Target Insertion and Injection For High Power Lasers

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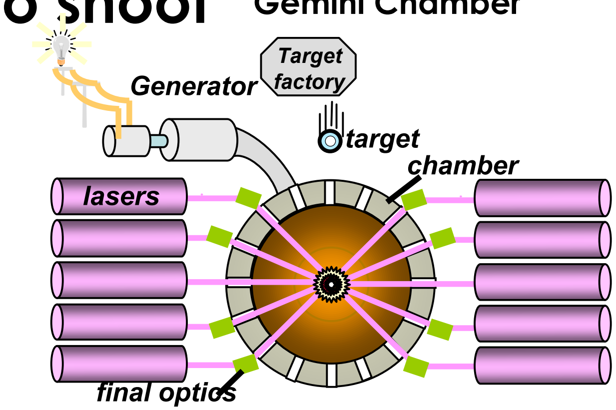
GENERAL ATOMICS

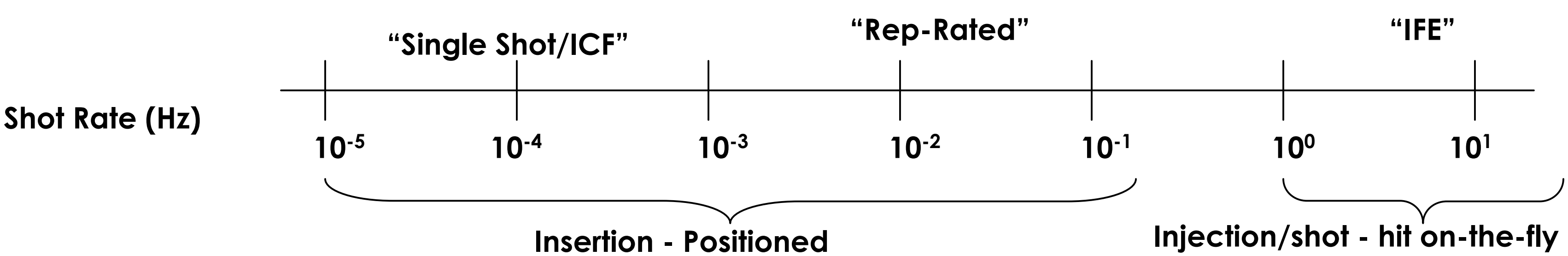
Shooting lots of targets benefits from specialized target fielding systems

- **Rep-rated (~1/min) facilities are available**
  - GEMINI at RAL
    - More than 1000 targets/day can be shot
    - Each day's target could be different
  - Targets can be placed and held while shot
    - **"Insertion"**

Gemini Chamber

- **Inertial Fusion Energy (IFE) systems need to shoot many millions**
  - Power plant designs typically 5 to 10 Hz
  - ~Million/day, 24/7
  - Target must be shot on-the-fly
    - **"Injection"**

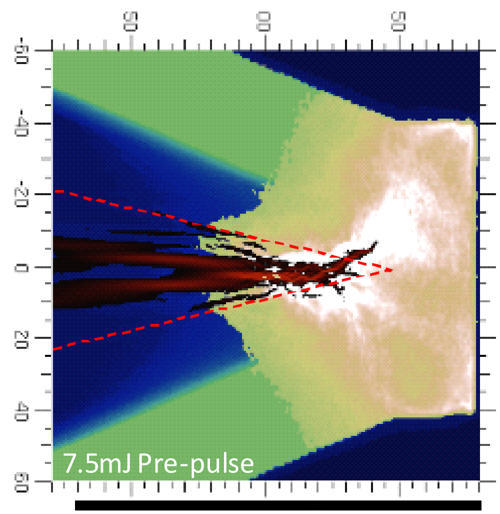


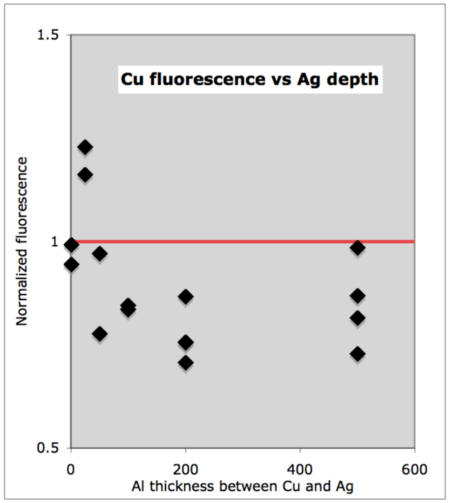


More targets –> More data

Small data sets limit our understanding

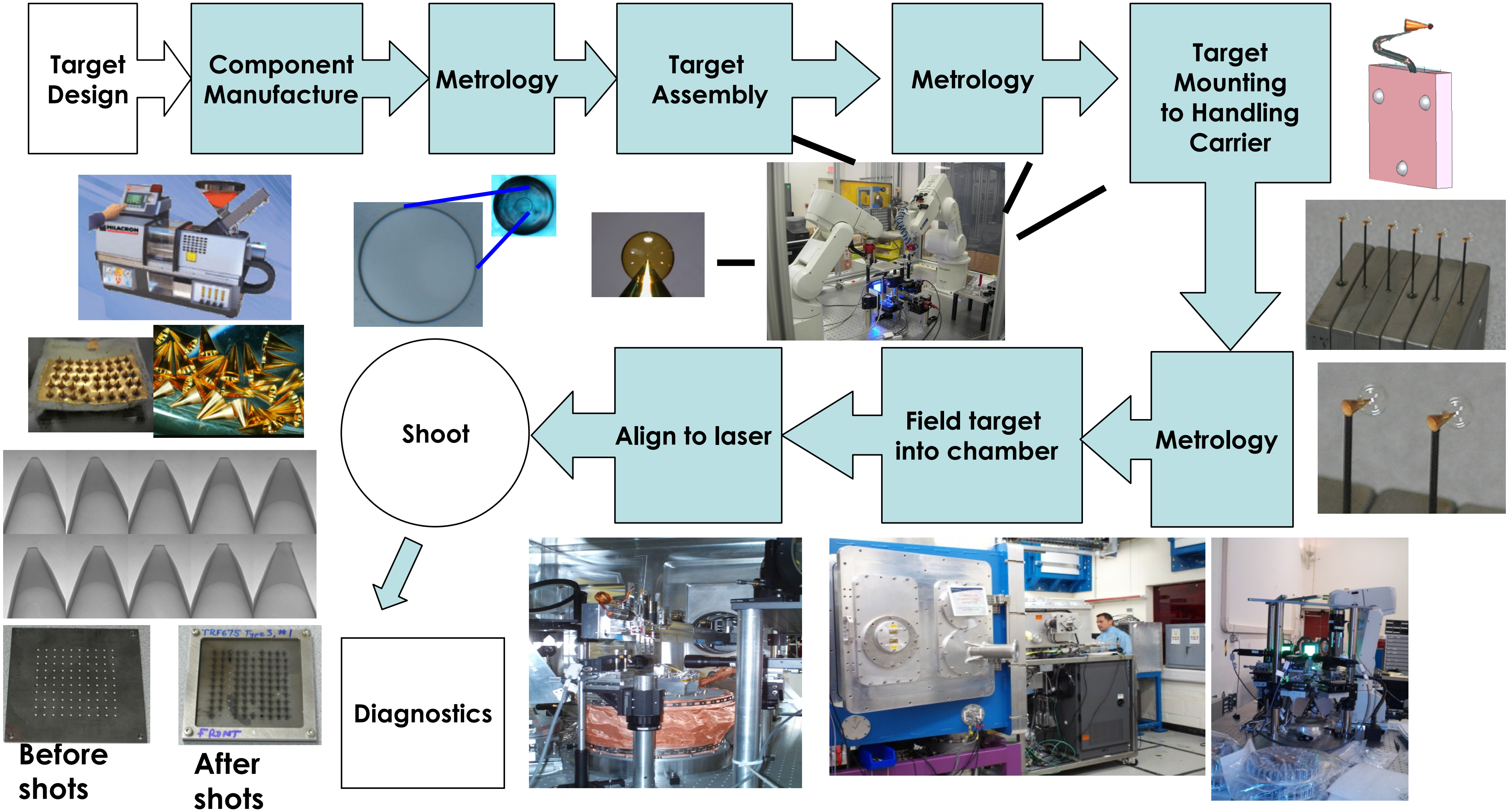
- Simulations show laser-solid interactions are stochastic if plasma present
- Data sets suggest this has a large effect on electron production
- But campaigns can't include enough shots to investigate.





