RIKEN NiSHiNA CENTER

SHOGUN

a next generation γ ray spectrometer for fast beams at the RIBF

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SHOGUN

S cintillator based
H igh-res**O**lution
O
G amma-ray spectrometer for
U nstable
N uclei

- γ ray spectrometer optimized for **in-beam** γ ray spectroscopy at **RIBF beam energies**
- Construction proposal submitted to last NP-PAC (Dec. 2009)

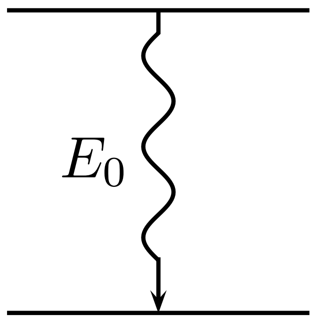
Doppler Shift and Broadening

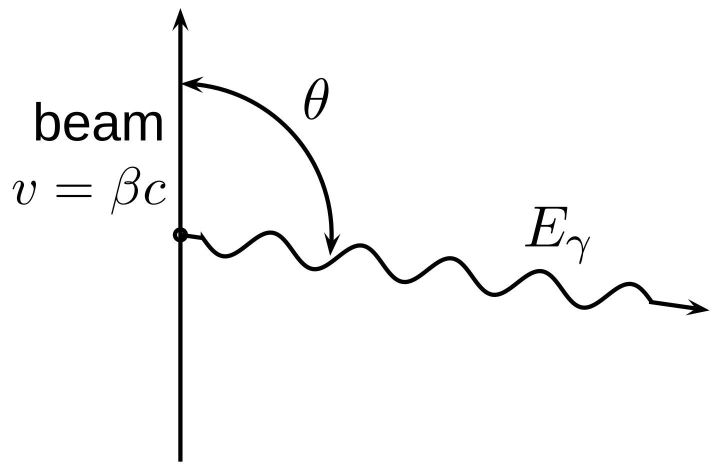
Doppler Shift

- Lorentz transformation of 4-momenta between laboratory frame and frame of emitting nucleus

$$E_\gamma = \frac{E_0}{\gamma(1-\beta\cos\theta)} \qquad d\Omega_0 = \left(\frac{E_\gamma}{E_0}\right)^2 d\Omega$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$





Doppler Broadening

Due to:

- uncertainty in beam velocity β: $\Delta\beta$
- uncertainty of emission angle θ: $\Delta\theta$

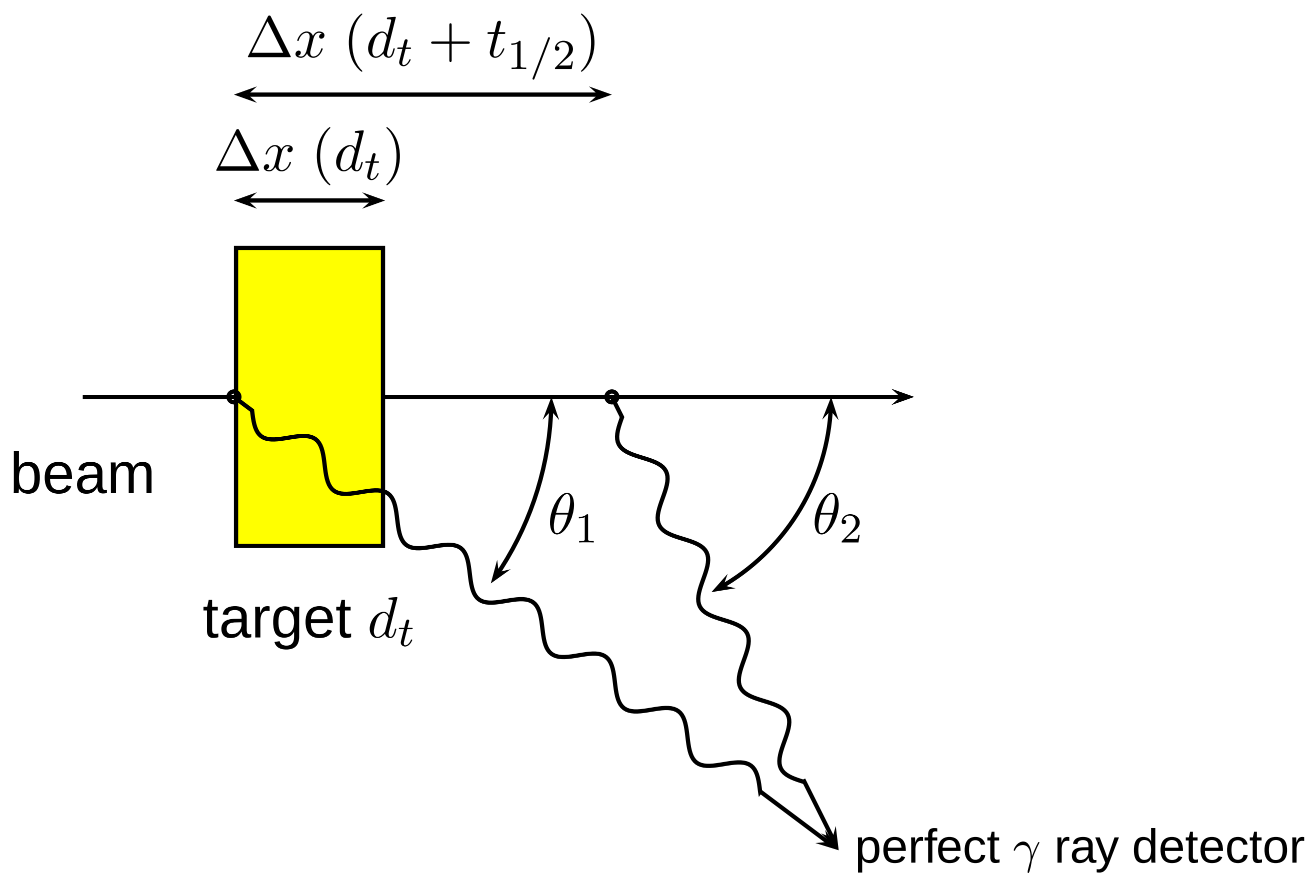
$$\Delta E^2 = \left(\frac{\partial E}{\partial \beta}\right)^2 \Delta\beta^2 + \left(\frac{\partial E}{\partial \theta}\right)^2 \Delta\theta^2$$

$$\frac{1}{E}\frac{\partial E}{\partial \beta} = \frac{\cos(\theta)}{1-\beta\cos(\theta)} - \beta\gamma^2$$

$$\frac{1}{E}\frac{\partial E}{\partial \theta} = \frac{\beta\sin(\theta)}{1-\beta\cos(\theta)}$$

