The upgrade of the Belle II forward calorimeter

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on behalf of

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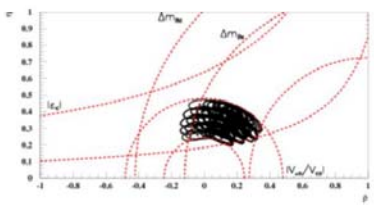
Outline

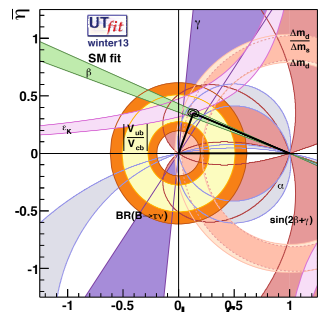
- Motivation for Belle II calorimeter upgrade, focusing on the forward region
- Characterization of optical properties and radiation hardness of CsI crystals
- R&D on photodetectors, wavelenght shifters and read-out electronics
- Impact of pile-up from cosmic ray data and simulations

From Belle to Belle-II

- Precision measurements, performed at B factories BaBar and Belle, crucial in understanding the Standard Model in the last decade

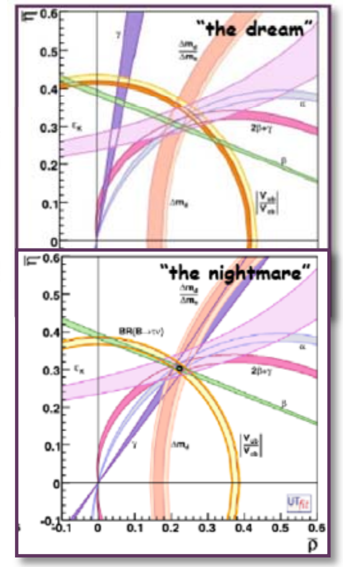


UT triangle before B factories…



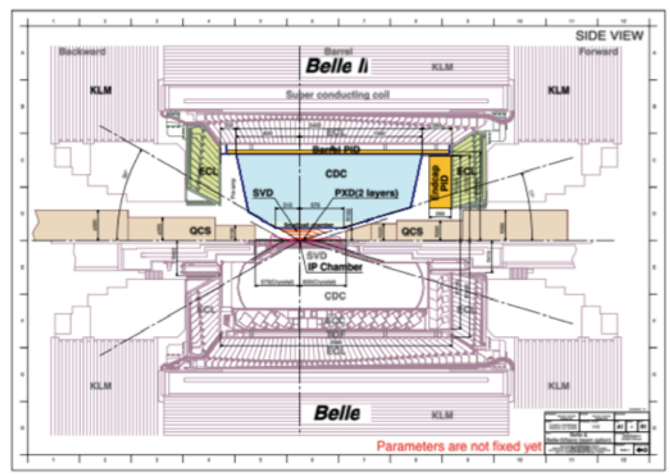
..and after

what's next?



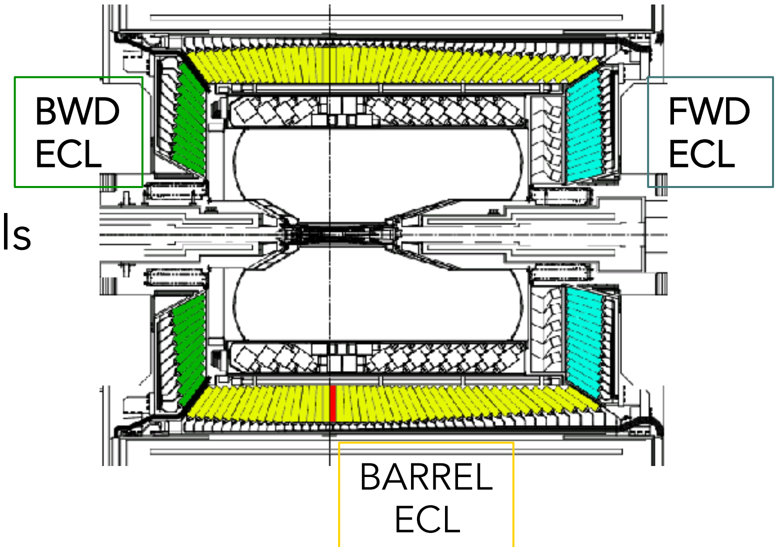
- 2^{nd} generation B factory: From KEKB to SuperKeKB
  - upgrade of the KEKB accelerator (Tsukuba, Japan)
  - 40x luminosity, 50 ab^{-1} in 10 years of data taking

- From Belle to Belle-II: upgrade of the detector to cope with higher particle rate while maintaining ~ same or better performances on physics

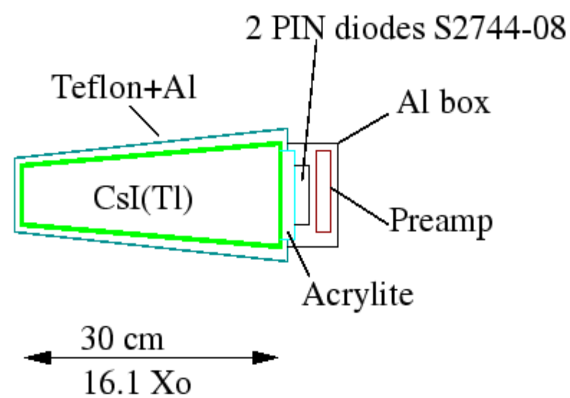


Belle II Electromagnetic calorimeter

- 1/3 of B decay products = π^0 or other neutrals producing γ in [0.02,4] GeV energy range



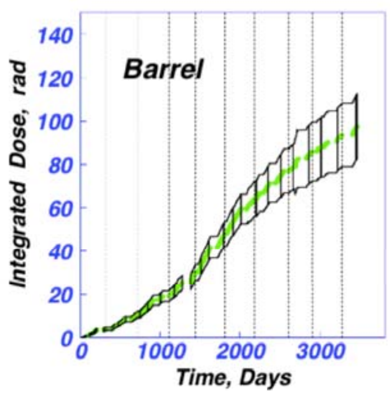
- Reuse Belle Electromagnetic Calorimeter (ECL)
  - 8736 300x(50-80)x(50-80) mm^3 CsI(Tl) crystals
  - 10x20 mm^2 PIN photodiodes, 2 x crystal
  - CSP+ CR-$(RC)^4$ shaper with τ=1μs
  - Light Output = 5K p.e./MeV
  - Equivalent noise energy~ 200keV
  - Performances (E in GeV): $\frac{\sigma_E}{E} = \sqrt{\left(\frac{0.066\%}{E}\right)^2 + \left(\frac{0.81\%}{\sqrt[4]{E}}\right)^2 + (1.34\%)^2}$
    (2% @ 100 MeV)

