Tentative to do list

- The coupler project.
- Haipeng will send the CST file for the coupler.
- Bench test prep.
- May's cavity model dig up → multi-physics simulations
- Report to Mark, Haipeng, Bob
- ELEGANT simulation
- Jiqun's request for a single tuner action.
- Jiquan's request for error analysis on kicker profile and bunch arrival.
- Jiquan's old request on 4-mode operation (or my scheme).
- FEL study
- Impedance simulation
- XFELO paper
- Gain formula
- Mirror reflection

A Harmonic kicker for the RCS (Rapid Circulating Synchrotron)

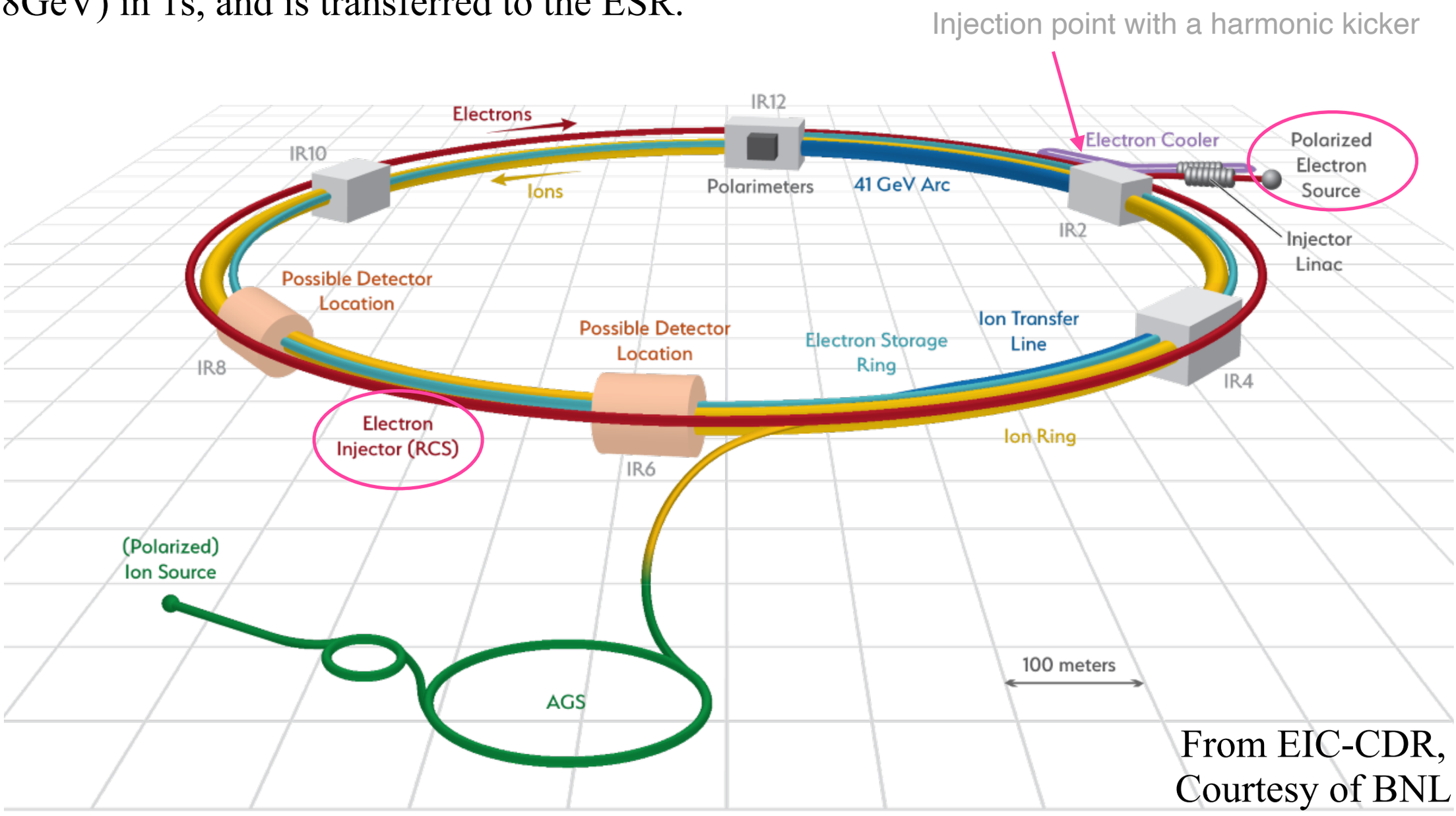
An ultrafast kicker in pulsed mode operation

Gunn Tae Park, Jiquan Guo, and Andrew Hutton, Haipeng Wang

Oct. 20 2020

The overview of the RCS

- A rapid cycling synchrotron (RCS) of the EIC is an electron energy booster while generating electron bunches with high bunch charges by merging the bunches with lower charges.
- Upon completion of an injection cycle, two bunch trains with 4 (or 8 for upgrade) bunches with 7nC bunch charge in each train circulate the RCS @ 400MeV.
- Each train quasi-adiabatically merges to a large bunch with 28nC bunch charge, gets accelerated (to 5-18GeV) in 1s, and is transferred to the ESR.



From EIC-CDR, Courtesy of BNL

The beam parameters of the RCS (I)

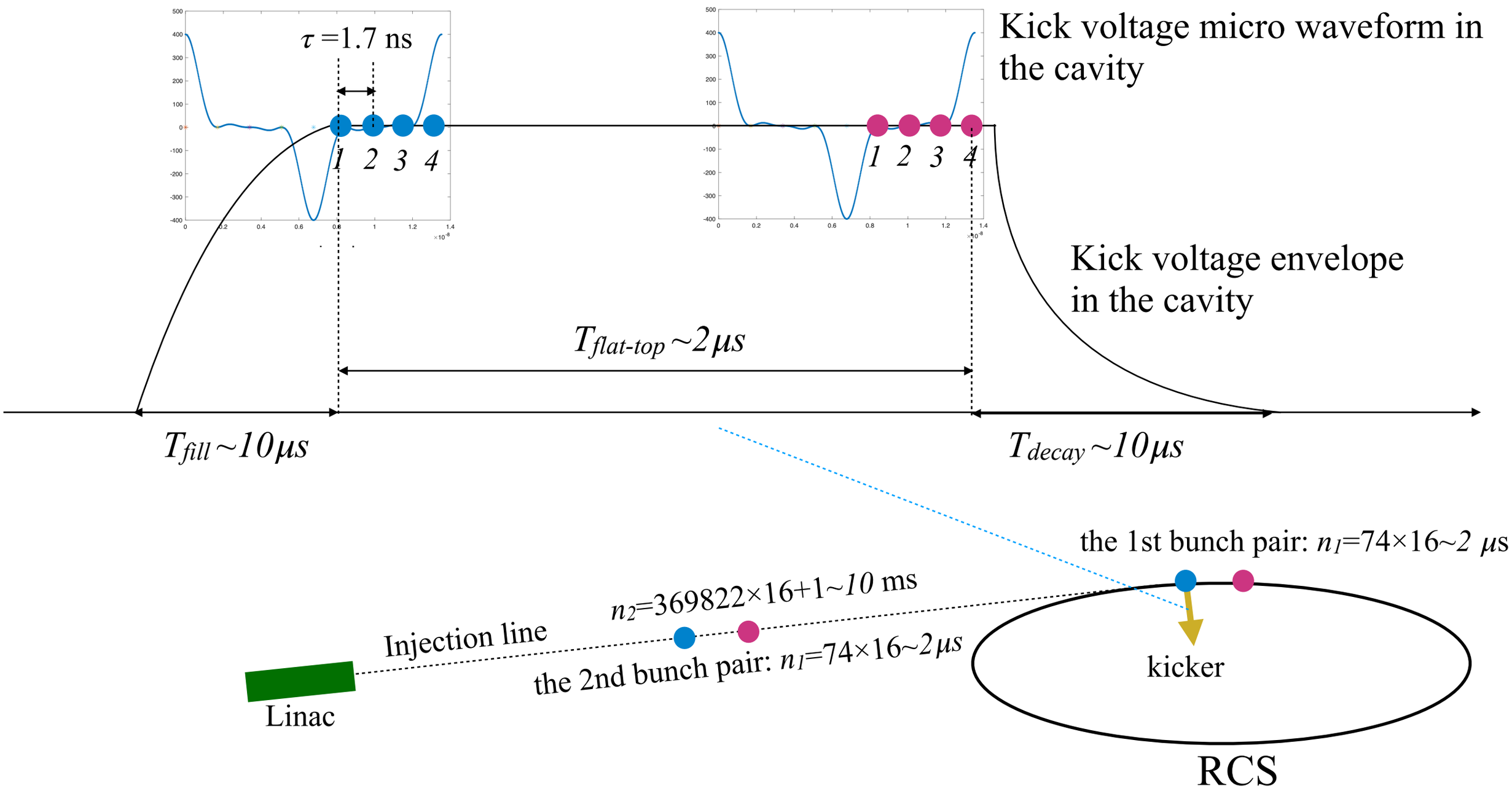
Parameter	Description	Unit	Value
f_b	RF frequency	MHz	591.258
h_n	Harmonic number of the ring	-	7576
L_{RCS}	Circumference	m	3841.35
T_{rev}	Revolution period	μs	12.8
E_{beam}	Beam energy	MeV	400
Q_b	Bunch charge	nC	7
	Longitudinal Bunch distribution	-	Gaussian
l_b	Bunch length	cm	12
δ	*rms* Energy spread	-	2.5×10^{-3}
θ	Kick angle	rad	1
r_a	Beam aperture	mm	40
f_{ramp}	Ramping repetition rate	Hz	1
	Acceleration time	ms, turns	100, 8000

The beam parameters of the RCS (II)

Parameter	Description	Unit	Value
	Transverse Bunch distribution	-	Gaussian
ε^n_x	Horizontal emittance	mm mrad	26
ε^n_y	Vertical emittance	mm mrad	26
α_x	Horizontal Twiss parameter	-	0.81956
β_x	Horizontal Twiss parameter	m	11.137
α_y	Vertical Twiss parameter	-	-2.0339
β_y	Vertical Twiss parameter	m	36.438
η_x	Horizontal dispersion	m	0.6
η'_x	Horizontal dispersion slope	-	0.5
η_y	Vertical dispersion	m	0
η'_y	Vertical dispersion slope	-	0
Q_x	Horizontal tunes	rad	57.632
Q_y	Vertical tunes	rad	60.732

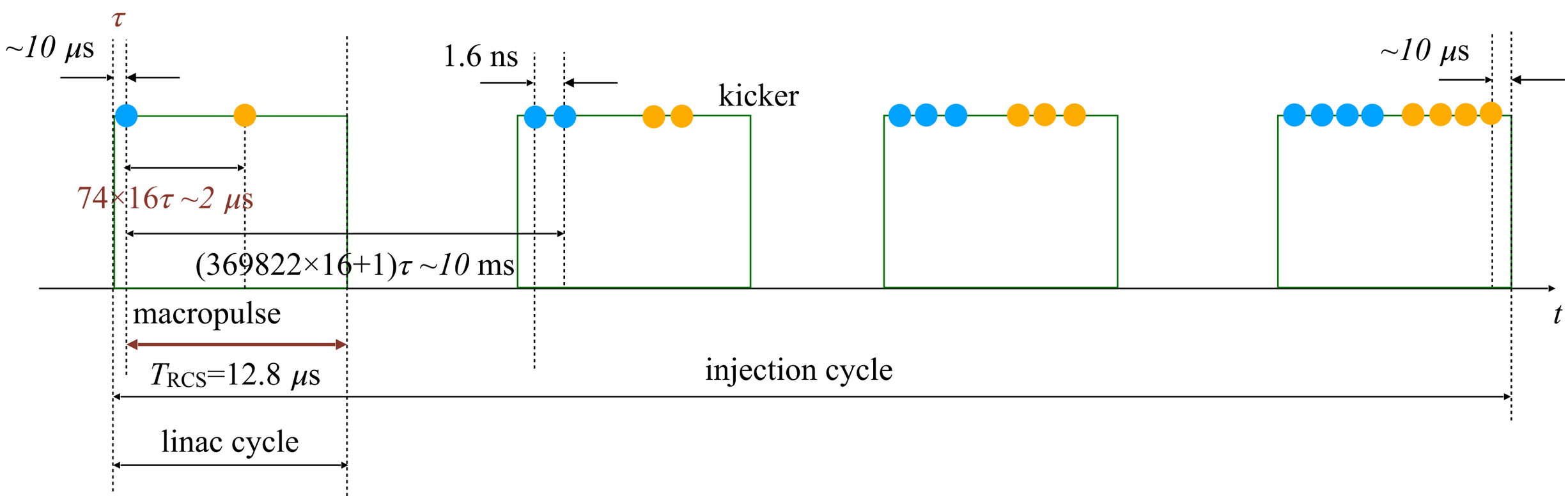
The injection scheme of the RCS

- The injection is done in four steps. In each step, a pair of bunches from the polarized electron source is injected to the two trains (one for each train).



