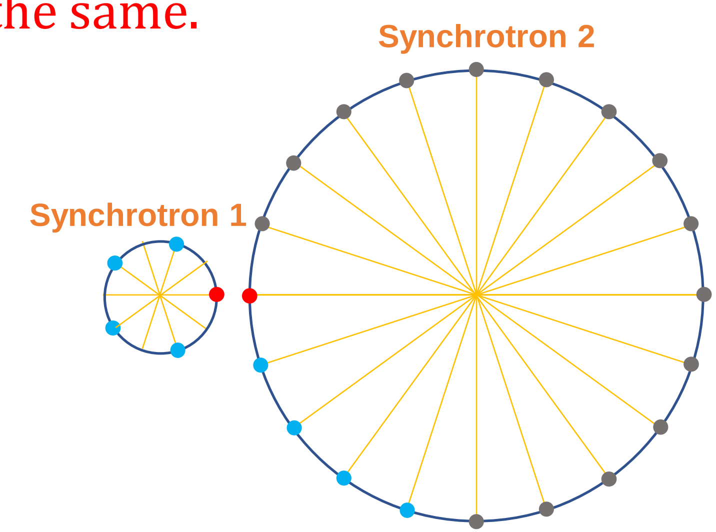
- Basic principle: velocity during transfer is the same.

$$\frac{C_2}{C_1} = \frac{v \cdot T_{rev,2}}{v \cdot T_{rev,1}} = \frac{f_{rev,1}}{f_{rev,2}} = \frac{n_1}{n_2}$$

$$f_{rev} = \frac{f_{RF}}{h}$$

Assume $f_{RF,1} = f_{RF,2}$

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



$T_{rev,1,2}$ -- revolution periods
$h_{1,2}$ -- harmonic numbers
$C_{1,2}$ -- circumference

- $n_{1,2}$ integers should be kept as small as possible
- Transfer is allowed every $n_2 \cdot T_{\mathrm{rev},2}$

Examples

➢ SPS to LHC transfer $27 \cdot T_{rev,SPS} = 7 \cdot T_{rev,LHC}$

Previous presentations see:

✓148th FCC-ee Optics Design Meeting & 19th FCCIS WP2.2 Meeting (I. Karpov, H. Damerau)
✓FCC-ee parameters meeting # 08 (H. Damerau, I. Karpov, L.H. Zhang)
✓FCC-ee parameters meeting # 09 (H. Damerau, I. Karpov, L.H. Zhang)
✓Discussion on the FCC circumference constraints from the injectors and the RF system (H. Damerau, I. Karpov, L.H. Zhang)

Starting point

- ❑ **Keep the possibility of SPS & LHC as potential injectors**
- ❑ **Proposed FCC circumference: 91172.7 m (PA31-1.0)**
- ❑ **LHC RF frequency ~400.79 MHz was initial baseline option for FCC-hh**

	Circumference (m)	Harmonic number (400.79 MHz)
FCC	91172.7 (intended)	2x4x4x13x293 **= 121888**
LHC	$2\pi\cdot$**11**$\cdot 100\cdot$**27/7**= 26658.7	2x3x4x5**x11**x**3x9** = 35640
SPS	$2\pi\cdot$**11**$\cdot 100$ = 6911.5	2x3x4x5**x11**x**7** = 4620x2

- **Why is 121888 unfavourable harmonic number?**
  - **No continuous bunch clock for 25 ns spacing**
  - **Not suited for synchronous transfer (h_{FCC}/h_{LHC} = 15236/4455)**
- **Note that the ratio of harmonic numbers of LHC and SPS is 27/7 (fixed), which comes from the ratio of circumferences of LHC and SPS**
- **Note that the factor 11 in the harmonic numbers of SPS and LHC comes from the ratio of circumference of SPS and PS, which will be not a constraint assuming PS replacement as FCC-hh pre-injector**

Baseline FCC-hh harmonic

- **Fixed RF frequency: 400.79 MHz**

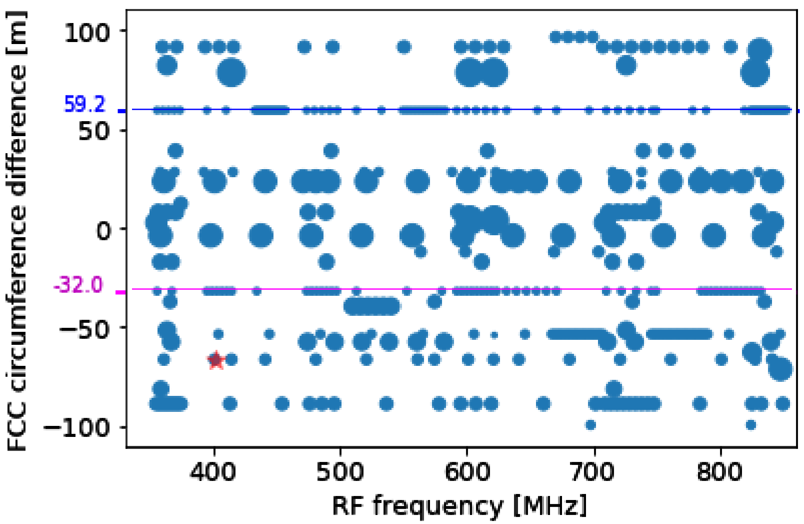
	Circumference (m)	Harmonic number (400.79 MHz)
FCC	91106.187 (shorted by 66.5 m)	2x3x4x5**x5x7x29 = 121800**
LHC	$2\pi\cdot$**11**$\cdot 100\cdot$**27/7**= 26658.7	2x3x4x5**x11**x**3x9** = 35640
SPS	$2\pi\cdot$**11**$\cdot 100$ = 6911.5	2x3x4x5**x11**x**7** = 4620x2

