SUPA

First SPES School on Experimental Techniques with Radioactive Beams

INFN LNS Catania – November 2011

Experimental Challenges
Lecture 1: The Toolbox

Tom Davinson

School of Physics & Astronomy

THE UNIVERSITY OF EDINBURGH

Course Objectives

To describe some of the techniques used with Radioactive Ion Beams (RIBs)
- emphasis on silicon detector systems

- The Toolbox
  - beam properties
  - diagnostics & ancillary detectors
  - silicon detectors & instrumentation

- Detector Systems
  - inverse kinematics
  - design constraints
  - current silicon detector systems

- Future Detector Systems
  - ASICs
  - HELIOS

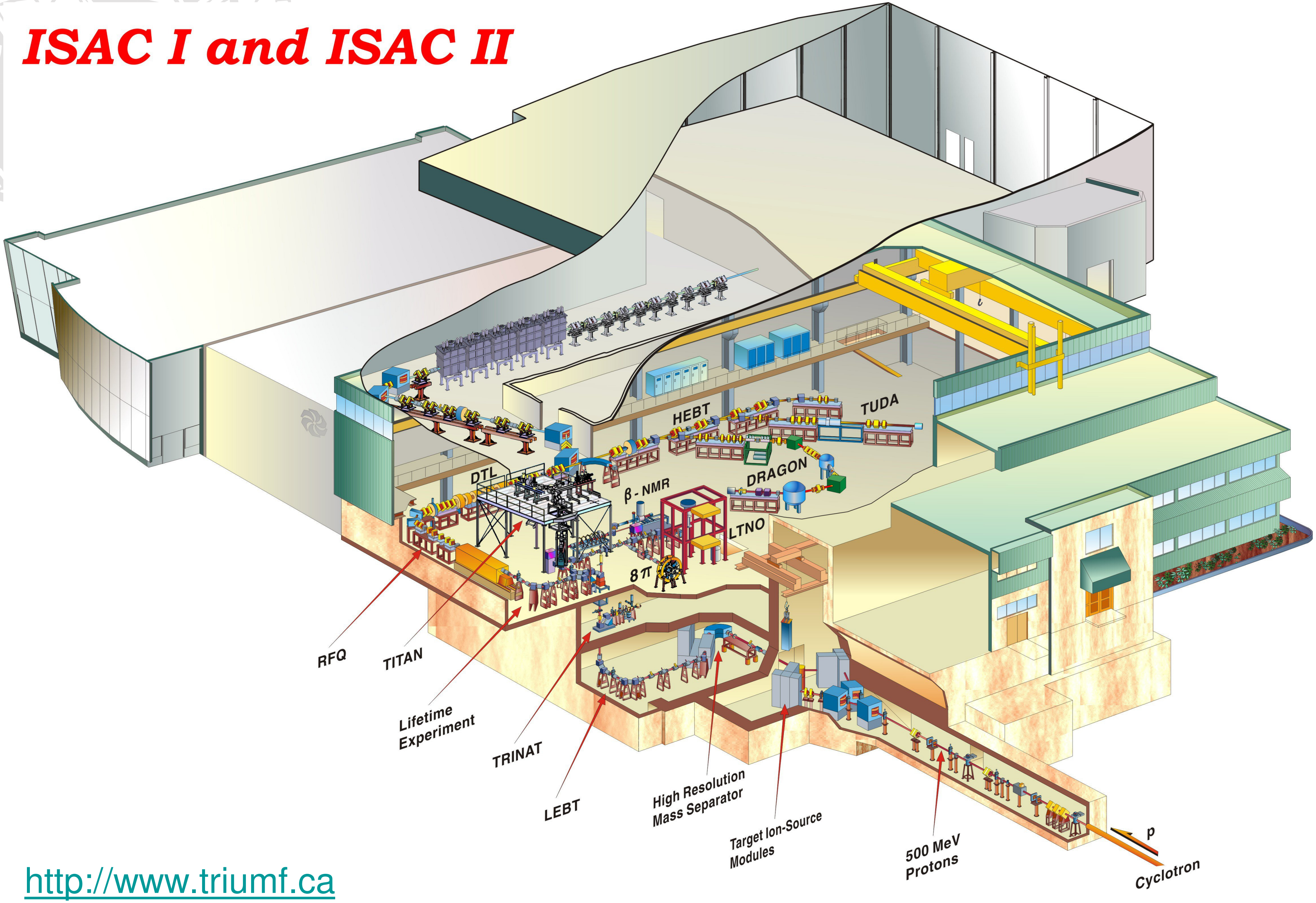
- Digital Signal Processing
  - introduction to concepts
  - hardware

Outline

- Discussion of properties of ISOL generated RIBs
  - tuning
  - intensity
  - beam emittance
  - isobaric purity
  - diagnostics
- Experimental methods
  - tagging
  - γ-rays
  - kinematics
  - stripping
- Detectors and Instrumentation

