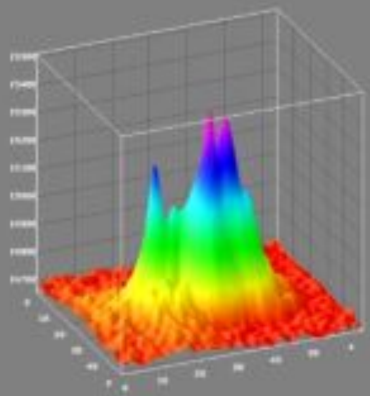
Exercise: low energy low current radioactive beam diagnostics



Paolo Finocchiaro

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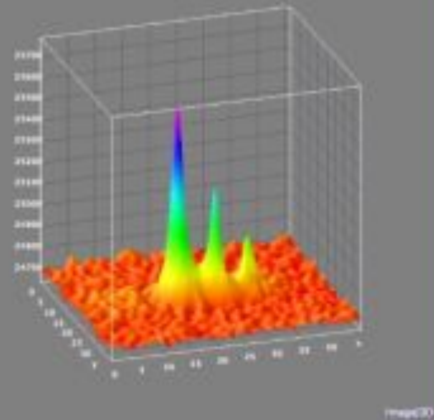
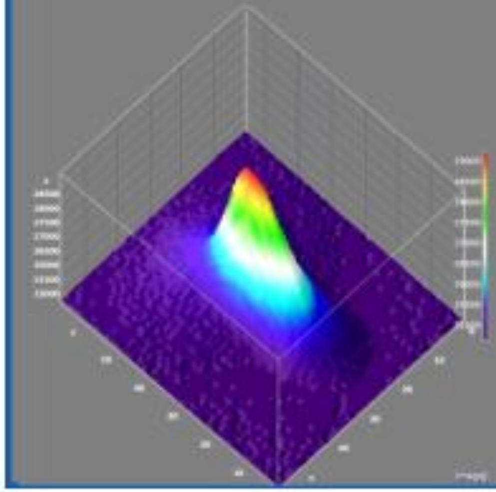
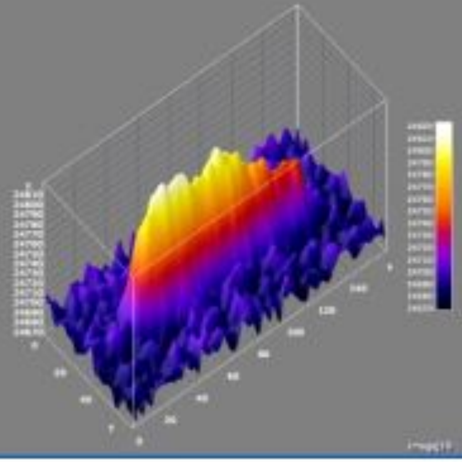
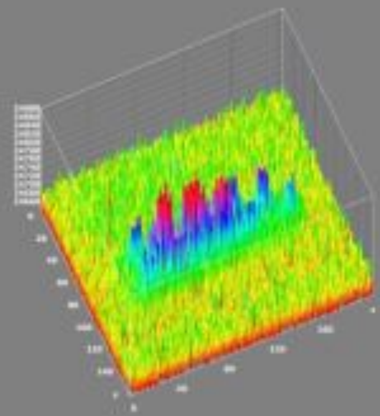
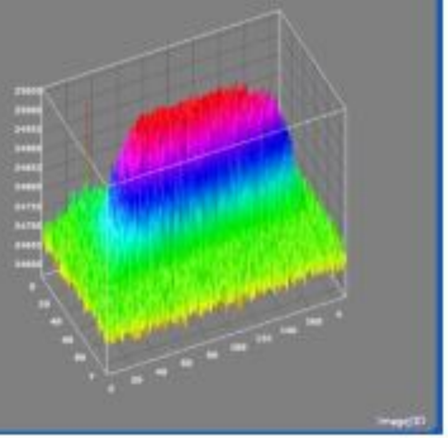
Catania, Italy











a real case...

This is a work of fiction

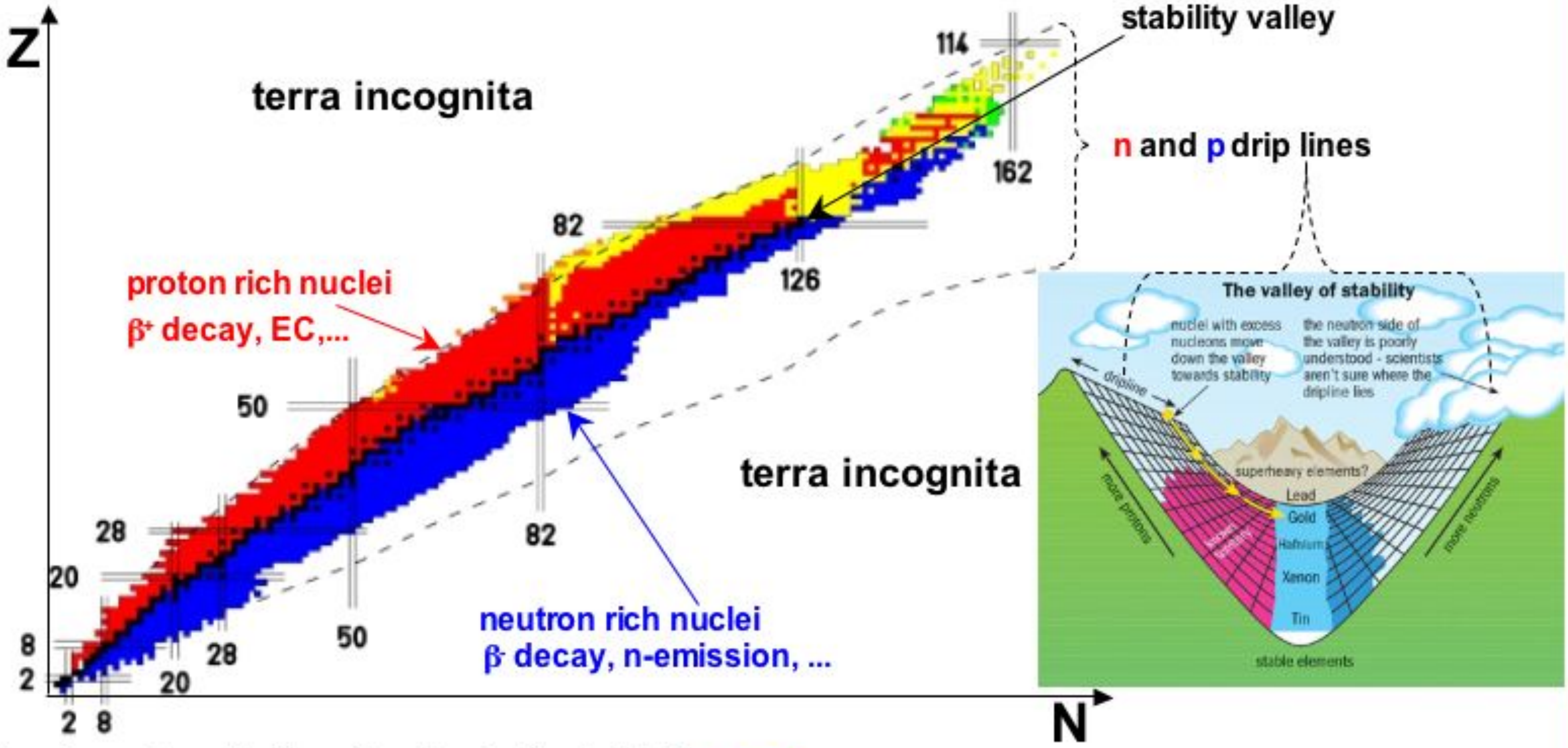
Names, characters, places and incidents either are the products of the author's imagination or are used fictitiously

Any resemblance to actual persons, events or locales is entirely coincidental

??!?

I imagine to thank two fictitious collaborators of mine: Luigi Cosentino and Alfio Pappalardo

what exactly is a radioactive ion beam?

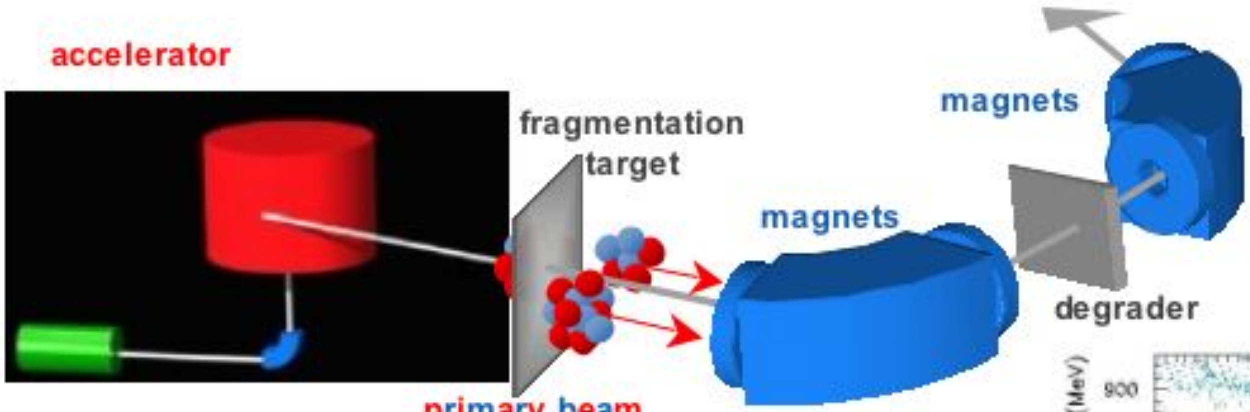


the closer to a drip line, the shorter the half-life ⇒ study by stable particle bombardment not feasible

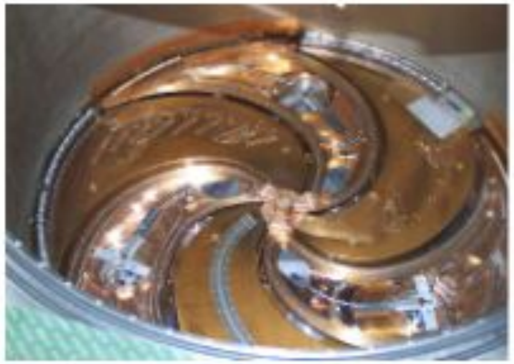
⇒ solution: use the radioactive species as a projectile onto stable targets

how to produce a radioactive ion beam?

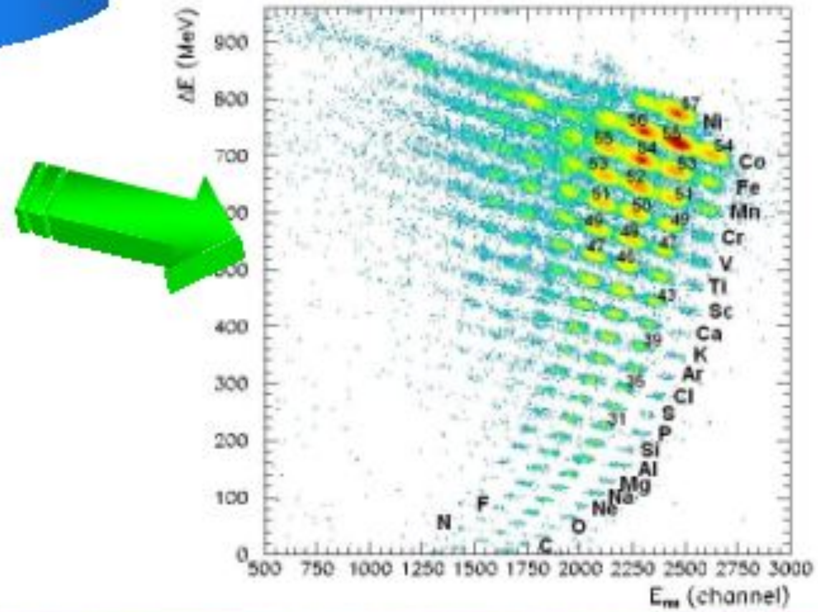
basically two methods: <u>in-flight fragment separation</u> ...



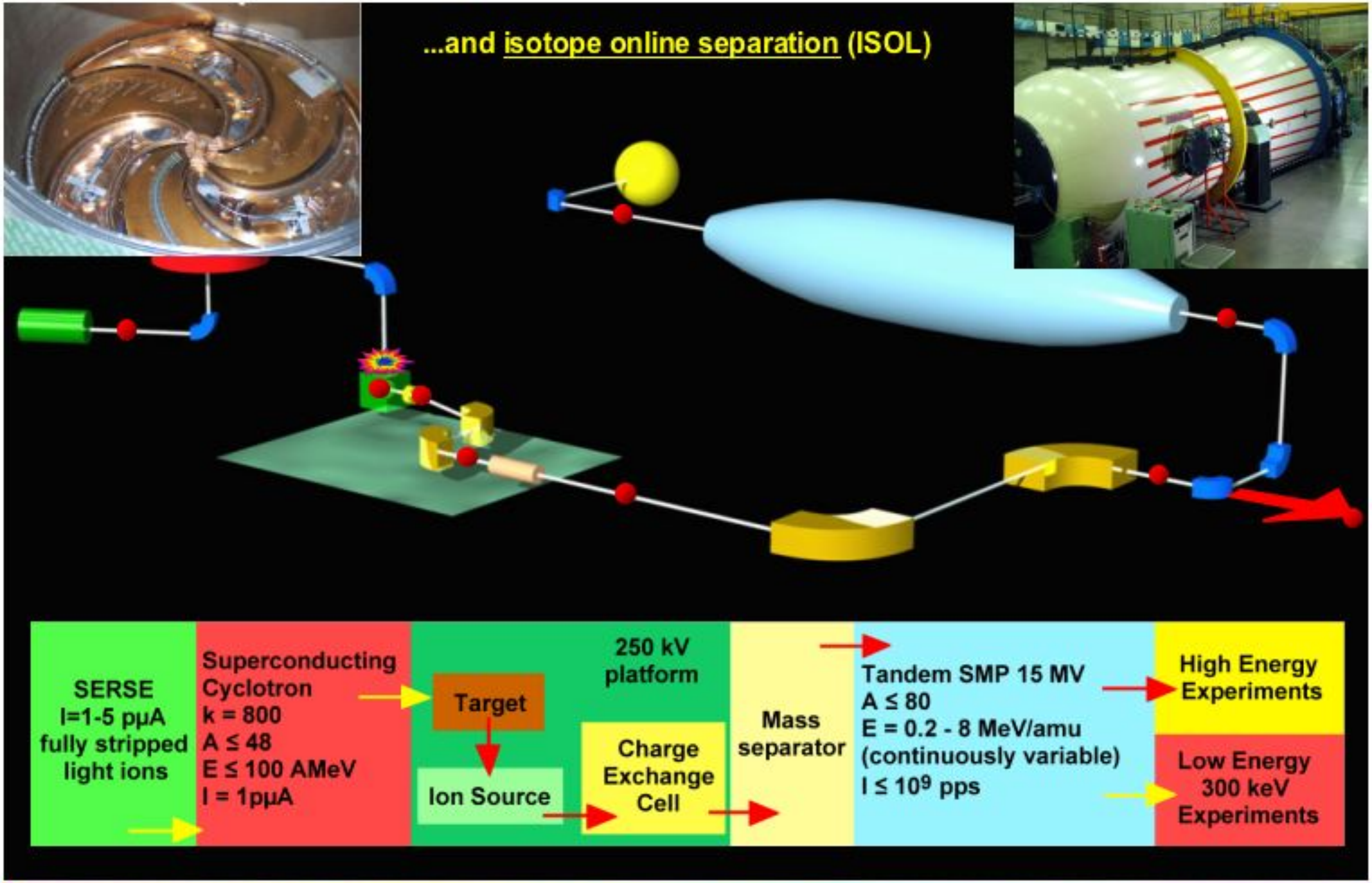
FRIBs at INFN-LNS Catania



Superconducting Cyclotron



how to produce a radioactive ion beam?



ISOL method: re-acceleration

1. *ionization of chemical species (heat, microwaves, ...)*
2. *selection of ion species (electric fields and magnets)*
3. *pre-acceleration (electric fields)*
4. *selection of nuclear species (dipole magnets)*
5. *acceleration (RF, electric fields)*
6. *beam transport (magnetic and electric multiplets)*
7. *tuning (beam diagnostics)*

beam diagnostics always and everywhere

ISOL: which beams, intensity and energy?

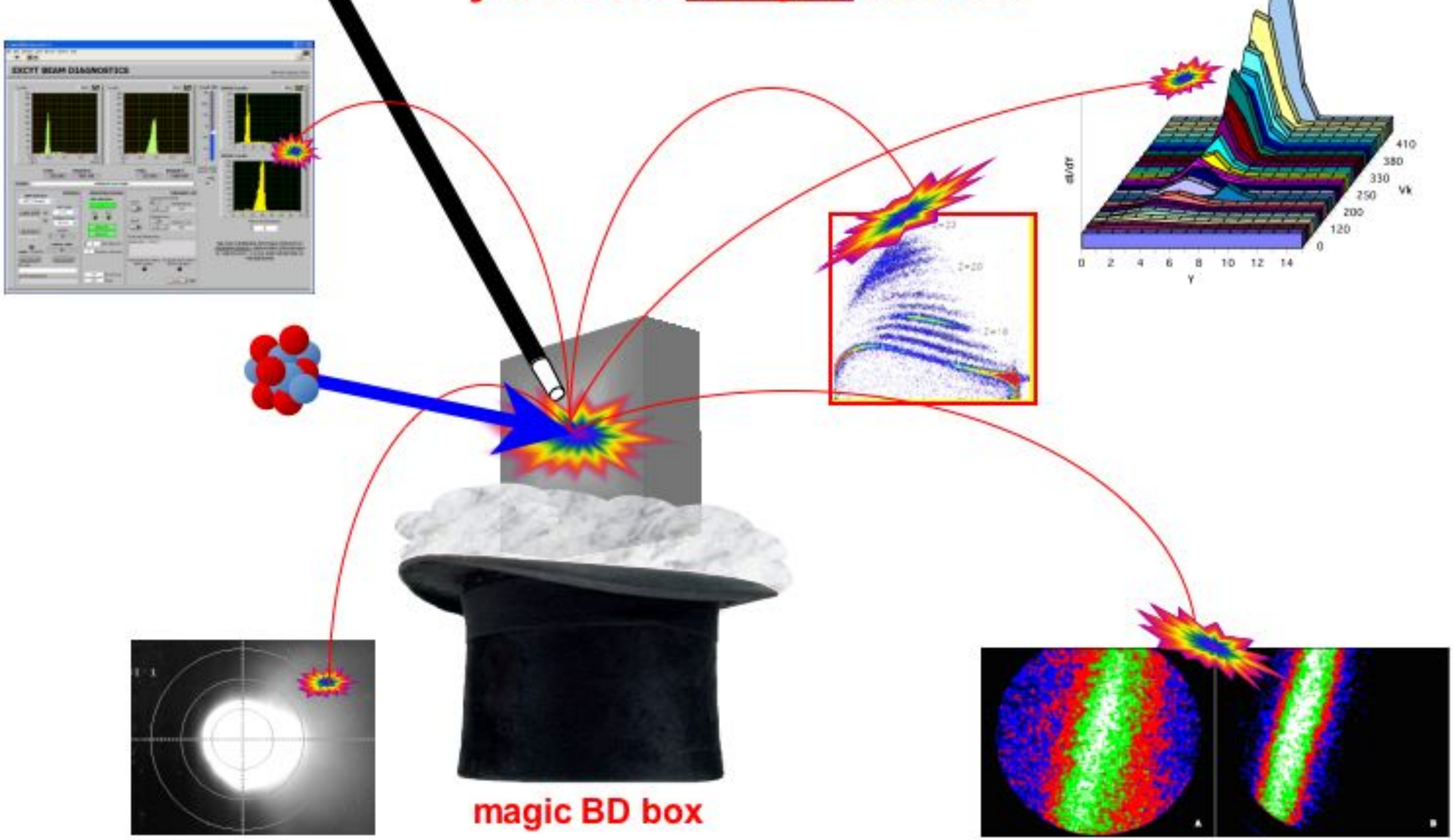
- ^{8}Li
- ^{11}Li
- ^{11}C
- ^{14}O
- ^{15}O
- ^{19}O
- ^{22}O
- ^{17}F
- ^{20}Na
- ^{30}P
- ^{30}S
- ^{33}Cl
- ^{34}Cl
- ^{69}As
- ^{73}Se
- ^{74}Br

10^3 - 10^7 pps

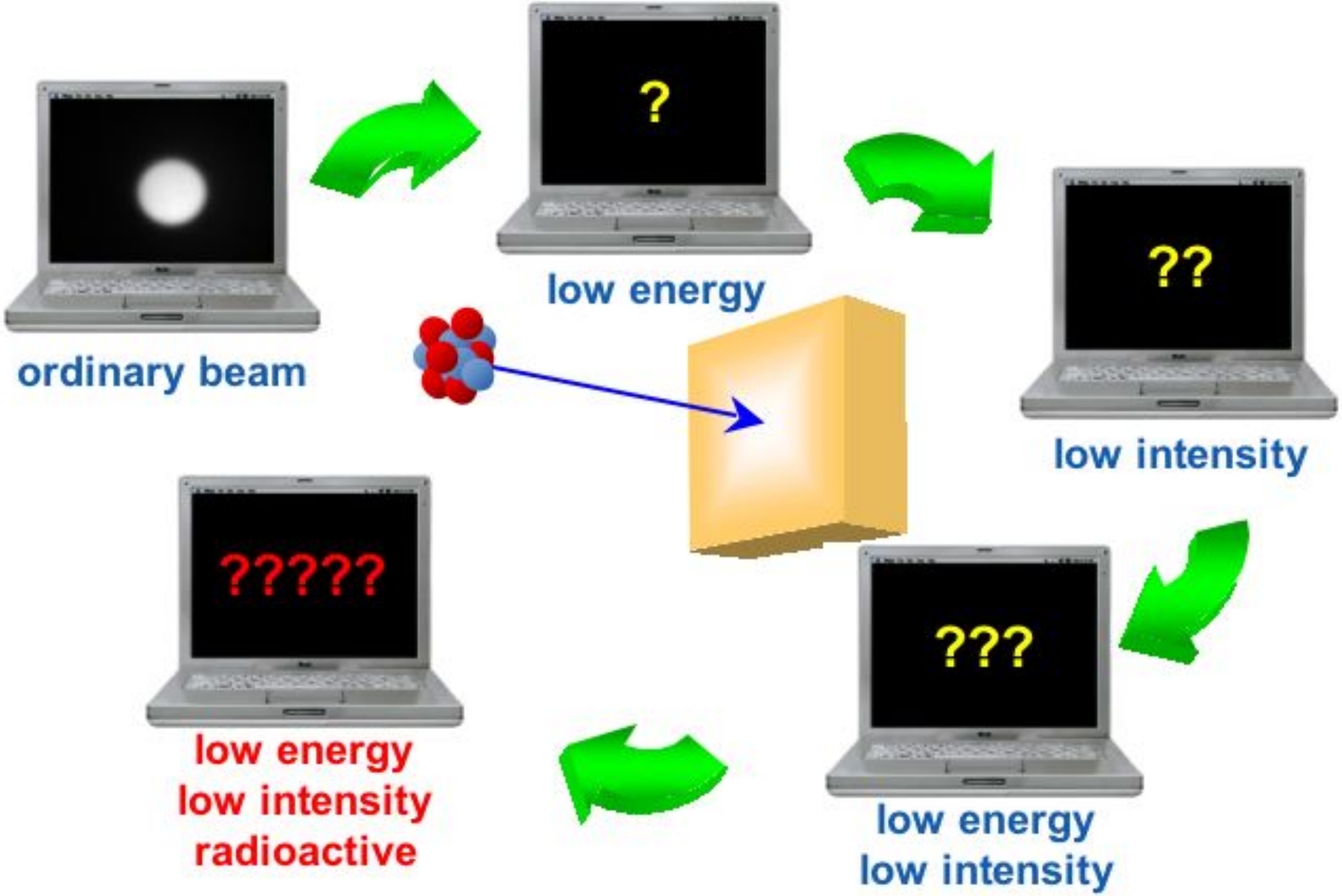
100 - 250 keV
few MeV/A

this is the ideal case table, as originally proposed

"Paolo, we don't need a sophisticated BD: just one simple device"

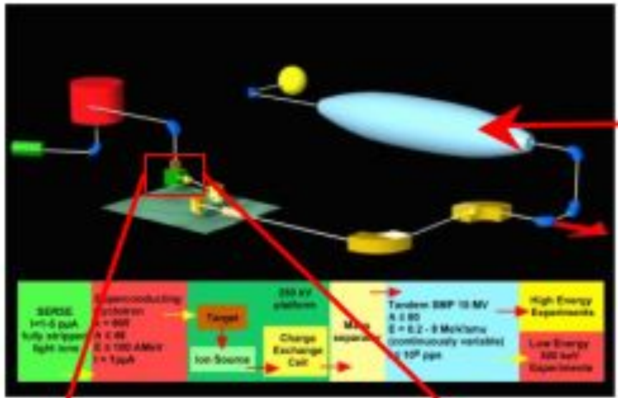


unfortunately the real case is different

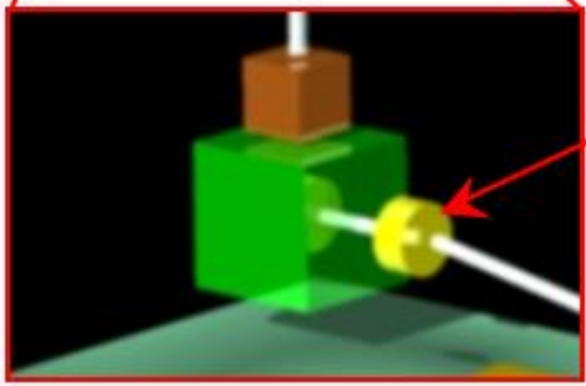


and the real intensity range starts from zero!...

and the energy value is smaller than foreseen!...



