# Advanced Accelerator Research at BNL

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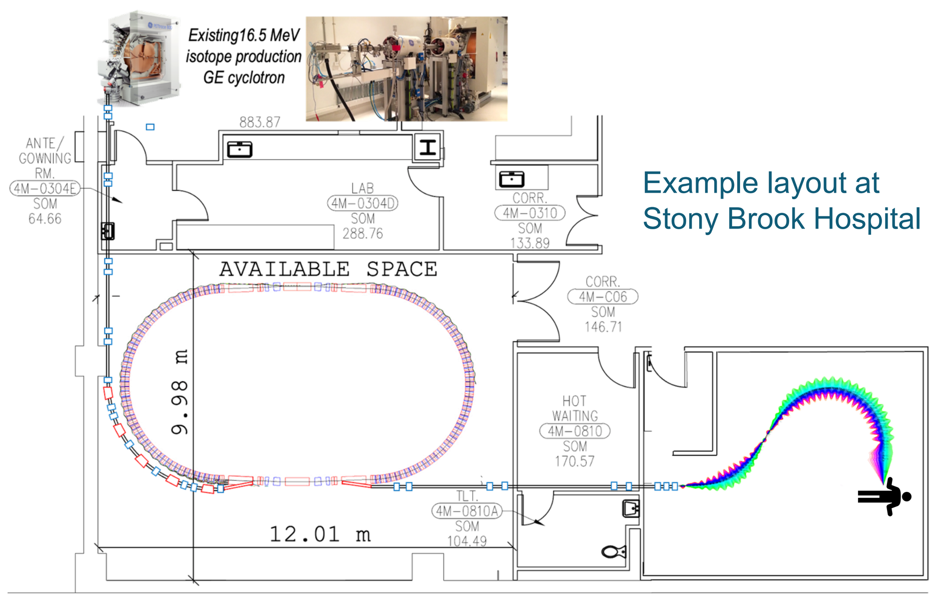
LDRD 22-013 (Type B) High-Gradient Permanent Magnets for Emerging Accelerator Applications
LDRD 24-010 (Type B) Section of Fast-Cycling FFA Synchrotron
LDRD 24-006 (Type B) Ion trap test stand and laser cooling studies of ultra-low emittance bunches for high luminosity
LDRD 26-055 (Type C) Laser System for Doppler Ion Cooling

## Permanent Magnet Accelerator Design for Fast Hadron Therapy Treatments

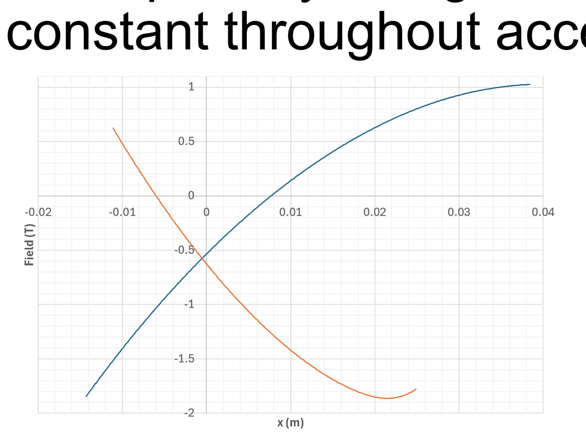
Fixed-field accelerators (FFAs) allow the acceleration of beams without ramping magnetic fields: the orbit shifts to higher field regions instead. This avoids limits on machine cycle rate from magnetic inductance and forms the basis of the very-rapid-cycling medical accelerator facility shown below, producing high dose rates required for FLASH therapy as well as rapid energy scanning for 3D coverage of the tumor.

