KARVE: a Nanoparticle Accelerator for Space Thruster Applications

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John W. Lewellen, L. Danielson,
A. Essunfeld, J. Hollingsworth,
M.A. Holloway, E. Lewis*

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* Johnson Space Center, NASA

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Outline

- What issues are we addressing?
  - Rocket fuel
  - High DC voltages in space applications
- How do we accelerate nanoparticles?
- What kind of performance can we expect?
- What next?

A few notes up front…

This work partially supported by the Los Alamos LDRD program.

This work is related to other efforts at LANL to develop compact, highly redundant and fault-tolerant, solid-state-driven accelerators. These types of accelerators are highly relevant for space science missions, as well as terrestrial applications in medicine, industry and security.

What issues are we addressing?

“Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space.”

— Douglas Adams, *The Hitchhiker's Guide to the Galaxy*

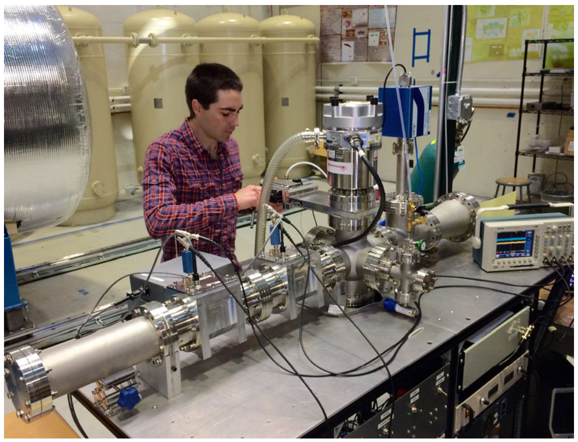
Right now, for space missions, we have to choose between high-thrust, but relatively inefficient, chemical propellants; and highly efficient, but low-thrust, ion engines for deep space missions.

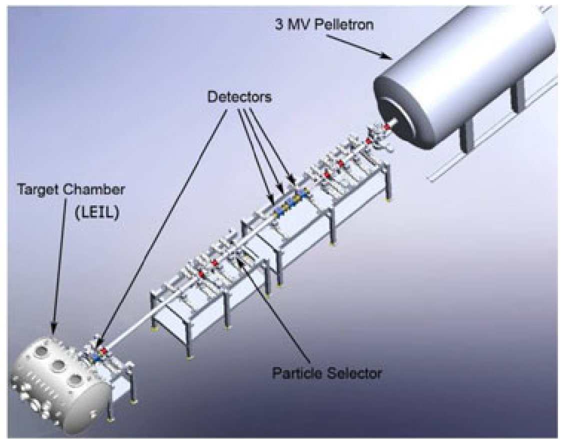
We also can’t refuel when we get to our destination, which means if we want the spacecraft to come back, we need to send it out with all the fuel it needs to get there and back.

A nanoparticle thruster can provide a “middle ground” between chemical and ion thrusters, in terms of efficiency and available thrust. And there are prospects for being able to refuel mid-mission without having to build a chemical refinery.

How do we accelerate nanoparticles?

DC accelerators are used to accelerate nanoparticles right now, to simulate micrometeoroid impacts.





A 20-keV dust accelerator at the Dust Accelerator Lab, IMPACT Institute, UC Boulder, CO, USA; and a layout of their 3-MeV accelerator

The 2-MeV dust accelerator at Heidelberg

We want to take an approach similar to what we use for heavy ions

- DC preaccelerator to get the particles moving; then
- RF-driven structures to final energy

