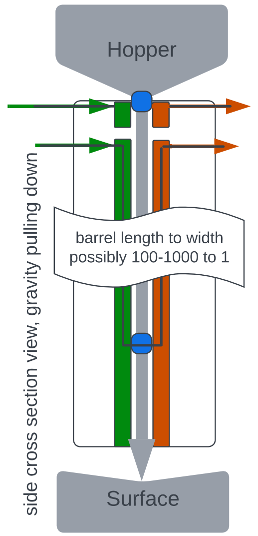
Concept Sheet: A Polymer 3D-printable Metal Capable EM-CSAM 3D Printhead with Micro Railgun Array

5 March 2023 - David E Jones - Public Domain or CC0 + No Patent

- these are concept designs, not production blueprints
- the ideal ratios between conductors, insulators, barrel voids, and distance between barrels for different characteristics is unknown, needs prototyping and testing
- education: Electroboom Water Railgun https://www.youtube.com/watch?v=Qy81O7LrB84
- the grid unit size is limited by ability for FDM or other printer to 'print void' down to 2x grid size, surrounding materials are more flexible if not printed precisely; if barrel is rough it is okay, can be smothed or will be anyway during initial use; hope is for 0.2 to 0.4mm but the relationship between barrel width, length, print target distance, and accuracy or print resolution is unknown; larger barrels may perform well, with higher throughput but at the cost of higher minimum effective energy input; if some sort of magnetic field shaping to focus the spray could be added to the rail design then higher print resolutions could be achieved without reducing barrel size
- this concept can be built on a small scale without a 3D printer by drilling channels into solid blocks of insulator; drilling, assembling, etc are problematic for scale production but for small scale or manual production not even requiring a 3D printer to fabricate further lowers the barrier to entry
- research has been done in this type of railgun where the entire unit was 0.5mm wide using micormeter precision manufacturing techniques; this can be scaled down a great deal with better production tools
- due to limited liquid flow in small tubes material loss from dripping should be minimal and can be avoided by increasing viscosity of the fluid if needed, even to the point of a paste pushed into the barrel
- the target ejection speed for binding on impact is 1000 meters per second, adequate for a wide variety of materials; 500m/s should be adequate for temporary binding of steel (needs enough to survive sintering); with voltage or PWM tuning the induction current over time can be adjusted for lower speeds
- when using high speeds the machine may be loud and require a sound dampening enclosure, the speeds needed for many metals far exceed the speed of sound so the machine may sound like a stream of tiny sonic booms
- the ideal barrel length is also unknown, with increased output velocity for a given electrical current but also increased drag (depending on the surface and flow material properties); varying the length of the barrel for different print materials would be difficult, but could be helpful for better supporting a wide variety of materials (similar with barrel width); initial plan is for a 100mm (~4") barrel, meaning the printhead block is about 100mm tall, plus height for a gravity feed reservoir
- the material in the barrel must conduct electricity, and the force it receives for the voltage used will be higher the better it conducts electricity; to a certain extent higher voltage can be used to overcome material resistance, but only to the point of arcing; a conductive fluid is best for high surface contact to avoid arcing and turning an additive printer into a plasma driller, unless that is what you want as an alternative to CNC machining or other means of subtractive manufacturing, this could carve with high precision; the fluid can have high viscocity at room temperate, and possibly high viscocity at higher temperatures with some pressure beyond gravity added to the reservoir to introduce material into the barrels
- for continuous flow the current must be alternating, but only if run continously, ie more than a single pulse; while sinusoidal alternating current might be most efficient, for this purpose the simple switching of a high speed solid state relay should provide both small/fine pulse ability and with continuous switching also continuous operation
- for polymer 3D printing resistive materials are the norm but there are conductive filaments available, some using graphene but the best conductors using other materials; there is potential for graphene, but limited options; the best current material to embed graphene in is PEEK or PEKK (operating temp 260C), basic PLA based graphene filament may be adequate but current available is high resistance and supports limited current
- one option is printing sinterable metal filaments (80-90% metal in heat released binder), but sintering temperature is too high for insulator plastic; better/cheaper to use metal inserts like solid core copper wire

