Activation monitoring and prediction models

2nd Slow Extraction Workshop, 9 - 11th November 2017

A.C. Araujo Martínez, D. Björkman, M.A. Fraser,
B. Goddard, V. Kain, P.M. Schicho, C. Theis, H. Vincke, CERN

Overview

- Why model the build-up of Induced Radioactivity?
- History of SE-induced radioactivation of SPS
- Introduction to empirical models of $\mathrm{IR(t)}$
- A practical implementation of $\mathrm{IR(t)}$:
  – Instrumentation, data logging, fitting
- Predictive power of $\mathrm{IR(t)}$:
  – Cool-down times for future operational scenarios:
    - YETS 2017-18 and future SPS BDF operation
- Conclusion:
  – Future studies and development, e.g. online tool

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- Slow extraction is a lossy, resonant process and it's efficiency is sensitive to the smallest machine parameters
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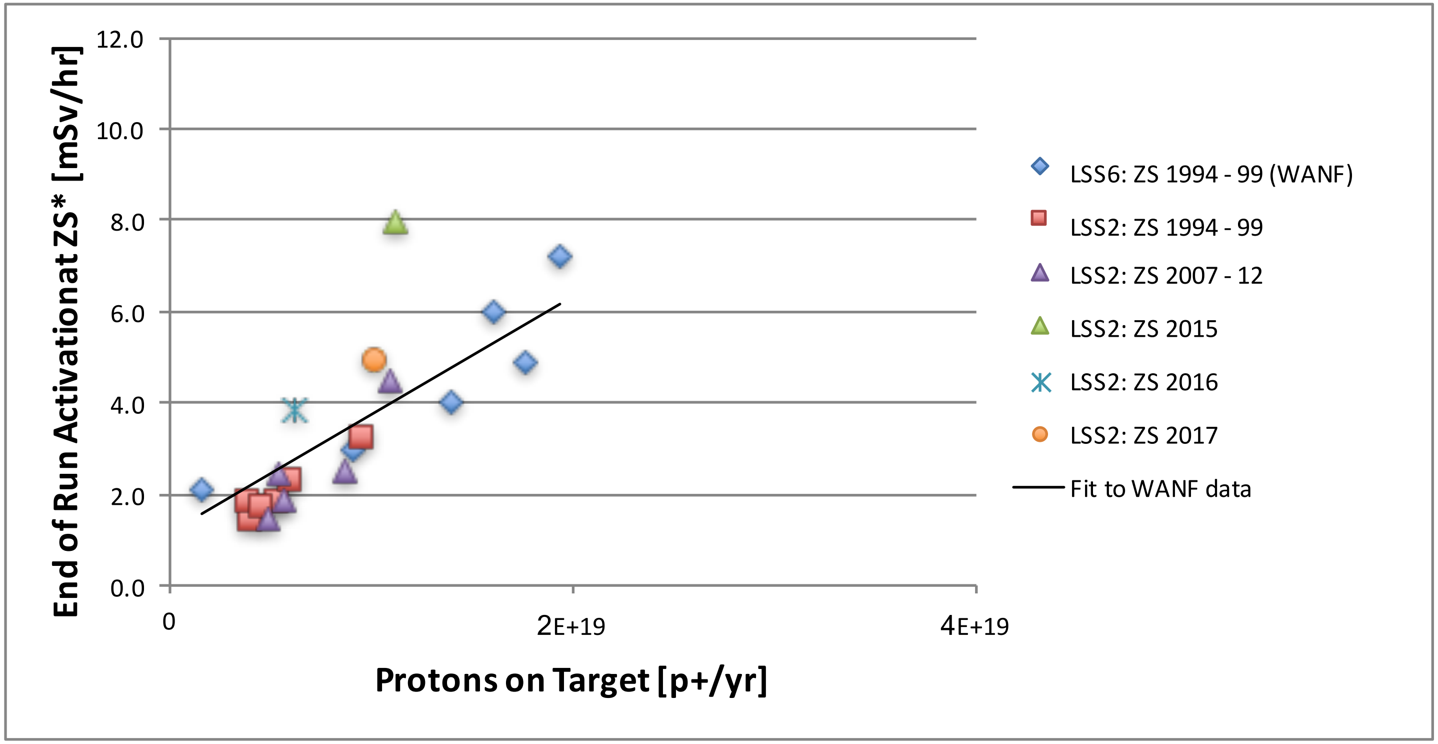
  - We learnt this the hard-way at CERN SPS with elevated activation in 2015
  - Feedforward, or feedback OP systems, will be the solution in the longer term
- We want to monitor and empirically model the $\mathrm{IR(t)}$:
  - Full numerical calculations are too computationally intensive: we are look for a simple but reliable empirical approximation
  - Keep an eye on activation levels before the end-of-year RP survey: avoid local radioactive hotspots!
  - Understand cool-down times as a function of Protons On Target (POT)
  - Predict activation levels for future operational scenarios as a function of extraction efficiency and POT

Activation levels at ZS in LSS2

- Analysis of archived yearly end-of-run RP survey data shows a rough linear correlation of activation vs. POT:



*Measured ~30h after shutdown at ~1 m from beam line, peak at ZS in LSS2 plotted. Correlation shown is a rough rule of thumb: time from end of last slow-extraction can vary, along with the length of the annual proton run and extraction rate. WANF data is ½-integer quad. driven "fast-slow" extraction: ~10 ms spills.

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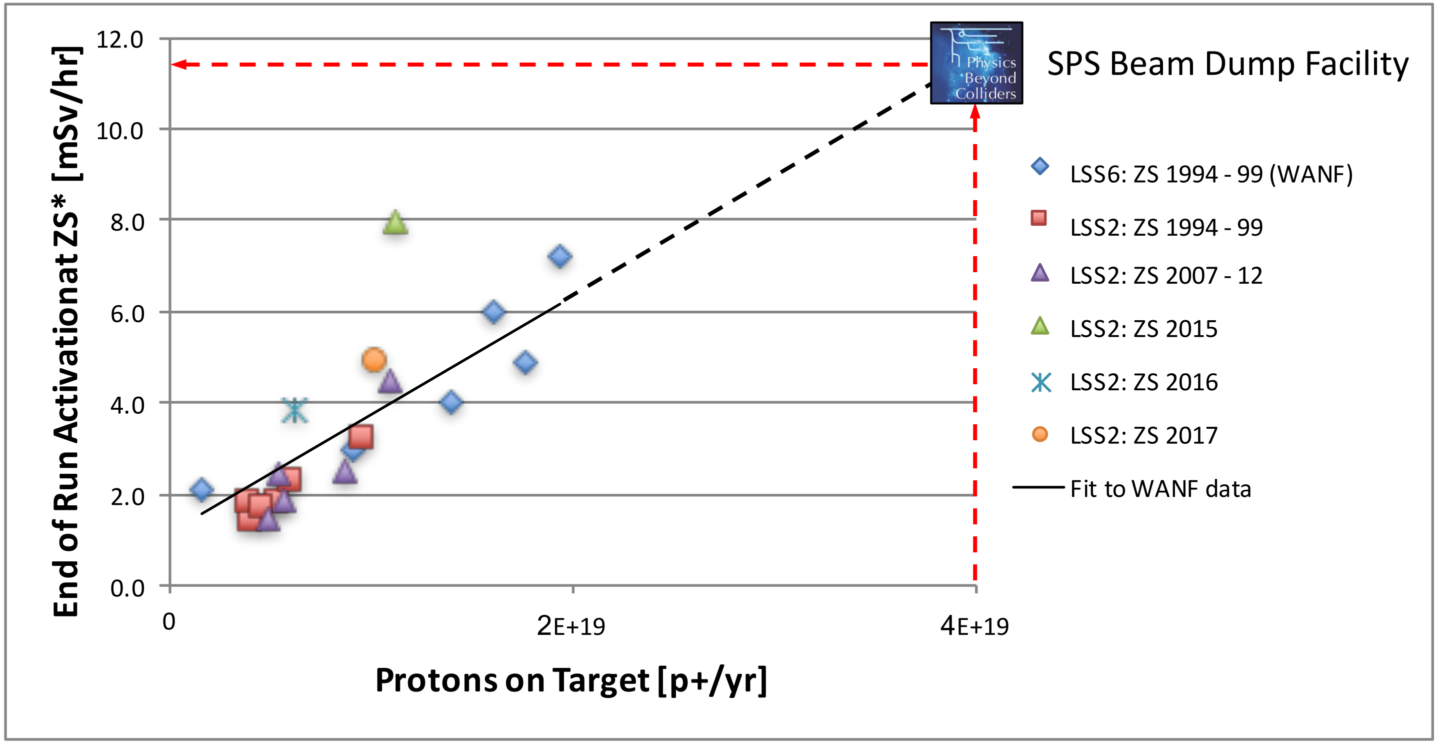

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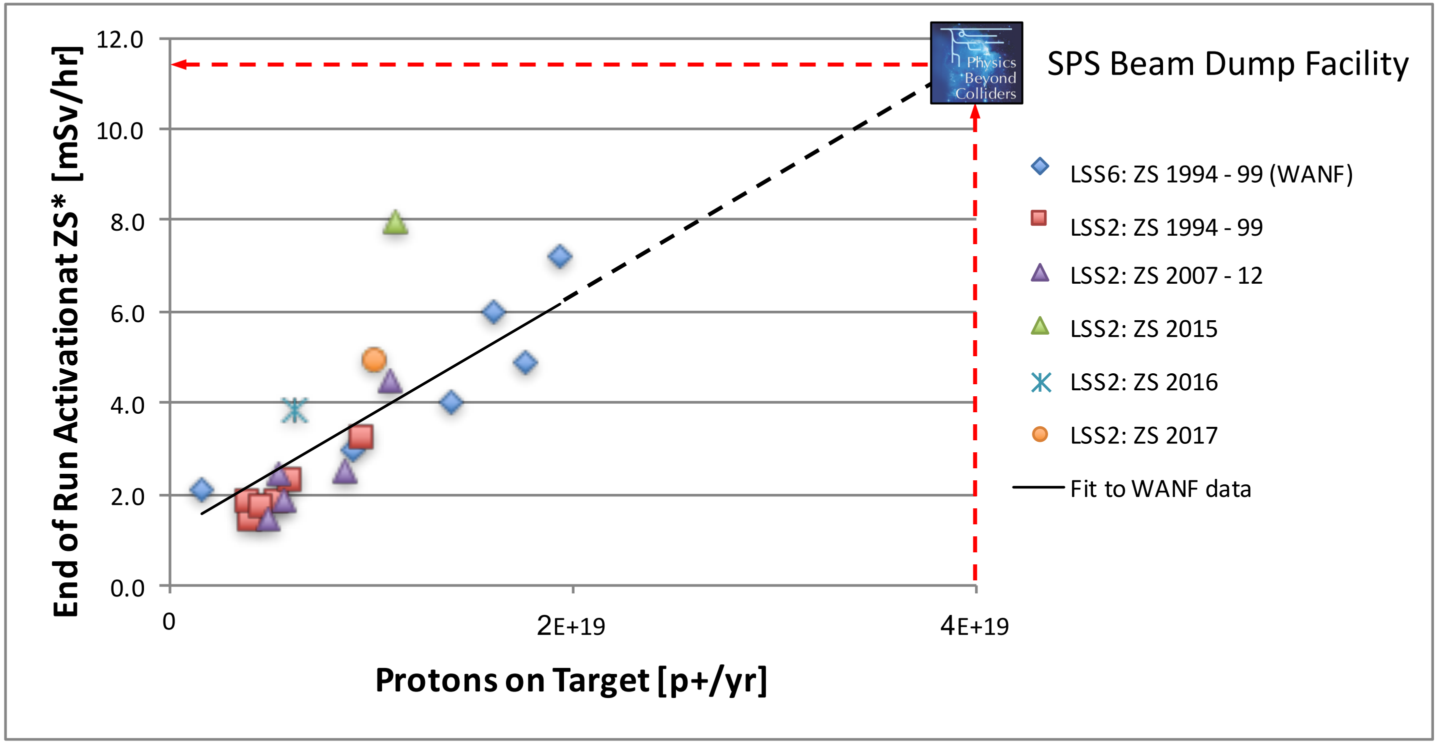