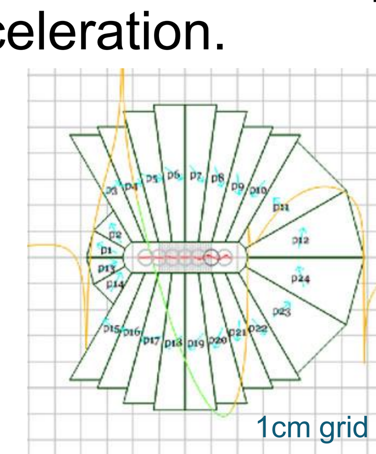


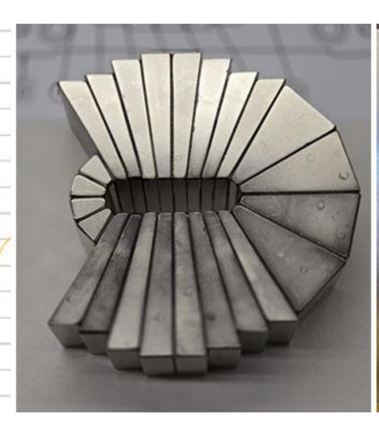

Example layout at Stony Brook Hospital

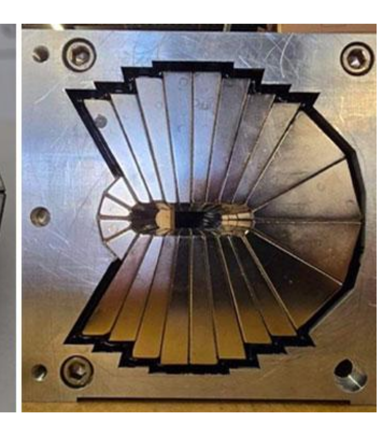
| Parameter | Value | Unit |
|---|---|---|
| Injection $E_k$ | 10-30 | MeV |
| Extraction $E_k$ range | 65-250 | MeV |
| Arc radius | 3.5 | m |
| Machine cycle rate | 500-800 | Hz |
| Energy gain / turn | 30-45 | kV |
| Treatment charge | 60 | nC |
| Treatment time | 75-250 | ms |

The wide 10-250MeV energy range of the accelerator is allowed by NdFeB permanent magnets with a peak field of 1.85T, shown below. The specially-designed nonlinear field profile keeps the machine tune constant throughout acceleration.

