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Numerical study of 5 MeV SRF electron linac for wastewater purification

Anjali B. Kavar[1,*], Shigeru Kashiwagi[1], Toshiya Muto[1], Hayato Abiko[1], Fujio Hinode[1], Kodai Kudo[1], Ikuro Nagasawa[1], Kenichi Nanbu[1], Kotaro Shibata[1], Ken Takahashi[1], Hiroki Yamada[1], Hiroyuki Hama[1]

[1]Research center for accelerator and radioisotope science, Tohoku Univ., Sendai, 982-0826, Japan
*e-mail: kavar.anjali.bhagwan.r4@dc.tohoku.ac.jp

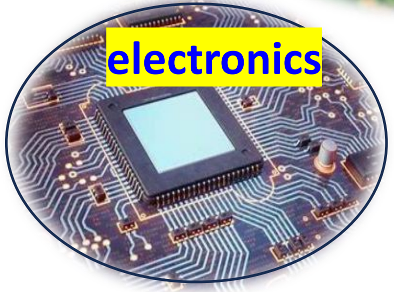
Outline

- Introduction
  - Wastewater, PFAS
  - Water purification using Electron Beam (EB)
- Development of high current electron linac
  - Configuration of SRF linac
  - Electron gun with RF gating
  - Low-beta 3 cell buncher
- Present status of gun development
- Summary

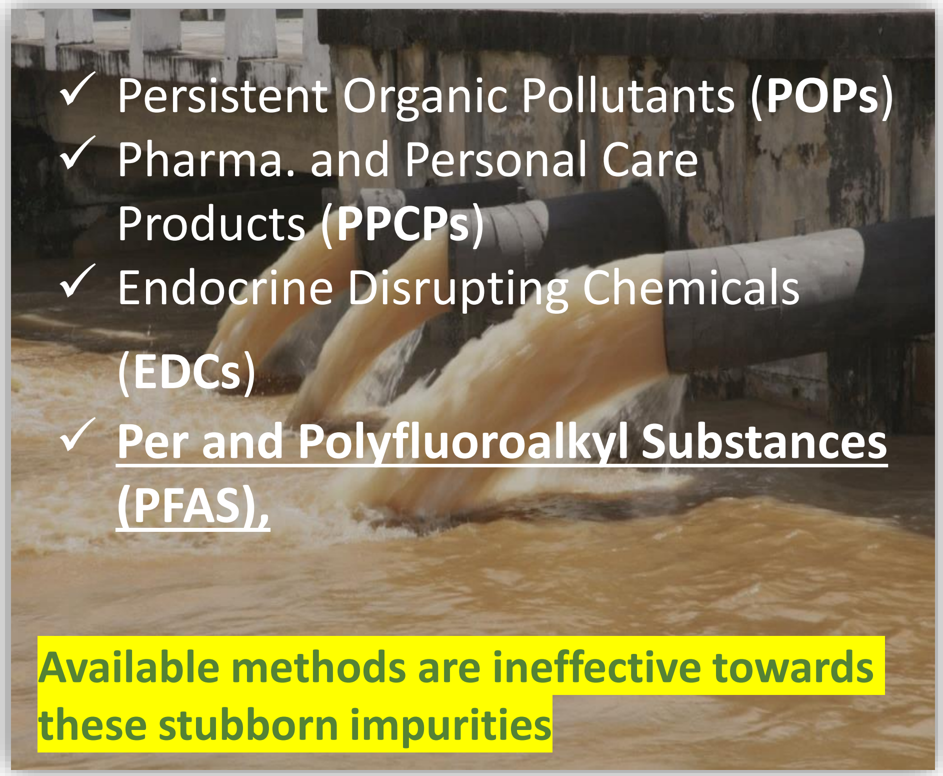
Introduction

Wastewater: Used water/liquid waste which can't be reused without treatment

Improved life-style & hence industrialization



Harmful & stubborn new Impurities: CEC's



- ✓ Persistent Organic Pollutants (**POPs**)
- ✓ Pharma. and Personal Care Products (**PPCPs**)
- ✓ Endocrine Disrupting Chemicals (**EDCs**)
- ✓ **Per and Polyfluoroalkyl Substances (PFAS),**

Available methods are ineffective towards these stubborn impurities

A Call to action for a new technology

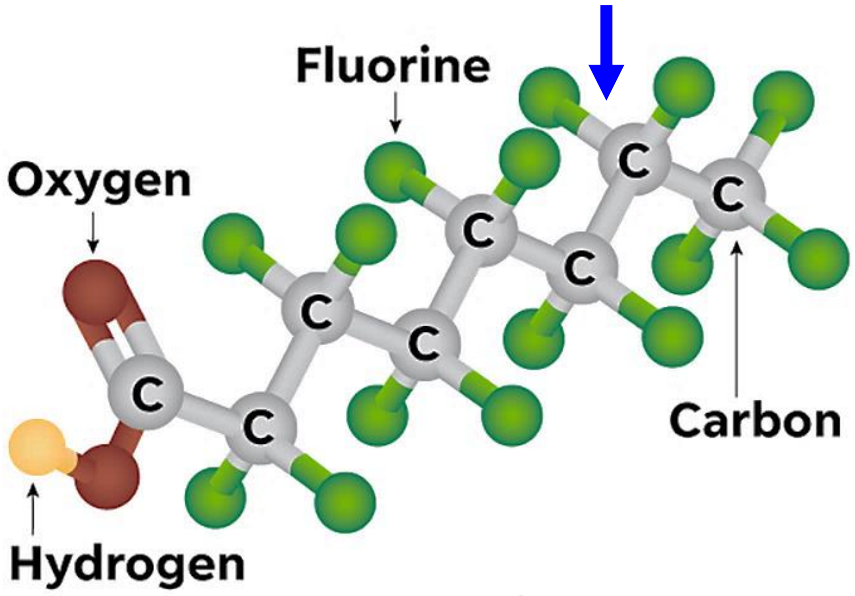
What is PFAS?

Good side

- Resistant to heat, water, oil
- Chemically inert
- High dielectric strength
- Resistant to UV
- Wide cost range

Useful in almost every sector ➔Increased global Usage

Very High stability of C-F bond



PFOA

Bad side

- Can never degrade naturally
- Forever chemical
- Health hazardous

(Detection in **water**, soil, human blood & in the milk of lactating women !)

➔ No conventionally available method can destruct PFAS other than radiation processing (EB)

*K. Londhe et al., , ACS ES&T Eng. 1, 827 (2021).

Decomposing PFAS using electron beams is most promising

➔ We want a High-power EB source.