Averages and variances will need to be determined –> lots of targets

With 1000's of targets, each step in building and fielding targets should be as automated as possible



We are developing automated methods for target production and fielding

Overview of Gemini Target Insertion System

TARGET INSERTER

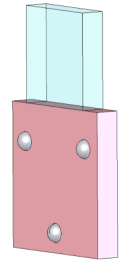
GEMINI TARGET CHAMBER

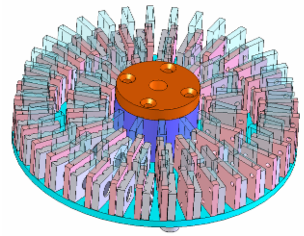
The system was designed to the following specifications

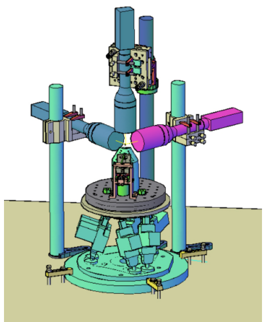
- ±2 um repeatability perpendicular to the beam
- ±4 um repeatability in the direction of the beam
- ±1 mrad angular repeatability
- System must accommodate changing the target carousel without venting the main chamber (load lock)
  - ≥50 targets/carousel
- System designed and built to operate at 10^{-6} Torr
- Target must be capable of being translated ± 5 mm and ± 5°degrees rotation, not simultaneously
- Accommodate shot rate of 1/min; with goal of 1/20sec
- Field 900 targets per 18 hours
- Target inserter to have 908 mm reach into chamber
- Accommodate target volumes of 20x20x6 mm
- Metrology station to handle target misplacement of up to ±130 μm
- Environment for inserter ±0.5°C, metrology station ±2°C, measured to ±0.5°C

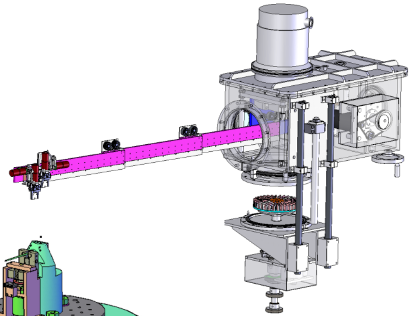
There are several subsystems in the Gemini Target Insertion System

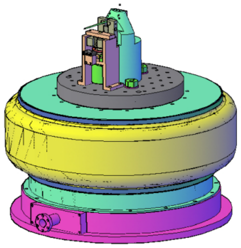
- **Target Carrier**
  - Holds targets
  - Provides a stable handling platform
- **Target Carousel**
  - Platform to hold batch of target carriers
- **Metrology Station**
  - Determine offset of target between carriers
- **Target Inserter**
  - Load locks target carriers into chamber
  - Coarsely places targets onto Target Positioner
- **Target Positioner**
  - Fine positioning of target in chamber



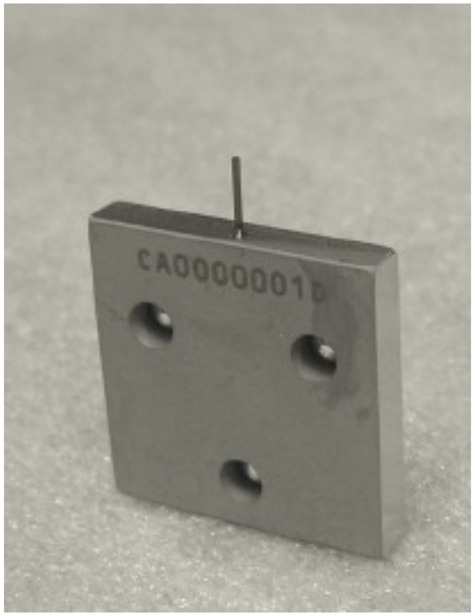


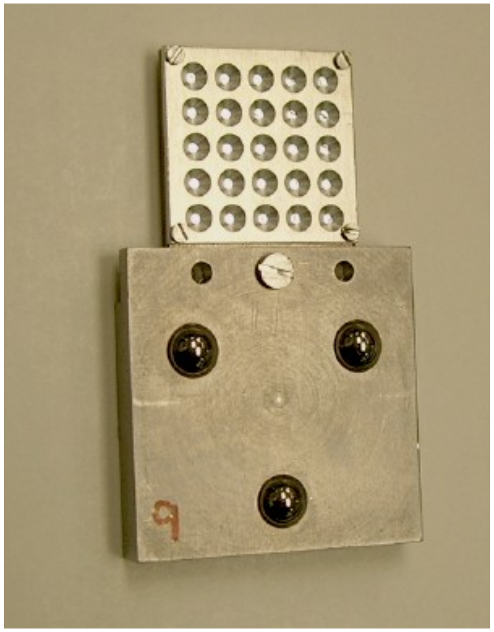






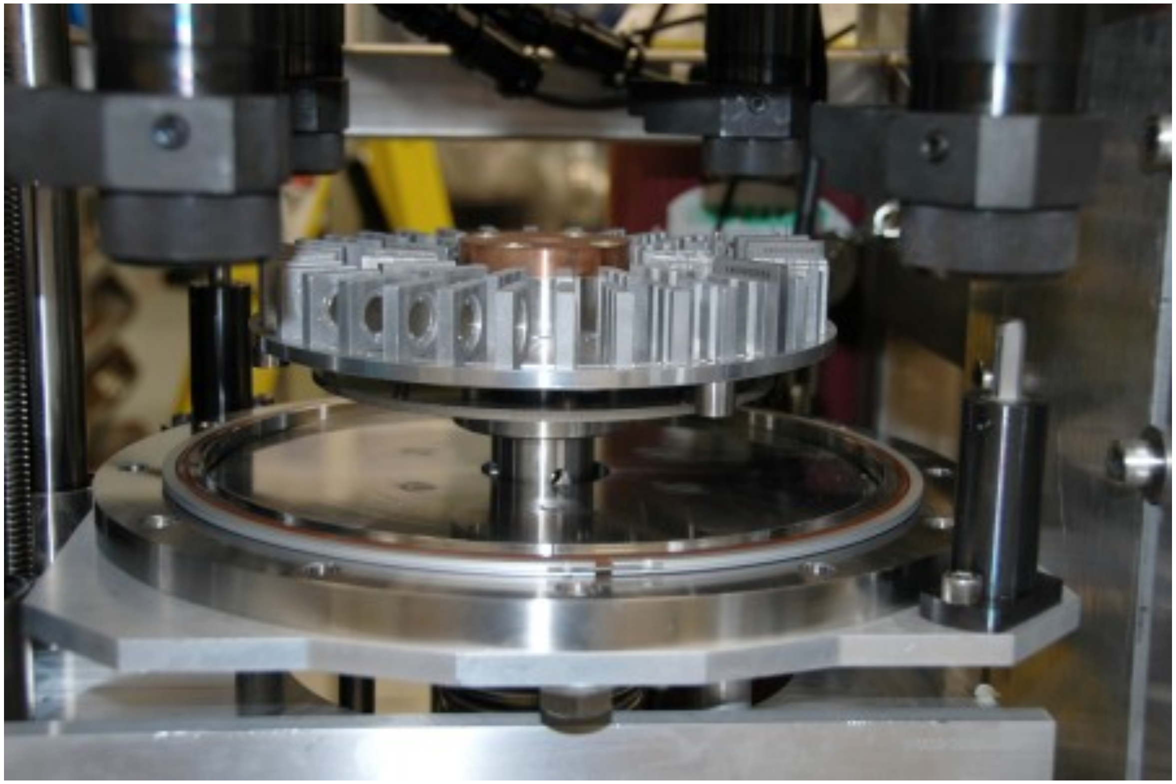
RAL has mounted as many as 25 targets in a 5 X 5 array to target carriers





- The target carrier has a kinematic mount

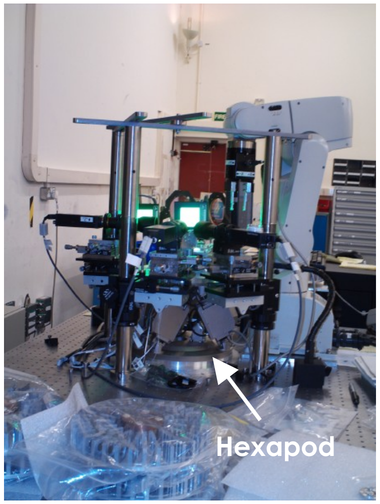
Target carousels hold 50 carriers and 1 kinematic adapter plate



