



Application of high gradient RF technology for medical therapy accelerators

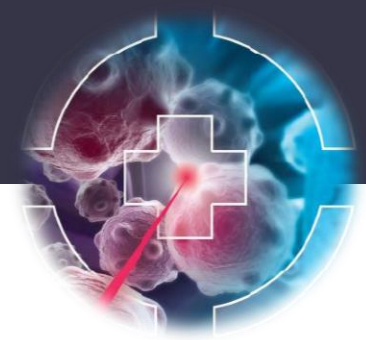
ESR 13: Vnuchenko Anna (IFIC, CSIC –UV)



Topical Workshop on Facility Design Optimization for Treatment



Outline



□ Introduction

- Applications of High Gradient (HG) technology
- RF design for HG structures

□ RF design of HG structures

- Experimental studies of breakdowns
- CLIC prototypes: BTW and ProBE

□ Overview of testing facilities

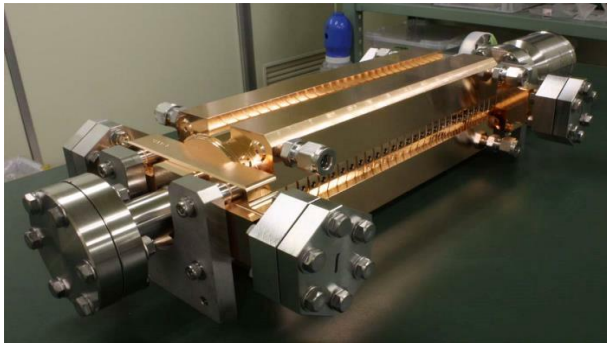
□ Conditioning status of 3 GHz BTW

Comparison of the conditioning vs. gradient / norm. gradient / Esurf.

□ The IFIC-HGRF lab: design aspects and progress.

□ Conclusions

Introduction: Applications of HG technology



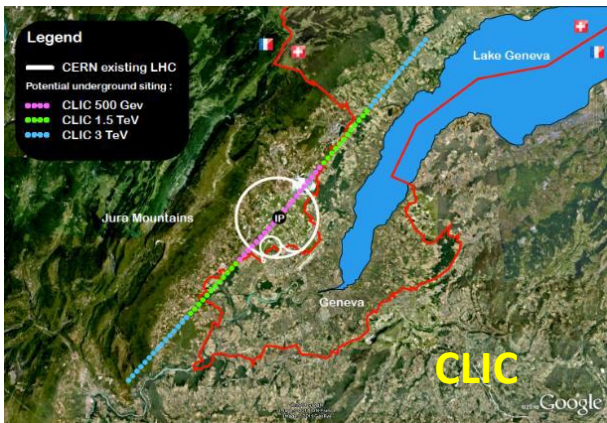
Recent developments in design and production of normal-conducting RF structures raised the achievable accelerating gradient of **20-100 MV/m**.

HG technology could be exploited in certain applications:

- **Future Linear Colliders**
X-band (12GHz)

- **Free Electron Lasers (FEL)**
C-band (5.7GHz)

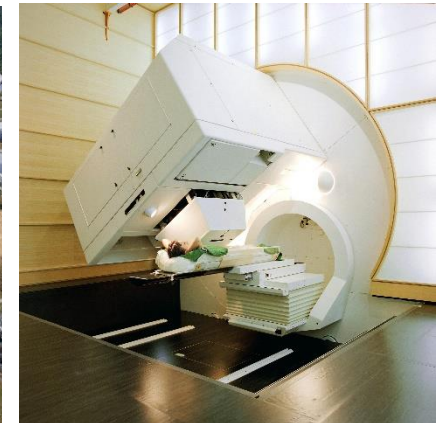
- **Hadron therapy**
S-band(3GHz)/C-band



Linear collider - TeV



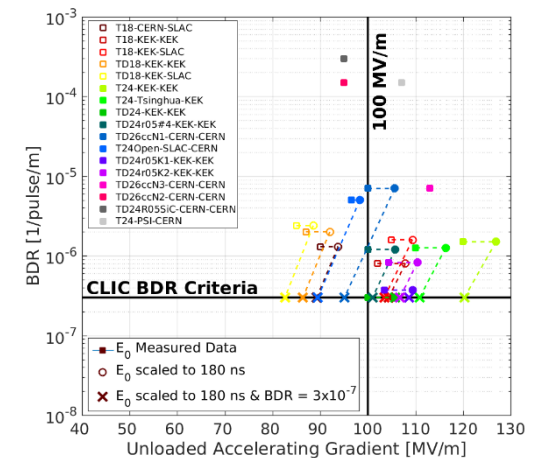
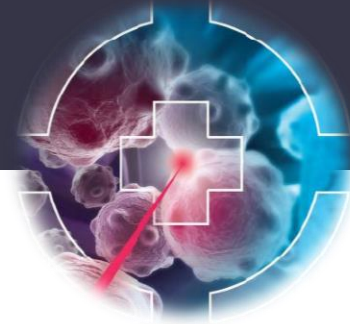
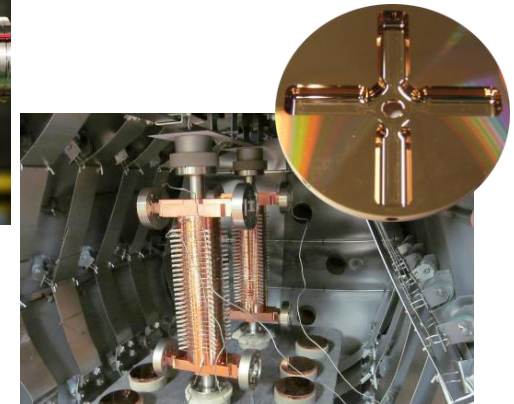
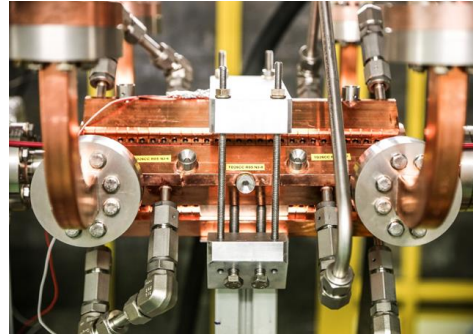
XFEL – 1 to 10 GeV



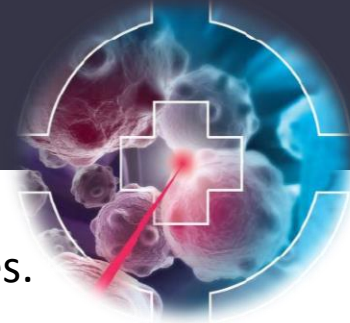
250 - 350 MeV

HG Technology: What is it?

- Accelerating structures;
- Fabrication technology;
- HG RF test stand;
- Prototype performance;
- High-efficiency klystrons and RF components.



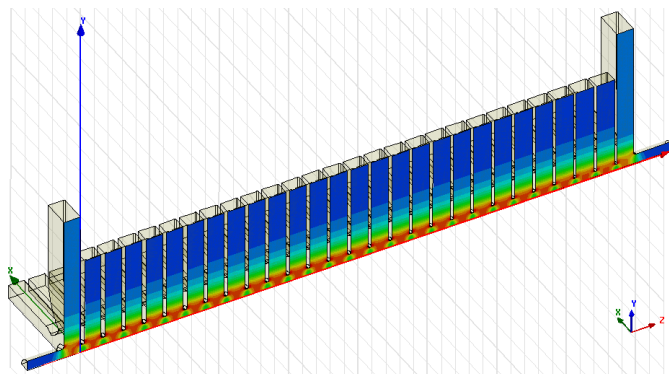
RF design for high gradient



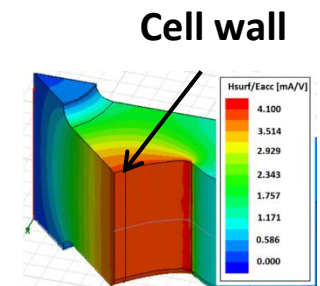
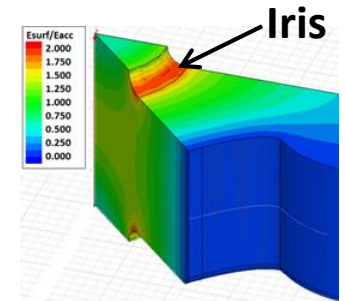
Well developed RF design can **predict the gradient** of pulsed HG structures.

The criteria which **limit accelerating gradient**:

- Surface electric field
- Surface magnetic field/pulsed surface heating
- Power flow



New CLIC 3 TeV baseline
H.Zha, A Grudiev

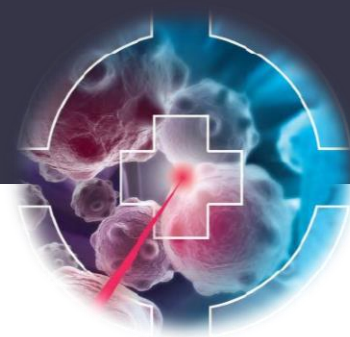


$$\Delta T = \sqrt{\frac{\mu_0}{2\pi} \frac{\omega t_P}{\sigma \lambda \rho c_H}} \hat{H}^2$$

$$\Delta T \approx \sqrt{t_P f} E_{acc}^2$$

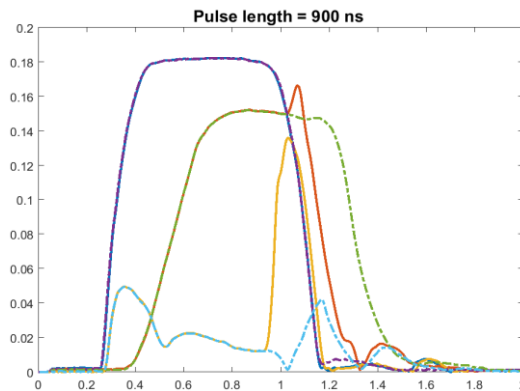
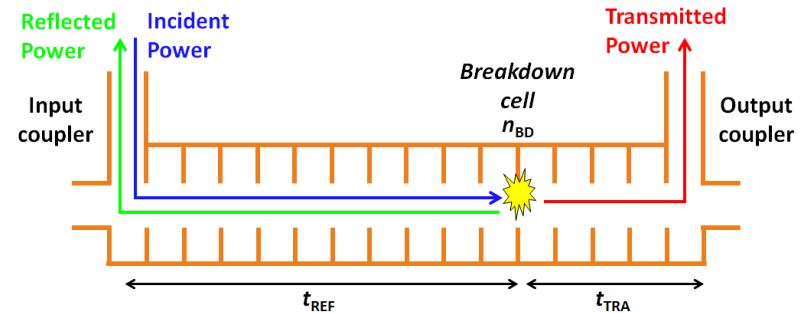
- Efficiency reduction;
- Erosion of surface;
- Material fatigue, cracks;
- Detector backgrounds.