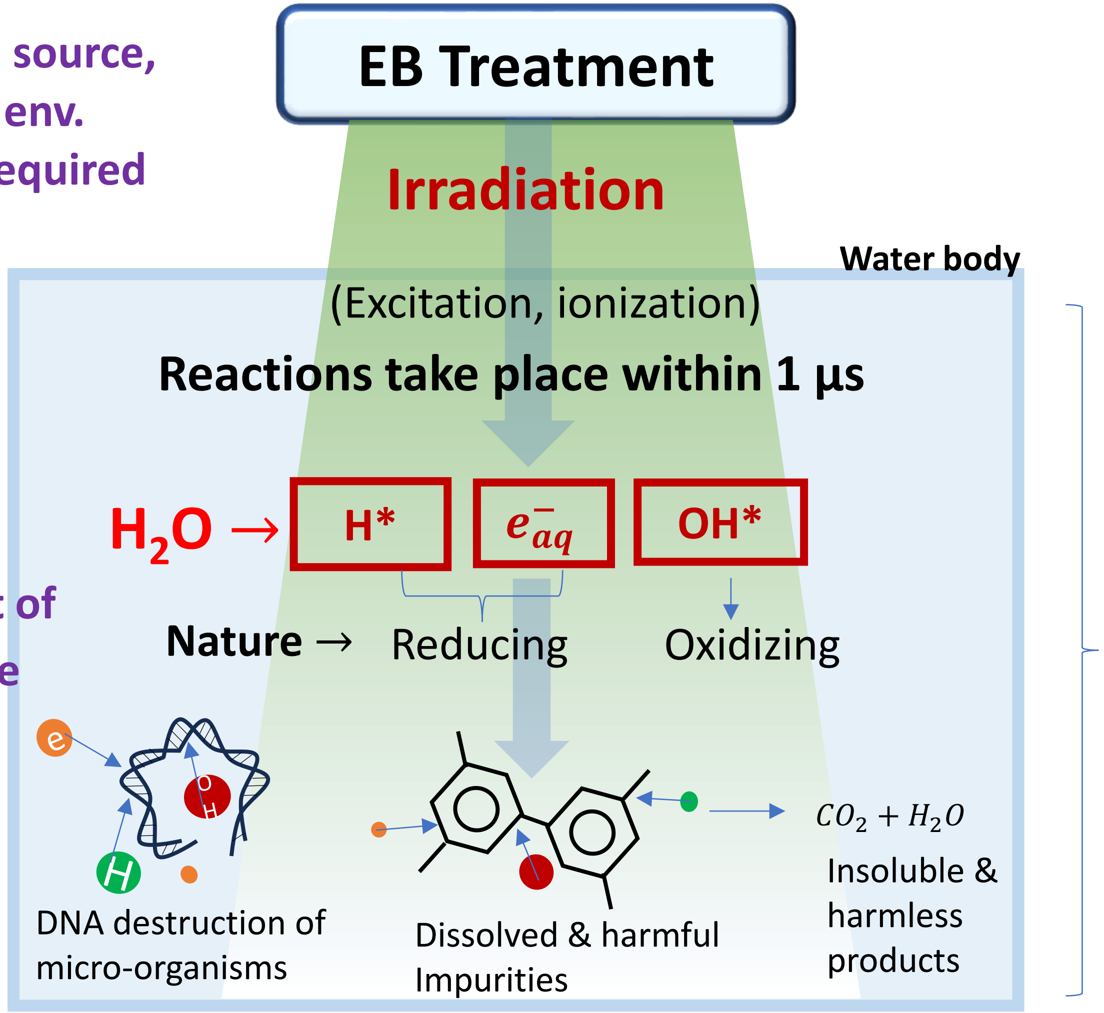
Water purification using Electron Beam (EB)

Automated source, No specific env. condition required

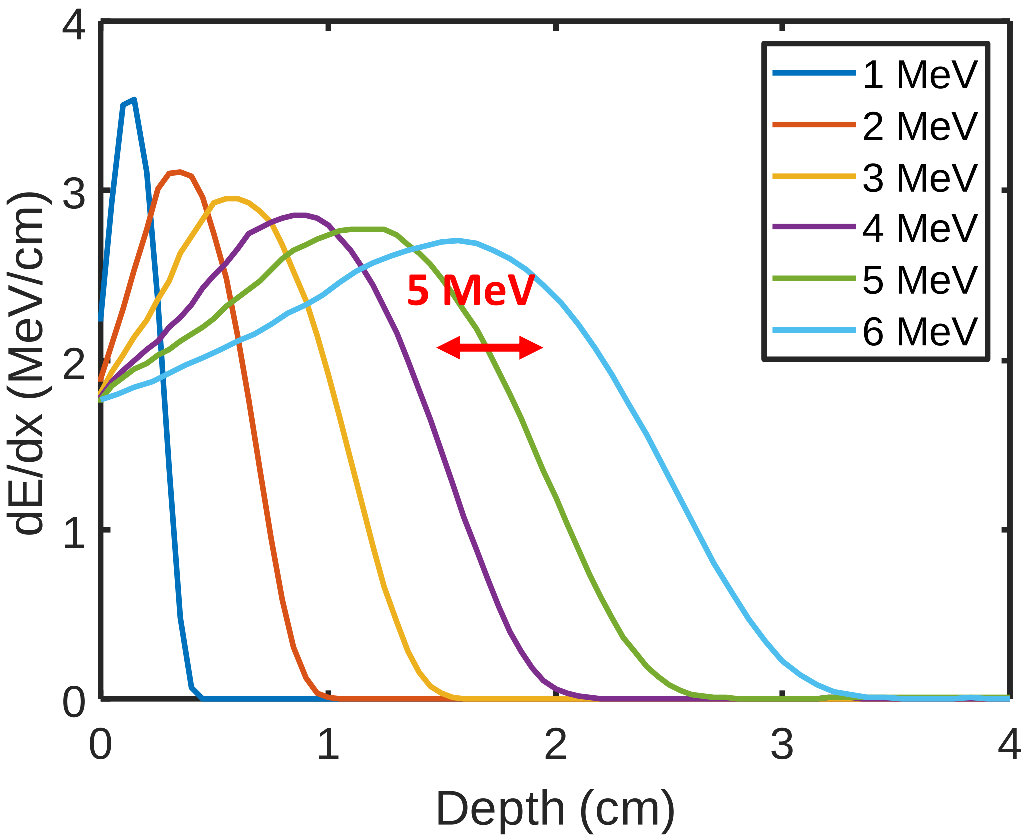
Faster processing

Independent of Impurity type

No harmful by-prod.



- **Smaller energy, smaller penetration depth**
- **5MeV beam => 2cm thickness of flowing water**



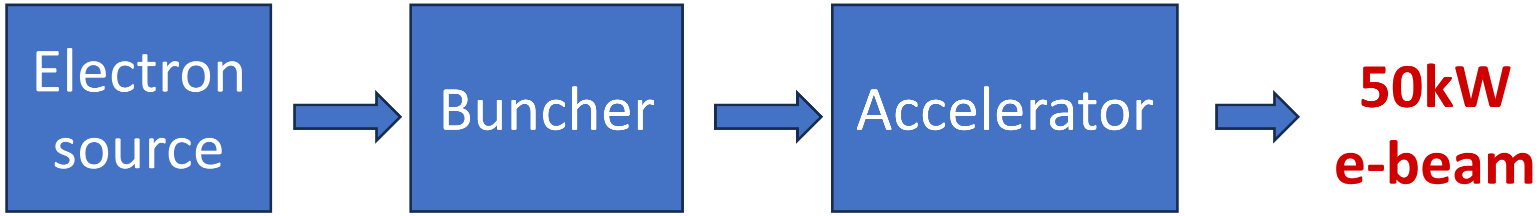
Higher the current, better the processing rate

Development of high current electron linac

Design Goal: High-current, Compact & Simple system

- ✓To achieve high current beam, ***CW operation*** is desirable
- ✓***Superconducting RF linac*** is most promising candidate.
- ✓There should be ***no beam loss***, to avoid quench of SRF cavity.

General Layout of accelerator



Ave. Beam curr. = 10 mA
Energy= 5 MeV

Important issues

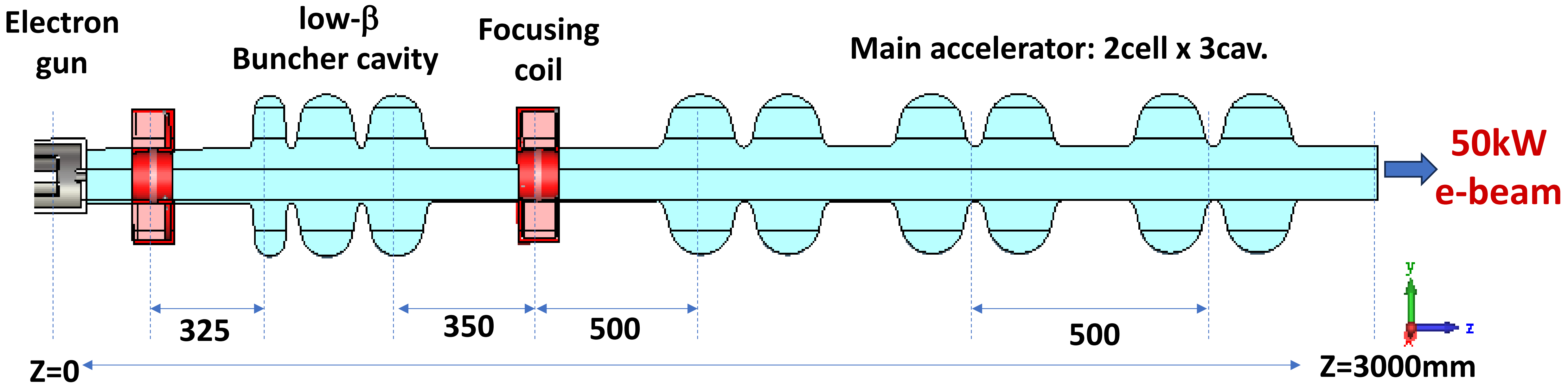
- ➔ **Electron gun (CW operation & short pulse)**
- ➔ **Buncher cavity (Combined buncher & booster cavity)**

Configuration of electron linac

- ***Liquid-He free superconducting rf (SRF) linac*** is designed.

