THE UNIVERSITY of York

A “HELIOS” spectrometer for HIE-ISOLDE

TSR@ISOLDE workshop

David Jenkins

Outline

- ★Physics cases
- ★Transfer reactions in inverse kinematics
  - ★Solenoidal spectrometer
- ★Test-bed system
  - ★Details
  - ★Status and outlook
- ★Ideal system
  - ★Simulation
  - ★Design ideas

Beams already post-accelerated

Structure of light nuclei

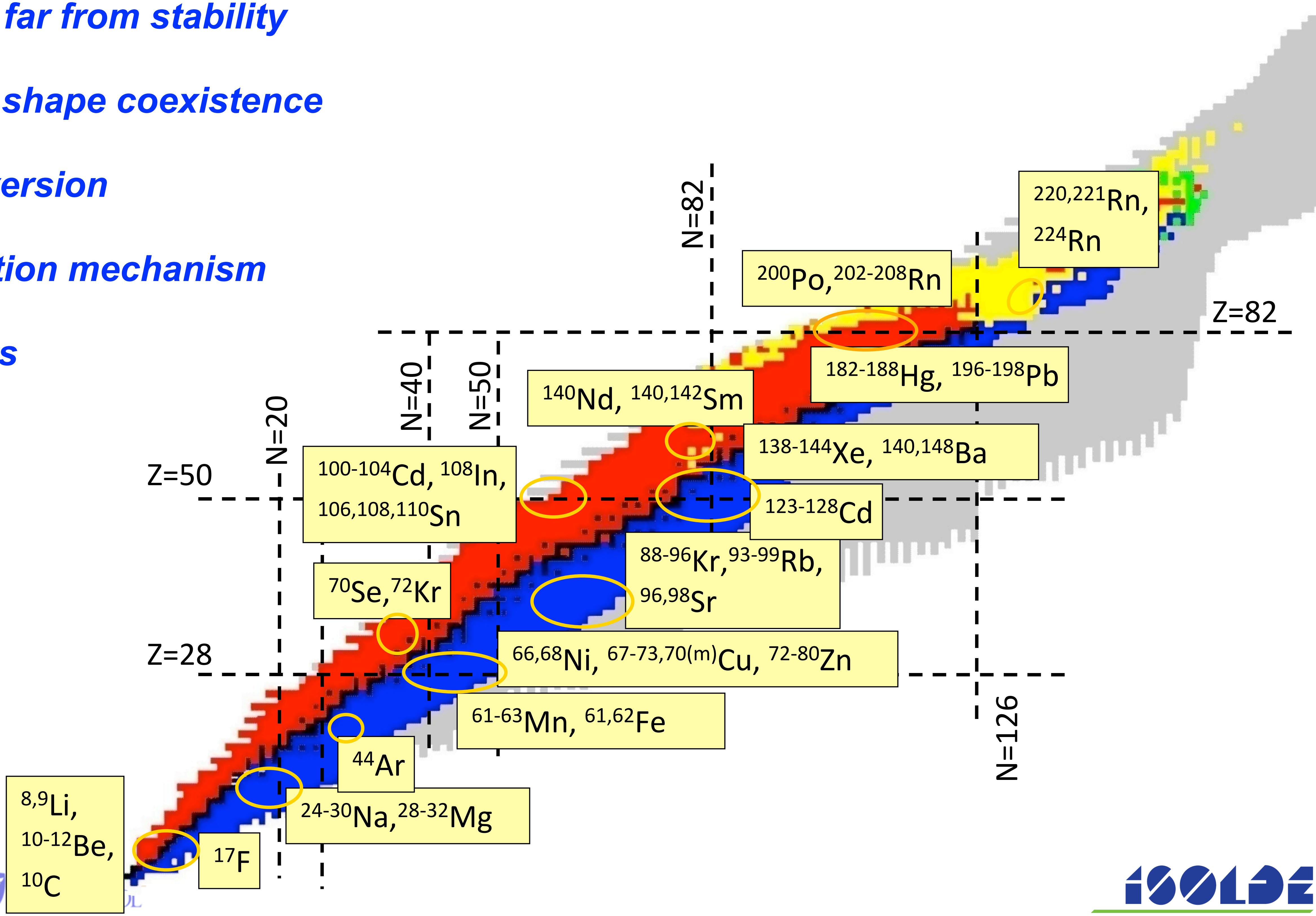
Shell-model far from stability

Shapes and shape coexistence

Island of inversion

Fusion reaction mechanism

Astrophysics

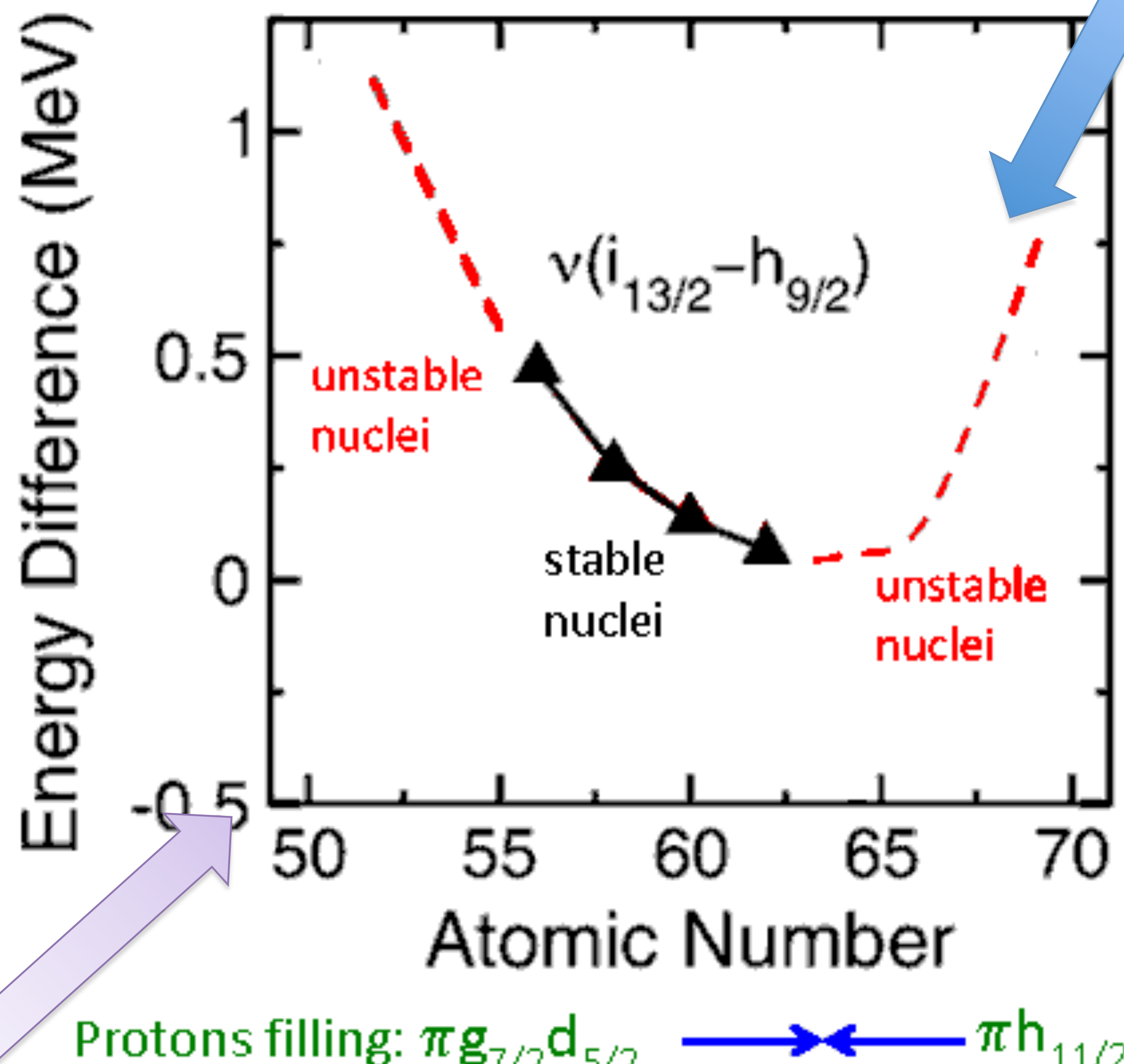


Nuclear Structure (example)

Tensor interaction between protons and neutrons has been proposed as a mechanism driving shell evolution in nuclei….other than deuteron gs, largely ignored in nuclear structure…

Transfer reaction measurements to locate single-neutron *particle* states outside *inert core*.

Expect turnaround in trend, if tensor force drives changes, for higher Z.



Test with transfer using radioactive beams ***unique*** to ISOLDE with high yields: ^{146}Gd, ^{148}Dy, ^{150}Er

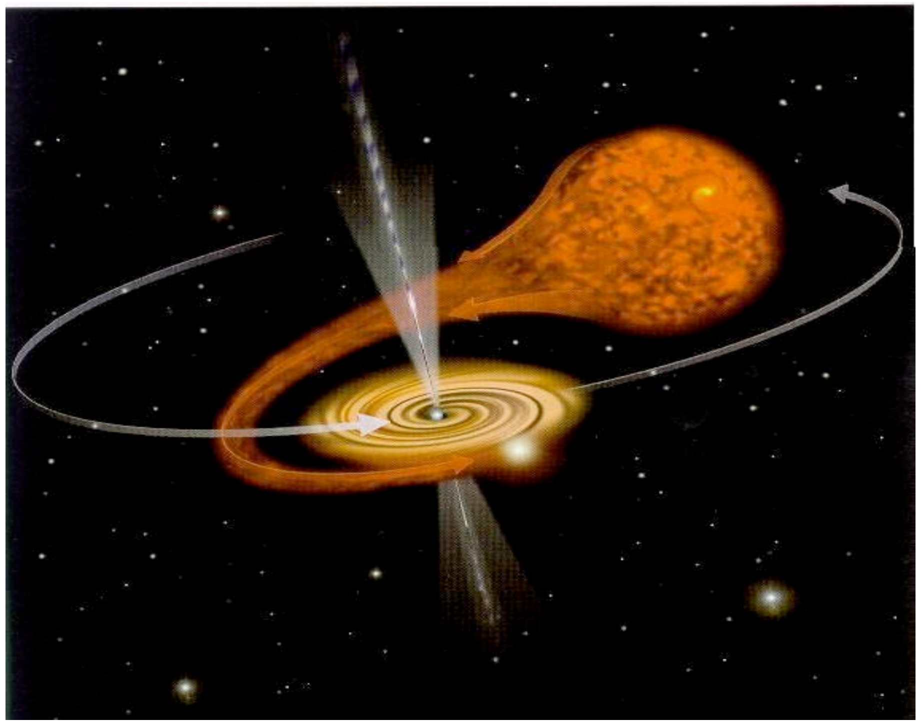
No other facility to measure particle states with these beams.

If see turnaround, tensor mechanism sound.
If not, need a dramatic rethink

ISOLDE also has ^{132}Sn & ^{134}Te at high intensity.

HIE-ISOLDE also allows testing outside N=126 using unique beams: ^{206}Hg, (^{210}Po), ^{212}Rn and ^{214}Ra

X-ray bursts (rp-process)



Dominated by (p,γ) and (α,p) reactions

HIE-ISOLDE: $(^3He,d)$ as surrogate of (p,γ)
(p,α) as inverse of (α,p)
Key beams available

FAIR: Break-up reactions – i.e (γ,p) – can only do a few cases

ISAC-1: Direct (p,γ) – possible cases largely exhausted already and for A<30 only

Supernovae (r-process)

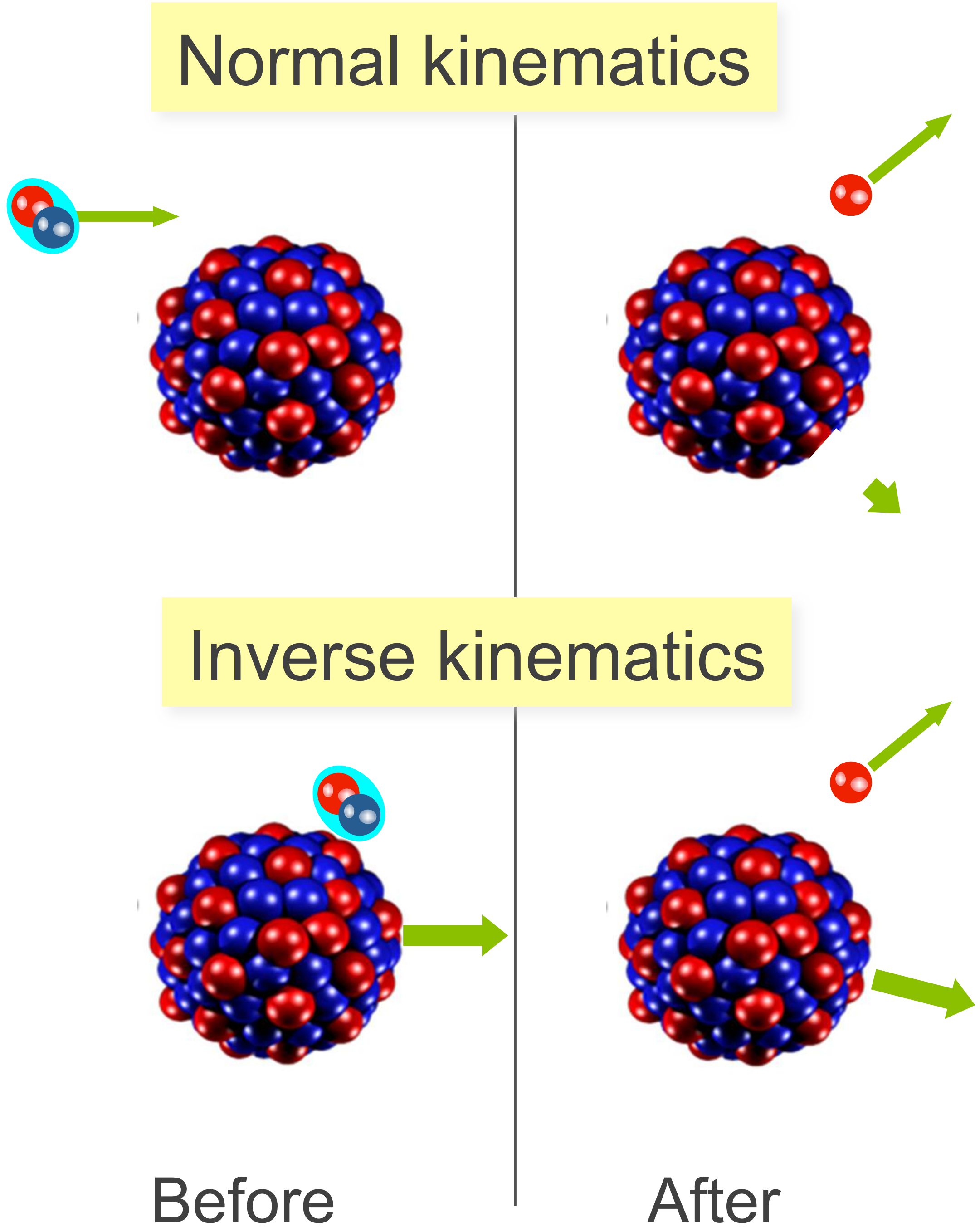
Dominated by (n,γ) reactions but r-process pathway largely undefined

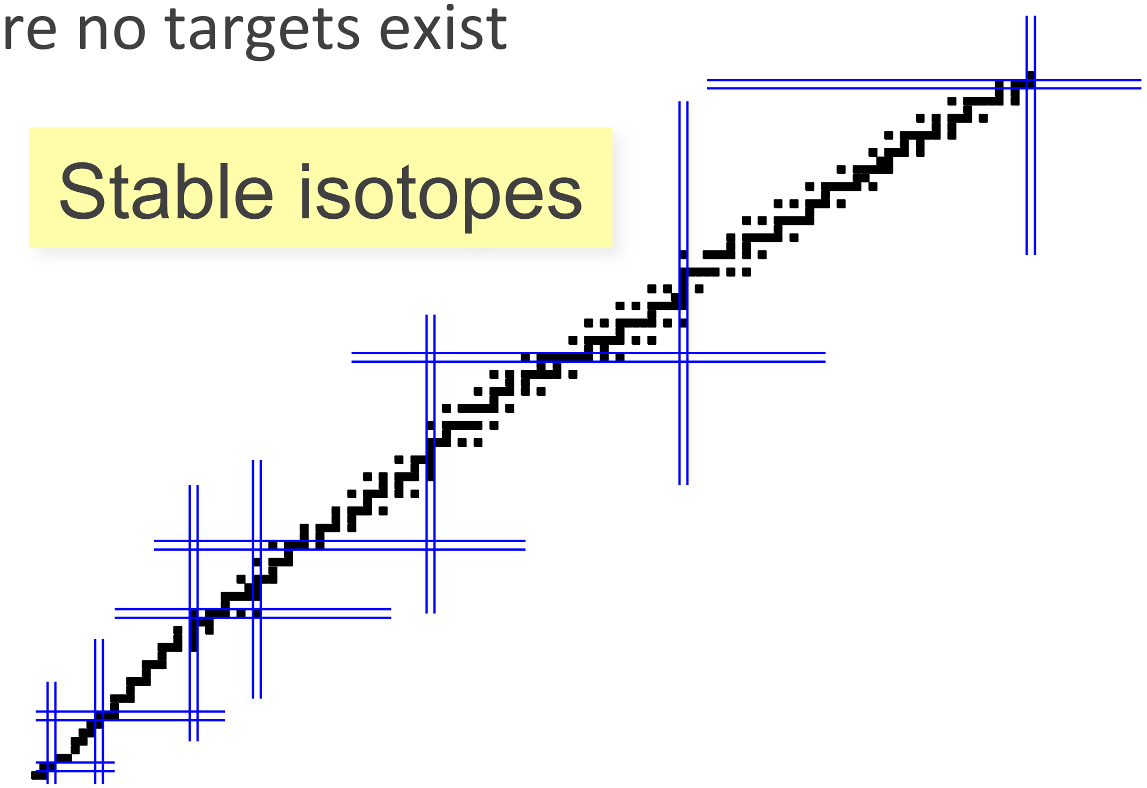
HIE-ISOLDE: (d,p) as surrogate of (n,γ)
- can contribute through study of shell evolution

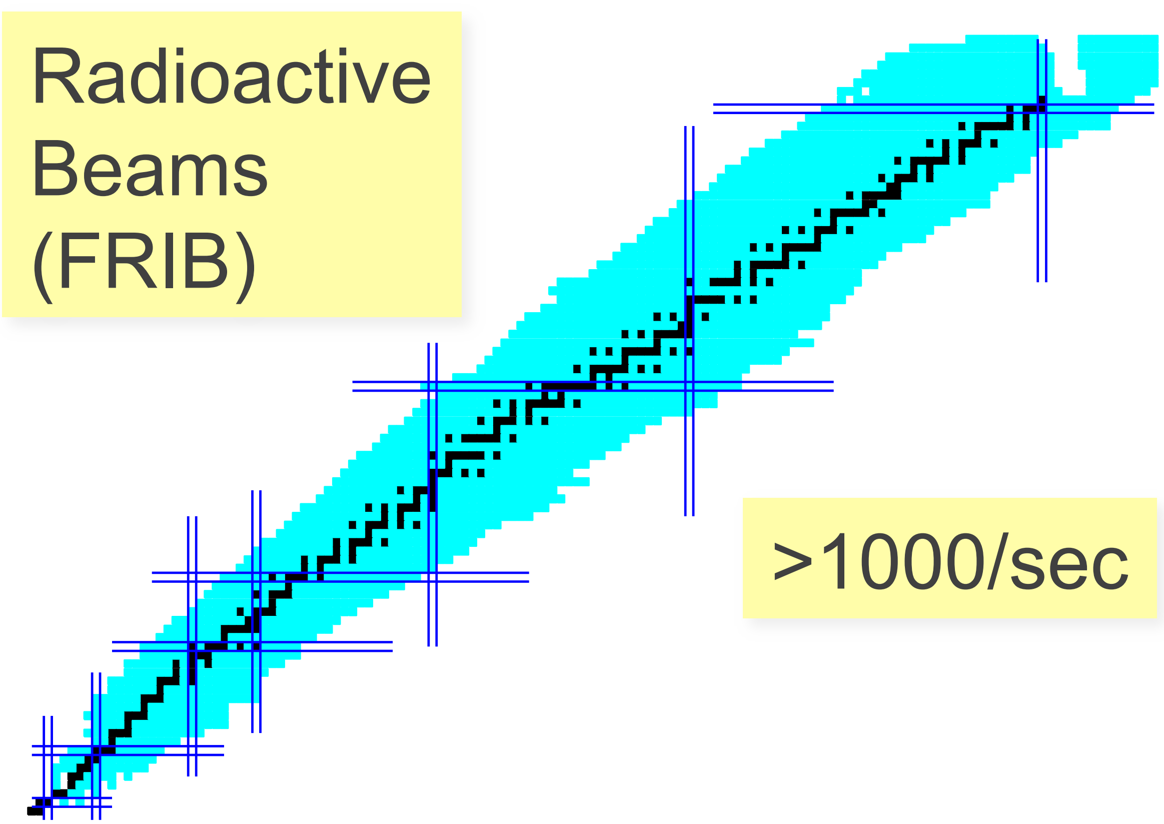
FAIR: Can map out global properties such as mass and lifetime and look for broader trends of behaviour at extremes of neutron-rich

