Design and commissioning of a two-harmonic pre-buncher for extended bunch spacing at LEAF

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Outline

① TOF need

- ~100 ns spacing required.

② Chopper limitation

- 87.5% beam loss.

③ Pre-buncher strategy

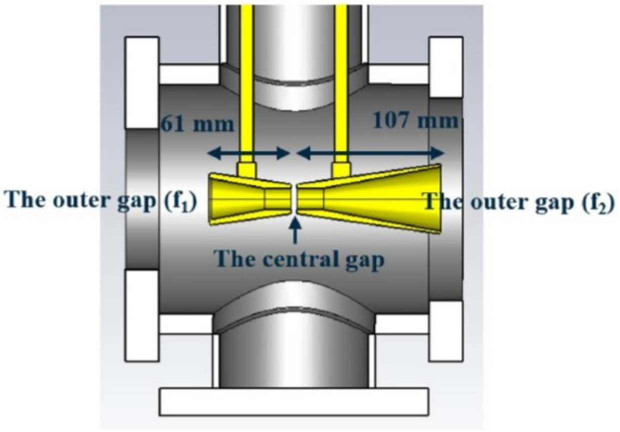
- 1st & 2nd harmonics
- Velocity modulation

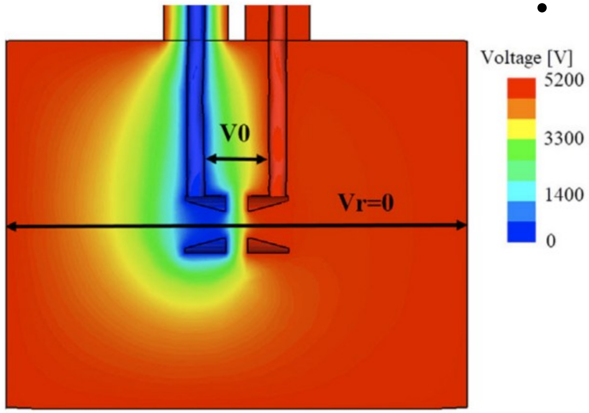
④ Validation

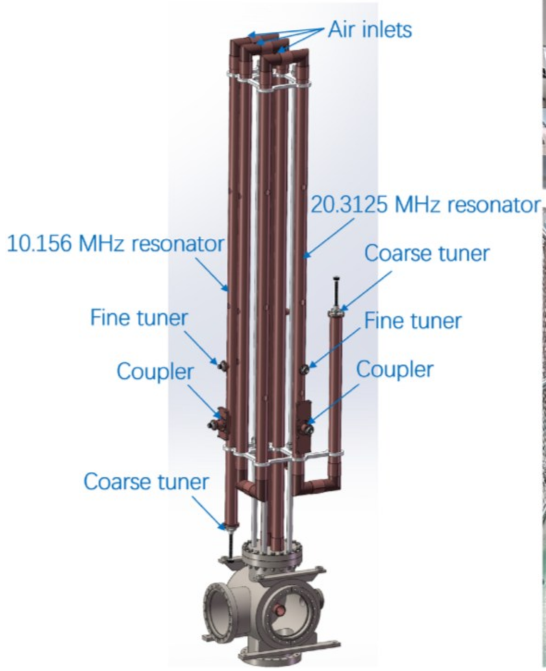
- 76.8% acc-eff
- 98.4 ns spacing

⑤ Critical boundary

- Satellite bunches remain







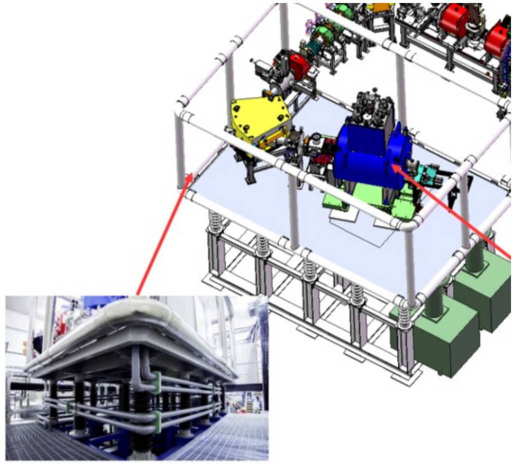
이온 가속기 설계!
ECR Source
RF
전자(Electron) +
강한 자기장(Magnetic Field)
→ 플라즈마 생성!
이온 발생!
RFQ
RF(고주파 전기장)로
이온을 모으고 가속!
다음 단계로!
설계 완료!
이온을 가속해서
더 높은 에너지로!
^_^
설계 포인트!
이온 발생 (ECR)
이온 집속 및 가속 (RFQ)
빔 품질 향상
목표 (Goal)!
High Current
High Reliability
High Efficiency

Background: Electron Cyclotron Resonance (ECR) ion source

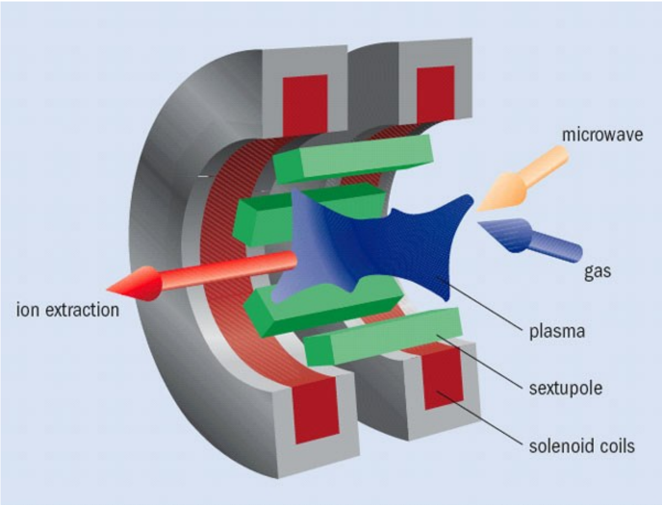
From neutral gas to extracted ion beam

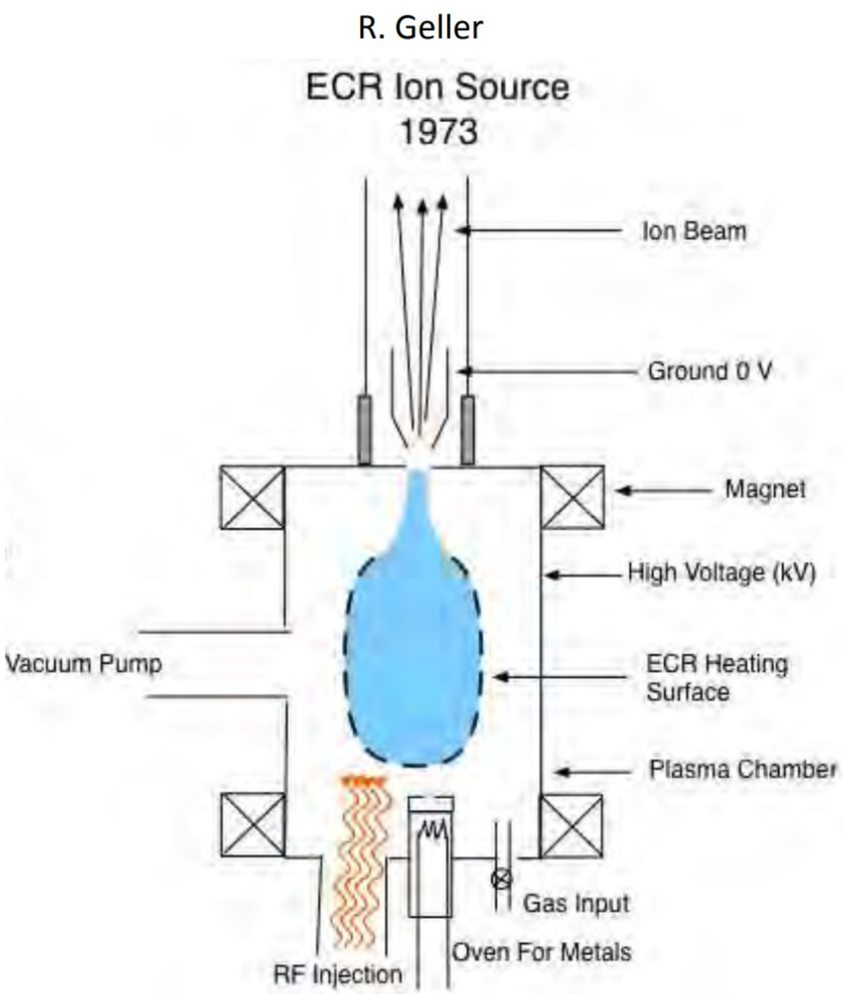
ECR heating and ion extraction

1. Microwave ECR heating creates hot electrons.
2. Hot electrons ionize neutral gas into positive ions. ($\omega_{ec} = \frac{eB}{m_e}$)
   - Initial step: $e^- + X \rightarrow X^+ + 2e^-$
   - n$^{\text{th}}$ step: $e^- + X^{q+} \rightarrow \boldsymbol{X^{(q+1)+}} + 2e^-$
3. Magnetic confinement sustains the plasma.
4. Ions are extracted by a DC field and selected by A/q. ($\boldsymbol{\beta \sim 0.005 - 0.05}$)



High voltage platform



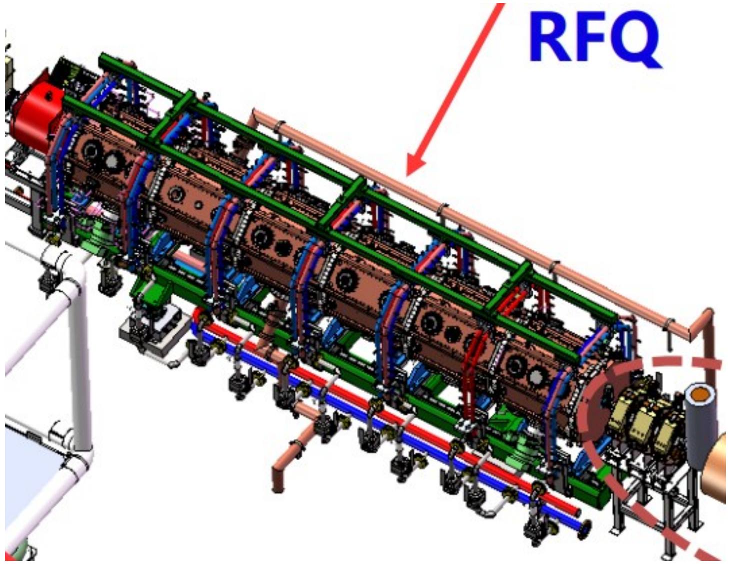


Background: Radio-Frequency Quadrupole (RFQ)

Converting a low-energy DC ion beam into RF microbunches

Focusing, bunching, and acceleration in a single RF structure

1. Transverse focusing by RF quadrupole electric fields
2. Longitudinal bunching by vane modulation
3. Acceleration of captured ion bunches



