CNRS MITI

INVESTIGATION OF ADVANCED LASER DRIVEN-PROTON SOURCES PRODUCED BY THE INTERACTION OF RELATIVISTIC LASER PULSE WITH LOW DENSITY FOAMS AND THEIR APPLICATIONS TO PROTON-BORON FUSION

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Contents

Introduction

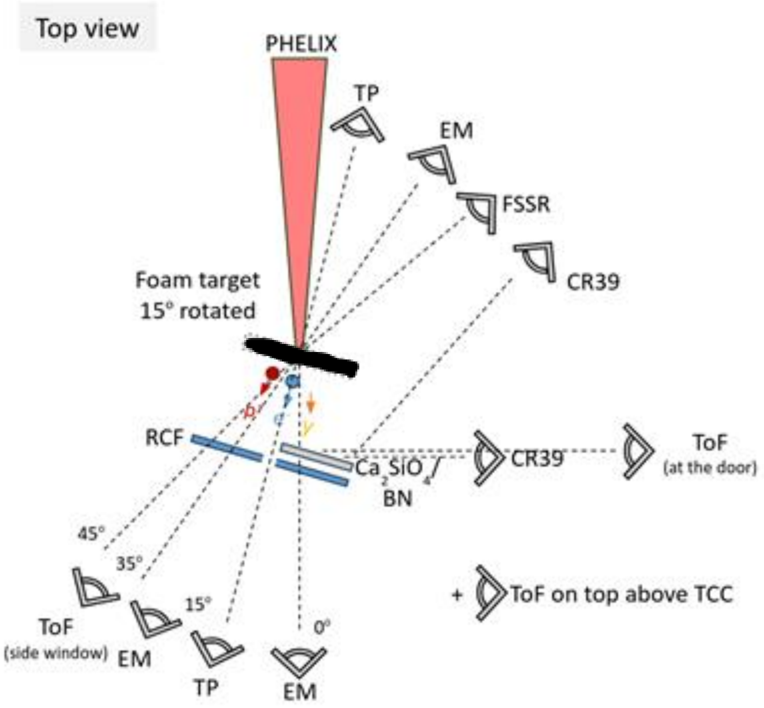
Foam targets should produce more intensive proton beams as compared to solid targets:

- Solid target: TNSA mechanism = surface effect on the dust in the back surface of thin foil, induced by fast electron produced in the front surface by ultra high intensity laser
- Foam target: DLA/RPA mechanism =volume effect= increasing the coupling of the laser to the ions.

The goal of the experiment:

Investigation of the process of p^+ acceleration in very long scale-length laser-generated plasmas using foam targets, higher efficiency of laser absorption into protons and maximise the p-BN nuclear reaction number

Experimental setup PHELIX LASER GSI



TARGET / PITCHER:

- Low-density foams (some with foil on the back side)
- The angle between target normal and to laser axis = 15°

DIAGNOSTICS

ACTIVATION SAMPLES / CATCHER : Ca2SiO4/BN for gamma-ray activation measurements

- RCF: radiochromic films for proton and ion diagnostics
- TP: two Thomson parabolas in front and behind the target
- CR39: plastic nuclear track detectors for alpha-particle measurements
- ToF: three time of flight detectors:
  - 270° position: multichannel pixelated time-of-flight detector
  - Chamber roof position: simple ToF detector
  - 45° position: simple ToF detector
- FSSR: high-resolution X-ray spectrometer
- EM: electron magnetic spectrometers

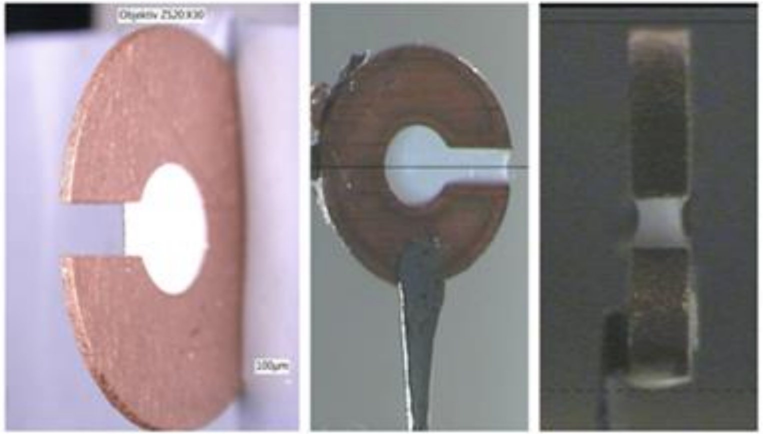
Experimental parameters

Target

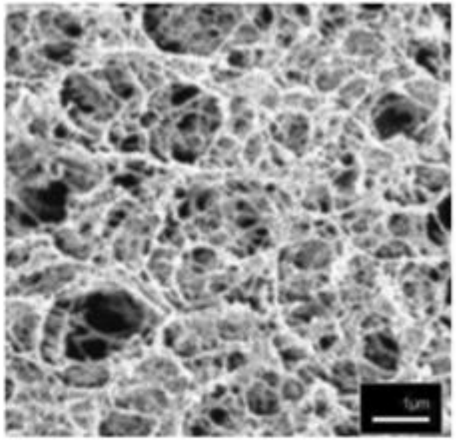
- Thickness: 300/500/1000/2000 um
- Density: 2/2.3/5/10 mg/cc
- Diameter: 1 – 4 mm
- Optional doping: 2% Ti; 40% B
- Optional additional layers: Ti foil 13 um: Au foil 13 um

Laser

- Energy: 57 – 80 J
- Duration: 600 fs
- Prepulse: none/ 3 ns 0.3 % energy/ 3 ns 3% energy



Foam target inside a copper washer



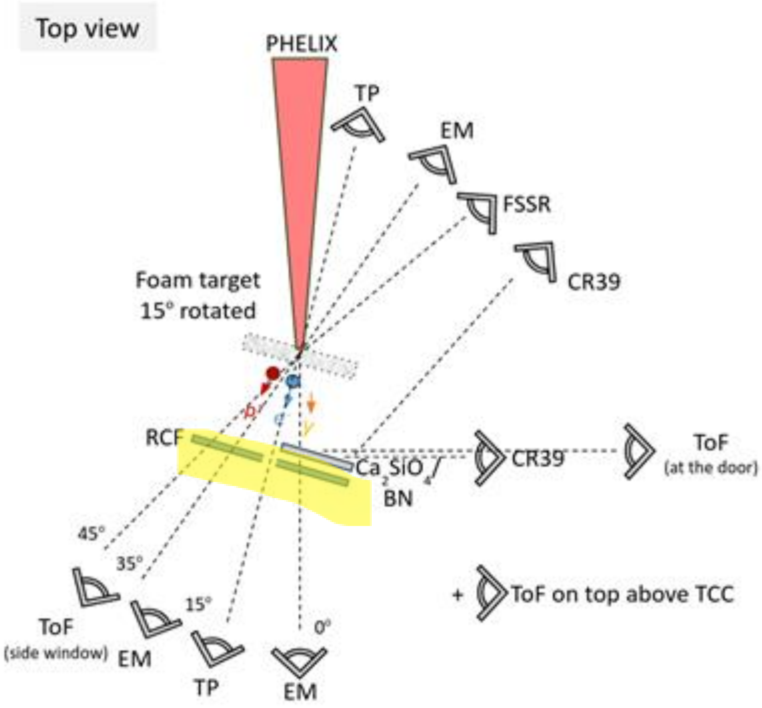
Target mounted on a holder

Shots list parameters

the devil is in the details

	A	I	J	K	L	N	Q	U	W	AA	AC	AH
1		**Pitcher (primary laser target)**				**Catcher - back (secondary p+ target)**			**Laser: ps**		**Laser: ns**	
2	Shot #	Type	Specification		Where from	Type	Position (**front and back**)	type	Energy received (full)	Intensity	requested energy	delay (ns-first)
3			**foam:** density / thickness	**foil:** thickness, µm			distance to pitcher, mm		J	W/cm2	%	ns
4	1	Ti foil	–	Ti 10 µm	GSI	Ca2SiO4	100	ps only	67	1.26E+19	–	
5	2	foam	5 mg/cc, 500 µm	–	China (Bing L…	BN	100	ps only	70	1.31E+19	–	
6	3	Ti foil	–	Ti 10 µm	GSI	Ca2SiO4	105	ps only	64	1.20E+19	–	
7	4	foam	2 mg/cc, 500 µm	–	China (Olga)	BN	100	ps only	57	1.07E+19	–	
8	5	foam	2 mg/cc, 500 µm	–	China (Olga)	BN	100	ps only	70	1.31E+19	–	
9	6	foam	10 mg/cc, 500µm + 40% B	–	China (Olga)	Ca2SiO4	**35**	ps + ns	64	1.20E+19	**3%**	5
10	7	foam	2 mg/cc, 500 µm	–	China (Olga)	BN	**30**	ps only	65	1.23E+19		
11	8	foam + foil	2 mg/cc, 500 µm	Ti 10 µm	China (Olga)	BN	**30**	ps + ns	67	1.26E+19	0.3%	3
12	9	Ti foil	–	Ti 10 µm	GSI	BN	22	ps only	69	1.30E+19	–	
13	10	foam + foil	2 mg/cc, 500 µm	Ti 10 µm	China (Olga)	BN	22	ps + ns	75	1.42E+19	0.3%	3
14	11	foam	2.3 mg/cc, 2 mm + 2% Ti	–	Australia (HB…	BN	22	ps + ns	79	1.48E+19	**3%**	**5**
15	12	foam + foil	2 mg/cc, 500 µm	Ti 10 µm	China (Bing L…	BN	74	ps + ns	78	1.48E+19	0.3%	3
16	13	foam	2 mg/cc, 500 µm	–	China (Olga)	BN	22	ps only	75	1.41E+19	–	
17	14	foam	2.3 mg/cc, 1 mm	–	Australia (HB…	BN	22	ps + ns	73	1.38E+19	**3%**	**5**
18	15	foam	2.3 mg/cc, 2 mm + 2% Ti	–	Australia (HB…			ps + ns	66	1.25E+19	3%	5
19	16	foam	2.3 mg/cc, 1 mm	–	Australia (HB…	BN	74	ps + ns	74	1.40E+19	3%	5
20	17	foam	2 mg/cc, 500 µm	–	China (Bing L…	BN	74	ps only	75	1.41E+19		
21	18	foam + foil	5 mg/cc, 500 µm	Ti 10 µm	China (Bing L…	BN	74	ps + ns	76	1.44E+19	3%	5
22	19	foam + foil	2 mg/cc, 500 µm	Ti 10 µm	China (Bing L…	BN	74	ps + ns	73	1.37E+19	0.3%	3
23	20	Ti foil	–	Ti 10 µm		BN	74	ps only	80	1.51E+19	–	
24	21	foam + foil	2 mg/cc, 500 µm	Au 10 …	China (Olga)	BN	74	ps + ns	67	1.27E+19	0.3%	3
25	22	foam	2 mg/cc, 500 µm	–	China (Bing L…	BN	74	ps only	63	1.19E+19	–	
26	23	foam + foil	2 mg/cc, 500 µm	Ti 10 µm	China (Bing	BN	74	ps + ns	68	1.29E+19	0.3%	3
27	24	foam	3 mg/cc, 300 µm	–	Natalia	BN	74	ps only	68	1.27E+19	–	
28	25	foam	2 mg/cc, 500 µm	–	China (Bing L…	BN	74	ps + ns	75	1.41E+19	0.3%	3
29	26	foam + foil	2.3 mg/cc, 1 mm	Ti 10 µm	Australia (HB…	BN	74	ps + ns	70	1.32E+19	**0.3%**	**3**
30	27	foam	2.3 mg/cc, 1 mm	–	Australia (HB…	BN	74	ps + ns	72	1.36E+19	**3.0%**	**5**