Experimental studies of breakdowns

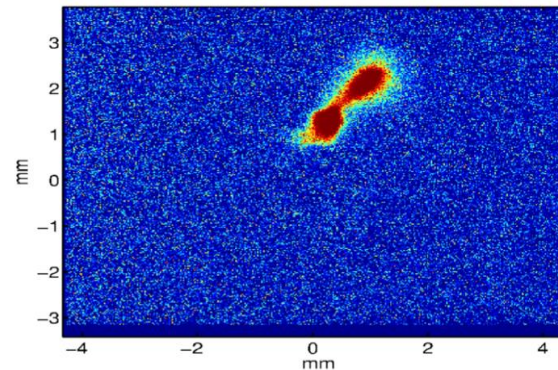


We are interested in **finding the regions which limit the overall performance** of the structure.

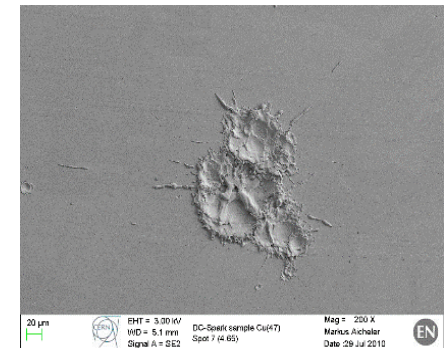
BD location technique: compares the time of detection in which the reflected power rises and the transmitted drops.



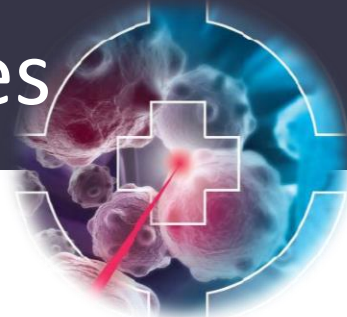
Pulse shape of incident (INC), reflected (REF) and transmitted (TRA) signals



Influence of BD on beam shape and structure surface



CLIC accelerating structure prototypes



T18 (TD18)



→ T24

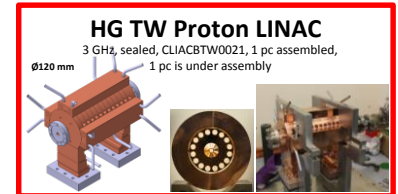


Medical structures 3 GHz

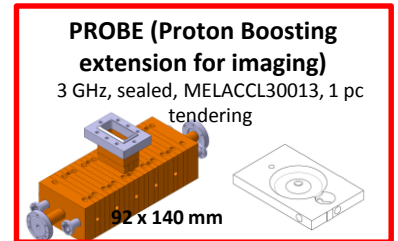
TD24



→ TD26 R05 CC → TD26 R1 CC

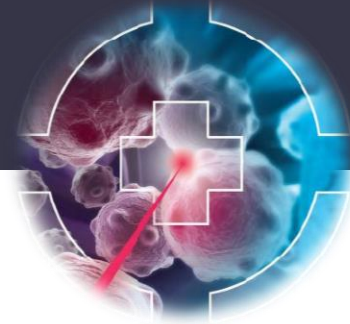


↓ TD24 SiC

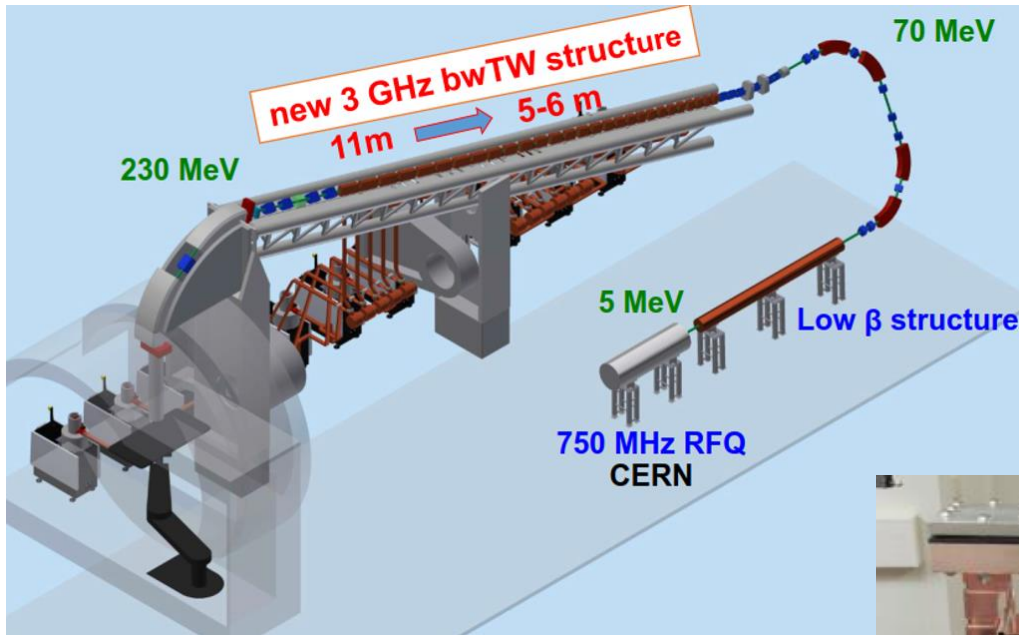


→ TD26 CLEX

TUring Linac for Protontherapy

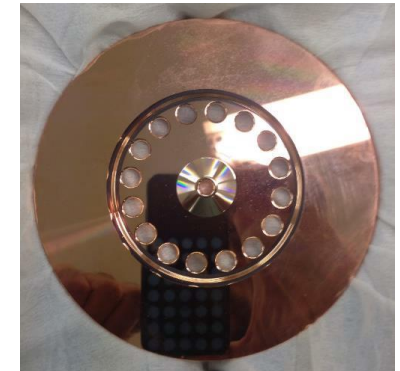


There are a number of initiatives to develop linac-based proton and ion treatment facilities.

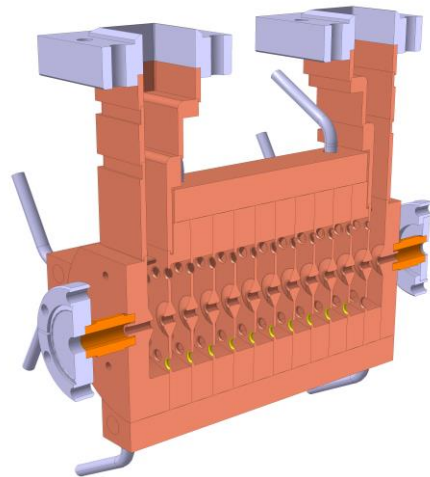
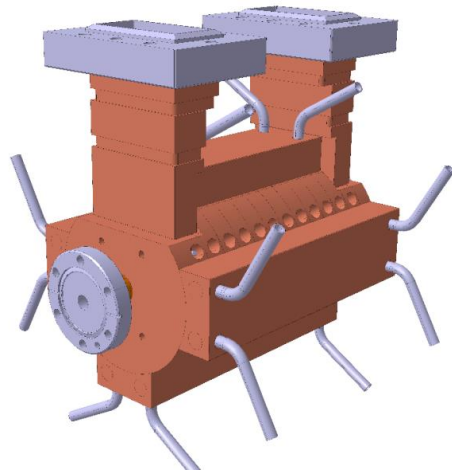


We are testing a $\beta=0.38$ (70 MeV protons) cavity since this is the starting energy of the TULIP HG section: 6m-long linac mounted directly on the gantry.

TULIP – an example of a HG linac based single room proton treatment facility.



Backward Travelling Wave (BTW)



- novel HG accelerating structure designed to reach an accelerating gradient of **50 MV/m** for proton (TULIP project);
- 2.9985 GHz mode with $5\pi/6$ phase advance;
- The small iris aperture guarantees the low group velocity required to achieve HG.

Number of RF cells	12
Geometric β – RF Ph. Adv.	0.38 – 150 deg
Total length	189.84 mm
Max Sc/Ea^2	0.29 mA/V
Max Es/Ea	3.9
Pin @ 50 MV/m	20.16 MW
Filling time	220 ns
Group velocity (first/last)	0.39 / 0.21 %c

PROBE: Proton Boosting extension for Imaging and Therapy



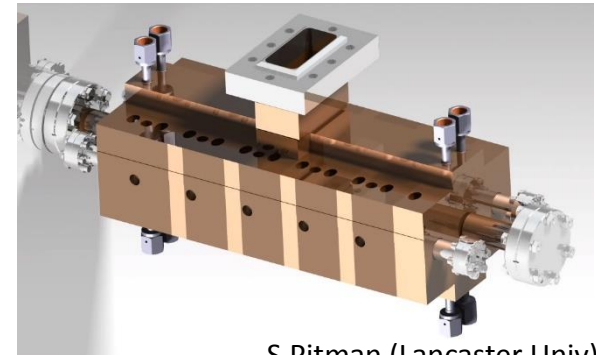
Cyclotron produces 250 MeV protons for therapy, then ProBE linac accelerates to **350 MeV for imaging**.

Small Aperture: 65 MV/m

- 5 cavities (0.3m) and 4 matching (0.35m) cells.