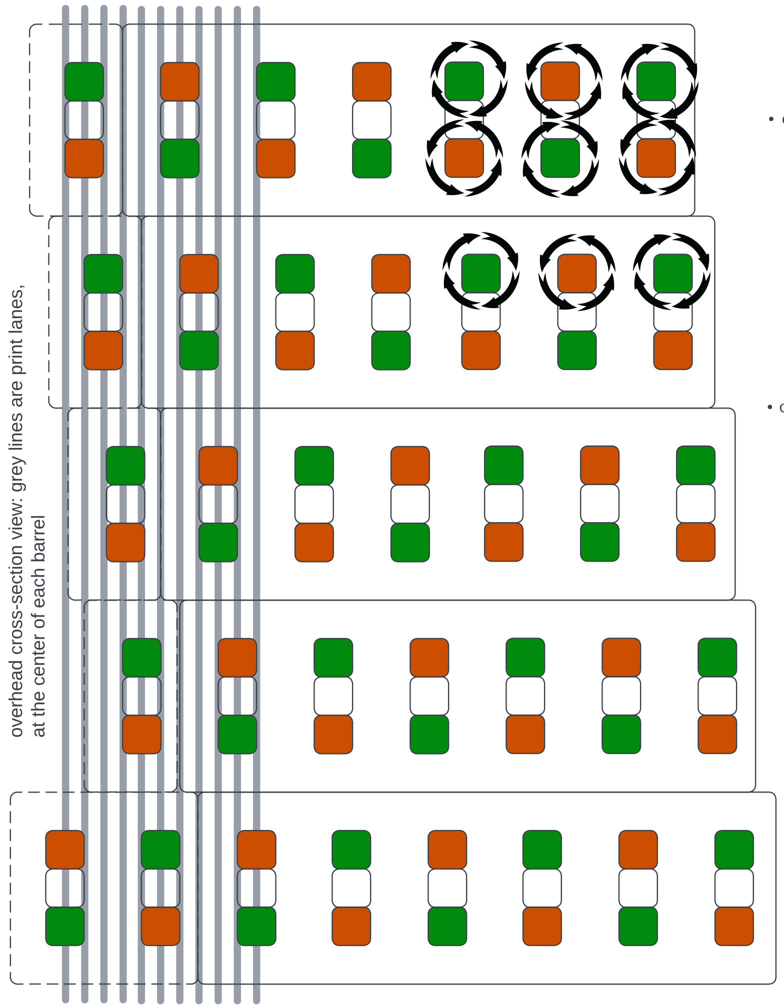
for target velocity 1000 m/s and 0.2x0.2x100mm (0.1m) barrel:

- for a rough estimate use inductance per unit length (L) of 0.6 microhenries / meter (or 0.0006 henries / meter; see https://en.wikipedia.org/wiki/Railgun)
- a full barrel will have 0.2 * 0.2 * 100 = 4 mm^3 of material
  - 4 mm^3 of solid steel weighs 0.008g/mm^3 * 4 mm^3 = 0.032g 3.2E-5kg
  - acceleration in m/s^2 = v^2/2s = 1000^2 / (2*0.1) = 5,000,000 or 5E6
  - force in N = kg*m/s^2 = 3.2E-5 * 5E6 = 160
  - A^2 = 2 * N / L = 2 * 160 / 0.0006 = 533,333 so A = 730 impractical current!
  - continusous streaming of a full barrell to supersonic speeds is not practical
- a small cubic pellet 0.2mm wide
  - 0.2^3 = 0.008 mm^3, weighs 0.008 g/mm^3 * 0.008 mm^3 = 6.4E-8 kg
  - N = 6.4E-8 * 5E6 (acceleration above) = 0.32
  - A^2 = 2 * 0.32 / 0.0006 = 1067 so A = 32 amperes
  - t^2 = 2s/a = 2 * 0.1 / 5E6 = 4E-8 so t = 0.0002 (0.2ms)
- 1000 m/s is very fast, min speed for steel weak sinter is around 500 m/s
  - acceleration in m/s^2 = v^2/2s = 500^2 / (2*0.1) = 1,250,000 or 1.25E6
  - N = 6.4E-8 * 1.25E6 = 0.08 (1/2 speed, 1/4 force)
  - A^2 = 2 * 0.08 / 0.0006 = 266 so A = 16, current ~linear with final velocity
  - t^2 = 2s/a = 0.2 / 1.25E6 = 1.6E-7 so t = 0.0004 (0.4ms)
- may need a mechanism to pelletize incoming material if does not separate on acceleration; if too much material is in the barrel at once speeds will drop unless the entire system can handle the increased current
- one possible option: two phase accelerator, first small rail phase pelletizes, 2nd accelerates to target velocity; each phase controlled indepedently so that controller can control the loading and launching as needed
- a perpendicular coil design for the loader/pelletizer could work and could suspend the material in a magnetic field before firing; requires more complex printing for coil loops around the barrel, but a much better solution to introducing material into the main barrel because it pulls material (parallel rails push)