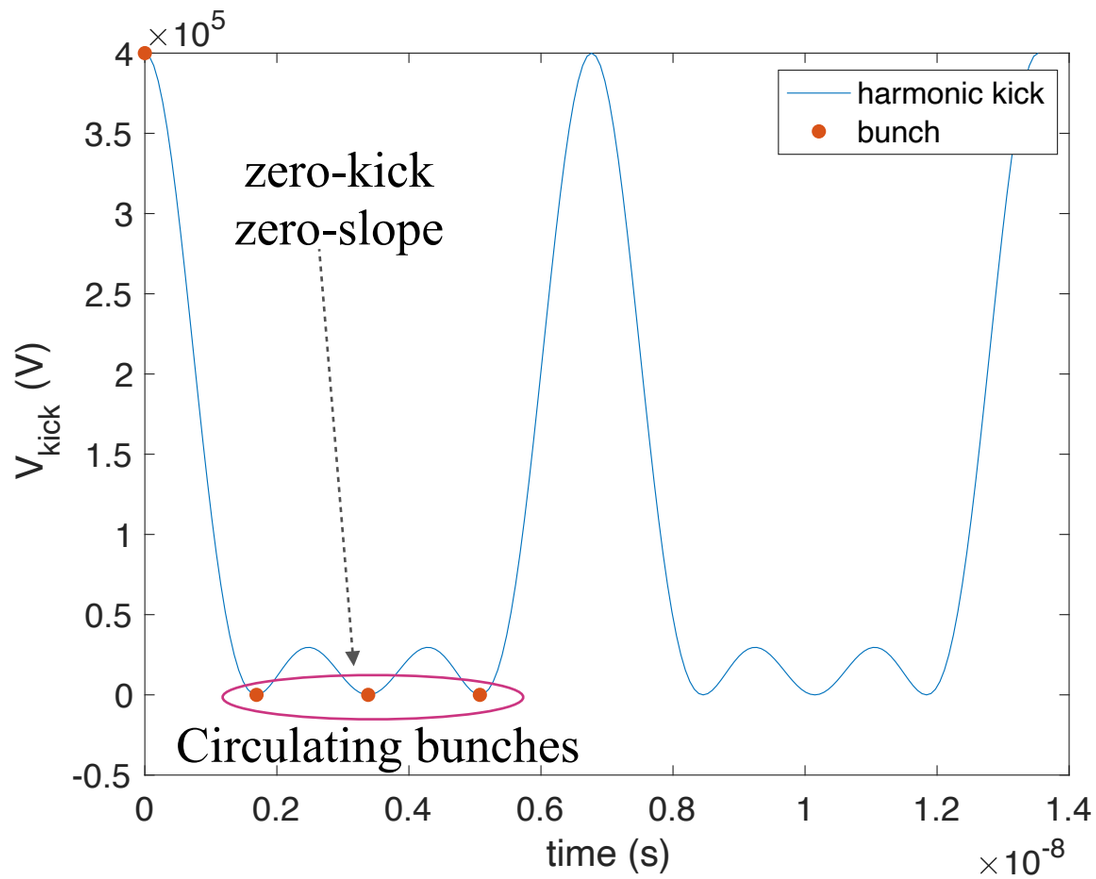
The baseline waveforms in injection

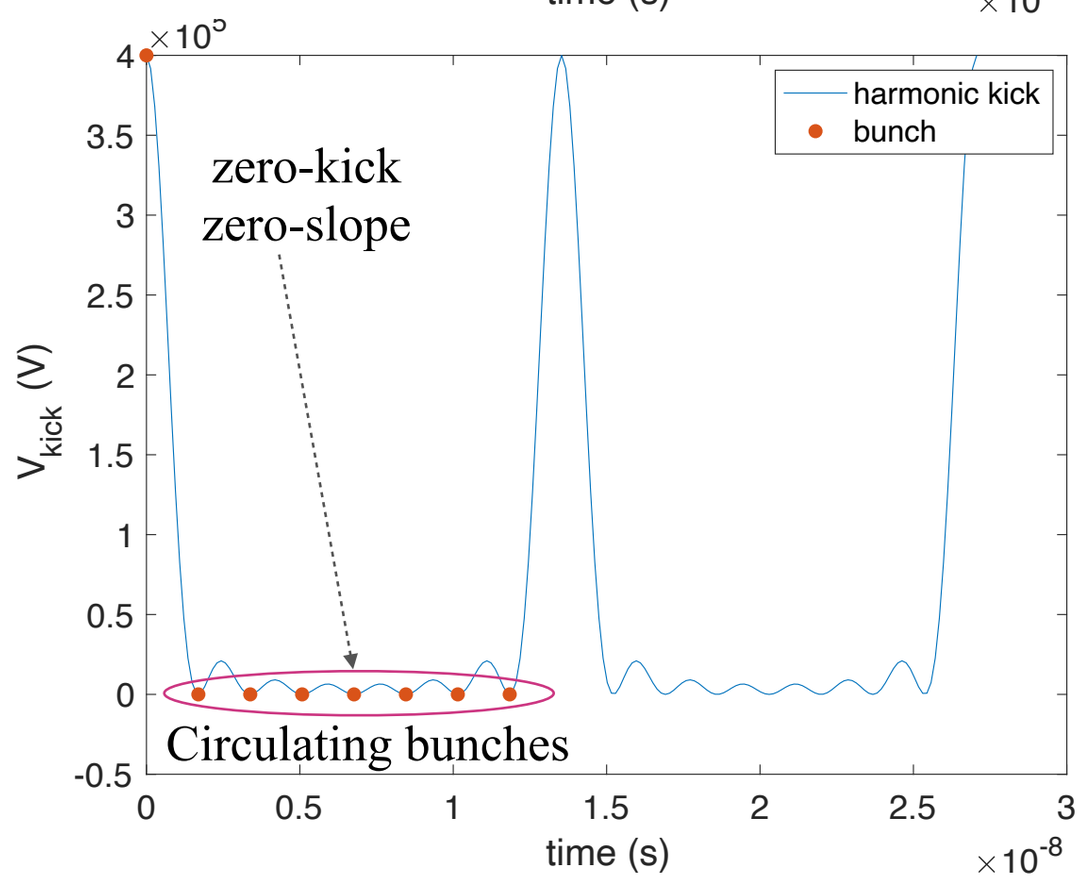
- In each injection cycle, two bunch trains with 4 (or 8 for upgrade) bunches in each train are injected. A pair of bunches are injected to two trains (one for each train) in one linac cycle.



- Injection cycles are separated by 0.5-1*s* to form a ramping cycle.

The baseline waveforms





Harmonic kicker for 4 bunch scheme

Mode	f (MHz)	V (kV)
DC	0	100
1	147.8	150
2	295.5	100
3	433.3	50

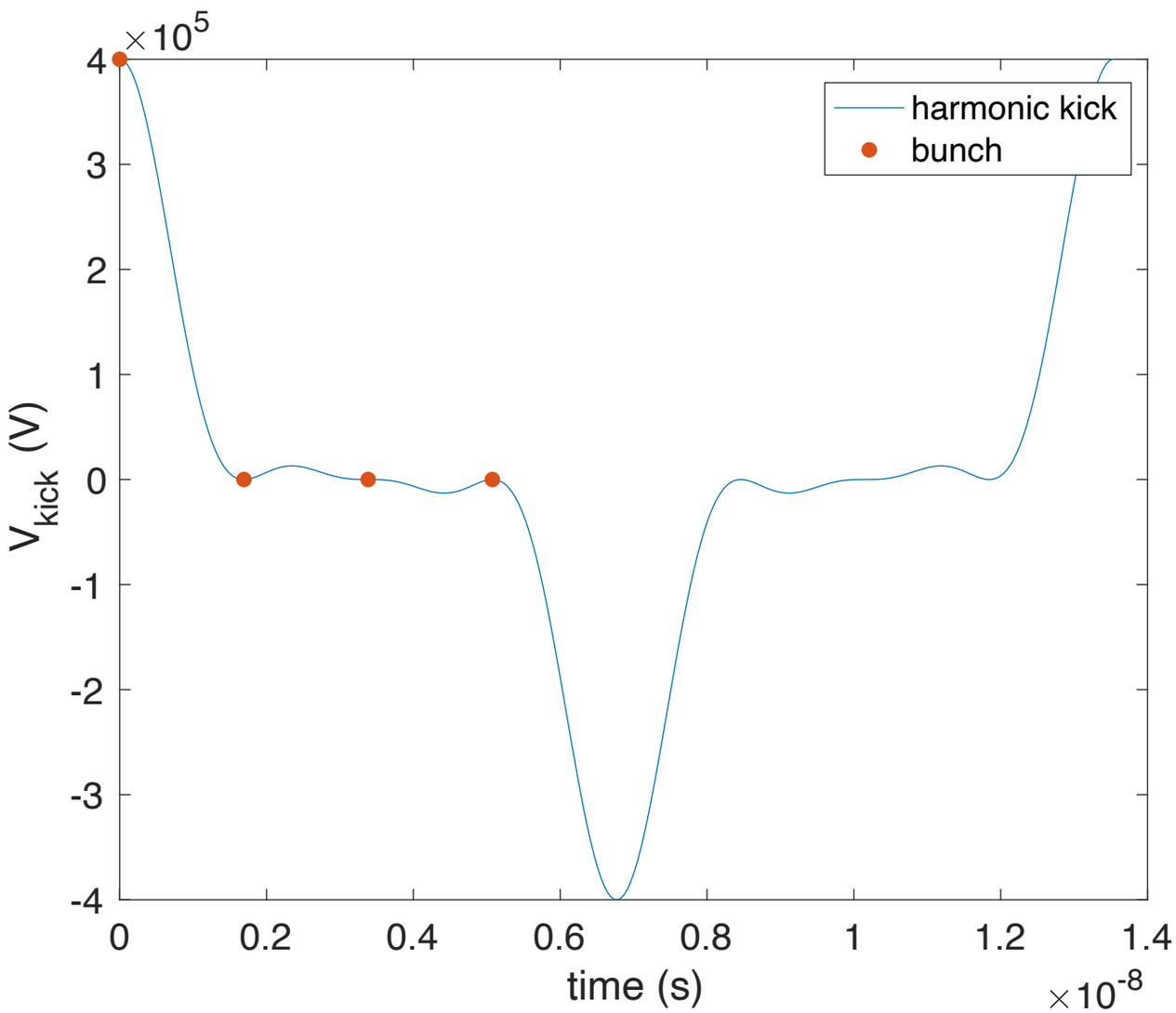
Harmonic kicker for 8 bunch scheme

Mode	f (MHz)	V (kV)
DC	0	50
1	73.9	87.5
2	147.8	75
3	221.6	62.5
4	295.5	50
5	369.4	37.5
6	443.3	25
7	517.1	12.5

The alternative waveforms

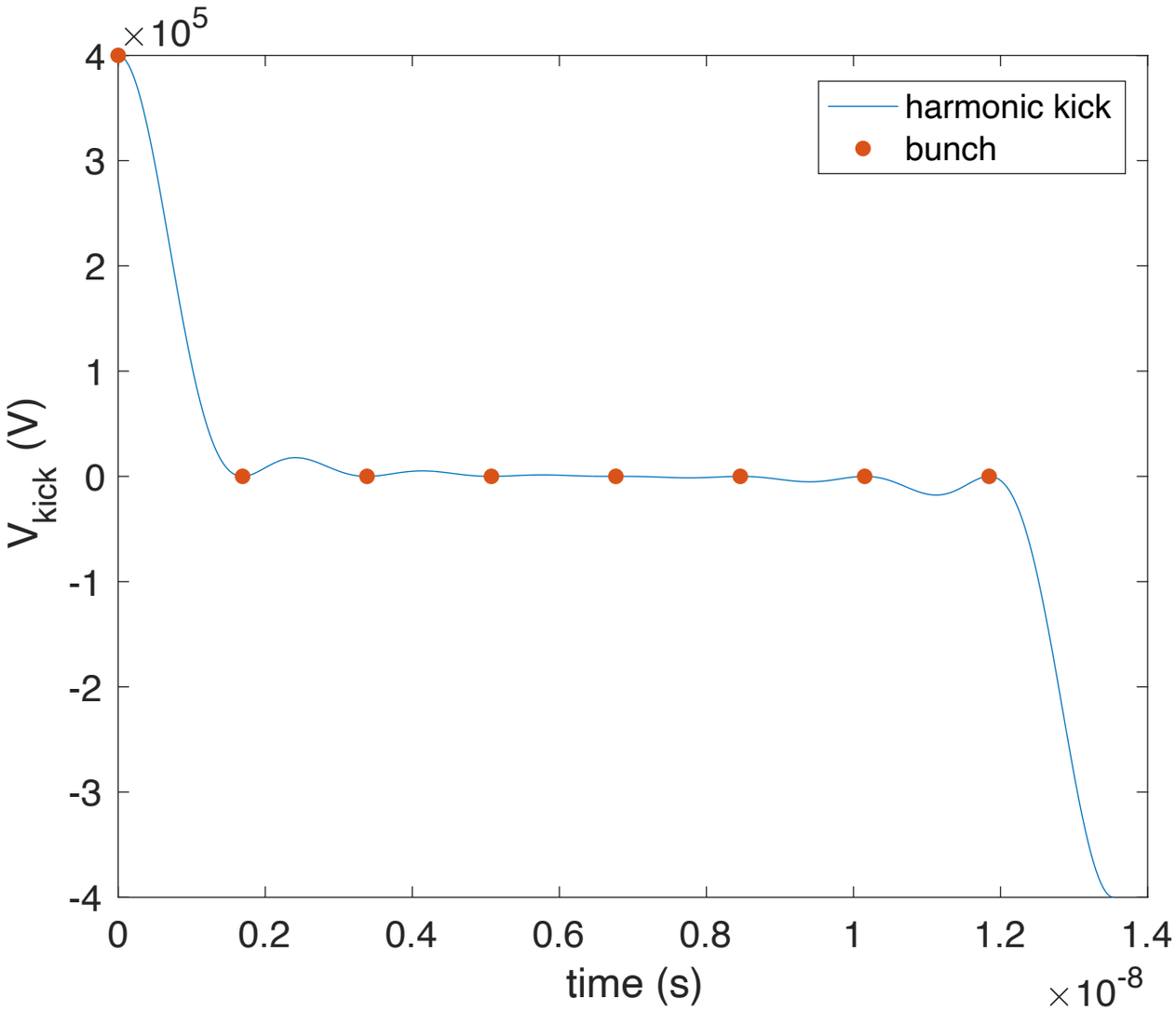
- Because of a large enough gap of 2μs, kick number n_k>=4 is available for 4 bunch injection. With this relaxation, one can have even multiples of *4* as n_k: n_k=8 (for 4 bunch mode) and 16 (for 8 bunch mode).
- Then one can have zero kick and zero-slopes on the passing (circulating) bunches.

- 4 bunch mode option



Modes	Freq. (MHz)	Amp. (kV)
1	73.875	175
3	221.625	125
5	369.375	75
7	517.125	25
-	DC	0

- 8 bunch mode option

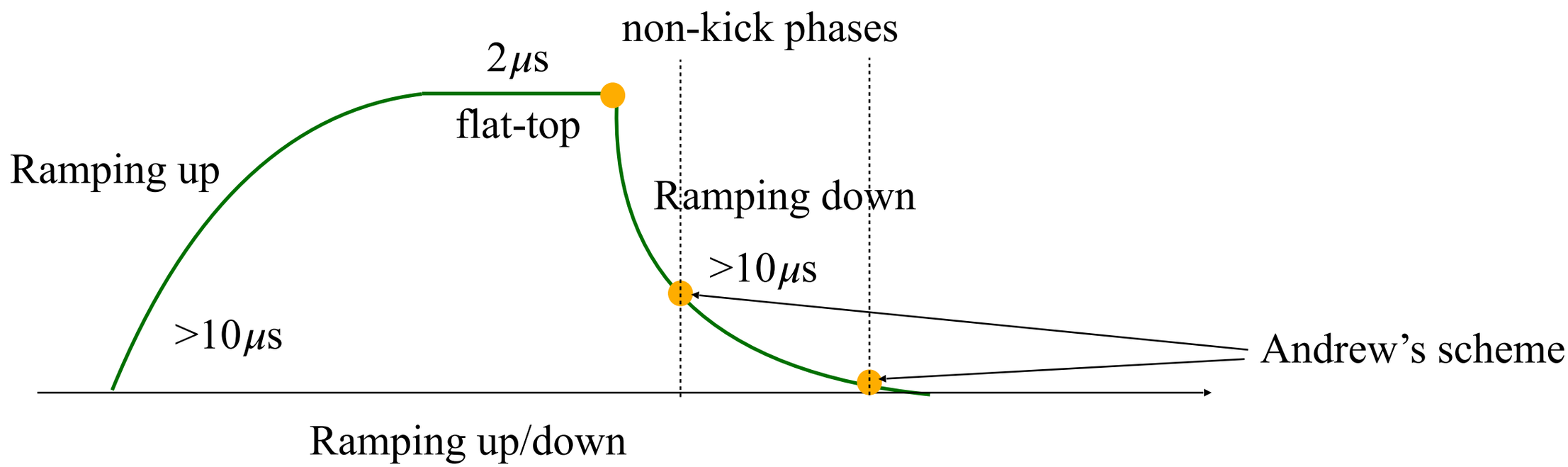


Mode	Freq. (MHz)	Amp. (kV)
1	36.9375	93.75
3	110.8125	81.25
5	184.6875	68.75
7	258.5625	56.25
9	332.4375	43.75
11	406.3125	31.25
13	480.1875	18.75
15	554.0625	6.25
-	DC1	0
-	DC2	0

- The longest cavity with mode1 would be 2m long. There is a danger of having TE modes as 11, 13th harmonics.

The fitting the waveform into pulse structure

- Putting the waveform into macropulse: with separation of trains by $(74\times16)\tau = 2\mu$s, the waveform repeats on the bunches in the second train.
- In Andrew's scheme with the modified harmonic number, the ramping up/down time can be extended if harmonic number±1 is divisible by kick number. By allowing the bunches to pass (the kicker) multiple times with the RF kick at no-kick phase when they pass. But this would lead to the injection into the bunch trains that is "unsymmetrical" within the macropulse.



- The new option has a dip at the 4th bunch (4 bunch mode) and 8th bunch (8 bunch mode), which forces ramping up/down time less than one revolution time, i.e., 10.8μs (just as in Jiquan's scheme).