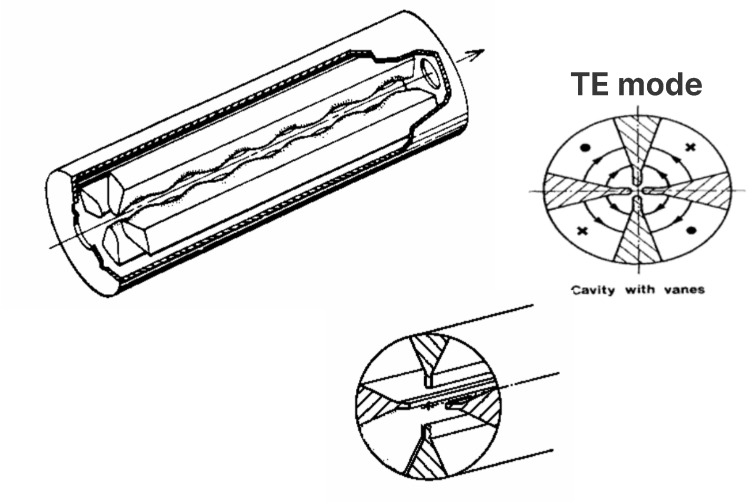


Fig. 2: Sketch of an RFQ cavity—courtesy T. Wangler

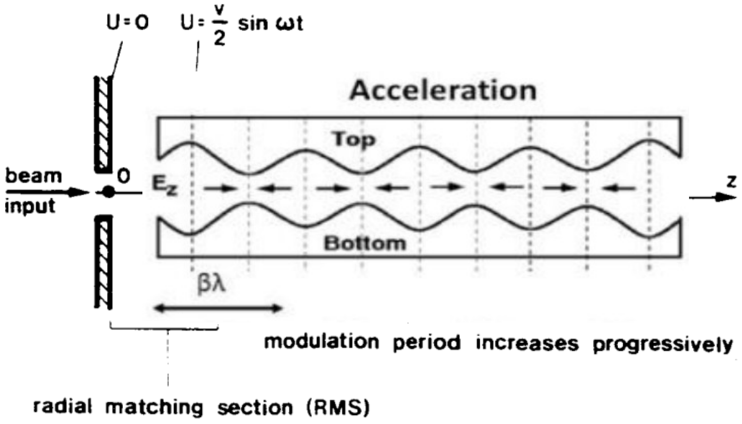


Fig. 10 Typical vane shape in an RFQ

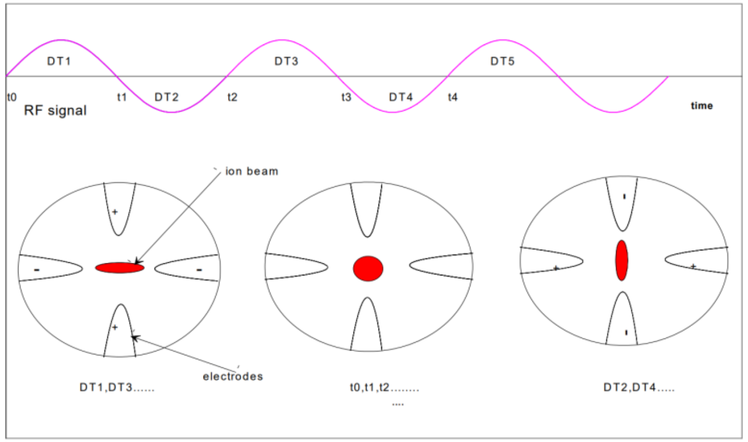
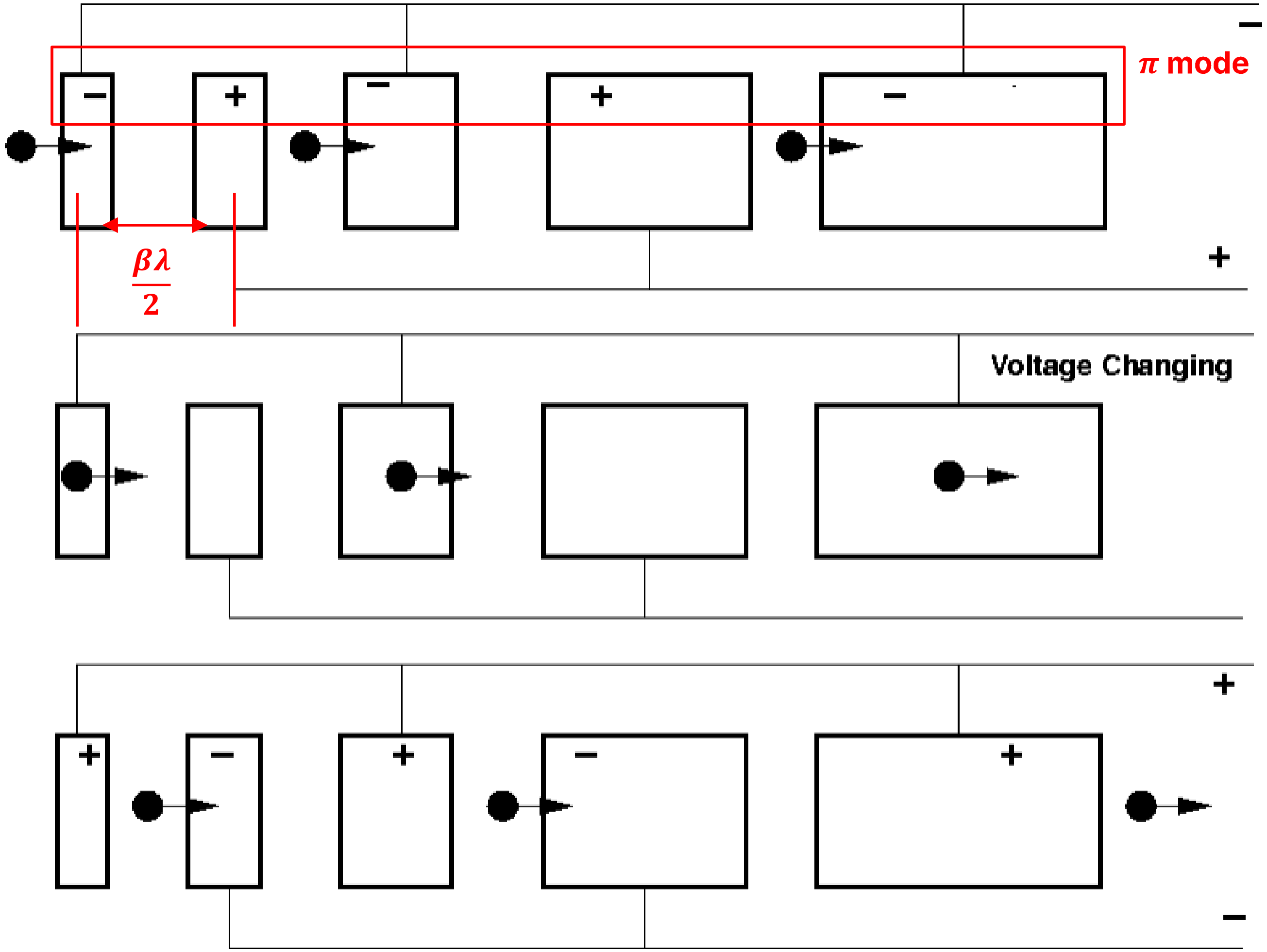


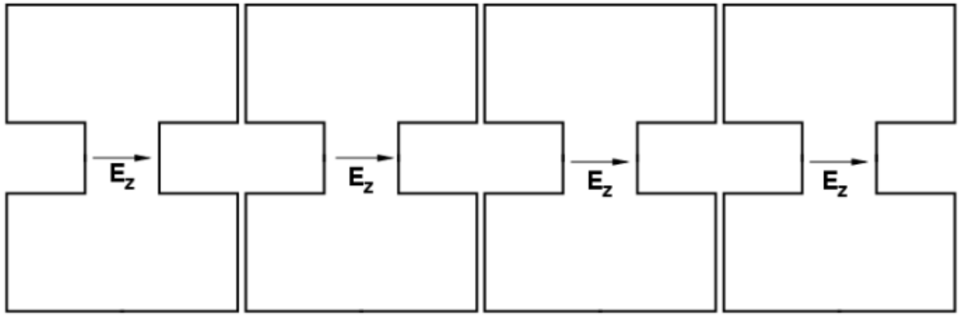
Fig. 6: Time-varying transverse focusing field in a RFQ

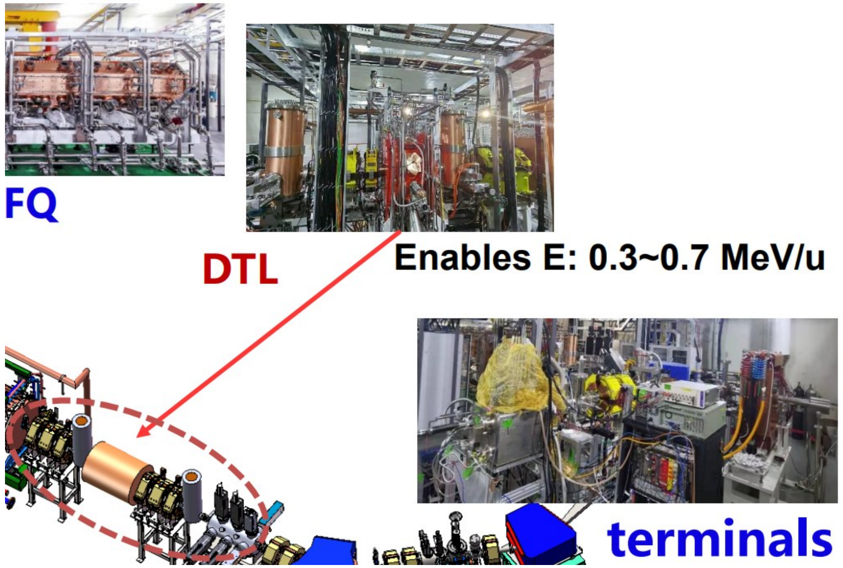
Background: Drift tube linac (DTL)

