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Compact Dielectric Wall Accelerator For Proton Therapy

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Abstract

A design of a compact proton accelerator for proton therapy is presented. To achieve this design, the first linear optics model of a dielectric wall accelerator is derived. The complex accelerating field generated by the DWA is analytically described using the relativistic particle Hamiltonian. The model of the DWA, along with an integrated pulse timing routine enable a complete end-to-end simulation of the accelerator.

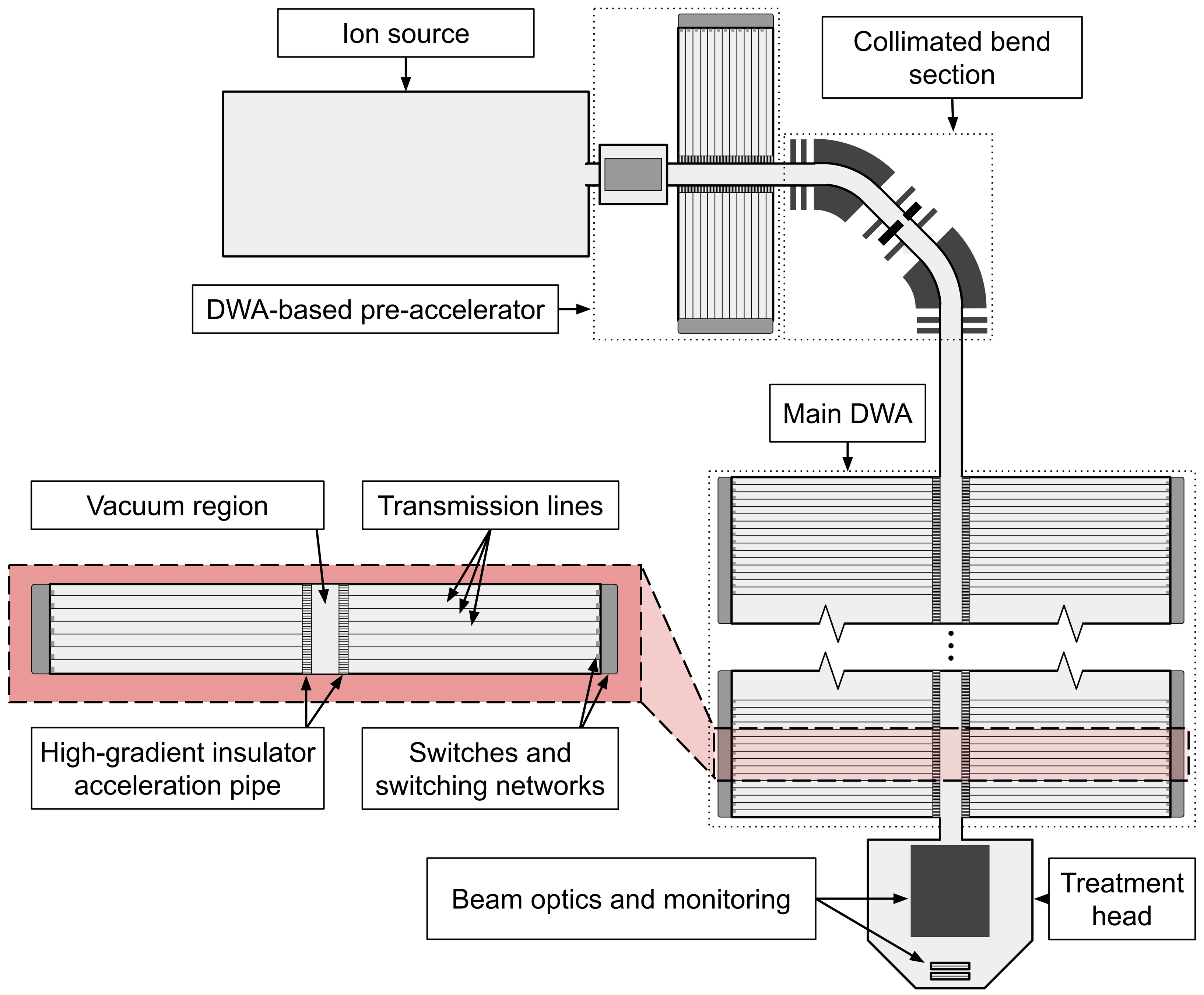

Figure 1: Schematic of the accelerator design, not to scale. The system consists of a proton source with a DWA based bunching and acceleration system. A collimated bend section allows for precise energy selection before injection into the main accelerator.

DWA Field Representation

A single module, is described by its firing time t_0 and its longitudinal position along the beamline, z_0. Its on-axis longitudinal accelerating field is assumed to be separable in time: $E_z(z,t) = \mathcal{E}(z-z_0)\Gamma(t-t_0)$, where $\mathcal{E}$ is the peak electric field profile and Γ is the time profile of the activation pulse.