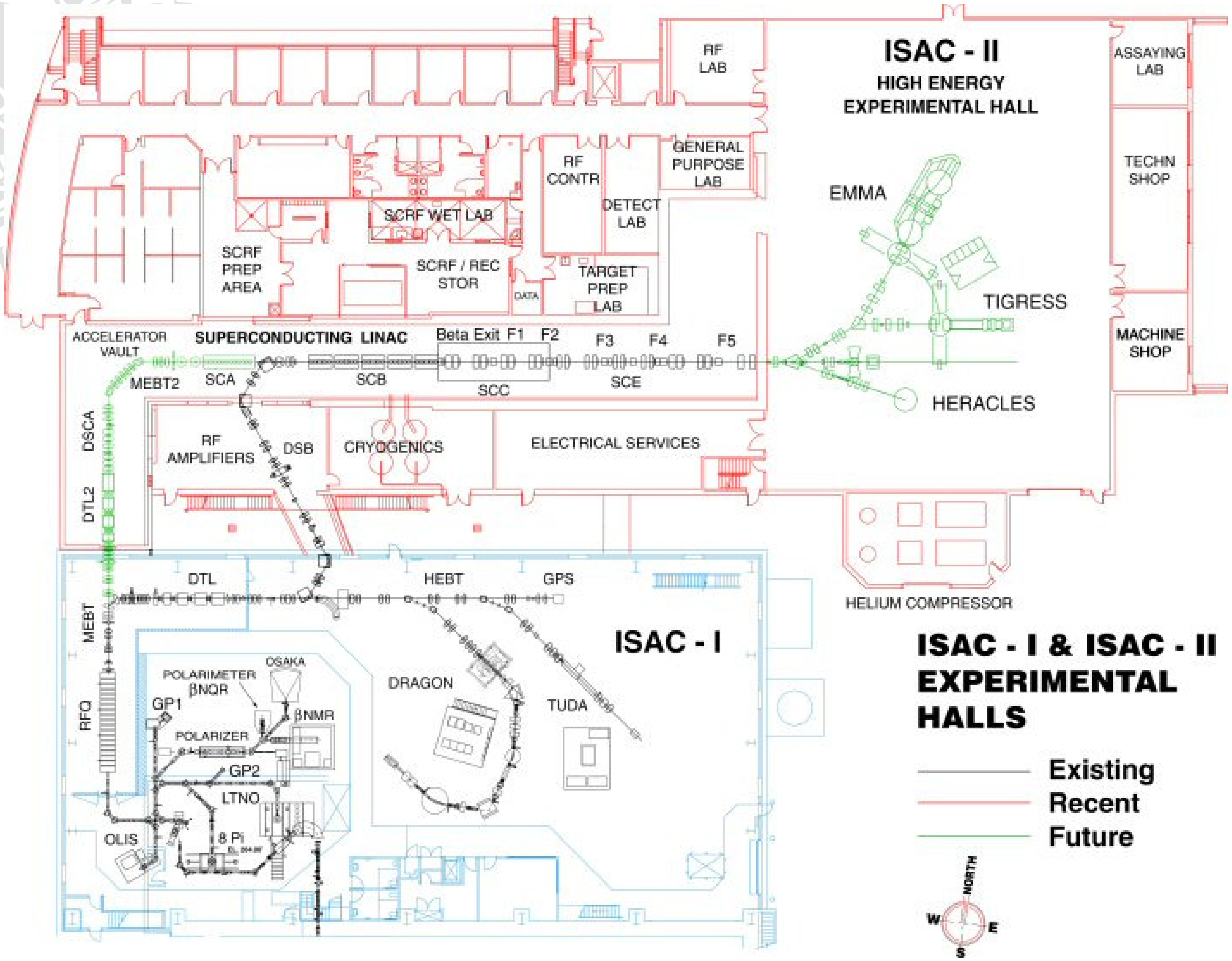
ISAC Facility

ISAC I and ISAC II



http://www.triumf.ca

ISAC Facility



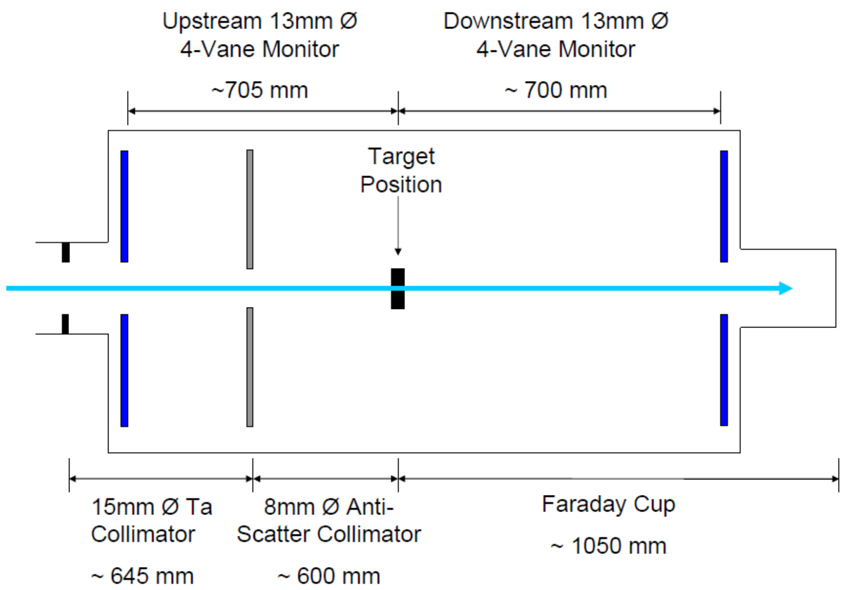
http://www.triumf.ca

ISAC-I & ISAC-II Beam Characteristics

• standard beam transverse dimension	~2mm
• normalised transverse emittance	0.2-0.3 π mm.mrad
• normalised longitudinal emittance	1.5 keV/u.ns
• ISAC-I energy spread	0.1% FWHM (Δt = 4ns @ 1.5MeV/u)
• ISAC-I time spread	1ns FWHM (ΔE = 0.4% @ 1.5MeV/u)
• ISAC-I max energy	1.53MeV/u (A/q=6) 1.90MeV/u (A/q=2)
• ISAC-II energy spread	0.2% FWHM
• ISAC-II max energy	6.5MeV/u (A/q=6) 16.5MeV/u (A/q=2)

http://www.triumf.info/wiki/exp-prog/index.php/ISAC_%28Isotope_Separator_and_ACcelerator%29

TUDA Beam Tuning



- Radioactive beam ~ 10^3-10^9/s (~ 0.16pfA - 0.16pnA)
  - typical FC noise ~ 0.25pA rms
- Initial tuning – stable isobar
  - >0.1enA using standard instrumentation
  - shield or remove detectors
- Optimise tune using aligned collimators
  - 10mm dia 100% transmission
  - 3mm dia >80% transmission
- Check beam spot with ZnS scintillator & CCTV camera
  - >10^5/s @ 2mm dia observable

Transverse Emittance

Illustrative figures from TUDA @ ISAC-II

Normalised transverse emittance $\beta\gamma\varepsilon_{xy}$ = 0.3π mm.mrad

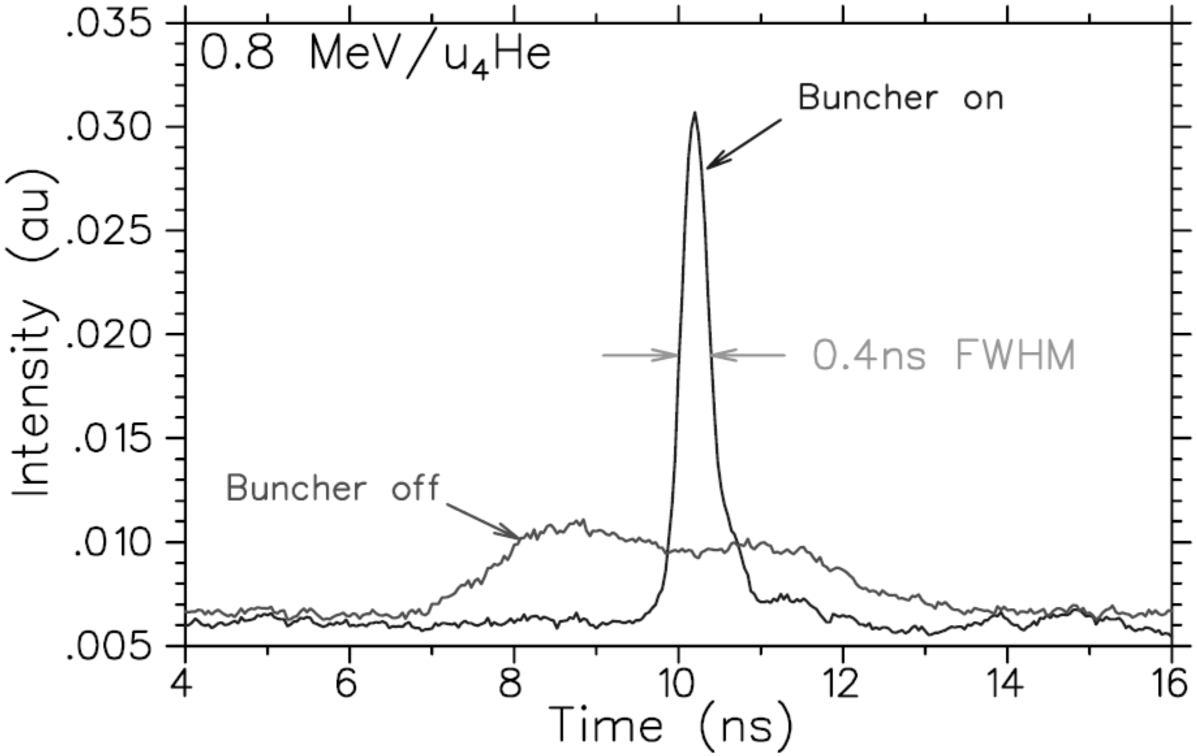
6MeV/u 26Al β = 0.113, γ ~1

emittance = 0.3 / 0.113 = 2.66π mm.mrad

r(cm)	*d*(mm)	*d*θ(mrad) *w*=0cm	*d*θ(mrad) 0.025cm	*d*θ(mrad) 0.5cm
10	1.03	7.27	7.38	26.0
20	1.45	5.14	5.18	13.5
50	2.30	3.25	3.26	5.96
100	3.25	2.30	2.30	3.40

r target-detector distance
d optimal beam spot size
*d*θ optimal angular resolution (@ optimal beam spot size)
w strip width