❑ *High average current electron gun*
- ✓ ***DC high voltage***
- ✓ ***Thermionic cathode***
- ✓ ***RF gated gridded electron gun***

❑ *Buncher & Accelerating cavity*
- ✓ ***Freq. =1.3 GHz***
- ✓ ***SRF cavities (** Nb_3Sn **, 10MV/m)***
- ✓ ***Conduction cooled***



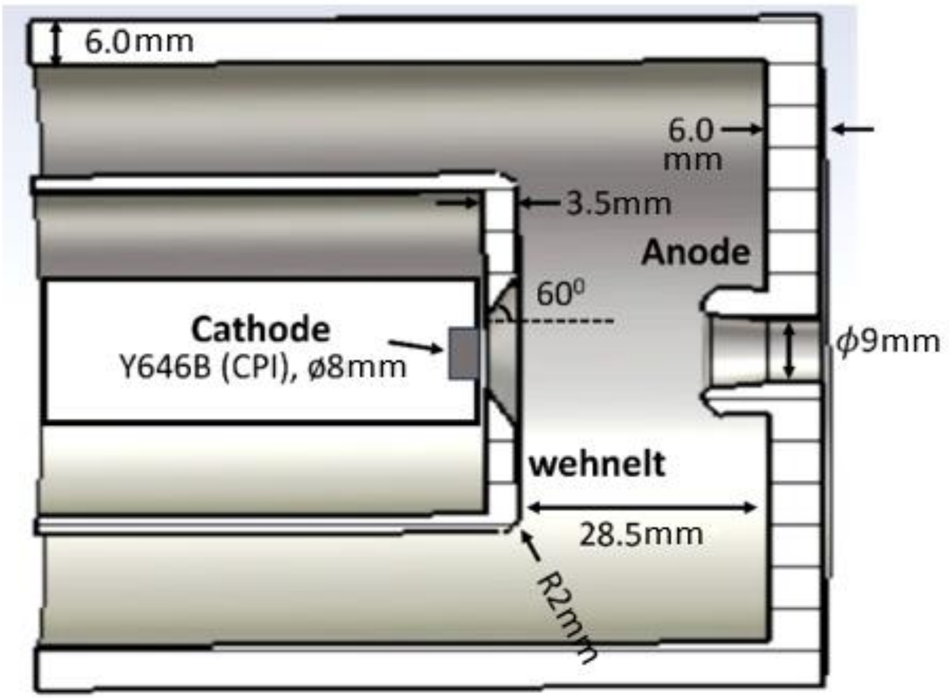
✓ Beam simulations were performed using KUCODE.

Electron gun

Requirements for the e$^-$ gun:

Robust, Easy maintenance, Not expensive,
Short e- bunch generation with CW operation

- ✓ Thermionic gridded gun
- ✓ cathode = Y646B, 8 mm diameter (commercially available)
- ✓ DC, High Voltage = 100 kV
- ✓ Emittance < 20 mm-mrad

