AITANA

MATTER AND TECHNOLOGY

High-Gradient Radiofrequency Accelerators for Radiotherapy

M. Boronat on behalf of IFICs accelerators team.

Workshop on Technologies & Applied Research at the Future Valencian Proton-Therapy Facility

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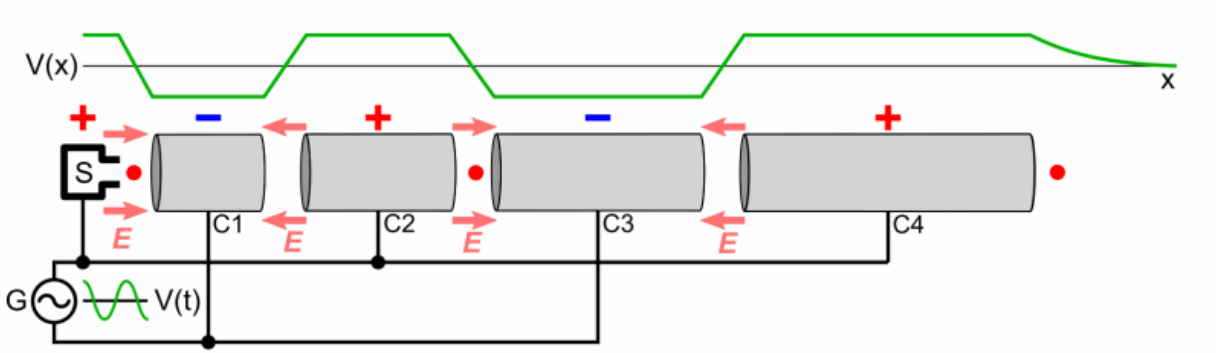
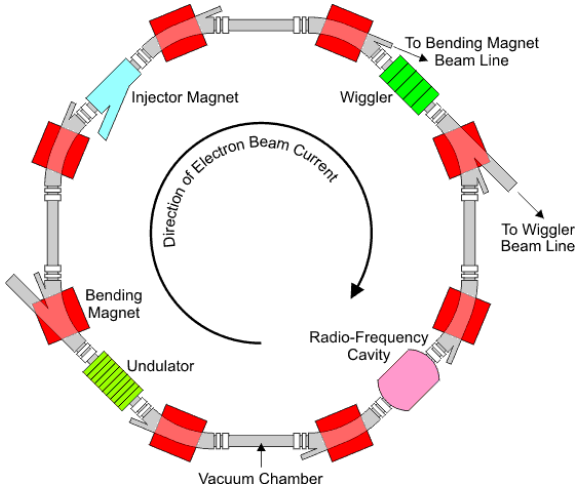
RF Accelerators

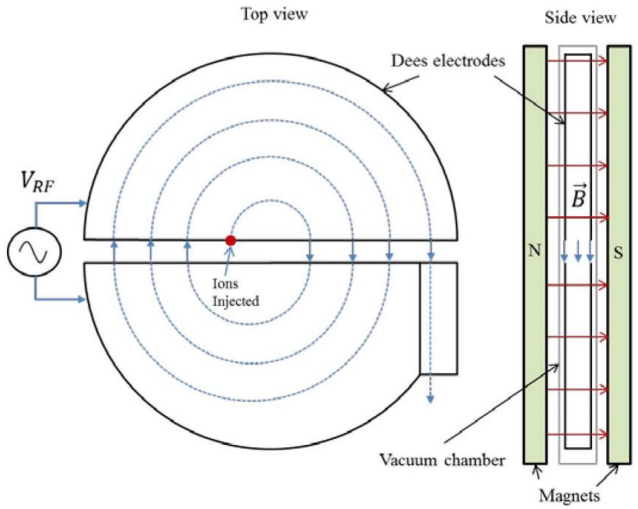
Linear accelerator (Linac)



Synchrotrons



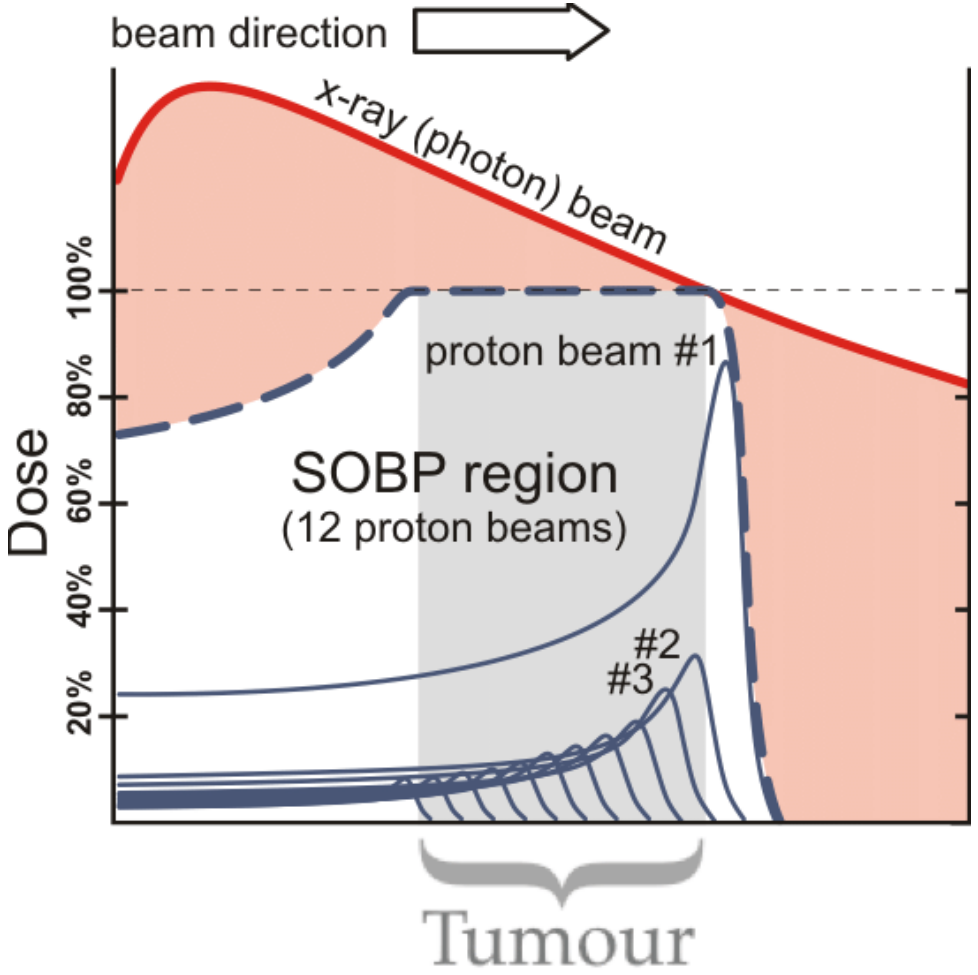
Cyclotron



- Radiofrequency (RF) accelerators use the oscillation of electromagnetic waves to accelerate charged particles.
- Accelerating gradient: Refers to the rate at which the energy of a particle changes per unit of length, measured in units such as MV/m.

Nassiri, A et al. 10.1109/TNS.2015.2485164.

Linacs for hadrontherapy



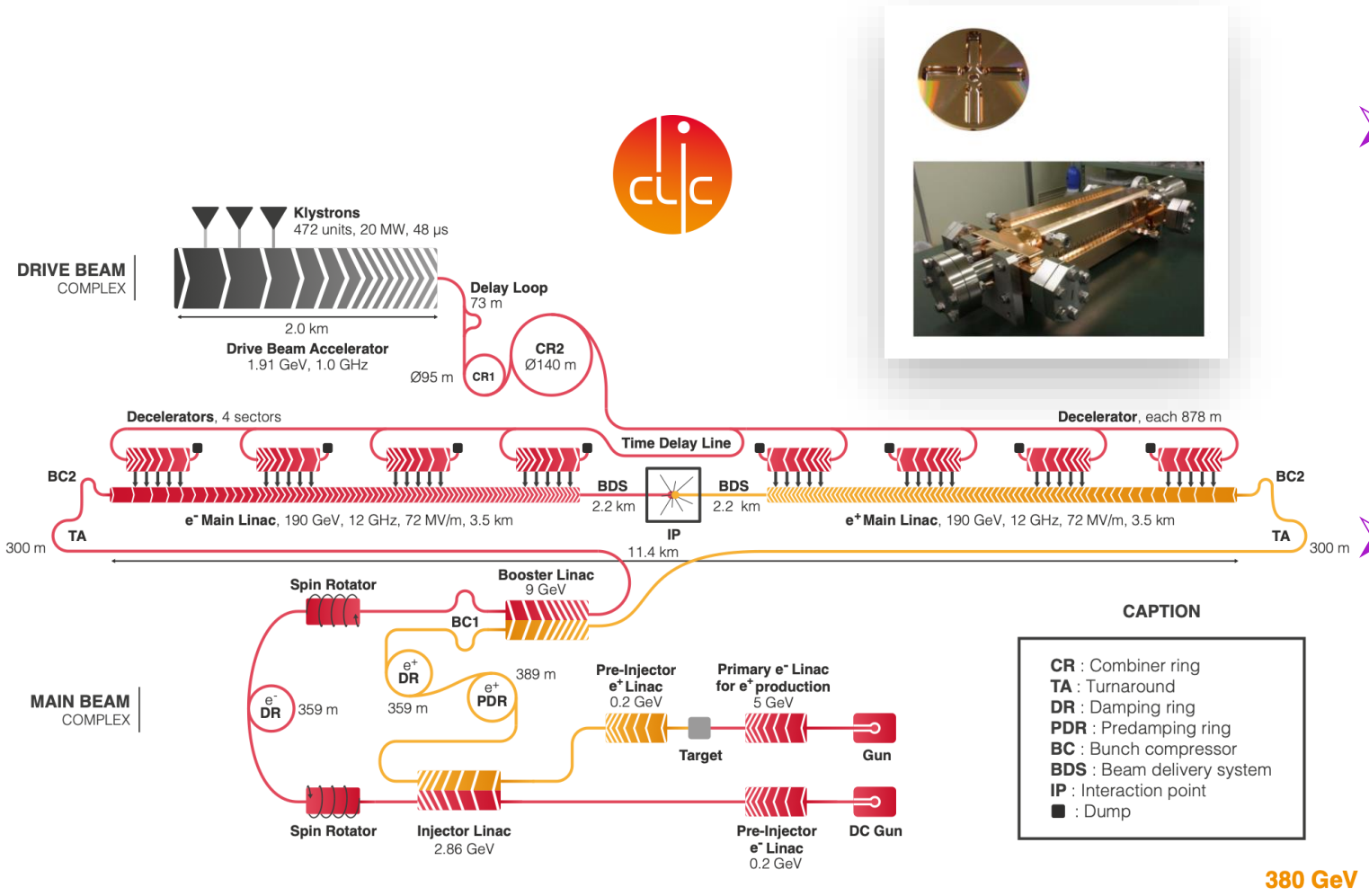
- Linacs are capable of ultra-fast amplitude-phase modulation.
- Fast energy changes, within the 10 ms range, have the potential to enable ultra-fast multipainting therapy sessions.

