The Montreal X-17 Project

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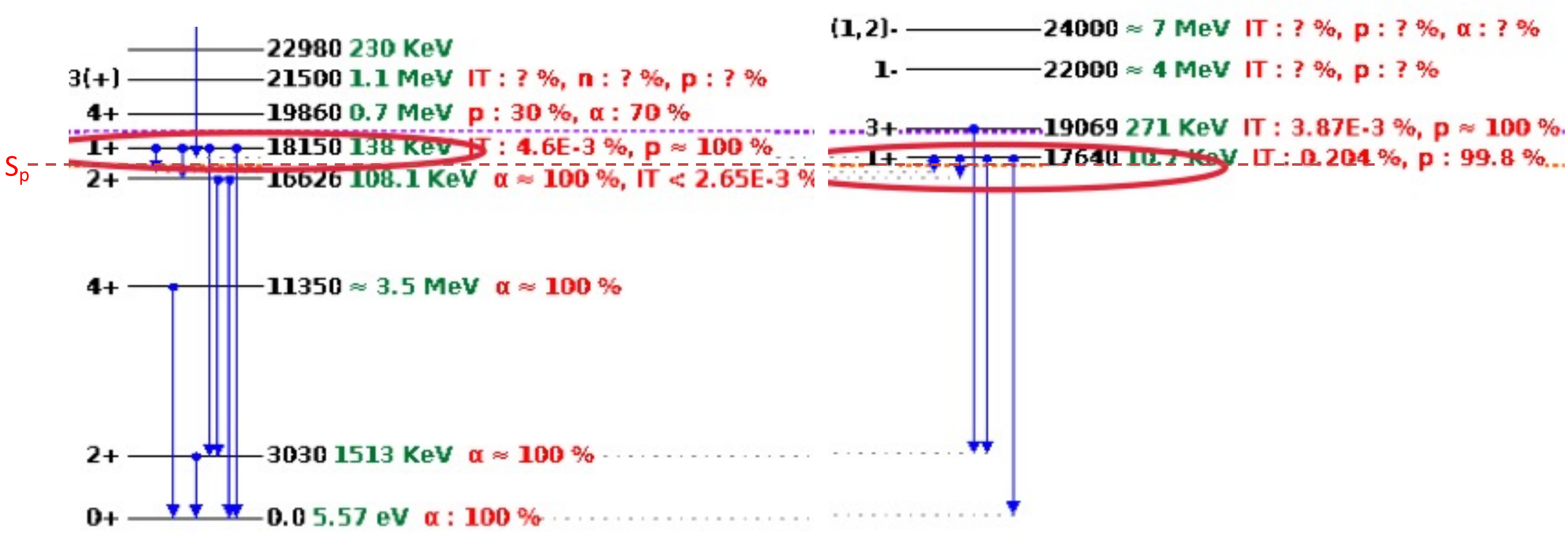
Main goals:

- Verification of ATOMKI results
- Start with existing equipment and home-made electronics
- Increase acceptance → 0.95 x 4π
- Improve statistics & angular resolution
- Eventually extend to other nuclei: ^{10}B , ^{12}C, ^{4}He

^{8}Be levels



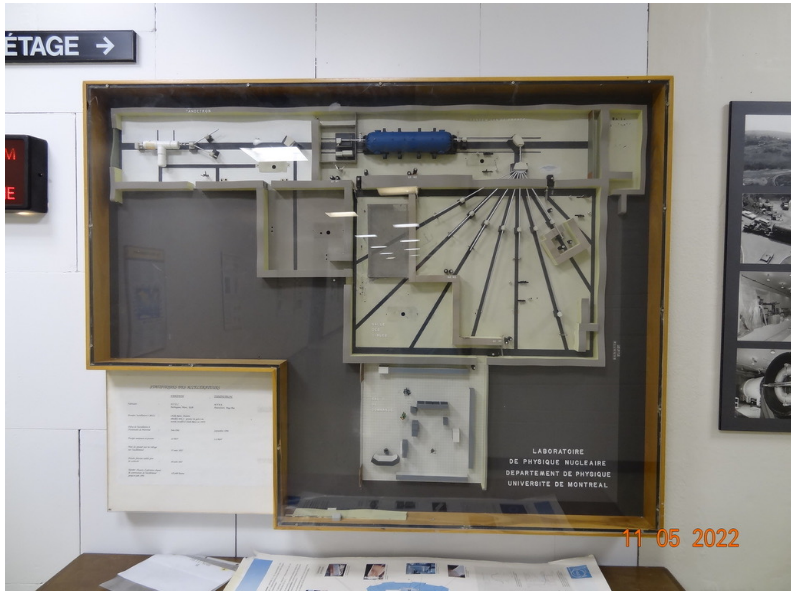
18.15 MeV resonance (M1: $1^+ \to 0^+$)

- IPC coefficient: 3.9×10^{-3}
- $\frac{B(X\to e^+e^-)}{B(^8Be^*\to\gamma)} = 5.8 \times 10{-}6$ (Atomki)

$$\frac{B(X\to e^+e^-)}{B(^8Be^*\to e^+e^-)} = 1.5 \times 10^{-3}$$

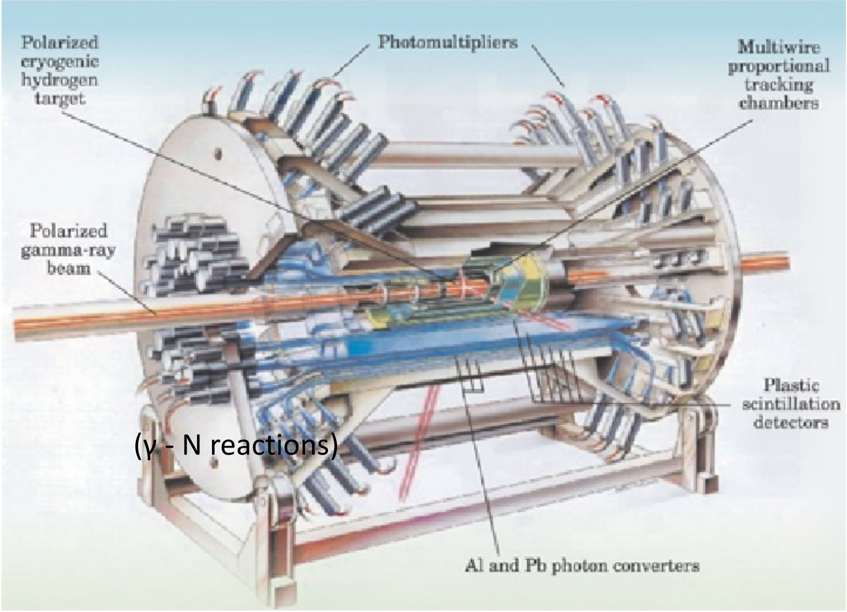
UdeM 6 MV Tandem Van de Graaff Facility

- 2 μA proton beam on target (possibly up to 20 μA)
- E - resolution of 2 keV for E_p = 0.4 - 1 MeV



The Montreal X-17 Project

- Use parts of the DAPHNE experiment (Saclay/Mainz*)
- Tracking MWPC chamber & 16 scintillators (NE102A)
- Scints & MWPC from U. Mainz → now @ Montreal
- Phototubes and some ADC/TDC's borrowed from TRIUMF

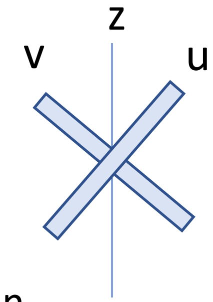


Large solid angle coverage → 0.95 x 4π

*Many thanks to L. Doria & U. Mainz!

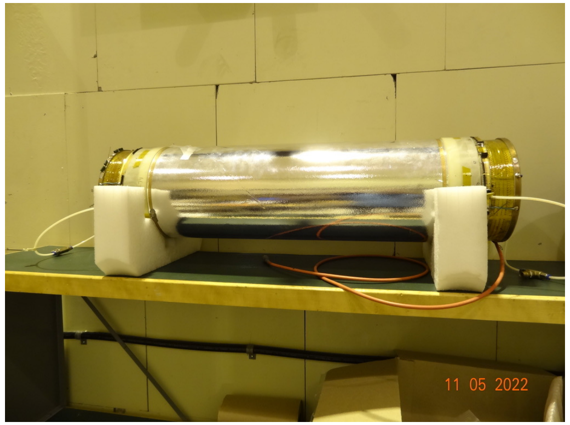
The DAPHNE Tracking Chamber

- ID 12 cm / OD 14 cm - Length 36 cm
- Cathode-anode distance: 4 mm;
- 192 Anode wires: 20 µm diam; spacing: 2mm
- 60/68 cathode strips at 45^0 w.r. to wires; width 4mm
- Gas mixture: « magic gas »*