Experimental setup PHELIX LASER GSI



STACKS OF RCF:

radiochromic films for proton and ion diagnostics

Several RCF Stack types

10 differents RCF stacks

Layer	Shots 1-2
1	My13
2	Al13
3	H2(1.5)
4	H2(3.4)
5	My250
6	My250
7	H2(8.8)
8	My250
9	My250
10	My250
11	My250
12	H2(14.6)
13	My250
14	My250
15	My250
16	My250
17	My250
18	H2(19.9)
19	My250
20	My250
21	My250
22	My250
23	E3(23.8)
24	My250
25	My250
26	My250
27	My250
28	My250
29	E3(28)
30	My250
31	My250
32	My250
33	My250
34	My250
35	E3(31.8)

Layer	Shots 3-5
1	My13
2	Al13
3	H2
4	H2
5	My250
6	My250
7	H2
8	My250
9	My250
10	My250
11	E3
12	My250
13	My250
14	My250
15	My250
16	E3
17	My250
18	My250
19	My250
20	E3
21	My250
22	My250

Layer	Shots 6-9
1	My13
2	Al13
3	H2
4	H2
5	My250
6	H2
7	My250
8	My250
9	My250
10	E3
11	My250
12	My250
13	My250
14	E3

Layer	Shot 10
1	My13
2	Al13
3	H2
4	H2
5	My250
6	H2
7	My250
8	My250
9	My250
10	H2
11	My250
12	My250
13	My250
14	My250
15	H2
16	My250
17	My250
18	My250
19	My250
20	E3
21	My250
22	My250
23	My250
24	My250
25	My250
26	E3
27	My250
28	My250
29	My250
30	My250
31	My250
32	E3

Layer	Shot 11-12
1	My13
2	Al13
3	H2
4	My250
5	H2
6	My250
7	H2
8	My250
9	My250
10	My250
11	E3
12	My250
13	My250
14	My250
15	E3
16	My250
17	My250
18	My250
19	E3

Layer	Shot 13-14
1	My13
2	Al13
3	H2
4	My250
5	H2
6	My250
7	My250
8	E3
9	My250
10	My250
11	My250
12	E3
13	My250
14	My250
15	My250
16	E3
17	My250
18	My250
19	My250
20	E3

Layer	Shot 16, 17, 25, 25
1	My13
2	Al13
3	H2
4	H2
5	My250
6	My250
7	H2
8	My250
9	My250
10	My250
11	E3
12	My250
13	My250
14	My250
15	E3
16	My250
17	My250
18	My250
19	E3

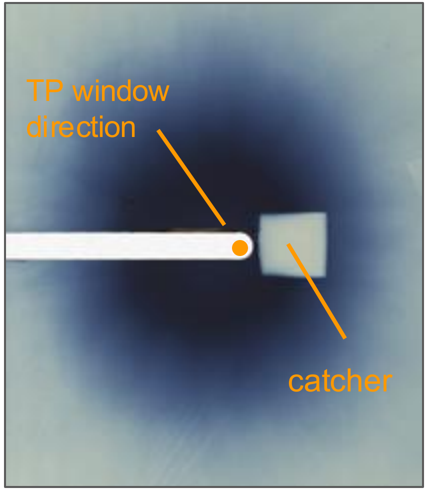
Layer	Shot 18-23
1	My13
2	Al13
3	H2
4	H2
5	My250
6	H2
7	My250
8	My250
9	My250
10	H2
11	My250
12	My250
13	My250
14	My250
15	E3
16	My250
17	My250
18	My250
19	My250
20	E3
21	My250
22	My250
23	My250
24	My250
25	My250
26	E3
27	My250
28	My250
29	My250
30	My250
31	My250
32	E3
33	My250
34	My250
35	My250
36	My250
37	E3

Layer	Shot 26
1	My13
2	Al13
3	H2
4	H2
5	My250
6	H2
7	My250
8	My250
9	My250
10	H2
11	My250
12	My250
13	My250
14	My250
15	H2
16	My250
17	My250
18	My250
19	My250
20	E3
21	My250
22	My250
23	My250
24	My250
25	My250
26	My250
27	My250
28	E3
29	My250
30	My250
31	My250
32	My250
33	My250
34	My250
35	My250
36	E3
37	My250
38	My250
39	My250
40	My250
41	My250
42	My250
43	My250
44	My250
45	E3

Layer	Shot 27
1	My13
2	Al13
3	H2
4	H2
5	My250
6	My250
7	My250
8	E3
9	My250
10	My250
11	My250
12	My250
13	My250
14	My250
15	E3

RCF data : 2D image of the proton distribution

- Stacks positioned normal to pitcher back surface
- Slit is cut out to provide direct proton beam visibility for TP normal to the target direction
- Two catcher positions:
    - Mounted directly before the first RCF
    - On a holder 15mm closer to pitcher
- 13 um Al filter, 13 um Mylar filter

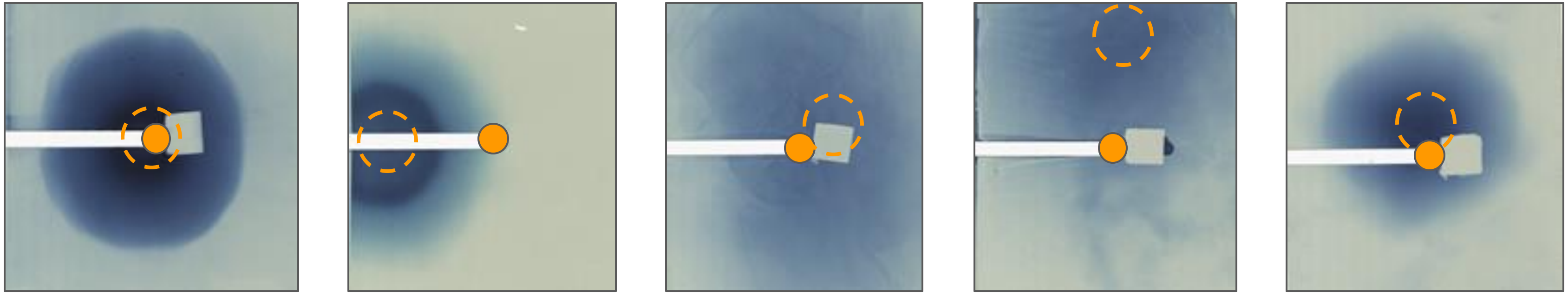


RCF image stack for one shot with respective proton energy threshold. Images 1-4: HD-V2 films, 5-6: EBT-3 films.

Proton beam pointing instability from shot to shot

Likely caused by target parameters

Target surface curvature



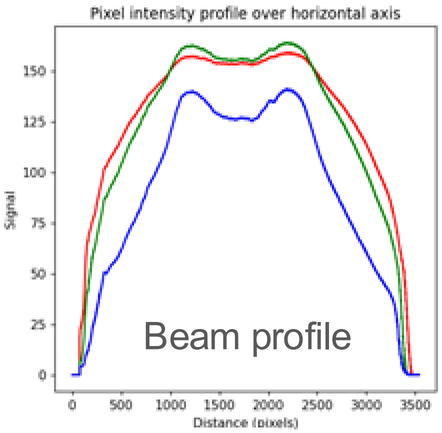
RCF images demonstrating beam pointing deviations for different shots

Approximate beam center position

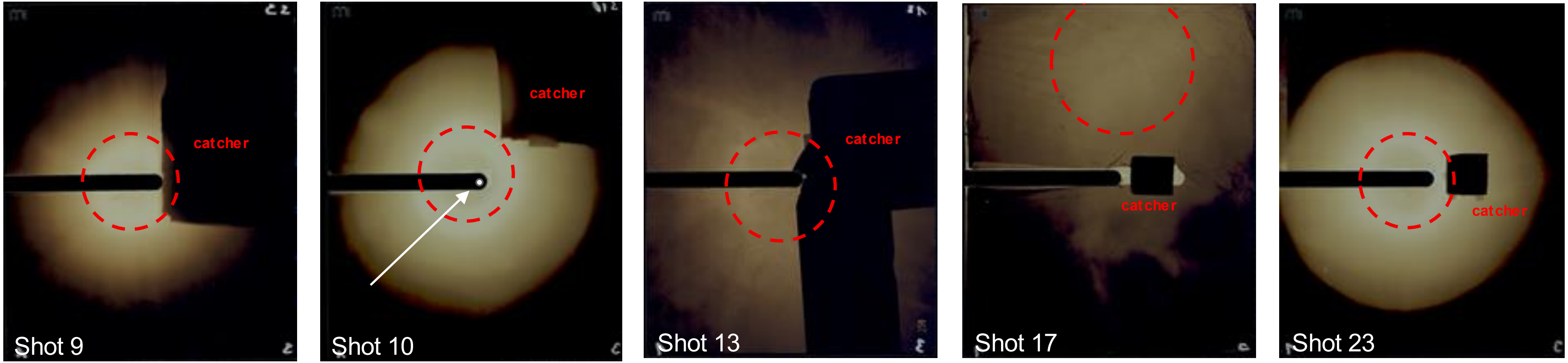
Thompson Parabola entrance slit position μsr aperture