Accelerator Type	Energy variation by electronic means	Energy variation delay
Cyclotron	NO	80 -1 00 ms (*)
Synchrotron	YES	1 – 2 second
Linac	YES	1 – 2 miliseconds

(*) with advanced movable absorbers

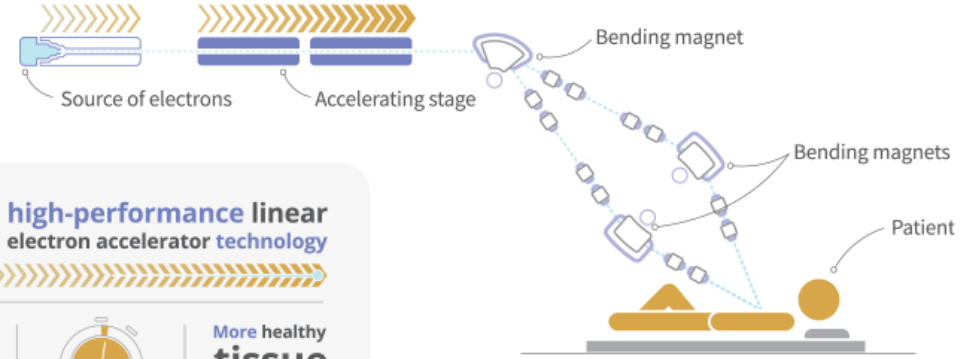
De Simoni et al. 1548. 012020. 10.1088/1742-6596/1548/1/012020

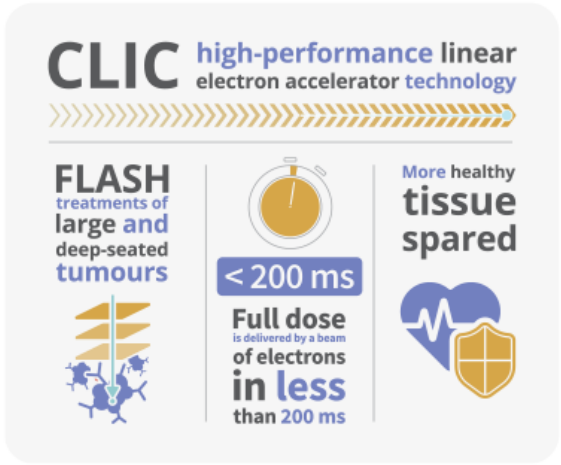
CLIC Project

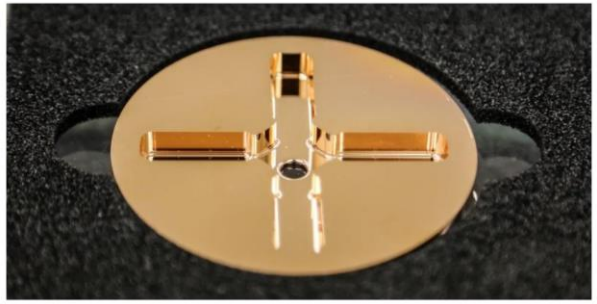


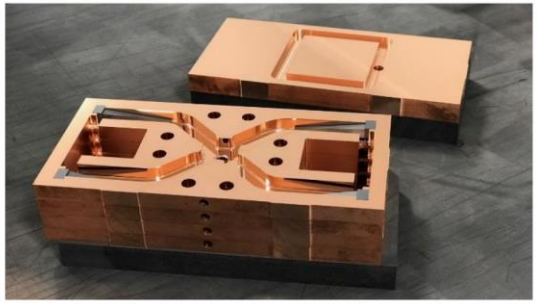
- **CLIC:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **High-Gradient (HG)**: In particle physics, HG signifies increased energy at the interaction point, while in other application, HG means compact machines.

e^- machine: The DEFT project





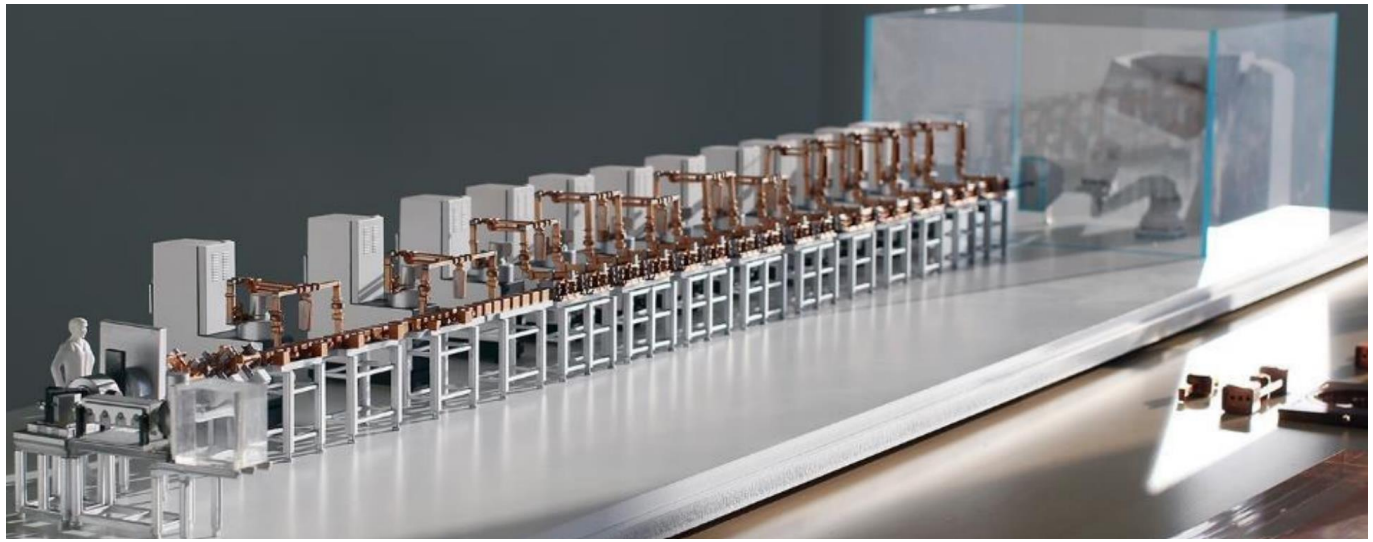




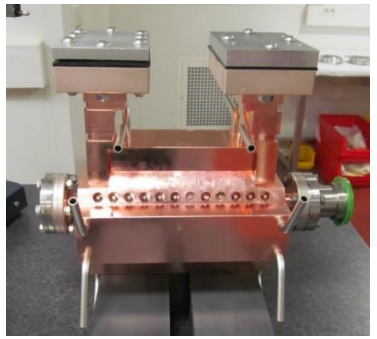
- The DEFT (Deep Electron FLASH Therapy) facility.
- The CHUV-CERN facility for FLASH treatment of large, deep-seated tumors
- Very high energy electron beams (VHEE) of 100 to 200 MeV
- CLIC Capability: 160 MeV energy gain in 2 m long