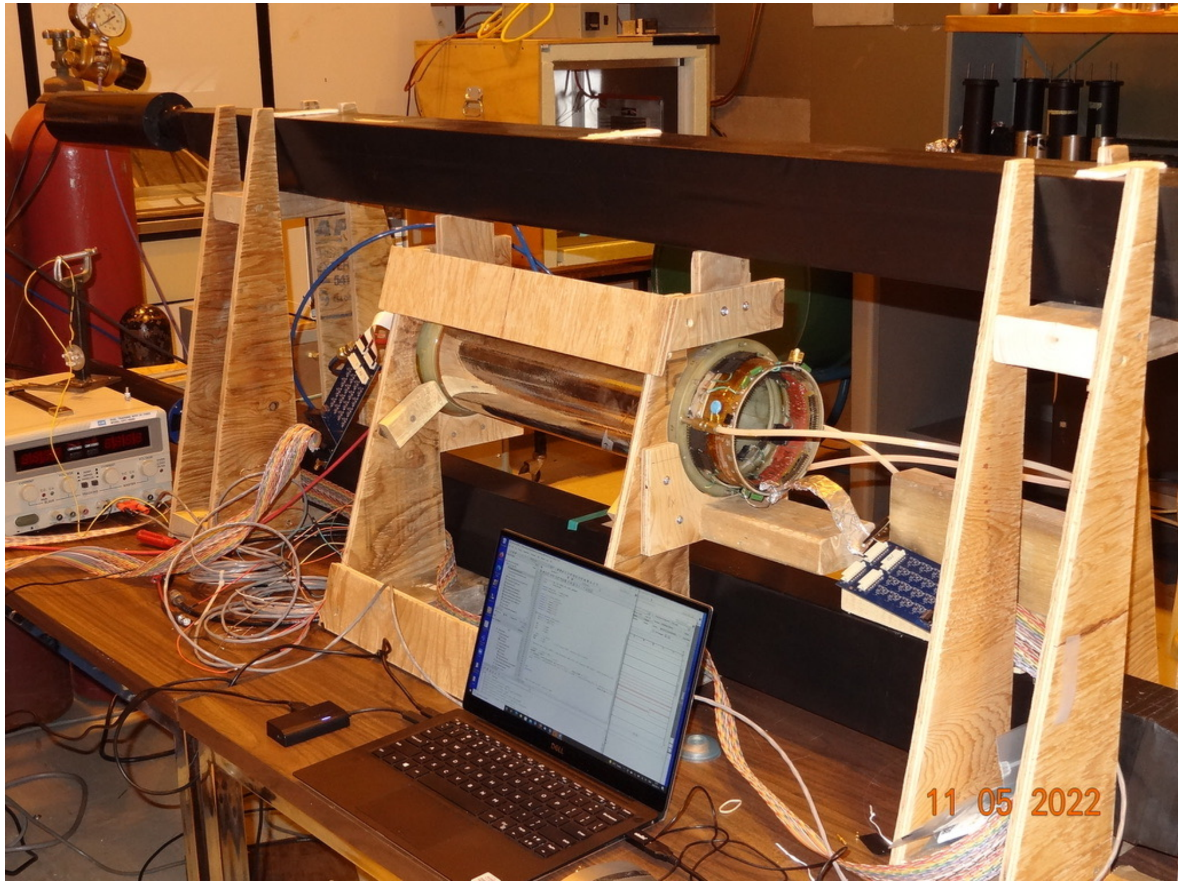


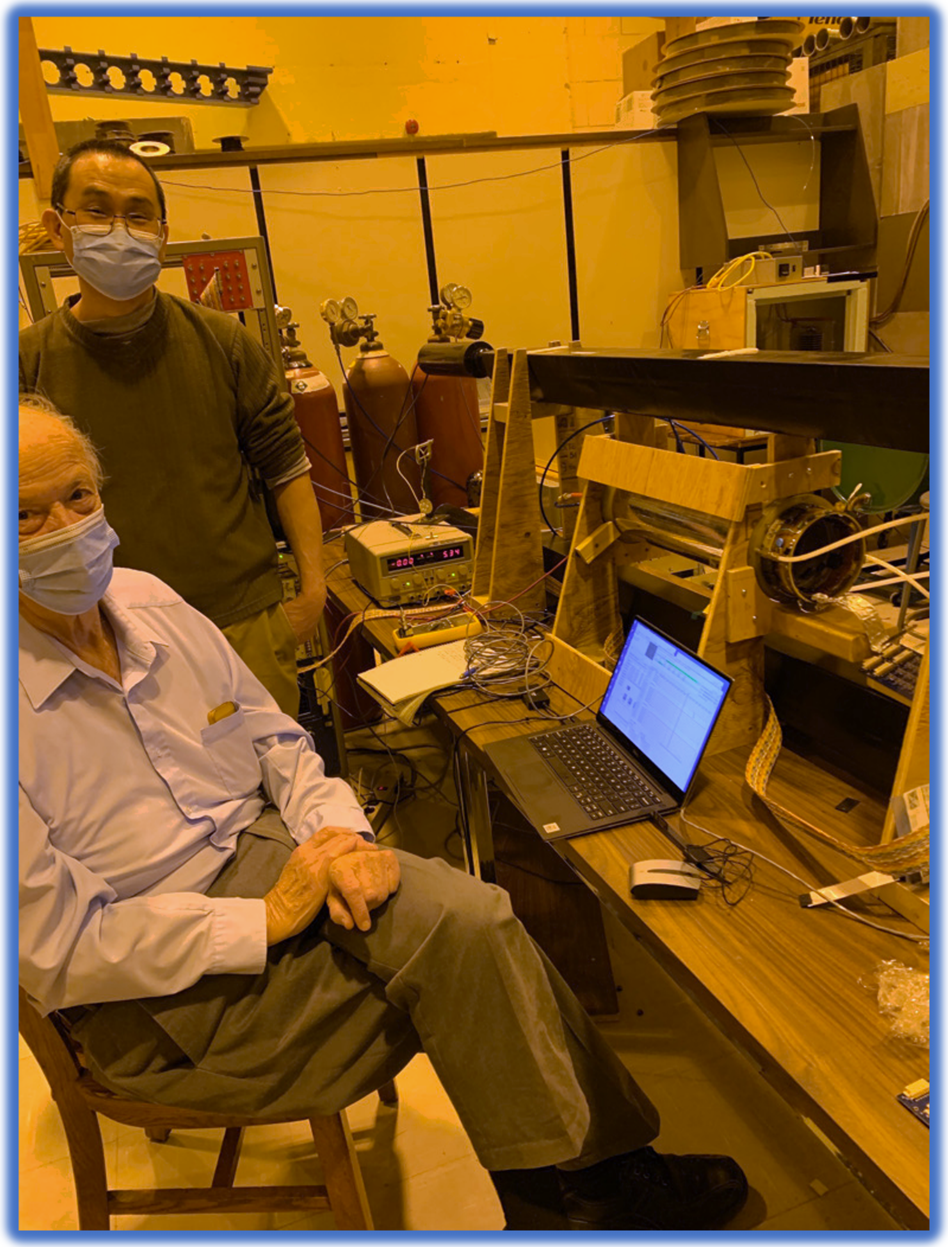
* 74.5% Ar, 25% Ethane, 0.5% Freon

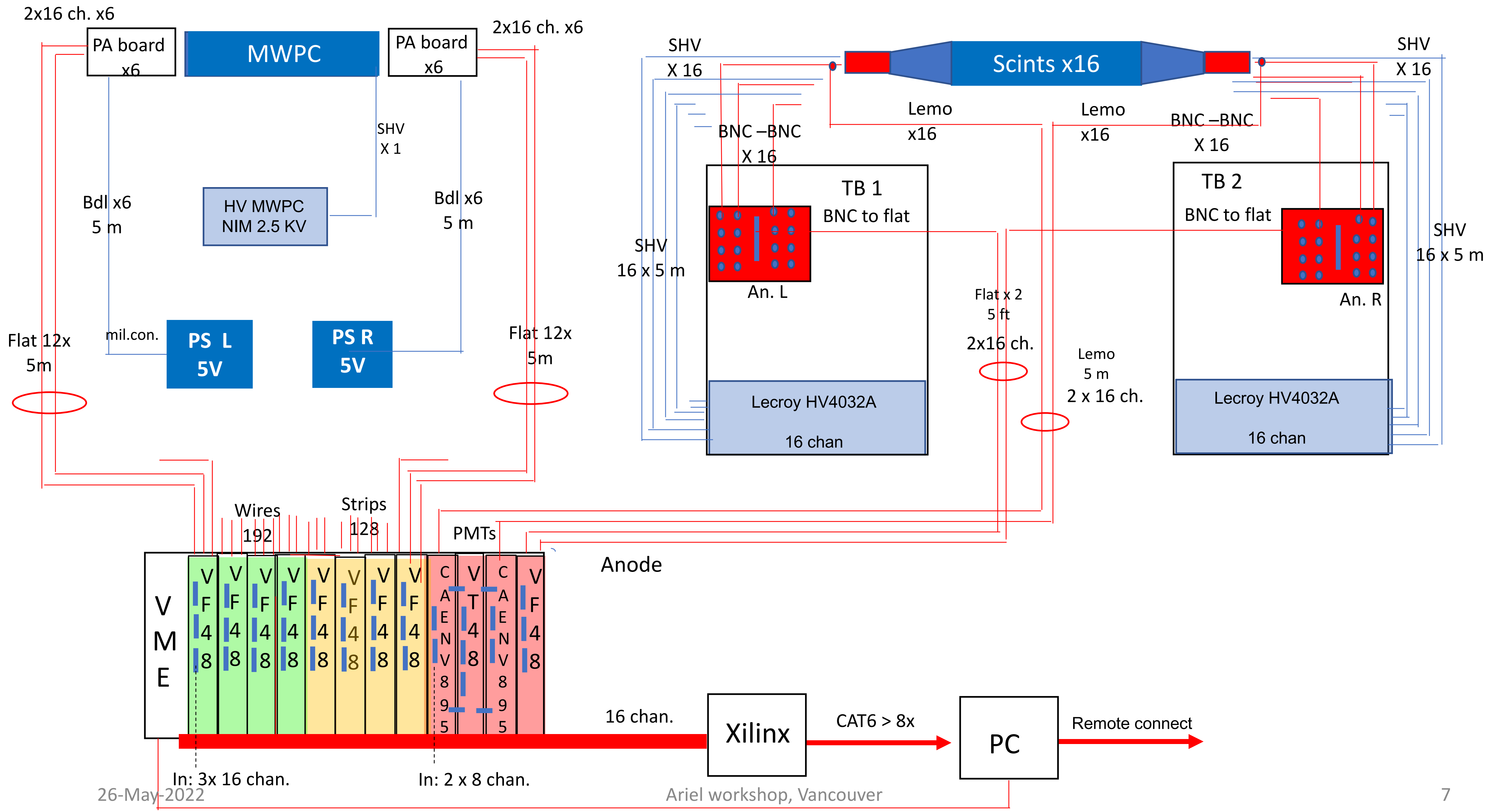
- Angular res.: $\Delta\theta \sim 2^0$ (FWHM)
- Low density material to avoid EPC!



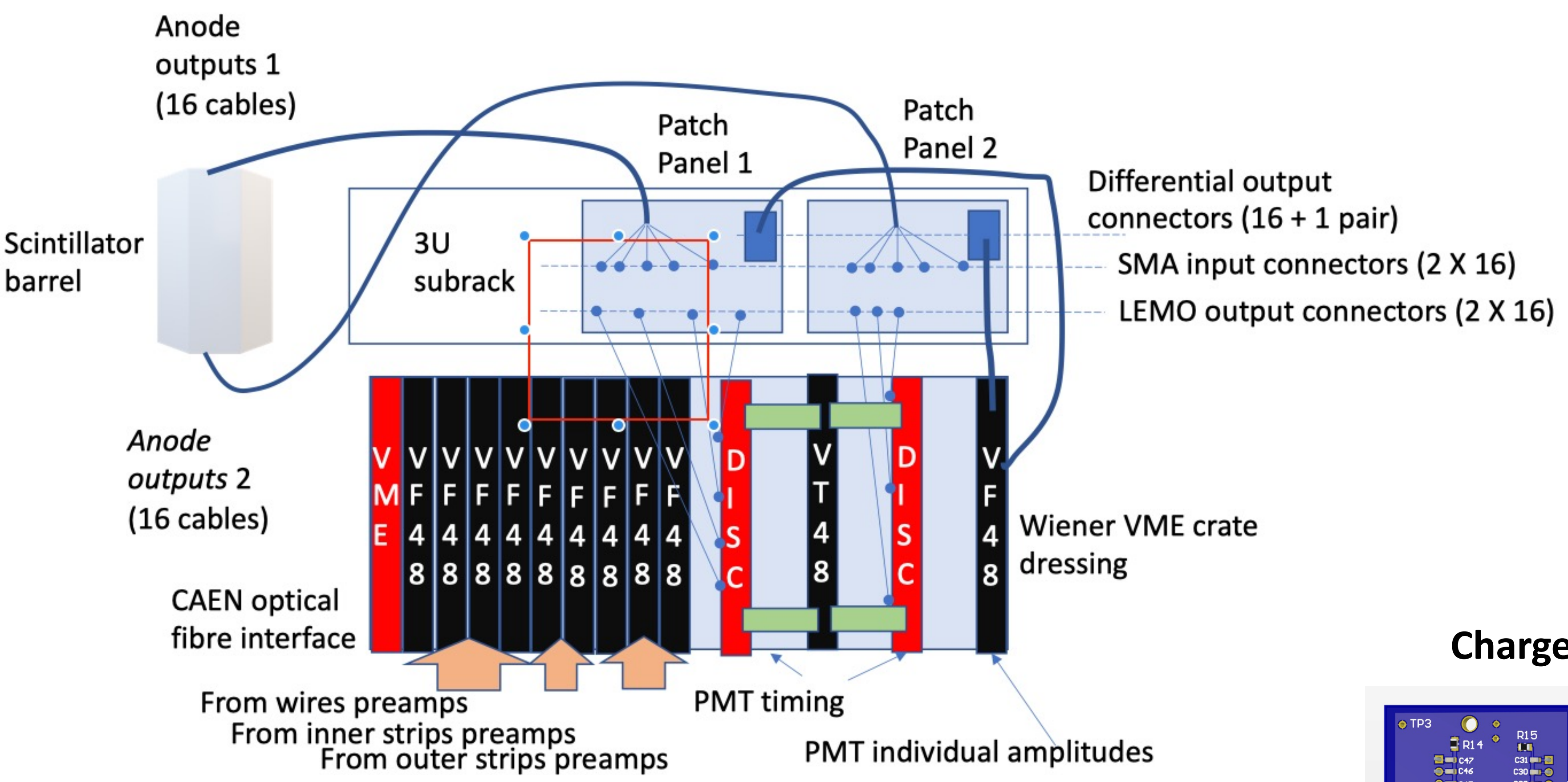
Testing of electronics and data acquisition with Cosmic Rays



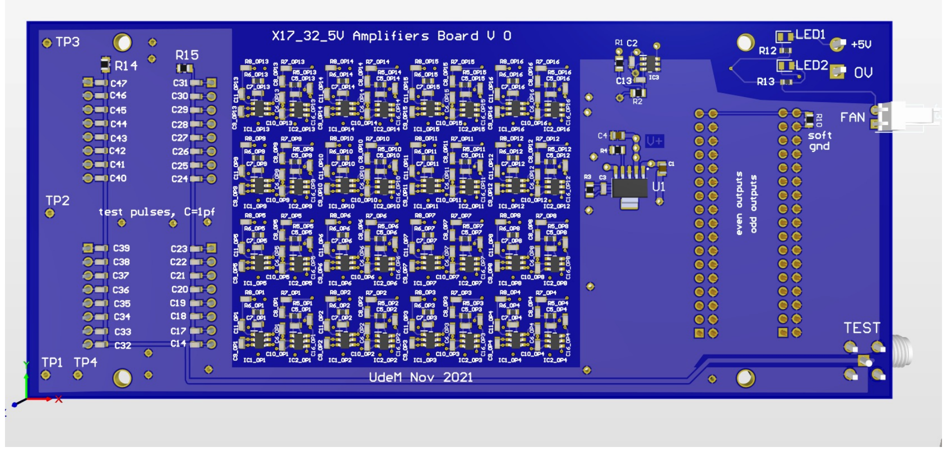



2x16 ch. x6
PA board x6
MWPC
PA board x6
2x16 ch. x6
SHV X 1
Bdl x6 5 m
HV MWPC NIM 2.5 KV
Bdl x6 5 m
mil.con.
PS L 5V
PS R 5V
Flat 12x 5m
Flat 12x 5m
SHV X 16
Scints x16
SHV X 16
Lemo x16
Lemo x16
BNC –BNC X 16
BNC –BNC X 16
TB 1
BNC to flat
An. L
TB 2
BNC to flat
An. R
SHV 16 x 5 m
SHV 16 x 5 m
Flat x 2 5 ft
2x16 ch.
Lemo 5 m 2 x 16 ch.
Lecroy HV4032A 16 chan
Lecroy HV4032A 16 chan
Wires 192
Strips 128
PMTs
Anode
VME
VF48
CAENV895
VT48
16 chan.
Xilinx
CAT6 > 8x
PC
Remote connect
In: 3x 16 chan.
In: 2 x 8 chan.

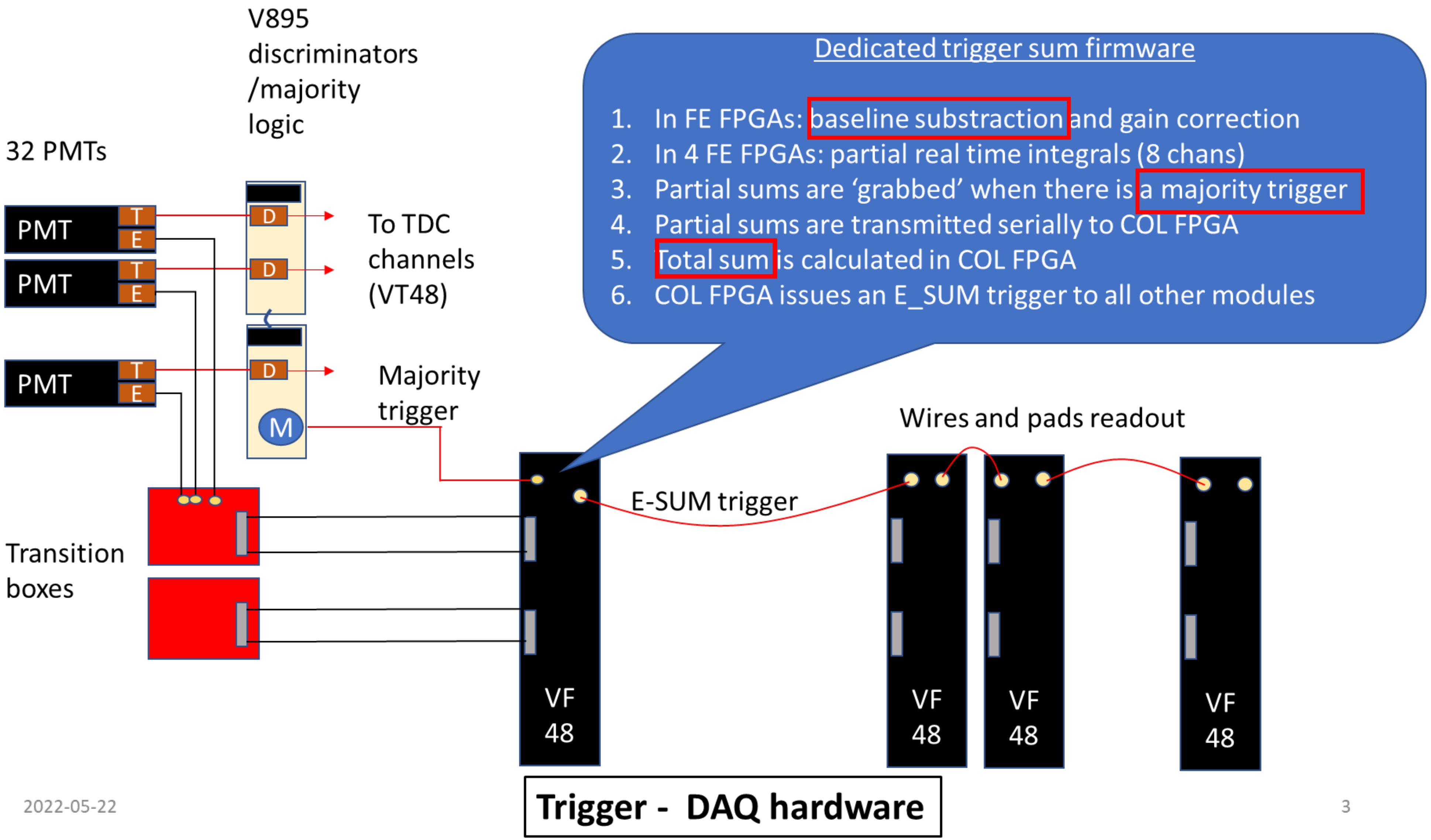
Level 1 Trigger experimental architecture for X17



