EXPLORING OF ADVANCES IN HIGH GRADIENT TECHNOLOGIES FOR USE IN HADRON THERAPY ACCELERATORS

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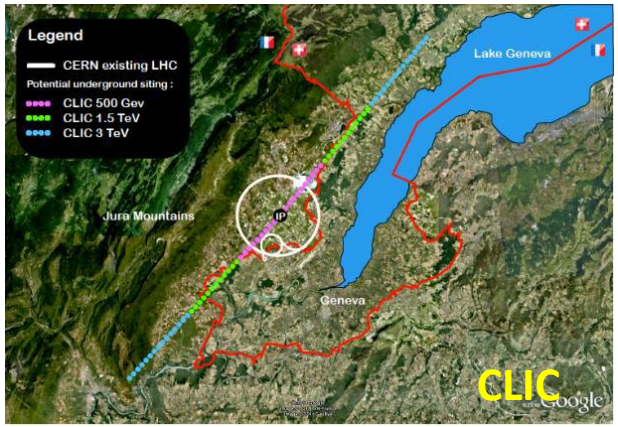
Outline

- Introduction:
  - Applications of High-Gradient technology,
  - High-Gradient limiting quantities.
- 3 GHz structure for protontherapy:
  - Conditioning of the structure,
  - Breakdown position analysis.
- 352 MHz and 750 MHz RFQs:
  - Technical specification of the RFQs,
  - Breakdown study.
- Conclusions

Introduction

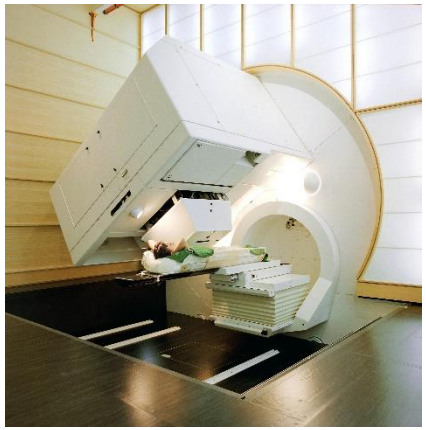
- The **High-Gradient (HG) technology** is being developed with the purpose of building **feasible, compact** and **efficient** accelerators: increasing HG from **20-30 MV/m** up to **100-120 MV/m**.
- The main idea of the study: **Transfer Knowledge** from **High-Energy Physics to other applications:**

- **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



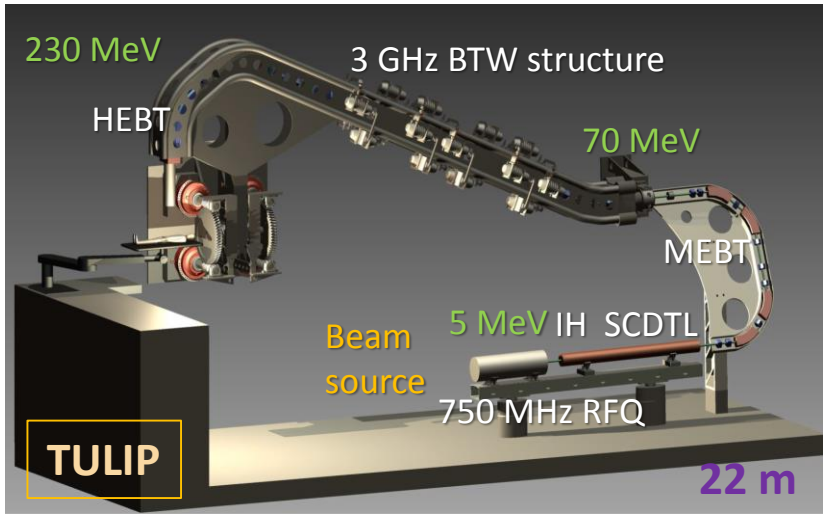
350 MeV

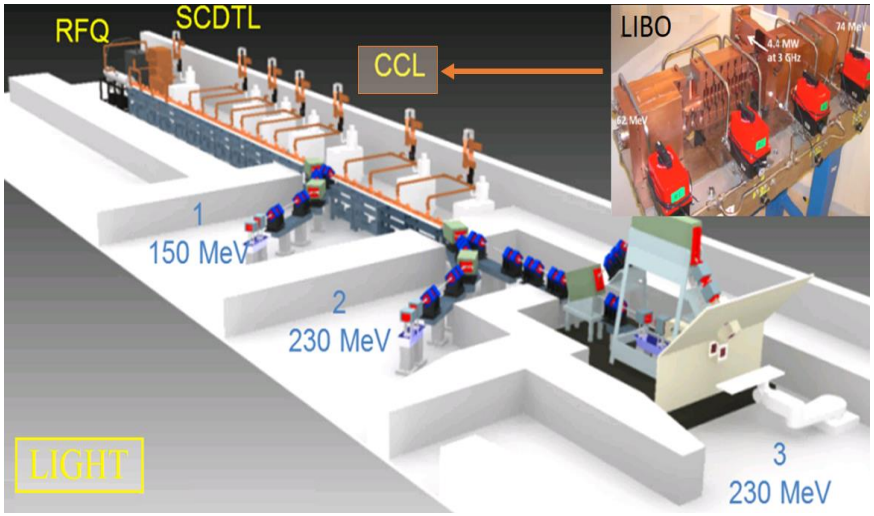
Why Linear Accelerator?

The linear accelerator (**Linac**) looks as the most promising option on terms of **size**, **complexity** and **efficiency**.

Advantages:

- ✓ active energy variation (pulse to pulse),
- ✓ treatment time (a high repetition rate).





TULIP: Single-room proton therapy

Advantages: footprint (200 m^2, 70 ton), shielding

BTW (Backward Travelling Wave) structure with a design gradient of **50 MV/m**.

LIGHT: Linac for Image Guided Hadron Therapy

Advantages: beam current, power consumption

CCL (Coupled Cavity Linac) based on the TERA design of LIBO with a gradient of **15.7 MV/m**.

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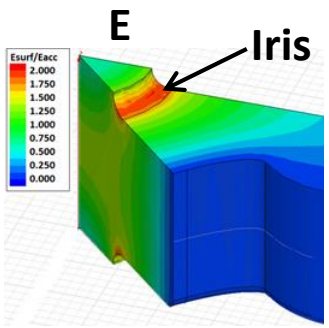
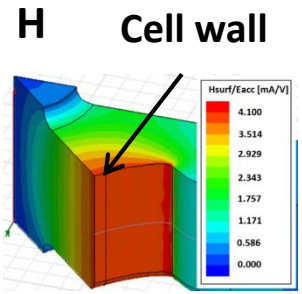
High-Gradient limiting quantities

The accelerating efficiency is strongly dependent on the type of structure used and on the beam energy.