Linear proton-therapy machine

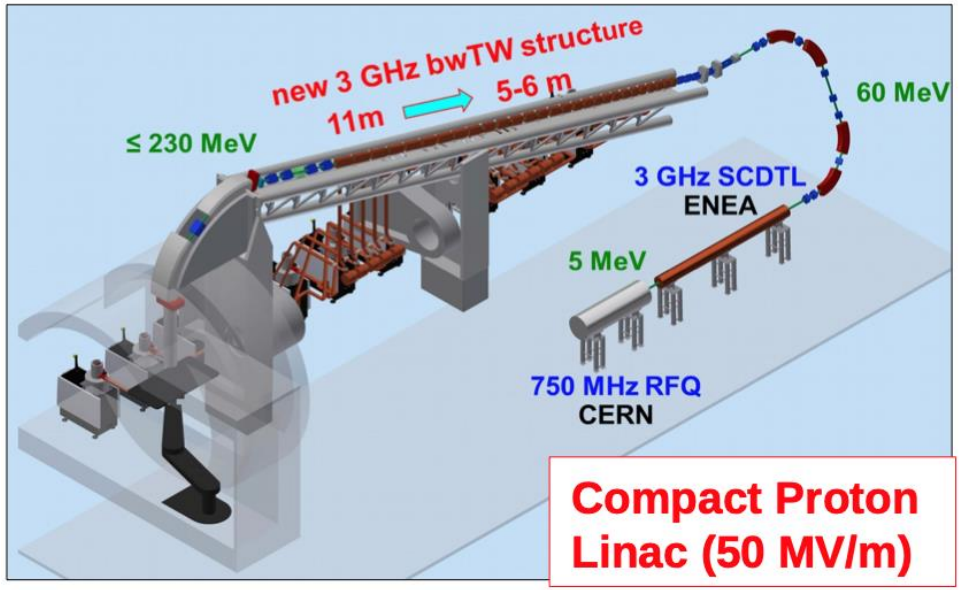
- ADAM, spin-off of CERN and TERA foundation is developing a proton linear accelerator to be installed in a hospital in England
- Normal Cavities: 18-20 MV/m
- Total length: 28 m for 230 MeV



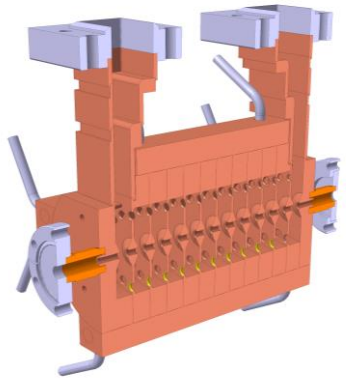
- High Gradient: 50 MV/m



TULIP: Backward Traveling Wave (BTW)



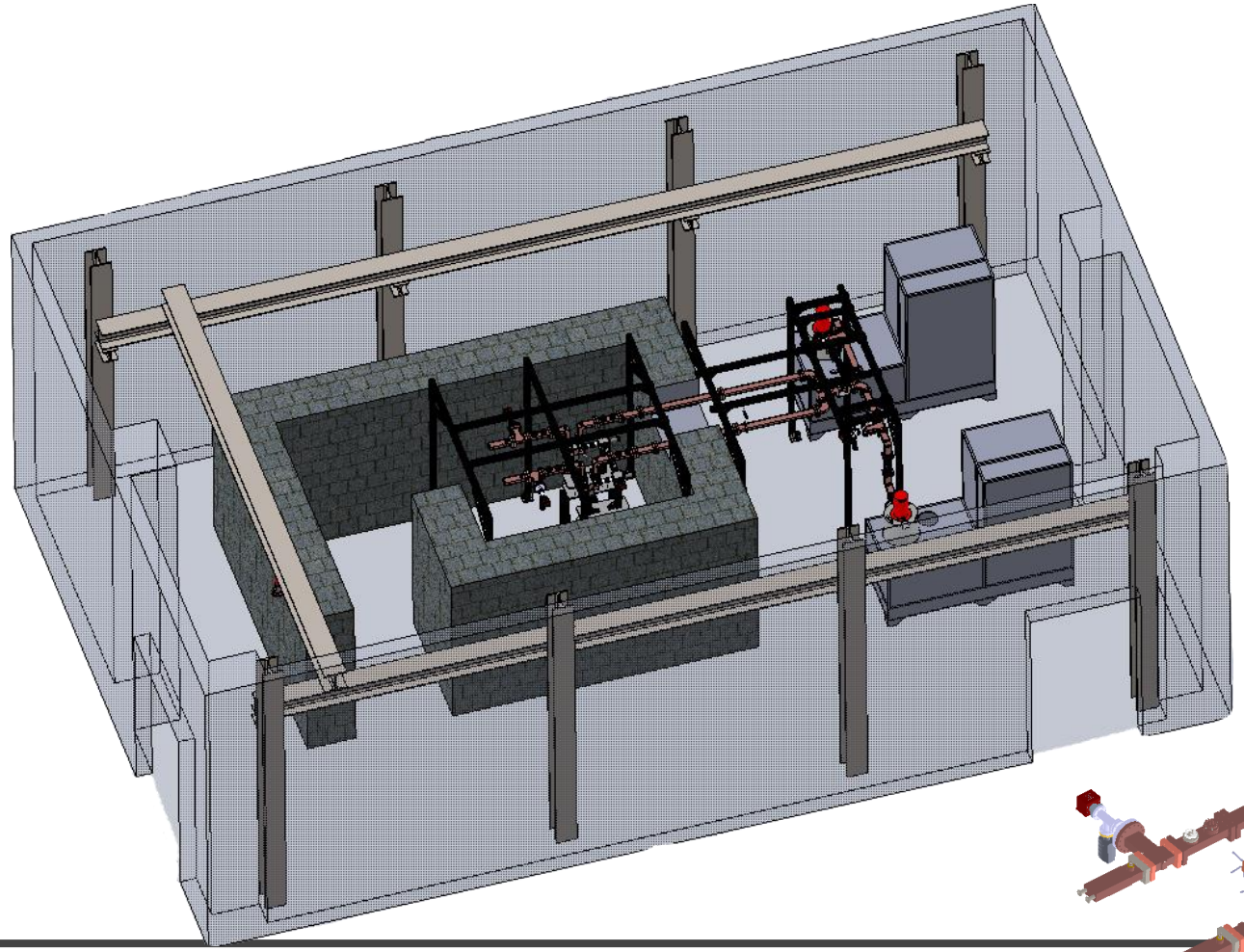
- TULIP (TUrning LInac for Protontherapy) project: Conceptual design of a compact linear proton therapy machine
- HG accelerating structure designed to reach an accelerating gradient of **50 MV/m** for protons



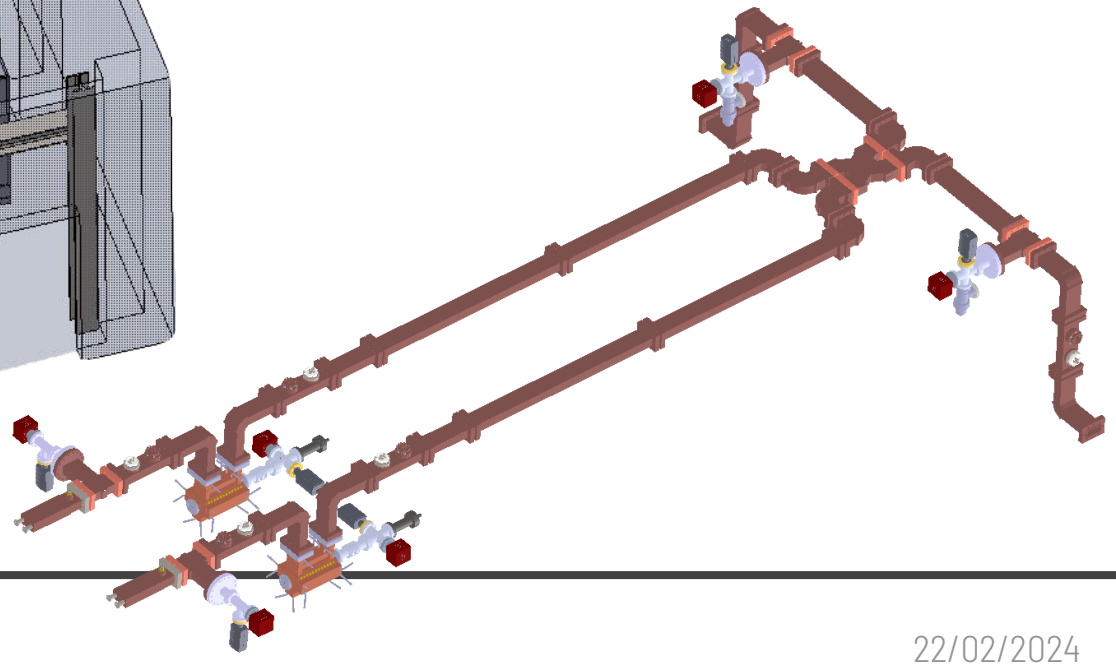
- Frequency: 2.9985 GHz mode with 5π/6 phase advance

Number of RF cells	12
Geometric ß	0.38
RF Ph. Adv.	150 deg
Total length	189.84 mm
Pin @ 50 MV/m	20.16 MW
Pout @ 50 MV/m	11.24 MW
Filling Time	220 ns