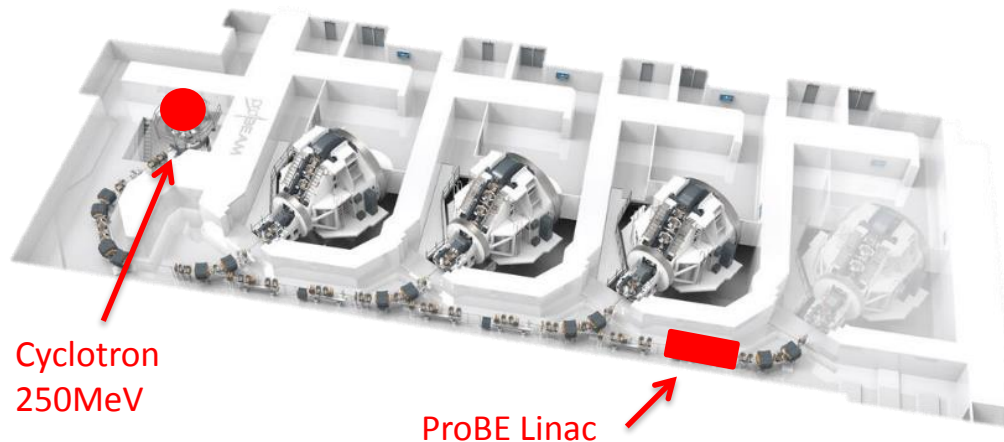
Large Aperture: 55 MV/m

- Larger aperture requires less focussing magnets between structures.
- 7 structures in 3 m instead of 6.



S.Pitman (Lancaster Univ)

ProBE prototype



Cyclotron
250MeV

ProBE Linac

TERA BTW achieved 50 MV/m:

- Need slightly higher gradient.
- 6.5mm aperture - need higher transmission

Overview of testing facilities



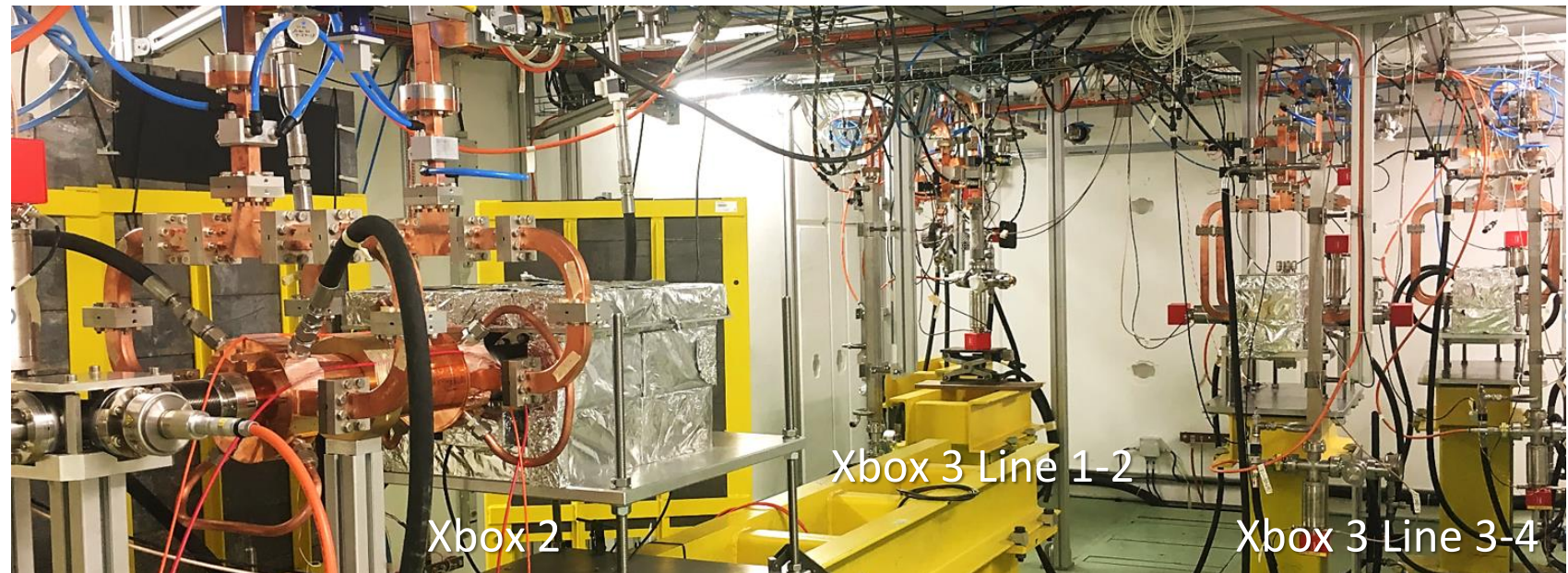
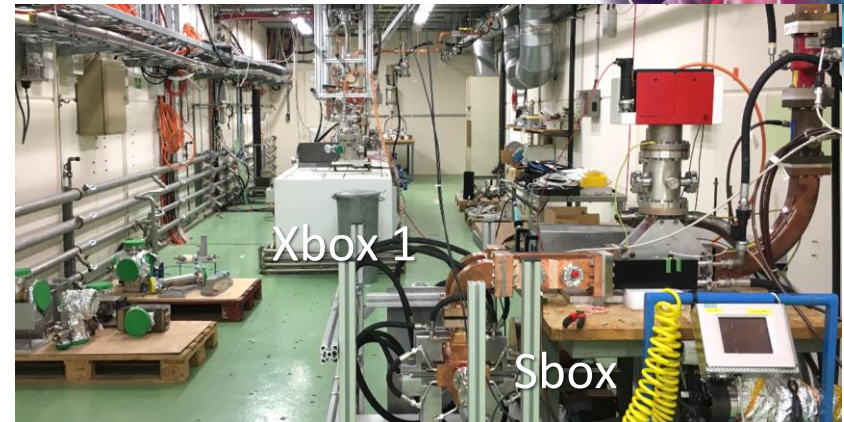
Klystron-based test stands at CERN:

❑ **11.994 GHz, X-band:**

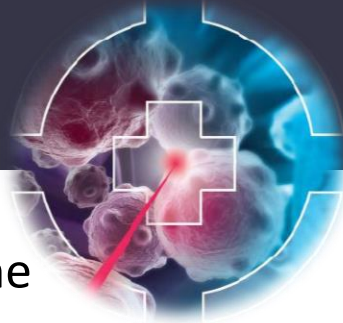
Xbox 1 - 2: 50 MW klystron, 50 Hz,

Xbox 3: 4x6 MW klystrons, 50 - 400 Hz,
4 structure test slots.

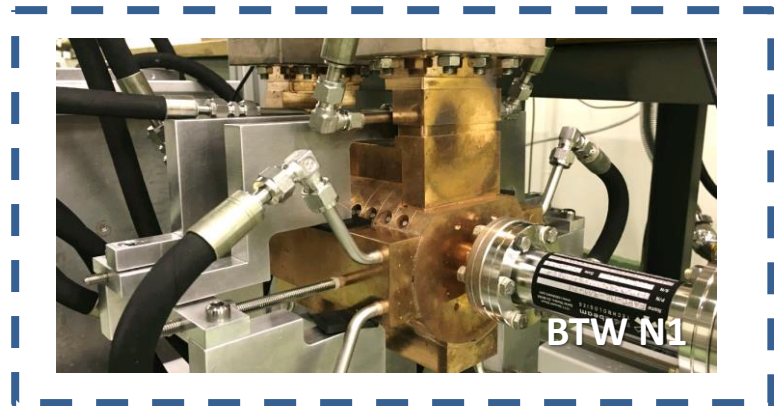
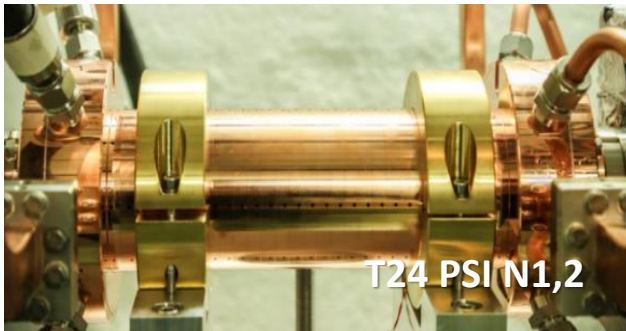
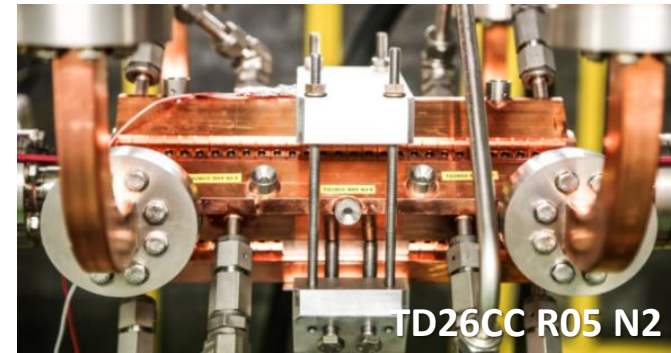
❑ **2.9985 GHz, S-band, 25Hz (Sbox).**



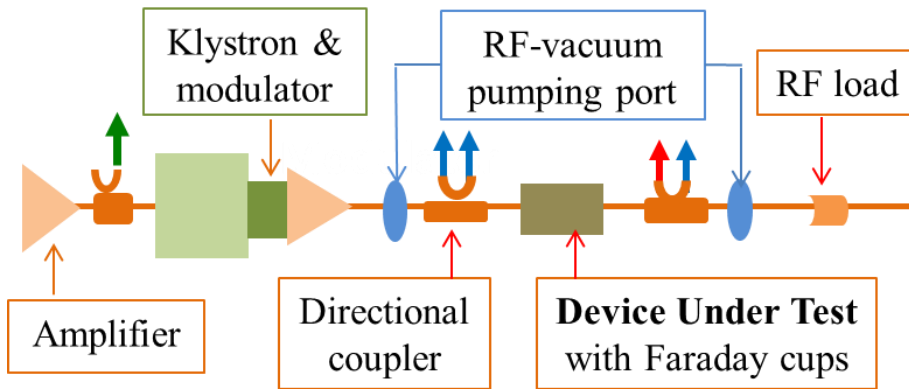
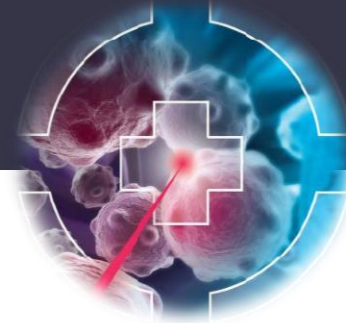
High Power testing of AS prototypes