- The injection of the new solution is making use of the pulsed mode operation of the kicker. This gives flexibility on how to put the bunches in time line. When the (k+1)th pair of bunches is injected into the trains at t_{k+1} after the kth pair at t_k, i.e., after the time $h_n M\tau$ =10ms ($M=781$ passes), the phase of the kicker is to be adjusted (by the LLRF) so that

Kicker in "zero-kick phases" & k th bunch passes @$t_{k+1} = t_k + h_n M\tau$

Kicker in "kick phase" & ($k+1$) th bunch passes @$t_{k+1} = t_k + (h_n M+1)\tau$

Achieving and maintaining the flat top in the presence of freq. fluctuations requires piezo-tuner or the LLRF control.

- There exist two concrete solutions for the injection scheme of the RCS. This new proposal is to achieve a required harmonic kick in a single cavity (for 4 bunch mode) and two cavities (for 8 bunch mode) without slopes on passing bunches and also having to change the overall harmonic number (of the RCS).

RF pulsed operation

Comparison with other schemes

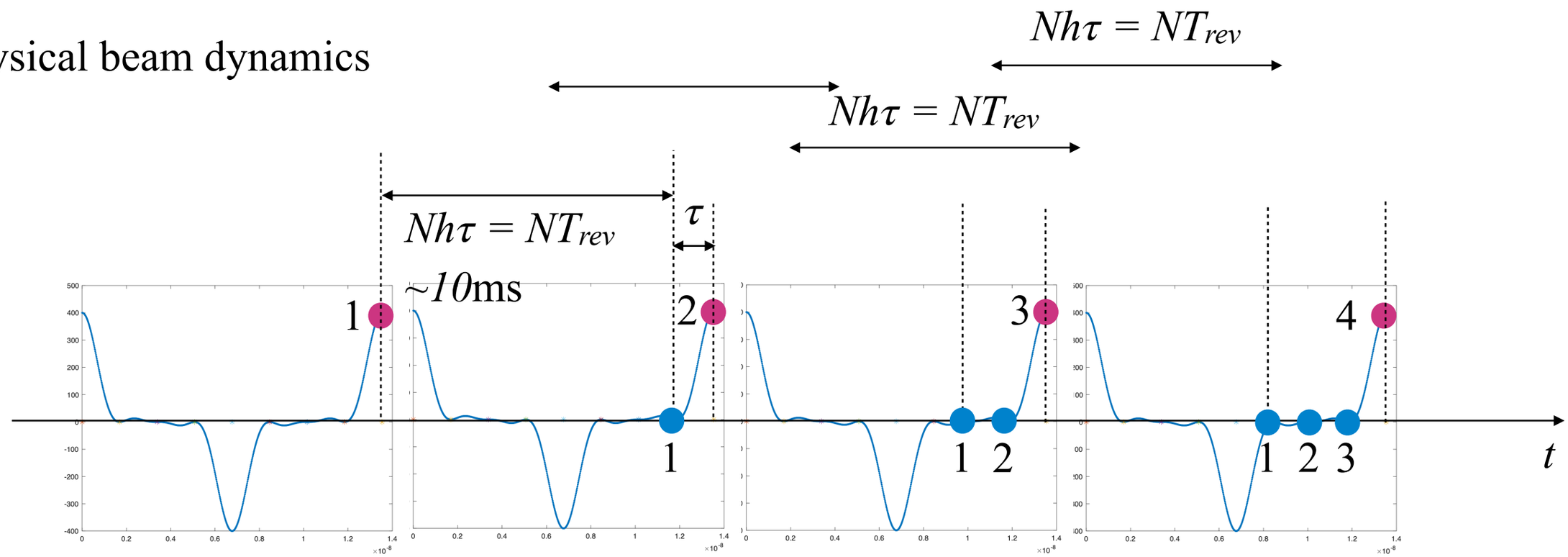
- There exist two concrete solutions for the injection scheme of the RCS. This new proposal is to achieve a required harmonic kick in a single cavity (for 4 bunch mode) and two cavities (for 8 bunch mode) without having to change the overall harmonic number (of the RCS) with zero kick and slope on passing bunches.

Characteristics	Guo	Hutton	Park
Harmonic number	7576	7576+α	7576
Amplitude option	Zero-slope (n_k=4/8)	Equal amplitude (n_k=7/11)	Mixed (n_k=8/16)
Beam dynamics	Little degradation	Slope	Little degradation
no. of cavity	2/3	1/1	1/2
rise/fall time	10 μs	>17.6 μs	10 μs
Bunches in macropulse	Perfectly symmetrical	Quasi-symmetrical	Perfectly symmetrical

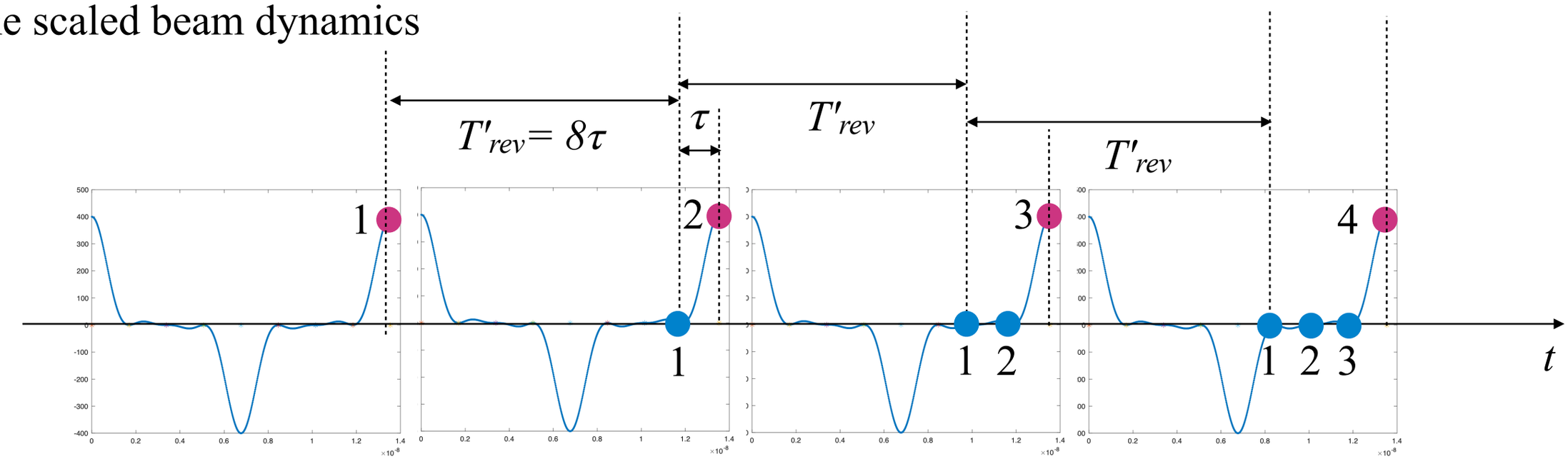
The ELEGANT simulation

- The pulsed mode operation test can be done while keeping the same base beam rep. rate

Physical beam dynamics



The scaled beam dynamics



1st kicker system 2nd kicker system 3rd kicker system 4th kicker system

One-turn matrix of the RCS

$$
\begin{bmatrix}
\cos 2\pi Q_x + \alpha_x \sin 2\pi Q_x & \beta_x \cos 2\pi Q_x & 0 & 0 & 0 & \eta_x \\
-\gamma_x \cos 2\pi Q_x & \cos 2\pi Q_x - \alpha_x \sin 2\pi Q_x & 0 & 0 & 0 & \eta'_x \\
0 & & \cos 2\pi Q_y + \alpha_y \sin 2\pi Q_y & \beta_y \cos 2\pi Q_y & 0 & \eta_y \\
0 & & -\gamma_y \cos 2\pi Q_y & \cos 2\pi Q_y - \alpha_y \sin 2\pi Q_y & 0 & \eta'_y \\
0 & & 0 & 0 & 1 & 0 \\
0 & & & 0 & 0 & 1
\end{bmatrix}
$$

Sorry to reply late.

The unit of Qx, Qy should be unitless. Qx and Qy are a ratio of betatron oscillation to revolution frequency. So, when you use them in your formula, I think it should be like sin(2Pi*Qx) for each turn.

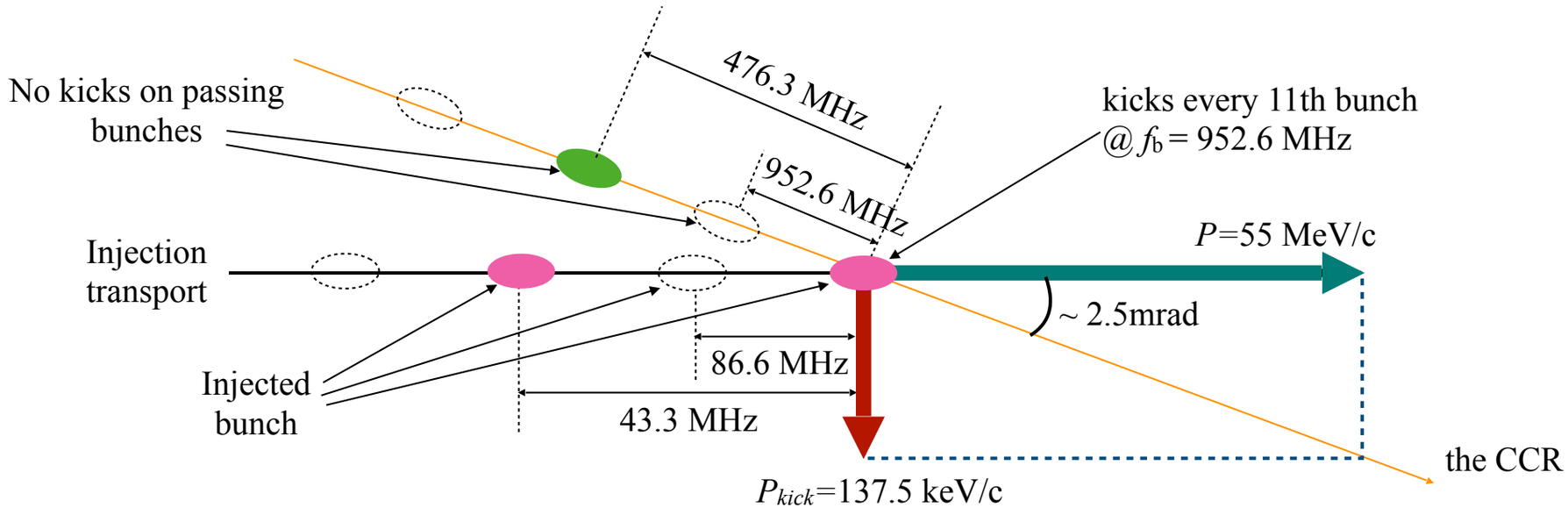
Another possible issue is the synchrotron-betatron coupling. How many turns are concerned in your study?

Shaoheng

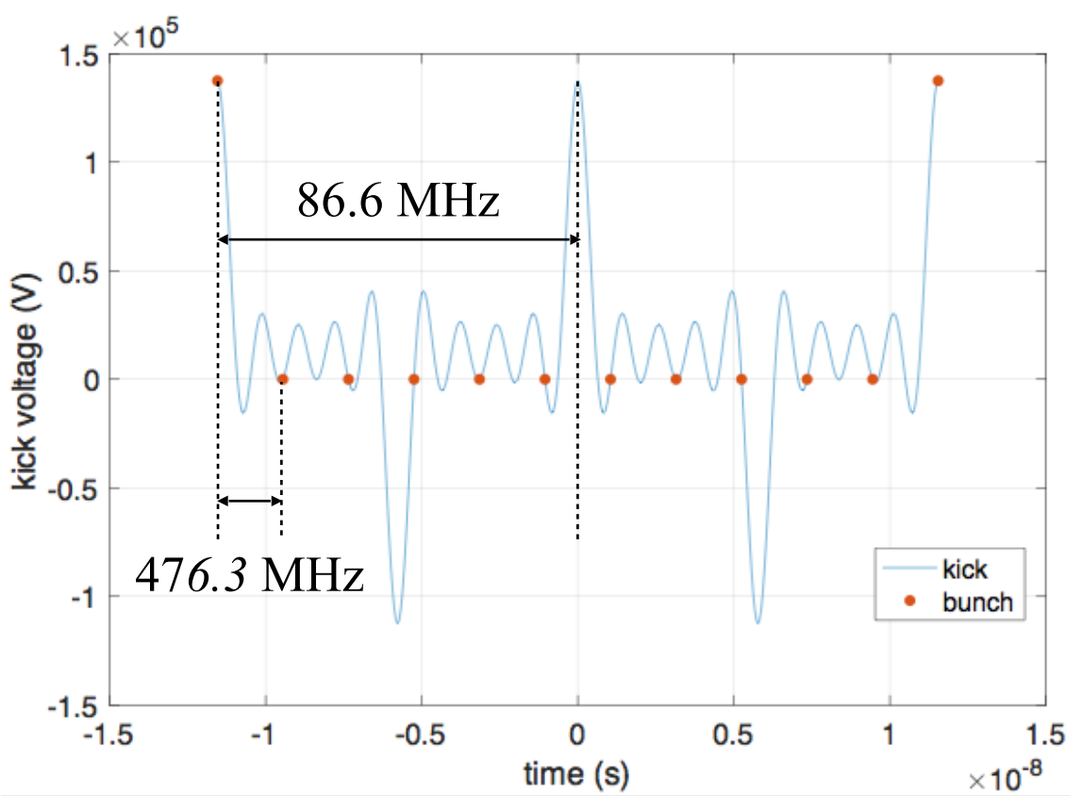
Beam test plan at the UITF

The original application of the kicker for the CCR/JLEIC

- A harmonic kicker cavity is a normal conducting quarter wave resonator (QWR) that deflects the beam by a few mrads, using a linear combination of harmonic modes.



- It was originally developed for the Circulating Cooler Ring (CCR) of the JLEIC. The prototype, which will be ready for the test in a couple of months, has the specification based on the CCR/JLEIC beam dynamics.



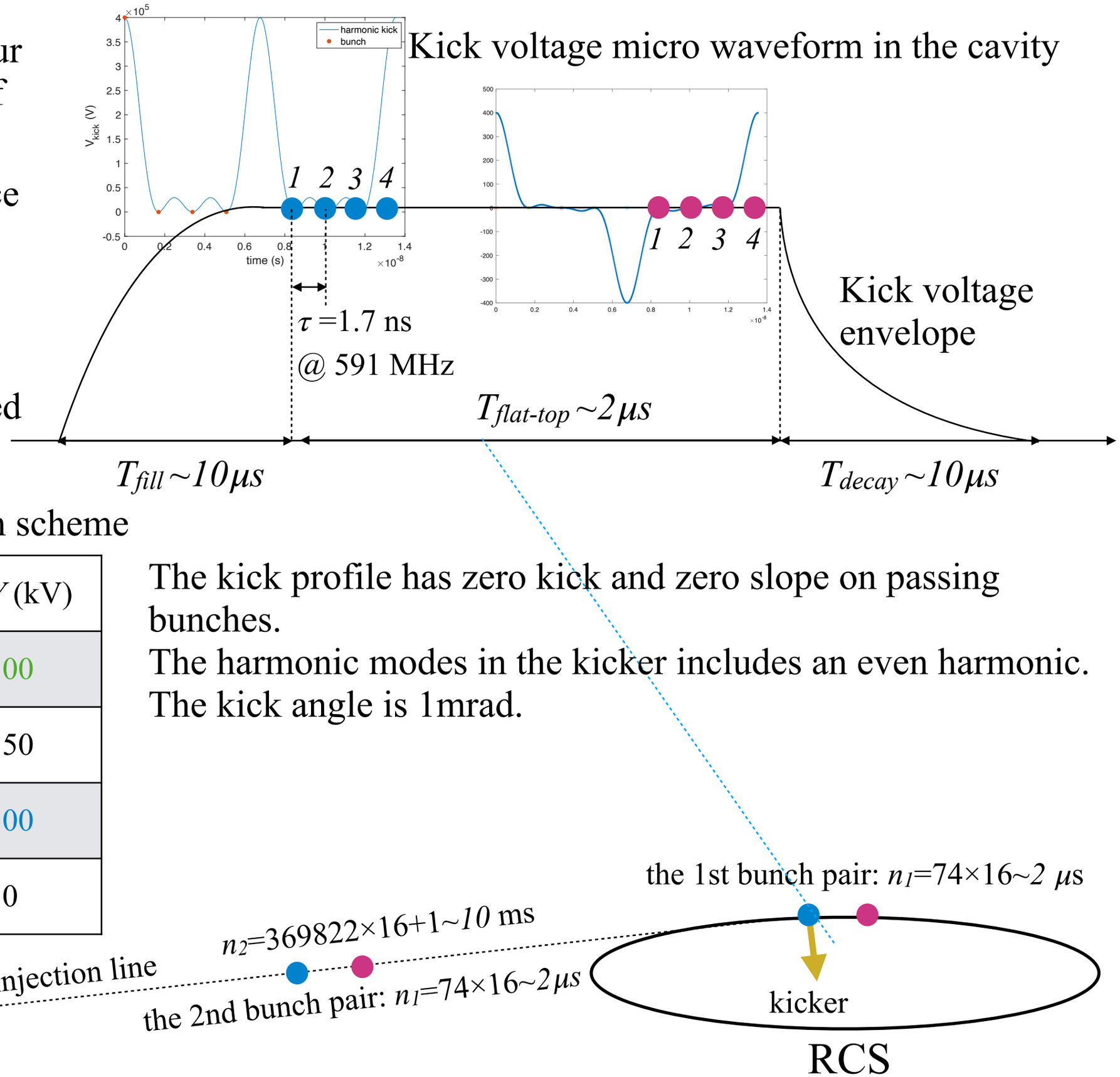
The profile of a harmonic kick with equal amplitudes.

