WG3, AFAD 2026

Design and Preliminary Experimental studies of a High-Average-Current Compact Injector System for SRF Electron Linacs

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This work is based on my doctoral study at Tohoku University, Japan

Outline

- **Introduction**
  - Motivation, PFAS
  - Water purification using Electron Beam (EB)
- **Development of High-Average-Current Compact Electron Injector**
  - Configuration of SRF linac (5 MeV, 10 mA)
  - 3-cell low beta cavity
  - Electron gun for short pulse e-beam generation
    - **RF gated thermionic gridded electron gun**
- **Preliminary experimental studies for short pulse e-beam generation**
  - µs grid pulser experimental setup
    - Development of Faraday cup
    - Gun performance (g_{21} measurement)
  - RF gating test set up
- **Summary**

Motivation

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



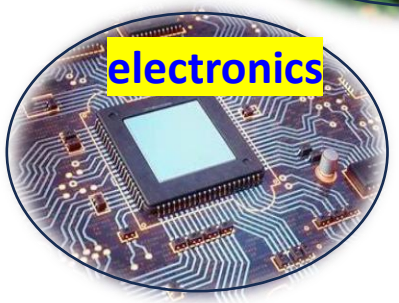




Improved life-style & hence industrialization

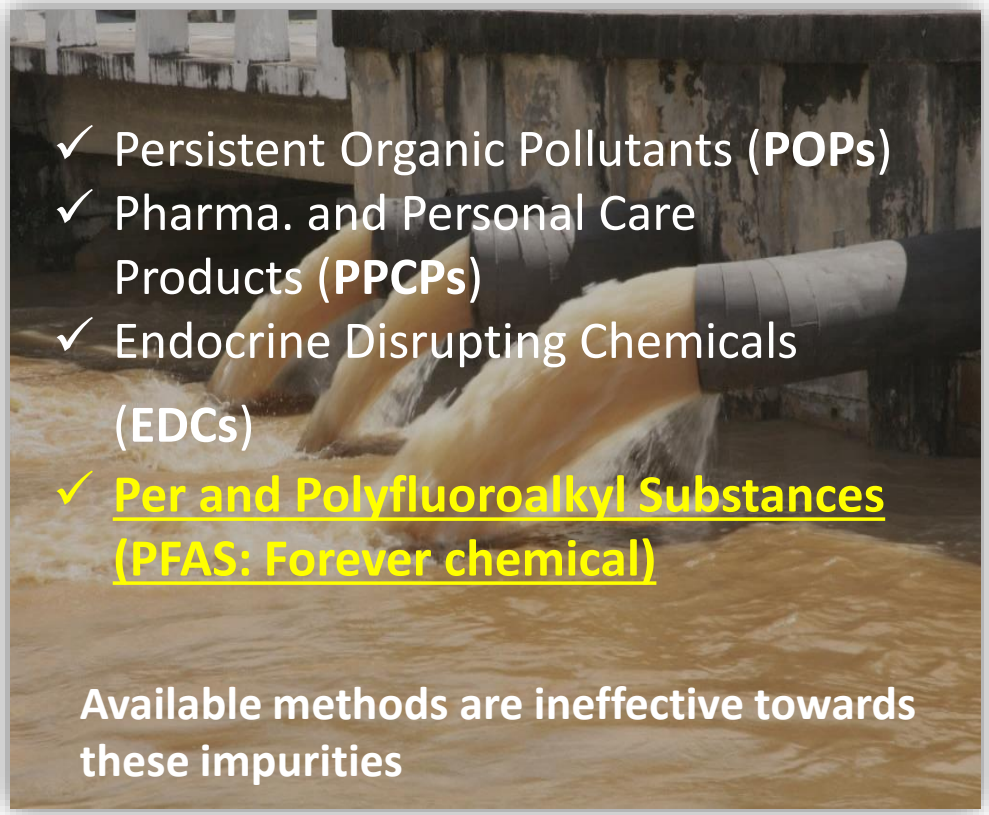






Harmful & stubborn new Impurities





Electron beam treatment: proven to degrade such impurities.

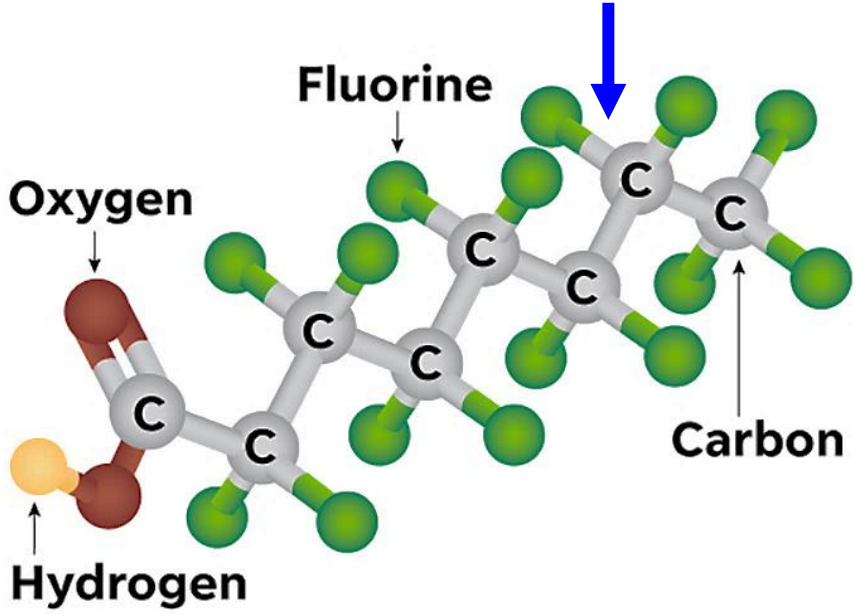
What is PFAS?

Good side

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

Useful in almost every sector ➔Increased global Usage

High Stability of the 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)

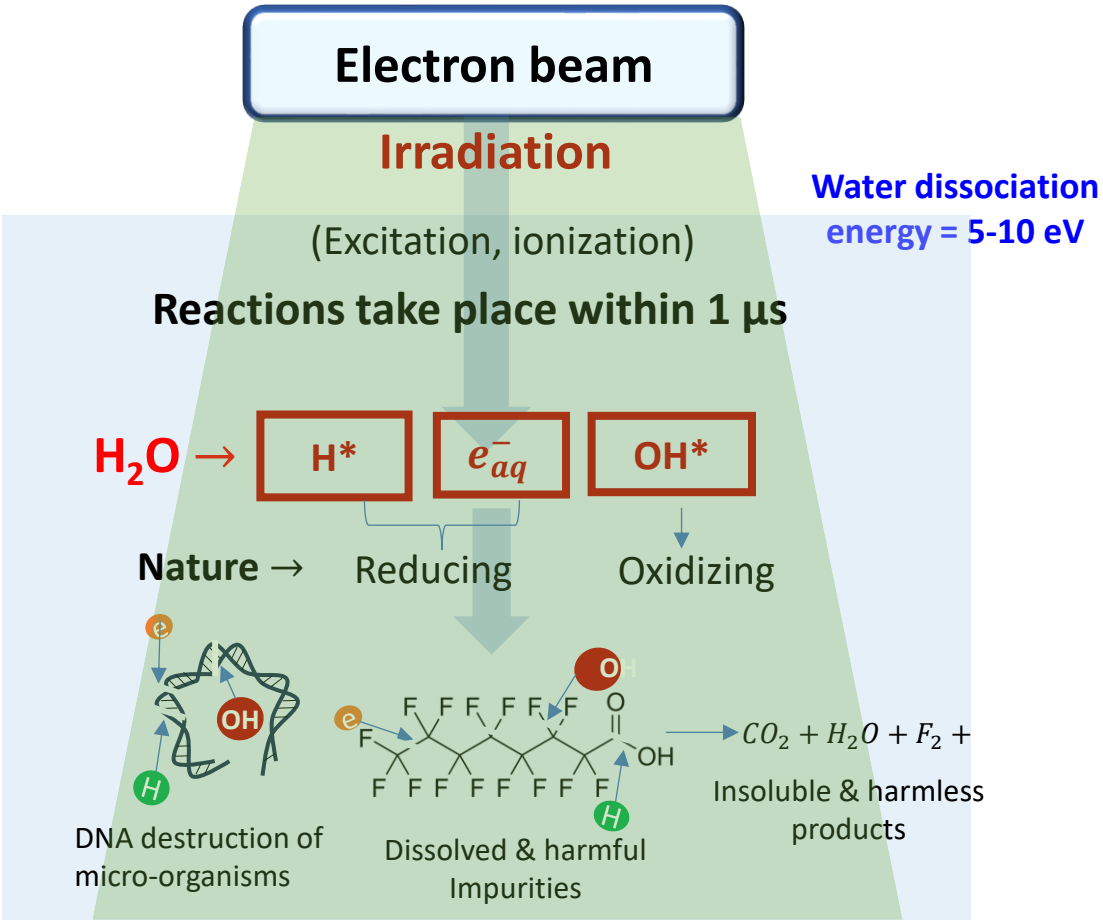
*K. Londhe et al., , ACS ES&T Eng. 1, 827 (2021).