- The different designs of the HG acceleration structures of the CLIC baseline currently under test at CERN:



S-band test stand at CERN



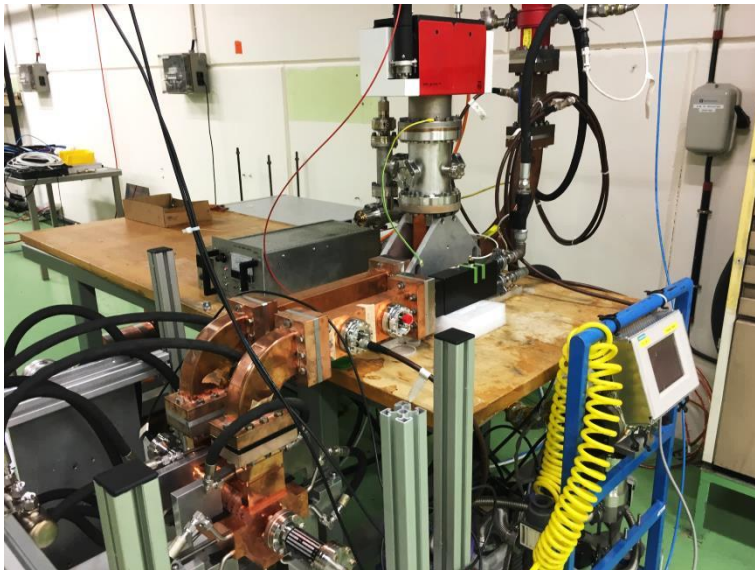
Schematic layout of the DUT (BTW).

Low level RF (LLRF):

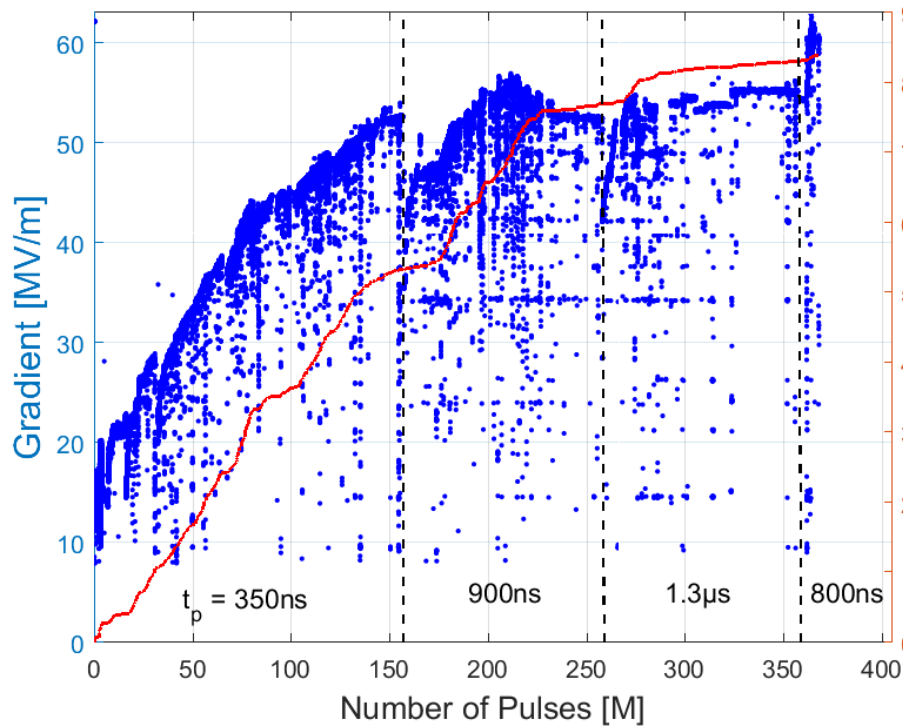
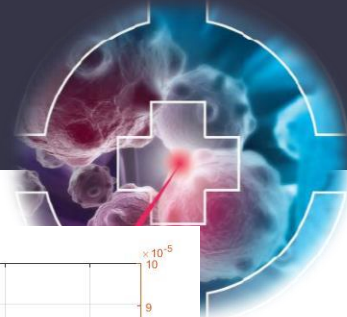
real-time control system perform a loop control of input power of the structure and phase of the signals.

High Power RF (HPRF):

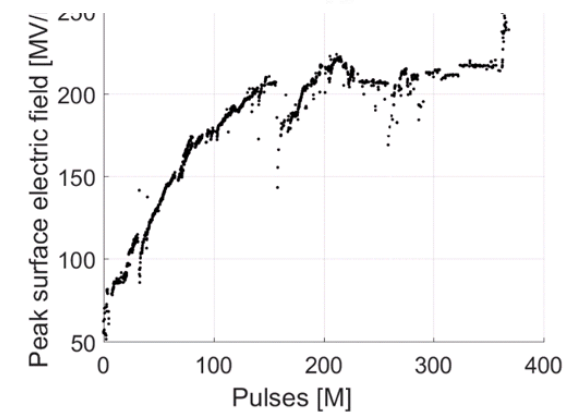
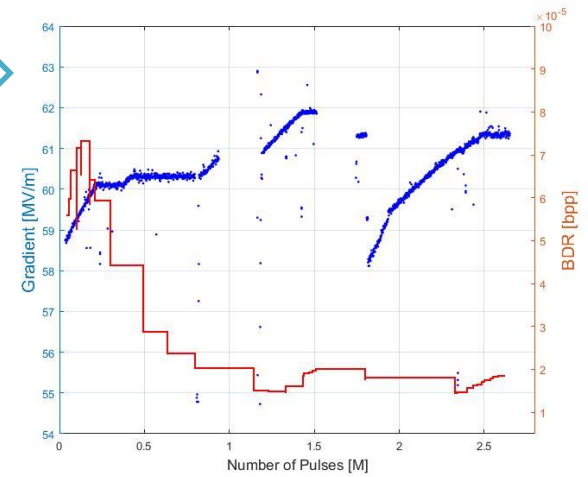
25 Hz Modulator, 43 MW Klystron



Conditioning status of 3 GHz BTW



Number of BDs [$\times 10^3$]



Pulse width, ns	350	900	1300	800
Gradient, MV/m	52	55.6	54	62

Very high surface electric fields, over 200 MV/m

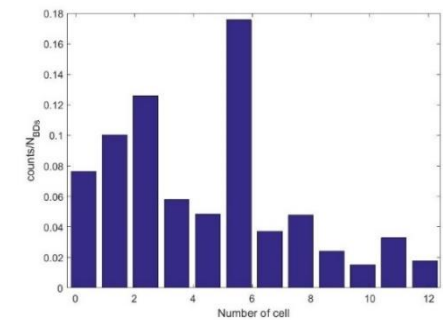
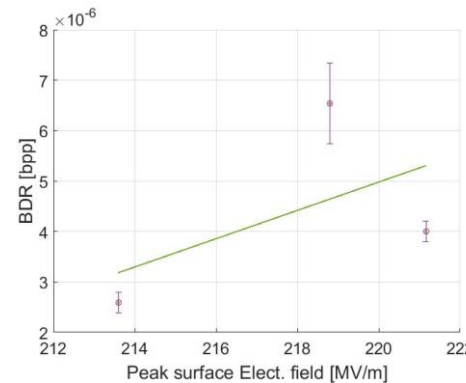
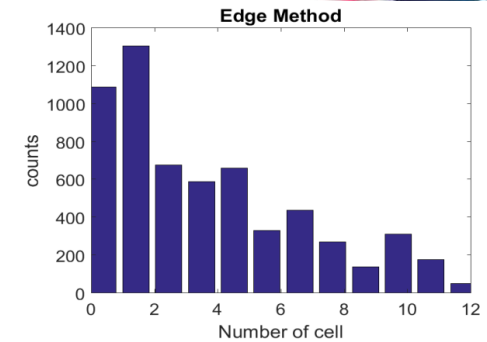
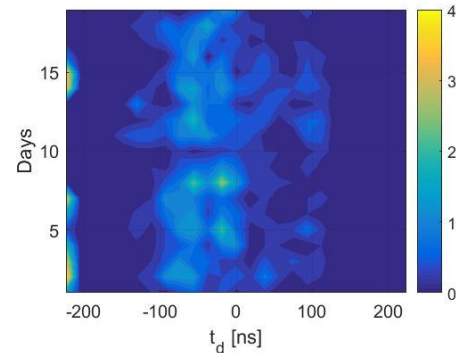
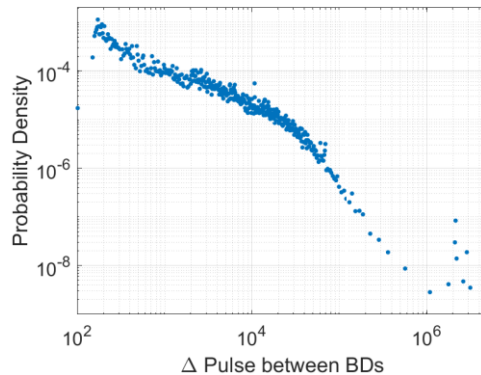
$\beta=0.38 c$, 50 MeV/m expected. Just passed 60 MV/m, testing continues.

Conditioning status of 3 GHz BTW



HG physics studies:

- RF conditioning,
- BD localisation,
- Dependence of BDR on field,
- Dark current measurements.