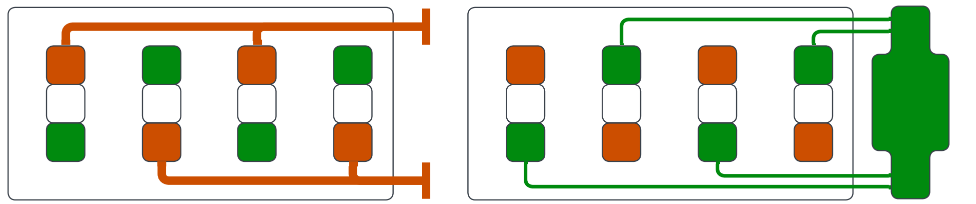


- basic layout with 2 conductors and one barrel void each 2 units wide
- green and red areas are conductors, the space between them a void (the barrel), and the rest is electricly resistive but heat conductive material
- the consequence of additional rows is void space within the printing area (with lower speed precise positioning workarounds)

- the conductors are alternated so that each conductor next to another is 180 degrees out of phase for constructive instead of destructive interference; control software may need to correct for interference when determining the voltage for each barrel
- additional spacing may be needed if interference causes excessive material loss (sprayed from inactive barrels but at velocity too low to bind, recoverable waste)

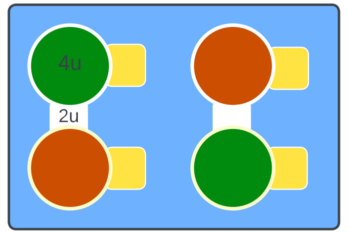


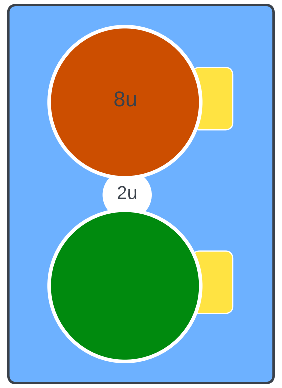
the leads for both poles are at one end of the unit in a separate layer for each pole for more convenient external wiring, one wired in common (ground) and one wired independently for switching

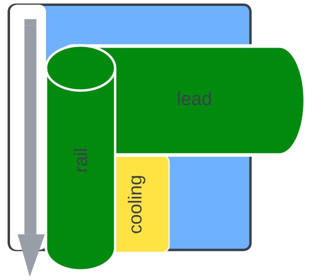


- electrically conductive material
  - Electrifi 0.006 ohm-cm 100g for $215 ($2,150/kg) 3x ohm vs copper
  - Black magic 3D 0.6 ohm-cm $1,000/kg
    - 300x ohm vs copper, ~3 ohm for 1' vs 0.01 ohm for 20 AWG cu
  - zinc 0.0059 ohm-cm, melts 420C (small FDM up to 480C), zinc alloy filaments rare, might be a better print-in-place solution than Electrifi or PLA/etc graphene blends
  - bound metal filaments
    - sintering temperature is too high for concurrently printed plastics, and melting too low for ceramics like aluminum nitride or silicon carbide
    - Virtual Foundry Copper Filament $165/kg; 0.0017 ohm-cm; print FDM sinter 1052C
      - VF 316L Steel $310/kg sinter 1260C
  - or use stock metal inserts, copper wire in 3D printed frame, solid core wire readily available and cheap; use slightly larger wire size than barrel area so wire channels hold them in place; wire diameter 2x barrel width should work well, larger may work too
  - copper is very low resistance, est with 1 foot length, needs very low voltage across rail circuit
    - 14 AWG 1.6281mm 32.0A - 0.078v drop for 15A, 0.156v 30A - 2.525 ohm/kft
    - *20 AWG 0.8128mm 11.0A - 0.314v drop for 15A, 0.627v 30A - 10.15 ohm/kft
    - *26 AWG 0.4038mm 2.20A - 1.259v drop for 15A, 2.518v 30A - 40.81 ohm/kft
    - 30 AWG 0.2540mm 0.86A - 3.166v drop for 15A, 6.333v 30A - 103.2 ohm/kft
    - 32 AWG 0.2032mm 0.53A - ?v drop for 15A, ?v for 30A - 164.1 ohm/kft
    - for 0.2mm material like a steel cube:
- electriclly resistive thermally conductive material
  - TCPoly ice9 6 W/m-K $250/kg best option for electrically insulating and thermally conductive
  - other important properties are electrical insulator and strong for the force of the rails trying to separate (why totally enclosed)
  - durability is critical unless barrel surface is coated with a different material; with more erosion on softer side plastic the barrel will get wider and impact performance; it may be that more durable materials (carbon fiber blends) perform adequately and will last longer; in multi-material builds the area around the barrel can be more durable and the rest heat dissipating
  - others vs TCPoly @ 6: PLA 0.13, ABS 0.25, PETG 0.29, PEEK 0.25
  - UHMWPE okay thermal conductivity (vs TCPoly?), lower temp, prints poorly, blocks are cheap
  - ceramics like aluminum nitride, boron nitride, and silicon carbide have excellent heat dissipation (closer to copper), can be printed & sintered but with high temps like 1830C for AlN
  - with limited heat dissipation, must limit pulse rate and print speed
  - optionally print in shaped liquid cooling channels; put to the sides of each rail to keep material toward the ends where separation forces are high
- controller
  - PWM (12-16khz) may be best for pulsed DC, cheaper vs MOSFET
  - for testing a manual cotroller 10-55V 60A $15
  - for printer control RPi hat(s) with PWM motor controller
  - voltage for current required extremely low, need low voltage controllers or much higher frequency for effective PWM in a 0.2ms time window, 16khz only has 3.2 cycles in 0.2ms