Decomposing PFAS using electron beams need high dose

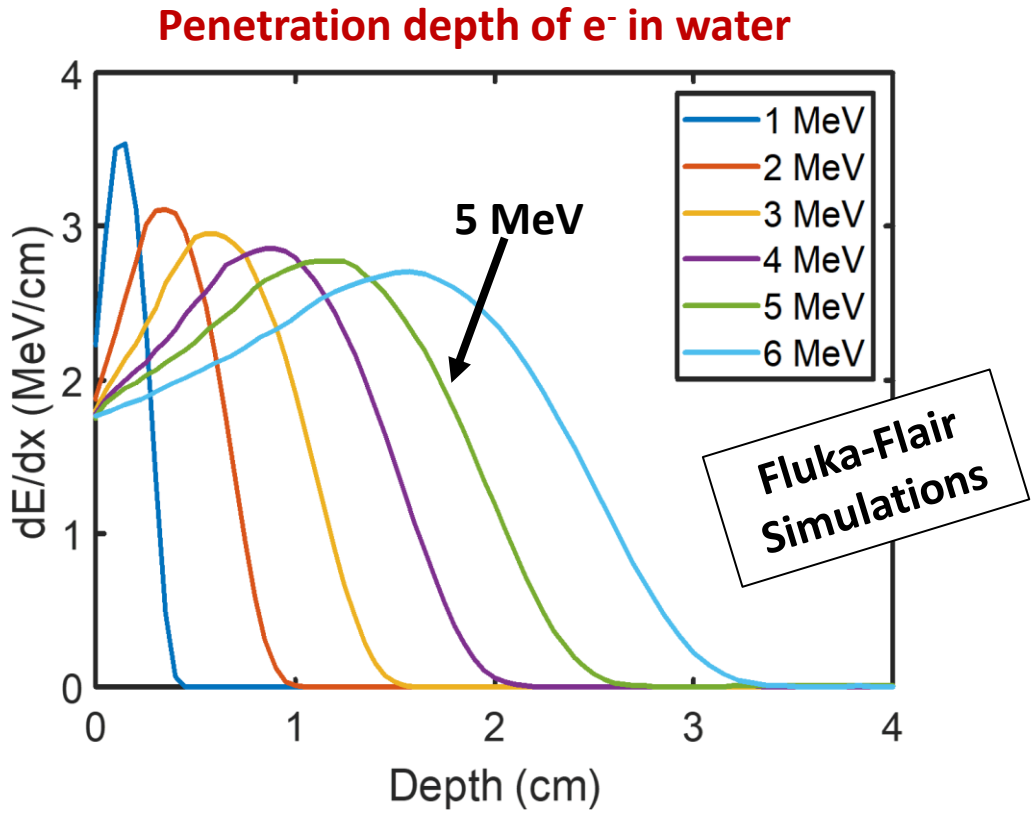
➔ We want to develop high-average-current accelerator

Wastewater purification using electron beam (EB)

- **Water purification using electron beam**



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



Higher the current, better the processing rate

(First target ➔ 5 MeV, 10 mA accelerator)

Configuration of electron linac

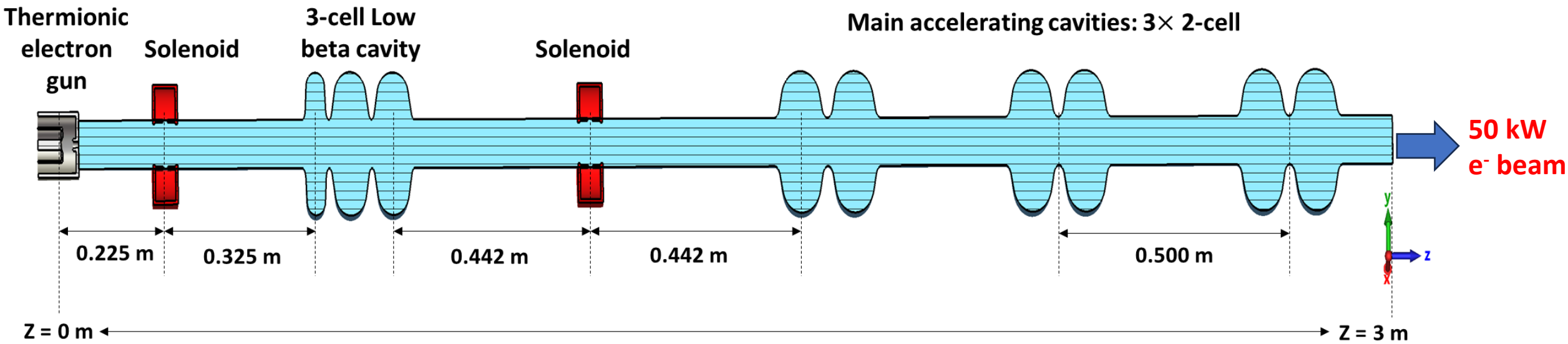
■ **5 MeV Liquid-He free SRF linac** is designed using **KUCODE***

* K Masuda, *Development of Numerical Simulation Codes and Application to Klystron Efficiency Enhancement*, Ph. D Thesis, Dept. of Engineering, Kyoto Univ. (1998).

Requirements : Compact, CW, High-average-current, SRF, No beam loss

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

❑ ***High average current e^- gun***
- ✓ *DC high voltage (80 kV)*
- ✓ *Thermionic cathode*



Buncher cavity design ← a gaussian bunch @ cathode of the gun

3-cell low beta cavity

Design aim:

No beam loss

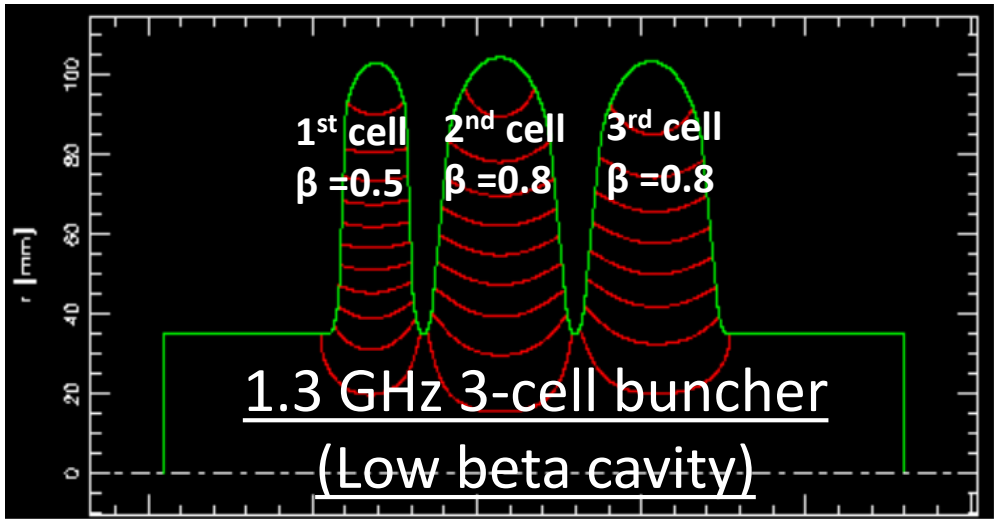
Bunching & Energy boost **(β~1)**

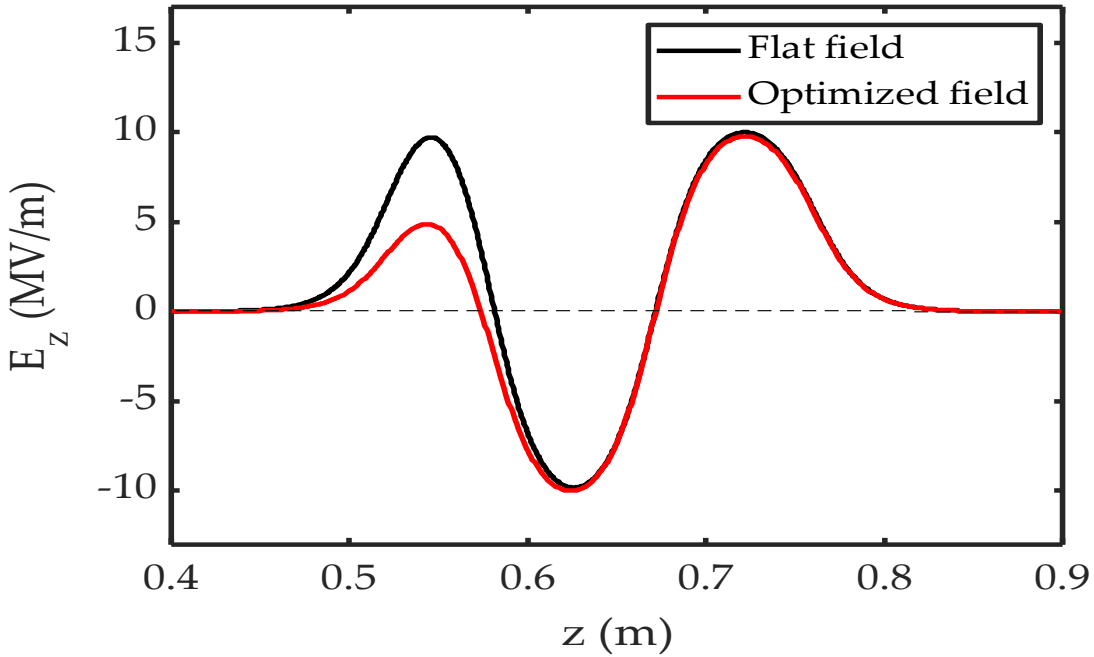
Parameters

- ✓ Gun HV: 80 kV ➔ β = 0.5
- ✓ 1st cell is a buncher
- ✓ 2nd & 3rd cells are Booster
- ✓ Beam energy in 2nd cell ➔ ~ β = 0.8