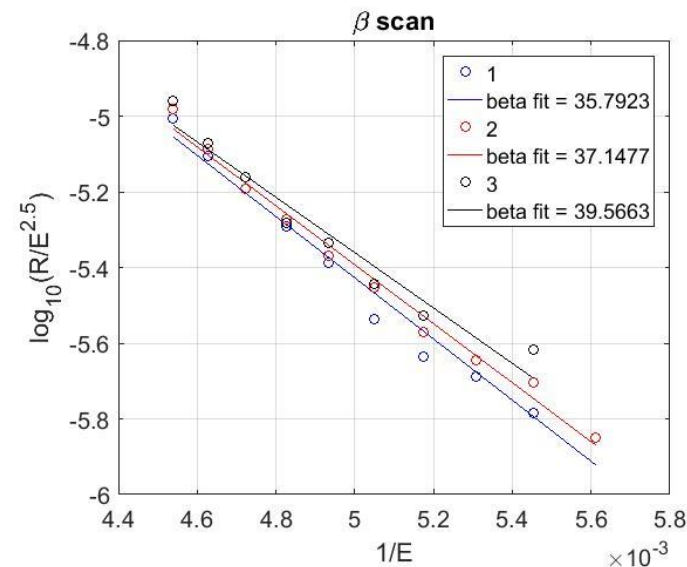
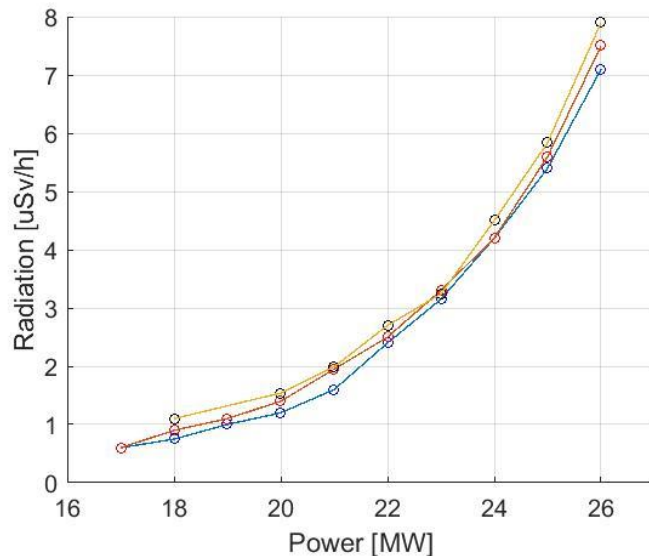
- The statistical distribution of the number of pulses between BDs => BDs are not **uncorrelated random events**.

- **Secondary** breakdowns: higher BDR (“clusters”), follow-up as consequence of the damage

Conditioning status of 3 GHz BTW: DC study



Dark current (DC) is measured by Faraday cups and Radiation Monitors.

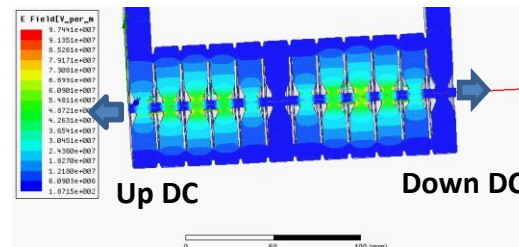
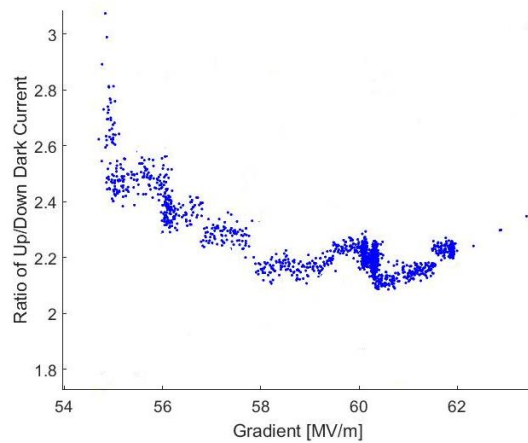
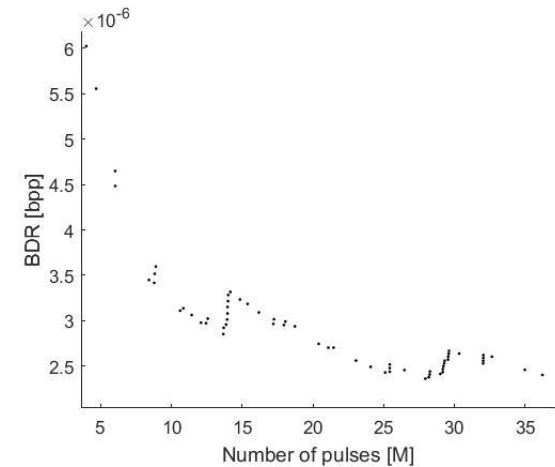
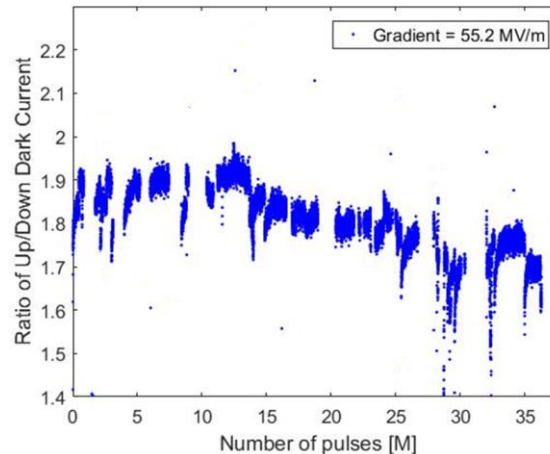
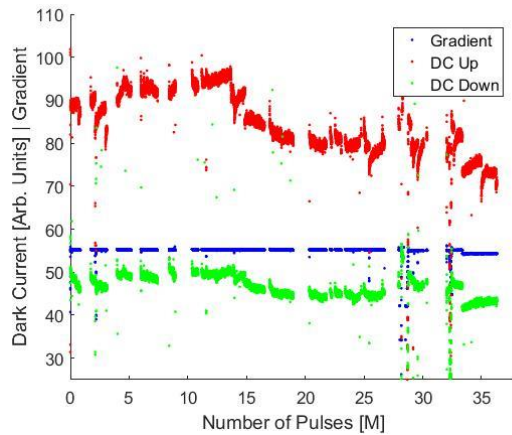


Field enhancement factor $\beta_{FE} = 35-40$.

Field emission current (analytical expression):

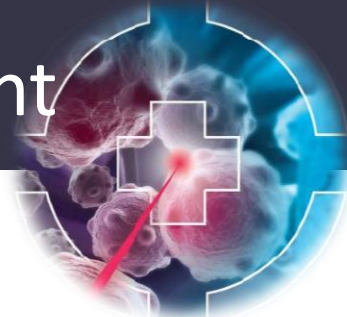
$$I_{FE} [A] = (5.7 \times 10^{-12}) \cdot 10^{4.52\phi [eV]^{-0.5}} \cdot A_e [m^2] \frac{(\beta_{FE} E_s [V/m])^{2.5}}{\phi [eV]^{1.75}} \exp\left(-\frac{6.53 \times 10^9 \phi [eV]^{1.5}}{\beta_{FE} E_s [V/m]}\right)$$

Conditioning status of 3 GHz BTW: DC study



- Up DC is twice (1.7 - 2.3) the value of Down DC, measured by Faraday cups.
- the opposite direction in comparison with CLIC AS.

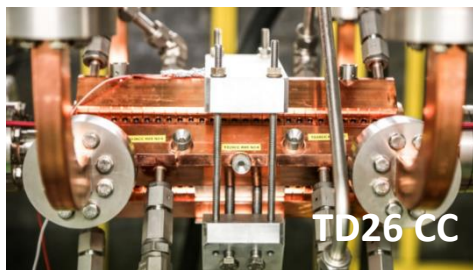
Comparison of the conditioning vs. gradient



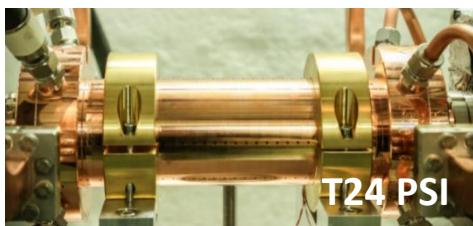
Accelerating structures do not run right away at full specification: **pulse length** and **gradient** need to be gradually increased while pulsing.



