Simulation study of a hybrid (laser-RF) compact proton accelerator

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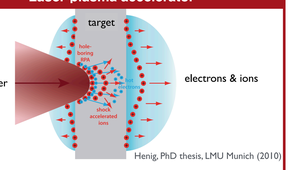
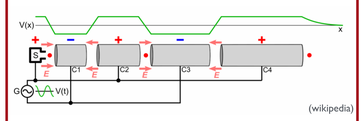
Laser-plasma and RF accelerators can have complementary advantages for ion acceleration

Laser-plasma accelerator



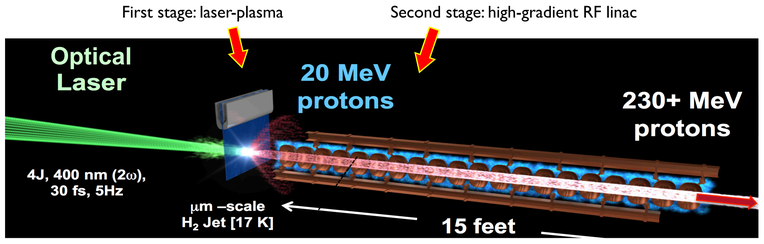
- Pros
  - high-gradient acceleration
    - over TV/m
    - compact accel. to 10s MeV (for protons)
  - high charge, low emittance
- Cons
  - hard to control beam quality
  - hard to achieve very high energies (>100MeV for protons)

Linear accelerator (proton linac)



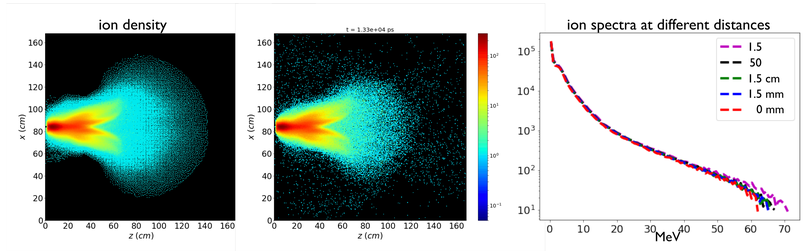
- Pros
  - beam quality:
    - mono-energetic, small emittance
  - energy tunability
- Cons
  - inefficient accel. for low (<10MeV) energies
    - expensive and large scale
  - relatively small accel. gradient (< 50MV/m)

A laser-RF hybrid accelerator is envisioned to reduce physical size and achieve high-quality and high-rep rate simultaneously



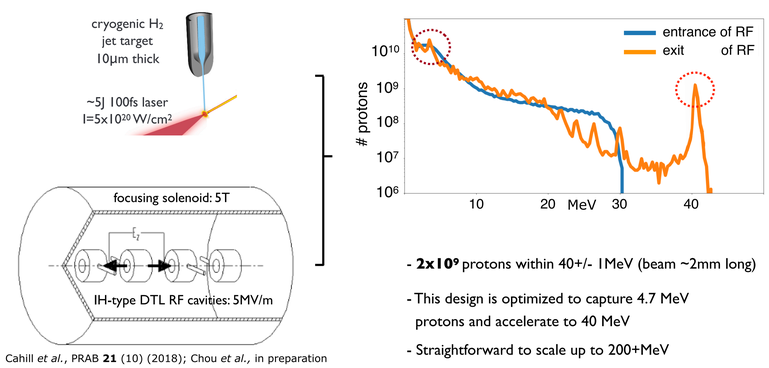
It is critical to understand how space-charge fields affect ion quality during meter-scale transport and RF-acceleration

Self-consistent 2D PIC simulations show that the proton beam transport is nearly ballistic over meter scale in vacuum



Electron cloud neutralizes ion beam and space-charge fields do not affect transport in vacuum

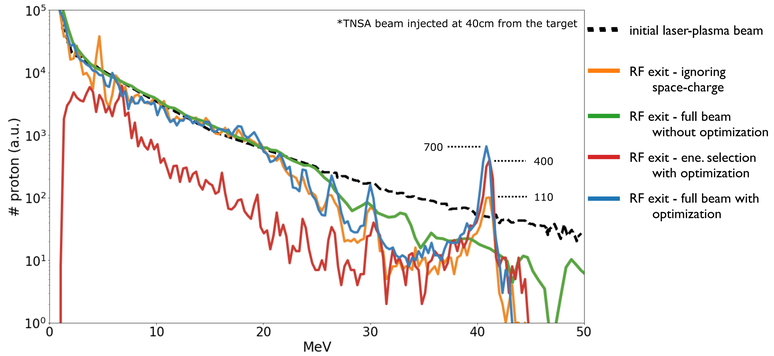
End-to-end 3D simulations of an initial design show that > 10^9 protons can be accelerated with ~1% energy spread without space-charge fields in RF structure