Modes	freq.	Amp.
1	86.6 MHz	25 kV
2	259.8 MHz	25 kV
3	433 MHz	25 kV
4	606.2 MHz	25 kV
5	779.4 MHz	25 kV
DC	-	12.5 kV

The RF parameters of a harmonic kicker

The injection scheme of the RCS

- The injection is done in four steps. In each step, a pair of bunches (~2 μs apart) from the polarized electron source is injected to the two trains (one for each train).
- Unlike CCR/JLEIC, the injection kick is pulsed for each step, which is separated by 10ms.



Harmonic kicker for 4 bunch scheme

Mode	f (MHz)	V (kV)
DC	0	100
1	147.8	150
2	295.5	100
3	433.3	50

The kick profile has zero kick and zero slope on passing bunches.
The harmonic modes in the kicker includes an even harmonic.
The kick angle is 1mrad.

The beam test plan @ UITF

- The beam parameters of the UITF is not compatible with those of the CCR/JLEIC nor the RCS/EIC.
- We wan to test the prototype (for the CCR/JLEIC) to demonstrate the general feasibility of the kicker concept in the RCS: the beam deflection, selective kicks, the effects of the kicks, operation stability, pulsed mode operation,.

Beam specification at the UITF

Parameters	Unit	Available	Test
Beam Energy	MeV	5~10	10
Beam mode	-	CW/pulsed	CW/pusled
Bunch rep. rate	MHz	1497/*m*	136.1/*l*
Kick freq.	MHz	86.6/*n*	12.37
Bunch charge	pC	< 5	<1
deflection	mrad	-	< 2

The general relation between kicker freq. and bunch rep. rate

$$\frac{n}{f_Q} = \frac{1}{f_k} = \frac{m}{f_b}$$

QWR kick freq.

The actual kick freq.

UITF rep.rate

- The master freq. of the UITF: f_M=1497 MHz.
- The kicker freq.: f_Q = 86.6MHz = 7/11^2× f_M.

$$\frac{m}{n} = \frac{11^2}{7l}$$

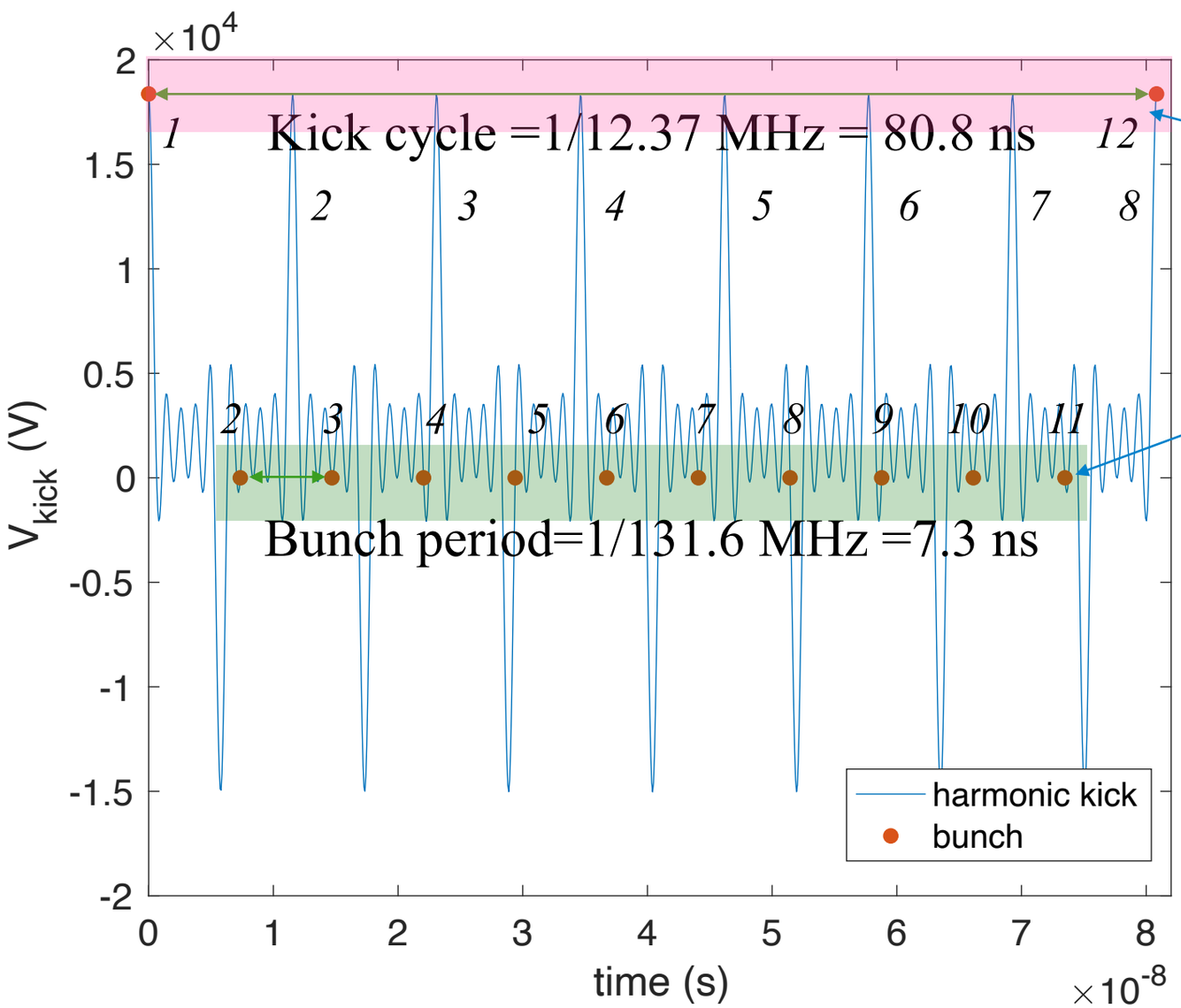
choice of rep. rate with respect to f_M

- The proposed beam from the laser @ f_{laser} =136.1MHz =1/11× f_M.
- The kick freq. is f_k =12.37 MHz =1/11^2× f_M =1/11× f_{laser} =1/7 × f_Q.

Baseline test-0

The CW operation of the RF source

- A baseline test is a selective kick on the CW beam, while the kick is operated in the CCR/JLEIC scheme in CW mode (mimicking the flat-top operation of the RCS/EIC).
- With bunch rep. rate of f_b=136.1MHz in CW against the RF kicker freq. of f_Q= 86.6MHz, every 11th bunch is kicked @ f_k=12.37 MHz.
- Because time resolution of the BPM is wider than rep. rate f_b, there would be the need for (at least) two BPM's in separate beam pipes. We would need two beam pipes branching out horizontally.

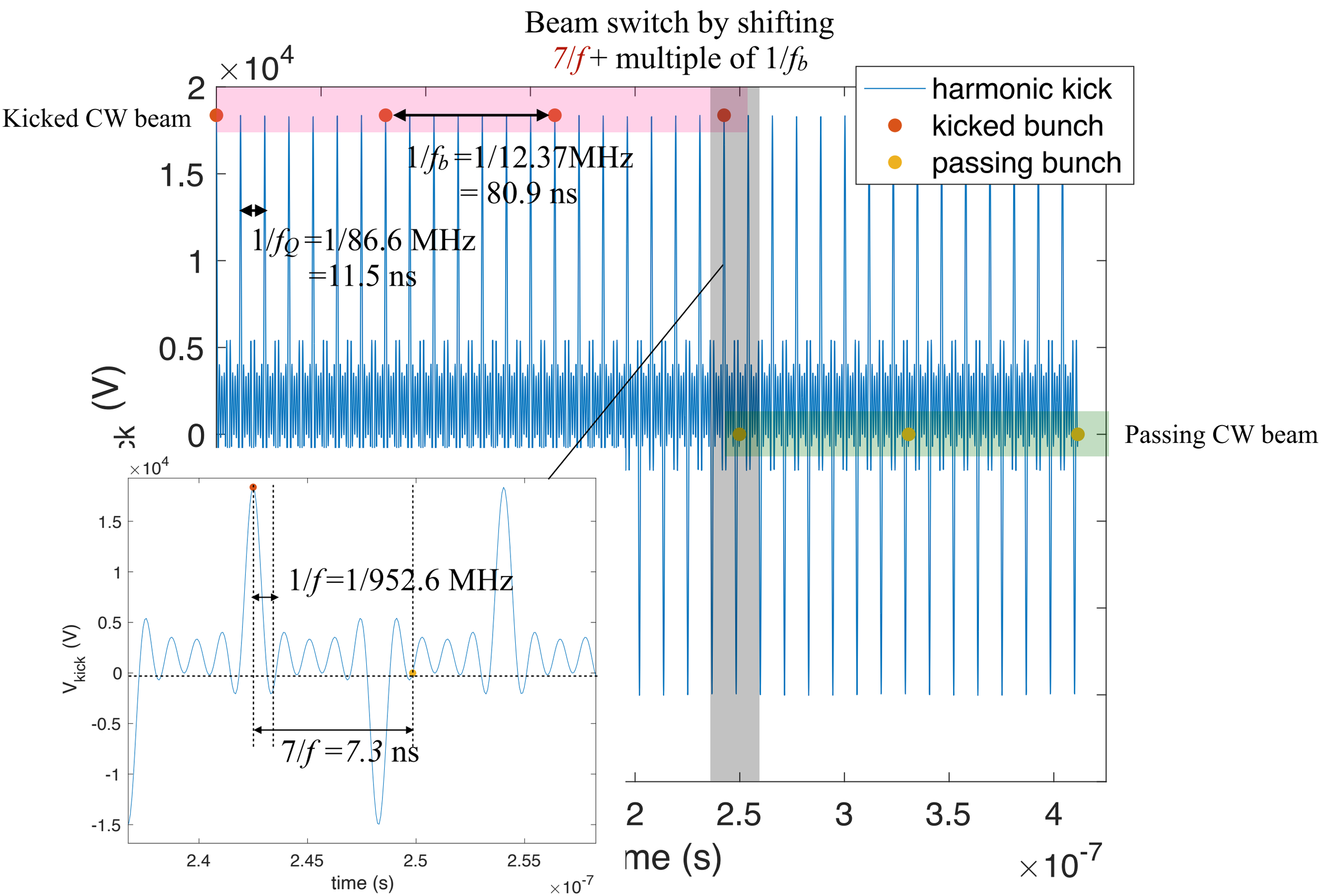


Beam pipe A

Beam pipe B

- The demonstration:
  - The target deflection angle, the rise/fall time of the kick, effects of residual kicks + phase control over long period~μs.
  - One can obtain the generic errors in the system + effectiveness of the LLRF (feedback system)

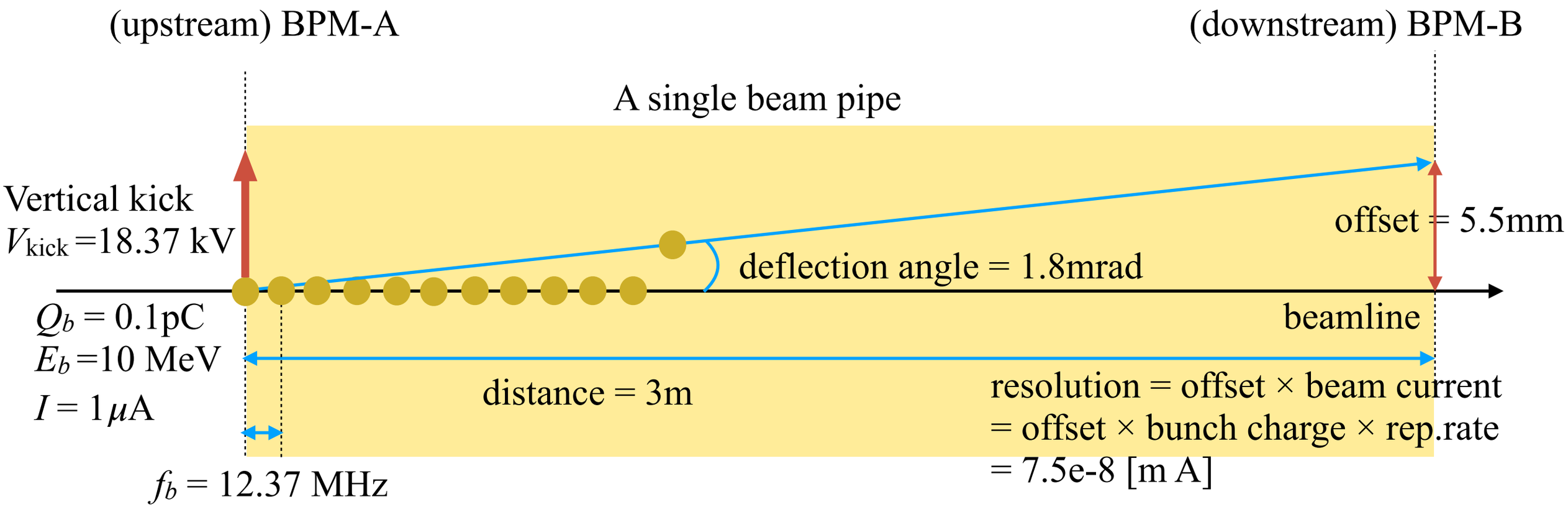
Baseline test-1



- A baseline test is a selective kick on the CW beam, while the kick is operated in the CCR/JLEIC scheme in CW mode (mimicking the flat-top operation of the RCS/EIC).
- With bunch rep. rate of f_b=136.1MHz in CW against the RF kicker freq. of f_Q= 86.6MHz, every 11th bunch is kicked @ f_k=12.37 MHz.
- Because time resolution of the BPM is wider than rep. rate f_b, there would be the need for (at least) two BPM's in separate beam pipes. We would need two beam pipes branching out horizontally.