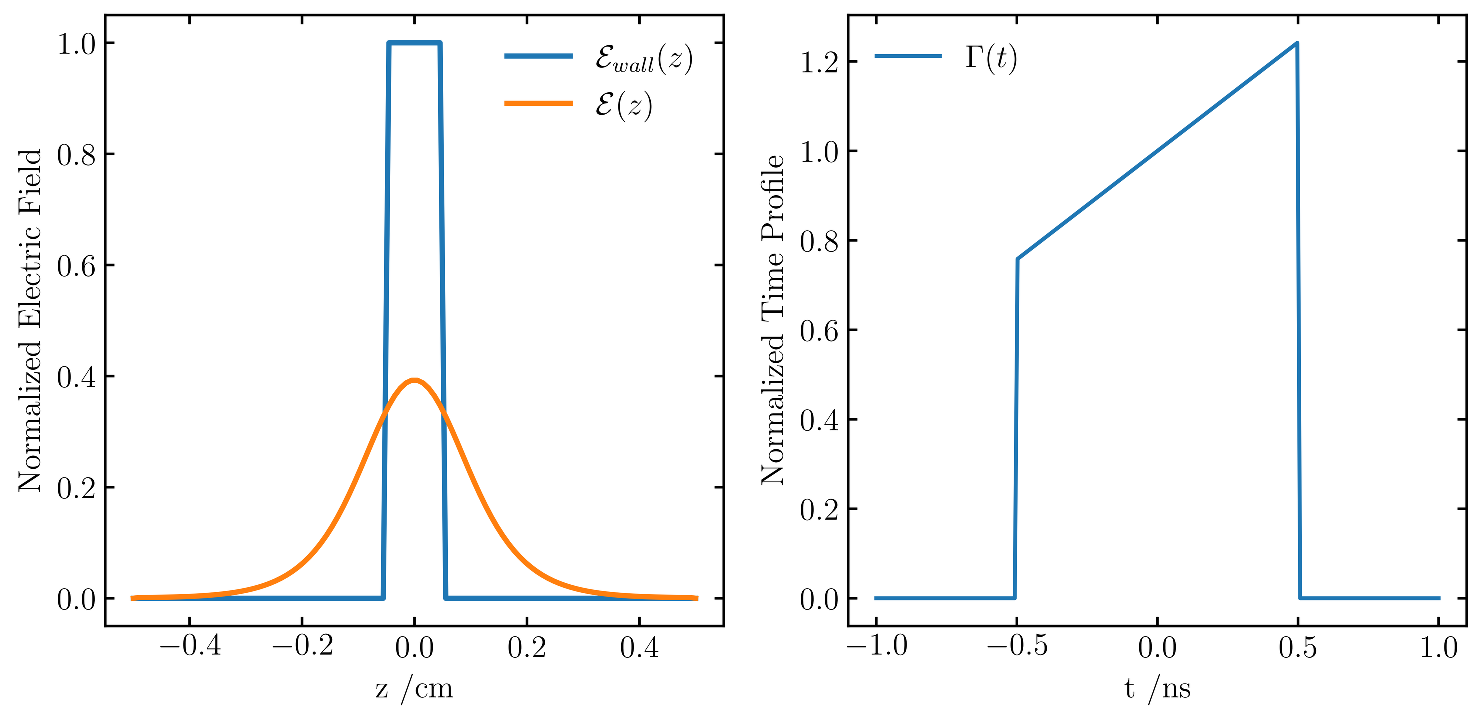

Figure 2: The field description for an ideal 1 mm thick module, with an aperture radius of 1 cm, a pulse width of 1 ns and peak accelerating field of 100 MV/m. The field on the wall is assumed to be square. The on-axis field is derived from the wall-field. On the right, the time profile is plotted. The linear time gradient provides longitudinal focusing.

