Irradiation history and resulting isotope decay scheme influence on yttrium sample gamma activity

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Yttrium-89 activation reactions taken into account

Reaction	Produced Isotope	T1/2	Reaction Threshold [MeV]	γ-line Energy [keV]	γ-line Intensity [%]
Y89(n,g)	Y90	3.19h	-6.8570*	202.51	97.3
				479.17	90.74
Y89(n,2n)	Y88	106,65d	11.5	898.042	93.7
				1836.063	99.2
Y89(n,3n)	Y87m	13,37h	20.8	380.79	78
	Y87	79,8h	20.8	388.53	82.00
				484.805	89.7
Y89(n,4n)	Y86	14,74h	32.7	1076.64	82.00
Y89(n,5n)	Y85	2.68h	42.633	231.67	84.00
		4.86h	42.633	231.67	22.8

A typical formula for isotope production rate

$$\frac{N_A \sigma_k}{A} \equiv I_k = \frac{S_\gamma \cdot 100}{m \cdot \varepsilon_p \cdot I_\gamma \cdot \phi \cdot COI} \cdot \frac{\lambda_k \cdot t_{ir}}{\left(1 - e^{-\lambda \cdot t_{ir}}\right)} \cdot \frac{1}{\left(1 - e^{-\lambda t_{real}}\right)} \cdot \frac{t_{real}}{t_{live}} \cdot e^{\lambda t_+}$$

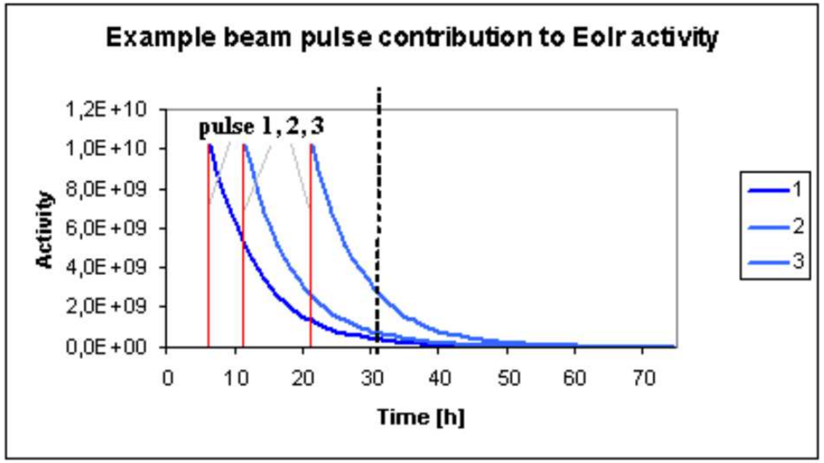
N_A – Avogadro's number
A – sample's gram atom
σ_k – reaction channel *k* cross section
I_k – isotope *k* production rate per gram
$S\gamma$ – gamma peak area
m – activation sample mass [g]
ε_p – gamma spectrometer efficiency

I_γ – correction for gamma line intensity [%]
ϕ - deuteron fluence
COI – correction for gamma quanta coincidence
λ_k – isotope decay constant
t_{ir} – irradiation time
t_{real} – real time of measurement
t_{live} – live time of measurement

The formula is based on constant accelerator beam assumption

$$\frac{\lambda_k \cdot t_{ir}}{\left(1 - e^{-\lambda \cdot t_{ir}}\right)}$$ - correction for irradiation time

Irradiation history – constant beam case



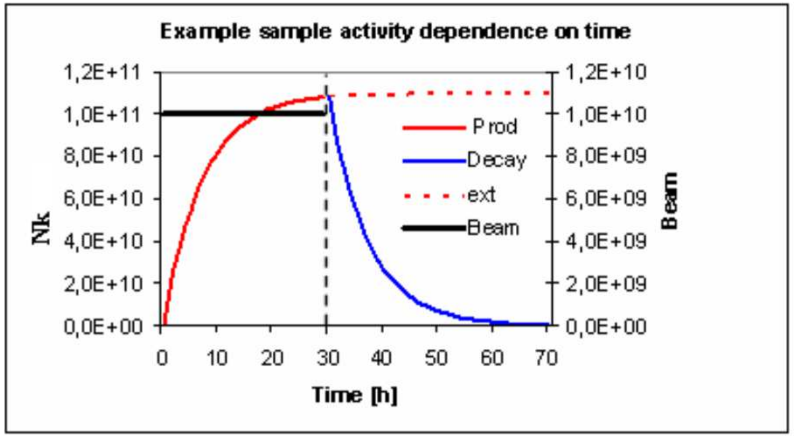
φ_i - neutrons in pulse *i*

$$\varphi_i = const = \frac{\phi \Delta t}{t_{ir}}$$

$N_k(tir)$ – isotope *k* nuclei at the EoIr

$$N_k(t_{ir}) = \frac{mN_A\sigma_k}{A}\frac{\phi\Delta t}{t_{ir}}\sum_{i=1}^{t_{ir}} e^{-\lambda_k(t_{ir}-t_i)}$$