- The demonstration:
  - The target deflection angle, the rise/fall time of the kick, effects of residual kicks + phase control over long period~μs.
  - One can obtain the generic errors in the system + effectiveness of the LLRF (feedback system)

Beam diagnostics



- For pulsed mode beam test, a customized BPM would be needed to resolve longitudinal pulsed beam structure (<60 MHz)
- If the kicked/unkicked bunches mix up at higher than ~100MHz, the beam line must be separated in horizontal direction, which might cause some sagging for the kicker cavity (plus need two sets of diagnosstics).

keV region overview

Polarized Source Inverted Gun with 450 kV HVPS

(9) Viewer

(1) Harp

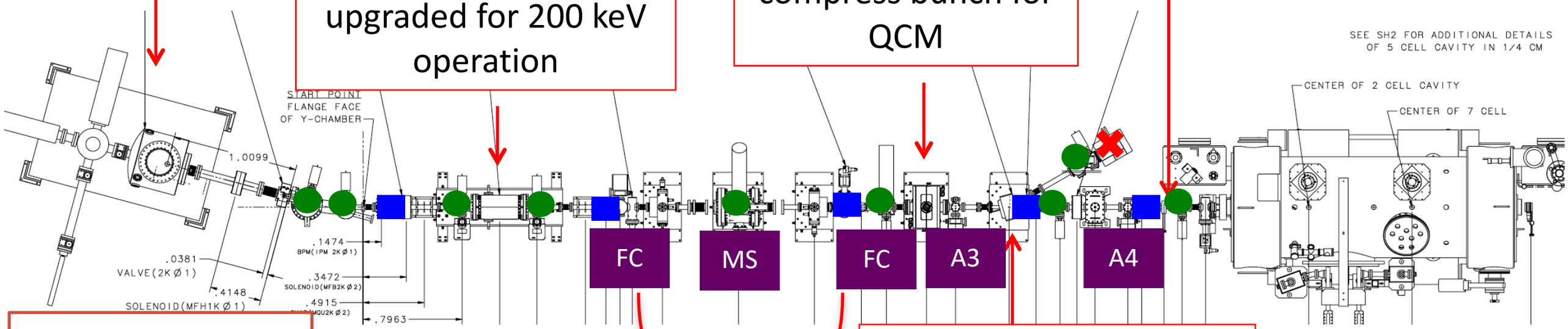
(5) BPM

(5) Current

Yao or Brock cavity to optimize bunching

CEBAF style Wien filter upgraded for 200 keV operation

750 MHz buncher to compress bunch for QCM



Pulsed beam @

Y-chamber to introduce laser normal to the photocathode

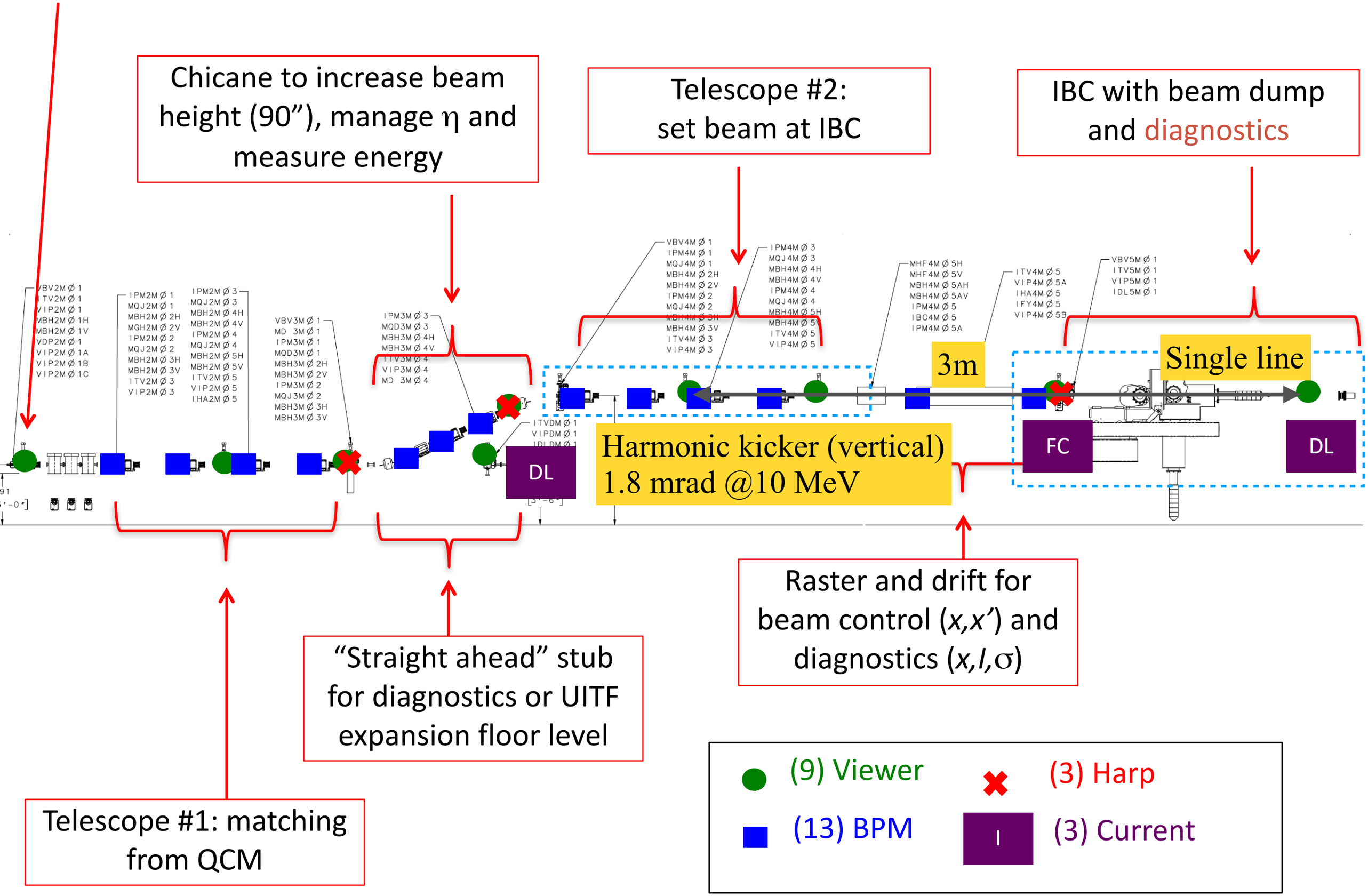
1497 MHz chopper to set low current (pA) and measure longitudinal profile

Spectrometer to calibrate buncher gradient and measure energy spread

New QCM to achieve 5-10 MeV beam (depends on klystrons)

MeV region overview

(optical layout inspired by D. Douglas)



The CW RF operation

The figures of merit for the QWR prototype

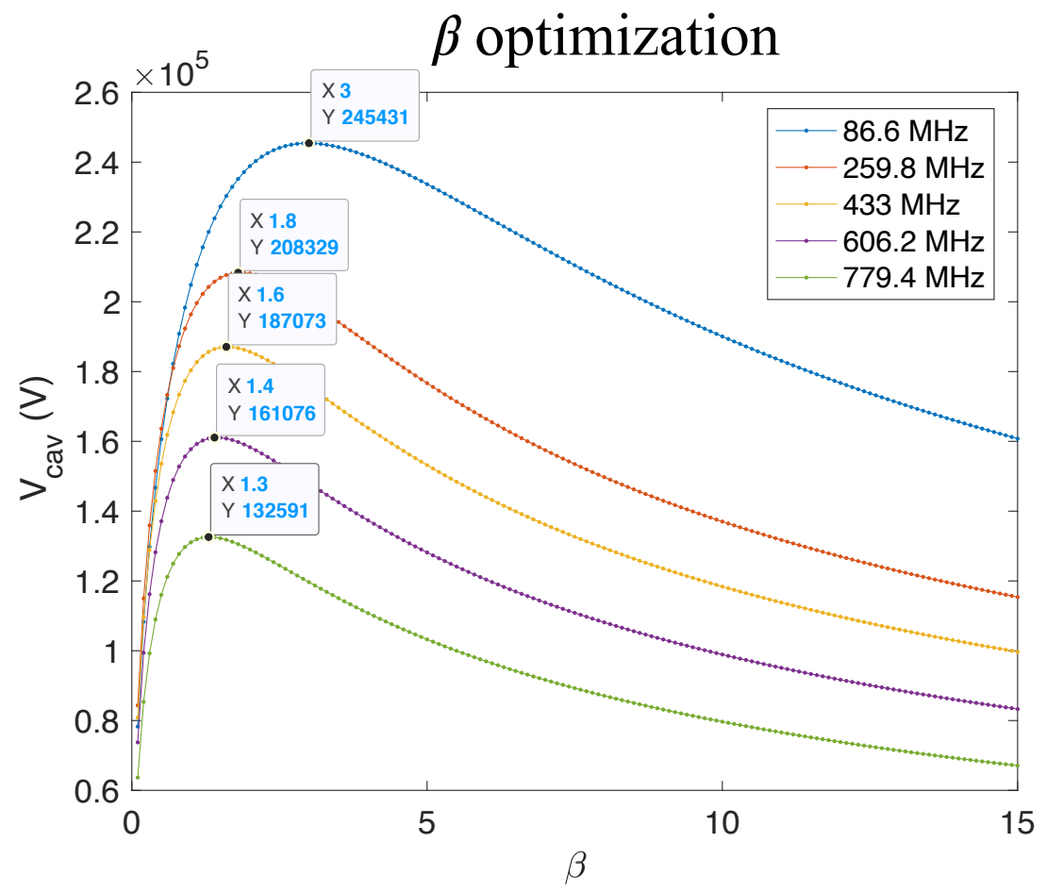
Parameters	Unit	86.6 MHz	259.8 MHz	433 MHz	606.2 MHz	779.4 MHz
Q_0	V	1	200	200	200	200
R_{sh}	MΩ	1.38	0.71	0.53	0.37	0.24
G	Ω	15	43	77	107	133
R_s	MΩ	2.7	4.6	6.0	7.1	8.0
β (critical)	-	0.74	1.21	1.22	1.20	1.25

The RF parameters of the QWR prototype

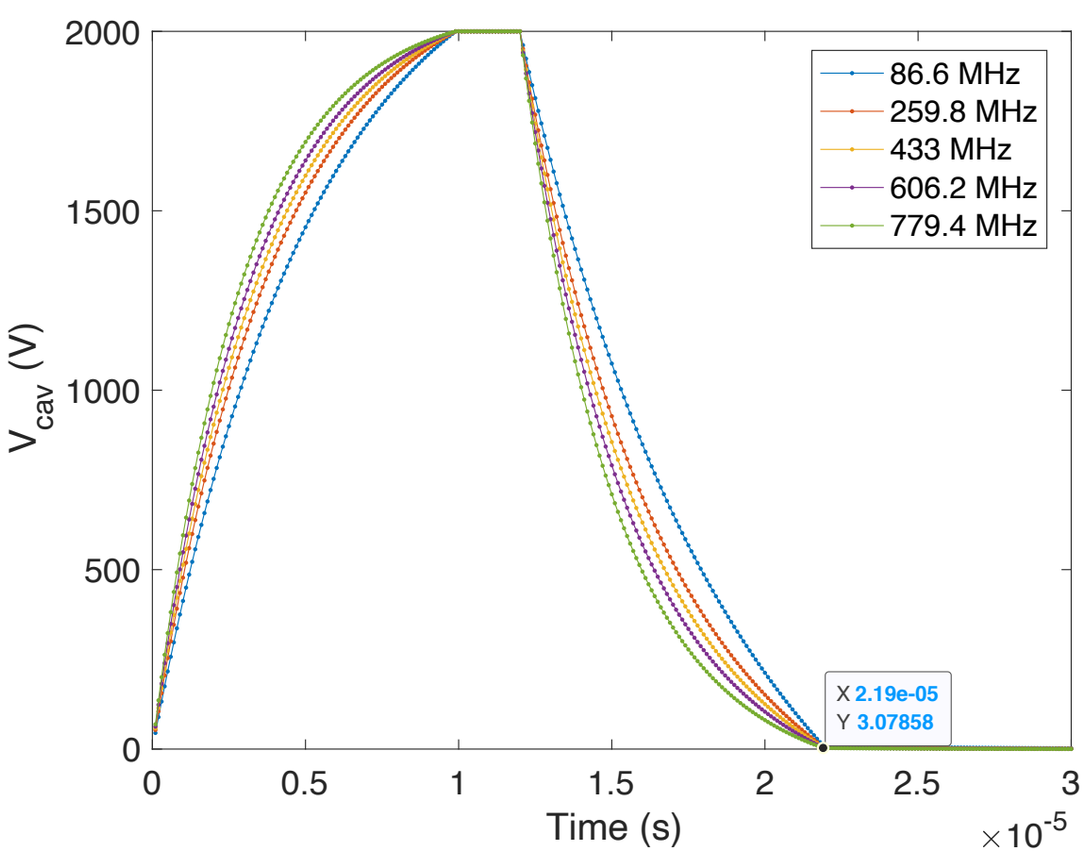
Parameters	Unit	DC	86.6 MHz	259.8 MHz	433 MHz	606.2 MHz	779.4 MHz
V_{kick0}	kV	1.67	3.34	3.34	3.34	3.34	3.34
P_{kick0}	W	-	8.1	15.7	21.0	30.2	46.5
U_{cav0}	μJ	-	83.5	89.5	99.8	120.0	157.7
V_{fwd0}	V	?	20.4	28.1	32.6	39.0	48.4
P_{fwd0}	W	?	8.3	15.8	21.2	30.4	46.9

RF pulsed operation (without beam)

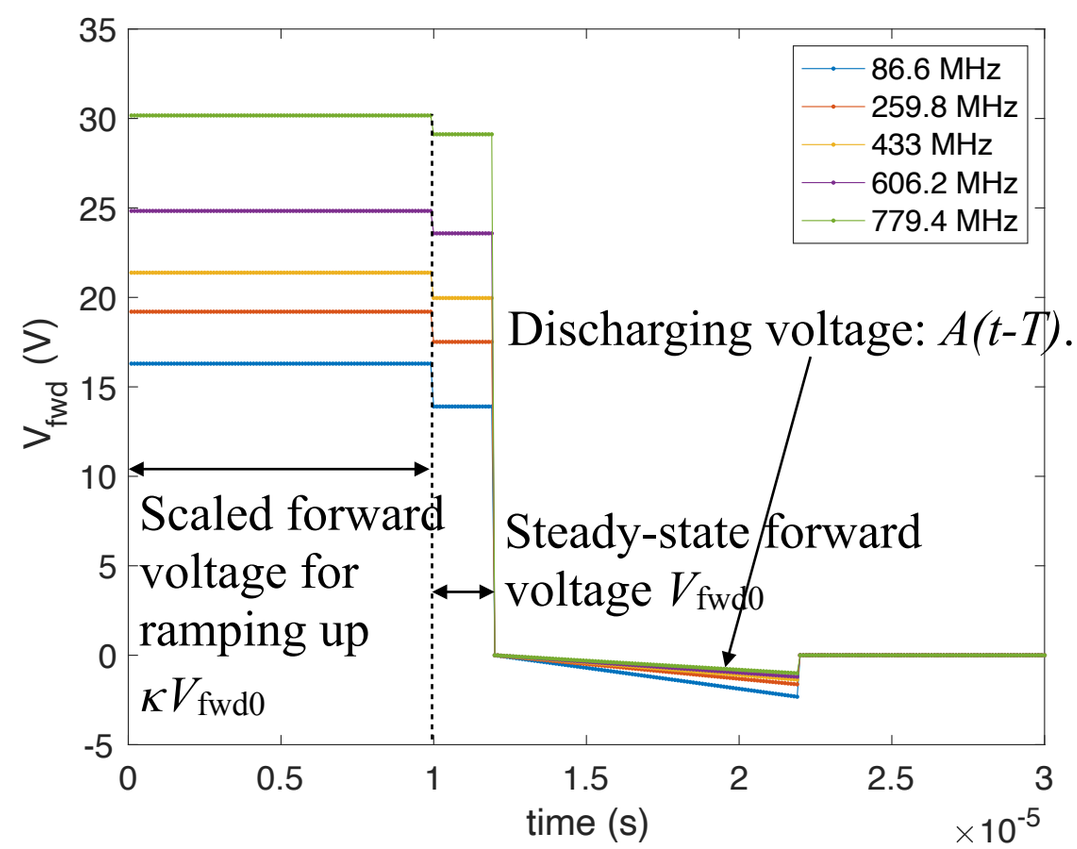
- Without beam, the RF power in baseline CW mode (5 modes, equal amplitude) is turned on/off within the target filling/decay time.
- To minimize the filling time, the optimum coupling is determined.
- In addition, one would need DC magnet for