Low-β ion acceleration using RF gaps and drift tubes

Principle of drift-tube acceleration

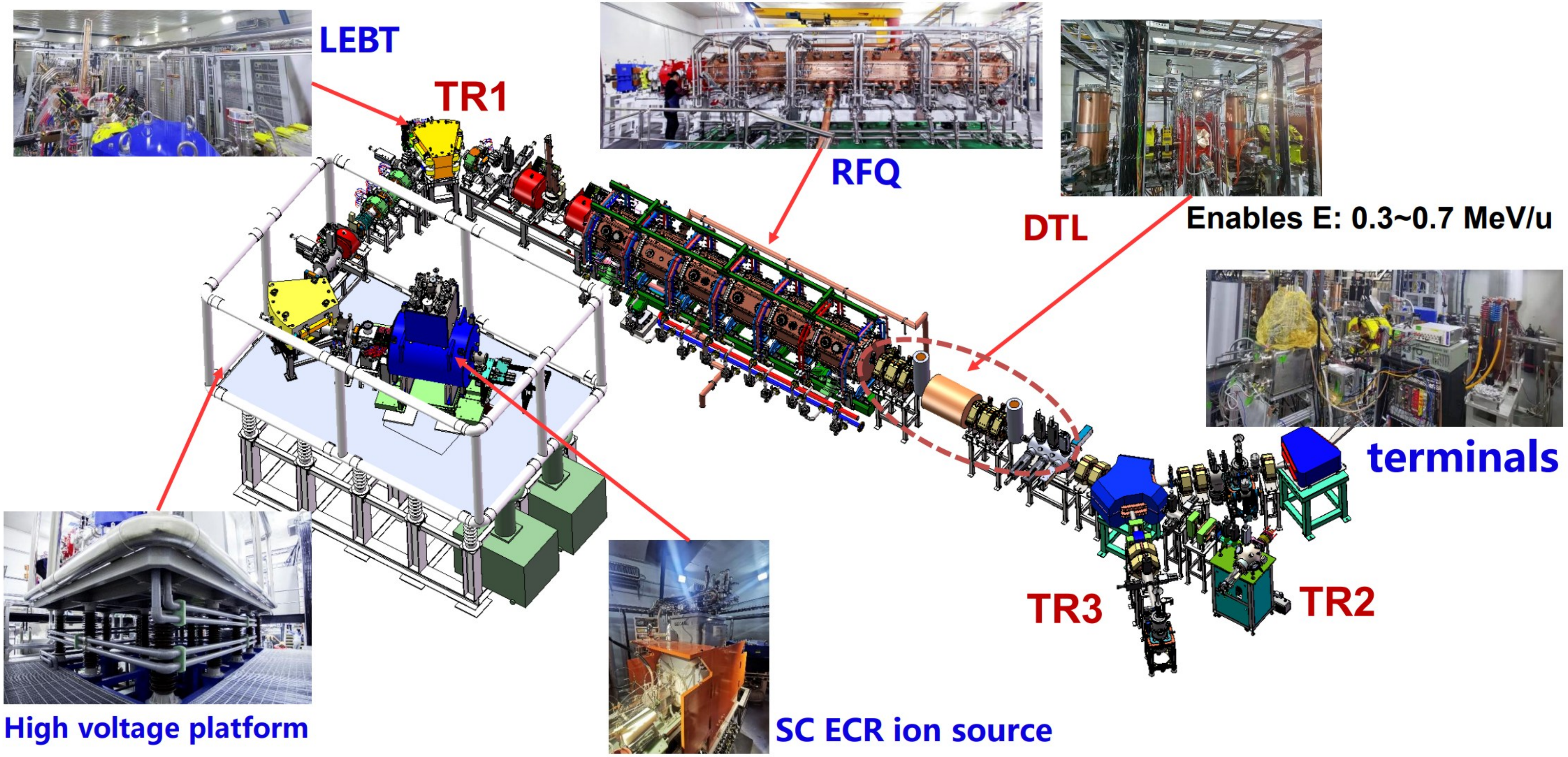


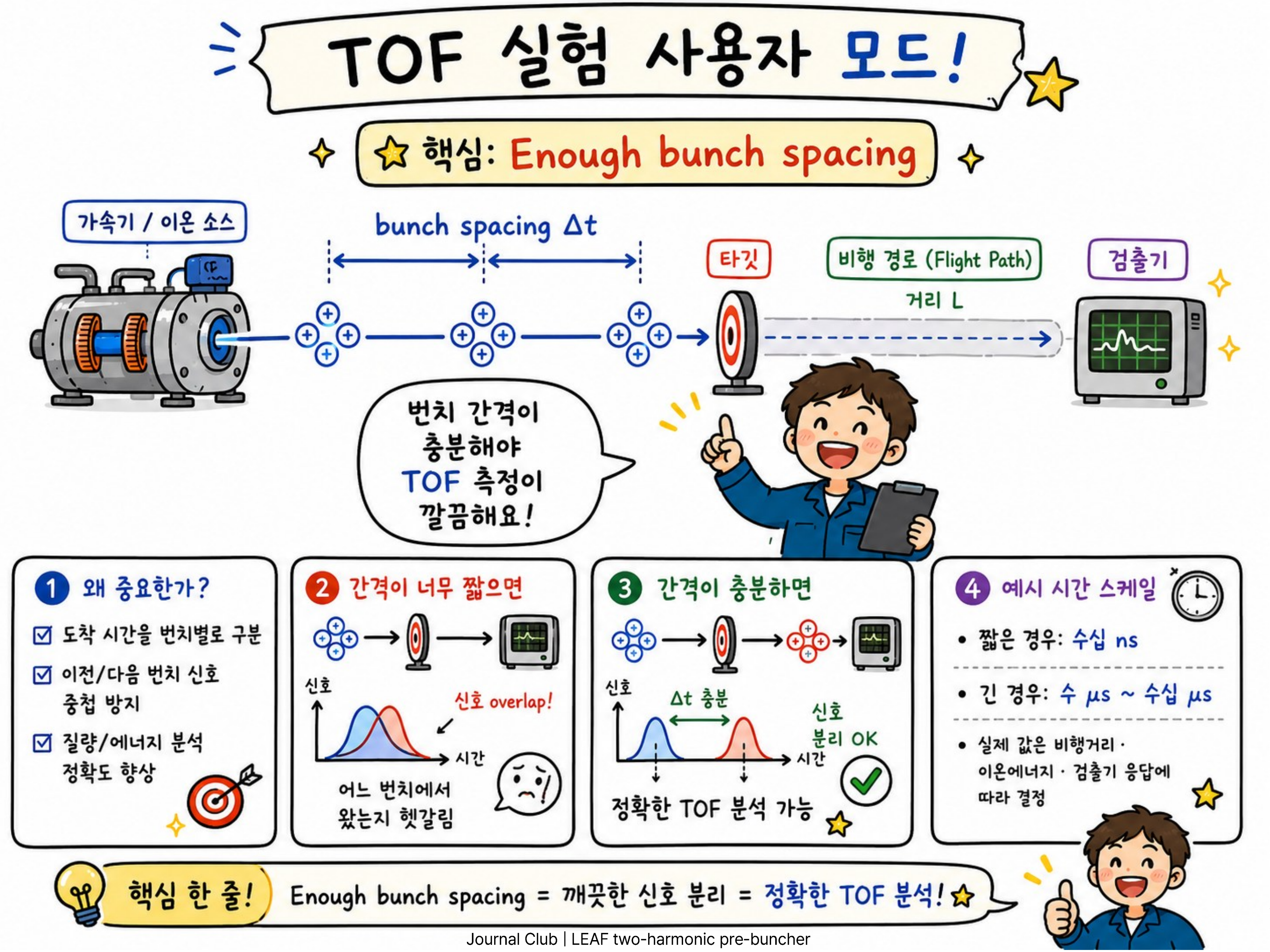




Background: LEAF facility

Using pre-buncher cavity increases the bunching efficiency compared to the chopper





TOF 실험 사용자 모드!
핵심: Enough bunch spacing
가속기 / 이온 소스
bunch spacing Δt
타깃
비행 경로 (Flight Path)
거리 L
검출기
번치 간격이 충분해야 TOF 측정이 깔끔해요!
1 왜 중요한가?
도착 시간을 번치별로 구분
이전/다음 번치 신호 중첩 방지
질량/에너지 분석 정확도 향상
2 간격이 너무 짧으면
신호
신호 overlap!
시간
어느 번치에서 왔는지 헷갈림
3 간격이 충분하면
신호
Δt 충분
신호 분리 OK
시간
정확한 TOF 분석 가능
4 예시 시간 스케일
• 짧은 경우: 수십 ns
• 긴 경우: 수 μs ~ 수십 μs
• 실제 값은 비행거리 · 이온에너지 · 검출기 응답에 따라 결정
핵심 한 줄! Enough bunch spacing = 깨끗한 신호 분리 = 정확한 TOF 분석!

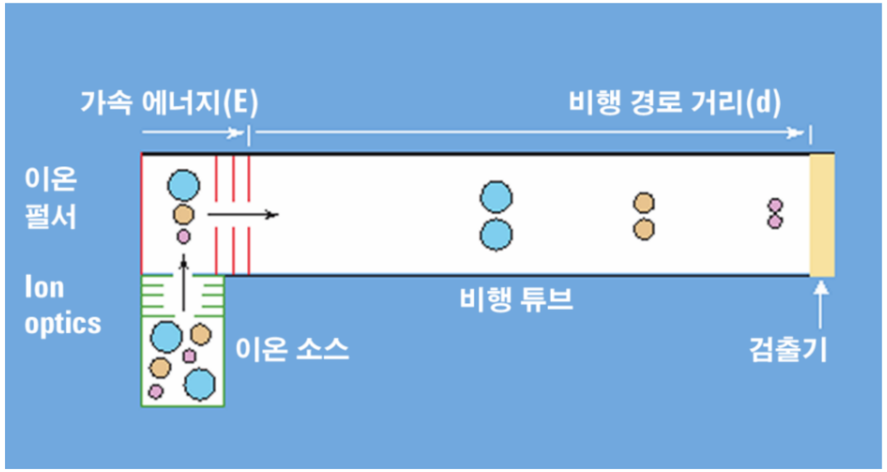
Background: Time-of-flight (TOF) experiment

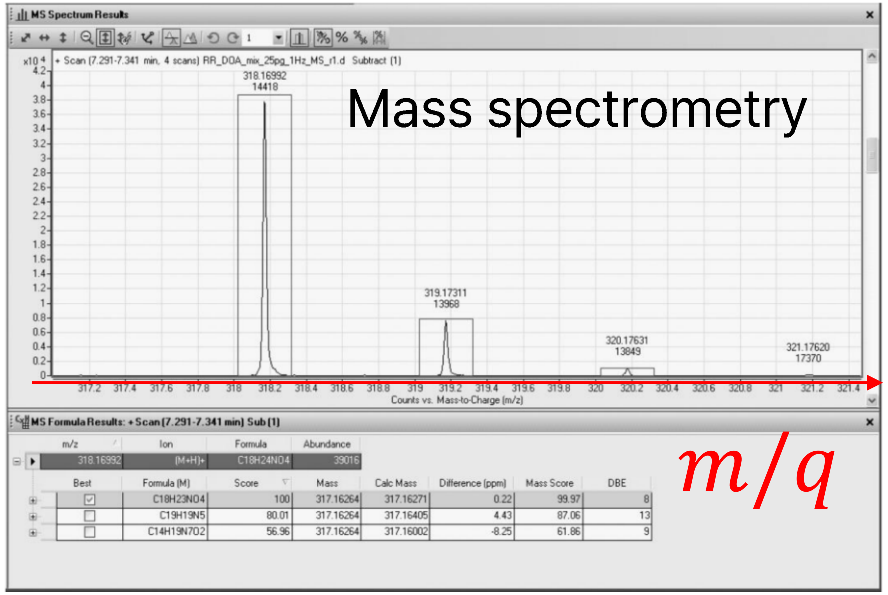
Particle energy measurement using flight time → Particle identification

Principle of TOF measurement

1. A particle travels over a known flight path length.
2. The arrival time is measured relative to the beam timing signal.
3. The velocity is obtained $v = \frac{L}{t_{\mathrm{TOF}}}$.
4. The kinetic energy is reconstructed from $K = \frac{1}{2}mv^2$.

$$m = 2K\left(\frac{t_{TOF}}{L}\right)^2$$ → Particle identification





Short bunch spacing

→ frame overlap → ambiguous TOF assignment

Trivial solution: Chopper

Selecting RF bunches before DTL injection

Fast transverse kicker for controlled beam removal

1. DTL freq. is 81.25 MHz, giving the spacing of ~ 12.3 ns
2. Such a short spacing is unsuitable for TOF measurements!!
3. Chopper removes unwanted bunches

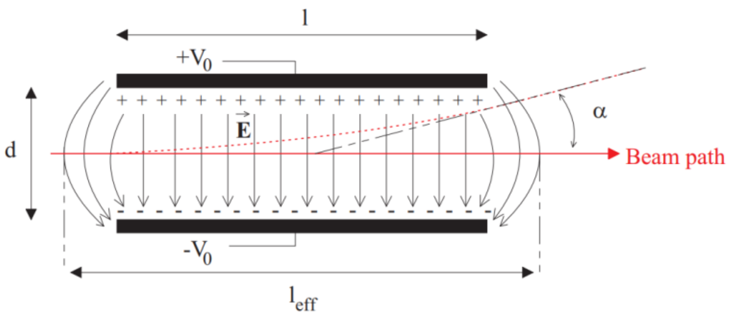


Figure 2.1: theoretical chopping scheme

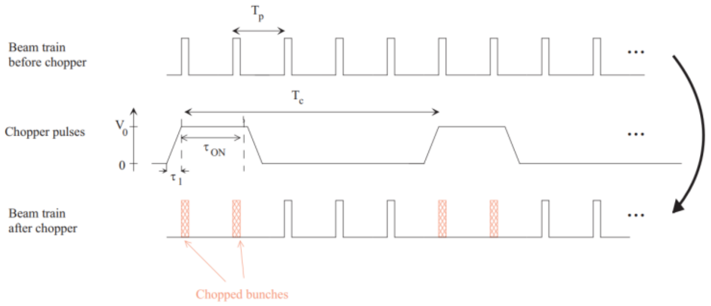
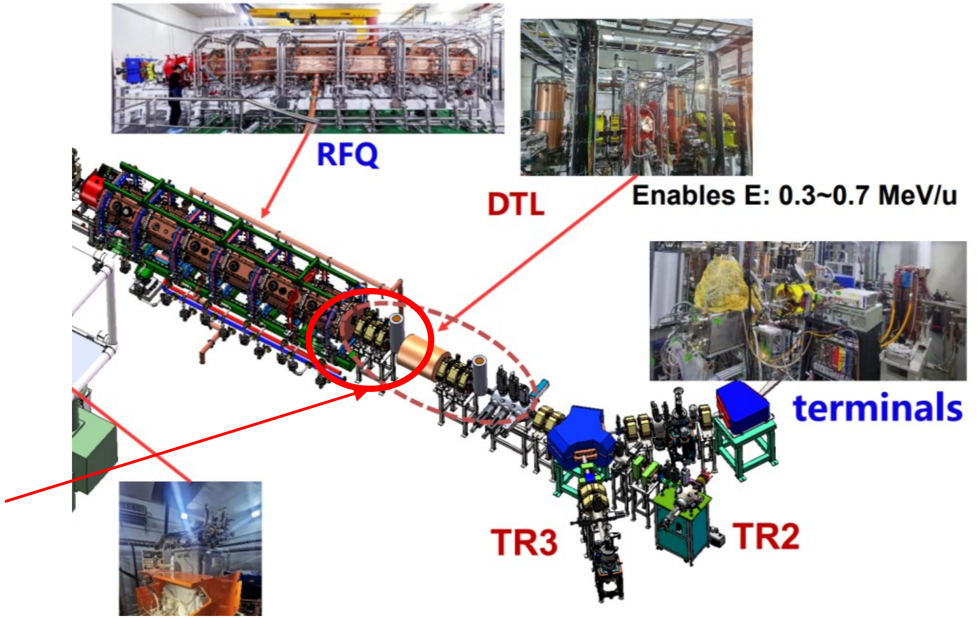


Figure 2.3: chopping time structure



- **Target spacing:** 100 ns
- **Current spacing:** 12.3 ns
  - To reach 100 ns, 7 of every 8 bunches must be removed.
- **Theoretical beam loss:** 87.5%