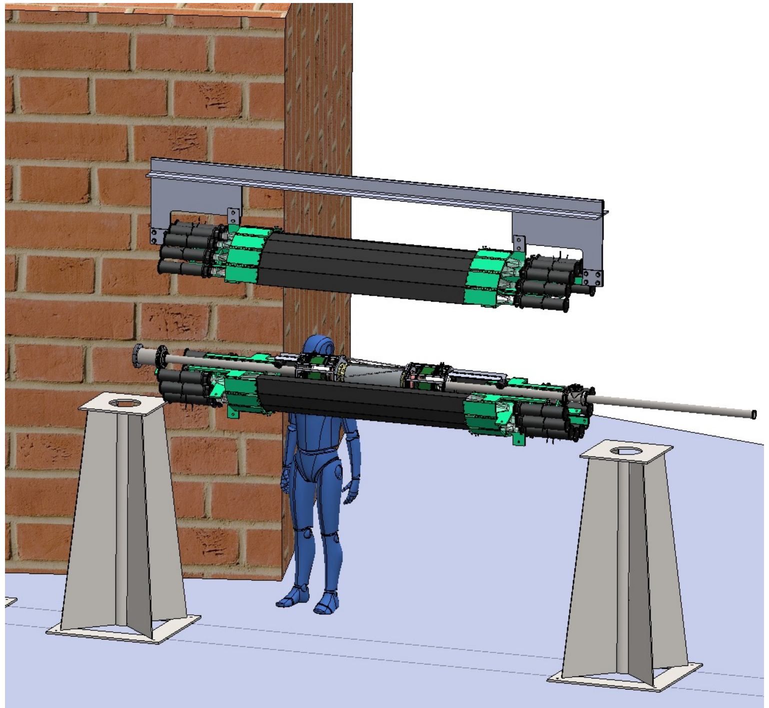
Charge preamp card, 32 channels,

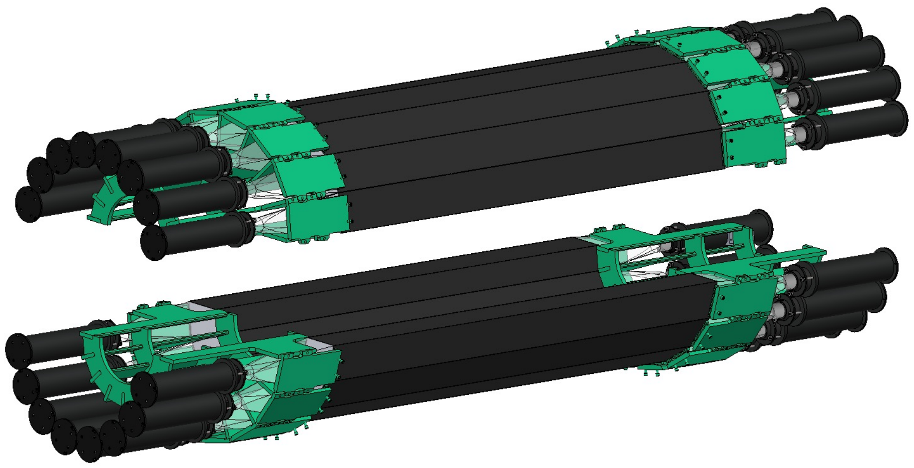


VF48 and VT48 designed by J-P Martin for TRIUMF
now borrowed from TRIUMF

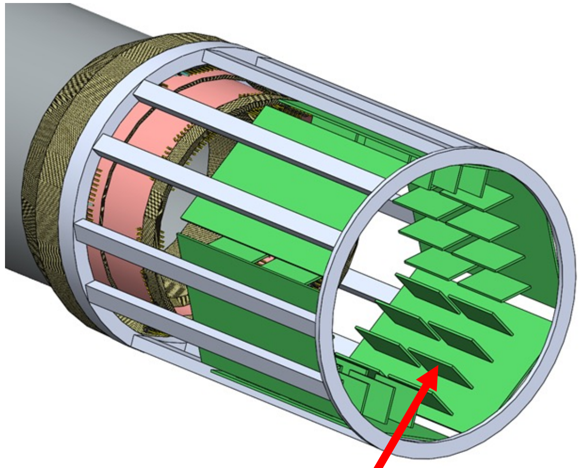

V895 discriminators /majority logic
32 PMTs
PMT
T
E
D
M
To TDC channels (VT48)
Majority trigger
Transition boxes
Dedicated trigger sum firmware
1. In FE FPGAs: baseline substraction and gain correction
2. In 4 FE FPGAs: partial real time integrals (8 chans)
3. Partial sums are 'grabbed' when there is a majority trigger
4. Partial sums are transmitted serially to COL FPGA
5. Total sum is calculated in COL FPGA
6. COL FPGA issues an E_SUM trigger to all other modules
Wires and pads readout
E-SUM trigger
VF 48
VF 48
VF 48
VF 48
2022-05-22
Trigger - DAQ hardware
3

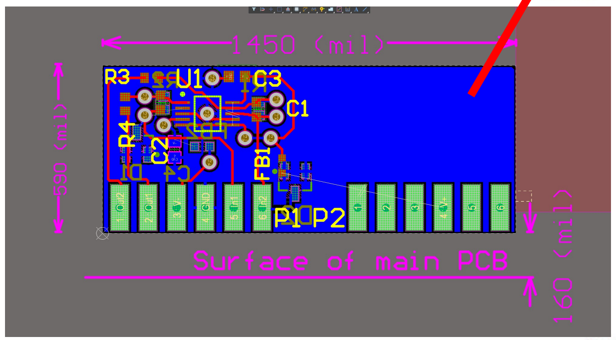
Status Set-UP



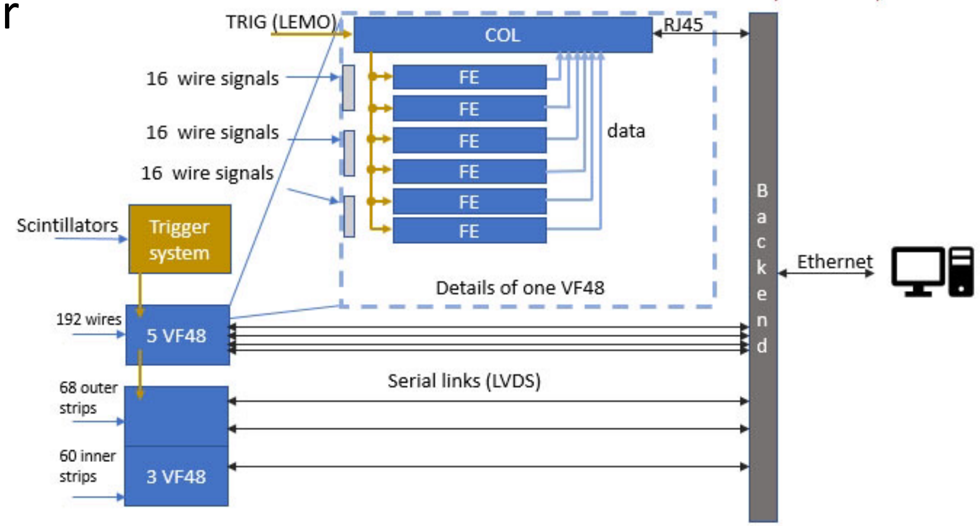


- MWPC: first wires tested with preamps & complete R/0
- 332 channels total → VF48 digitizers (TRIUMF)
- FPGA firmware ready
- Max. R/O speed: 40 kHz
- Add ΔE –scint. layer
- Add Cosmics veto

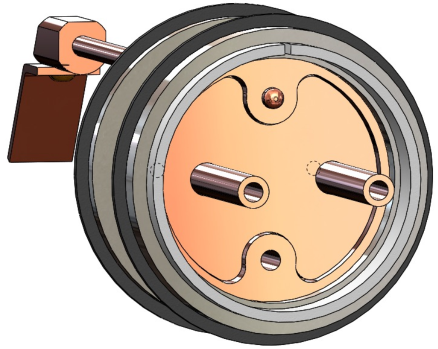




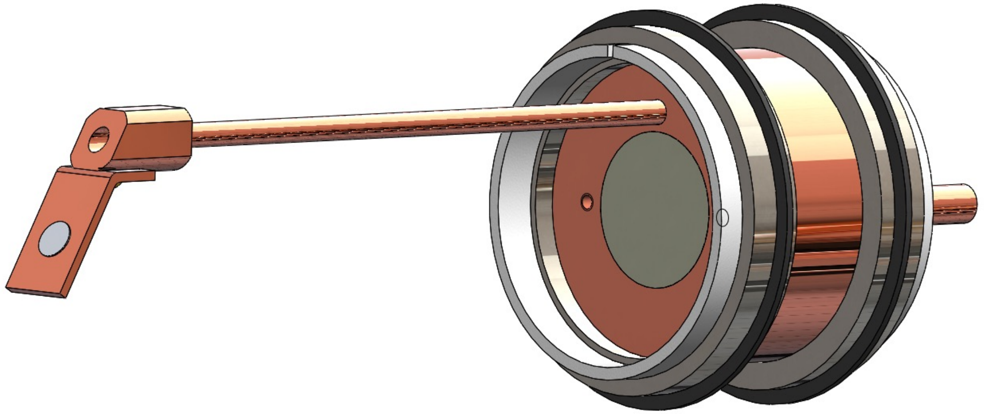
(J.-P. Martin)

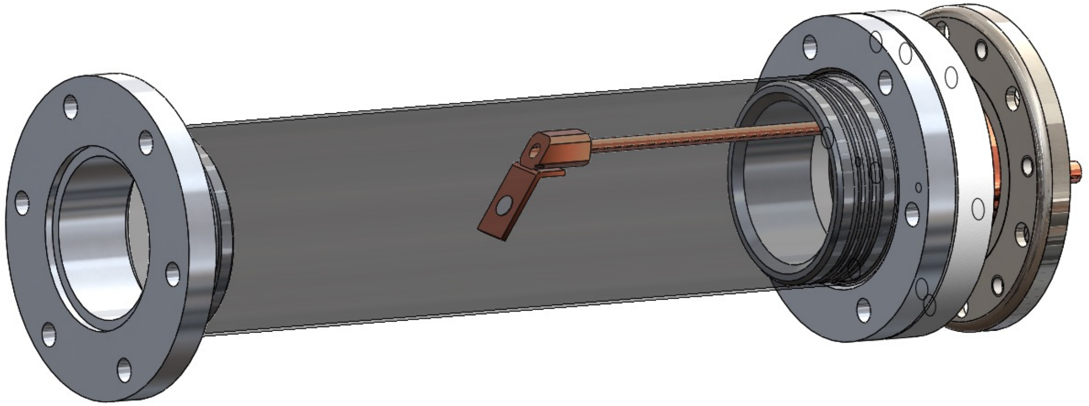


Prototype target holder



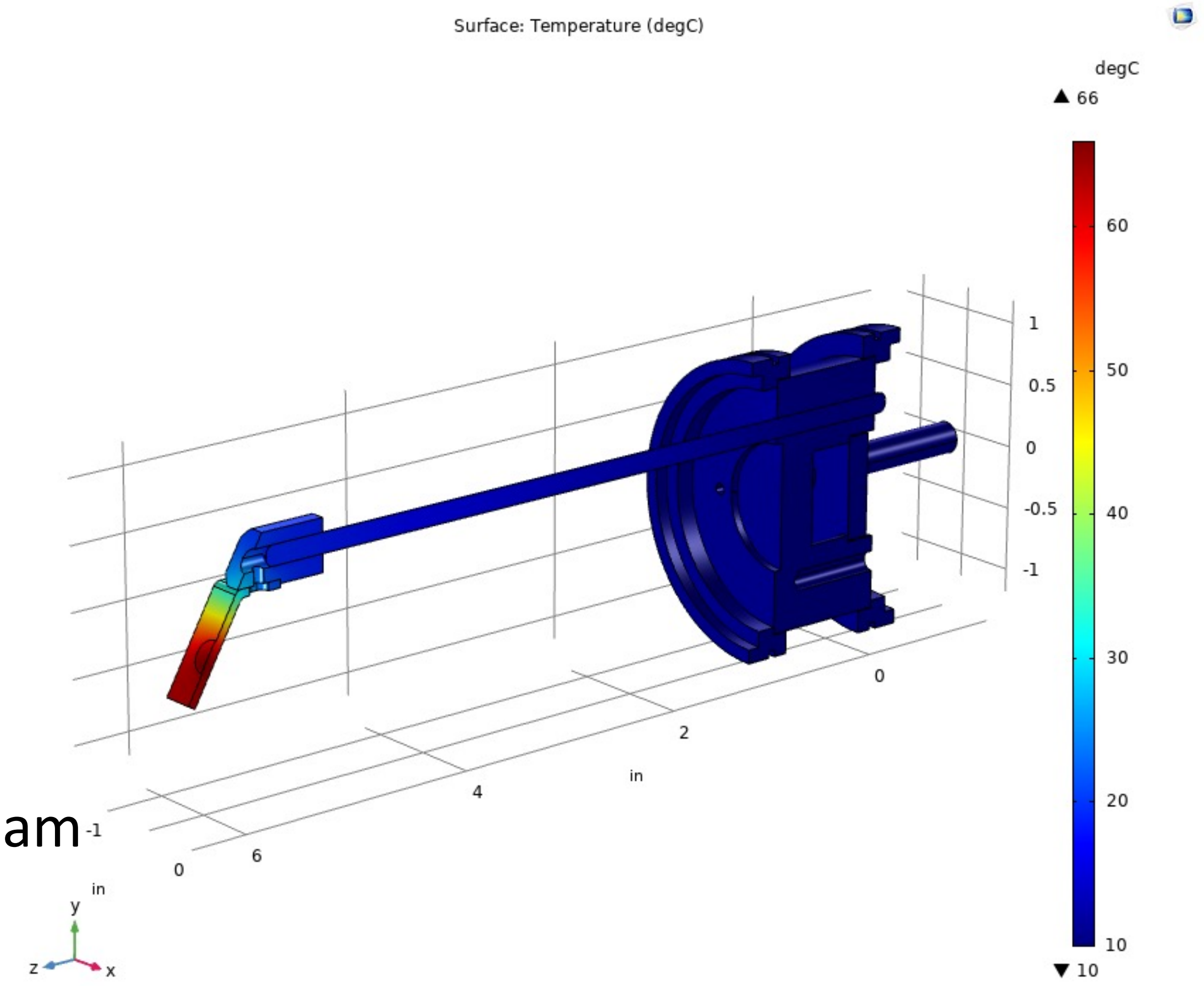
- 1” long, 2” OD copper heat exchanger, water cooled
- SS brazed 2” Dependex rings
- Cu brazed (Ag) heat pipe support
- 4 mm x 150 mm heat pipe
  - Rated 20W @ effective length
  - 1 uA proton @ 1 MeV = 1W
    - Goal 20 uA beam -> 20W max of heat
- Target bent @ 45°
- Substrate ½” x 7/8” x 1/16” thick
- Brass screw to hold target and easy replace
- Tantalum beam stop disc