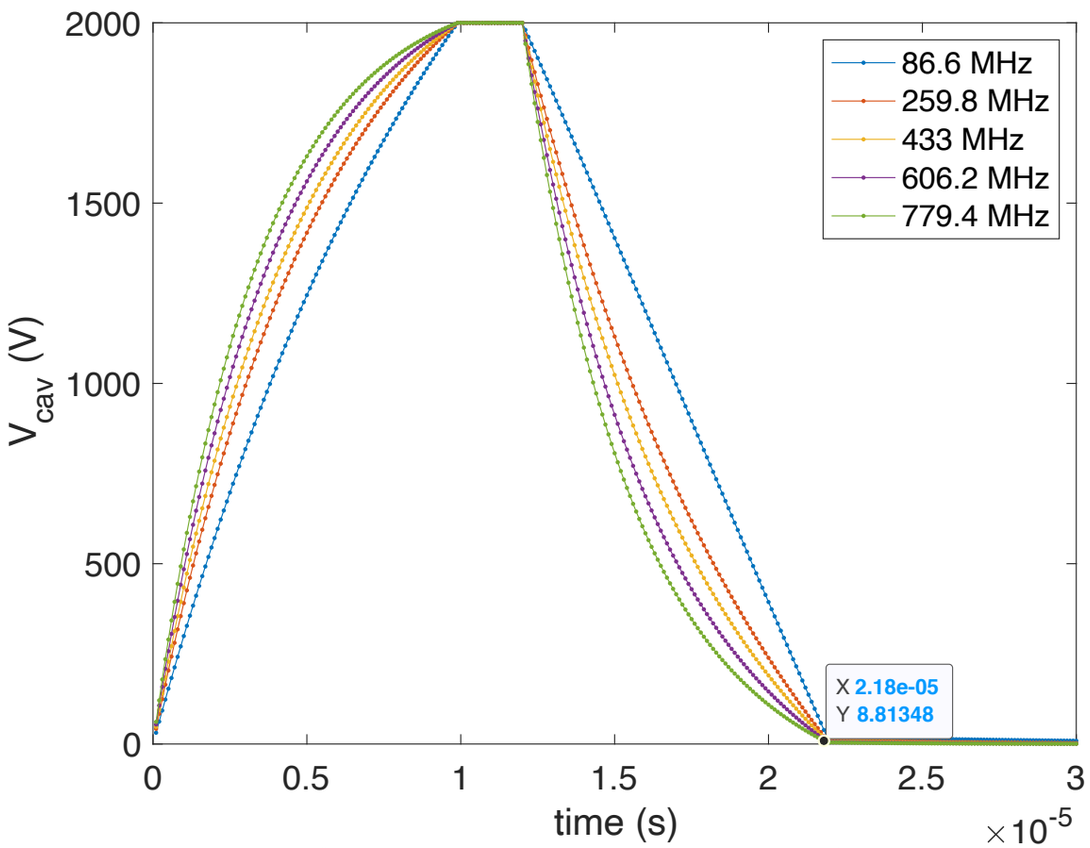
- The pulsed profile of the kick voltage



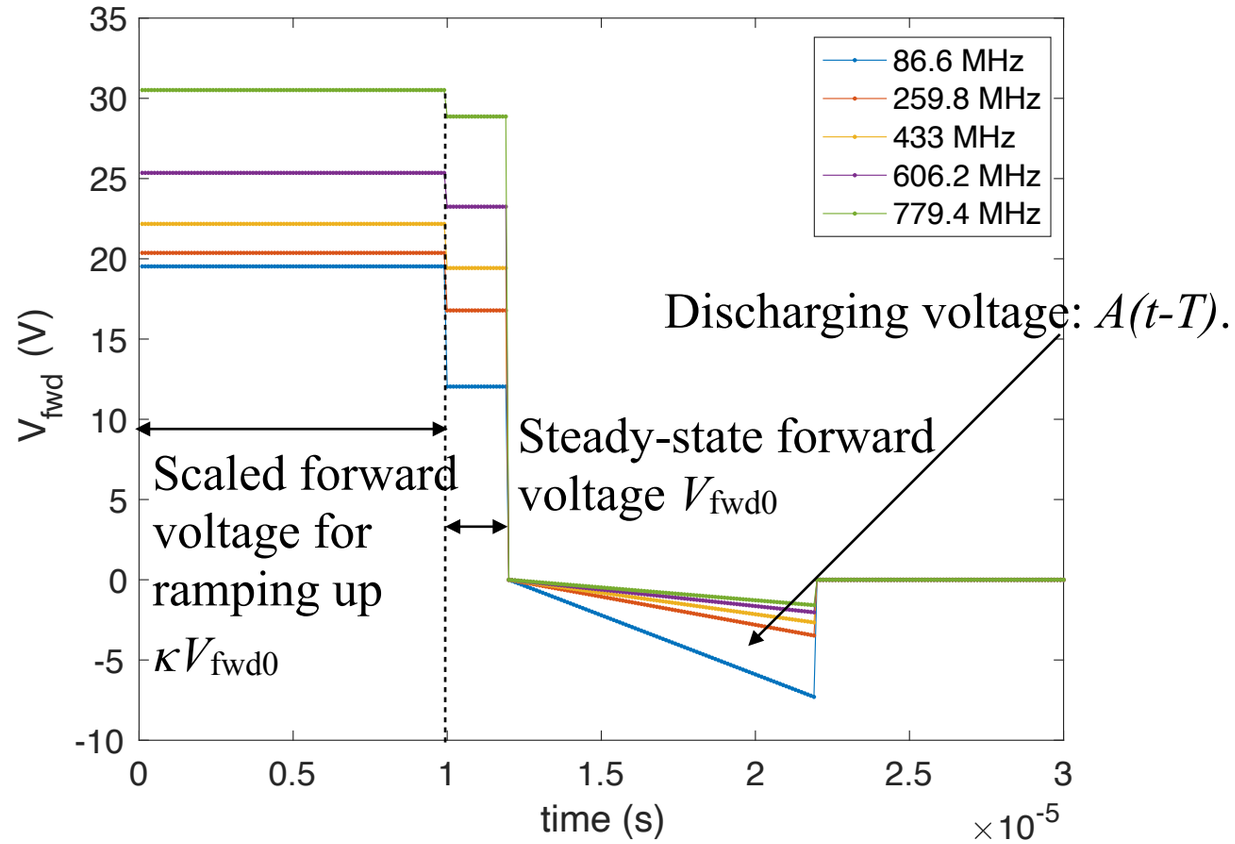
- The forward voltage profile



❋ Construct time profile with critical coupling



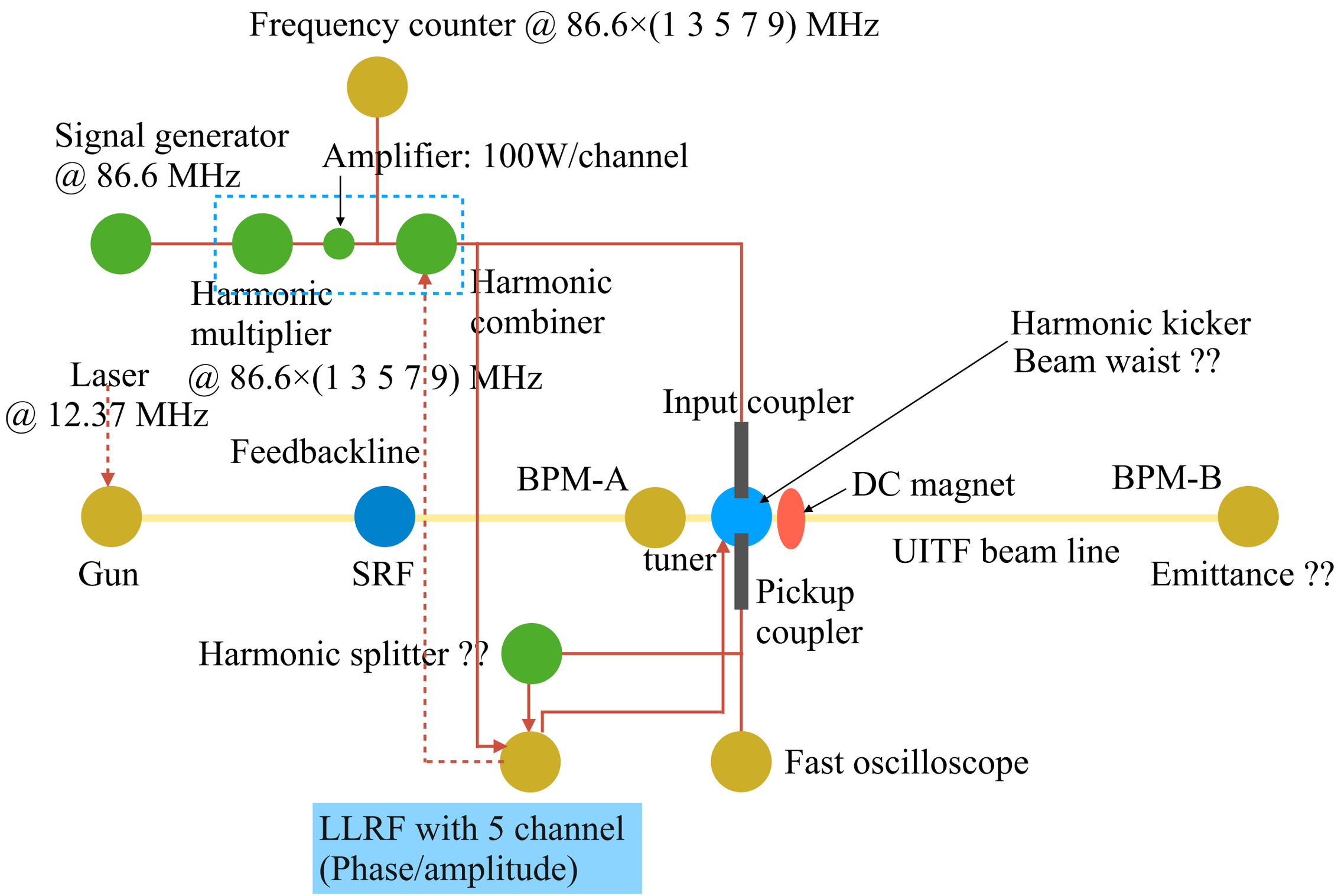
Kick voltage in the cavity



Forward voltage from the RF source

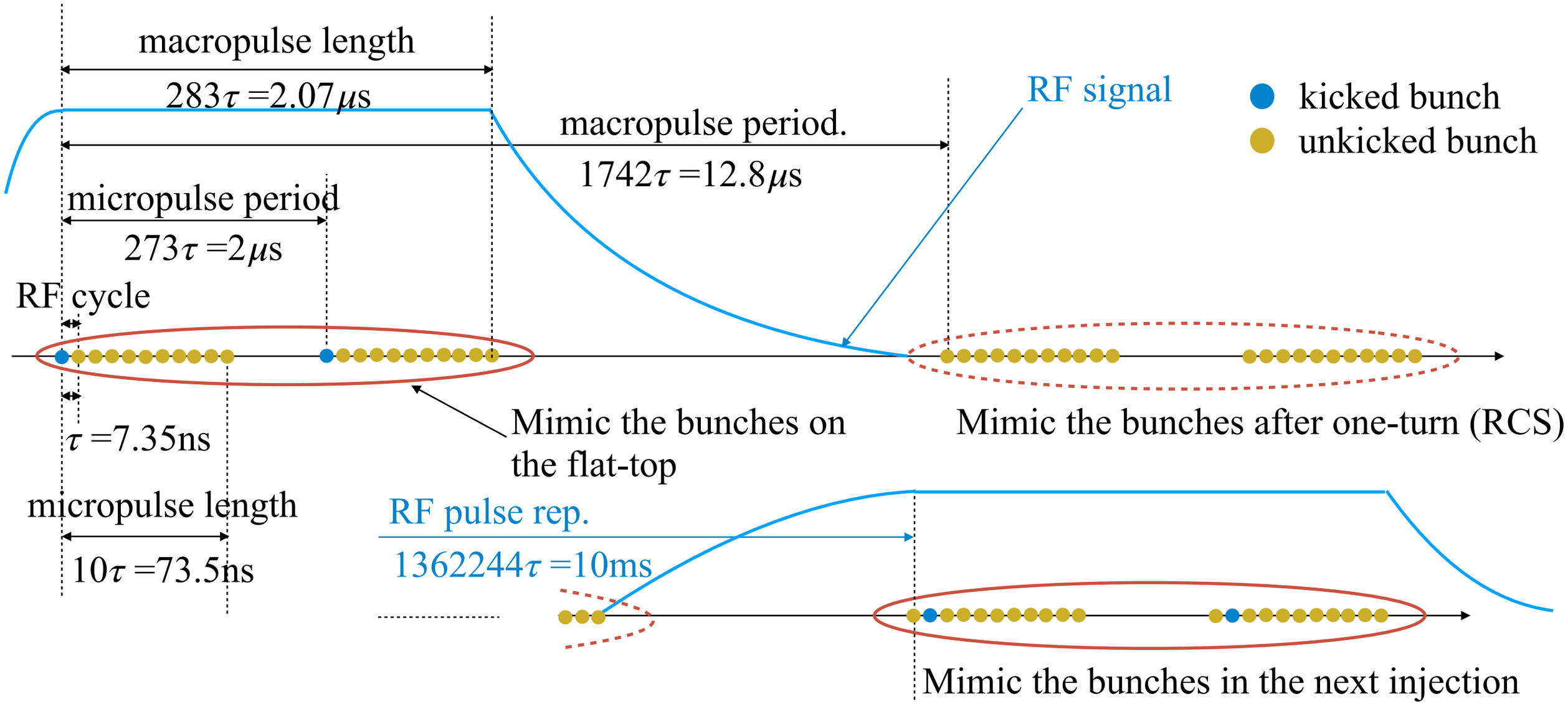
Parameters	Unit	86.6 MHz	259.8 MHz	433 MHz	606.2 MHz	779.4 MHz
Steady state kick voltage V_{kick0}	kV	2	2	2	2	2
Steady state cavity power P_{kick0}	W	2.9	5.6	7.5	10.8	16.7
Steady state stored energy U_{cav0}	μJ	30.0	32.1	35.8	43.0	56.5
Steady state forward voltage V_{fwd0}	V	13.9	17.5	20.0	23.6	29.1
Steady state forward power P_{fwd0}	W	3.9	6.1	8.0	11.1	17.0
Steady state backward power P_{bwd0}	W					
Average forward	W					

Test system layout



Pulsed mode test

- The pulsed mode operation test can be done while keeping the same base beam rep. rate.