Longitudinal Emittance



Fast Faraday Cup – high beam currents required

ISAC-I Low/High β bunchers

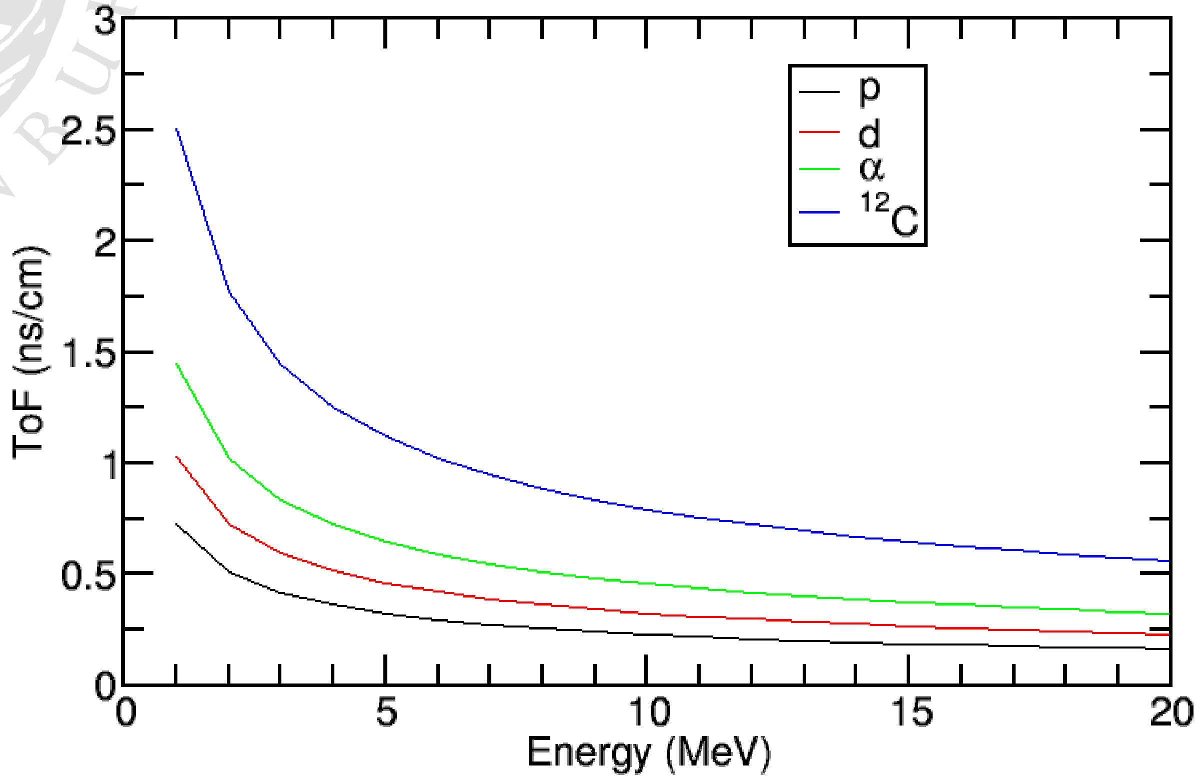
$\Delta E \Delta t$ = constant (within limits)