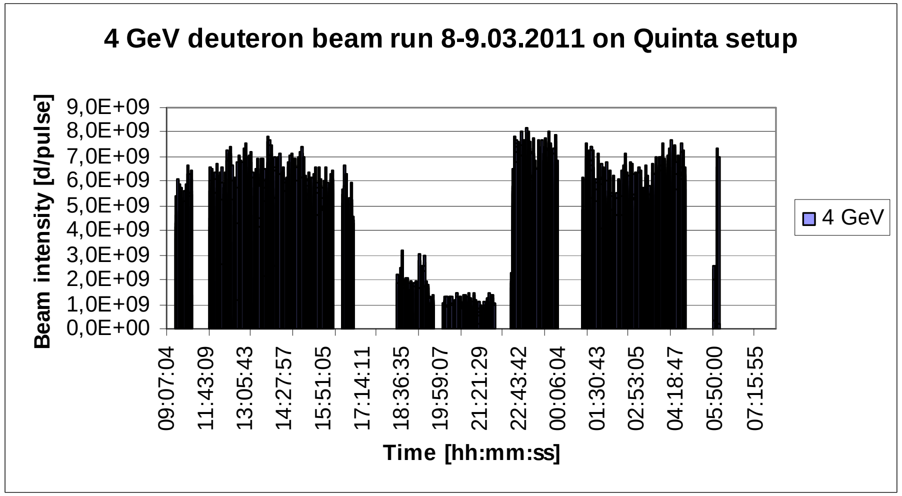
$$\Rightarrow \frac{mN_A\sigma_k}{A}\frac{\phi}{t_{ir}}\int_0^{t_{ir}} e^{-\lambda_k(t_{ir}-t)}dt$$



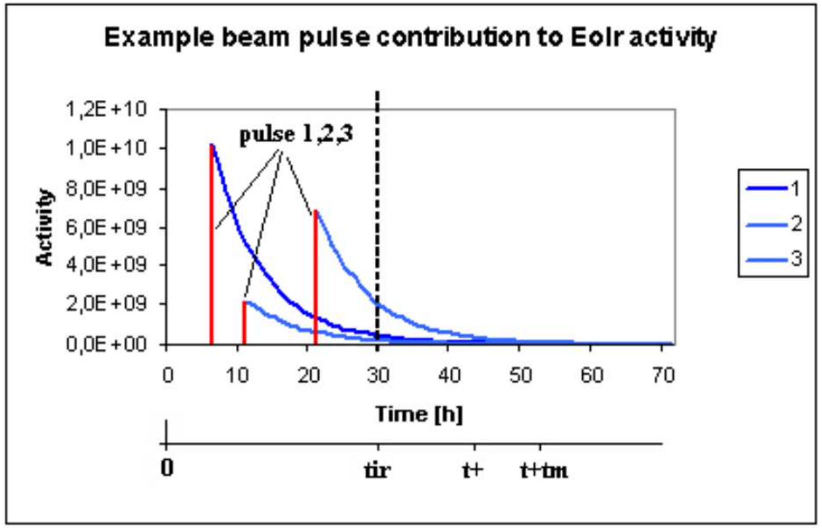
$$N_k(t_{ir}) = \frac{mN_A\sigma_k}{A}\frac{\phi}{\lambda_k t_{ir}}\left(1-e^{-\lambda_k t_{ir}}\right)$$

$$N_k(t_+) = N_k(t_{ir})e^{-\lambda_k t+}$$

Variable beam case

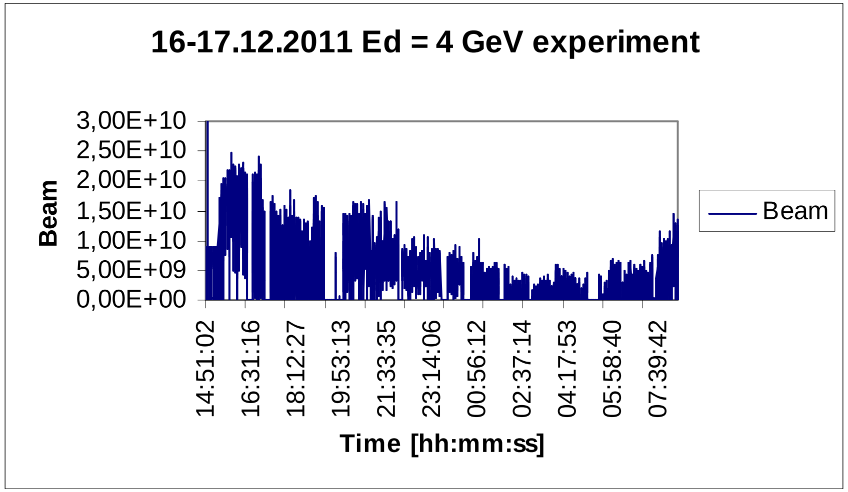


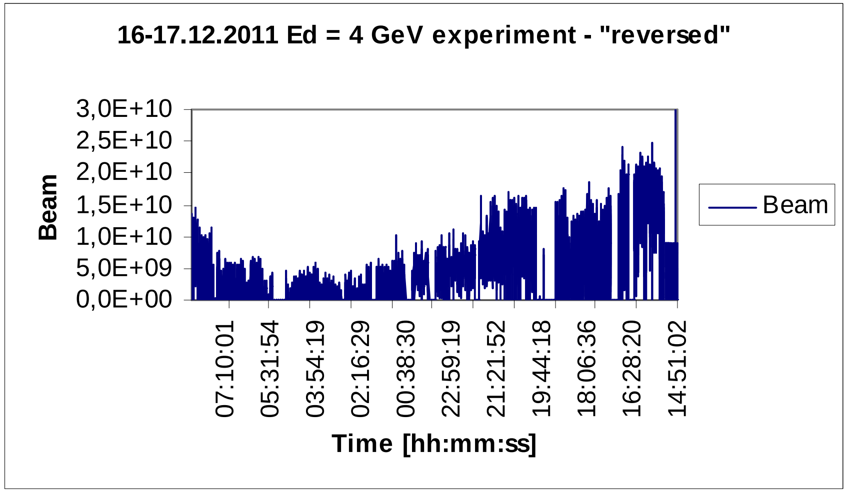
Here the constant beam approximation can't be applied! Each pulse contribution should be calculated separately.