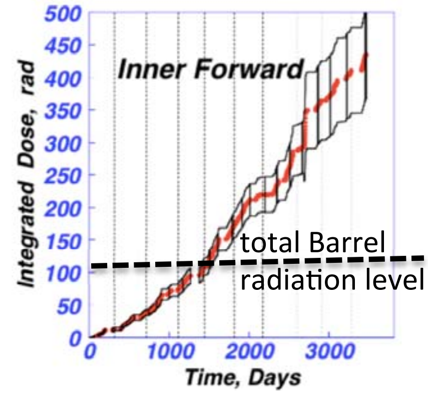


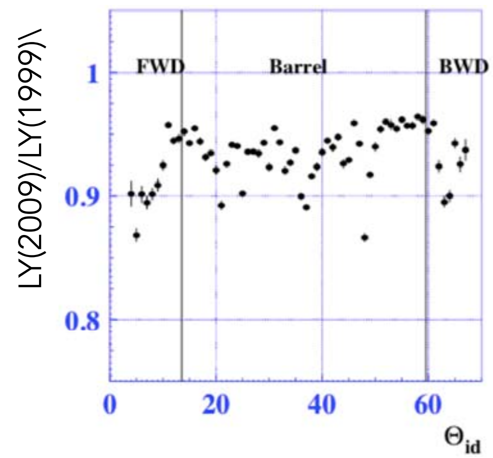
Running ECL at higher luminosity

Two main issues needs to be addressed

1. Radiation damage:
   – after Belle data taking (1 ab^{-1}):



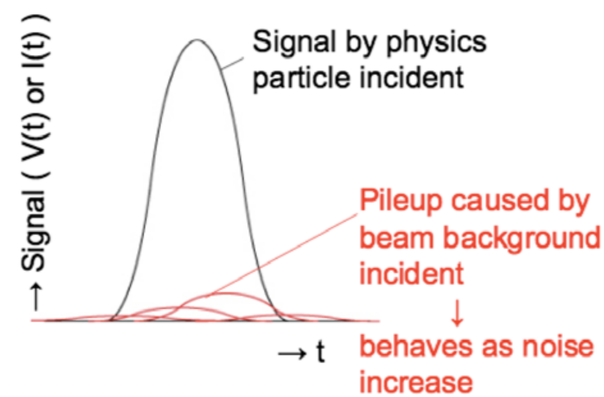




   – Expected dose in crystal @ Belle-II in FWD ECL: 3 Gy/yr x 10 yr of data taking → a factor of 7.5 higher than in Belle

2. Increased particle pile-up:

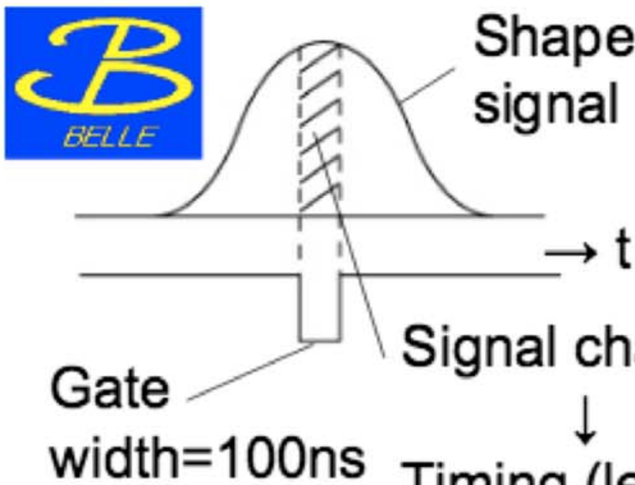
CsI(Tl)
Scintillation decay time is ~1μs



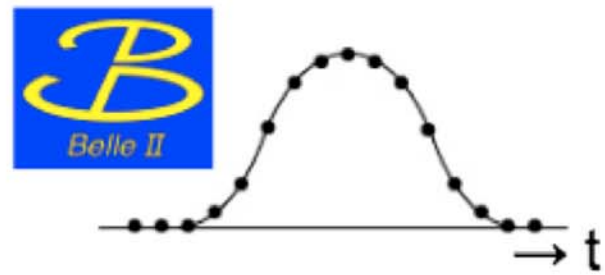
→ need RAD-HARD and FAST detector

Upgrade strategy (I)

- Read-out electronic upgrade for both Barrel and Fwd



Signal charge
↓
Timing (leading/trailing edges) with range information by QtoT converter (MQT300A)
↓
Digitized by TDC



1.76MHz, 18bits digitizer, waveform fit to get energy and timing (i.e. Digital Signal Processing)

Reduction factors;
×7 BG showers
×1.5~2 pileup noise

Upgrade strategy (II)

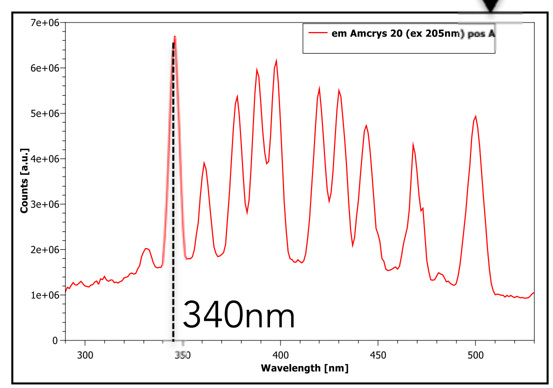
- For FWD ECL, electronic upgrade may not be enough: replace CsI(Tl) with faster crystals

Crystal	CsI(Tl)	CsI
Density (g/cm^3)	4.51	4.51
Melting Point (°CC)	621	621
Radiation Length (cm)	1.86	1.86
Molière Radius (cm)	3.57	3.57
Interaction Length (cm)	39.3	39.3
Refractive Index[a]	1.79	1.95
Hygroscopicity	Slight	Slight
Luminescence[b] (nm) (at Peak)	560	420 310*
Decay Time[b] (ns)	1220	30 6
Light Yield[b,c]	165	3.6 1.1
d(LY)/dT[b,d] (%/°CC)	0.4	−1.4

- same density and radiation length allow to reuse Belle mechanical structure

- much lower light yield
  - fast component of emitted light in the near-UV region
- much faster light decay time
  - but slow component is an issue for pile-up