Tandem accelerator wants negative ion input



a Charge Exchange Cell is needed
but its efficiency came out lower than foreseen

how to improve it?
lower the beam energy ⇒ lower the ion-source extraction voltage
from initial 50kV to actual 5-10 kV

the real particles to be accelerated come out from CEC at 0-10^5pps and 5-10keV

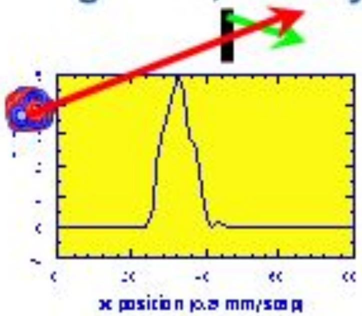
challenge: how can we make BD on such a kind of beams?

let's fix a few boundary conditions:

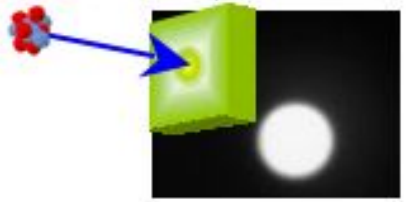
1. decide which beam we start with ⇒ ^{8}Li
2. assume a reasonable energy value ⇒ 8-10 keV
3. assume a low but realistic intensity ⇒ 10^6 - 10^3 pps
4. examine the possible ways of detecting the beam

possible ways of detecting the beam

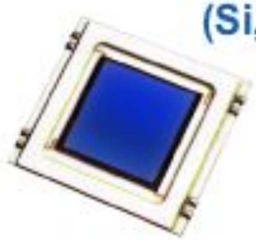
electromagnetic (scanning wires, faraday cups)



optical (scintillating quartz, phosphor screens, alumina screens)

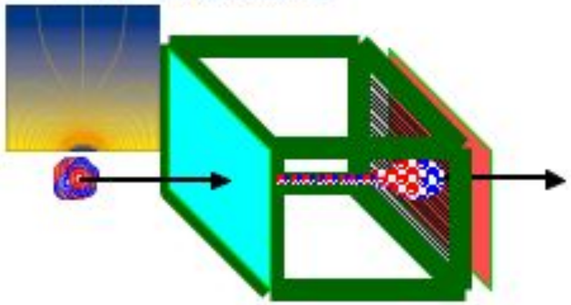


Semiconductors (Si, Ge)

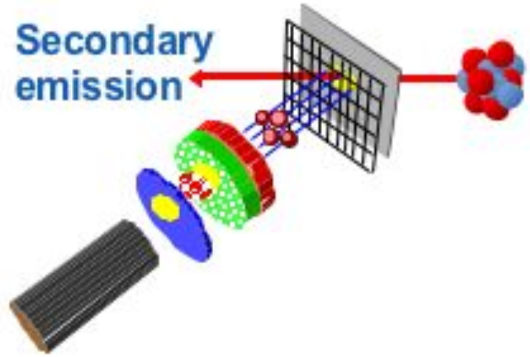


Diamond

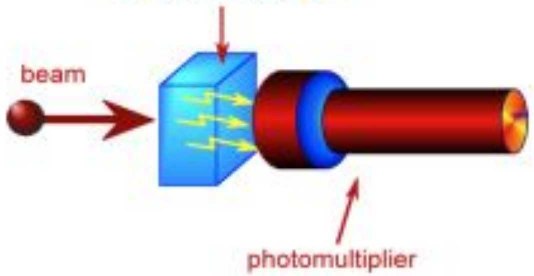
Gas detectors



Secondary emission



Scintillators



Cherenkov

Others, etc.

list the chosen RIB properties

^{8}Li, 8-10 keV, 10^{6} - 10^{3} pps

Nuclide	Half life	Possible contaminants	Average beta energy	Gamma peaks	Useful detectors?
^{8}Li	0.838 s	^{8}B M/ΔM = 3800 ΔM/M = 2.6E-4	6243 keV	No peaks	???

^{8}Li mass: 8.02248736
^{8}B mass: 8.0246072

electromagnetic?

phosphor screens?

semiconductors?

cherenkov?

gas?

diamond?

secondary emission?

others?

scintillators!

choose the viable solutions, reject the unfeasible ones

any ideas? suggestions?

last minute requirement:
"by the way, Paolo, I would also like to BD the stable pilot beam"

⇒ we also need a route adjustement for the stable beam detection

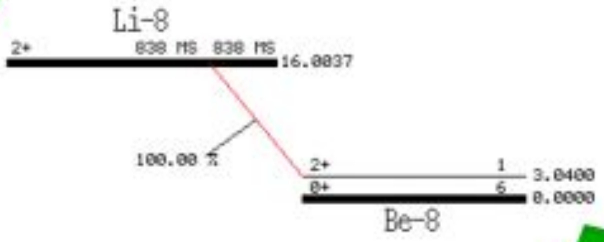
proposal

radioactive beam diagnosis by exploiting beta decay

stable beam diagnosis by exploiting scintillation

beta decay of ^{8}Li

```
Parent state: G.S.
Half life: 838 MS(6)
Q(gs): 16003.7(8) keV
Branch ratio:        1.0
```



Beta ray:

Max.E(keV)	Avg.E(keV)	Intensity(rel)	Spin	2+
12963.7(-)	6243(15)	100(AP)		2+

are there scintillators sensitive enough?
should we just count particles or
is imaging possible?

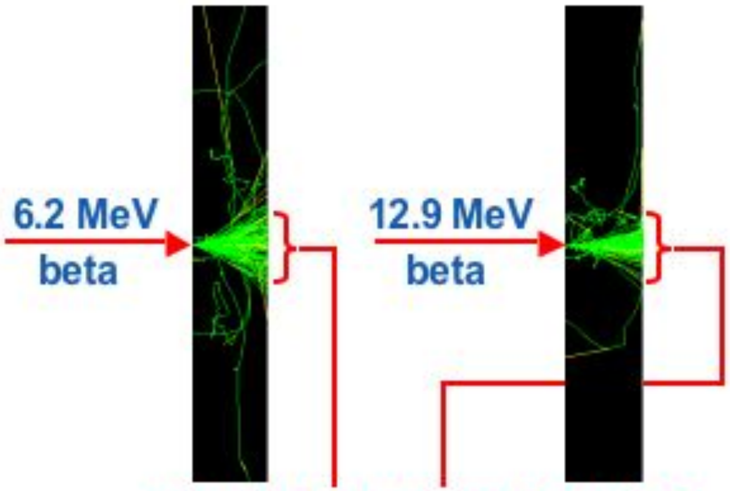
imaging by means of CsI(Tl)

plastic scintillators

radioactive beam diagnosis by exploiting beta decay

imaging

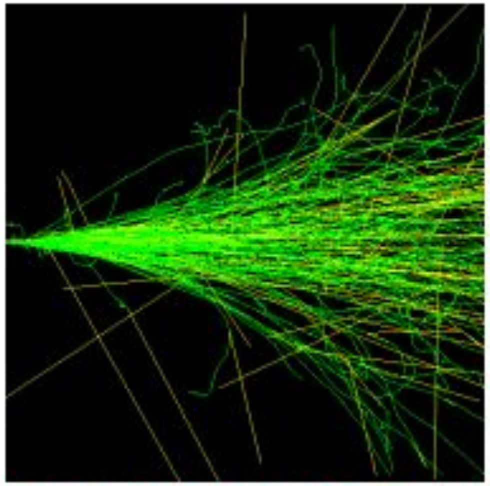
<6 MeV> beta ray mostly will cross a 1mm CsI(Tl) screen



expected space resolution of the same order as the thickness

counting

12.9 MeV beta ray is well contained by 5x5x5 cm³ plastic scintillator



counting single beta particles is possible by means of a plastic and a PMT

in both cases the average energy loss is <E> ≈ 1MeV

≈50000 visible photons/beta

≈10000 visible photons/beta

stable beam diagnosis by exploiting scintillation

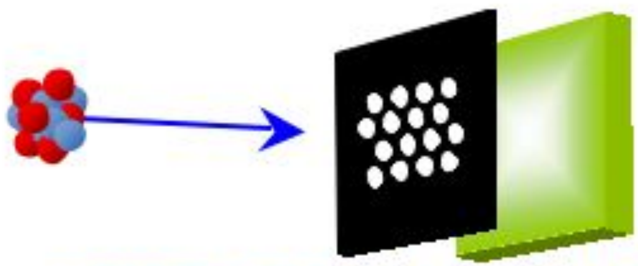
imaging

^{7}Li stable pilot beam at 8-10 keV in CsI stops in nanometers

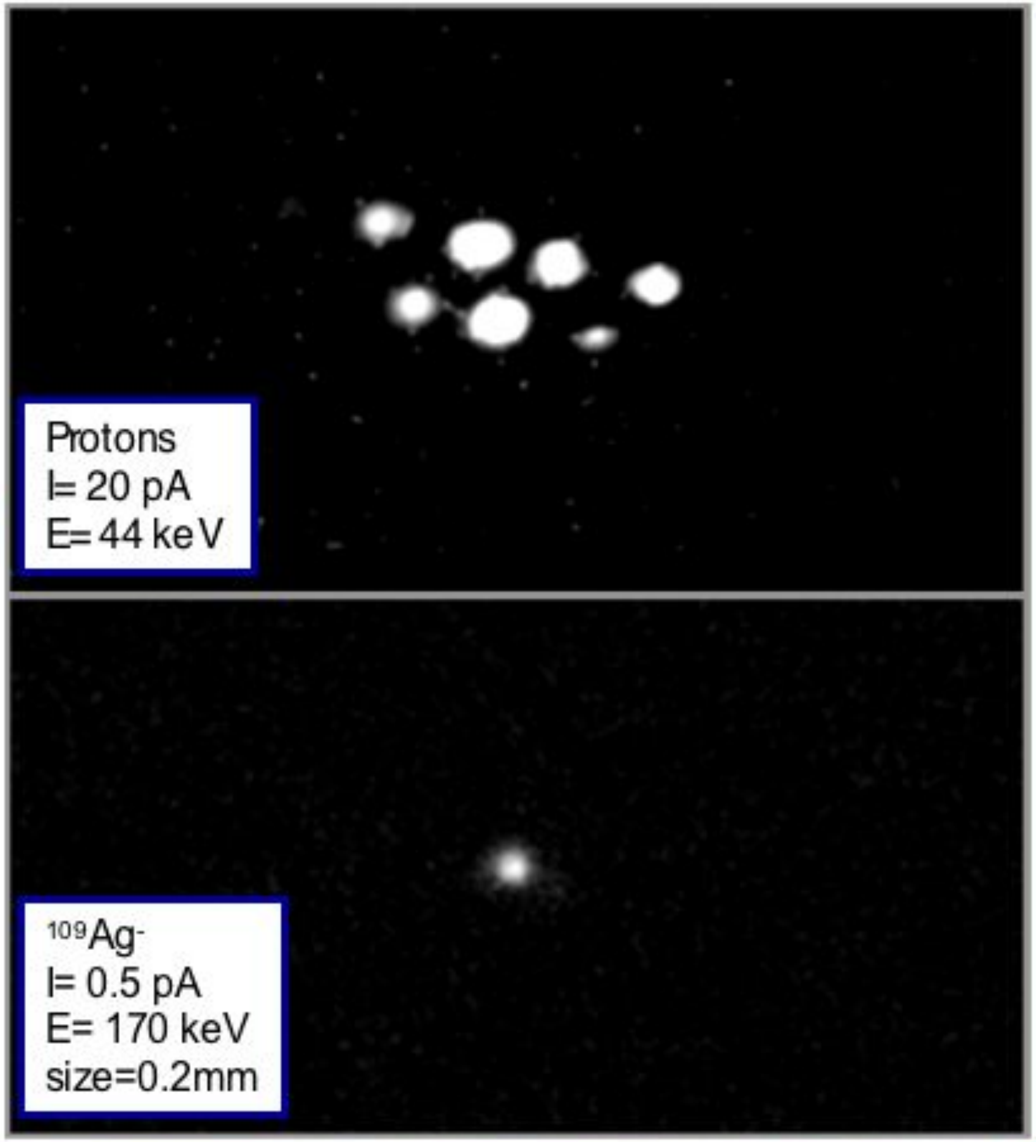
will it still produce light? If so, good space resolution expected

will the beam current be enough?

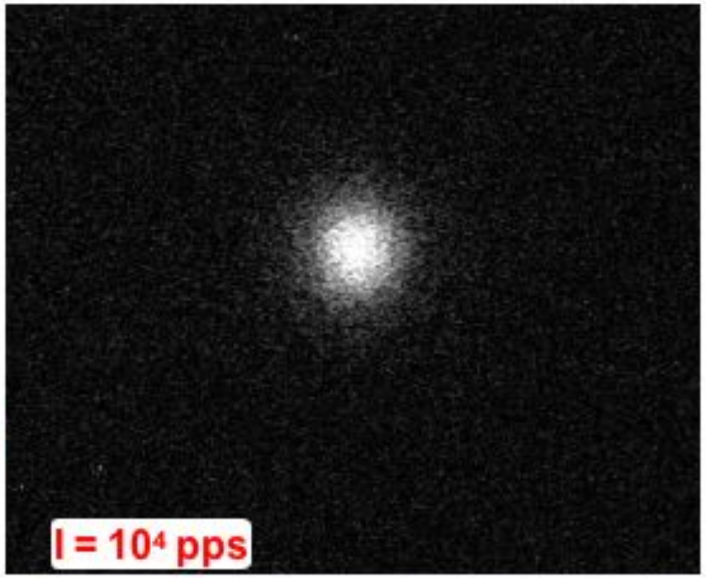
tests required!

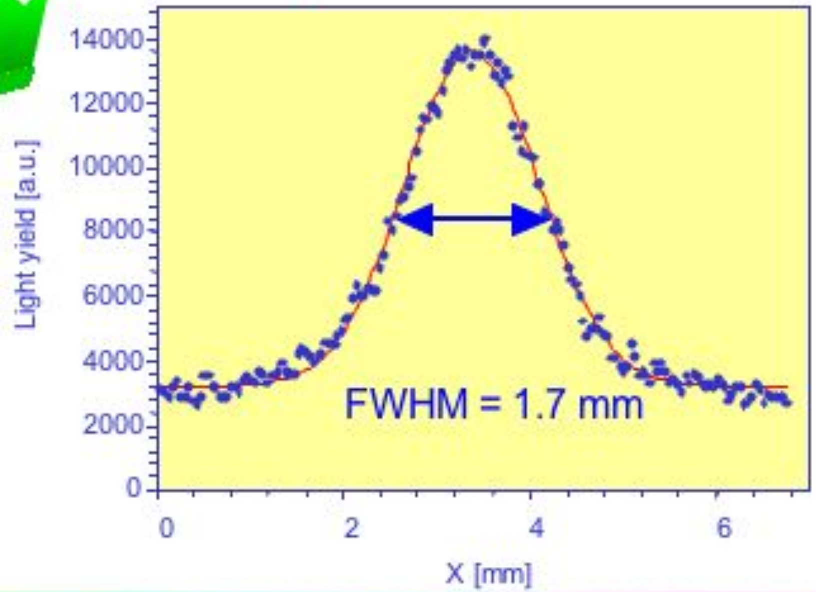


pepperpot mask, ∅ 0.2mm holes



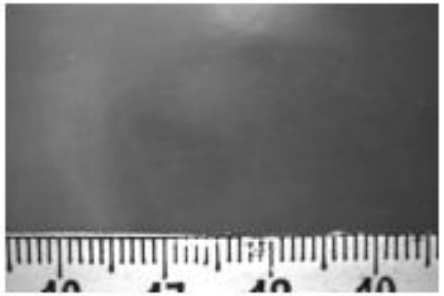
beta-ray source test: imaging with CsI(Tl) plate
2 beta particles, endpoints E= 546, 2280 keV



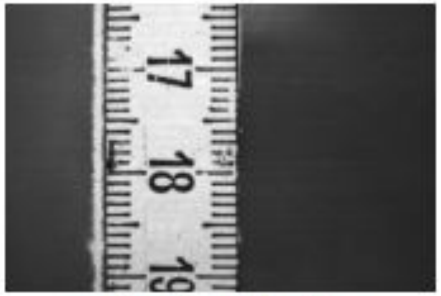


let's see how...

beta-ray source test: imaging with CsI(Tl) plate
2 beta particles, endpoints E= 546, 2280 keV

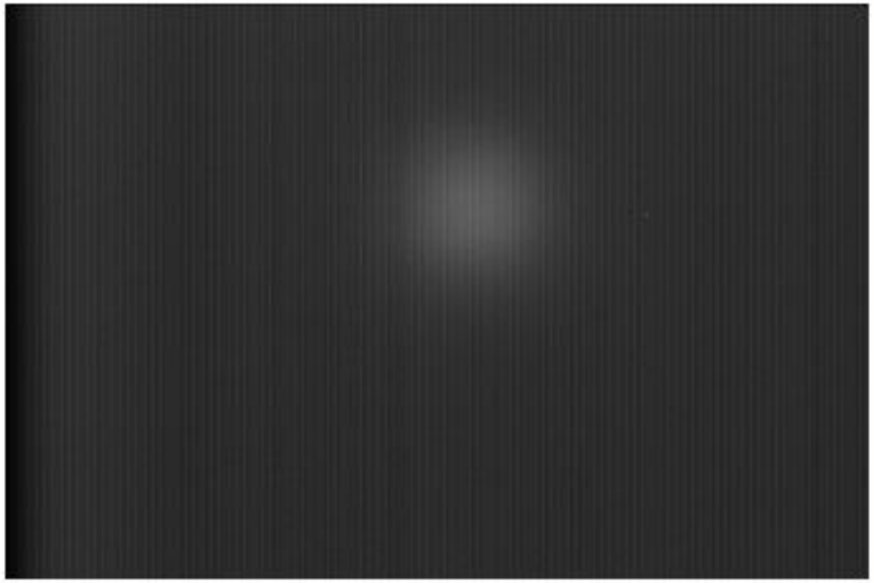


horizontal calibration
41mm ⇔ 768 pix
≈0.052 mm/pix



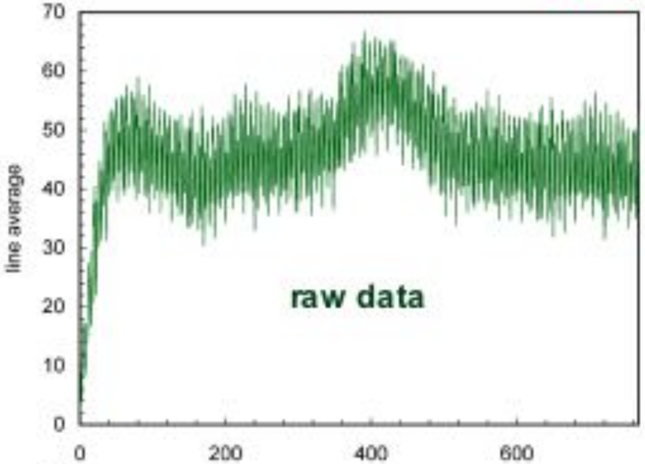
vertical calibration
27mm ⇔ 512 pts
≈0.053 mm/pix