IFIC HG RF Laboratory

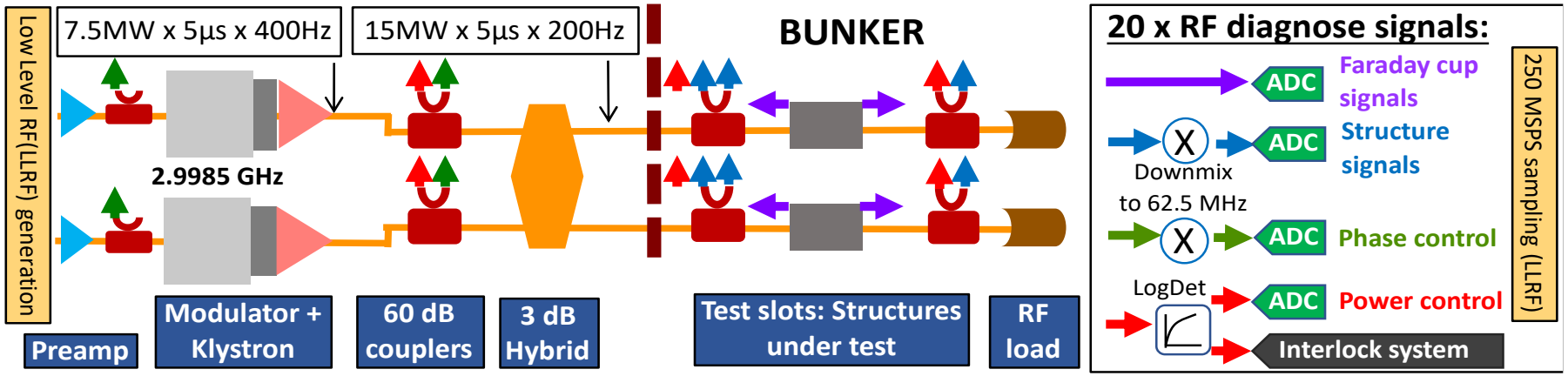


- 2 x pulsed power klystron+modulator (to 7.5 MW, 5 us pulse, **400 Hz**)
- High power waveguide RF network that allows power combining enables to test 2 structures at a time at up to 15 MW, 5 us pulse, 200 Hz repetition rate
- Running on Ultra-High vacuum (10^{-9} mbar)



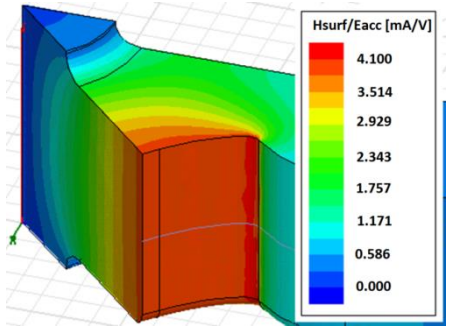
IFIC HG RF Laboratory

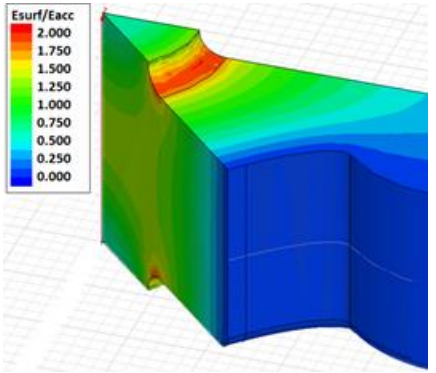
- **Conditioning** S-Band (3 GHz) high-power component
- Study of EM phenomena such breakdowns, dark current and radiation
- Maximum power reached of 12MW.



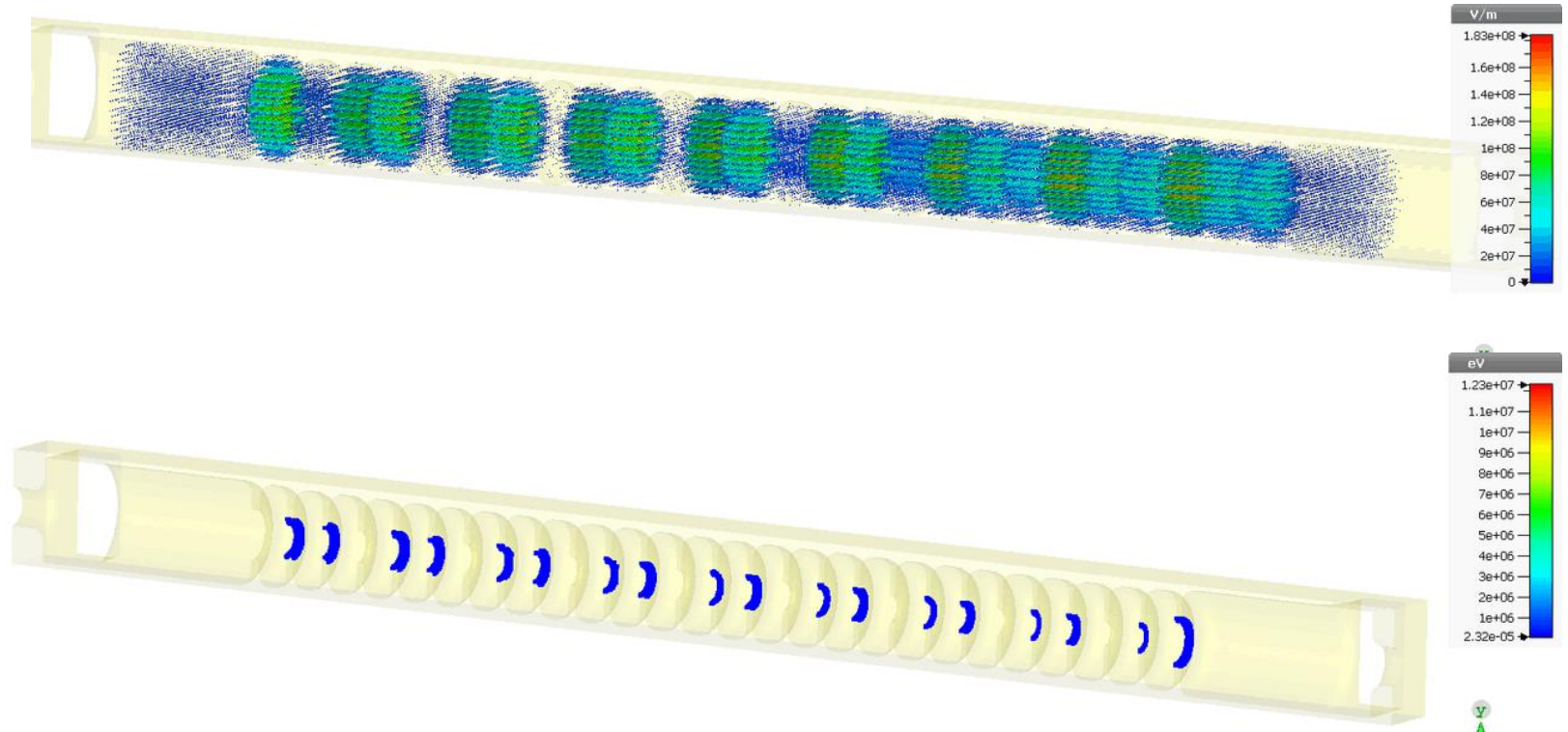
Limitation in HG Technology

- **Surface magnetic field**
  - Pulsed surface heating produced material fatigue -> cracks
- **Field emission due to surface electric field**
  - RF Breakdowns; Electron emission initiates vacuum arcs. The exact mechanism is still unclear. New theoretical models and scaling laws being developed;
  - Breakdown rate (BD/pulse) -> Operation efficiency
  - Local plasma triggered by field emission -> Erosion of surface
  - Dark current capture -> Efficiency reduction, detector backgrounds.