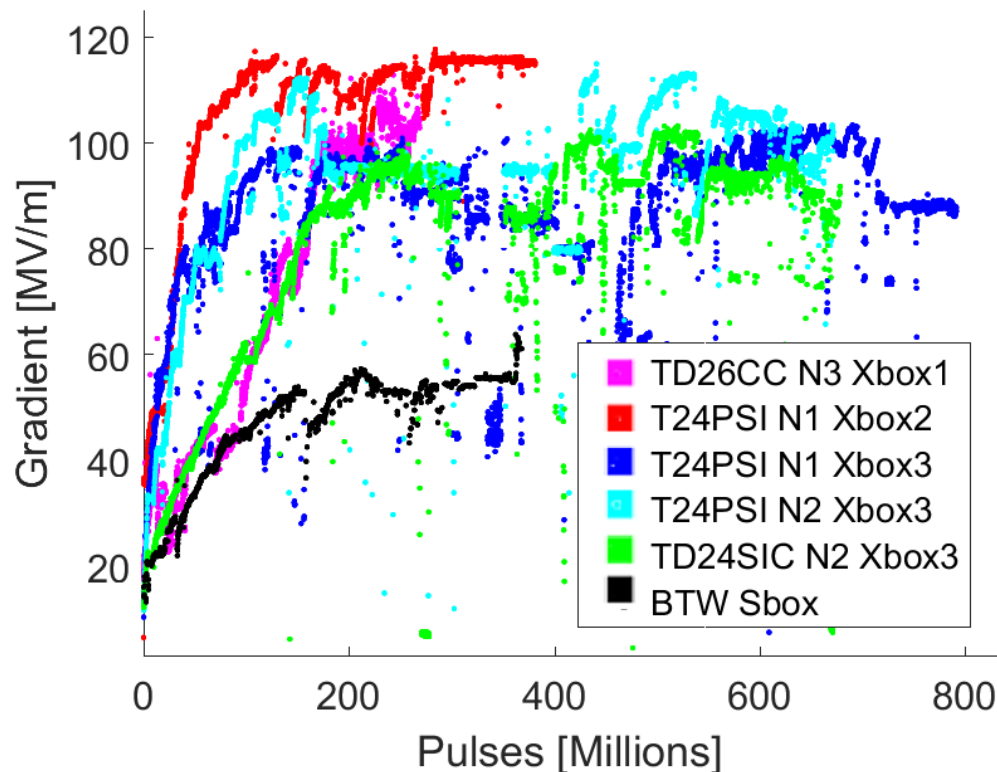
TD24 SiC



TD26 CC

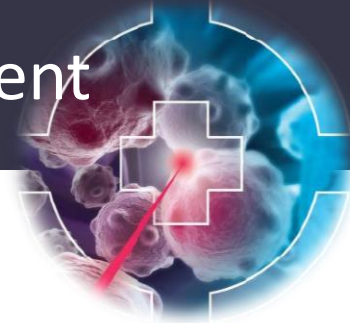


T24 PSI

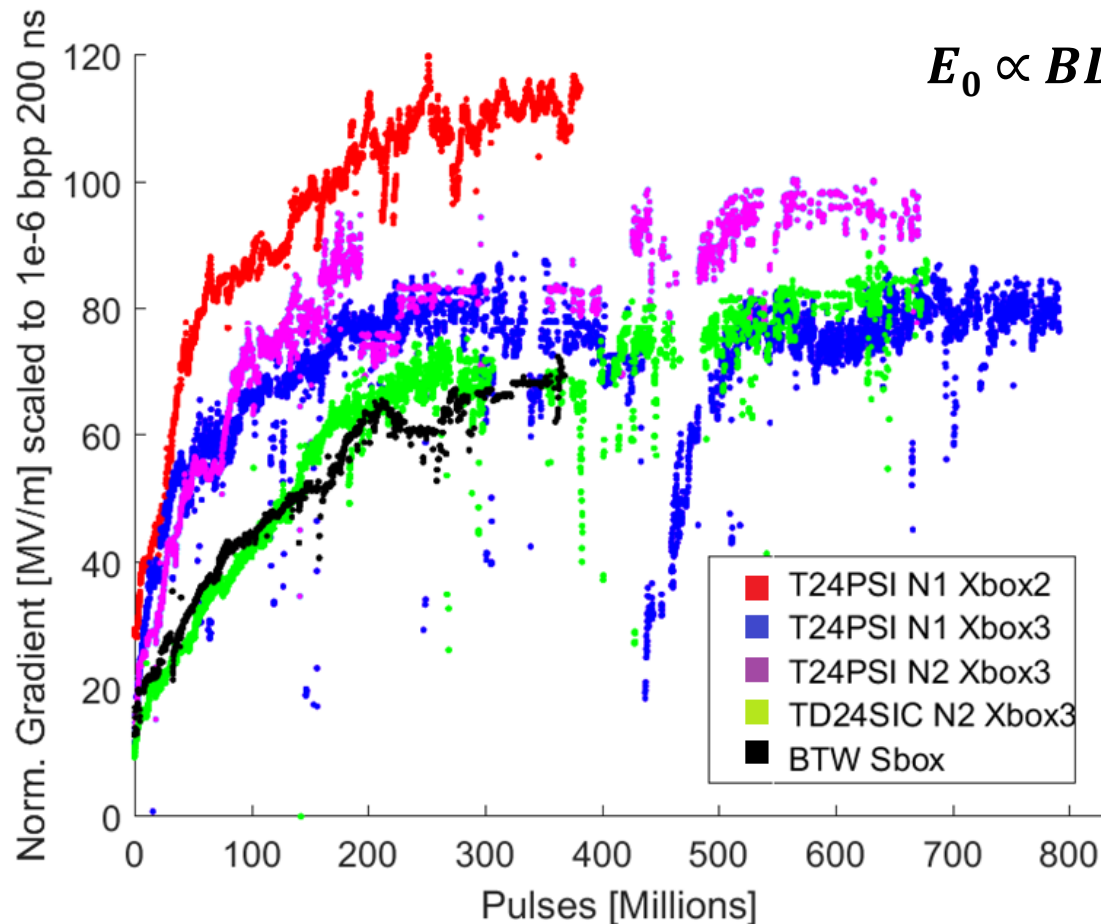


Comparison of the gradient of different prototypes tested at CERN.

Comparison of the conditioning vs. norm. gradient



- Conditioning algorithm strongly affects the conditioning progress.



$$E_0 \propto BDR^{1/30} * \tau^{-1/6}$$

for normalisation

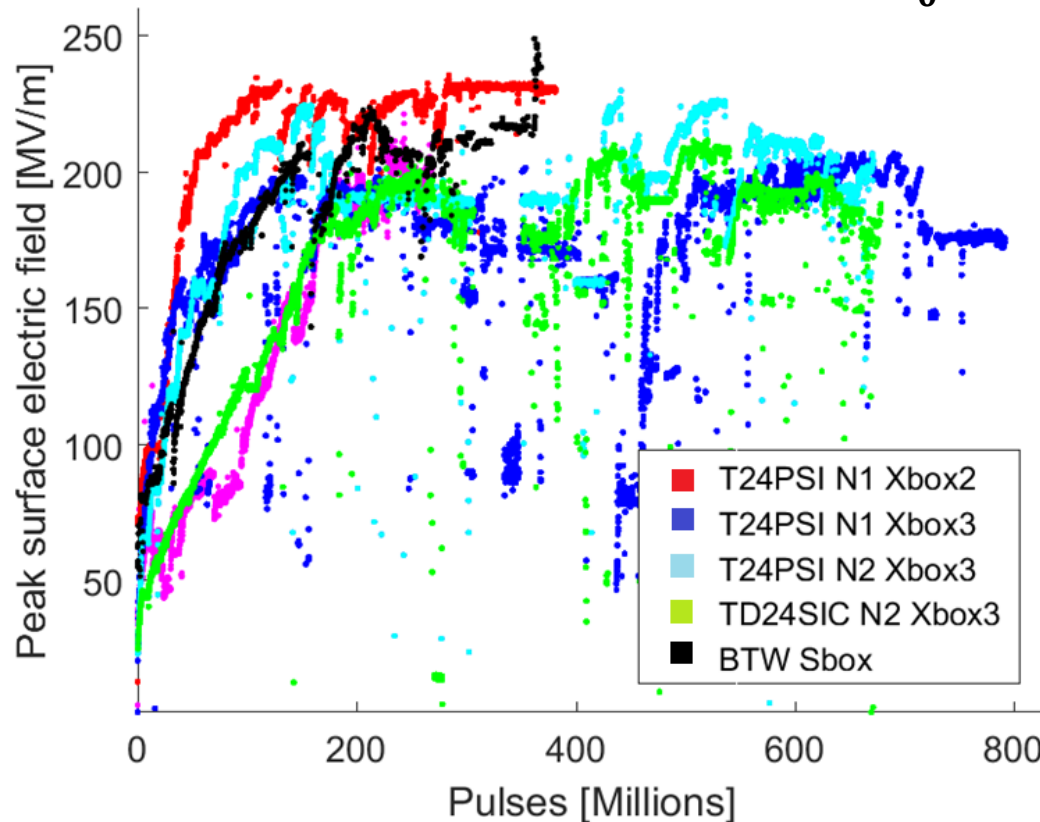
Comparison of the conditioning vs. the Esurf



The surface electric field is presented in comparison with CLIC structures ($E_s/E_c \approx 2$) and BTW ($E_s/E_c = 3.9$).

$$E_0 \propto BDR^{1/30} * \tau^{-1/6}$$

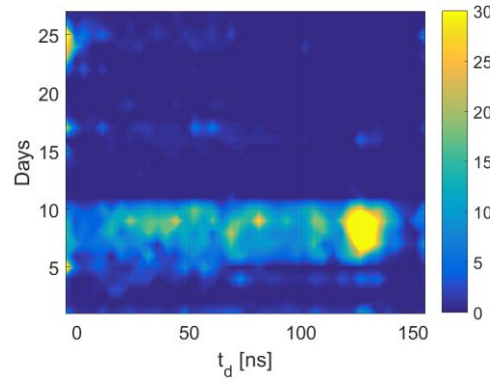
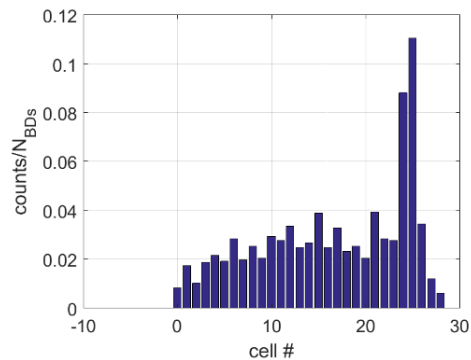
for normalisation



Connection between control and BDs location

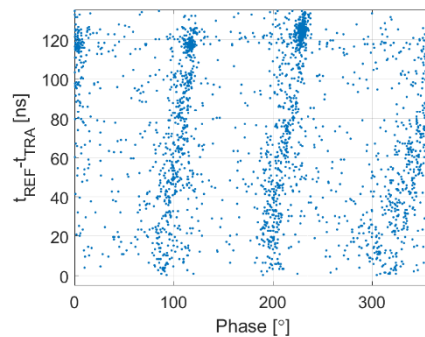


Example: TD24 SiC N2

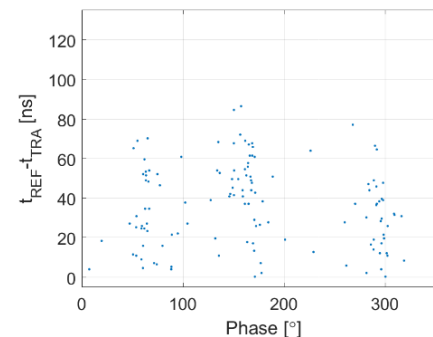


- Phase distribution of the BDs spaced by 120 degrees.
- Combination of timing and phase information gives better accuracy in BD localization.