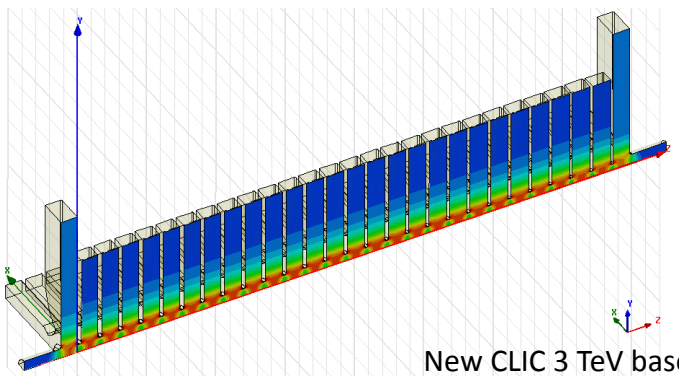


The criteria which **limit accelerating gradient:**

- **Surface electric field** $E\ surf = 200\ MV/m$
- **Surface magnetic field/pulsed surface heating**
- **Power flow:** modified Poynting vector, $S_c = 5\ MW/mm^2$



$$\Delta T \propto H_s^2 \sqrt{t_p}, \quad T_{\max} = 50^{o}\mathrm{C}$$



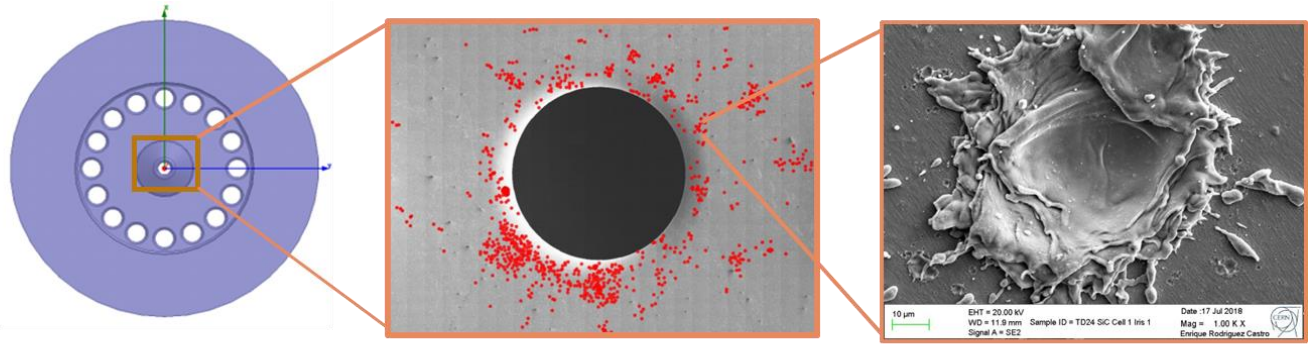
New CLIC 3 TeV baseline
H.Zha, A Grudiev

- Efficiency reduction;
- Erosion of surface;
- Material fatigue, cracks;
- Detector backgrounds;
- Breakdowns (vacuum arcs).

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

Breakdowns in accelerating structures

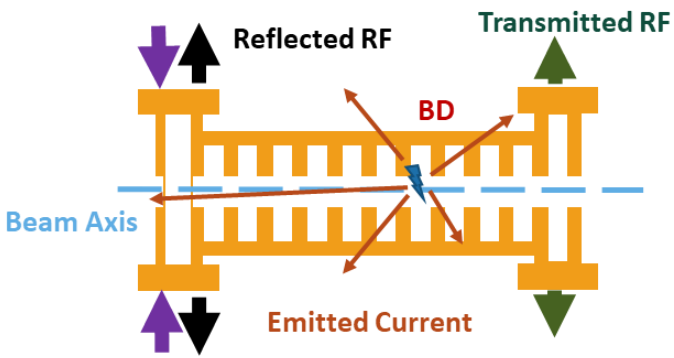
- BDs can **damage the surface** and induce **instabilities** into the beam.



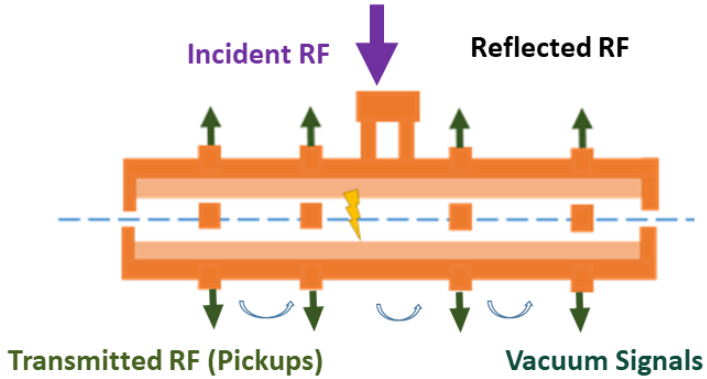
Disk of a BTW accelerating structure — SEM microscopy — Breakdown Crater

- **Objective**: studying of the **HG performance** of various accelerating structure, definition of **limiting factors** to further optimize the structure design.