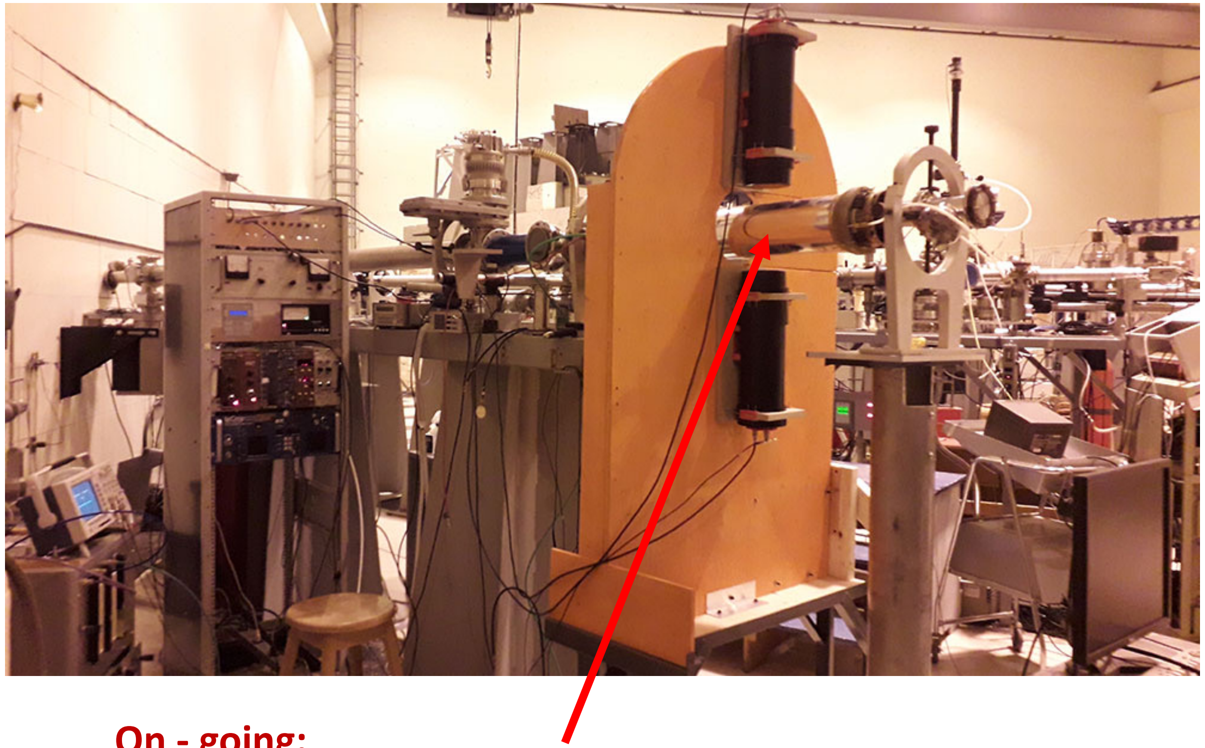
COMSOL simulations

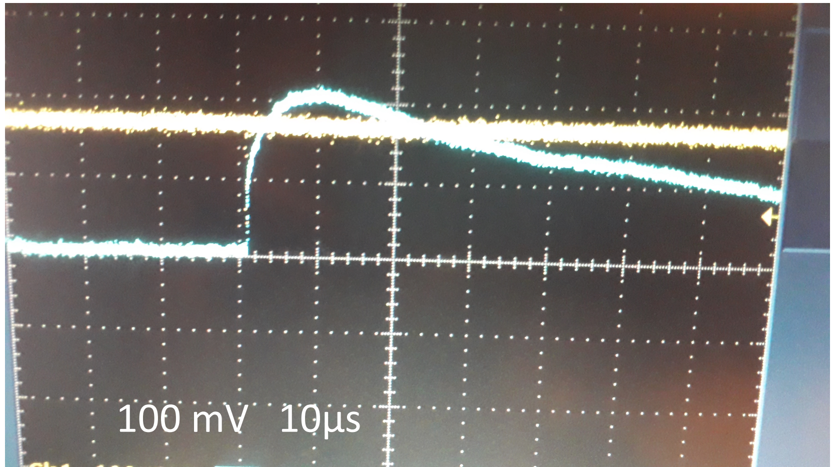
- Heat transfer module
  - No radiation
  - No outside air natural convection
- Heat pipe
  - Effective thermal conductivity
    - 24 000 W/(m*K)
- Water cooling to 10°C
- Target temp below 70°C
  - 20 W heat at target from 20 uA beam (Li melts at 180°C)



Test – Beam Measurements

- Dedicated Beam Line for X17 – project





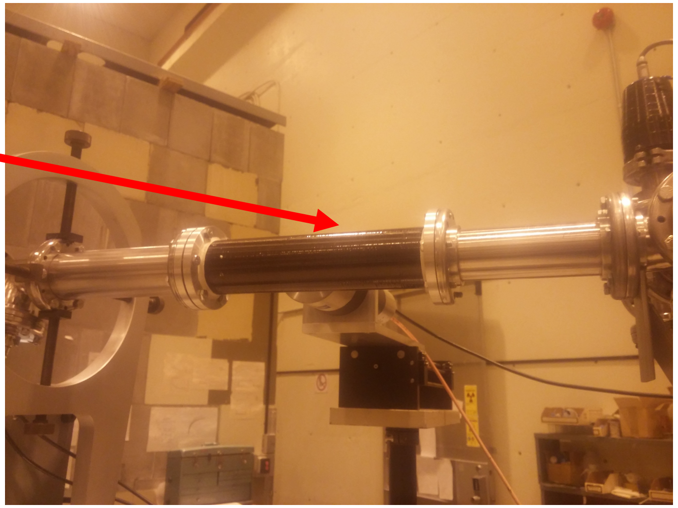
On - going:

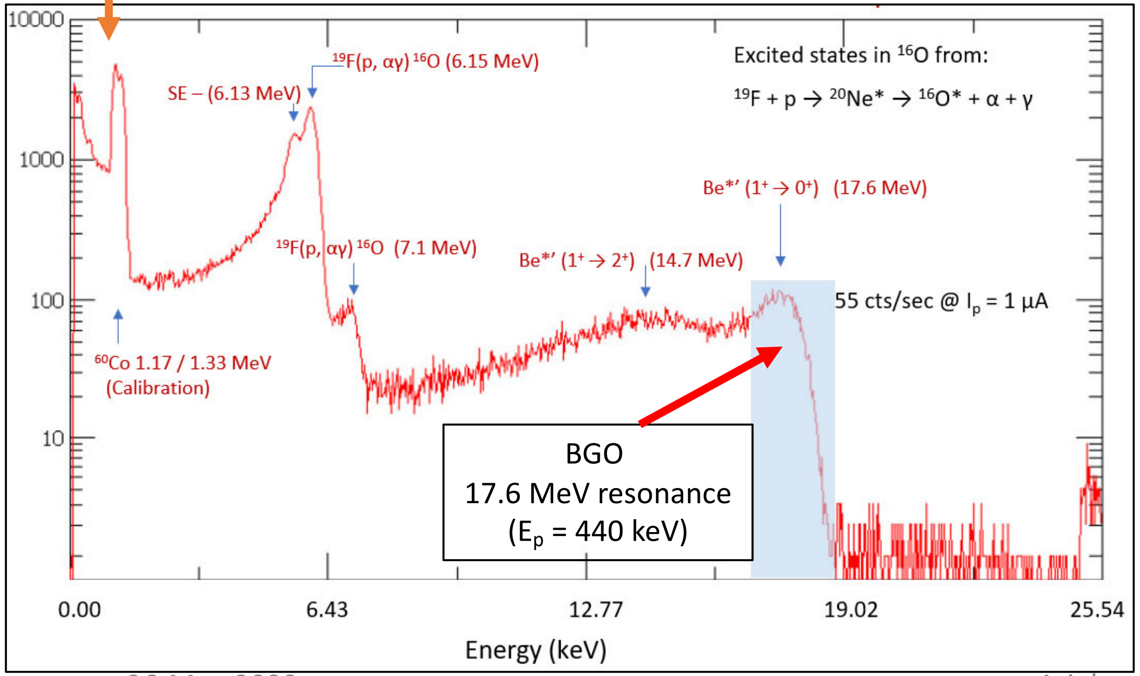
- Testing of DAPHNE MWPC (cosmics + beam)
- Deploy full MWPC read-out
- Be* e+ e- coincidences w. MWPC
- Next: deploy the 16 DAPHNE scintillators

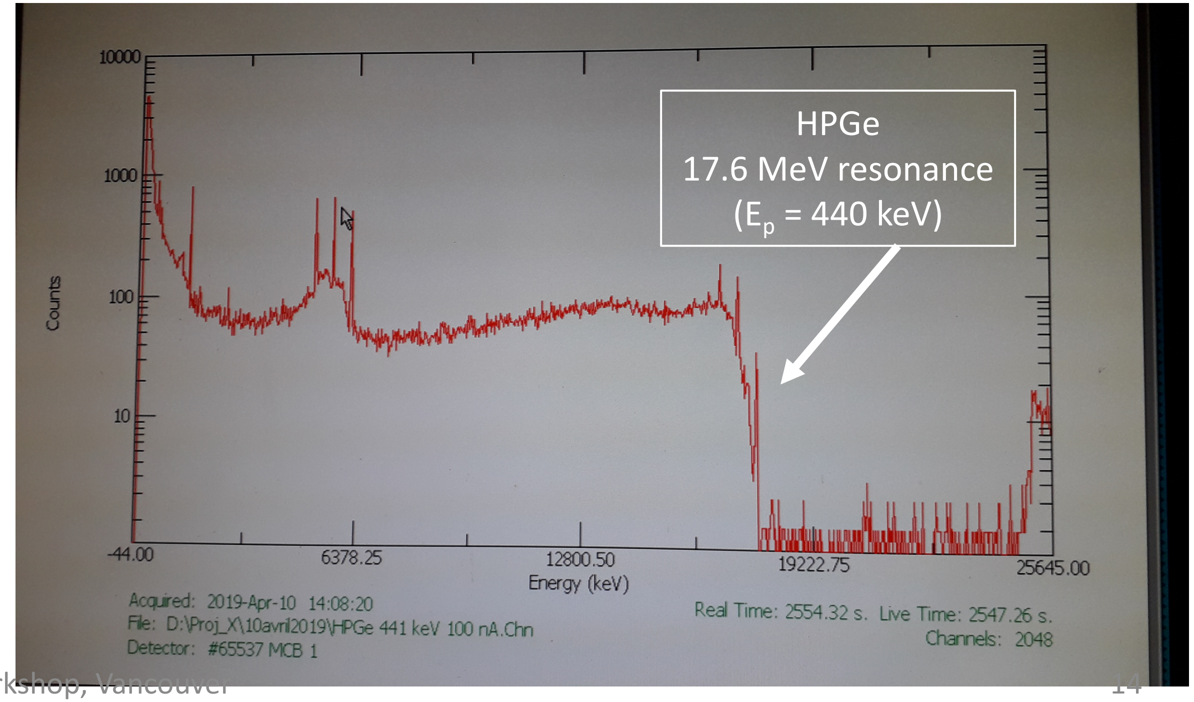
Test – Beam Measurements

Exploring Be* physics

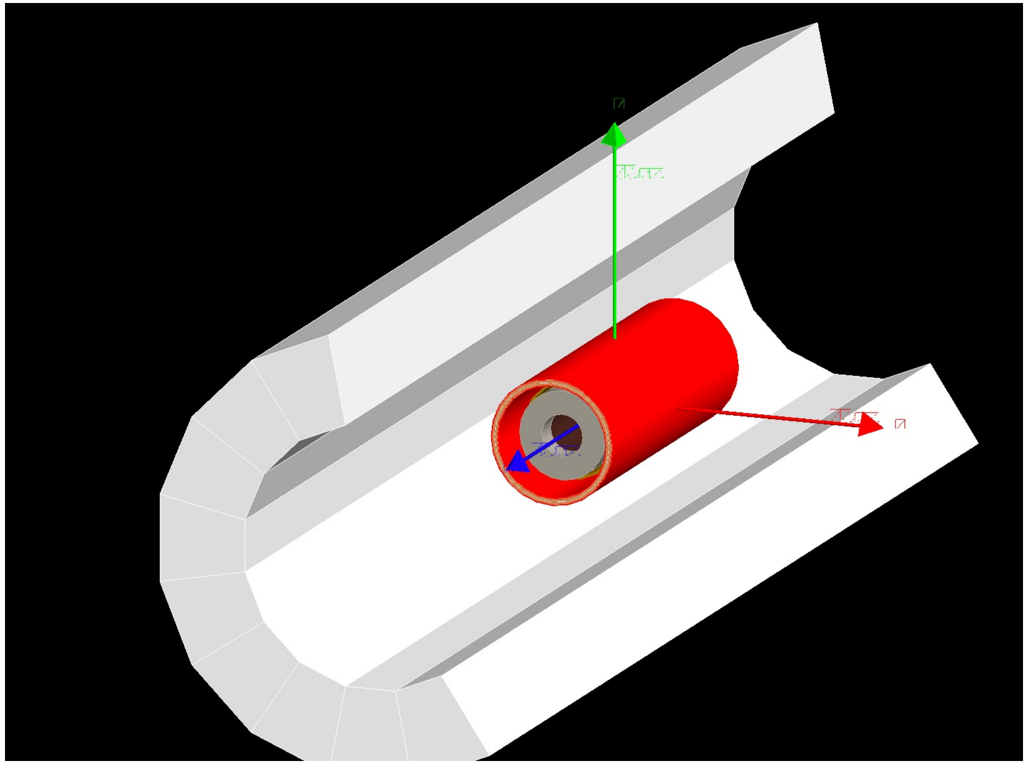
- 0.8 mm thick C-beam pipe
- Target: 0.2 µm LiF (52 µg/cm^2)
- Beam current: I_p = 2 µA
- γ – spectra with BGO , HPGe
- 478 keV line serves as reference