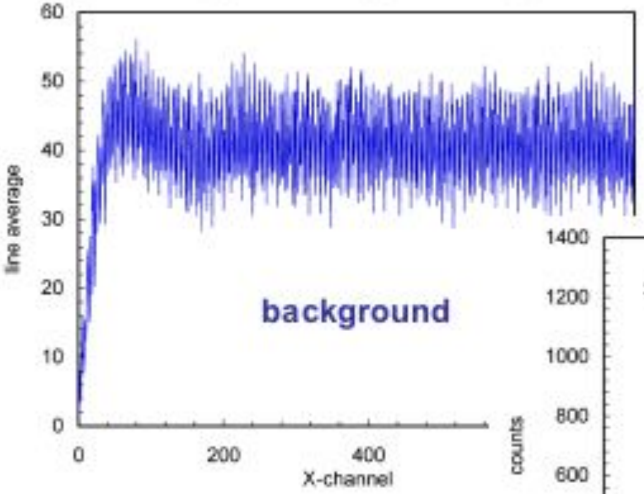
image with source



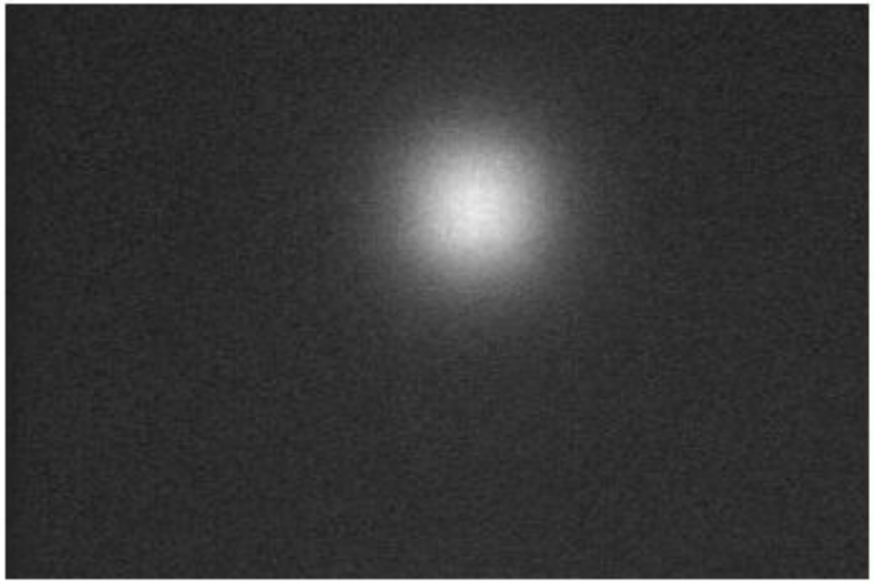
background

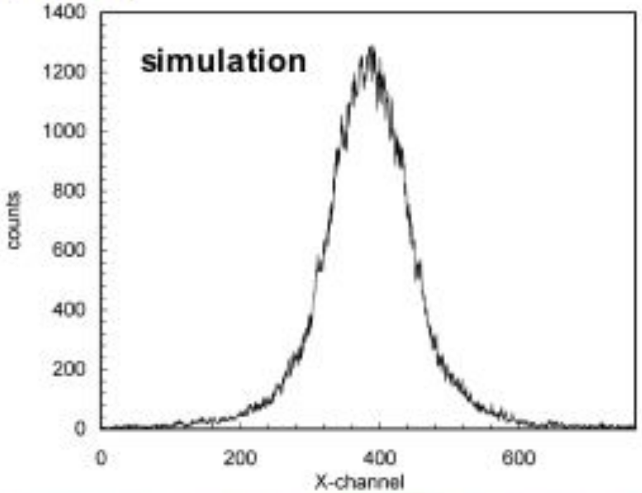
beta-ray source test: imaging with CsI(Tl) plate
2 beta particles, endpoints E= 546, 2280 keV





source - background =
----
cleaner image





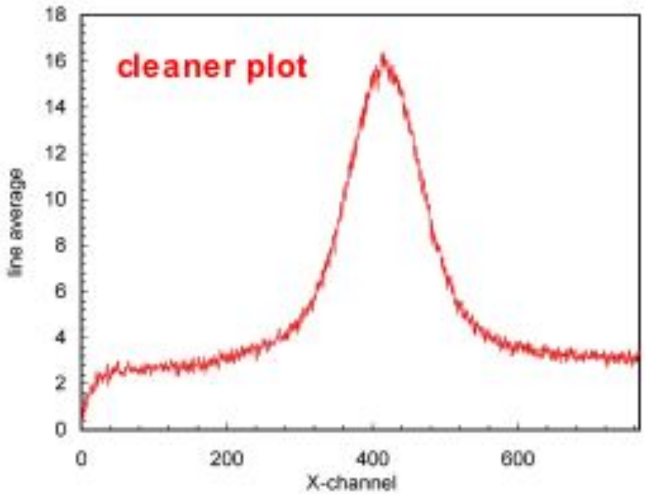
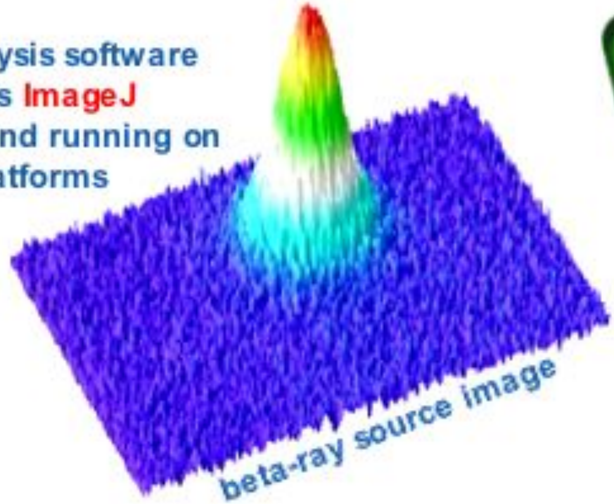


image analysis and fit procedure

the image analysis software used here is **ImageJ** written in Java and running on all the platforms

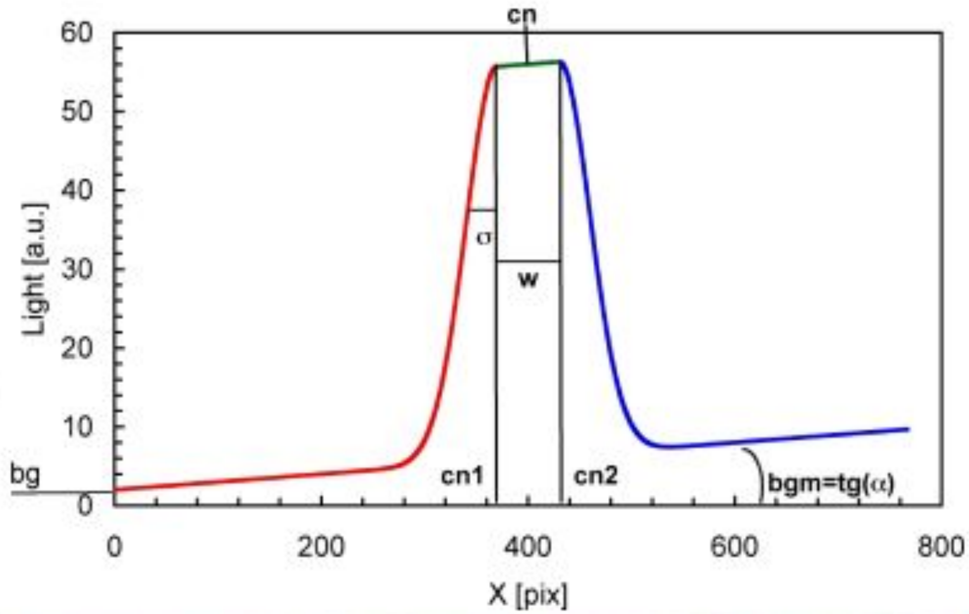


the fits will be done using **Microsoft Excel** by minimizing:

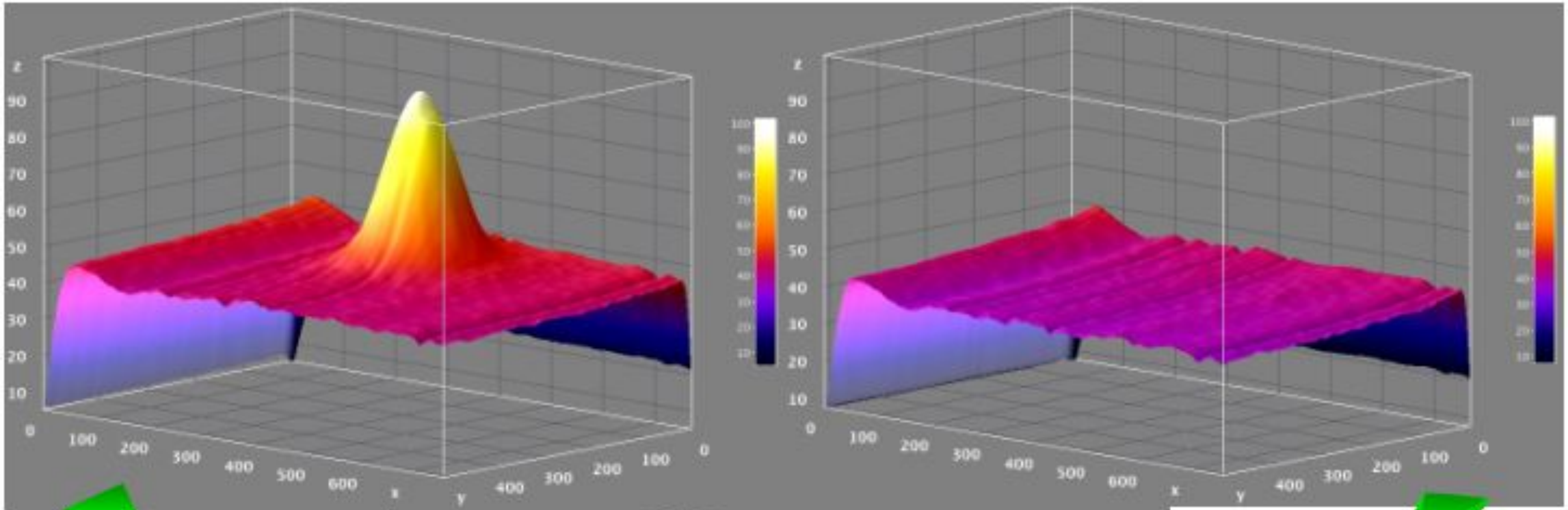
$$\chi^2_{red} = \sum_x \frac{\left(C(x) - fit(x)\right)^2}{\max\left(1, \frac{|fit(x)|}{\sqrt{y_{size}}}\right)}$$

fit function

$$fit(x) = bg + m_{bg} \cdot x + \begin{cases} x < cn_1 : & a \cdot e^{\frac{(x-cn_1)^2}{2\sigma^2}} \\ cn_1 \le x \le cn_2 : & a \\ x > cn_2 : & a \cdot e^{\frac{(x-cn_2)^2}{2\sigma^2}} \end{cases}$$



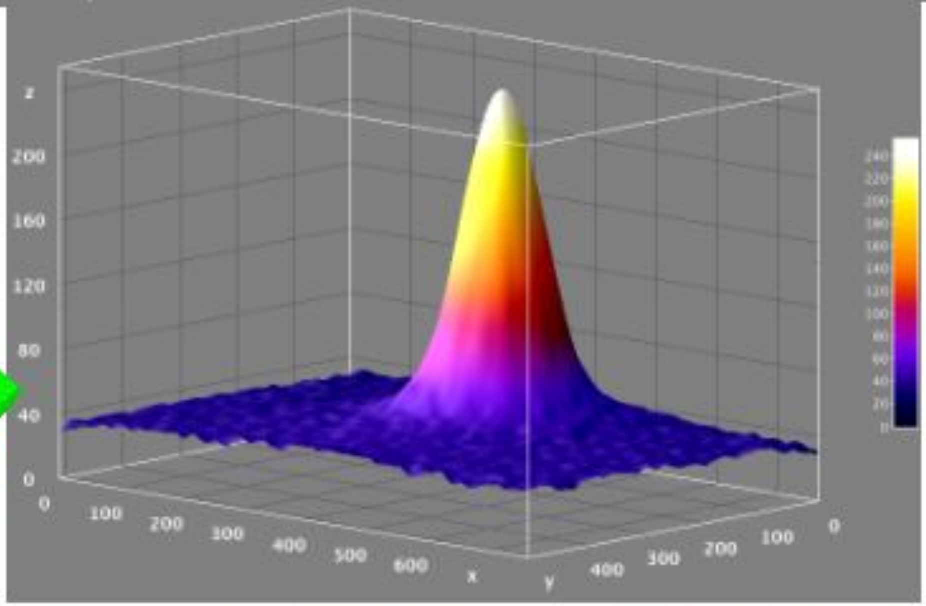
beta source, non-collimated



raw data

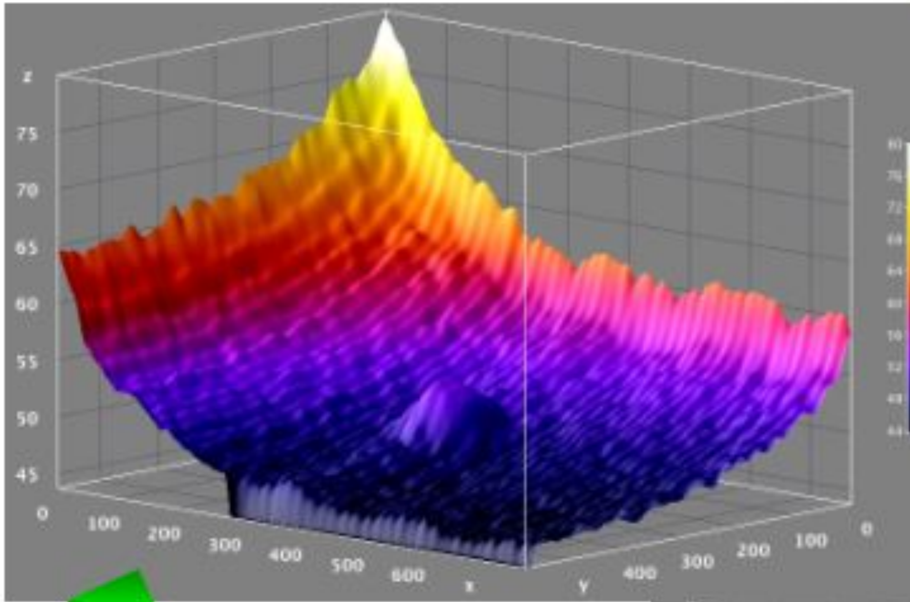
background

CCD systematic noise is evident

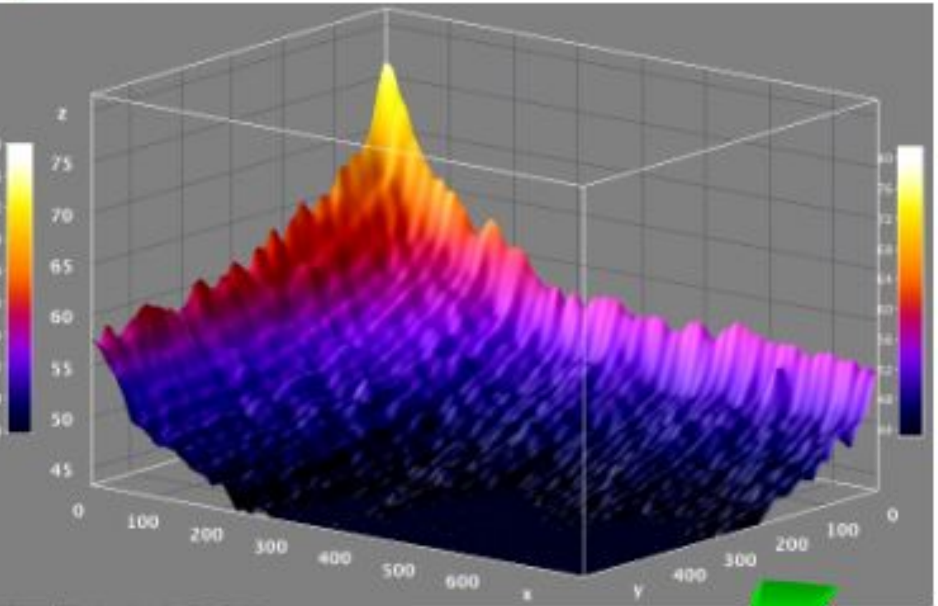


after subtraction

beta source, collimated

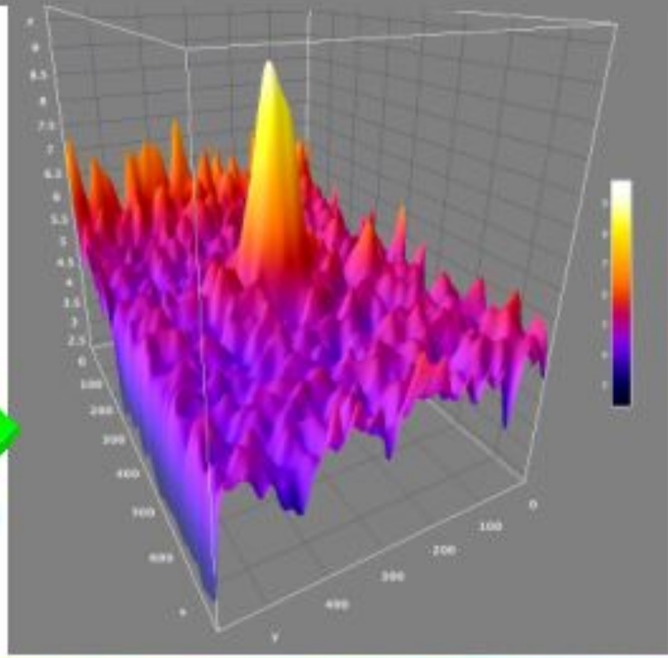


raw data



background

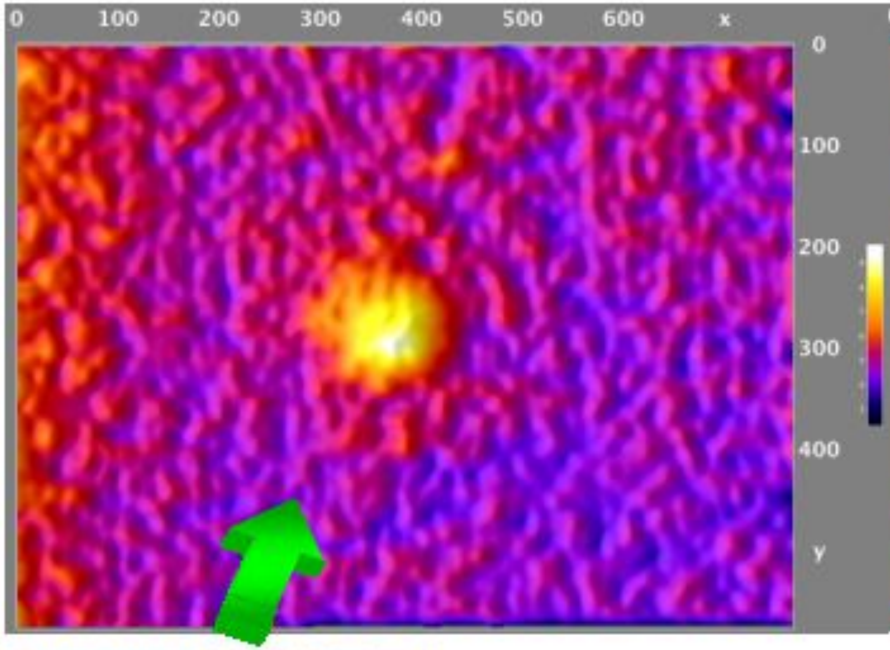
CCD systematic noise plus light leaking in from a corner



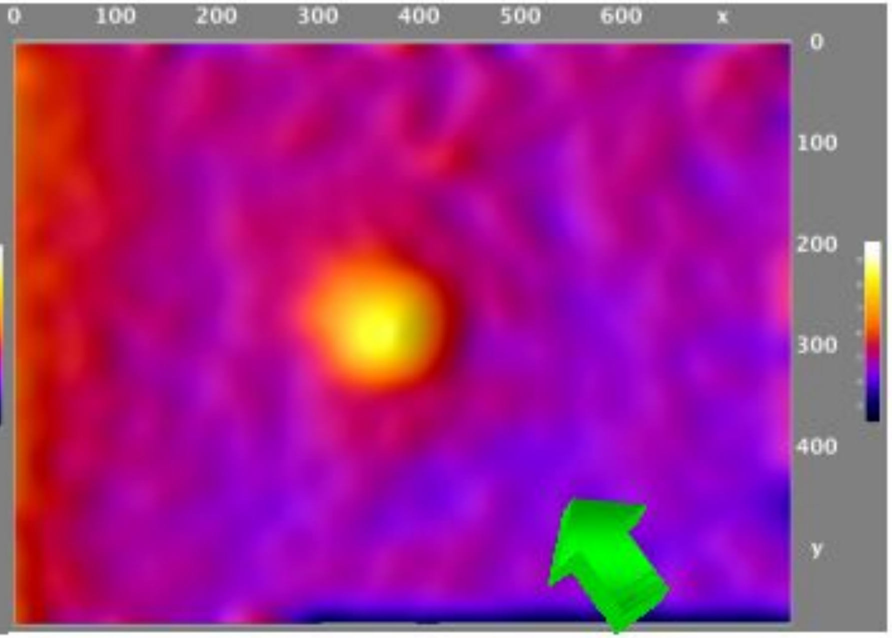
after subtraction

beta source, collimated

smoothing images (i.e. binning data) improves statistics losing details (i.e. space resolution)



lower smoothing (binning)



higher smoothing (binning)

now let's do it

beta source, non-collimated:

display
x-projections
BG image subtraction

fit procedure

3D plots manipulation

beta source, collimated:

display
x-projections
BG image subtraction

fit procedure

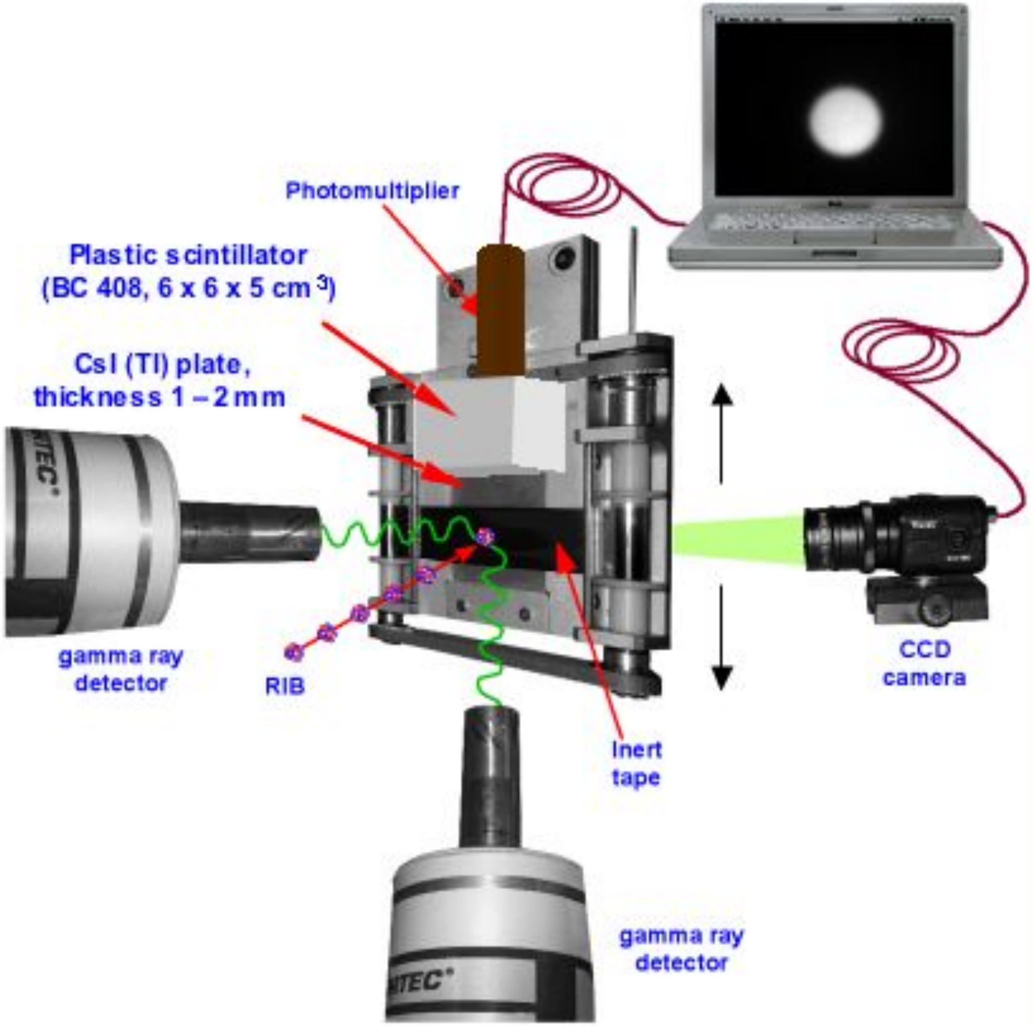
3D plots manipulation

....