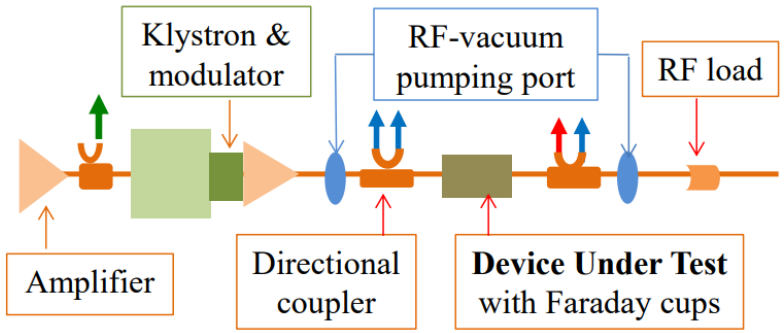
Traveling-wave structure



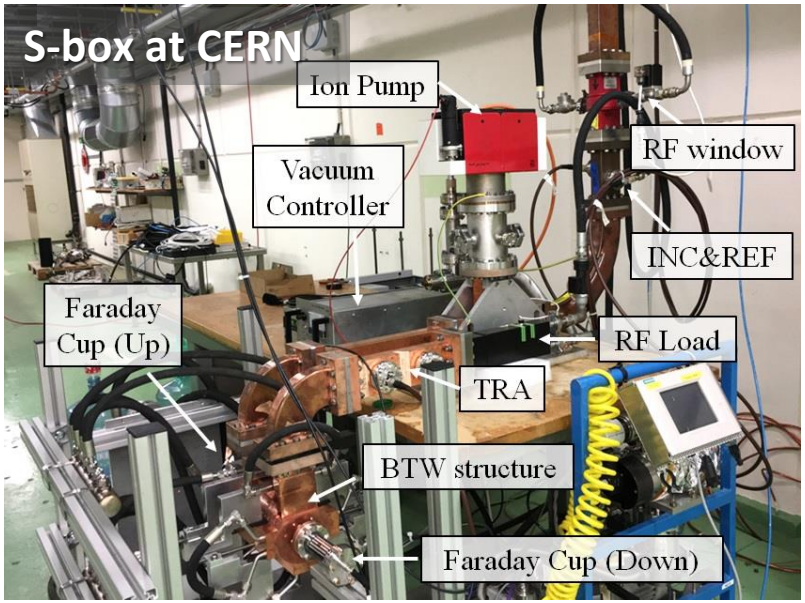
Standing-wave structure



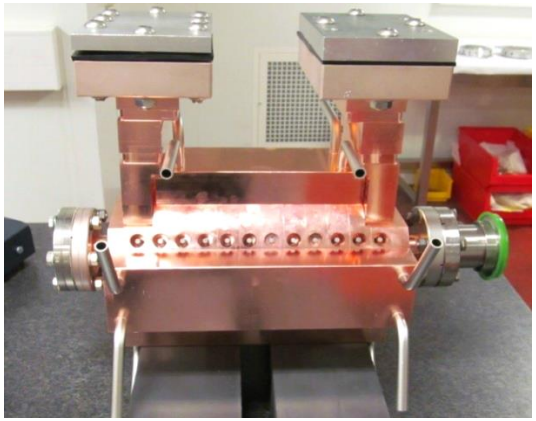
I. S-band medical linac structure (BTW)



Functional diagram of S-band test facility



Dec 2017 – May 2018



BTW structure (TULIP), **3 GHz**

2.5 µs, 50 MV/m

Number of RF cells	12
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
Filling time	220 ns
Group velocity (1st/last)	0.39 / 0.21 %c

✓ 10 MeV energy gain from this structure

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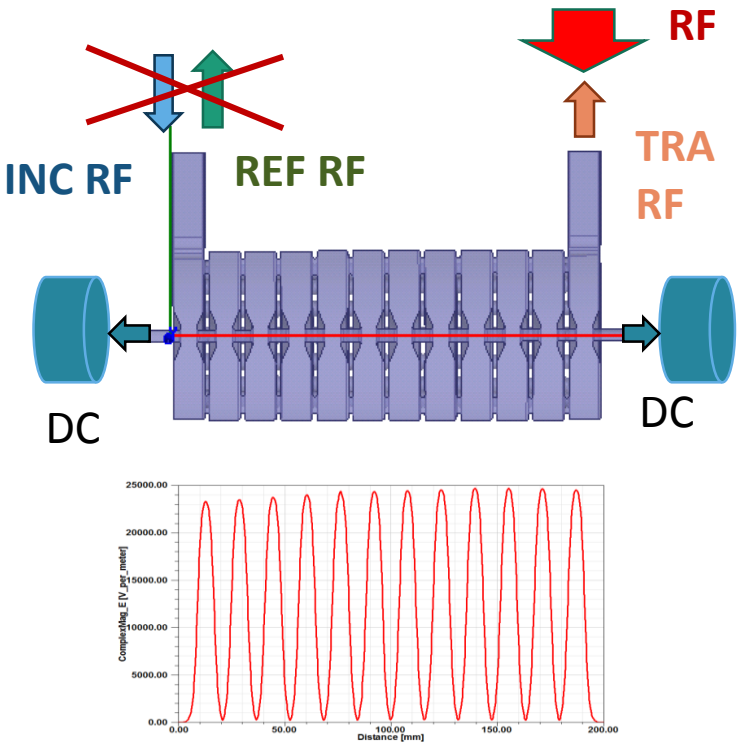
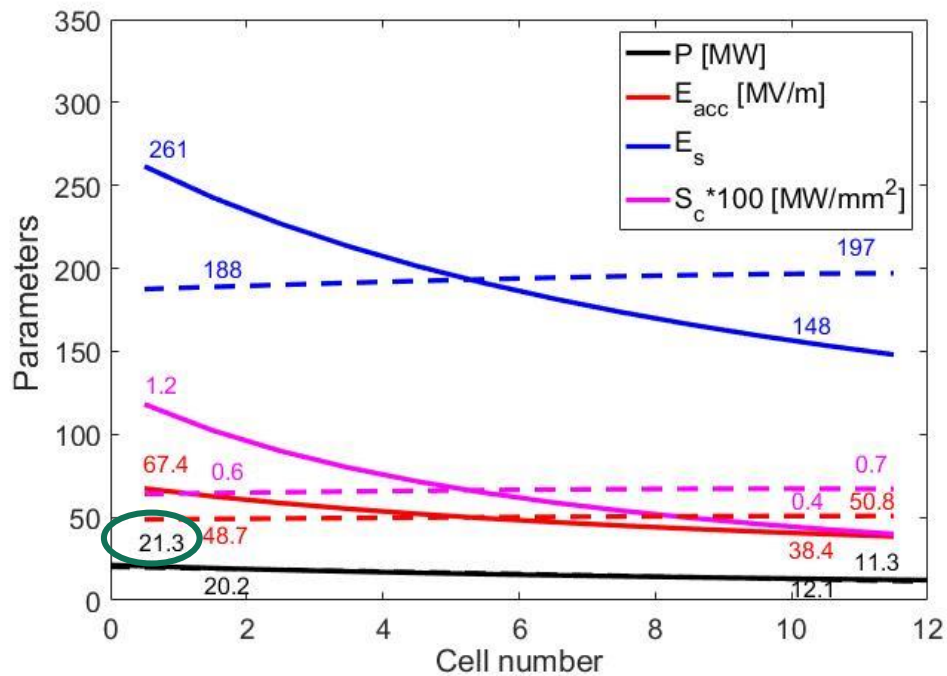
RF parameters of BTW structure