- must reduce $\boldsymbol{\Delta}\beta$ and $\boldsymbol{\Delta}\theta$

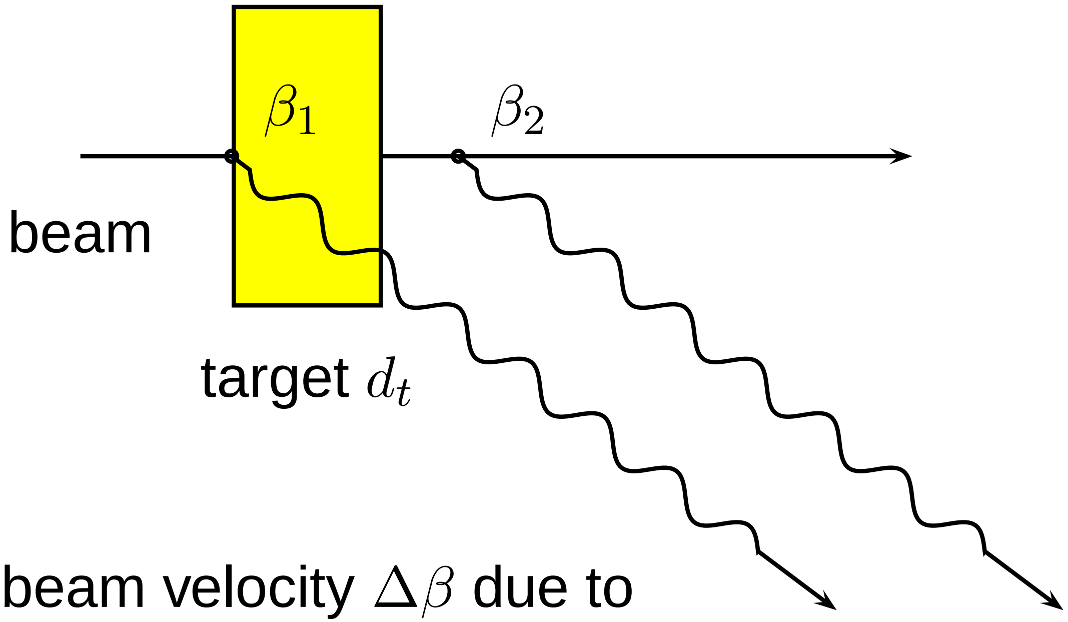
Doppler Broadening: Emission Angle



Uncertainty Δx of point of γ emission due to

- target thickness: $d_{\mathrm{t}} \sim 1 \ldots 20$ mm
- γ decay in-flight: 100 ps ➨ 15 mm

Doppler Broadening: Velocity



Uncertainty in beam velocity $\Delta\beta$ due to

- energy loss in the target: $\Delta E \sim 10\text{–}20\%$

$$\frac{\Delta\beta}{\beta} \sim \begin{cases} 5\text{–}10\% & \text{if } \gamma\beta t_{1/2} < d_t \\ \text{small} & \text{if } \gamma\beta t_{1/2} > d_t \end{cases}$$

- very small uncertainty in beam velocity vector $\vec{\beta}_2$
  - beam mom. spread and reaction mech. do not contribute to $\Delta\beta$

Doppler Broadening: Summary

- There is a sizable **Doppler broadening** even with a perfect detector, due to an **uncertainty**
  - in the **beam velocity** and (energy loss in the target)
  - in the **emission point** of the γ ray (target thickness, lifetime of excited state)
- These contributions are **not due** to detector properties.

In-beam γ ray Spectroscopy at the RIBF

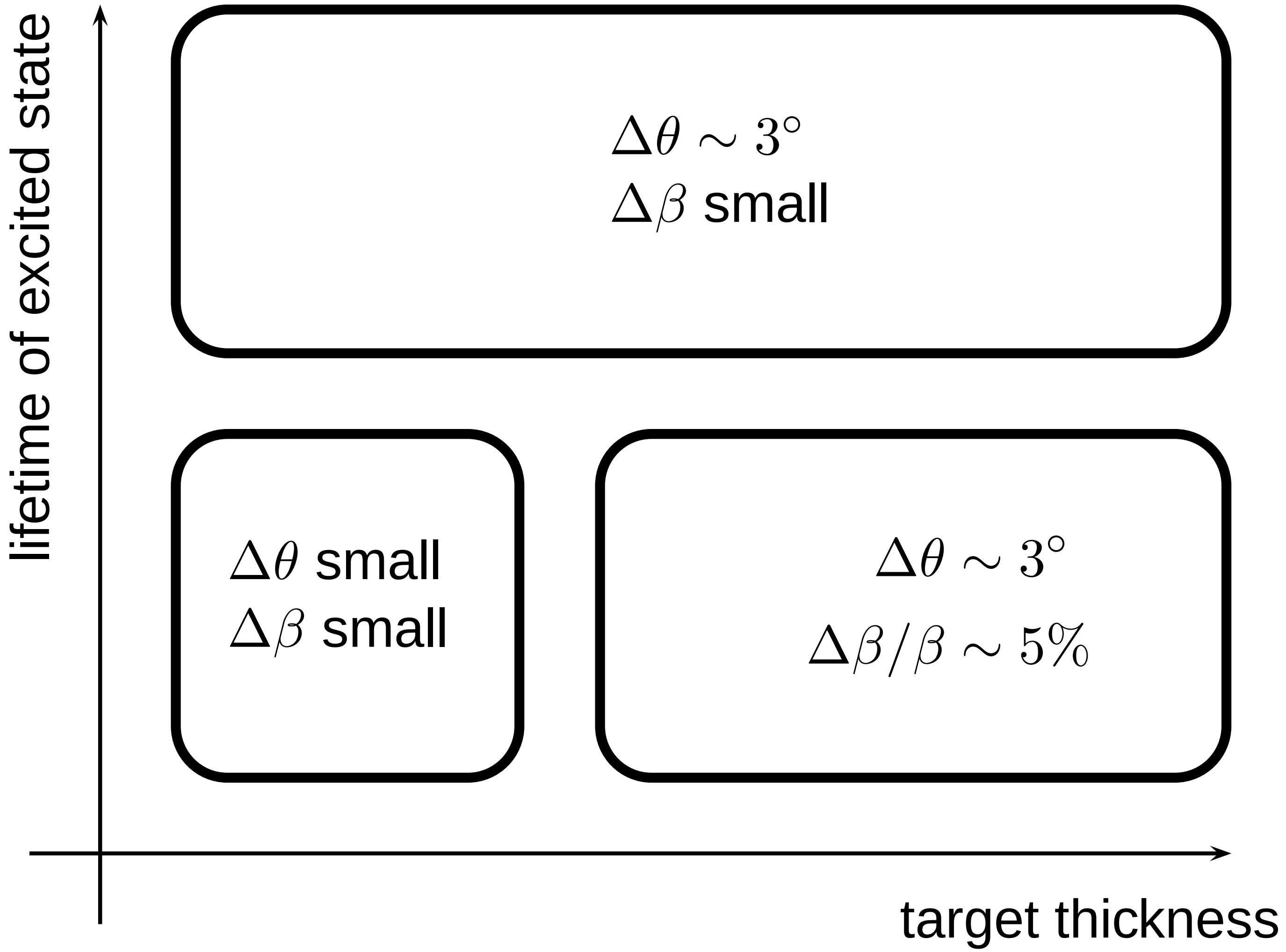
Boundary Conditions

for in-beam γ ray spectroscopy at the RIBF:

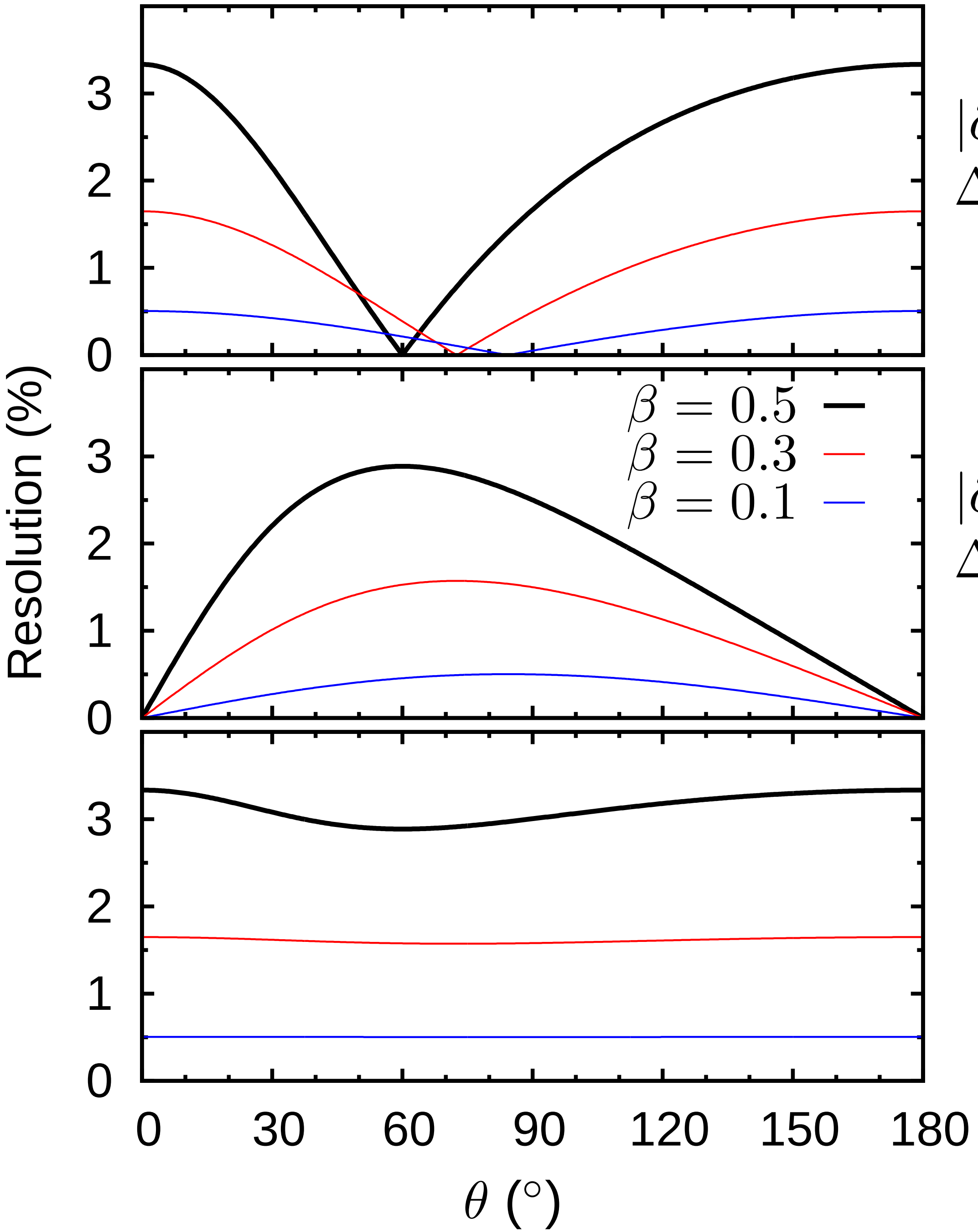
- beam energy: 200 MeV/u $\quad v/c = \beta = 0.5$
- target thickness: $d_{\mathrm{t}} \sim 1 \ldots 20$ mm
- γ decay in-flight: 100 ps ➨ 15 mm
- achievable angular resolution: $\Delta\theta = 3^\circ = 50$ mrad
  (assuming a detector distance of 25 cm)
- 10–20% energy loss in target: $\Delta\beta = 5$–10%
- NB: $\Delta\theta$ does not include detector contributions

Angular and Velocity Uncertainties

for in-beam γ ray spectroscopy at the RIBF:



Doppler Broadening



$|\partial E/\partial \beta| \cdot \Delta\beta$
$\Delta\beta/\beta = 5\%$

$|\partial E/\partial \theta| \cdot \Delta\theta$
$\Delta\theta = 50$ mrad

achievable
energy resolution:

3%

Which Detector?

Which detector should be used?

RIKEN	CNS GRAPE	**OR**	DALI2
MSU	SeGA	**OR**	CAESAR/APEX
GSI	RISING	**OR**	HD-DA Crystal Ball
GANIL	EXOGAM	**OR**	Chateau de Cristal
	HPGe based	**OR**	scintillator based
	(good) resolution	**OR**	good efficiency

Problems of Current Arrays

(for in-beam γ ray spectroscopy with fast beams)

- HPGe
  - high intrinsic resolution cannot be utilized
  - very high cost for high efficiency array
  - large operational costs
- Scintillator (NaI(Tl), CsI(Tl), CsI(Na))
  - very poor energy resolution
- both
  - relatively poor time resolution
  - count rate is limited

Lanthanum Bromide

Which detector?

$LaBr_3$(Ce) based detectors!

$LaBr_3$(Ce)

- new scintillation crystal invented in 2001 by Delft University, Netherlands; licensed to Saint-Gobain
- marketed under name: Bril**La**n**Ce** 380
- most remarkable property:
  - energy resolution of **2.6%** at 662 keV
  - compare to NaI(Tl): 6.5%
- but, until recently no large(ish) crystals
  - strong anisotropic thermal expansion (a-axis: 22 ppm/K; c-axis: 8 ppm/K)
    - prone to cracking during cooling after growth
- now: “127 mm ingots . . . are routine” (Saint-Gobain)

$LaBr_3$(Ce)

- comparison to common scintillators:

	NaI(Tl)	BaF_2	$LaBr_3$(Ce)
Light Output (1/keV)	38	2 10	**>71**
Decay Time (ns)	250	.7 630	**16**
Z	11, 53	56, 9	57, 35
Density (g/cm^3)	3.67	4.88	**5.1**
Temp. Coef. (%/K)	-0.3	0 1.1	**0.0**
Max. Sc. Wavel. (nm)	415	220 310	380
Energy Res. (%)	7	12	**2.5**
Time Res. (ns)	2.5	0.2	**0.2**
Linearity	low	low	**very high**
Hygroscopic	yes	no	yes