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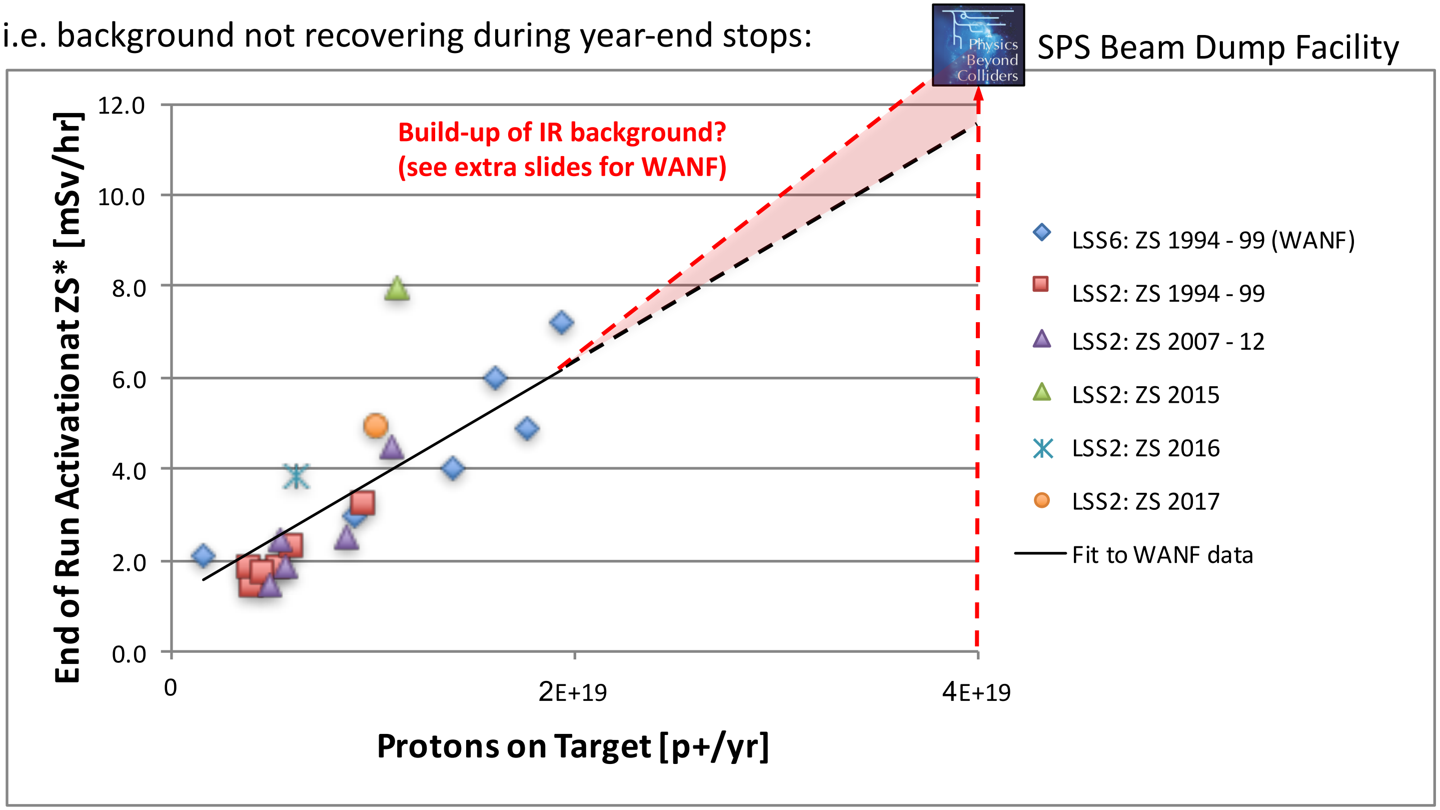

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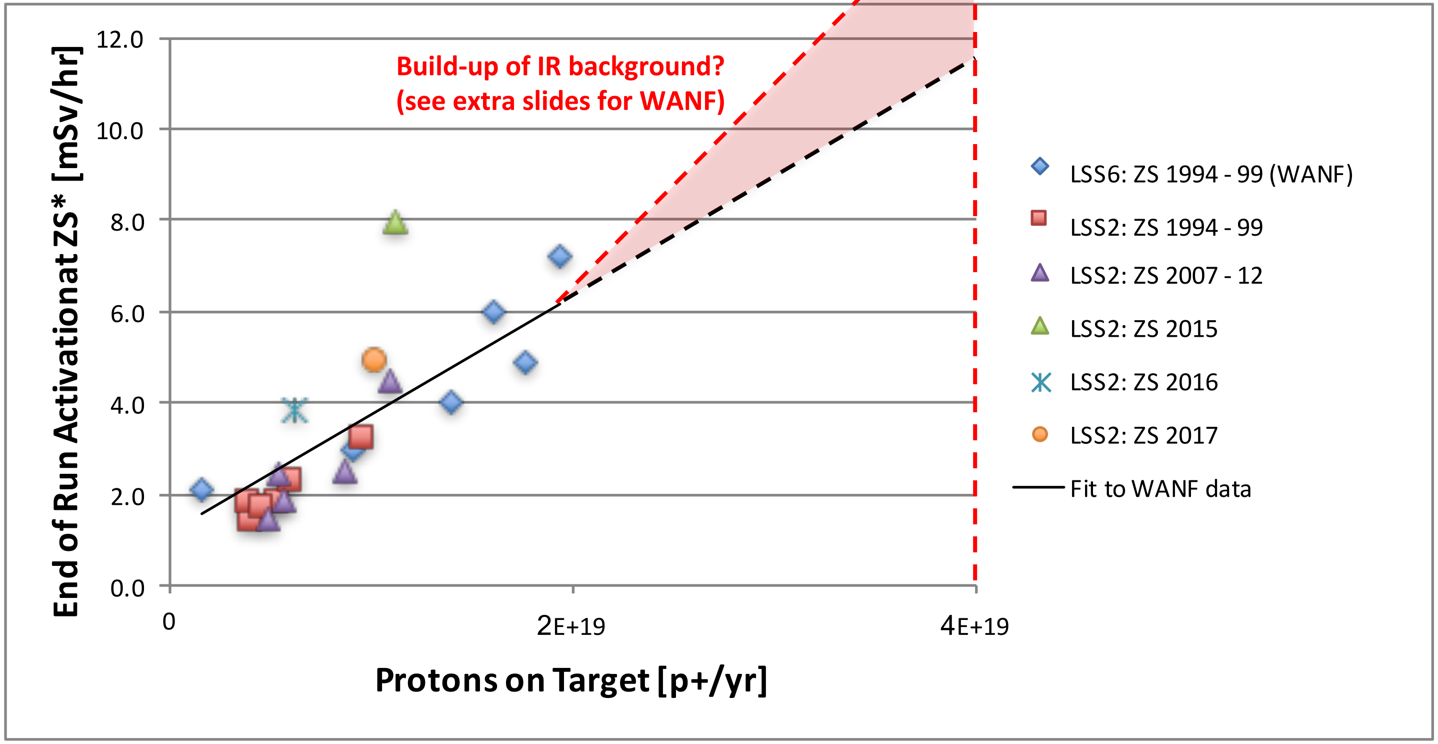
SPS Beam Dump Facility



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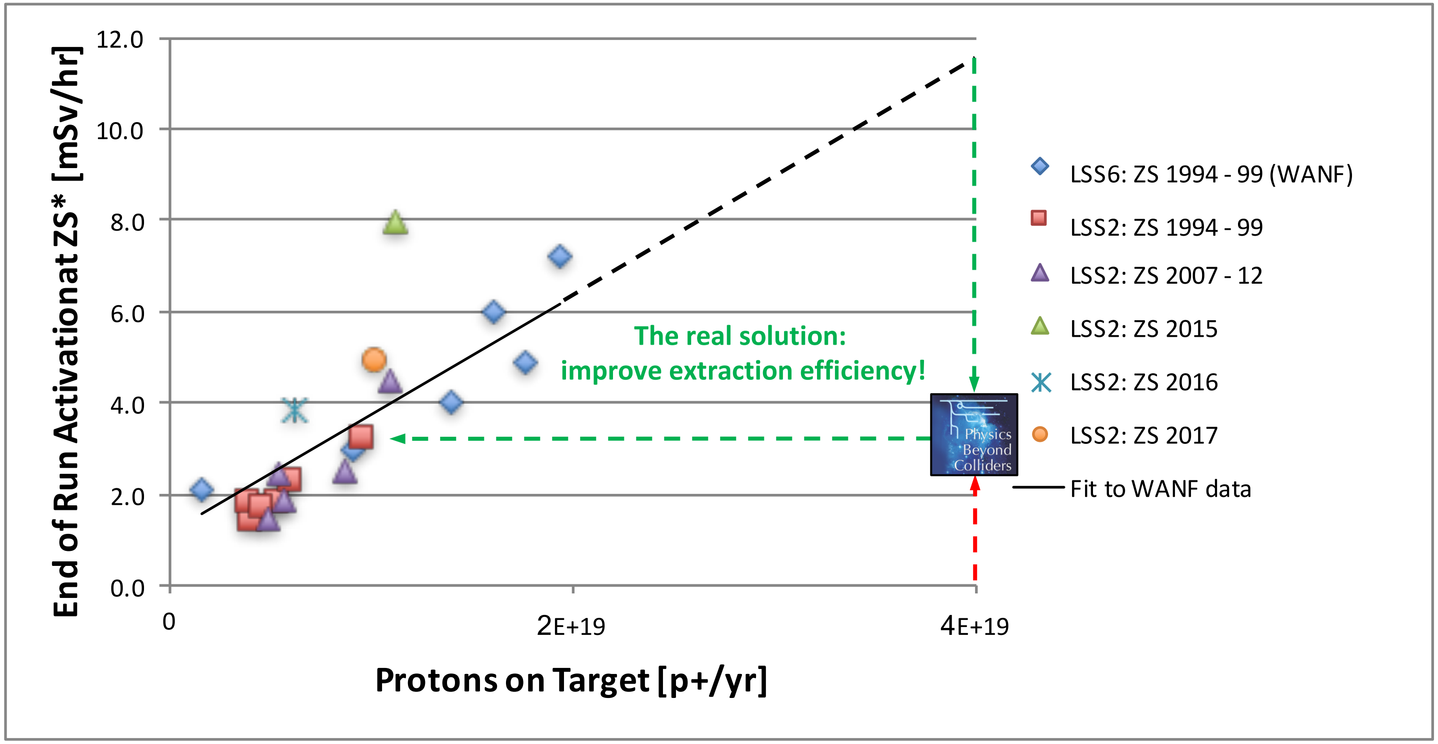

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An empirical model for IR(t)

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- The effective half-life describes the non-linear time dependence of IR generated by the mixture of different radionuclides produced during the initial irradiation and in the resulting chains of of radioactive decay
- $t_{\mathrm{eff},1/2}$ increases towards ∞ (stability) at an exponentially slower rate, which is what we might expect physically: $\lim_{t\to\infty} t_{\mathrm{eff},\frac{1}{2}} = \infty$ and $\lim_{t\to\infty} \frac{\partial t_{\mathrm{eff},\frac{1}{2}}}{\partial t} = 0$

Effective half-life for different IR(t) models

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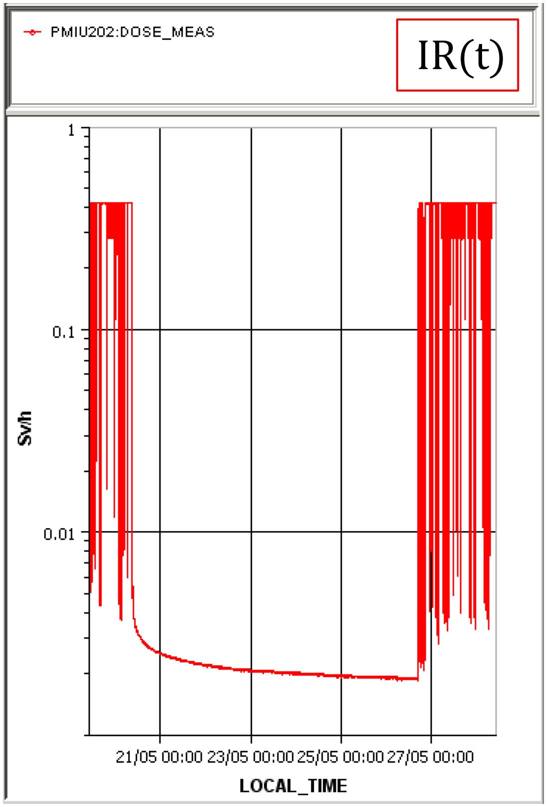

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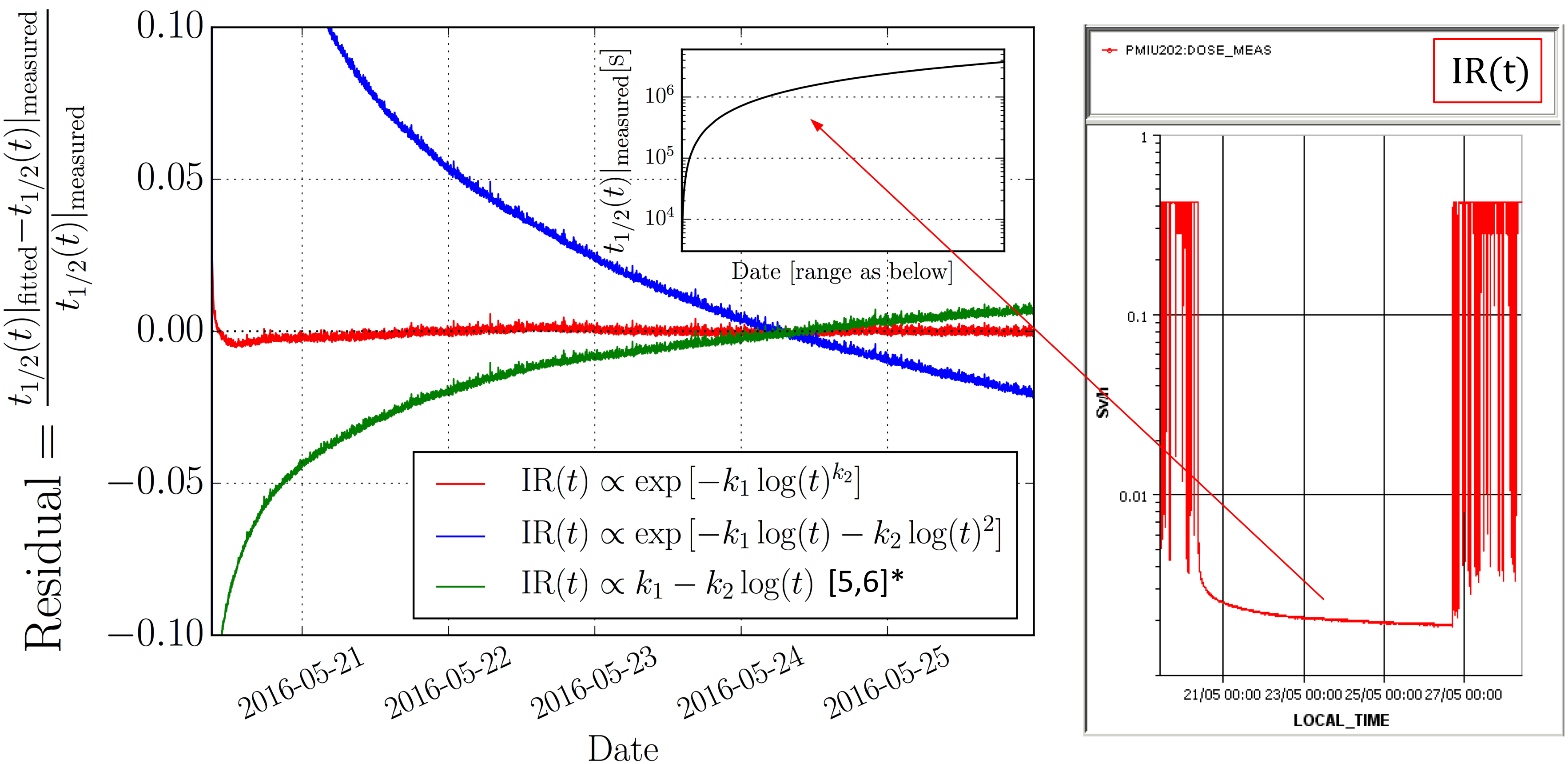