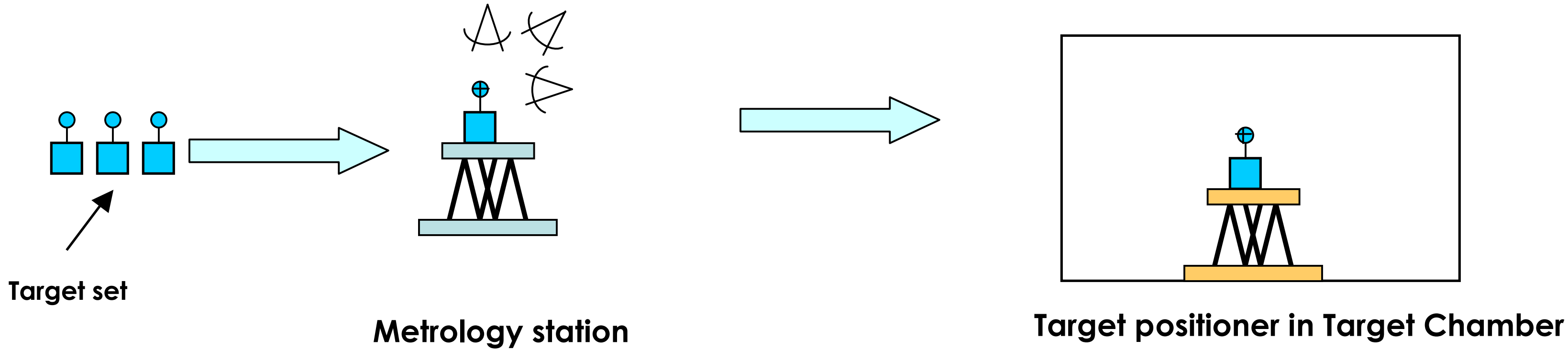
- **Carousels are vacuum load-locked into the system**
  - main target chamber is not vented

An external metrology station is used to determine variation in mounting location between targets

- **Targets are mounted on kinematic bases (Target Carriers)**
  - Each base has a bar code for target tracking
- **Two “identical” target positioners use 6 ODF hexapods**
  - Metrology station positioner,
  - Chamber target positioner
- **All targets positioned to same point at metrology station**
  - Use to null out variations in target mounts to bases
  - Optics can be close to target
- **First target aligned to desired point in chamber**
  - Use to null out variation between positioners
- **Subsequent targets, using metrolology info, are placed directly to the first target’s location**

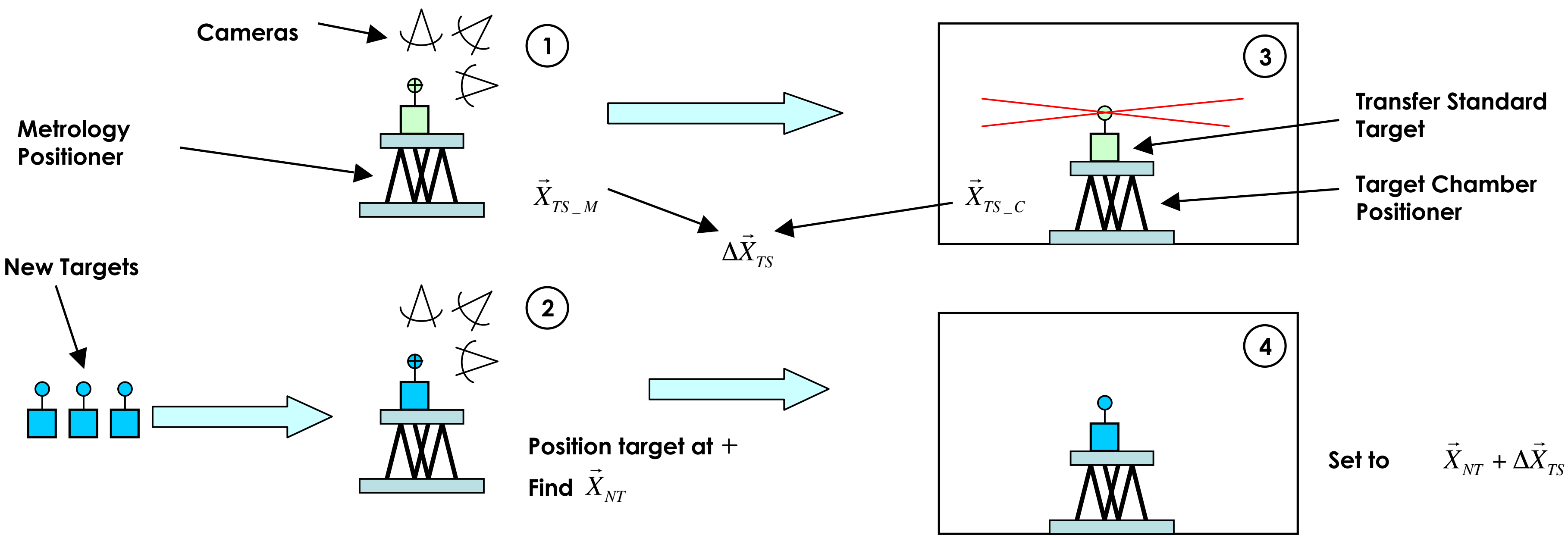


METROLOGY STATION FOR GEMINI INSERTER

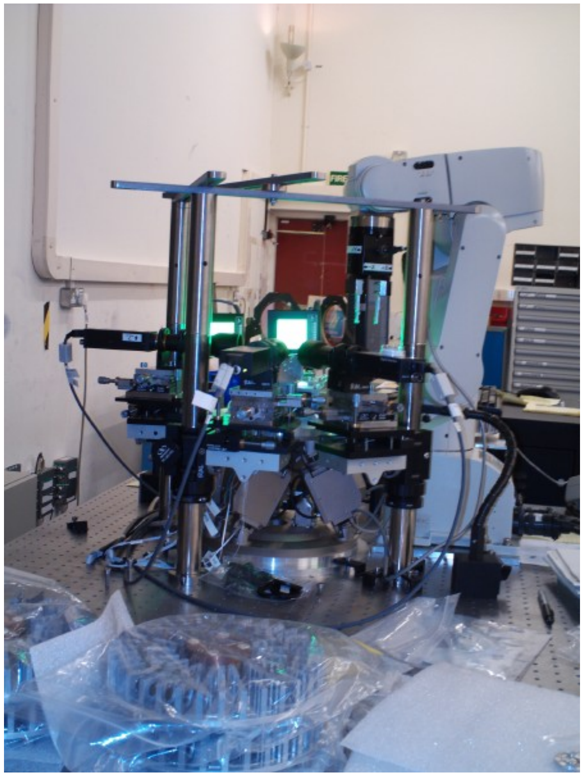


An external metrology station used to establish new targets' locations

- **A transfer standard target is used to determine offset between positioners in metrology station and target chamber**
  1. Take transfer standard target to metrology station and establish a "home" location/center in stations field of view
  2. Locate a new targets at "home" position of metrology station (null)
  3. Align transfer standard target to target chamber "center" {We need to understand how this will be done}
  4. Locate new target in target chamber at "home" position plus offset determined between steps 1. and 3.



The metrology station has a robot arm to move targets from carousels into the measurement position

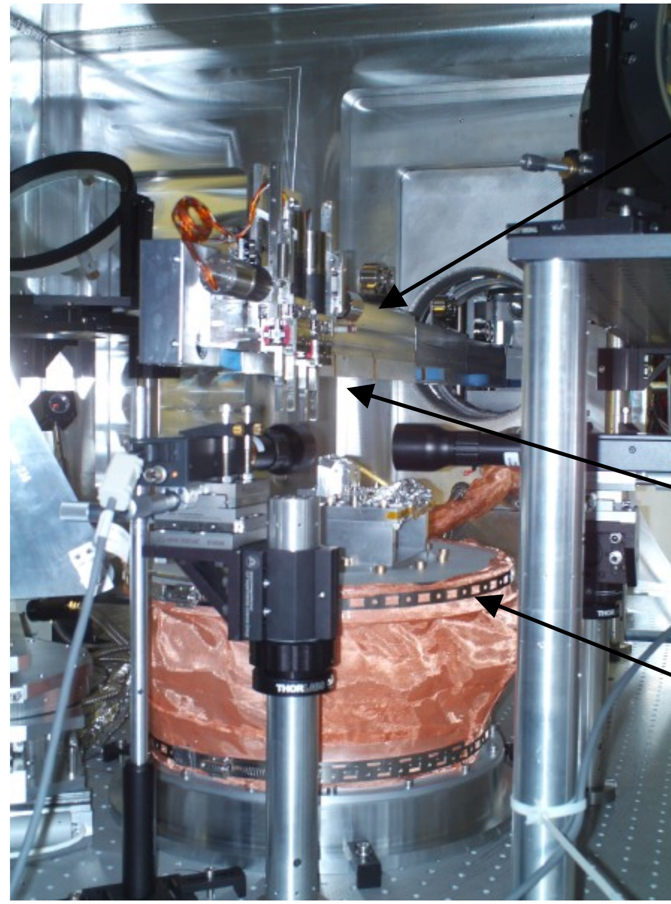


- **Target offsets are stored in data file that is used by target positioner to compensate for variation in target mounting positions on carrier**