* fast light component @ 310 nm from datasheet; measured emission spectra



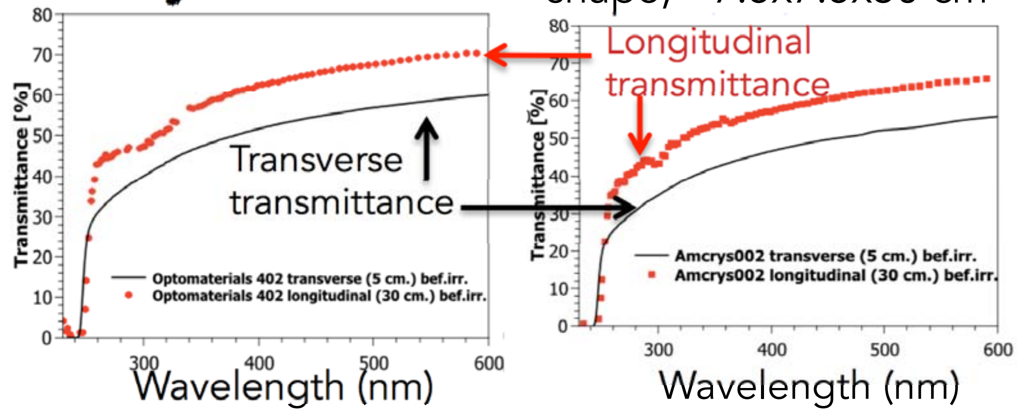
- Use of Pure CsI requires R&D studies on:
  - photodetectors in the near-UV and wavelength shifters
  - radiation hardness of crystals, photodetectors, and wavelength shifters
  - electronics

CsI crystal optical properties: Transmittance

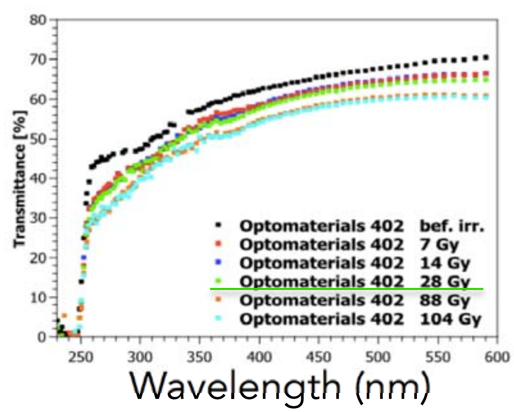
- No irradiation
- @ 310 nm: L.T. ~ 50%, T.T. ~ 40% for Optomaterials, lower for Amcrys

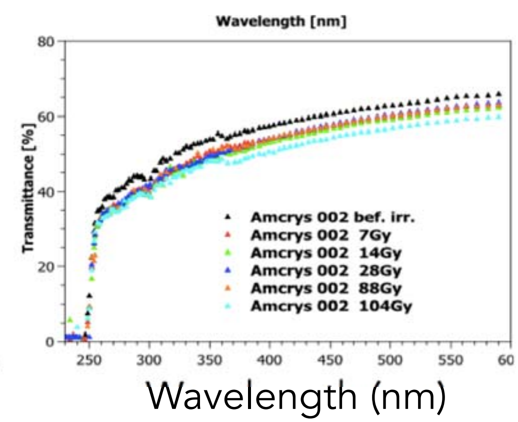
Optomaterials (Italy), 5x5x30 cm^3

Amcrys (Karchov, Ukraine), trapezoidal shape, ~7.5x7.5x30 cm^3



- Transverse transmittance at different irradiated doses (7 to 104 Gy)
- Maximum variation @ 310 nm ~ -7%
- Saturation effects
- Completed and fast recovery for doses < 7 Gy (not shown here)



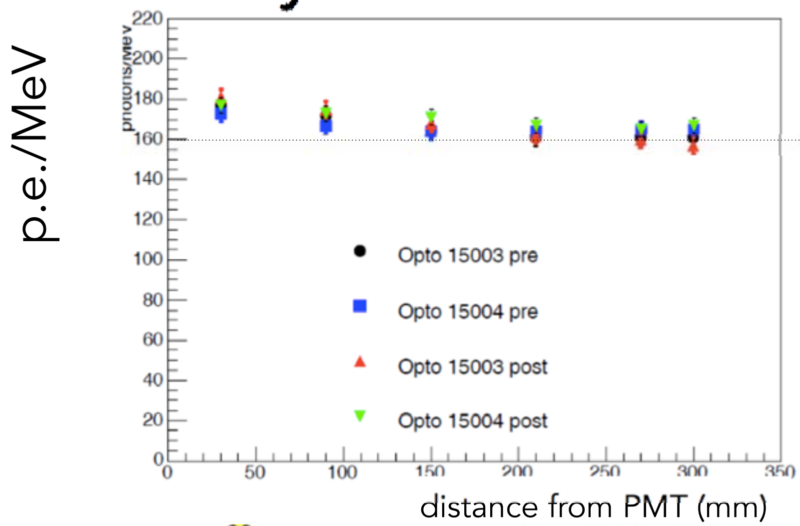


Also a **SICCAS (Shanghai, China)** has been studied

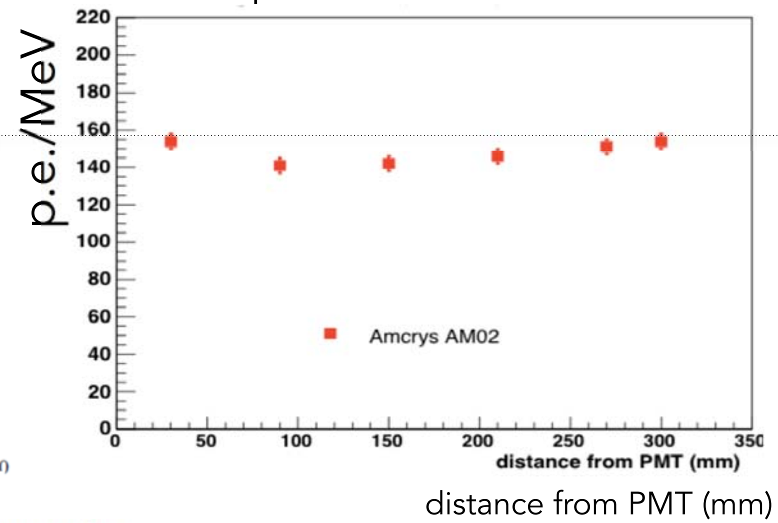
- about the same size as Amcrys, poor wrt other vendors (e.g. Long. Trans. ~ 18% @ 310 nm)

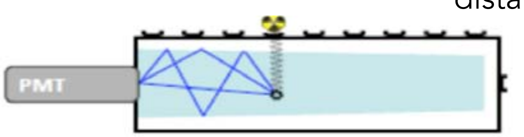
CsI crystal optical properties: Light Yield