Cahill *et al.*, PRAB **21** (10) (2018); Chou *et al.*, in preparation

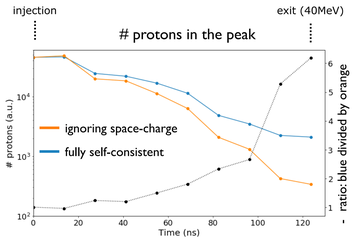
- **2x10⁹** protons within 40+/- 1MeV (beam ~2mm long)
- This design is optimized to capture 4.7 MeV protons and accelerate to 40 MeV
- Straightforward to scale up to 200+MeV

It is possible to obtain a high-quality, high-charge proton beam by optimizing injection distance from the laser-plasma source



	typical proton linac	hybrid* (TNSA to RF)	
		inj. at 40 cm	at exit
peak current	100 mA	30 A	1 A
# protons	$10^7 \sim 10^8$	10^{10}	10^9
bunch length	1 mm	1.5 mm	10 mm
RF gradient	5 MV/m		
beam density	10^{10} cm^{-3}	10^{10} cm^{-3}	10^9 cm^{-3}
$\varepsilon_{N,trans.}$**	< 1 mm-mrad	10 mm-mrad	25 mm-mrad

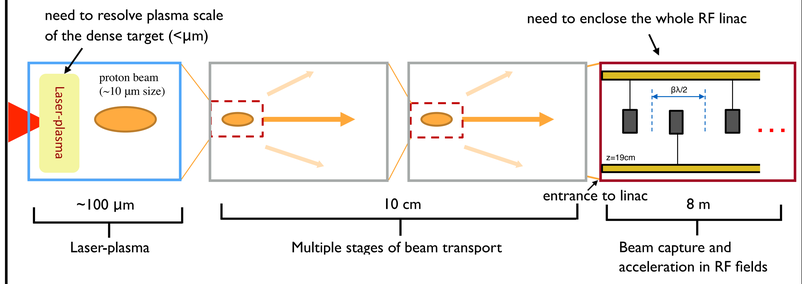
*Quantities only accounting for the particles residing in the relevant energy peak
**Emittance measurements are subject to finite-particle effects. Here showing 50% emittance.



- Presence of mild space-charge field helps preservation of particles during the acceleration

Our next steps are 3D simulations of a system with a high-rep-rate laser and RF to produce 200MeV+ proton beams

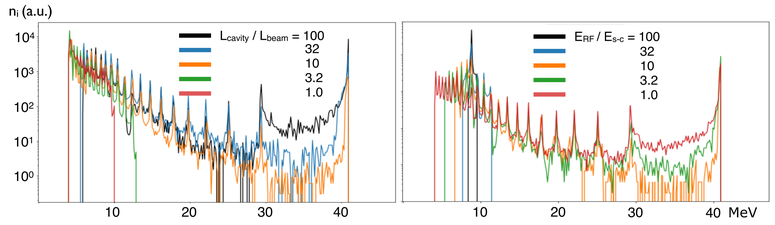
Multi-scale simulations were developed to enable end-to-end modeling of particle dynamics from micron to meter scales



We have performed a series of multi-stage simulations* using an adaptive mesh scheme to model the entire system self-consistently

*PIC simulations performed with OSIRIS 4.0

The density and the size of the injected beam need to be optimized due to the strong space-charge fields upon removal of the electrons inside RF



- Effective synchronous accel. requires

$$L_{\text{beam}} \ll L_{\text{cavity}}$$

- Effective accel. requires

$$E_{\text{s-c}} \approx 8\pi e n_i L_{\text{beam}} \lesssim E_{\text{RF}}$$

Conclusions and future perspectives

- **We have performed end-to-end PIC simulations of a (proof of principle) hybrid laser-RF proton accelerator**
- **Our initial results show the possibility to control space-charge effects and reach high-charge ion beams (>10^9 particles) with <1% energy spread**
- **We continue to investigate the mitigation of space-charge effects and optimization of beam properties in the RF structure**
- **The RF structure could be straightforwardly extended to produce ion beams with > 100 MeV within a few meters**