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IR(t) vs. numerical computation, e.g. ActiWiz

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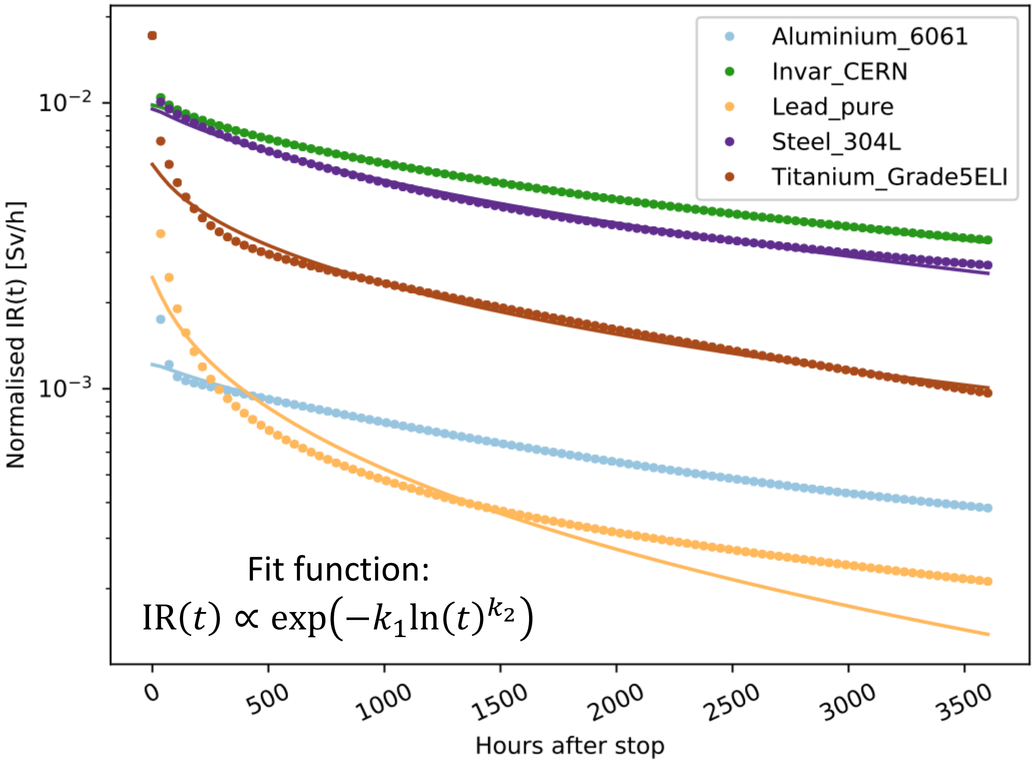

Material	Fit constants: $\mathrm{IR}(t) \propto \exp\left(-k_1 \ln(t)^{k_2}\right)$	
	k_1 [$\times10^{-4}$]	k_2
Aluminium	0.19	5.25
Invar	0.25	5.09
Steel 304L	0.45	4.89
Titanium	7.78	3.68
Lead	13.10	3.66

- Fit to *ActiWiz* data is generally poorer when change in IR is too large over the range of interest, i.e. the empirical model has its limits

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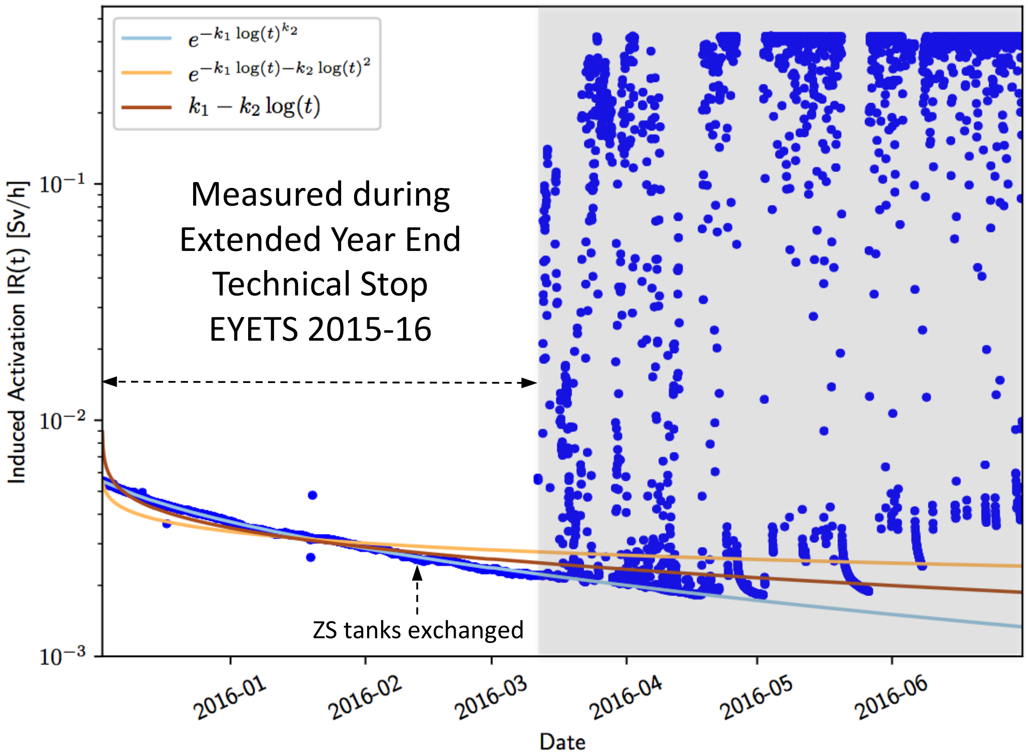

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Measured ZS Tank 2 EYETS15-16	**0.39**	**4.91**

- Measured fit constants consistent with material composition of the ZS:
  - SS 304L vacuum tank and, SS 304L or Invar anode support [8]

A predictive model for IR(t) (1)

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$$\text{IR}(t_n) = G \sum_{i=1}^{n} \underbrace{N_{L,n+1-i} P_{ex,n+1-i}}_{L_{BLM,n+1-i}[\text{Gy}]} \exp\left(-k_1 \ln\left((i-1)\Delta t\right)^{k_2}\right)$$

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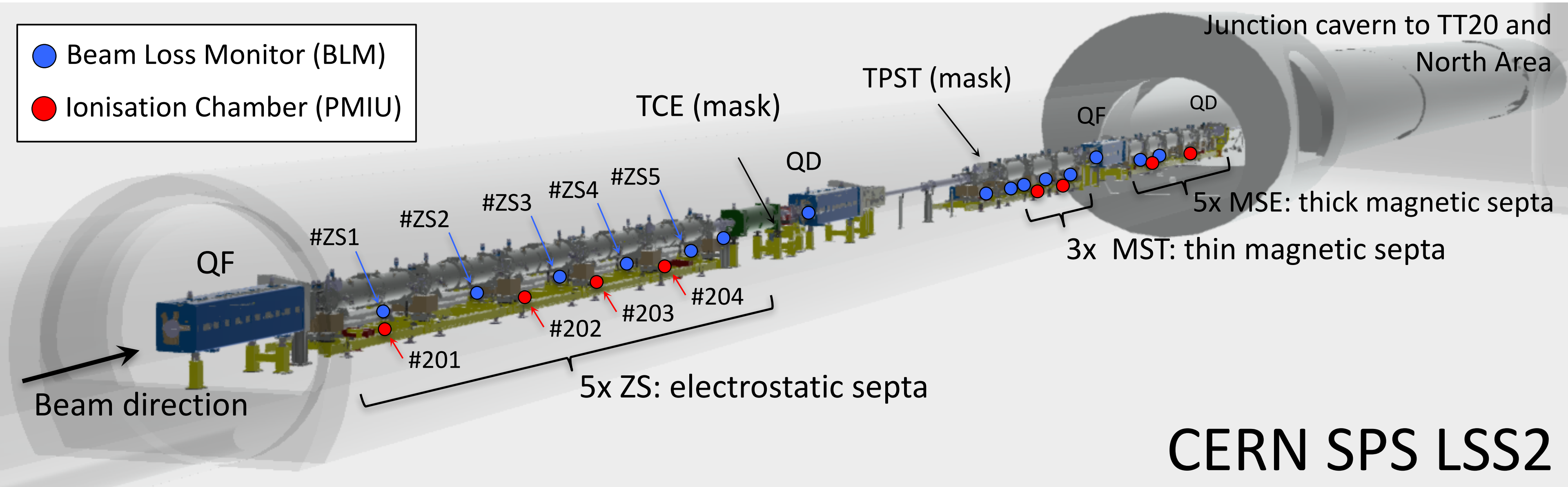
  - P_{ex} is the number of extracted protons and N_L is the specific loss (per proton)
- To account for the changing extraction efficiency observed last year we linked the IR measured on a given PMIU detector to the prompt loss L_{BLM} measured at the nearest BLM: we fit to measured values of L_{BLM}:

$$L_{BLM}[\mathrm{Gy}] = N_L \left[\frac{\mathrm{Gy}}{\mathrm{p}^+}\right] P_{ex}[\mathrm{p}^+]$$

A predictive model for IR(t) (2)

- We have a network of radiation monitors in LSS2:
  - BLMs for prompt extraction dose measurements: $L_{BLM}(t)$
  - PMIUs for residual, induced radioactive (without beam): $\mathrm{IR}(t)$
  - We use the ring BCT to normalise to the number of protons extracted: $P_{ex}(t)$
- All the data is logged by the CERN Accelerator Logging Service:
  - We use an API (via pyTimber) to access all time series data in CALS before preparing aligning, binning and filtering the data for fitting



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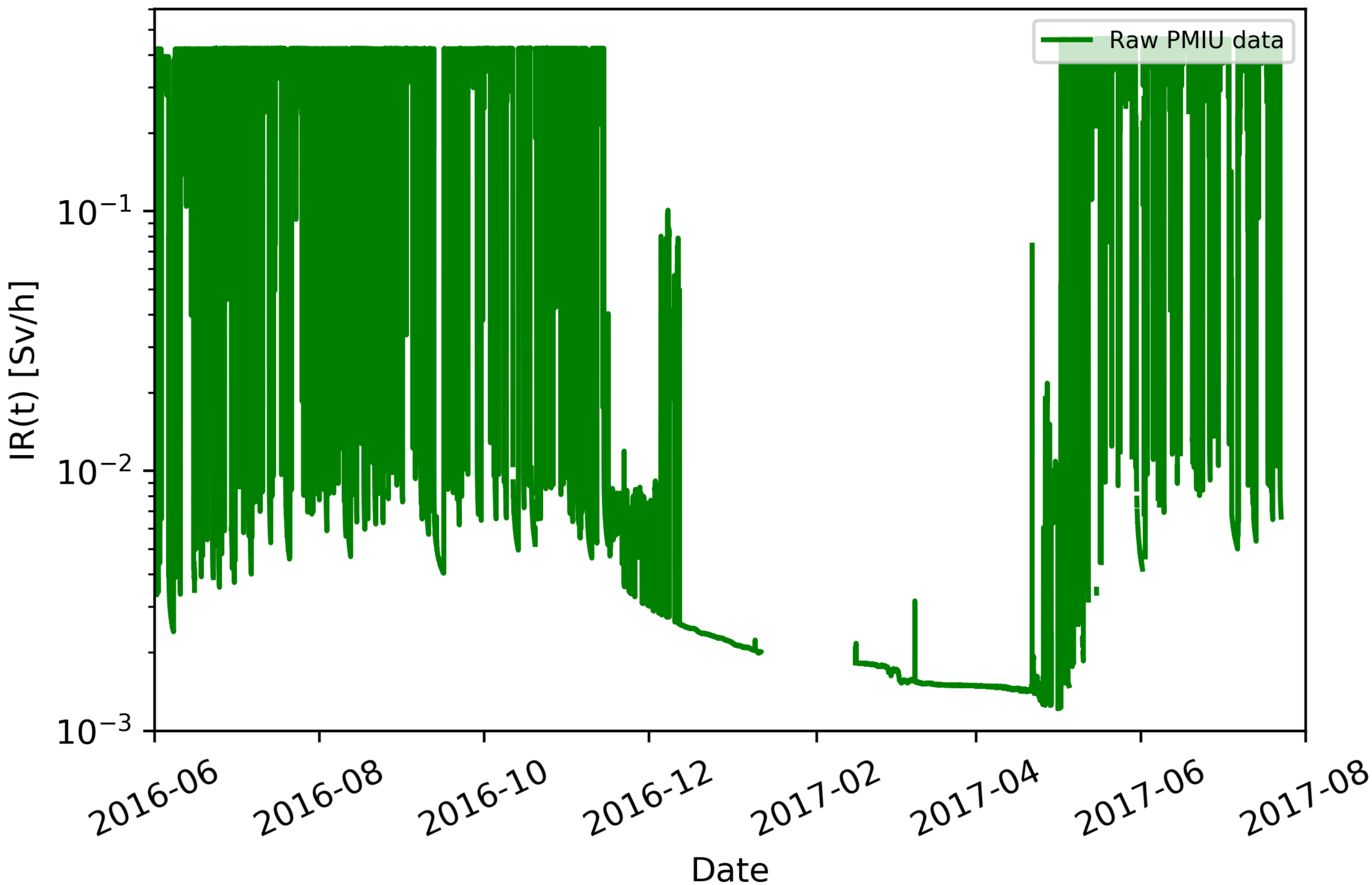