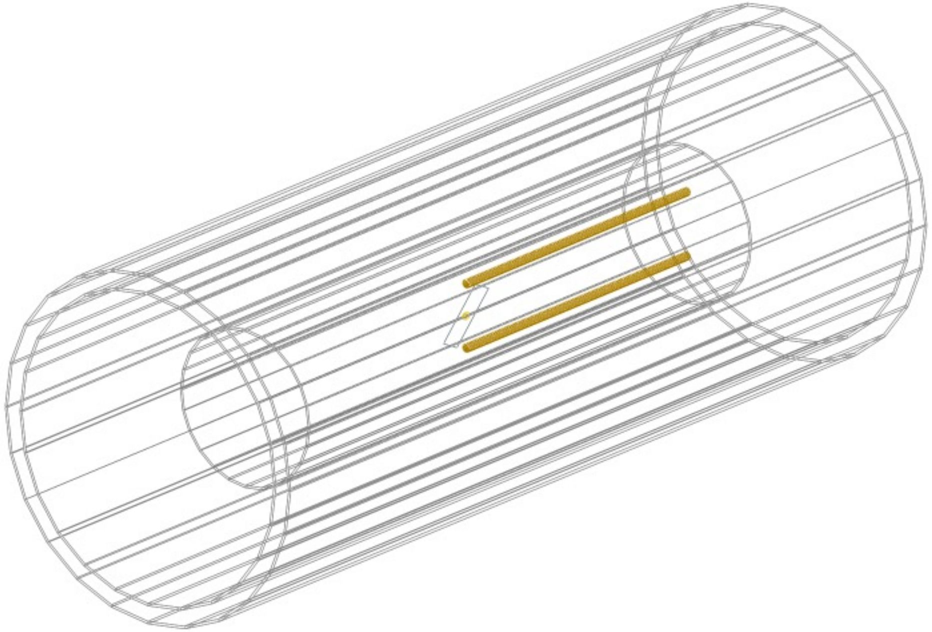


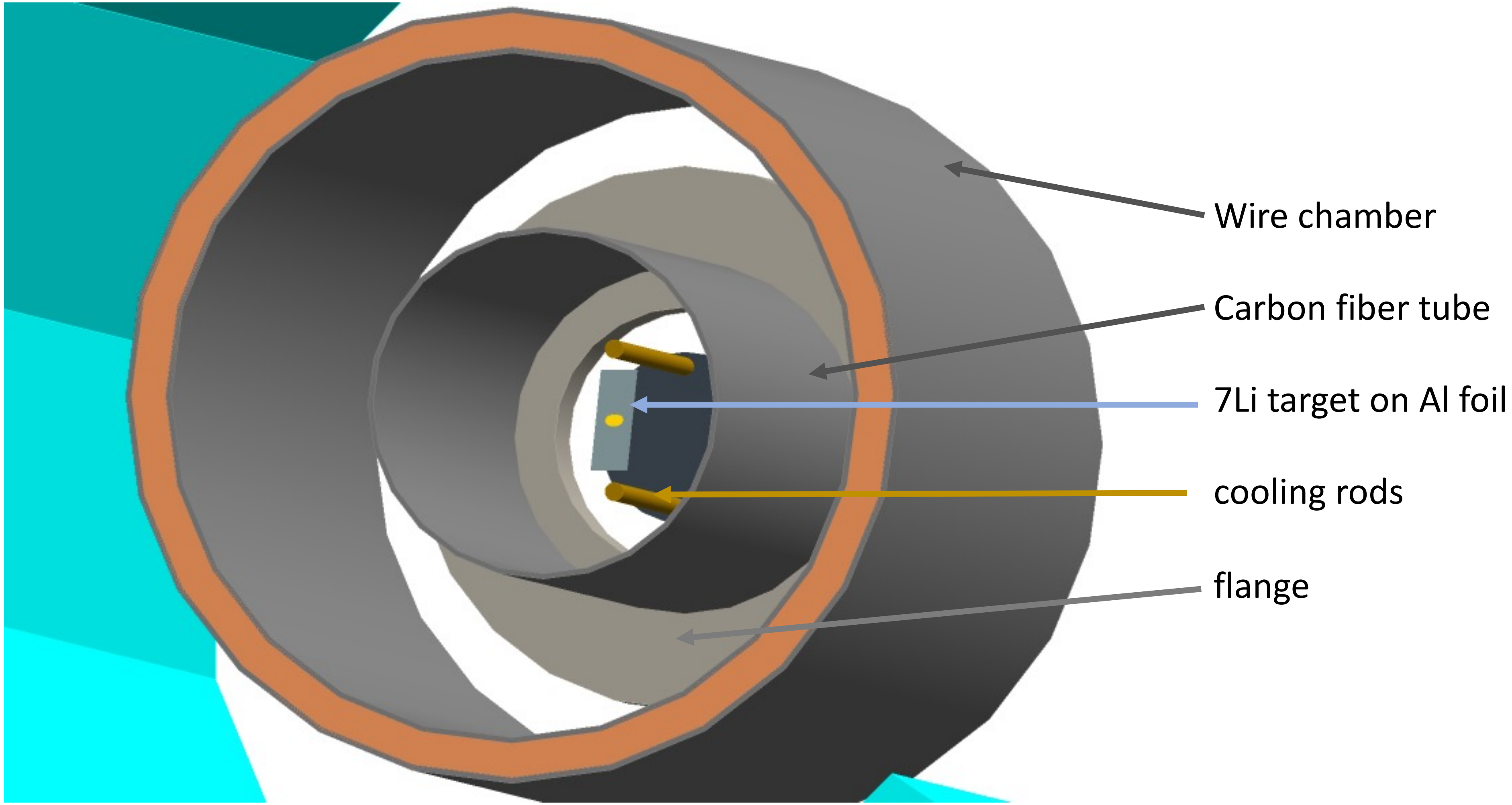


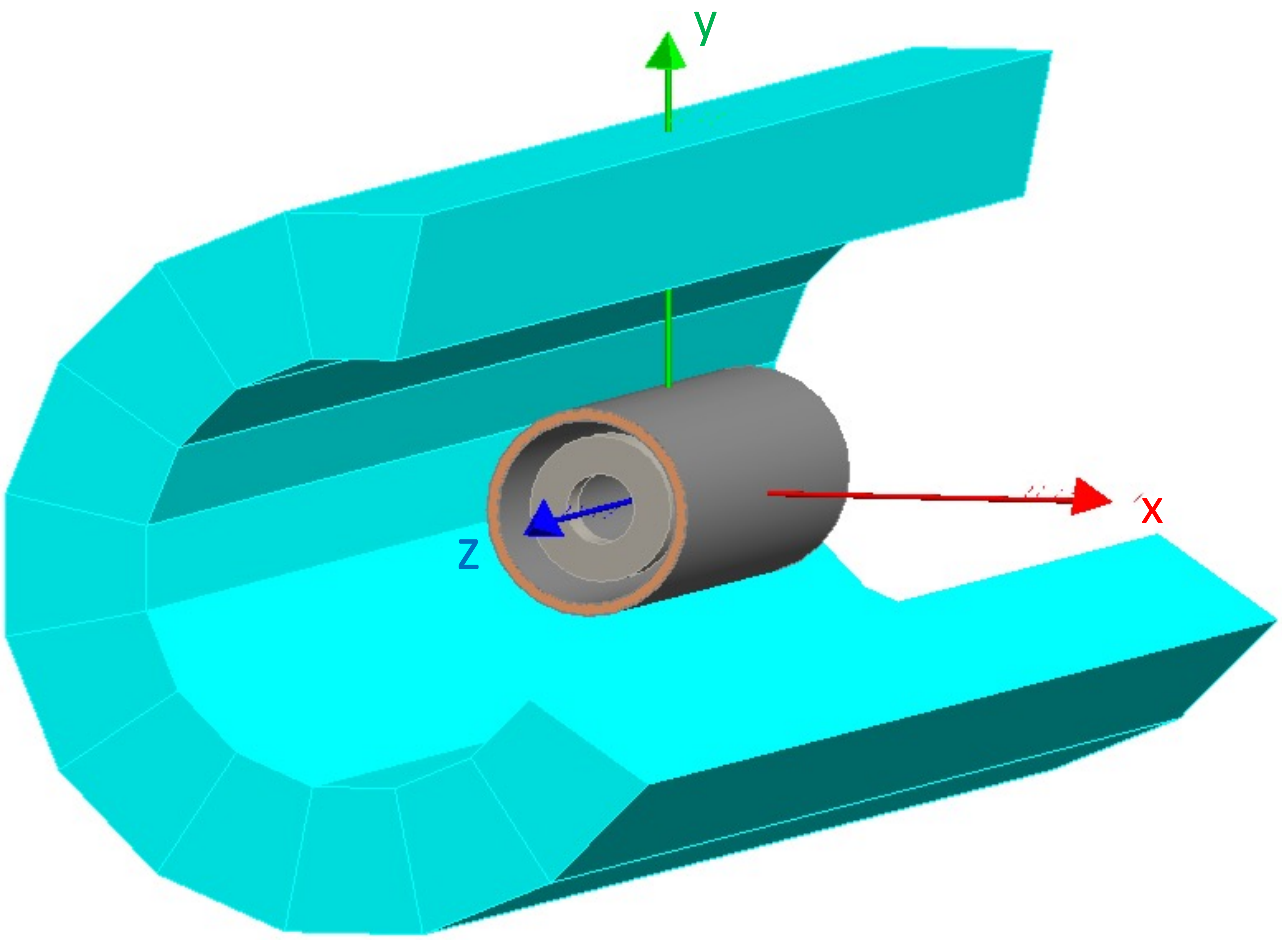


Monte Carlo simulation with Geant4






Wire chamber
Carbon fiber tube
7Li target on Al foil
cooling rods
flange

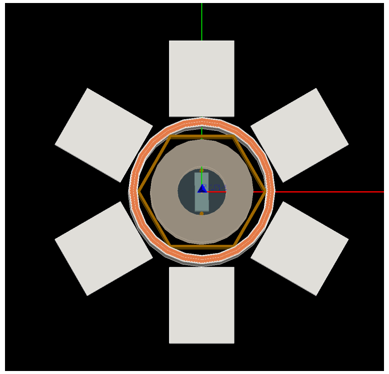


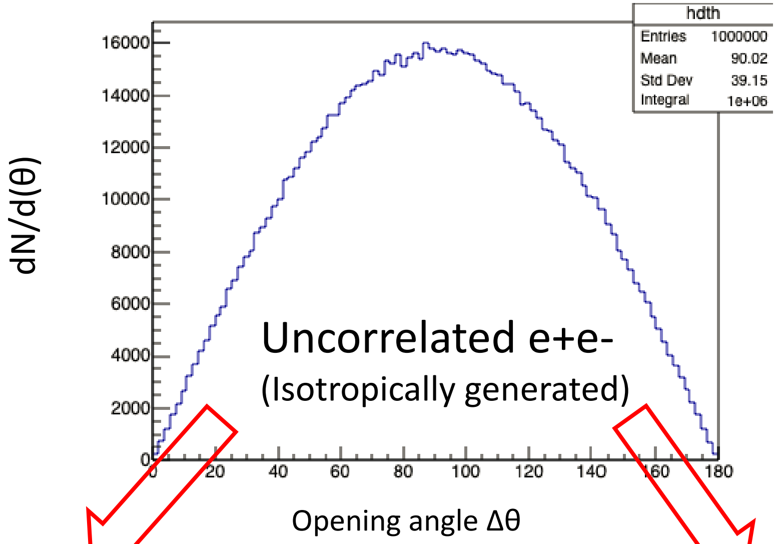
MWPC
- angular resolution: 2°

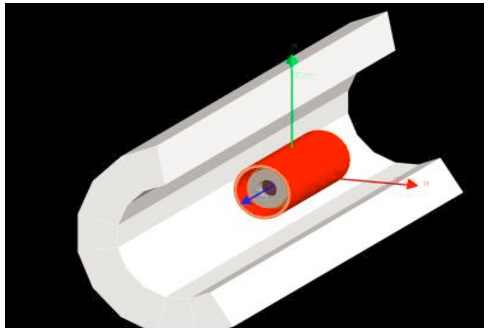
Scintillator bars:
- energy resolution ~ $7\,\%/\sqrt{E(MeV)}$
- position resolution: ~ 5 cms FWHM in z direction from energy sharing and time difference at the two ends

Calibration/resolution of scintillators ongoing
- scintillator bars tested for light output and light attenuation length
- phototubes tested with LED's for gain and stability

Geant4 Simulation: Acceptances

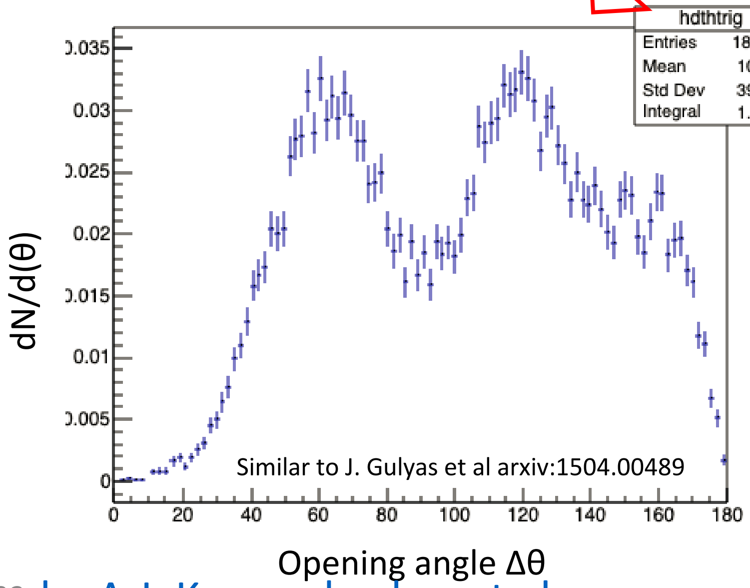


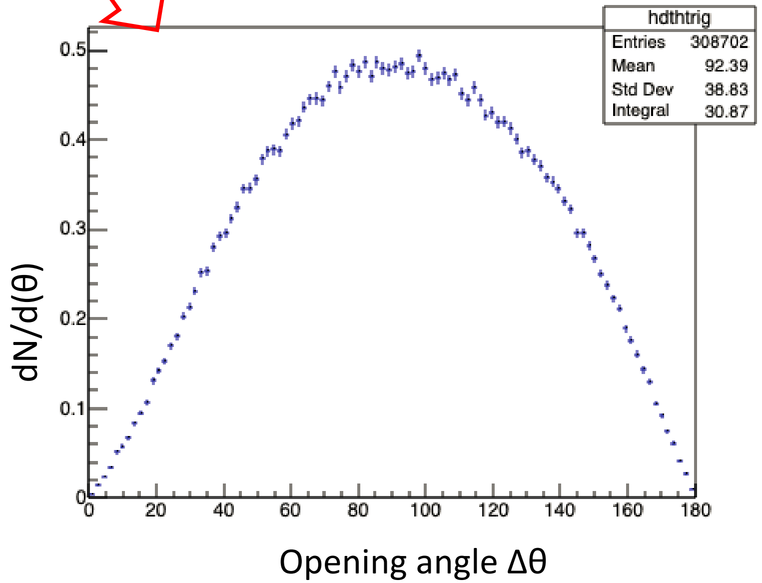




ATOMKI geometry

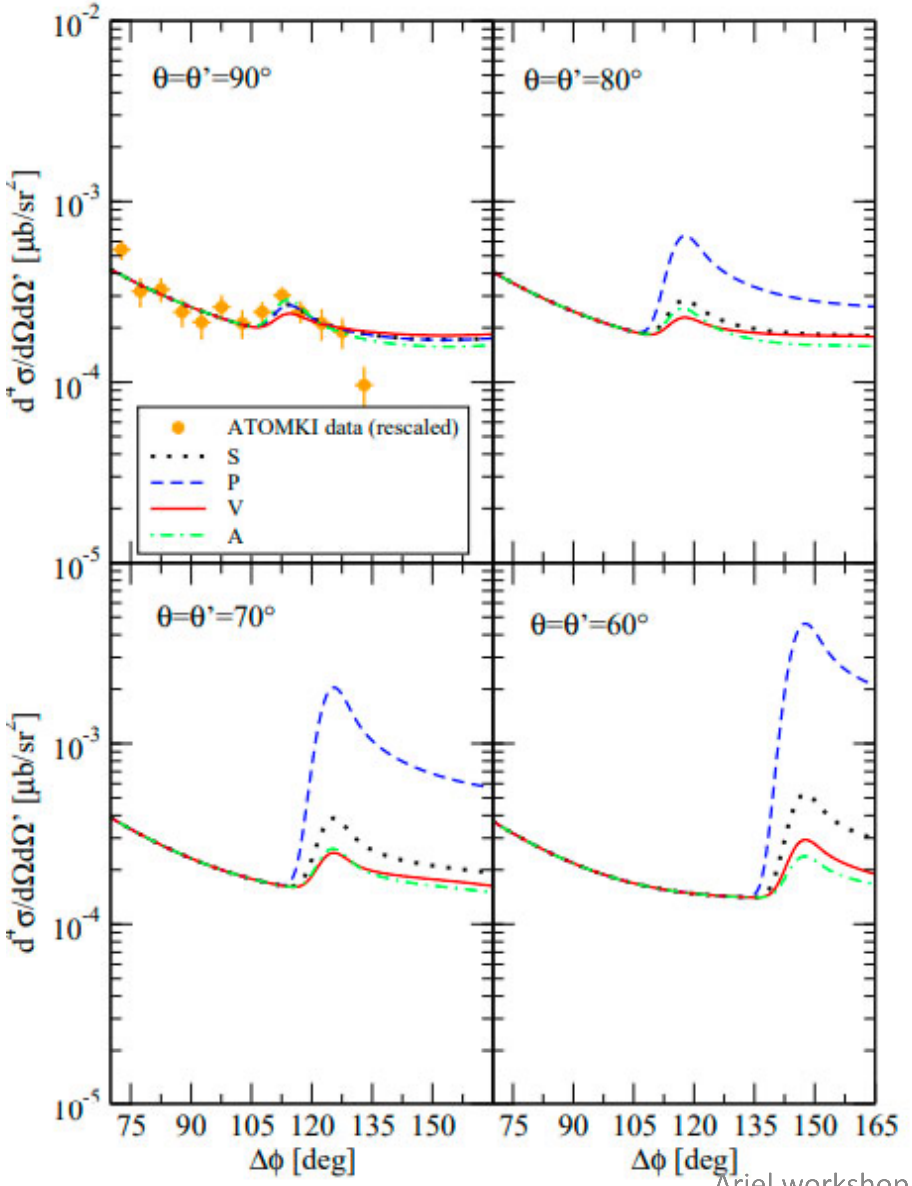
Montreal geometry





Gulyás J, et al. , A.J. Krasznahorkay et al.