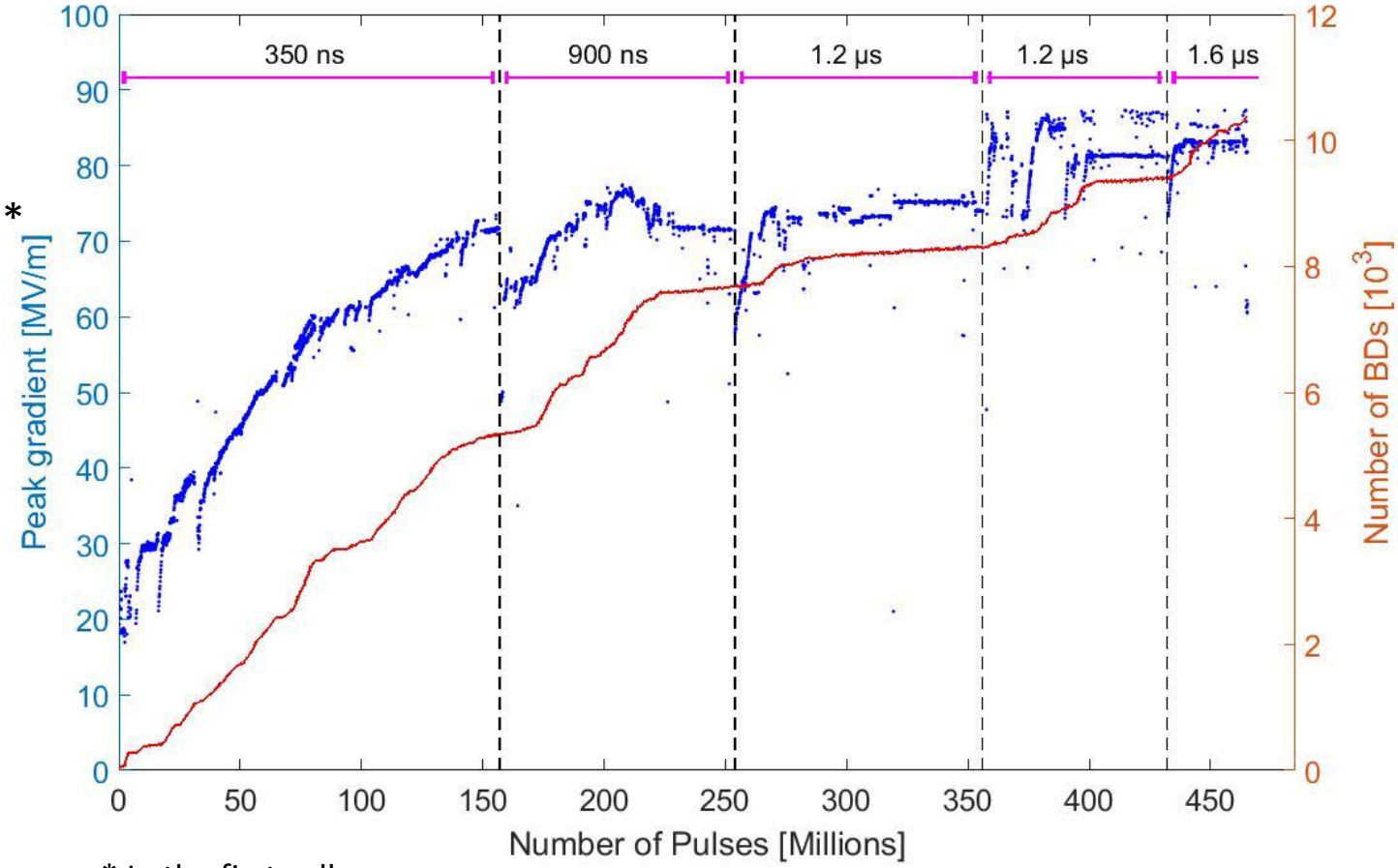


Electric field profile in the structure.



Distribution of the RF parameters along the structure for normal (dashed) and backward (solid) filled at average gradient of **50 MV/m** with a pulse width of **1.6 µs.**

Conditioning history of BTW prototype

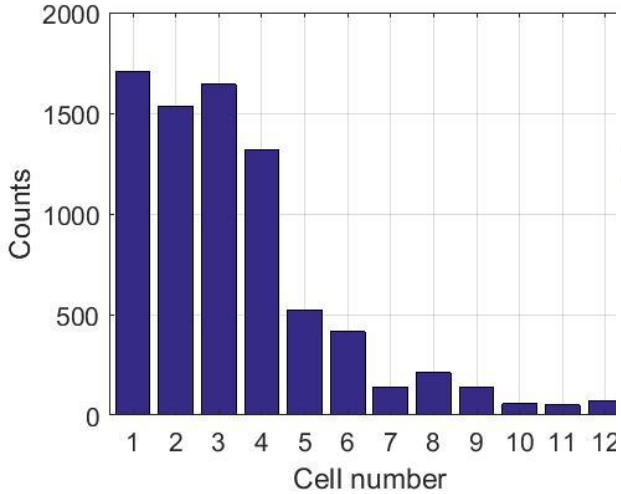


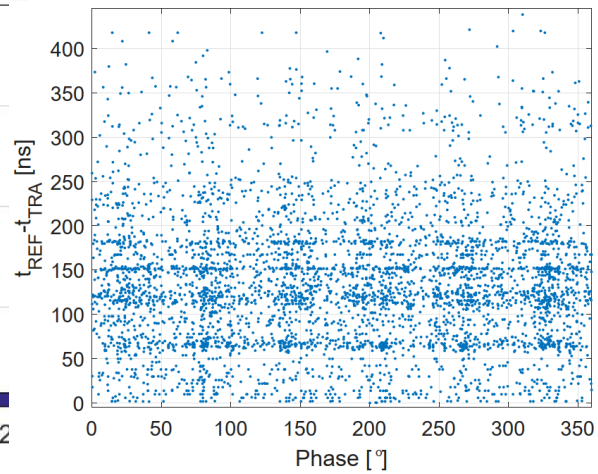
* In the first cell

✓ Accelerating gradient above **80 MV/m:**
BDR = 4x10^{-6} 1/pulse at 1.6 µs. ⟶ Surface electric field: **320 MV/m**

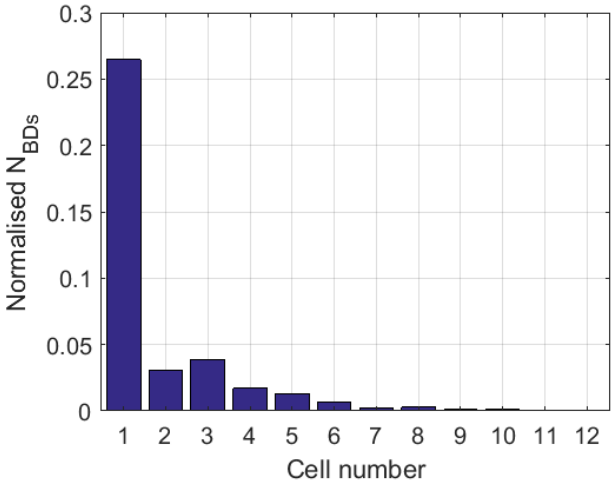
Position analysis of BTW structure

- Full history (edge and phase method)