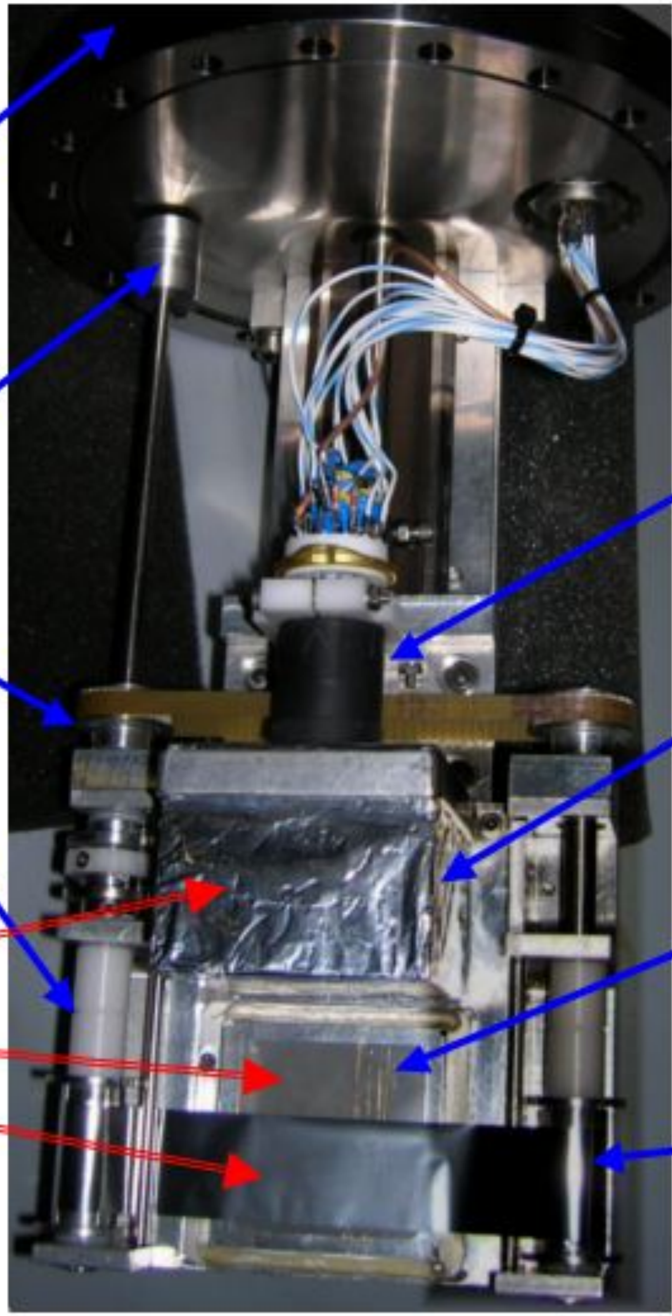
the LEBI device
Low Energy Beam Imager-Identifier

A diagnostics station that combines several techniques for beam detection and identification

- CsI(Tl) plate + CCD camera for direct imaging of stable beams
- CsI(Tl) plate + CCD camera for beta-ray imaging of implanted RIBs
- Plastic scintillator + PMT for radioactive decay counting of implanted RIBs (determination of $T_{1/2}$)
- Gamma detectors for RIBs spectroscopic fingerprinting



LEBI is the LNS solution for beam diagnostics of low energy radioactive beams.



step motor

tape transport system

Photomultiplier

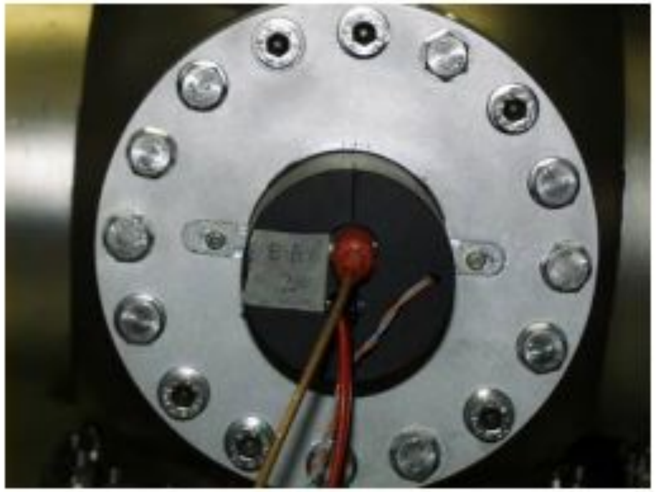
Plastic scintillator BC 408

CsI (Tl) plate

mylar tape 6 μm

3 measurement positions

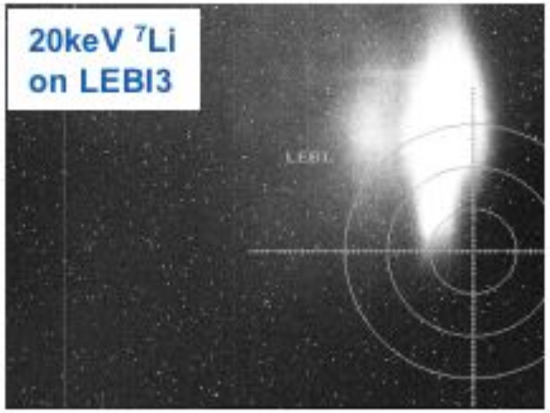
- Beam rate measurement
- Imaging of stable (pilot) beams
- Imaging of radioactive beams

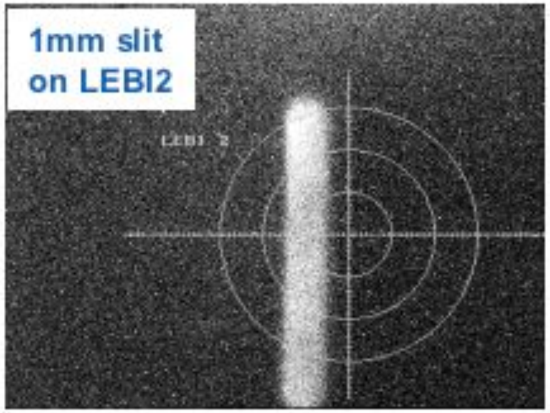


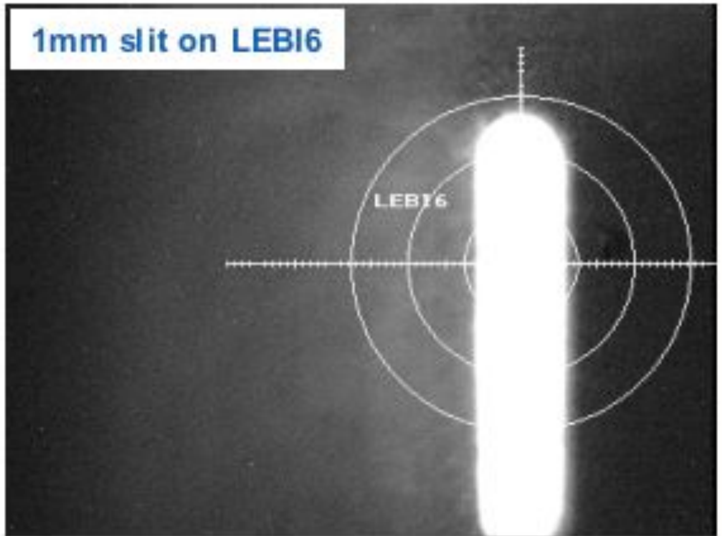
ccd camera watec 902H

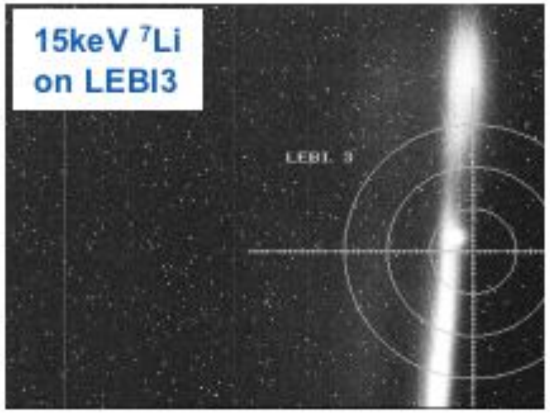
•sensitivity 10^{-4} lux
•spatial calibration
•reference of the beam axis

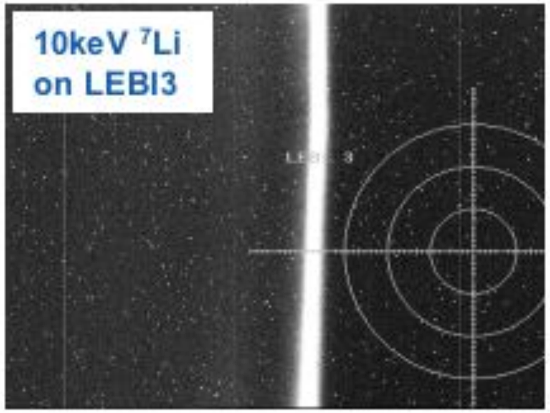
^{7}Li stable beam online snapshots

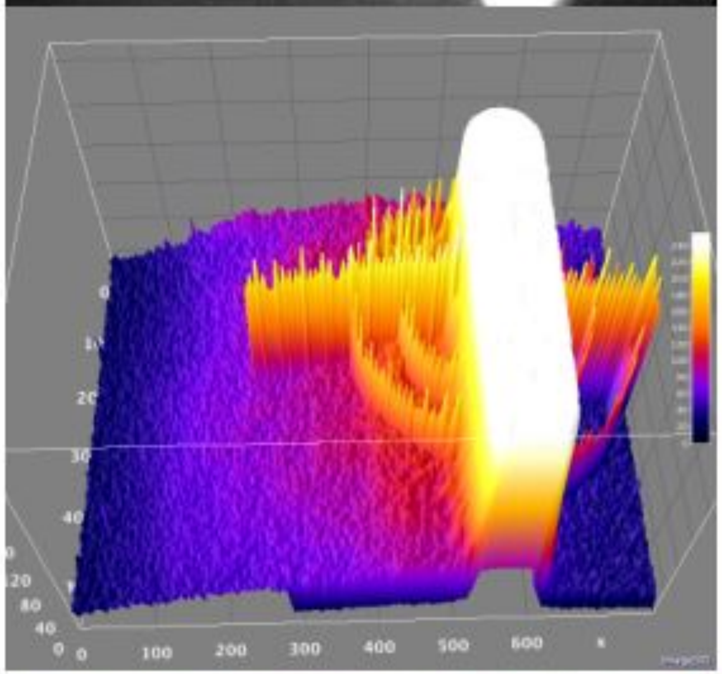






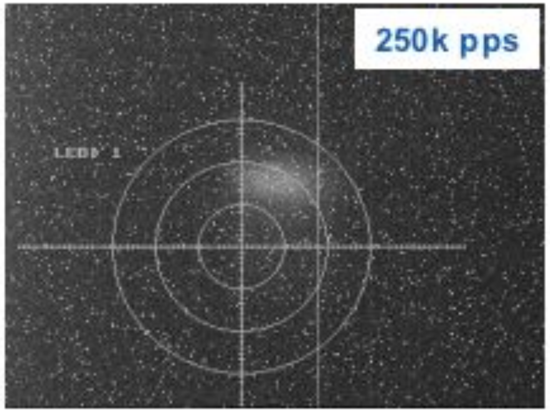


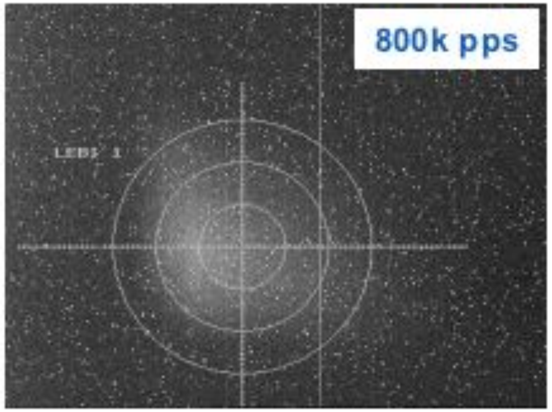


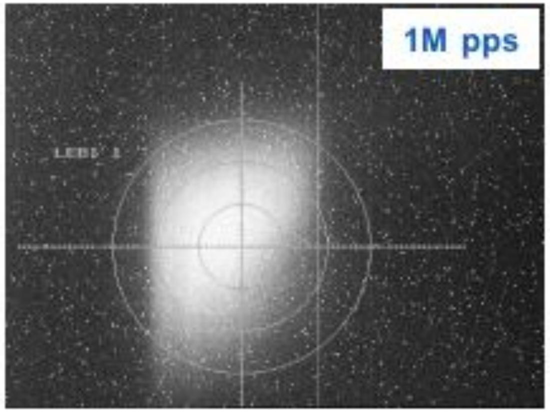


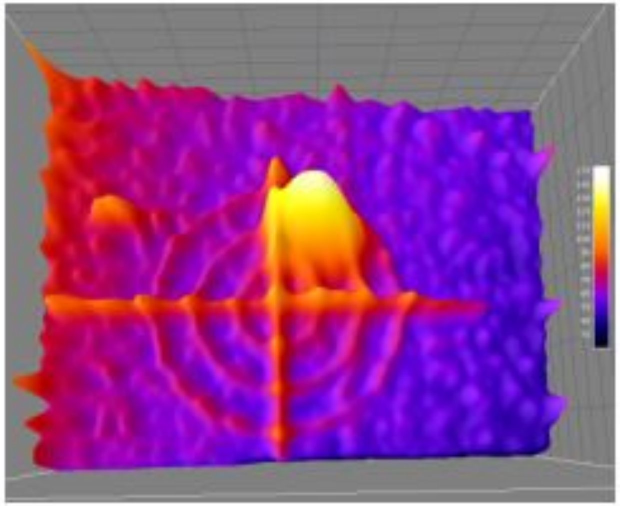
the bull's-eye is added electronically and was aligned with the beam axis

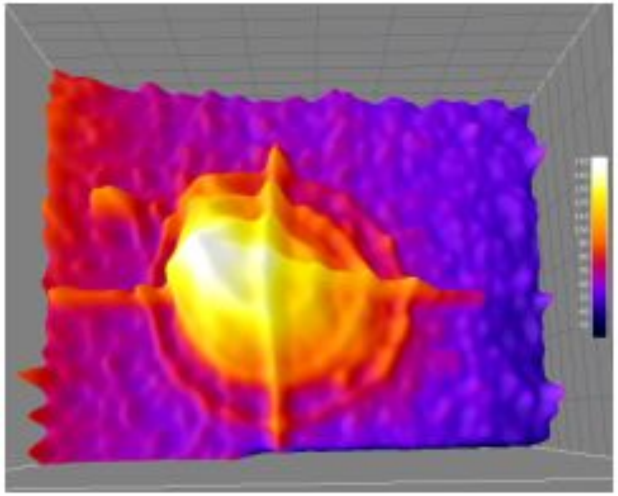
^{7}Li radioactive beam online snapshots

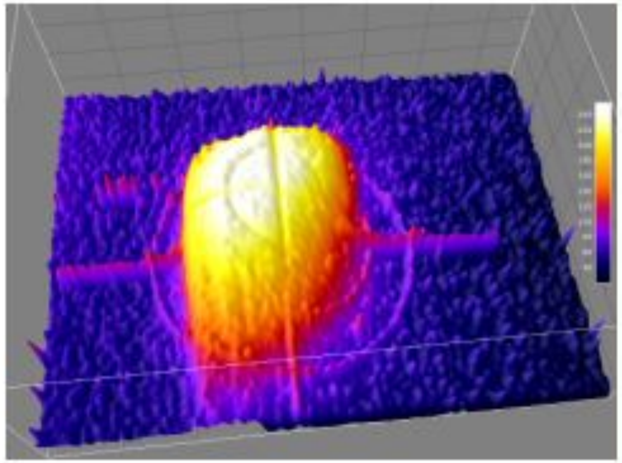






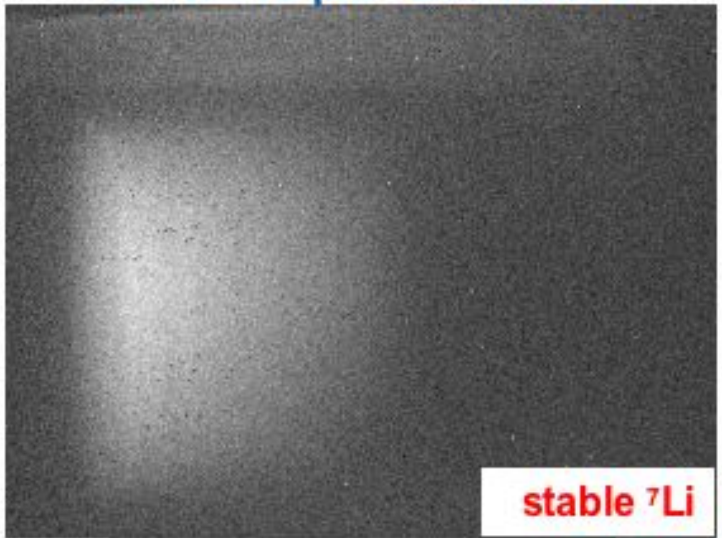


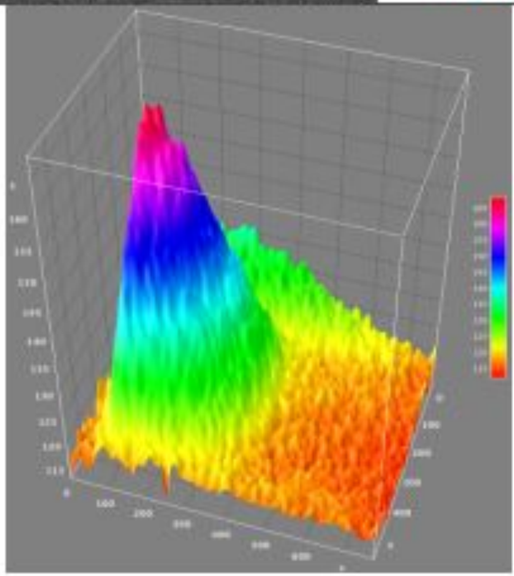




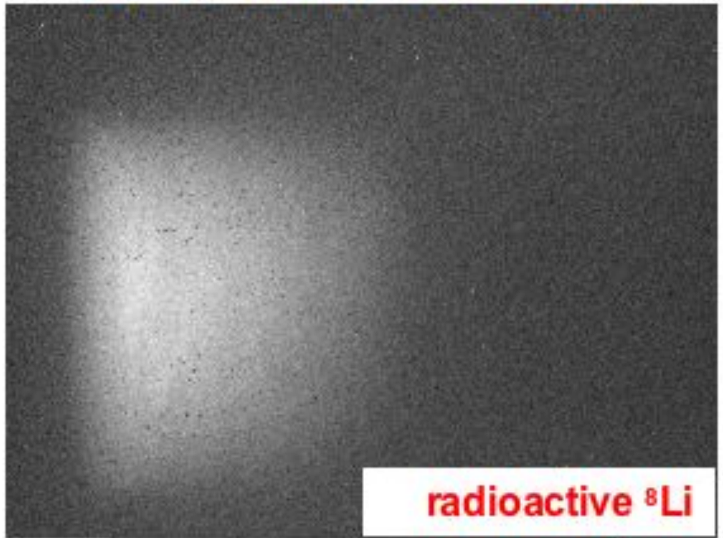
switched the dipole magnet from ^{7}Li to ^{8}Li during the same run