X17 – Parameter Space to Explore in Nuclei



M. Viviani et al., arXiv:2104.07808v1

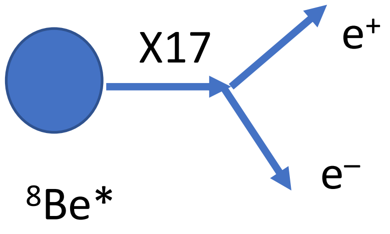
If X17 produced in direct E1-capture (^4He,^{10}B..)

Angular distribution of the e^+e^- pair depends on the X17 quantum numbers

Large angular acceptance allows discrimination btw. different decay modes

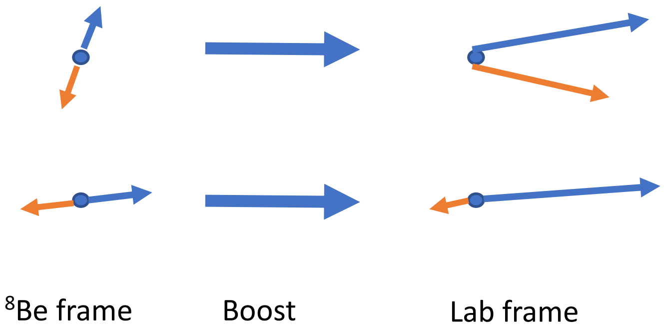
Motivation for a large ang. acceptance experiment!

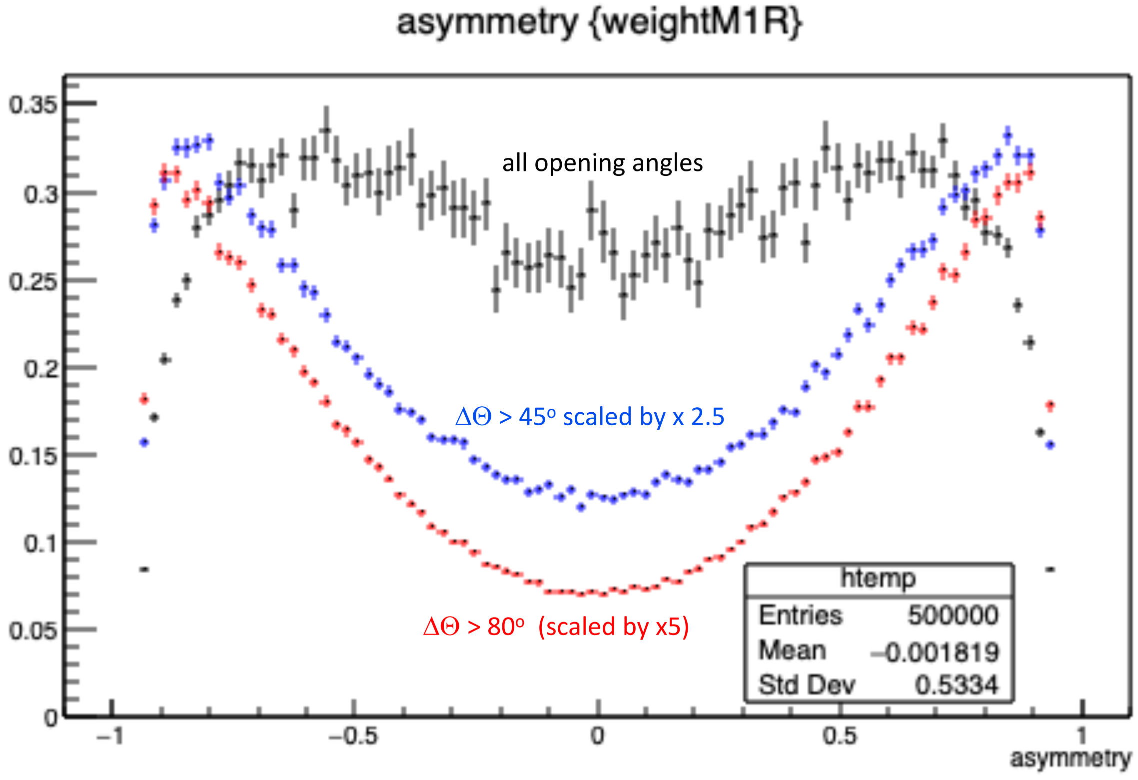
Geant4 Simulation, reconstruction



3 basic observables for e^+e^- pair

- opening angle
  - heavy particle ➞ small boost
    ➞ large opening angle
- asymmetry: $y \equiv \frac{|E_1 - E_2|}{E_1 + E_2}$
  - for low m_{ee}, large opening angles correlated with large asymmetry.
- invariant mass m_{ee}
  - preselection of large m_{ee} removes a lot of background and fake signals





Simulation – ^{8}Be* (IPC & X17)

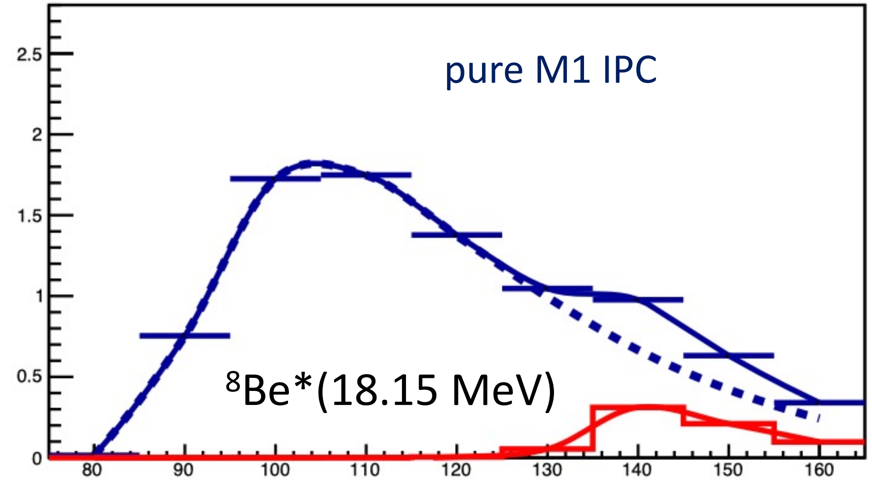
Full detector geometry:

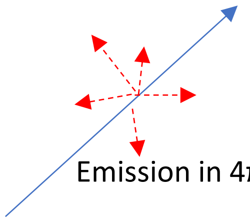
- M1- IPC: E_γ = 18.15 MeV
- $\Delta\theta \sim 2^0$ (FWHM); $\Delta E/E \sim 7.4\%/\sqrt{E}$
- |y| < 0.45; m(ee) > 12 MeV/c^2
- $B(X/IPC) = \frac{B(X/\gamma)}{B(IPC/\gamma)} = \frac{5.8\times10^{-6}}{3.9\times10^{-3}} = 1.5\times10^{-3}$
- Signal/Background in region of interest:

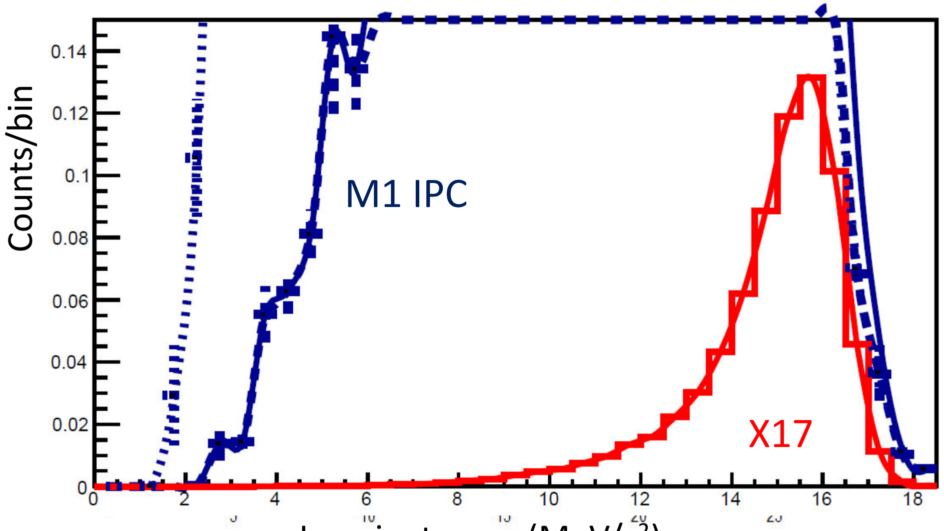
$$S/B \approx 0.6$$

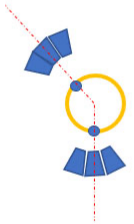
$(135^0 \le \theta \le 180^0)$

- ….later optimization w. neural net analysis
  - input raw observables
  - account for full 4π geometrical correlations
  - account for shape of IPC background instead of cuts on m(ee) and asymmetry









Simulation – ^{8}Be* (IPC & X17)

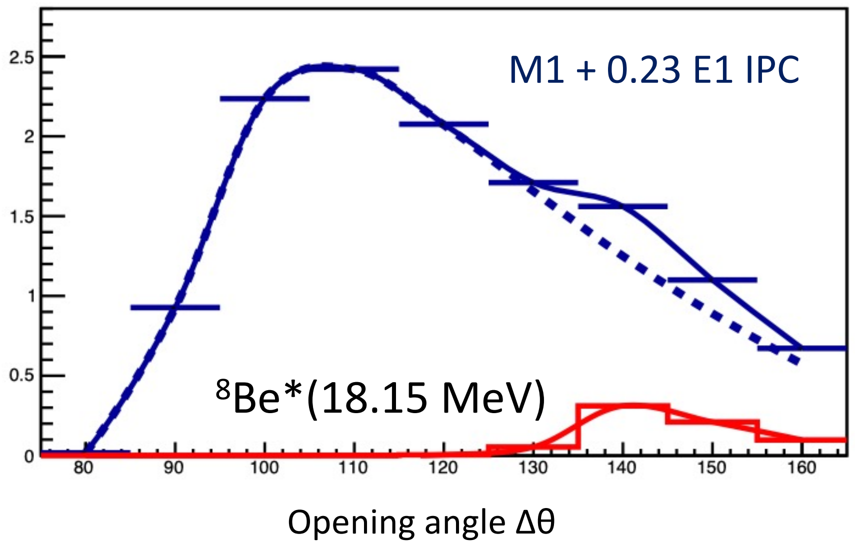
strong dependence on E1/M1 ratio

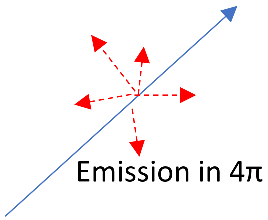
Full detector geometry:

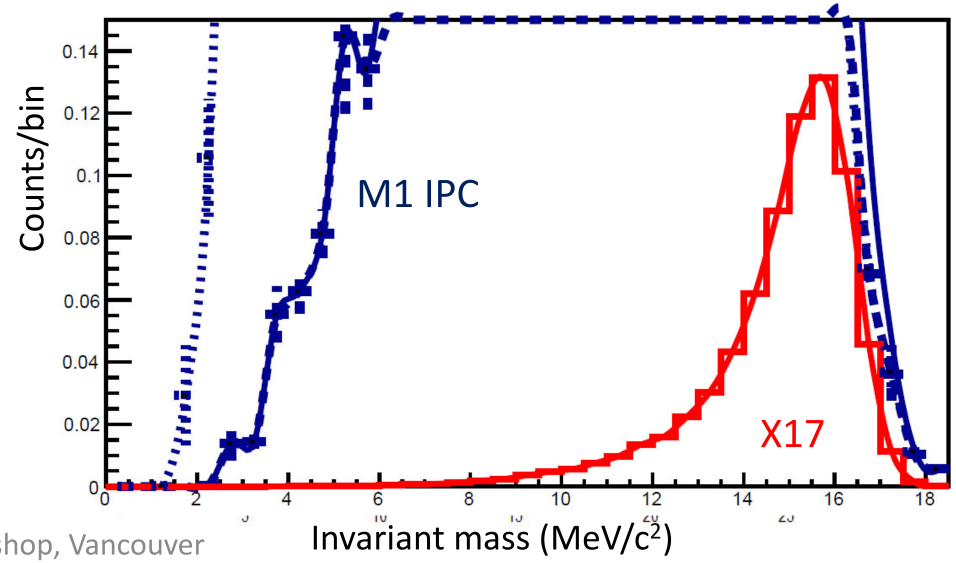
- M1- IPC: E_γ = 18.15 MeV
- $\Delta\theta \sim 2^0$ (FWHM); $\Delta E/E \sim 7.4\%/\sqrt{E}$
- $|y| < 0.45$; m(ee) > 12 MeV/c^2
- $B(X/IPC) = \frac{B(X/\gamma)}{B(IPC/\gamma)} = \frac{5.8\times10^{-6}}{3.9\times10^{-3}} = 1.5\times10^{-3}$
- Signal/Background in region of interest:

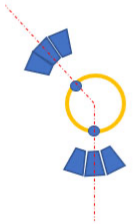
$$S/B \approx 0.3$$

$(135^0 \leq \theta \leq 180^0)$







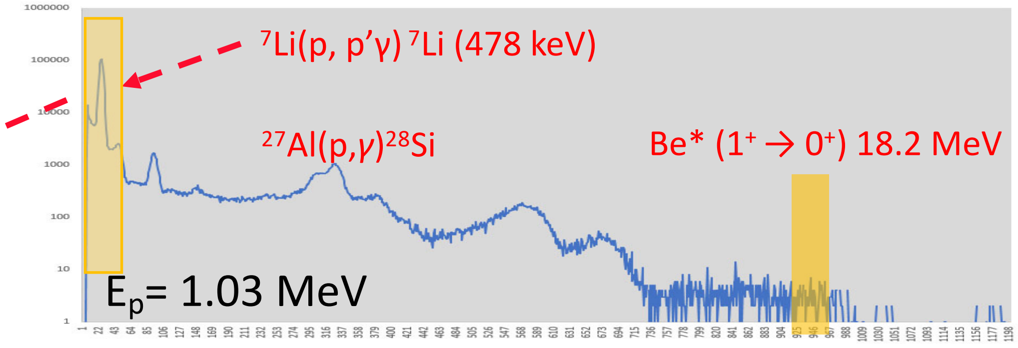


- ….later optimization w. neural net analysis
  - account for full 4π geometrical correlations
  - account for shape of IPC background instead of cuts on m(ee) and asymmetry

Signal Rates: $^{8}Be^{*}$ IPC / X17

- Measured BGO rates @ I_p = 2μA extrapolated to 0.9 x 4π – coverage:

E_γ = 478 keV: $R_\gamma = 5.7 \times 10^{5}\ s^{-1}$



B(IPC/γ) = 3.9×10^{-3}

$$\frac{\sigma^{7}Li(p,\gamma)^{8}Be^{*}}{\sigma^{7}Li(p,\gamma)^{7}Li} = 7.5\times10^{-4}$$