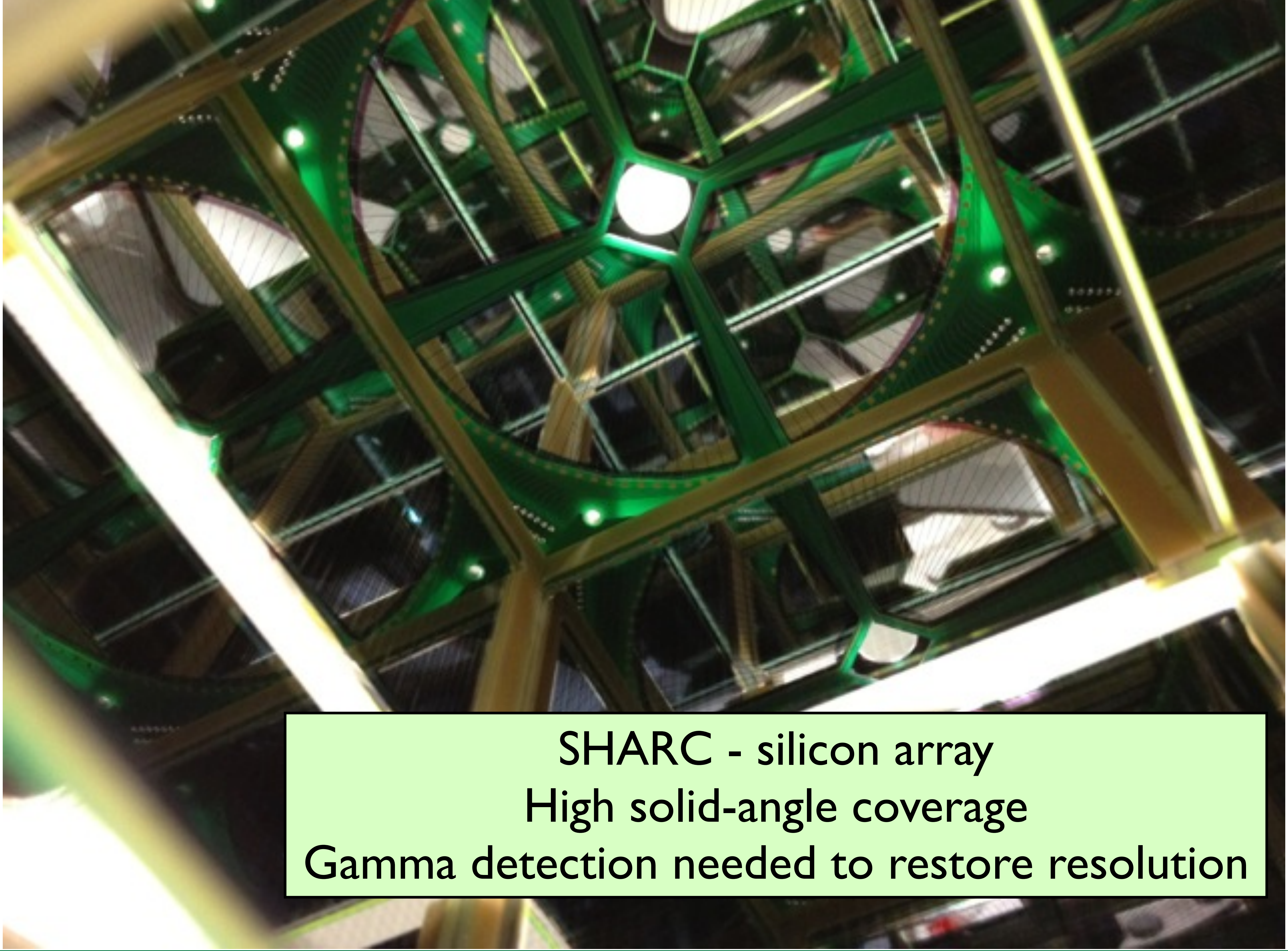
Inverse kinematics - wide applications

- Precision studies of nuclei in regions where no targets exist









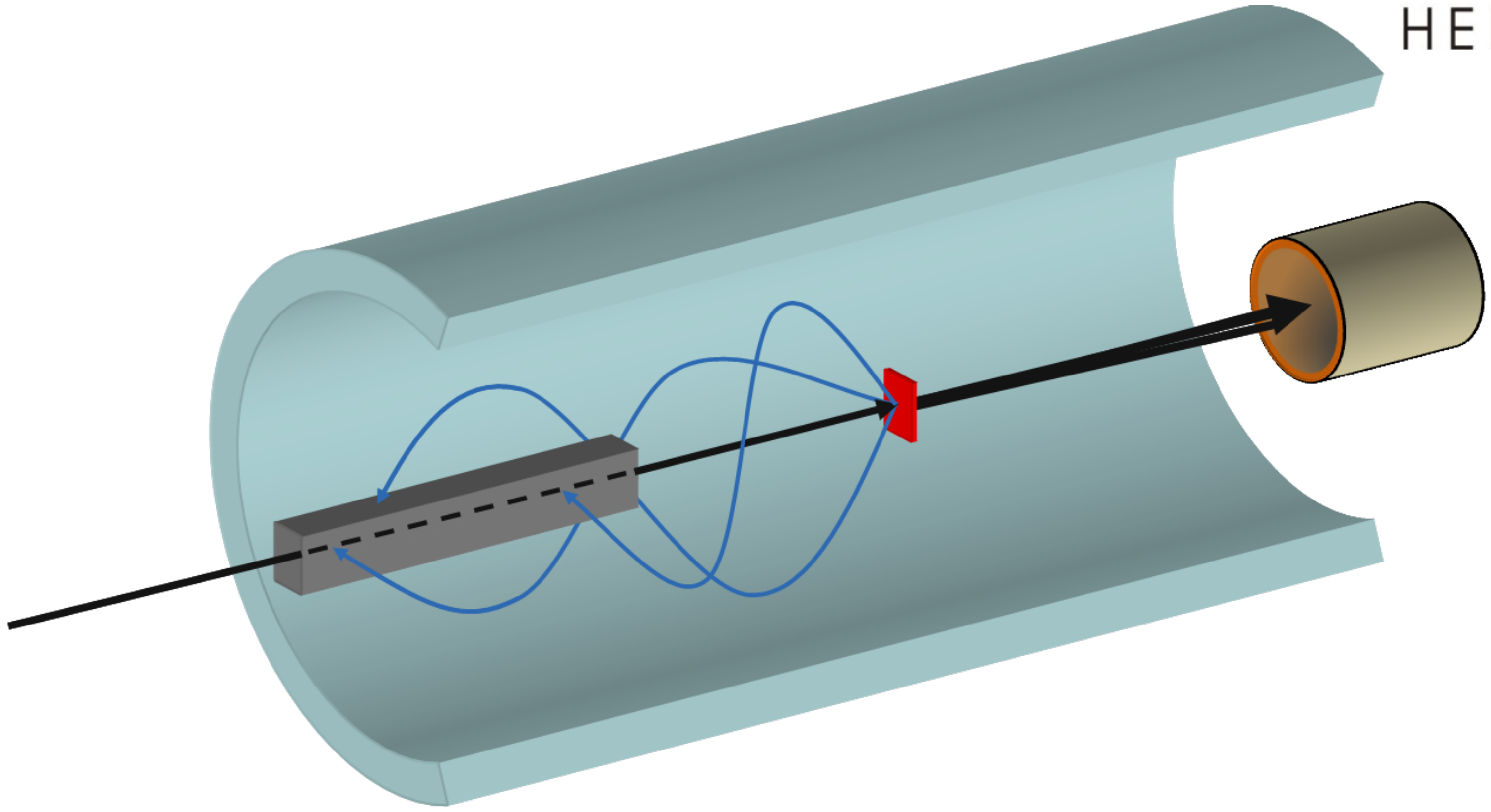
SHARC - silicon array

High solid-angle coverage

Gamma detection needed to restore resolution

Principle of operation

HELIOS



Measured quantities

Flight time:	$T_{flight}=T_{cyc}$
Position:	z
Energy:	E_{lab}

Derived quantities

Part. ID:	m/q
Energy:	E_{cm}
Angle:	θ_{cm}

$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} q e B}{2\pi} z$$

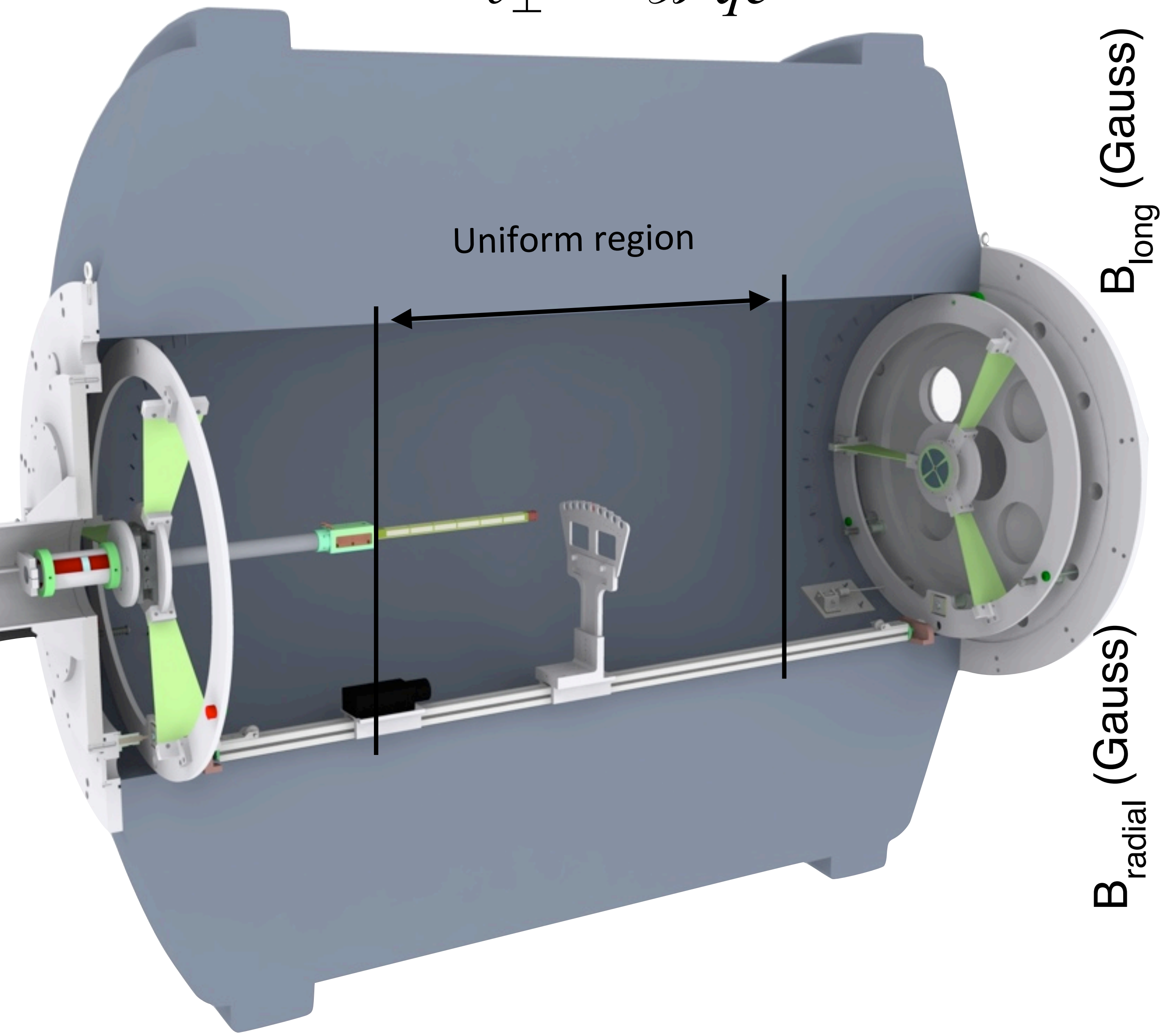
$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - m V_{cm} q e B z / \pi}} \right)$$

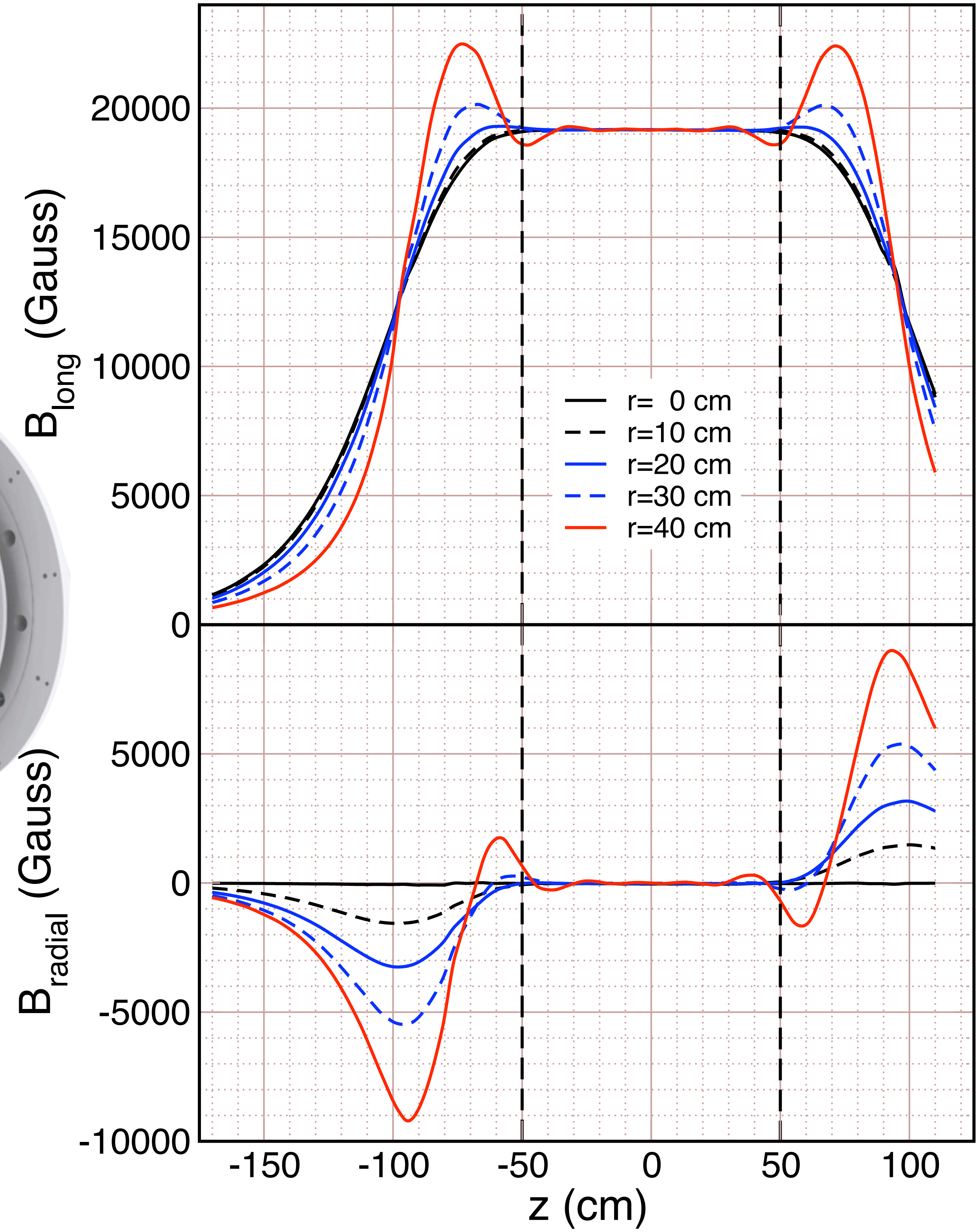
B=2T

Particle	T_{cyc} (ns)
p	34.2
$^3He^{2+}$	51.4
d, α	68.5
t	102.7

The field – uniformity is key

$$T_{\text{cyc}} = \frac{2\pi r}{v_\perp} = \frac{2\pi}{\mathscr{B}}\frac{m}{qe}$$





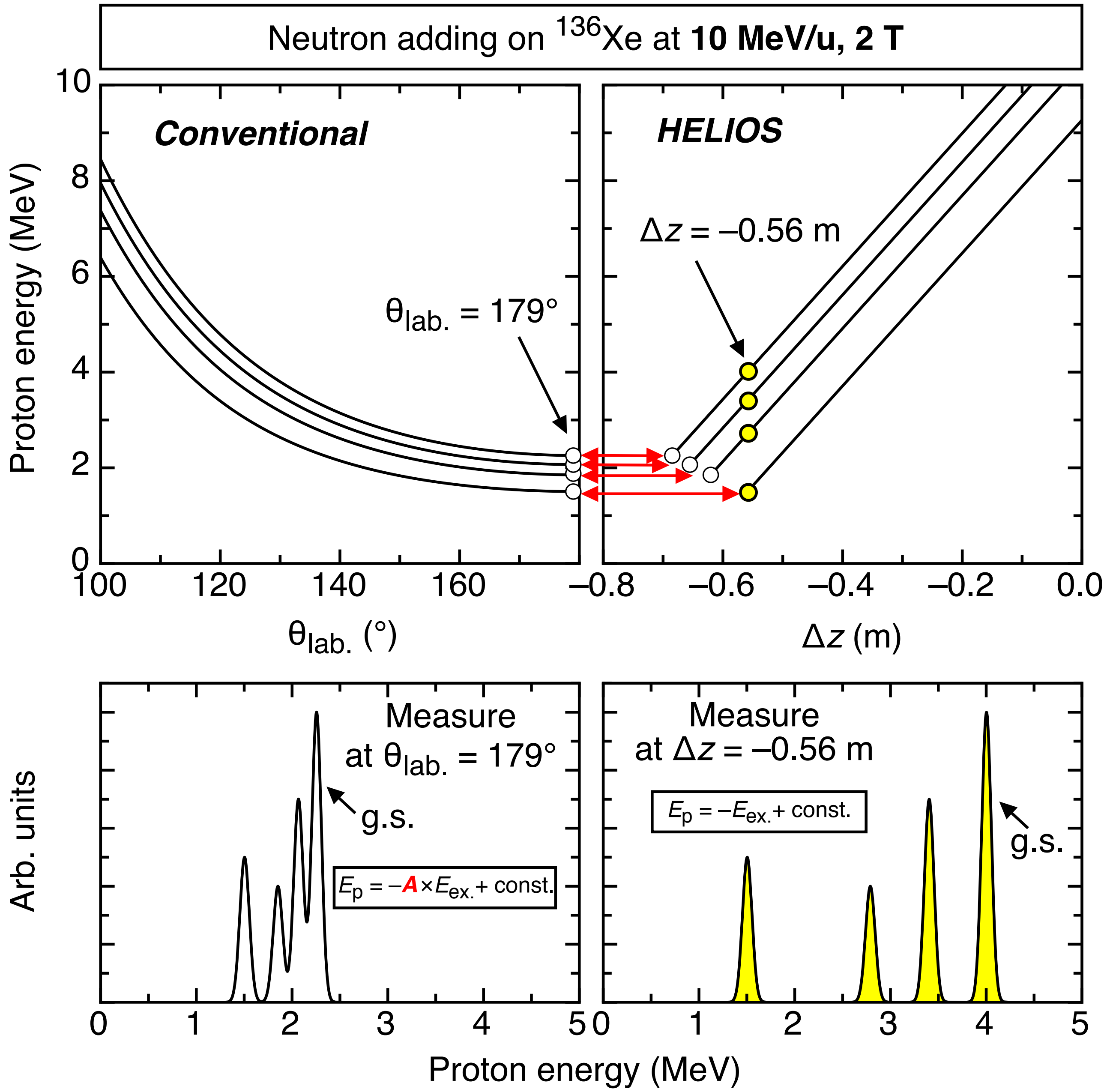
$$E_{\text{cm}} = E_{\text{lab}} + \frac{m}{2}V_{\text{cm}}^2 - \frac{mV_{\text{cm}}z}{\boxed{T_{\text{cyc}}}}$$

Medical imaging (MRI): 1-5 parts in 10^7 (<µT)

Nuclear physics: 1 part in 10^3 (mT)

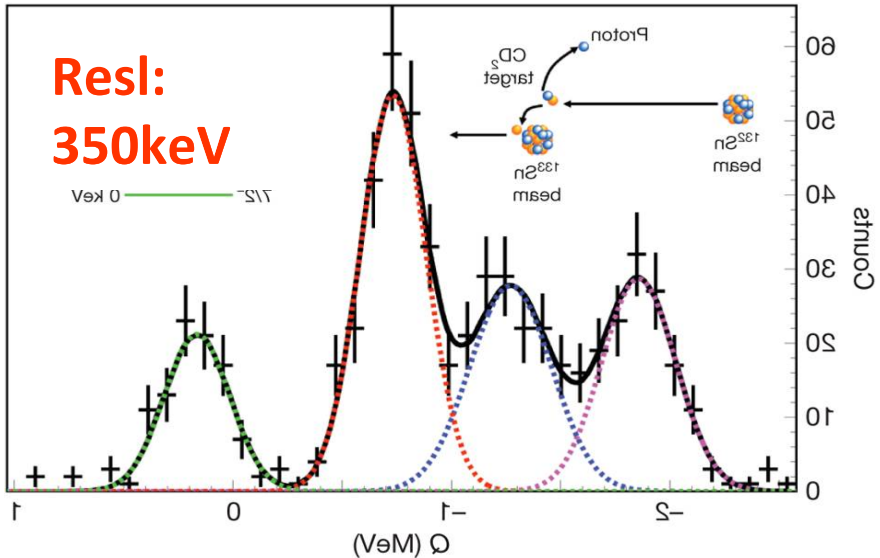
The HELIOS approach, backward hemisphere

Negative-Q-value reaction, target at Δz = 0 m



- There is ***no kinematic compression for a fixed distance Δz***. The excitation energy in the lab. and c.m. are related by only an additive constant
- The ***kinematic shift in Δz is linear*** and modest [<15 keV/mm for (*d*,*p*) at 2 T, Δ*z* resolution in HELIOS <1 mm]
- PID through cyclotron period, energy independent, readily identify ions with energies as low as ~200 keV

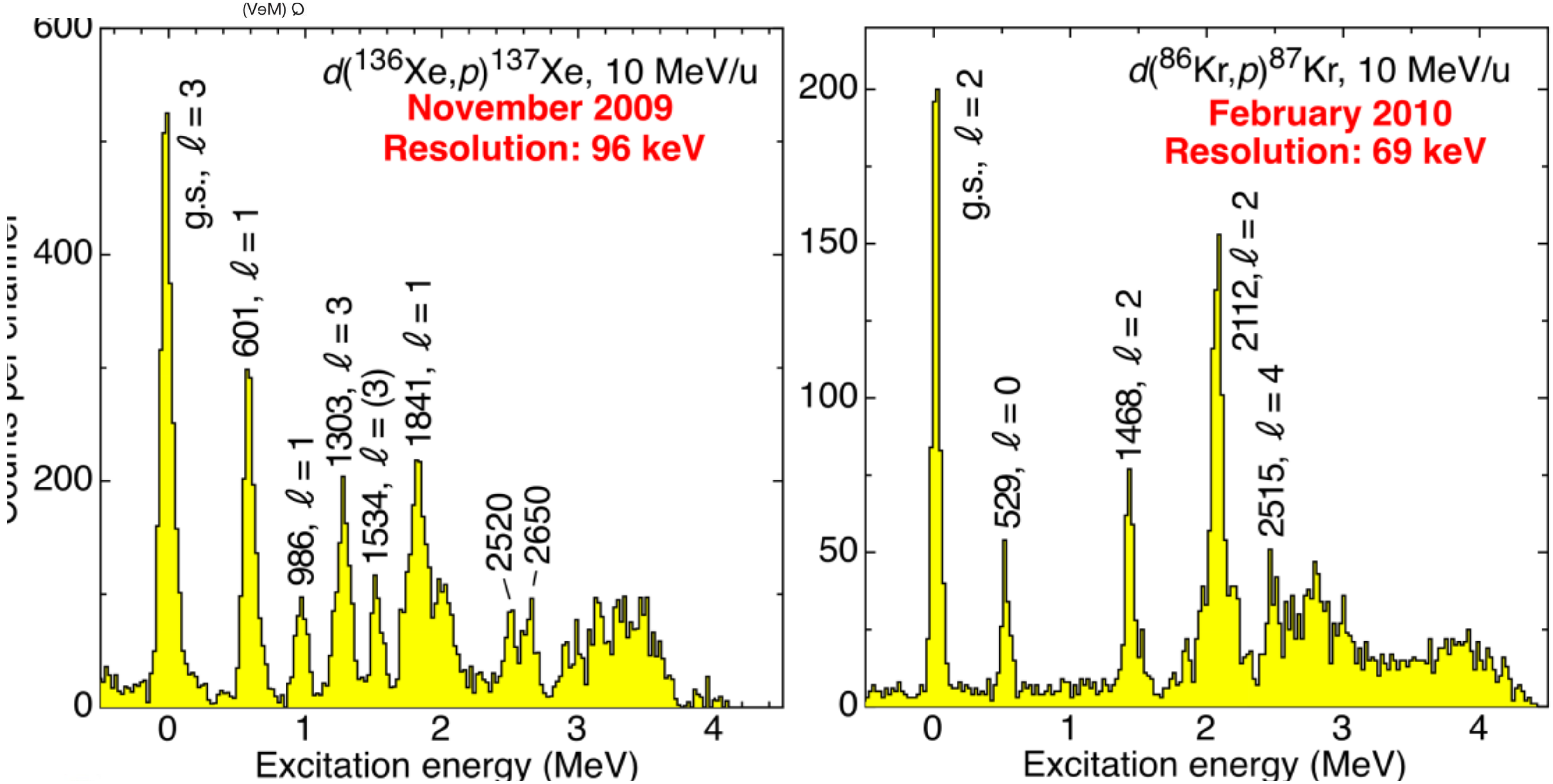
$$E_{\rm cm} = \boxed{E_{\rm lab}} + \frac{m}{2}\boxed{V_{\rm cm}^2} - \frac{m\boxed{V_{\rm cm}}\,\boxed{z}}{T_{\rm cyc}}$$



HELIOS vs. Si-detector arrays

Tiara, T-REX, Sharc, ORRUBA

K. L. Jones *et al.*,
Nature **465** 454–457 (2010).



Comments on use with TSR

- Excellent beam properties for cooled beam - means we can improve Q-value resolution

- Need to wait for beams to be cooled so the most exotic nuclei are excluded but we probably need 10^4 /s to make any feasible measurement....