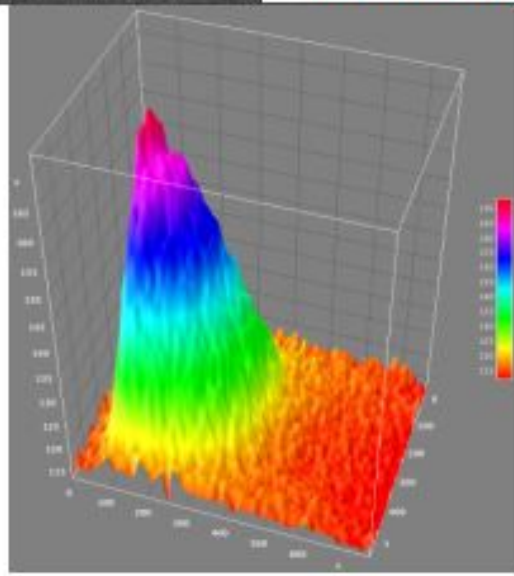
^{7}Li I = 10 pA E = 10 keV





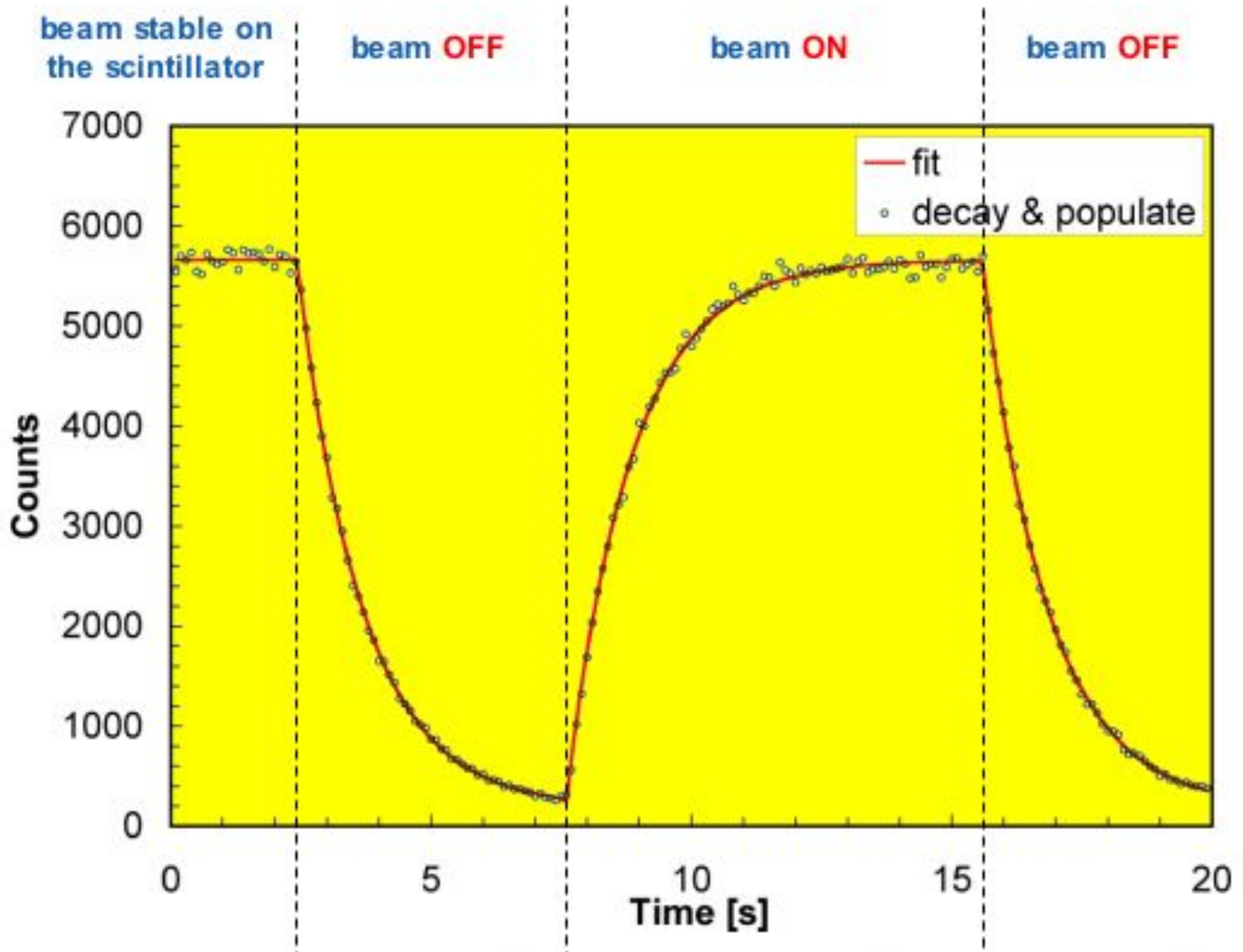
^{8}Li I = 100 fA E = 10 keV





OK but... are we sure we got the right species?

let's have a look at the plastic scintillator for counting



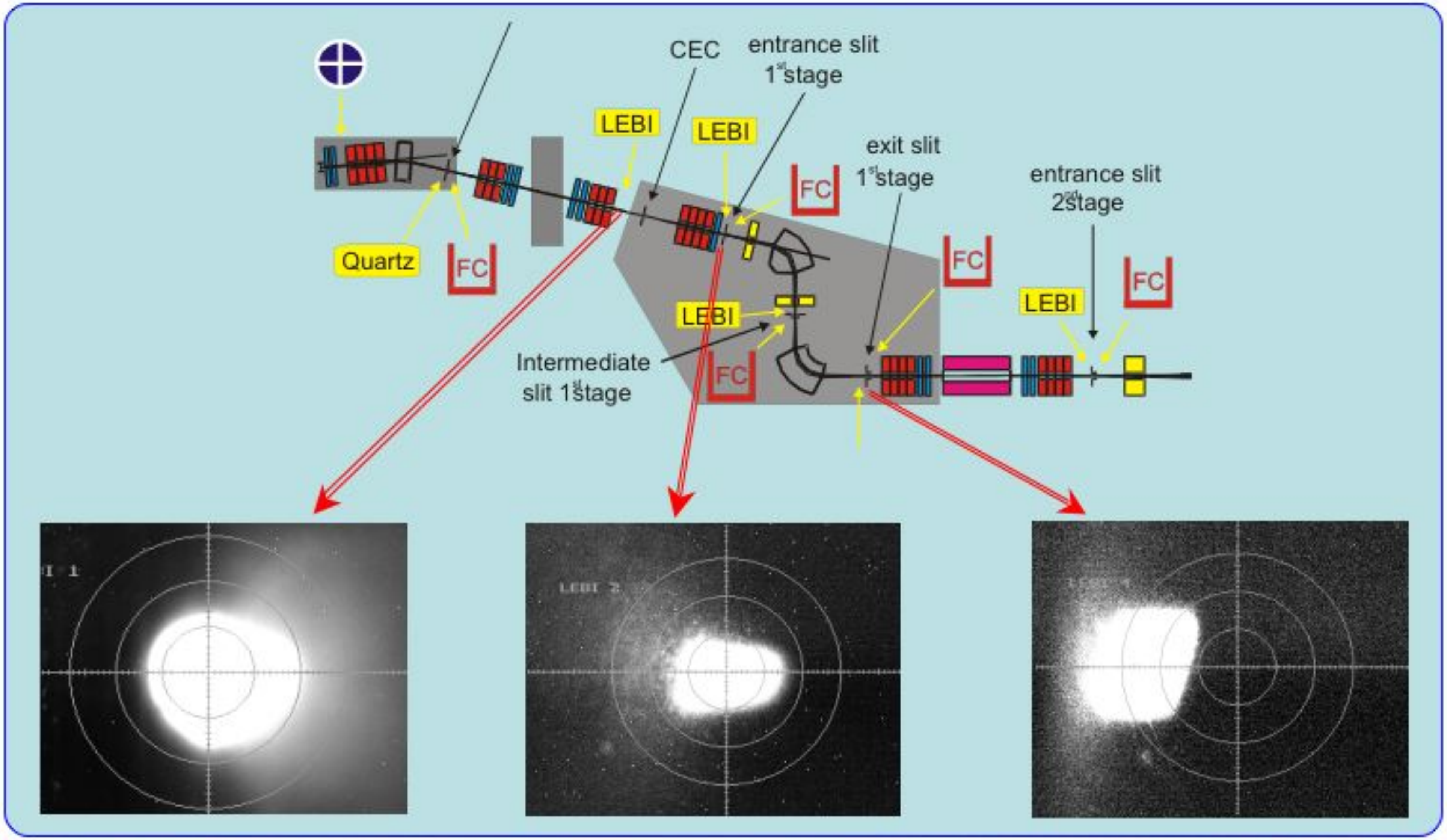
$$r \cdot e^{-\ln(2)\cdot\frac{t}{T_{1/2}}} \qquad r \cdot (1 - e^{-\ln(2)\cdot\frac{t}{T_{1/2}}}) \qquad r \cdot e^{-\ln(2)\cdot\frac{t}{T_{1/2}}}$$

Identification of ^{8}Li by means of its β decay curve

$T_{1/2}$ = 840 ms

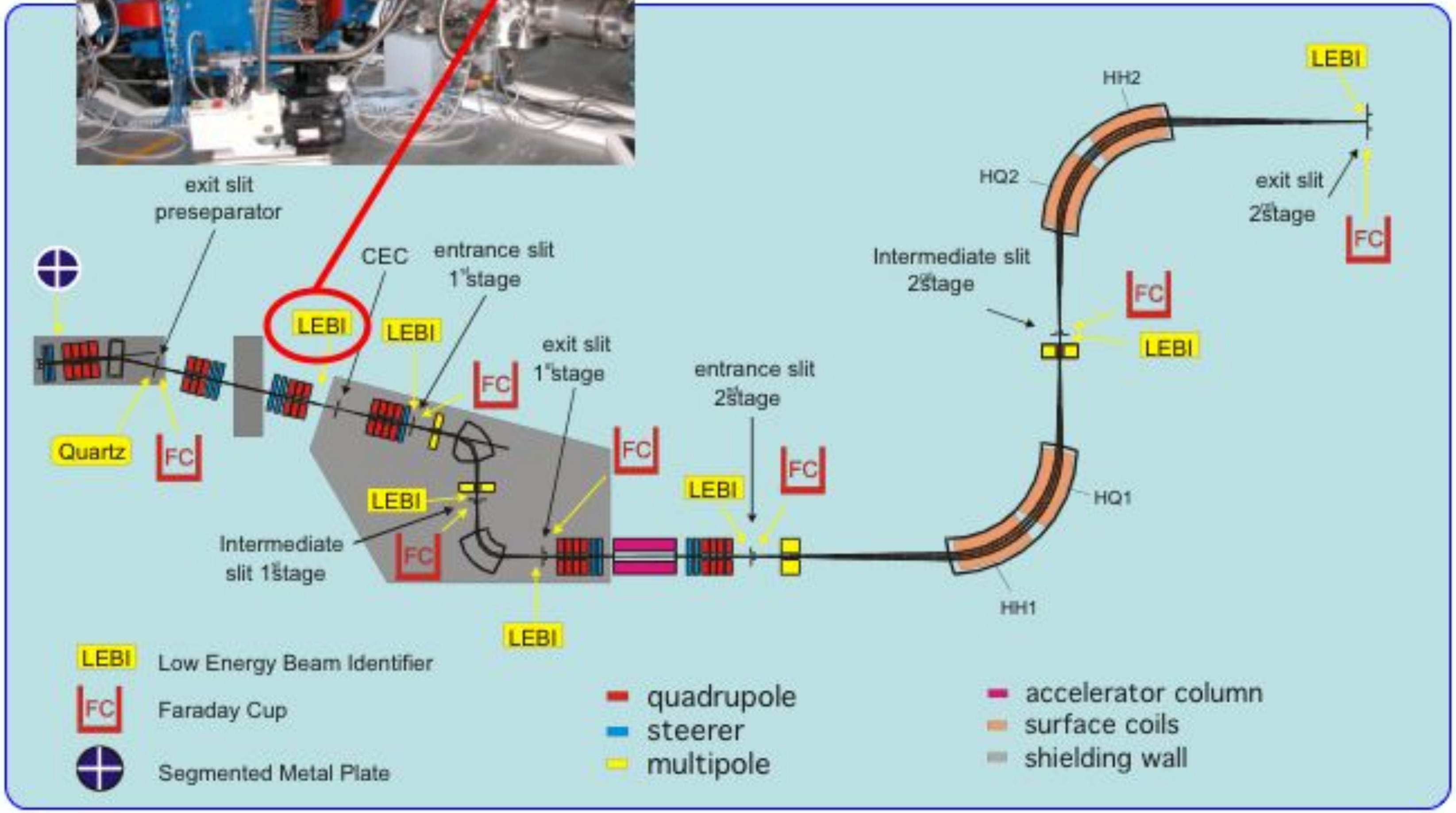
OK, now I want to transport the beam across the mass analyzer and further: install several LEBIs

fA ^{8}Li "miracle" beam transport



currently 9 LEBIs are installed

2 are ready and going to be installed soon



Detectors for new beams ?

Nuclide	Half life	Possible contaminants (M/ΔM)	Average energy of beta (keV)	Gamma peaks (keV)	Detectors to be used
^{8}Li	0.838 s	^{8}B (3800)	6243	No peaks	Plastic scintillator. Spectra reconstruction.
^{9}Li	0.178 s	^{9}C (2120)	A lot of beta's	No peaks	Plastic scintillator. Difficult for threshold estimation. Too short half life.
^{10}C	19.255 s	^{10}Be (3020), ^{10}B* (2560)	No beta's	718, 1021	CsI and germanium. Peaks recognition.
^{11}C	20.39 min	^{11}Be (1080), ^{11}B* (5170)	385.6	No peaks	Plastic scintillator. Spectra reconstruction.
^{15}C	2.449 s	^{15}N* (1430), ^{15}O (1990)	4649, 2032	5297	Plastic scintillator and germanium
^{15}O	112.24 s	^{15}N* (5070), ^{15}C (1990)	735	No peaks	Plastic scintillator. Spectra reconstruction.
^{19}O	26.9 s	^{19}N (1410), ^{19}F* (3670)	2200 (4%), 2103 (45.4%), 1442 (54.4%)	A lot of peaks	Plastic scintillators and germanium. Difficult for threshold estimation.
^{20}O	13.51 s	^{20}N (1040), ^{20}F (4890), ^{20}Na (6110), ^{20}Mg (1350)	1197	1056	Plastic scintillators (spectra reconstruction) and germanium.

Detectors for new beams ?

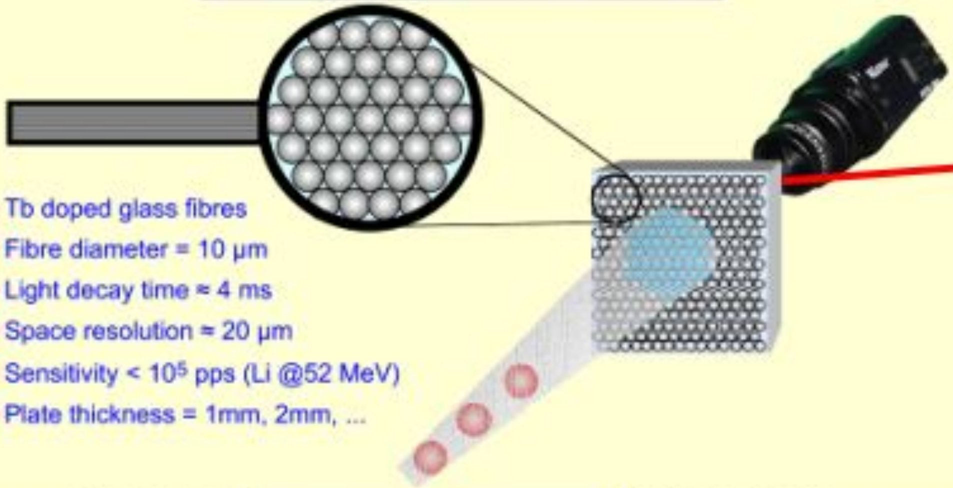
Nuclide	Half life	Possible contaminants (M/ΔM)	Average energy of beta (keV)	Gamma peaks (keV)	Detectors to be used
^{17}F	64.49 s	^{17}N (2680)	740	No peaks	Plastic scintillator. Spectra reconstruction.
^{18}F	109.77 min	^{18}N (1370), $^{18}O^*$ (10130)	250	No peaks	Plastic scintillator. Spectra reconstruction.
^{20}F	11.16 s	^{20}Na (2710), ^{20}O (4880), ^{20}Mg (1060)	2481	1633	Plastic scintillator and germanium
^{25}Al	7.183 s	$^{25}Mg^*$ (5440), ^{25}Na (52700), ^{25}F (1150), ^{25}Si (1830)	1460		Plastic scintillator. Spectra reconstruction.
^{29}Al	6.56 min	^{29}Mg (3570), ^{29}Na (1300), $^{29}Si^*$ (7340), ^{29}P (21360), ^{29}S (1790)	1023 (90%), 670 (3.8%), 490 (6.3%)	Several peaks with energy > 1200 keV	Plastic scintillators and germanium. Difficult for threshold estimation.
^{33}Cl	2.511 s	$^{33}S^*$ (5500), ^{33}P (5760), ^{33}Si (60100), ^{33}Ar (2640)	2096	No appreciable peaks	Plastic scintillator. Spectra reconstruction.

Detectors for new beams ?

Nuclide	Half life	Possible contaminants (M/ΔM)	Average energy of beta (keV)	Gamma peaks (keV)	Detectors to be used
^{34}Cl	1.526 s (spin 0^+), 32.00 min (spin 3^+)	^{34}S* (5760), ^{34}P (270490), ^{34}Si (7060), ^{34}Ar (5220)	– 0^+: 2052 – 3^+: 1099 (28.4%), 555 (25.6%)	– 0^+: no peaks – 3^+: a lot of peaks	Easy (Plastic scintillator. Spectra reconstruction) if the 0^+ is favourite
^{38}Cl	37.24 min	^{38}S (12040), ^{38}P (2310), ^{38}Ar* (7190), ^{38}K (35500), ^{38}Ca (4570)	2244 (57.6%), 1181 (10.5%), 420 (31.9%)	1642 (31.9%), 2167 (42.4%)	Plastic scintillators and germanium. Difficult for threshold estimation.
^{39}Cl	55.6 min	^{39}S (5470), ^{39}P (2120), ^{39}Ar (10550), ^{39}K* (9060), ^{39}Ca (14380)	A lot of beta's	A lot of gamma's.	Plastic scintillators and germanium. Difficult for threshold estimation.
^{40}Cl	1.35 min	^{40}S (7910), ^{40}P (1940), ^{40}Ar* (4980), ^{40}K (6230), ^{40}Ca* (5110), ^{40}Sc (5300)	A lot of beta's	A lot of gamma's.	Plastic scintillators and germanium. Difficult for threshold estimation.

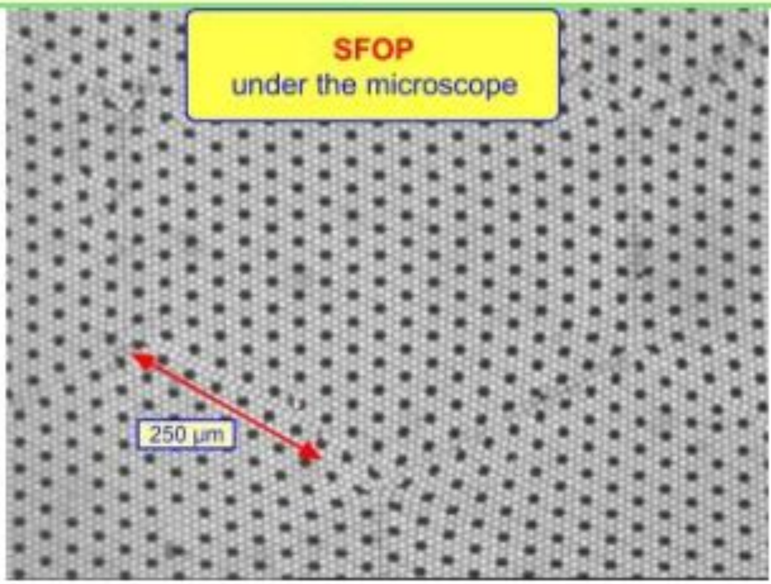
* Stable isotope

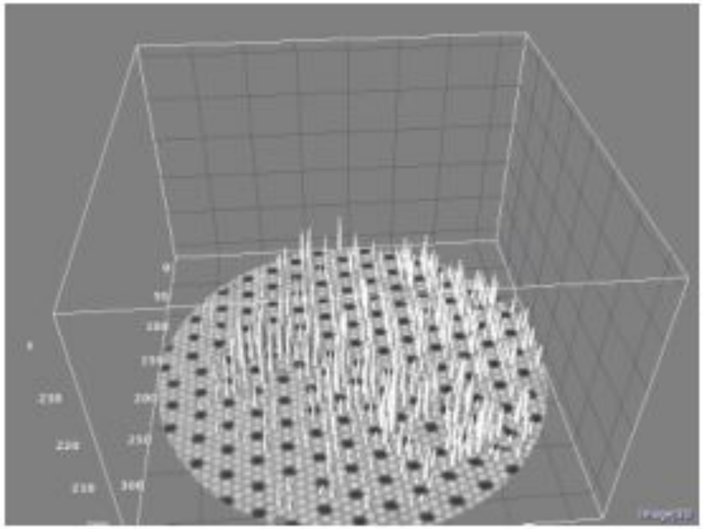
SFOP
Scintillating Fiber Optic Plate



- Tb doped glass fibres
- Fibre diameter = 10 µm
- Light decay time ≈ 4 ms
- Space resolution ≈ 20 µm
- Sensitivity < 10^5 pps (Li @52 MeV)
- Plate thickness = 1mm, 2mm, ...

