Agenda

• Review PHELIX results
• Targets for the Titan beam time
Review of 2012 PHELIX campaign
Principle of “passive” beam focusing

- **Problem**: electric self-field **defocuses** beam; magnetic self-field (B) **focuses**. In vacuum, $E > B \rightarrow$ net transverse expansion.
- **Approach**: beam fills gap between conductors; image charge builds up and generates counteracting field (shortens out the beam field).
- Stack many foils. If $E \leq B$ than net focusing possible.

**Strength of the net E-field** is determined by the aspect ratio (e.g. diameter of the beam to distance between planes).
- E-field decreases non-linearly with increasing ratio.
- Reduced to 1/4 of its vacuum value, when the distance equals diameter.
- Less 1% a percent, when the distance is 1/8 of diameter.

- S. M. Lund et al., "Envelope model for passive magnetic focusing of an intense proton or ion beam propagating through thin foils", submitted to Physical Review Special Topics: Accelerators and Beams (2012)
Design of experiment

- TNSA proton beam is generated by focusing a laser on a gold hemi-sphere-shaped foil.
- Hemi-sphere reduces initial beam divergence.
- Stack of foils (lens) attenuates the space charge field.
- Beam diameter is measured on RCF stack placed at the exit.
- Reference experiment: same conditions but the lens is replaced by one foil of thickness equivalent to those of all foils in the lens.

Various physics phenomena occur:
- Beam energy loss and scattering
- Knock on electrons: generation and absorption
- Warm-dense-matter hydrodynamics and conductivity
- Enhanced dE/dx stopping in plasma

Proof of principle experiment: compare diameters in the “lens” shot to those in reference experiment.
Design of experiment (2)

For target design, used beam envelopes estimated with a simplified model (single particle, no scattering, full energy spectrum, finite length of the beam, etc). For more elaborate estimates see paper by S. M. Lund.

Three representative gap sizes

- **25 \( \mu \text{m} \)** gap leads to a strong E-field attenuation (short focus)
- **50 \( \mu \text{m} \)** spacing provides less attenuation, which results in a longer focal length, but still makes it possible to contain the beam.
- **100 \( \mu \text{m} \)** distance does not provide enough E-field cancelation to focus the beam and can only decelerate the space-charge driven expansion.

**Summary**: a several folds difference in diameters that can be easily detected. The number of foils required for these initial proof of experiments, depending on the gap size, ranges from 100 to 400.

**Objective of experiment** is straightforward: demonstrate the effect by observing diameter variation.
Target design (by General atomics)

50 \( \mu \text{m} \)-gap target:

- Hemi-sphere assembly:
- Foil and washer assembly:
  - \( \varnothing 22 \)
  - \( \varnothing 12 \)
  - Washer

0.05 \( \mu \text{m} \) Al foil

Laser-drilled hole for pumping

0.65 \( \mu \text{m} \) Al foil

x300

Target assembly:

Reference target:

- Al foil
- 0.2
- 0.36

Dimensions in mm, NOT TO SCALE

Proton TSNA assy sketch v1_2
18 October 2012
By N Alexander

- Targets are manufactured by Neil Alexander (GA)
- 100-\( \mu \text{m} \) target is similar in design (only washer thickness differs)
Thanks to GA we had in total 15 targets to shoot:
1. 100 um-gap, 30 mm length (5)
2. 50 um-gap, 15 mm length (5)
3. Reference (5)
Beam distortion by the lens: what to expect?

- For the purpose of demonstration, chose an economical option: stacked commercially available 0.650 mm foils \( \leftrightarrow \) OK for the POP experiments, but should be thinner in the future.
- 300 aluminum foils net in \(~200\ \mu\text{m}\) integrated thickness

![Energy loss of proton beam in 200 \(\mu\text{m}\) Aluminum](image1)

![Estimation of proton spectrum](image2)

- Per A. Yuen’s estimates, lateral straggling in 200 \(\mu\text{m}\) is not too critical.
- The target will noticeably alter the beam energy but still sufficient to see the phenomena.
Beam profile measurement with RCFs

- Radio-chromic films (RCF) are used to measure dose and beam geometry.
- Upon radiation the darkening due to polymerization occurs.
- Dose is proportional to the optical dentistry (OD).
- Each RCF corresponds to a Bragg peak of certain energy.
- In case of broad energy spectrum, there is also contribution of protons at higher energies, beyond the Bragg-peak.

