ENGINEERING PROTOTYPE FOR A COMPACT MEDICAL
DIELECTRIC WALL ACCELERATOR*

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Abstract

A compact accelerator system architecture based on the
dielectric wall accelerator (DWA) for medical proton
beam therapy has been developed by the Compact
Particle Acceleration Corporation (CPAC). The major
subsystems are a Radio Frequency Quadrupole (RFQ)
injection system, a pulsed kicker to select the desired
proton bunches, and a DWA linear accelerator
incorporating a high gradient insulator (HGI) with stacked
Blumleins to produce the required acceleration energy.
An engineering prototype has been constructed and
characterized, and these results will be used within the
next three years to develop an extremely compact 150
MeV system capable of modulating energy, beam current,
and spot size on a shot-to-shot basis.

CPAC’S SYSTEM ARCHITECTURE

Proton beam therapy (PBT) for cancer treatment is
considered superior to other conventional external beam
therapy such as X-rays because of its ability to precisely
locate the radiation dosage and avoid collateral damage to
neighbouring healthy tissue. Tumours of different sizes
and depths can be effectively treated using the proton
beam’s highly localized Bragg peak by tuning the energy
profile. The current dedicated PBT systems, as well as the
limited converted physics facilities were all constructed
with large footprint accelerators that are expensive to
build and maintain. The Compact Particle Acceleration
Corporation (CPAC) is leveraging advances in high
gradient insulators (HGI) and the dielectric wall
accelerator (DWA) to develop a compact proton
accelerator for radiotherapy and radiosurgery that will be
only a fraction of the footprint of current systems, which
could be located in a single treatment room with
significantly less infrastructure investment [1]. In
addition, this architecture can provide real-time energy
modulation to match the proton beam’s Bragg peak to
target tumours at different depths. Existing systems
achieve this using a scattering mask, which results in
production of neutrons that can pose health concerns for
patients and treatment providers. In addition, the DWA
system will be capable of a range of spot size control
unmatched by existing PBT systems to enable treatment
of different sizes and shape tumours.

As a key milestone to full commercial deployment of
this system, CPAC has successfully built a prototype
DWA system to demonstrate operation of the subsystems
and to retire engineering integration risks related
particularly to the synchronization of the Radio
Frequency Quadrupole (RFQ) to the DWA, operation of
the Blumleins and solid state optical switches at high
charge voltage of >25 kV, and effectiveness of the HGI in
the presence of a proton beam. The compact DWA
prototype system starts with a proton beam generated in a
duoplasmatron ion source and extracted at 35 keV. The
protons are transported into the RFQ by two Einzel lenses
that maintain the low emittance and focus the beam
through the accelerator gating “kicker.” The kicker fields
steer the beam out of the acceptance of the RFQ, and then
one or more RFQ buckets are filled by a fast deflecting
pulse that nulls these fields. This kicker pulse, the 425
MHz of the RFQ and the laser pulse to the DWA switches
are all timed with an innovative ultra-low jitter timing and
control subsystem. The RFQ accelerates and bunches the
input beam to output energy of 2 MeV which the DWA
accepts and accelerates to the final system energy. To
enable operation of the DWA, other subsystems include a
high power pulsed laser, a fiber optic distribution system,
an electrical charging system, and beam diagnostics. Fig.
1 shows a block diagram of the complete system.

Figure 1: Prototype DWA system block diagram.

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SOURCE, LEBT, AND PULSED KICKER
The proton ion source is a commercial duoplasmatron from AccSys Technology, Inc., also the manufacturer of the RFQ linac. The low-energy beam transport (LEBT) originally supplied by AccSys used a single Einzel lens between the source and RFQ that was not suitable to match the beam to the pulse selection deflector (“kicker”). This LEBT was replaced by a double Einzel lens design developed specifically for the DWA system [2]. Trajectories for a 35 mA proton beam in the final LEBT are shown in Fig. 2. The ion source gate valve cover on the left and the RFQ end plate on the right are used as the ground electrodes of the Einzel lens assembly. The kicker is built into a redesigned thicker RFQ end plate. The RFQ vanes are not shown on the right.

As described above, the kicker changes the angle of the input protons so that they are either accelerated in the RFQ (no angle) or not accepted (outside of acceptance phase space). Calculated beam transmission vs. deflection angle at the RFQ entrance show that a deflection angle of only 100 mrad stops the beam from being accelerated. Fig. 3 shows a schematic representation of the kicker and the actual RFQ end plate with the kicker assembly.