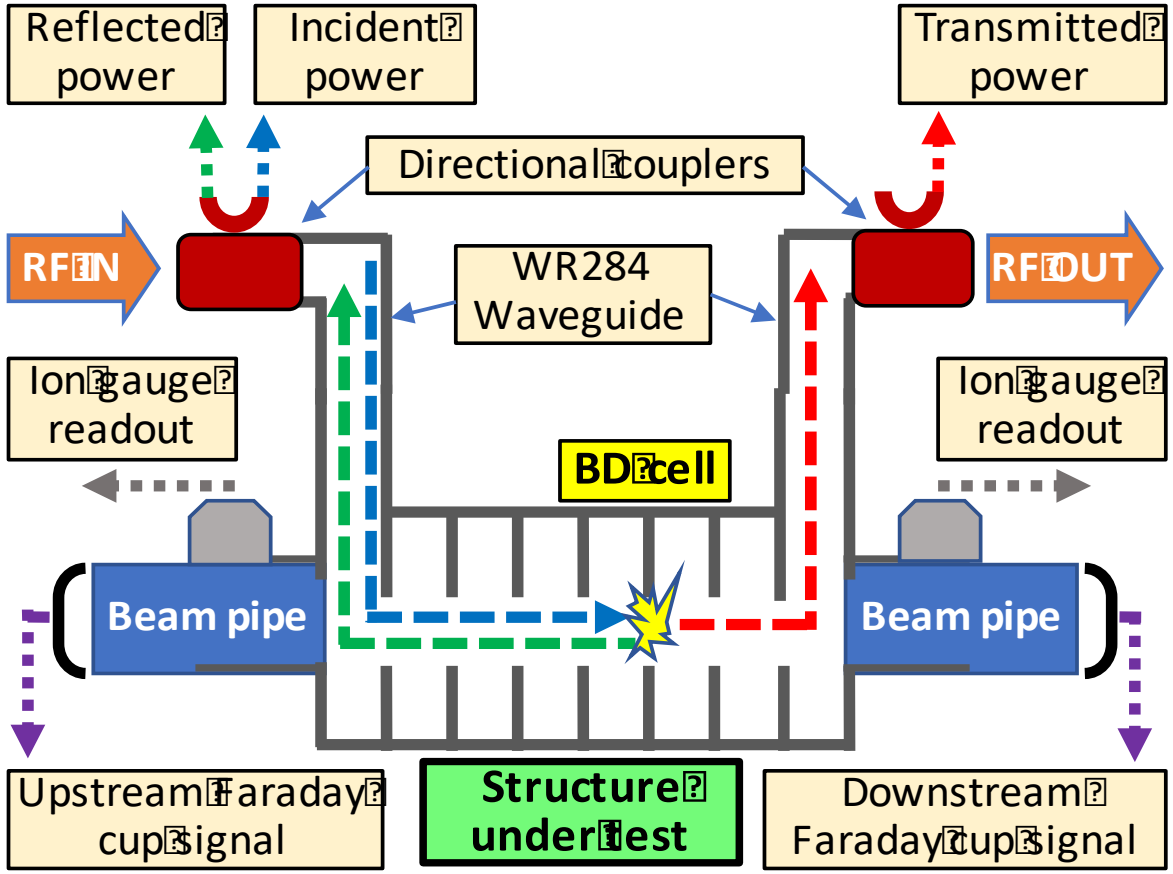
Dark Current



Fowler Nordheim $- J = aE^2 e^{\frac{-b}{E}}$

- It is originated by field emitted electrons that couple to the RF and start to bunch
- Process: Quantum tunneling of the potential barrier gives an electron current
- Efficiency reduction, detectors backgrounds and radiation around the accelerator.

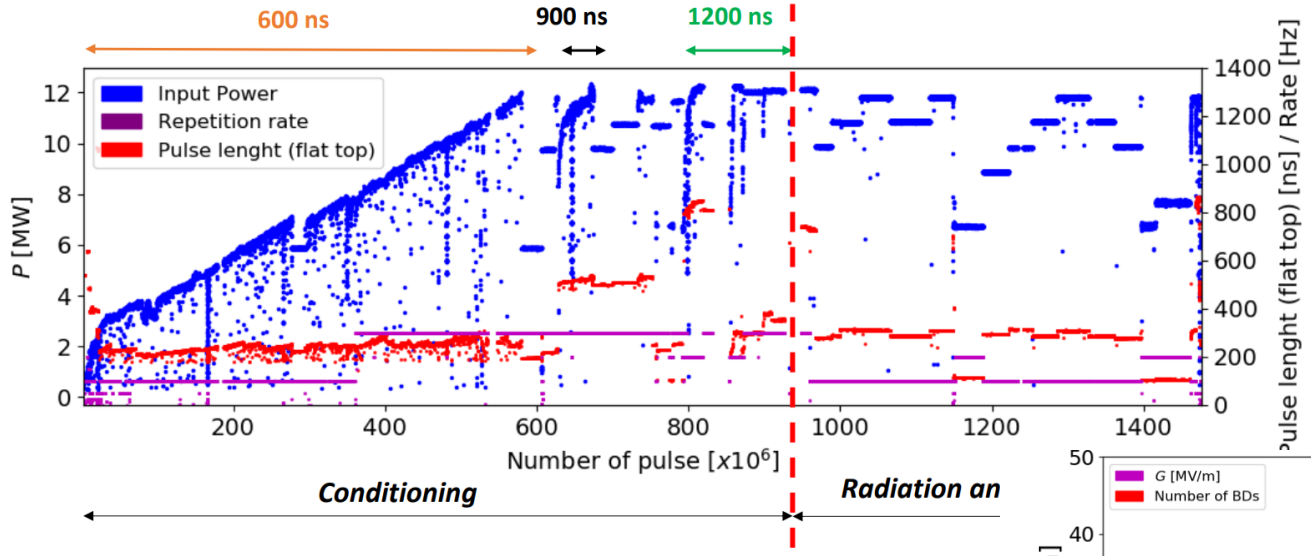
Breakdowns



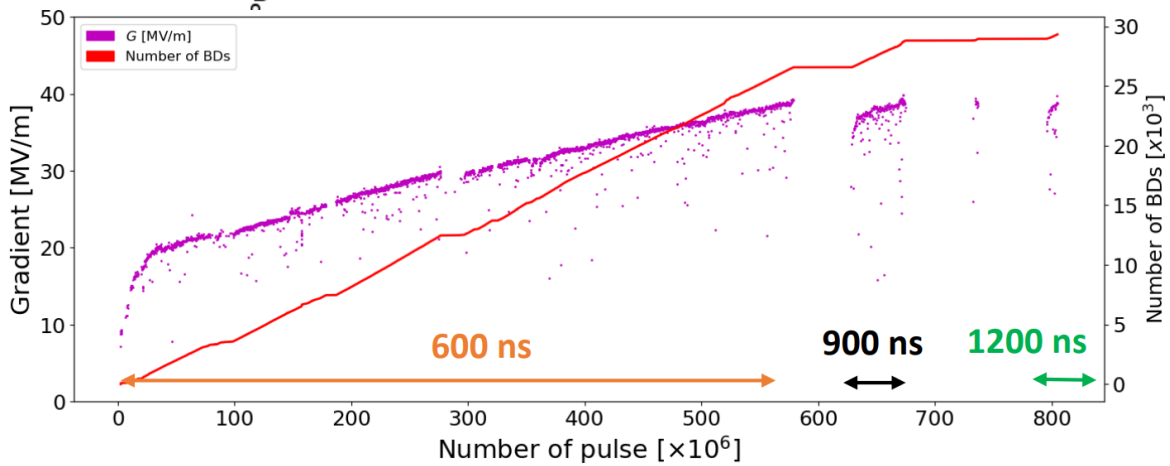
- Breakdowns are a probabilistic phenomenon dependent on the conditioning state of the accelerator structure.
- Conditioning: Start at low electromagnetic field level. Gradually increase field keeping a safe breakdown rate.
- When a BD occurs, the RF fields collapse, cutting the RF transmission.
- Studying the reflected and transmitted signals the breakdown location can be determine

Structure Conditioning

- **Maximum power 12 MW** in ~570M pulses (short pulse length).
  - R:100 ns + FT: 200 ns + F:300 ns
  - R:100 ns + FT: 500 ns + F:300 ns
  - R:100 ns + FT: 800 ns + F:300 ns



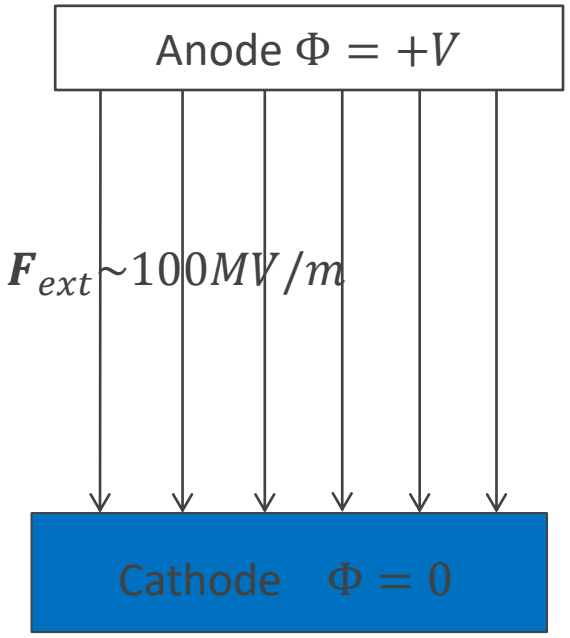
Power	38 MW
Gradient	50 MV/m
Total length	1.5 μs



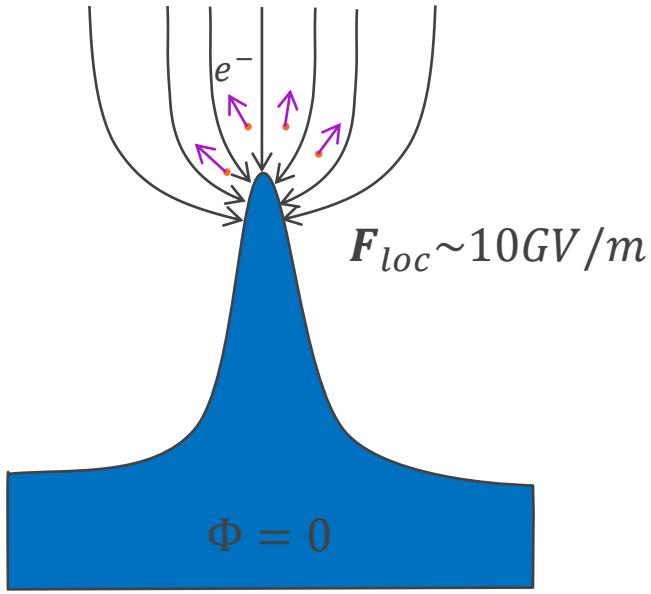
- Current set-up capable to reach an accelerating gradient of ~39 MV/m
- Upgrade in power is required.