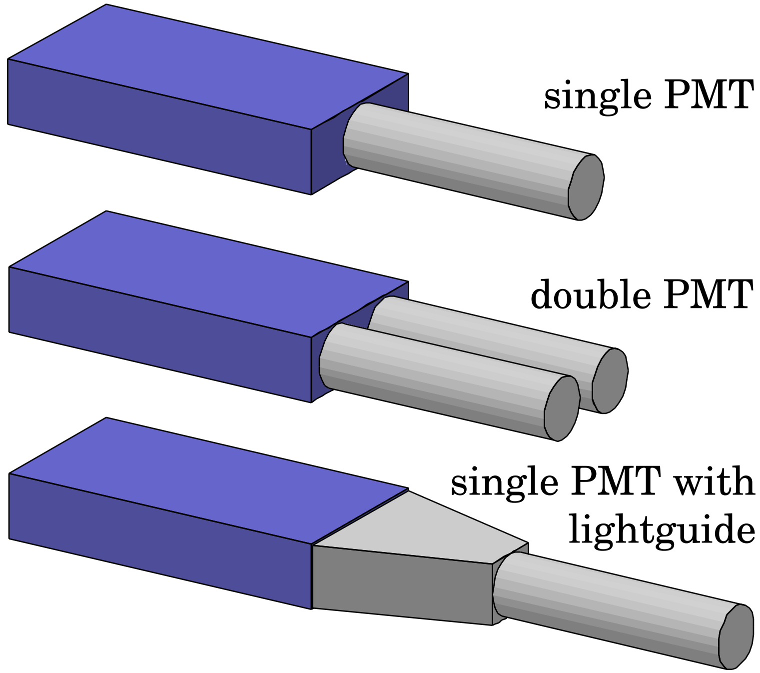
- for same detector volume

$$\epsilon_{FEP} \propto \rho^{1.5} \times Z^{3.5}$$

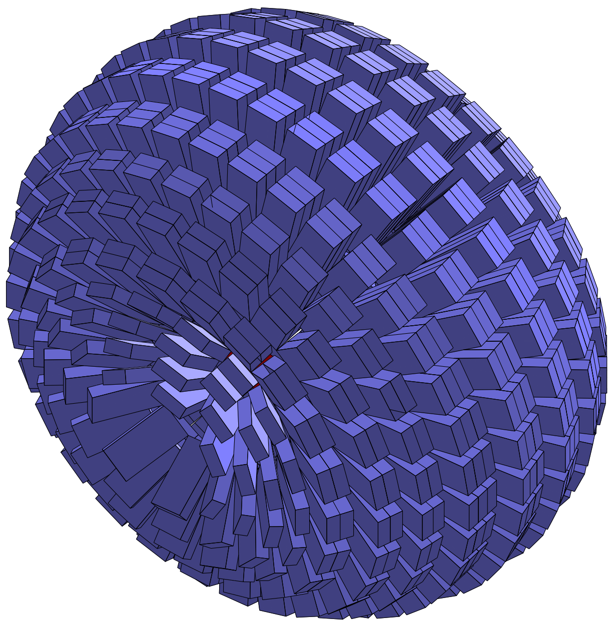
SHOGUN

Detector Shape

- only one detector shape to reduce detector design/development cost
- possibly place 2–3 detector in one housing, to reduce inactive material
- cuboid: 1.5 cm $\times$ 4 cm $\times$ 8 cm

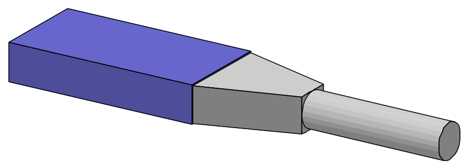


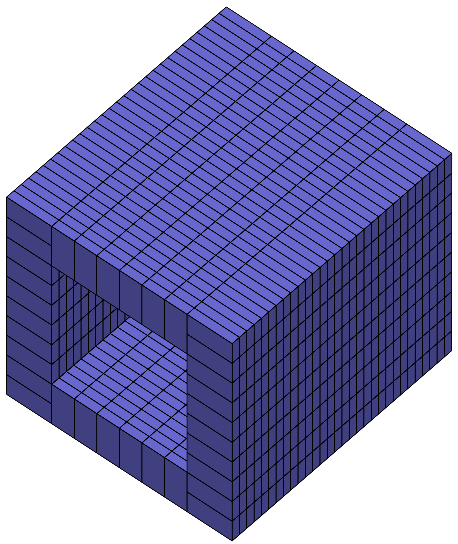
Possible Configurations



fast beam setup ($v = 0.6c$)			
	$\frac{\Delta E}{E}$ (%)	ϵ_γ (%)	$\epsilon_{\gamma\gamma}$ (%)
NaI(Tl) DALI2	10.0	23.5	5.5
RISING	1.9	2.8	0.08
SHOGUN 1000	**3.2**	**35.0**	**12.2**