ISAC-II Can use final accelerator cavity

long drift length

R.E.Laxdal, NIM B 204 (2003) 400

Time of Flight



Example

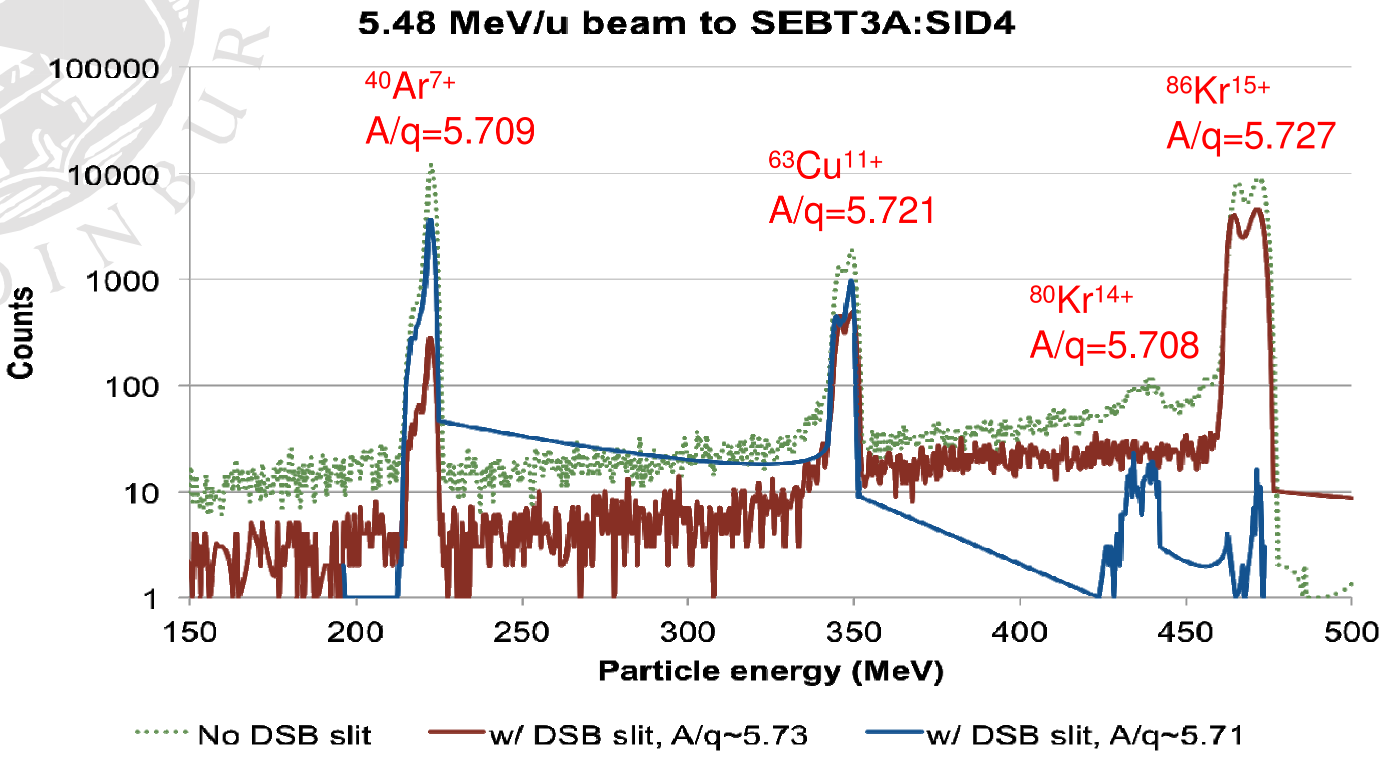
p-α discrimination @ 10MeV

~0.23ns/cm   10cm flight path => ~2.3ns

assume 4σ separation => σ = 2.3ns/4 = 0.57ns = 1.34ns FWHM

assume beam Δt = 1ns FWHM => detector Δt = 0.9ns FWHM

Beam Contaminants

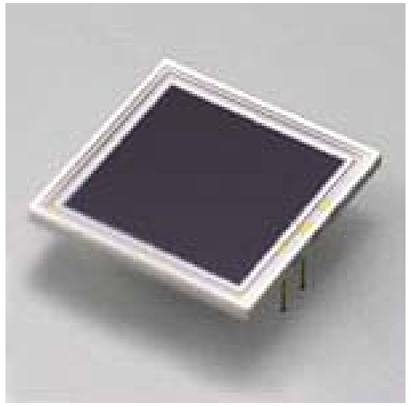


- Contaminants from OLIS multi-charge source (Supernanogan)
  $^{80}Kr^{14+}$, $^{86}Kr^{15+}$, $^{40}Ar^{7+}$, …
- *A/q* selection using ‘S-bend’ between ISAC-I DTL and ISAC-II
- In-beam Si detector diagnostic (with attenuation)

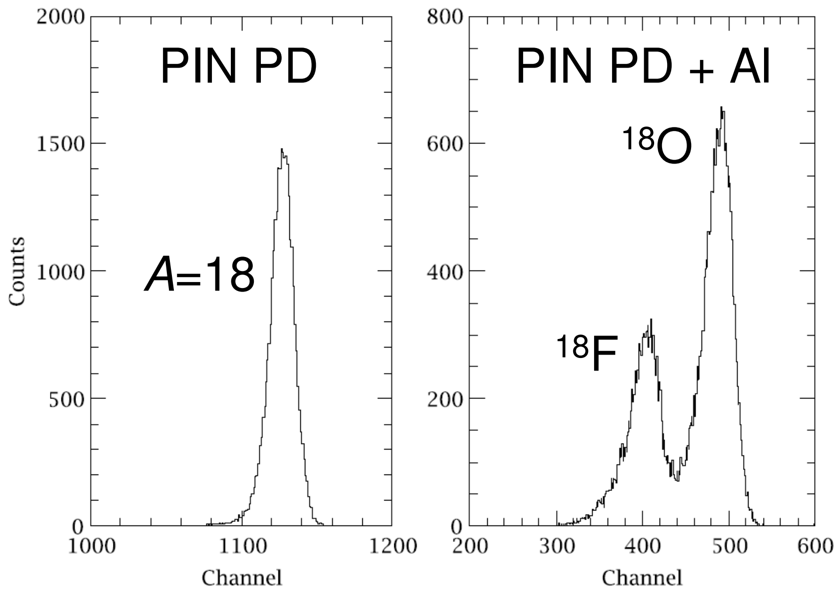
Courtesy Colin Morton, TRIUMF

PIN Photodiodes

http://jp.hamamatsu.com/products/sensor-ssd/pd041/pd054/pd058/index_en.html



Hamamatsu Si PIN photodiode (unsealed – no epoxy)
area 10mm x 10mm – 28mm x 28mm
thickness 0.3mm
dead layer ~ 0.5µm
cost ~ €120 (10mm x 10mm)



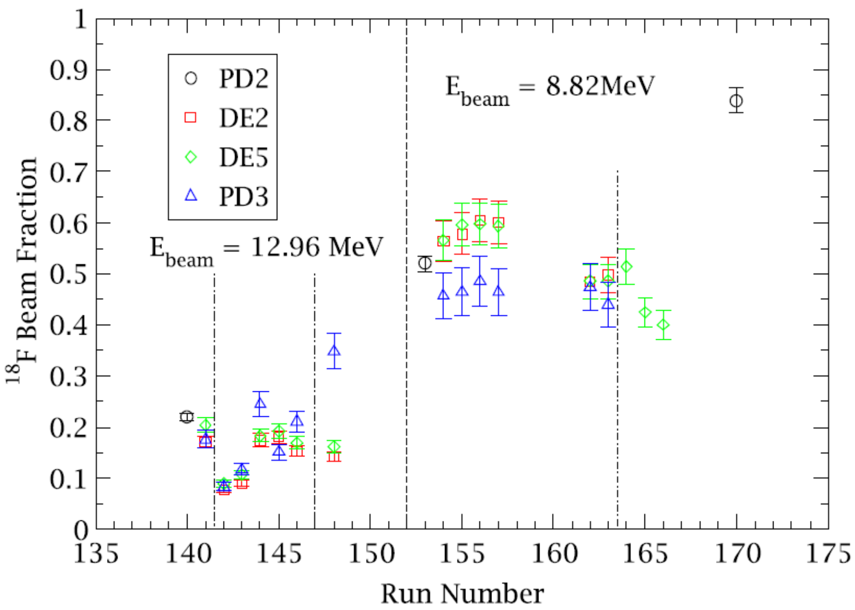
target ladder mounted PIN PDs with/without Al degrader

beam attenuators required to limit rates ~10^3/s

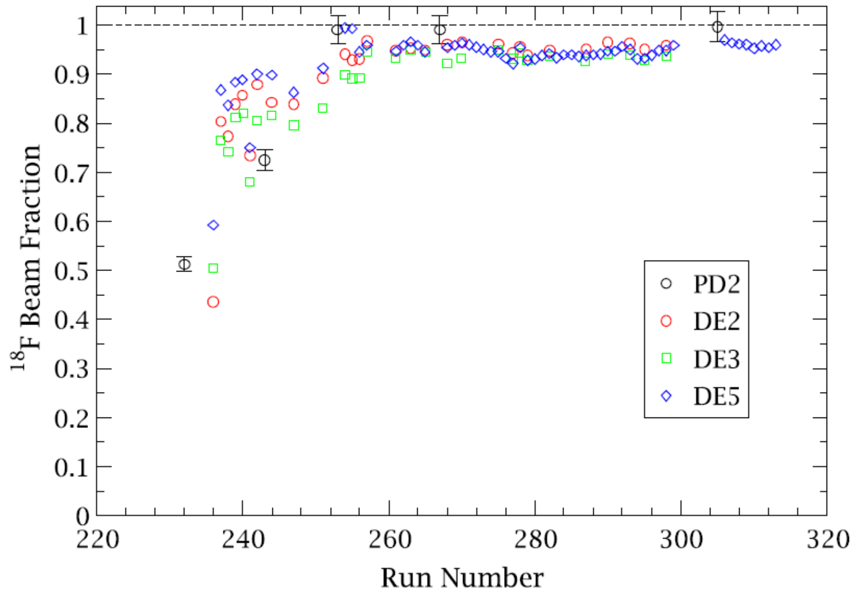
8.82MeV ^{18}F+^{18}O
C.E.Beer, PhD thesis, University of York, 2010