$$N_k(t_{ir}) = \frac{mN_A\sigma_k}{A}\sum_i \varphi_i \cdot e^{-\lambda_k(t_{ir}-t_i)}$$

Variable beam case





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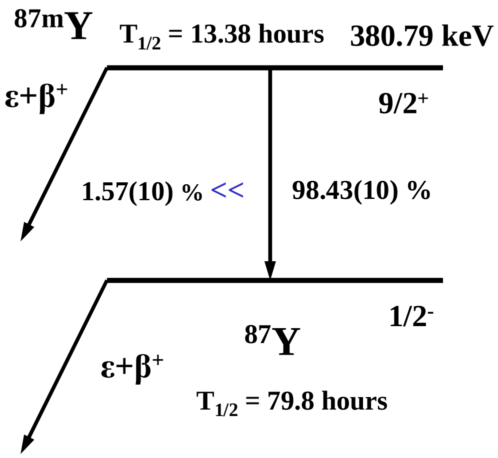
Example irradiation history influence on yttrium isotopes production

	Y88	Y87m	Y87	Y86	Y85
Beam run averaged	1,00	1,00	1,00	1,00	1,00
Reversed beam run	1,00	1,18	1,03	1,16	1,83
Real beam run	1,00	0,84	0,97	0,86	0,55

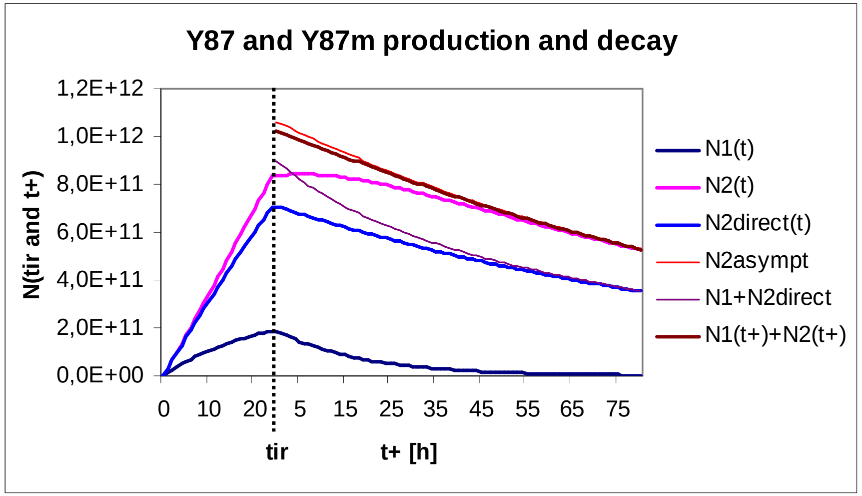
Irradiation history has negligible effect on Y88 production. For Y86 this effect can’t be neglected. Shorter isotope half life time the irradiation history makes larger effect on measured production.

Residual isotope decay scheme effect on production - Y87 example – constant beam case



$$\frac{dN_1}{dt} = \frac{mN_A\sigma_1\varphi}{A} - \lambda_1 N_1$$

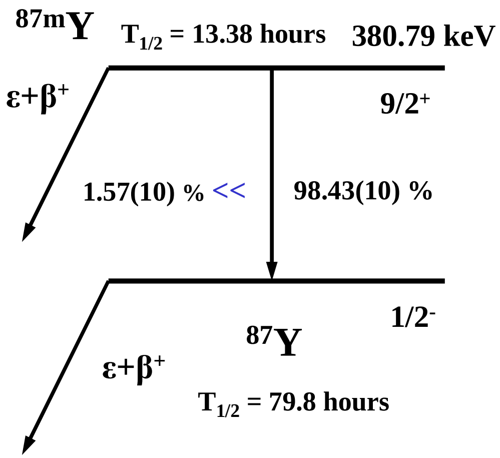
$$\frac{dN_2}{dt} = \frac{mN_A\sigma_2\varphi}{A} + \lambda_1 N_1 - \lambda_2 N_2 \quad \Bigg| \; t < t_{irr}$$



$$\frac{dN_1}{dt} = -\lambda_1 N_1$$

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \quad \Bigg| \; t_+ > t_{irr}$$