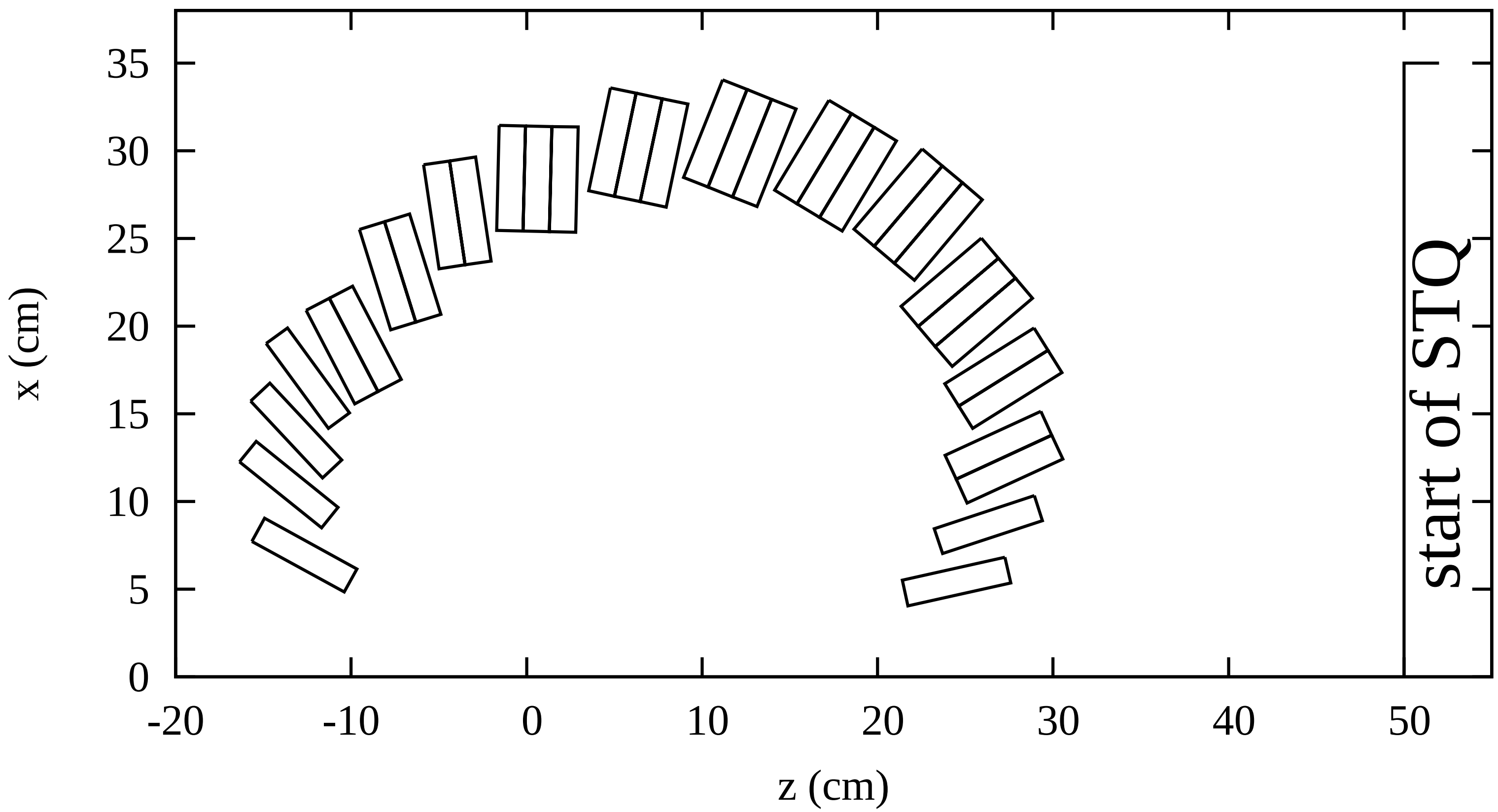
$8 \times 4 \times 1.5$ cm^3





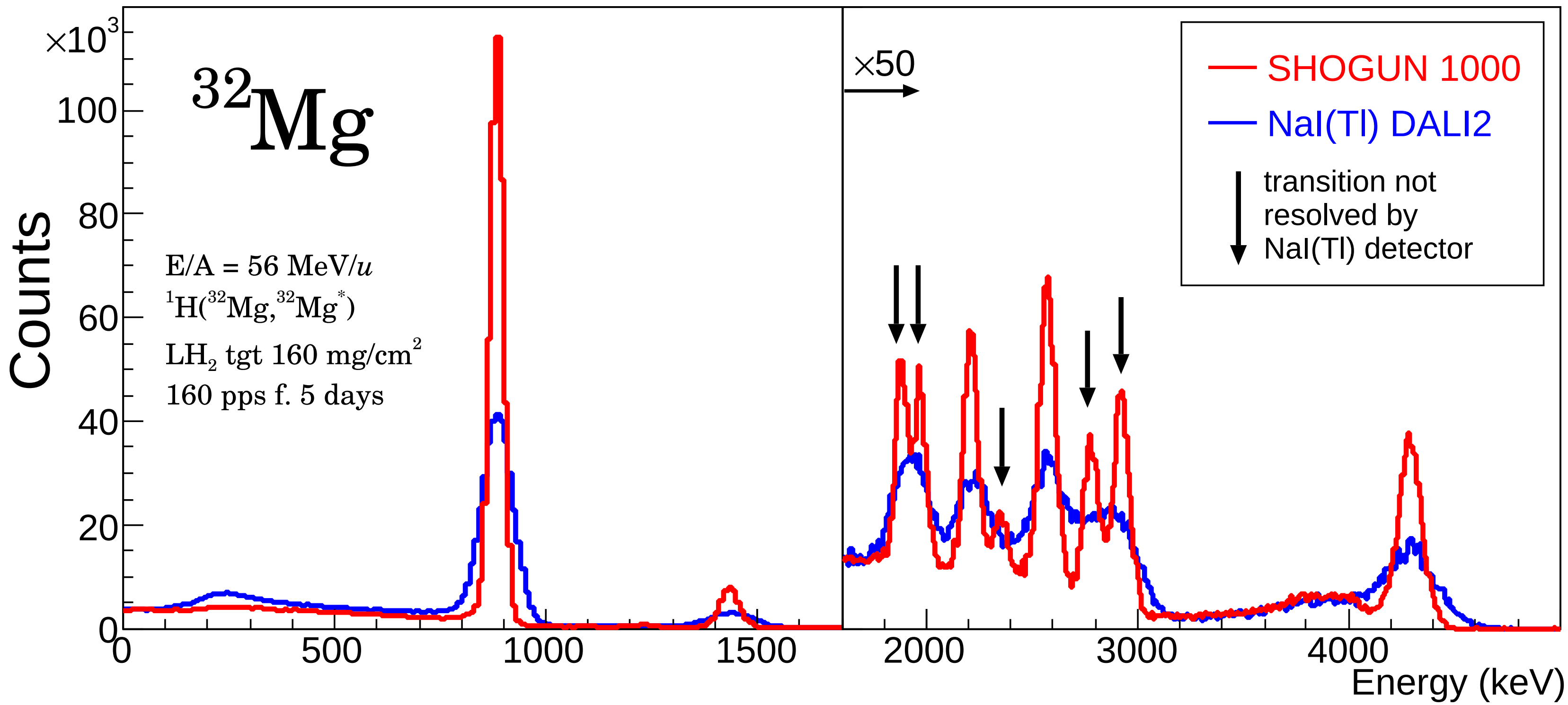
slow/stopped beam setup			
	$\frac{\Delta E}{E}$ (%)	ϵ_γ (%)	$\epsilon_{\gamma\gamma}$ (%)
RISING	0.2	15.0	2.25
SHOGUN 1000	2.4	**56.0**	**31.3**

Setup at F8



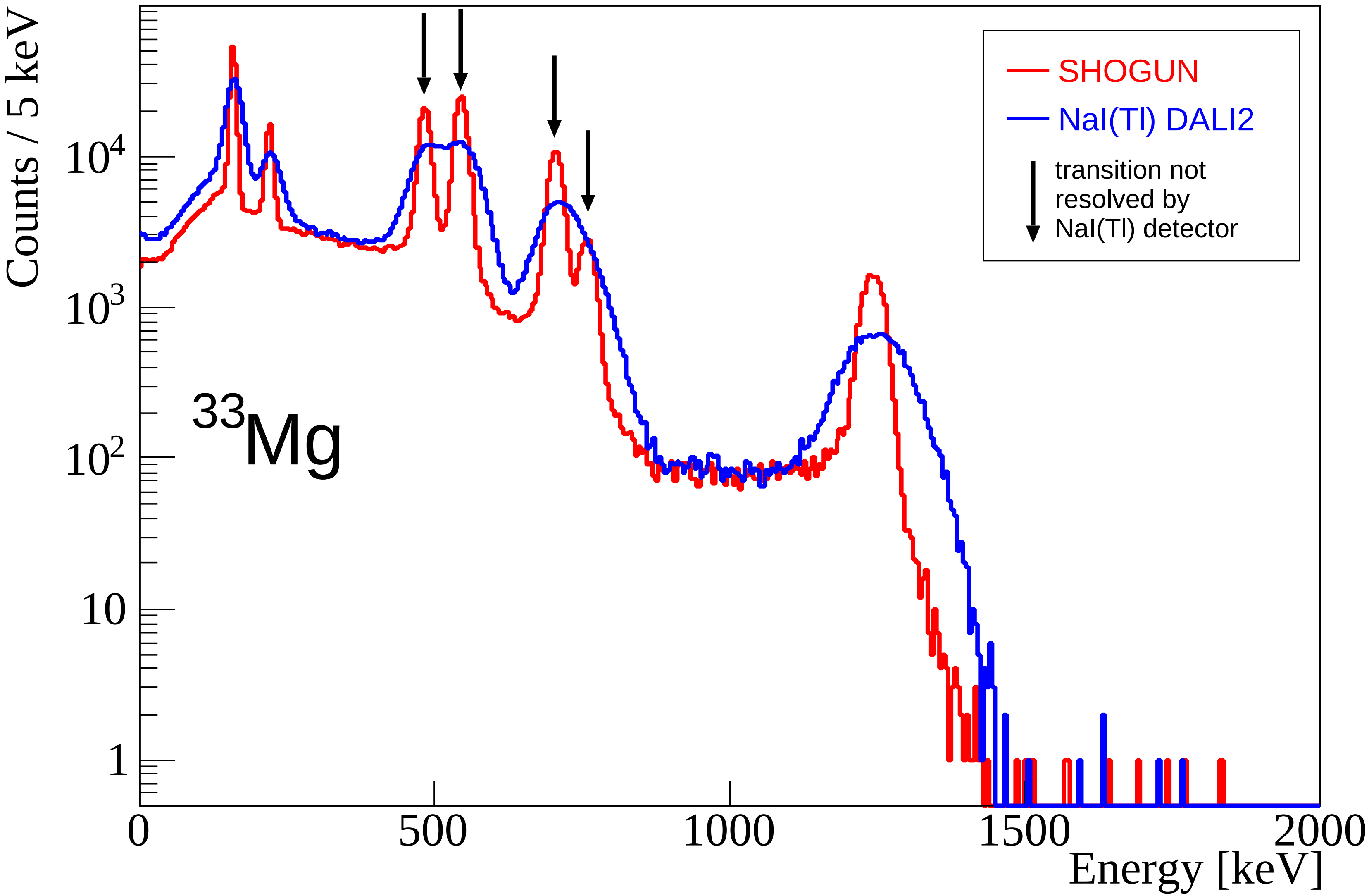
- easily fits at high acceptance position of ZeroDegree
- standard HPGe cannot be accommodated at forward angles