Time/history dependent beam purity

12.96MeV & 8.82MeV



6.66MeV & 4.75MeV



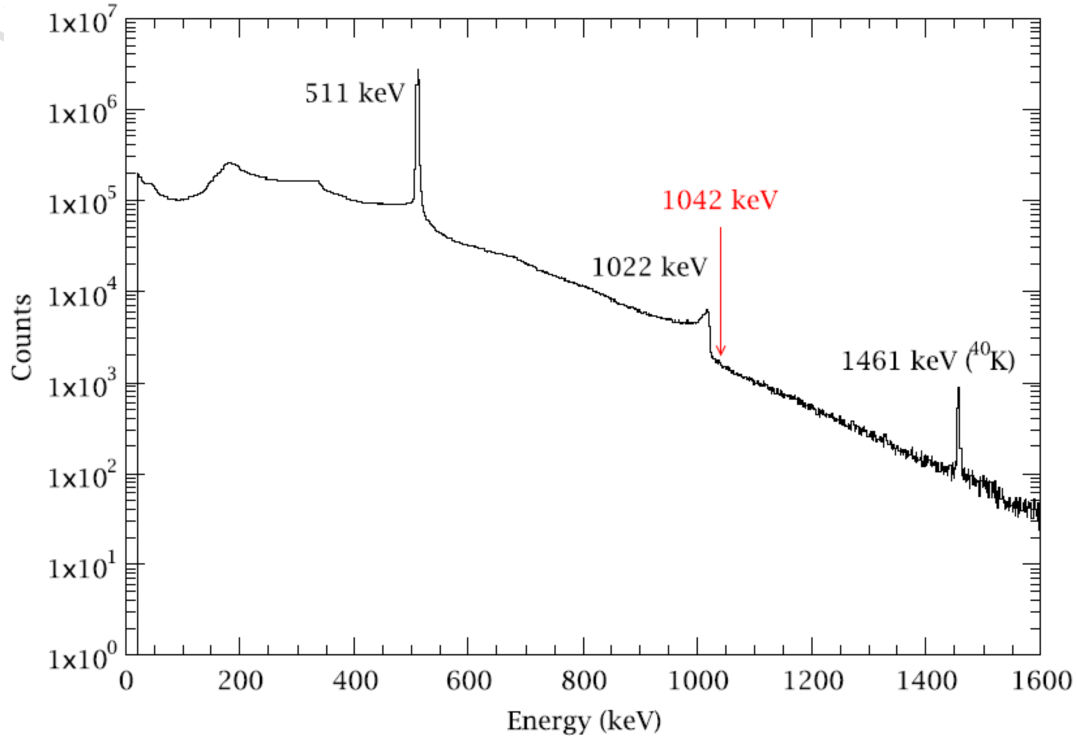
Beam purity can vary dramatically with

- time
- operational history of production target & ion source

C.E.Beer, PhD thesis, University of York, 2010

Gamma-ray Detection

Characteristic γ-ray decays can be used to confirm what *is* (or *is not*) in the beam