Optomaterials (Italy), 5x5x30 cm^3



Amcrys (Karchov, Ukraine), trapezoidal shape, ~7.5x7.5x30 cm^3





Measured without wrapping and without optical grease

- Longitudinal LY (~160-180) for **different doses**
- Longitudinal LY variation
  - before irr. : ~ 6-10%
  - after irr: ~ 7-15%
- LY variation before and after irr.: ~1-5%

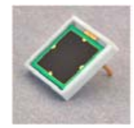
- **No irradiation**
- Longitudinal LY ~140-160
- Longitudinal LY variation < 10%

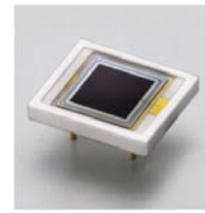
Photodetector Options

- Requirement: photodetector ENE < pile-up noise (O(1MeV))
- Photodetector options:

Hamamatsu photonics
R11283 photopentode
Belle-II baseline

Excelitas
APD
C30739ECERH-2





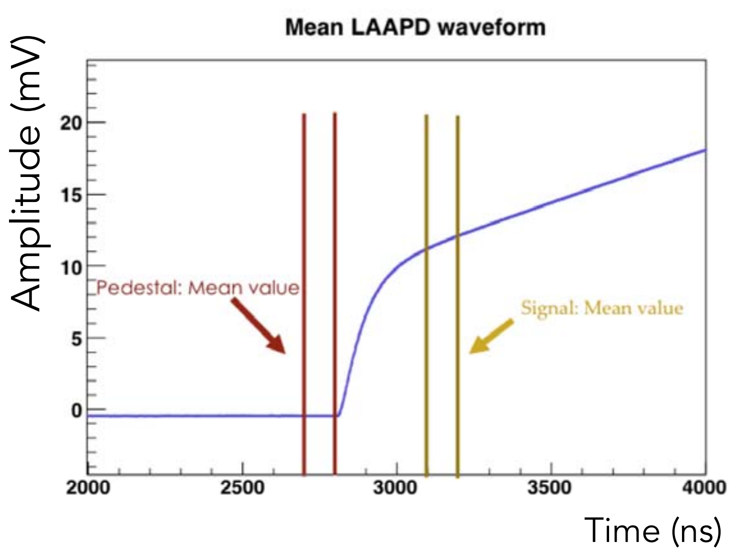
Hamamatsu
photonics
Large Area
APD
R8664-1010

	PP	EXC. APD	LAAPD
C (pF)	10	60	270
Gain @ V_{op}	150-250[*]	250	50[**]
Q.E. @ 310 nm (%)	25	35	50
Area	20 cm^2	5.6x5.6 mm^2	10x10mm^2
Comments	• [*] gain reduced by 75% in 1.5T magnetic field • 1 PP per crystal, no redundancy • back plane of the mechanical structure need to be replaced	• lower capacitance and higher nominal gain wrt LAAPD • small area • 2/4 EXC. APD per crystal	• [**] special production with G=200 • higher Q.E. wrt EXC. APD • 2 LAAPD per crystal

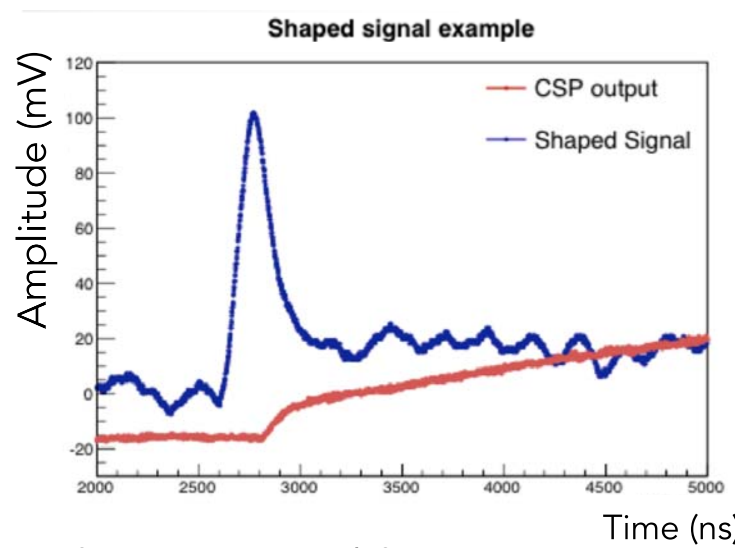
R&D on APD's (I)

- ENE estimation with cosmic ray (MPV ~ 30 MeV)
  - CsI crystal wrapped with Tyvek and coupled to APD's with optical grease
  - Readout with commercial CREMAT CR-110 charge-integrating amplifier (CSP) + Software CR-(RC)^4 filtering (<u>τ=75ns</u>)

- Signal extraction:

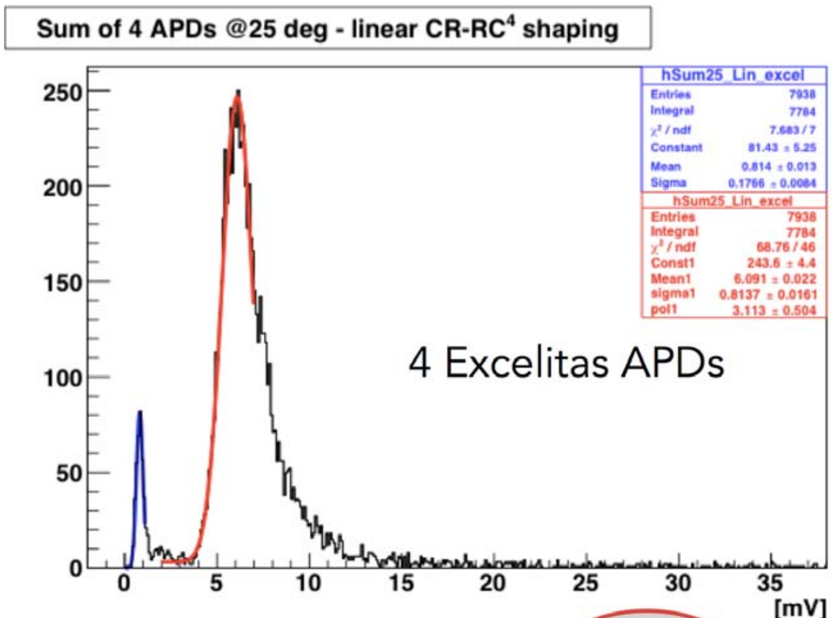


CSP response= Signal - Pedestal

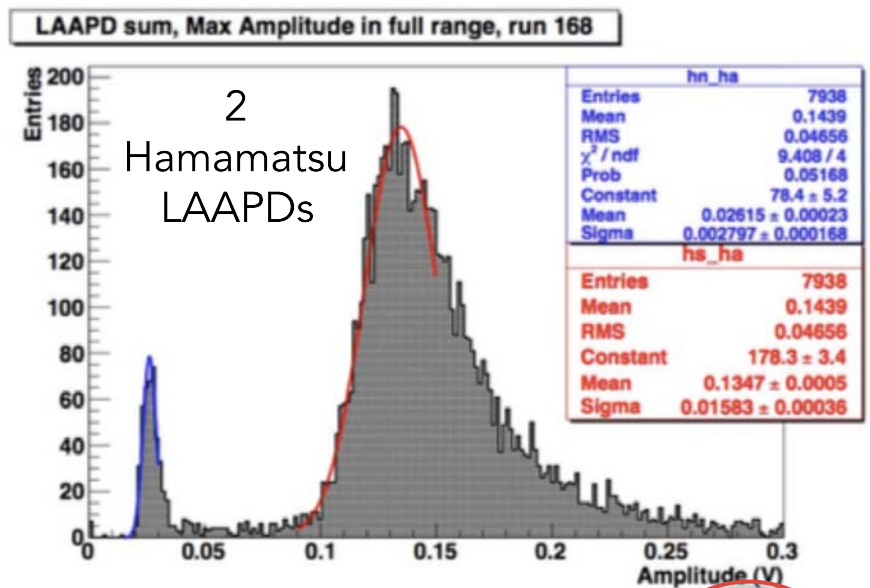


Software CR-(RC)^4 filter response= maximum of shaped signal (in a <u>10μs</u> window around expected signal position)

R&D on APD's (II)



σ [μV]	Signal [mV]	S/N	ENE [MeV]
177±8	5.27±0.03	30±1	1.00±0.05

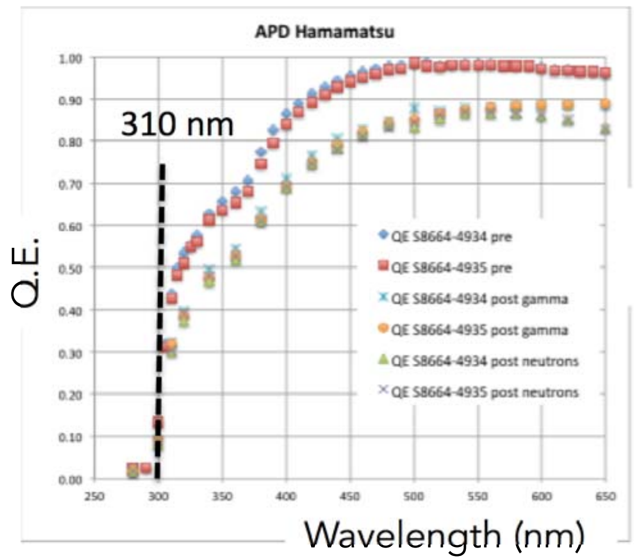


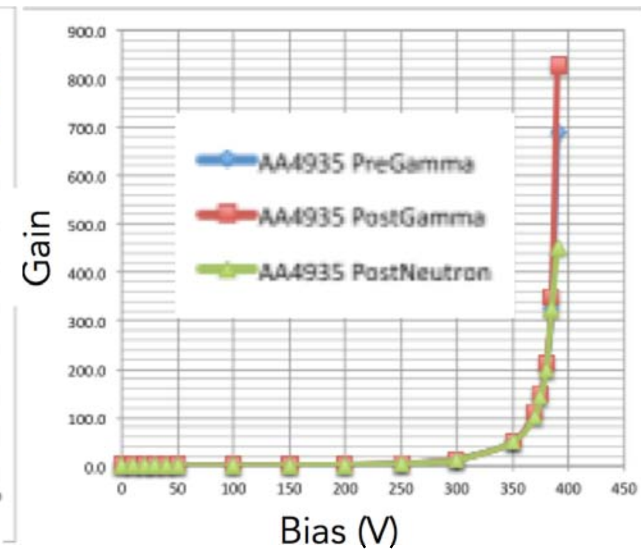
σ[mV]	Signal [mV]	S/N	ENE[MeV]
2.80±0.17	108.6±0.6	38.8±2.4	0.77±0.05

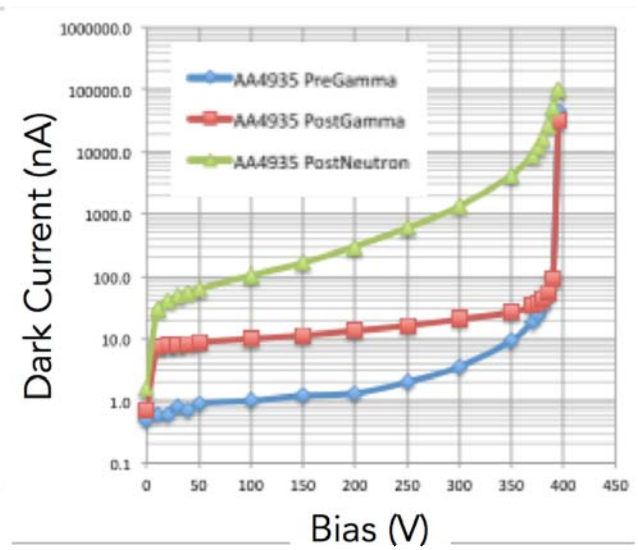
- Excelitas APD and LAAPD performs similarly in terms of ENE (and performance-dependence on temperature)
  - both meet the experiment requirement (ENE<1MeV)
- Using Excelitas APD would double the electronic channel
- LAAPD is our choice

LAAPD irradiation (I)

- Study effect of **ionizing and non-ionizing radiation**:
  - **gamma**: 250 Gy = 10 y data taking x **~50 safety factor**
  - **Neutron** fluence: 10^{12} n/cm^2 = 10 y data taking **x 5 safety factor**







Quantum efficiency:
- decrease for LAAPD after irradiation with γ at 250 Gy
- no further effect due to neutrons

Gain:
- almost stable

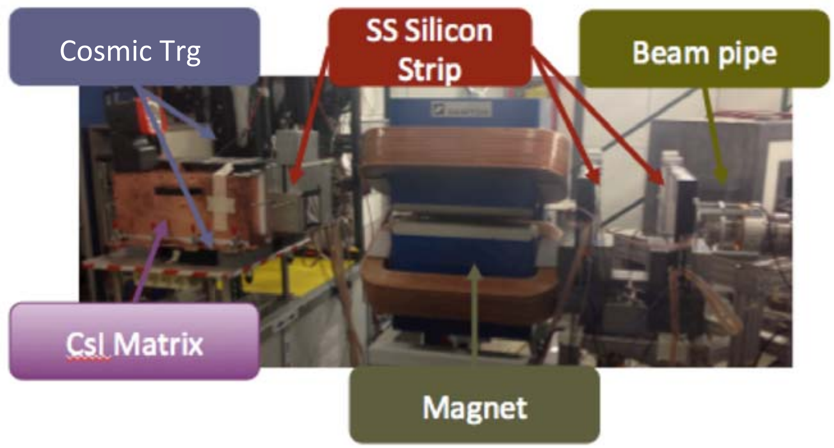
Dark current:
- 2 orders of magnitude increase after neutrons + gamma