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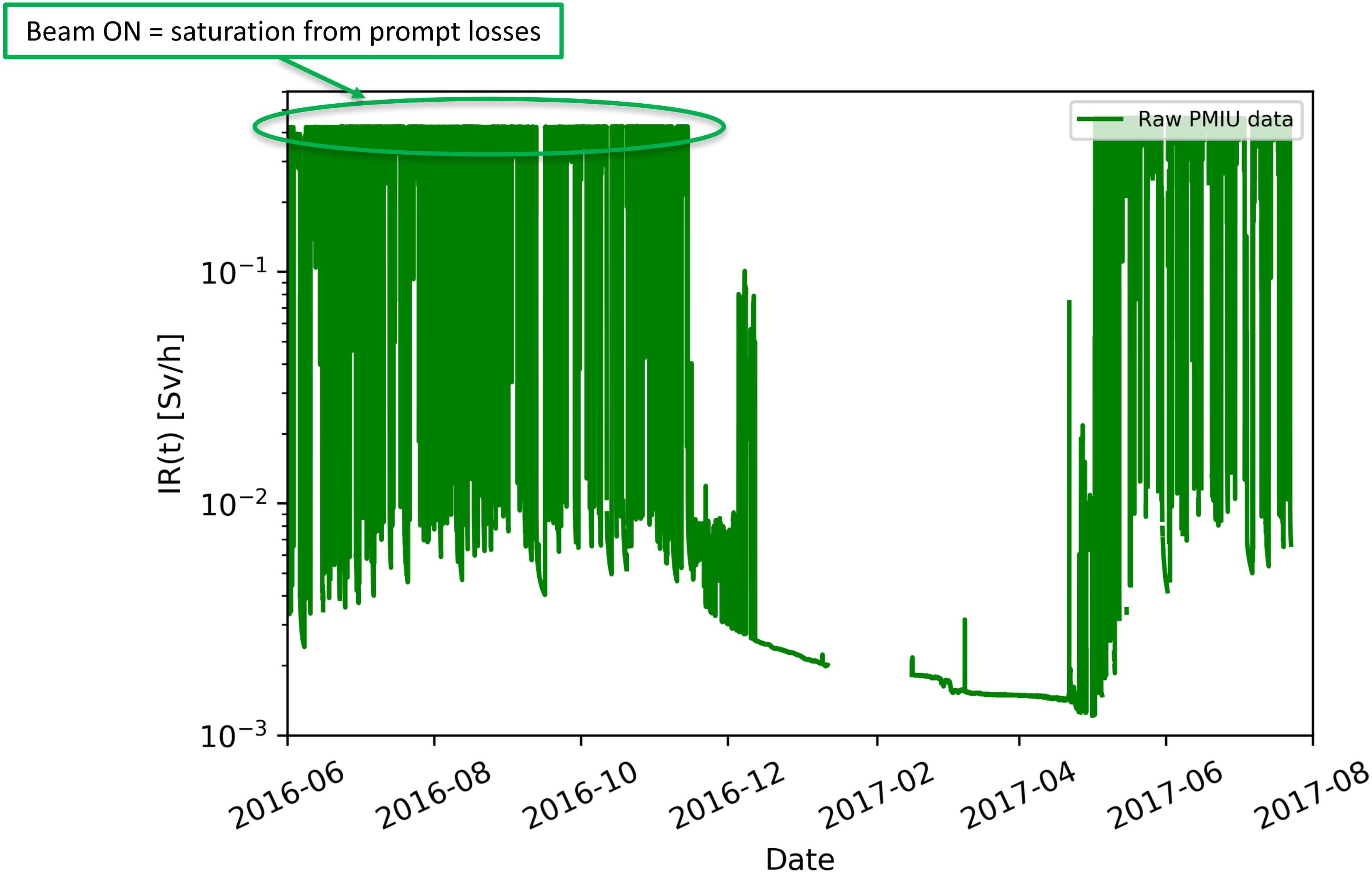

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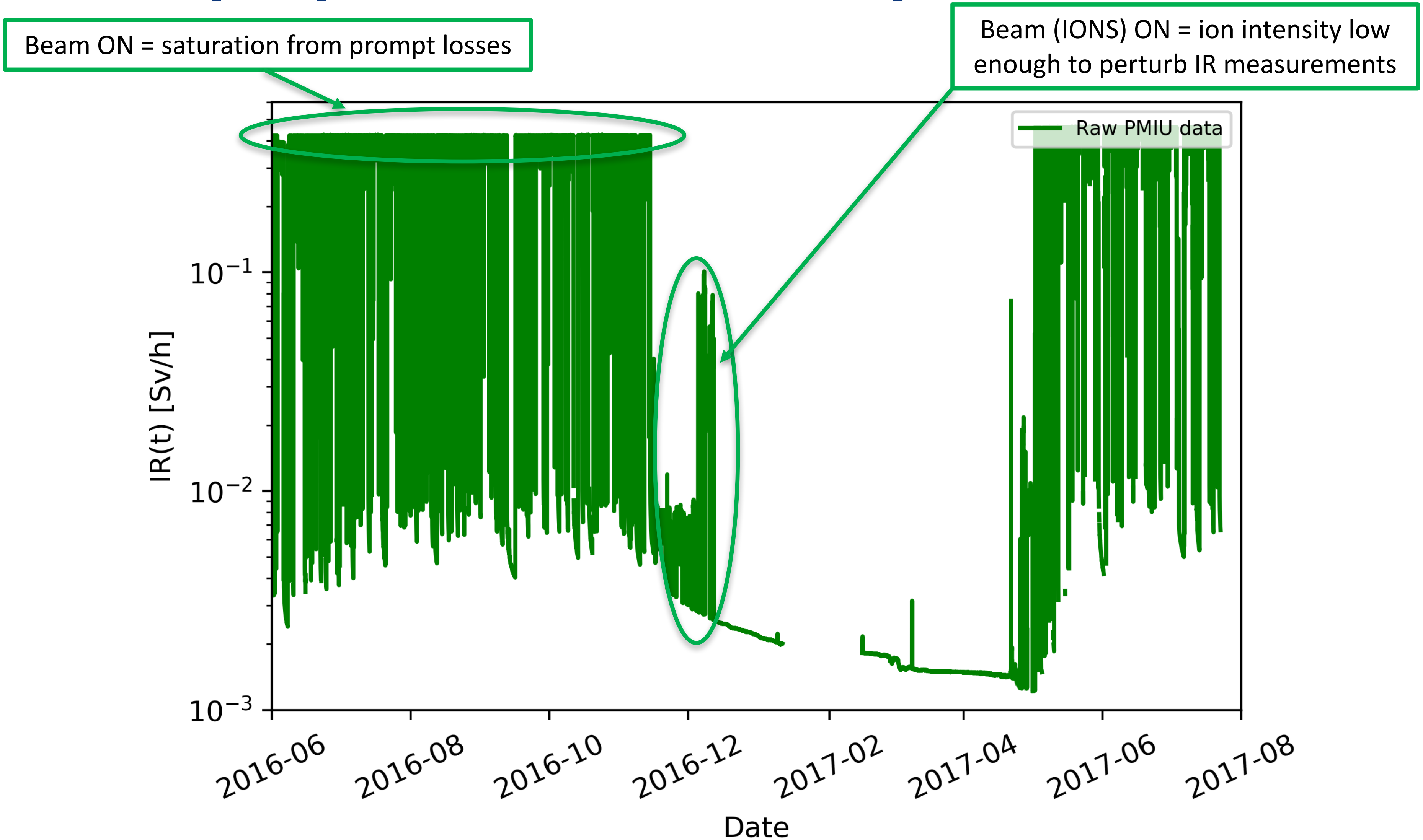

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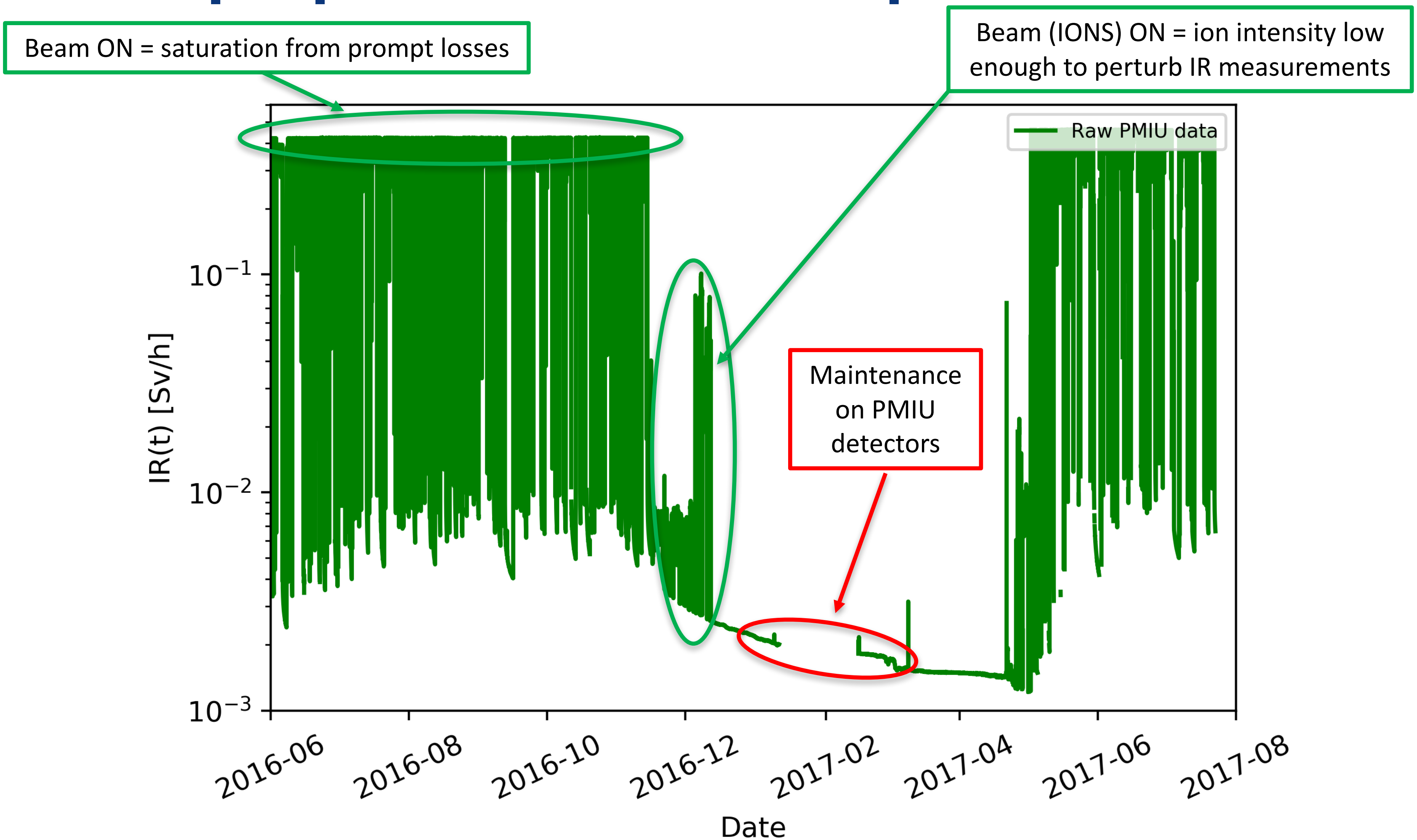