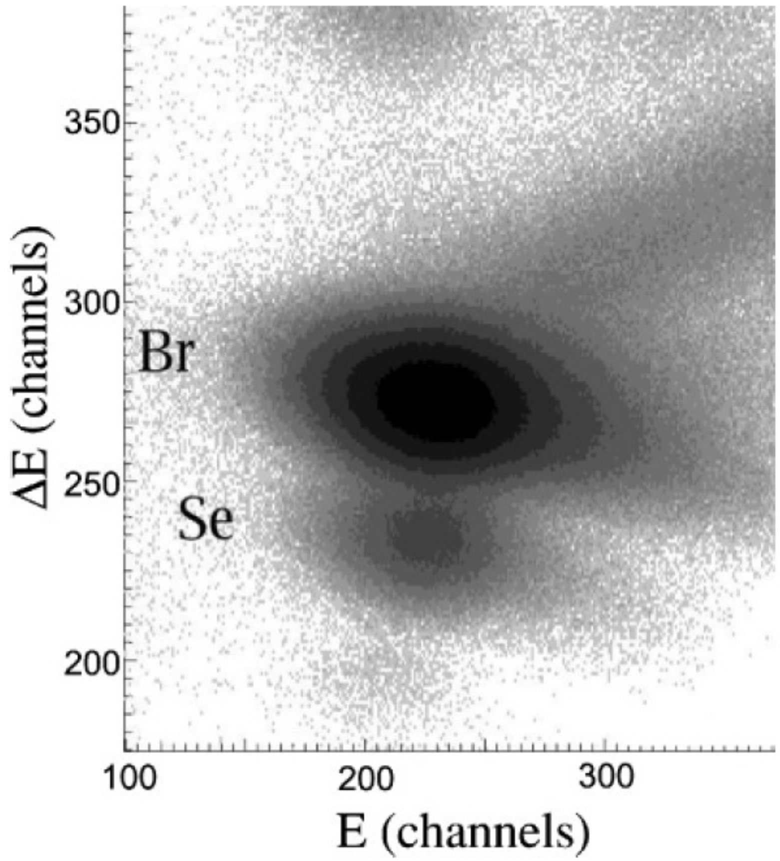


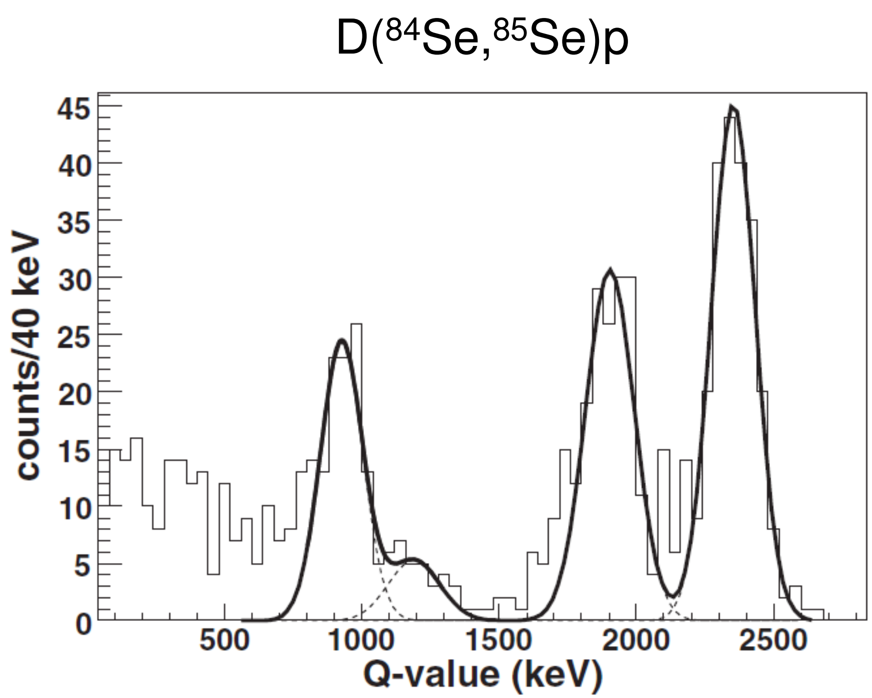
HPGe detector @ TUDA Faraday Cup

6.66MeV ^{18}F - ^{18}Ne beam fraction <0.05%

C.E.Beer, PhD thesis, University of York, 2010

Gas Ionisation ΔE-E Detector

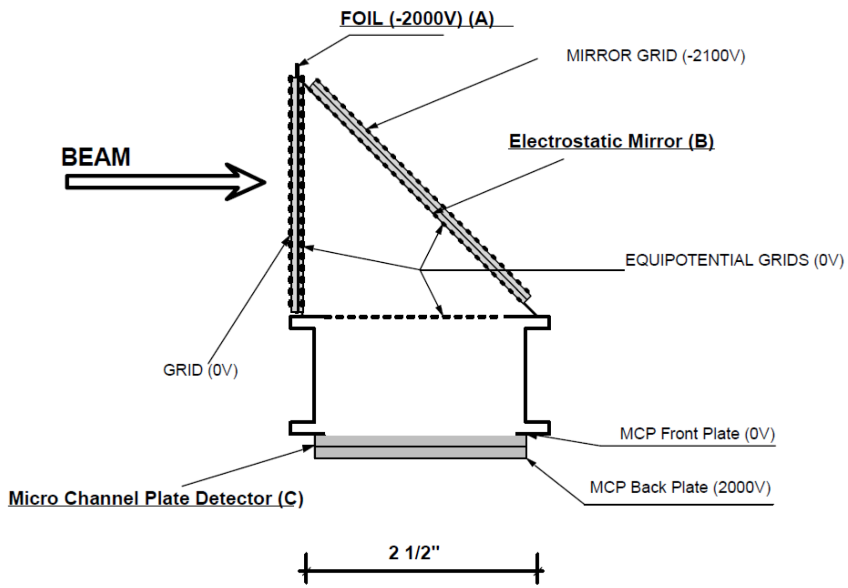


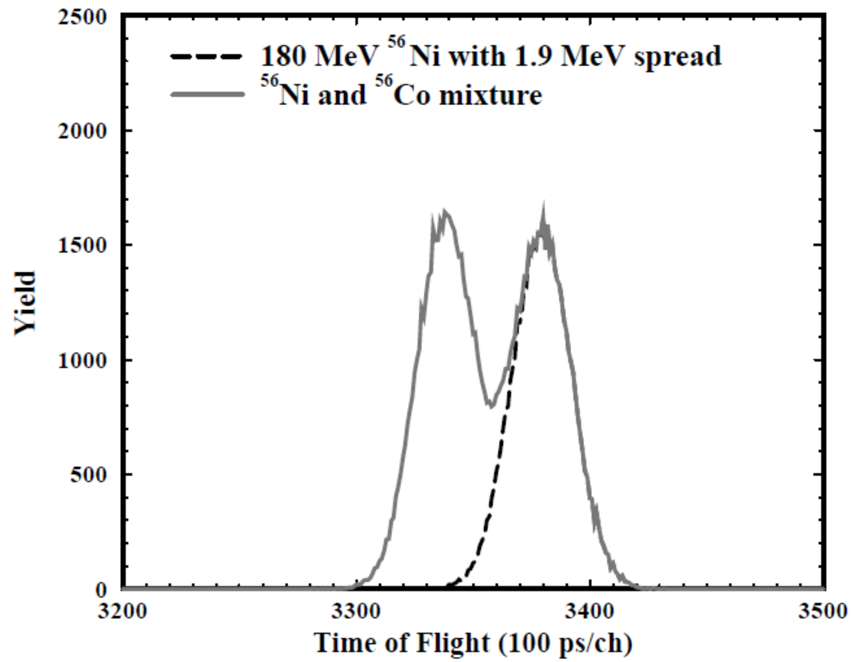


Beam current 9×10^4/s A=84 isobars (93% ^{84}Br, 7% ^{84}Se)
Coincident p – ^{85}Se detection
zero degree ΔE-E gas ionisation counter for ^{85}Se

J.S.Thomas *et al.*, Phys. Rev C76 (2007) 044302

Fast Tagging

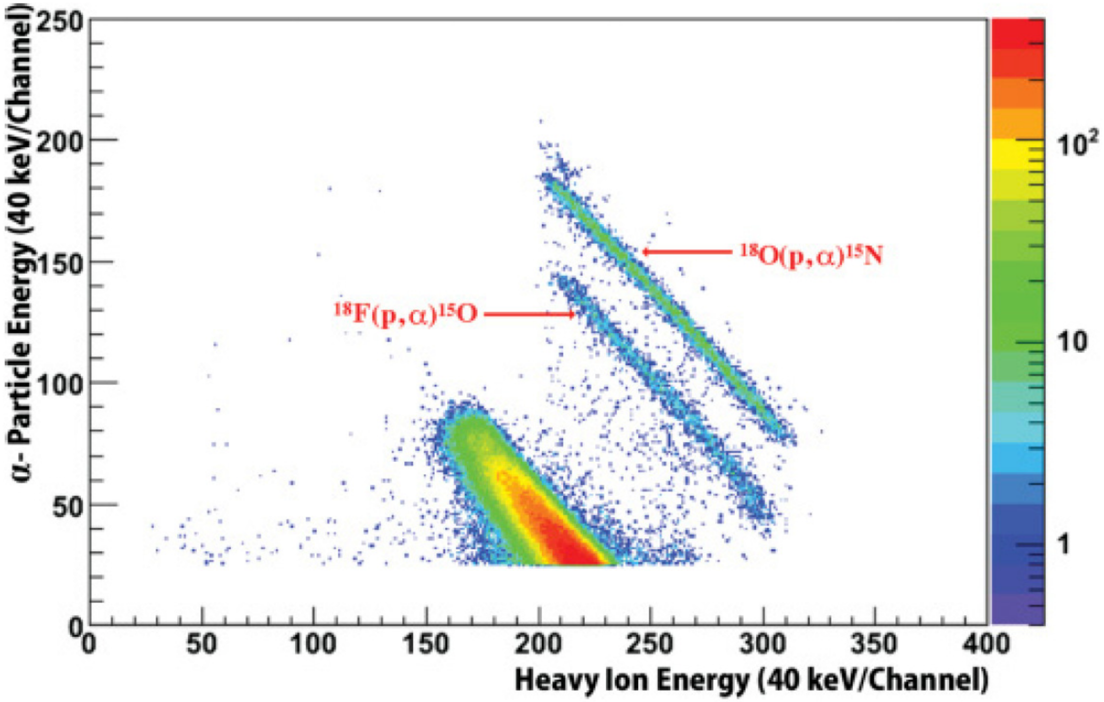




In-beam detector - downstream or upstream/downstream
Thin foil – minimise energy loss and straggling, multiple scattering
(Relatively) high rates ≤10^7/s

D.Shapira *et al.*, NIM A490 (2002) 159

Kinematically Complete Measurements



C.E.Beer *et al.*, Phys. Rev. C 83 (2011) 042801(R)

Select reaction *Q*-value

For high energy reactions heavy fragment very forward (~0°)
spectrometers/separators
fast, rad-hard detectors (MCPs, Diamond? …)

Stripping

- fully-stripped proton-rich beams
  e.g. ^{17}F & ^{18}F ~2-4MeV/u with some loss of intensity

- beam purification of higher *Z* beams possible for
  >5MeV/u
  lighter contaminants (cf. isobars)