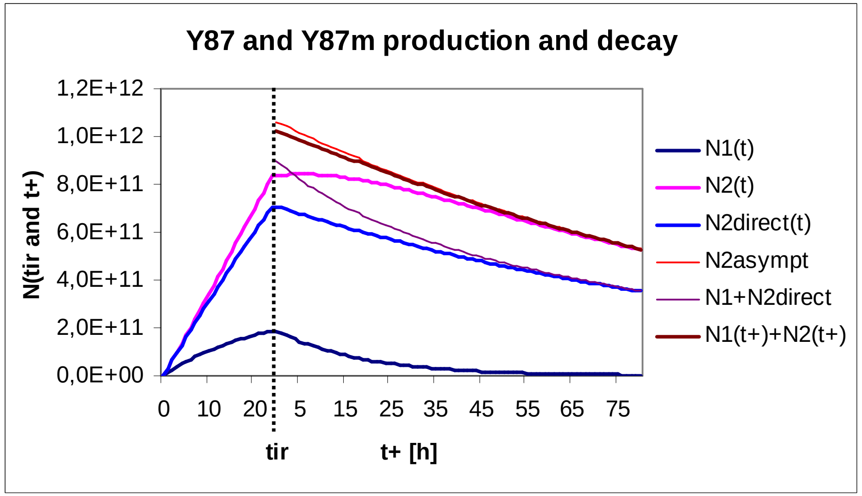
Residual isotope decay scheme effect on production - Y87 example – constant beam case



$$N_1(t_{ir}) = mI_1 \frac{\phi\left(1-e^{-\lambda_1 t_{ir}}\right)}{\lambda_1 t_{ir}}$$

$$N_2(t_{ir}) = mI_2\phi \frac{\left(1-e^{-\lambda_2 t_{ir}}\right)}{\lambda_2 t_{ir}}$$

$$+ mI_1\phi\left[\frac{\left(1-e^{-\lambda_2 t_{ir}}\right)}{\lambda_2 t_{ir}} - \frac{\left(e^{-\lambda_2 t_{ir}} - e^{-\lambda_1 t_{ir}}\right)}{(\lambda_1 - \lambda_2) t_{ir}}\right]$$

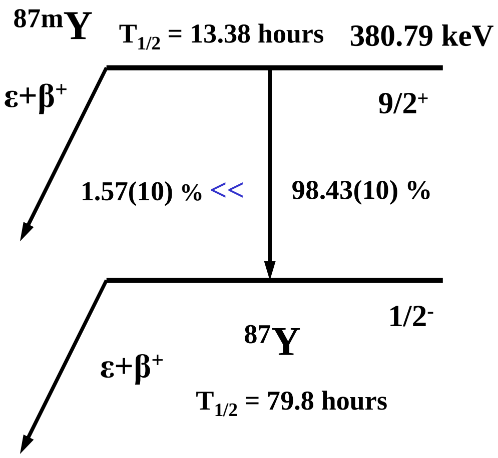


$$N_1(t_+) = N_1(t_{ir}) e^{-\lambda_1 t_+}$$

$$N_2(t_+) = N_2(t_{ir}) e^{-\lambda_2 t}$$

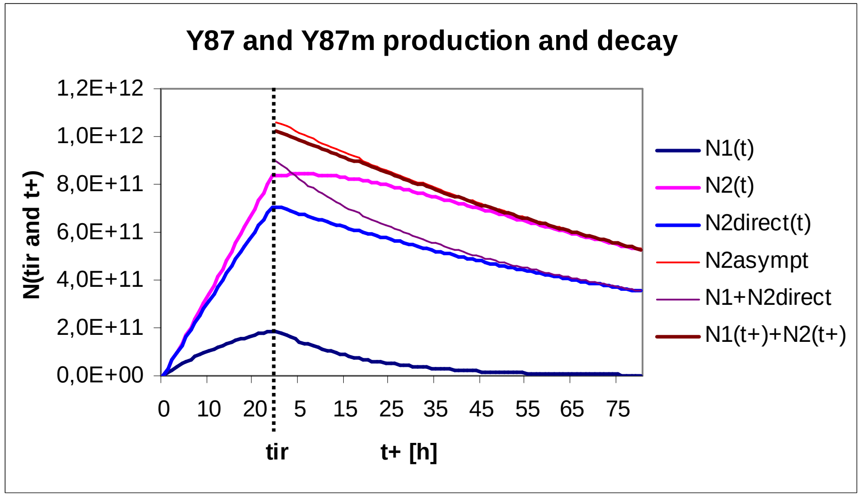
$$+ N_1(t_{ir}) \frac{\lambda_1}{(\lambda_1 - \lambda_2)} \left(e^{-\lambda_2 t_+} - e^{-\lambda_1 t_+}\right)$$

Residual isotope decay scheme effect on production - Y87 example – variable beam case



$$N_1(t_{ir}) = mI_1 \sum_{i=1}^{ir} \varphi_i e^{-\lambda_1 (t_{ir} - t_i)}$$

$$N_2(t_{ir}) = mI_1 \sum_{i=1}^{ir} \varphi_i \left(1 - e^{-\lambda_1 (t_{ir} - t_i)}\right) e^{-\lambda_2 (t_{ir} - t_i)} + mI_2 \sum_{i=1}^{ir} \varphi_i e^{-\lambda_2 (t_{ir} - t_l)}$$

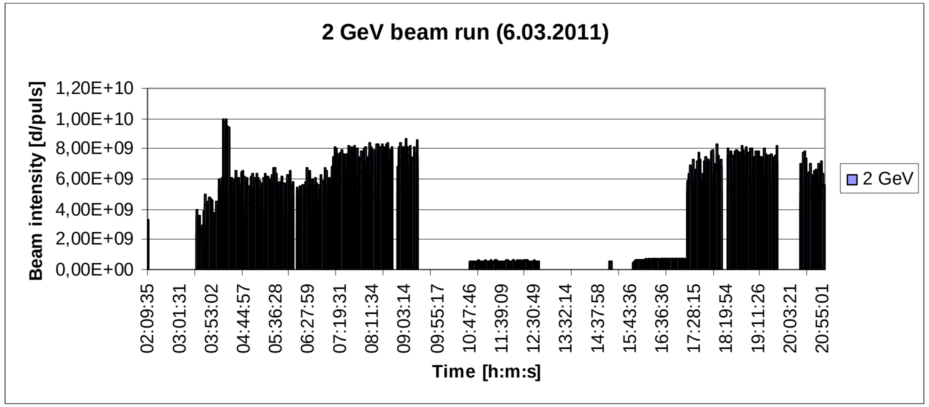


$$N_1(t_+) = N_1(t_{ir}) e^{-\lambda_1 t_+}$$

$$N_2(t_+) = N_2(t_{ir}) e^{-\lambda_2 t} + N_1(t_{ir}) \frac{\lambda_1}{(\lambda_1 - \lambda_2)} \left(e^{-\lambda_2 t_+} - e^{-\lambda_1 t_+}\right)$$