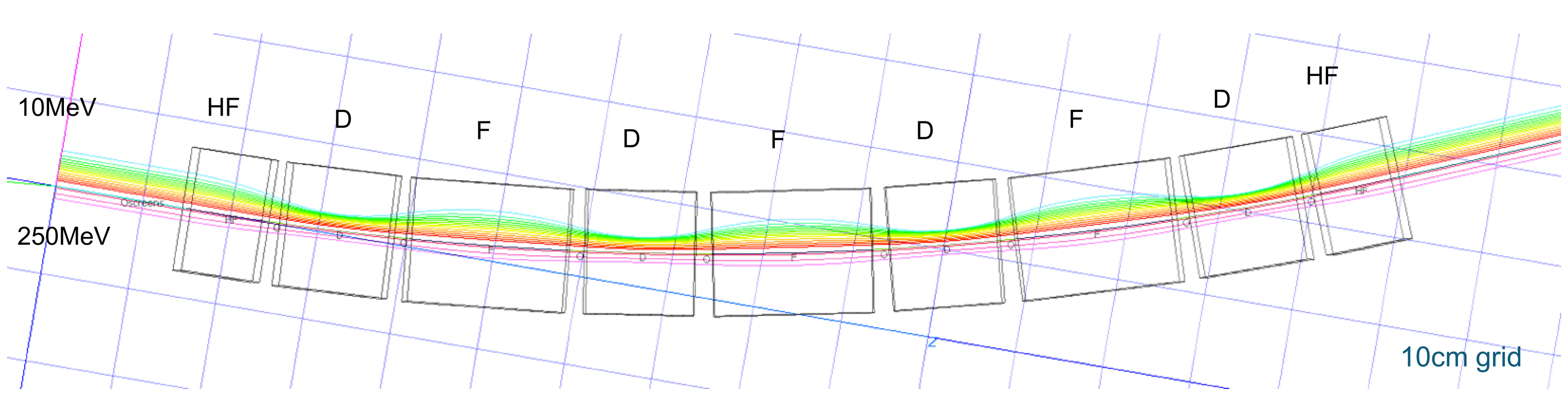




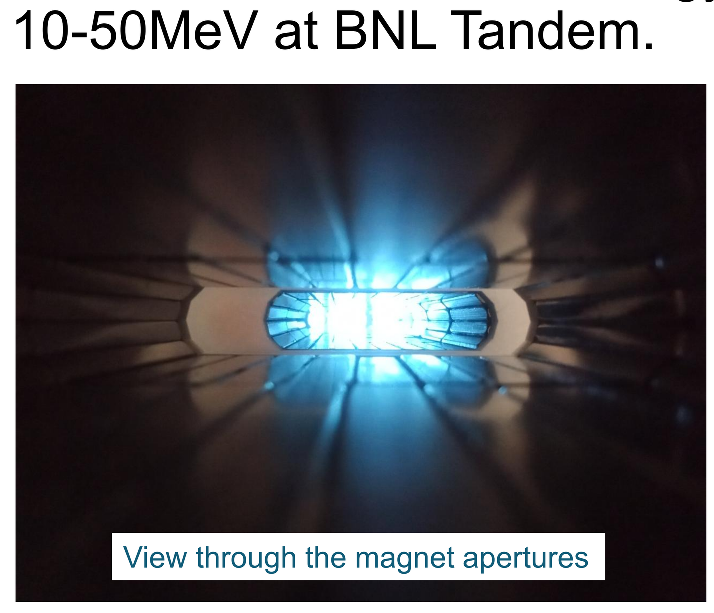





## Beamline Tested at NSRL and Tandem

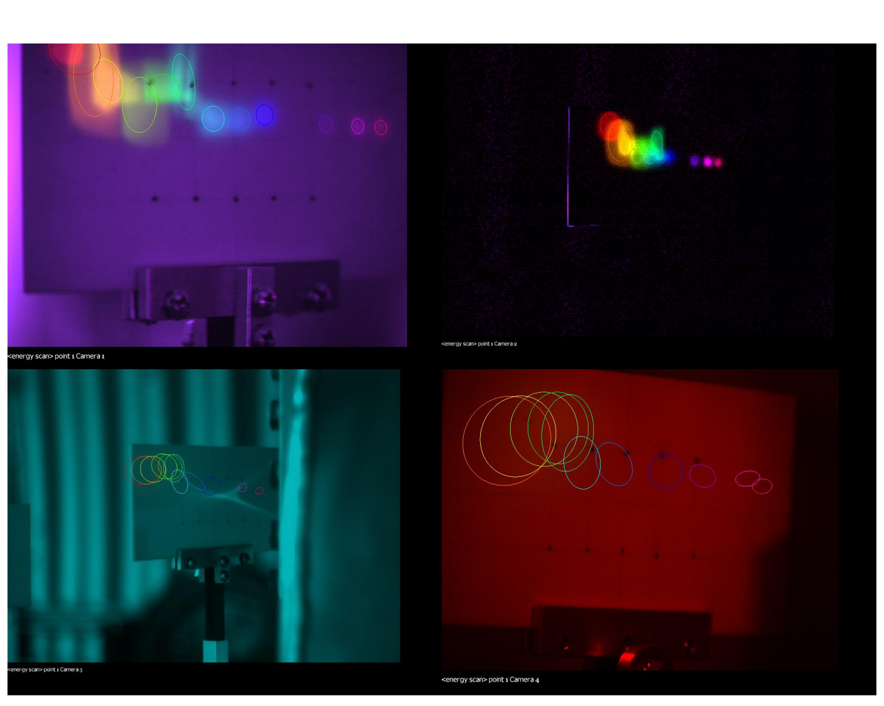



A 100% scale, full-field section of the arc with nine magnets (22.5°) was built and tested for beam transmission across the entire energy range: 50-250MeV protons at NSRL and 10-50MeV at BNL Tandem.