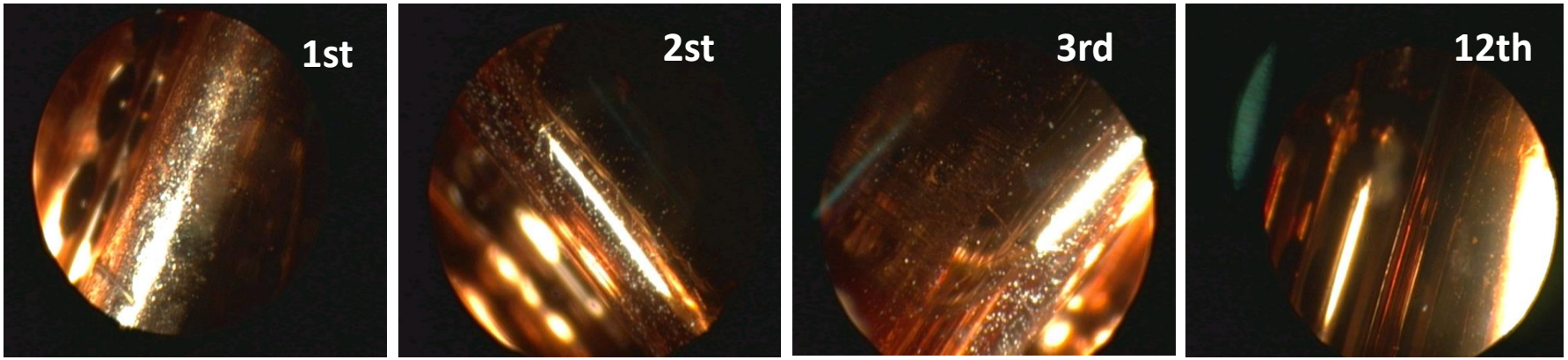




- History at end of run



- Borescope measurement



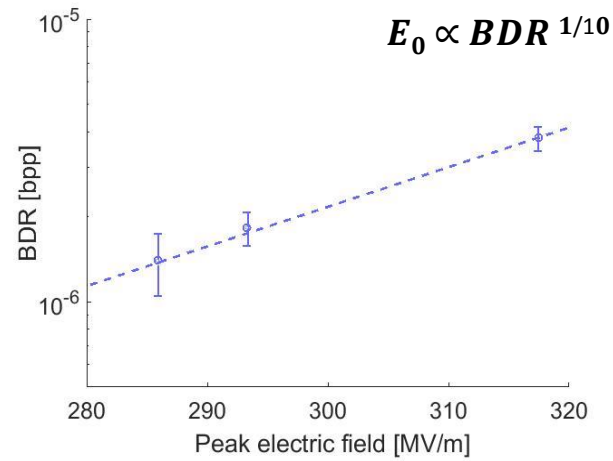
Courtesy of Serge Lebet

Conclusions of BD study in BTW structure

- ✓ **Long term conditioning** estimation of BDR:

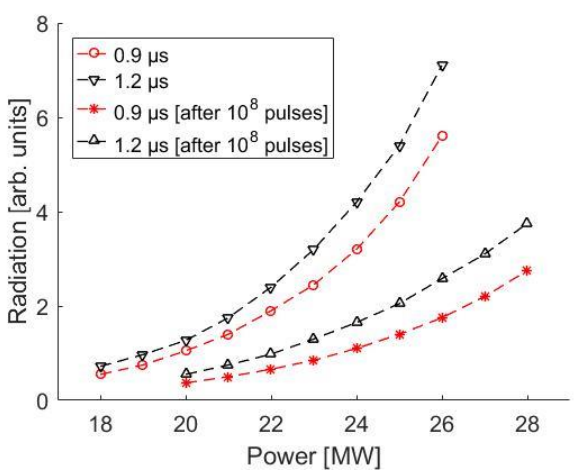
  for 12 GHz: $E_0 \propto BDR^{1/30} * \tau^{-1/6}$

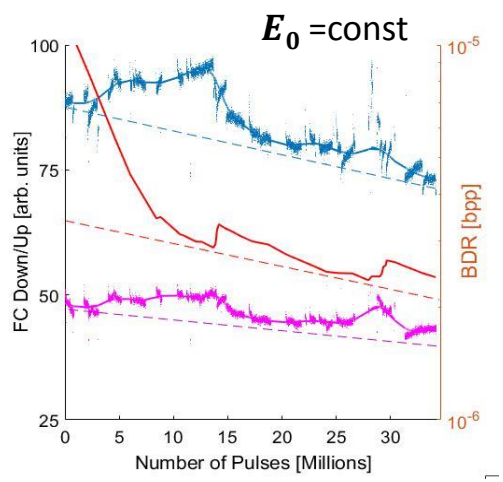
  for 3 GHz: $E_0 \propto BDR^{1/10}$

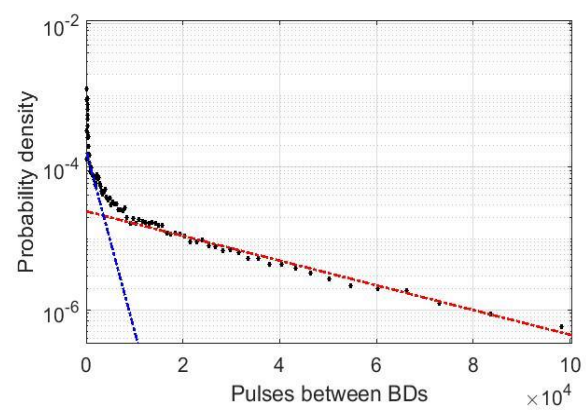


- ✓ **Dark current measurements**: radiation depends on pulse length and BD activity of the structure.

- ✓ **Statistic of BD event**: the number of primary BDs is predominant when conditioning of the structure, but this ratio changes for a well-conditioned structure.







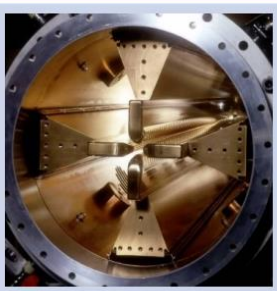
Surface field limitations of RFQ

The **RFQ** is a linear accelerator which

- ✓ Focuses,
- ✓ Bunches,
- ✓ Accelerates.

All-Linac (RFQ+DTL "injector") medical facility.