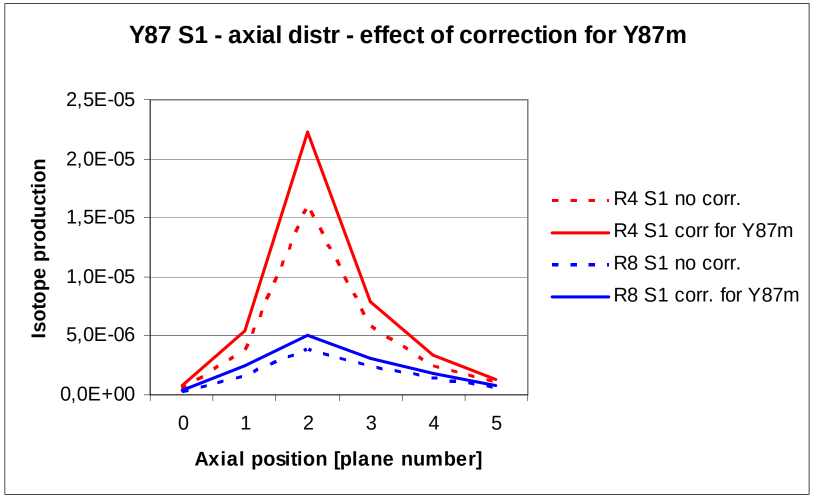
Experiment by experiment illustration
of irradiation history and decay scheme influence
on yttrium isotope production final results
will follow

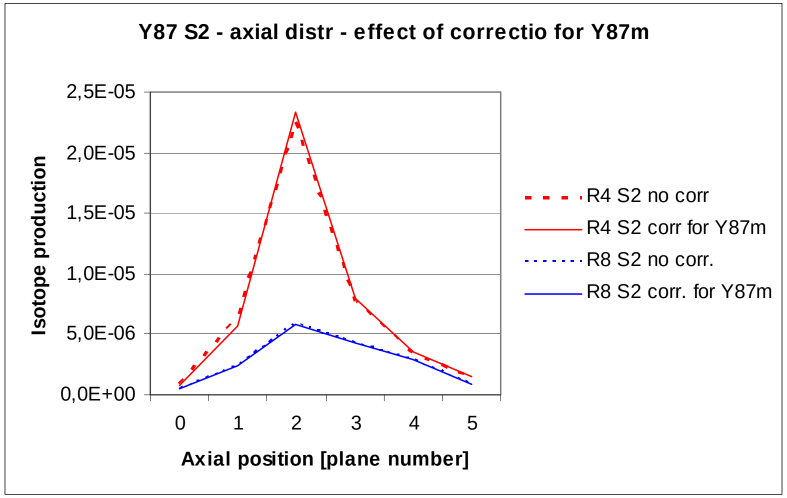
Experiment QUINTA 2011-03-5-6 2 GeV



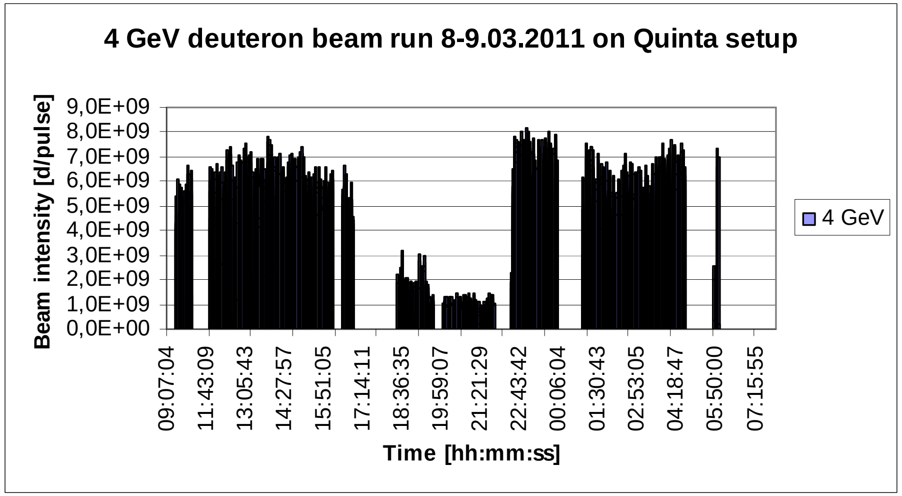
Variable beam to constant beam treatment ratio.				
Y88	**Y87m**	**Y87**	**Y86**	**Y85**
1,00	1,09	1,01	1,08	1,56