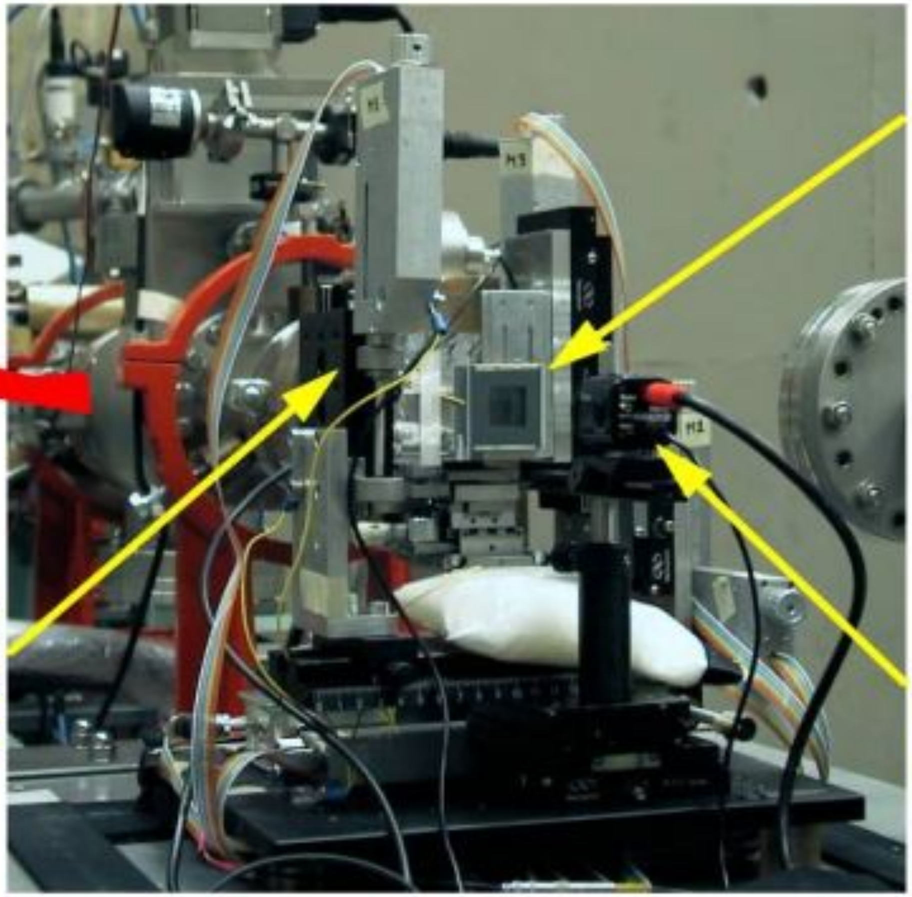
Micro-beam diagnostics the SFOP





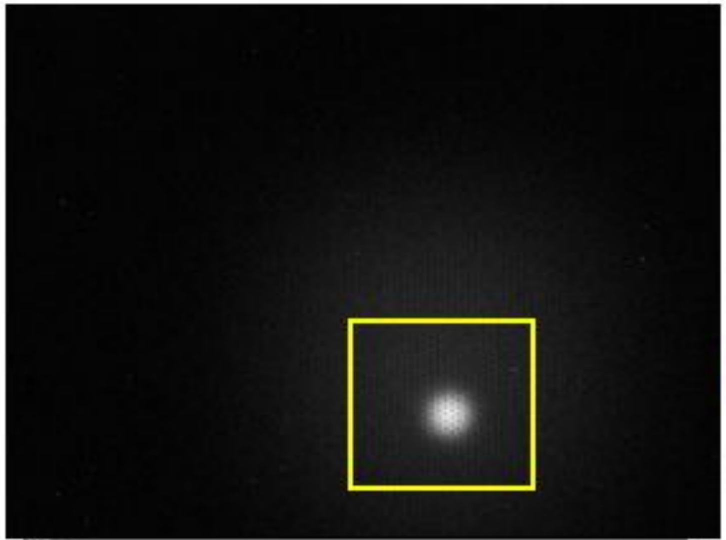
Micro-beam diagnostics
the SFOP

μ-SFOP

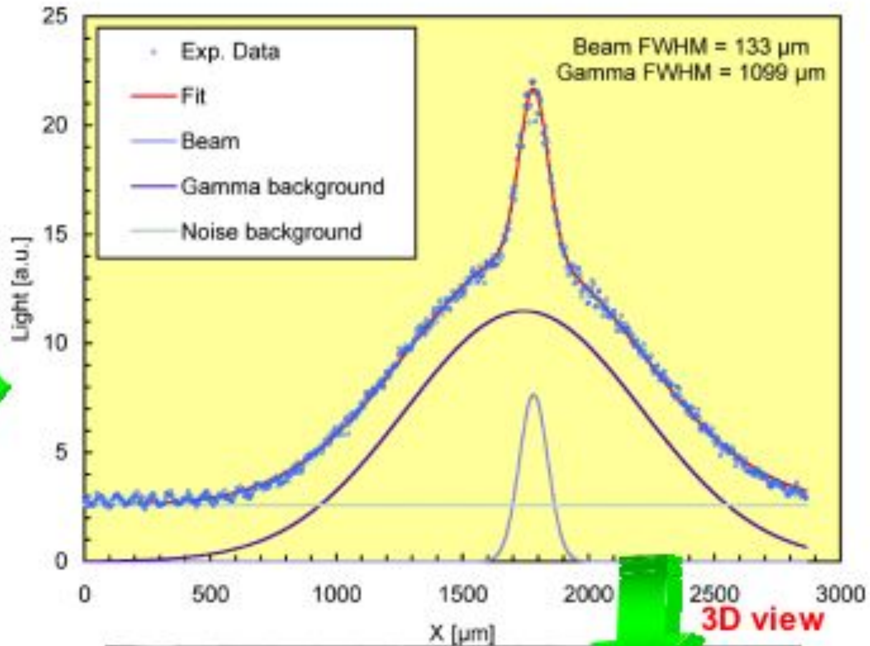


Micro-beam diagnostics
the SFOP

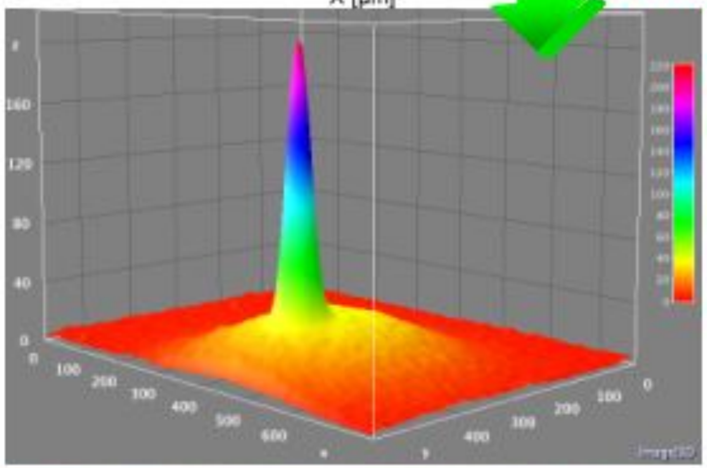
collimator: 150μm
primary beam current: 30pA, protons



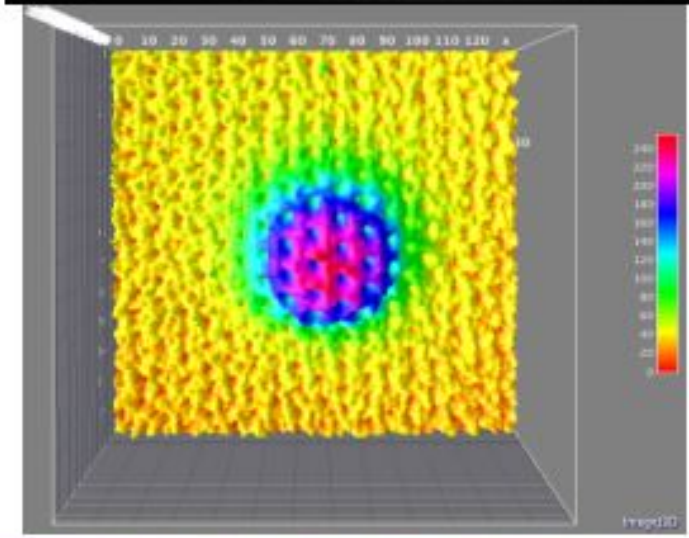
project and fit



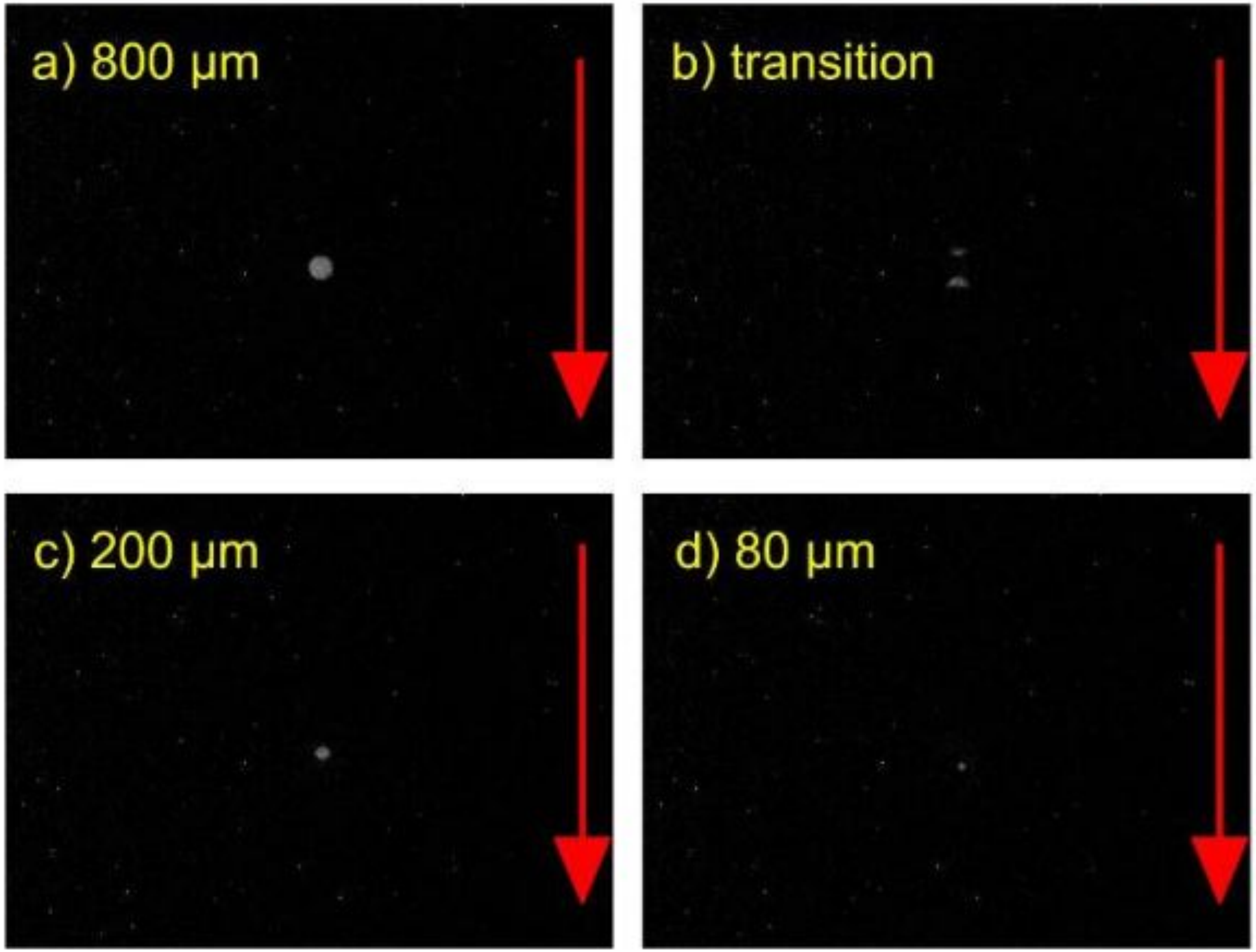
3D view



zoom



4 frames extracted from a real time movie taken while the multi-collimator mask was sliding down

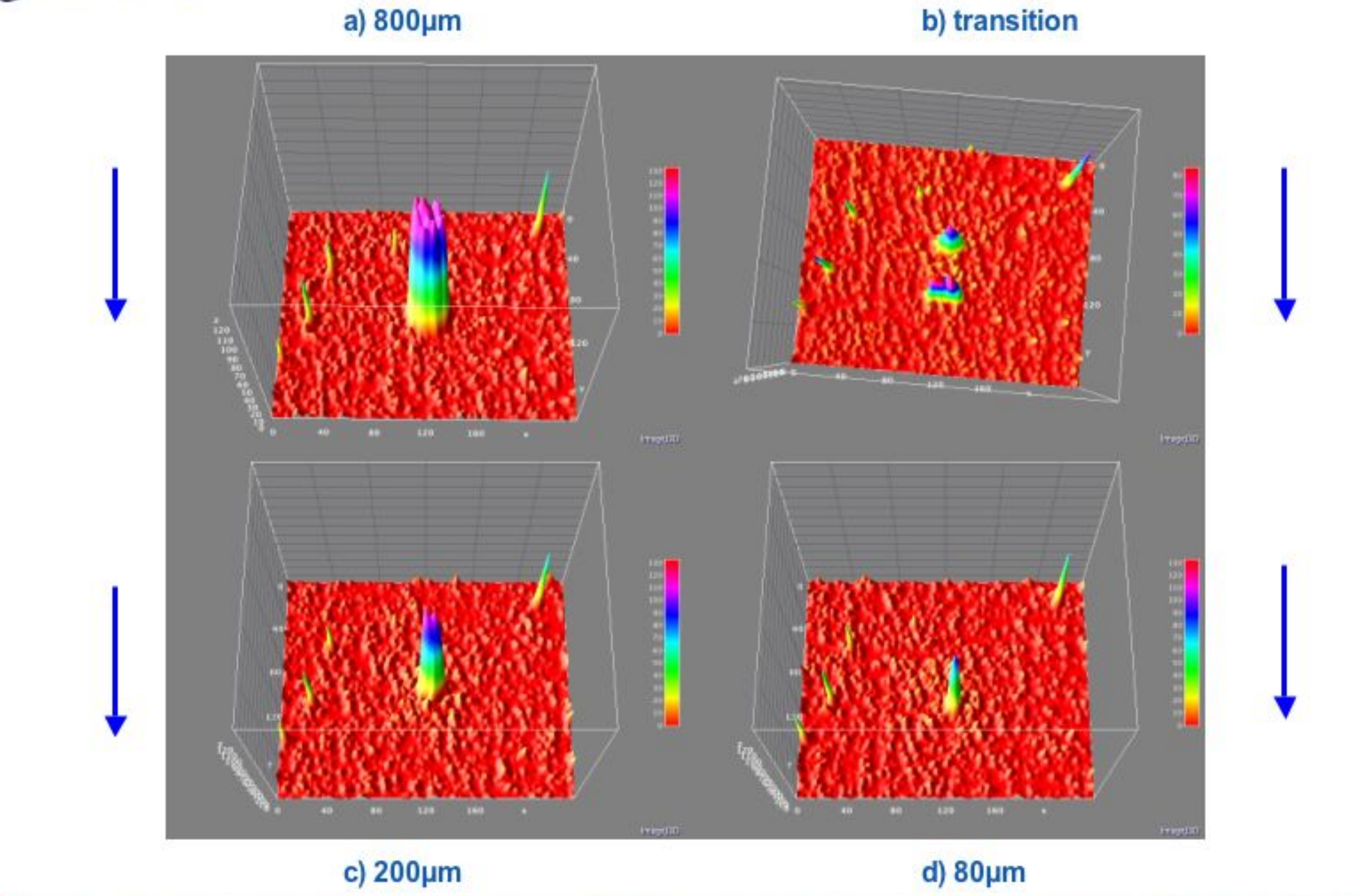


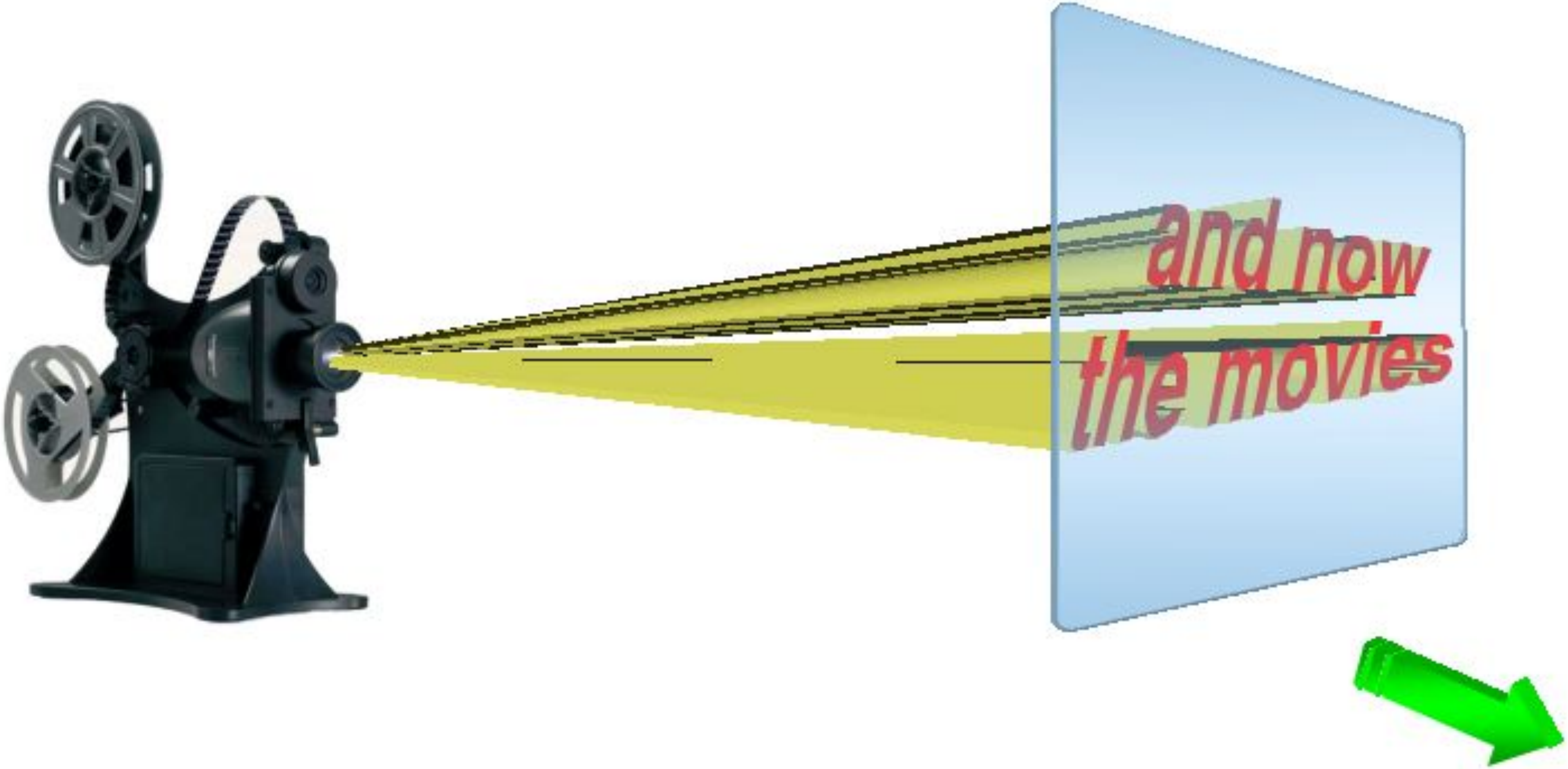
µ-SFOP

The mask slides down, scanning several holes (the CCD lens magnification is low in this run)

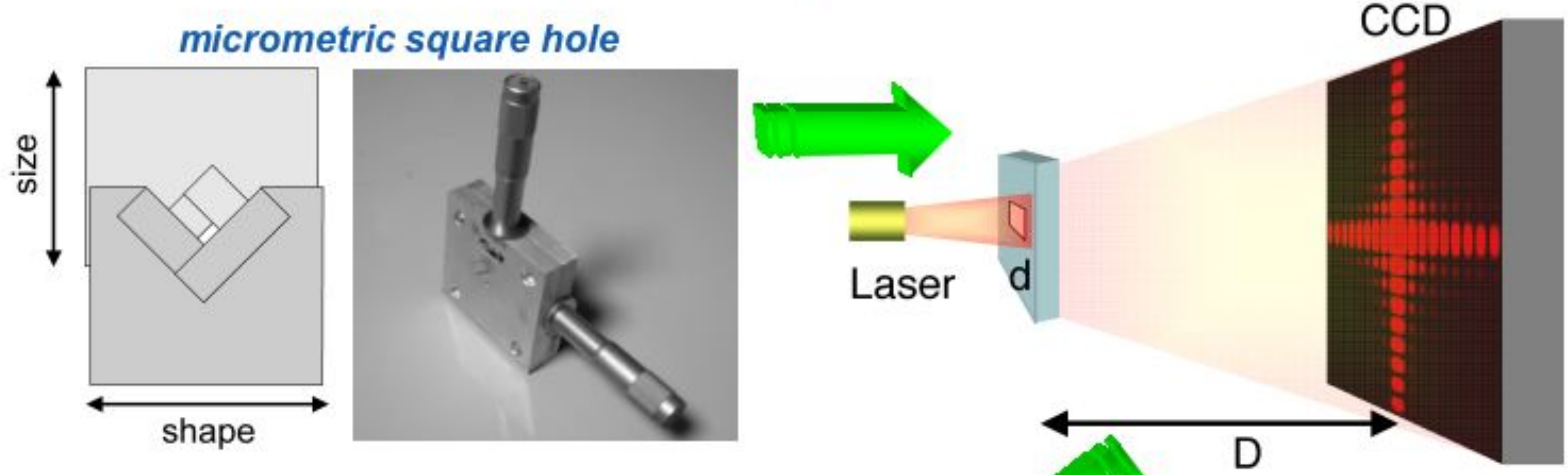
spotted the beam down to 20µm diameter

watch the movie...