- TSR provides isobaric purity - perfect for this technique as we can completely dispense with beam identification

- Isomeric beams are available in a pure form - also unique

- Beams up to A~200 available

- Time structure would have to be reimposed to use cyclotron period to identify particles (not necessary in all cases)

Test-bed system for HIE-ISOLDE

The Nottingham magnet

0.5 ppm homogeneity over 50-cm d.s.v.
1-m physical bore
(92 cm with shims)
2.45 m in length
Persistence mode
No active shield (significant stray field)

- 3-T solenoid (very similar to Argonne magnet) available for 'free' from the University of Nottingham - located via contacts from YNIC.
- Magnet is Oxford Instruments prototype for 3-T full body magnet
- Bought initially for £452k + VAT
- Magnet operated smoothly for 20 years barring power supply fault on decommissioning (likely trivial)

Cryogenics

- Separate nitrogen and helium compartments
- 5000 l of He required to initially cool
- 500 l / 6 weeks to top up
- Standard Filling from non-ferromagnetic dewars
- Would need safety assessing as far as quench is concerned - large space overhead makes this an unlikely issue (requirements discussed in manual)
- Cold heads/ seals etc. need some servicing after 20 years' use

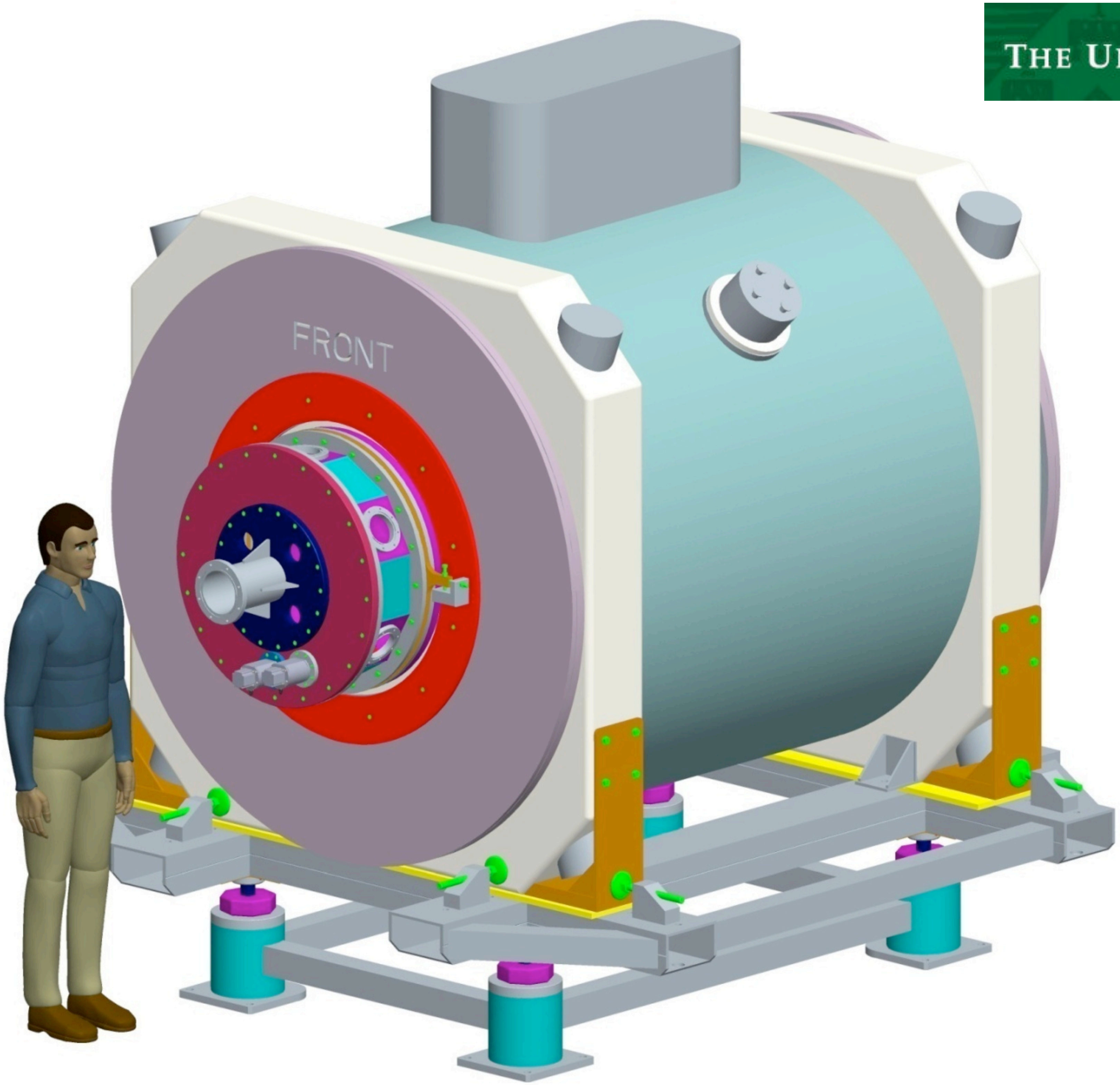
- Cost of helium - how to cover running costs? Helium not presently paid for at ISOLDE

Moving the Nottingham magnet

Status

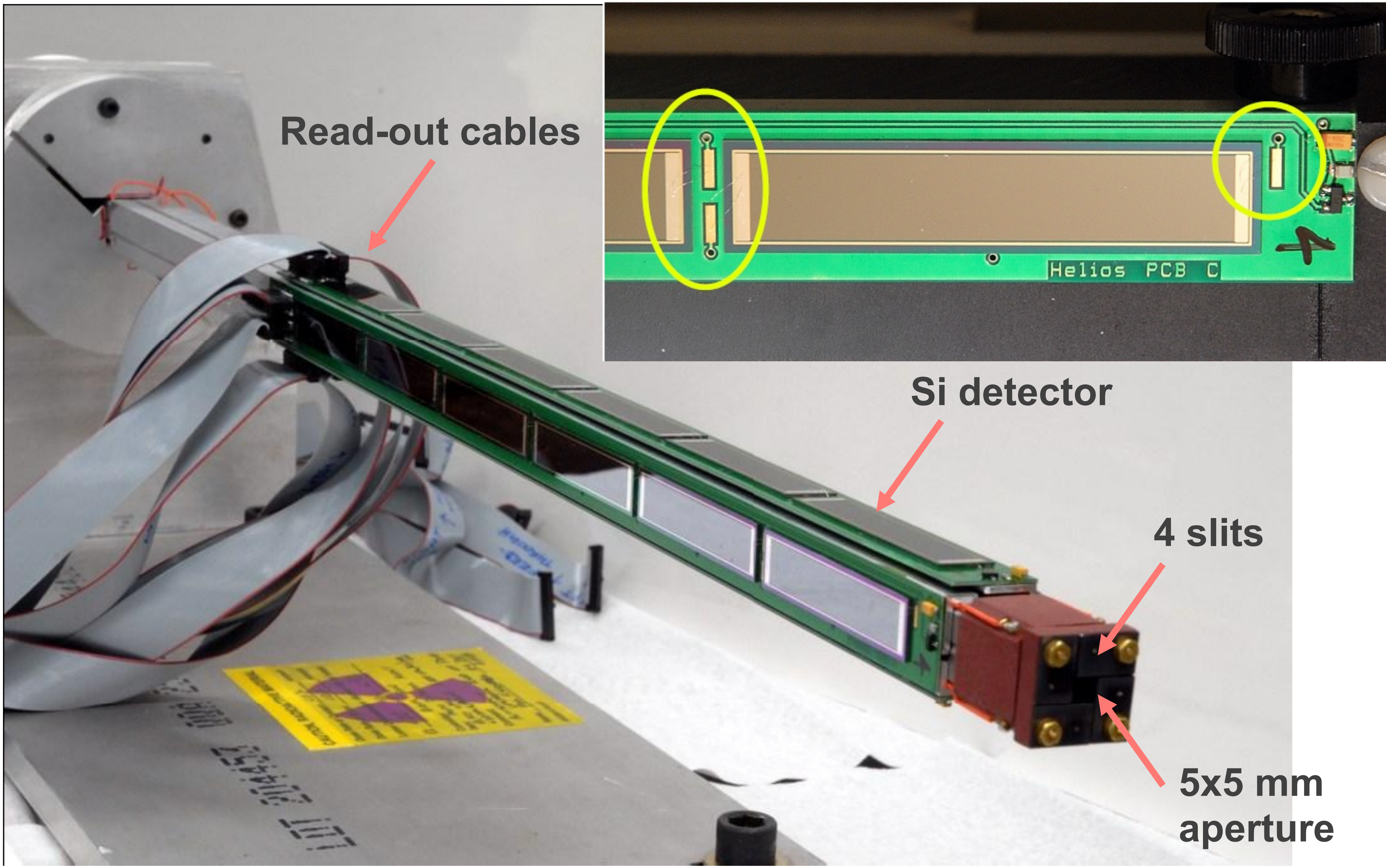
- Magnet in its final position

- 5 Gauss boundary line marked
  No issues w.r.t. space and interference
  with the activities in the neighbourhood



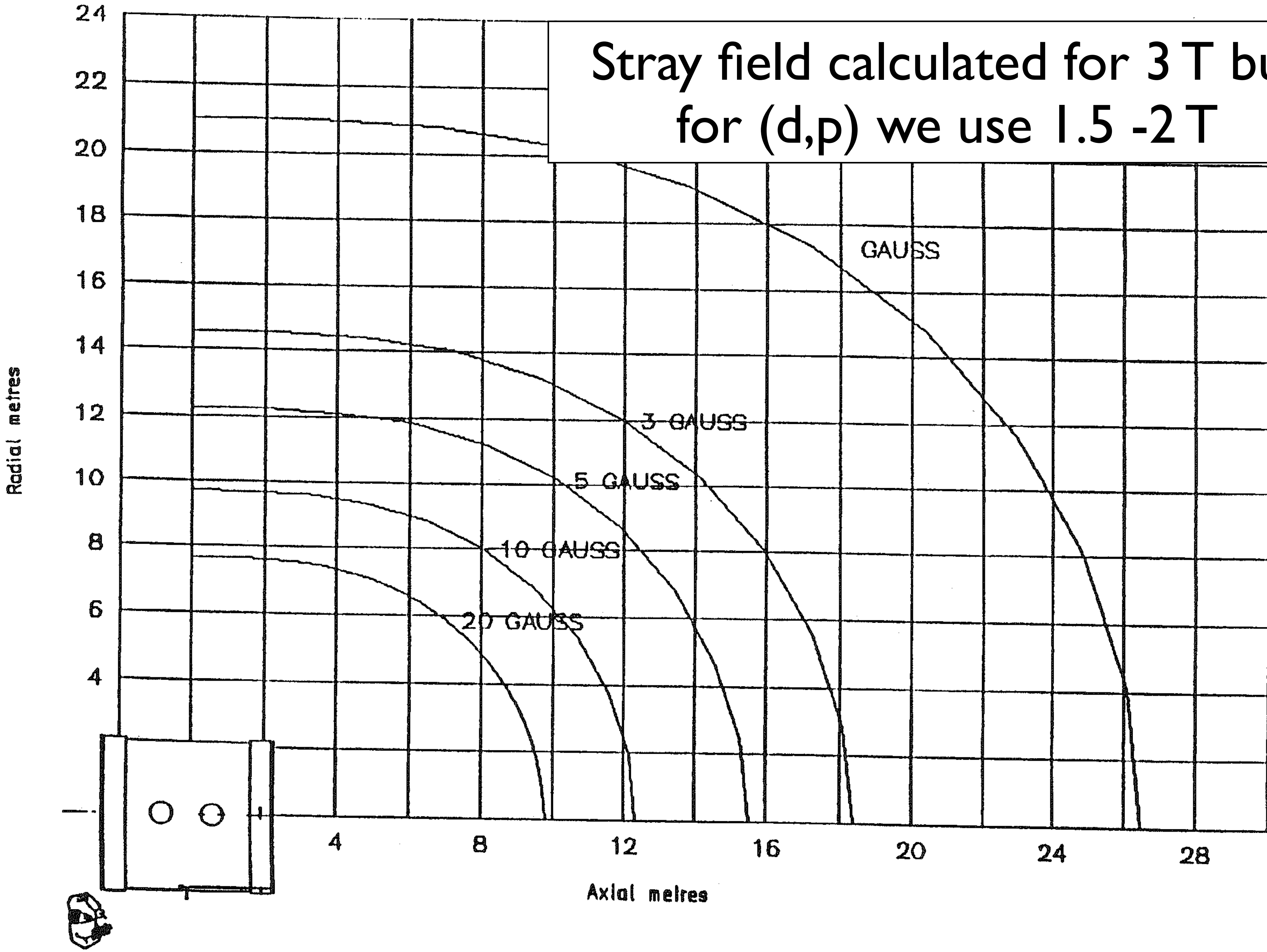
Design scheme from May 2012

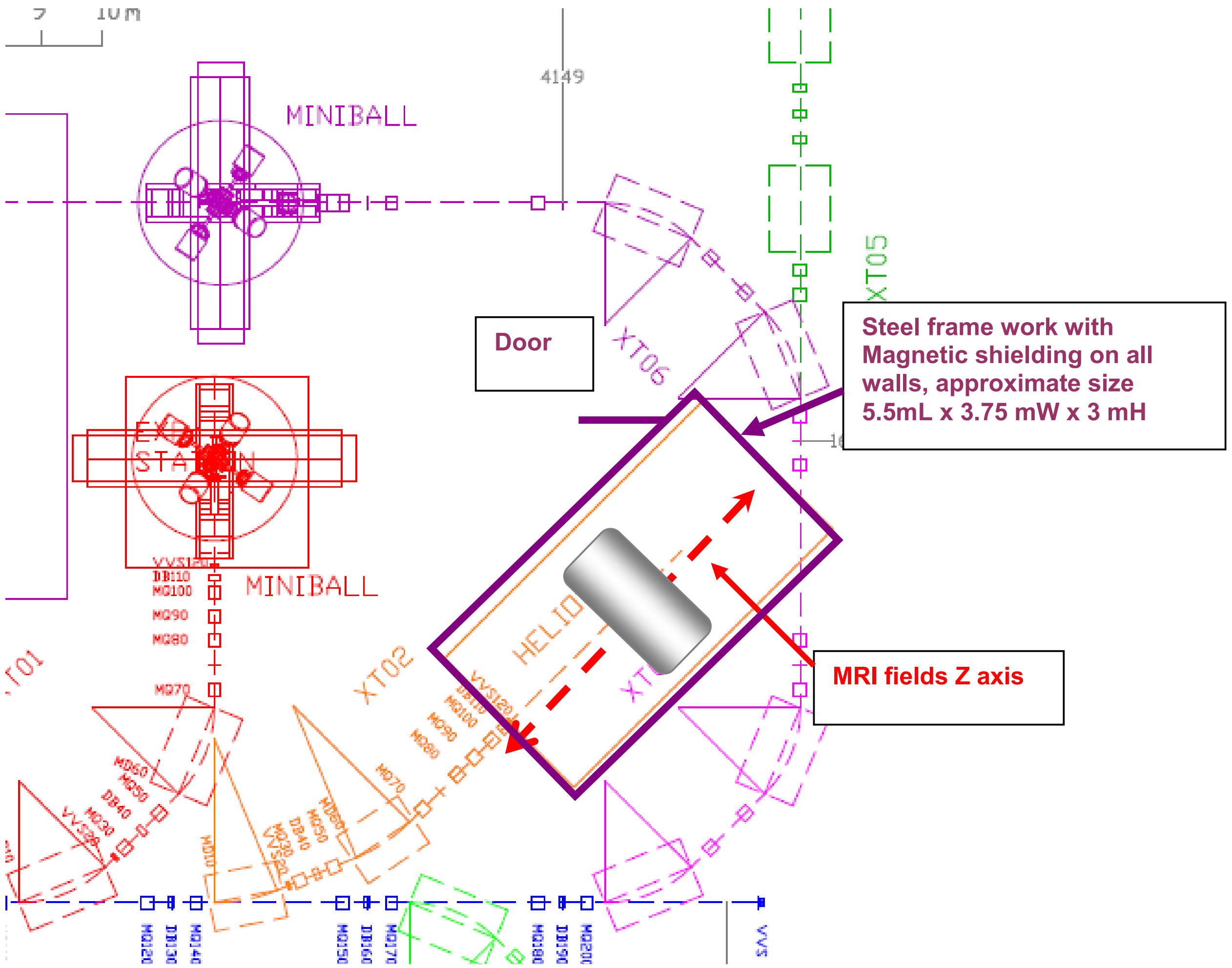
Assembled prototype array

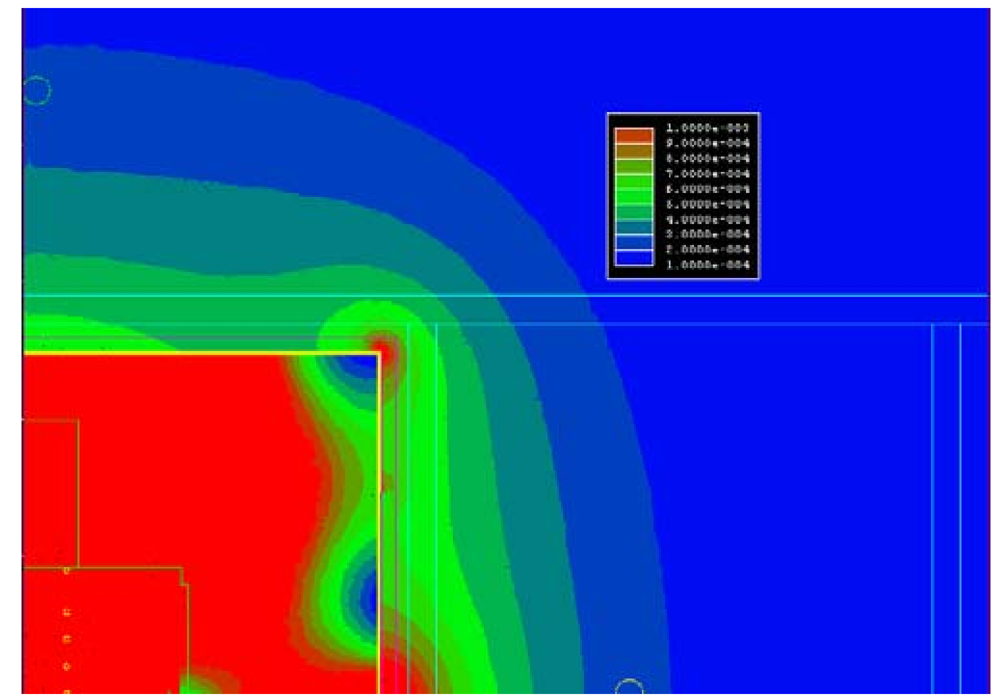


Stray field

Stray field calculated for 3 T but for (d,p) we use 1.5 -2 T







Aim is to reduce 5G magnetic field dimensions to that of Siemens or GE 3T scanner

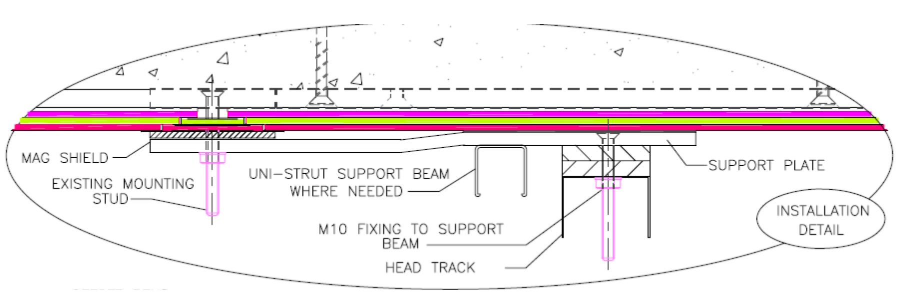
Based on of isocentre of magnet, all dimensions are radii

X= vertical axis, Y = horizontal axis, Z = length axis

GE Signa 3 T	**X - Y**	**Z**
Field line	0.5 mT (5 G)	0.5 mT (5 G)
Distance (m)	2.8	5.0

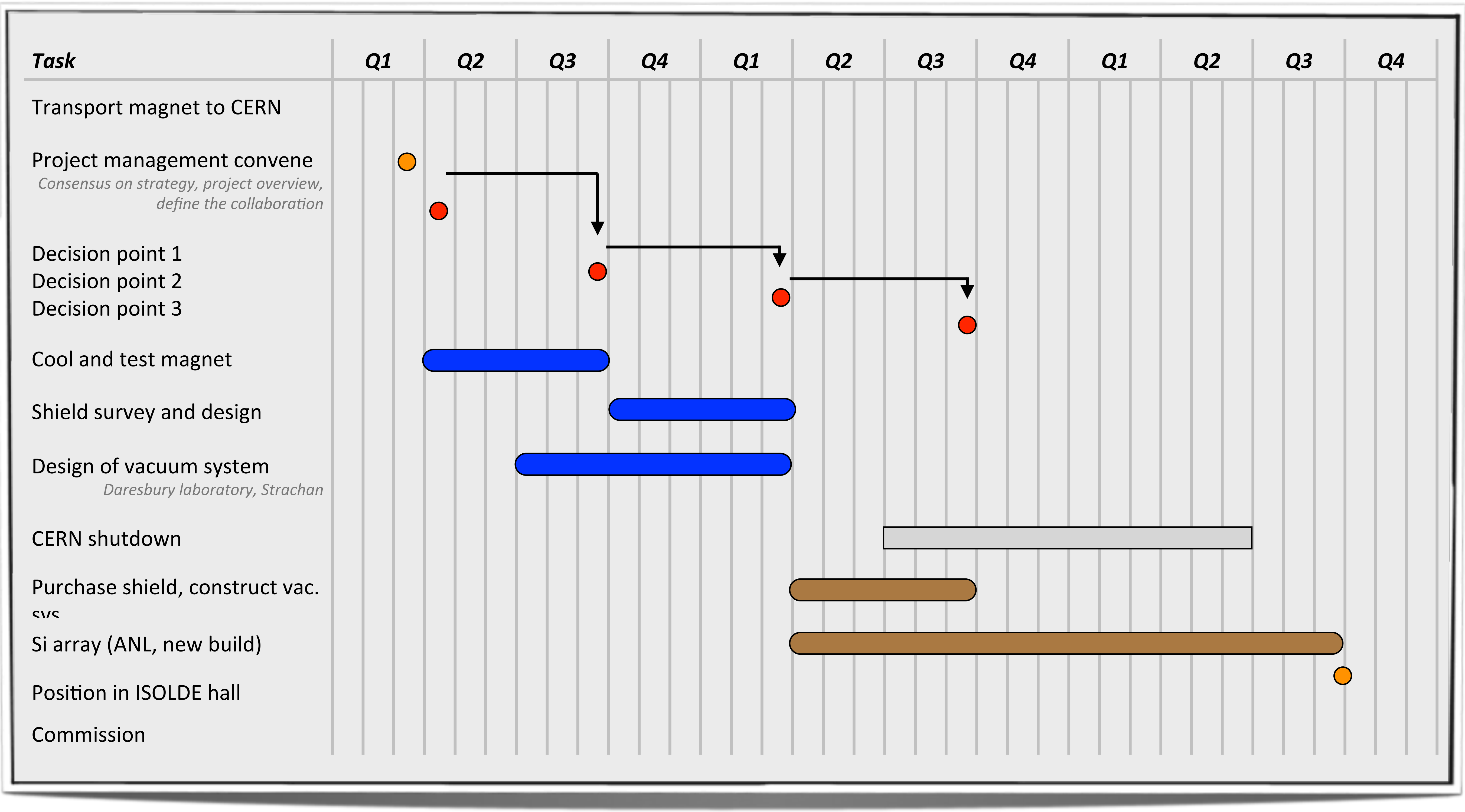
Siemens 3T Magnetom	**X - Y**	**Z**
Field line	0.5 mT (5 G)	0.5 mT (5 G)
Distance (m)	2.6	4.5

Proposal from European EMC Products Ltd.