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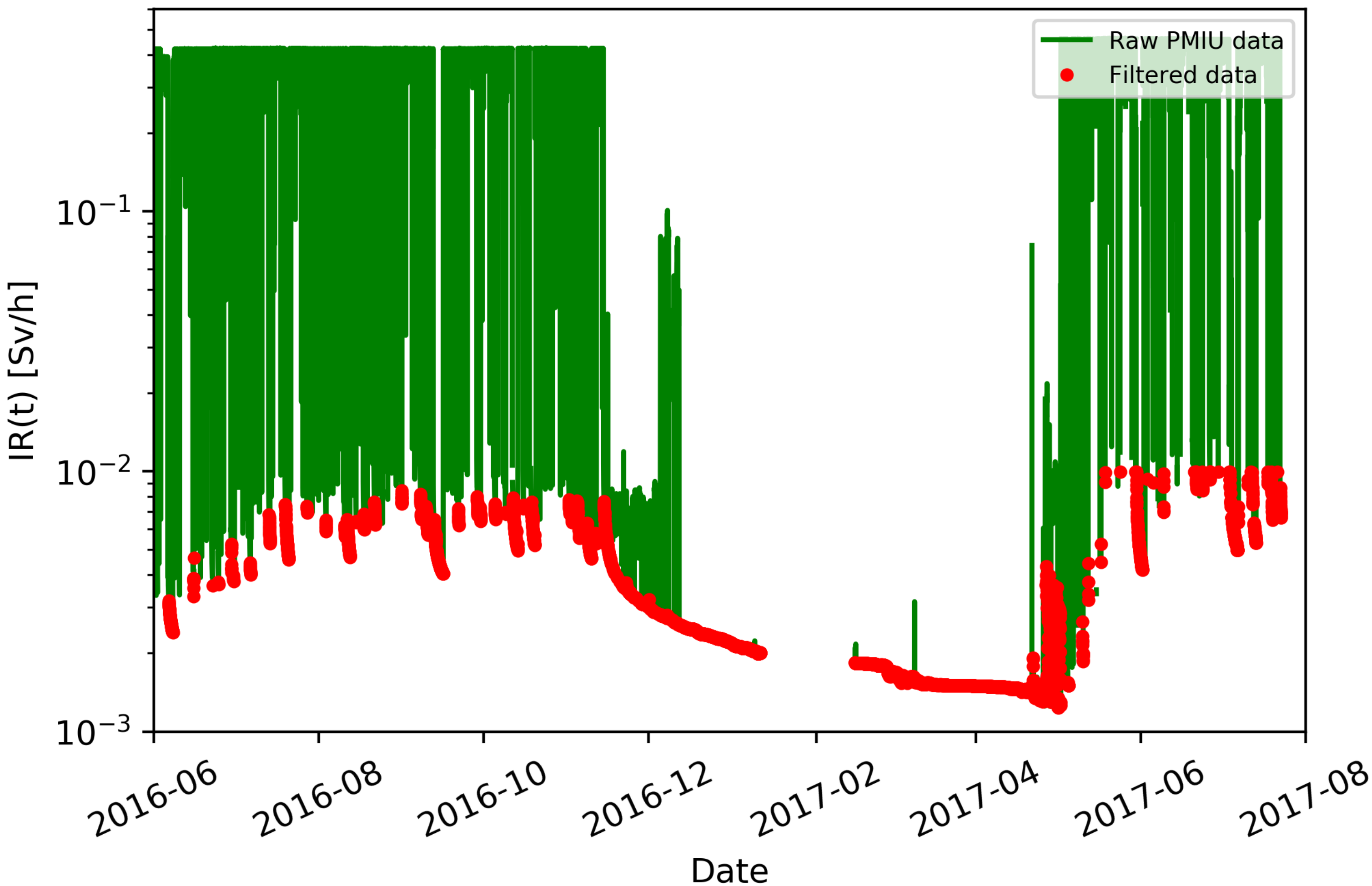

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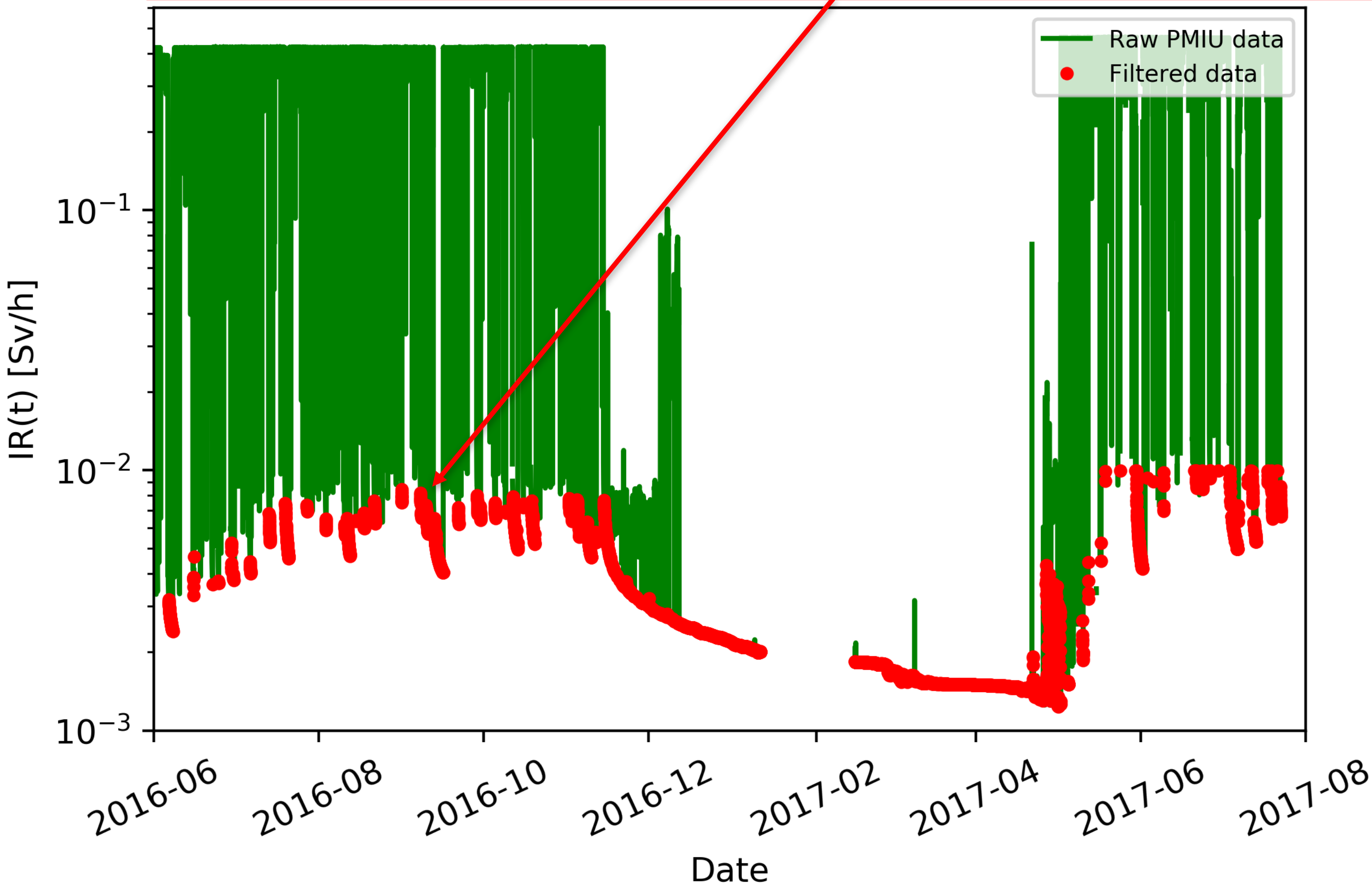

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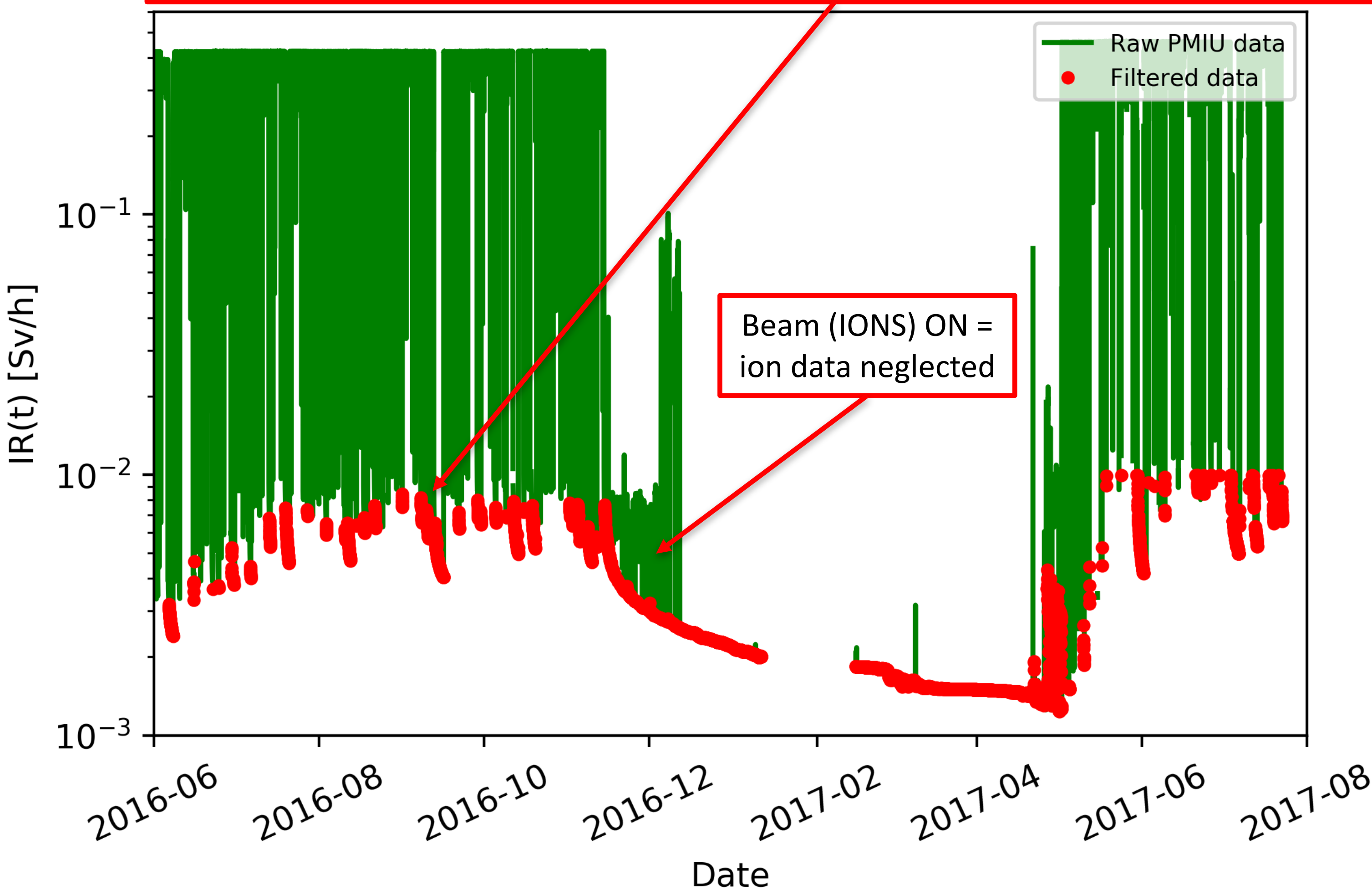

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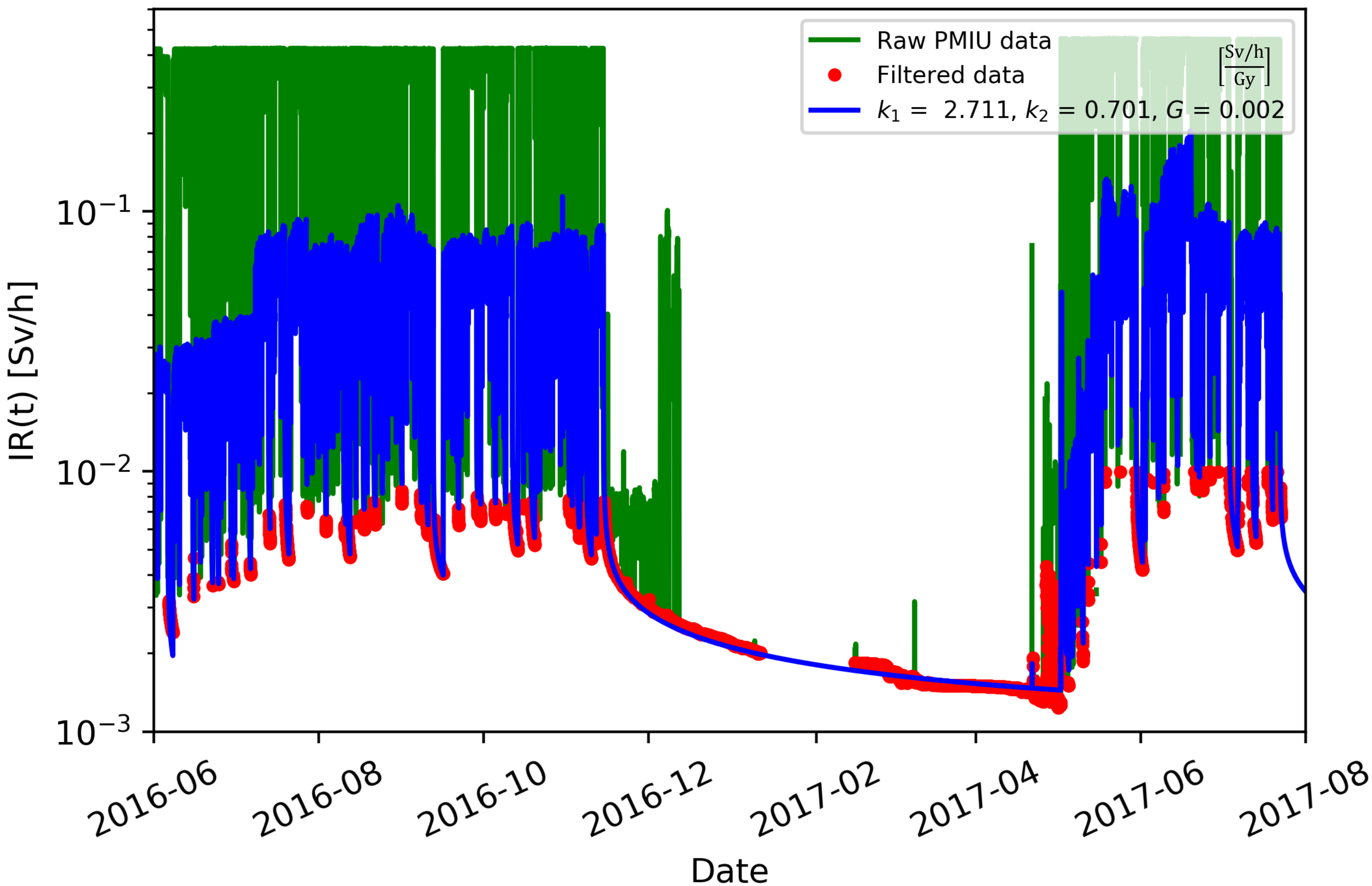