The target inserter moves the carriers from the carousel to the target positioner

Gemini Chamber

Target Inserter Chamber



Inserter arm

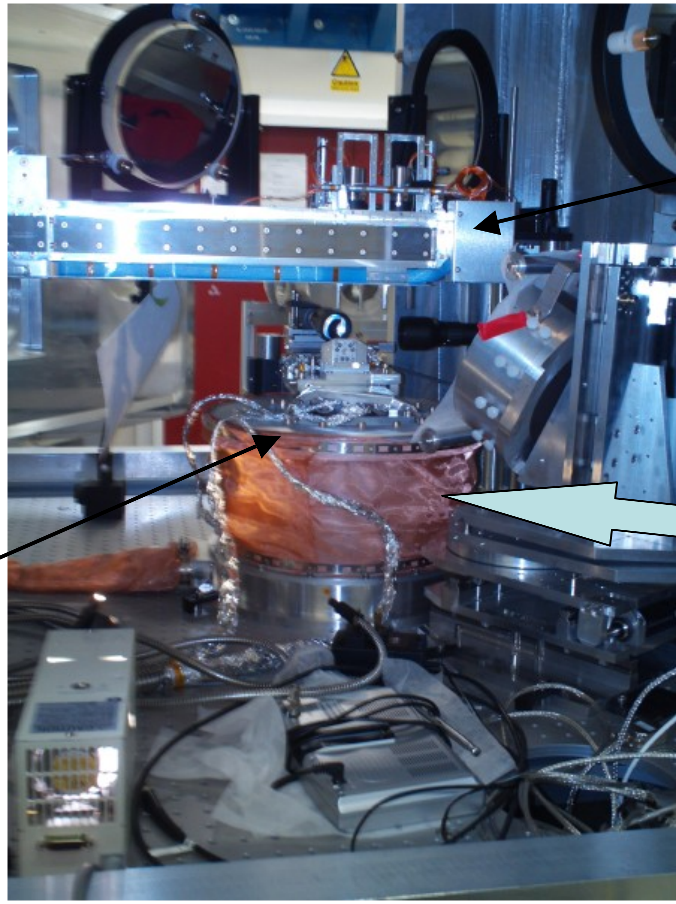
Jaws

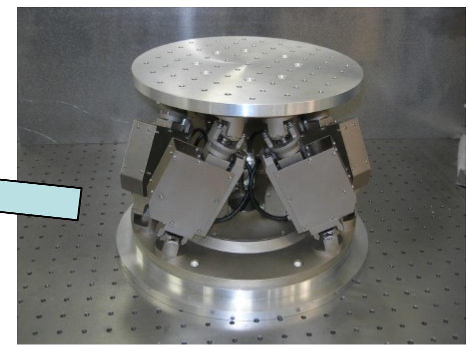
Target Positioner

Inside Gemini Chamber

- **Two jaws on inserter arm, one to remove old carrier, other to install new carrier**

Target positioner is EMI shielded





Hexapod inside of shielding

- **Target positioner contains a 6 DOF hexapod positioner**
  - X, Y, Z translations
  - Θ,Φ,Ψ rotation about any point x, y, z

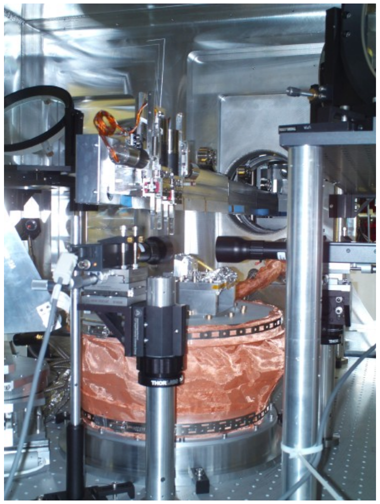
Many of the operations are automated

- Video

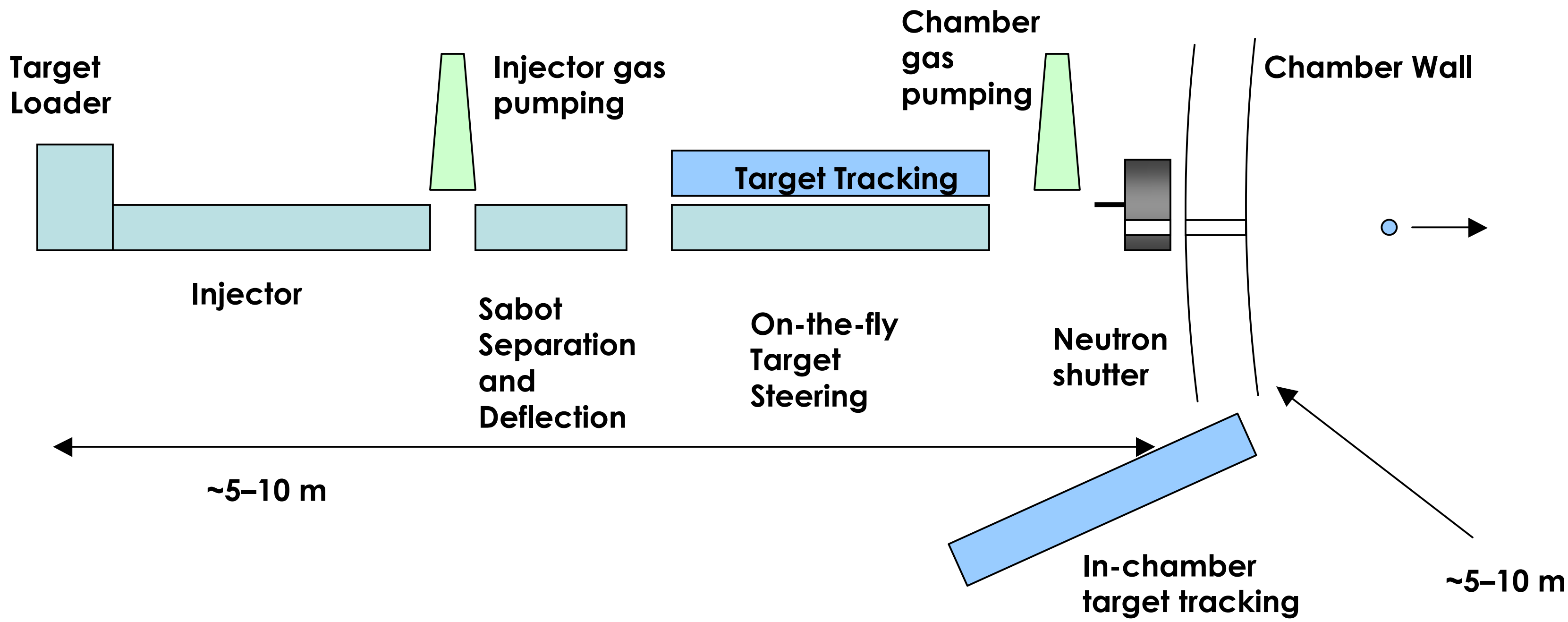
Target inserter is available for use on Gemini

- **Most beneficial for 3D solid targets**

- **Limitations**
  - Target positioner base takes up space (Ø 30 cm)



IFE target injectors have many sub-systems



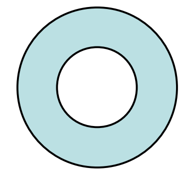
- **Not all sub-systems may be needed**
  - Dependent on technologies selected, reactor design, and target design

Laser and ion driven IFE power plants need injection

- **Typical shot rate 5 - 10 Hz**
- **Chamber radius ~~5 - 10 m**
- **Difficult for mechanical systems to span these distances this quickly**
- **Target designs are high yield (~~150 MJ)**
  - Would generate shrapnel from any target support structure
    - Damage optics, first wall
  - Would erode inserter but reactors need long life