- Radiation may be an issue for LAAPD (dark current and Q.E.), studies with simulations on shielding and with beam on background rate ongoing in Belle II

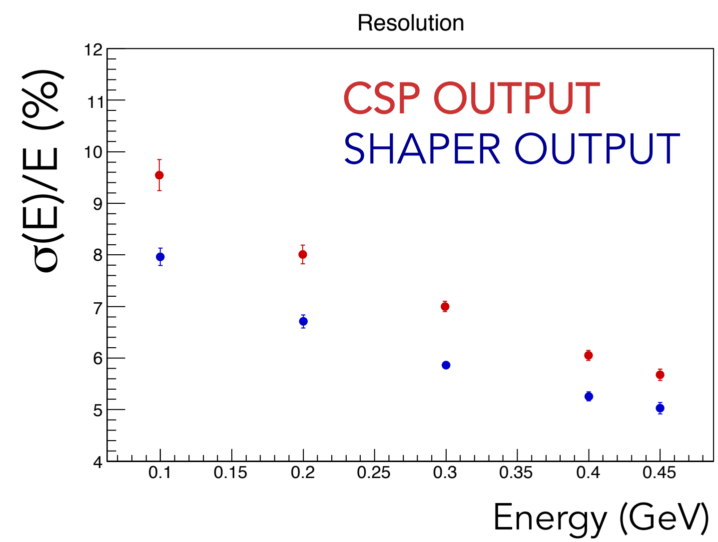
Test Beam with CsI+LAAPD

- Test with **electron beam** @ LABORATORI NAZIONALI DI FRASCATI – INFN
  - 4x4 (Amcrys) CsI matrix + LAAPD (G@ V_{op}=200)

- Development of costum made charge preamplifier:
  - Gain = 1.4V/pC (same as CREAMT CR-110)
  - Integration time reduced from 140 μs (CREAMT CSP) to 200 ns to minimize pile-up contribution



  - Preliminary results:

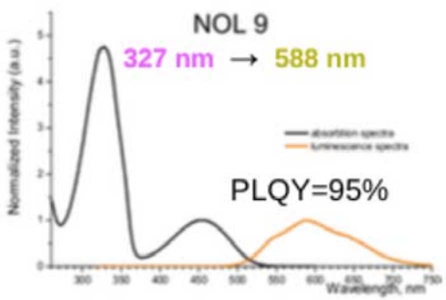


- Resolution higher than experiment expectations (2% 100 MeV vs measured 8%)
- Beam-related background probably introduce a distortion in the reconstructed energy
- New tests in cleaner beam environment performed @ **MAMI FACILITY (MAINZ)**, data analysis underway.

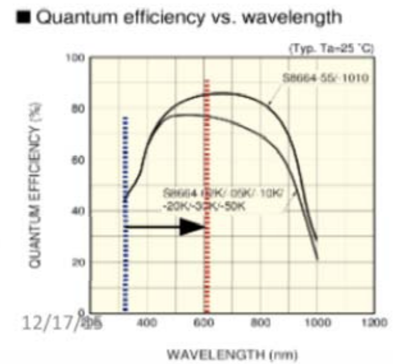
R&D on wavelength shifter (I)

- Novel wavelength (WLS) plates containing nanostructured organosilicon luminophores provides essential increase in light output

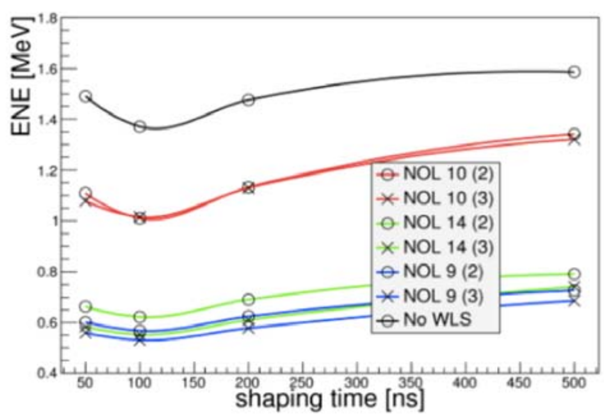
LuminoTech Co, (60x60x2 mm^3) WLS plates



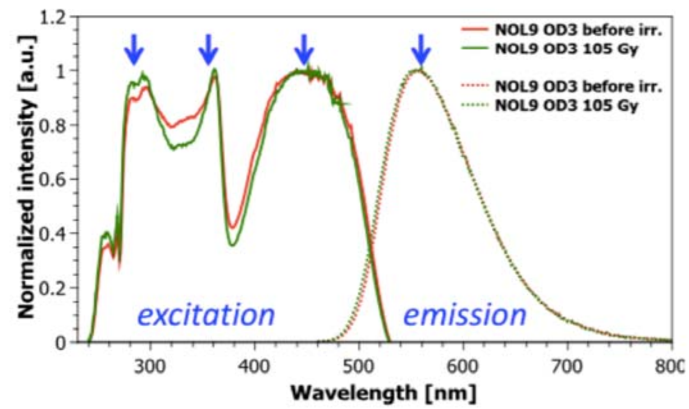
Increase in LAAPD Q.E. of a factor of 2-3



- Results:



Enhancement on signal of a factor of about 3 (n.b. test performed with G=50 LAAPD)



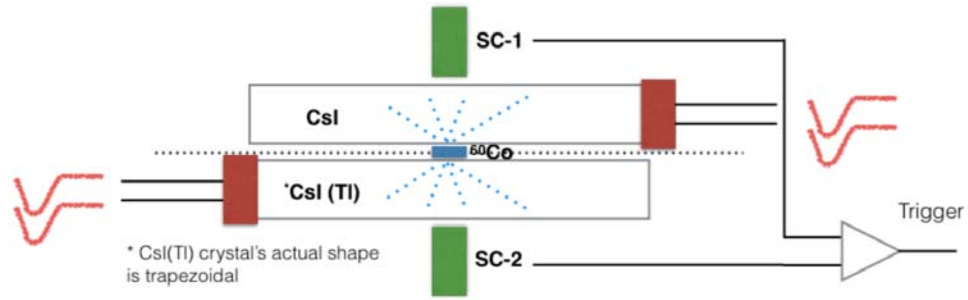
Radiation hardness tests on NOL9 WLS: no irradiation effects on excitation/emission peaks up to 105 Gy