Proton beam pointing instability from shot to shot

catcher and RCF at different distance

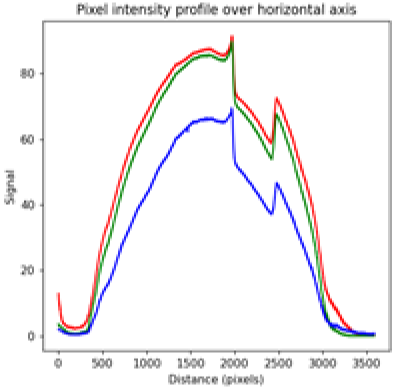


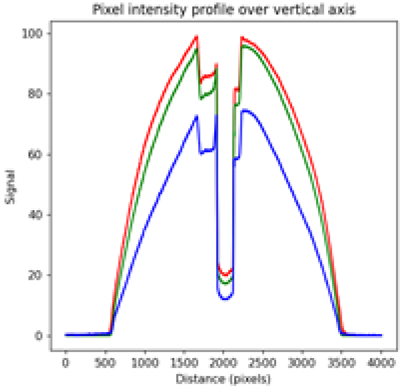
Separate RGB image channels

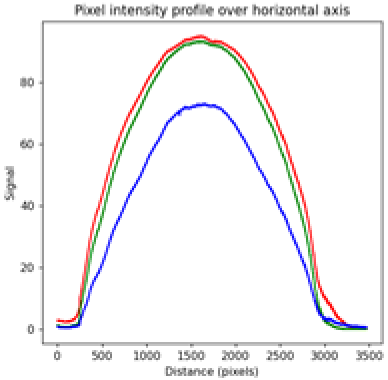


Extrapolation of the exposed catcher surface correction and RCF holder hole

Background subtraction
+ extrapolation applied

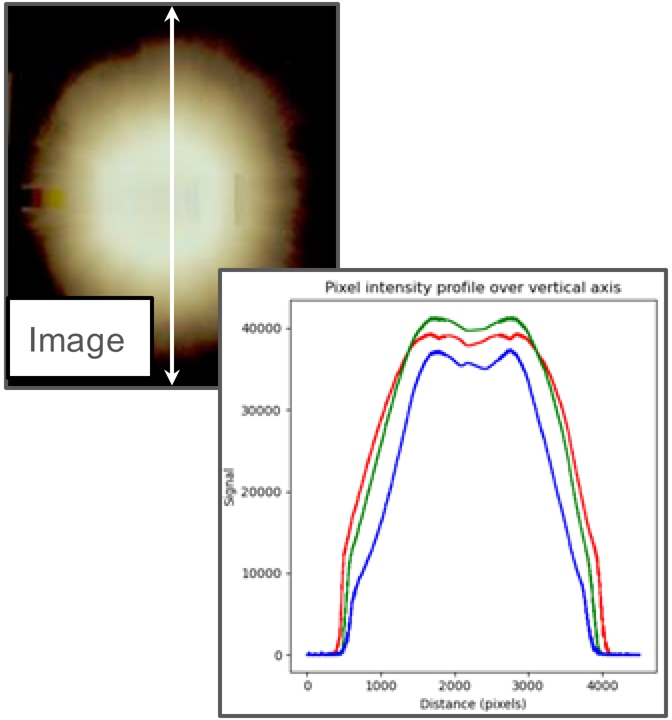


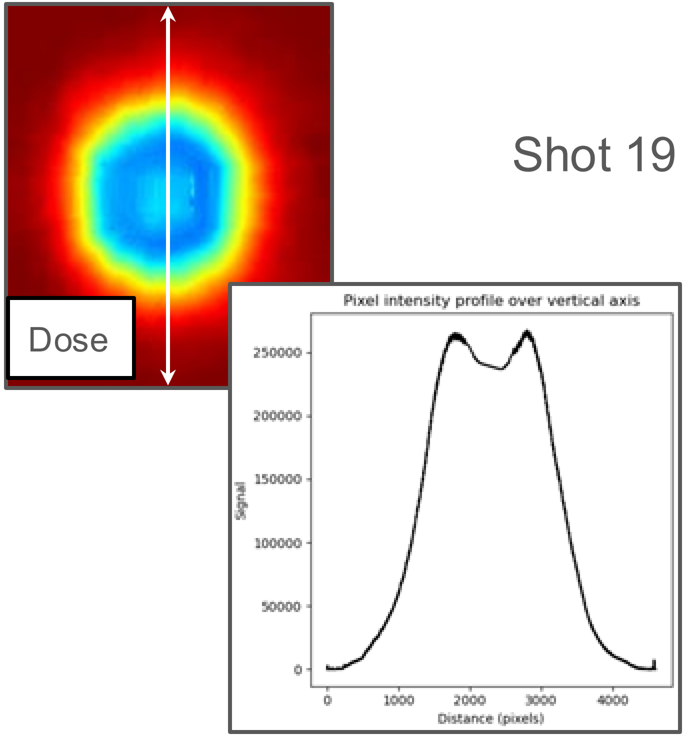




Separate RGB image channels

Proton beam profil : from optical density to dose





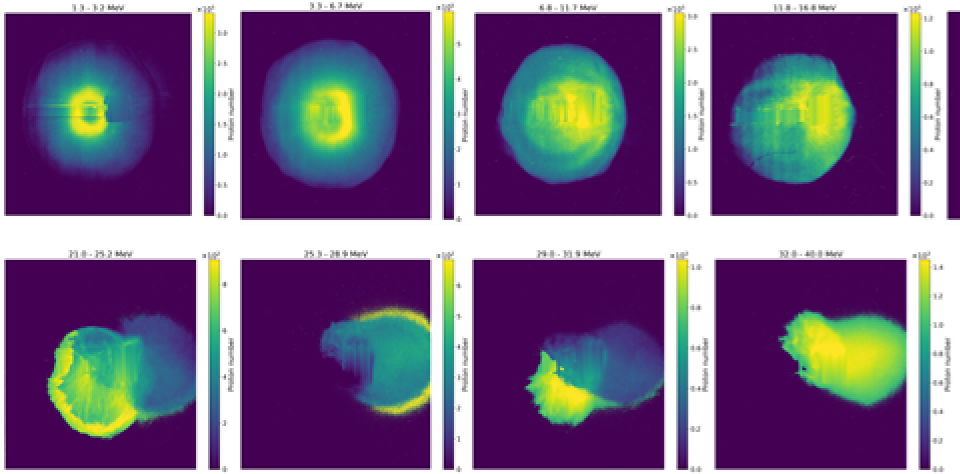
Shot 19 RCF1

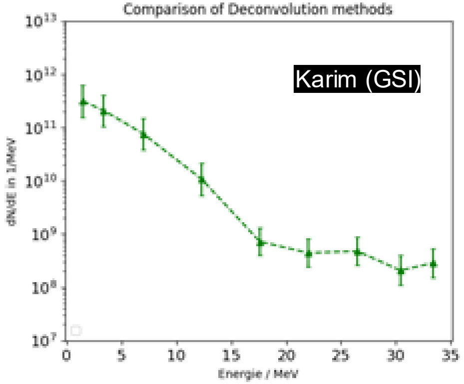
Separate RGB image channels

Proton spectrum :
from RCF Stack deconvolution

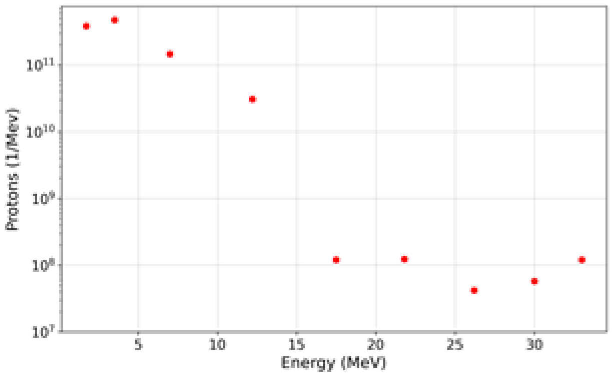
2 mg/cc, 500 um + foil
73J + 0.3% ns

Shot 19





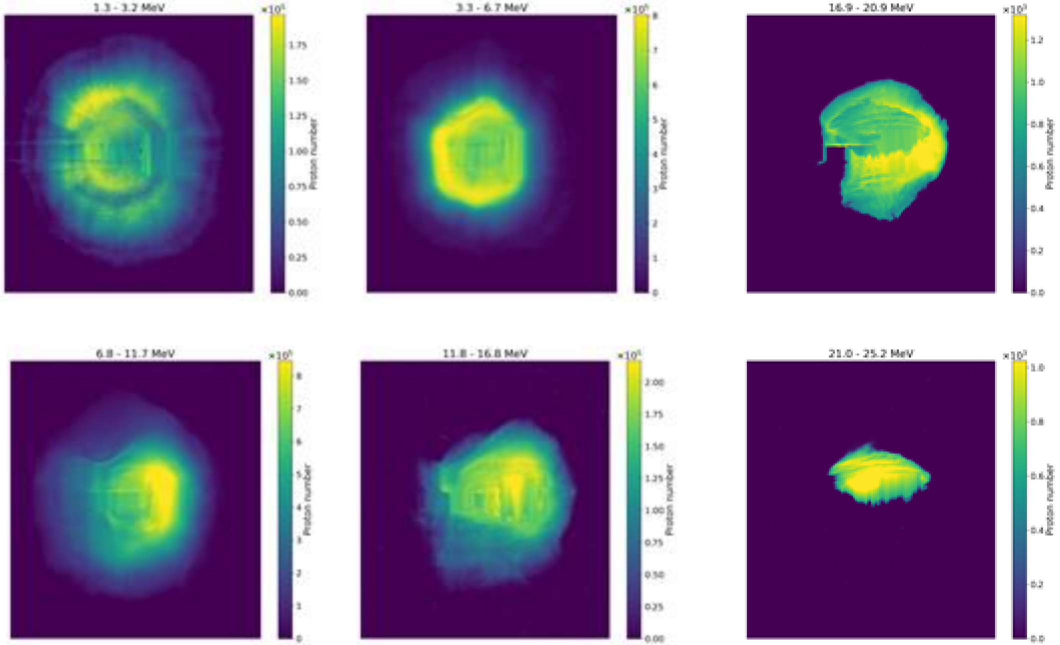
Number of protons per MeV

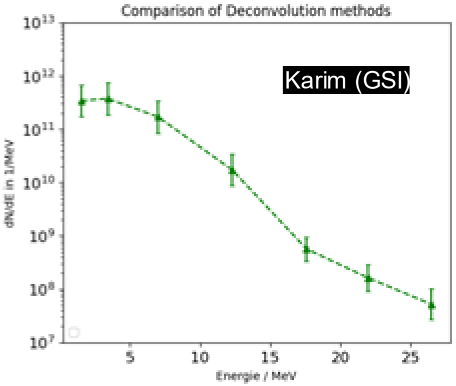


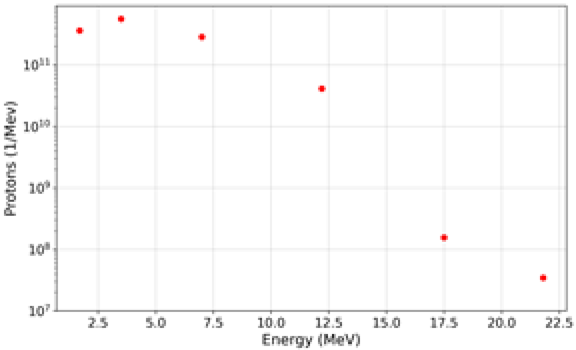
Proton spectrum :
from RCF Stack deconvolution