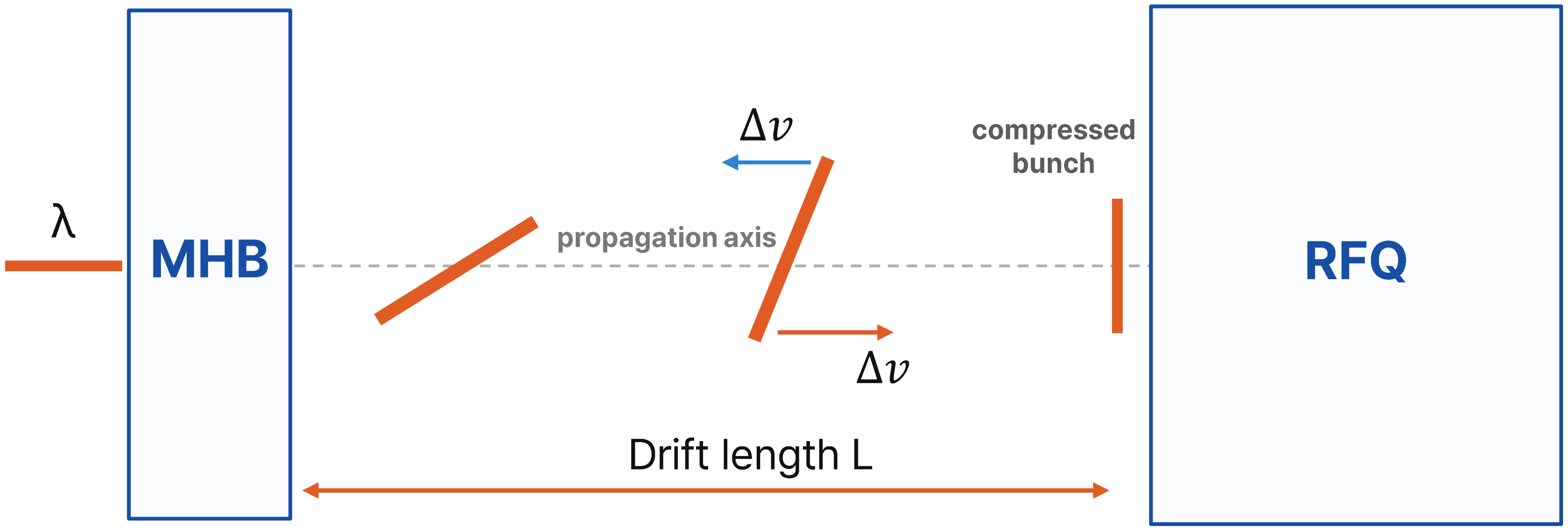
➢ **Result:** beam current becomes too low for users.

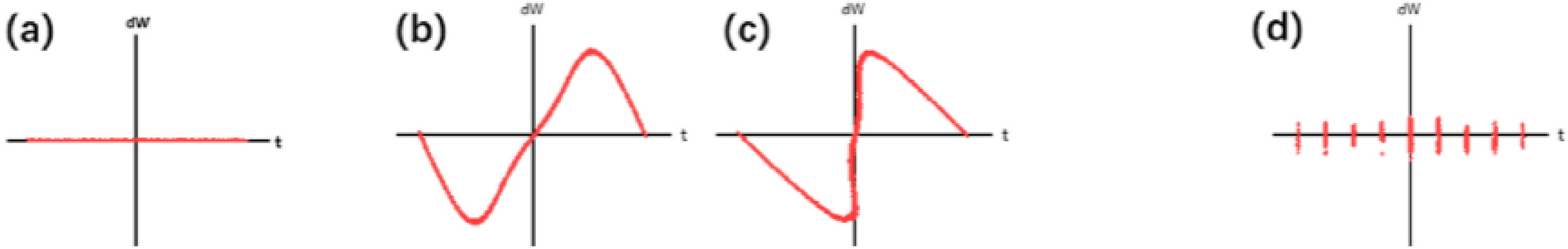
Motivation: 1/8 Sub-harmonic Pre-buncher

10.156 MHz = 81.25 MHz / 8, enabling ~98.5 ns effective bunch spacing

Increasing bunching efficiency without discarding 87.5% bunches

- **Target:** T_{target} ~ 100 ns
- **Harmonic:** $\frac{T_{\text{target}}}{T_{\text{RF}}} \approx 8.13$



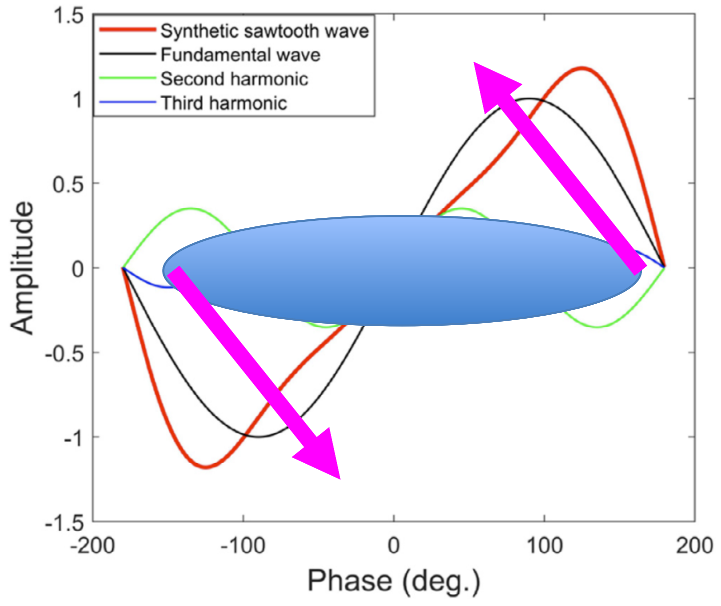


Simulation: Pre-buncher for RFQ capture

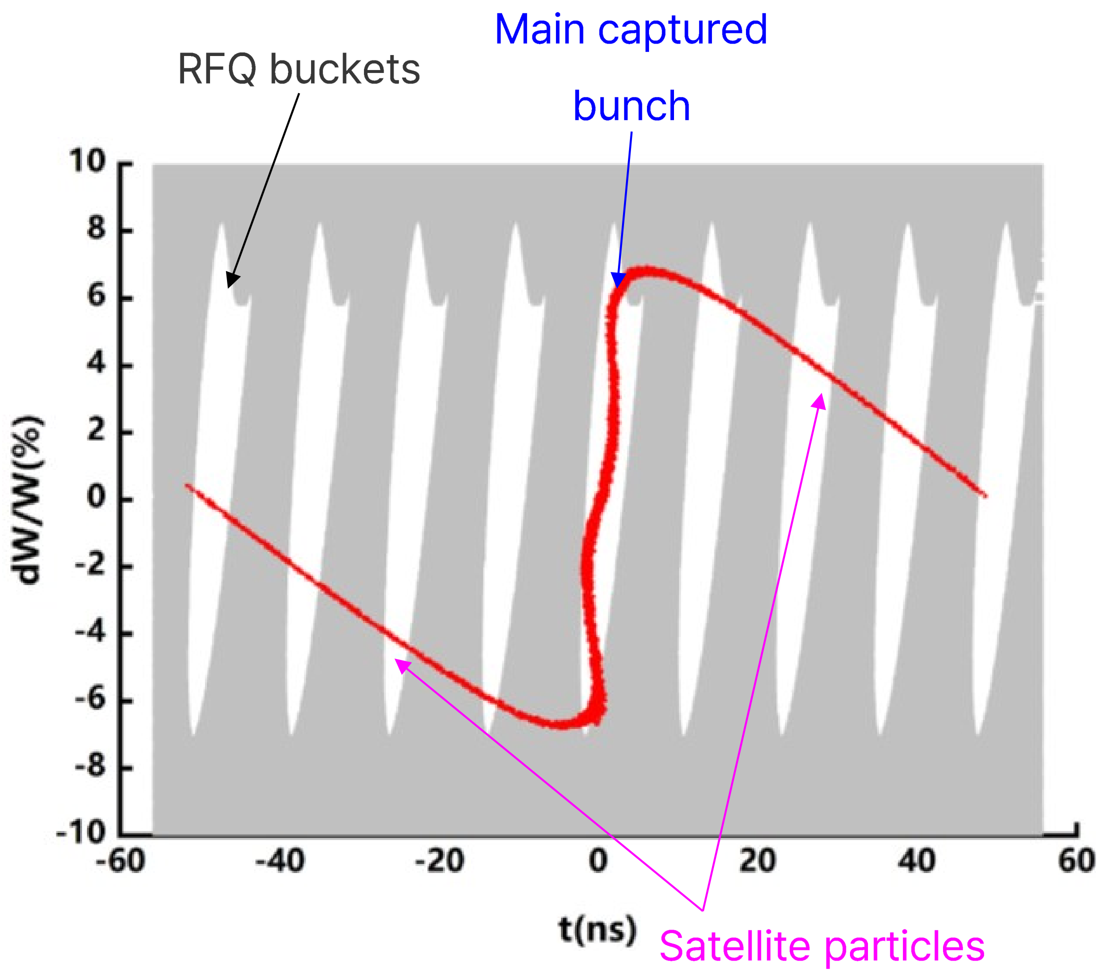
Simulation indicates improved capture without rejecting most RF bunches

Simulated velocity modulation for RFQ capture

- Sawtooth-like voltage waveform modulates the beam velocity.
- $V_{(t)} = V_m(\sin\omega t - 0.40 \sin 2\,\omega t + 0.18 \sin 3\,\omega t - \cdots + C_n \sin n\,\omega t)$
- Satellite particles remain as a source of imperfect capture.
- No beam energy change.



<Synthesized pre-buncher voltage waveform>



<Simulated longitudinal phase space at RFQ injection>

Simulation: Effect of harmonic components

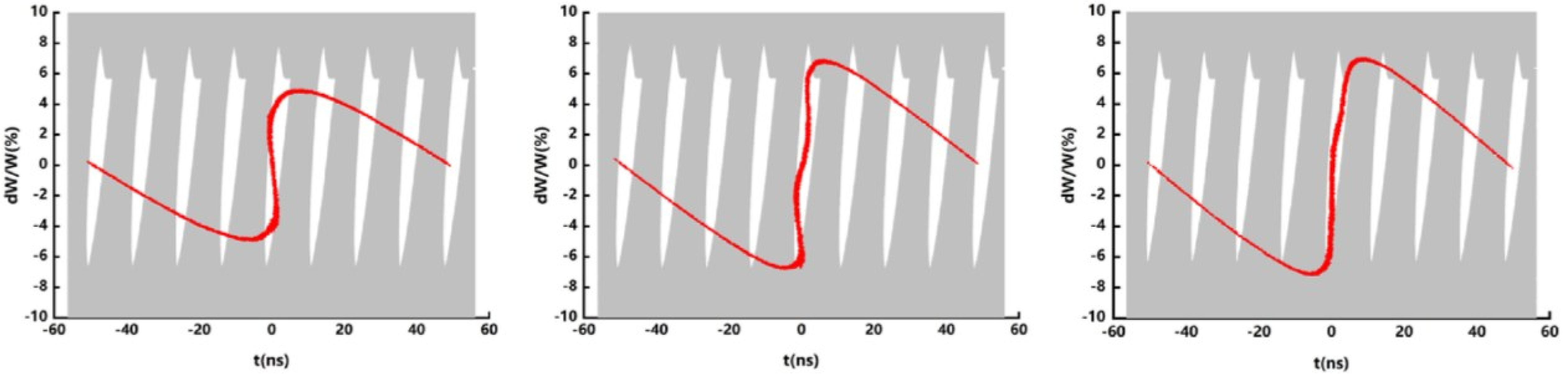
3-harmonic gives only a marginal efficiency gain over 2-harmonic

Bunching efficiency versus harmonic order

- Bunching efficiency increases with harmonic order.
- 1-harmonic: 70.0% → 2-harmonic: 75.8% → 3-harmonic: 77.0%.
- The 3rd harmonic provides only a small additional gain.
- 2-harmonic operation is selected as a practical compromise.