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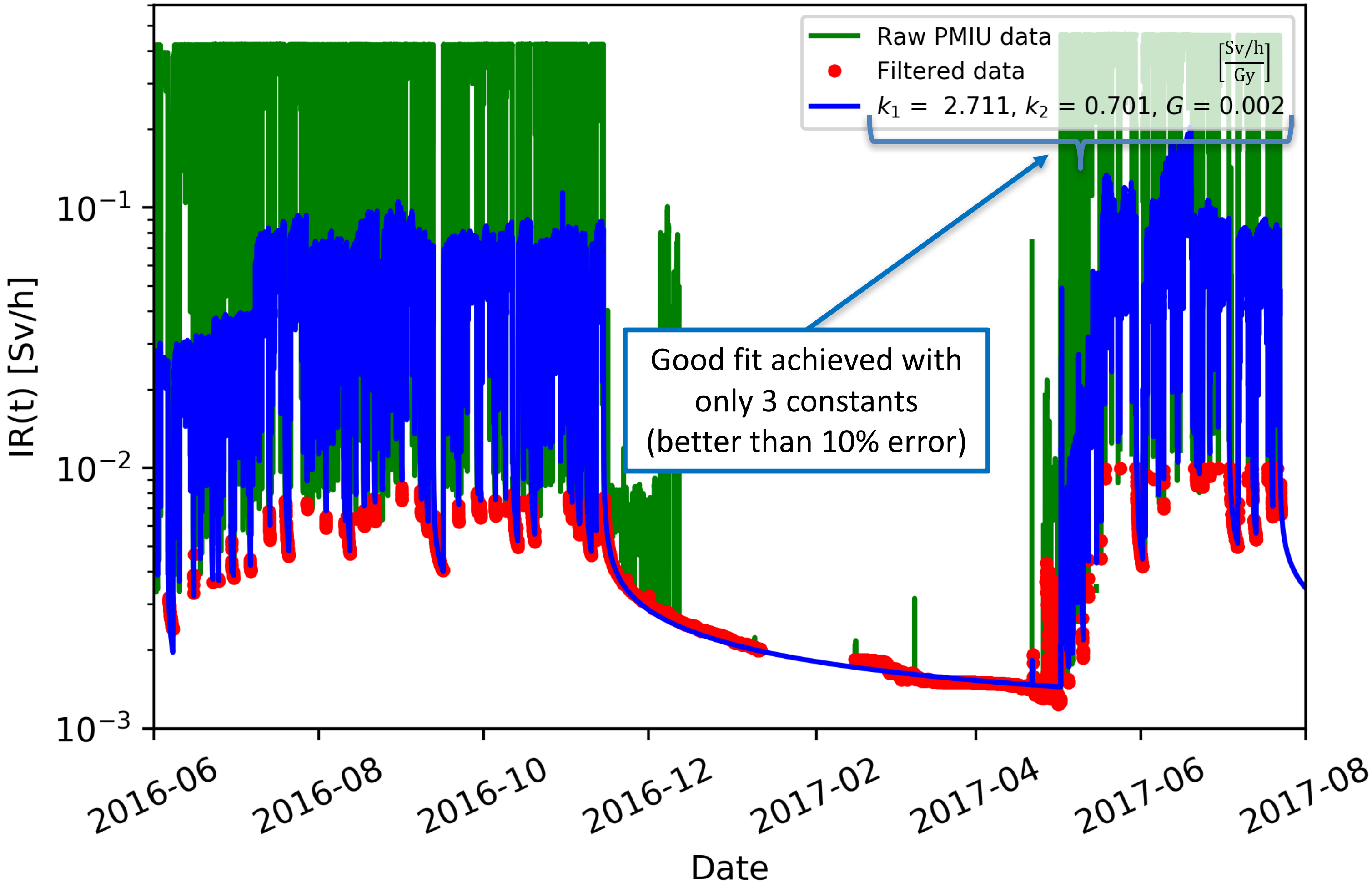

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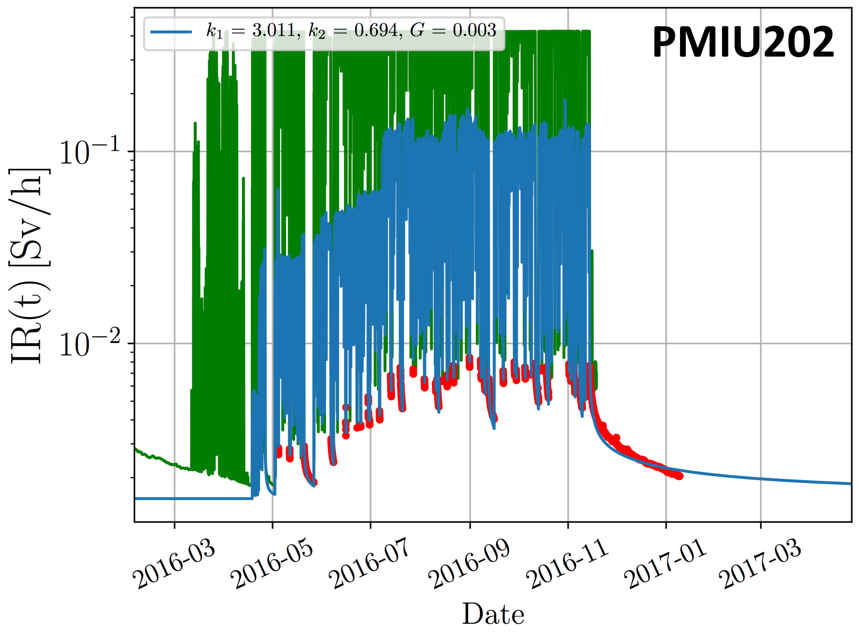
Fit constants for different detectors

PMIU #	Paired with BLM.ZS #	Fit constants $\mathrm{IR}(t)$*		
		k_1	k_2	G $\left[\frac{\mathrm{Sv/h}}{\mathrm{Gy}}\right]$
1	201	3.14	0.69	0.0062
2	**202**	**3.01**	**0.69**	**0.0027**
3	203	2.73	0.66	0.0007
4	204	2.44	0.76	0.0008
average	average	3.31	0.67	0.0016

*Fit constants will depend on unit of time chosen: care when comparing different datasets, c.f. cooldown data presented earlier

Fitting only on 2016 data: full cool-down not included



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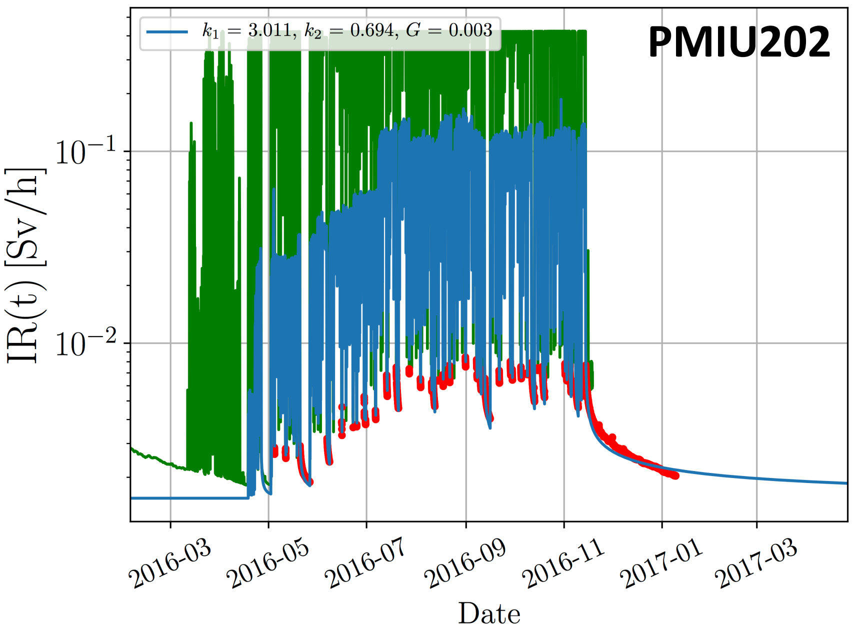
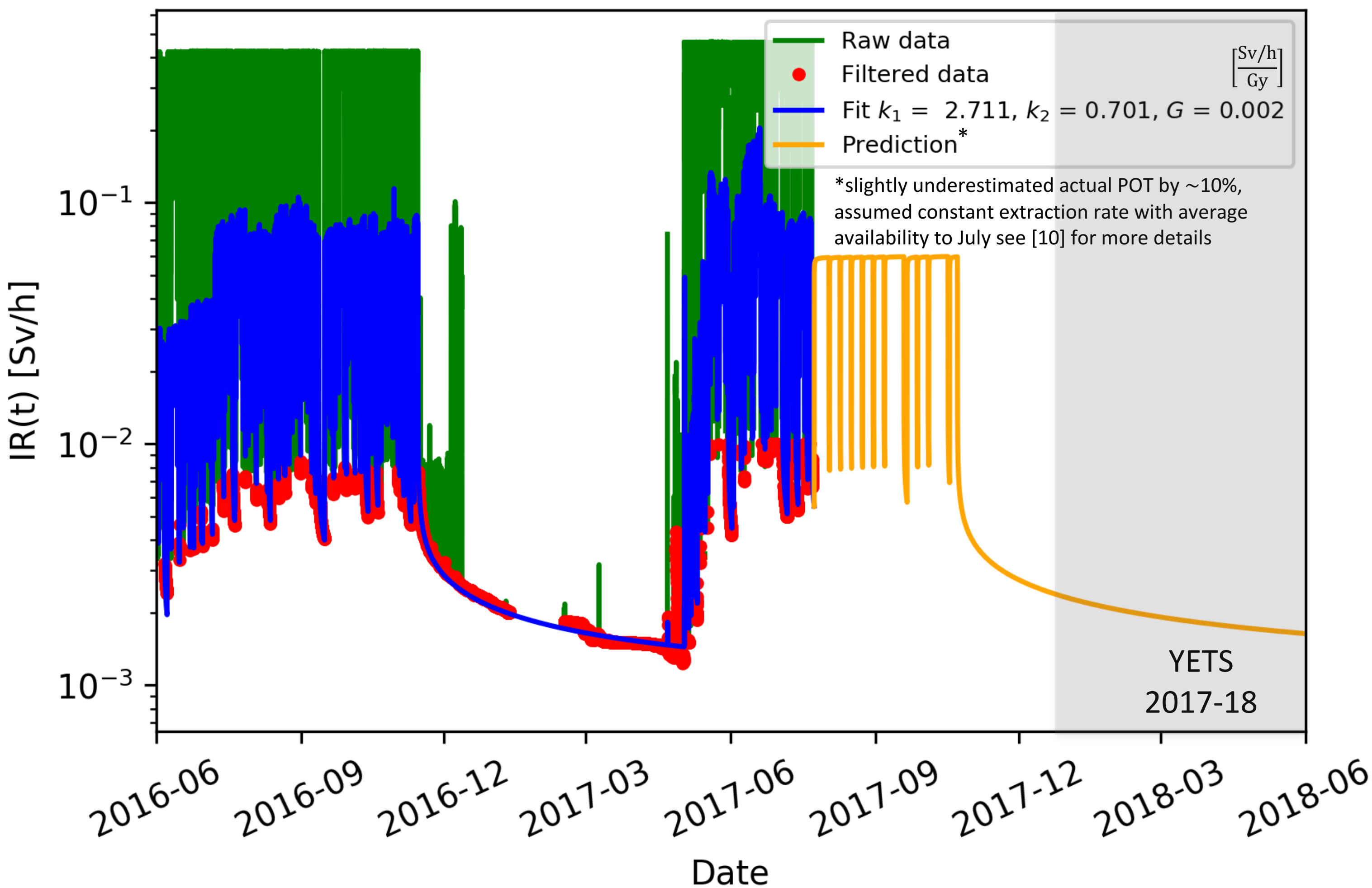


- Variation in G is due to different relative positions of BLMs and PMIUs
- Difference in k_1 and k_2 indicate spatial difference in the decay rate:
  - Local differences of materials composing equipment or being activated?
- Predictive power of model was also tested using fit constants with older data, dating back to 2011: agreement to about 10% was found [9]

Predictions for IR in YETS 2017



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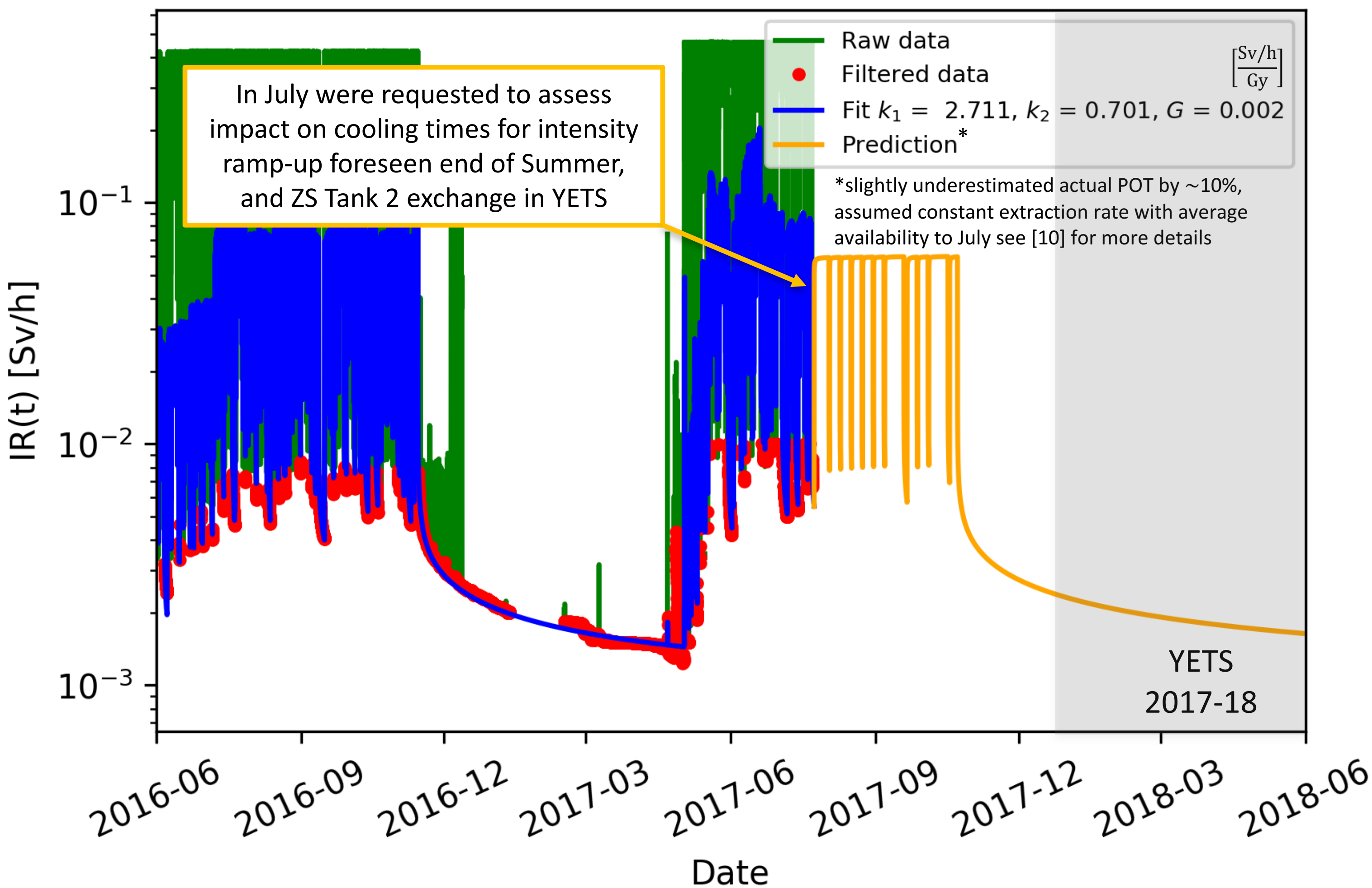