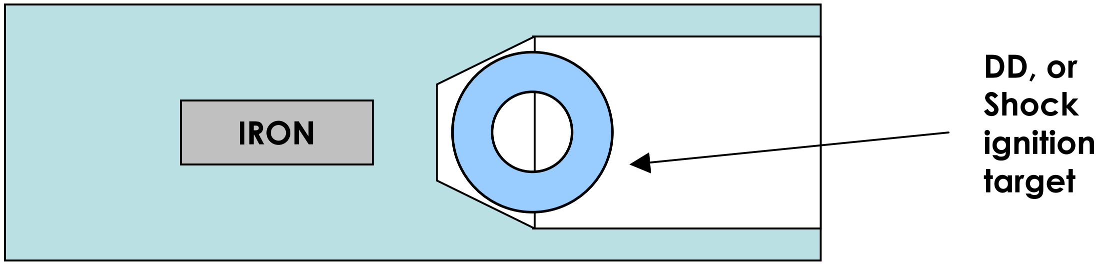
Need only targets at chamber center –> Shoot/Inject targets into chamber

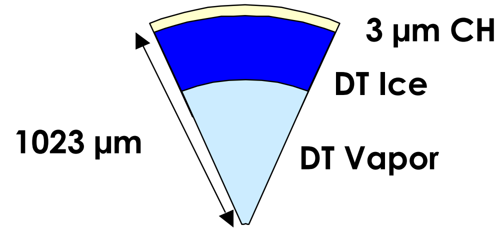
Injector requirements are demanding



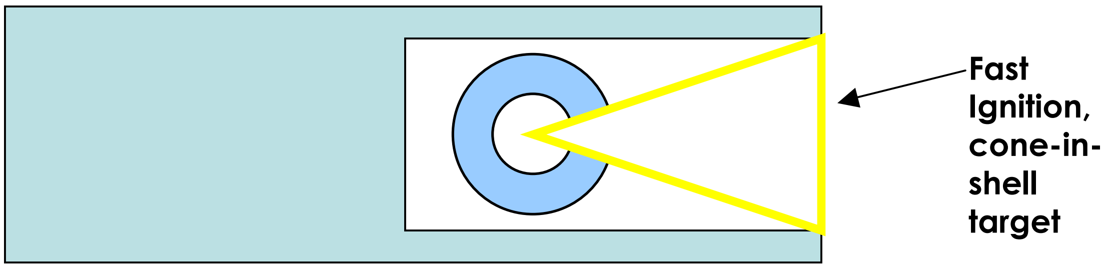
- **Shot rate ~ 5 - 10 Hz, 24/7, for years**
- **Speed ~75 to 1000 m/s**
  - Reactor and target design dependent
    - Gas pressure in chamber
    - Chamber size
    - Heat protection features for target (e.g. reflective outer layer)
- **Accurate**
  - ~10 micron would eliminate beam steering
    - Very challenging
  - 1 - 10 mm to limit challenge of slewing beams quickly
    - Need to add target tracking (~20 to 200 μm accuracy)
- **<~1000 g acceleration**
  - From target designs at 18.2K, DT is soft near triple point
  - Colder can be higher, but layering Thick DT less known

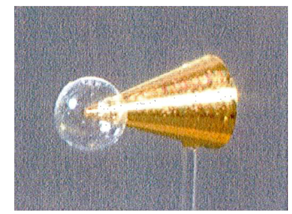
Often sabots are needed for targets in injector





Sector of spherical HiPER target

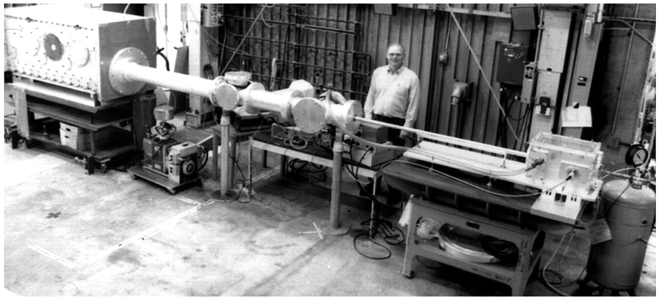



HiPER Cone-in-shell target

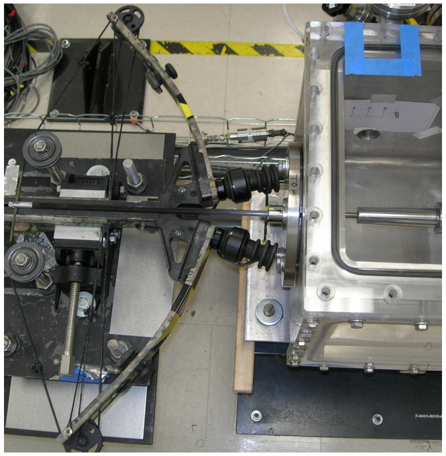
- **Protect target**
  - Heating (e.g. gas
  - Damage (e.g. barrel contact)
- **Impart force, torque (e.g. magnetic)**
  - Spin stabilize non spherically symmetric targets

Sabot adds subsystem to remove sabot

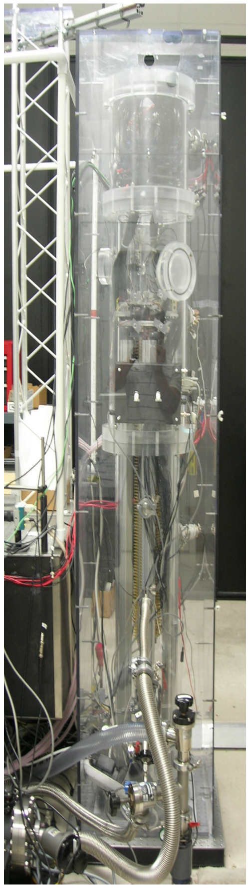
We have previously built a number of target injector prototypes