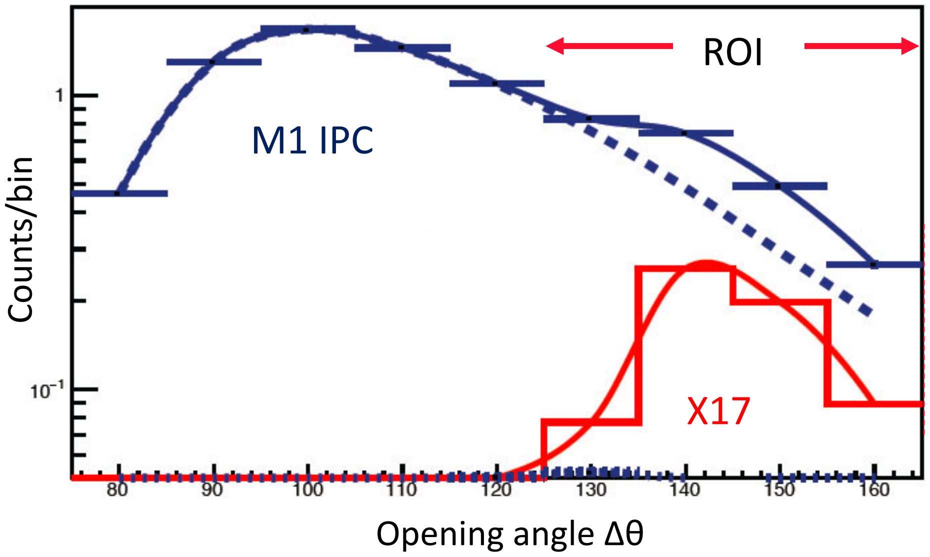
R_{IPC} (18.2 -> GS) = $1.7\ s^{-1}$

cuts on γ, ROI

Geant4

R_{IPC} (in ROI) = $15\ h^{-1}$

R_{X17} (in ROI) = $9\ h^{-1}$



(Data taking 1 - 2 weeks @ I_p = 2μA)

(Expected $R_{trigger}(\gamma\gamma)$ (E_γ > 6 MeV; $E_1 \wedge E_2$) = 30 Hz)

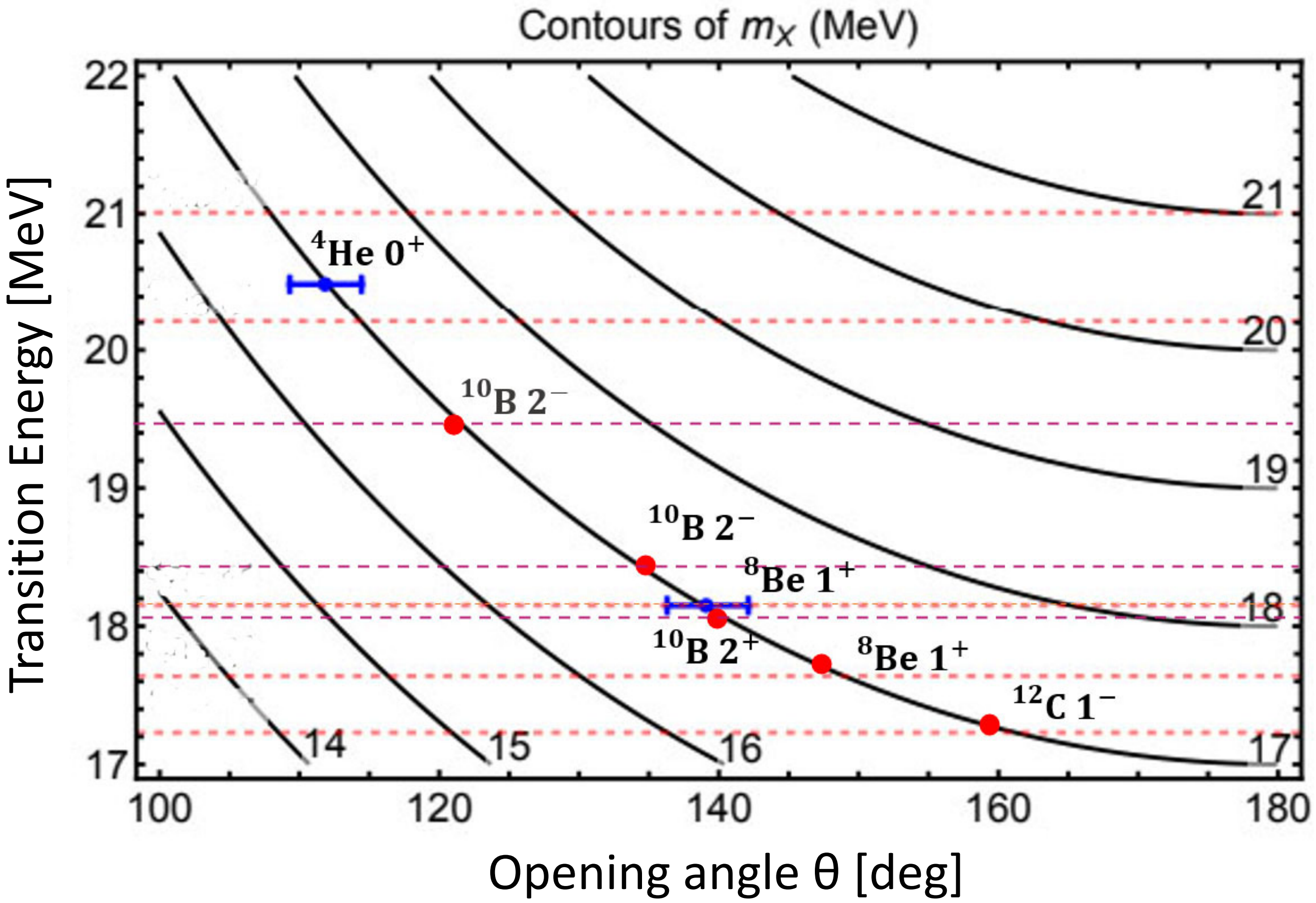
Where Else Can We look? Other nuclei!

	N_*	$J_*^{P_*}$	T_*		Γ_{N_*} (keV)
$^7Li(p,\gamma)^8Be$ →	^{8}Be(18.15)	1^+	0	M1 IV	138
	^{8}Be(17.64)	1^+	1	M1 IS	10.7
$^{11}B(p,\gamma)^{12}C$ →	^{12}C(17.23)	1^-	1	E1 IV	1150
$^3H(p,\gamma)^4He$ →	^{4}He(21.01)	0^-	0	M0	840
	^{4}He(20.21)	0^+	0	E0	500
$^7Li(^3He,\gamma)^{10}B$ →	^{10}B(19.3)	2^- (-3^+)	1	E1	280
	^{10}B(18.1)	2+ (-1^+)	1	M1	< 600
	^{10}B(18.4)	2^- (-3^+)	1	E1	280
	^{10}B(17.0)	1^- (-2^+)	1	E1	280

^{3}He – beam available!

J.L. Feng et al; arXiv:2006.01151

X17 – Consistency Checks

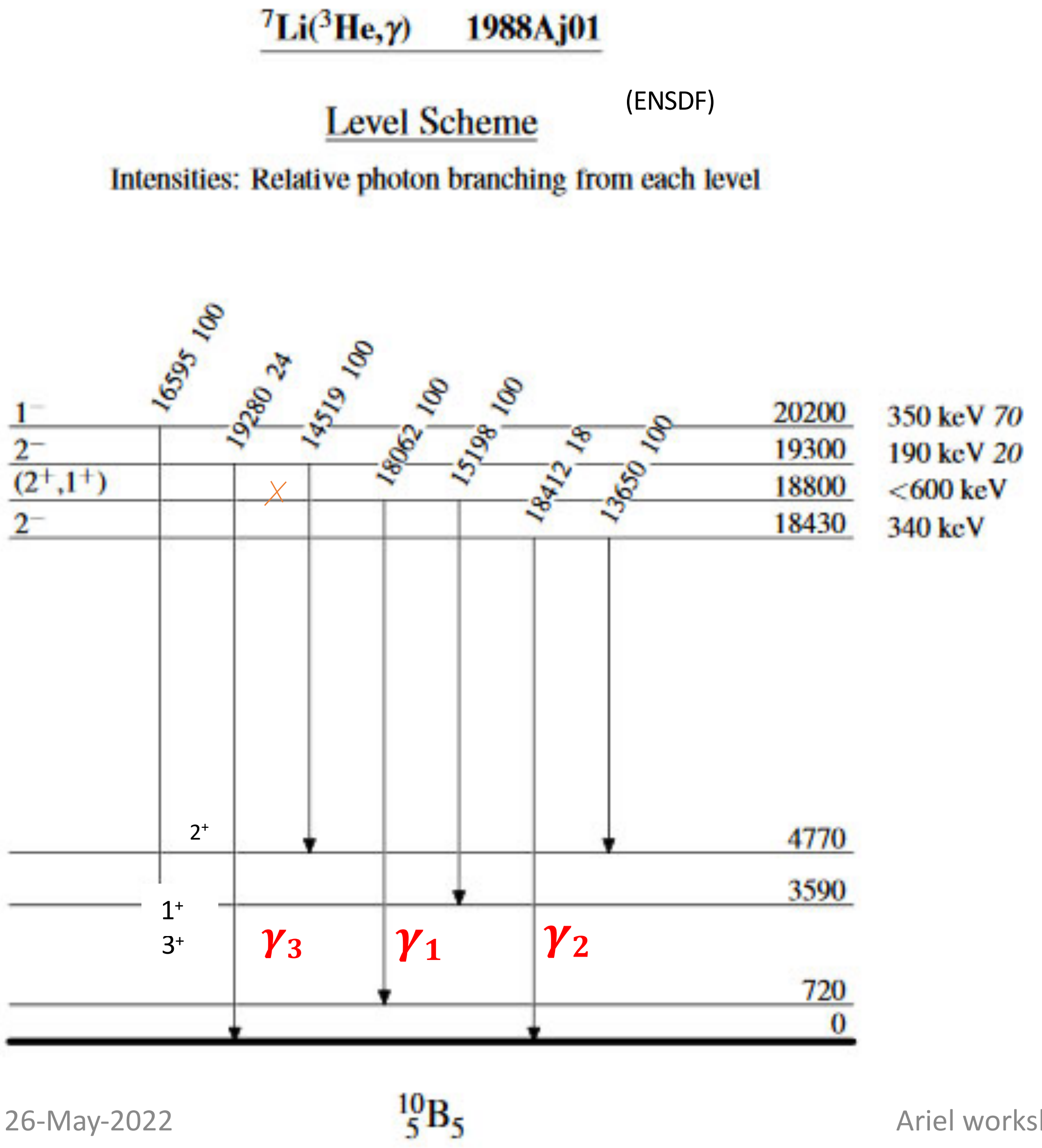


- Has been measured
- Could be measured

- $^{7}Li(p,\gamma)^{8}Be$
- $^{11}B(p,\gamma)^{12}C$
- $^{7}Li(^{3}He,\gamma)^{10}B$
- $^{3}H(p,\gamma)^{4}He$

Modified from J.L. Feng et al; arXiv:2006.01151

Where else can we look?
Interesting Transitions in ^{10}B!



γ_1 : E= 18.1 MeV; BR= 100%; M1/E2/E3

γ_2 : E= 18.4 MeV; BR= 18%; M1/E2/E3/M4/E5

γ_3 : E= 19.3 MeV; BR= 24%; E1/M2/E3/M4

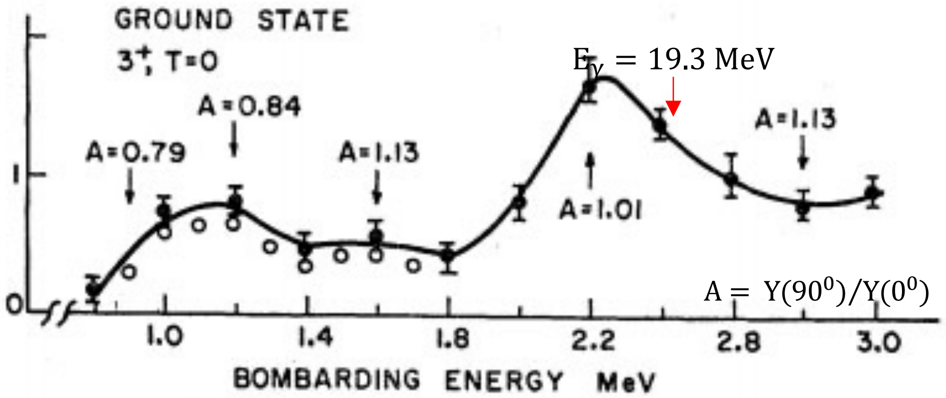
Weisskopf single particle estimates of $\lambda(sec^{-1})$:

$$\frac{\lambda(E1)}{\lambda(M2)} = \frac{10^{14} A^{2/3} E_\gamma^3}{2.2 \cdot 10^7 A^{2/3} E_\gamma^5} = 1.4 \cdot 10^4$$

$$\frac{\lambda(M1)}{\lambda(E2)} = \frac{3 \cdot 10^{13} E_\gamma^3}{7.3 \cdot 10^7 A^{4/3} E_\gamma^5} = 3.5 \cdot 10^5$$

We do have ^3He! (7L @1b)

X - Sections for Radiative Capture of ^{3}He by ^{7}Li



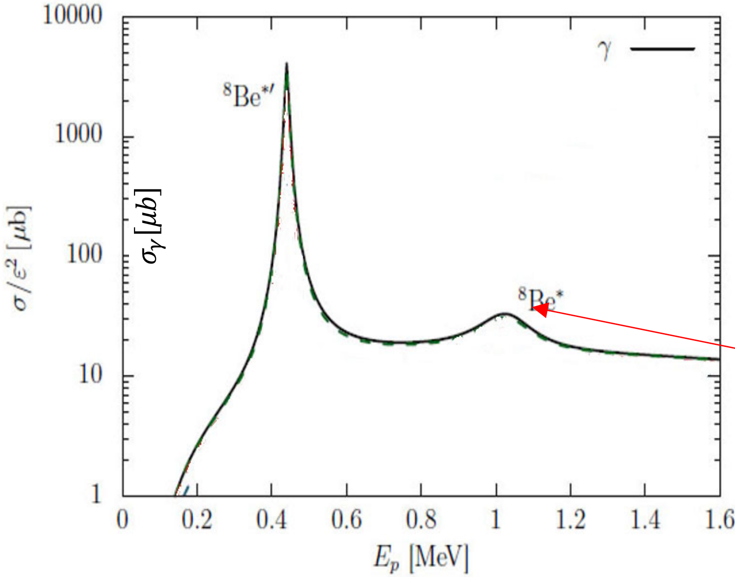


TABLE I. Resonances observed in radiative capture of He³ by Li⁷.

E_{res} (lab) (MeV)	Γ_{tot} (c.m.) (keV)	Final states in B¹⁰ (MeV) and their spins		$\frac{d\sigma}{d\Omega}$ (90°) (μb/sr)	Possible spin-parity assignments[a,b]
1.1	<500	0	3^+	0.8	(1^+), $2^\pm$, 3^+
		4.77	$(2^+,3^+)$	2 3.6	
1.4	<600	0.717	1^+	2.0	(0^+), $1^\pm$, $2^\pm$, (3^+)
		3.59	2^+	2.2	
2.2	$280<\Gamma<420$	0	3^+	1.8	~~(1^+), 2^+, 3^+~~ 2^-
		4.77	$(2^+,3^+)$	5.3	

dσ/dΩ (19.3 → GS) = 1.8 μb/sr → **σ_{tot} = 23 μb**

Comparable to 18.15 MeV resonance in ^{8}Be*!