foil
80J

Shot 20



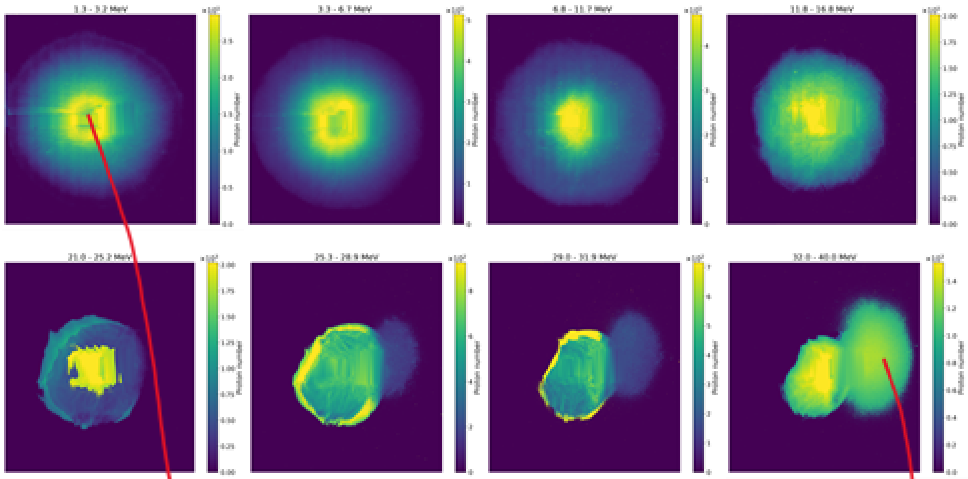


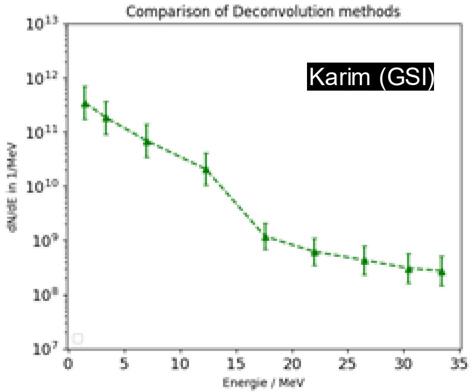


Proton spectrum :
from RCF Stack deconvolution

2 mg/cc, 500 um + gold foil
67J + 0.3% ns

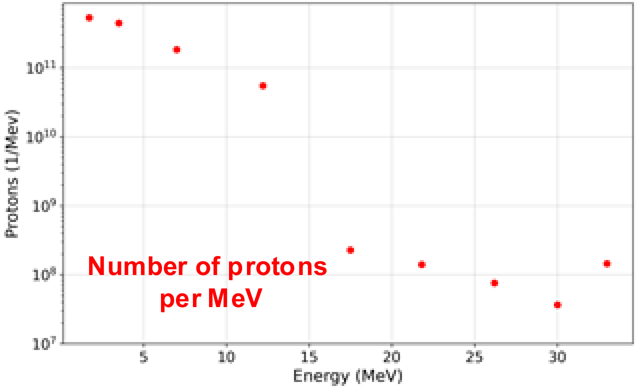
Shot 21





target normal direction

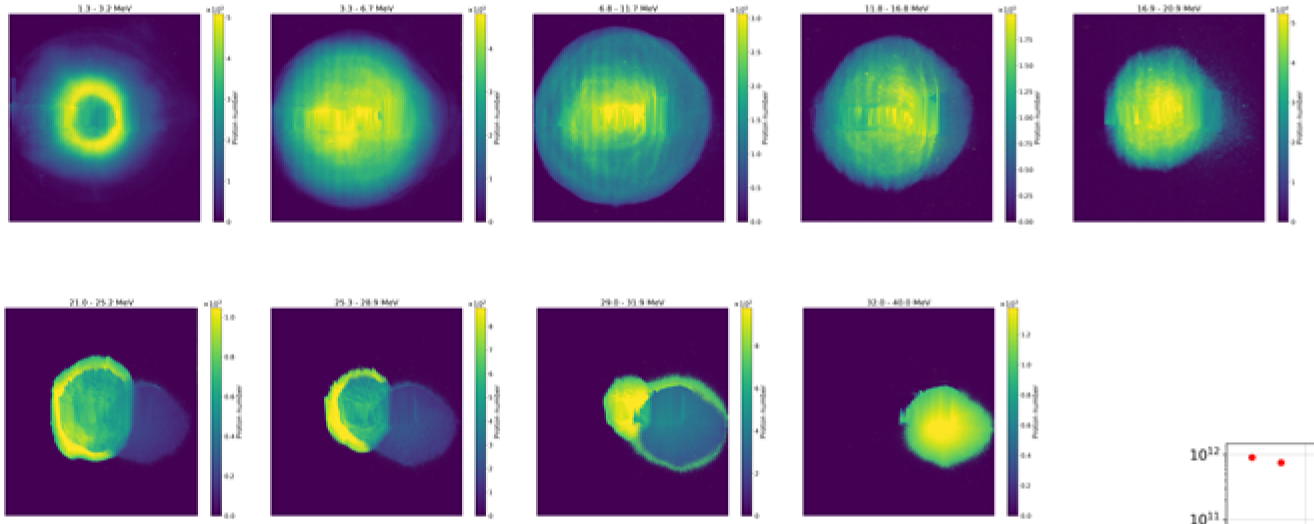
2nd proton beam or others particles at higher energy in the direction of the laser axis or presence of catcher ?

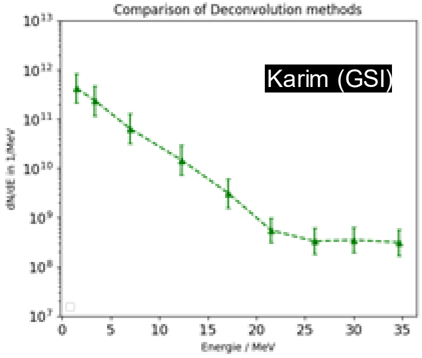


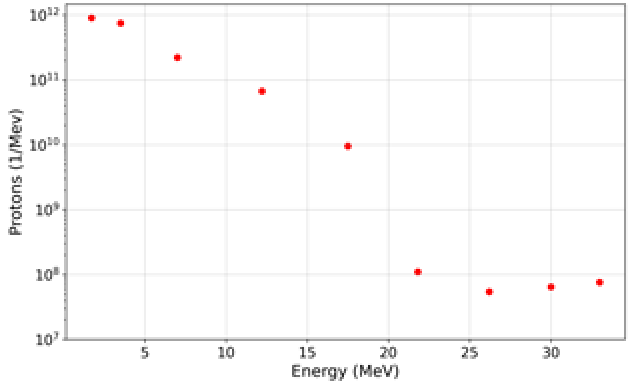
Proton spectrum :
from RCF Stack deconvolution

2 mg/cc, 500 um + foil
68J + 0.3% ns

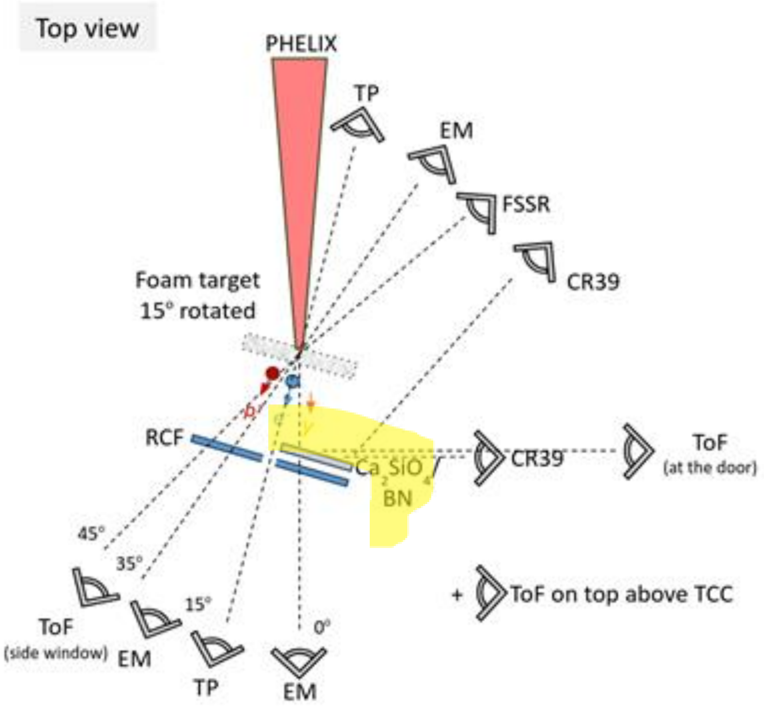
Shot 23







Experimental setup PHELIX LASER GSI

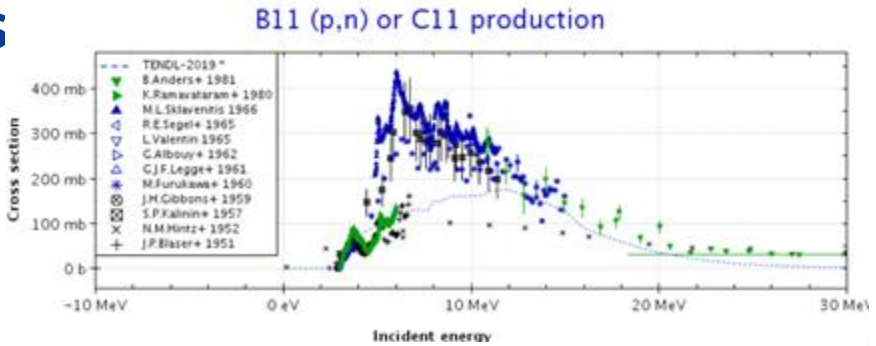


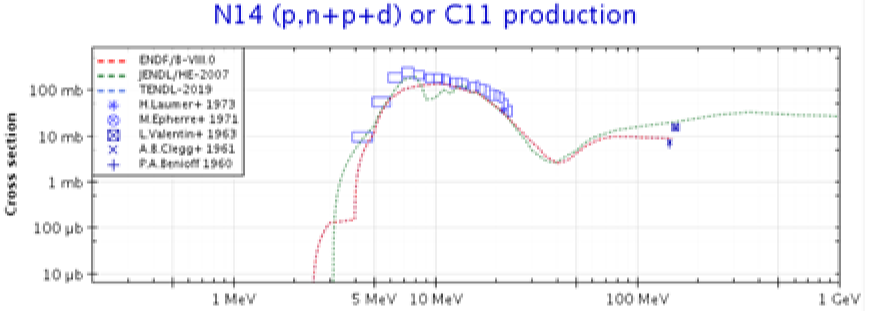
Ca2SiO4 or BN : activation samples for gamma-ray activation measurements

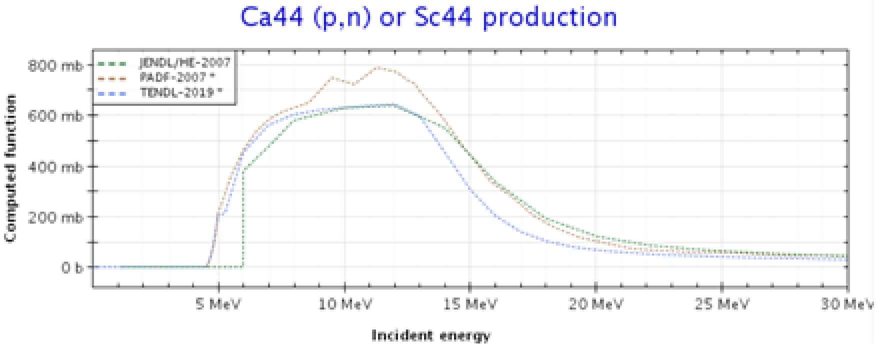
Activation measurements

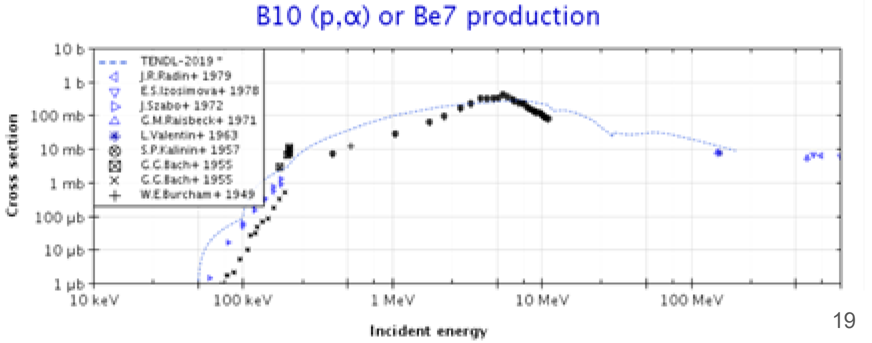
nuclear cross section
see Anton Moroz talk

- **Two HPGe detectors to measure γ ray**
- **Two types of activation samples/catcher**
  - **BN - used in most shots**
    Isotopes produced:
    - **^{11}C ($T_{1/2}$ = 20 min)**
    - **^{7}Be ($T_{1/2}$ = 52 days)**
  - **Ca_2SiO_4**
    Isotopes produced:
    - **^{44}Sc ($T_{1/2}$ = 3.87 hours)**
- **For some shots, samples were placed in front of <u>and behind</u> the target**









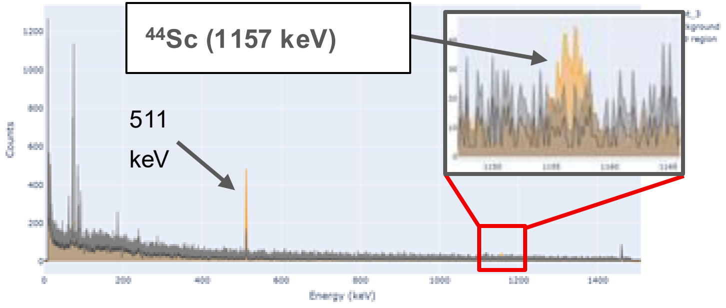
Activation measurements
γ ray lines signature

Workflow:

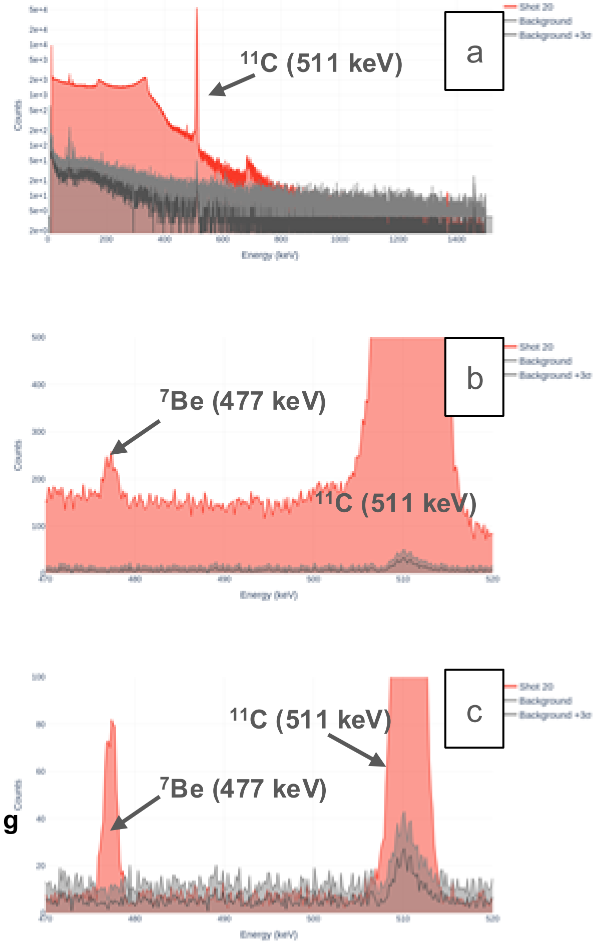
- Measurements done after each shot
- Remeasurements for long-lived isotopes performed afterwards (up to 60 h acquisition time)

Decay schemes:

- $^{11}C \rightarrow {}^{11}B + \beta^+ + \nu_e$
  $e^- + \beta^+ \rightarrow 2\gamma$ (511 keV)
- $^{7}Be + e^- \rightarrow 7Li + \nu_e + \gamma$ (477 keV)
- $^{44}Sc + e^- \rightarrow {}^{44}Ca + \nu_e + \gamma$ (1157 keV)



Ca_2SiO_4 activation spectrum. Background with 3σ-significance interval highlighted in grey.



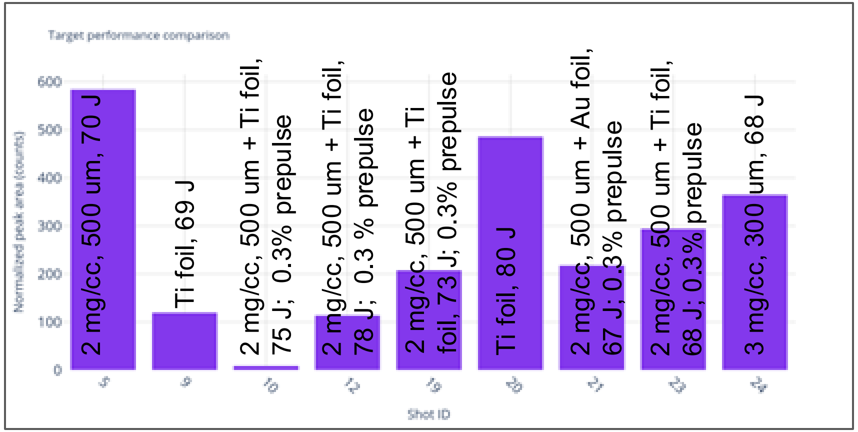
BN activation spectra:
a) full spectrum;
b) region of interest featuring Compton continuum;
c) region of interest after $10*T_{1/2}(^{11}C)$

Activation measurements

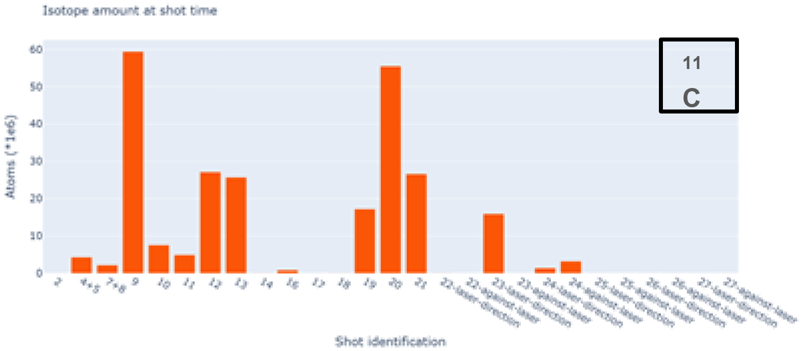
histogram number of atoms versus shot

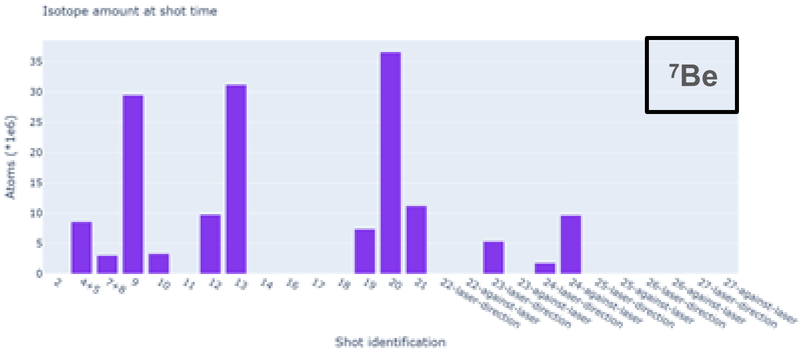
Based on HPGe detector data, amounts of isotopes produced per shot were determined:

- **^{11}C: up to 35 kBq or 6×10^{7} atoms**
- **^{7}Be: up to 6 Bq or 3.6×10^{7} atoms**



Target comparison by ^{7}Be counts normalized by acquisition time and activation sample exposure.
Target density and thickness with laser energy are indicated

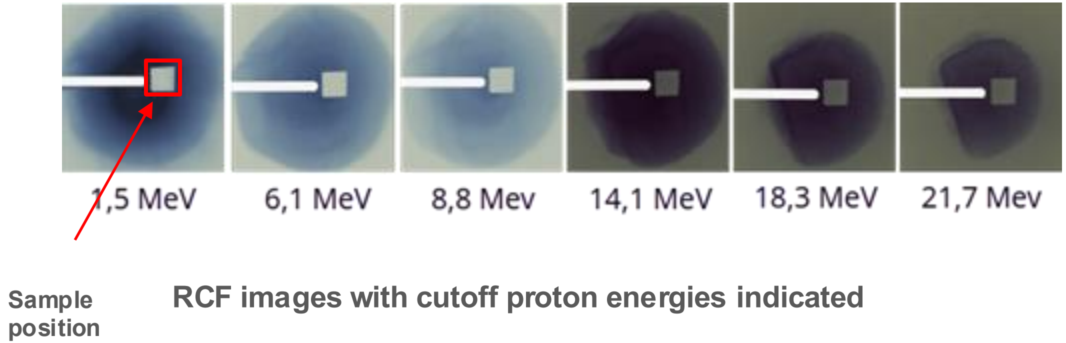




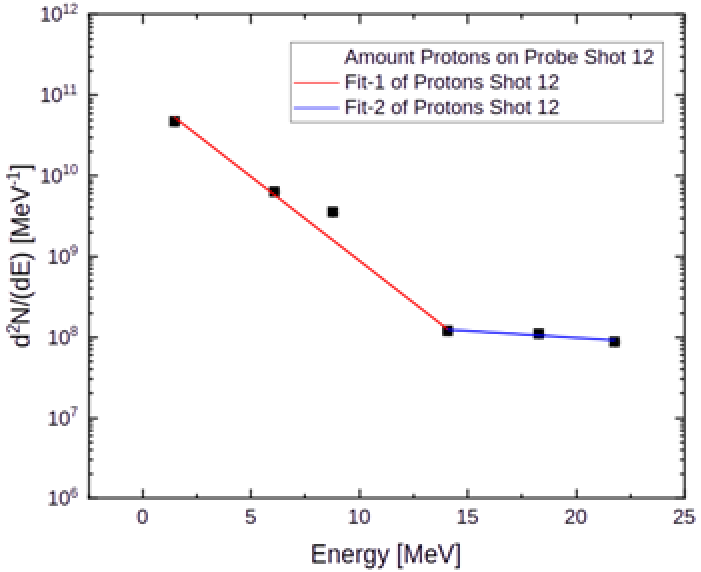
RCF and Activation data comparison

1. Estimating the spectra of protons crossing the activation sample surface from RCF images
2. Considering reaction cross-sections and proton range in activation sample
3. Calculating expected isotope activity
4. Comparing with activation data

Parameters: foam + foil 2 mg/cc 500 µm, 74 J 0.3% ns pulse



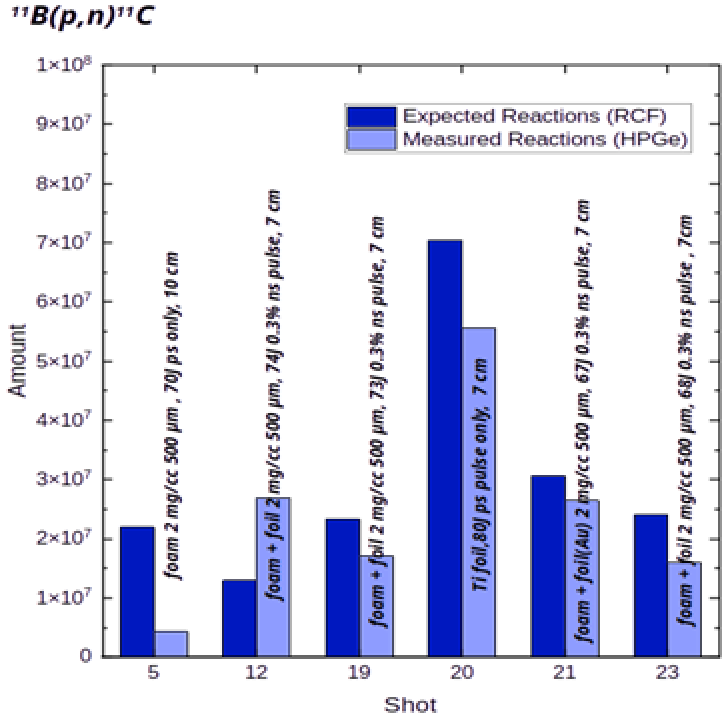
RCF images with cutoff proton energies indicated