Advantages

- ✓ No pre-bunching cavity, Compact
- ✓ Simplified phase adjustment system
- ✓ Minimal leakage field : long bunch-injection @ 1.3 GHz

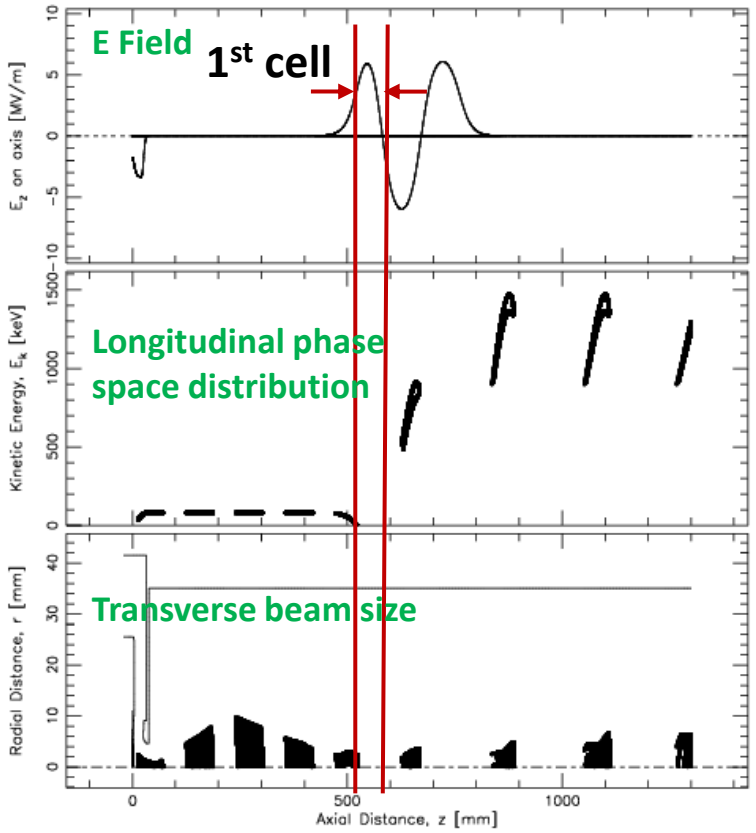




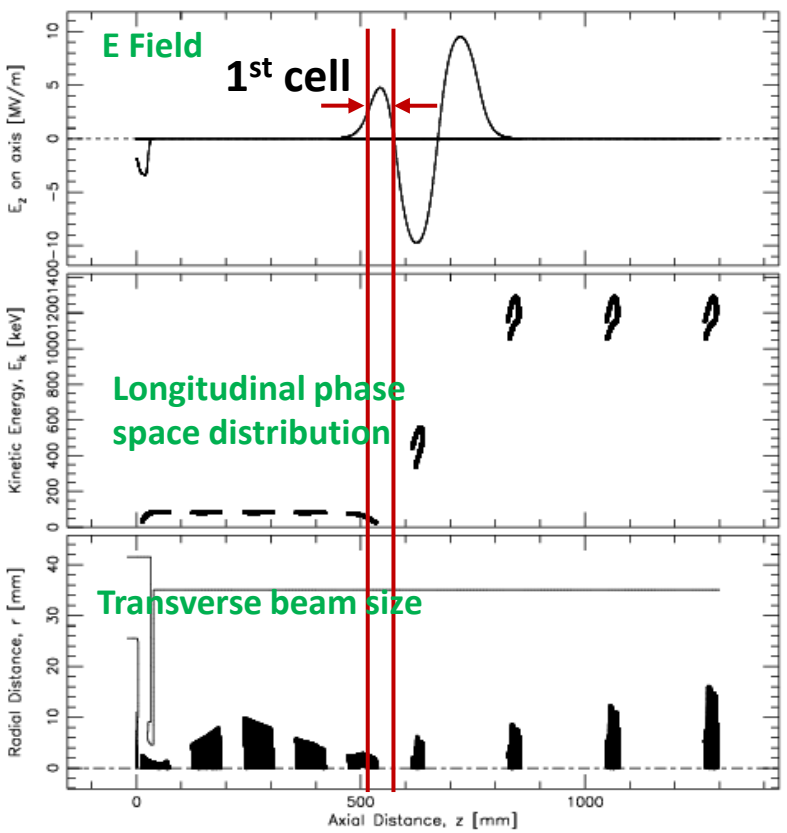
Bunching process & Output beam

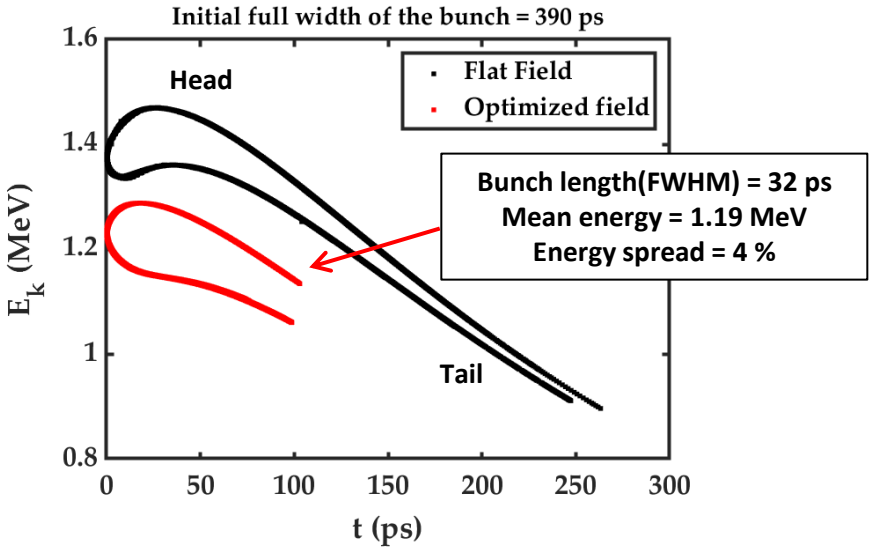
- Strength and distribution of field in 3 cells are important parameters.
- Bunch length was assumed to be σ = 65 ps (FW: 390 ps) at gun cathode.

Flat field (10MV/m)



Optimized field

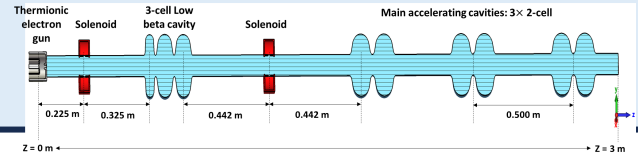


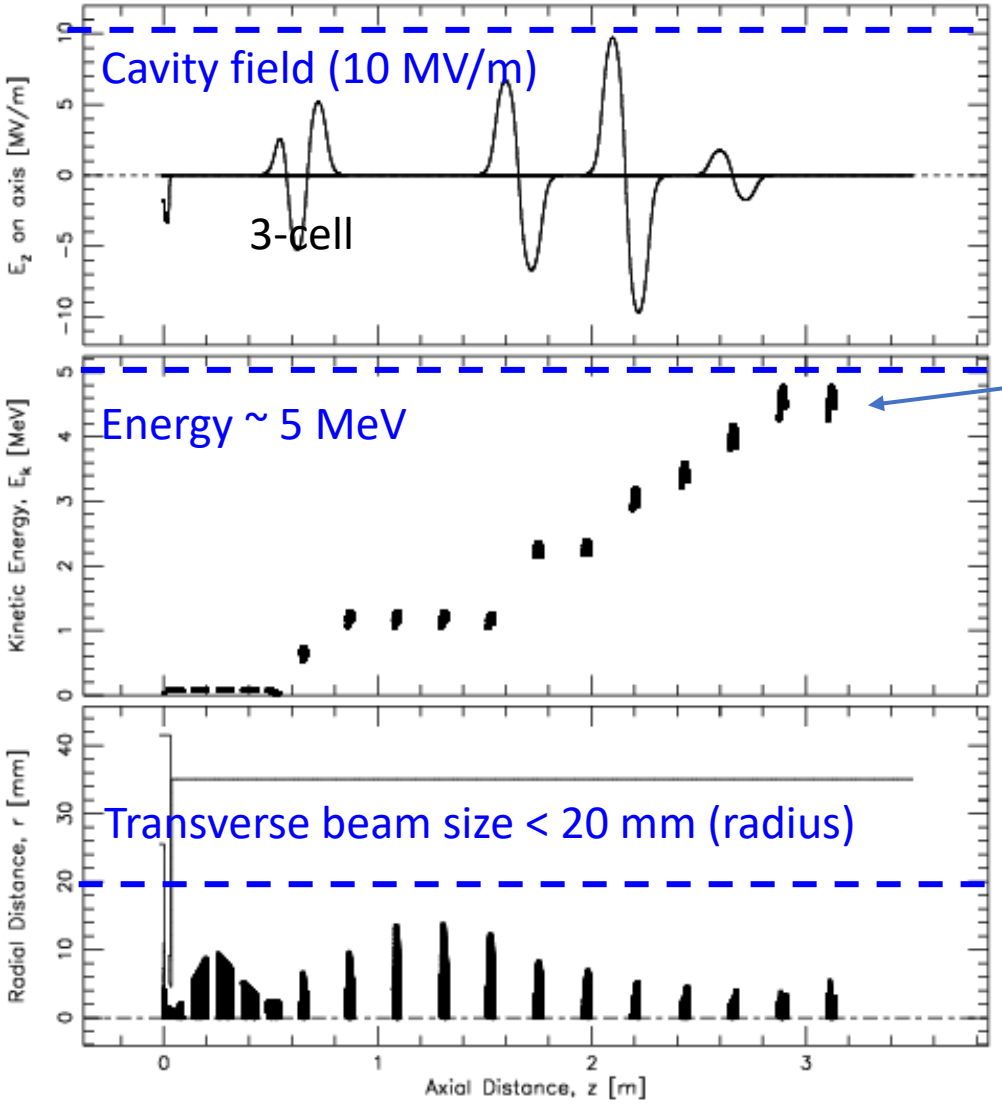


✓ Requirement from the gun ➔ bunch-length of ***390 ps (FW) @ 1.3 GHz Repetition rate in CW mode***