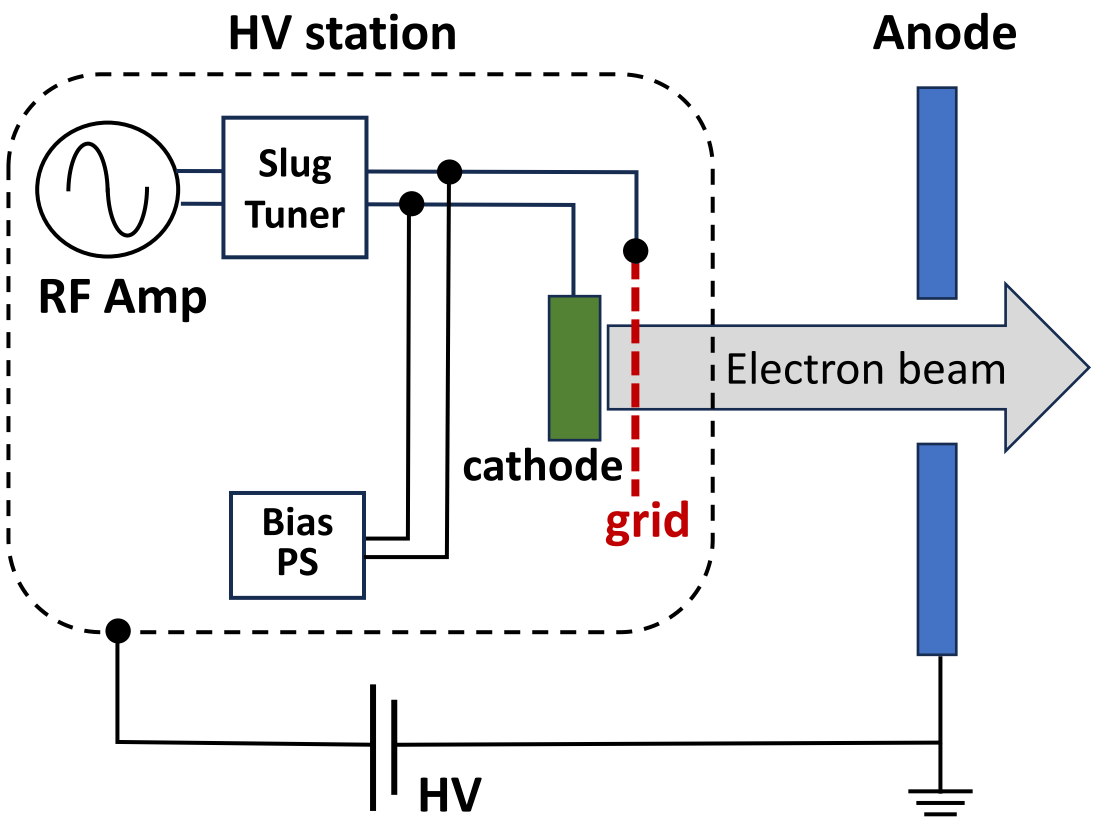


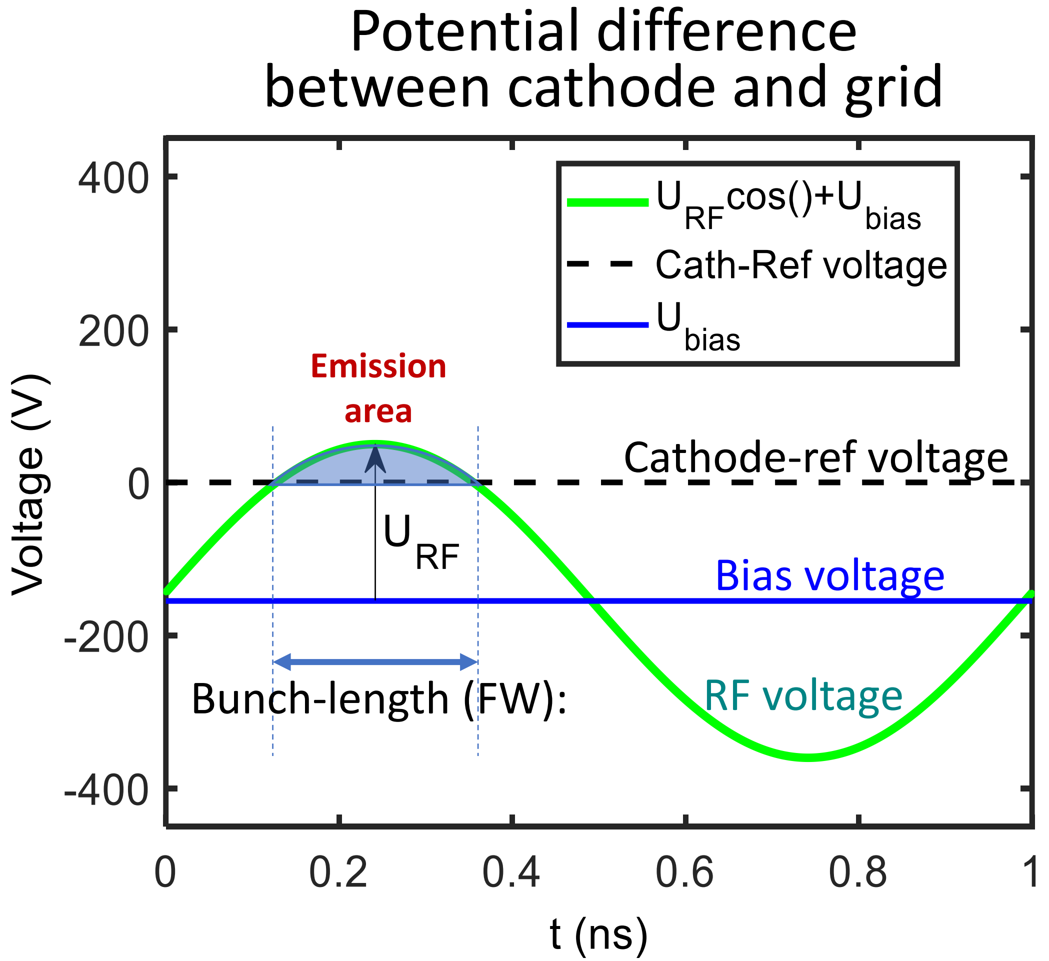
Grid drive is a challenge

☹ Avalanche pulser (~kHz)
😐 FET pulser (~10MHz)
☺ RF gating of the grid (GHz-order repetition is achievable)

Short e-bunch generation

- **RF drives the electron gun grid.**

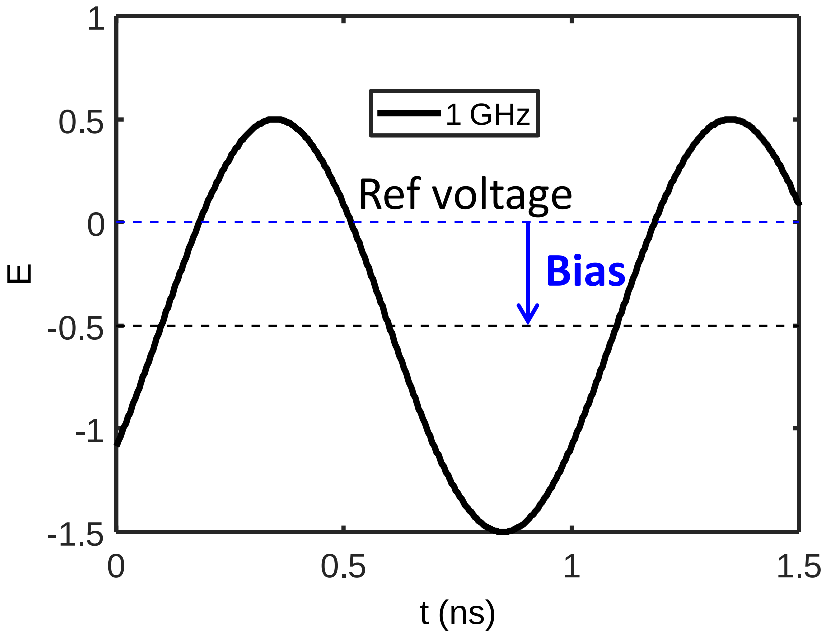




Ref.1(FOM institute, Netherlands): R.J. Bakker et. Al., Nucl. Instrum. Methods Phys. Res., Sect. A 307 (1991) 543.
Ref.2 (Naval Research Lab., USA): S.H. Gold et. Al., Phys. Rev. ST Accel. Beams 16, 083401 (2013)

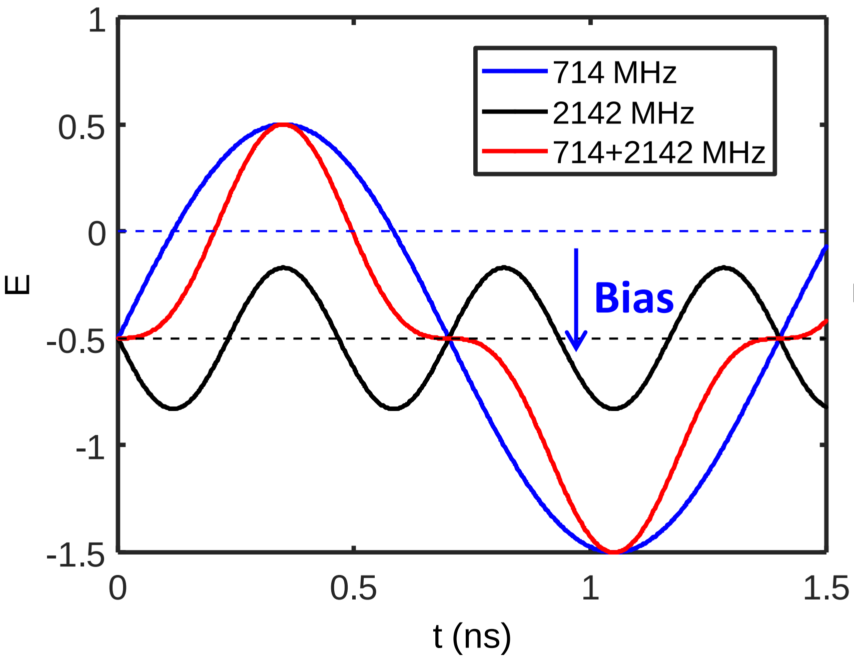
Short bunch generation using RF gating

Single frq. (1 GHz)
***FOM, Netherlands**



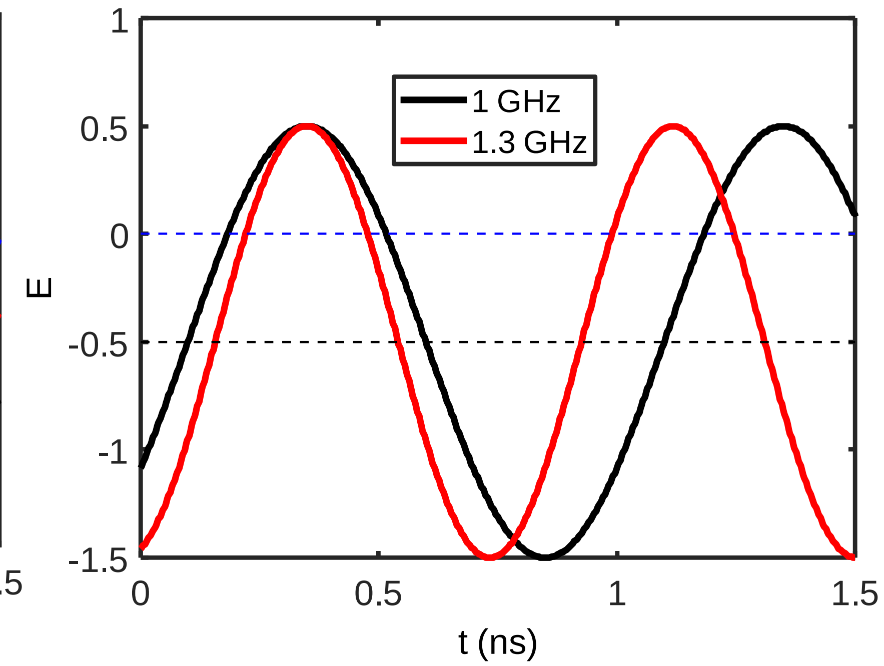
264ps (FWHM), 110pC
(Measured)

Dual freq. (714 MHz & 2142MHz)
***Naval Res. Lab., USA**



235ps (FWHM), 135pC
(Measured)

Single freq. (1.3 GHz)
Our case



210 ps (FWHM), 8 pC
FW = 300 ps

- ✓ The longitudinal shape is not Gaussian, but a sinusoidal shape.
- ✓ It is discussion in terms of full width (FW) of bunch.