80 m/s rifled gas gun

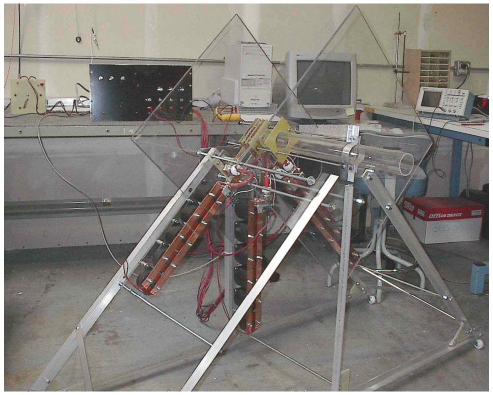


40 m/s mechanical



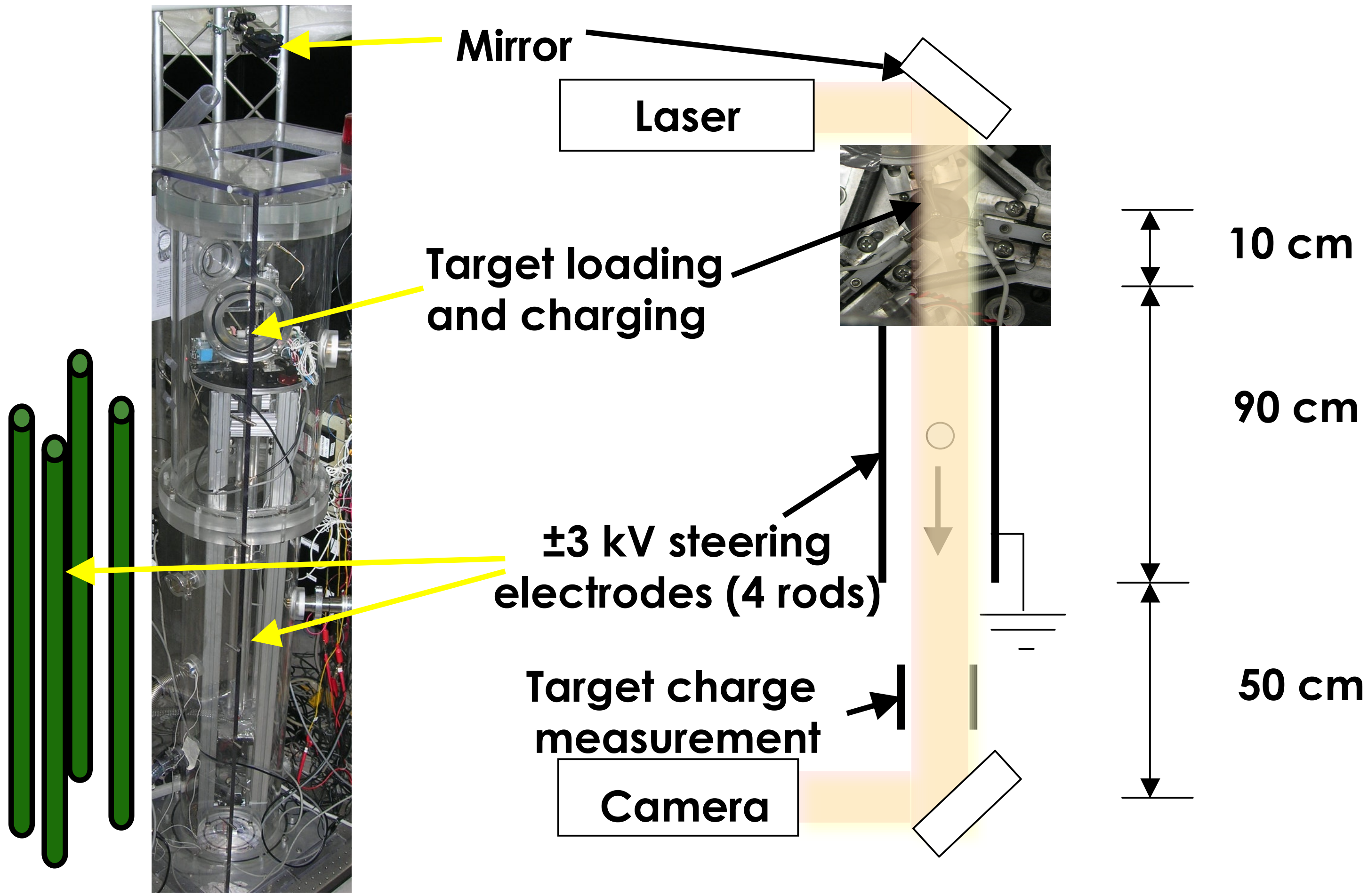
7 m/s Electrostatic Accelerator

400 m/s gas gun

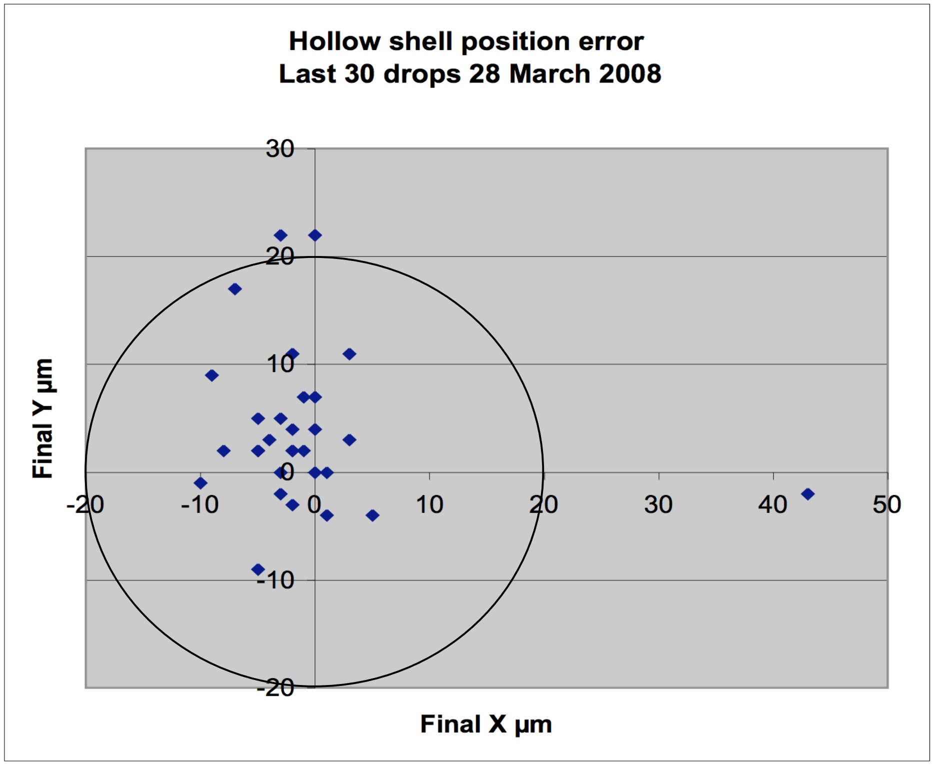


32 m/s Coil Gun

Electrostatic steering was previously shown to improve placement accuracy



Excellent target positioning repeatability achieved with hollow shells in vacuum

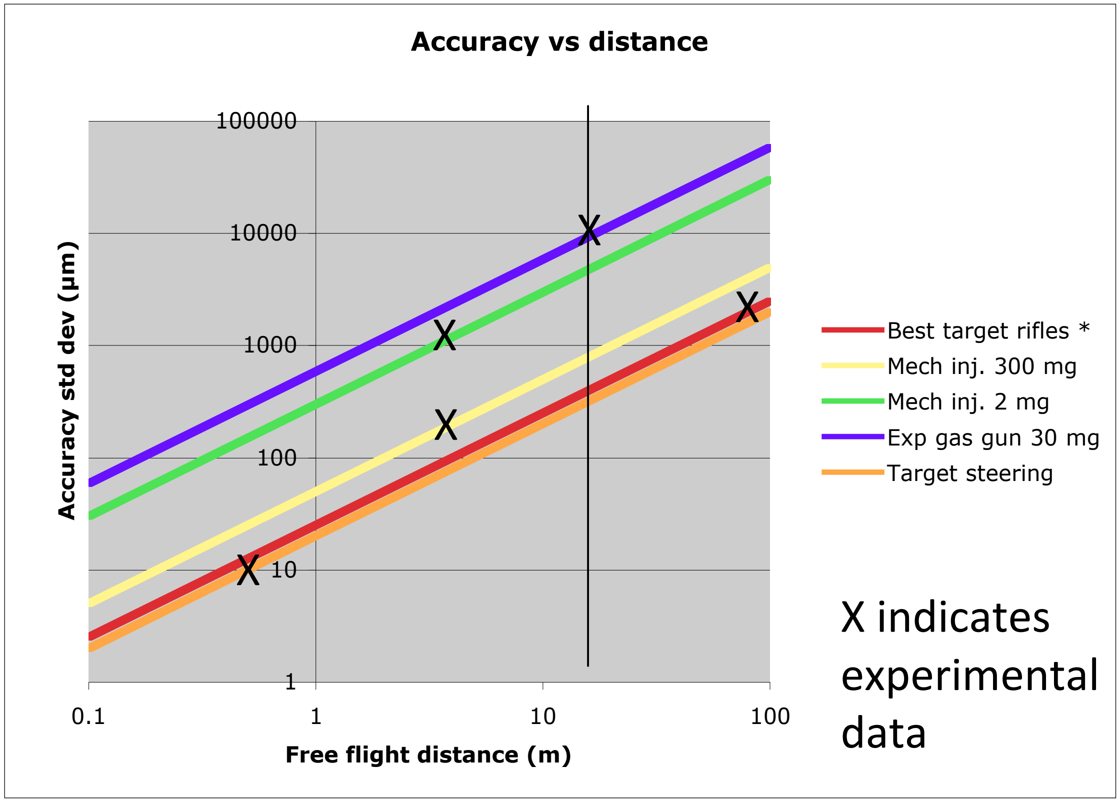


Without target steering
$\sigma_x \approx \sigma_y \approx 500$ µm

With target steering
$\sigma_x = 9$ µm $\sigma_y = 7$ µm
- **X offset = -1 µm; Y offset = 4 µm**
- **27 of 30 in 20 µm radius from aim point**

In-flight target steering could be used to improve accuracy of a target injection system

High accuracy is desirable



- **Higher accuracy reduces beam steering range**
- **An accuracy of ~10 µm would eliminate beam steering**
  - Challenging

There are many potential options for IFE target injectors

- **Electro-static**
  - no sabot, non-contacting, but weak force
- **Gas gun**
  - simple, high force, but hot gas
- **Rail gun**
  - simple, high force, but high wear and heat
- **Coil gun**
  - high force, but high impulse and contacting (wear)
- **Magnetic induction accelerator**
  - non-contacting (low wear), but high speeds need high frequency AC
- **Conventional magnetic ("iron insert sabot")**
  - high force, but high impulse and contacting (wear)
- **Mechanical (crank arm, compound spring, lever and cam, pneumatic piston)**
  - simple, well understood, but low speed and contacting (wear)

Each has advantages and disadvantages

Options can be evaluated against criteria particular to requirements of each facility