Fluence 1,54E+13
t-irr[hh:mm:ss] 18:50:29



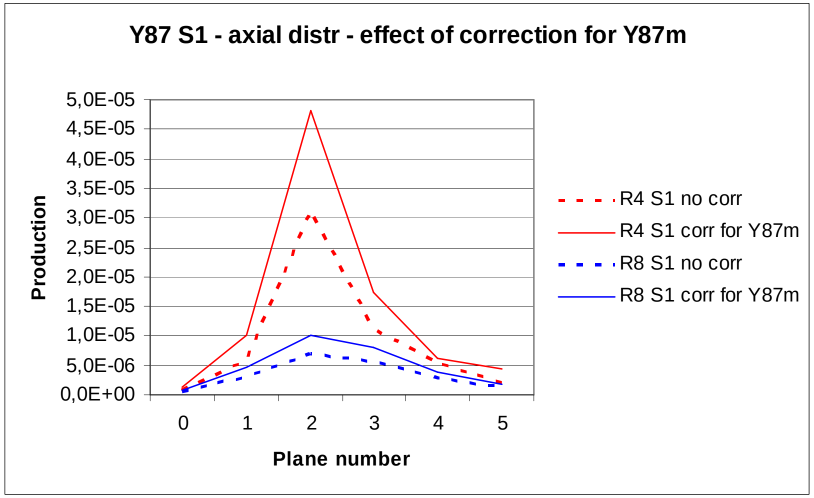


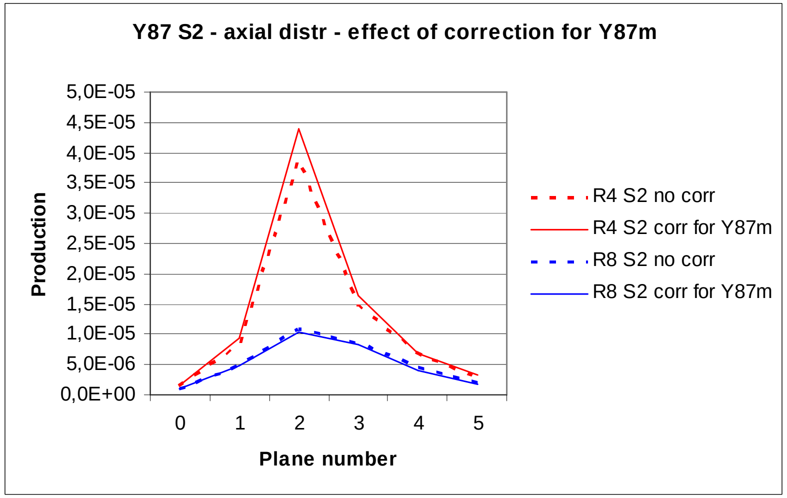
Experiment QUINTA 2011-03-8-9 4 GeV



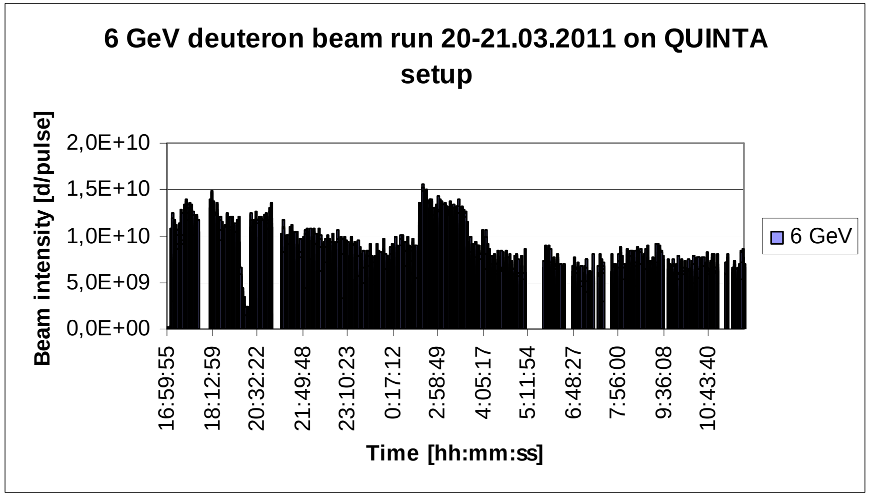
Variable beam to constant beam treatment ratio.				
Y88	**Y87m**	**Y87**	**Y86**	**Y85**
1,00	1,04	1,01	1,04	0,85