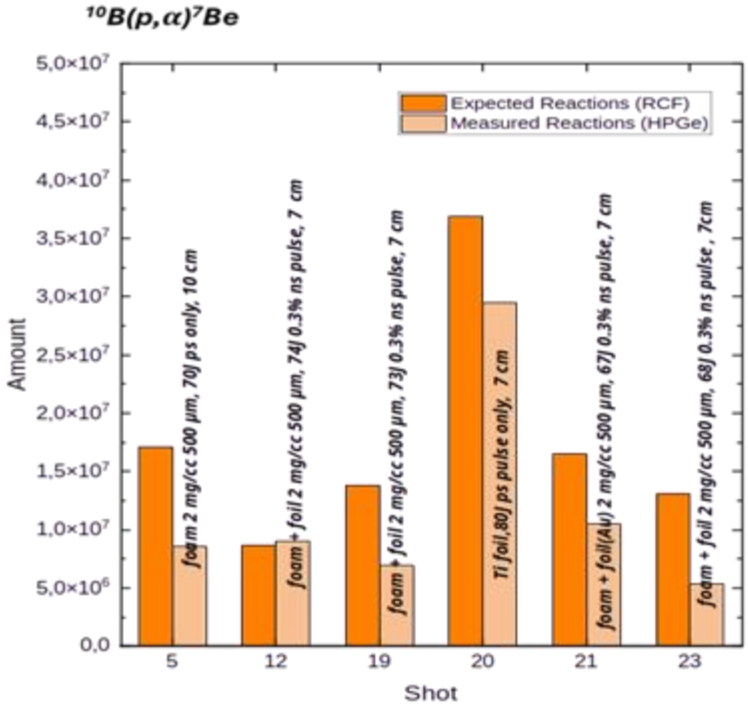


Estimated proton spectrum over the activation sample surface

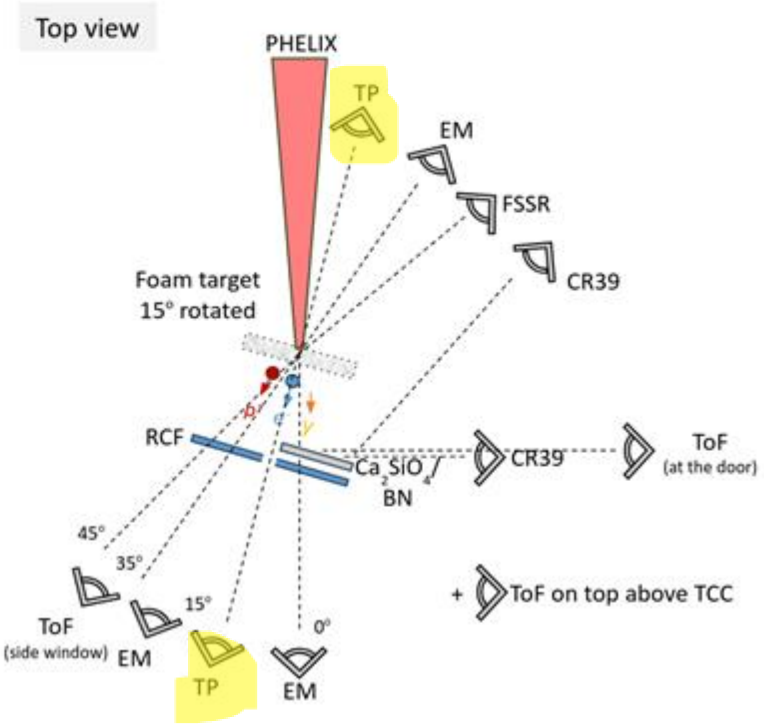
RCF and Activation data comparison

Sebastian Busch





Experimental setup PHELIX LASER GSI

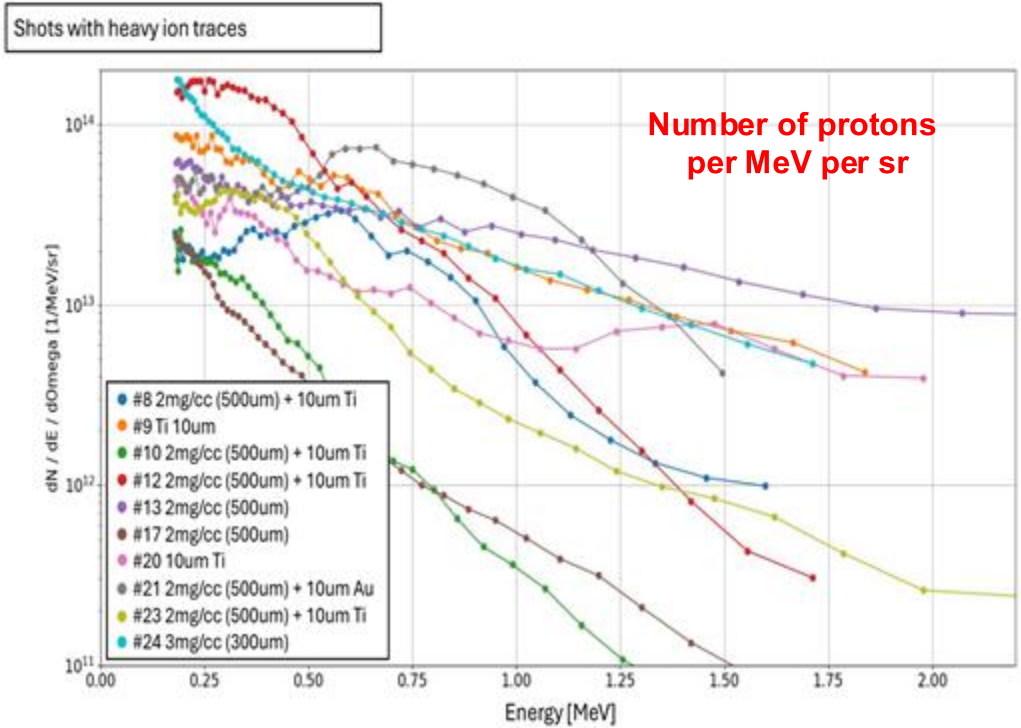


TP : two Thomson Parabolas in front and behind the target

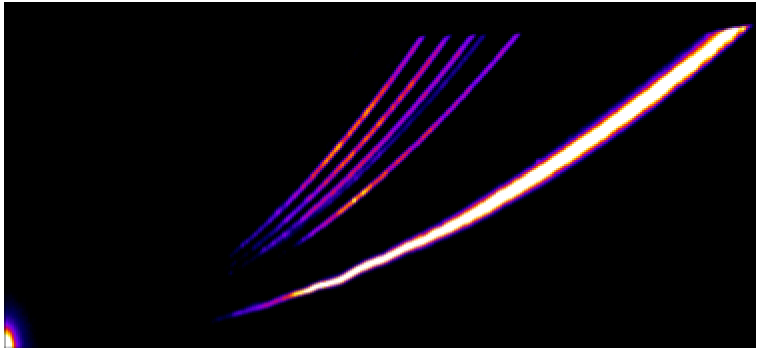
Thomson Parabola TP data

Two detectors in front of and behind the target

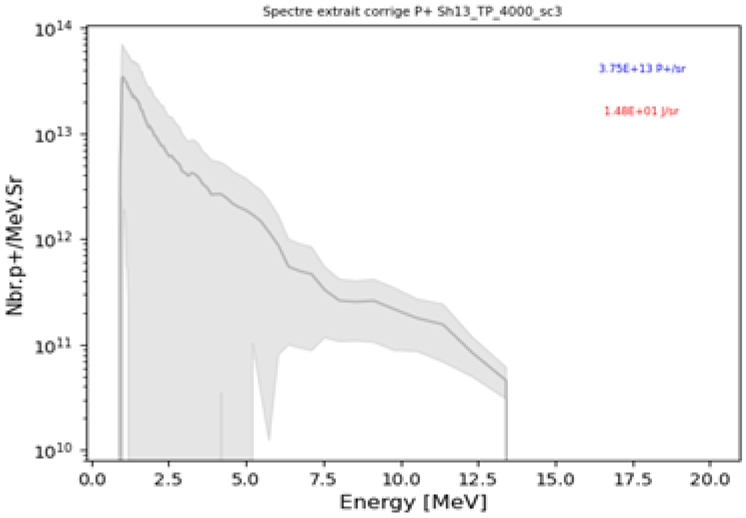
solid angle < μsr



Proton spectrum from the back in low energy range
NOT CORRECTED BY THE BEAM POINTING INSTABILITY !