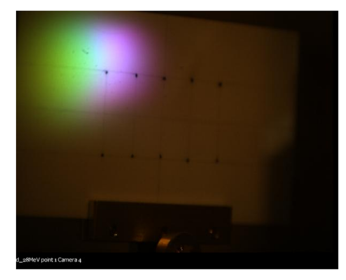



Beam in

Beam out



Composite image of the 12 input beams from 10MeV (left) to 250MeV (right) at both facilities.
Lower plots show ellipses fitted to the output beams.

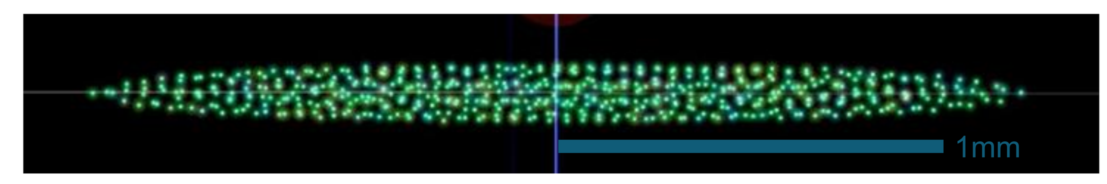


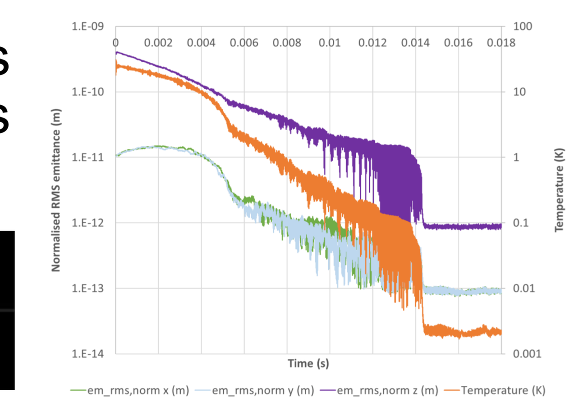
Tandem

NSRL

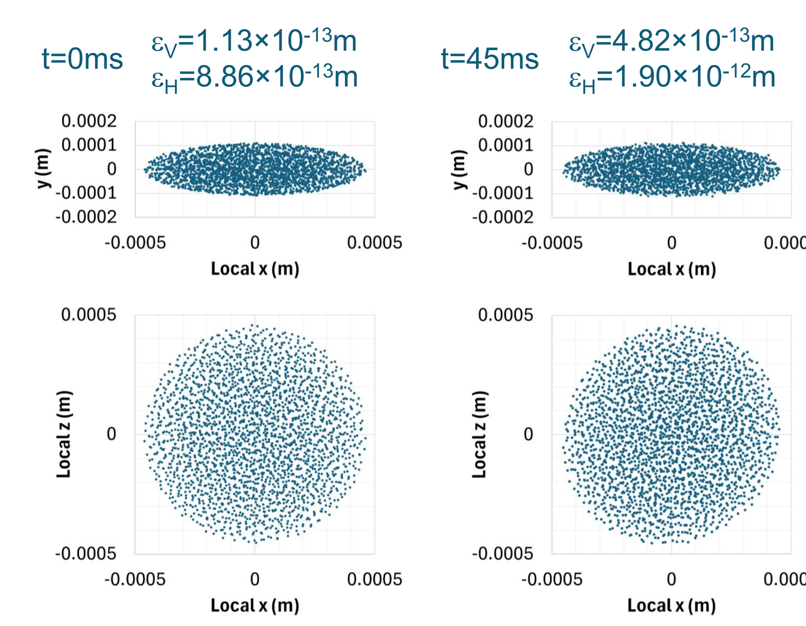
## Simulations of Crystalline Beam Stability in the BNL Booster