Fluence	1,50614E+13
t-irr[hh:mm:ss]	22:53:01



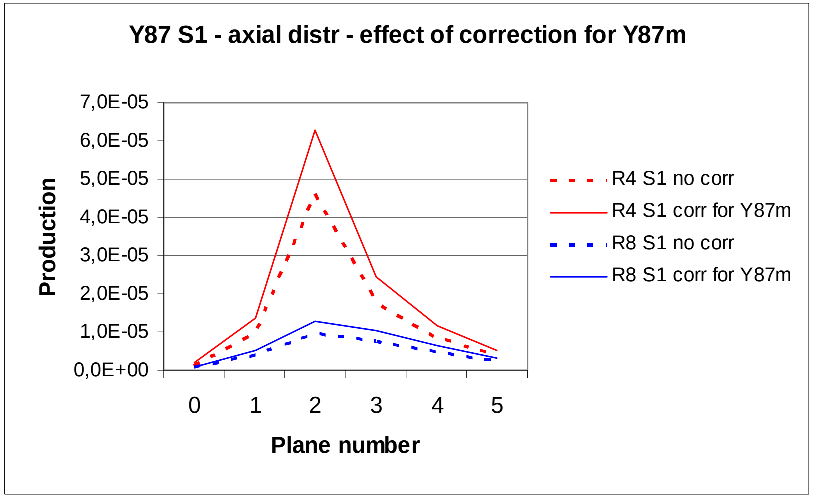


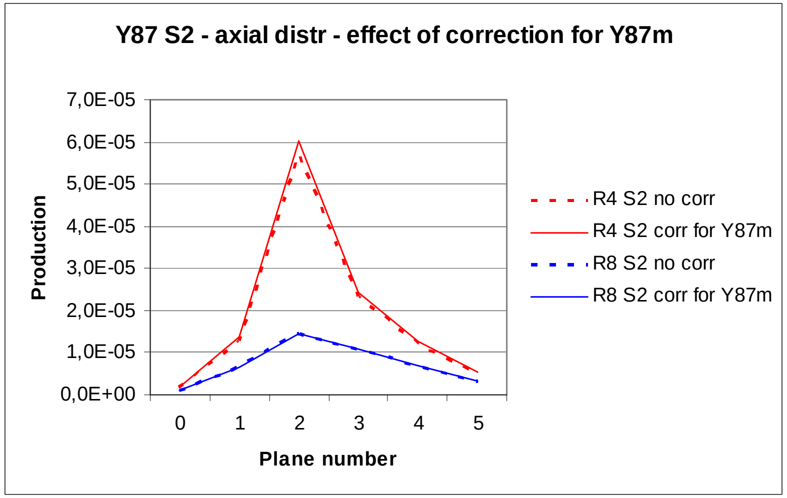
Experiment QUINTA 2011-03-20-21 6 GeV



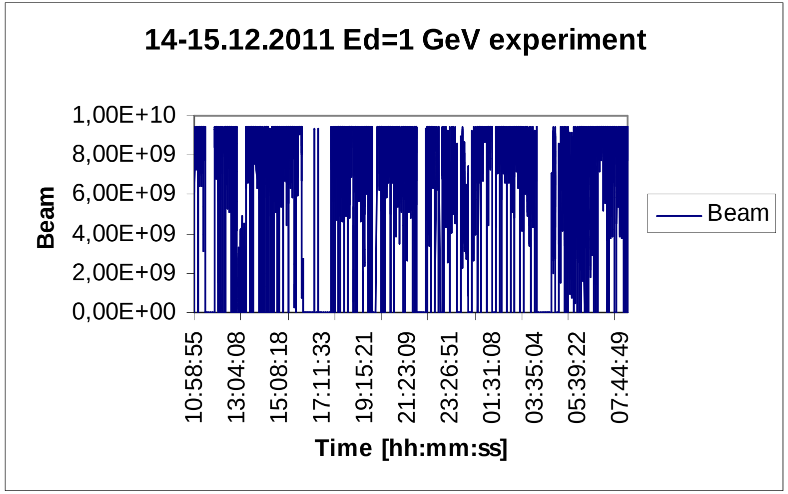
Variable beam to constant beam treatment ratio.				
Y88	**Y87m**	**Y87**	**Y86**	**Y85**
1,00	1,05	1,01	1,04	1,11