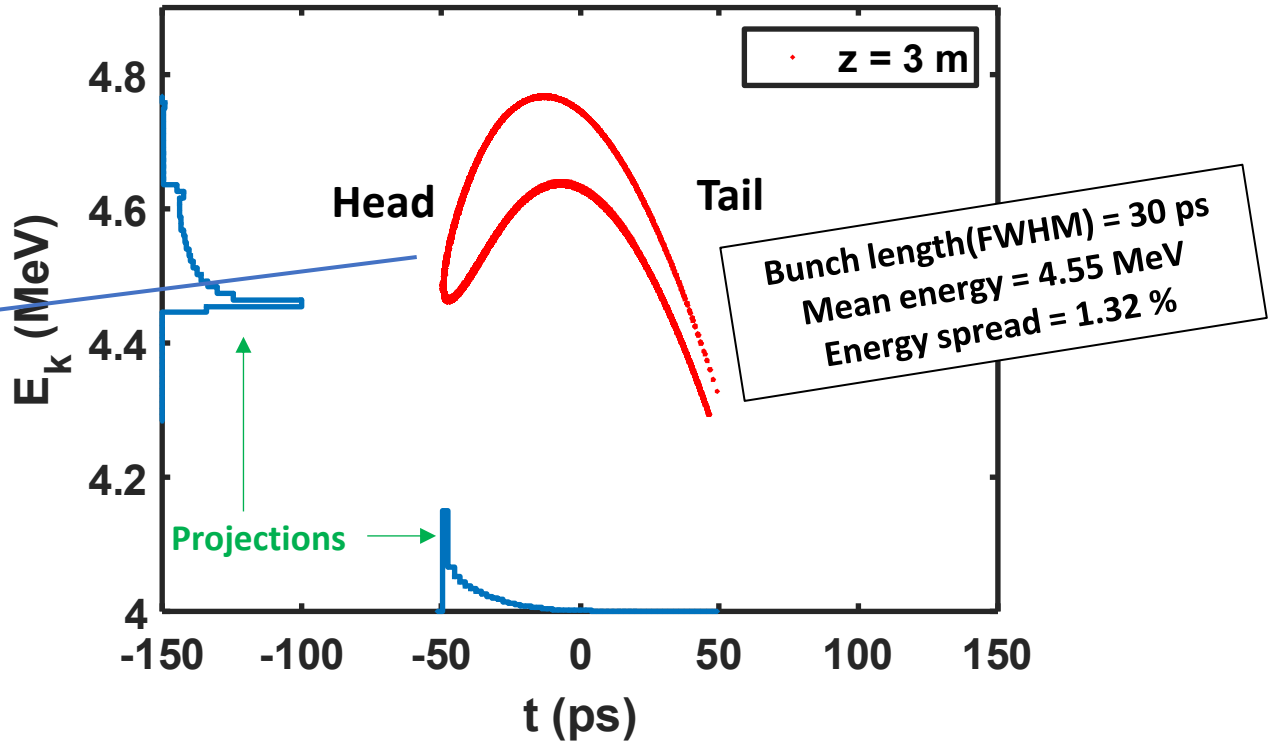
With optimized/smaller field in low beta cavity ➔ smaller surface field

Linac output beam





Longitudinal phase space distribution



- ✓ ~ 5 MeV energy gain with zero beam loss
- ✓ Norm. tras. beam emittance = 20 mm-mrad
- ✓ **Require bunches of FW ≤ 390 ps with 1.3 GHz × 8 pC**

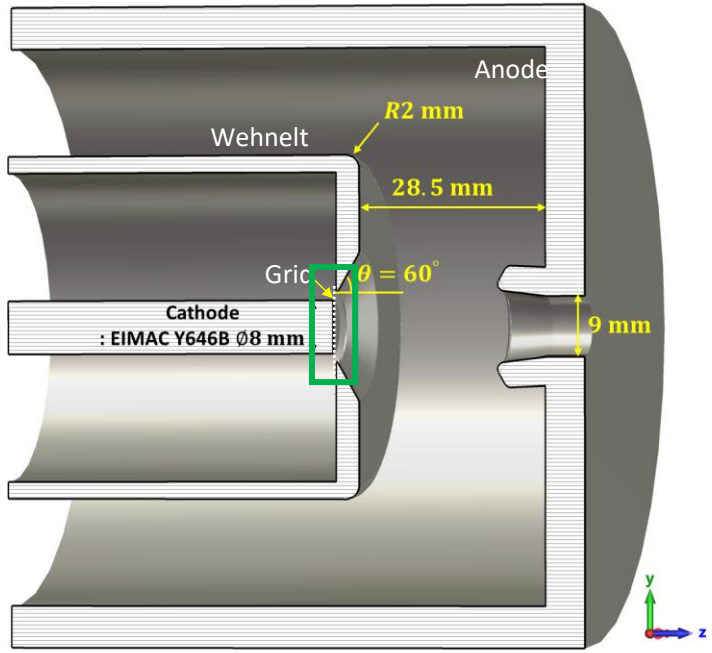
Thermionic gridded electron gun

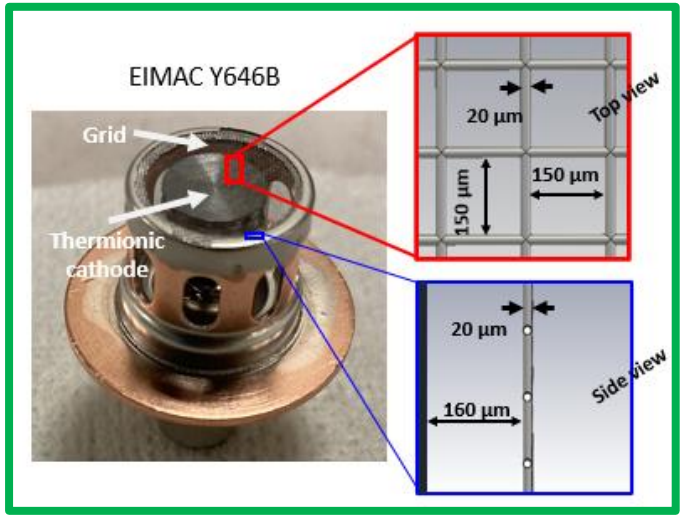
Requirements for the e⁻ gun:

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

Target :

- ✓ **FW< 390 ps**
- ✓ **1.3 GHz × 8 pC = 10mA**





Electron gun geometry & it's cathode-grid assembly @ RARiS

Grid drive: a challenge

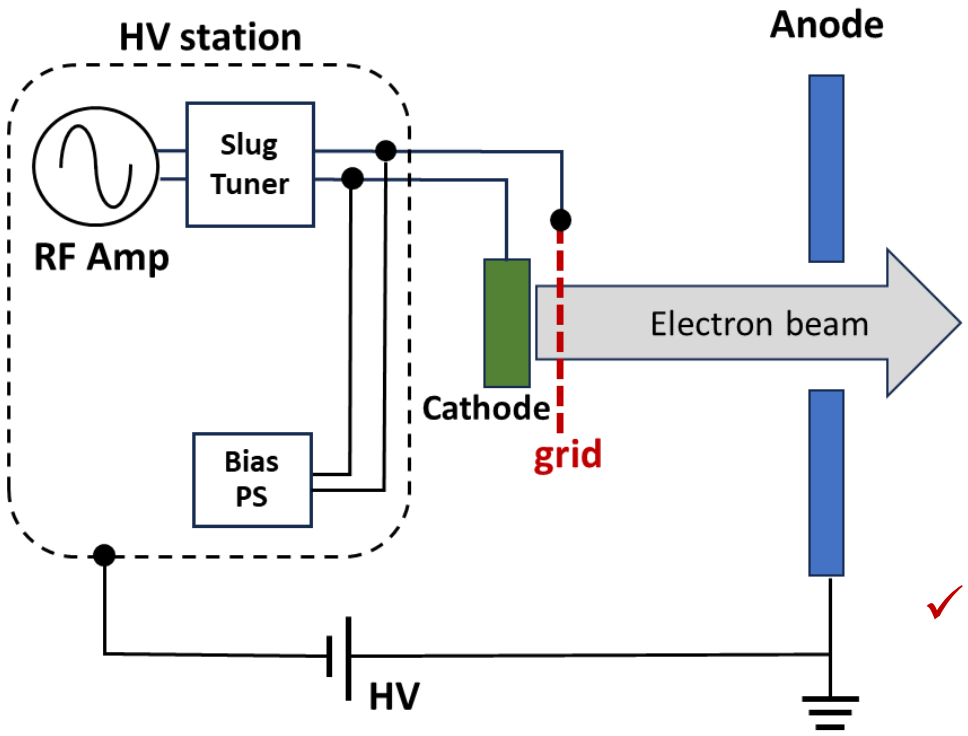
☹ Avalanche pulser (~kHz)