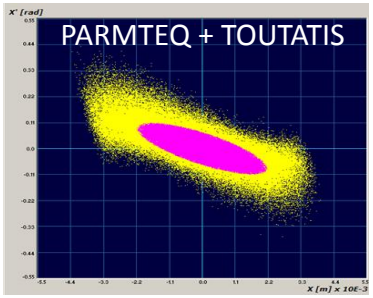
1988-92	2008-13	2014-16
Linac2 RFQ2	LINAC4 RFQ	HF-RFQ
202 MHz	352 MHz	750MHz
0.5 MeV /m	1MeV/m	2.5MeV/m
Weight : 1000 kg/m	Weight : 400kg/m	Weight : 100 kg/m
Ext. diameter : 45 cm	Ext. diameter : 29 cm	Ext. diameter : 13 cm



200 MHz → 350 MHz → 750 MHz

High peak fields increase the RFQ **performance** in areas of:

- ✓ Higher acceptance (larger emittance beams);
- ✓ Greater space charge capability;
- ✓ Accept heavy ions with lower charge state;
- ✓ Shorter RFQ;



The main problem: the expected transmission through the RFQ.

(measured emittance (yellow) and RFQ acceptance (pink))

but also have the effect of:

- ➢ Increased probability of **sparking**;
- ➢ More **RF power** required;
- ➢ Tighter machining and **alignment tolerances**.

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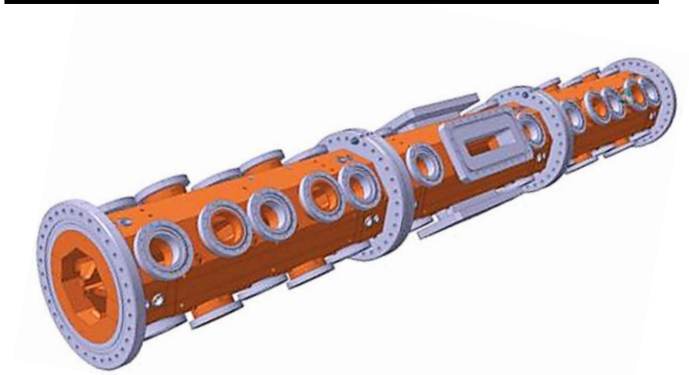
II. Technical specification of the RFQs

RFQ at ADAM

- 4-vane structure with 2 brazing steps
- Operation: 480 kW, 750 us, 1.2 Hz

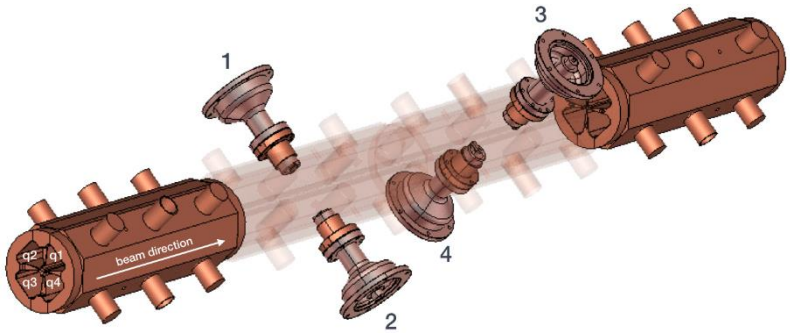
Source and RFQ parameters	
Frequency	**352.2 MHz**
Length	3.06 m
Vane voltage	78.27 kV
Max field on pole tip	34 MV/m
RF total peak power	600 kW
Beam Input Energy	45 keV
Beam Output Energy	3.0 MeV



RFQ at Linac4

- 4-vane structure with 3 brazing steps
- Operation: IOT 4*100 kW, 10 us, 200 Hz

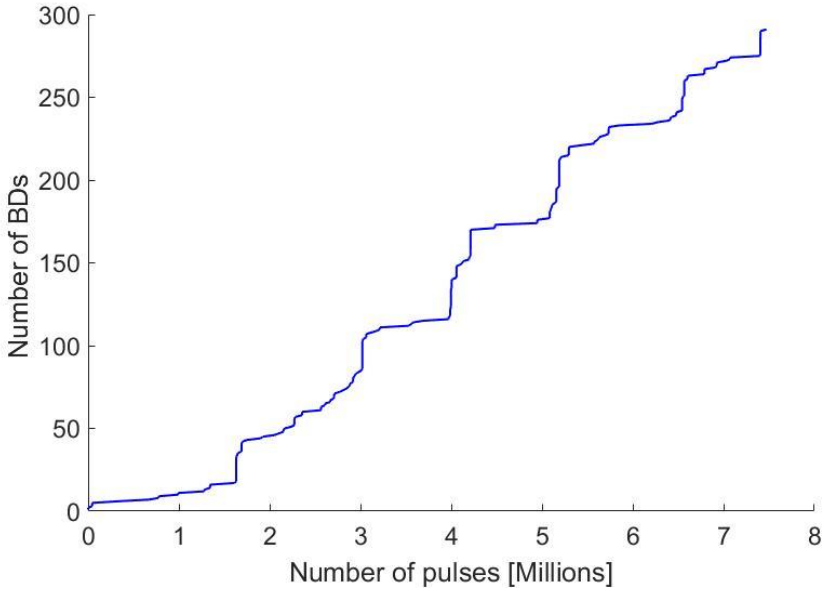
Source and RFQ parameters	
Frequency	**750 MHz**
Length	2 m
Vane voltage	65 kV
Max field on pole tip	50 MV/m
RF total peak power	400 kW
Beam Input Energy	40 keV
Beam Output Energy	5 MeV



Operation history of RFQs at ADAM and Linac4

RFQ at Linac4

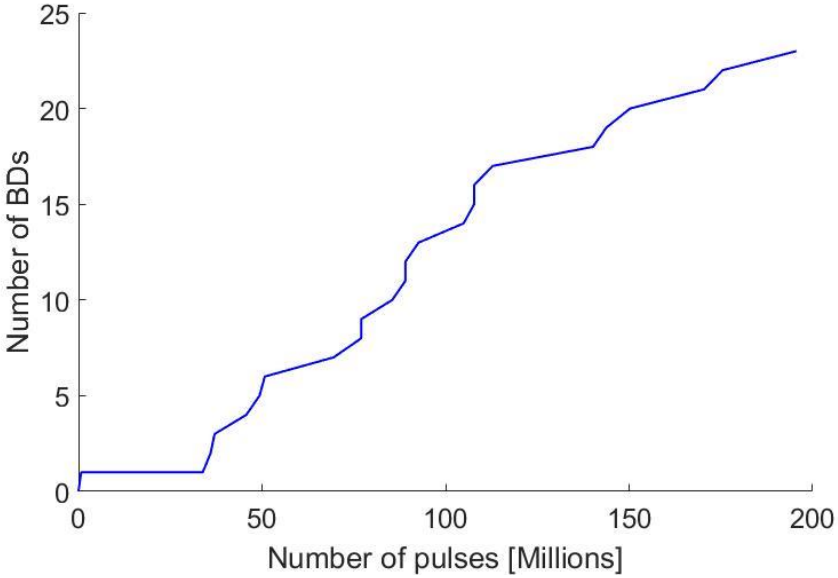
Forward power = **440 kW**
Pulse length = **750 us**