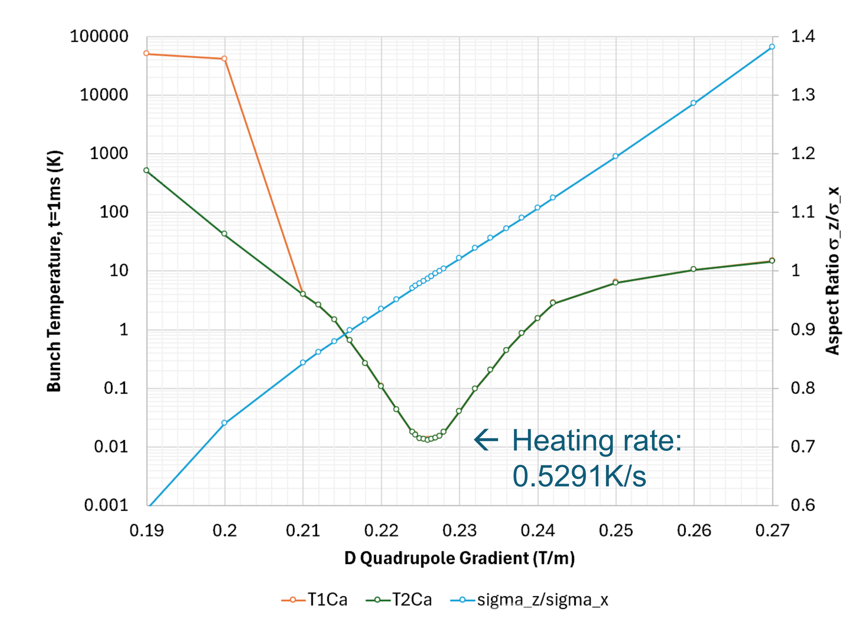
Laser Doppler cooling can cool ion bunches into solid "Coulomb crystals", for example this simulated $Ca^+$ crystal at 2mK temperature.

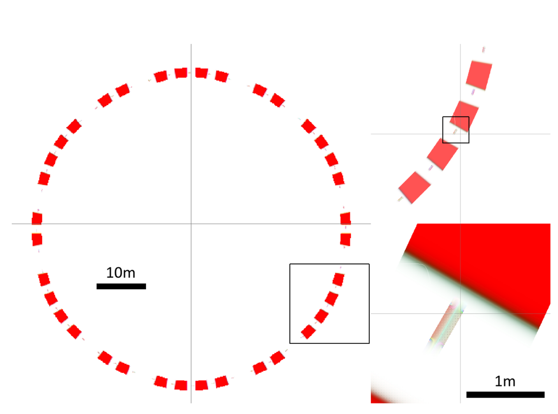


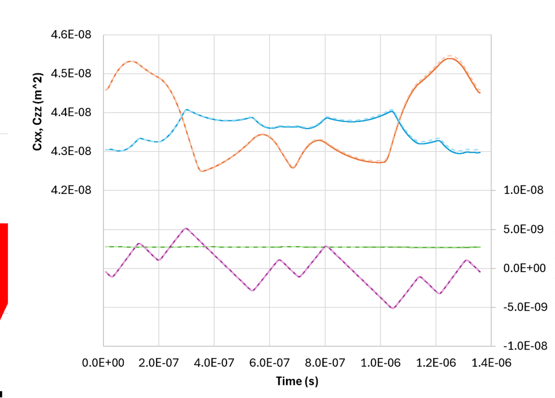



Such a crystal distribution was placed into a magnetic field model of the BNL Booster synchrotron for 5500 turns (45ms). Quadrupole settings were found that reduced heating rates to less than 1K/s and preserve the solid state, even without additional laser cooling.