- **The pros and cons of h_{FCC} = 121800 @ 400.79MHz**

Pros	• **Keep the same RF frequency as LHC** • **Continuous bunch clock for experiments for bunch spacings of 2.5, 5.0, 7.5, 10, 12.5, 15, 17.5, 25 ns** • **PS can still be possible as FCC-hh pre-injector**
Cons	• **LHC-to-FCC transfer wait time may be a little long (297 turns in FCC, corresponding to ~90.2 ms)** • **The prime number of 29 in the division ratios relatively large**

Why stick to f_{RF} = 400.79 MHz?

- **Scanned h_{LHC} from 30000 to 76000, f_{RF}: 337 ~ 854 MHz**
  - → **Scaling laws: h_{LHC}=35640 + 27*n, h_{SPS}=2*4620 + 7*n**
- **Requirements and assumptions:**
  - → **h_{FCC} dividable by 2 (sufficient for 4 IPs);**
  - → **$\Delta C_{FCC} < \pm 100$ m;**
  - → **Largest prime factor** in the factorization of FCC/LHC/SPS harmonic number **< 200;**
  - → **Denominator in h_{FCC} / h_{LHC} and h_{FCC} / h_{SPS} < 300**
  - → **Maximum bunch spacing less or close to 25 ns**



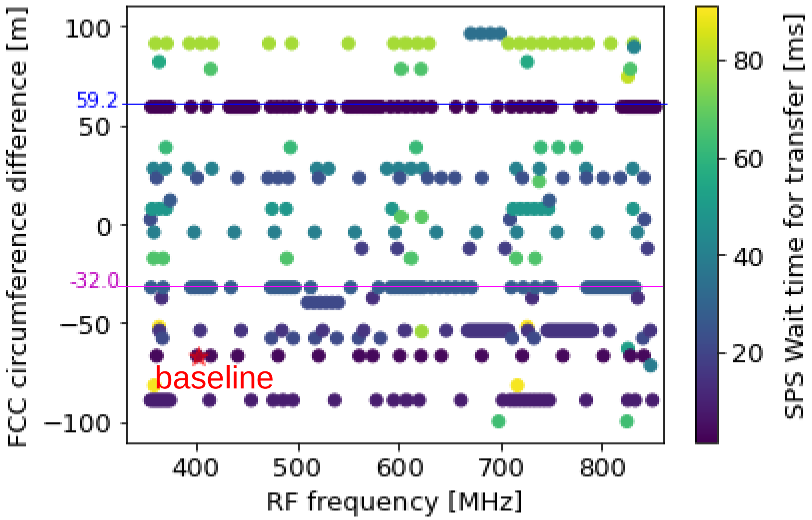
Point size indicates the largest prime factor

Flexible option for RF frequency

Small largest prime factor

Why stick to f_{RF} = 400.79 MHz?

- **Scanned h_{LHC} from 30000 to 76000, f_{RF}: 337 ~ 854 MHz**
  - → **Scaling laws: h_{LHC}=35640 + 27*n, h_{SPS}=2*4620 + 7*n**
- **Requirements and assumptions:**
  - → **h_{FCC} dividable by 2 (sufficient for 4 IPs);**
  - → **ΔC_{FCC} < ±100 m;**
  - → **Largest prime factor** in the factorization of FCC/LHC/SPS harmonic number **< 200;**
  - → **Denominator in h_{FCC} / h_{LHC} and h_{FCC} / h_{SPS} < 300**
  - → **Maximum bunch spacing less or close to 25 ns**

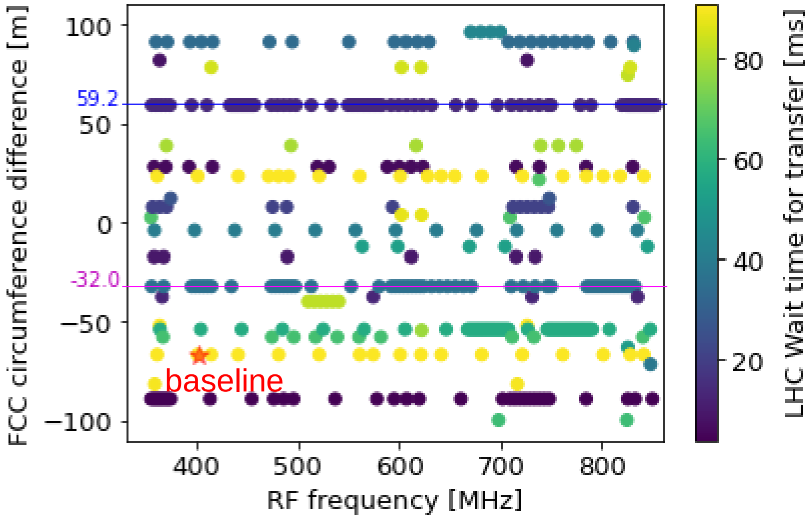


Flexible option for RF frequency

Small largest prime factor

Why stick to f_{RF} = 400.79 MHz?