<Efficiency gain from 2nd to 3rd harmonic: +1.2%>

Harmonic	U_1	U_2	U_3	Bunching Efficiency
Without pre-buncher	0	0	0	50%
1-harmonic	5.15 kV	0	0	70%
2-harmonics	6.4 kV	1.6 kV	0	75.8%
3-harmonics	6.5 kV	1.8 kV	0.18 kV	77%

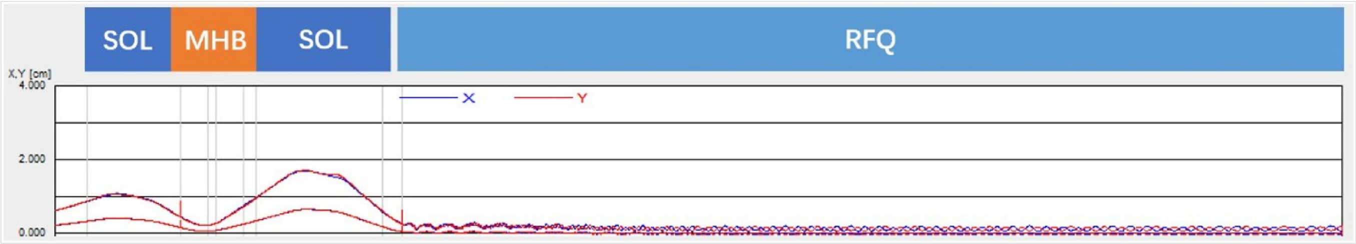


Simulation: Bunching efficiency with pre-buncher

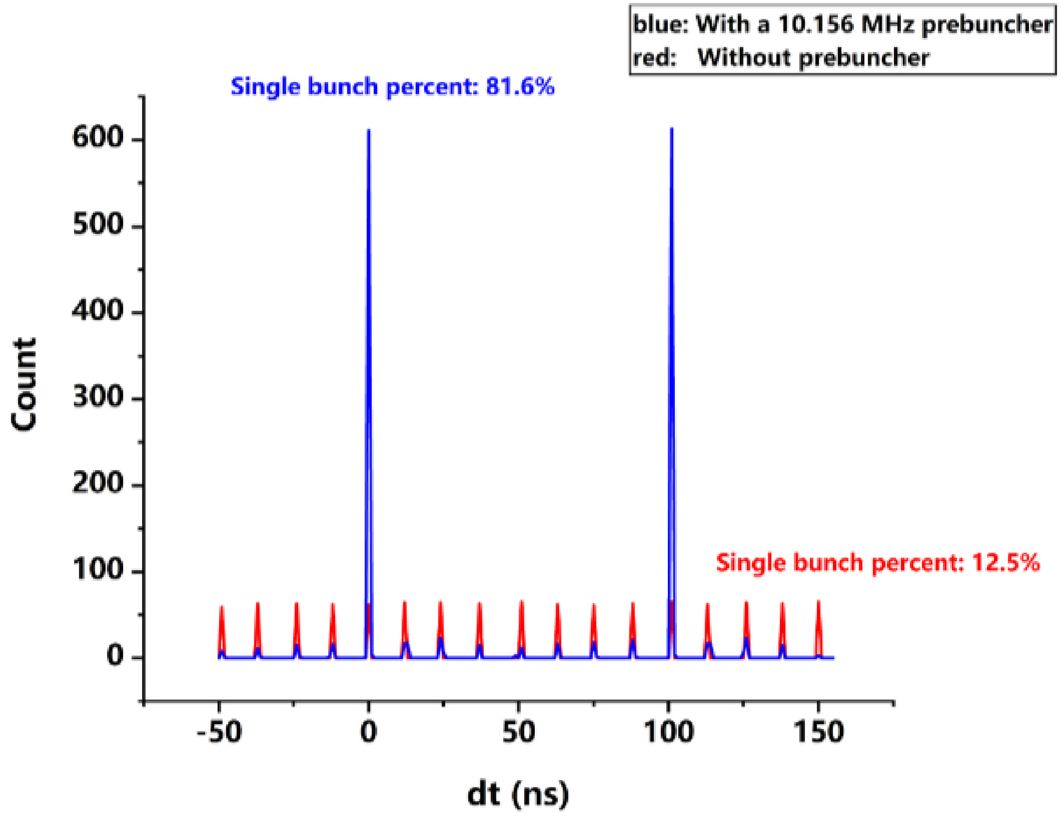
Single-bunch fraction increases from 12.5% to 81.6%

Pre-buncher enhances single-bunch capture

- **Pre-buncher single-bunch fraction:** 81.6%
- **Chopper case 1/8 selection:** 12.5%
- **Relative current gain:** ~6.5x
- Most particles are concentrated into the selected RF bucket.



<Simulated beamline>



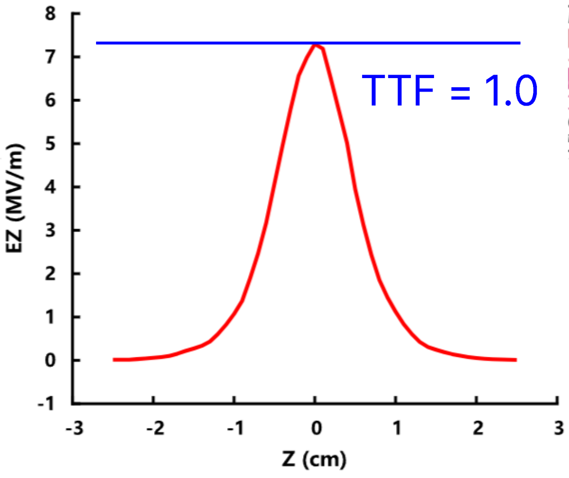
<Bunch distribution with and without 10.156 MHz pre-buncher>

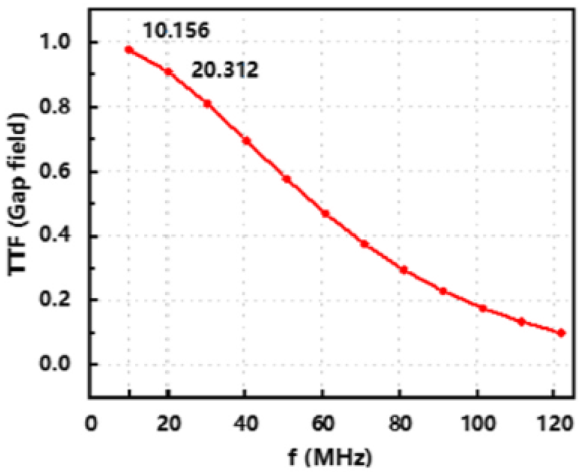
Simulation: Effective RF voltage in the pre-buncher

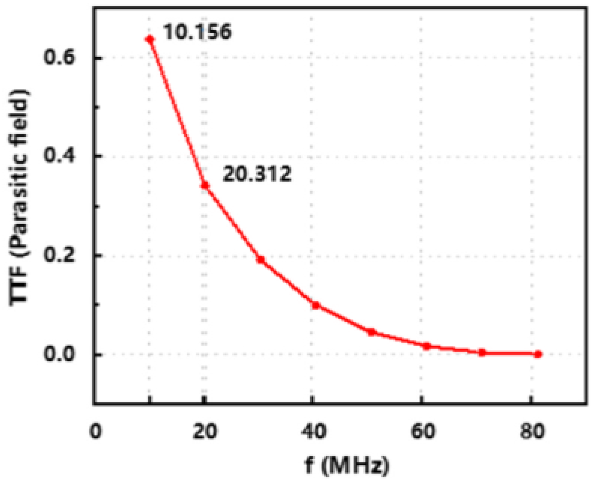
Higher harmonics suffer stronger transit-time reduction

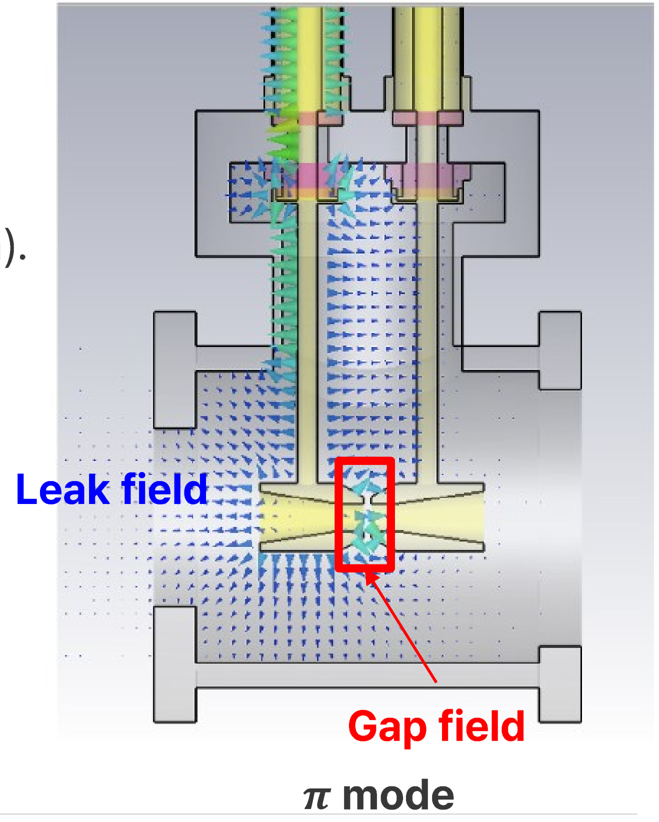
Effective voltage seen by low-β ions: using the leak field as bunching

- $T = \frac{\int_{-L/2}^{L/2} E(0,z)\, \cos\left(\frac{2\pi z}{\beta\lambda}\right) dz}{\int_{-L/2}^{L/2} E(0,z)\, dz}$
- $\cos(\frac{2\pi z}{\beta\lambda})$ where $\lambda = c/f$ is RF wavelength.
- Higher freq. → Lower TTF
- Gap and leak fields could be included in the effective voltage (Better power consumption).









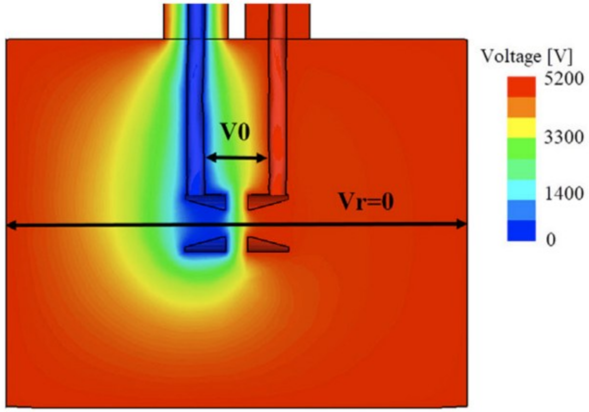
Simulation: Effective RF voltage in the pre-buncher

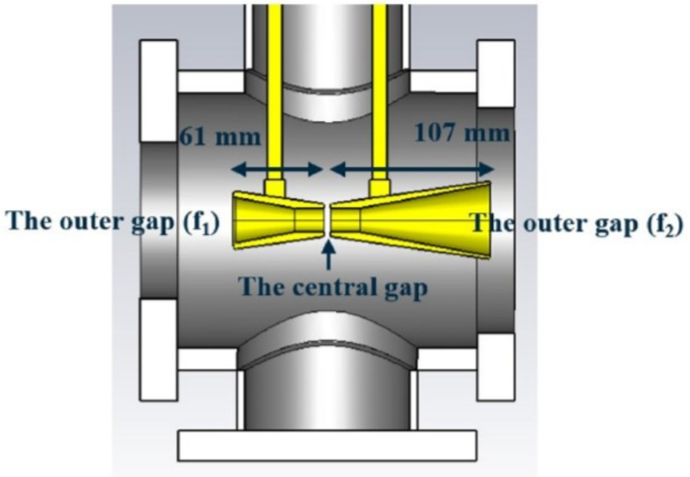
Gap spacing and leakage fields determine the usable modulation voltage

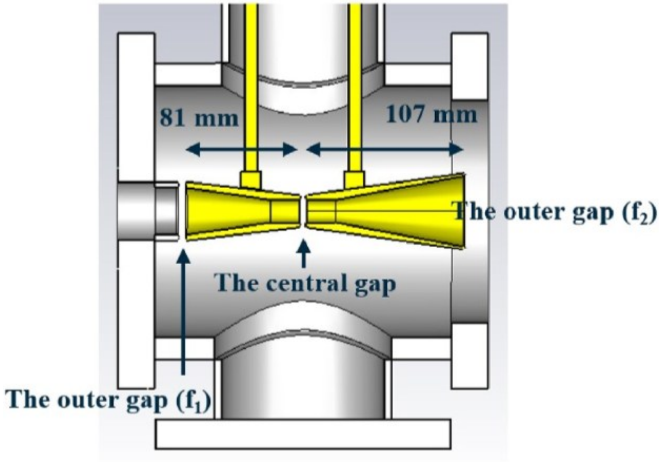
- Beam energy: 14 keV/u
- β = 0.0054826
- f_{RF} = 81.25 MHz
- f_1 = 10.15625 MHz