T1 = 32.0 C

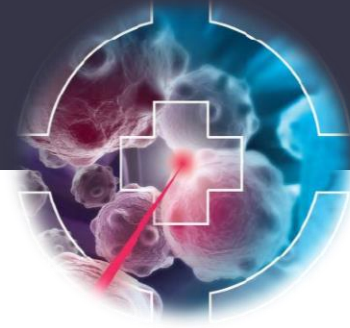


T2 = 29.8 C



- Indicates the detuning of the structure

The IFIC-HGRF lab: design aspects

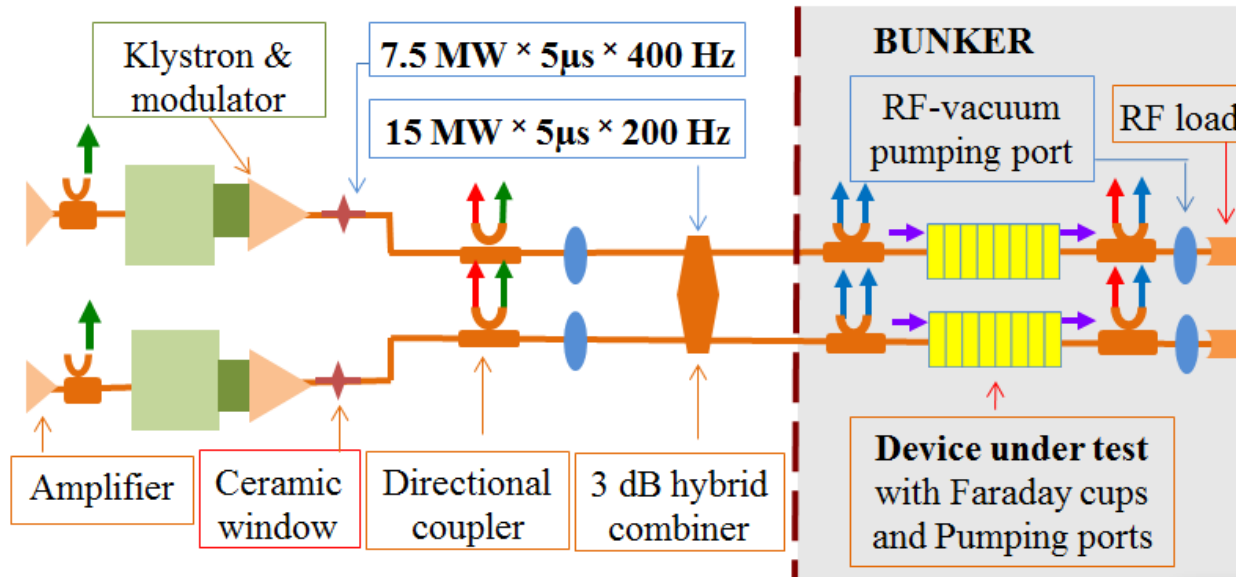


The main objective of the laboratory:

HG research topics at S-Band (2.9985 GHz).

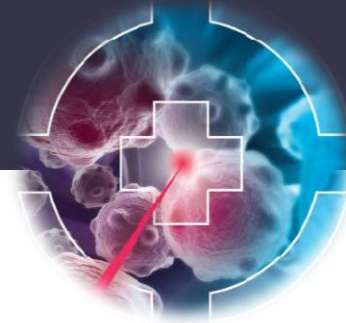
The RF **design** inspired by the **Xbox-3** (X-band (**11.994 GHz**) klystron - based test stands at CERN).

HG physics studies: RF conditioning, BD studies, dark current measurements.



Layout of the high-power components of the IFIC HG RF laboratory

The IFIC-HGRF lab: design progress



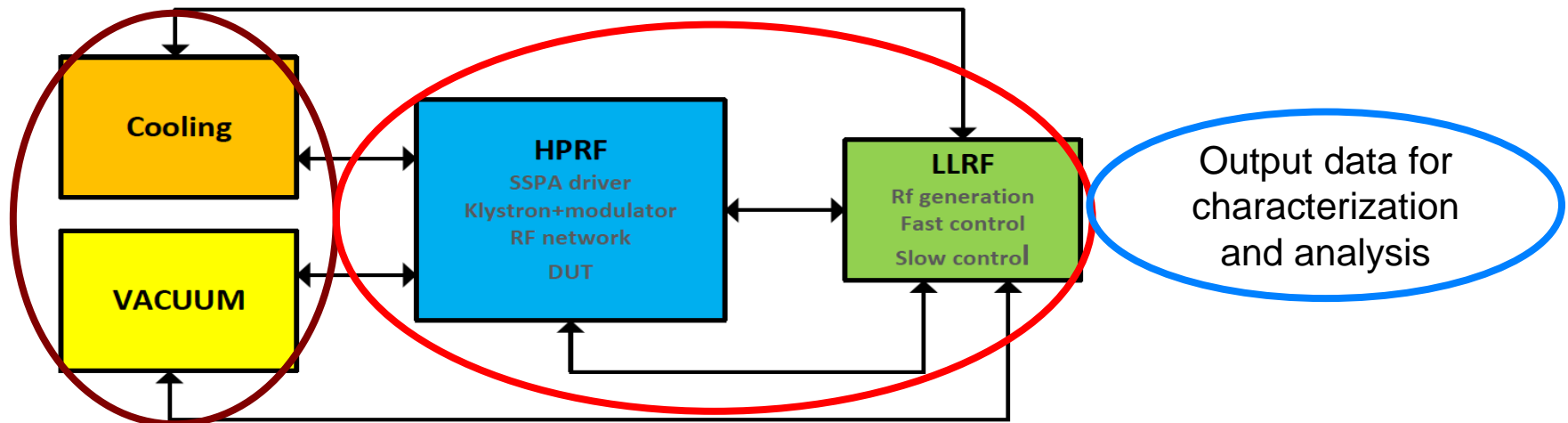
We're on installation process:

- Lab building construction is ready;
- Lab design concept mostly performed (RF generation, control);
- Redesign of some of the LLRF elements done;
- Vacuum system tests ongoing.

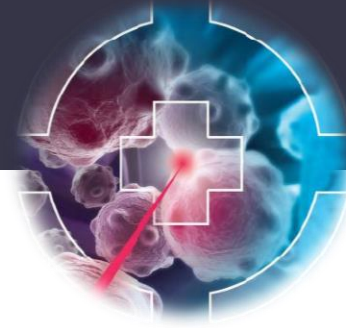
Why still?

Delays in some infrastructure (done):

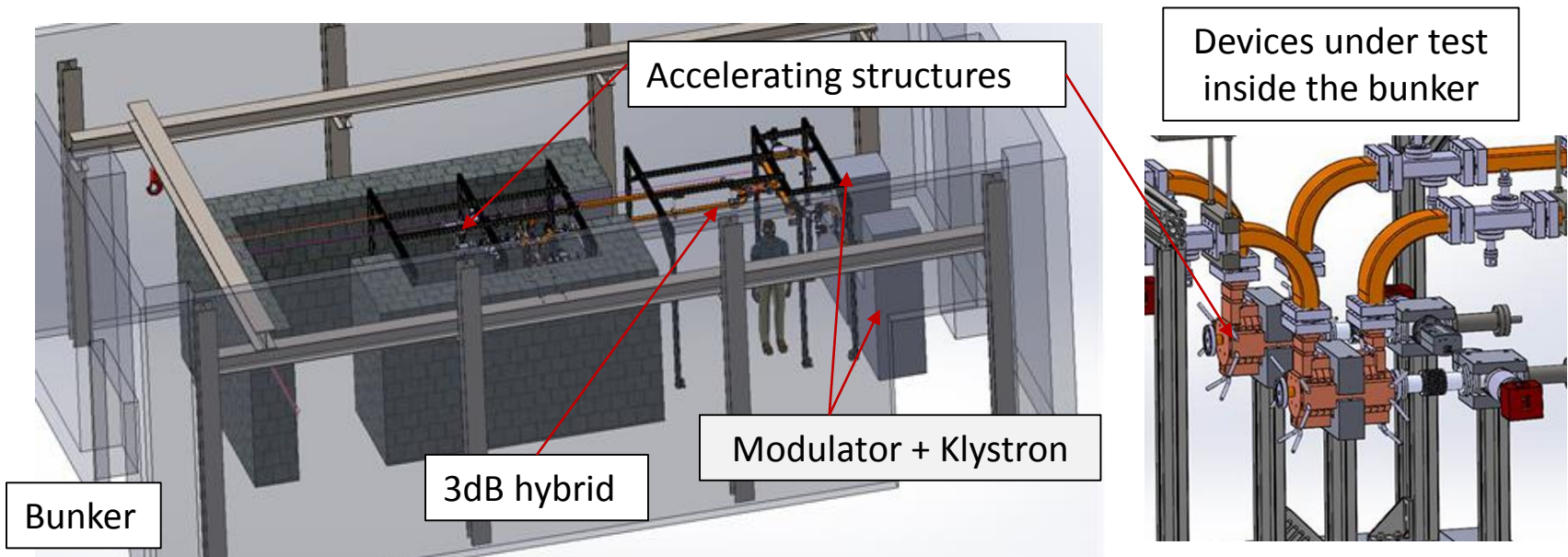
- Electrical power upgraded;
- Demineralizer cooling system;
- Modulator pulse to pulse stability was not acceptable ($\leq 0.1\%$).