- **Scanned h_{LHC} from 30000 to 76000, f_{RF}: 337 ~ 854 MHz**
  - → **Scaling laws: h_{LHC}=35640 + 27*n, h_{SPS}=2*4620 + 7*n**
- **Requirements and assumptions:**
  - → **h_{FCC} dividable by 2 (sufficient for 4 IPs);**
  - → **ΔC_{FCC} < ±100 m;**
  - → **Largest prime factor** in the factorization of FCC/LHC/SPS harmonic number **< 200;**
  - → **Denominator in h_{FCC} / h_{LHC} and h_{FCC} / h_{SPS} < 300**
  - → **Maximum bunch spacing less or close to 25 ns**



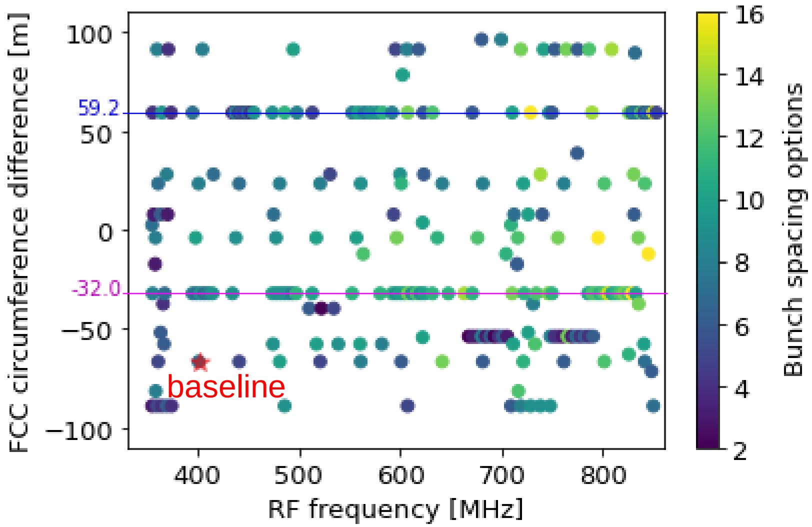
Flexible option for RF frequency

Small largest prime factor

Short wait time for transfer

Why stick to f_{RF} = 400.79 MHz?

- **Scanned h_{LHC} from 30000 to 76000, f_{RF}: 337 ~ 854 MHz**
  - → **Scaling laws: h_{LHC}=35640 + 27*n, h_{SPS}=2*4620 + 7*n**
- **Requirements and assumptions:**
  - → **h_{FCC} dividable by 2 (sufficient for 4 IPs);**
  - → **$\Delta C_{FCC} < \pm 100$ m;**
  - → **Largest prime factor** in the factorization of FCC/LHC/SPS harmonic number **< 200;**
  - → **Denominator in h_{FCC} / h_{LHC} and h_{FCC} / h_{SPS} < 300**
  - → **Maximum bunch spacing less or close to 25 ns**



Flexible option for RF frequency

Small largest prime factor

Short wait time for transfer

Many bunch spacings possible

Attractive alternative

	Circumference (m)	Harmonic number (497.34 MHz)
FCC	91140.710 (shorted by 32.0 m)	$2 \times 3^3 \times 7 \times 4 \times 5 \times 4 \times 5$ = **151200**
LHC	$2\pi \cdot \mathbf{11} \cdot 100 \cdot \mathbf{27/7}$ = 26658.7	$2 \times 3^2 \times 7 \times \mathbf{13} \times \mathbf{3^3}$ = 44226
SPS	$2\pi \cdot \mathbf{11} \cdot 100$ = 6911.5	$2 \times 3^2 \times 7 \times \mathbf{13} \times \mathbf{7}$ = 5733x2

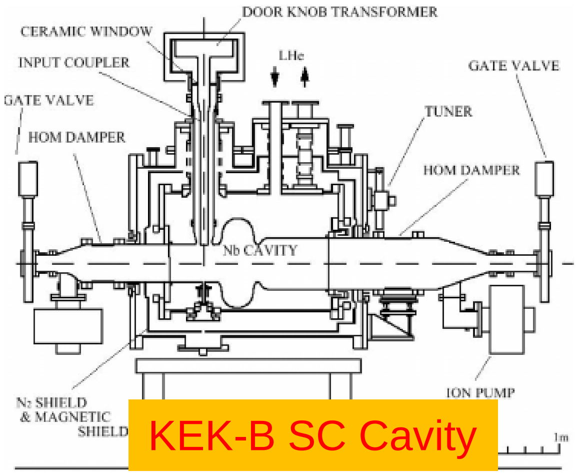
- **The pros and cons of h_{FCC}=151200 @ 497.34** MHz