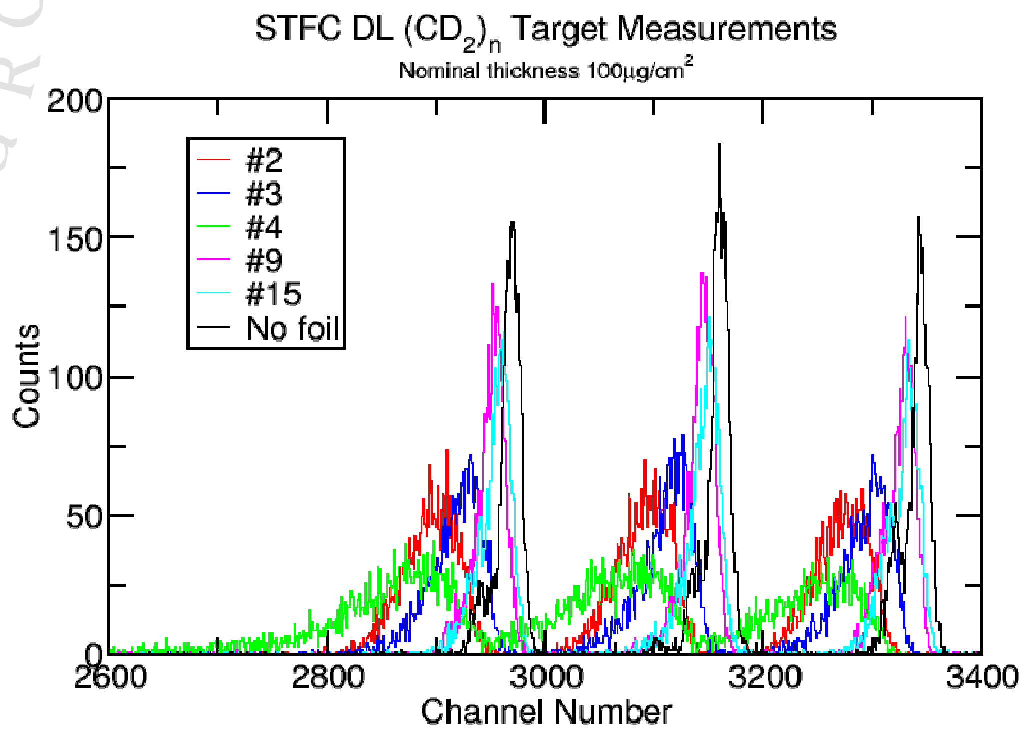
- selection by dipole & exit slits immediately upstream of experimental area

Example

From earlier example of 5.48MeV/u ‘cocktail’ beam from ISAC CSB

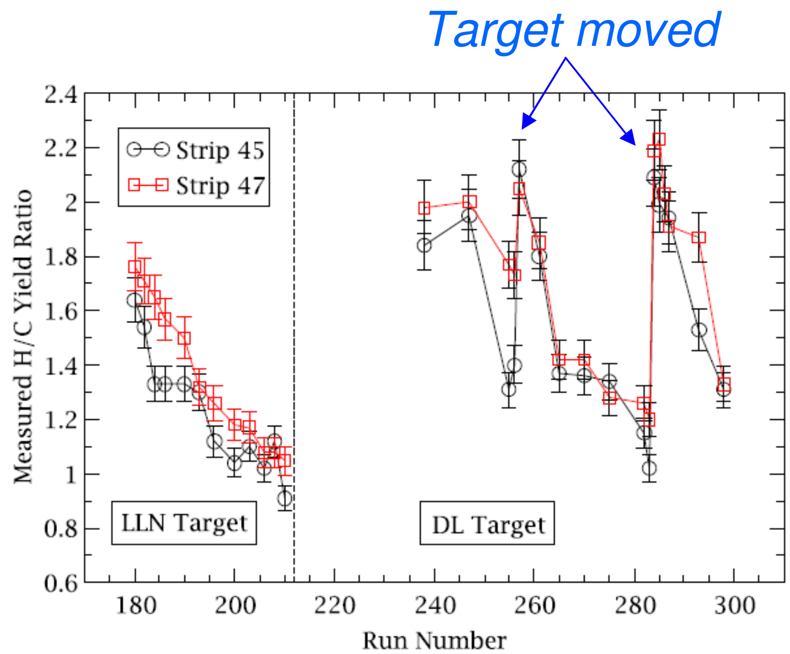
			A/q	~90% range
220MeV $^{40}Ar^{7+}$	~44%	$^{40}Ar^{16+}$	2.500	(2.353 - 2.667)
350MeV $^{63}Cu^{11+}$	~31%	$^{63}Cu^{25+}$	2.520	(2.333 - 2.739)
470MeV $^{86}Kr^{7+}$	~27%	$^{86}Kr^{30+}$	2.867	(2.688 - 3.185)

(Deuterated) Polyethylene Foils



- determine thickness **and** uniformity before use
- all targets appeared identical by visual inspection
- only 2 of 15 foils (#9 & #15) showed increases in peak widths consistent with the calculated energy straggling corresponding to actual foil thickness
- important to monitor H (or D) content as function of integrated beam dose for high intensity RIBs

Target Deterioration



Beam ~5x10^6/s 4.75MeV 18F + ~50µg/cm^2 $(CH_2)_n$
Beam spot diameter ~ 1mm dia
Effect of ~100h beam exposure shown

H:C ratio decreases with integrated beam dose

C.E.Beer, PhD thesis, University of York, 2010

Silicon Detector Technology

Current Technology

Single, double-sided, resistive strip

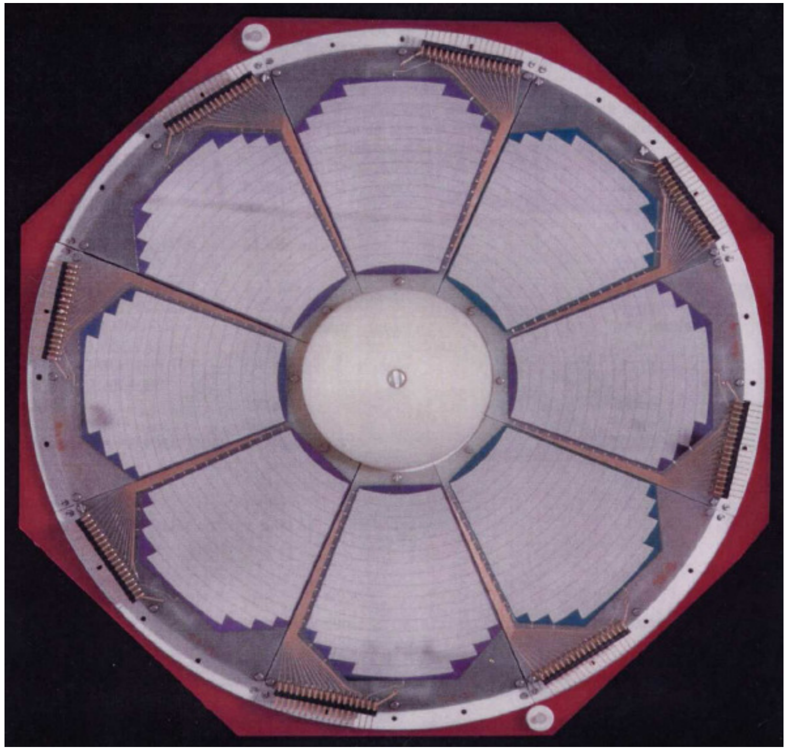
Thin Junctions
p^+ 0.1μm *cf.* ~ 0.4μm

Integrated Components
Coupling Capacitors
Bias Resistors

3” & 4” Wafers
- Thicknesses ~ 20 – 1500μm
- Max. Area ~ 70cm^2

6” Wafers
- Thicknesses ~ 200 – 1000μm
- Max. Area ~ 160cm^2

Manufacturers – MSL, Canberra, Hamamatsu, SI etc.