😐 FET pulser (~10MHz)

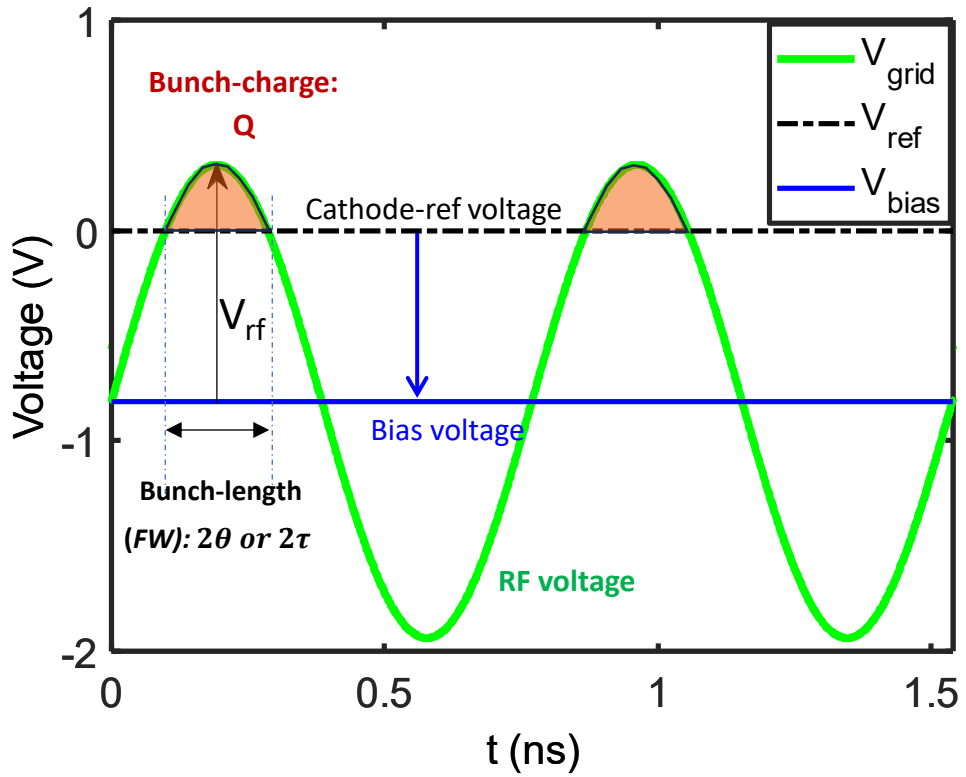
☺ RF gating of the grid (GHz-order repetition is achievable)

Short e-bunch generation

- ***RF signal & DC biasing drives the electron gun grid.***



Potential difference between cathode and grid

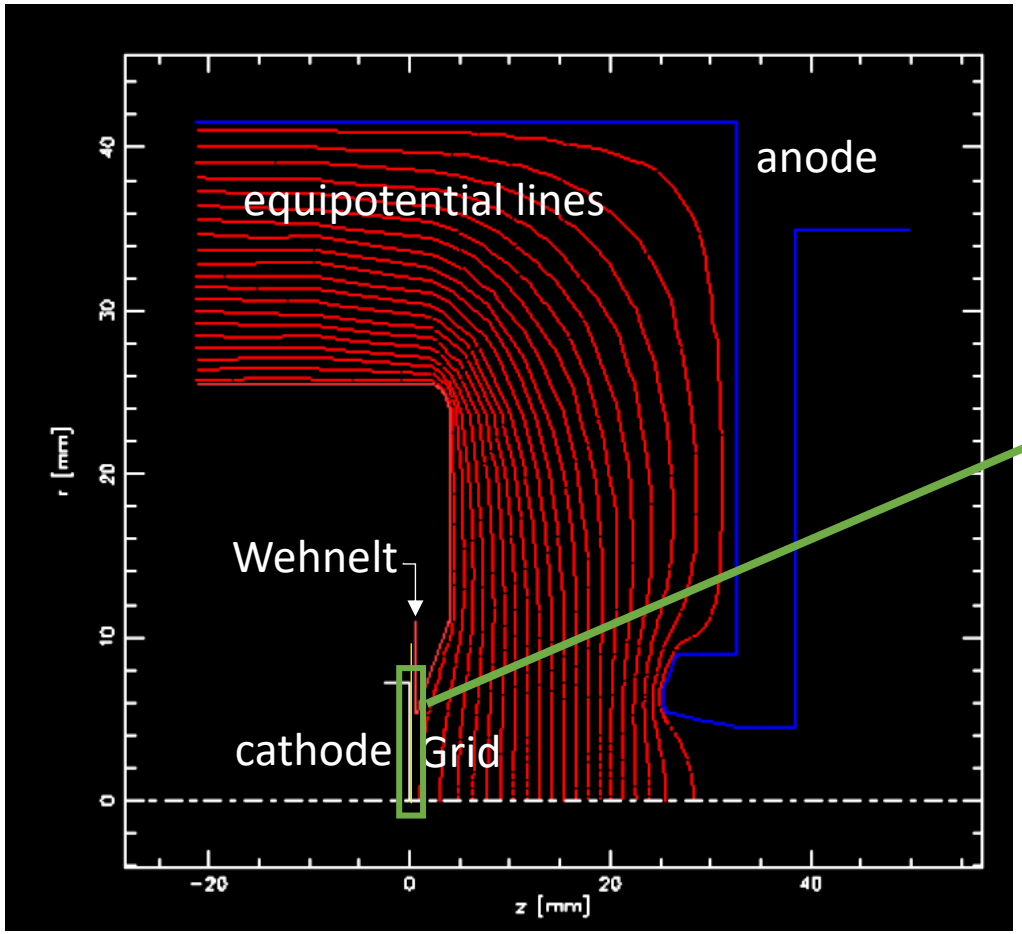


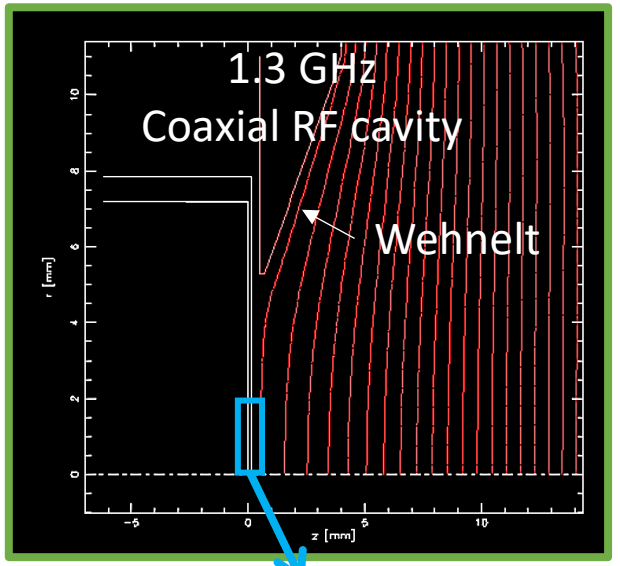
✓ **Electron bunch (Q & 2θ) is governed by following parameters.**

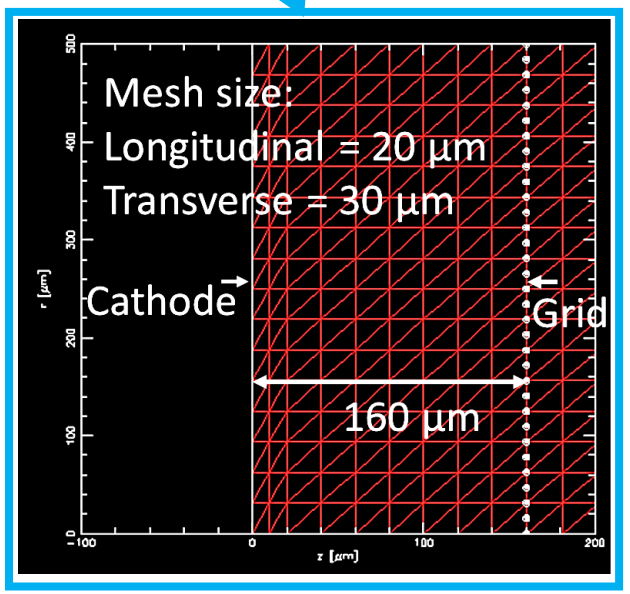
- **RF amplitude [V]:** V_{rf}
- **Bias voltage [V]:** V_{bias} $\quad * V_{grid} = V_{\mathrm{rf}} cos(\omega t - \theta) - V_{bias}$
- **Emission coefficient [A/V]:** $g_{21} = \left(\frac{dI_{beam}}{dV_{grid\ voltage}}\right)$