TP image



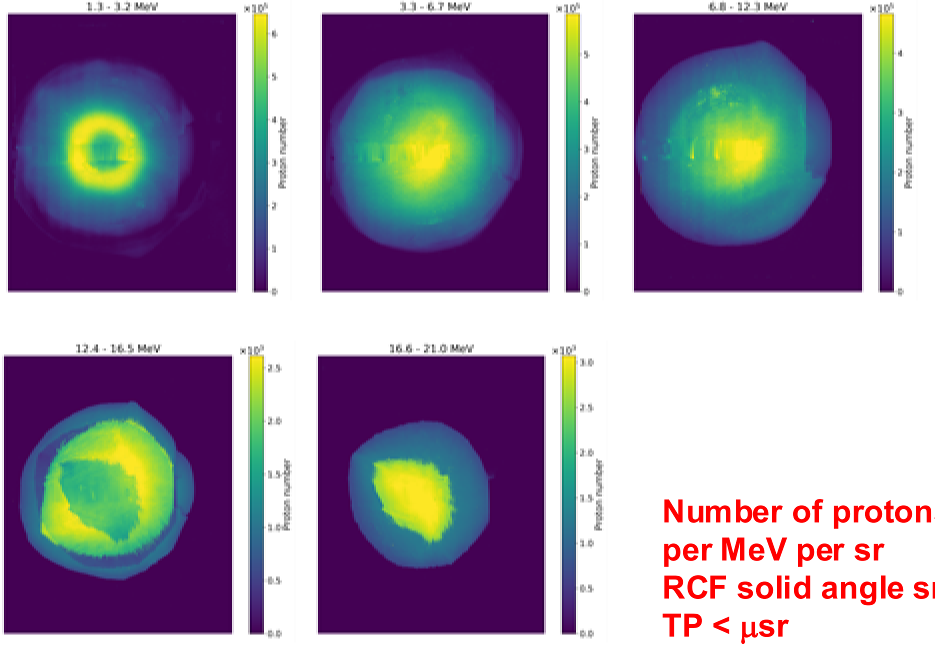
Proton spectrum from the front

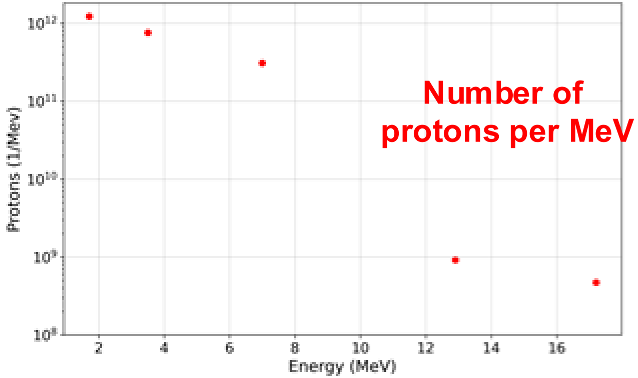
Reconstruction of the proton spectrum

using RCF and TP data
see Anton Moroz talk

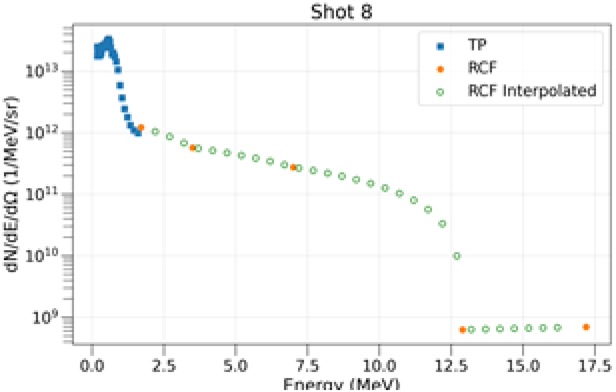
2 mg/cc, 500 um + foil
67J +0.3% ns

Shot 8

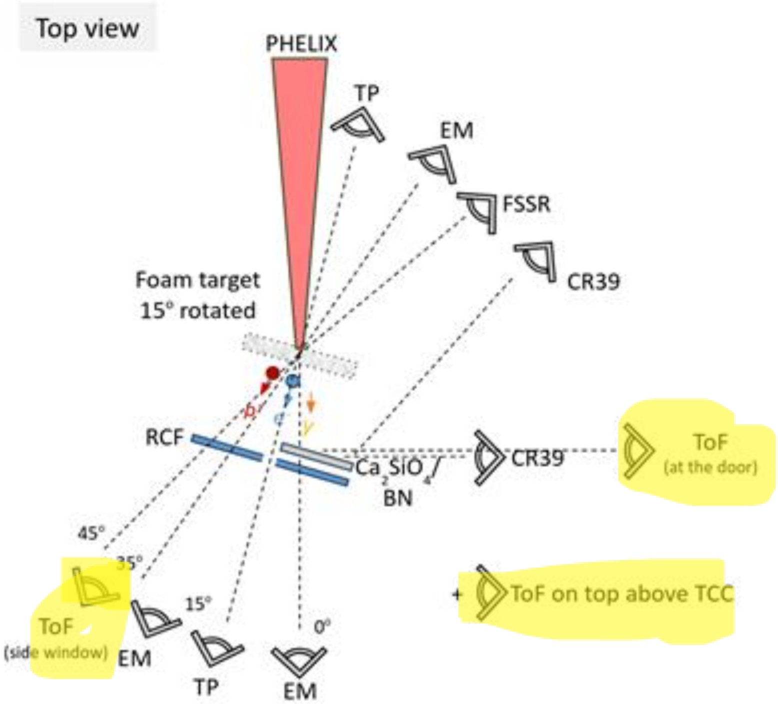




Number of protons per MeV per sr
RCF solid angle sr
TP < μsr



Experimental setup PHELIX LASER GSI



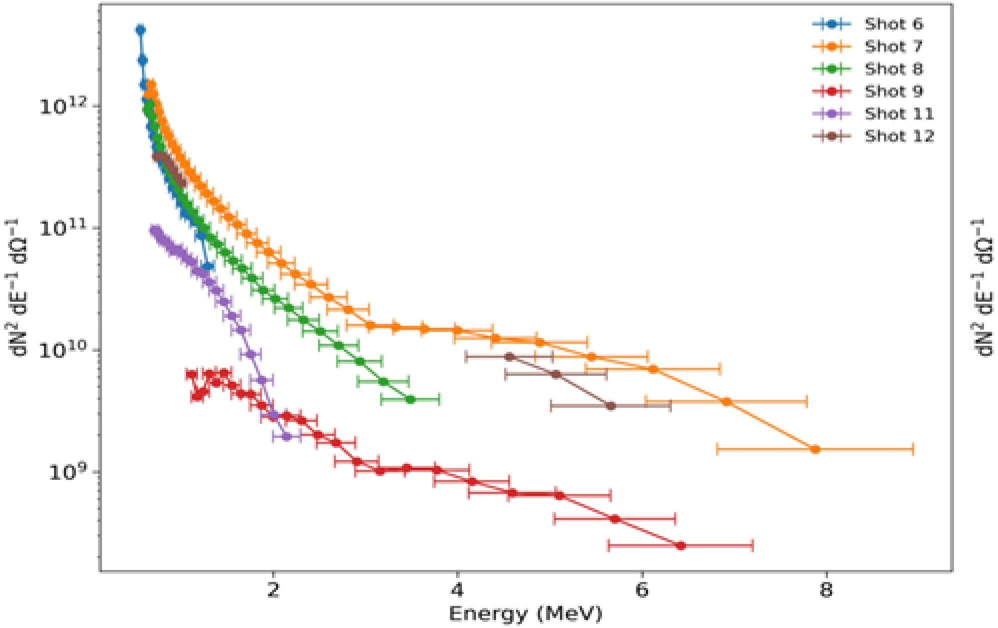
ToF : three time of flight detectors:

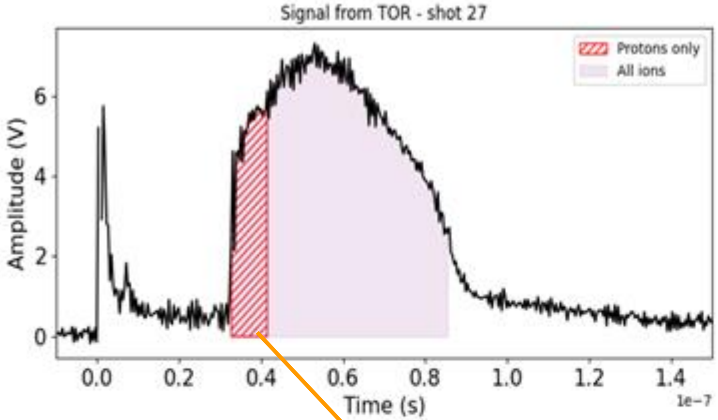
- **270° position: multichannel pixelated time-of-flight detector**
- **Chamber roof position: simple ToF detector**
- **45° position: simple ToF detector**

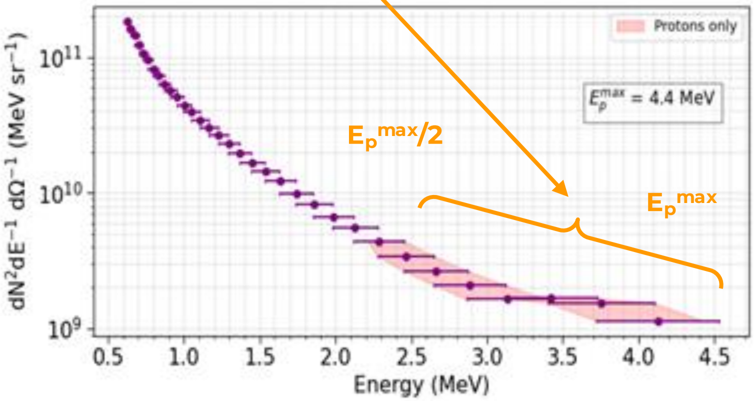
Time of Flight TOF data

Angelo Raso, Marco Tosca

- Three detectors (2 diamond, 1 silicon)



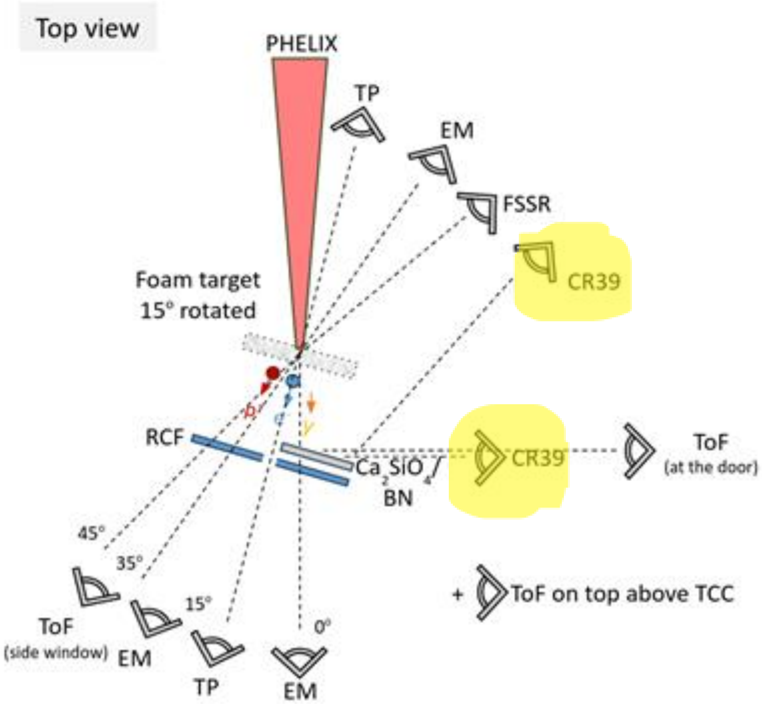




Proton spectra for selected shots (30° front diamond detector)

A single spectrum demonstrating the "proton-only" region

Experimental setup PHELIX LASER GSI

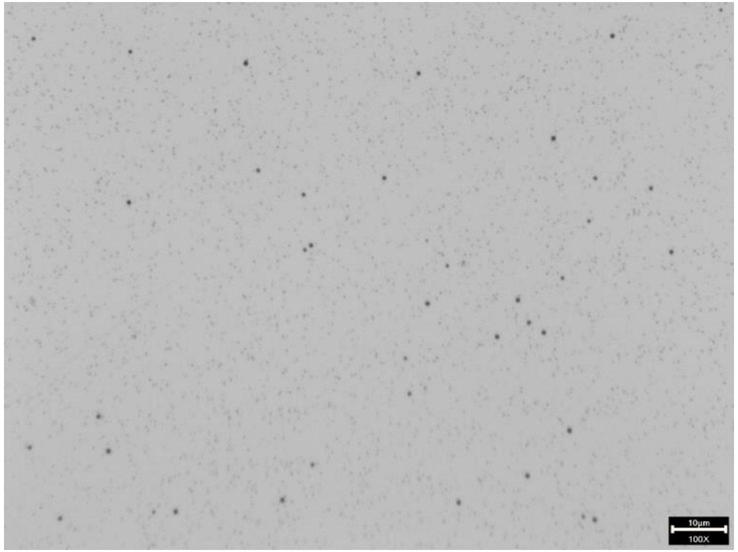


CR39 : plastic nuclear track detectors for alpha-particle measurements

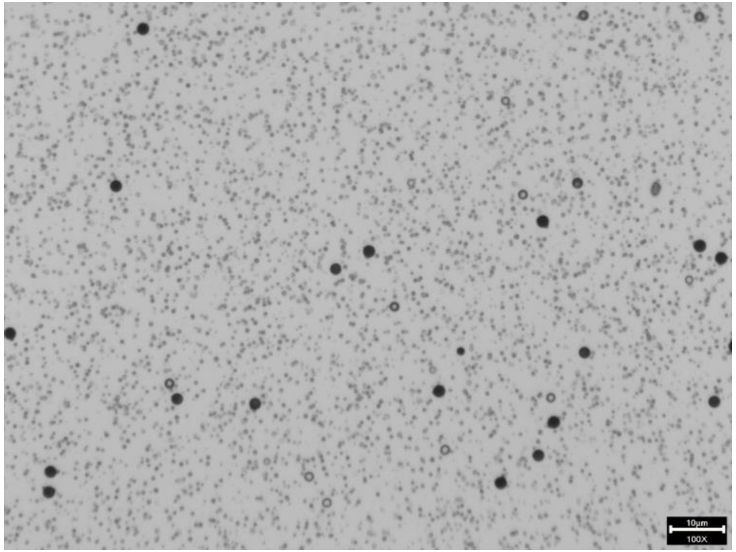
CR39 TRACK DETECTOR

SHOT 15 : BACKGROUND

Massimiliano SCISCIO



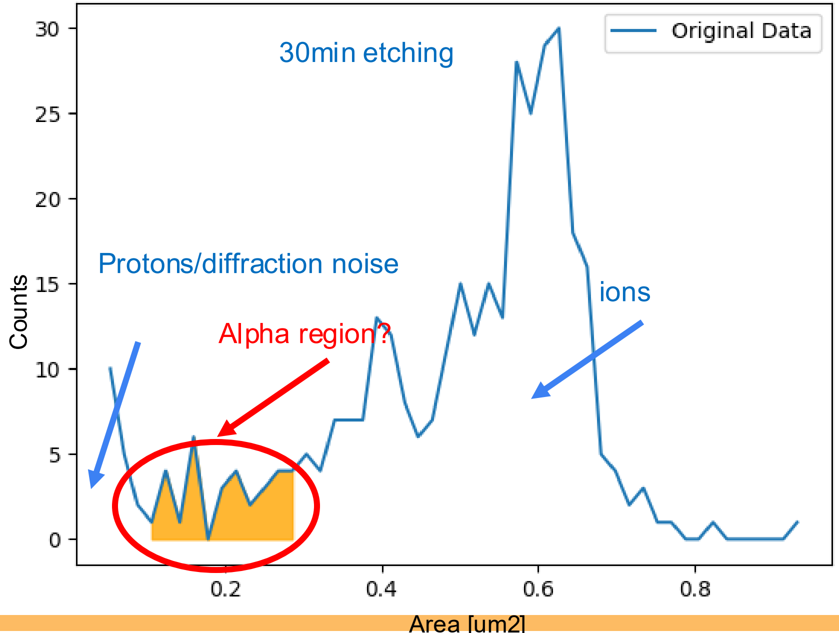
Foam, no catcher, 5 um Al, 30 min etching