Simulation: SHOGUN 1000 and DALI2



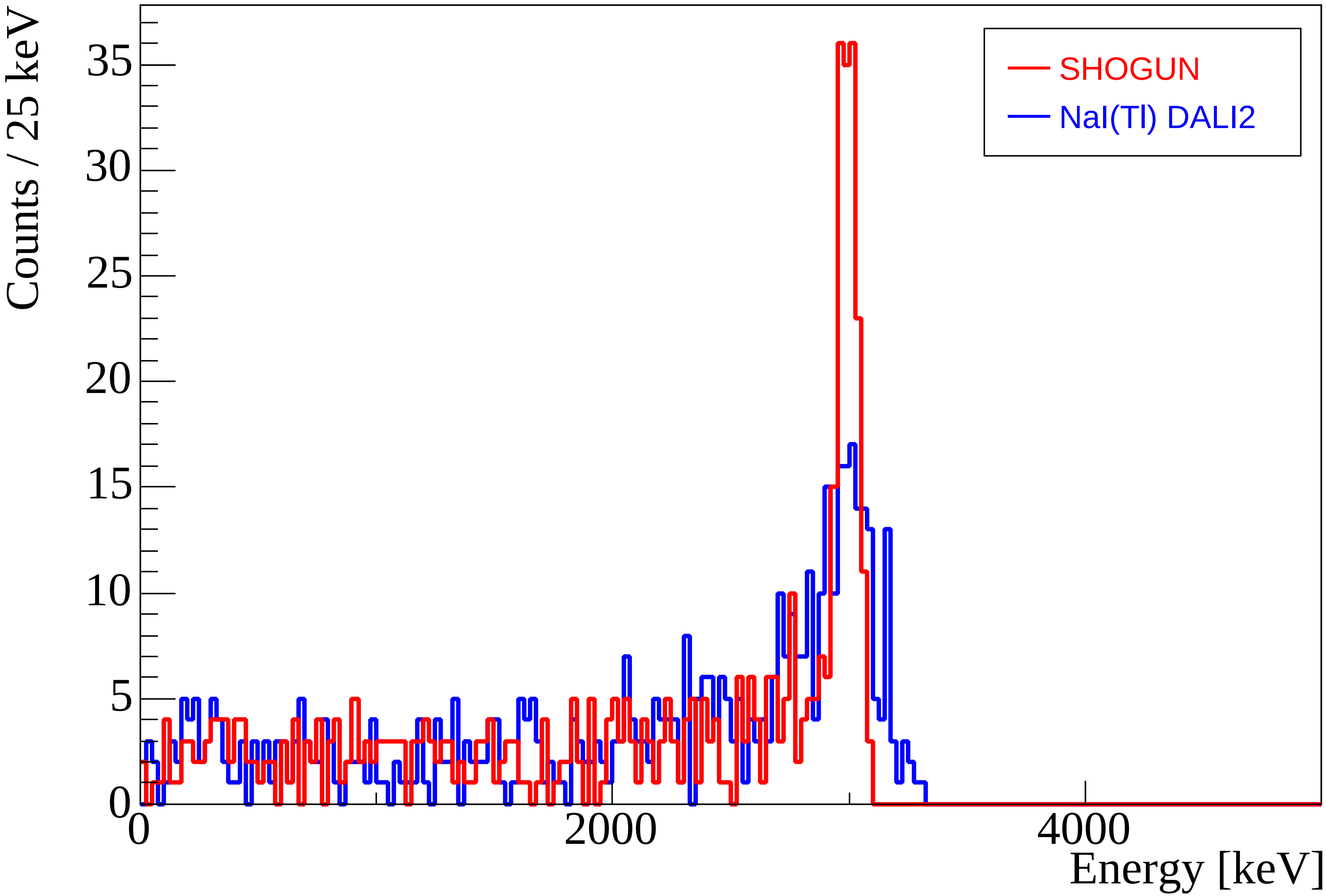
Simulation by P. Doornenbal
based on experimental data of
S. Takeuchi *et al.*, PRC 79, 054319 (2009)