An RCF film corresponding to Bragg peak of 6.4 MeV also contains exposure from protons at E>6.4 MeV:

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Spot size characterization

Processing in image ImageJ:
• Determine the contour containing 90% of the signal → area and total count
• Best fit ellipse → length of major and minor axis, center position and angles
• Error of dimensions with and without background is less 5%.
Experimental results: best shot

Shown Optical density for all RCFs (placed 22 mm away) in a stack for a reference and a lens shot (50 um spacing). The beam propagates 15 mm in stack and 7 mm in vacuum.

Images (in false colors) are scaled equally for a direct spatial comparison.

A noticeable difference between reference and lens shots provides the evidence!!!
Experimental results: a closer look

- Focused beam has a structure
- The shape is elliptical in both type of experiments
- For each energy, intensity is a contribution of Bragg peak protons, beyond Bragg-peak (more energetic) protons, x-rays and electrons.

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<td>75 um</td>
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<td>22 mm</td>
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<tr>
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<tr>
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Beam transverse size and divergence at 22 mm distance

In many cases, spot shape is ellipse-like; showing major and minor axis of a “best-fit” ellipse:

- There is a noticeable focusing effect, i.e. the lens collimates the initially diverging beam.
- Envelope radius vs energy is a “smooth” function.
- Lower energies are focused stronger (→ higher currents, means higher focusing B).
- “The ellipse” shape(axis) evolves unequally.
Beam area and “focusing strength

• “Area” is an integral of the region confined by the contour (containing 90% of signal).
• “Focusing strength” is ratio between reference and lens-shot

- Focal spot area reduction up to 3.5 times.
- Lower energies (higher current) focused stronger.
- Higher energies have “constant” degree of focusing.
- High deviation of focusing strength at 18.7 MeV is true, and not understood.
Beam transverse comparison to a “primitive” simulation

An initial attempt to compare with simulations (idealized, initial beam conditions from Bellei et al.)

- Reference shot matches pretty good.
- Lens does not match at all: the entrance diameter should be 2-3 times smaller
- Need a full scale simulations. With electrons, scattering, full spectrum, realistic injection, etc.

Alignment of focal spot on the apex of the hemi was one of the major problem. Mainly due to:
- Lack of appropriate equipment/experience
- Target did not have an explicit guiding fiducials, e.g. it was hard to navigate at the surface of the hemi.

We shot all the targets, not all of them worked…

1. **Reference targets**: 4/5.
2. **100 um-gap-size**: 0/5. No useful shots because either
   a) the beam could not be transported: the target was too long to transport the beam, with the alignment capabilities → clipped the exit hole
   b) the beam expanded to the size larger than the exit hole.
3. **50-um-gap-size**: 3/5. Focusing phenomena could be clearly observed. In all others a severe misalignment.

The good shots were obtained during the last day, after we
- Found an appropriate RCF recipe.
- Found a suitable RCF distance.
- Improved alignment.
Shots overview (2)

Among the same types of shots parameter variations include:

- Laser energy (uncontrollable)
- Apex to entrance distance (uncontrollable)
- Distance from apex to RCF \( \leftarrow \) must be as close as possible but end up with rcf saturation issue

The graph shows average divergence in all shots.
- There is an apparent trend: statistically shots with the lens have smaller divergence.
- The effect is more pronounced for smaller energies.

<table>
<thead>
<tr>
<th>Shot ID</th>
<th>Type</th>
<th>Laser spot, ( \mu \text{m} )</th>
<th>Laser Energy, J</th>
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1. Make first entrance foil thicker (1um) to block all the e for sure.
2. More accurate hemi placement (both orientation and distance to the entrance foil) → large scatter in distance affected the generated beam diameter.
3. Have some alignment fiducials/guides on the hemi surface. In the last campaign it was really hard to navigate on the hemi surface, in many cases missed the apex. Can the apex be concentric with the cut of the hemi? Notches?
4. Insert one mesh in the stack → can monitor the beam profile distortion and magnification. A tentative setup: place 1 mm from the entrance, 10 um period, 1 um thick (possible?).
5. Plastic washers instead Al → use a x-ray to make a side on backlighting to check integrity of foils. Shortcut all the washers with a conducting epoxy (similar to the previous design)
6. Larger opening holes and washer size (twice would be good but there might be technical limits) → less sensitive to off-axis misalignments, no clipping.
7. Thinner foils (e.g ~300 nm possible?) → less beam distortion
8. Make the exit square Al holder thinner. We need an ability to place the RCF as close to the last foils as possible.
Experimental area