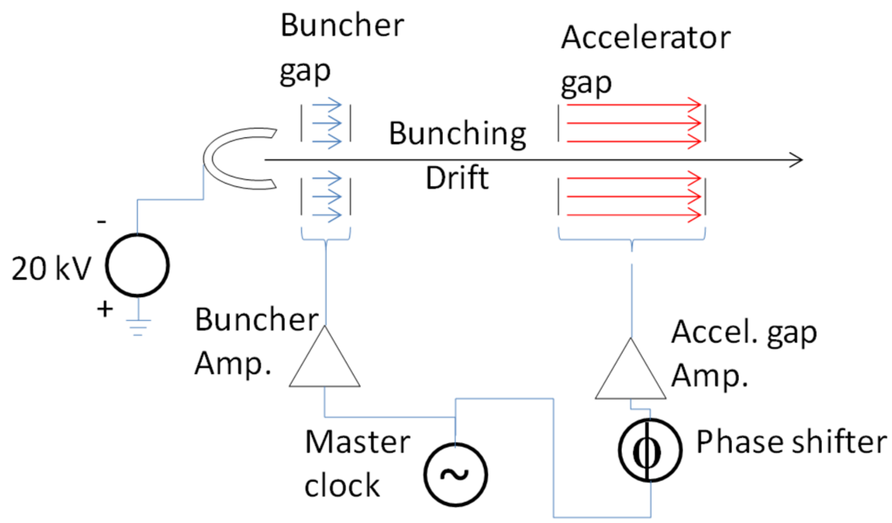
Some initial scoping factors…

Our presumptive nanoparticle is a 6-nm diameter iron nanoparticle: around 9600 iron atoms, with a mass of ~$5.3 \cdot 10^6$ AMU, ionized to a charge state of +10 q_e. Assume a 20-kV preaccelerator.

$$L_g = \frac{1}{2}\beta\lambda_{rf} = \frac{\beta\ c}{2f_{rf}}$$

The relationship between particle speed (β), RF frequency and accelerating gap length; our nanoparticle at 20 keV has $\beta \sim 2.8 \cdot 10^{-5}$, or 8.5 km/s. For a convenient gap length of 1 cm, $f_{rf} \sim$ 0.42 MHz.

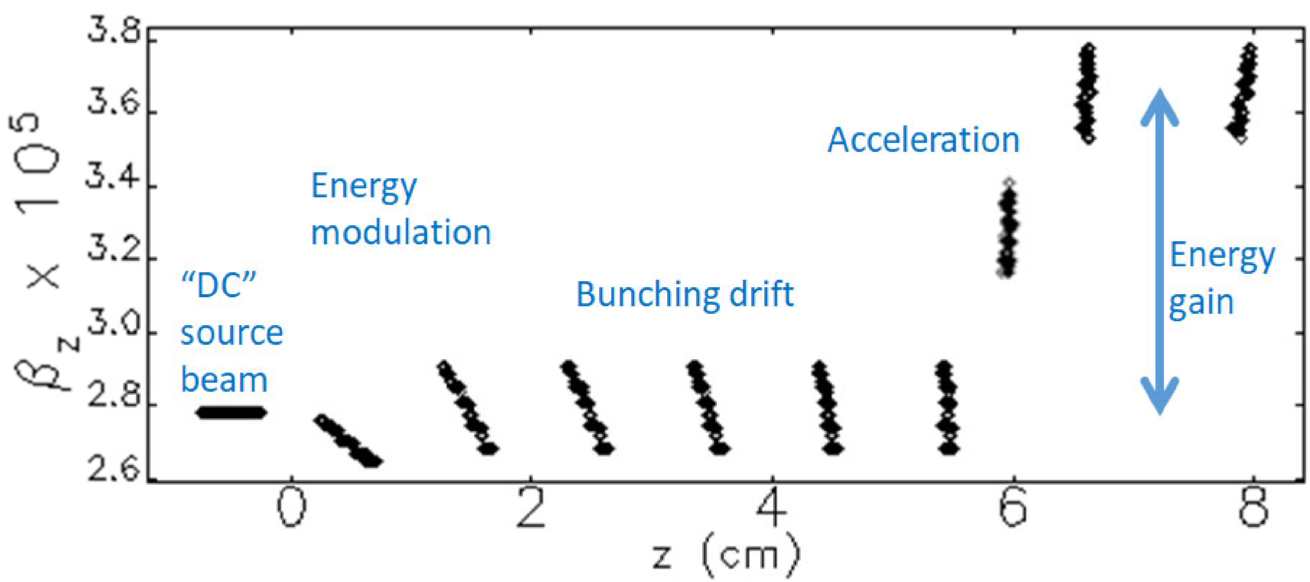
Conceptual single-accelerating-gap accelerator



A conceptual, simple single-gap nanoparticle accelerator with beam buncher.