Simulation setup for RF gating

- **A carefully refined mesh was applied to the geometry in KUCODE.**

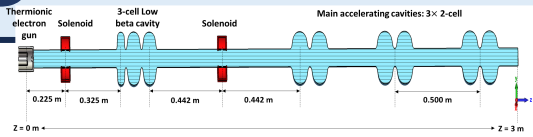






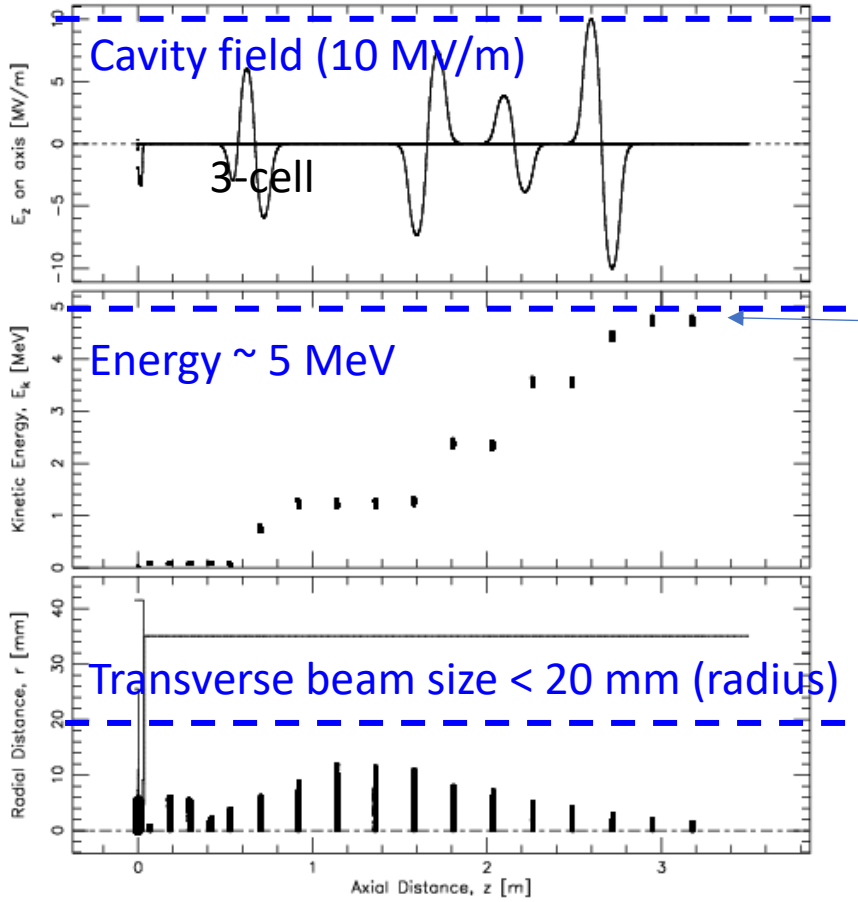
No initial bunch shape and length was assumed !

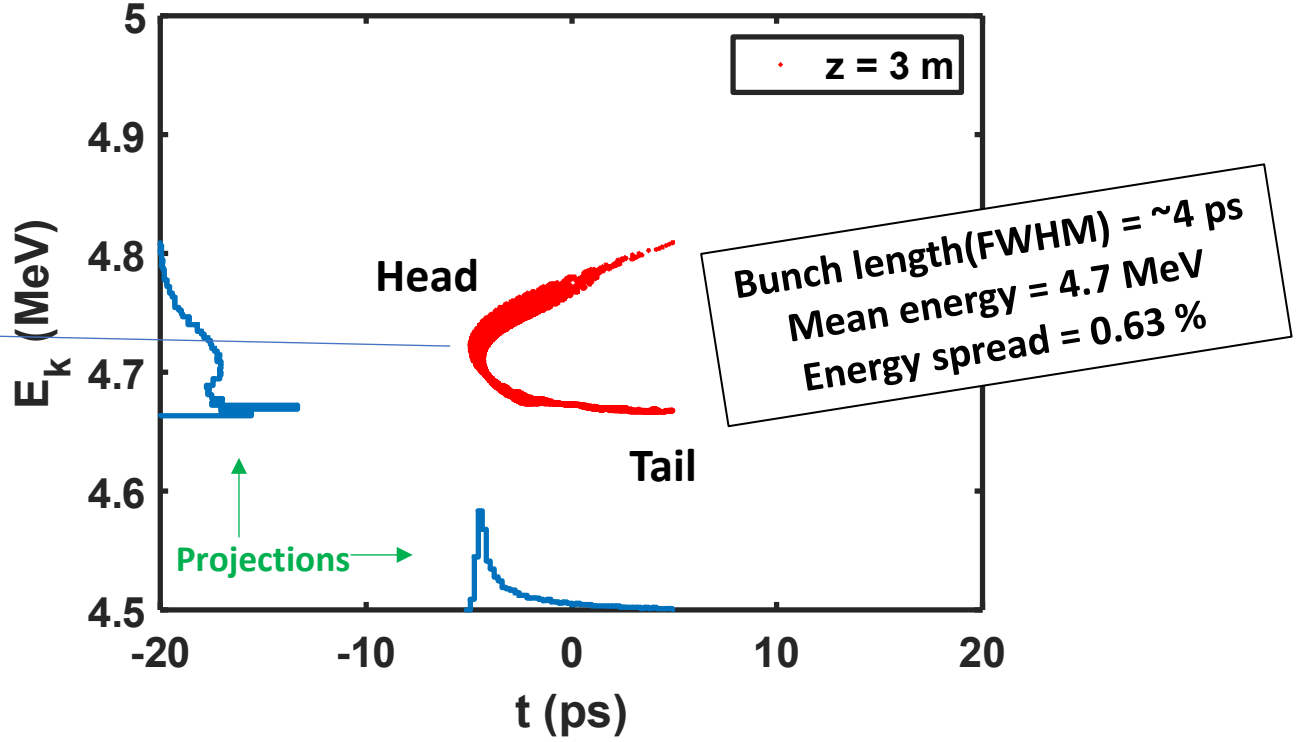
5 MeV output beam with RF gated gun



With 1.3 GHz RF amplifier (max. 100W) present at our facility

- ✓ **Cathode - grid impedance @1.3 GHz: ~45 Ω (meas.) ➔ Max. RF voltage (V_{rf}) = ~65 V**
- ✓ **V_{bias} = -50 V & $J_{cathode}$ = 0.4A/cm² ➔ for "Shortest bunch :10 ps" and "Q_{bunch}: ~8 pC"**



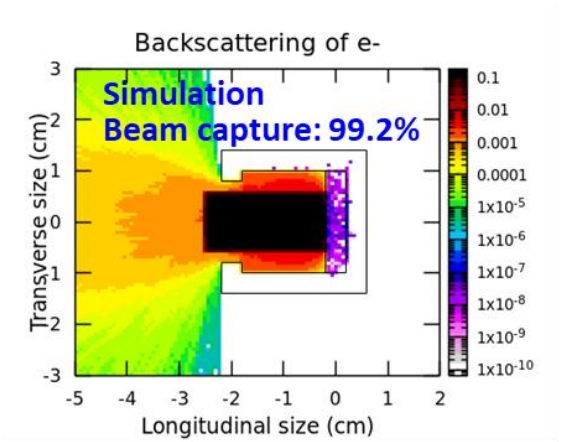


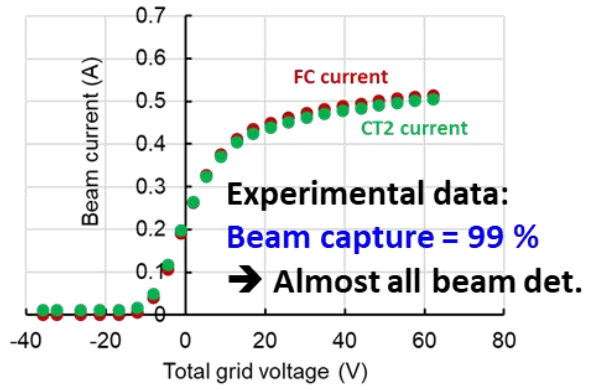
- ✓ **Norm. tras. emittance = 10 mm-mrad**
- ✓ **Suitable for high energy stages**