Simulation: SHOGUN 1000 and DALI2



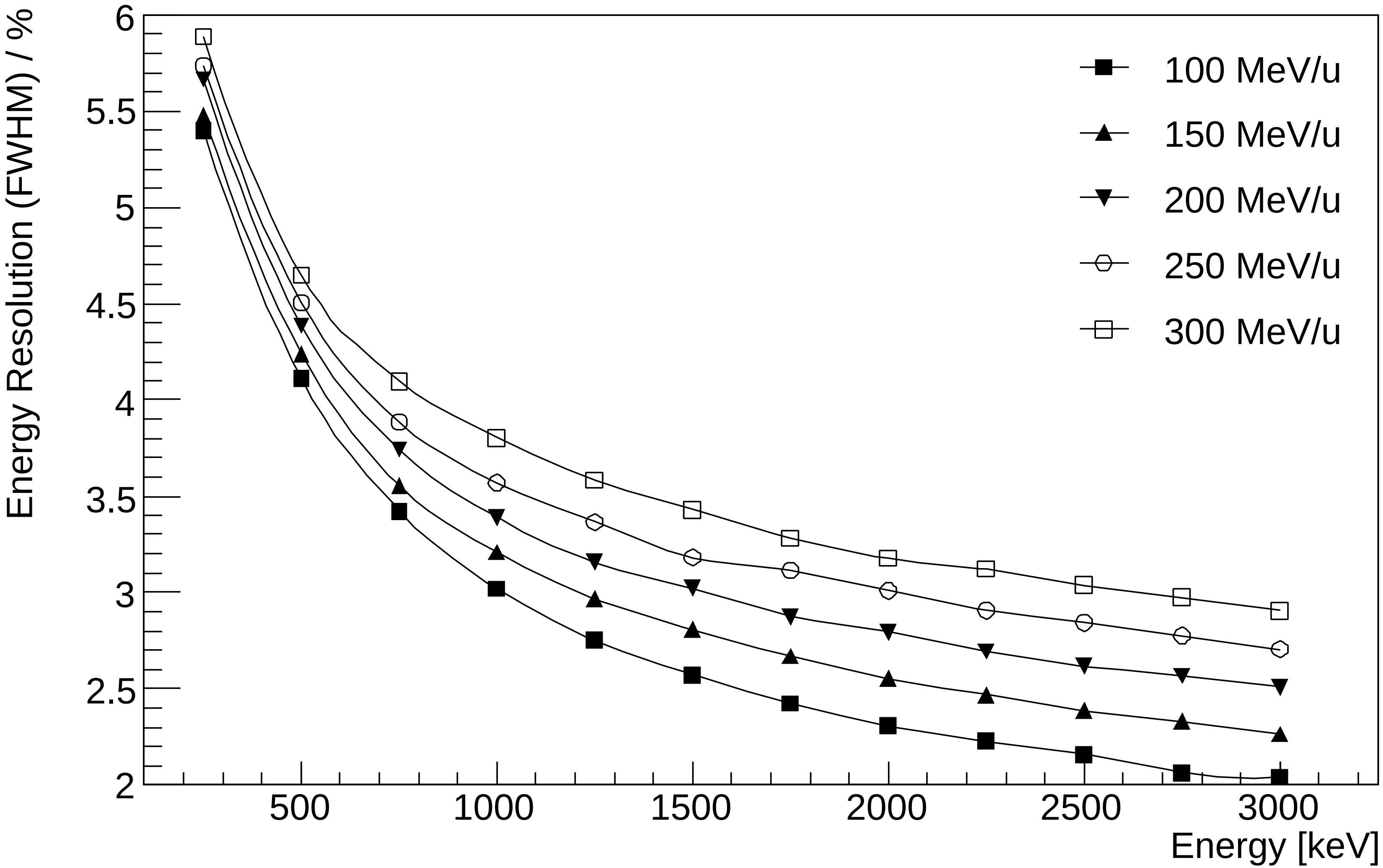
- E/A = 250 MeV/u
- 1n-removal from ^{34}Mg

Simulation: SHOGUN 1000 and DALI2



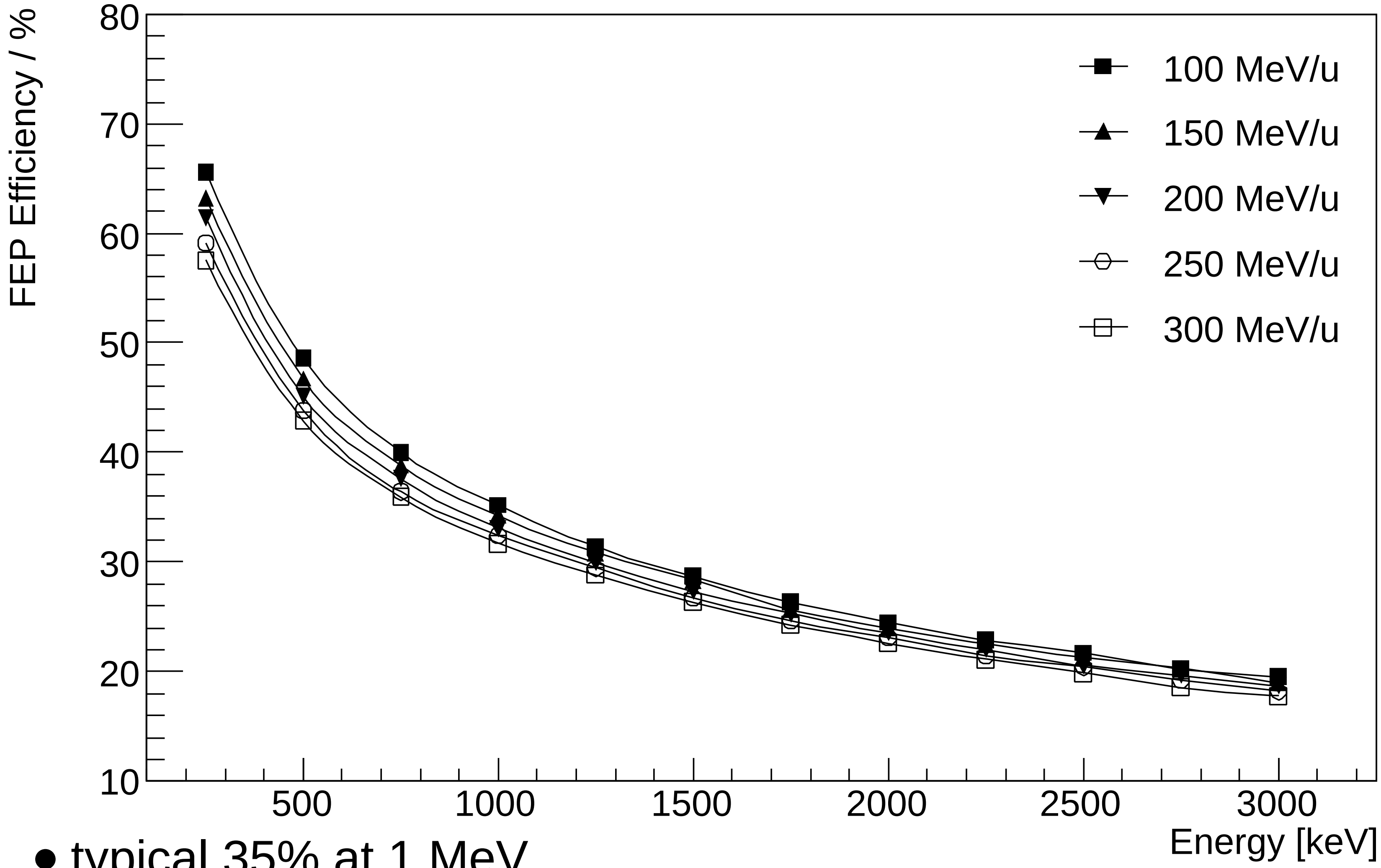
- E/A = 250 MeV/u
- high-energy γ ray with low statistics