Other solutions undoubtedly exist e.g. local shielding

Possible timeline



International interest

Two international workshops held:
York in May 2012
Daresbury in October 2012

Attended by scientists/engineers from:
•Birmingham, Liverpool, Manchester, Surrey, Daresbury, York + Oxford Instruments
•Argonne, CERN, Darmstadt, Jyvaskyla, Leuven, Lund, Munich, Saclay

Five proposals submitted to INTC for Day-One experiments at HIE-ISOLDE

Ideal system

Kinematics (...not exhaustive)

Single-nucleon transfer

- Neutron adding: (d,p), (t,d), (α,^{3}He)
- Neutron removing: (p,d), (d,t), (^{3}He,α)
- Proton adding: (^{3}He,d), (α,t)
- Proton removing: (d,^{3}He), (t,α)
- ...

Pair transfer

- Neutron-pair removal: (p,t) ... ?
- Neutron-pair adding: (t,p)
- *np*-pair adding: (^{3}He,p)

Charge exchange

- (^{3}He,t), (t,^{3}He) ...
- (d,^{2}He)?
- ...

Inelastic scattering

- (p,p), (d,d), (α,α)
- ...

Astrophysics

- (^{3}He,d)
- (α,p)
- (p,α)
- (^{6}Li,d) ...

Coulex with ^{12}C

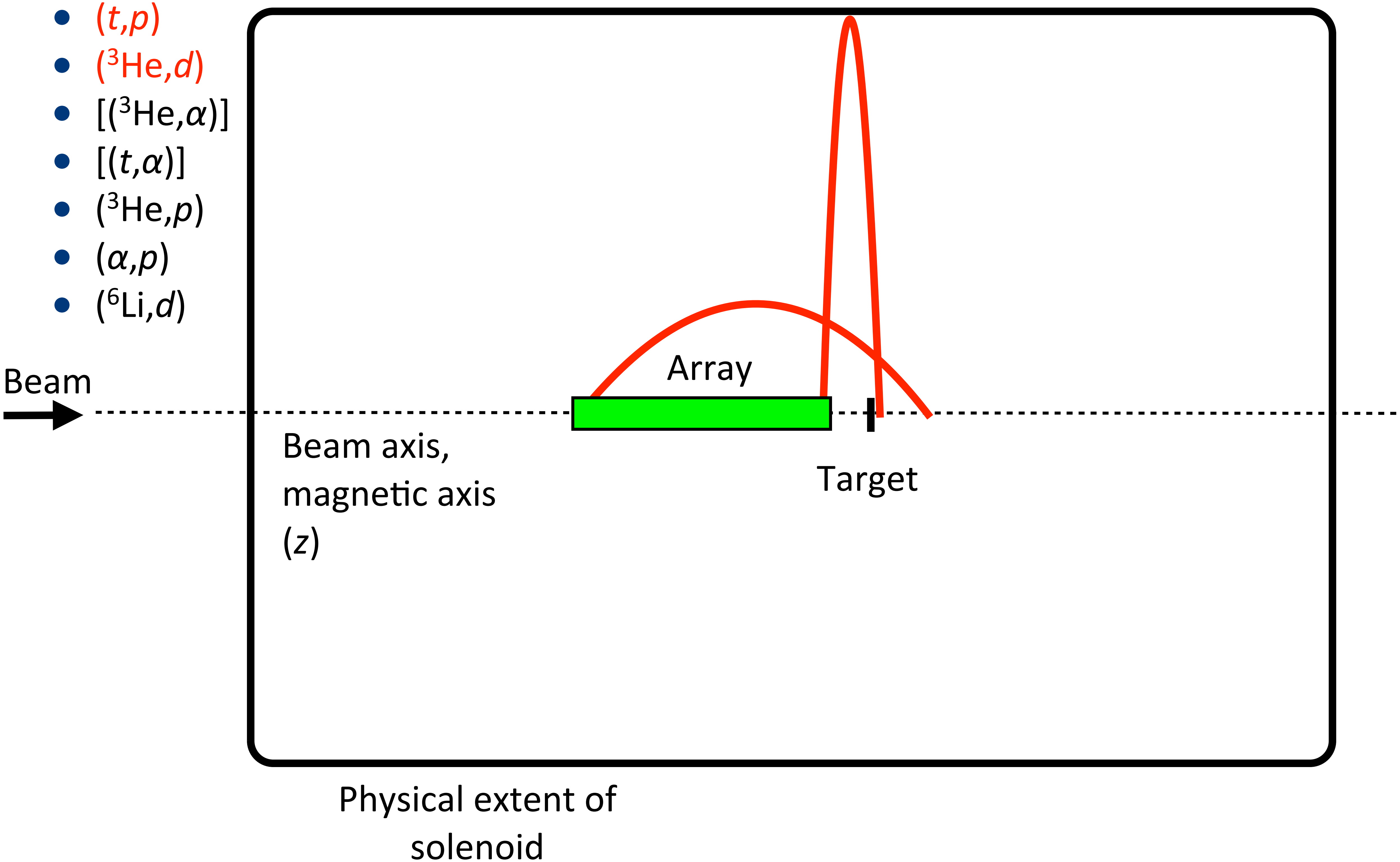
All considerations focused on ***direct reactions*** for ***nuclear structure*** and ***astrophysics***

Work on assumption of up to ***10-MeV/u beams***

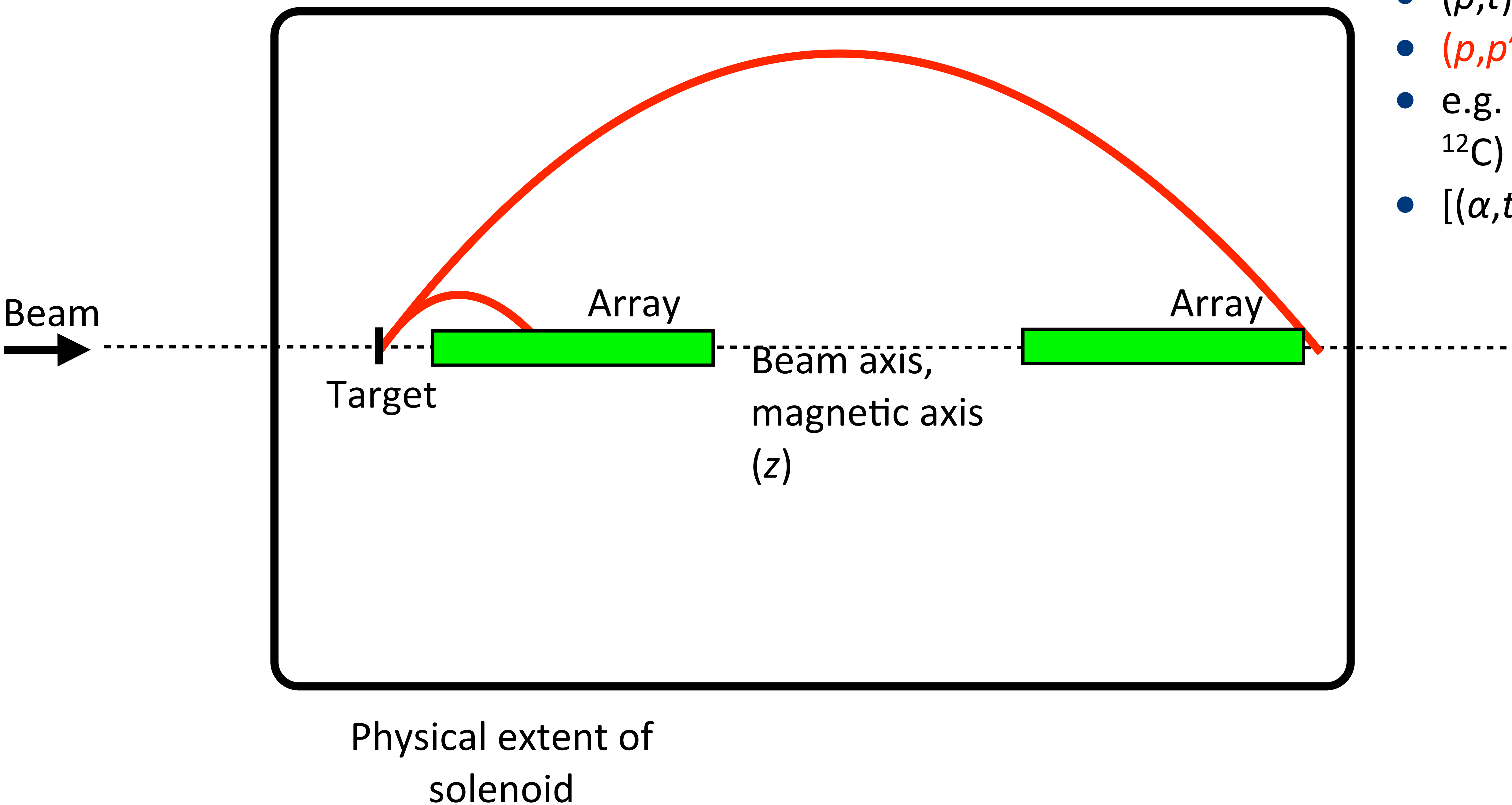
Kinematics – which hemisphere?

Backwards

- (d,p)
- (t,p)
- $(^{3}\mathrm{He},d)$
- $[(^{3}\mathrm{He},\alpha)]$
- $[(t,\alpha)]$
- $(^{3}\mathrm{He},p)$
- (α,p)
- $(^{6}\mathrm{Li},d)$



Kinematics – which hemisphere?



Forwards

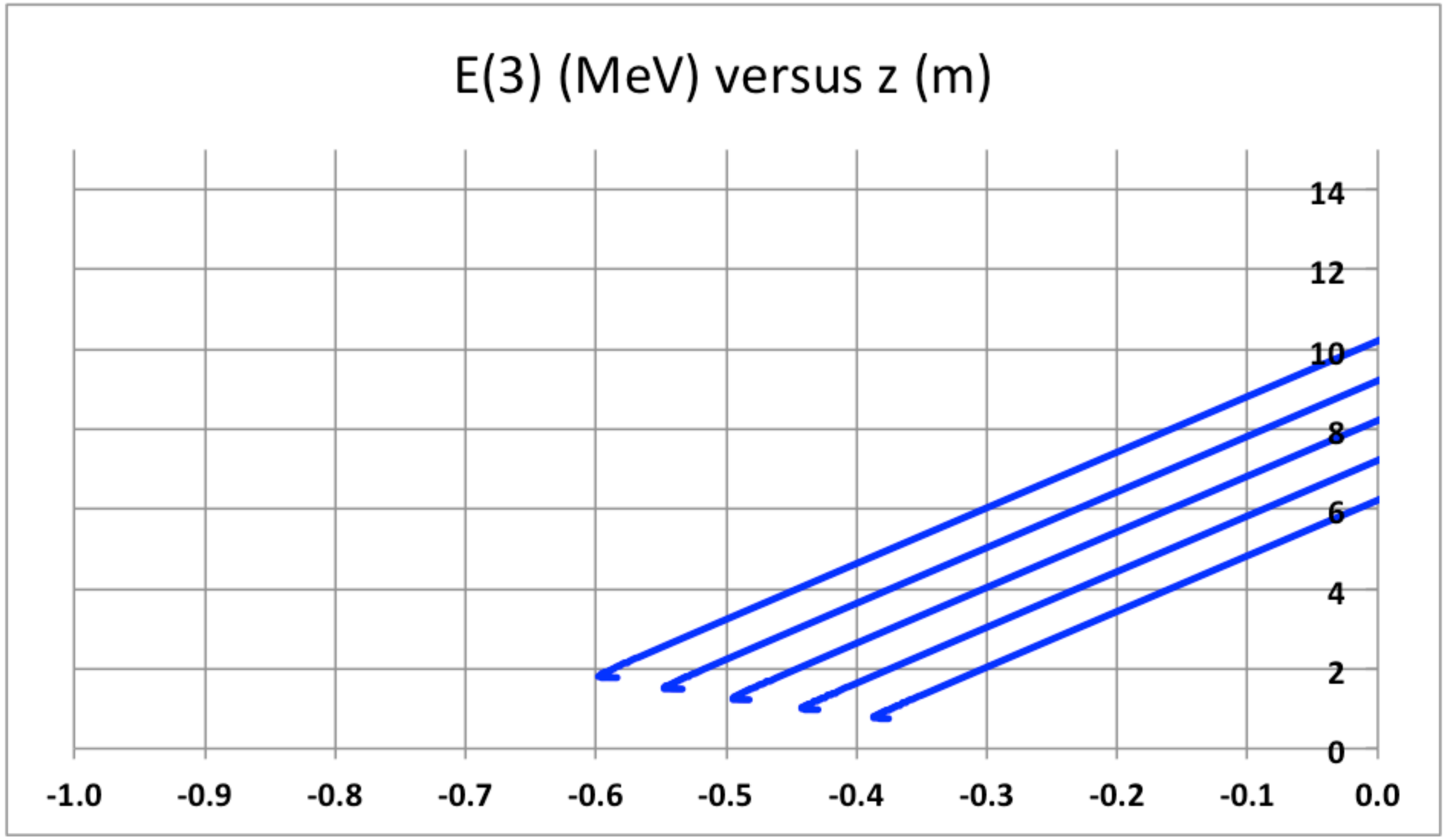
- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (p,t)
- (p,p'), etc
- e.g. (^{12}C, ^{12}C)
- [(α,t)]

Kinematics – some (arbitrary) examples

***(d,p)* on ^{132}*Sn* at *10 MeV/u*, *2 T*, Q value = *+0.25* MeV**

Backwards

- *(d,p)*
- (*t*,*p*)
- (^{3}He,*d*)
- (^{3}He,*p*)
- (α,*p*)
- (^{6}Li,*d*)
- (^{7}Li,*t*)



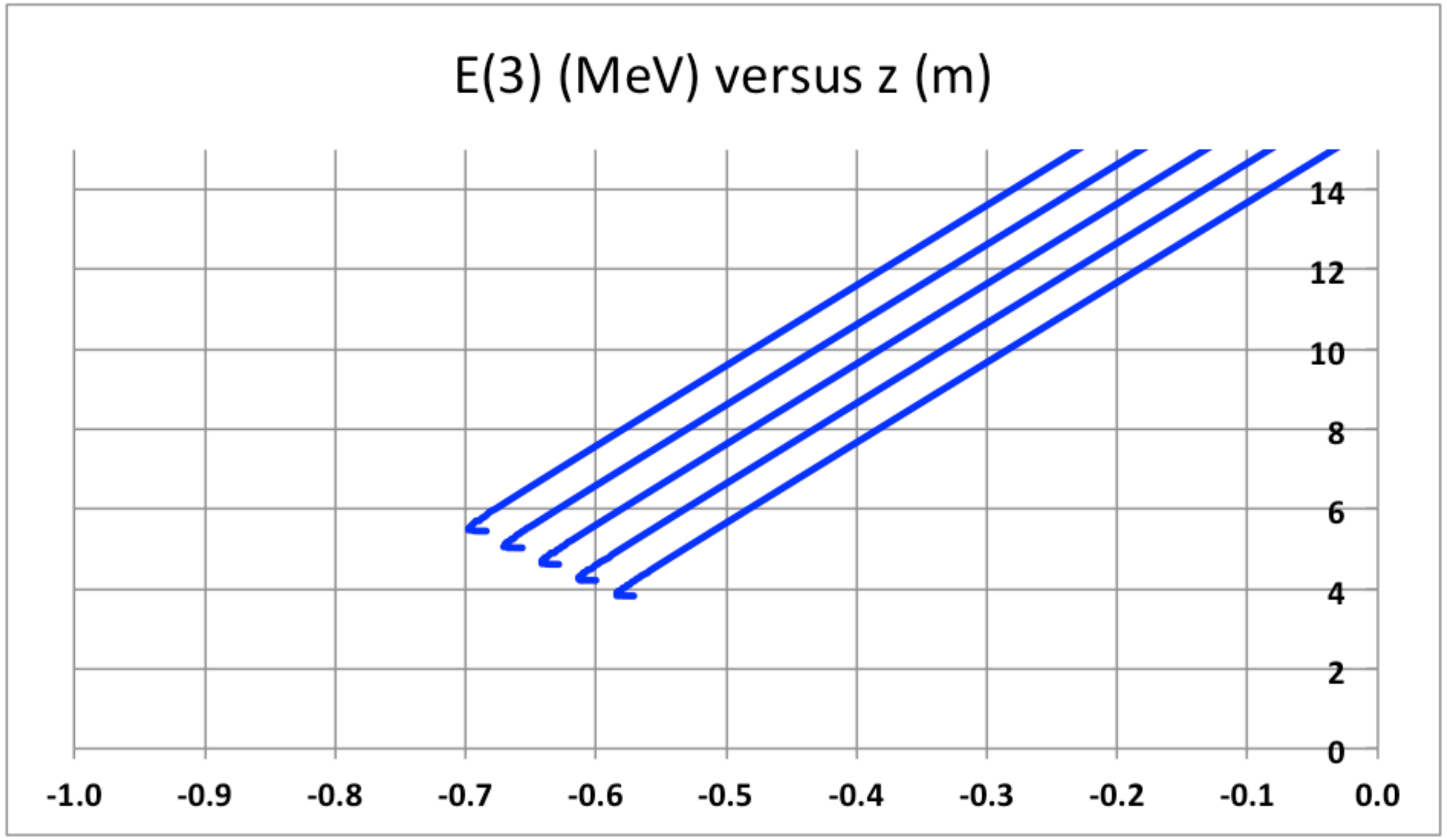
1-mm of Si stops ***about*** 12 MeV protons, 17 MeV deuterons, 20 MeV tritons
Always 0, 1, 2, 3, 4, and 5 MeV excitations (fictional states)
Target always at z = 0 m

Kinematics – some (arbitrary) examples

***(t,p)* on ^{50}*Ca* at *10 MeV/u*, *3 T*, Q value = *+0.6* MeV**

Backwards

- (*d*,*p*)
- (*t*,*p*)
- (^{3}He,*d*)
- (^{3}He,*p*)
- (α,*p*)
- (^{6}Li,*d*)
- (^{7}Li,*t*)

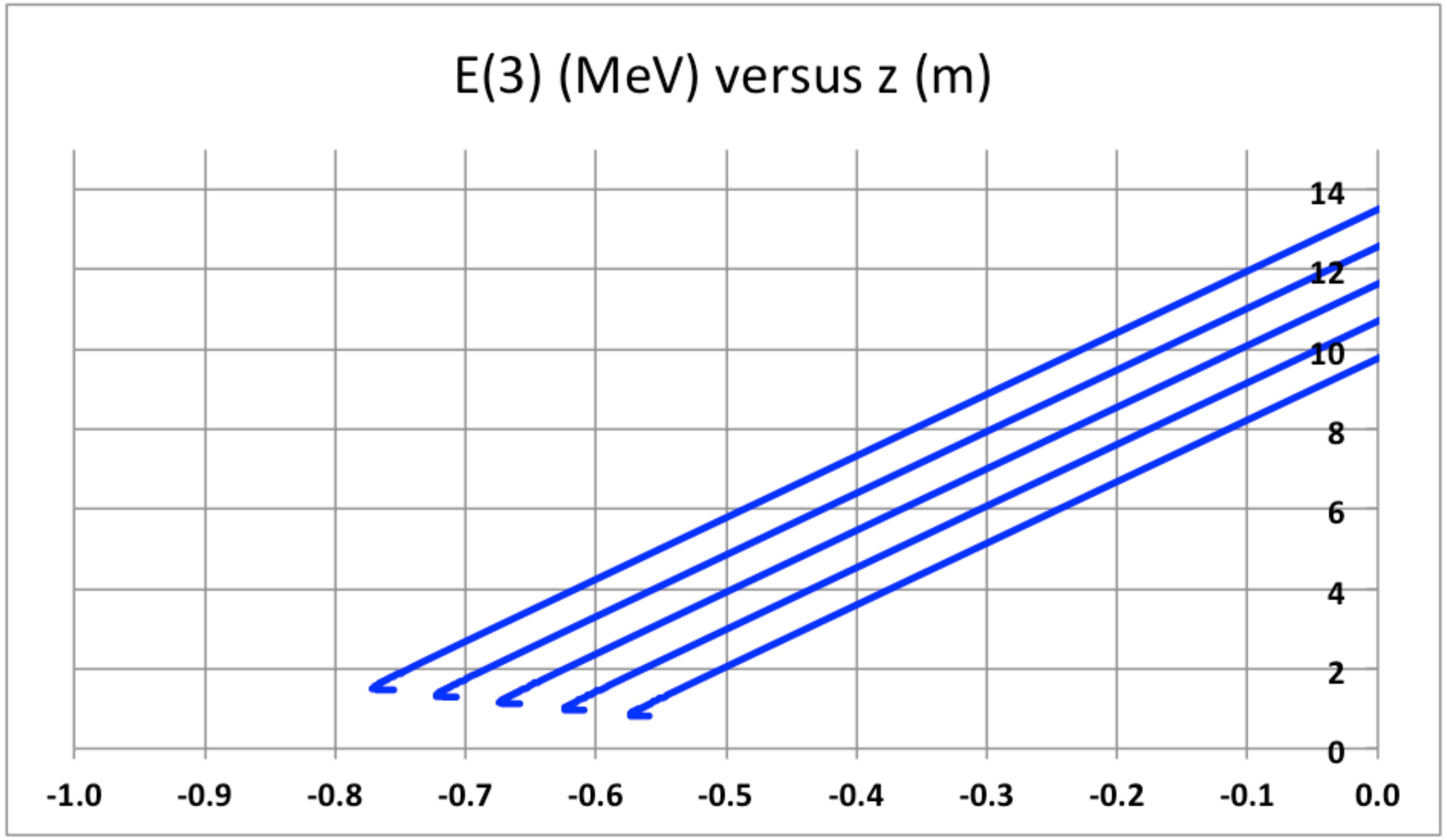


Kinematics – some (arbitrary) examples

(^{3}He,d) on ^{25}Al at 15 MeV/u, 2 T, Q value = +0.02 MeV

Backwards

- (*d*,*p*)
- (*t*,*p*)
- (^{3}He,*d*)
- (^{3}He,*p*)
- (α,*p*)
- (^{6}Li,*d*)
- (^{7}Li,*t*)