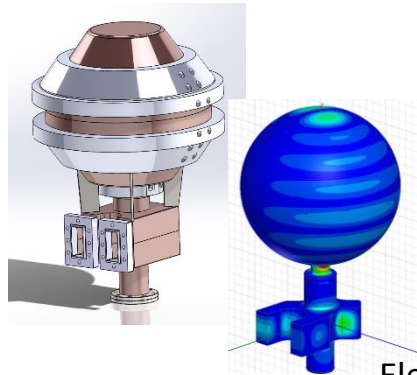
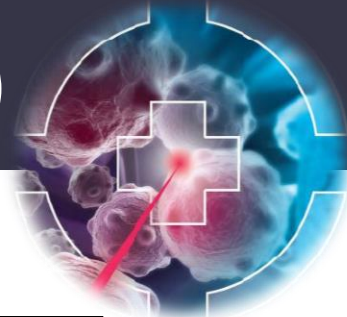
The IFIC-HGRF lab: next steps



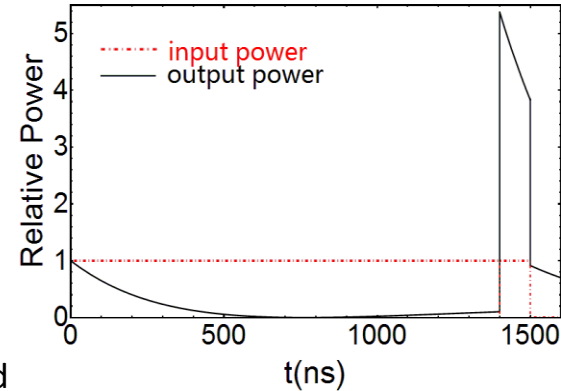
- Modulator commissioning with Klystron;
- Control software to be readapted;
- Commissioning;
- Take care of the pulse compressor.
- **New integration plan to be done due to modulator size mismatch.**



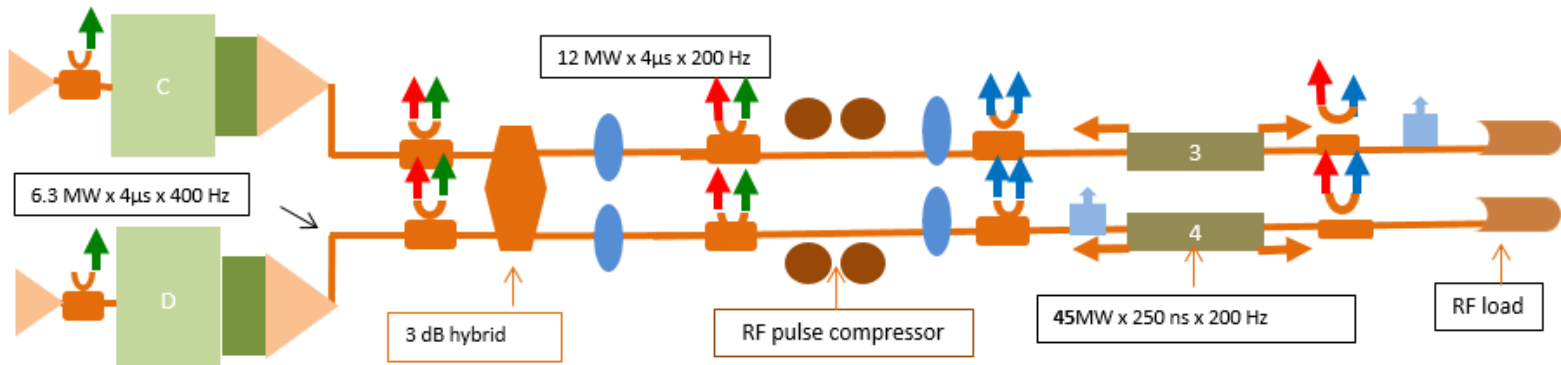
The IFIC-HGRF lab: Pulse Compressor (PC)



RF pulse compressors

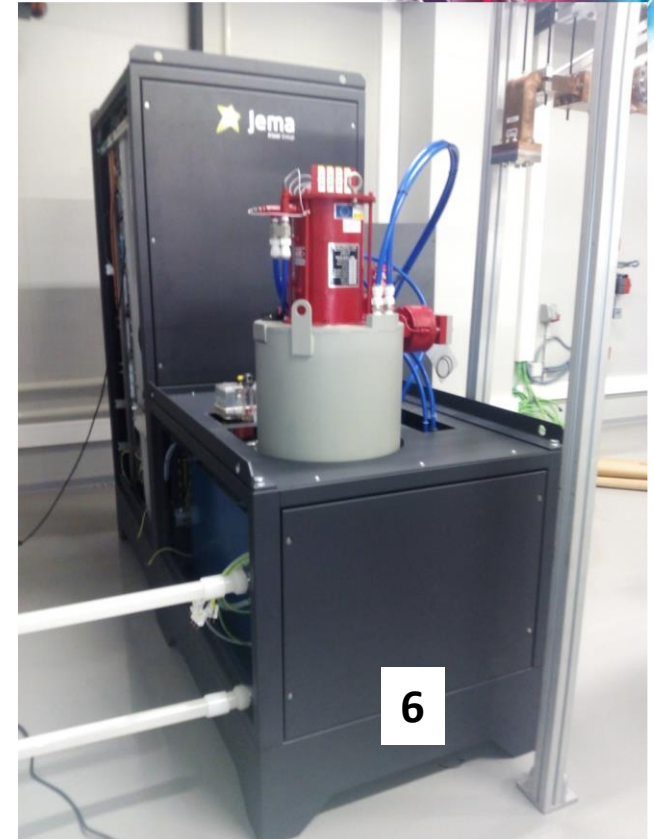
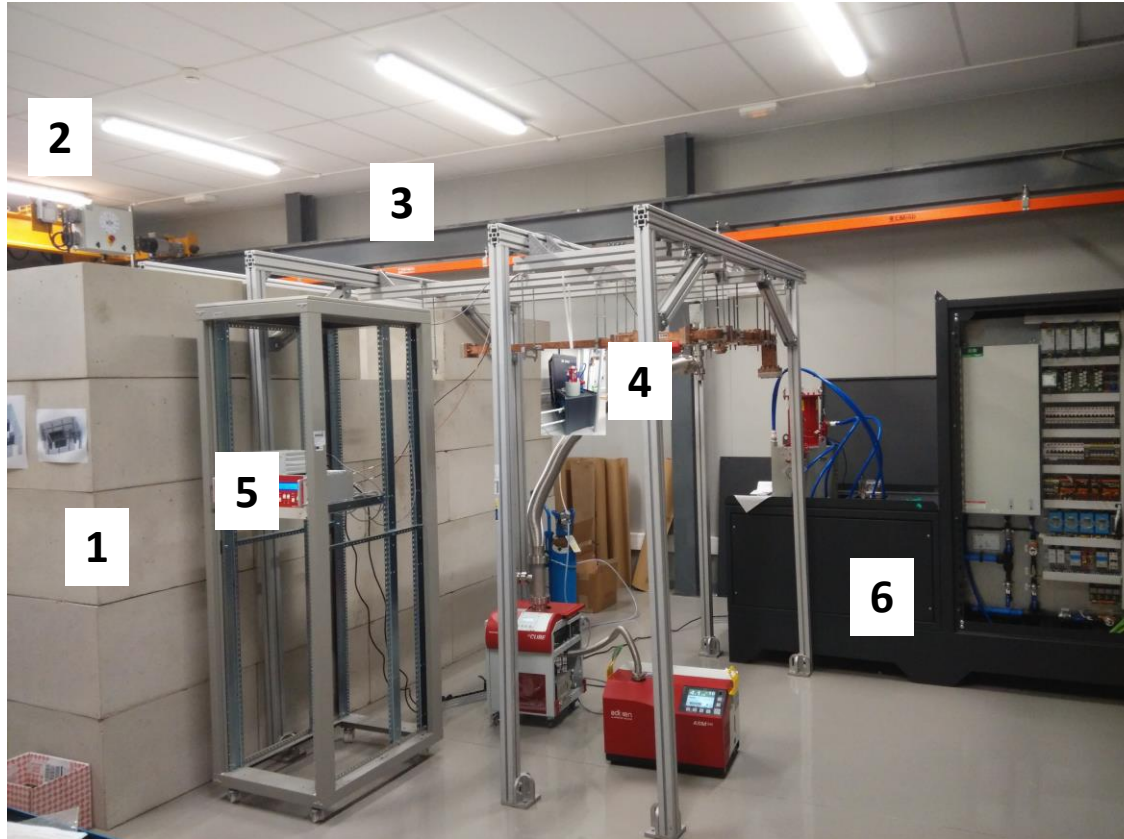


Incident and Pulse after PC



Layout of the high-power components of the Xbox3 at CERN

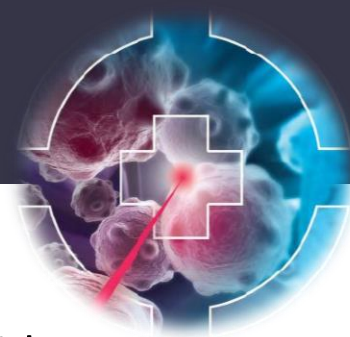
The IFIC-HGRF lab: Components



The bunker:

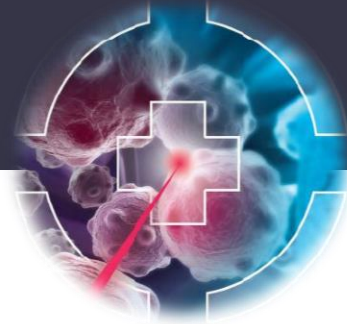
- The bunker (1), the crane (2) and the supporting structure (3)
- Waveguides (4)
- Rack for vacuum components (5)
- Modulator and Klystron connected (6)

Conclusions:



- ❑ Technology developed for **high-energy physics** can provide a significant performance improvement for **medical hadron linacs**.
- ❑ HG RF technology is extremely important in a variety of medical applications.
- ❑ Development of HG technology is on-going towards more **compact** and **more** efficient accelerators!
- ❑ S-bend test stand at Valencia will be new RF lab with **high-power / high-gradient / high-rate testing capability**.

Thank you for attention!



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