Phelix laser bay
Target chamber area
Target chamber interior
Lead shielding

Countdown
Shot crew room

After a shot:
Summary

• Focusing effect observed: diameter of expanding beam was reduced up to a factor of 3.5. As expected, lower the energy higher the focusing strength.
• For the first time observed magnetic pinch effect for heavy ions.
• Obtained motivation to continue further research
• Fulfilled the objectives of the DOE HEDLP proposal.
• Publication in preparation
Stack foil focusing technique: a global roadmap

Proof of principles experiments
(done)

Apply elsewhere
(conventional accelerators,
e.g. NDCX-II, GSI, etc)

Investigate limitations of the technique
(Smallest possible spot, degree of control,
target manufacturing, etc)

Collimation and moderate focusing

Tight focusing

Accelerators
Transport and coupling of 20+ MeV ps-pulses into RFQ accelerators.

Medical application
Proton cancer therapy

Fusion energy
• Focusing of p+, D+ for fast ignition
• X-target ignition pulse

HEDLP
• Generation of WDM
• Radiography
• Neutron generation

Investigate limitations of the technique
(Smallest possible spot, degree of control,
target manufacturing, etc)

Apply elsewhere
(conventional accelerators,
e.g. NDCX-II, GSI, etc)
Titan strategy: two types of experiments

1. A detailed investigation of a proven to work moderate focusing target (50 um-gap). Obtain statistically reliable data for a close comparison with simulations. Check consistency and repeatability of the technique. Test few targets with a gap filled with an insulator. This is a lower risk work since we already have a developed platform from PHELIX. This part is more an optimization, hence less scientific excitement.

2. Heat a REAL target (e.g. 10 um thick Al foil) with a short focus/small spot lens (e.g. 25 um-gap). Use Streak optical pyrometer (SOP) to measure hot-spot size and temperature. This is more exciting and impactful experiment, since it will be a first demonstration, in which the stack focusing is put to a real (useful) work. This choice is more risky, because it will require a new target design and an additional SOP diagnostic.
**Target type-1 (moderate focusing)**

The specs are the same as in the previous 50um design + improvements mentioned earlier. We will need

1. 10 standard (x300, 0.3 um thick, 50 um gap)
2. 6 reference targets for 1
3. 3 targets similar to 1 but all the washers are made from plastic. Is 300 nm thickness realistic? if not than 1 um is OK.

4. 3 targets similar to 1 but vacuum gap is replaced with an insulator. No candidate for insulator material yet. Any suggestions (mylar, plexiglass)? An insulator must be low density to prevent the beam losses. Any examples from the fusion targets?

- Targets 1, 2 and 3 will generate an impact on a level of POP publication. It will give more opportunity to validate the simulations, necessary for future fusion related designs.
- Target 4 is very important for the further practical development of the technique. Presumably having insulators is better from the manufacturing and handling point of view, which is critical in the practical applications of the lens.
Target type-2 (strong focusing)

1.10 standard (x100, 0.1 um thick, 20um gap) \(\leftarrow\) tentative
2.5 reference targets for 1
3.10 standard (x100, 0.05 um thick, 20um gap) \(\leftarrow\) tentative
4.5 reference targets for 2

- These shots are critical for the fusion HEDLP community. All the people care is a tight focus on a target. If we want to push into the fast ignition business we must demonstrate target heating.
- This is a very risky experiment. However, if proven to work it will greatly help to raise money in the future and certainly will lead to a “prl”, “nature” publication.
- We are in the process of finalizing the final design. Will have exact specs in January
A possible approach to build a small gap thin foil target

1) Layer of coated Al

2) A large piece of photo-resist substrate

The plate is laser-cut in smaller pieces

Pieces stacked up in a tube holder

3) Solvent (e.g. acid) is applied to create a gap

4) Tube has a milled slots to let the acid in.

inner walls of tube are covered with glue to hold the foils

held by glue

Same approach can be applied to a target with insulator. No dissolving is required