Energy Resolution



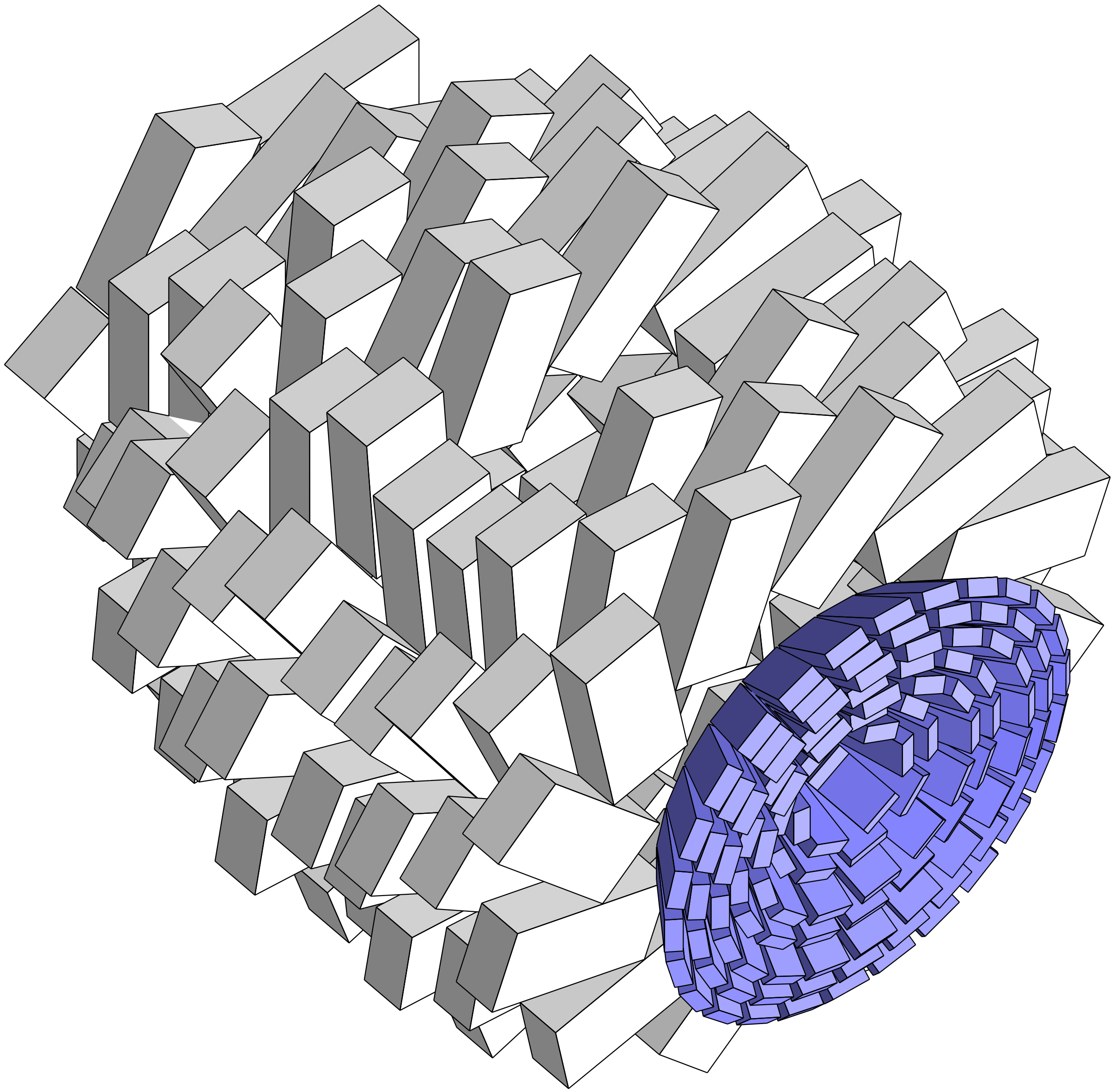
- typical: 3.5% at 1 MeV

Full Energy Peak Efficiency



- typical 35% at 1 MeV
- can still be increased by
  - longer crystals (8 cm ➡ 10 cm)
  - tapered crystals, eps. for forward angles

SHOGUN 100 and DALI2



Problems

Procurement and Patent Issues

- only one supplier: Saint-Gobain
  US patent 7,067,816 B2 claims
  - $La_{1-x}Ce_xBr_3$ with $2\% < x < 90\%$
  - single crystal > 10 mm^3 grown using Bridgeman process

Alternatives

Alternatives (1)

- $LaCl_3$(Ce): it seems there is no patent, but
  - **worse resolution** of 3.8% at 662 keV
  - relatively **strong slow component** in light output
  - high **temperature coefficient** (0.7%/K)
  - **low density**
- $LaBr_3$(Ce)
  - who can produce $LaBr_3$(Ce) detectors
    - produce it ourselves?
    - when will patent expire (???)
  - larger detectors with position sensitivity?

Alternatives (2)

- liquid Xe detectors?
  - scintillator + electron drift
  - exellent energy resolution
  - who has experience?
- $SrI_2(Eu)$:

	Z_{eff}	Light Yield (photons/MeV)	Energy Resolution (662 keV)	Emission Range	Decay Time (ns)	Non-propor
SrI_2:0.5% Eu^{2+}	50	68,000	5.3%	~400-460	1,100	4.8%
SrI_2:2% Eu^{2+}	"	84,000	3.9%	"	"	6.2%
SrI_2:5% Eu^{2+}	"	120,000	2.8%**	"	"	2.0%
SrI_2:8% Eu^{2+}	"	80,000	4.9%	"	"	5.1%
$LaBr_3$:Ce	45.7	63,000*	2.8%*	~325-425	15(97%),66(3%)	4% (60-12
SrI_2:0.5% Ce^{3+}/Na^+	50	16,000	6.4%	~350-475	25(47%),159(53%)	8% (60-12
SrI_2:2% Ce^{3+}/Na^+	"	11,000	12.3%	"	32(46%),450(53%)	6% (60-12

  - e.g. Wilson *et al.*, Proc. of SPIE Vol. 7079 707917 (2008)
  - no patent
  - so far only very small crystals

Light Conversion

Photo Multiplier Tubes

- low quantum efficiency
- high gain
  - too high for $LaBr_3$(Ce)
  - light output of $LaBr_3$(Ce) a factor of **25** larger than NaI(Tl)
- low gain (only few dynodes) PMT needed
- probably still the best choice
- alternative are ...

Si-based Light Conversion

- (p-i-n) photo diode (PD)
  - high quantum efficiency
  - no gain
  - capacitance scales with detection area
- avalanche photo diode (APD)
  - same as PD but gain of about 100
  - recently high resolution with $LaBr_3$(Ce) obtained
  - but, only small size (few mm)
- silicon drift detectors (SDD)
  - high quantum efficiency
  - low capacitance independent of area
  - best resolution expected of 2.15% at 662 keV
    (Moszynski *et al.*, IEEE Trans. Nucl. Sci.)
  - but, time resolution not good

Summary

Current Status

- in contact with other groups: PARIS, Milano group
- prototype detectors being manufactured by Saint-Gobain
- SHOGUN workshop on Feb. 4-5
  - expand physics program
  - use at other (Japanese/East-Asian) facilities
- open questions
  - energy resolution of SHOGUN detectors
  - price per detector
  - funding: **?**

Summary

- We propose to build a next-generation **S**cintillator based **H**igh-res**O**lution **G**amma-ray spectrometer for **U**nstable **N**uclei (SHOGUN)
- advantages (fast beam)
  - high (optimum) resolution (3.5% FWHM at 1 MeV)
  - very high FEP efficiency (35%)
  - fast timing
  - **easy operation**
  - **very low running cost**
- workhorse for in-beam γ ray spectroscopy at the RIBF

The End