Pros	• **More flexible native bunch spacings 2.01, 4.02, 6.03, 8.04, 10.05, 12.06, 14.07, 16.09, 18.10, 20.11, 24.13 ns** • **LHC-to-FCC or SPS-to-FCC transfer wait times are favorably small: 35.5 ms or 27.6 ms** • **The corresponding circumference allows many other RF frequencies** • **The largest prime factor (13) small** • **Robust optimum, also for larger max. bunch spacing (e.g. 25 → 50 ns)**
Cons	• **Requires new RF systems for SPS and/or LHC** • **Exact bunch spacings like 25 ns proposed in FCC-hh CDR need to vary** • **PS needs to be replaced as FCC-hh pre-injector**

500 MHz RF system

- **Advantage of 500 MHz**
  - **Smaller cavity size**
  - **More beneficial to single bunch stability (for FCC-hh)** [Discussion on the FCC circumference constraints from the injectors and the RF system (April 26, 2022) · Indico (cern.ch)]
  - **Higher break down voltage, higher gradient**
- **Consequence:**
  - **Need new RF systems in SPS/LHC**
- **Examples using 500 MHz RF system**
  - **Mainly in Electron Storage Ring**
  - **TPS, SLS, BESSY… (synchrotron radiation light sources)**
  - **CESR, KEK-B, BEPCII…(electron-positron colliders)**

Taiwan Photon Source (TPS)



KEK-B SC Cavity

Summary

Scheme	Baseline	Alternative
RF frequency [MHz]	400.79	497.34
C_{FCC} [m]	91106.187	91140.710
h_{FCC}	121800	151200
RF system	based on LHC	new
Bunch spacing [ns]	2.5, 5.0, 7.5, 10, 12.5, 15, 17.5, 25 (proposed in FCC-hh CDR)	2.01, 4.02, 6.03, 8.04, 10.05, 12.06, 14.07, 16.09, 18.1, 20.11, 24.13 (More flexible)
LHC-to-FCC transfer	297 revolutions in FCC	117 revolutions in FCC
SPS-to-FCC transfer	11 revolutions in FCC	91 revolutions in FCC
FCC-hh pre-injector	allows PS (1959!)	new
Largest prime factor	29	13

- Baseline scheme of FCC-hh circumference and RF frequency basically meets all requirements proposed in CDR
- Attractive alternative option could offer more flexibility

Thanks for your attention!

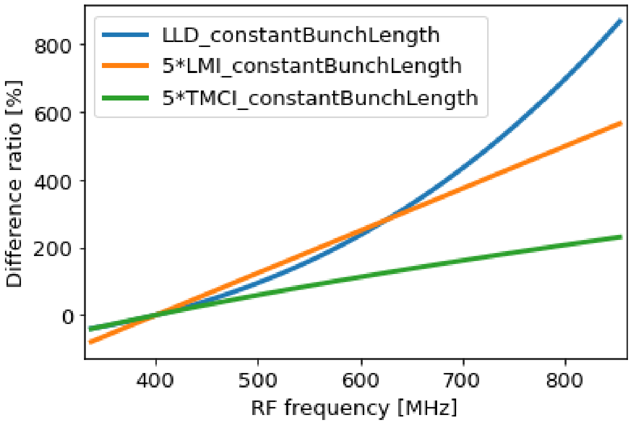
Spare slides

Impact of RF frequency on beam dynamics

- From single bunch instability point of view:
  - Loss of Landau damping[1]:

$$N_p = -\frac{V_0 cos\phi_{s0}}{q\omega_0 \mathrm{Im}\, Z/k} \frac{\pi\phi_{max}^4}{32\mu(\mu+1)hk_{max}} \propto \frac{(h\tau)^4}{h} = h^3\tau^4$$

→ $N_p \propto h^3\tau^4$ for a constant bunch length
→ $N_p \propto h^2$ for a constant longitudinal emittance



  - Longitudinal microwave instability[2]:

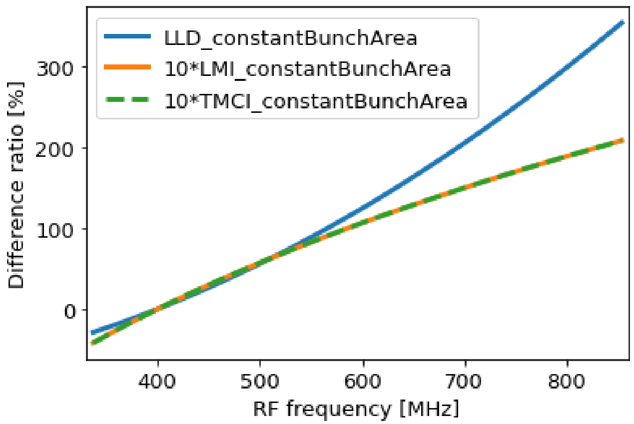
$$N_p = \frac{3\pi}{q\omega_0} \frac{hV_0}{|(Z_L/n)_{eff}|} \left(\frac{L}{2\pi R}\right)^3 \propto h\tau^3$$

→ $N_p \propto h\tau^3$ for a constant bunch length
→ $N_p \propto h^{1/4}$ for a constant longitudinal emittance