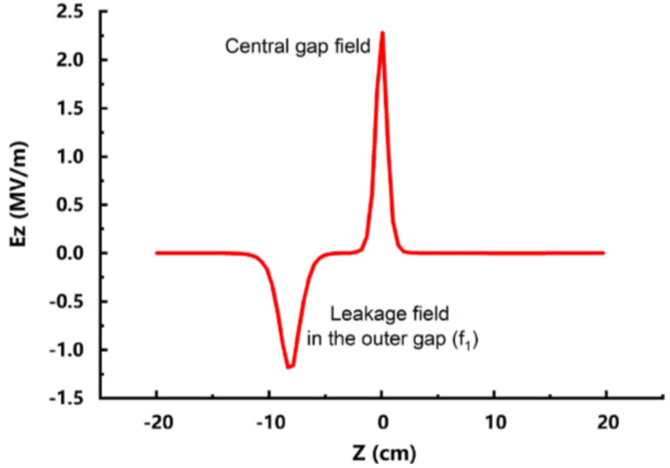
Gap-spacing optimization for low-β ions

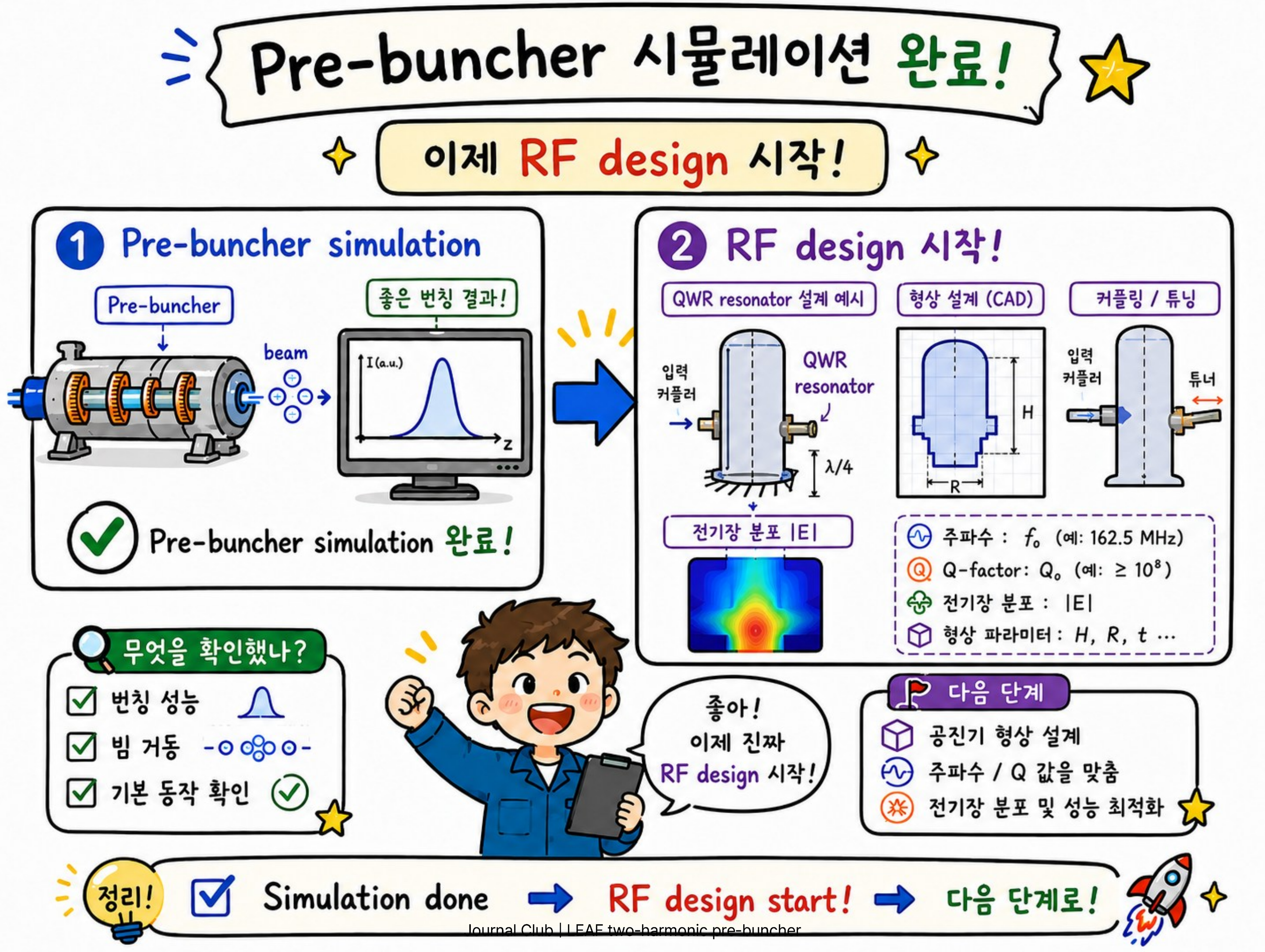
- Gap spacing must follow the RF phase advance of low-β ions.
- Fundamental: $d_1 = \beta\lambda_1/2 \approx 81$ mm.
- 2nd harmonic: $d_2 = \beta\lambda_2/2 \approx 40.5$ mm, difficult to realize mechanically.
- The outer gap was shifted to 107 mm to use the opposite-polarity leakage field.
- Effective voltage improves only for 1st harmonics, but RF power loss increases by ~6×.











Pre-buncher 시뮬레이션 완료!
이제 RF design 시작!
1 Pre-buncher simulation
Pre-buncher
beam
좋은 번칭 결과!
I (a.u.)
z
Pre-buncher simulation 완료!
2 RF design 시작!
QWR resonator 설계 예시
형상 설계 (CAD)
커플링 / 튜닝
입력 커플러
QWR resonator
λ/4
H
R
튜너
전기장 분포 |E|
주파수 : f_0 (예: 162.5 MHz)
Q-factor: Q_0 (예: ≥ 10^8)
전기장 분포 : |E|
형상 파라미터 : H, R, t …
무엇을 확인했나?
번칭 성능
빔 거동
기본 동작 확인
좋아! 이제 진짜 RF design 시작!
다음 단계
공진기 형상 설계
주파수 / Q 값을 맞춤
전기장 분포 및 성능 최적화
정리!
Simulation done → RF design start! → 다음 단계로!

RF design: QWR-based two-harmonic pre-buncher

Two coaxial quarter-wave resonators generate 10.156 MHz and 20.3125 MHz bunching voltages

Low-frequency resonators for high-voltage bunching

- Two QWR resonators generate 10.156 and 20.3125 MHz voltages.
- Harmonic synthesis forms a sawtooth-like bunching waveform.
- QWR design handles low-frequency, kV-level bunching voltage.

Harmonic	1st	2nd
Loop area (cm^2)	27	11.3
Q_0	480	670
Q_{ext}	446	637
$\beta = Q_0 / Q_{ext}$	1.07	1.05

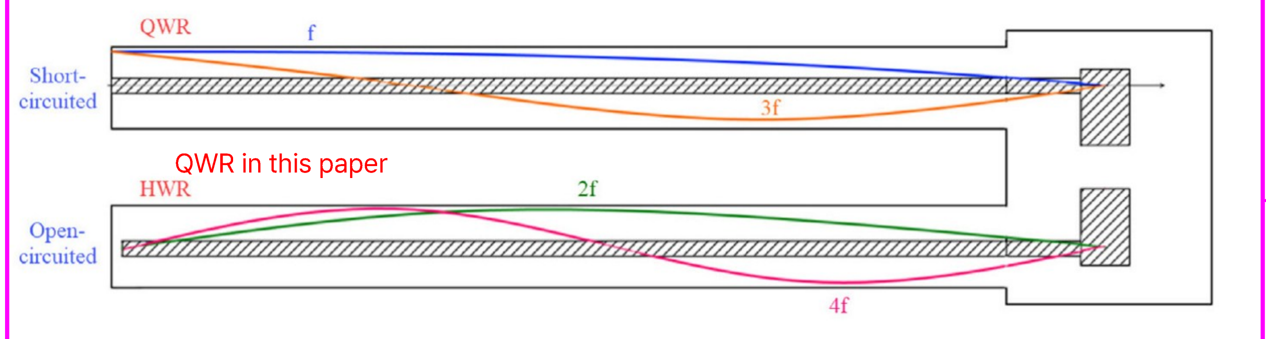
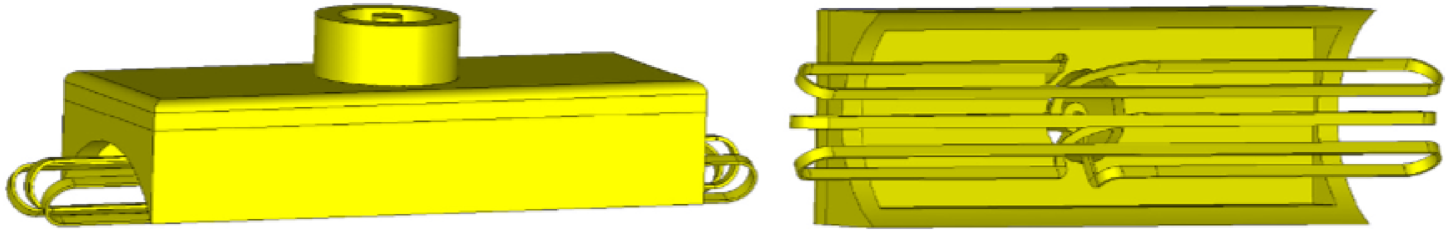
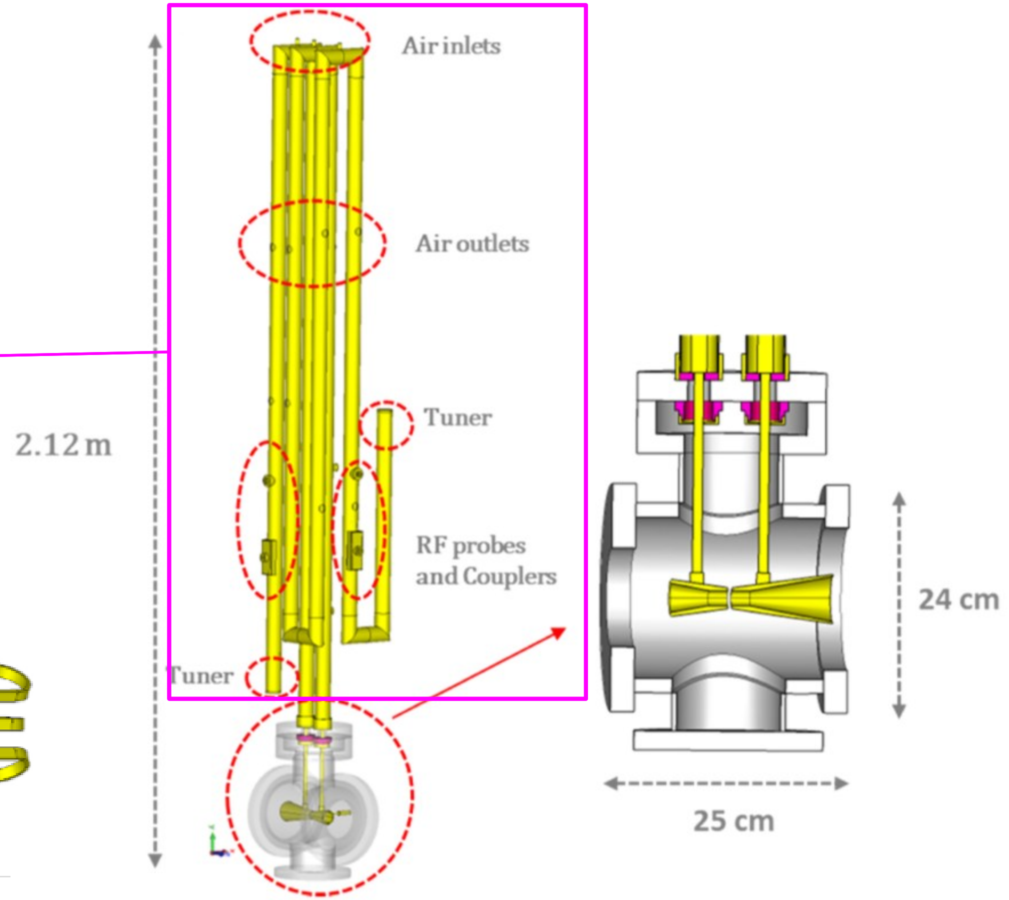


Fig. 4. MHB schematics and magnetic field profiles along resonators axes.