Due to the low frequency, we presume we can gate the emission from the DC source (2.4 μs period)

GPT simulation of nanoparticle energy gain through a 20-kV gap. This is not a surprising result – good!



Some rocket performance terms…

Specific impulse is exhaust velocity divided by a standard gravity:

$$I_{sp} = {}^{v_e}/_{g}$$

It is a measure of efficiency: the higher the I_{sp}, the less fuel you need to get a given change in velocity for your spacecraft.

Thrust is exhaust velocity times mass flow rate: how fast you throw something away, times how much per unit time you throw away.

$$F_{th} = v_e \dot{m} = I_{sp}\, g\, \dot{m}$$

Thrust says how fast you can change your spacecraft's velocity.

For an accelerator-turned-rocket engine like KARVE:

Specific impulse

$$I_{sp} = \sqrt{\frac{2\, N_g V_g Q_{np}}{m_{np} g^2}}$$

Thrust from a KARVE engine

$$F_K = I\sqrt{\frac{2 N_g V_g m_{np}}{Q_{np}}}$$

Where:

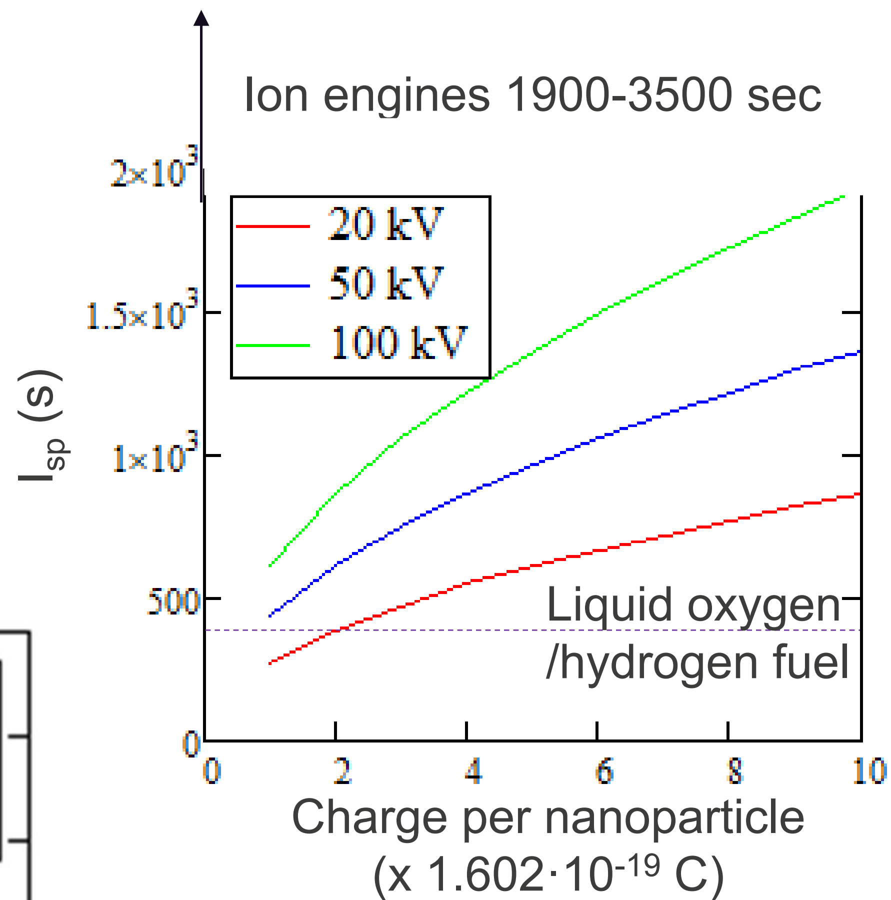
- N_g is the number of accelerating gaps in the KARVE engine;
- V_g is the voltage gain per gap;
- m_{np} is the nanoparticle mass;
- Q_{nm} is the nanoparticle charge state; and
- I is the beam current