Fluence	2,17E+13
t-irr[hh:mm:ss]	18:35:52



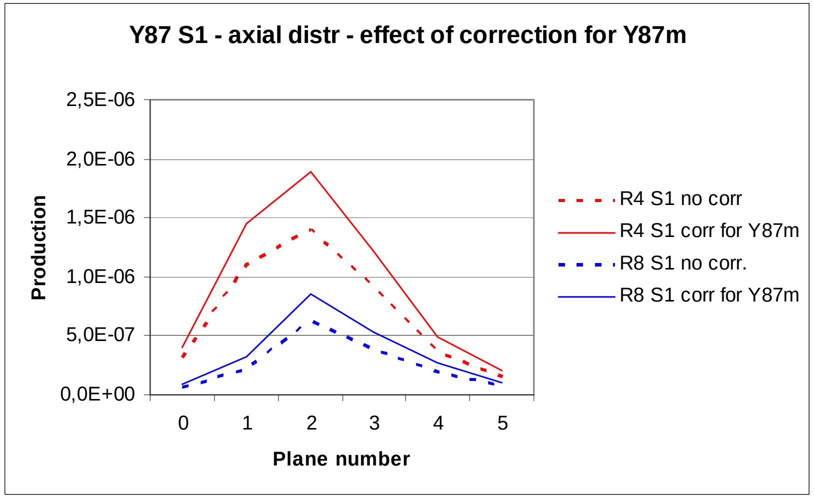


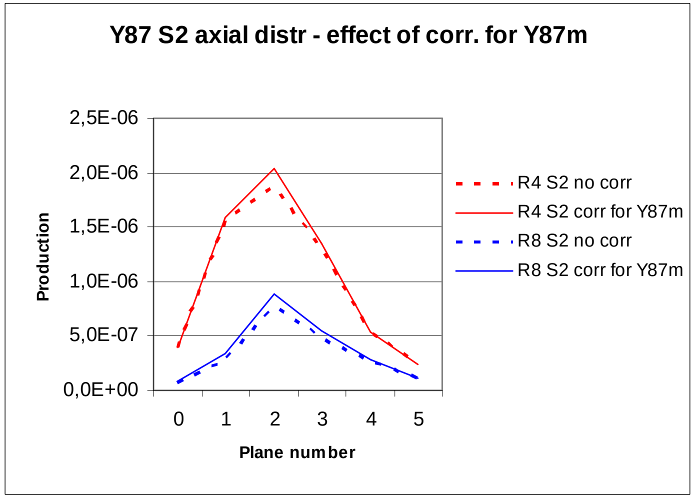
QUINTA experiment 2011-12-14-15 1 GeV



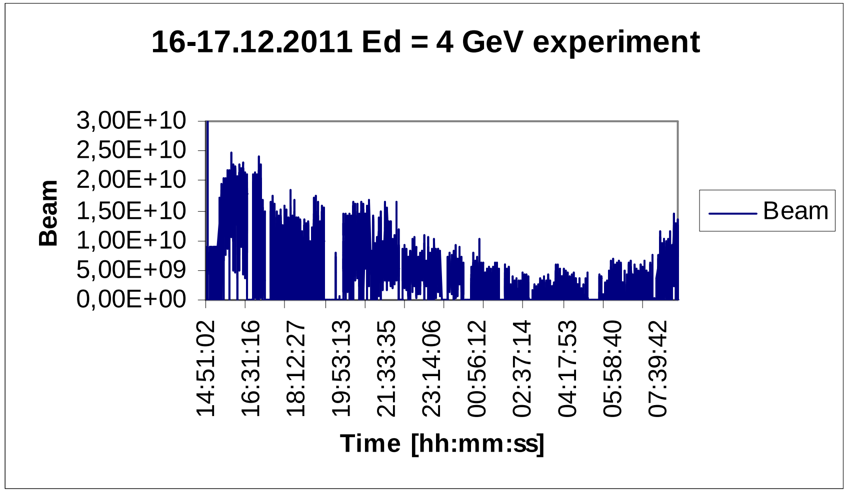
Variable beam to constant beam treatment ratio.				
Y88	Y87m	Y87	Y86	Y85
1,00	1,01	1,00	1,01	1,06

Fluence 6,791E+13
t-irr[hh:mm:ss] 21:07:06



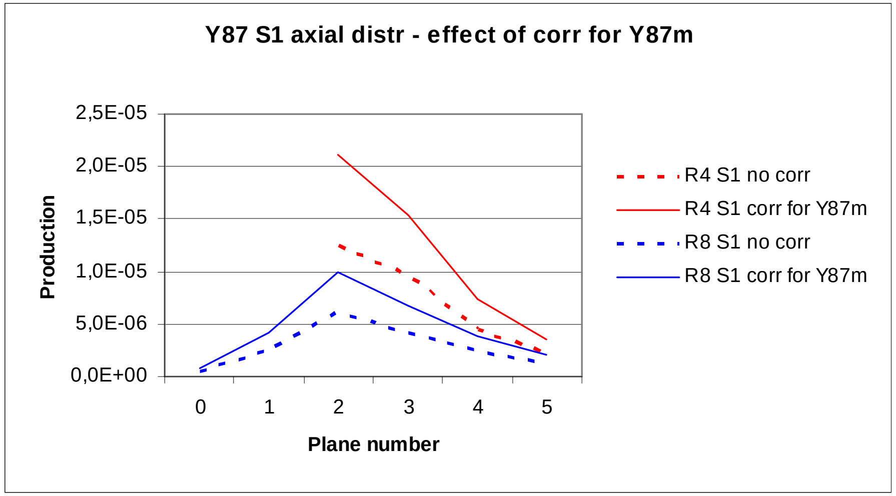


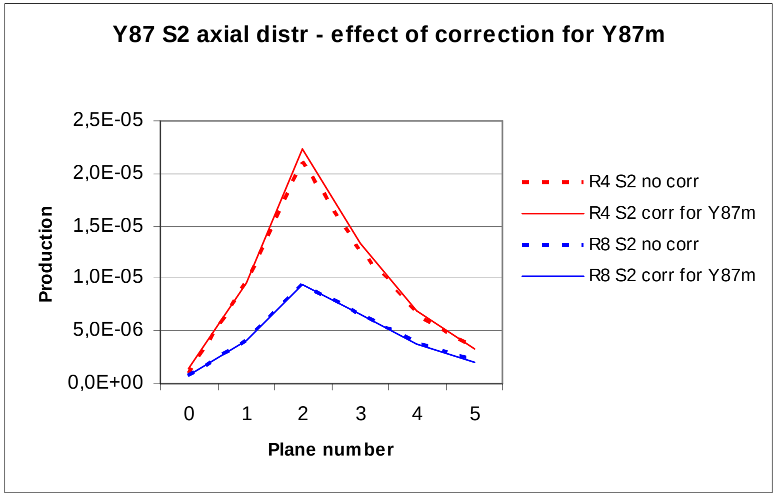
QUINTA experiment 2011-12-16-17 4GeV



Variable beam to constant beam treatment ratio.				
Y88	**Y87m**	**Y87**	**Y86**	**Y85**
1,00	0,84	0,97	0,86	0,55

Fluence 3,37E+13
t-irr[hh:mm:ss] 17:31:00





Conclusions

- In case of resulting isotope produced both directly and in decay chain the effect of decay scheme can be neglected if the measurement starts later than decaying parent isotope half life time.

- In case of variable beam the irradiation history (beam run) effect depends on produced isotope half life time. The effect is large for isotopes with half life time shorter than irradiation time and negligible for isotopes with the longer one. It is recommended, therefore , not to apply or apply with care the constant beam approximation while sample gamma activity working over.

Thank you for attention