3-cell buncher cavity

Design aim:

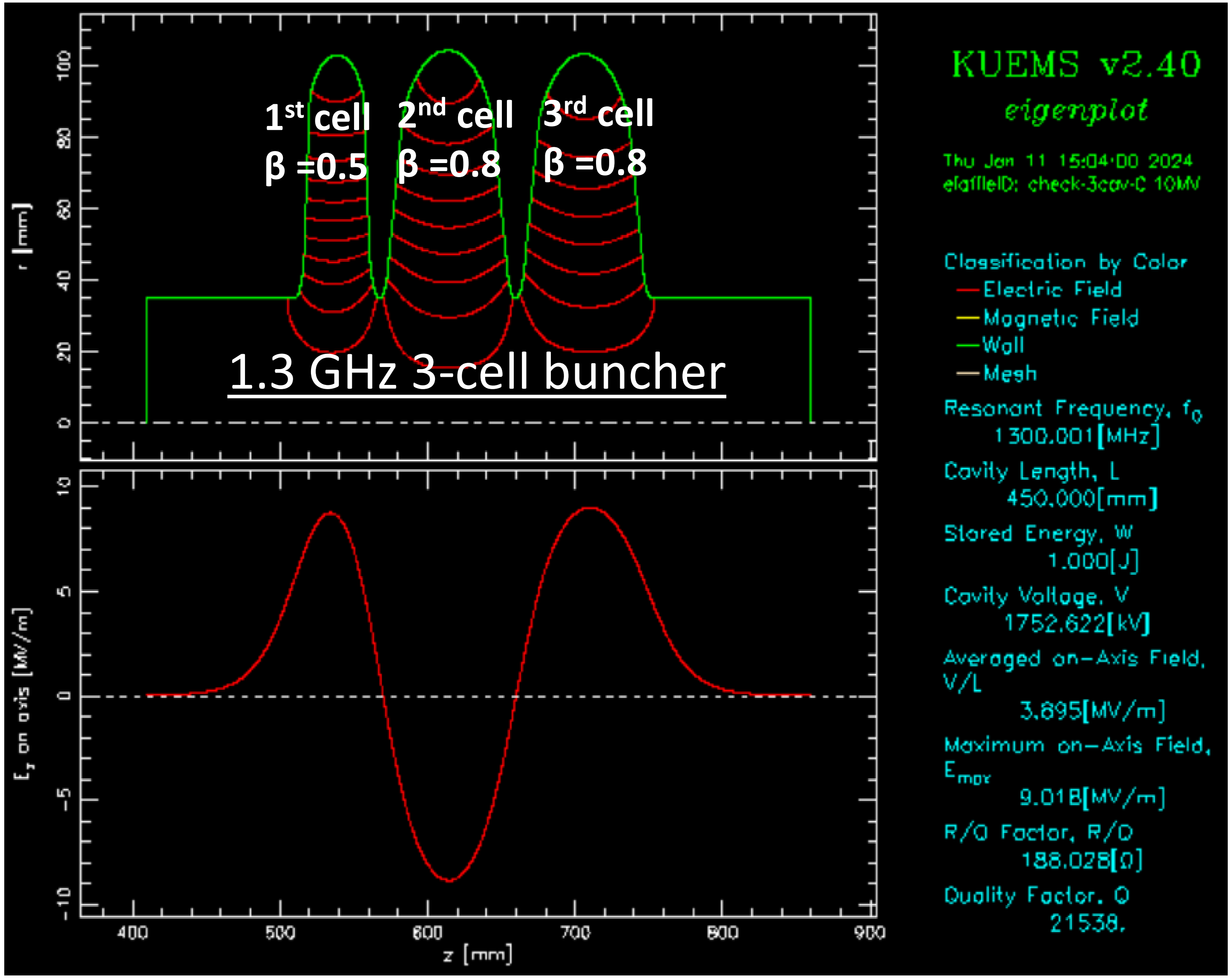
No beam loss
Bunching & Energy boost (β~1)

Parameters

- ✓ Gun HV: 100 kV ➔ β = 0.5
- ✓ 1st cell is a buncher
- ✓ 2nd & 3rd cells are Booster
- ✓ Beam energy in 2nd cell ➔ ~ β = 0.8

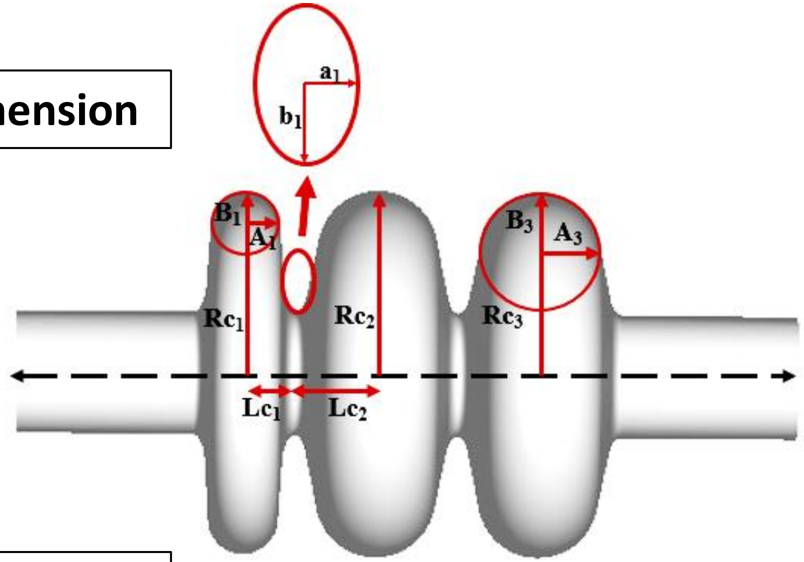
Advantages

- ✓ Compact (single cryomodule)
- ✓ Single power coupler
- ✓ Minimal leakage field