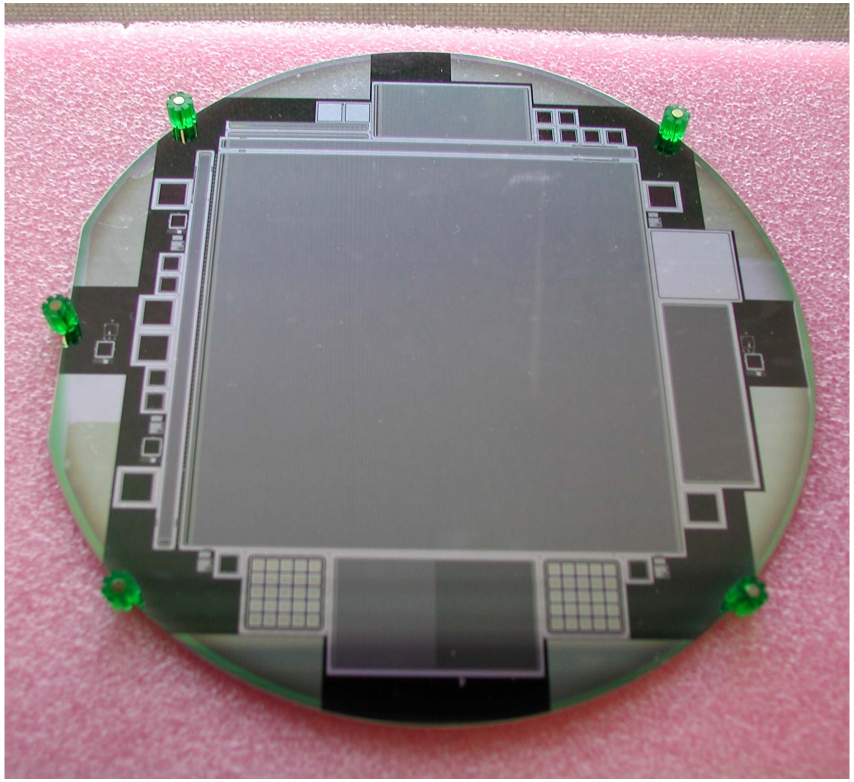
MSL type YY1 (LEDA)
- d.c. single sided
- 8 sectors, 16 strips/sector
- Strip Pitch 5mm
- Area 370cm^2

NIM A454 (2000) 350

Silicon Detector Technology contd.

GLAST Large Area Telescope (LAT)

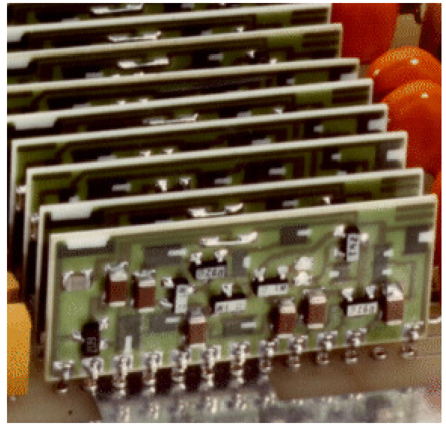
- Layers of silicon detectors interleaved with heavy-metal converters
- >20MeV γ-rays
- Area ~80 m^2
- ~10^6 channels
- integrated a.c. coupling and bias resistors
- >2000 detectors from Hamamatsu
  Very high quality:
  - Leakage current < 2.5 nA/cm^2
  - Bad channels < 1/10,000
  - Full depletion < 100 V.

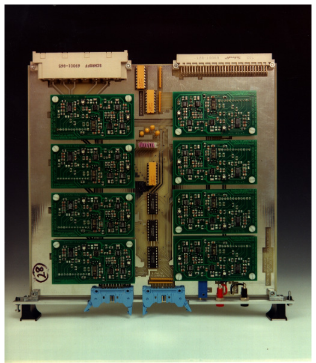


8.95 cm square Hamamatsu-Photonics SSD before cutting from the 6-inch wafer. The thickness is 400 microns, and the strip pitch is 228 microns.

Instrumentation

- Silicon strip detectors
  - mature, well established and accessible technology
- Segmentation provides position information
  - each strip an independent detector
    - per strip instrumentation
      - many channels of instrumentation required
- Current Nuclear Physics instrumentation
  - spectroscopy performance
    - dynamic range, stability, INL, DNL etc.
  - moderate system size (100s of channels)
    - strip pitches ~ several mm
  - high power density
    - ~ W/channel
  - high per channel cost (~$500/channel)
    - incl. preamplifier, amplifier, discriminator, logic, ADC, TDC etc.





custom Edinburgh/RAL RAL108, RAL109
NIM A288 (1988) 212 & 245

commercial Mesytec, Cremat, Swan, Clear-Pulse, Amptek, Endicott Interconnect (eV Products) etc.

The Limits To Energy Resolution

Silicon detector energy resolution

$$\Delta E^2 = \Delta E_s^2 + \Delta E_{stats}^2 + \Delta E_{coll}^2 + \Delta E_e^2$$

ΔE_s (keV FWHM Si) = $10.07\, z\, x^{1/2}$	energy straggling (Bohr estimate[1])
ΔE_{stats} (keV FWHM Si) = $1.519\, E^{1/2}$	statistics
ΔE_{coll} (keV FWHM) = $0.7\, z^{1/2} A^{4/3}$ [2]	nuclear collisions
ΔE_e (keV FWHM)	electronic noise

z - ion atomic number, *A* - ion atomic mass number, *x* - detector dead layer (μm) and *E* - particle energy (MeV)

Assume ΔE_e = 10keV FWHM, x = 0.05μm (~0.7μm is more typical)

ion	E	ΔE_s	ΔE_{stats}	ΔE_{coll}	ΔE_e	ΔE
p	1	2.3	1.5	0.7	10.0	10.4
α	5.5	4.5	3.6	6.3	10.0	13.2
^{12}C	120	13.5	16.6	47.1	10.0	52.7
^{58}Ni	580	63.1	36.6	831.5	10.0	834.7

[1] alternatively use SRIM/SSSM (http://www.srim.org)

[2] J.Lindhard & V.Neilson, Phys. Lett. 2 (1962) 209

An Ideal Facility?

Accelerator

- high resolution separator
  - beam purity
- beam emittance
  - transverse emittance – angular resolution
  - longitudinal emittance – beam time & energy resolution
- beam attenuators (x10^2-10^5)
  - in-beam diagnostics
- HEBT dipole & exit slits
  - high energy stripping

Diagnostics

- collimators
- FC
- FFC
- scintillator + CCTV
- Si PIN PD (+ degrader foil)
- other detectors
  - HPGe, ionisation, MCP, Bragg etc
  - *in-beam, out-of-beam, real-time …*