Breakdown initiation

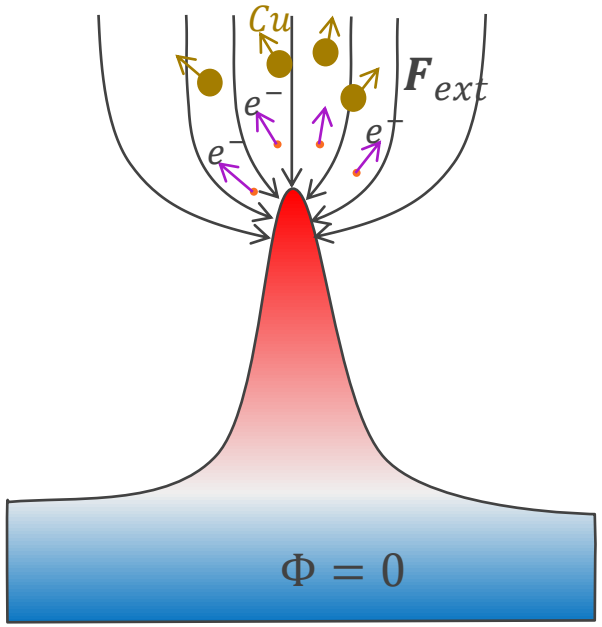
Stage 0: Flat surface



Stage 1: Field emission

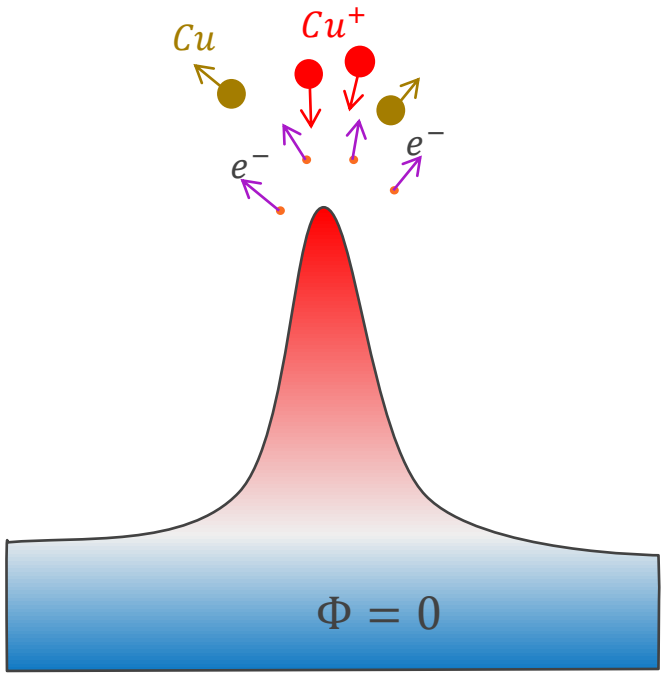


Stage 2: Field emitter Thermal Runaway

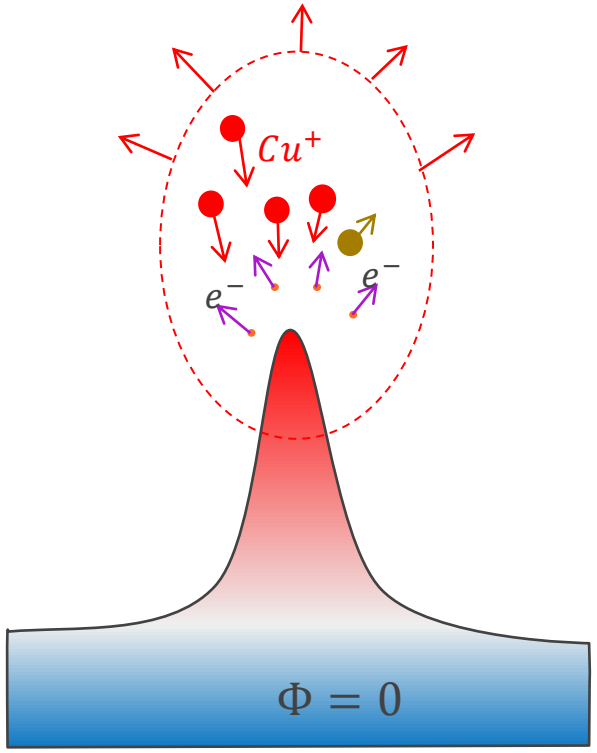


Breakdown initiation

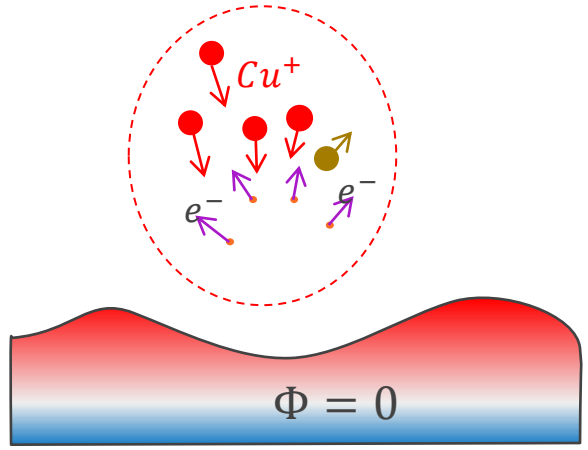
Stage 3: Ionization runaway & Plasma onset