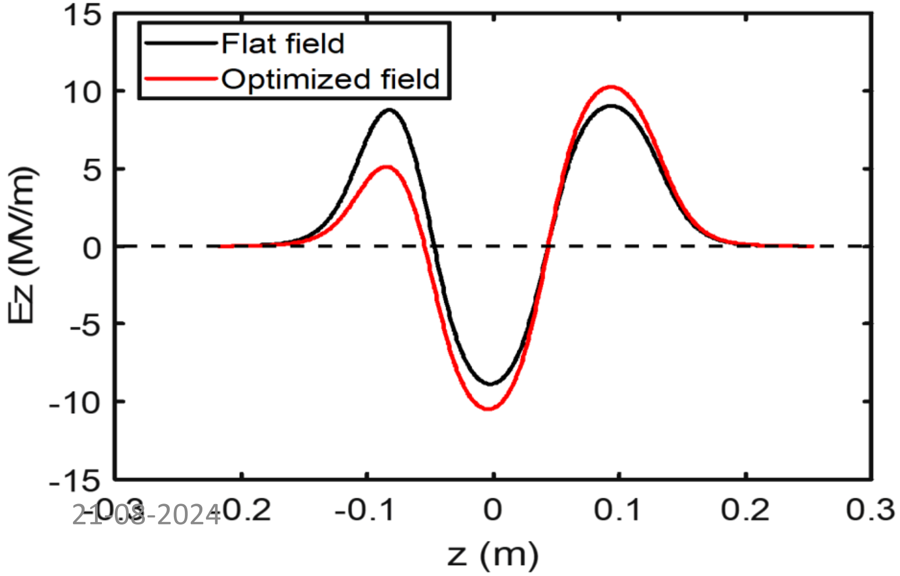


Cavity field

Cavity dimension



Field distribution

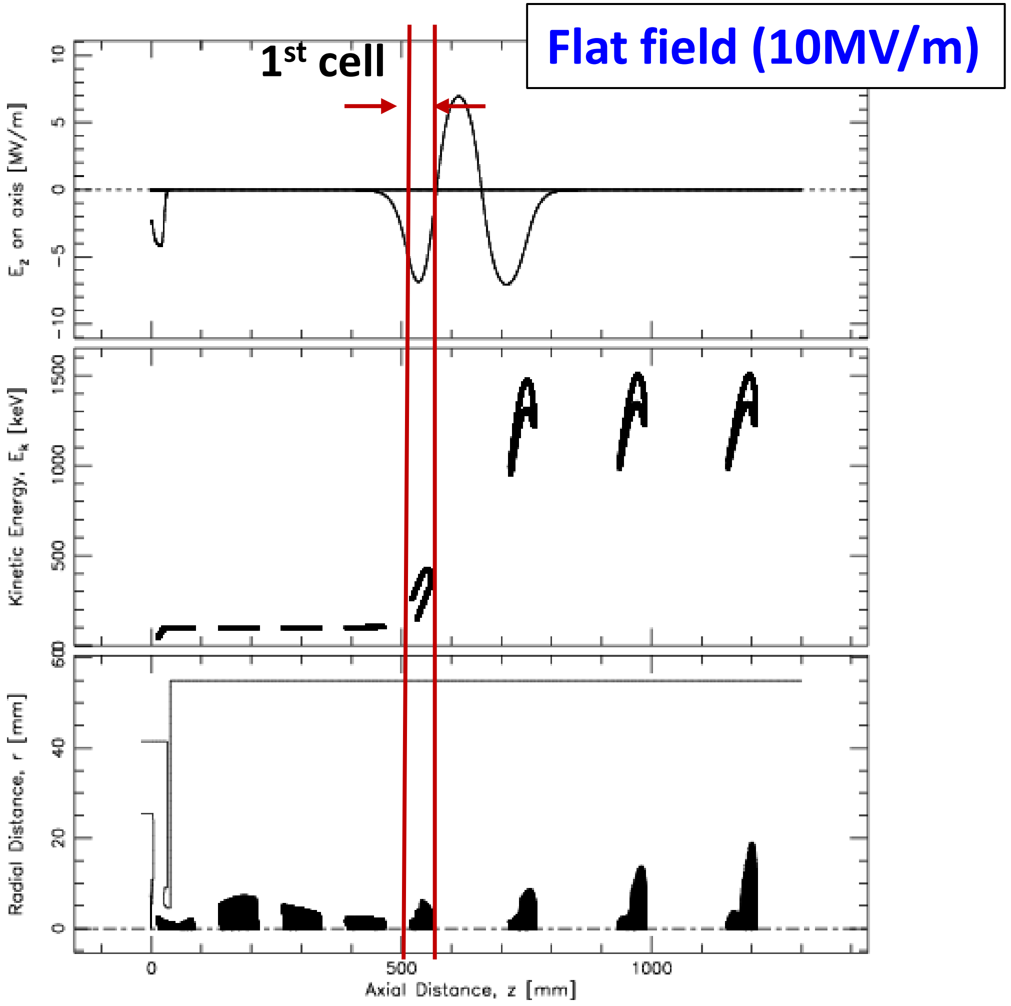


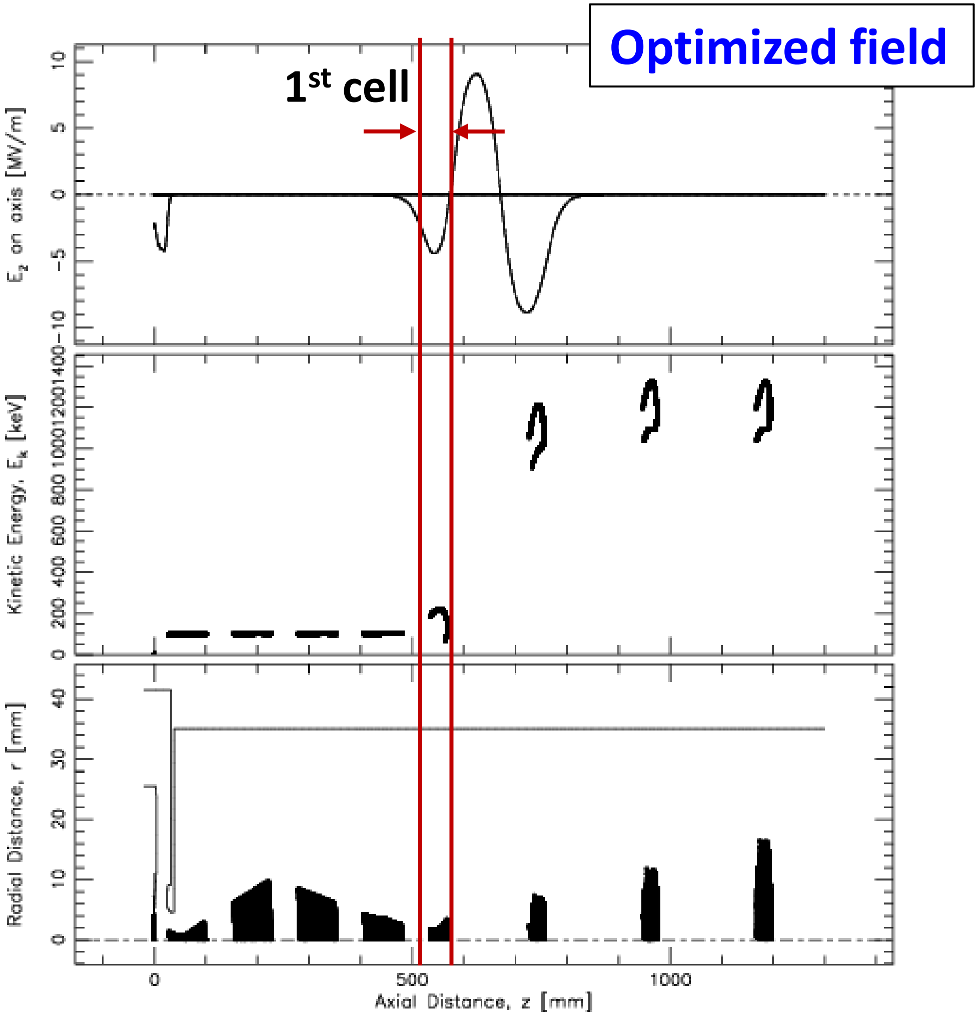
	Flat field	Optimized field
Parameter	Value	
Rc_1	103.12508 mm	103.9177 mm
Rc_2	104.48208 mm	104.0247 mm
Rc_3	103.46208 mm	103.524 mm
Lc_1	28.8461 mm	
$Lc_2 = Lc_3$	46.154 mm	
$A_1 = B_1$	19.8 mm	
$A_2 = B_2 = A_3 = B_3$	34 mm	
$a_1 = a_2 = a_3$	7 mm	
$b_1 = b_2 = b_3$	18 mm	
Resonant frequency	1.30000100 GHz	1.30000000 GHz

✓ The radius of the cavities was varied to change the resonant frequency and electric field distribution.

Bunching process

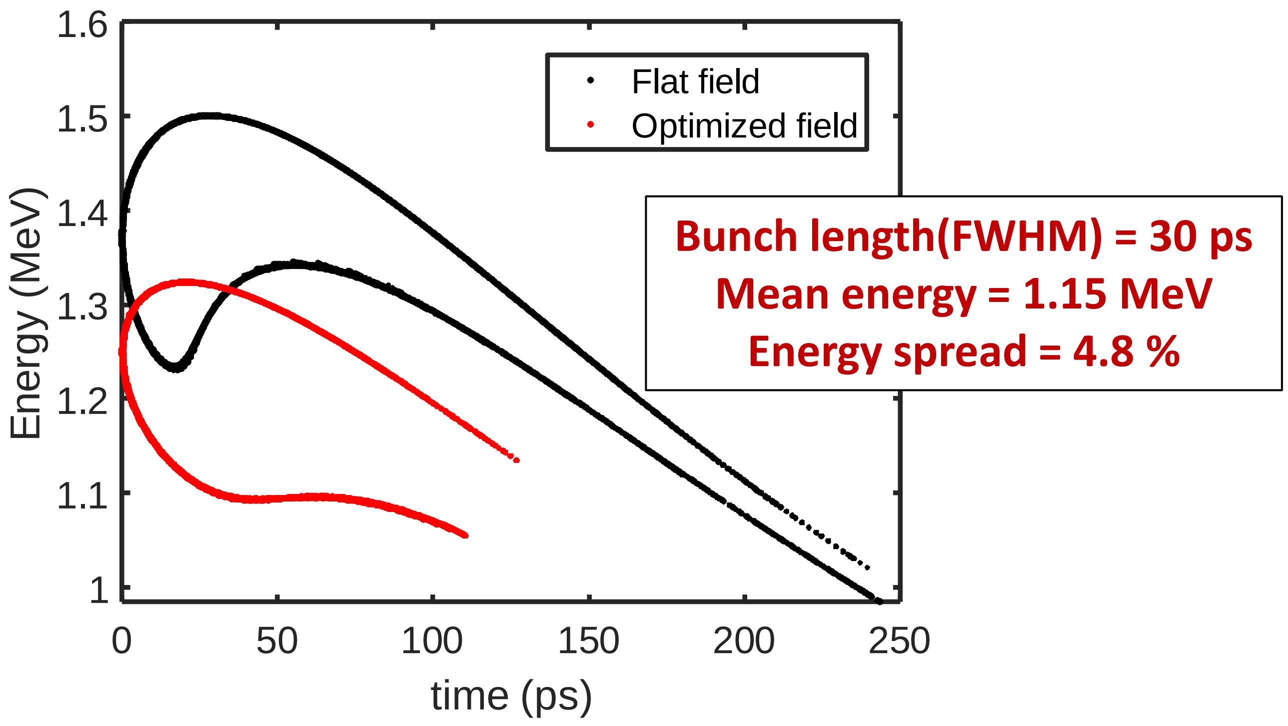
- Strength and distribution of field in 3 cells is important parameters.
- Bunch length was assumed to be σ = 70 ps (FW: 420 ps) at gun exit.