RF design: Frequency tuning of QWR-based pre-buncher

Coarse and fine tuners compensate fabrication errors and thermal frequency drift

Coarse and fine tuning for frequency control

- Coarse tuning: sliding plunger changes the effective QWR length. (385 kHz / 1032 kHz for 10 MHz / 20 MHz)
- Fine tuning: 16-mm screw tuner corrects residual frequency drift. (12 kHz / 29 kHz, sufficient for thermal drift correction)

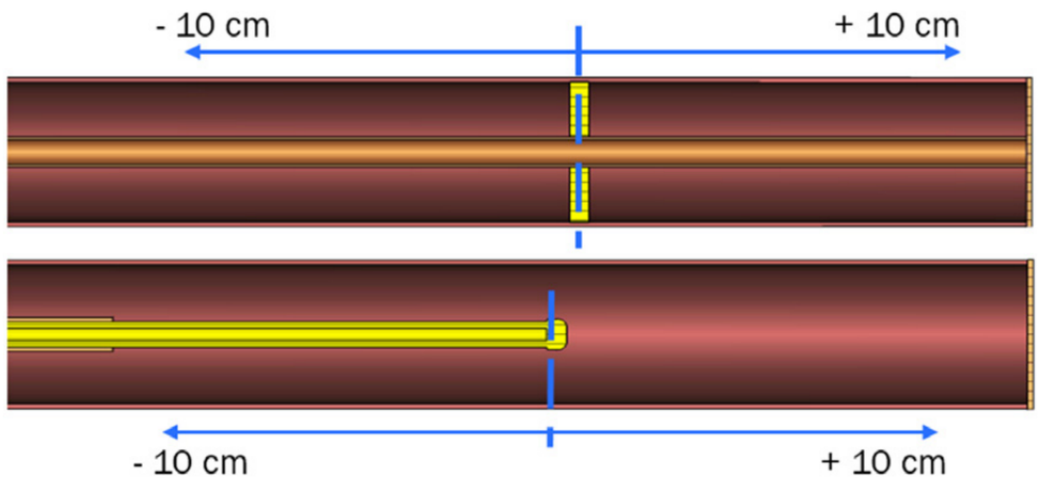


Fig. 12. Coarse tuners: sliding plunger for QWR (top) and telescopic inner conductor extender for HWR (bottom). Moveable parts are highlighted .

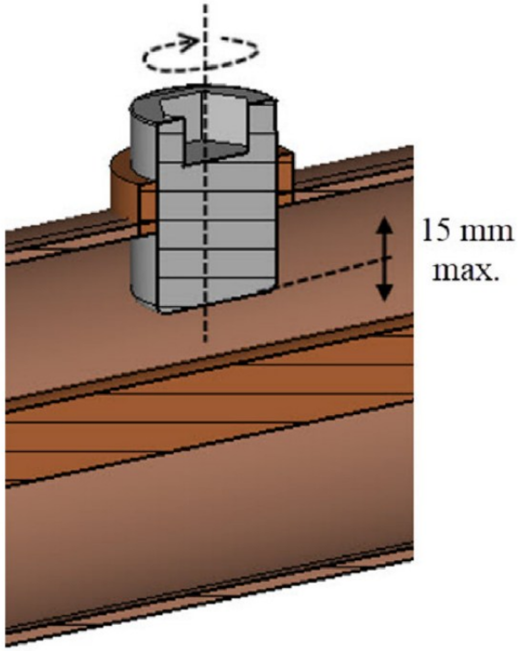


Fig. 13. Design of the tuning screw.

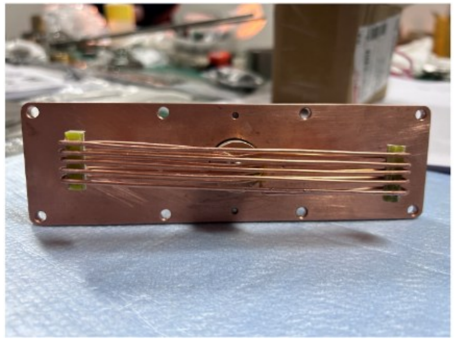
RF design and testing: QWR-based two-harmonic pre-buncher

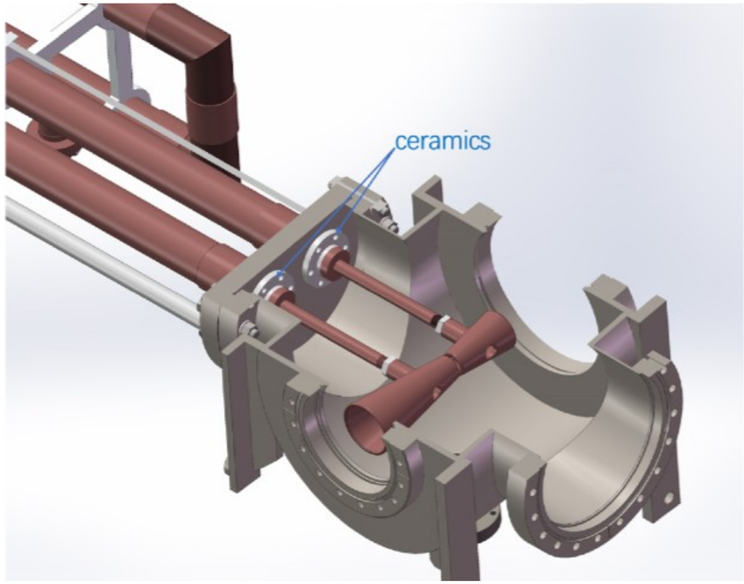
Dual QWR resonators for low-frequency, kV-level bunching voltages

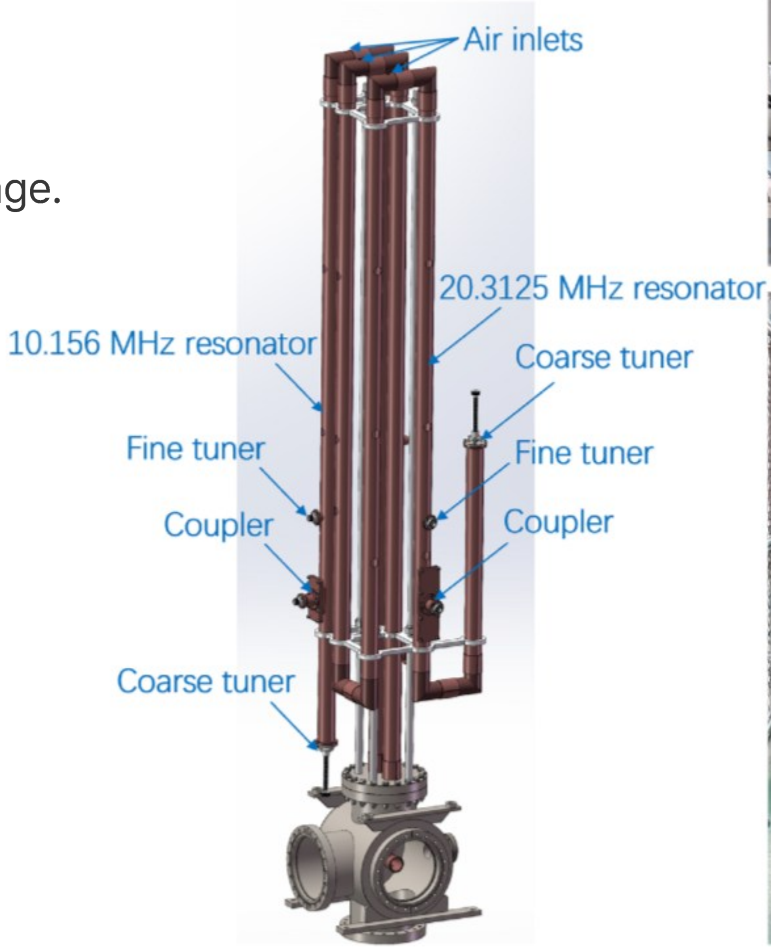
RF tuning and high-power validation

- **Matching result:** S_{11}=-32 dB @ 10 MHz / -39 dB @ 20 MHz.
- **Quality factor Q:** 67-70% of design.
- **Power margin:** 330 W/ 40 W feed powers recover required voltage.

220 W / 26 W of design.







Thermal drift remains within tuner range

Forced air cooling reduces temperature, deformation, and frequency shift

THERMAL STABILITY

Forced cooling

RF loss — **thermal load** — **mechanical Δx** — **frequency Δf**

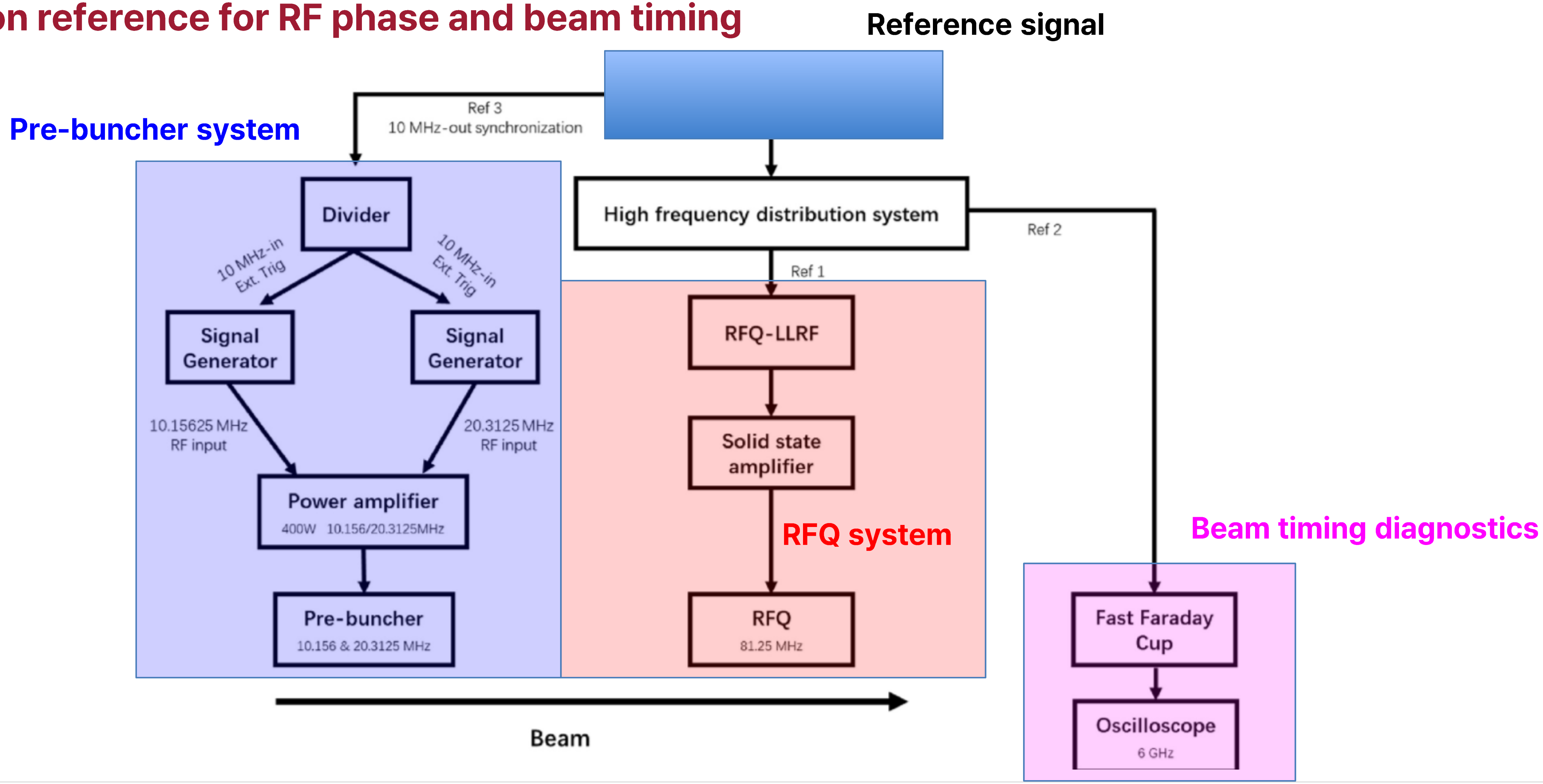
condition	10 MHz peak	20 MHz peak	Δf(10/20)
natural	107 °C	< 44 °C	5.9 / 5.18 kHz
forced air, simulated	< 44 °C	< 28 °C	1.6 / 1.06 kHz
forced air, measured	-	-	5.7 / 2.8 kHz