a) 800µm
b) transition
c) 200µm
d) 80µm


and now
the movies

Ultra Low Intensity microbeam production: tunable collimator

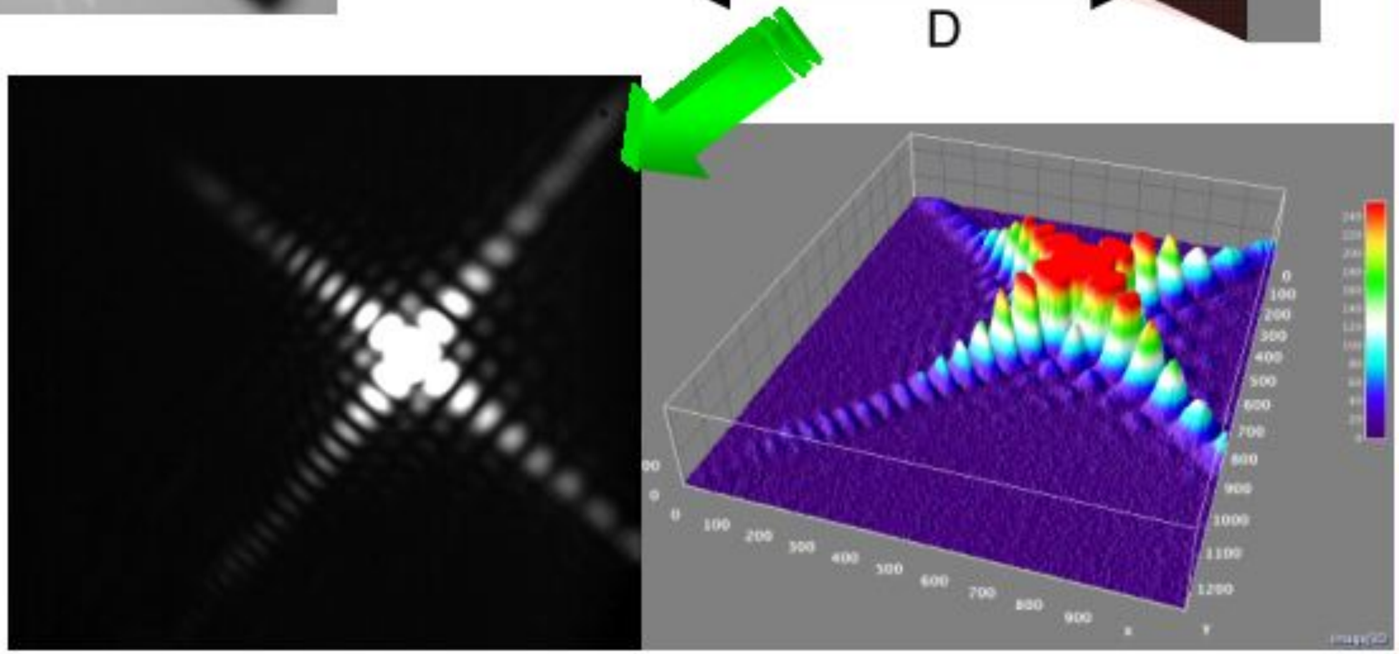


$$d \sin(\theta_{\min}) = n\lambda$$

Lambda is known,

we count n and measure theta_min:

we can deduce d



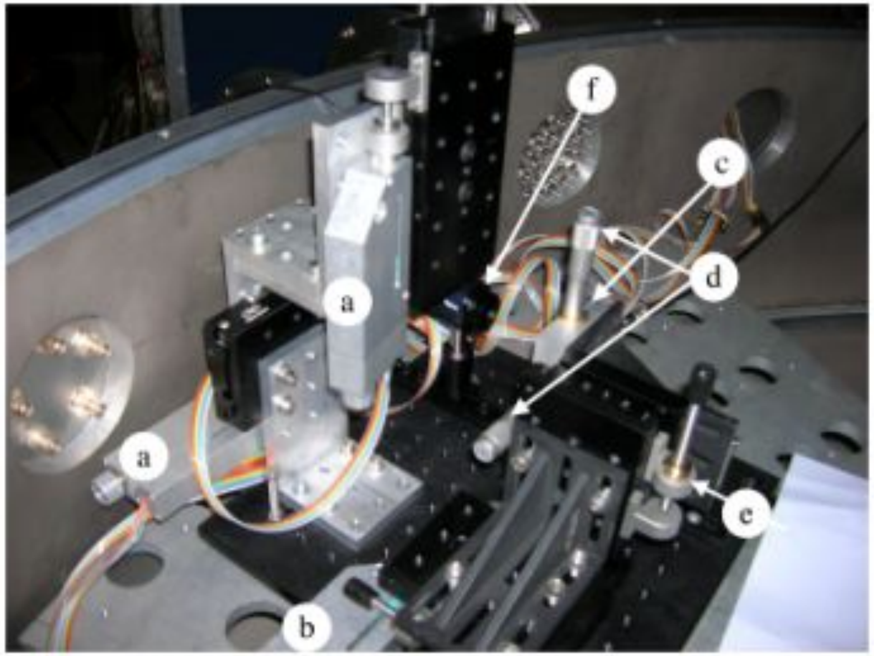
ULI microbeam diagnostics: position sensitive silicon strip telescope

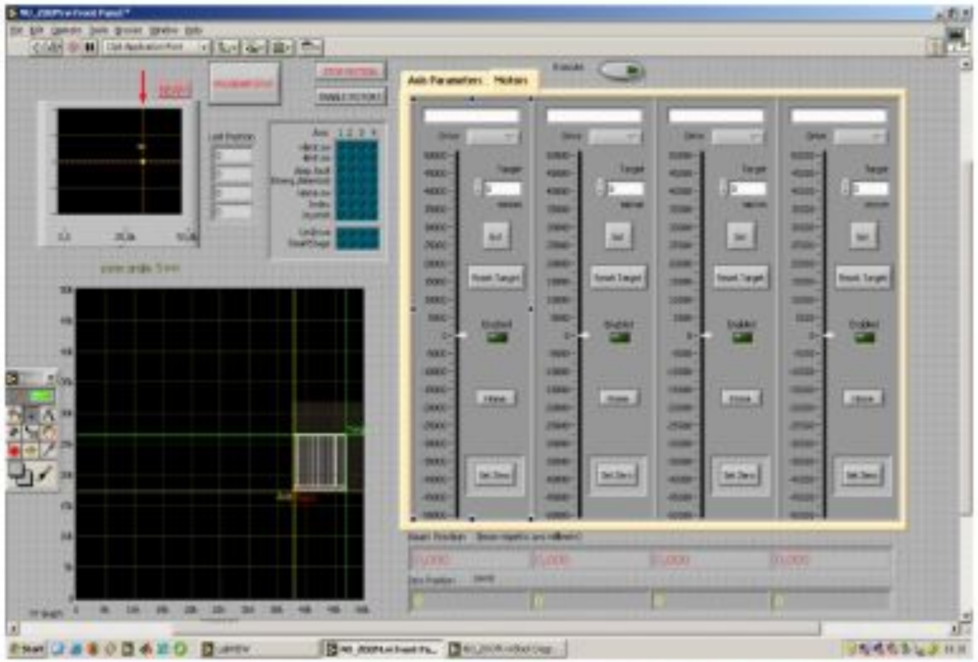
(a) Stepping motors for the XY translation stages of the telescope detector.
(b) Stepping motor for the X translation stage of the microcollimator.
(c) Microcollimator (φ<50μm).
(d) Shape and size micrometer knobs.
(e) Tip-and-tilt stage for the microcollimator.
(f) Lensless CCD camera (to be replaced by the silicon detector at irradiation time).

Micro-motion system: in-house developed LabView software

3 motorized degrees of freedom: (a) and (b)

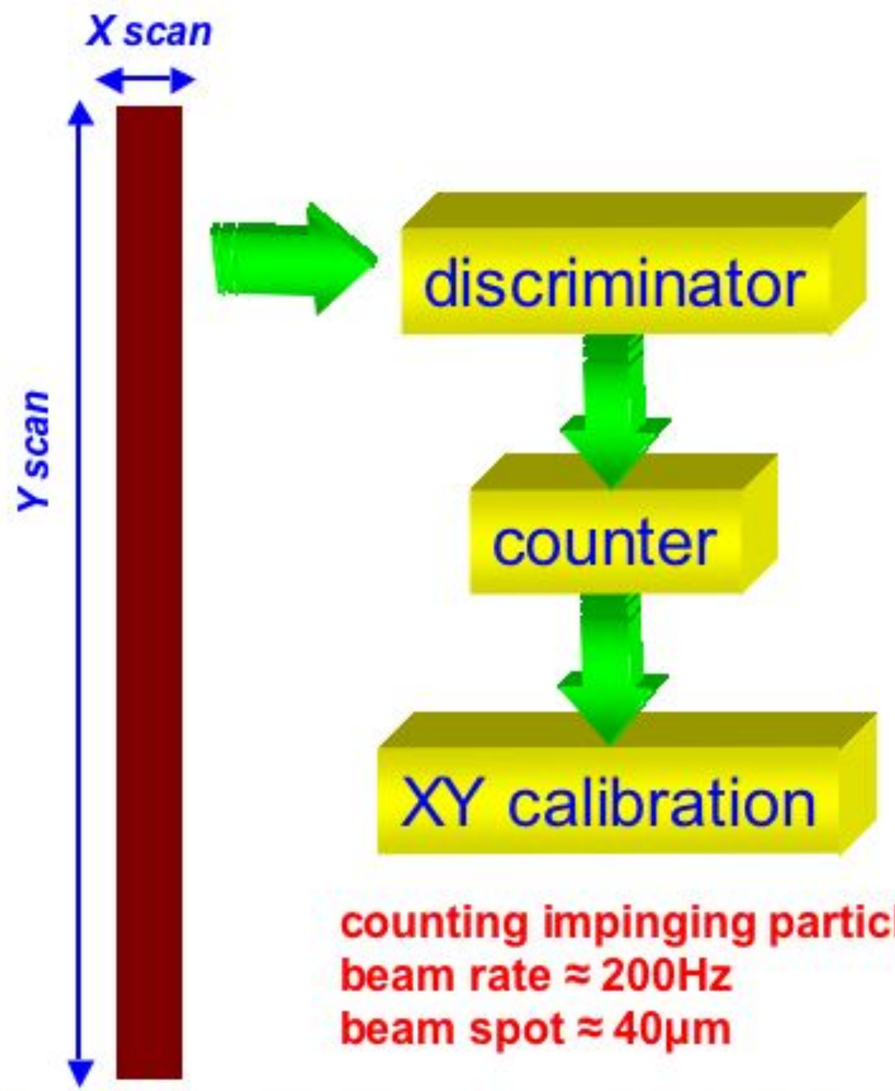
by means of 3 linear stages Newport High Performance Crossed-Roller Bearing model 426 and 436 (step: 50nm, range: 5cm)

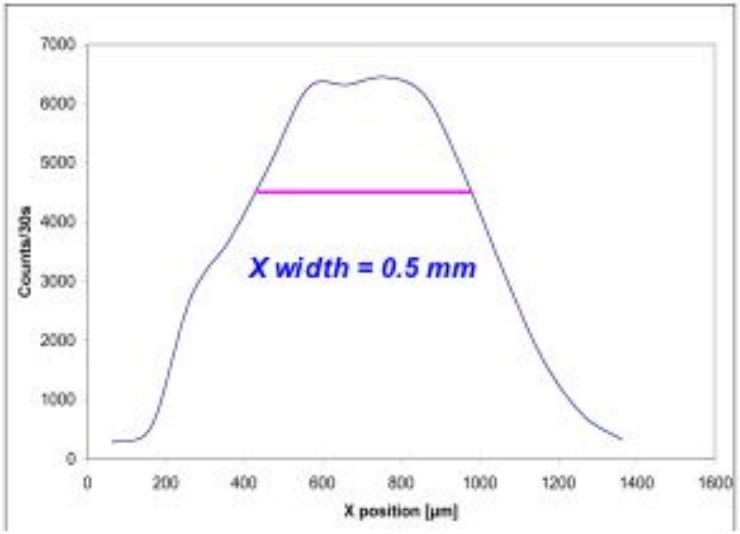


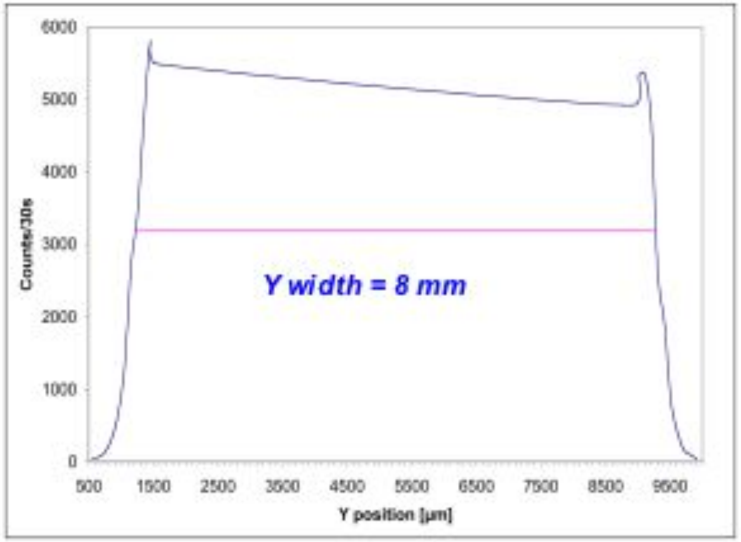


ULI microbeam diagnostics: silicon telescope calibration

irradiation with ^{12}C 30 MeV (200pps) by means of Tandem accelerator







counting impinging particles
beam rate ≈ 200Hz
beam spot ≈ 40µm

INFN LNS

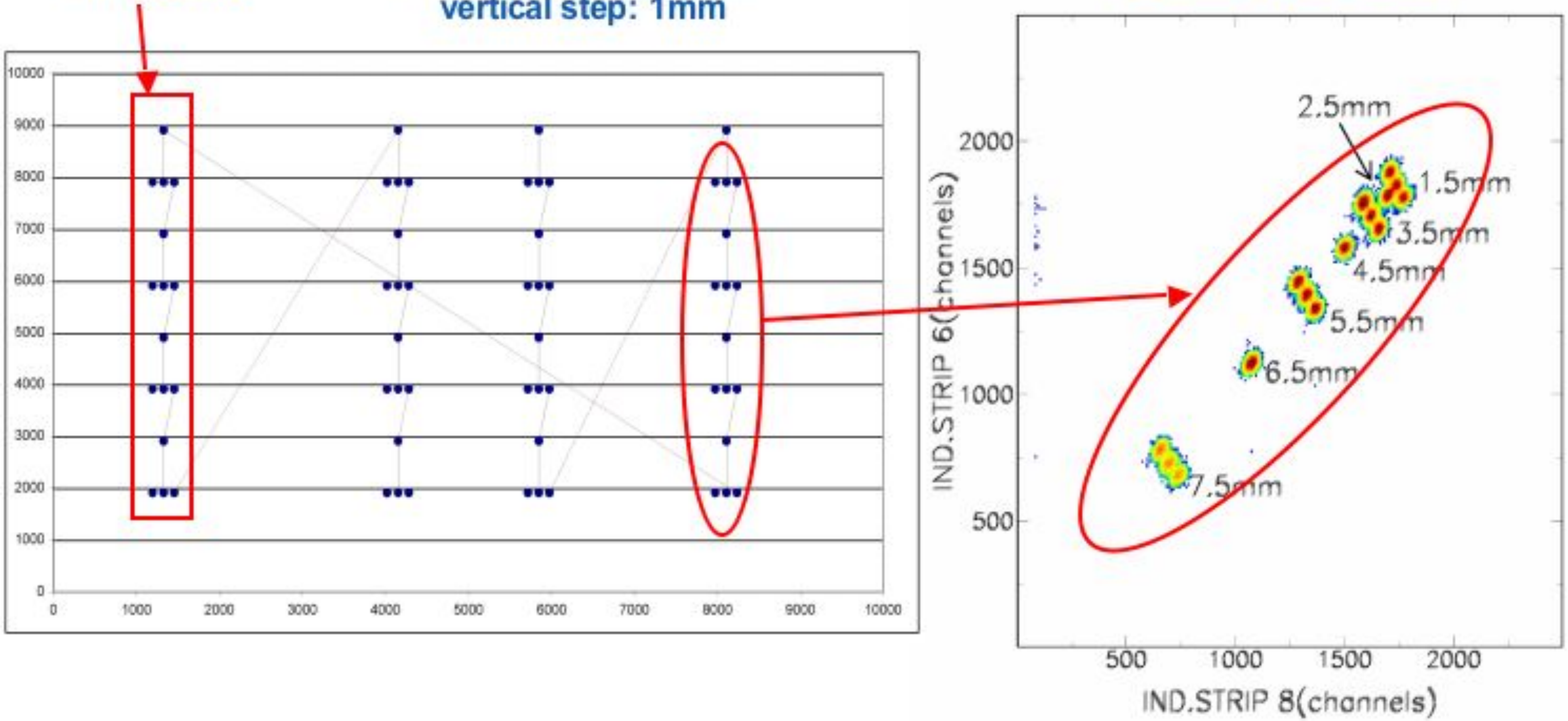
DITANET

ULI microbeam diagnostics: silicon telescope imaging

one strip

irradiation scheme
horizontal step: 125µm
vertical step: 1mm

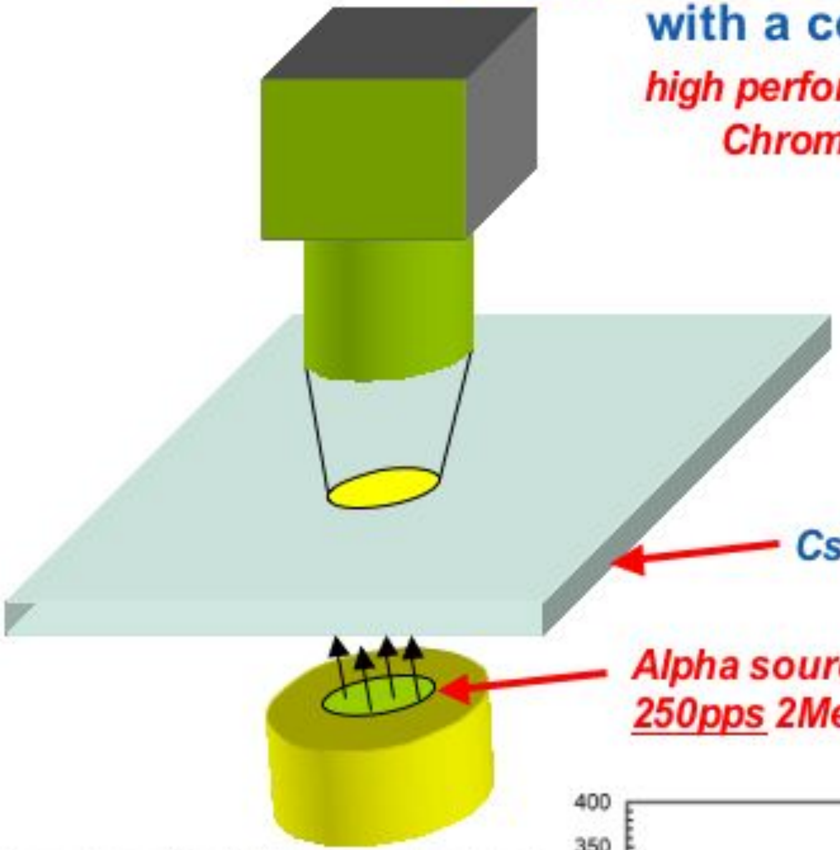
"snapshot" of the irradiated points (raw data)



DITANET

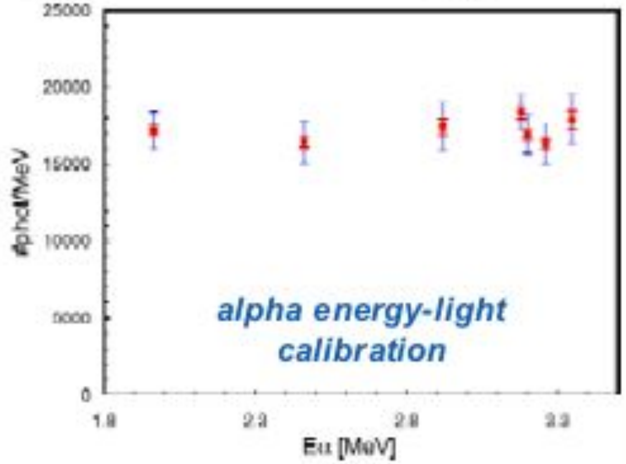
Scintillating screens for very low beam intensity with a cooled CCD still camera

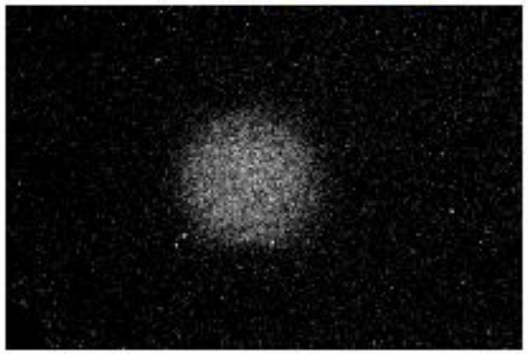
high performance photocamera
Chroma CX3 14-bit CCD