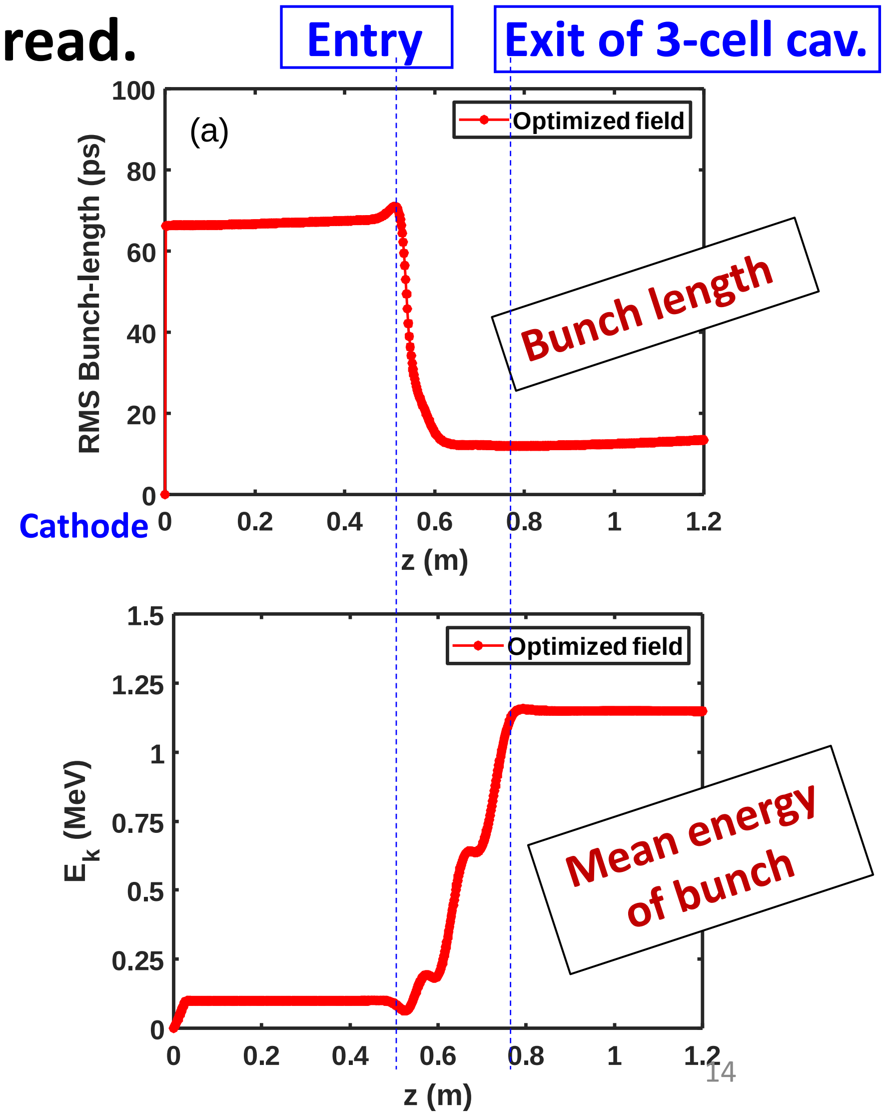




Bunching output beam

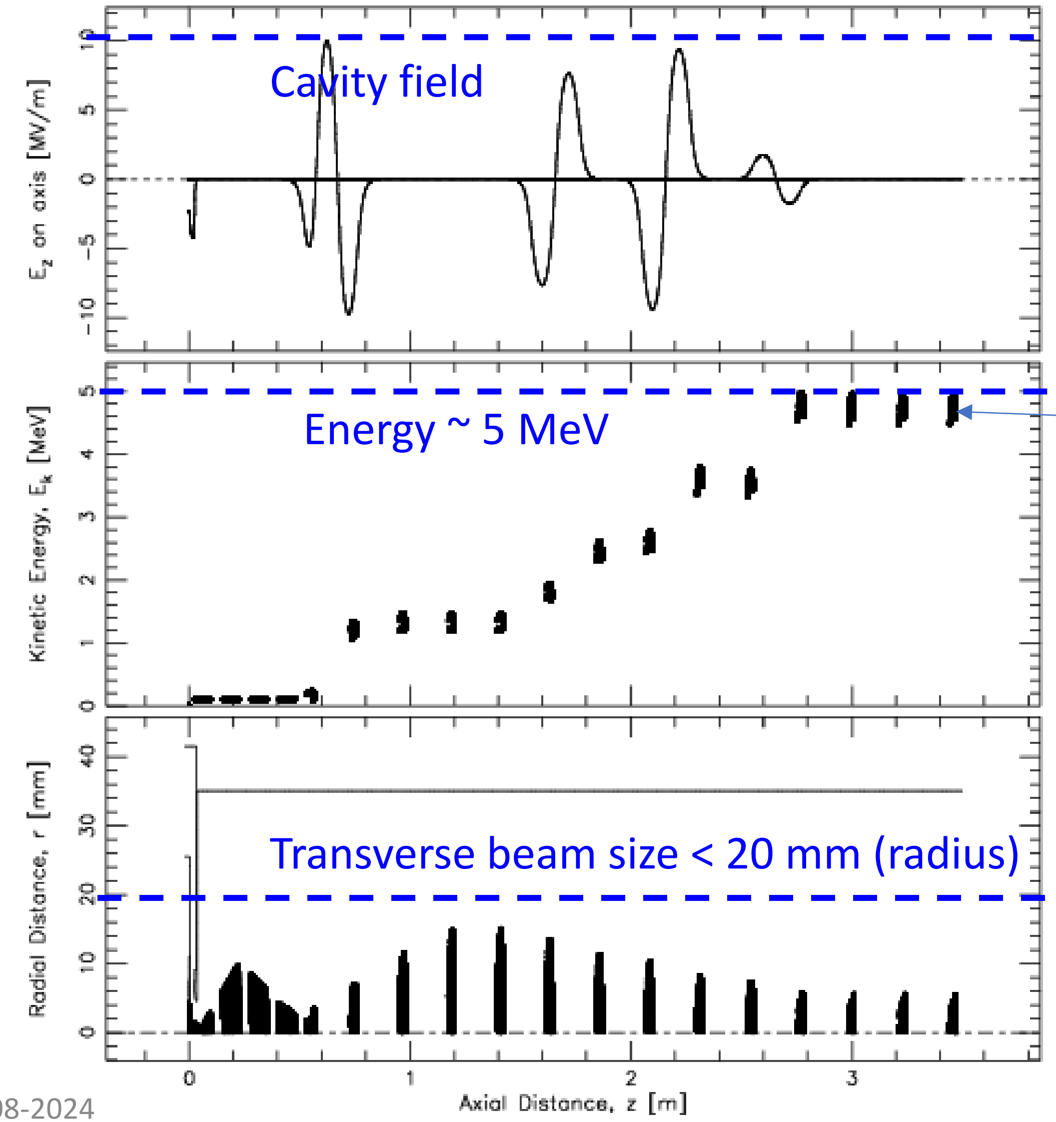
- Strength and distribution of field in 3 cells were optimized to minimize the tail of longitudinal distribution and energy spread.