RFQ INJECTOR DESIGN
The design parameters for the DWA injector RFQ linac are listed in Table 1 [3]. The RFQ structure is 1.2 m long and the current limit is more than twice the output current required for injection into the DWA, giving ample margin for its operation.

SYSTEM TIMING
In the prototype system, synchronization must be achieved across all seven major subsystems: (1) proton ion source, (2) kicker, (3) RFQ linac, (4) DWA, (5) Blumlein charging, (6) laser to trigger the switches and (7) the beam diagnostics. A diagram of the timing system is shown in Fig. 4.

Table 1: DWA Injector RFQ Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>425 MHz</td>
</tr>
<tr>
<td>Injection energy</td>
<td>0.035 MeV</td>
</tr>
<tr>
<td>Final beam energy</td>
<td>2.0 MeV</td>
</tr>
<tr>
<td>Design input current</td>
<td>50 mA</td>
</tr>
<tr>
<td>Current limit</td>
<td>80 mA</td>
</tr>
<tr>
<td>Transmission at 50 mA (%)</td>
<td>79 %</td>
</tr>
<tr>
<td>Input transverse emittance (norm)</td>
<td>0.3 mm-mm-rad</td>
</tr>
<tr>
<td>Nominal vane voltage</td>
<td>88 kV</td>
</tr>
<tr>
<td>Bore radius</td>
<td>2.54 mm</td>
</tr>
<tr>
<td>Maximum vane modulation</td>
<td>2.2</td>
</tr>
<tr>
<td>Structure length</td>
<td>1.16 m</td>
</tr>
<tr>
<td>Peak RF field surface gradient</td>
<td>45.6 MV/m</td>
</tr>
<tr>
<td>Pulsed structure power</td>
<td>175 kW</td>
</tr>
<tr>
<td>Pulsed beam power</td>
<td>80 kW</td>
</tr>
<tr>
<td>Total input RF power</td>
<td>260 kW</td>
</tr>
</tbody>
</table>

HIGH-GRADIENT INSULATOR
To sustain the high voltage generated by the Blumleins for accelerating the protons, high-gradient insulators (HGI) were developed as the acceleration tube. Surface flashover of insulators in vacuum is generally the limiting factor in the design of high voltage vacuum devices. The most widely-accepted theory of surface flashover holds that—an avalanche of secondary electrons occurs along the insulator surface, desorbing gas through which the breakdown occurs [4-7]. The HGI overcomes the flashover by inhibiting the breakdown process using closely-spaced, floating conductors, encapsulated in a dielectric. To validate the performance of the HGI, a special test setup with a 3 MV, 1 ns Optoel pulser was employed. Figure 5 shows a typical output waveform from this pulser used for these measurements.

Breakdown (i.e. arcing) was detected by monitoring light flashes inside the HGI and momentary pressure rises in the vacuum. Various samples were tested: 33 mm length HGI with varying conductor-to-dielectric thickness ratios and a 100 mm length HGI of a single conductor-to-dielectric thickness ratio, along with a baseline 33 mm long solid polyethylene piece. The maximum field on the best sample was >80 MV/m.
PROTOTYPE DWA RESULTS

The DWA section of the engineering prototype is shown in Fig. 6. Total length of the High Gradient Insulator was 10cm but only the center 3 cm were energized with two stacks of 15 blumleins each, positioned at diametrically opposite sides of the HGI. The Blumleins were approximately 60cm long, 2cm wide and 2mm thick. Not shown are the RFQ, laser and charging systems.

A time-resolved energy analyzer was constructed with NdFeB permanent magnets to deflect the protons along the horizontal axis and deflection plates with ramped voltage to separate the individual pulses out in time along the vertical axis. Images from this spectrometer are shown on the left of Fig. 7. The plot on the right is the energy gain of the middle pulse as the laser switch time of the DWA was varied during preliminary operation of the prototype, for several different charge voltages.

Acceleration was also measured by a time-of-flight technique. A fast ion collector was located 1 m from the prototype. The RFQ oscillator signal is used to derive a reference time for each proton bunch for comparison with the proton arrival time, and the energy is determined from change in flight time relative to unaccelerated bunches.

TOF data are shown in Fig. 8 for various charge voltages. The charge voltages are each represented by up to 25 shots filling in the acceleration waveform.

FUTURE MILESTONES

Development of the DWA components further to achieve higher charge voltages and energy gain per charge volt is underway. New illumination and high voltage systems are also being developed to simplify the construction, decrease cost and improve the overall reliability of the system. CPAC plans to complete the construction of a higher capability prototype by the middle of 2012. A 150 MeV fixed beam accelerator suitable for integration into a Proton Beam Therapy system is planned for completion by late 2013.

REFERENCES