BDR = 3.85 e-05 [1/pulse]

RFQ at ADAM

Forward power = **400 kW**
Pulse length = **10 us**

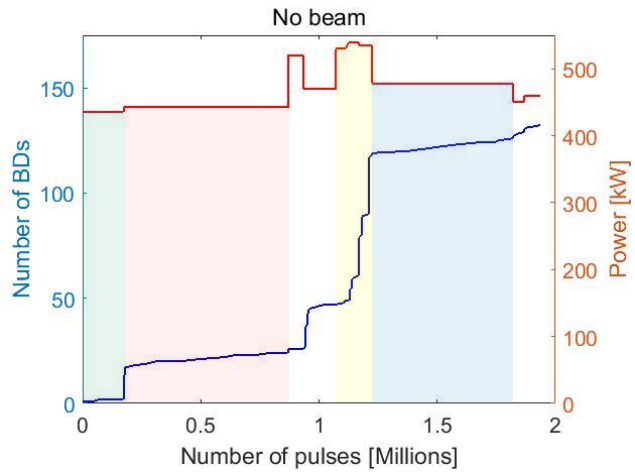


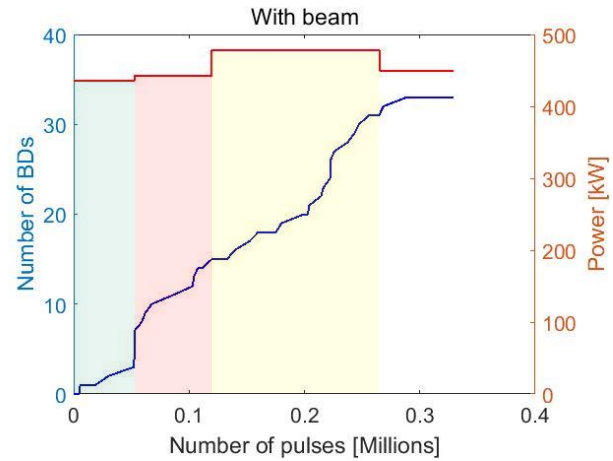
BDR = 1.28 e-07 [1/pulse]

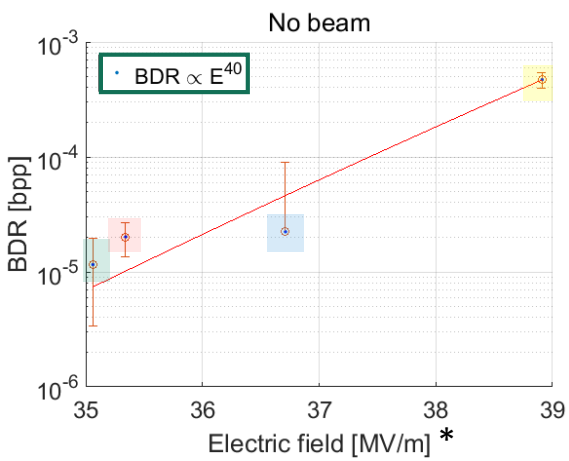
Measurement of BDs without impact on normal operation of the RFQs.

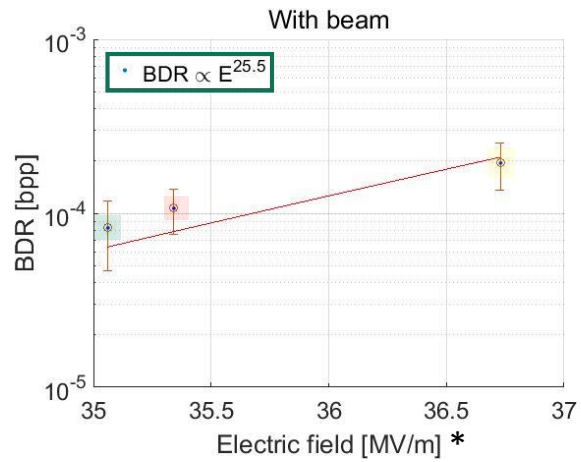
BDR vs Electric field measurement

- RFQ at Linac4 (1 month test during shutdown of LHC): **900 µs, power up to 540 kW.**