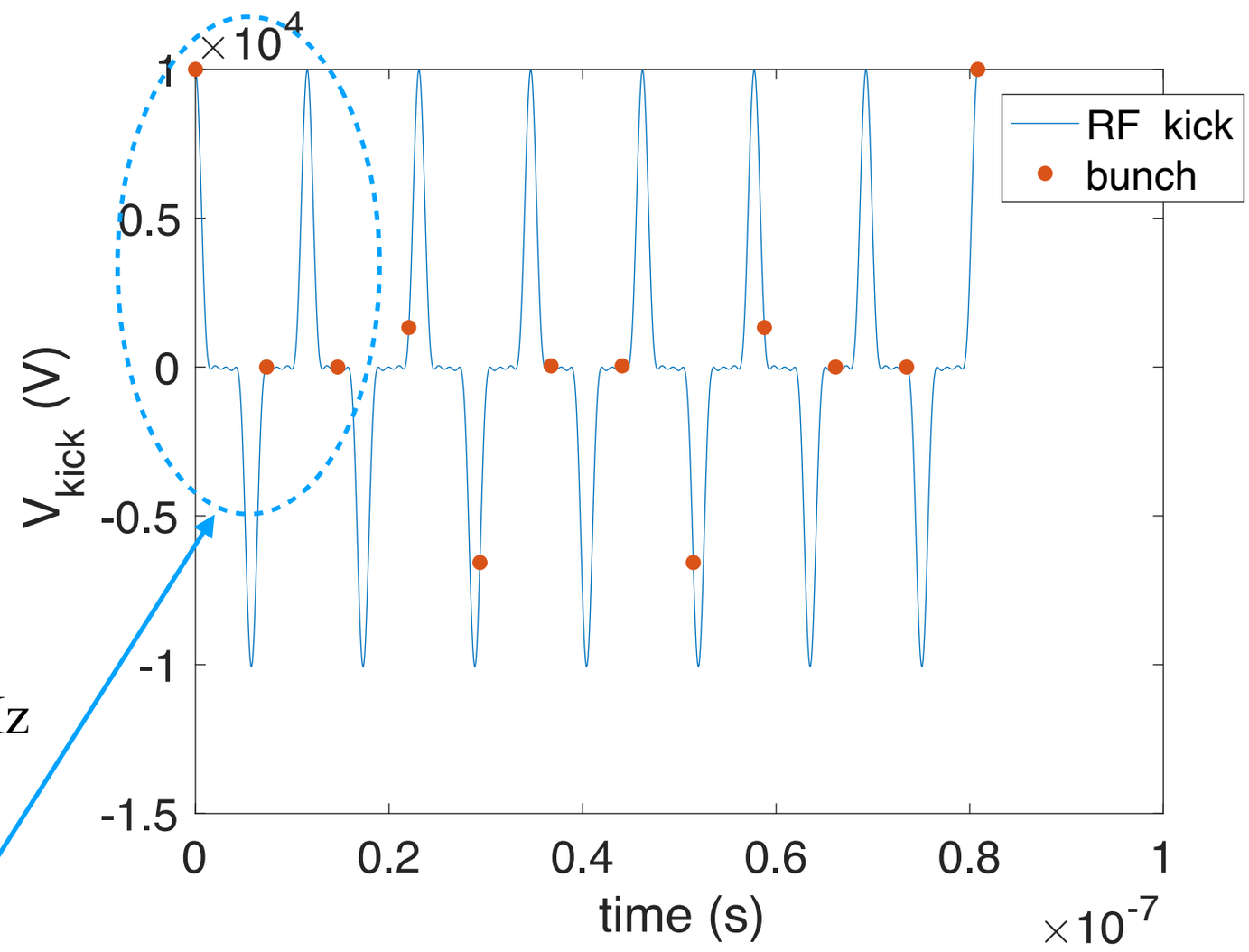


- One can additionally check on the ramping up/down time of the RF signal, control of the flat-top profile with the relative phase between passing bunches and the RF signal, and synchronization of the RF waveform after ramping up with respect to the incoming bunch.

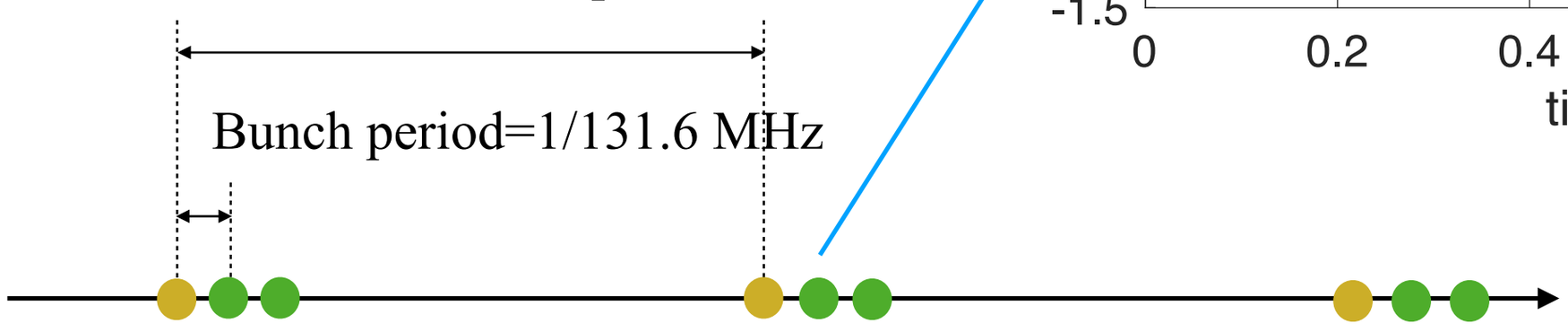
Zero-kick-zero-slope scheme test

- The zero-kick-zero slope scheme for the RCS can also be tested. The kicker is operated in the CW mode (the flat-top) with 4 harmonic modes, while the beam must be pulsed.

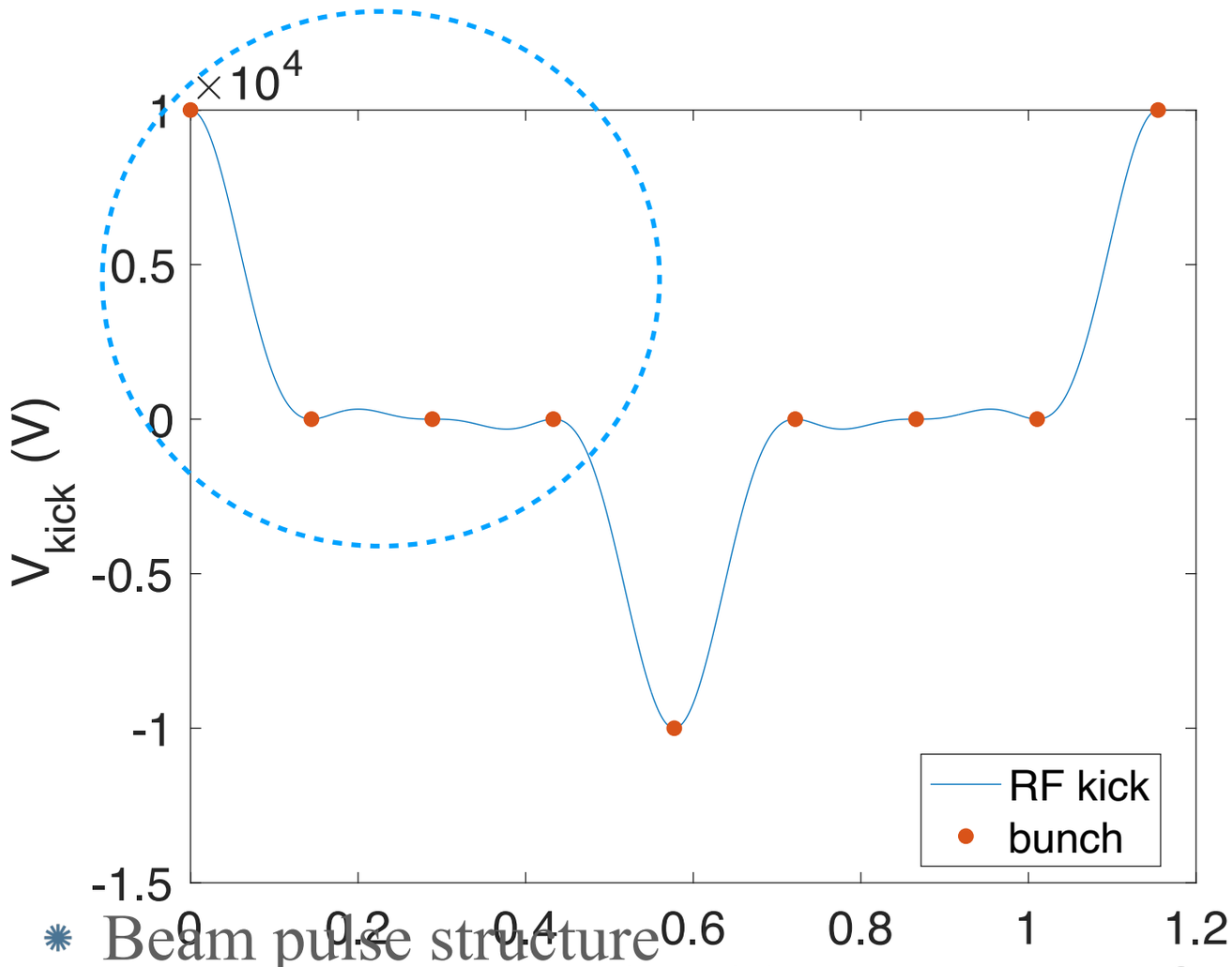
Modes	Amp
DC mode	-0.04 kV
86.6 MHz	4.52 kV
259.8 MHz	3.30 kV
433 MHz	1.71 kV
606.2 MHz	0.51 kV



Kick cycle = beam pulse period =1/12.37 MHz
Based on 4-mode operation

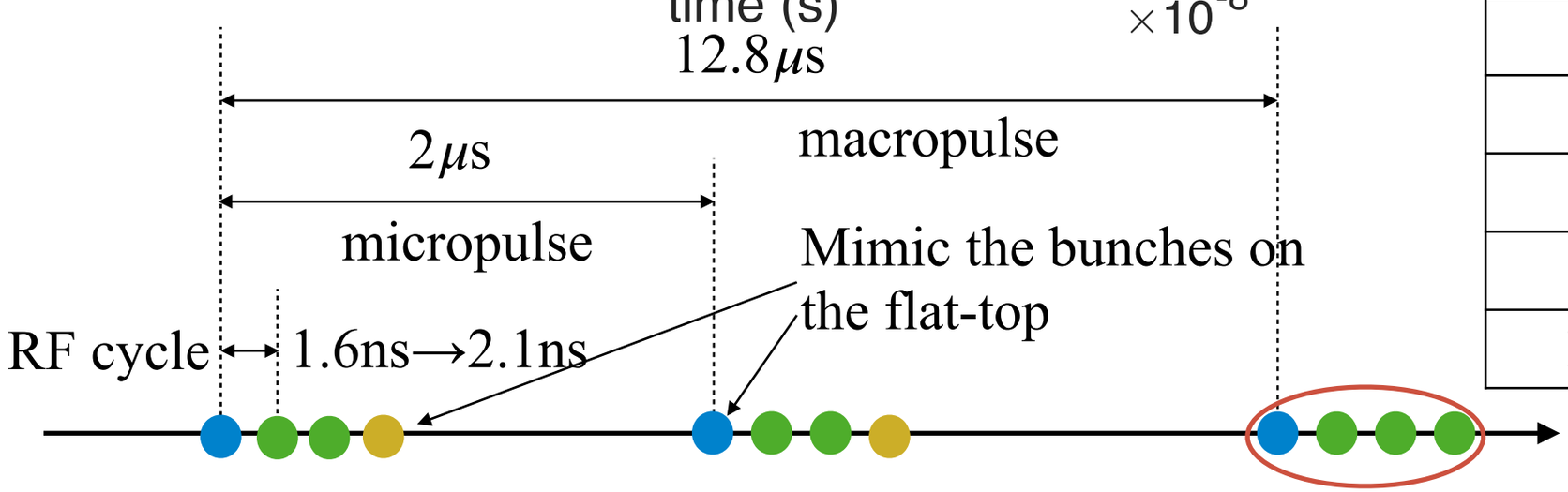


- The zero-kick-zero slope scheme that is exactly the same as the one in the RCS could be realized with f_b=692.83=56/121×1497 MHz and f_Q=86.6 MHz.



Modes	Amp
DC mode	0 kV
86.6 MHz	4.375 kV
259.8 MHz	3.125 kV
433 MHz	1.875 kV
606.2 MHz	0.625 kV

- Beam pulse structure



Parameters	Unit	Value
Energy	MeV	10
Deflection	mrad	1
Base freq.	MHz	591 (1.7 ns)
Micropulse	kHz	500 (2μs)
Macropulse	kHz	78.1 (12.8μs)

Mimic the bunches after one-turn (RCS)

The RF parameter table (optimum coupling)

Parameters	Unit	86.6 MHz	259.8 MHz	433 MHz	606.2 MHz	779.4 MHz
Steady state kick voltage V_{kick0}	kV	2	2	2	2	2
Steady state cavity power P_{kick0}	W	2.9	5.6	7.5	10.8	16.7
Steady state stored energy U_{cav0}	μJ	30.0	32.1	35.8	43.0	56.5
Steady state forward voltage V_{fwd0}	V	13.9	17.5	20.0	23.6	29.1
Steady state forward power P_{fwd0}	W	3.9	6.1	8.0	11.1	17.0
Steady state backward power P_{bwd0}	W					
Duty cycle η	-					
Average forward power P_{ave}	W					
Optimal β's	-	3.0	1.8	1.6	1.4	1.3
Scaling factor κ	-	1.17	1.10	1.07	1.05	1.03
Scaled forward voltage V_{fwd}	V					
Scaled forward power P_{fwd}	W	5.3	7.4	9.1	12.3	18.2
Discharging slope A	MV/s	-0.23	-0.16	-0.14	-0.12	-0.10

The RF parameter table (near critical coupling)

Parameters	Unit	86.6 MHz	259.8 MHz	433 MHz	606.2 MHz	779.4 MHz
Steady state kick voltage V_{kick0}	kV	2	2	2	2	2
Steady state cavity power P_{kick0}	W	2.9	5.6	7.5	10.8	16.7
Steady state stored energy U_{cav0}	μJ	30.0	32.1	35.8	43.0	56.5
Steady state forward voltage V_{fwd0}	V	12.2	16.9	19.5	23.3	29.0
Steady state forward power P_{fwd0}	W	3.0	5.7	7.6	10.9	16.8
Steady state backward power P_{bwd0}	W					
Duty cycle η	-					
Average forward power P_{ave}	W					
Critical β's	-	0.74	1.21	1.22	1.20	1.25
Scaling factor κ	-	1.79	1.17	1.11	1.07	1.04
Scaled forward voltage V_{fwd}	V	21.9	19.8	21.7	25.0	30.2
Scaled forward power P_{fwd}	W	9.6	7.8	9.4	12.5	18.2
Discharging slope A	MV/s	-0.96	-0.29	-0.21	-0.16	-0.12

The figures of merit of 5-mode cavity

Parameters	Units	1	2	3	4	5
f	MHz	36.9375	184.6875	258.5625	406.3125	480.1875
R_{sh} / Q_0	MΩ	1612	297	195	95	66
G	Ω	9.5	47.4	66.3	104.1	123.0
P_d (CW)	kW	1	1.3	1.1	0.6	0.3

Parameters	Units	1	2	3
f	MHz	147.8	295.5	443.3
R_{sh} / Q_0	Ω	1521	1282	907
G	Ω	34.5	61.6	84.7
P_d (CW)	W	1495	624	197
Q_0	-	9893	12500	14027
H	mm	491	236	150.2

All my calculations are in sheet 1 of the spreadsheet I sent you on Aug 28.

With each given frequency, Rt/Q and G, we first scale the Q0 with 80% copper conductivity. If we tentatively set beta and pfwd, we can have all the rest of parameters including Ql, fill time, voltage at equilibrium, as well as the voltage after 10us of filling.

Then I can use the excel optimizer to maximize V@10us by varying beta. After that, we can also vary pfwd so V@10us is our desired kicking voltage.