  - Transverse mode coupling instability[2]

$$N_p = \frac{4\pi}{q\omega_0} \frac{Q_s E/q}{\beta_{av} \mathrm{Im}(Z_T)_{\mathrm{eff}}} \frac{L}{R} \propto h^{1/2}\tau$$

→ $N_p \propto h^{1/2}\tau$ for a constant bunch length
→ $N_p \propto h^{1/4}$ for a constant longitudinal emittance

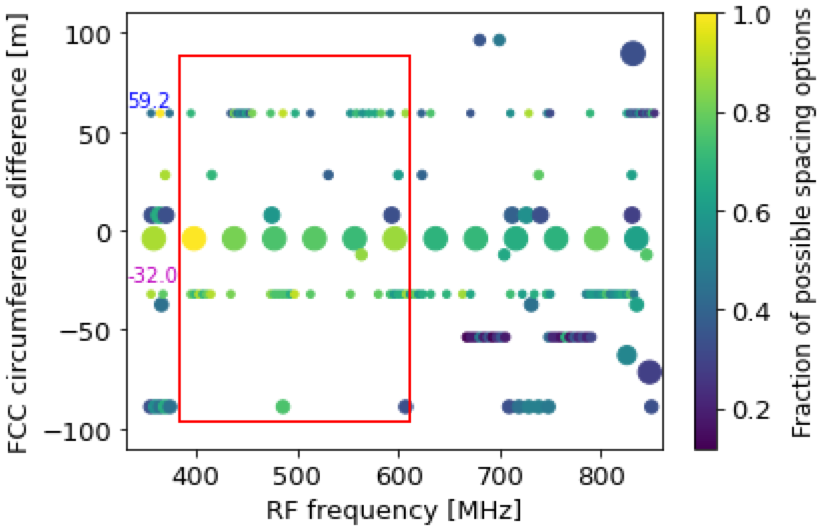


⇒ Higher harmonic number seems more beneficial to a higher bunch intensity

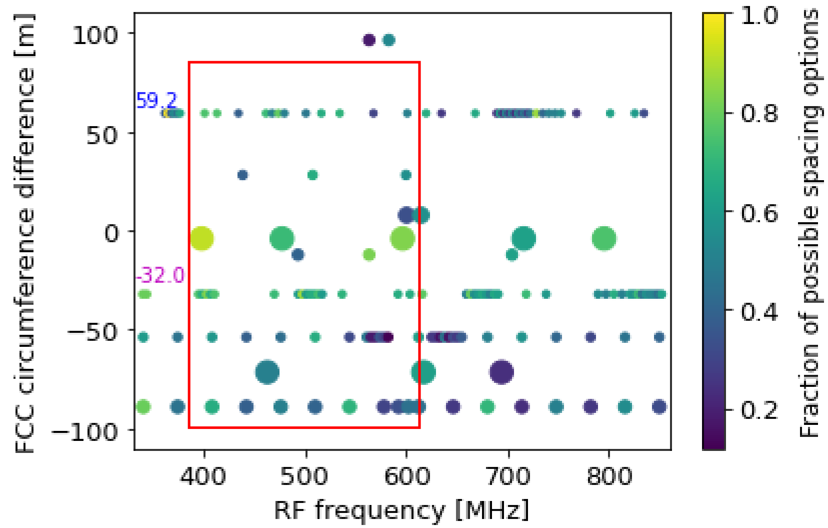
[1] Ivan Karpov, Theodoros Argyropoulos, and Elena Shaposhnikova, Phys. Rev. Accel. Beams **24**, 011002 (2021)
[2] Francesco Ruggiero, Single-Beam Collective Effects in the LHC, CERN SL/95-09 (AP)