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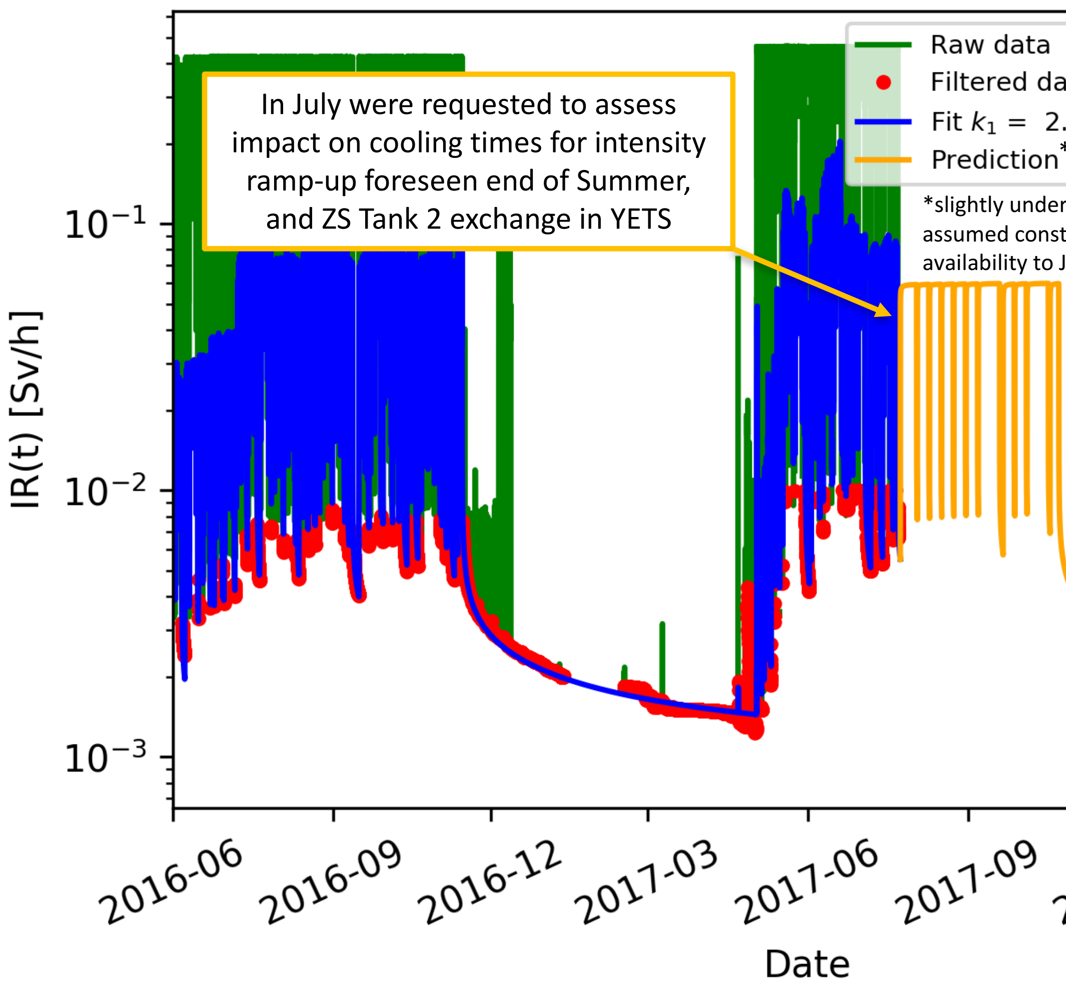

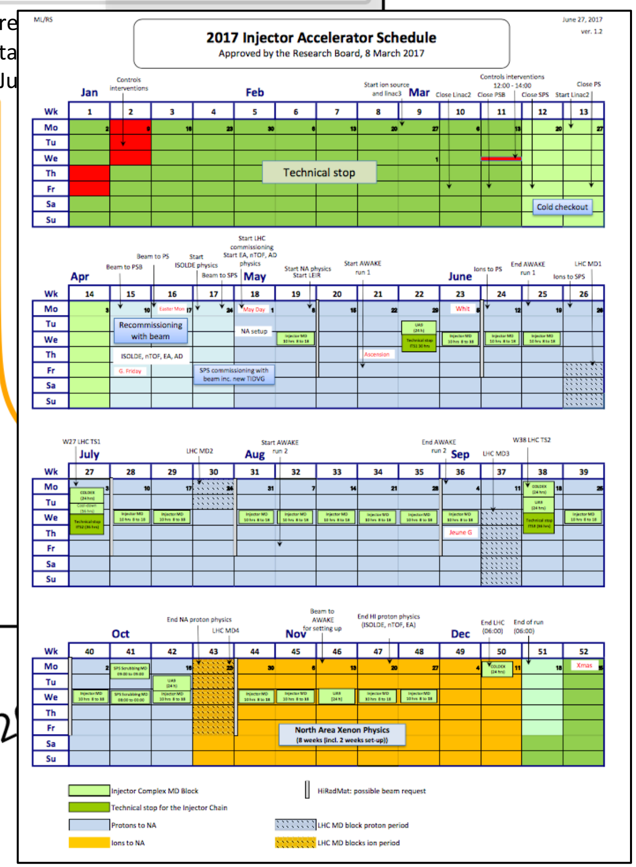

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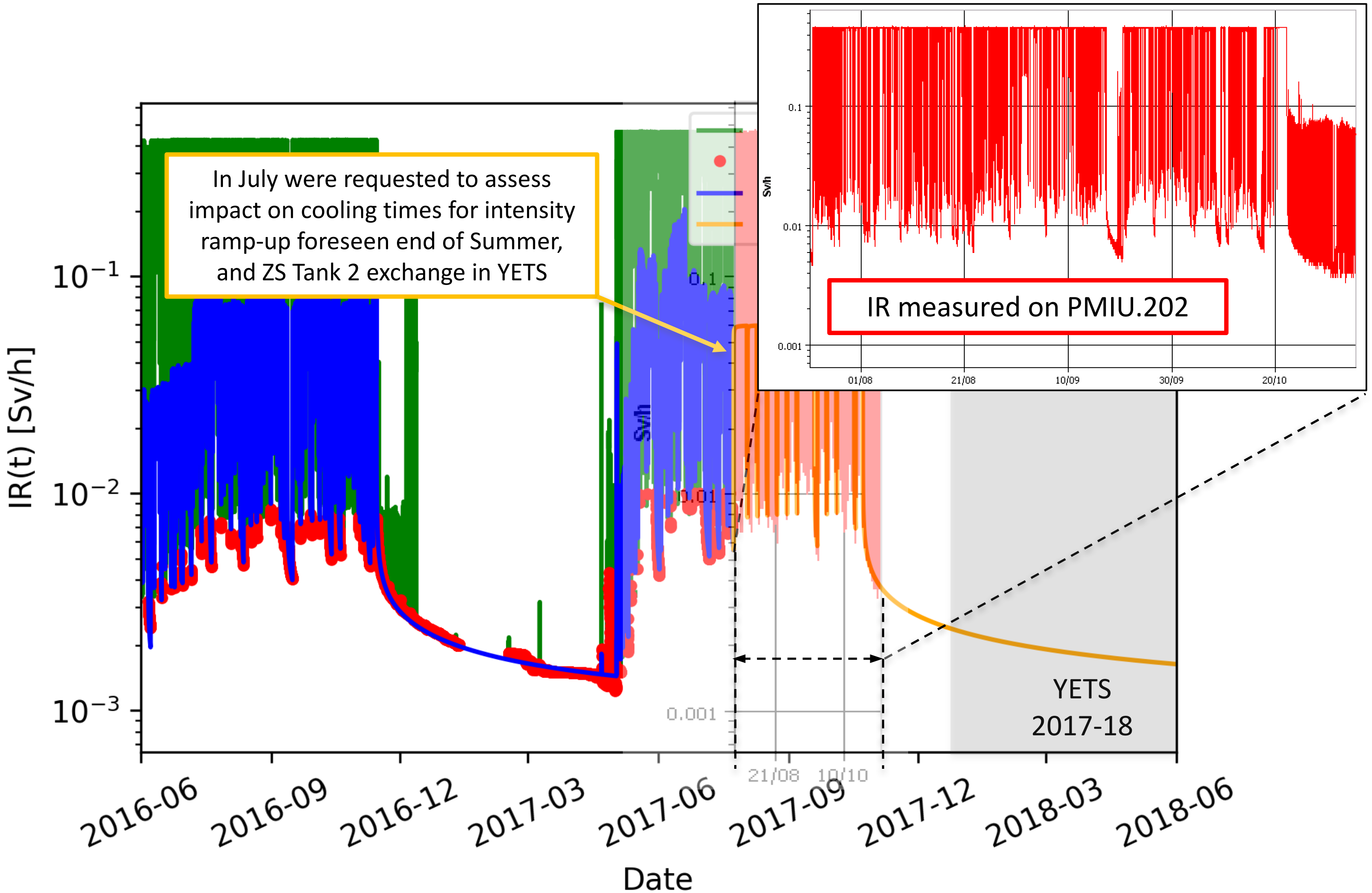