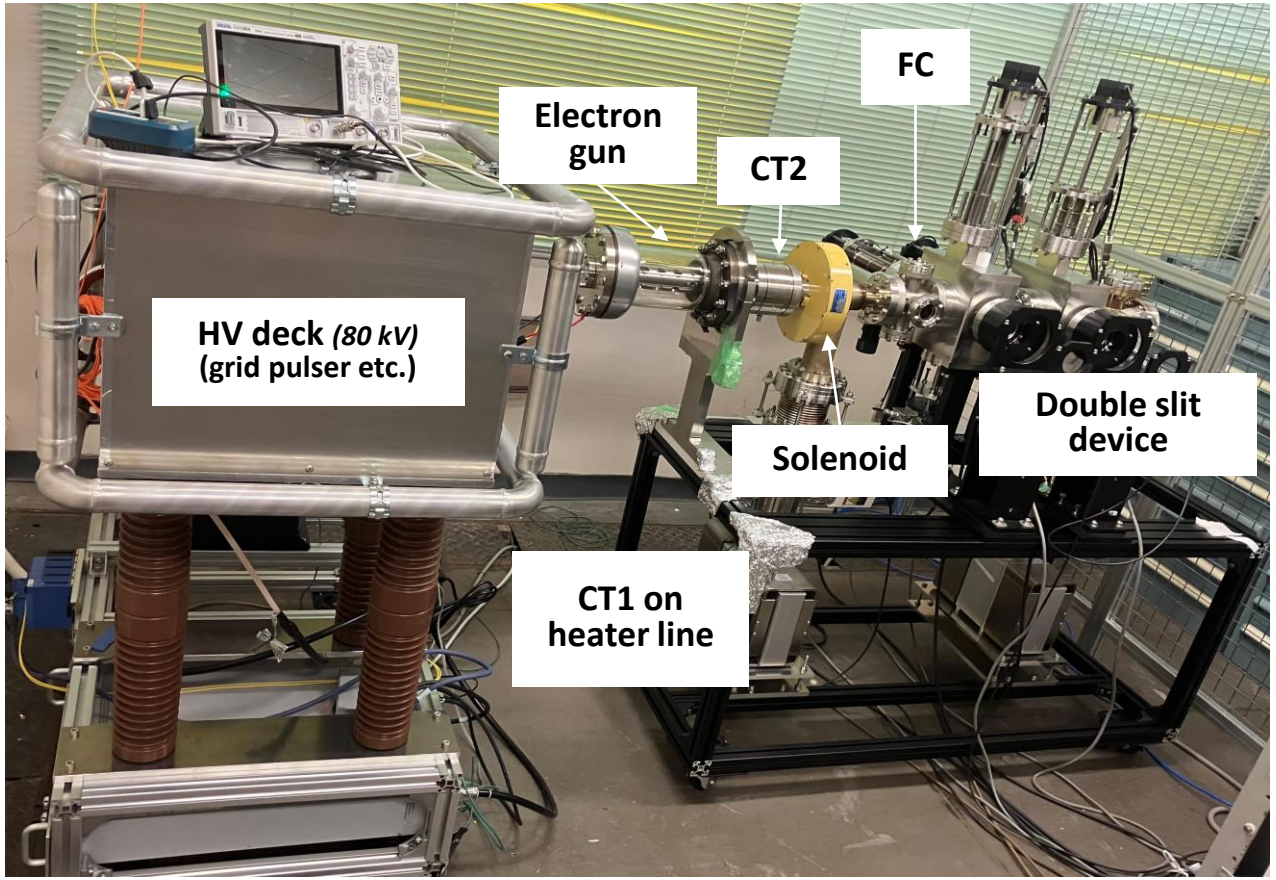
Preliminary experimental studies

- **Demonstration of CW high average current electron beam on test stand**
  1. **Construction of test stand including interlock system**
  2. **Micro-second electron beam generation (g_{21} measurement)**
  3. **Beam generation by RF gated method**



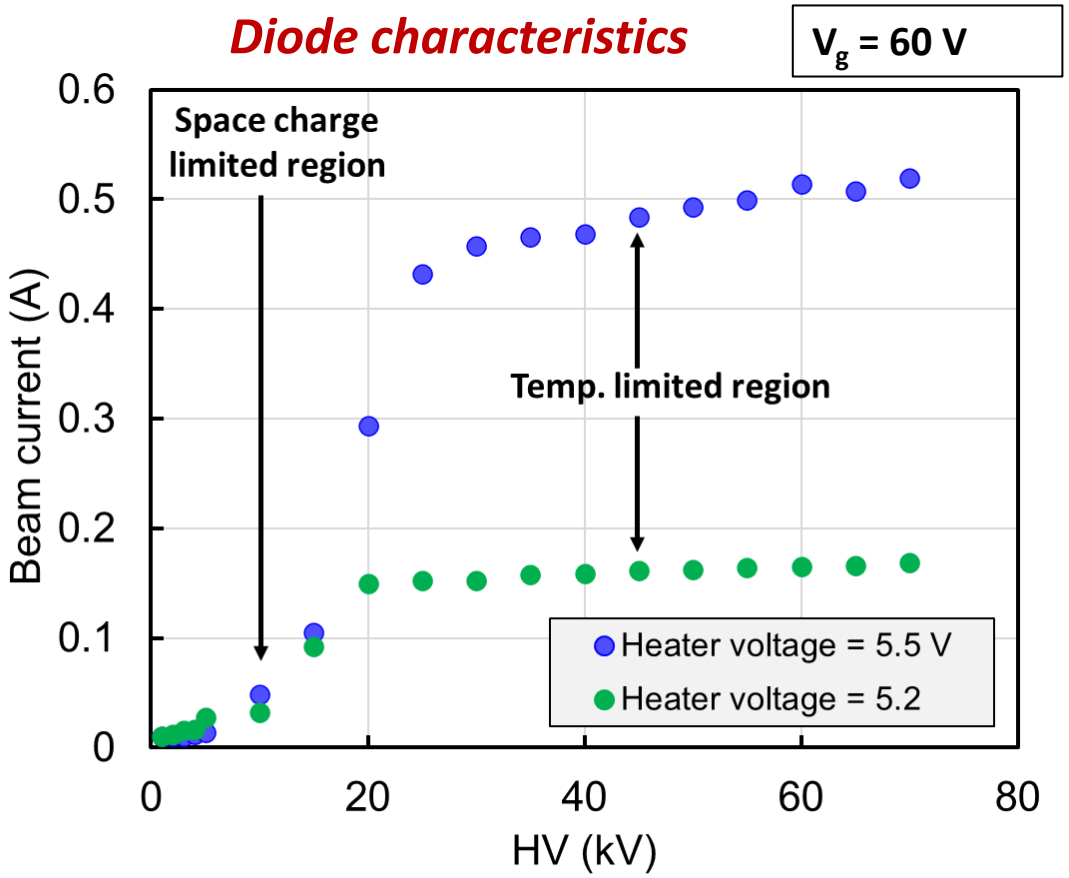


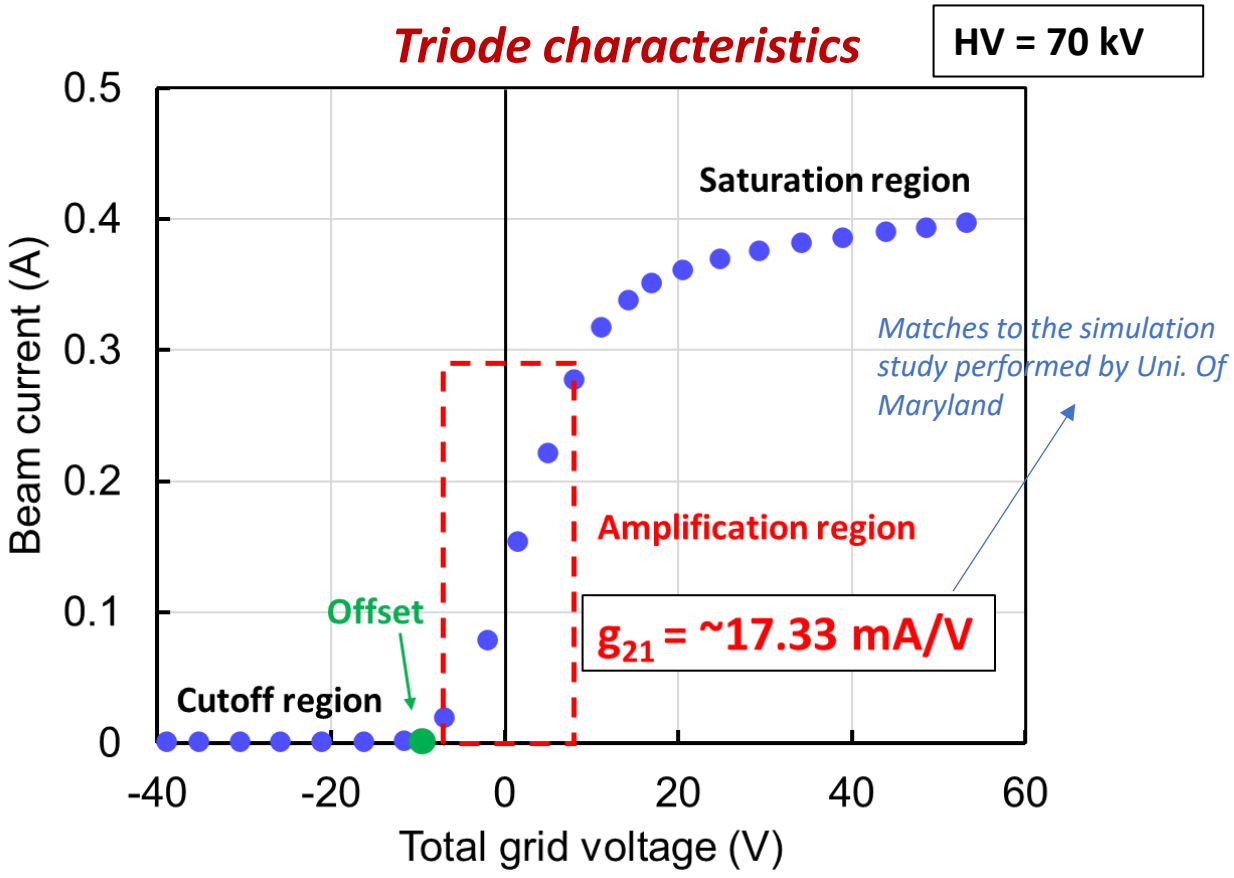




Gun characteristics measurement with μs pulser

- Diode and triode characteristics of the electron gun measured.
- The beam current was measured as a function of HV and grid voltage ($V_g=V_{rf}-V_{bias}$).