Requirement/ Parameter	Injector Req.	Iron Insert	Rail Gun	Induction	Gas Gun	Supercond Insert
Repetition Rate (Hz)	5-10 Hz					
Injection speed (m/s)	100 – 200 m/s					
Cryogenic compatiblity						
Target accuracy	±2 mm					
Confidence it would work						
Cost						
Reliability/ wear						
Development cost						
Usefulness for IFE (10^8 shot lifetime)						
Score						
Score without IFE & Reliability						

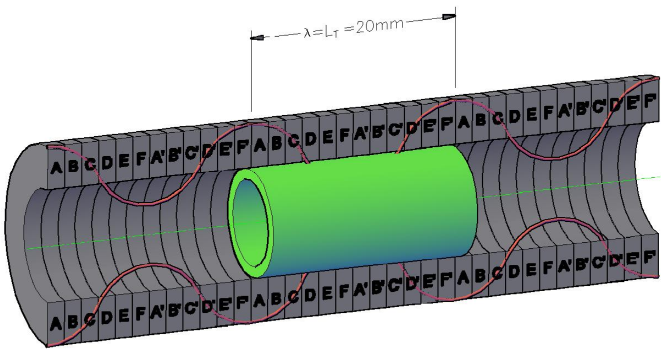
- **We have done this a number of times**
- **Typically, for high speed injectors for IFE, the high ranking options are:**
  - Magnetic induction accelerators
  - Gas guns
  - Rail guns when number of shots needed is low

We are starting to work on a prototype for an induction accelerator to gain experience with it, like we have with the gas gun

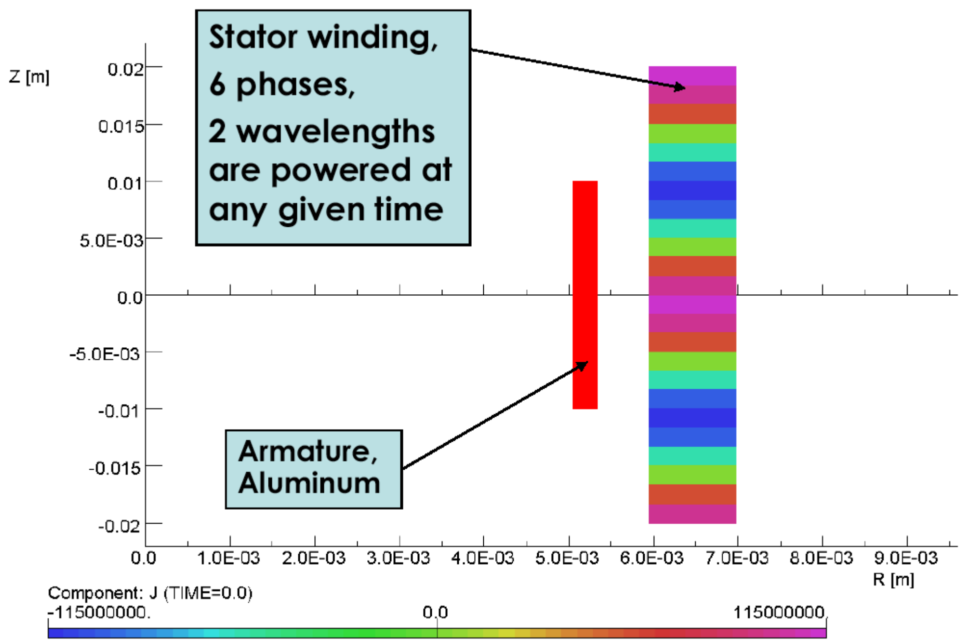
- **Gas guns work but warm gas and wear are drawbacks**

- **There are several advantages to induction accelerators**
  - Long life potential due to no physical contact
  - Superimposed rotating field can impart stabilizing spin to target
    - For non-spherical targets like FI cone-in-shell
  - No gas to dispose of prior to chamber entry

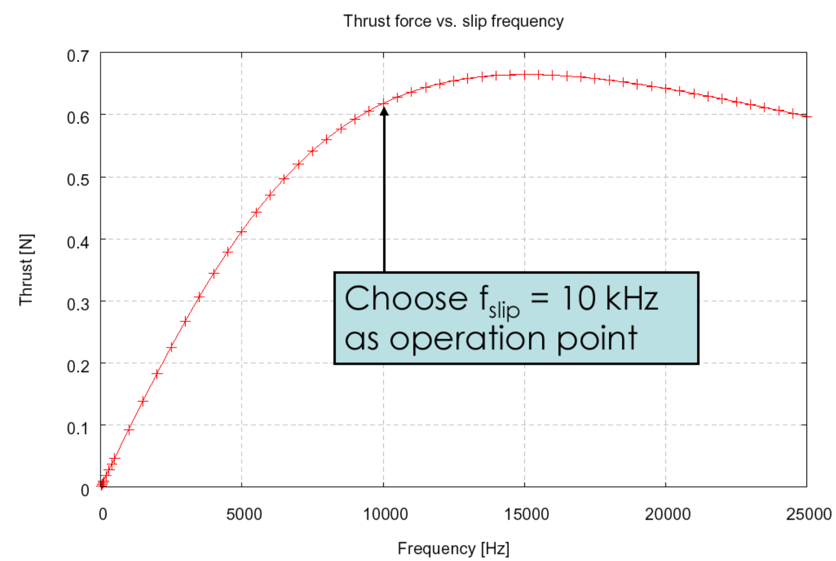
- **A laboratory injector will test suitability for target injection**
  - What accuracy and stability can be achieved?
  - Demonstrate electrical performance and viability