Pile-up impact: cosmic + radioactive source

- Signal from cosmic rays superimposed to 1.33 and 1.17 MeV γ produced by ^{60}Co
  - 1.77 ± 0.04 hits/μsec from source

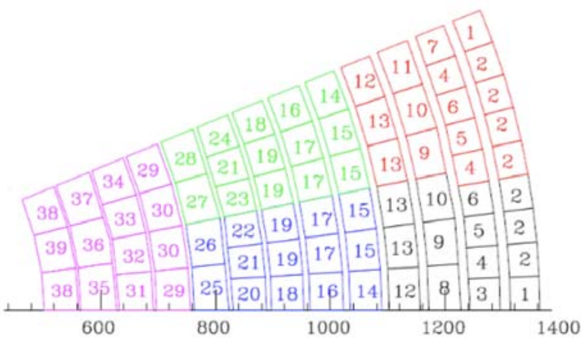
- From the difference in quadrature of the meas. with and without source, pile-up effect can be estimated: CsI(Tl) shows twice the ENE of pure CsI

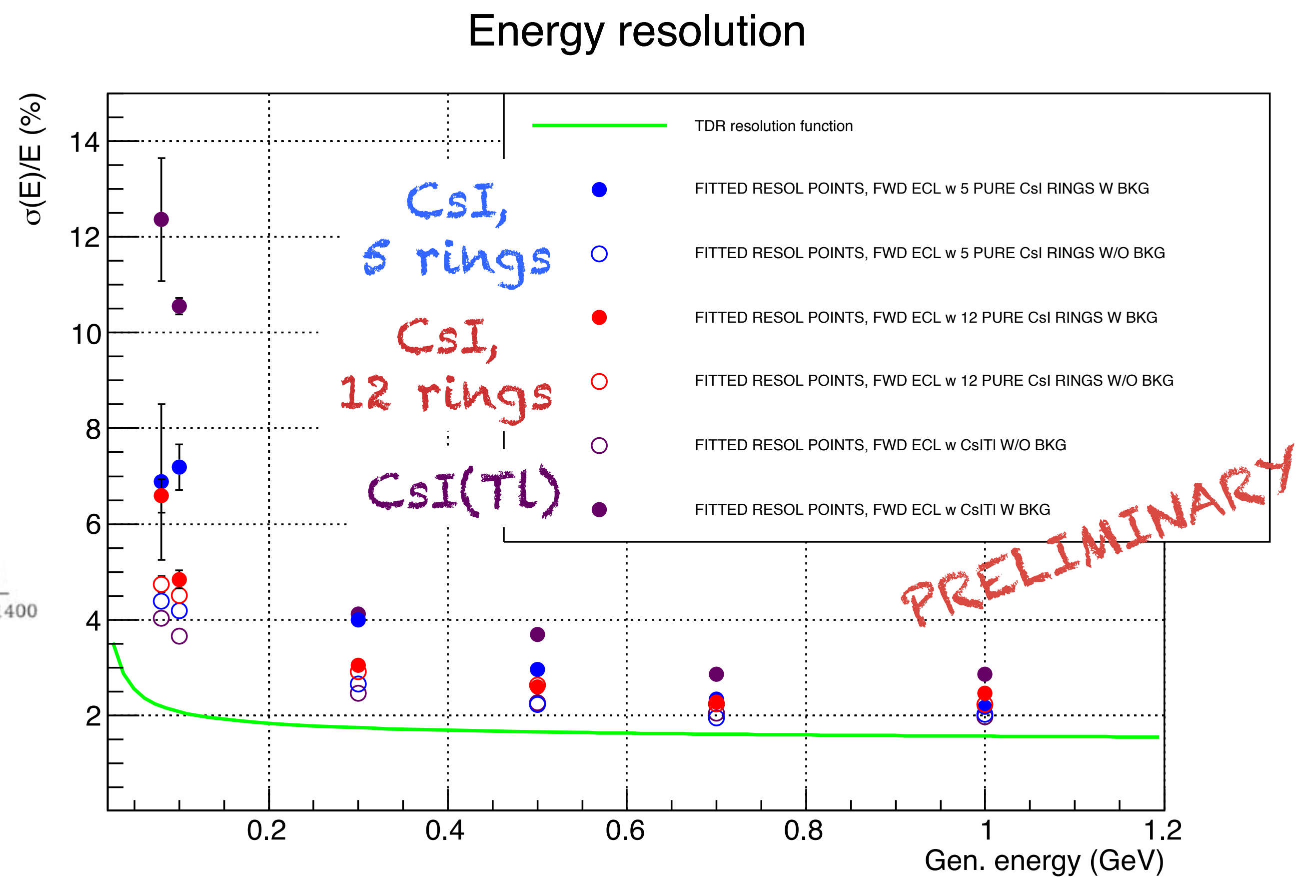
- [nb: wrt to pag 12 (ENE=0.77MeV), different shaping times and signal window used, optimization of such parameters underway]



The ENE with pile-up is ~**2 MeV** for pure CsI and ~**3 MeV** for CsI(Tl)

Pile-up impact: energy resolution from Belle-II Full simulation





- With current reconstruction code machine bkg estimation, resolution with CsI-12 rings + machine bkg at the level of bkg-free performances.
- Comparison of different FWD ECL configuration in physics channels underway.

Conclusions

Belle II higher particle rate, wrt Belle, requires an upgrade of the electromagnetic calorimeter in the forward region.