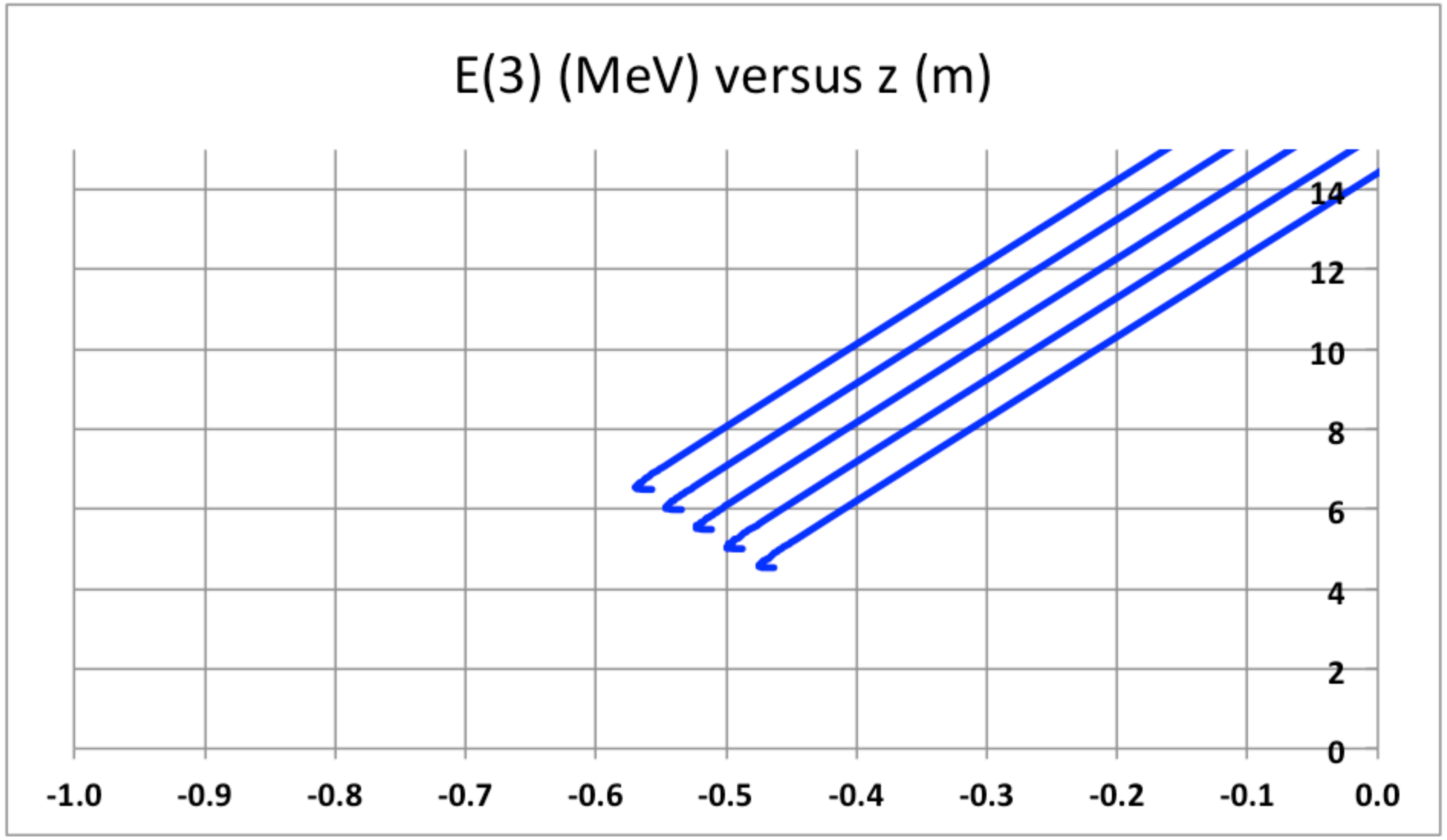


Kinematics – some (arbitrary) examples

(^{3}He,p) on ^{44}Ti at 6 MeV/u, 4 T, Q value = +7.2 MeV

Backwards

- (*d*,*p*)
- (*t*,*p*)
- (^{3}He,*d*)
- (^{3}He,*p*)
- (*α*,*p*)
- (^{6}Li,*d*)
- (^{7}Li,*t*)

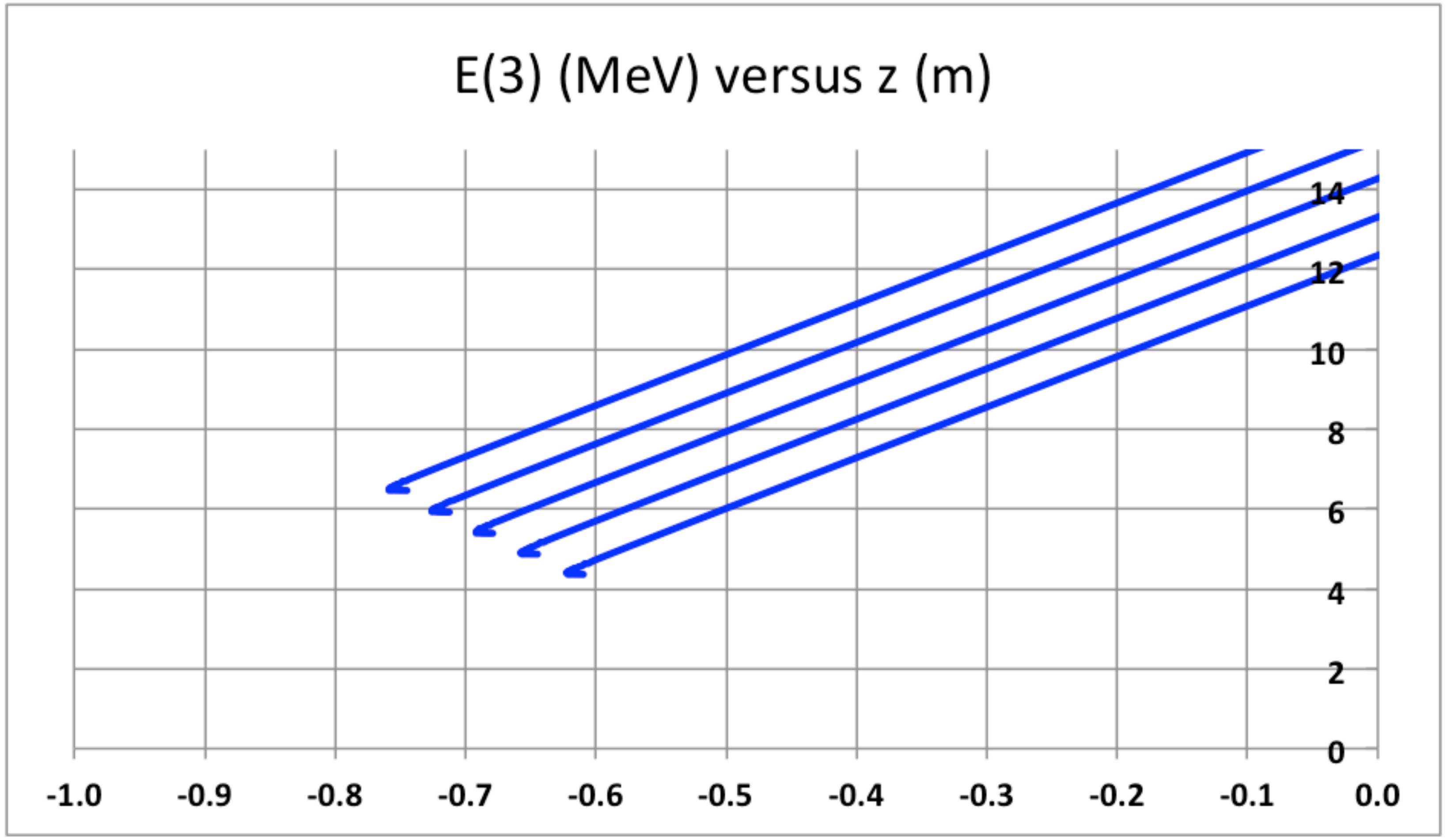


Kinematics – some (arbitrary) examples

(^{4}He,p) on ^{22}Mg at 5 MeV/u, 3 T, Q value = +3.7 MeV

Backwards

- (d,p)
- (t,p)
- (^{3}He,d)
- (^{3}He,p)
- (α,p)
- (^{6}Li,d)
- (^{7}Li,t)

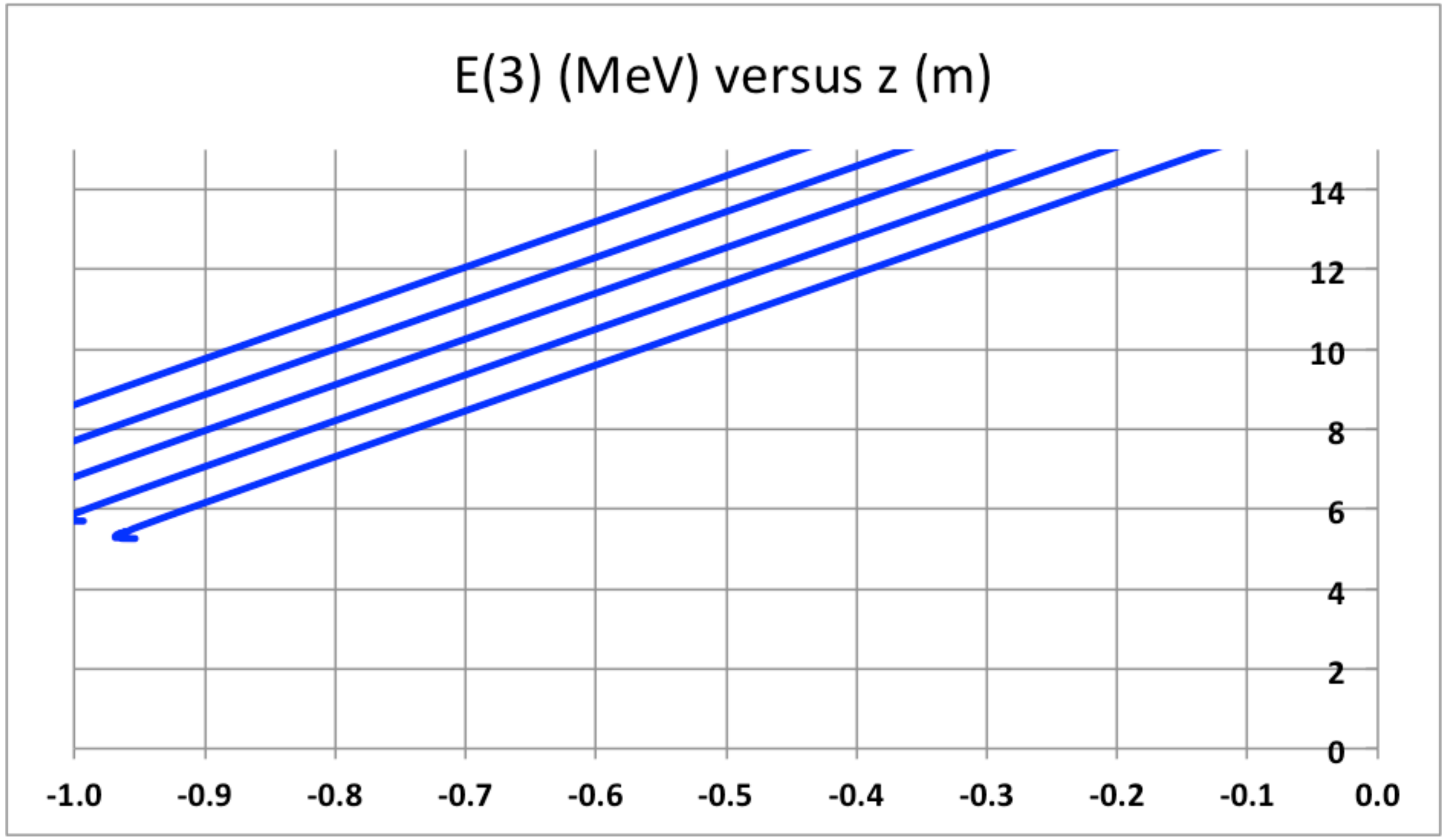


Kinematics – some (arbitrary) examples

(^{6}Li,d) on ^{14}O at 6 MeV/u, 3 T, Q value = +3.6 MeV

Backwards

- (d,p)
- (t,p)
- (^{3}He,d)
- (^{3}He,p)
- (α,p)
- (^{6}Li,d)
- (^{7}Li,t)

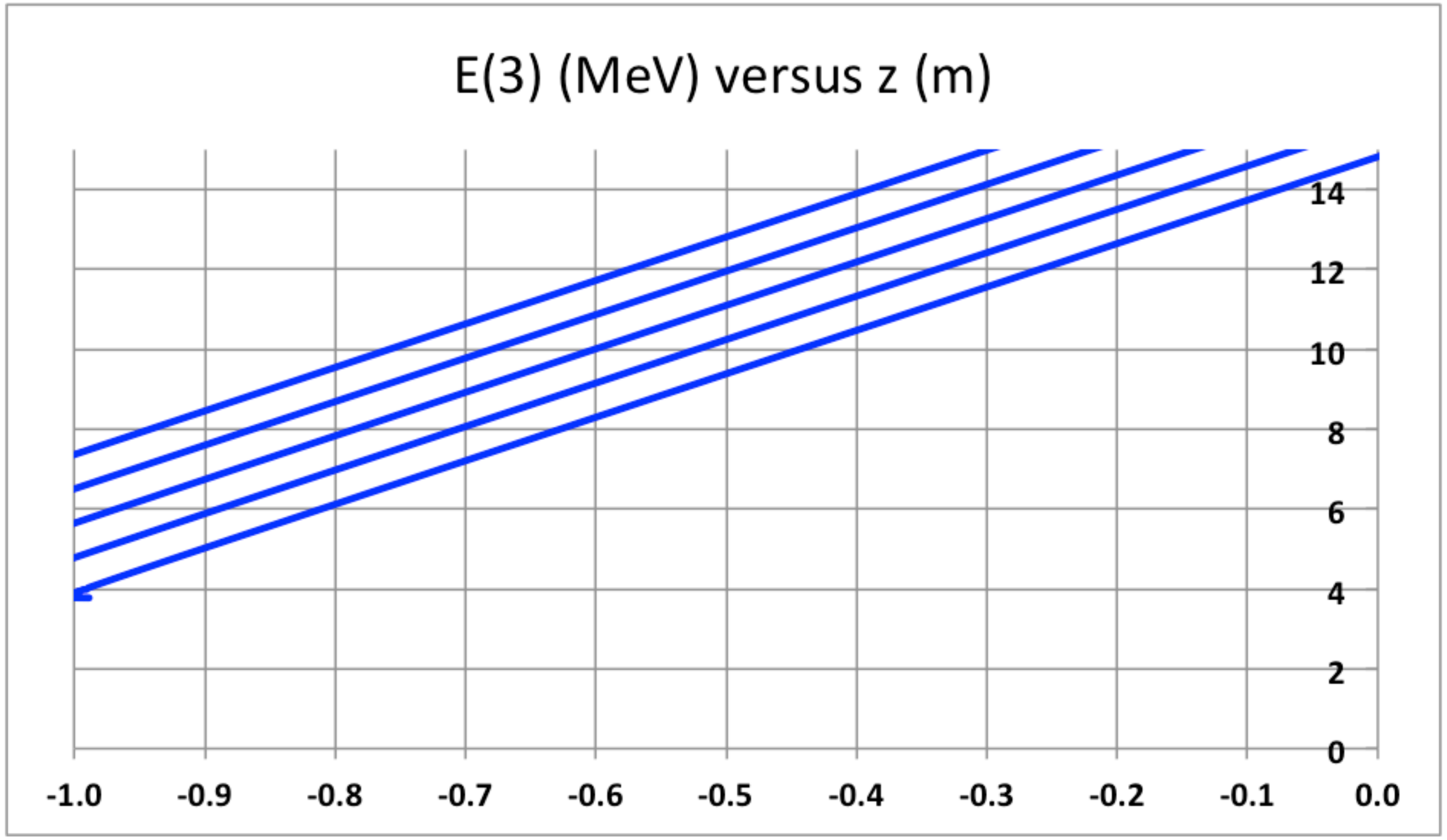


Kinematics – some (arbitrary) examples

(⁷Li,t) on ¹⁴O at 6 MeV/u, 3 T, Q value = +2.6 MeV

Backwards

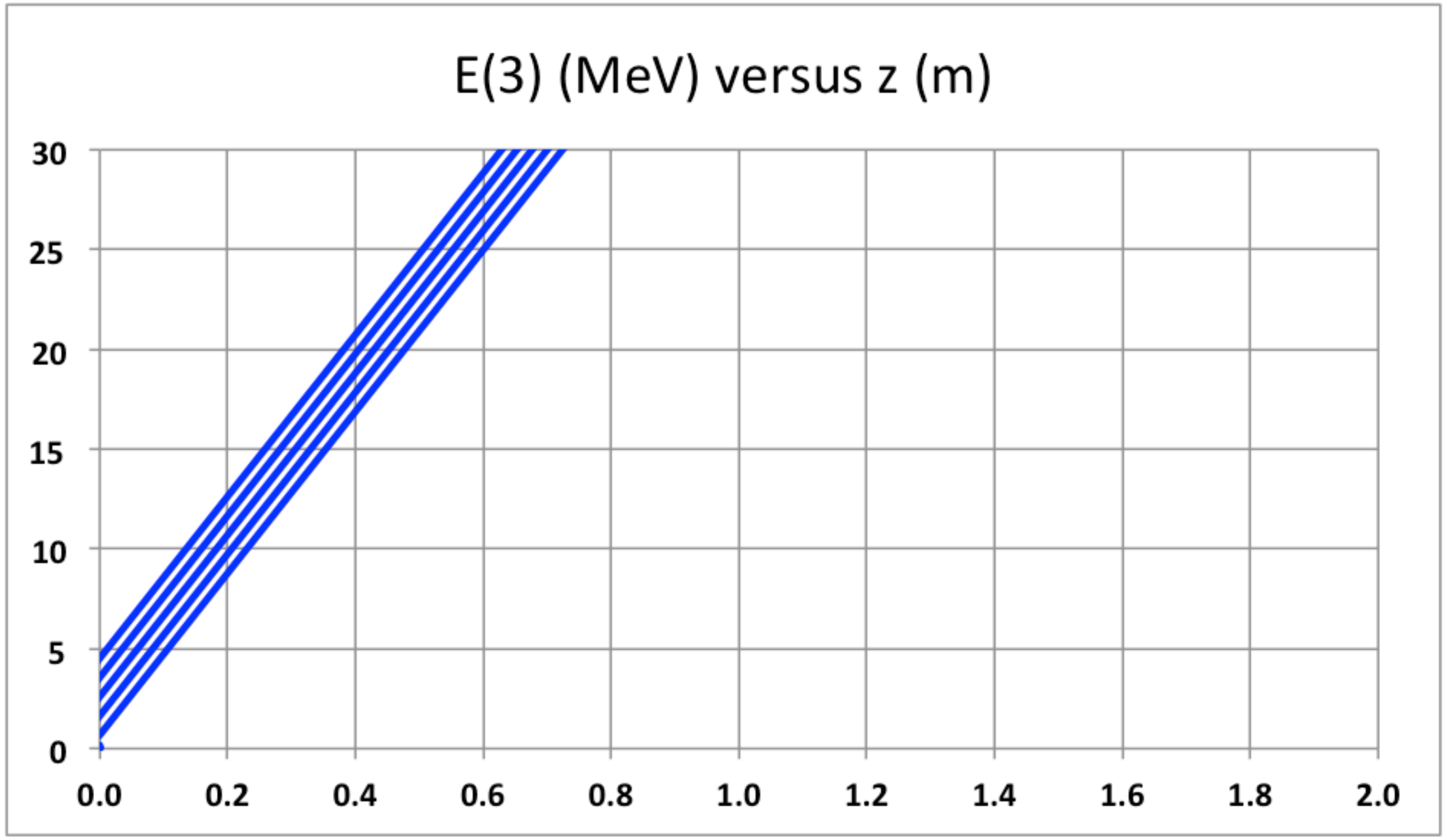
- (*d*,*p*)
- (*t*,*p*)
- (^{3}He,*d*)
- (^{3}He,*p*)
- (*α*,*p*)
- (^{6}Li,*d*)
- (^{7}Li,*t*)



So … by tuning the field between about ***2-4 T***, and within approximately ***1 m in z***, the vast majority of ***backward-hemisphere reactions*** can be performed. ***Outcome: up to 4-T field, about 1-m diameter bore.***

Kinematics – some (arbitrary) examples

***(t,^{3}He)* on *^{68}Se* at *10 MeV/u*, *3 T*, Q value = *+4.7* MeV**

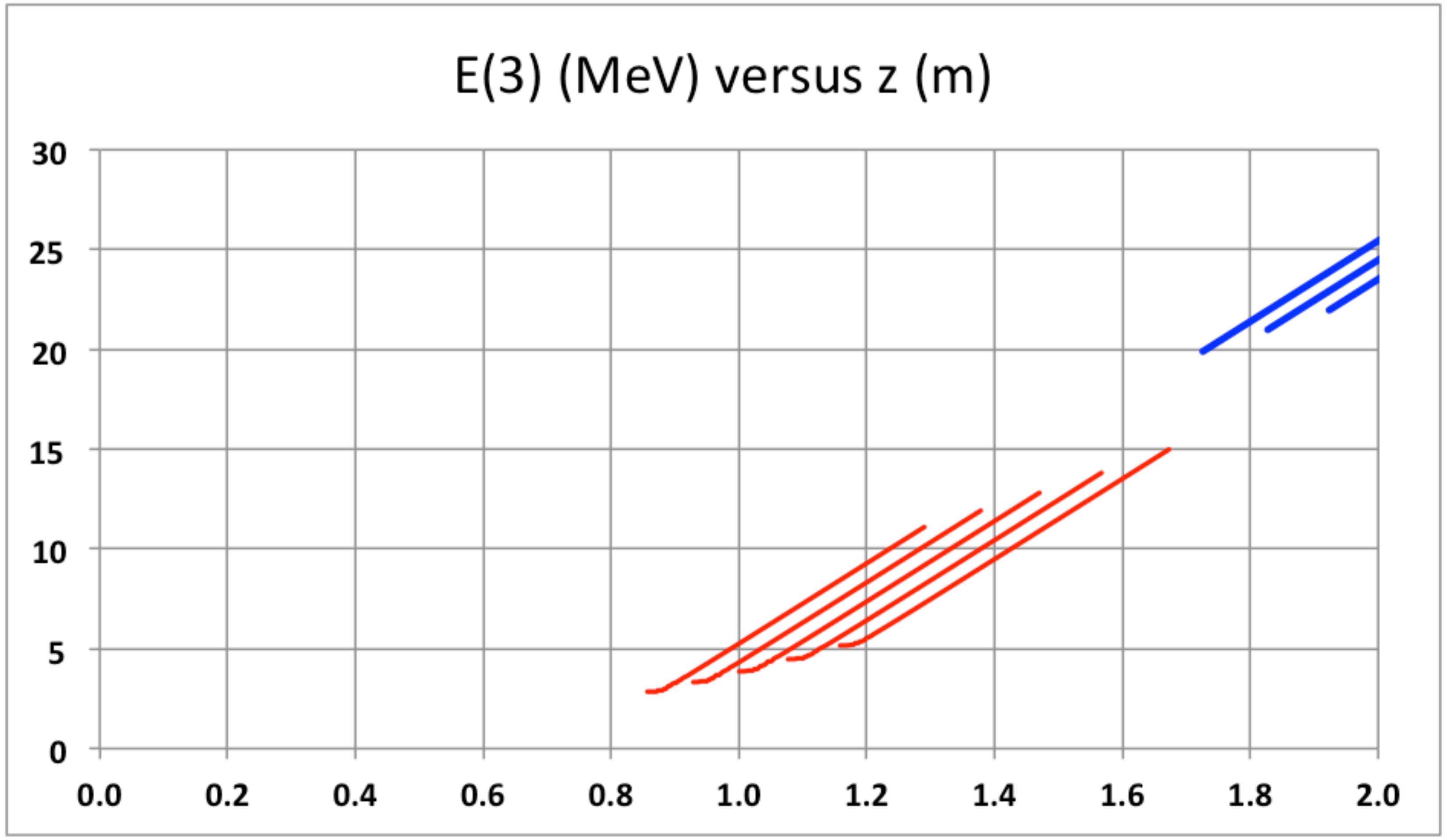


Forwards

- (*t*,^{3}He)
- (^{3}He,*t*)
- (*p*,*d*)
- (*d*,^{3}He)
- (*p*,*t*)
- (*p*,*p'*), etc
- e.g. (^{12}C, ^{12}C)