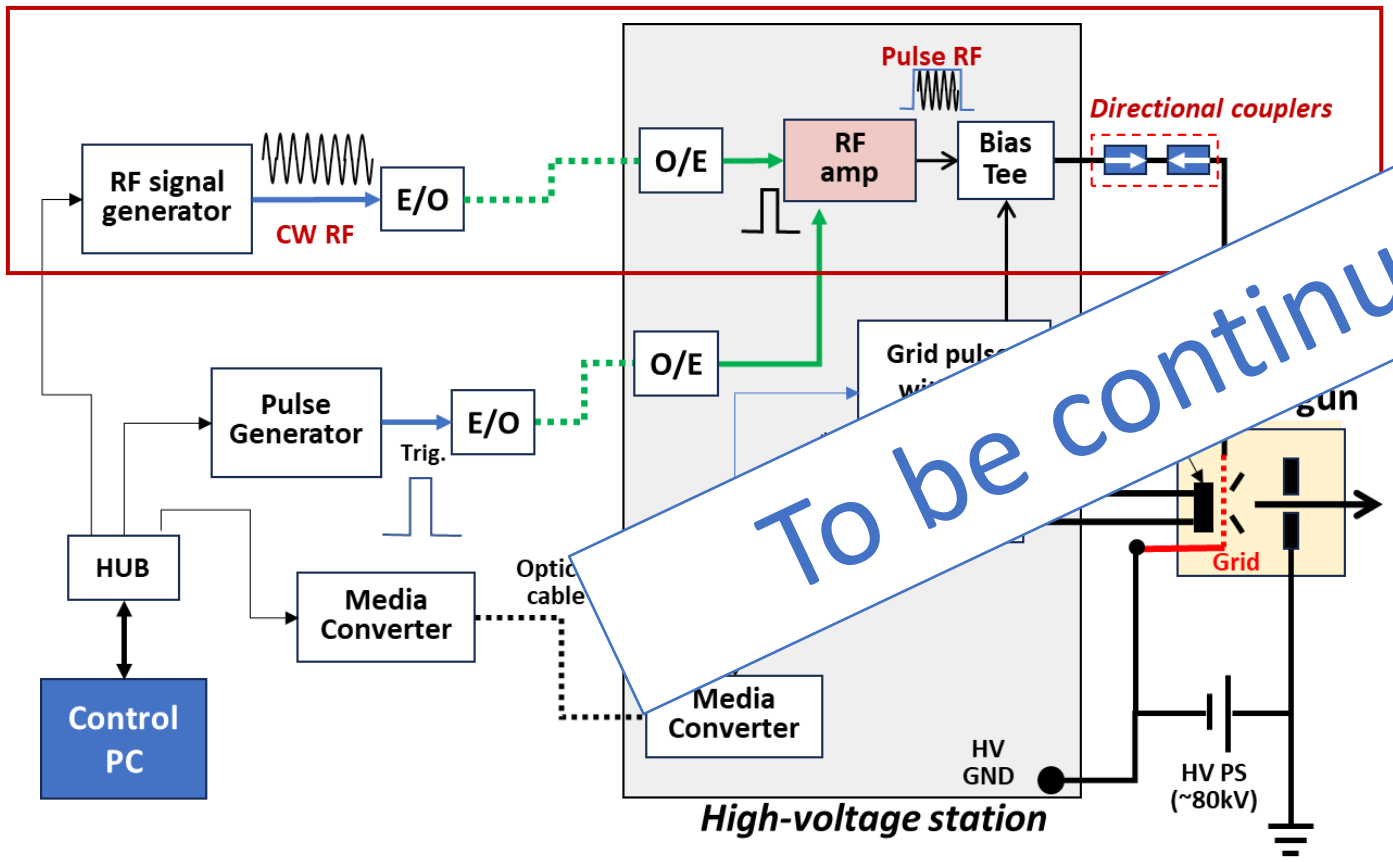




Electron gun characteristics measured accurately

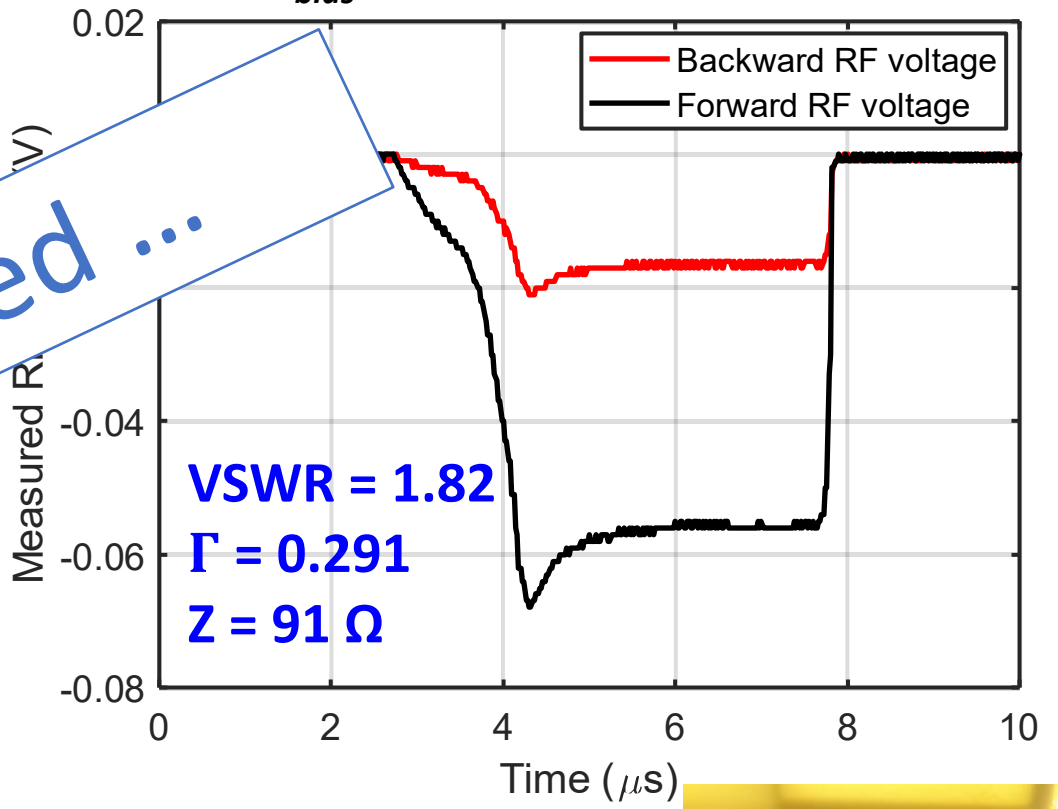
First test with RF gating

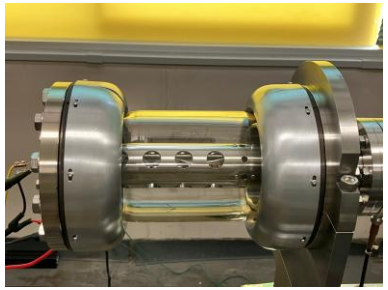
- The combined signal was applied to cathode-grid.
- Power reflection measured with Direct. couplers.



To be continued …

HV = 35 kV, Heater = 5.5 V,
V_{bias} = -10V, RF power = 100 W





Power reflection observed: need impedance matching

➔ Feed-through for the grid should be modified

Summary & Conclusion

- A ***CW, high-average-current electron injector***—crucial for applications in fundamental science, industry, and medicine—was developed.

- **A novel injector system—optimized for an SRF electron linac and composed of a thermionic electron gun and a 3-cell low-beta cavity—was designed.**

- **Simulations confirmed that RF gating applied to the grid of a thermionic gun** can generate **~150 ps (FW)** bunches with **8 pC (@1.3 GHz rep. rate, CW mode)** under V_{rf} = 65 V, V_{bias} = –50 V, and $J_{cathode}$ = 0.4 A/cm². **(No initial bunch-length and shape was assumed)**

- In the **5 MeV SRF injector system**, the bunch length compresses to **~10 ps (FW) with 8 pC (10 mA)**, indicating its suitability as an injector for high-energy accelerator stages. High average current of **70 mA (54 pC, FW = 80 ps)** is possible by only changing the V_{bias} = – 10 V. *By optimizing all parameters, current > 100 mA is possible.*

- Preliminary experiments using a µs grid pulser confirmed the **beam emission factor g_{21} = 17.33 mA/V**, and a **Faraday cup with >99%** efficiency was developed. For the RF gating exp., **feed-through for the grid need to be modified,** after this modification, CW short bunch generation will be performed.

Thank you