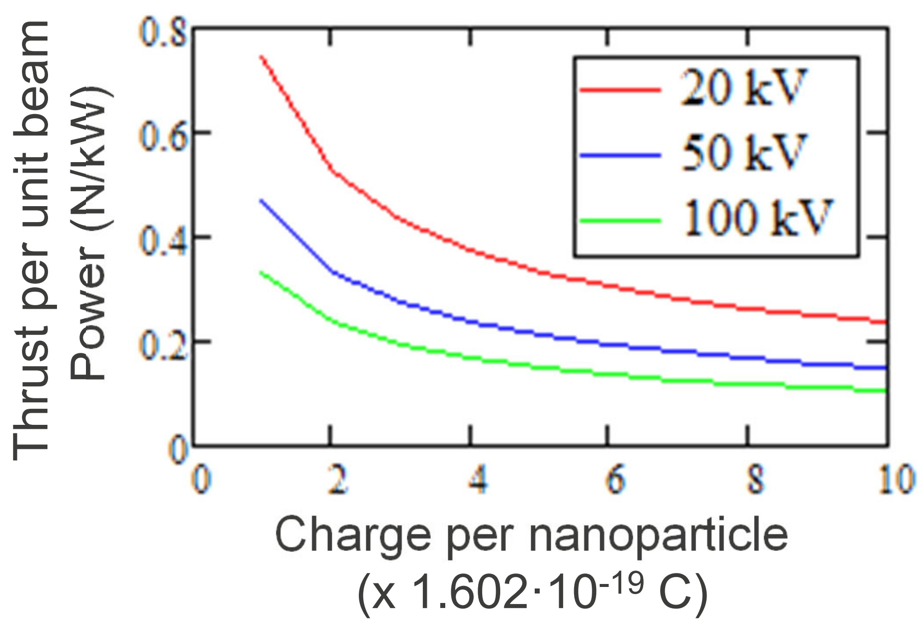
The equations for I_{sp} and F_K assume we remain in the non-relativistic regime.

A 1-A beam at 100 kV, for the nanoparticle mass and charge given above, provides approximately 10.5 N of thrust, with a specific impulse of $1.9 \cdot 10^3$ s.

And so…?

If we have a multi-gap KARVE engine, we have options to dynamically trade *thrust* versus *efficiency*: power down gaps, or change charge per nanoparticle.





(Changing the m/q would require also adjusting the RF frequency.)

What was that about refueling?

- Nanoparticles can be made from almost anything: lunar regolith, asteroids, parts of your spacecraft you don't need any more, etc. They can be made via a variety of techniques.

- The KARVE engine should care only about the nanoparticle charge-to-mass ratio … *not* the particular stuff the nanoparticle is made from.

- So … you can in principle "refuel" with more nanoparticles by using "found mass" at the destination, without having to find a specific material (e.g. xenon), and without having to bring along a full chemical refinery.

What's Next?

We are actively pursuing funding to:

- Extend the theoretical, simulation and design work
  - Consider effects of Q/M spreads on performance;
  - Consider options for RF improvement, e.g. harmonics
- Design a prototype
  - 20-kV preaccelerator (base on existing designs)
  - RF system
- Build a prototype
  - Verify basic operating parameters and performance scaling;
  - Develop appropriate diagnostics;
  - Measure generated thrust.
- Look for opportunities (e.g. Cubesat) to fly a prototype.