We can also calculate the beta vs V@10us curve with given pfwd (or beta vs pfwd with given V@10us). As I mentioned before, the curve is not very sharp. The spreadsheet is attached, with "input" parameters (f, conductivity, R/Q, and simulated Q0 using ideal conductivity) highlighted.

Back ups

The beam parameters of the RCS

Parameters	Unit	Values
Circumference L	m	3841.35
Revolution period T_{rev}	μs	12.8
Beam energy E_b	MeV	400
Bunch frequency f_b	MHz	591.258
Bunch charge Q_b	nC	7
Kick frequency f_k	MHz	147.8
Kick angle θ	mrad	1
Bunch distr.$_\perp$	-	Gaussian
Bunch distr.$_\parallel$	-	Gaussian
Horizontal Twiss parameter α_x	-	0.81956
Horizontal Twiss parameter β_x	m	11.137
Vertical Twiss parameter α_y	-	-2.0339
Vertical Twiss parameter β_y	m	36.438
Horizontal Dispersion η_x	m	0.6
Horizontal Dispersion slope η'_x	-	0.5
Vertical Dispersion η_y	m	0
Vertical Dispersion slope η'_y	-	0
Emittance ϵ_x^n	mm mrad	26
Emittance ϵ_y^n	mm mrad	26
Bunch length l_b	cm	12
rms Energy spread δ	-	2.5×10^{-3}
Beam aperture	mm	40
Max relative pol. loss	%	5
Ramping repetition rate	Hz	1
Acceleration time	ms, turns	100, 8000
Total number of spineffective superperiods	-	96
Horizontal tunes Q_x	-	57.632
Vertical tunes Q_y	-	60.732

You can do a quad scan to measure the emittance very easily, but only if you separate the two beams beforehand so you can center the beam of interest with respect to the lens

Unless, of course, the DAQ can be triggered to the pulses

This will depend on the time structure we can generate. We can either make CW beam and trigger the DAQ accordingly (potentially difficult due to high frequency) or design the time structure to only supply particles to either kicked or unkicked buckets

Screens can be used but have no time resolution

From what I've heard, the UITF is supposed to get a replacement cryomodule from CEBAF. Moving the current QCM out is not going to happen until January

We are getting back the cryogens sometime in the summer and will likely move out the current QCM in early 2022 as far as I understand

For CEBAF, 476.3MHz=1497*7/22.

To test the 952.6MHz kicker with UITF, we can send 136.09MHz(=952.6/7=1497/11) beam, and kick 1 in 11 of the bunches (12.37MHz), with the rest unkicked. We can ask Shukui for the lase capability.

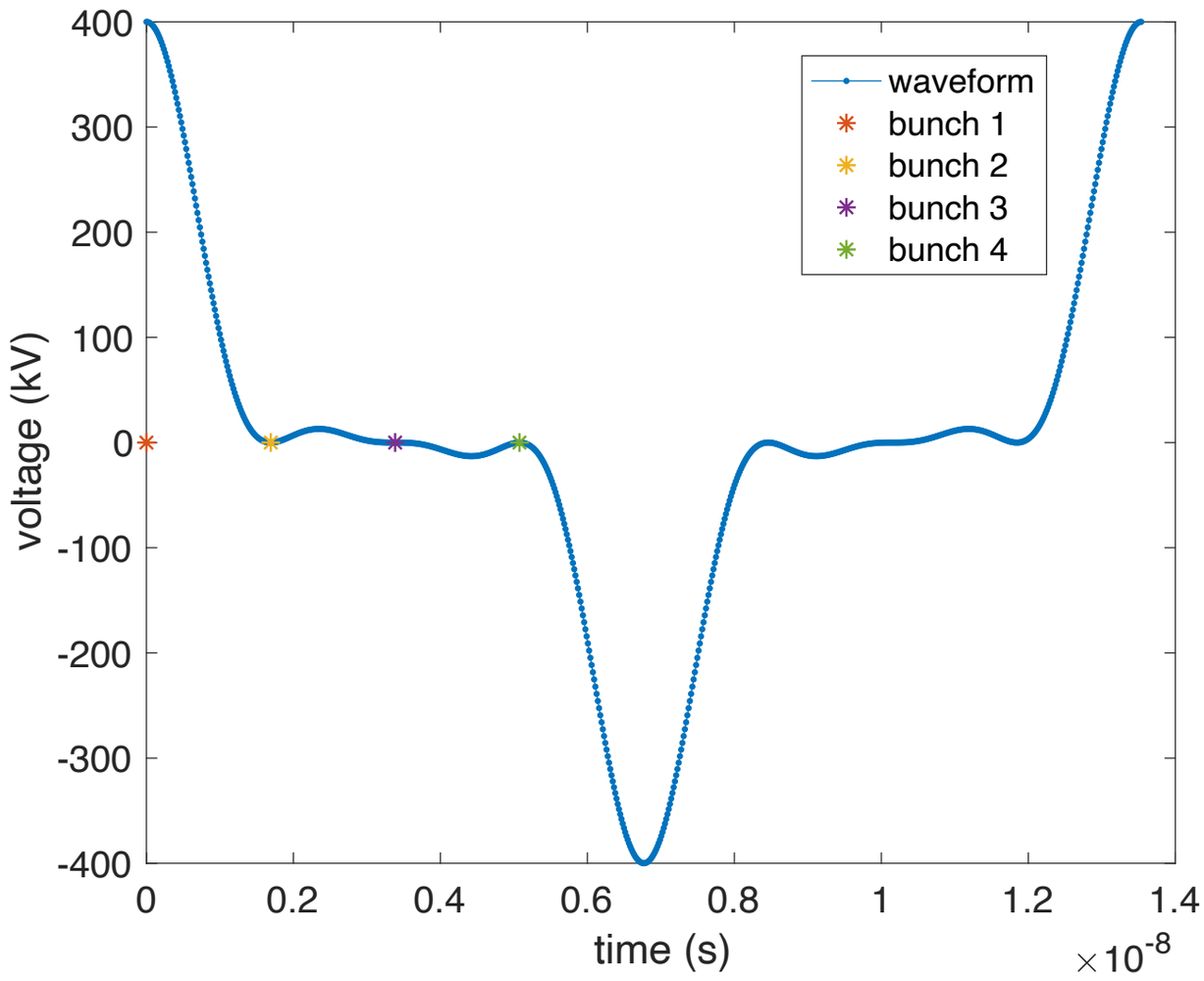
For the BNL EIC, we don't need to worry about testing at the exact frequency right now. What we can do is to test with your cavity at its own frequency and demonstrate the concept of syncing the modes in pulsed mode. Changing the design to something close to 147.8 MHz takes too much more effort for now. However, we can't demonstrate the 1.6ns rise time with 136 MHz, the best we can do is only ~7ns.

If we want to demonstrate the ~1.6ns rise time with your cavity design, we need to find a 476MHz beam to test on your cavity, which is not easy. The next option is to test with 433.3MHz beam, and run your cavity with only the first 2-3 modes. This could be done at IOTA?

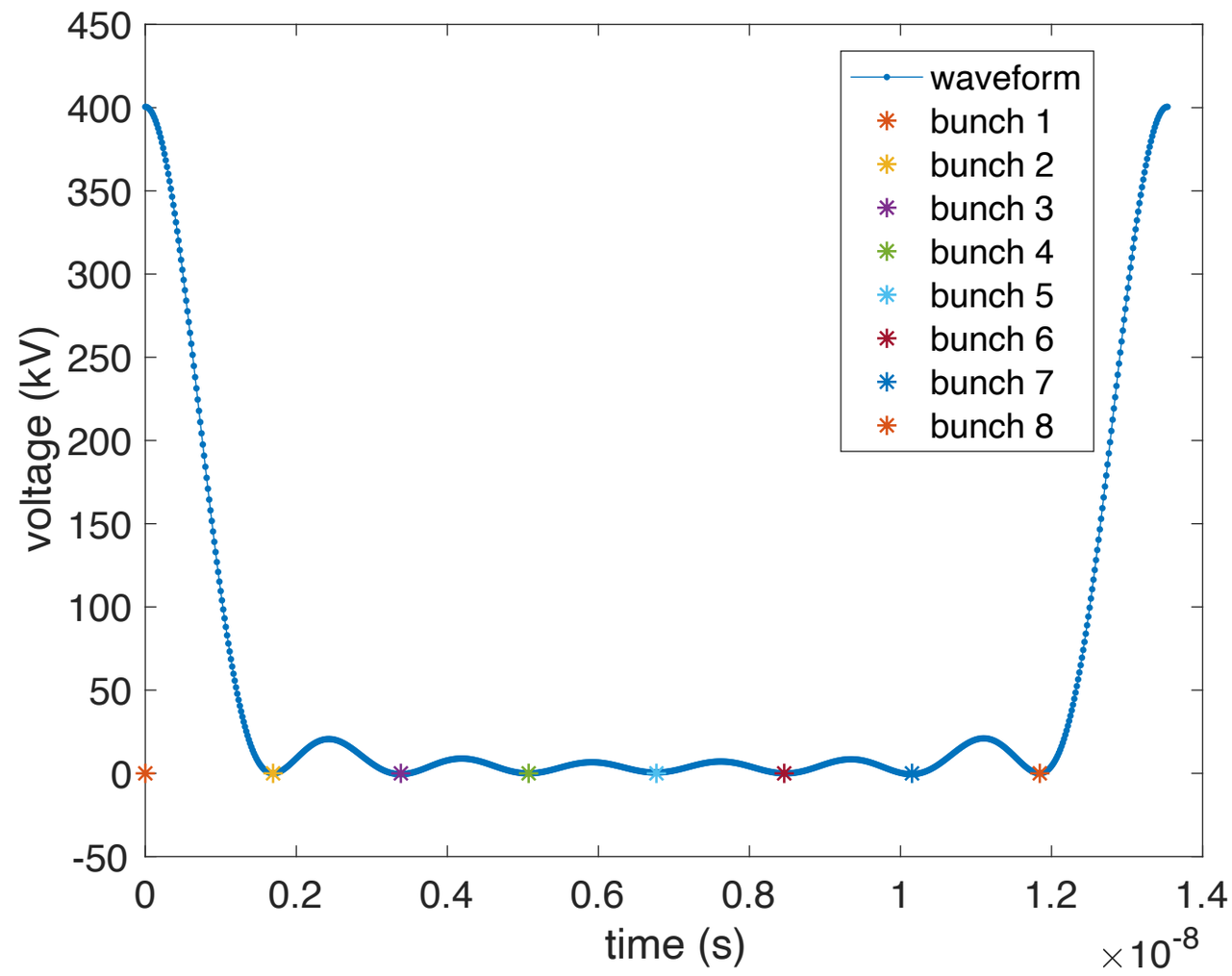
- RF source specification

- The RF harmonic driver/combiner up to 100W each mode (on 50 ohm).

Harmonic Modes	Freq. (MHz)	Amp. (kV)
1	73.875	175
3	221.625	125
5	369.375	75
7	517.125	25
DC	0	0



Harmonic Modes	Freq. (MHz)	Amp. (kV)
1	73.9	87.5
2	147.8	75
3	221.6	62.5
4	295.5	50
5	369.4	37.5
6	433.3	25
7	517.1	12.5
DC	0	50



At the injection point of the RCS = kicker location, the lattice parameters

Parameters	α_x	β_x	α_y	β_y	η_x	η'_x	Q_x	Q_y
Units	-	m	-	m	m	-	deg	deg
Values	0.8156	11.137	-2.0339	36.438	0.6	0.5	57.632	60.732

Table 3: The lattice parameter at the RCS injection point. In addition $\eta_y = \eta'_y = 0$ and $\gamma_{x,y} = (1+\alpha_{x,y}^2)/\beta_{x,y}$.

The corresponding one-turn matrix of the RCS

$$M = \begin{bmatrix} \cos Q_x + \alpha_x \sin Q_x & \beta_x \sin Q_x & 0 & 0 & 0 & \eta_x \\ -\gamma_x \sin Q_x & \cos Q_x - \alpha_x \sin Q_x & 0 & 0 & 0 & \eta'_x \\ 0 & 0 & \cos Q_y + \alpha_y \sin Q_y & \beta_y \sin Q_y & 0 & \eta_y \\ 0 & 0 & -\gamma_y \sin Q_y & \cos Q_y - \alpha_y \sin Q_y & 0 & \eta'_y \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix M acts on the phase space vector V defined as

$$V = \begin{bmatrix} x \\ x' \\ y \\ y' \\ t \\ \Delta p/p_0 \end{bmatrix}$$

❋ 4-bunch option

	CAV 1	CAV2	CAV3
Freq.	147.8 MHz	295.5 MHz	443.4 MHz
Transverse size	0.5 m	0.25 m	0.17 m
Longitudinal size	1 m+0.2 m	0.5 m+0.2 m	0.34 m+0.2 m

$\lambda/4$

$\lambda/2$ for maximum transit time

Total length : 2.4m+0.6m=3m

Beam pipe

DC magnet+margin

❋ 8-bunch option

	CAV 4	CAV5	CAV6	CAV7
Freq.	73.9 MHz	221.7 MHz	369.5 MHz	517.3 MHz
Transverse size	1 m	0.3 m	0.2 m	0.15 m
Longitudinal size	2 m+0.2 m	0.7 m+0.2 m	0.4 m+0.2 m	0.3 m+0.2 m

Total length : 3m+4.2m=7.2m

The cavity dimensions

Parameters	Units	Values
Heigts	mm	2200
Outer radius	mm	120
Inner radius	mm	40
Bea pipe	mm	120
Total length	Mm	560

3.6.3 RCS Ring Lattice

Each of the six arcs are made up of 16 cells. These cells are composed of two types of FODO cells that differ only by the family of sextupole magnets used in between the Focusing and Defocusing quadrupoles. We classify these as FODO CELL A and FODO CELL B. The A and B FODO cells with sector bending magnets is outlined in the Table 3.45. Here D represents drift space, QF0/D0 focusing and defocusing quadrupoles respectively and SBEND the sector bend magnet. In the drift spaces 4 families of sextupoles are inserted (not shown).

Table 3.45: A and B arc FODO cell.

QD0/2	D	SBEND	D	QF0	D	SBEND	D	QD0/2

The straight sections are composed to two identical lattices placed in mirror image around each straight section center point as shown in Table 3.46. Here D is the drift space of approximately 7.4 m, QF(1–8) and QD(0–8) represent focusing and defocusing quadrupole families. For some of the sections RF cavities and sextupole magnets and dipoles are inserted (not shown). The breaking of the symmetry caused by these insertions are managed by tuning the quadrupoles to suppress their contribution to the intrinsic resonance strength over the 400 MeV to 18 GeV energy range (see Section 3.6.8). The dipole positioning is described in Section 3.6.8 so as to navigate around the detectors and accommodate the RF assemblies. The orientation around the straight section center point is shown in Table 3.47. In this table, sixteen Arc A and B cells (16 $\times$ (ACell, BCell) are shown, connecting to the forward straight section (TM), and the mirror TM lattice (-TM) and back to next arc-cells.

Table 3.46: Straight section line (named TM).

TM	(QD0/2	D	QF1	D	QD1	D	QF2	D	QD2	D	QF3	D	QD3	D	QF4	D	QD4
	D	QF5	D	QD5	D	QF6	D	QD6	D	QF7	D	QD7	D	QF8	D	QD8/2)	

Table 3.47: Arc to Straight Section beamline.

16 $\times$ (ACell,BCell)	TM	-TM	16x(ACell,BCell)

With the straight sections, the tunes now become $Q_x = 57.632$ and $Q_y = 60.732$. However since the vertical arc tunes are still 50 our spin resonance structure remains unchanged. The beta and dispersion functions are plotted in Figure 3.130. The straight sections across each IP is shown in Figures 3.131 and 3.132.