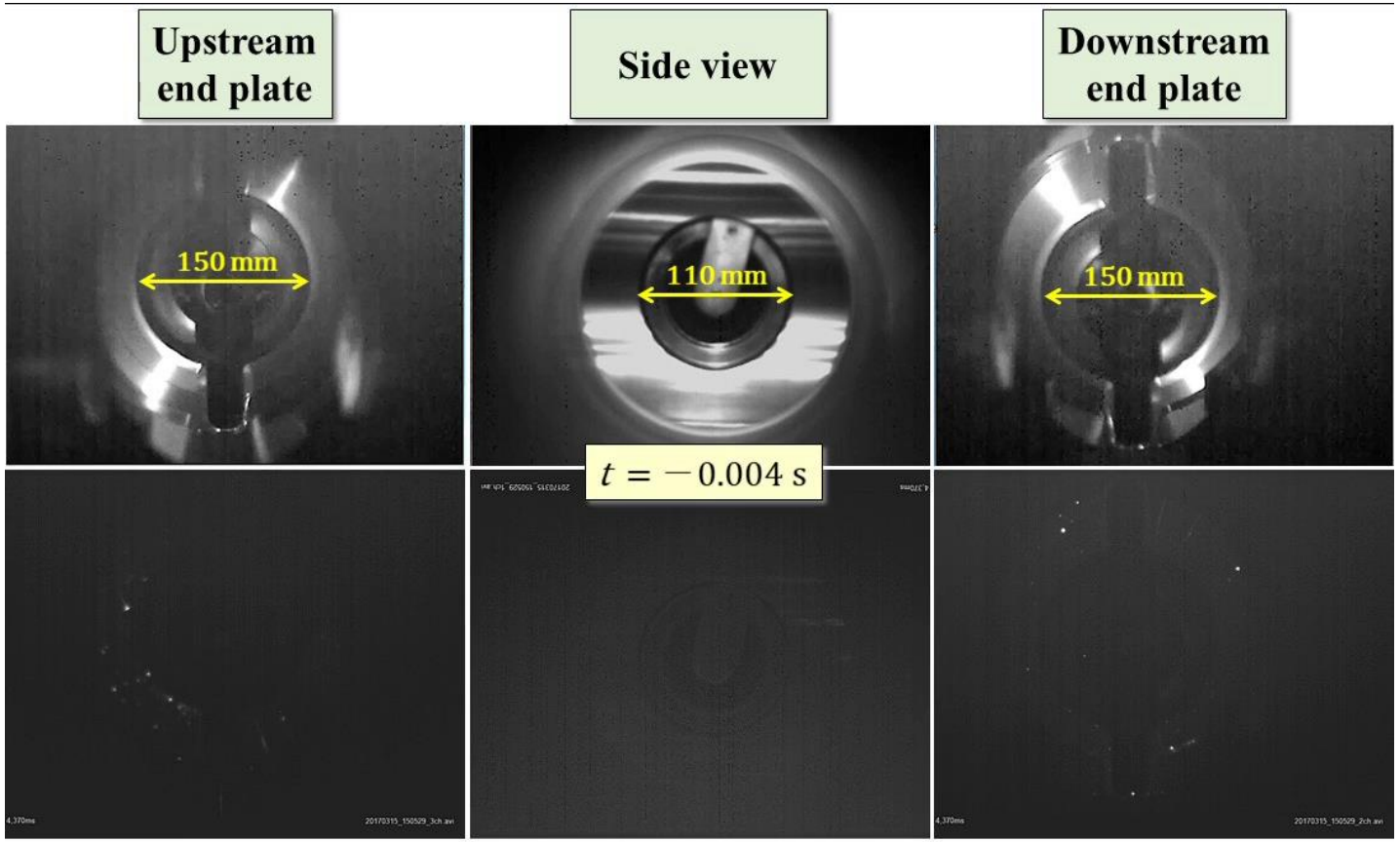
Stage 4: Plasma expansion



Stage 5: Burning arc, crater formation



Breakdown fireball



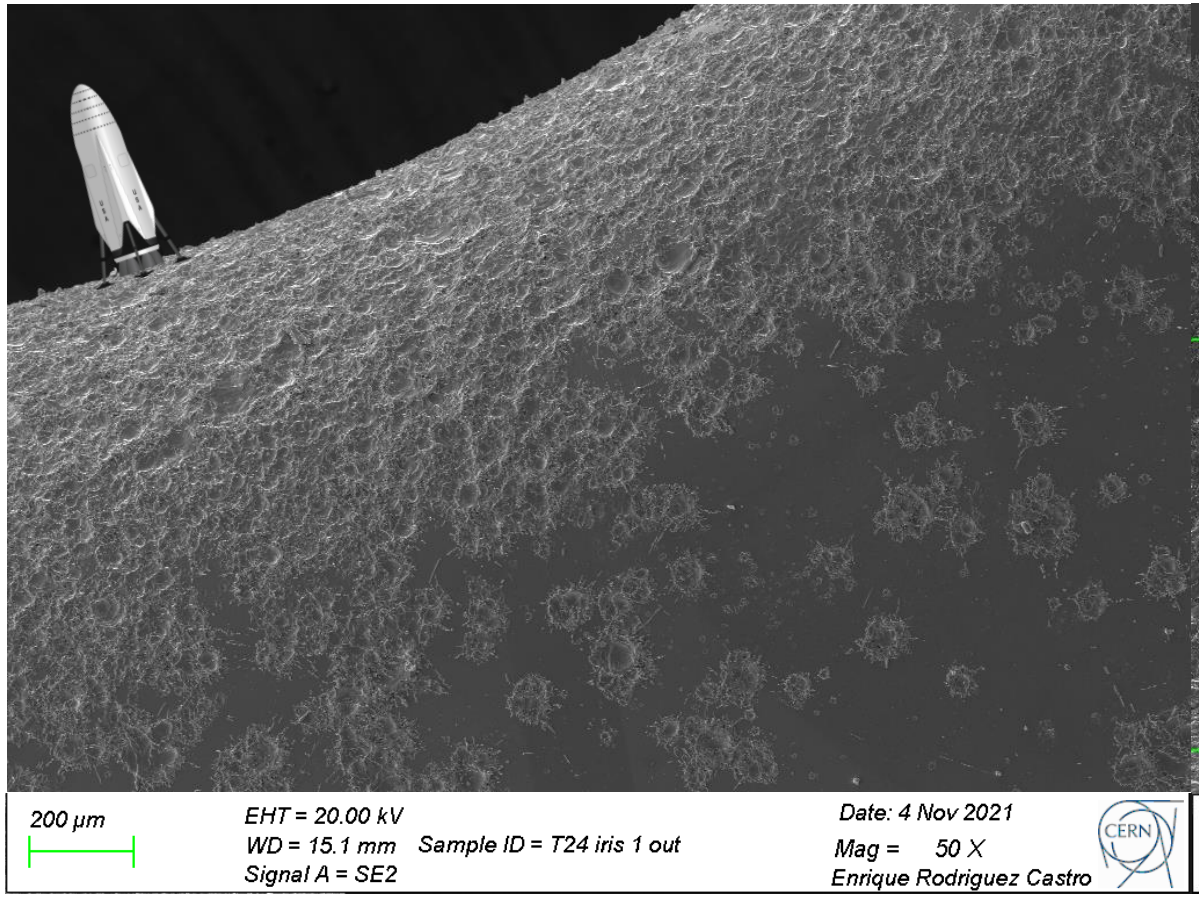
509 MHz cavity with a cavity gap voltage: 0.88 MV (= accelerating gradient: 3.4 MV/m)

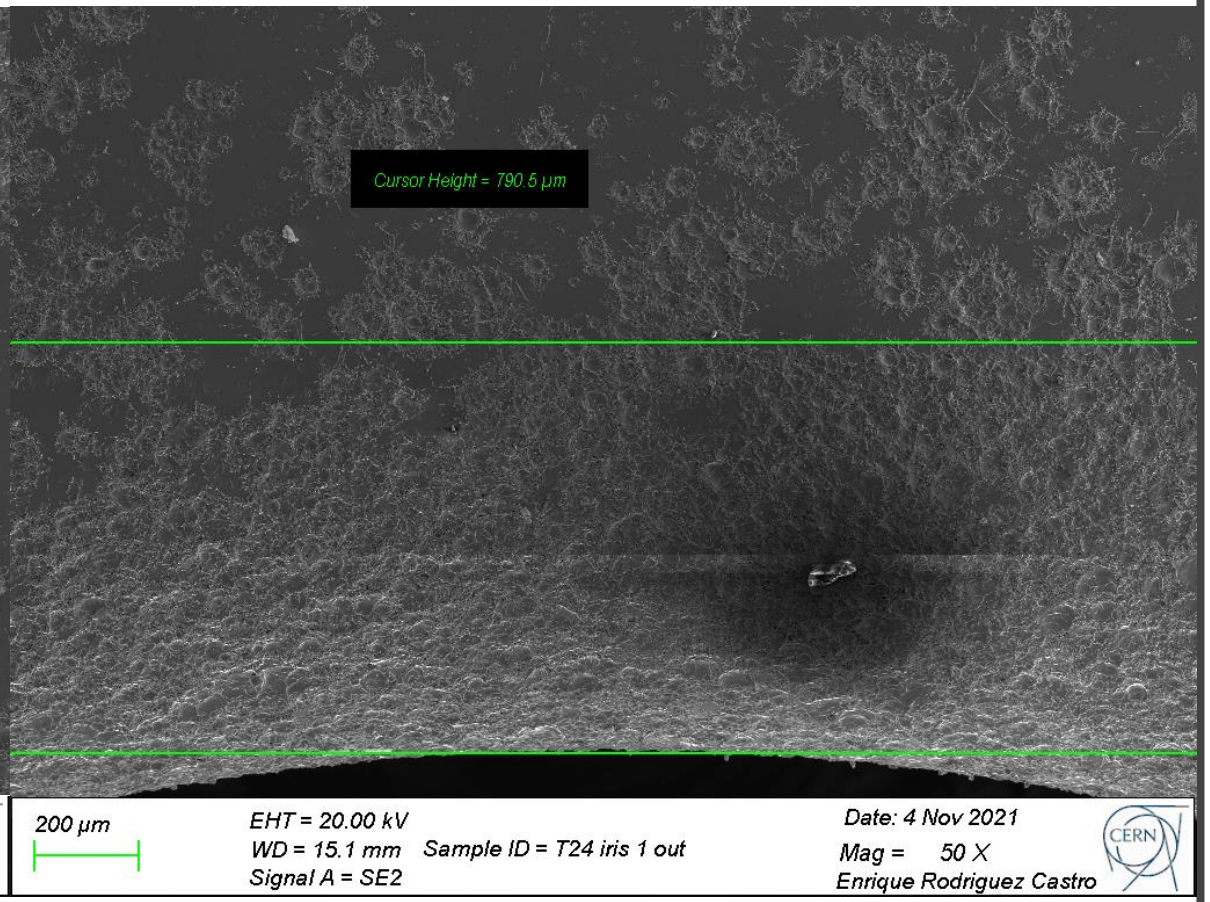
Recorded by Tetsou ABE (KEK)