Kinematics – some (arbitrary) examples

(^{3}He,t) on ^{68}Se at 10 MeV/u, 3 T, Q value = –15.6 MeV

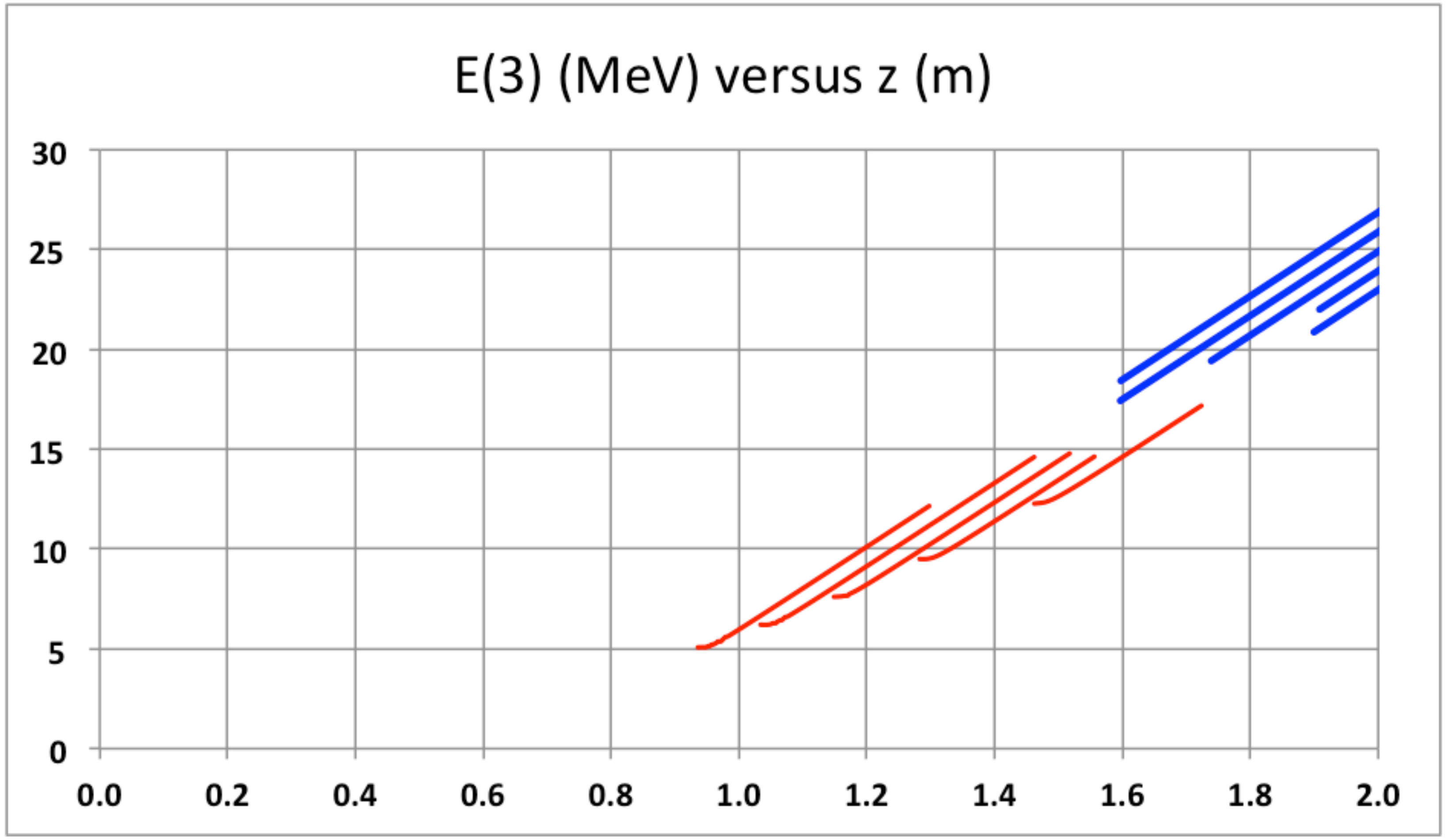


Forwards

- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (d,^{3}He)
- (p,t)
- (p,p’), etc
- e.g. (^{12}C, ^{12}C)

Kinematics – some (arbitrary) examples

(p,d)* on ^{132}*Sn* at *10 MeV/u*, *3 T*, *Q value* = *–5.1 MeV

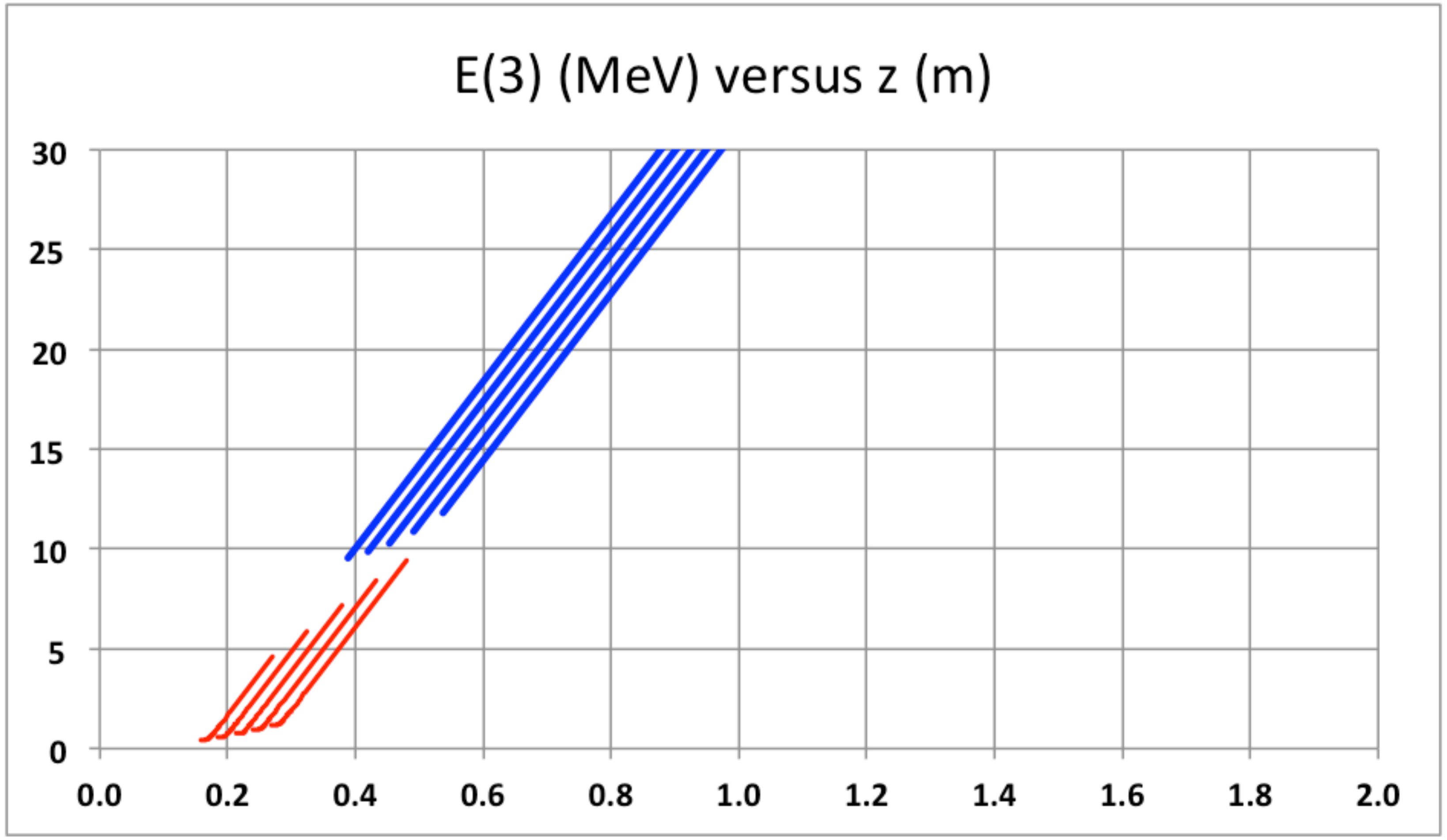


Forwards

- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (d,^{3}He)
- (p,t)
- (p,p'), etc
- e.g. (^{12}C, ^{12}C)

Kinematics – some (arbitrary) examples

(d,^{3}He) on ^{186}Pb at 10 MeV/u, 3 T, Q value = +3.3 MeV

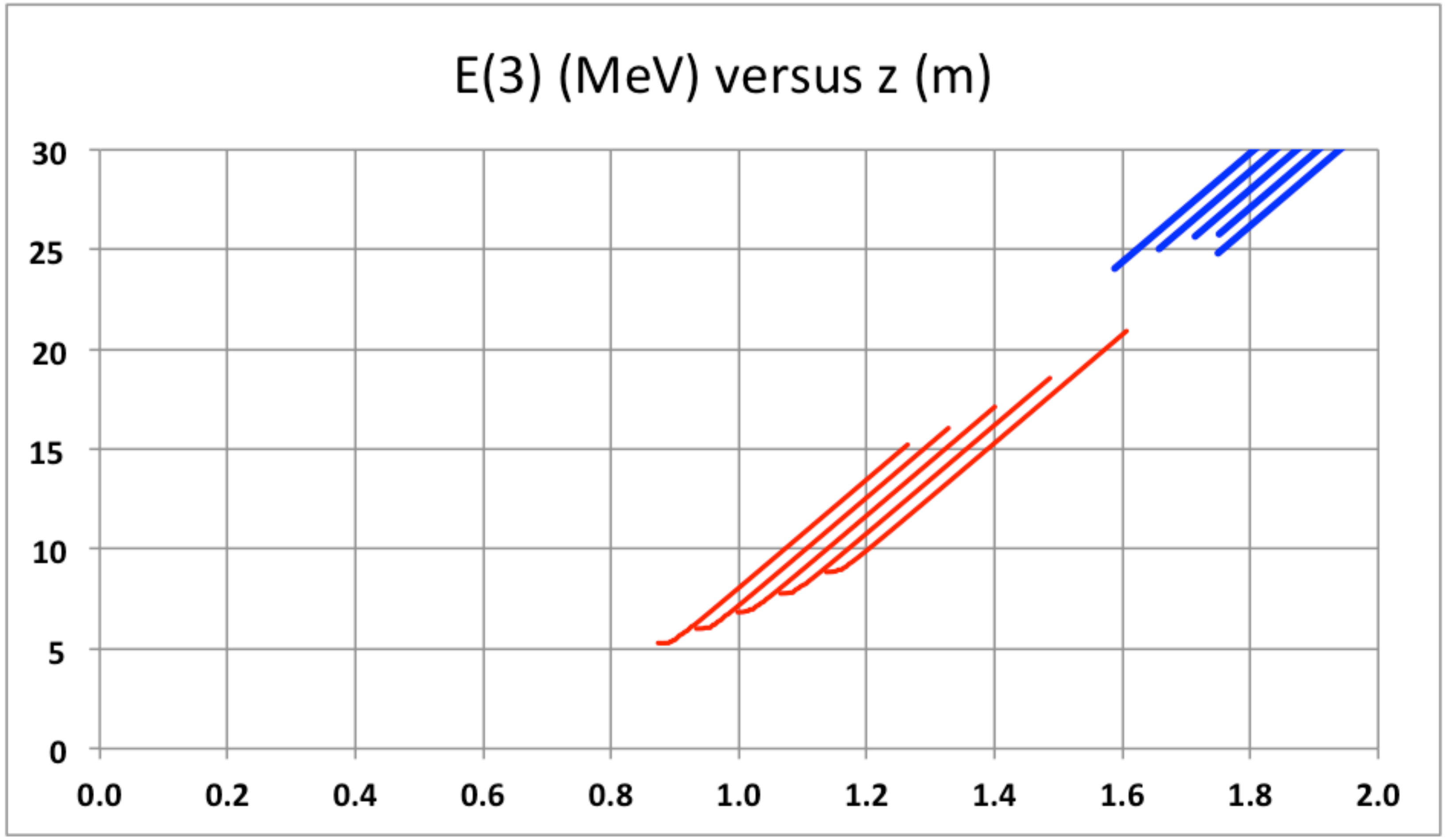


Forwards

- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (d,^{3}He)
- (p,t)
- (p,p'), etc
- e.g. (^{12}C, ^{12}C)

Kinematics – some (arbitrary) examples

***(p,t)* on *^{32}Mg* at *10 MeV/u*, *4 T*, Q value = *+0.3* MeV**



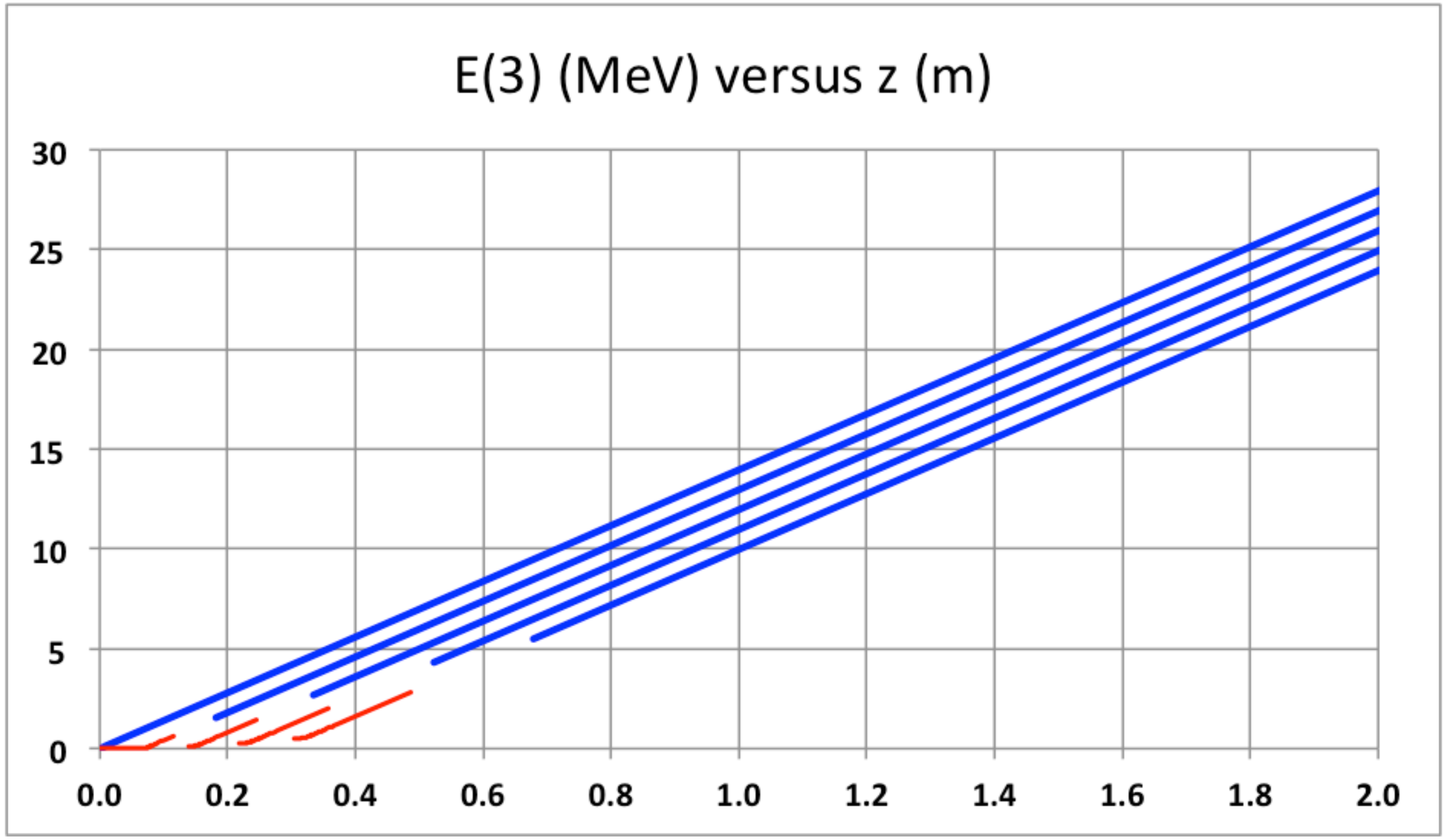
Forwards

- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (d,^{3}He)
- (p,t)
- (p,p'), etc
- e.g. (^{12}C,^{12}C)

Caution: (p,t) is awkward. Take Kr for example: p(^{96}Kr,t) has a Q value of +0.5 MeV whilst p(^{72}Kr,t) has a Q value of –19.9 MeV.

Kinematics – some (arbitrary) examples

(p,p')* on *^{100}Sn* at *10 MeV/u*, *2 T*, *Q value = +X MeV

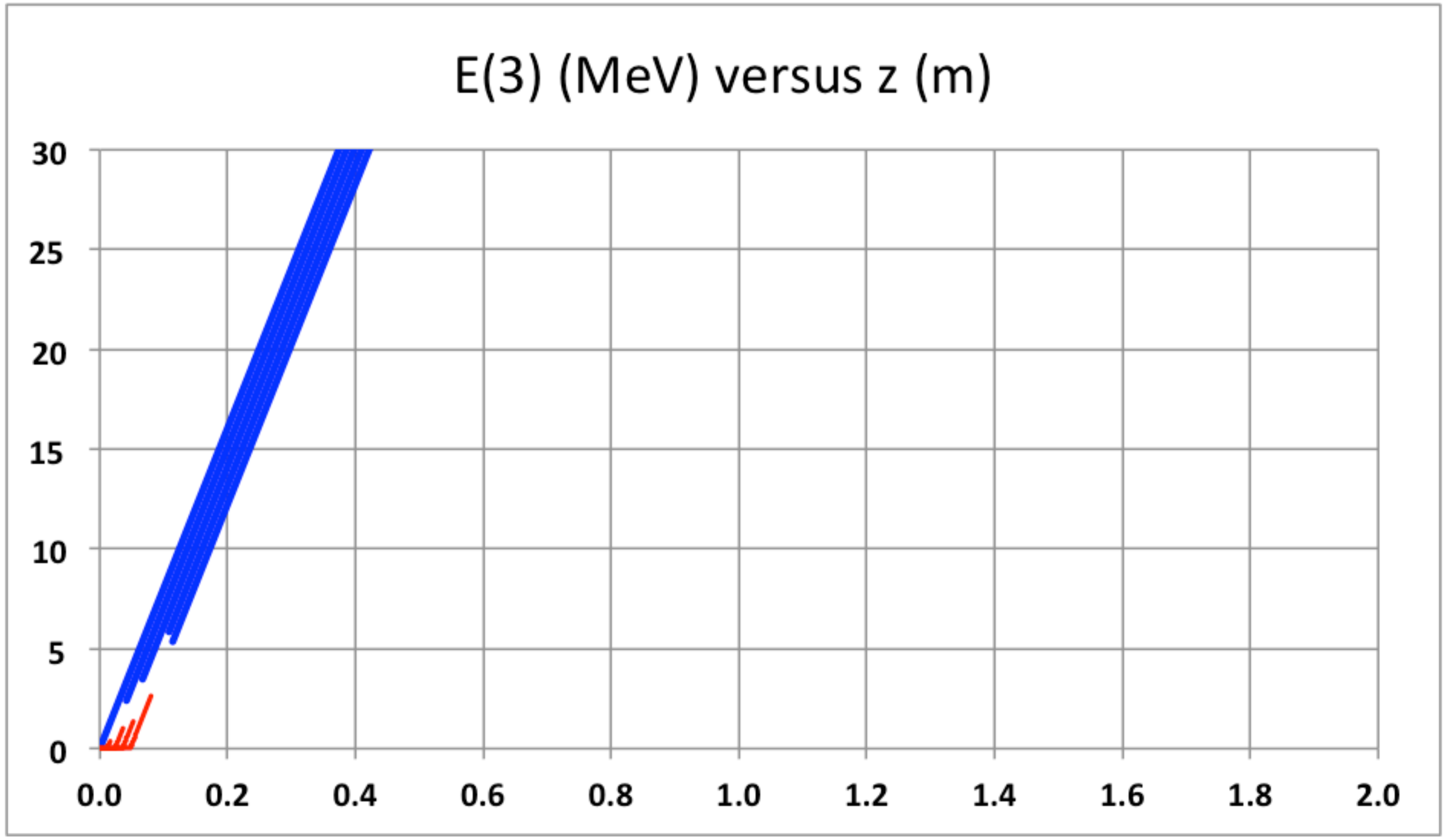


Forwards

- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (d,^{3}He)
- (p,t)
- (p,p'), etc
- e.g. (^{12}C, ^{12}C)

Kinematics – some (arbitrary) examples

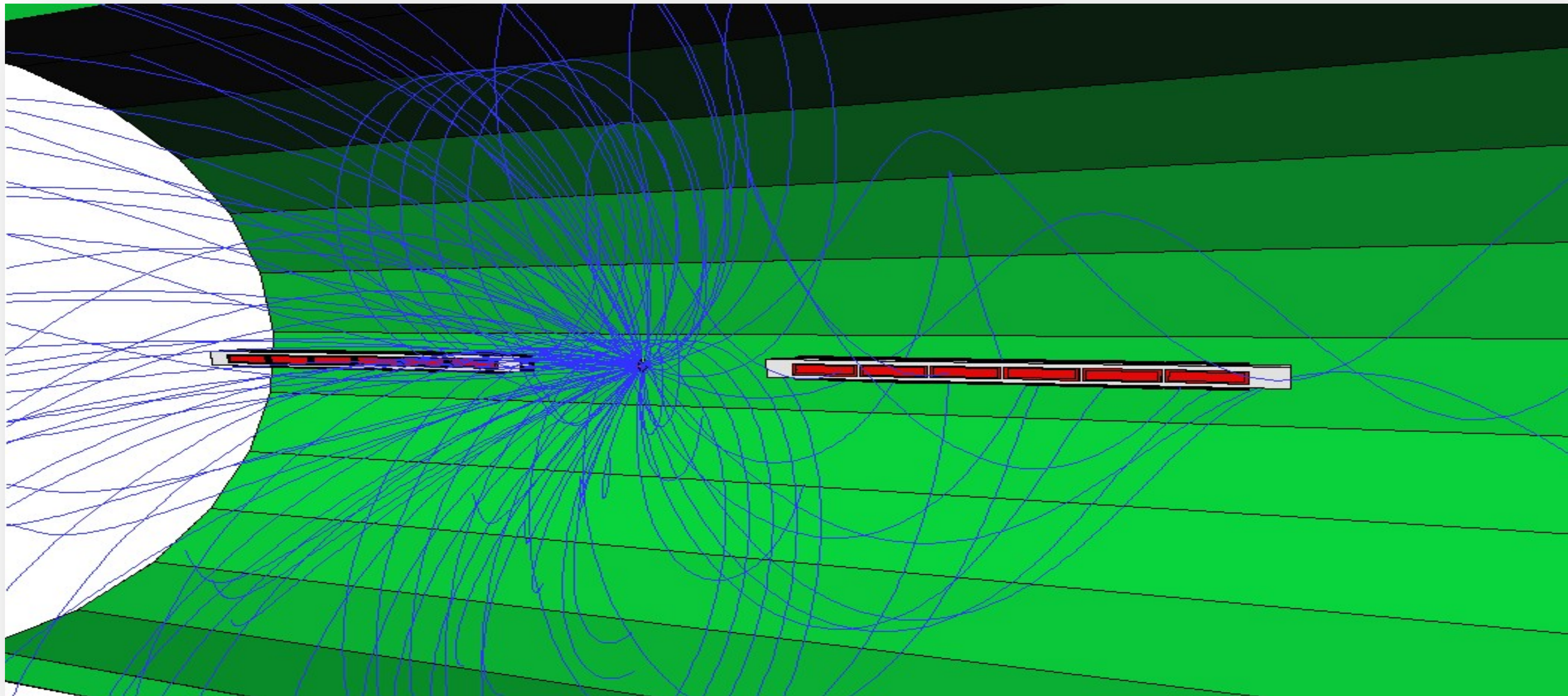
(^{12}C,^{12}C') on ^{224}Ra at 10 MeV/u, 2 T, Q value = +X MeV