Results for different $\tau_{spacing,max}$

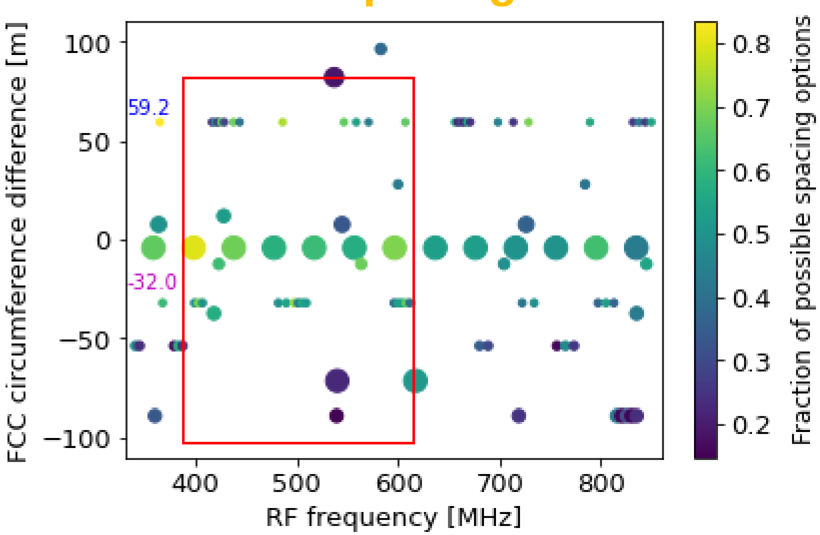
Max. bunch spacing < 25.5 ns



Max. bunch spacing < 30.5 ns



Max. bunch spacing < 50.5 ns

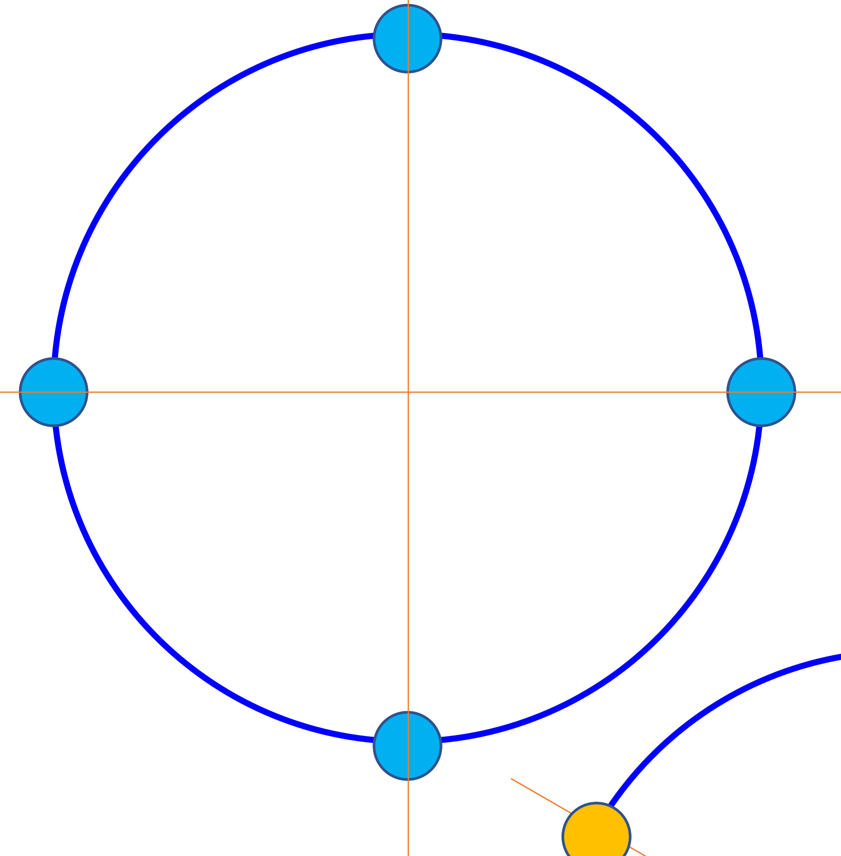


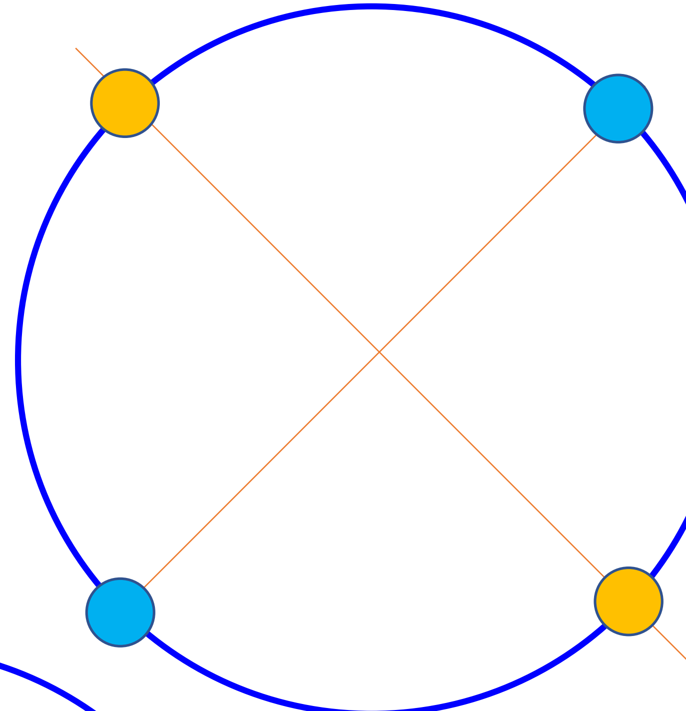
From 'Fraction of possible bunch spacing options' point of view, preferable frequency range:

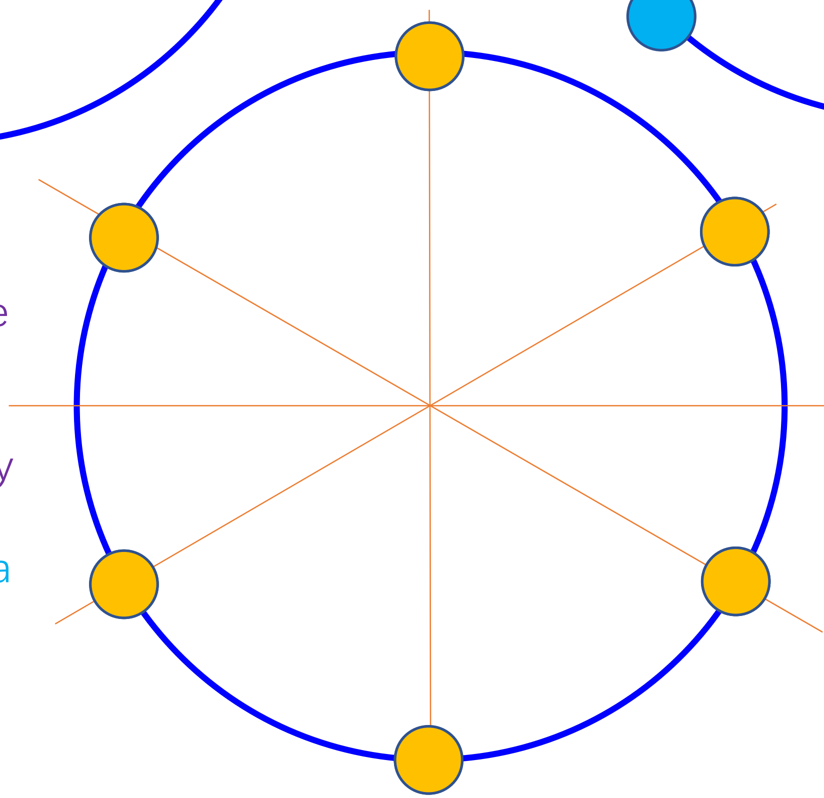
400 ~ 600 MHz

Comparison for different $\tau_{spacing,max}$

RF frequency (MHz)	Bunch spacings ≤ 25.5 [ns]	Percentage of possible spacings	Bunch spacings ≤ 30.5 [ns]	Percentage of possible spacings	Bunch spacings ≤ 50.5 [ns]	Percentage of possible spacings
364.35	2.74, 5.49, 8.23, 10.98, 13.72, 16.47, 19.21, 21.96, 24.70	**9/9 = 100%**	2.74, 5.49, 8.23, 10.98, 13.72, 16.47 19.21, 21.96, 24.7, 27.45, 30.19]	**11/11 = 100%**	[2.74, 5.49, 8.23, 10.98, 13.72, 16.47, 19.21, 21.96, 24.7, 27.45, 30.19, 32.94, 38.42, 41.17, 49.4]	**15/18 = 83.3%**
400.79	2.5, 5.0,7.5, 12.5, 15, 17.5, 25	**7/10 = 70%**	2.5, 5.0,7.5, 12.5, 15, 17.5, 25	**7/12 = 58.3%**	[2.5, 4.99, 7.49, 12.48, 14.97, 17.47, 24.95, 34.93, 37.43]	**9/20 = 45%**
497.34	**[2.01 4.02 6.03 8.04 10.05 12.06 14.07 16.09 18.1 20.11, 24.13]**	**11/12 = 91.7%**	**[2.01, 4.02, 6.03, 8.04, 10.05, 12.06 14.07, 16.09, 18.1, 20.11, 24.13, 28.15, 30.16]**	**13/15 = 86.7%**	**[2.01, 4.02, 6.03, 8.04, 10.05, 12.06, 14.07, 16.09, 18.1, 20.11, 24.13, 28.15, 30.16, 36.19, 40.21, 42.22, 48.26, 50.27]**	**18/25 = 72%**
563.54	[1.77, 3.55, 5.32, 7.1, 8.87, 10.65, 12.42, 14.2, 15.97, 17.74, 21.29, 24.84]	12/14 = 85.7%	[1.77, 3.55, 5.32, 7.1, 8.87, 10.65, 12.42, 14.2, 15.97, 17.74, 21.29, 24.84 26.62, 30.17]	14/17 = 82.3%	[1.77, 3.55, 5.32, 7.1, 8.87, 10.65, 12.42, 14.2, 15.97, 17.74, 21.29, 24.84, 26.62, 30.17, 31.94, 35.49, 37.26, 42.59, 49.69]	19/28 = 67.9%
607.26	[1.65, 3.29, 4.94, 6.59, 8.23, 9.88, 11.53, 13.17, 16.47, 18.11, 19.76, 23.05, 24.7]	13/15 = 86.7%	[1.65, 3.29, 4.94, 6.59, 8.23, 9.88, 11.53, 13.17, 16.47, 18.11, 19.76, 23.05, 24.7]	13/18 = 72.2%	[1.65, 3.29, 4.94, 6.59, 8.23, 9.88, 11.53, 13.17, 16.47, 18.11, 19.76, 23.05, 24.7, 32.93, 34.58, 36.23, 39.52, 41.17, 46.11, 49.4]	20/30 = 66.7%
607.86	[1.65, 3.29, 4.94, 6.58, 8.23, 9.87, 11.52, 13.16, 16.45, 18.1, 19.74, 23.03, 24.68]	13/15 = 86.7%	[1.65, 3.29, 4.94, 6.58, 8.23, 9.87, 11.52, 13.16, 16.45, 18.1, 19.74, 23.03 24.68]	13/18 = 72.2%	[1.65, 3.29, 4.94, 6.58, 8.23, 9.87, 11.52, 13.16, 16.45, 18.1, 19.74, 23.03, 24.68, 32.9, 34.55, 36.19, 39.48, 41.13, 46.06, 49.35]	20/30 = 66.7%
728.71	[1.37, 2.74, 4.12, 5.49, 6.86, 8.23, 9.61, 10.98, 12.35, 13.72, 15.1, 16.47, 19.21, 20.58, 21.96, 24.7]	**16/18 = 88.8%**	[1.37, 2.74, 4.12, 5.49, 6.86, 8.23, 9.61, 10.98, 12.35, 13.72, 15.1, 16.47, 19.21, 20.58, 21.96, 24.7, 27.45, 28.82, 30.19]	**19/22 = 86.4%**	[1.37, 2.74, 4.12, 5.49, 6.86, 8.23, 9.61, 10.98, 12.35, 13.72, 15.1, 16.47, 19.21, 20.58, 21.96, 24.7, 27.45, 28.82, 30.19, 32.93, 38.42, 41.17, 45.29, 48.03, 49.4]	**25/36 = 69.4%**
805.22	[1.24, 2.48, 3.73, 4.97, 6.21, 7.45, 9.94, 11.18, 12.42, 14.9, 18.63, 19.87, 21.11, 22.35, 24.84]	**15/20 = 75%**	[1.24, 2.48, 3.73, 4.97, 6.21, 7.45, 9.94, 11.18, 12.42, 14.9, 18.63, 19.87, 21.11, 22.35, 24.84, 29.81]	**16/24 = 66.7%**	[1.24, 2.48, 3.73, 4.97, 6.21, 7.45, 9.94, 11.18, 12.42, 14.9, 18.63, 19.87, 21.11, 22.35, 24.84, 29.81, 31.05, 37.26, 42.22, 44.71, 49.68]	**21/40 = 52.5%**
828.91	[1.21, 2.41, 3.62, 4.83, 6.03, 7.24, 8.44, 9.65, 10.86, 12.06, 14.48, 16.89, 18.1, 21.72, 24.13, 25.33]	**16/21 = 76.2%**	[1.21, 2.41, 3.62, 4.83, 6.03, 7.24, 8.44, 9.65, 10.86, 12.06, 14.48, 16.89, 18.1, 21.72, 24.13, 25.33, 28.95, 30.16]	**18/25 = 72%**	[1.21, 2.41, 3.62, 4.83, 6.03, 7.24, 8.44, 9.65, 10.86, 12.06, 14.48, 16.89, 18.1, 21.72, 24.13, 25.33, 28.95, 30.16, 33.78, 36.19, 42.22, 43.43, 48.26]	**23/41 = 56.1%**