P. Paul, S. L. Blatt, and D. Kohler Phys. Rev. 137 B493 (1965)

Simulation – $^{10}B^{*}$ (IPC & X17)

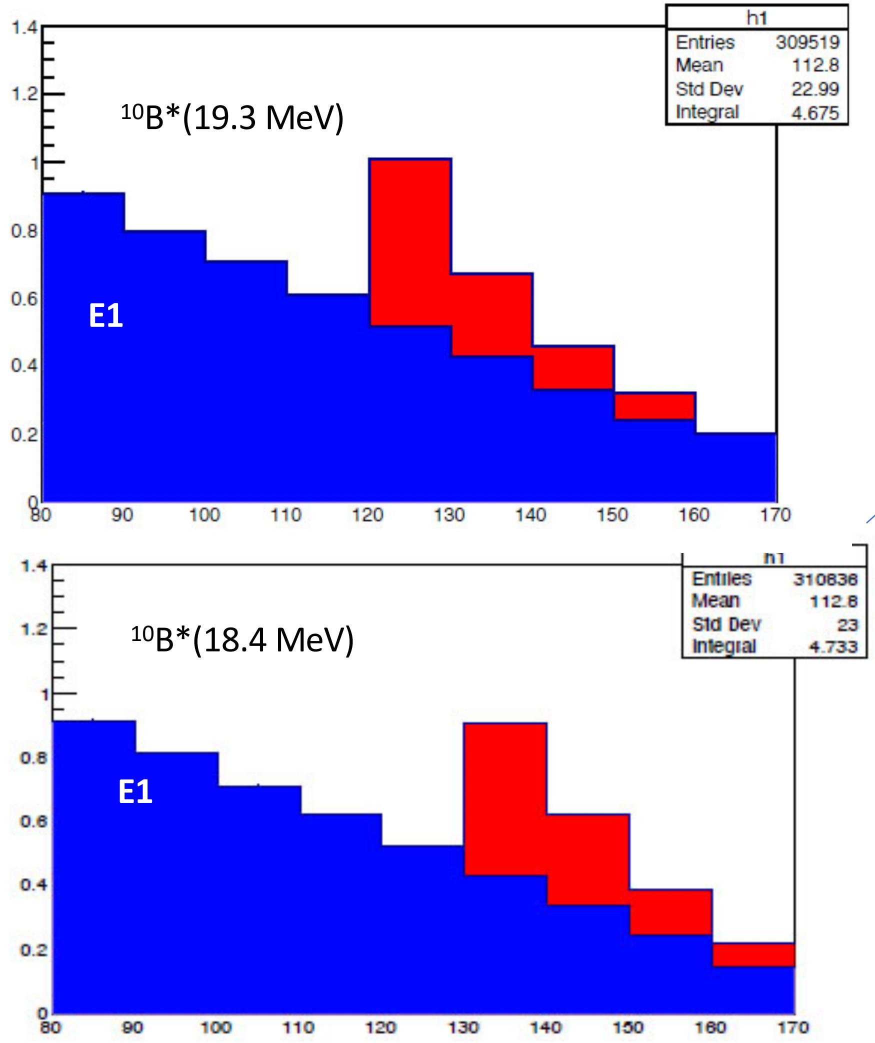
Full detector geometry:

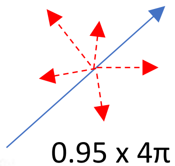
- Assume proto-phobic vector coupling
- E1 transitions @ 19.3/18.4 MeV:

$$B(X/IPC)_{^{10}B} = B(X/IPC)_{^{8}Be} \times (15 \pm 10)$$

Phase space & matrix el. M1 →E1
(derived from Feng et al., 2006.01151
-- needs to be confirmed)

- $S/B\ (in\ ROI) \approx 0.6$ (19.3 MeV)
- $S/B\ (in\ ROI) \approx 0.8$ (18.4 MeV)





0.95 x 4π
acceptance
|y| < 0.5

Opening angle Δθ

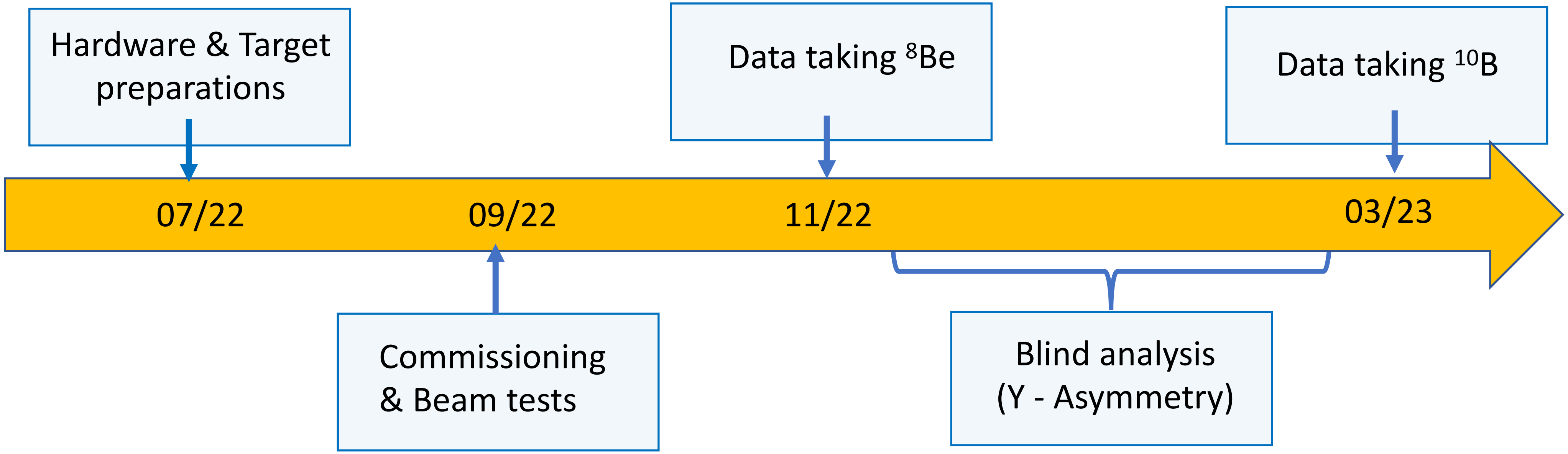
Different shapes of M1 & E1!

X17 – Parameter Space to Explore in Nuclei

Transition	Vector	Axial vector	Scalar	Pseudo scalar	Isospin
^{8}Be: 1^{+} 0^{+} M1-IS	L=1	L=0,2		L=1	ΔT=0
^{8}Be: 1^{+} 0^{+} M1-IV	L=1	L=0,2		L=1	ΔT=1
^{12}C: 1^{-} 0^{+} E1-IV	L=0,2	L=1	L=1		ΔT=1
^{10}B: 2^{-} 3^{+} E1-IV	L=0,2	L=1	L=1		ΔT=1
^{10}B: 2^{+} 1^{+} M1-IV	L=1	L=0,2		L=1	ΔT=1
^{10}B: 2^{-} 3^{+} E1-IV	L=0	L=1	L=1		ΔT=1
^{4}He: 0^{-} 0^{+} M0		L=1		L=0	ΔT=1
^{4}He: 0^{+} 0^{+} E0	L=1		L=0		ΔT=0

Variety of measurements could help pin down the nature of the X17 boson

The Montreal X-17 Project - Strategy



Conclusions

- UdeM – experiment for independent & timely verification of results from the ATOMKI collaboration in IPC from Be*

- Experimental setup progressing and in good shape

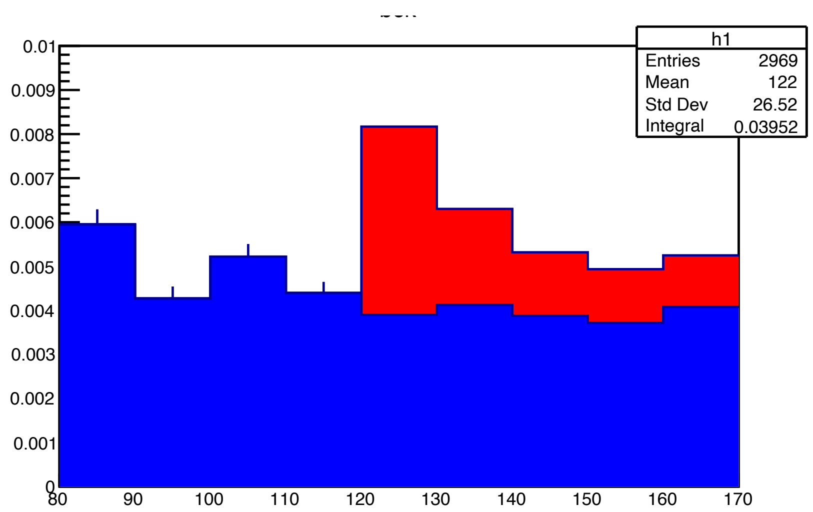
- Large solid angle increases coverage of param. space (V, AV P, PS)

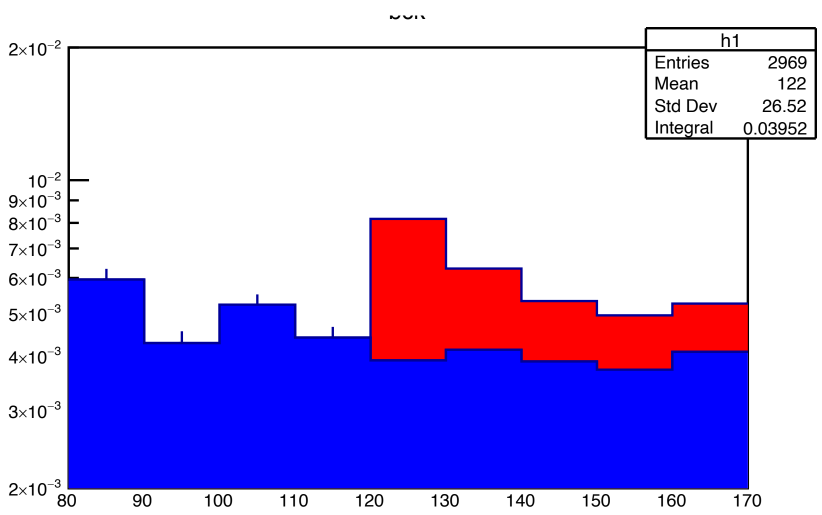
- Considering for next stage:
  - use second MWPC
  - Extend to other states & nuclei: ^{10}B(17.8), ^{10}B(19.3), ^{4}He (22 MeV), ^{12}C(17.2)

- Other searches: New JEDI, NuCReX17, Darklight, MAGIX, Na64, SHiP, SeaQuest, LHCb, PADME…
  (see INFN workshop, Sept. 2021)

Backup

$^{10}\mathrm{B}(19.28)$ *factor 15*

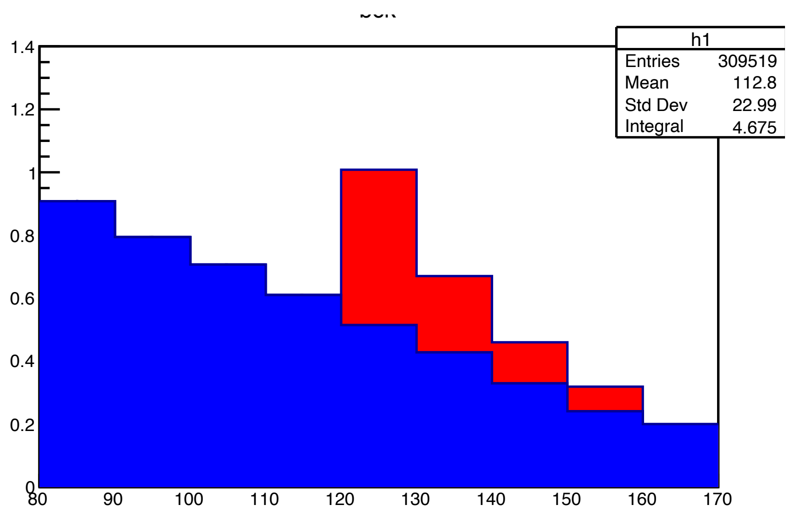


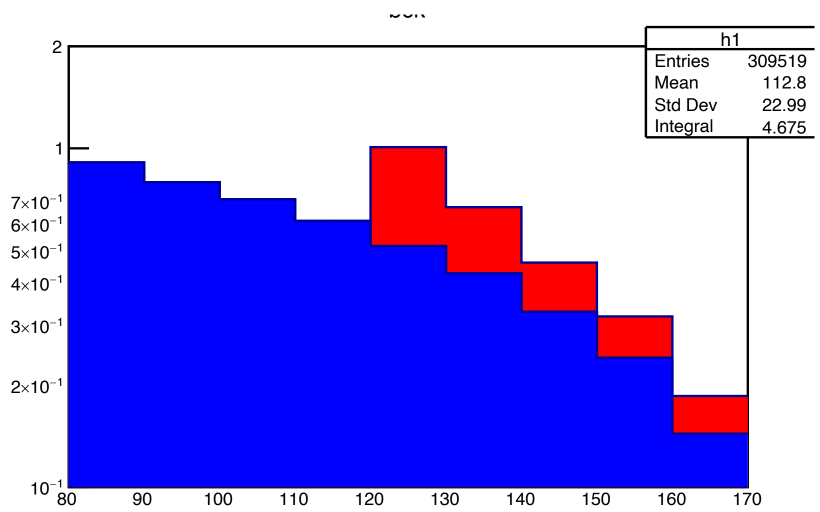


ring

$|\cos(\theta)| < 0.1$

$|y < 0.5|$





4π geometry

$|y < 0.5|$

Simulation – $^{10}B^*$ (IPC & X17)

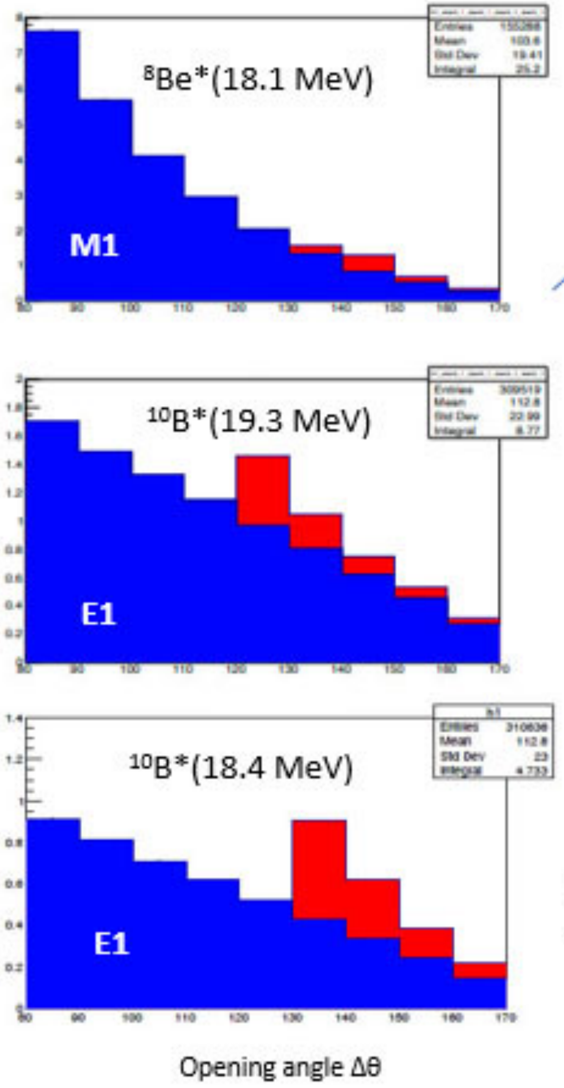
- Assume proto-phobic vector coupling
- X17: M = 17 MeV/c^2
- 10^4 events generated
- |y| < 0.5; acceptance: 0.9 x 4π

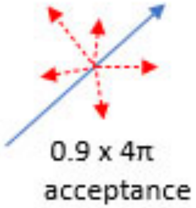
^{8}Be- Branching ratios

$$\frac{B(IPC/\gamma)}{B(X/\gamma)} = \frac{0.0039}{5.8 \times 10^{-6}} \times 15$$

Phase space & matrix el. M1 → E1

$\frac{S}{B} \approx 0.5$ (19.3 MeV)





....all plots in linear scales!

Different shapes of M1 & E1!

M1 concentrates at smaller opening angles!

Collecting PMT energy data in COL FPGA from FPGA#7