Extensive R&D studies on

- CsI crystals:
  - good quality crystals from different vendors available
  - satisfactory results from radiation hardness studies
- Photodetectors:
  - LAAPD from Hamamatsu meet experimental requirements in terms of ENE
  - Dark current may be an issue with high doses of gamma and neutrons
    - accurate studies on shielding and to estimate doses ongoing
  - Usage of rad-hard wavelength shifters produces and enhancement on signal of a factor of about 3

- Tests with electron beams on a 4x4 CsI+LAAPD matrix performed
  - costum made charge preamplifier with short integration time
  - data analysis ongoing

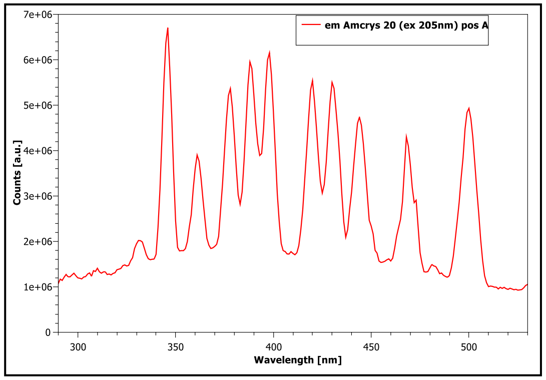
- Preliminary results on pile-up effect estimation from
  - cosmic ray + radioactive source
  - simulation

  show an improvement in terms of resolution when using pure CsI

On our to-do-list

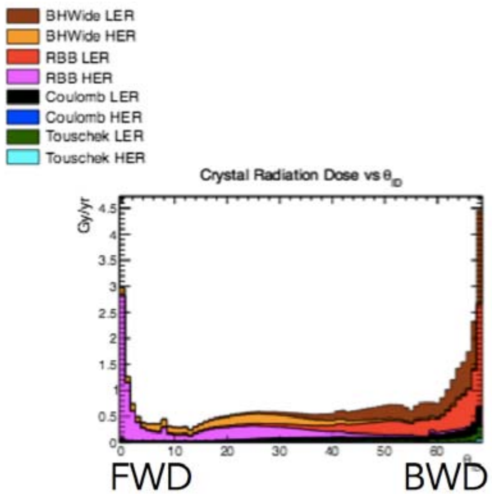
- Optimize cosmic **data analysis** (e.g. software shaping time constant, signal extraction) and finalize test beam data analysis
- Further development on **costume-made charge preamplifier** ongoing
  - larger decay time constant (6 μs vs 200ns), from preliminary studies: gain on S/N a factor of about 2.5 without shaping
- Investigation on the **usage of filters**
  - CsI has fast and slow light component
  - Slow component may act as pile-up from "previous" event
  - Is it possible to apply a light filter to suppress the slow component?

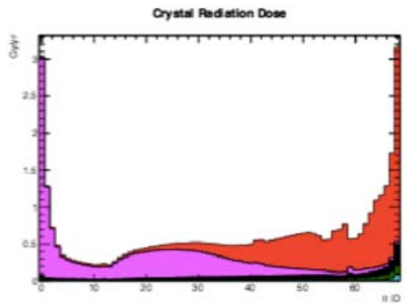
Characterization of emission peaks in terms of decay time needed for this purpose.



EXTRA SLIDES

Background studies

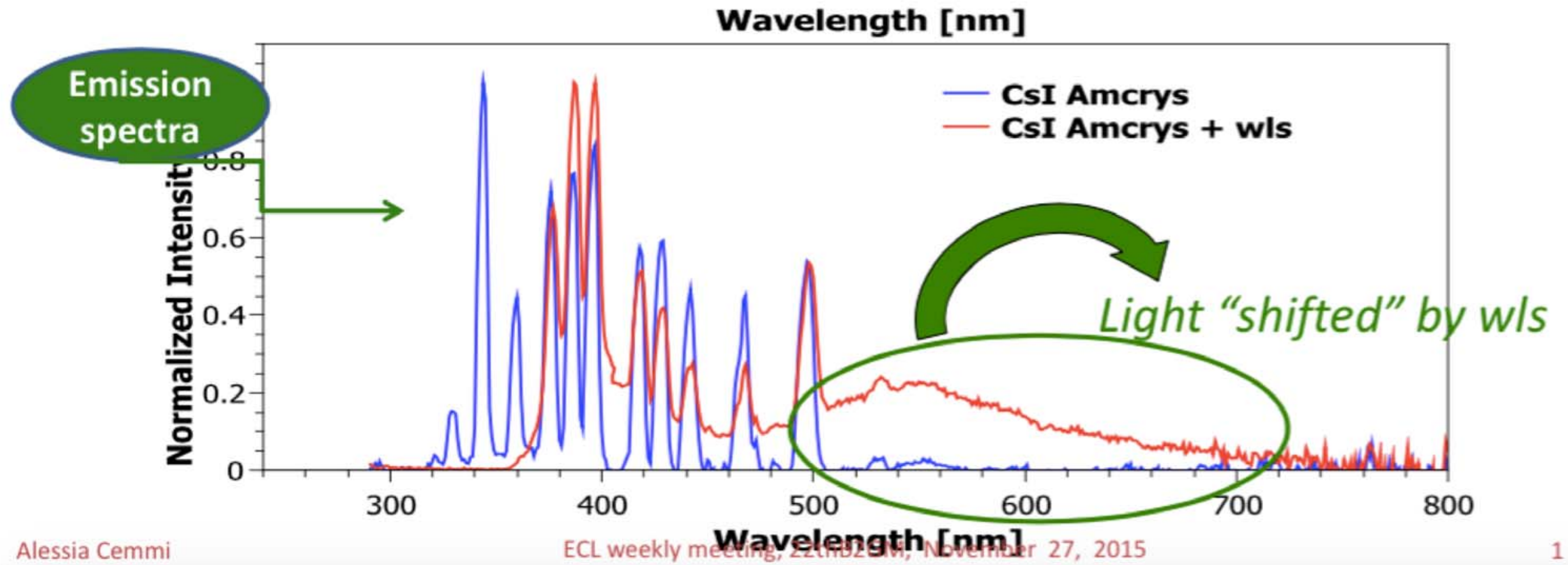




- 12th Campaign
- Maximum dose of 4.5 Gy/yr

- 11th Campaign
- Maximum dose of 3.15 Gy/yr

		12th Campaign	11th Campaign	Tolerance
Crystal Radiation Dose (Gy/yr)	Forward	3.0	3.0	
	Barrel	0.8	0.5	10
	Backward	4.5	3.1	
Crystal Neutron Flux ($\times 10^9 yr^{-1} cm^{-2}$)	Forward	23	24	
	Barrel	5	4	1000
	Backward	14	12.5	
Diode Radiation Dose (Gy/yr)	Forward	0.4	0.7	
	Barrel	<0.2	<0.2	70
	Backward	0.8	0.64	
Diode Neutron Flux ($\times 10^9 yr^{-1} cm^{-2}$)	Forward	23	24	
	Barrel	5	4	100
	Backward	15	12.5	
Pileup Noise (MeV)	Forward	4.3	3.8	
	Barrel	3.1	2	0.8 for Belle
	Backward	8.2	5.4	
Reconstructed Cluster		3.44	2.57	6 for Belle


Wavelength [nm]
CsI Amcrys
CsI Amcrys + wls
Emission spectra
Light "shifted" by wls
Normalized Intensit
0
0.2
0.4
0.6
0.8
300
400
500
600
700
800
Wavelength [nm]
Alessia Cemmi
ECL weekly meeting, November 27, 2015
1

ENE vs signal window