- alternate layouts for 4u (26 AWG) and 8u (20 AWG) wire
- inserted in printed frame instead of printed with it
- bigger so will need more rows to cover all print lanes
- optional liquid coolant channels to the sides







- need insulator above lead and below conductive material hopper or reservoir
- channels for leads printed for insertion from the side
- print channels tight then smooth channel with fine round file before inserting wire
- use electrically conductive epoxy to join and fill gaps

- heat delta (using https://www.calctool.org/thermodynamics/watts-to-heat)
  - a 0.2mm cube of copper to 1km/s in 100mm with ~30A in 0.2ms increases heat around 500C, and to 500m/s with 15A in 0.4ms increases heat around 250C; the melting point of copper is 1085C, so it won't even melt
  - the conductivity of steel is around 3-15% of copper
    - with 10% of conductivity steel would have 10x the resistance of copper leading to around 10x the heat, except that the density (slightly lower) and specific heat capacity (somewhat higher) of steel are different so it is more like 2,300C for 500m/s and 4,600C for 1km/s
    - most steel will melt by 1370C and vaporizes around 2862C; 500m/s would be liquid form, 1000m/s would be plasma
    - if the conductivity is 15% of copper instead of 10%, the 1000m/s temp drops to around 3070C, so still vapor but closer to liquid
    - steel with higher conducitiviy is viable, but it may not be cold-spray any more, we would want the minimum velocity that results in a liquid state, and it would be a hot liquid spray instead of a cold solid spray; is that more useful or less?
  - in general for materials and carrier fluids/pastes/gels want: higher conductivity, higher specific heat capacity, lower density
  - some materials will work for hot liquid state with the proper range of conducitivity and melting point

- alternative manual fabrication method: use square wire and rectangular cubes of insulator
- the diagram shows 8u wire (0.8mm, 20 gauge) and a 2u (0.2mm) gap
- wire with half hard copper (full hard would be better), apparently a common craft wire: https://www.amazon.com/Gauge-99-9-Copper-Square-110-10FT/dp/B09756H6LK/
- this design allows for separate barrel liner insulator material from the surrounding material; cheaper and stronger material can be used in for the lighter blue areas, and in the dark blue area more exotic, slippery, and durable ceramics (like aluminum nitride)
- the spacer insert approach with separate material also makes it easier to construct a small barrel from simple components
- the middle light blue insulator rectangles extend so that the whole thing can be wire-wrapped; the primary forces during firing try to push the two conductors apart, so they need to be held together
- during build use a 0.2mm tall round or square rod to hold the barrel space open until some pressure is on the sides of the rails to hold them in place (then remove; lubricate before so gentle pressure can be on side before removal; also consider other things to hold the barrel spacers in place, they are the one part without something to keep them away from the barrel (but are pushed away from barrel somewhat when fired)
- this diagram is not to scale, the light blue insulator material is meant to be significantly larger than the rails and barrel in order to keep it straight and stable; one problem with a 0.2mm wide 100mm long barrel is trying to keep it straight, this makes that easier by shifting what needs to be straight to the insides of the blocks around the core (as long as rail wire and bore spacers are consistently sized for the length of the barrel, and dependending on the elasticity of the surrounding material)
- dimensions, rough design:
  - 20 gauge square wire as described above (0.8128mm square)
  - 2x dark blue barrel spaces 0.2mm by 0.3mm
  - 2x top/bottom light blue blocks around 20mm wide by 10mm tall (and barrel length deep for all pieces, like 100mm)
  - 2x side blocks are 10mm wide by 0.8mm tall (needs to be less than 0.8128mm to slide freely between top and bottom when rail wires are in place as spacers so that pressure can be applied from the sides to keep them in place during firing with wire wrap or something)