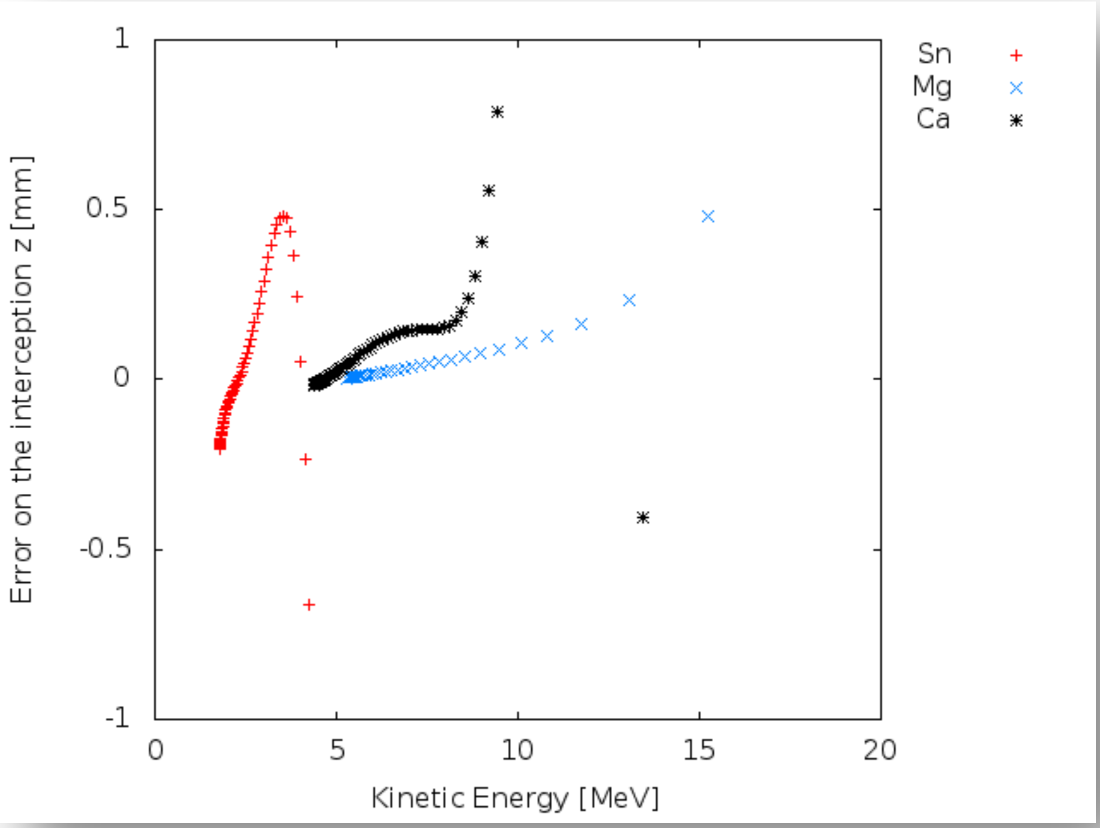
Forwards

- (t,^{3}He)
- (^{3}He,t)
- (p,d)
- (d,^{3}He)
- (p,t)
- (p,p'), etc
- e.g. (^{12}C, ^{12}C)

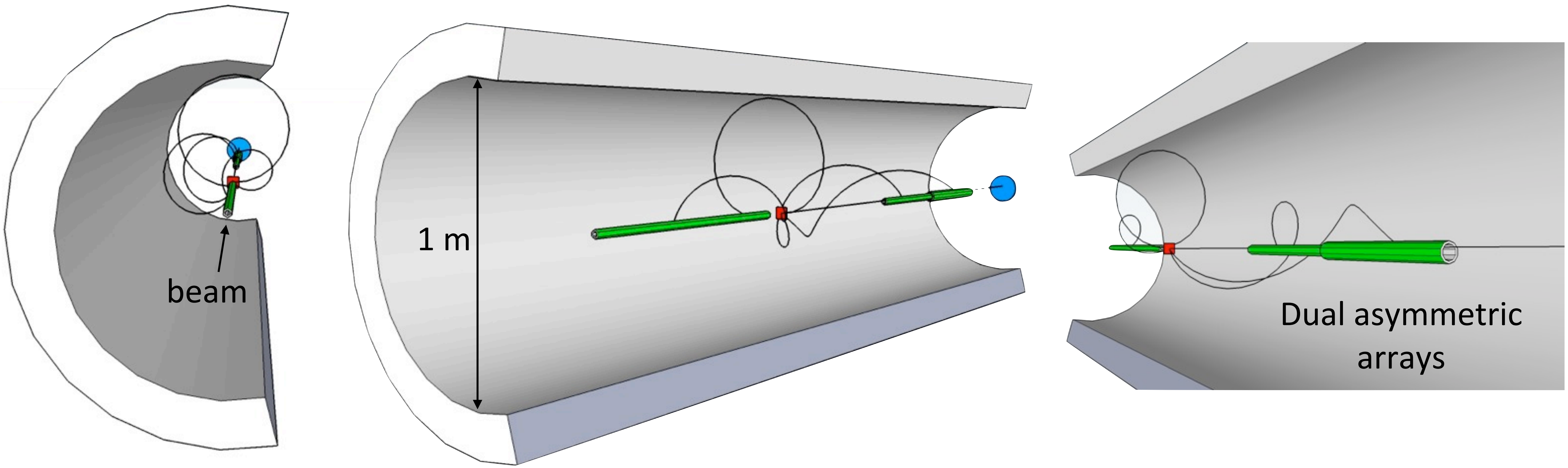
So ... by tuning the field between about ***2-4 T***, and within approximately ***2 m in z***, the vast majority of ***forward-hemisphere reactions*** can be performed. ***Outcome: up to 4-T field, about 1-m diameter bore*** and ***certainly 2 m long ... maybe a bit more depending on B_{max}***



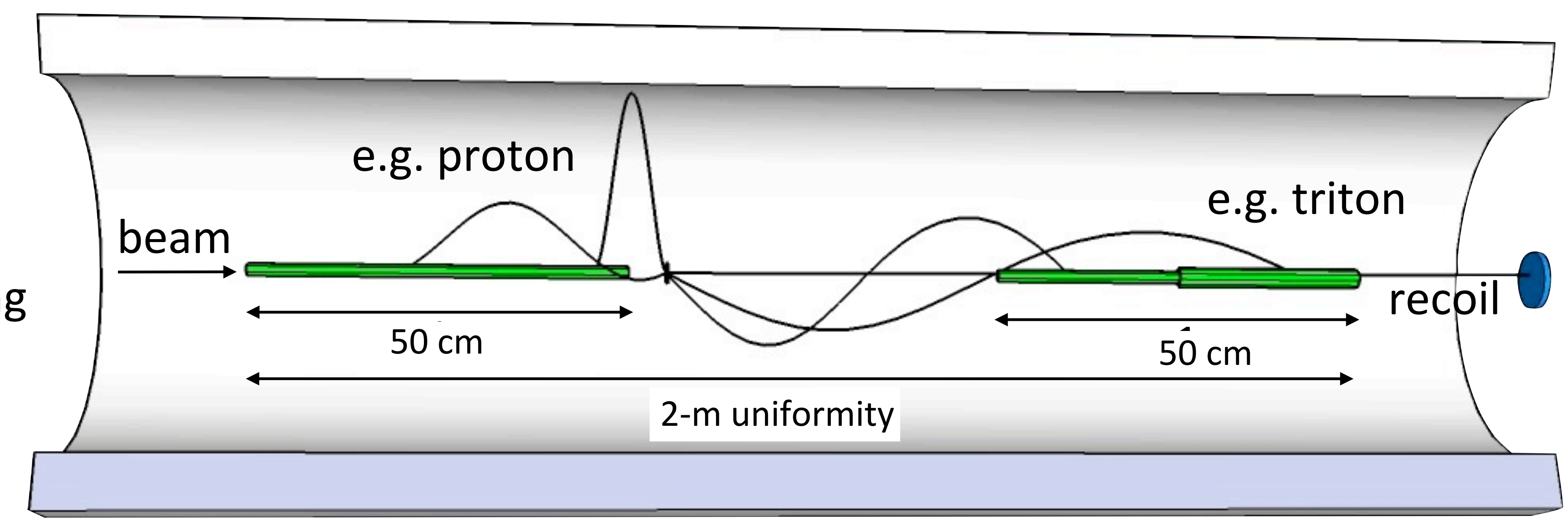
Simulation package available from Marc Labiche



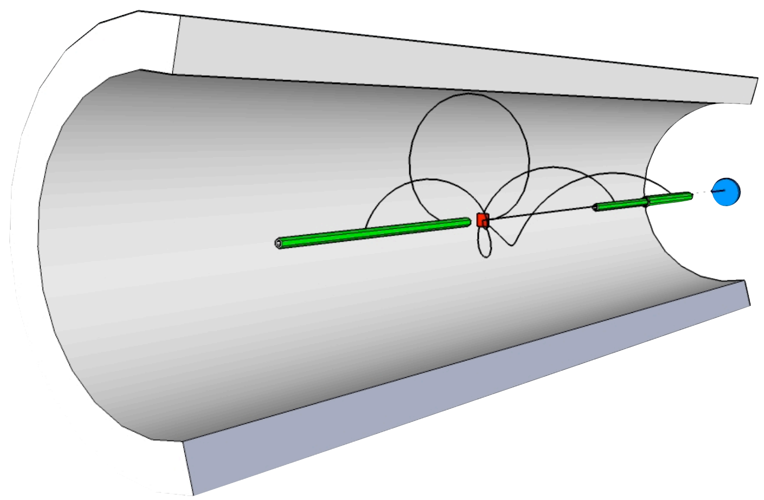
What could it look like?

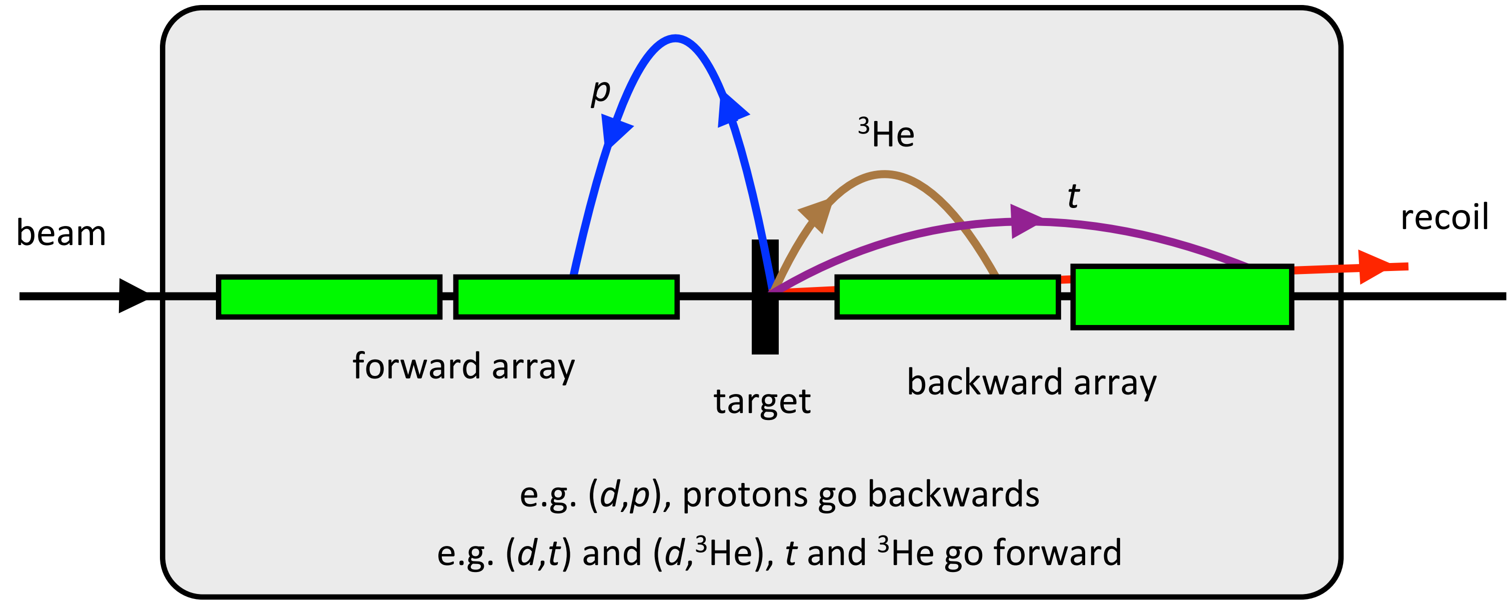


Up to 4 T bespoke superconducting solenoid

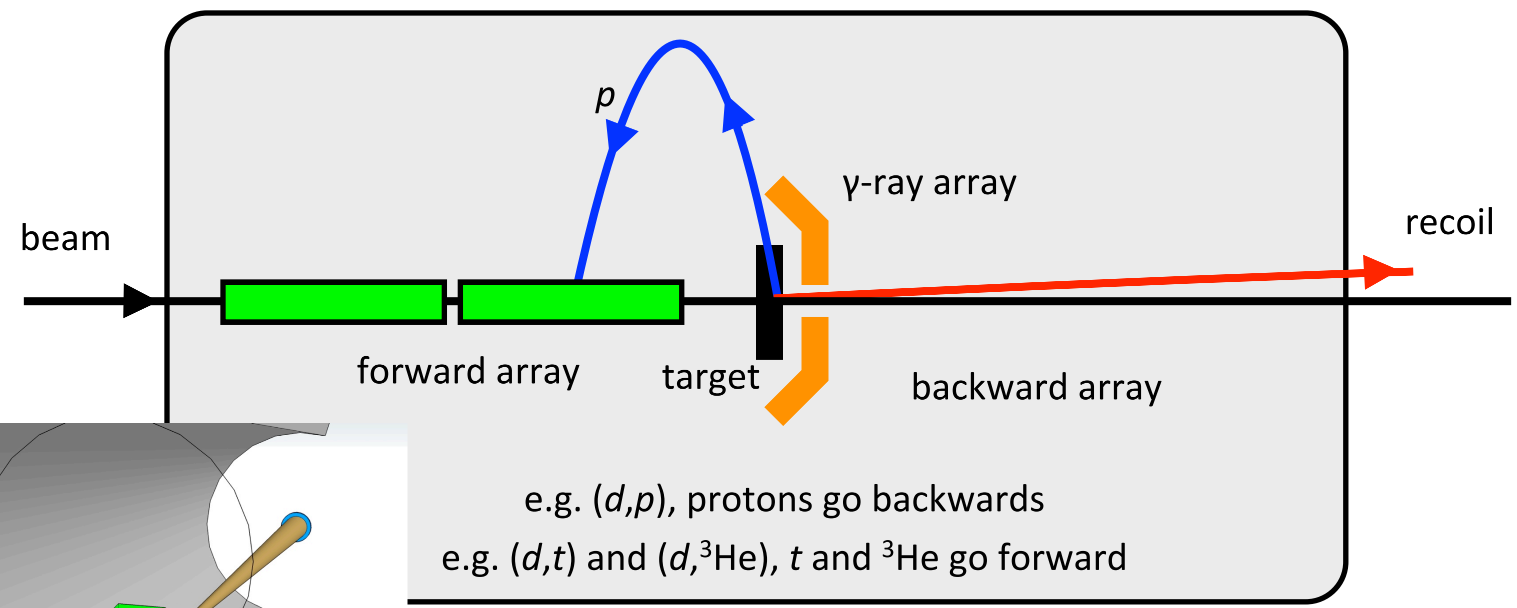


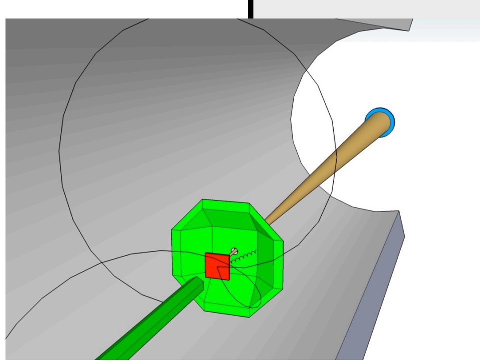
SOLAR ??





*e.g. dual, **multi-configuration**, arrays*

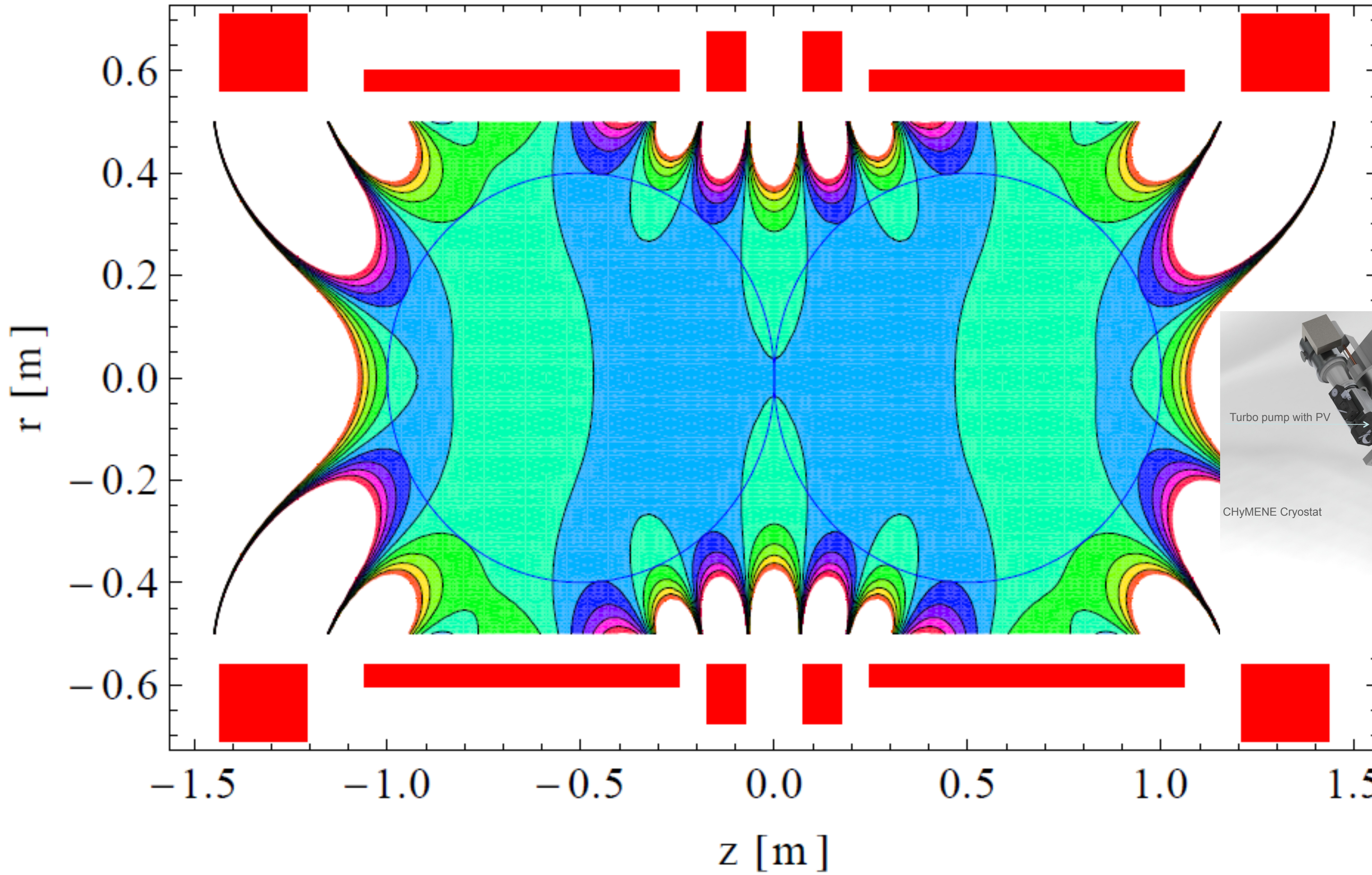


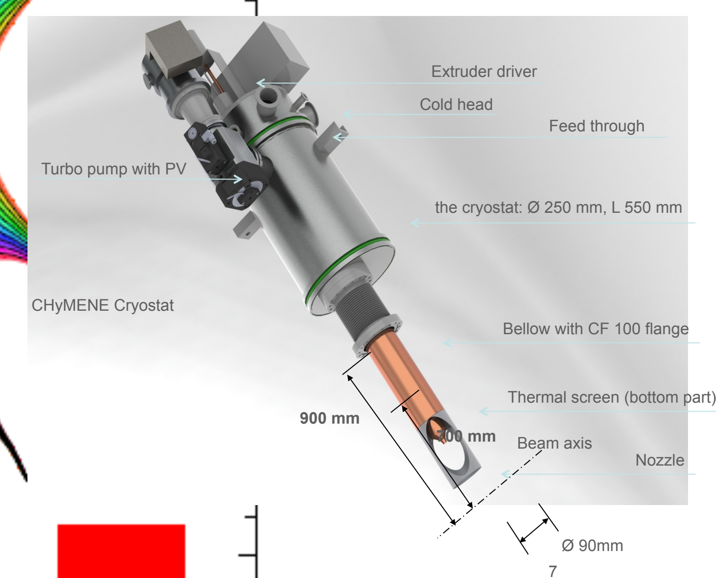


e.g. ~2π gamma-ray array

- Has to be flexible, will have modular arrays, gas-cell target, gamma-ray detection
- Measure reactions simultaneously and very well isolated PID (cyclotron period)

SupHex magnet design (CEA Saclay)