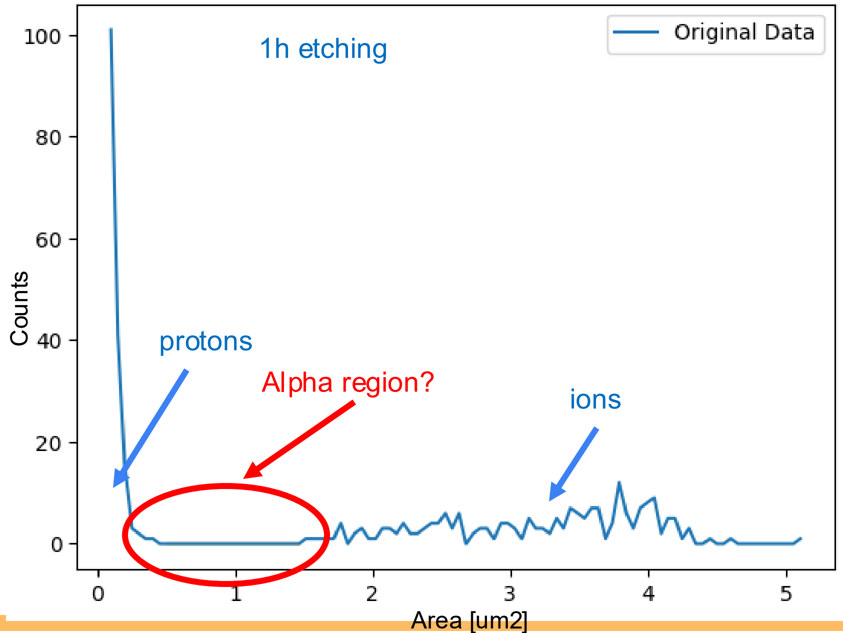


Foam, no catcher, 5 um Al, 1h etching

CR39

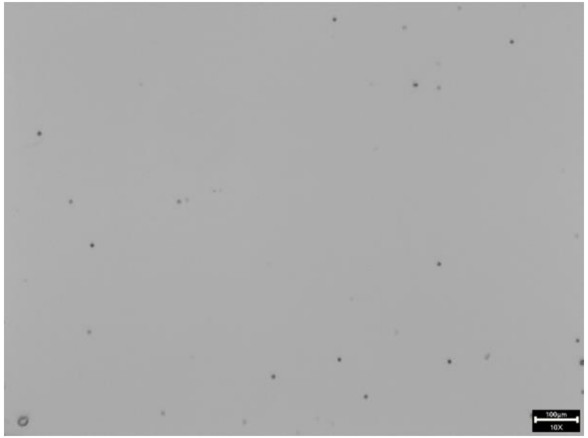
SHOT 15 : BACKGROUND histogram



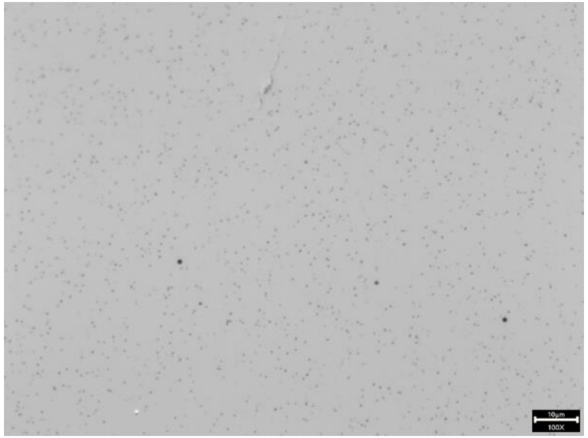


CR39 SHOT 8: Foam + foil + BN catcher

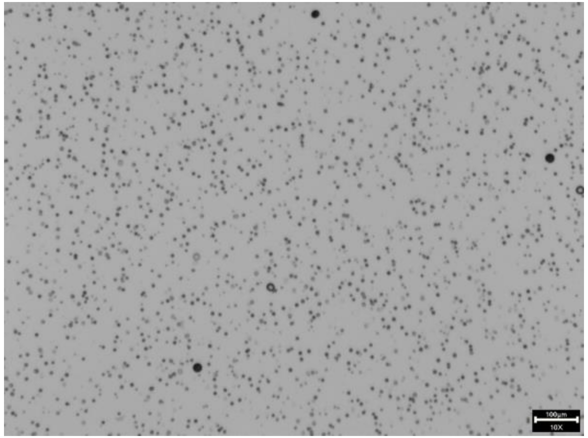
Looking only at catcher, 5 um Al, 30 min etching



Looking only at catcher, 5 um Al, 1 hour etching

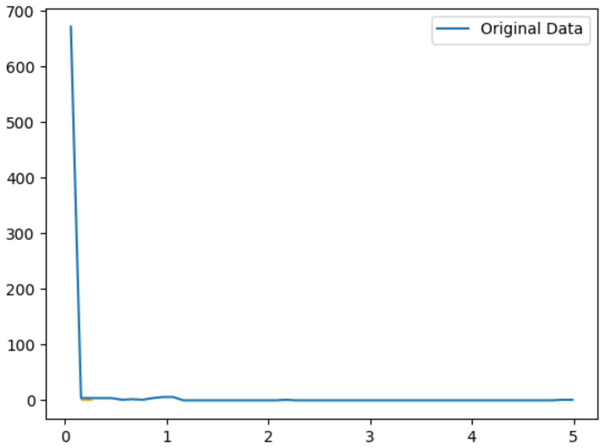


Looking at pitcher + catcher, 5 um Al, 30 min etching

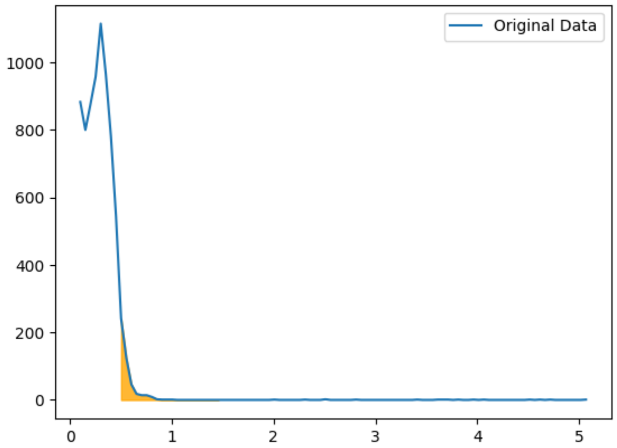


Looking at pitcher + catcher, 5 um Al, 1 hour etching

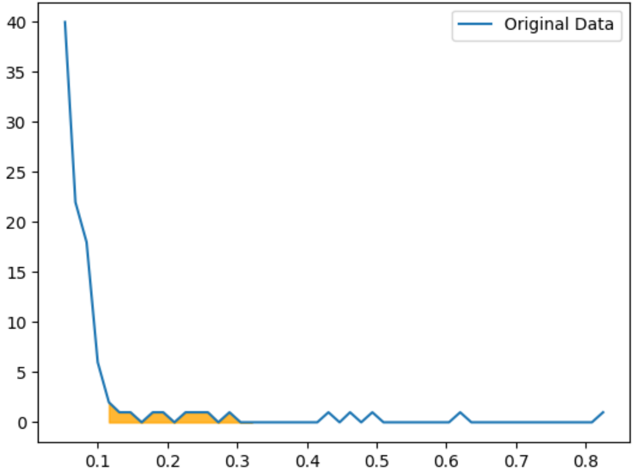
CR39 SHOT 8: Foam + foil + BN catcher histogram



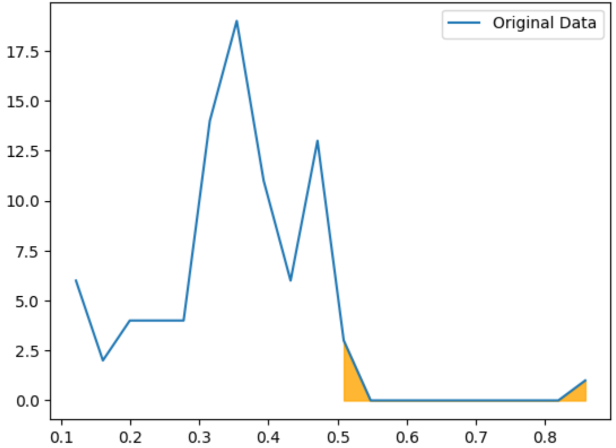
Looking only at catcher, 5 um Al, 30 min etching



Looking only at catcher, 5 um Al, 1 hour etching



Looking at pitcher + catcher, 5 um Al, 30 min etching



Looking at pitcher + catcher, 5 um Al, 1 hour etching

CR39

No alpha peak is clearly visible

Possible reasons:

- Alpha pit size superimpose with protons:
- CR39 was placed too far from TCC (solid angle too small), and alpha flux lower than LLD of 10^7 sr^{-1} .

CR39 DATA	Target	Protons above 600 keV	Protons above 800 keV	Protons above 1 MeV
Shot 7	Foam (Olga) 2 mg/cc, 500 μm	$5.09\cdot10^{10}$	$2.39\cdot10^{10}$	$1.67\cdot10^{10}$
Shot 9	Ti foil 10 μm	$9.37\cdot10^{10}$	$6.16\cdot10^{10}$	$1.86\cdot10^{10}$
Shot 10	Foam (Olga) 2 mg/cc, 500 μm + Ti foil 10 μm	$2.47\cdot10^{11}$	$1.17\cdot10^{11}$	$6.12\cdot10^{10}$
Shot 13	Foam (Olga) 2 mg/cc, 500 μm	$8.89\cdot10^{10}$	$6.42\cdot10^{10}$	$4.65\cdot10^{10}$
Shot 15	Foam (HB11) 2.3 mg/cc, 2mm	$2.91\cdot10^{11}$	$1.78\cdot10^{11}$	$1.09\cdot10^{11}$
Shot 16	Foam (HB11) 2.3 mg/cc, 1mm	$3.41\cdot10^{11}$	$2.01\cdot10^{11}$	$1.27\cdot10^{11}$
Shot 17	Foam (Bing Liu) 2 mg/cc, 500 μm	$4.34\cdot10^{11}$	$1.70\cdot10^{11}$	$9.58\cdot10^{10}$
Shot 19	Foam (Bing Liu) 2 mg/cc, 500 μm + Ti foil	$3.21\cdot10^{11}$	$1.28\cdot10^{11}$	$1.03\cdot10^{11}$
Shot 20	Ti foil 10 μm	$1.16\cdot10^{10}$	$6.71\cdot10^{9}$	$5.08\cdot10^{9}$
Shot 21	Foam (Olga) 2 mg/cc, 500 μm + Au foil 10 μm	$2.10\cdot10^{11}$	$1.37\cdot10^{11}$	$8.72\cdot10^{10}$
Shot 24	Foam (Natalia) 3 mg/cc, 300 μm	$8.96\cdot10^{10}$	$5.62\cdot10^{10}$	$3.30\cdot10^{10}$
Shot 26	Foam (HB11) 2.3 mg/cc, 1mm + Ti foil	$1.78\cdot10^{11}$	$1.32\cdot10^{11}$	$1.19\cdot10^{11}$

Approximation of pB-fusion reaction yield

pB needs large number of low energy protons

see Anton MOROZ talk on thursday

Summary

- Works are still in progress
- Correction on TP data has to be done due to beam pointing instability
- Absolute number and reconstruction of the full proton spectrum/angular distribution using several diagnostics

- Proton spectra with foams seems characterized :
  - by higher number at very low energy (Coulomb explosion ?)
  - and also at higher energy (super-ponderomotive acceleration for electrons ?)
  - but between 1-10 MeV, we seems do not see any difference with the Ti foil (TNSA)

Thank you for your attention!