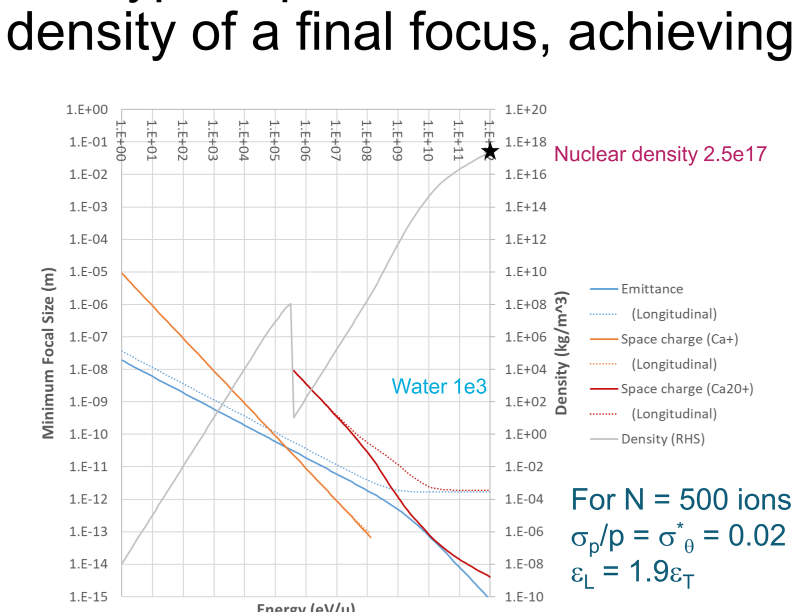
Left: magnetic field model of the Booster.

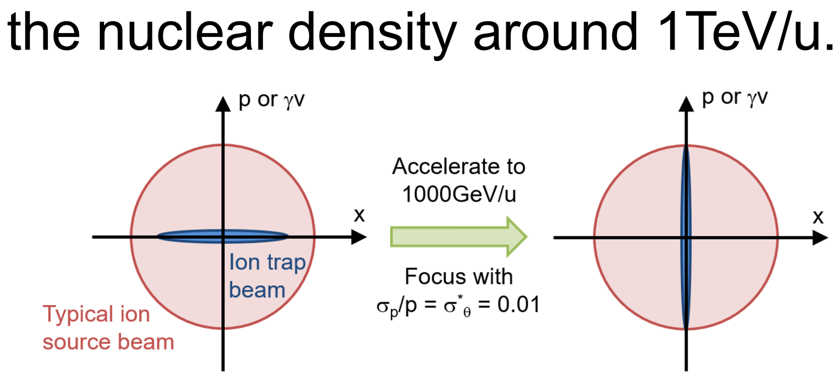
Center: bunch sizes and correlations in one Booster "superperiod" (1/6 of a turn).

Below: a non-crystalline bunch in the same accelerator setting also spontaneously forms into circular solitons under the space charge "vortex effect".

## Nuclear Density Focal Point Formation

The $10^5$ times smaller velocity spread of a crystalline beam compared to a typical plasma source can be converted into a $10^{15}$-fold increase in density of a final focus, achieving the nuclear density around 1TeV/u.



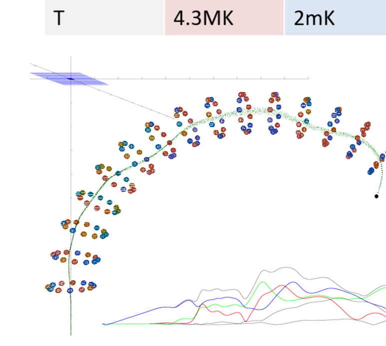

| Parameter | Ion source | Ion trap |
|---|---|---|
| N | $10^9$ | 500 |
| $\varepsilon_{norm,rms}$ | $10^{-7}$m | $2\times10^{-13}$m |
| $\sigma_x$ | 1mm | 90μm |
| $\sigma_v$ | 30km/s | 0.65m/s |
| T | 4.3MK | 2mK |