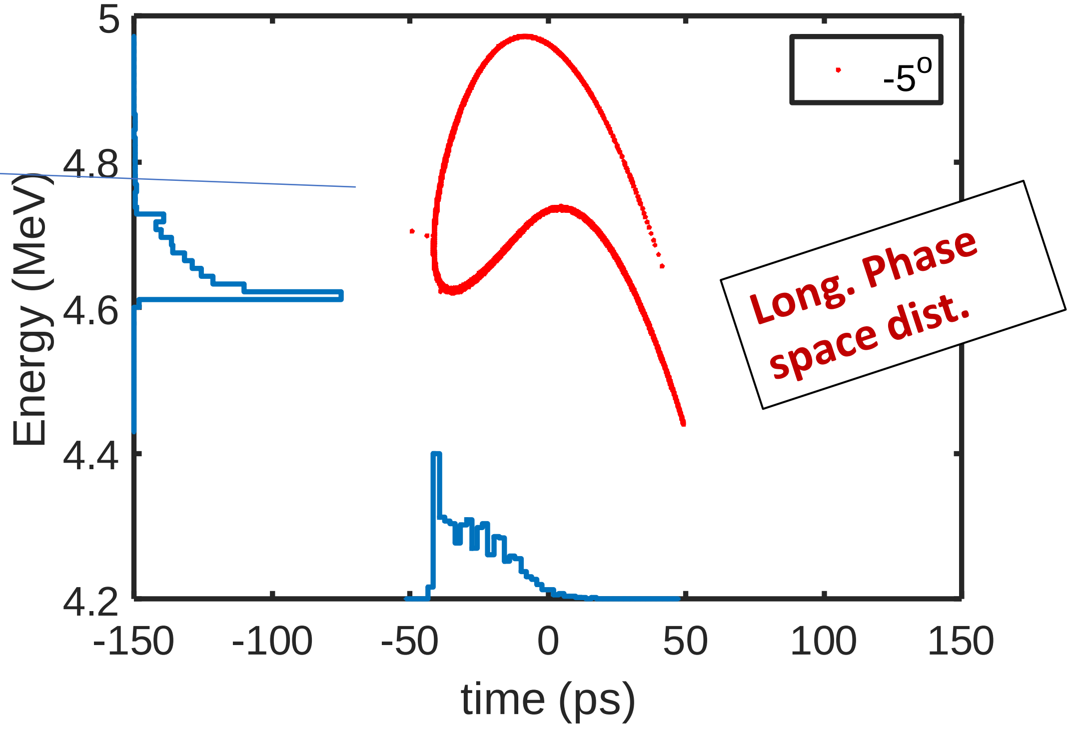


✓ Maximum of 400 ps (FW) can be passed through 3-cell buncher cavity.

Linac output beam



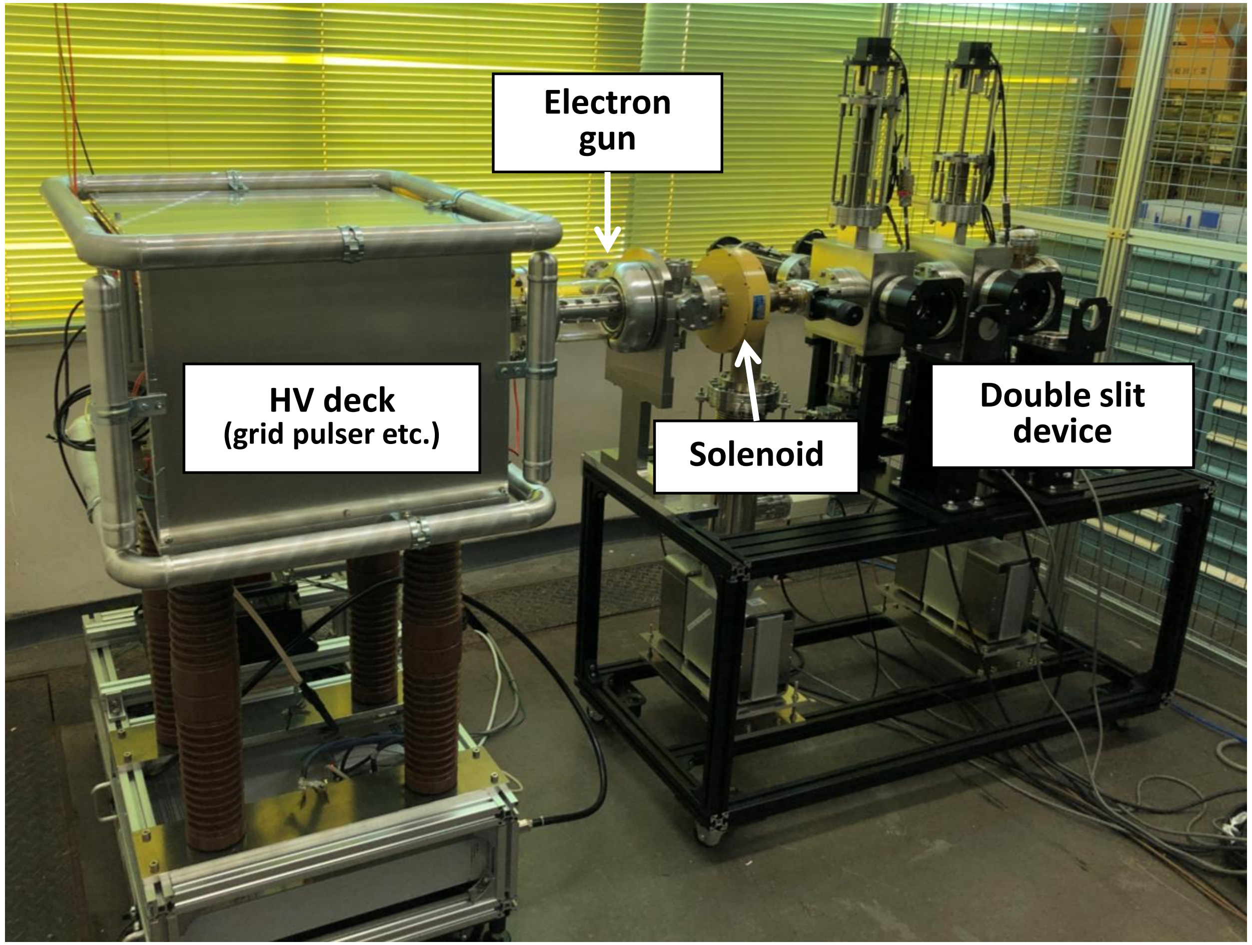
Bunch length(FWHM) = 32 ps
Mean energy = 4.68 MeV
Energy spread = 0.7 %



Present status gun development

- Electron gun test stand has been constructed to generate short pulse electron beams with high repetition.
  - ✓ DC HV: 80~100kV (max 120kV)
  - ✓ Cathode: Y646B(EIMAC, d=8mm)
  - ✓ Monitor: CT, Faraday cup, Double-slit

- Short bunch generation (RF gating)
  - ✓ Impedance @1.5 GHz: ~ 45 Ω
  - ✓ Max. grid voltage: ~67 V
  - ✓ Bunch charge: 8pC (175 ps (FWHM), 260 ps (FW)) *prediction



Summary & future prospects

- ❑ PFAS can only be degraded with EB radiation effectively.
- ❑ **Liquid-He free superconducting rf (SRF) linac** was designed (5 MeV, 10 mA). The linac consists of the 100 kV DC thermionic electron gun driven by RF gating grid and the 1.3 GHz Nb_3Sn SRF cavities using conduction cooling system. **The low β-buncher cavities of the three cells** were specially designed.
- ❑ Final simulations result
  - ➔ Bunch-length=32 ps (FWHM), Mean energy=4.68 MeV, Energy spread = 0.7 %
- ❑ The design need an electron gun generating pulses ~400 ps (FW)

Future prospects

- ❑ Test RF gating for available source of 1.5 GHz, 100 W (expected result ~ 260 ps FW)
- ❑ Measurement of bunch-length & emittance

Acknowledgement

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Thank you