Measured high-power drift: 5.7 / 2.8 kHz, still tunable by fine tuners

Synchronization of pre-buncher, RFQ, and beam diagnostics

All RF and diagnostic signals are phase-locked to the 81.25 MHz master reference

Common reference for RF phase and beam timing

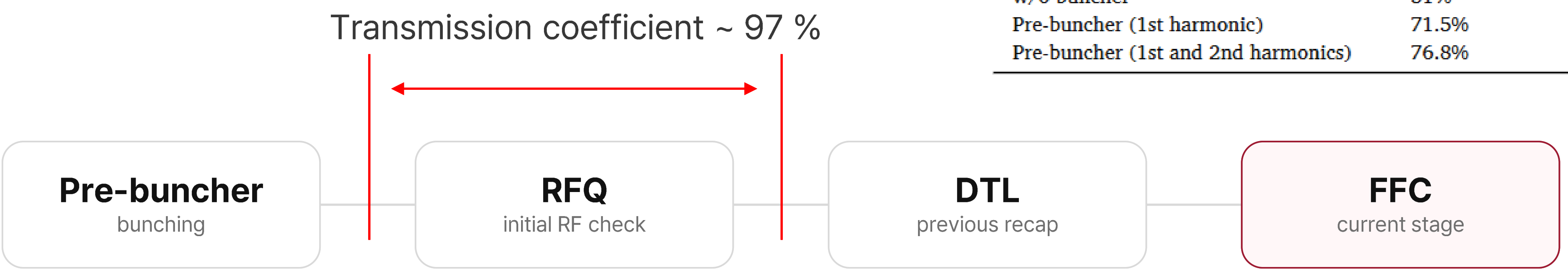


Results

Pre-buncher improves RFQ acceleration efficiency while maintaining high transmission

Improved RFQ capture with two-harmonic pre-bunching

Bunching mode	Measured acc-eff	Simulated acc-eff
w/o buncher	51%	50%
Pre-buncher (1st harmonic)	71.5%	70%
Pre-buncher (1st and 2nd harmonics)	76.8%	75.8%

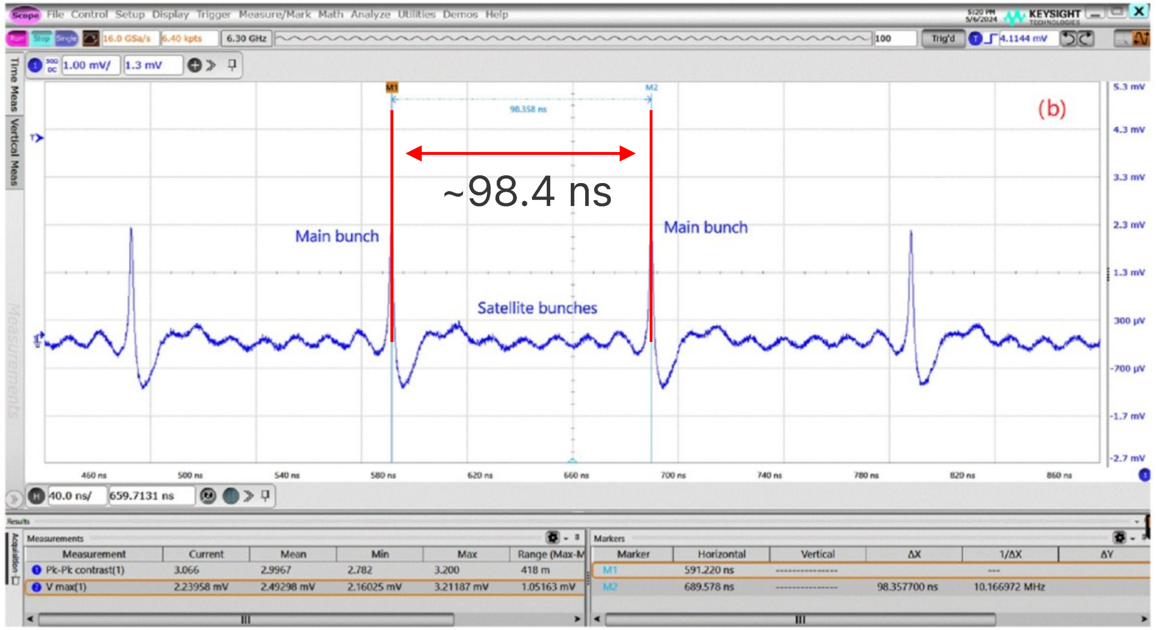


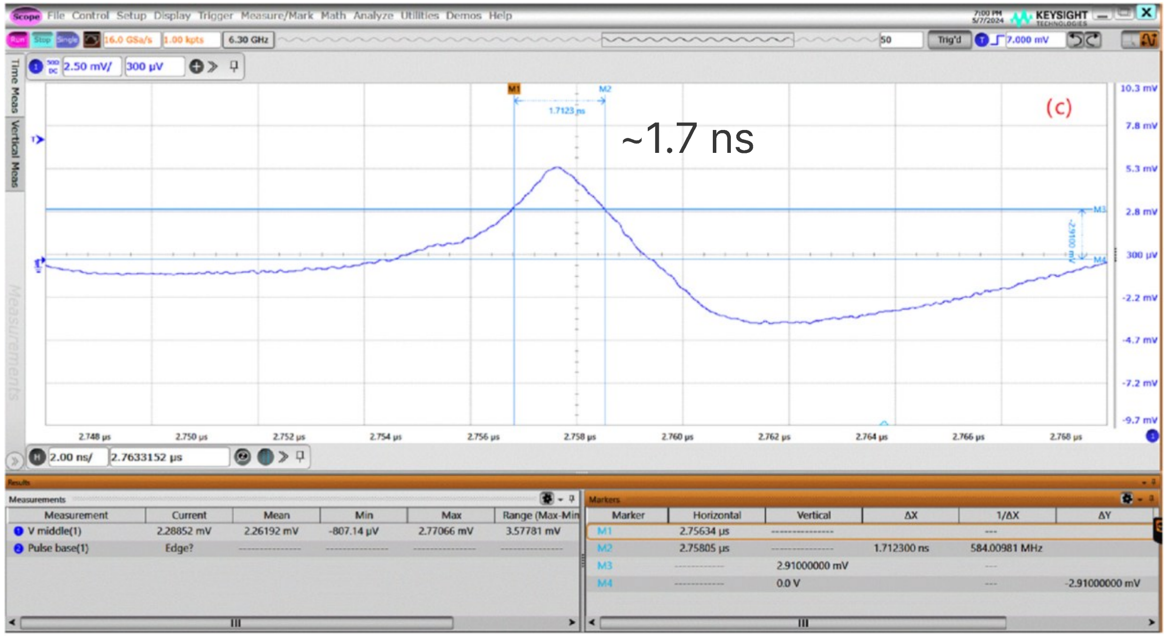
1. **RFQ transmission > 97%** from ACCT.
2. Pre-buncher increased acceleration **efficiency from 51% to 76.8%.**
3. Two-harmonic operation agreed well with simulation: **76.8%** measured vs. 75.8% simulated.
4. Result: higher useful beam current can be delivered to the target.

Temporal profile confirms main-bunch formation and residual satellite bunches

Bunch structure measured by Fast Faraday Cup

1. Fast Faraday Cup confirms the temporal bunch structure.
2. Main bunch width: FWHM ≈ 1.7 ns.
3. Residual satellite bunches require extinction by the MEBT chopper.





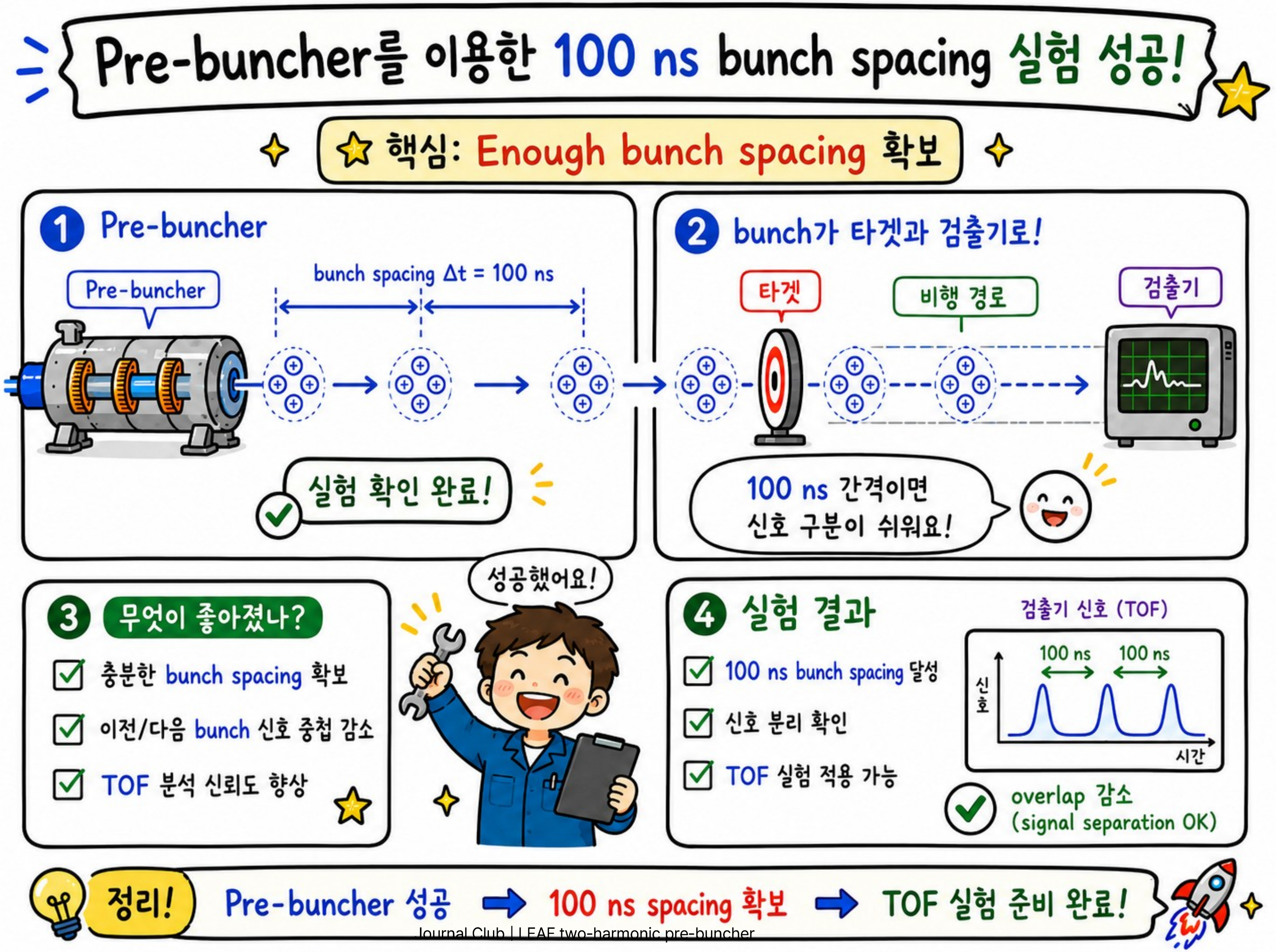
Discussion: Is 100 ns bunch spacing sufficient?

TOF requirement depends on the flight path and the slowest detected particles

100 ns is useful, but not universal

1. LEAF targets ~100 ns bunch spacing for TOF
2. Pre-buncher forms main bunches separated by 98.4 ns.
3. But, sufficient spacing depends on the TOF window.
4. Slow particles or long flight paths may still require larger spacing.

Wrap-up



Pre-buncher를 이용한 100 ns bunch spacing 실험 성공!
핵심: Enough bunch spacing 확보
1 Pre-buncher
Pre-buncher
bunch spacing Δt = 100 ns
실험 확인 완료!
2 bunch가 타겟과 검출기로!
타겟
비행 경로
검출기
100 ns 간격이면
신호 구분이 쉬워요!
성공했어요!
3 무엇이 좋아졌나?
충분한 bunch spacing 확보
이전/다음 bunch 신호 중첩 감소
TOF 분석 신뢰도 향상
4 실험 결과
100 ns bunch spacing 달성
신호 분리 확인
TOF 실험 적용 가능
검출기 신호 (TOF)
100 ns
100 ns
신호
시간
overlap 감소
(signal separation OK)
정리! Pre-buncher 성공 → 100 ns spacing 확보 → TOF 실험 준비 완료!

Wrap-up

Two-harmonic pre-bunching improves useful RFQ capture

① TOF need	• TOF needs ~100 ns spacing, not 12.3 ns.
② Chopper limitation	• Chopper-only solution gives 87.5% theoretical beam loss.
③ Pre-buncher strategy	• Two-harmonic velocity modulation improves RFQ capture.
④ Validation	• 76.8% acceleration efficiency and ~98.4 ns spacing were measured.
⑤ Critical boundary	• Full user-beam delivery still depends on satellite extinction.