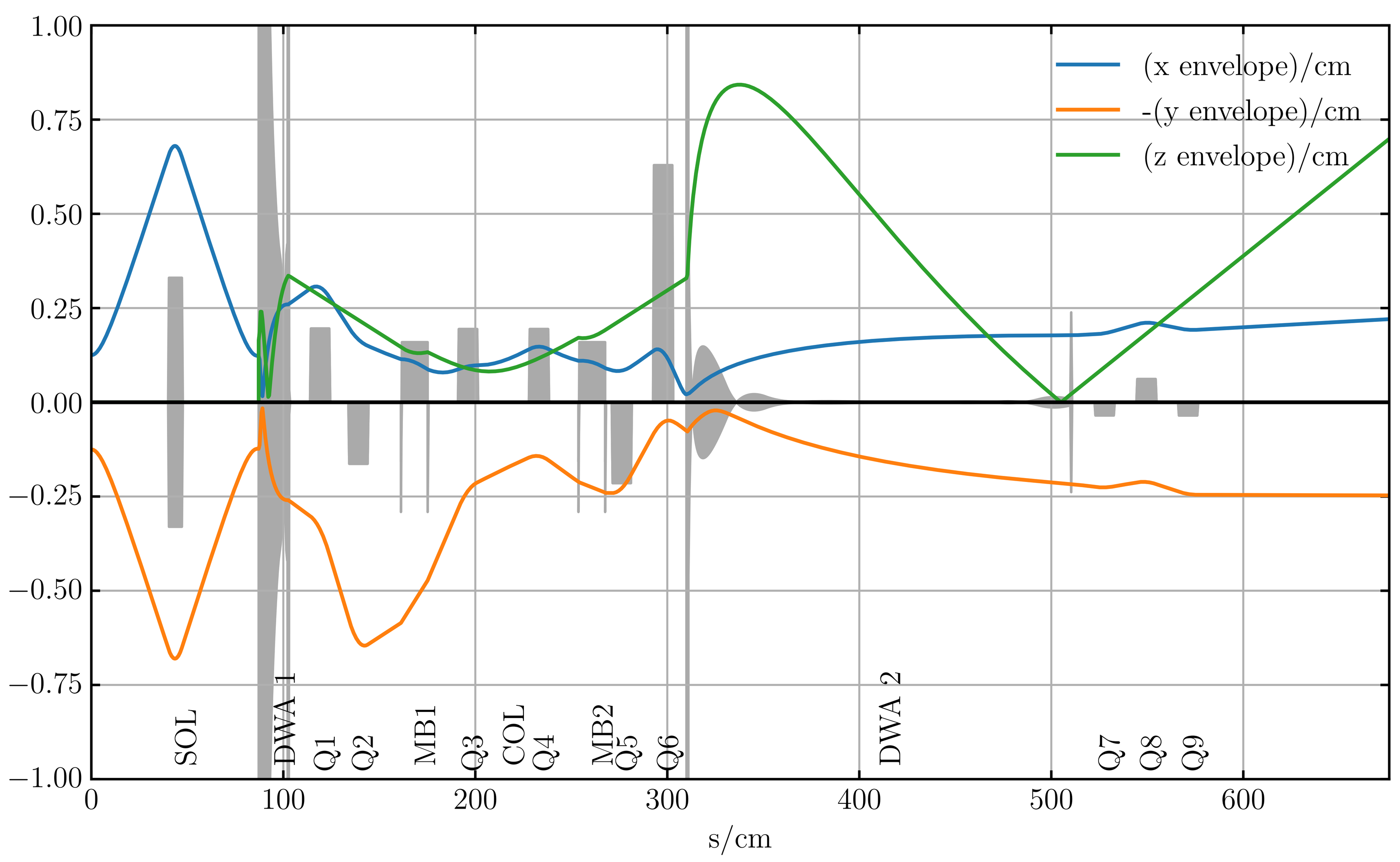

Figure 3: 2-RMS beam envelope throughout the acceleration process. The shaded areas indicate the transverse focal strength in arbitrary units. The first DWA at 95 cm bunches and accelerates the beam to 1 MeV, it travels through the collimated bend section and is accelerated up to 200 MeV by the main DWA.

Linear Optics Model

The potentials that yield the linear on-axis fields and satisfy Maxwell's equations are:

$$\phi(r,z,t) = \frac{r^2}{4}\sum_{i=1}^{N}\mathcal{E}'(z-z_i)\Gamma(t-t_i)\,, \tag{1}$$

$$A_z(r,z,t) = -\sum_{i=1}^{N}\mathcal{E}(z-z_i)\left(\int_{-\infty}^{t}\Gamma(\tau-t_i)d\tau + \frac{r^2}{4c^2}\Gamma'(t-t_i)\right) \tag{2}$$

where the values s_i is the longitudinal position and t_i is the pulse timing of the ith module respectively. The potentials are a superposition over the N independently controllable modules.
The linear optics code TRANSOPTR tracks the covariance matrix of the beam, $\boldsymbol{\sigma}$, with equation of motion: $\boldsymbol{\sigma}' = \mathbf{F}\boldsymbol{\sigma} + \boldsymbol{\sigma}\mathbf{F}^{\top}$, where $\mathbf{F}$ is the infinitesimal transfer matrix:

$$\mathbf{F} = \begin{bmatrix} 0 & \frac{1}{P} & 0 & 0 & 0 & 0 \\ \mathcal{A}(s) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{P} & 0 & 0 \\ 0 & 0 & \mathcal{A}(s) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\beta'}{\beta} & \frac{1}{\gamma^2 P} \\ 0 & 0 & 0 & 0 & \mathcal{B}(s) & -\frac{\beta'}{\beta} \end{bmatrix},$$

$$\mathcal{A}(s) = -\frac{q}{2c^2}\sum_{i=1}^{N}\left(\mathcal{E}(s-s_i)\Gamma'(t-t_i) + \frac{c}{\beta}\mathcal{E}'(s-s_i)\Gamma(t-t_i)\right),$$

$$\mathcal{B}(s) = \frac{q}{c^2\beta^2}\sum_{i=1}^{N}\mathcal{E}(s-s_i)\Gamma'(t-t_i)\,,$$

Conclusion

The linear optics model provides both accuracy and flexibility with the ability to quickly optimize any parameter in the model. A single run of the model, with pulse timing optimization, takes less than half a second, enabling fast iteration, for fully exploring the design space. The tools for analytically describing the field are useful for creating designs with an arbitrary amount of detail.

References

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Discovery, accelerated