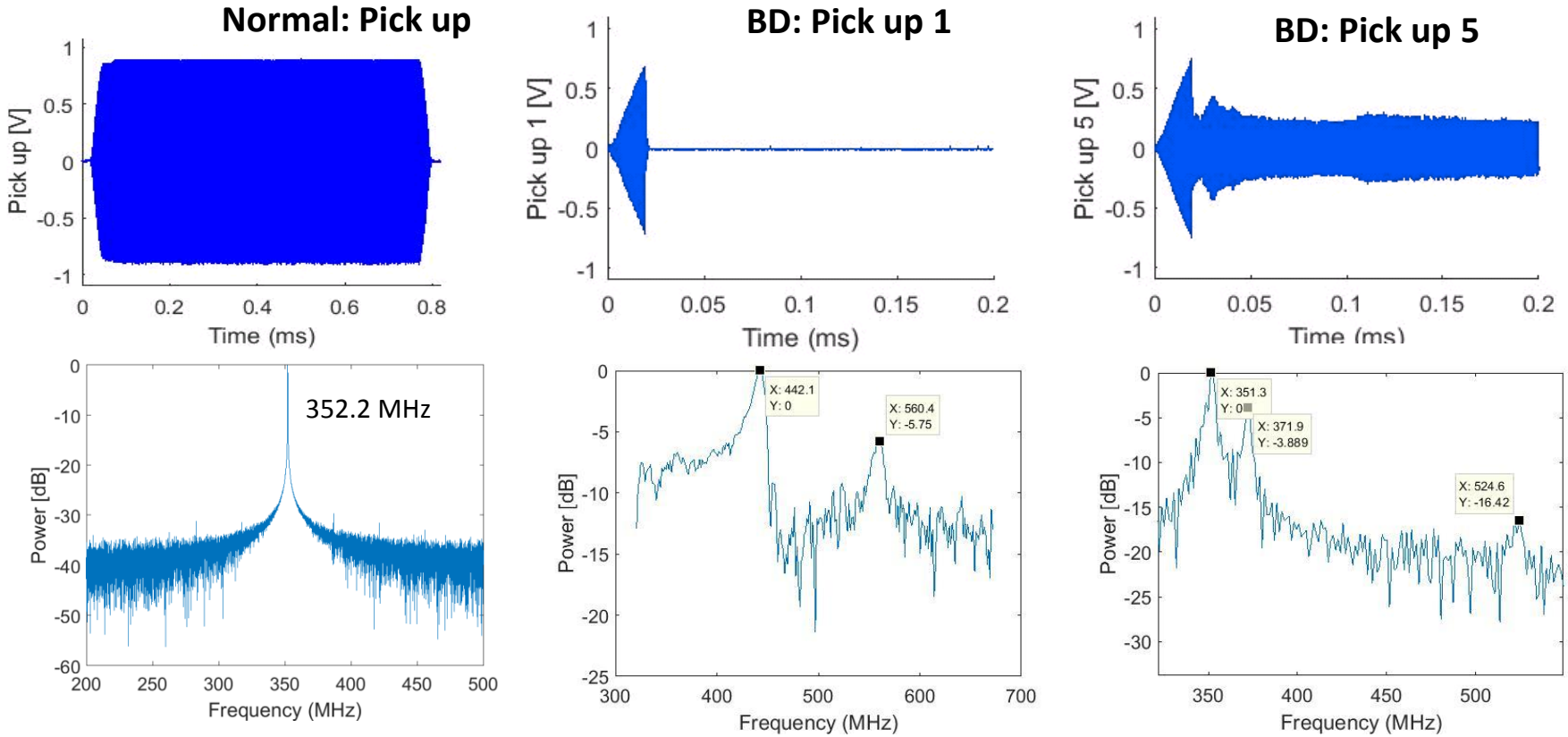




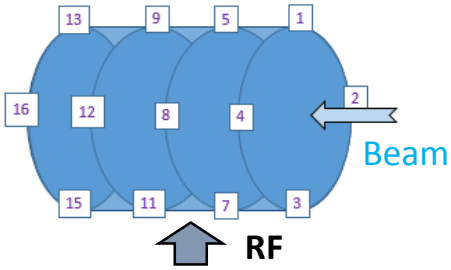
For **unloaded** forward power **440 kW** => BDR = **1.1E-05** 1/pulse; **loaded** => BDR = **8.2E-05** 1/pulse.

A high BDR can be explained that the structure has not been tested with such high power before.

RF parameters measurement



- When RF BDs occur, the cavity divided to 2 sections: power continue to flow into section with coupler and radiative value is driving with BD present.
- Non Resonant frequencies appear during BD, that depends on how far the BD event occur.



Conclusions of BD study in RFQ structure

- ✓ The first time measurements of the BD behaviour in the RFQs have been carry out in a **systematic** way.
- ✓ Measurements of two structures with different frequencies have been performed.
- ✓ Developed a **primary technique for determining the location BD** along the structure.

BD location in the RFQ at Linac4:

1st module: 10% , 2nd module: 20%, 3rd module: 60%, Unclear: 10%.

BD location in the RFQ at ADAM test bench:

Dominant BDs in the 2st and 3rd module (RF directional coupler): not enough available signals.

- ✓ Quality factor of the structure at BD is twice smaller compare to normal operating regime. The stored energy varied from event to event, require additional study with higher signal resolution:

Q-factor at Linac4/ADAM ≈ **6772/6500,** during BD = 2850 - 5700/1800 - 4500.

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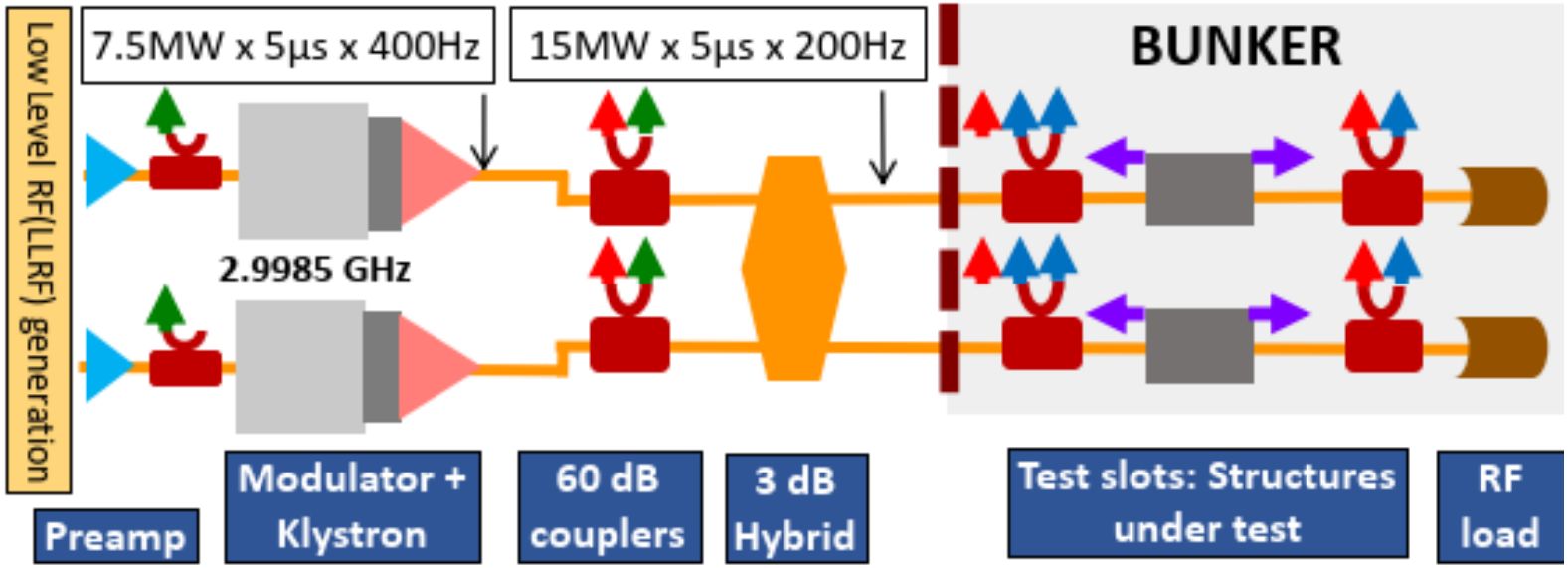
Conclusions

- 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.
- The high-power tests give oportunity determine the highest operation field at which the structure could operate reliably:
  - requirements to construct the test bench for S-band structures and RFQs for pre-conditioning and BD phenomenon study.
  - acceleration gradient of S-band structure for protons is above 80 MV/m for 1.6 μs and 50 MV/m for the 750 MHz RFQ .
- These results demonstrate the possibility to build all-linac facility for hadron therapy based on HG technology.

Thank you for your attention!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675265.

Backup slide: The IFIC – HGRF Laboratory



- **S-Band (2.9985 GHz)**
- **Pulsed High Power RF (HPRF):**
  - 2 x pulsed power klystron: 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.
- **Low level RF (LLRF)**: real-time control system with fast system interlock based on Ni-PXI acquisition system.
- Running on **Ultra-High vacuum** (10^{-9} mbar).

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