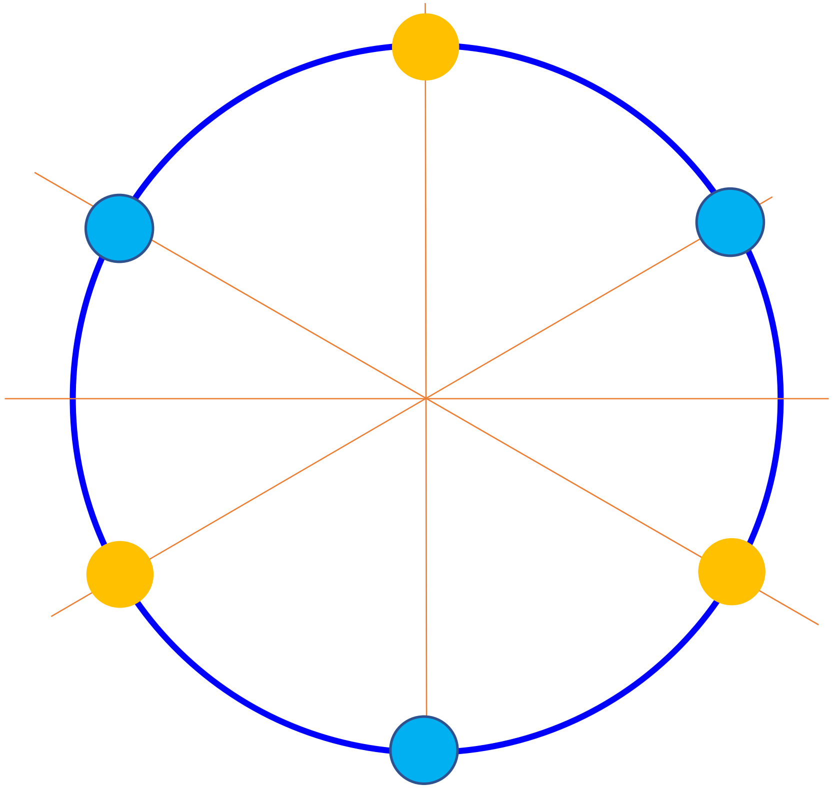






Bunch (trains) must have 4-fold symmetry to make particle collision occurring simultaneously in the 4 IPs; Two-fold symmetry only ensures a pair of IPs out of 4 IPs exist collisions at the same time

Question:
The 4-fold symmetry of bunch trains must require the 4-fold symmetry of the harmonics (or dividable by 4)?



Bunch (trains) must have 4-fold symmetry to make particle collision occurring simultaneously in the 4 IPs; Two-fold symmetry only ensures a pair of IPs out of 4 IPs exist collisions at the same time

Question:
The 4-fold symmetry of bunch trains must require the 4-fold symmetry of the harmonics (or dividable by 4)?