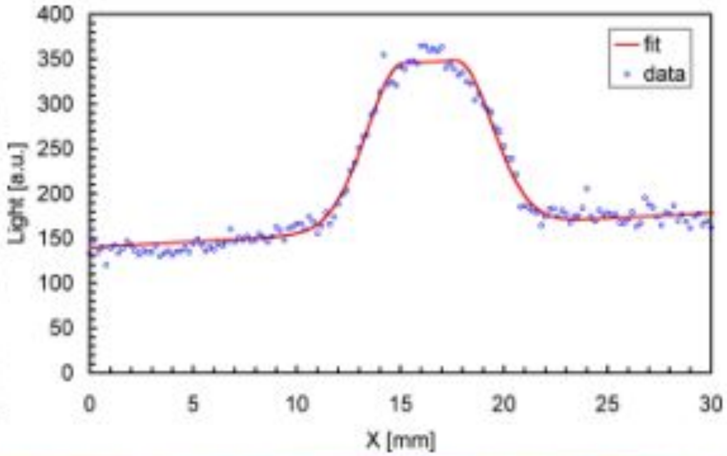


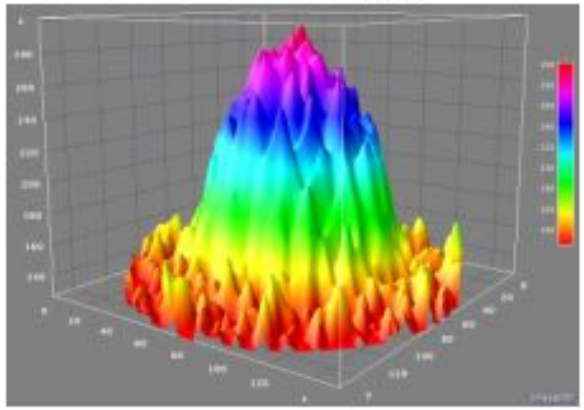
CsI(Tl) scintillator

Alpha source
250pps 2MeV



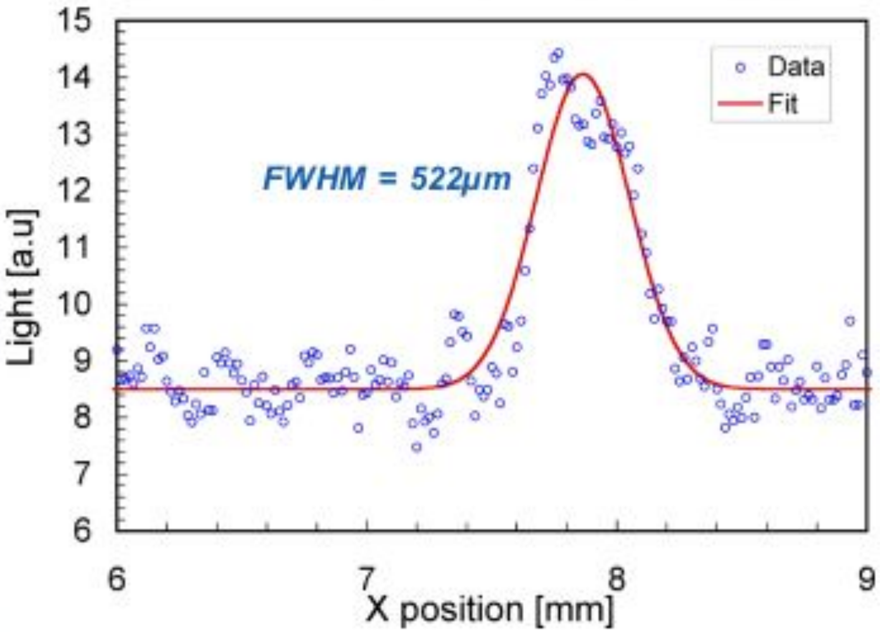


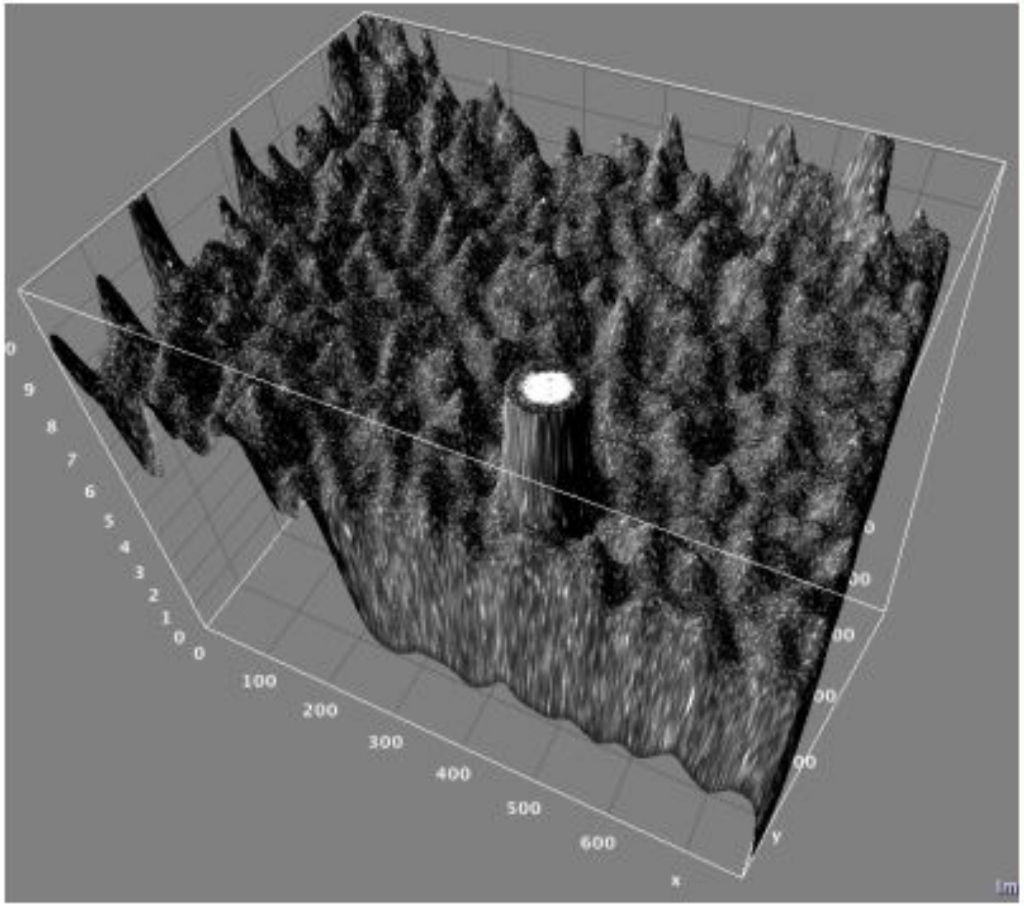




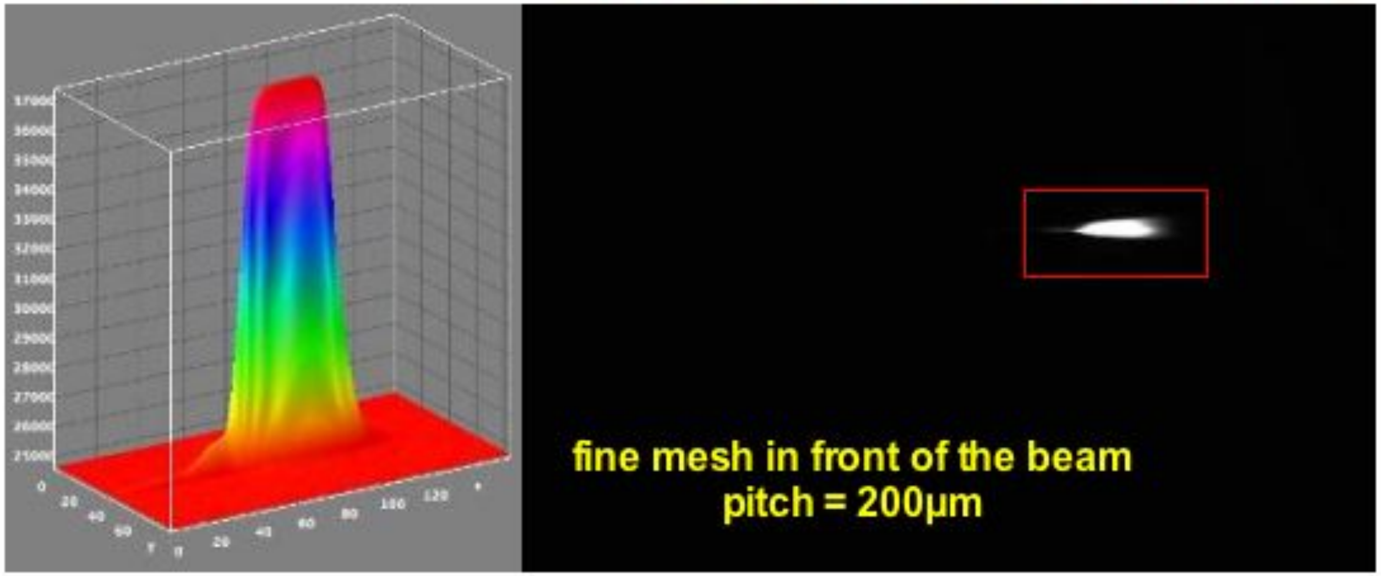
Ultra-thin CsI(Tl) Scintillating screens

test with protons at LNS 180 keV, 5 pA
CsI(Tl) ultra-thin scintillator (3 microns) standard video CCD





Scintillating screens for very low beam intensity with a cooled CCD still camera



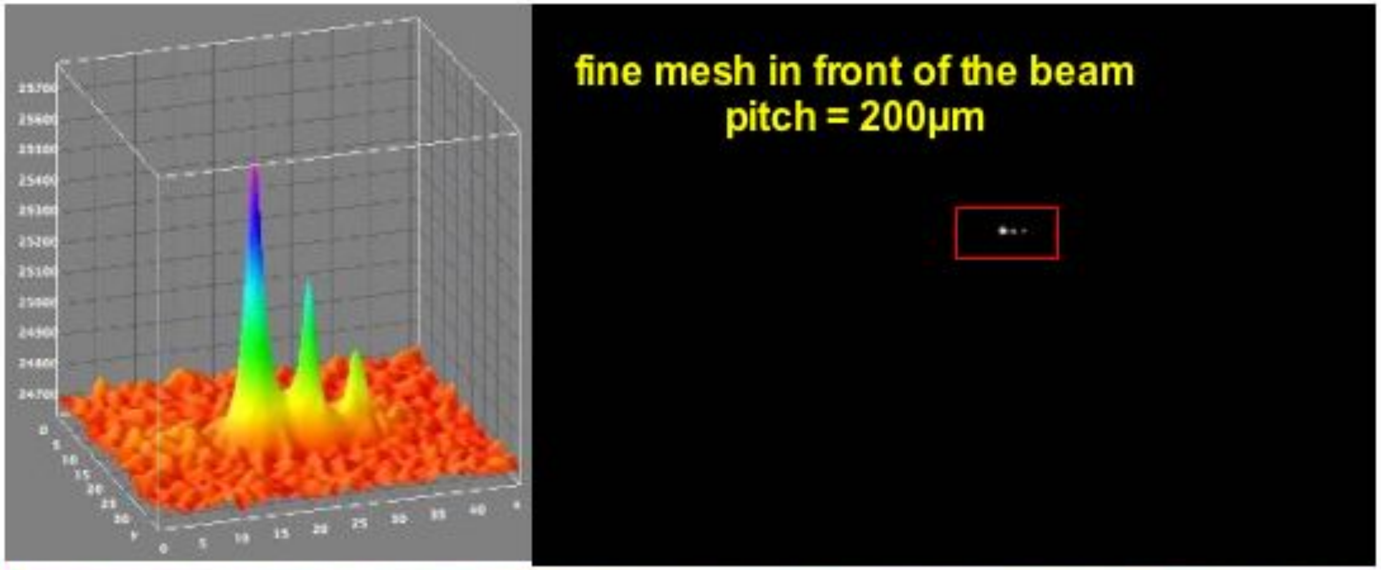
screen = CsI(Tl)

beam = protons

E = 50keV

I ≈ 5pA

$t_{exposure}$ = 60s



screen = CsI (Tl)

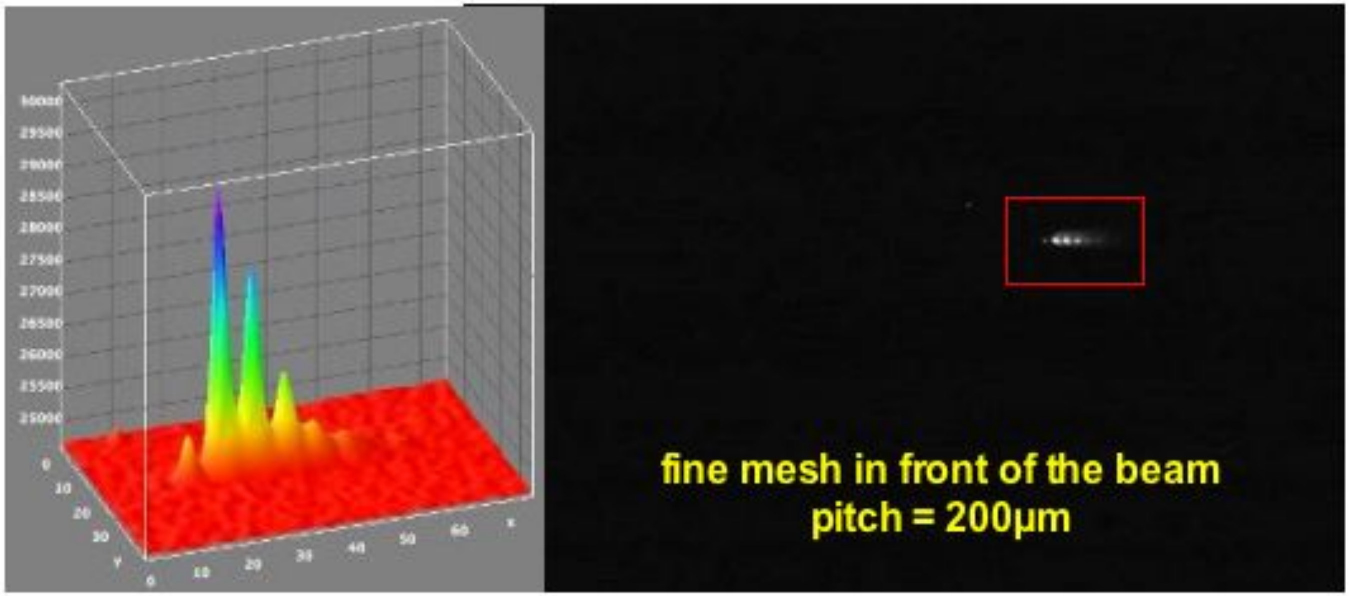
beam = protons

E = 200keV

I ≈ 2.5fA

$t_{exposure}$ = 20s

Scintillating screens for very low beam intensity with a cooled CCD still camera



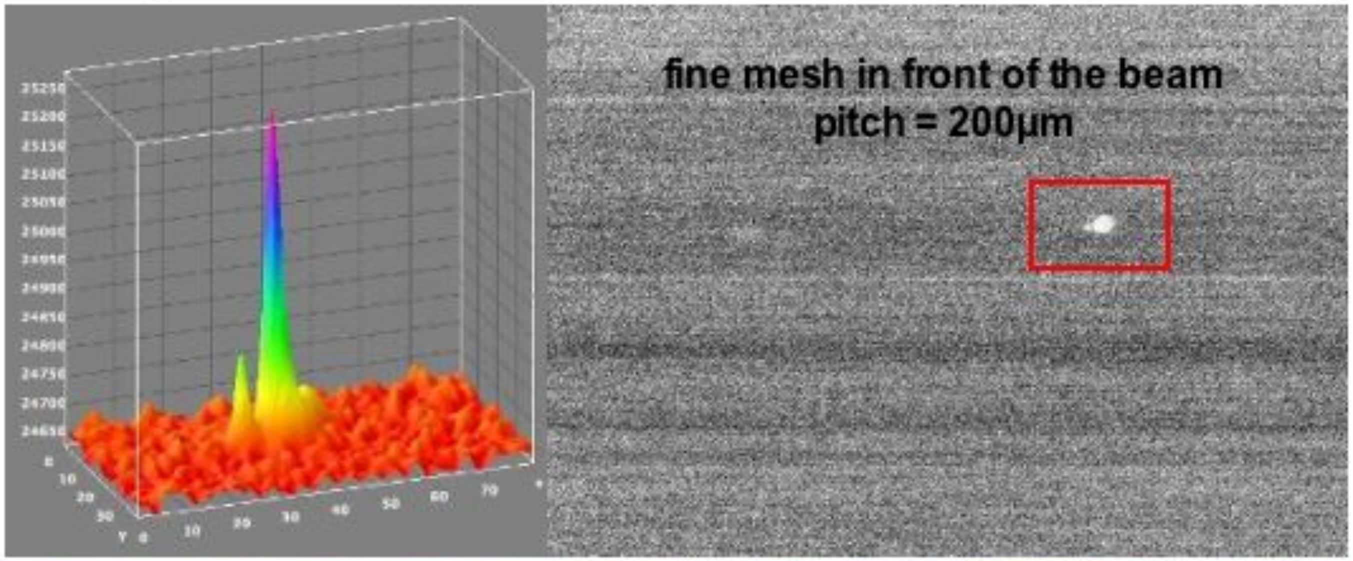
screen = SFOP

beam = protons

E = 200keV

I ≈ 50fA [5pA/100]

$t_{exposure}$ = 20s



screen = SFOP

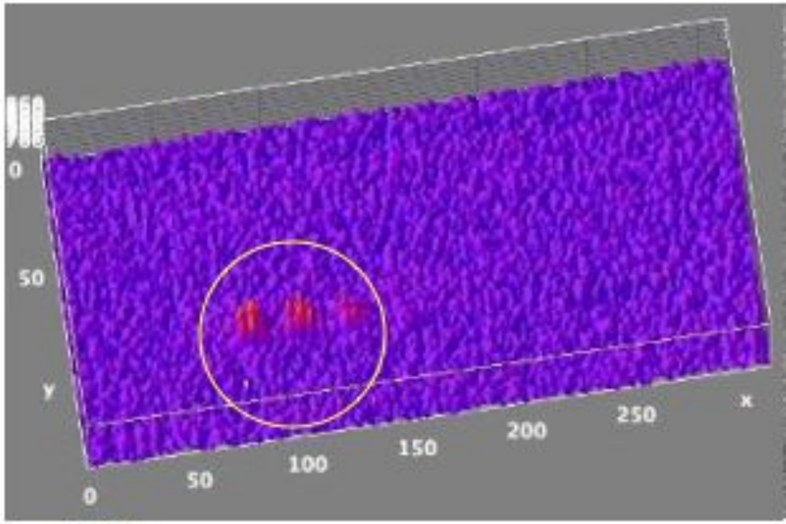
beam = protons

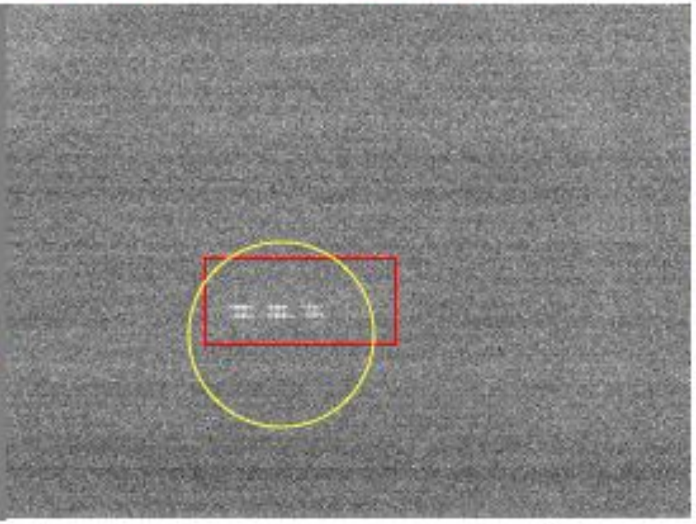
E = 200keV

I ≈ 2.5fA [5pA/2000]

$t_{exposure}$ = 20s

toward single particle imaging....!!!





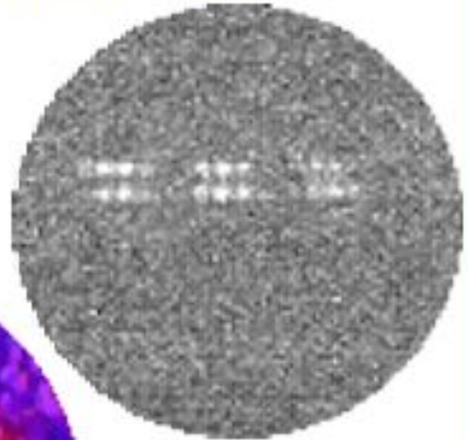
screen = CsI

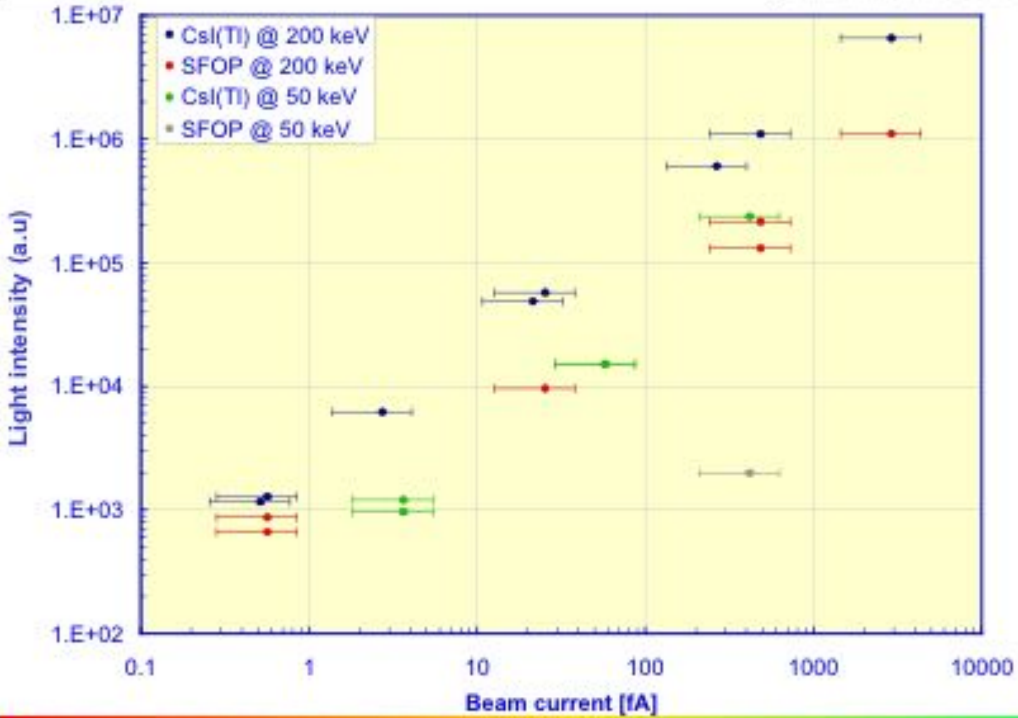
beam = protons

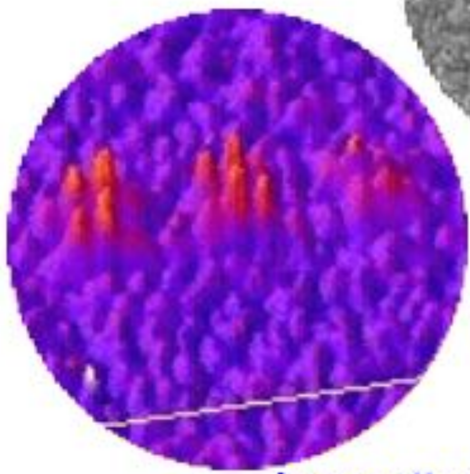
E = 50keV

I ≈ not measurable

$t_{exposure}$ = 60s







beam attenuated through a fine mesh, pitch ≈ 0.1mm

final considerations

when planning and designing new beam diagnostic systems

never trust the initial requests, they are always optimistic!!!

hope for the best, plan for the worst

Thanks for your attention
come visit me in Catania!!!

- introduction
- a "real" case?
- producing a RIB: ISOL vs FRIB
- ISOL: which beams, intensity and energy
- ideal case: table, I don't need a sophisticated BD, just one simple device
- real case: intensity range from 0 upwards
- initial energy is lower than foreseen CEC
- how can we make BD on such a kind of beams?
- fix a few boundary conditions
- decide which beam we start with
- assume a reasonable energy value
- assume a low but realistic intensity
- examine the possible ways of detecting the beam
- list the chosen RIB properties
- choose the viable solutions, reject the unfeasible ones (Scint, MCP, channeltron, gas, silicon...)
- last minute requirement: "by the way, I would also like to BD the stable pilot beam"
- consequent route adjustement for the stable beam detection
- beta decay: properties
- scintillator: CsI light yield, is that enough for beta rays? and for stable beam?
- CsI screen: imaging? space resolution? thickness?
- Beta ray source test: imaging with CsI plate
- picture x-projection, data analysis, fit procedure, excel example
- Test the plate with very low energy stable beam: OK, it works
- picture x-projection, data analysis, fit procedure, excel example
- the LEBI device
- RIB picture, x-projection, data analysis
- OK but... are you sure you got the right species? Use the plastic scint for counting
- half life measurement
- OK, now I want to transport the beam across the mass analyzer and further: install several LEBIs
- and in case of another RIB species? a heavier one? Well, add Ge detector(s)!

- microbeams: SFOP
- ULI microbeams: production (variable collimator), detection (position sensitive silicon telescope)

- additional tools in your box: 14-bit camera
- sample images from alpha source and low energy and intensity beams

- final considerations: never trust the initial requests, they are always optimistic
- hope for the best, plan for the worst