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

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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**

Legend:

- **CLIC Google**
- **SACLAC**
- **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 m², 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.
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, \( S_c = 5 \, MW/mm^2 \)

\[ \Delta T \propto H_s^2 \sqrt{t_p}, \quad T_{max} = 50^\circ C \]

- 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.

**Objective**: studying of the HG performance of various accelerating structure, definition of limiting factors to further optimize the structure design.
I. S-band medical linac structure (BTW)

Functional diagram of S-band test facility

S-box at CERN

BTW structure (TULIP), 3 GHz
2.5 μs, 50 MV/m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RF cells</td>
<td>12</td>
</tr>
<tr>
<td>β – RF Ph. adv.</td>
<td>0.38 - 150 deg</td>
</tr>
<tr>
<td>Total length</td>
<td>189.84 mm</td>
</tr>
<tr>
<td>Max Sc/Ea²</td>
<td>0.29 mA/V</td>
</tr>
<tr>
<td>Max Es/Ea</td>
<td>3.9</td>
</tr>
<tr>
<td>Filling time</td>
<td>220 ns</td>
</tr>
<tr>
<td>Group velocity (1st/last)</td>
<td>0.39 / 0.21 %c</td>
</tr>
</tbody>
</table>

✓ 10 MeV energy gain from this 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.

Electric field profile in the structure.
Conditioning history of BTW prototype

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

* In the first cell
Position analysis of BTW structure

- Full history (edge and phase method)
- History at end of run

- Borescope measurement

![Graphs showing data analysis](image)

Courtesy of Serge Lebet
Conclusions of BD study in BTW structure

- **Long term conditioning** estimation of BDR:
  - For 12 GHz: \( E_0 \propto BDR^{1/30} \times \tau^{-1/6} \)
  - 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.
The RFQ is a linear accelerator which
✓ Focuses,
✓ Bunches,
✓ Accelerates.

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

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.
II. Technical specification of the RFQs

RFQ at ADAM

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

<table>
<thead>
<tr>
<th>Source and RFQ parameters</th>
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</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Vane voltage</td>
</tr>
<tr>
<td>Max field on pole tip</td>
</tr>
<tr>
<td>RF total peak power</td>
</tr>
<tr>
<td>Beam Input Energy</td>
</tr>
<tr>
<td>Beam Output Energy</td>
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</tbody>
</table>

RFQ at Linac4

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

<table>
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<th>Source and RFQ parameters</th>
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<tbody>
<tr>
<td>Frequency</td>
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<tr>
<td>Length</td>
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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 carried 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:

1\textsuperscript{st} module: 10\%, 2\textsuperscript{nd} module: 20\%, 3\textsuperscript{rd} module: 60\%, Unclear: 10\%.

BD location in the RFQ at ADAM test bench:

Dominant BDs in the 2\textsuperscript{nd} and 3\textsuperscript{rd} module (RF directional coupler): not enough available signals.

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

  \[ Q\text{-factor at Linac4/ADAM} \approx \frac{6772}{6500}, \text{ during BD} = 2850 - 5700/1800 - 4500. \]
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 opportunity 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!

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- **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).
Backup slide: The IFIC – HGRF Laboratory