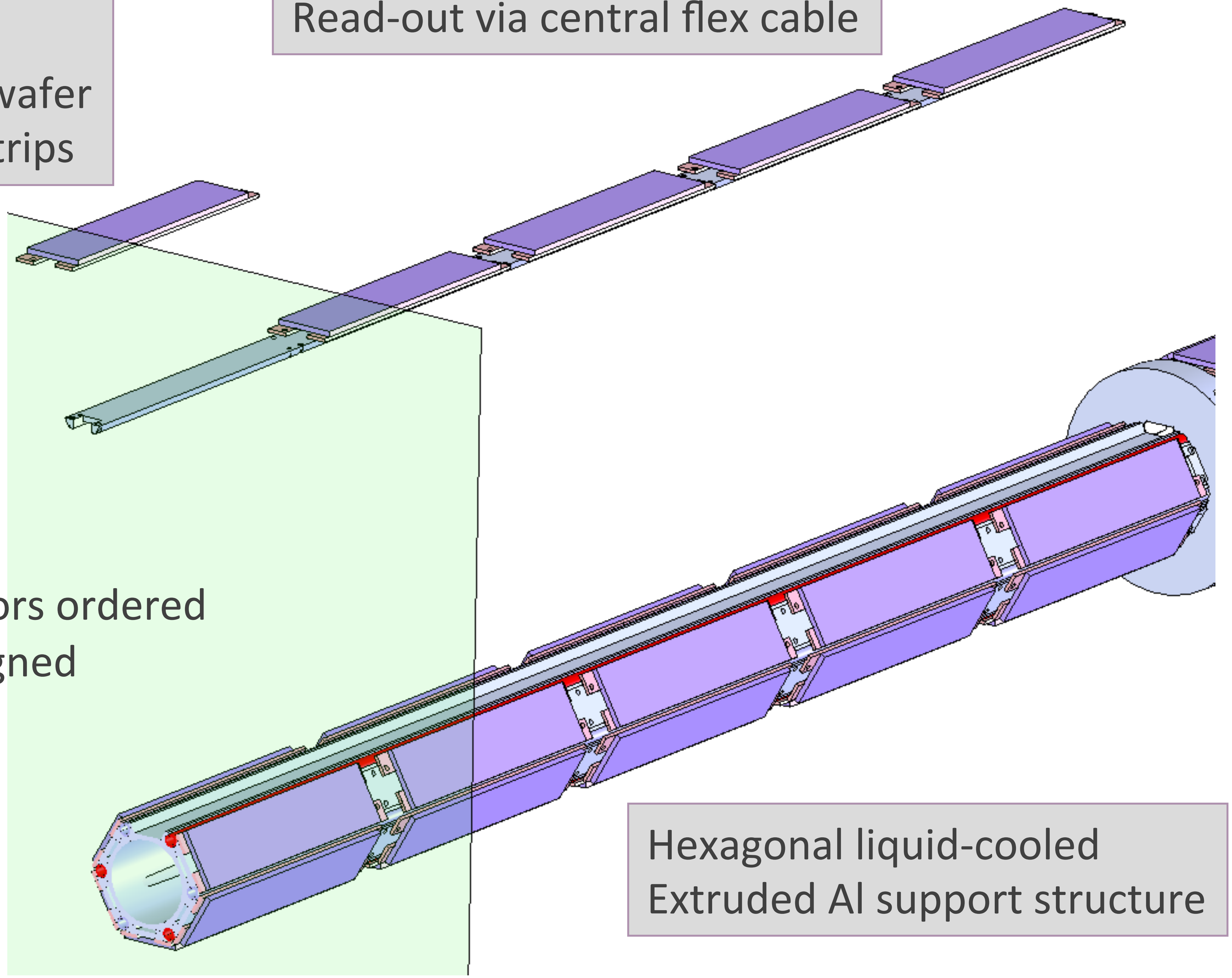




New efficient Si detector array

De-mountable
Resistive wire
11x53 mm^2 Si wafer
on 2 ceramic strips

Standard 5 detector module
Read-out via central flex cable



Status:
Prototype Si detectors ordered
Support frame designed

Hexagonal liquid-cooled
Extruded Al support structure

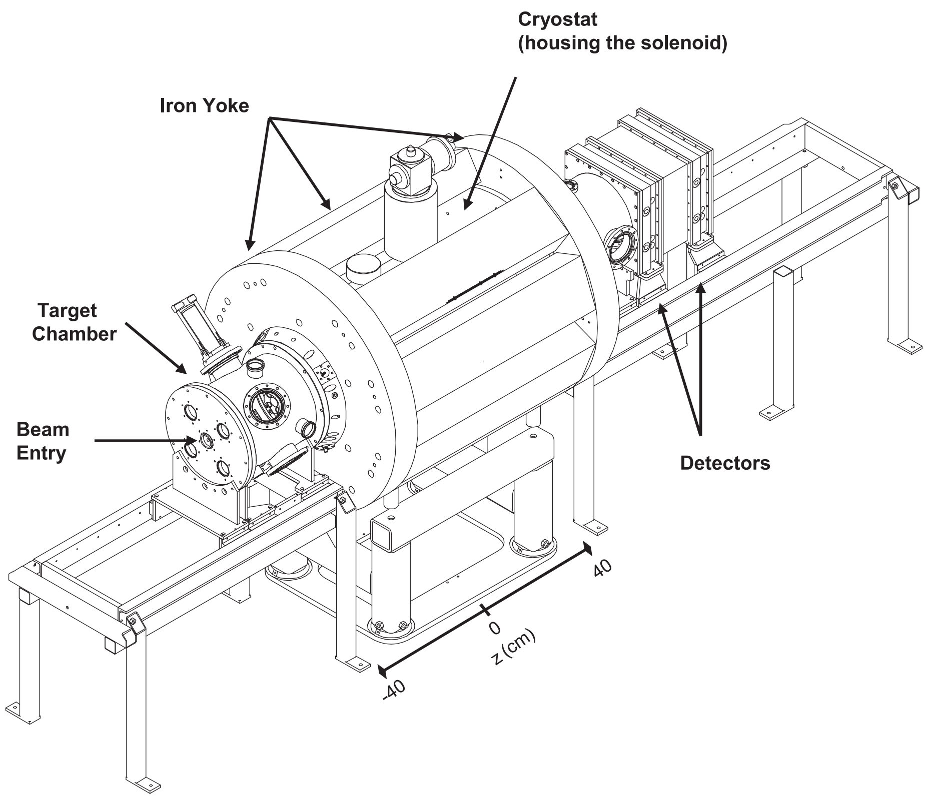
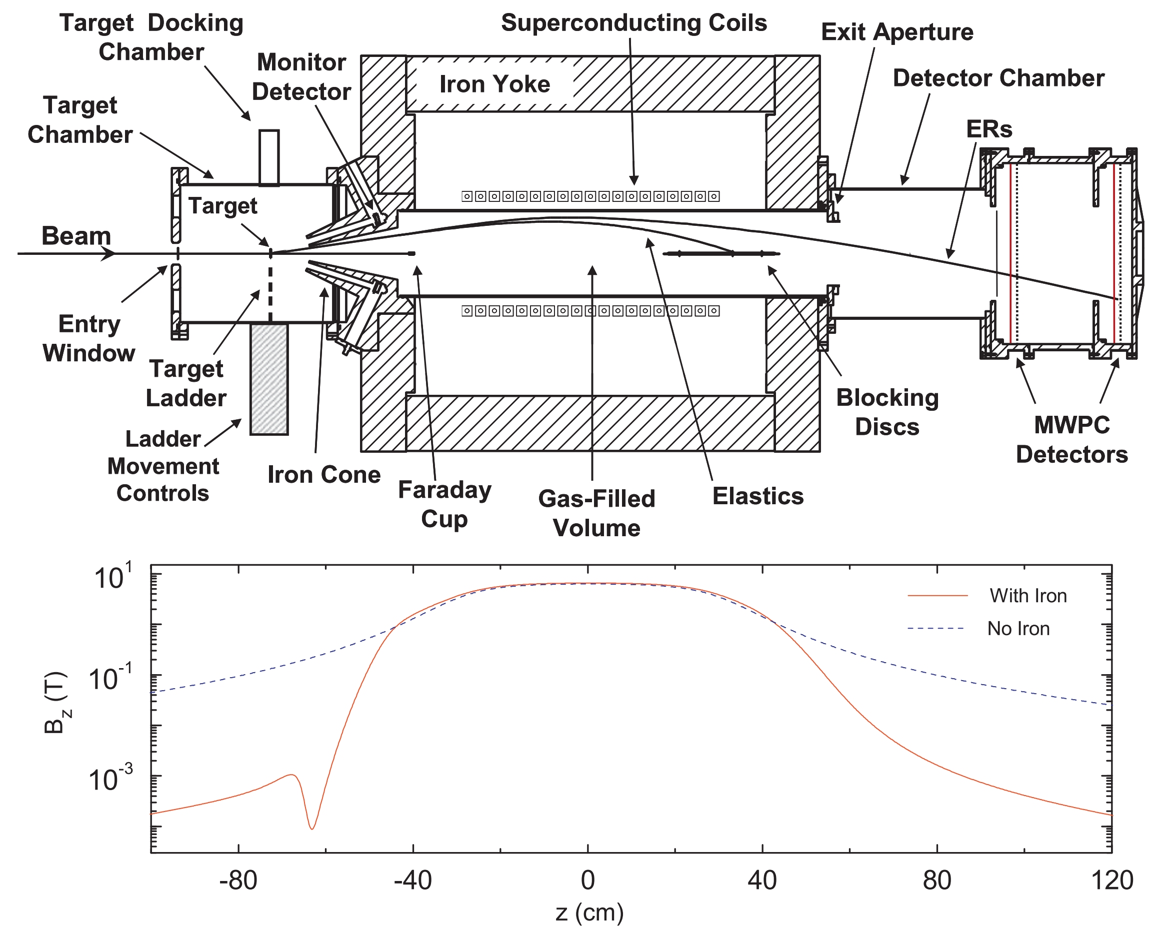


Fig. 1. External view of SOLITAIRE.



Nuclear Instruments and Methods in Physics Research A 614 (2010) 119–129

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in
Physics Research A

journal homepage: www.elsevier.com/locate/nima

SOLITAIRE: A new generation solenoidal fusion product separator

M.D. Rodríguez, M.L. Brown, M. Dasgupta *, D.J. Hinde, D.C. Weisser, T. Kibèdi, M.A. Lane [1], P.J. Cherry [2], A.G. Muirhead, R.B. Turkentine, N. Lobanov, A.K. Cooper, A.B. Harding, M. Blacksell, P.M. Davidson [3]

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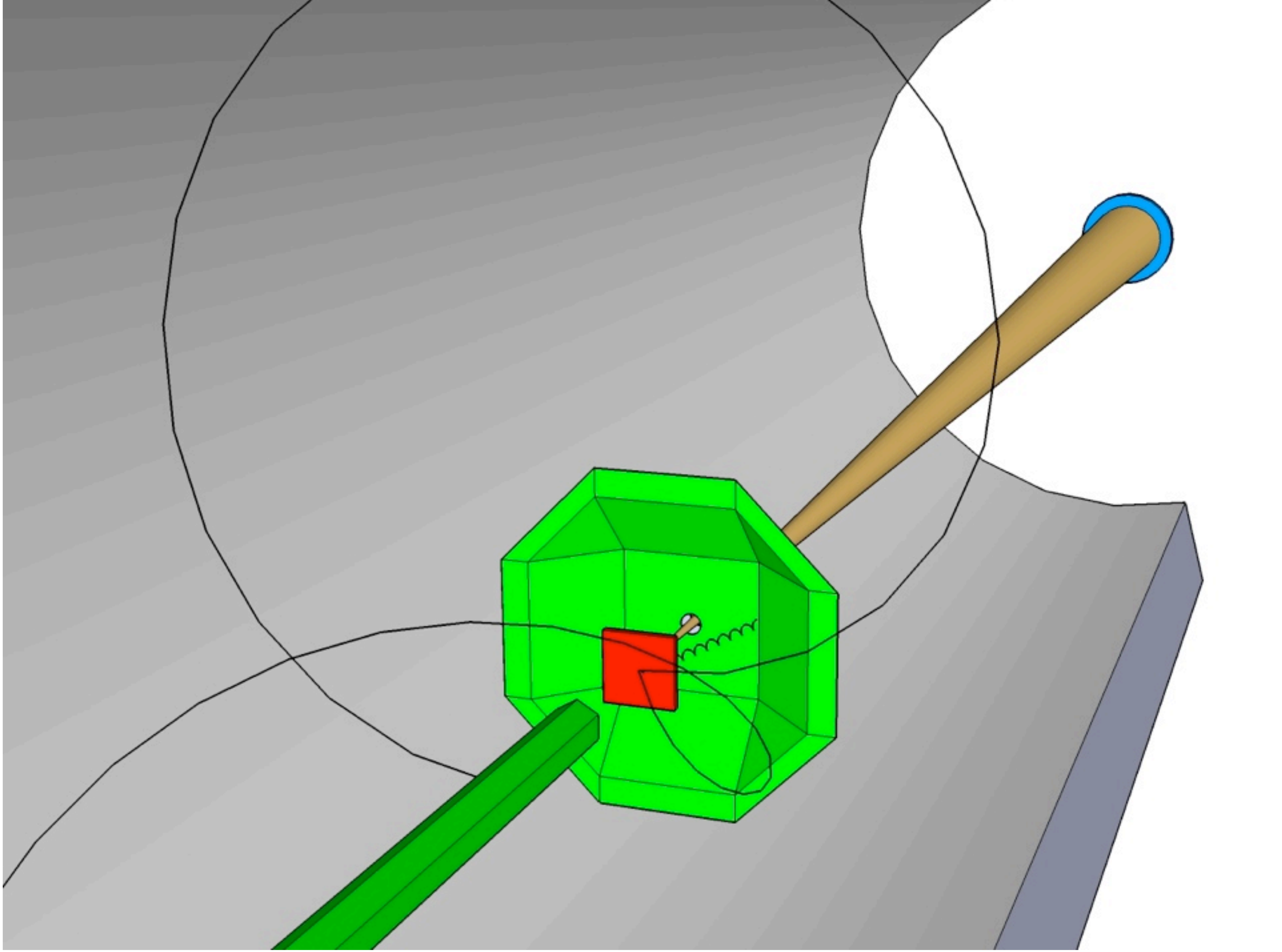
Thanks to Peter Butler, Ben Kay, Sean Freeman, Birger Back, Allan Wuosmaa, Lolly Pollacco, Alexandre Obertelli, Marc Labiche

Scintillator detectors and APDs in high magnetic field

Thoughts on gamma-detection for a future HELIOS

What would a gamma barrel look like?

- Why use gamma-ray detection?
  - Determine J^p of unknown states
  - Resolving doublets
  - Detect gamma rays in inelastic scattering
- Gamma array needs to be highly modular
  - Positioning limited by trajectory of ions
  - Some reaction types use only one hemisphere
  - Simulations needed to specify detector sizes
- Choice of scintillator material will heavily influence price/performance
- Could something like a PET barrel but with resolution be interesting?



APDs and silicon photomultipliers

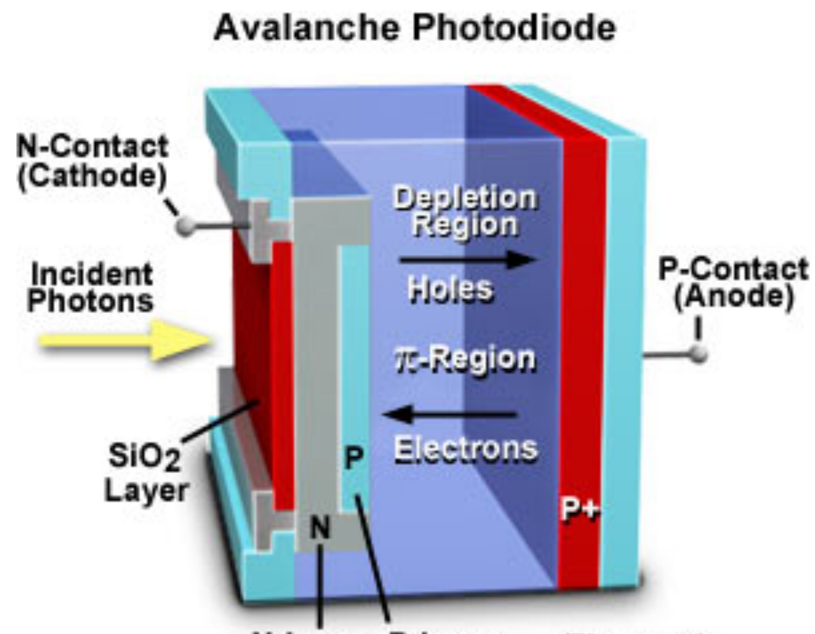
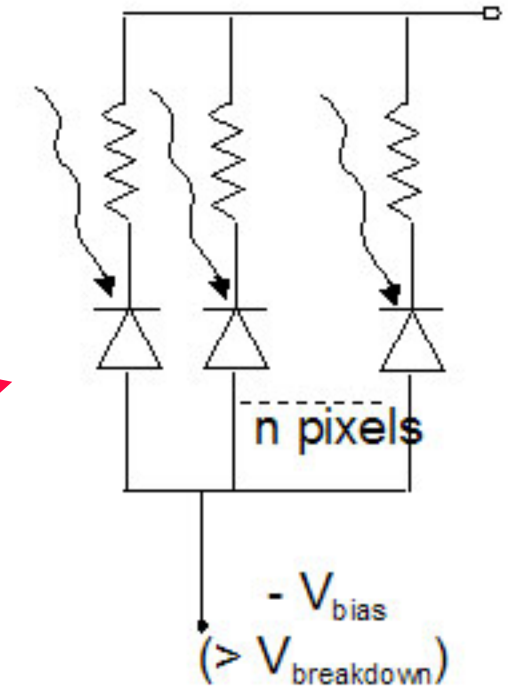
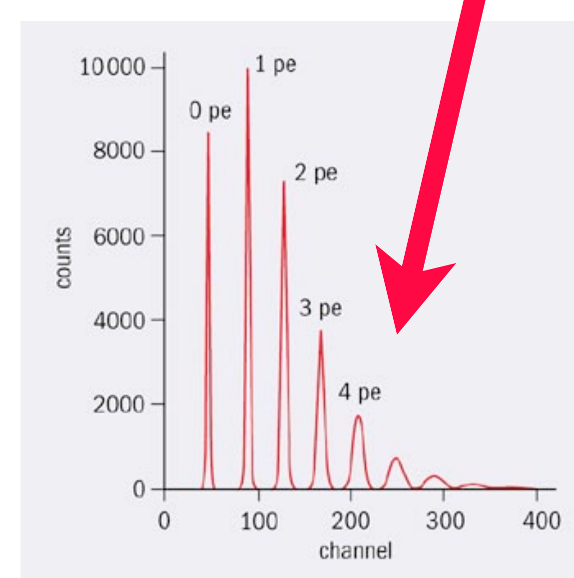


Figure 1

SiPM:

- matrix of n pixels (~1000) in parallel
- each pixel: GM-APD + $R_{quenching}$



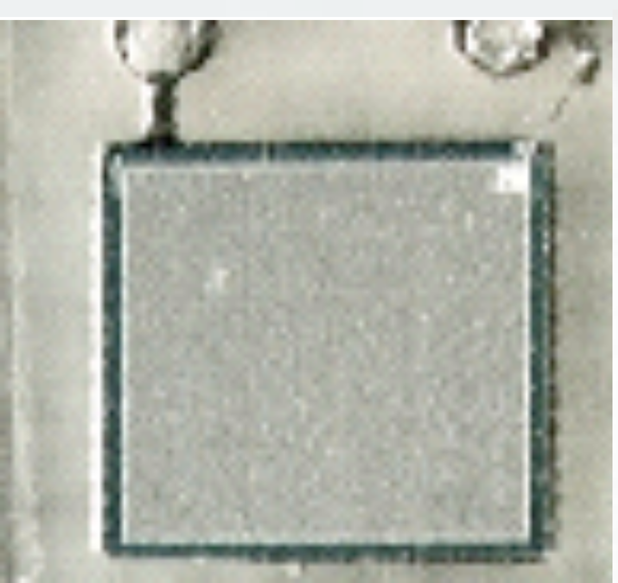
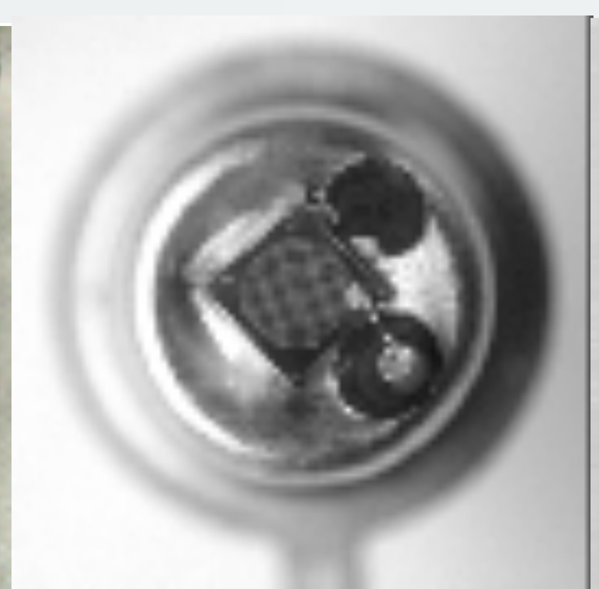
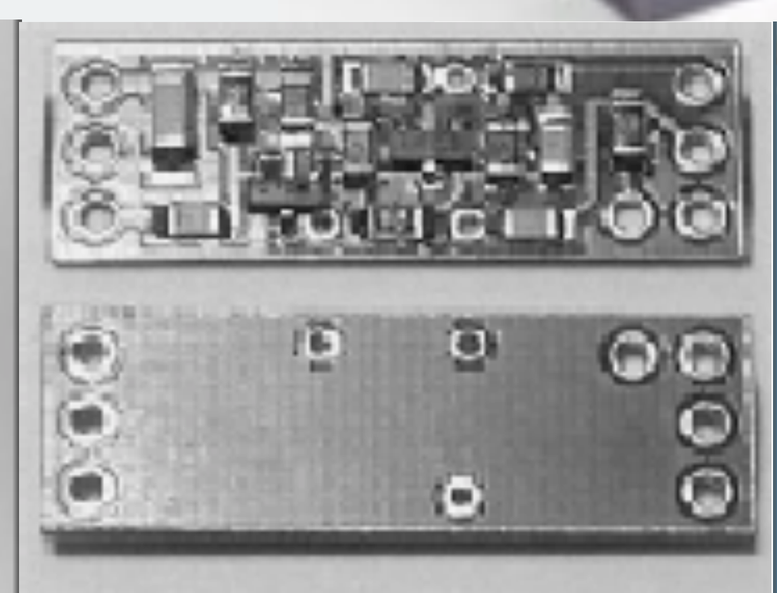
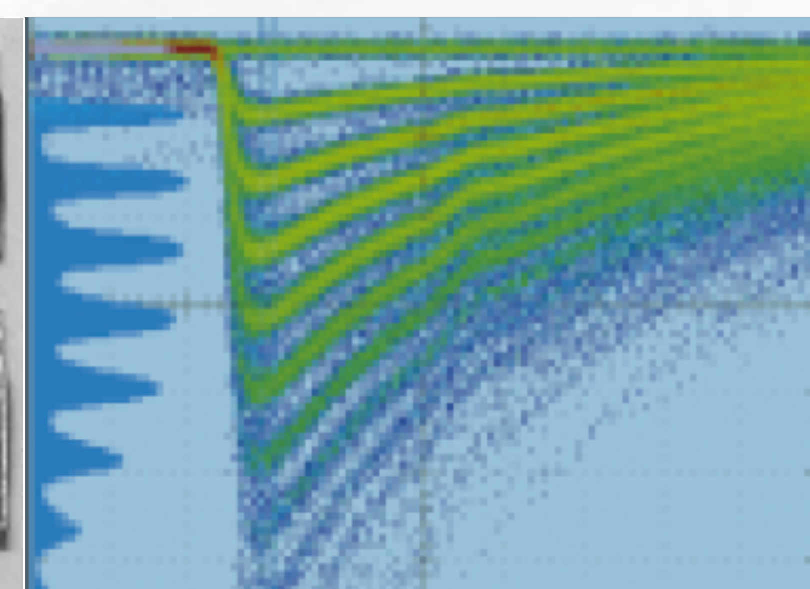


Silicon photomultipliers

- Potentially a generic replacement for photomultipliers
- Price needs to fall to reach competitive generic pricing but:
  - Works at low voltage
  - High output signal
  - Insensitive to magnetic fields unlike PMTs
  - Hence very interesting prospect for niche applications like simultaneous PET/MRI
- Challenges:
  - Small size - clever light collection needed
  - Gain stability with temperature
  - Timing resolution
  - Matching response to peak wavelength of scintillators

Devices available at York

- A variety of APD and SiPM (Si-photomultiplier).
  - SensL , Photonique (Advatech-UK) and Hammamatsu device
  - Various scintillators :
  - LaBr3 (Brilliance380), CsI(Tl), BGO, LYSO

SensL Silicon Photomultipliers

- Developments of large arrays of SiPMs
- Technology directed towards simultaneous PET and MRI
- Bespoke electronics and readout developed
- Suffer from high dark current
- Major gain instability with temperature
- Poor timing characteristics