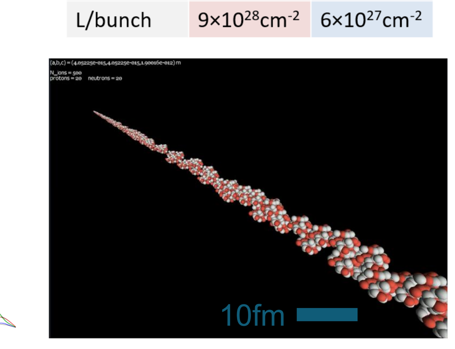
| Parameter | Ion source | Ion trap |
|---|---|---|
| N | $10^9$ | 500 |
| $\varepsilon_{norm,rms}$ | $10^{-7}$m | $2\times10^{-13}$m |
| $\sigma^*_x$ | 9.4nm | 18fm |
| $\sigma^*_\theta$ | 10mrad | 10mrad |
| L/bunch | $9\times10^{28}$cm$^{-2}$ | $6\times10^{27}$cm$^{-2}$ |

Above: focal density achievable as a function of beam kinetic energy.

Near right: generalized focusing beamline that makes a 3D aberration-free focus with 166 optimized parameters.

Far right: 500 $Ca^+$ nuclei shown to scale at the 1TeV/u nuclear density focus (long due to relativistic effects).

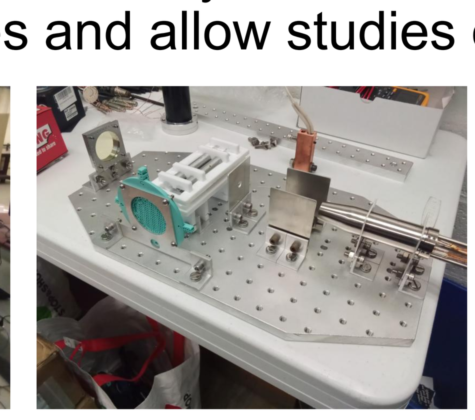




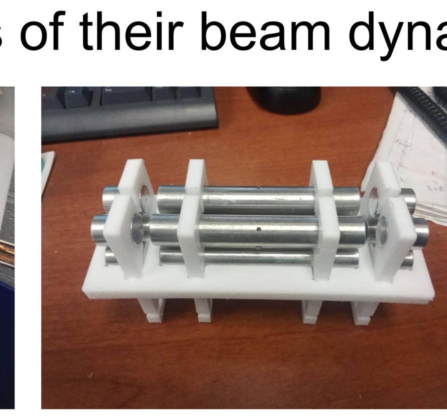

## Ion Trap Test Stand at BNL

Hardware for a $Ca^+$ ion Paul trap with laser Doppler cooling has been purchased at BNL. This system will be a source of ultra-low emittance crystalline bunches and allow studies of their beam dynamics.

Vacuum chamber, turbopump and racks



Experimental board with electron gun, ion trap and phosphor screen



Electrostatic quadrupole Paul type ion trap

Narrow-linewidth lasers at 397 and 866nm for Doppler cooling of $Ca^+$

Advanced Accelerator Research at BNL

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This poster presents two emerging accelerator technologies studied at BNL Collider-Accelerator Department.

One is the use of high-field permanent magnets, which have become commonplace in recent decades, as the main bending and focusing field of an accelerator, with fields up to 1.85 Tesla here.  These are used in a proposed hadron therapy facility, where a fixed-field accelerator (FFA) design allows proton beams to ramp from 10-250MeV without changes in the magnetic field (the beam orbit shifts instead).  Magnetic inductance effects do not have to be overcome in an FFA, leading to faster machine cycle rates of ~500Hz.  This allows ultra-high dose rate or FLASH therapy, with sub-second treatment times that benefit patient outcomes.

The second technology is the production of ultra-low emittance ion bunches via laser Doppler cooling.  These bunches have typical temperatures of a few milli-Kelvin and emittances roughly 10^5 times smaller than typical plasma ion sources.  Ions at this temperature form a solid lattice or "Coulomb crystal".  Simulations show these solid crystals can be transported for thousands of turns in the BNL Booster synchrotron, even without cooling, if quadrupole settings are chosen correctly.  The small emittance in X, Y and Z implies a potential 10^15 increase in density of focal points formed from crystalline bunches, with a path to creating bulk nuclear density matter (neutronium) at LHC-scale energies.