We have modeled an induction accelerator

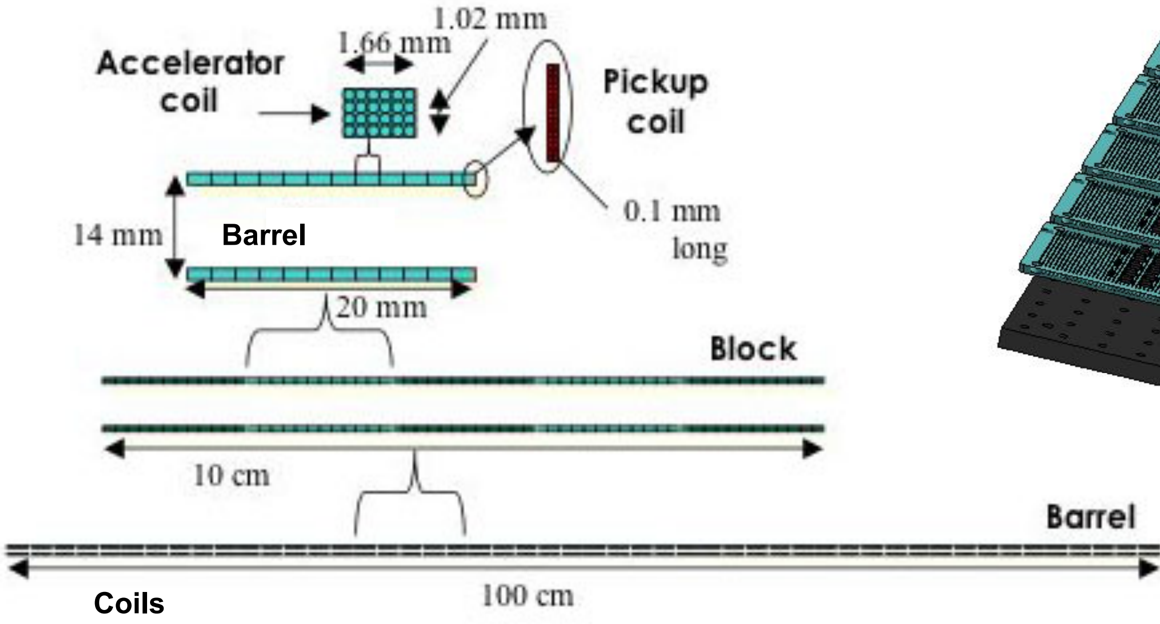


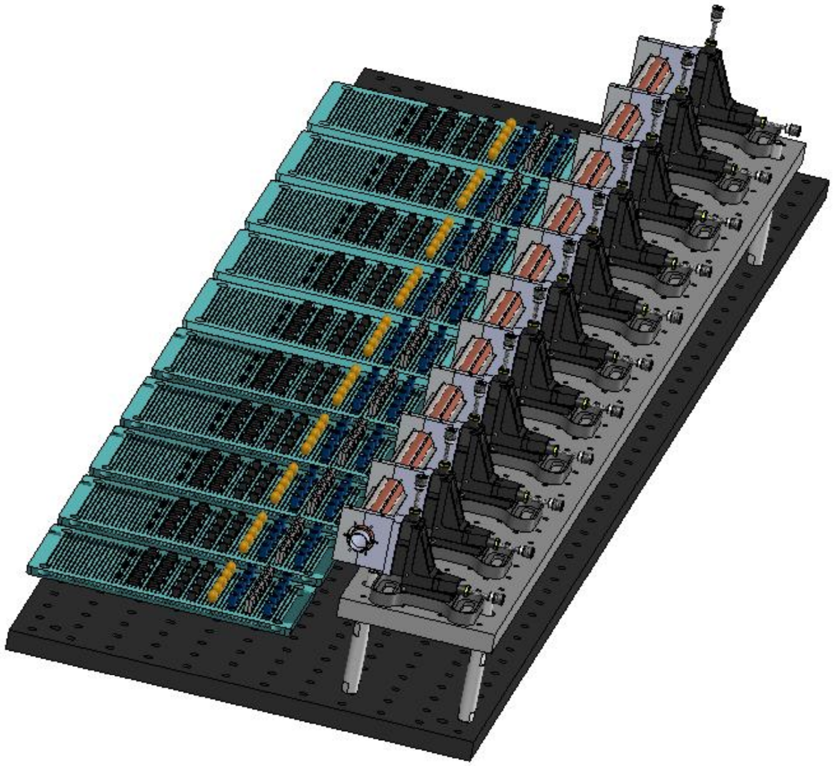
Armature Thrust vs. Slip Frequency



- Both finite element calculations and analytical models have been used

We are ready to proceed with induction accelerator hardware development





Summary

- **An rep-rated target inserter is available for use on Gemini**

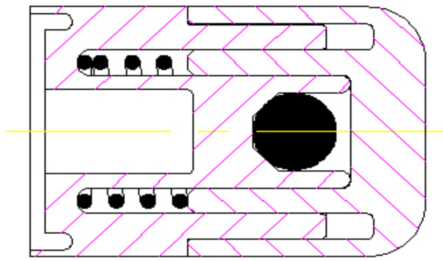
- **We are working to develop target injectors for IFE**
  - As well as target tracking, and on-the-fly steering

Portions of work supported by General Atomics and STFC/RAL under contracts 4154922 and 4162041

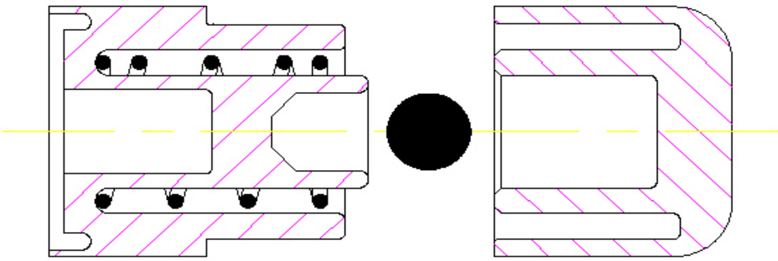
End of presentation

- **Backup slides follow**

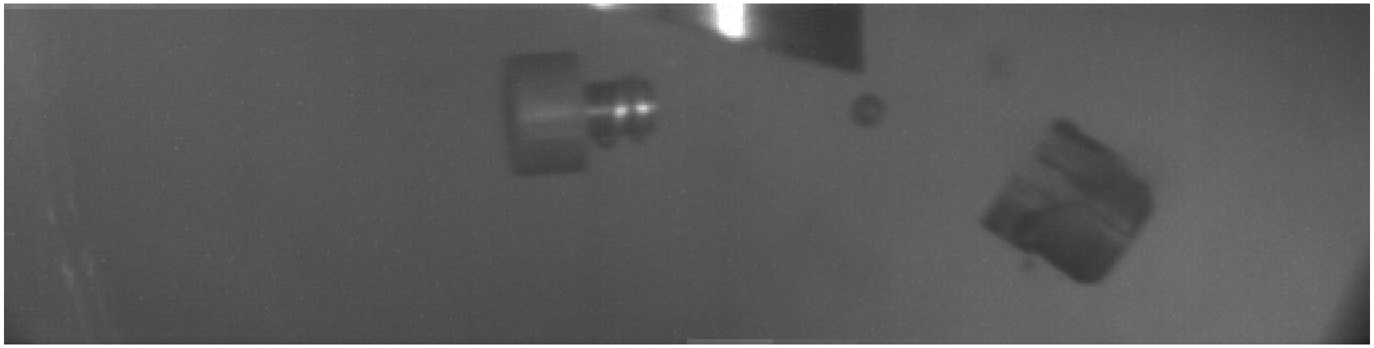
In the gas gun, a spring loaded two-piece sabot was used to protect the target



Sabot (engaged in barrel)

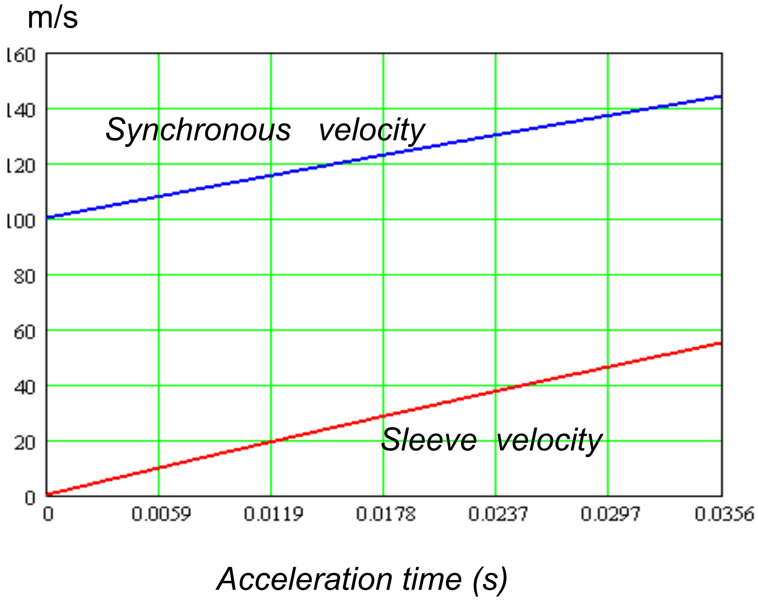


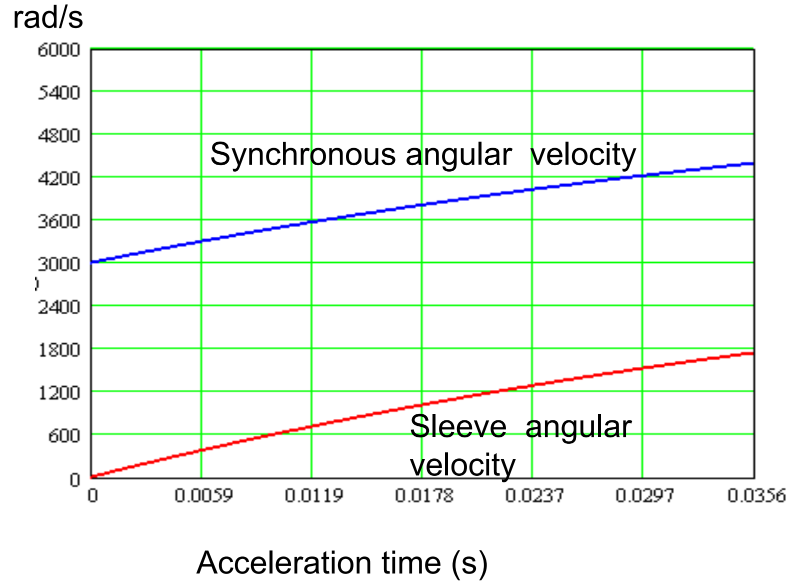
Sabot (disengaged in flight)



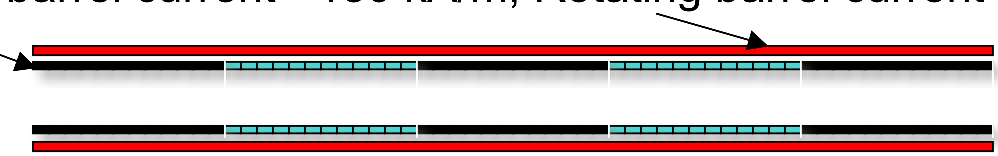
Sabot (deflected out of injection path after leaving barrel)

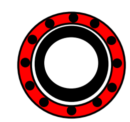
Superimposed fields can induce linear acceleration and rotation





Propulsion barrel current - 180 kA/m, Rotating barrel current - 40 kA/m (analytical model)





Modified rotation barrel windings will allow room for inner barrel windings and disassembly and mechanical support for propulsion barrel