Tetsou ABE - High Energy Accelerator Research Organization (KEK), Japan

Structure Post Morten

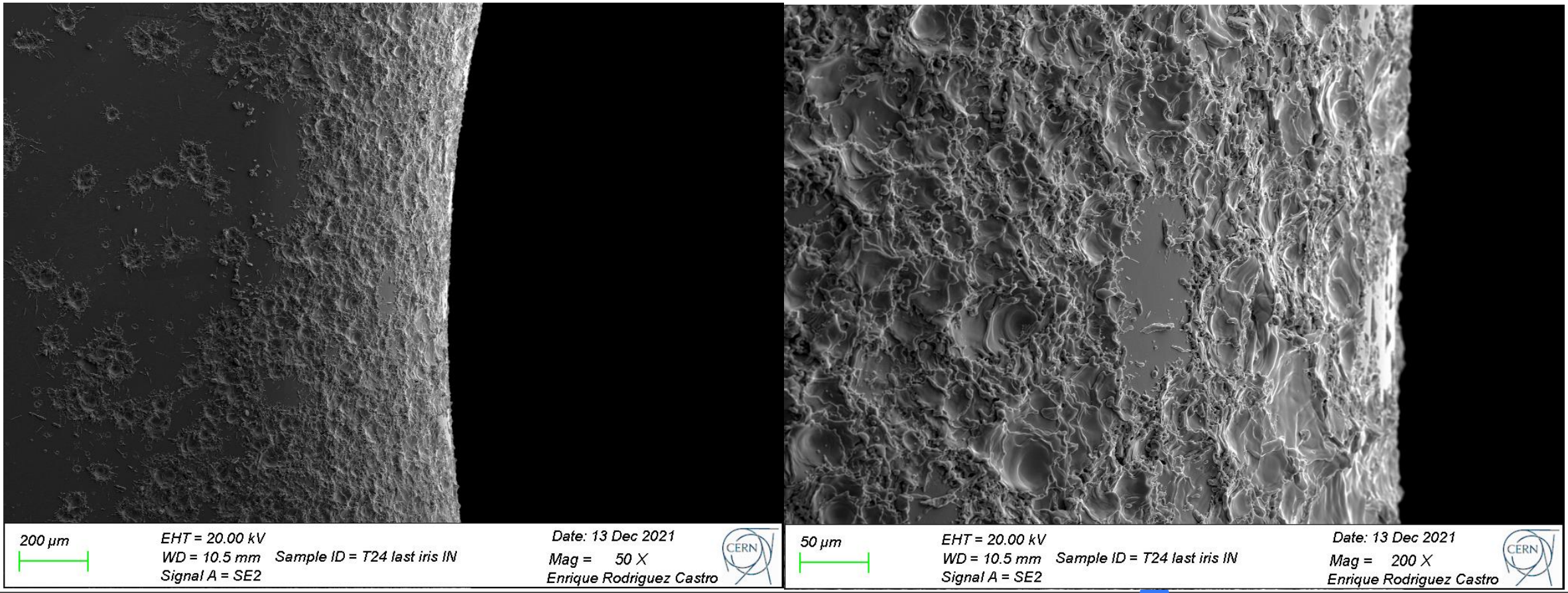
- Iris 1 - Output



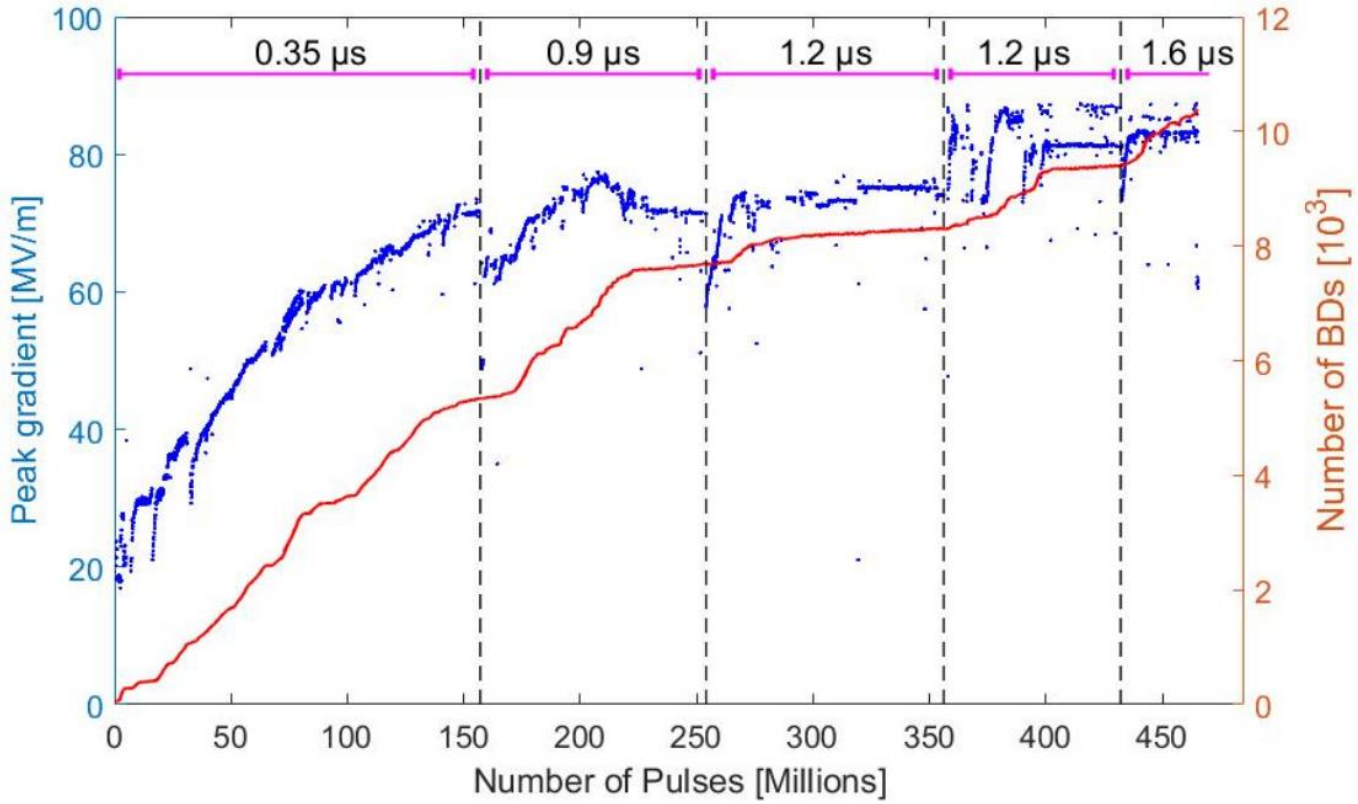


Structure Post Morten

- Iris 26 - Input



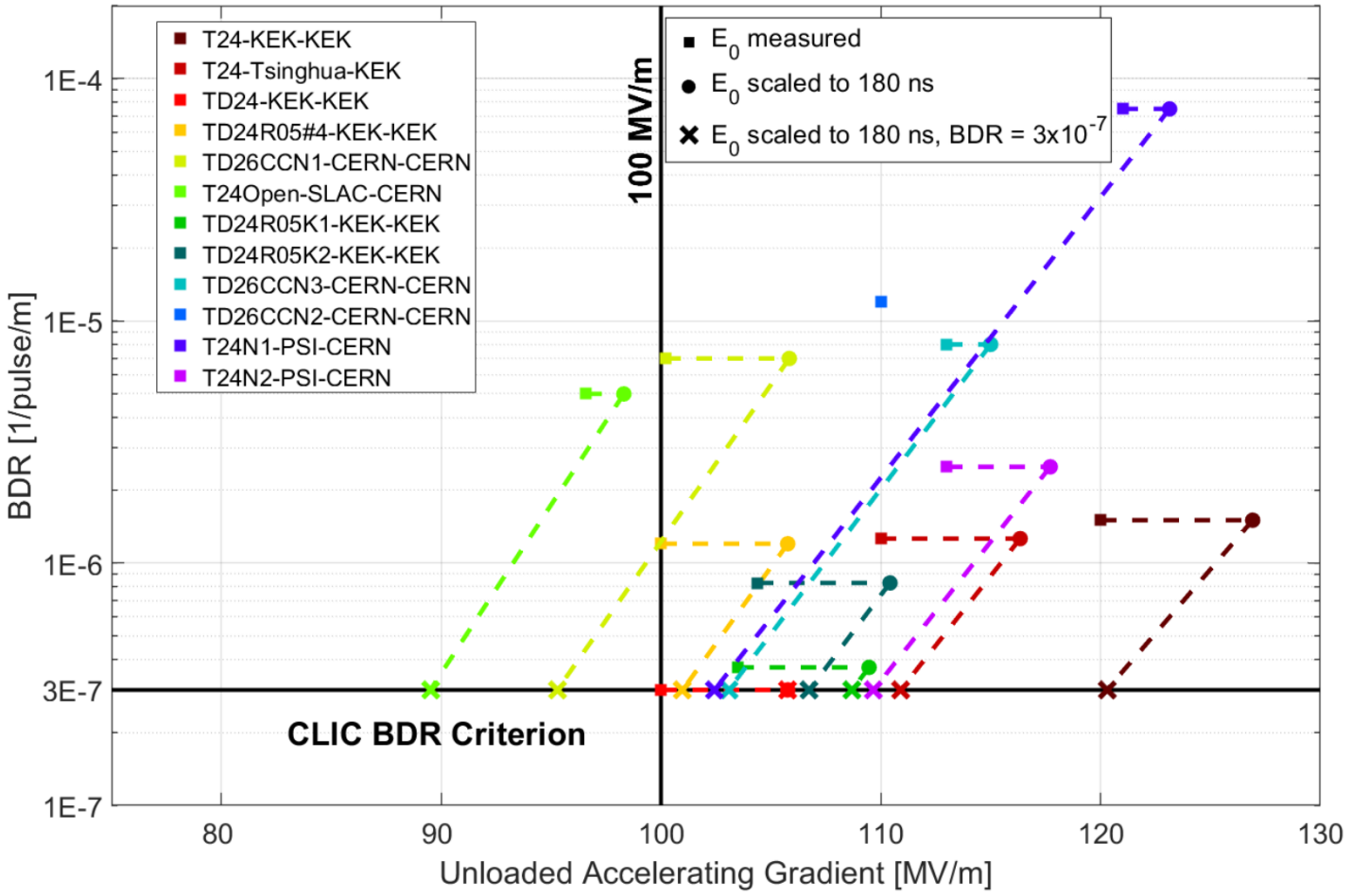
HG proton structures: BTW



Anna Vnuchenko- High-Gradient issues in S-band RF Acceleration Structure for Hadrontherapy accelerators and Radio Frequency Quadrupoles – PhD Universitat de Valencia 2019

- BTW Prototype for protons can over 70 MV/m with a breakdown rate below 10^{-6}, which means less than one breakdown per million pulses.

HG e^- structures for CLIC



- CLIC Prototypes for electrons can reach over 100 MV/m with a breakdown rate below 10^{-6}, which means less than one breakdown per million pulses.

Financiado por la Unión Europea
NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
GENERALITAT VALENCIANA
PROGRAMA PROMETEO
AGENCIA ESTATAL DE INVESTIGACIÓN

Thanks

… N. Fuster, D. Esperante, J. Fuster, B. Gimeno A. Menendez, D. Gonzalez, M. T. Andreu, C. Blanch, L. K. Pedraza, P. Martines, P. Martin, E. Martinez, J. C. Fernandez, J. Reina, J. Olivares …

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