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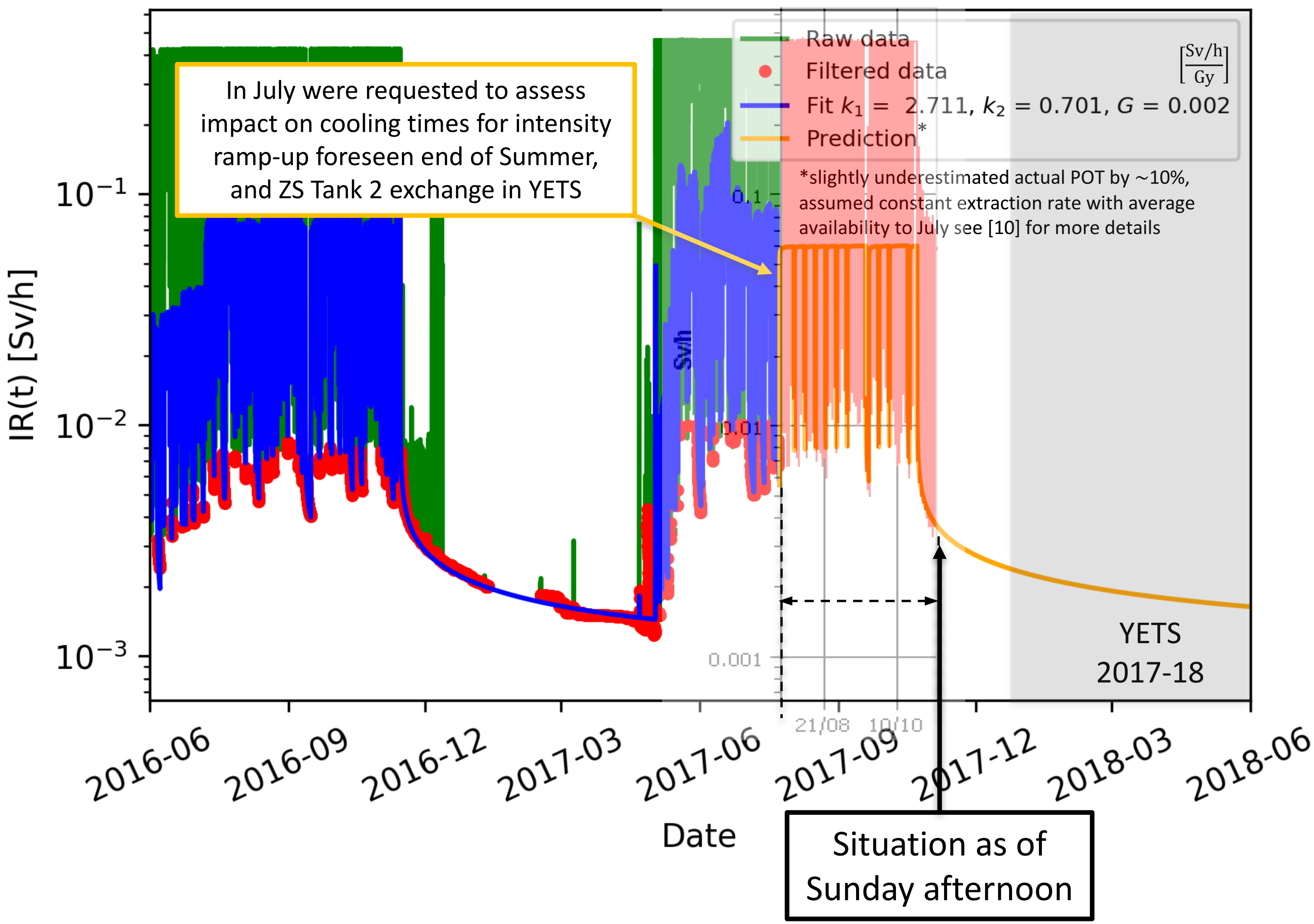
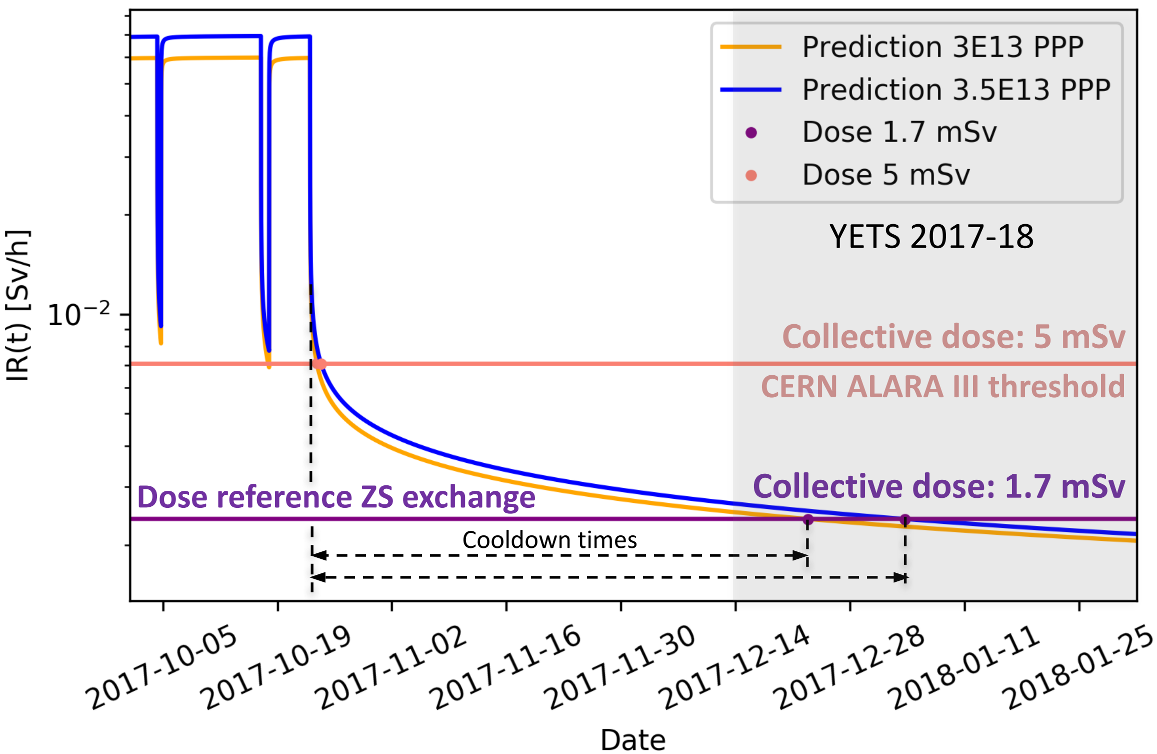


Cooldown predictions in YETS 2017

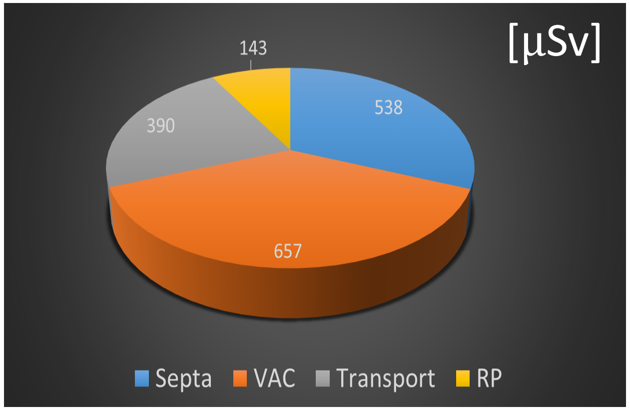


IR dose rate measured on PMIU.202 during exchange of a ZS tank (ZS.21639) combined with collective dose taken in February 2016 (100 days after stop) used as a reference:

Work dose estimation = 3.8 mSv

Collective dose taken = 1.7 mSv

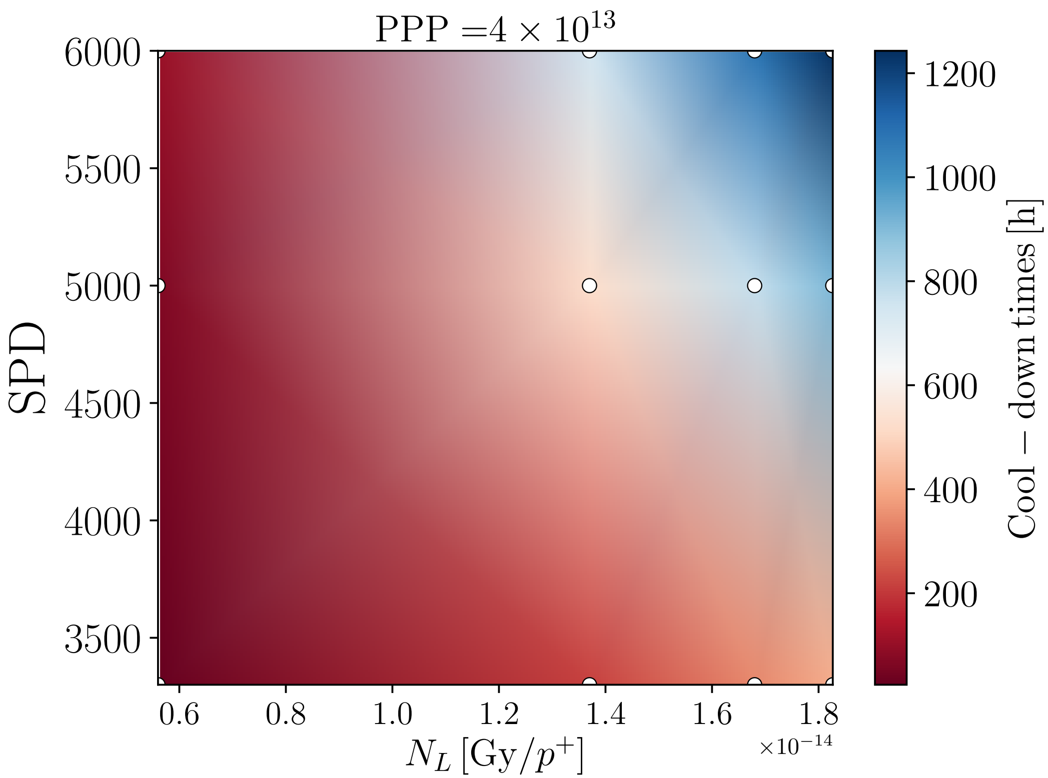
PMIU202 measured = 2.3 mSv/h



(E)YETS	Protons per pulse (av.) [ppp]	Spills per day (av.) [spd]	N_L (av.) [Gy/10^{14} p^+]	Protons extracted [$\times 10^{19}$]	Cooldown time for given dose	
					5 mSv	1.7 mSv
2017 – 18 (predicted)	3.0E13	2700	< 1.5	1.2	20 h	60 d 21 h
	3.5E13	2700		1.3	1 d 8 h	72 d 16 h
2015 – 16 (measured)	2.7E13	3300	1.8	1.6	5 d 19 h	100 d (reference intervention, above)

Cooldown predictions for SPS BDF

- Predicted cool-down time at the end of a year of SPS BDF operation [9]:
  - For a 5 mSv intervention based on the exchange of ZS Tank 2 carried out February 2016
  - PMIU202 is paired with the specific loss measured on the BLM next to ZS Tank 2
  - This neglects the build-up of longer living isotopes over many years of operation!



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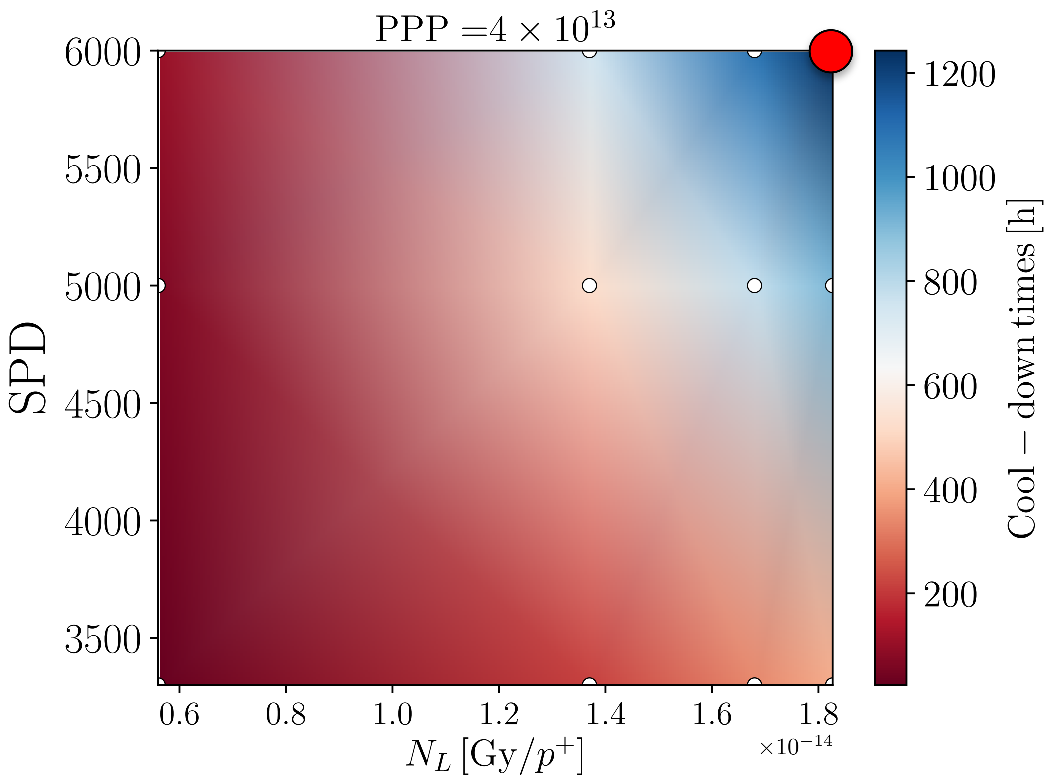

Key	Extraction efficiency (specific loss) N_L [Gy/10^{14} p^+]	Cool-down time
●	As in 2015: 1.8	~7 weeks

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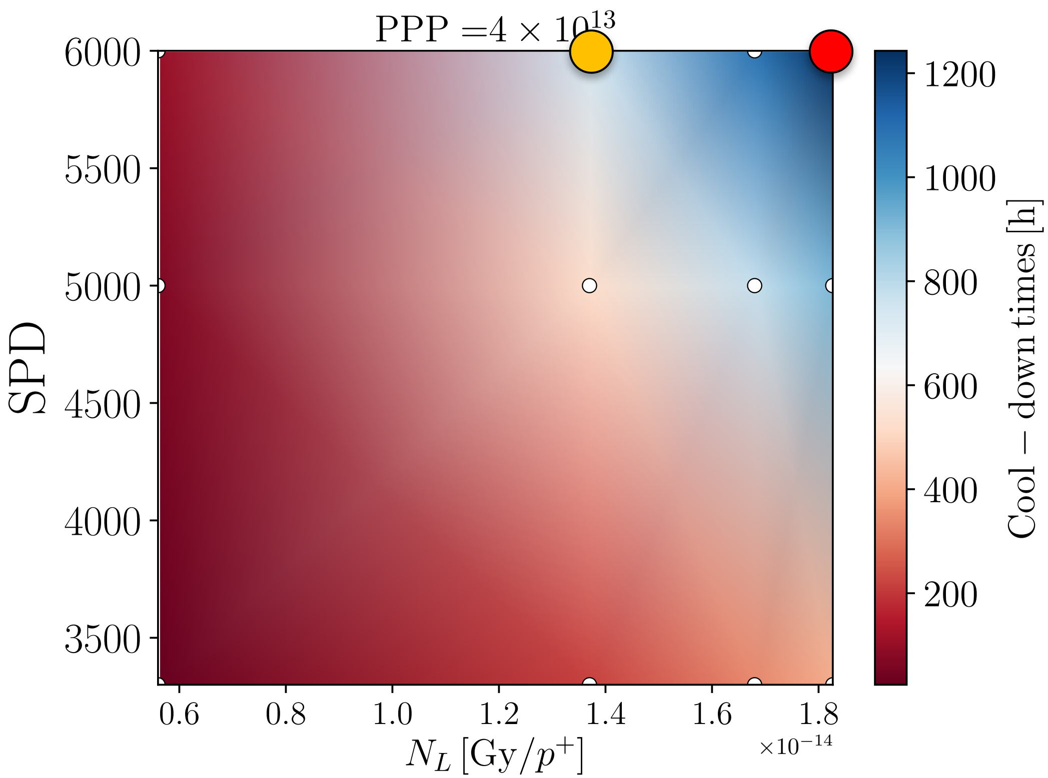

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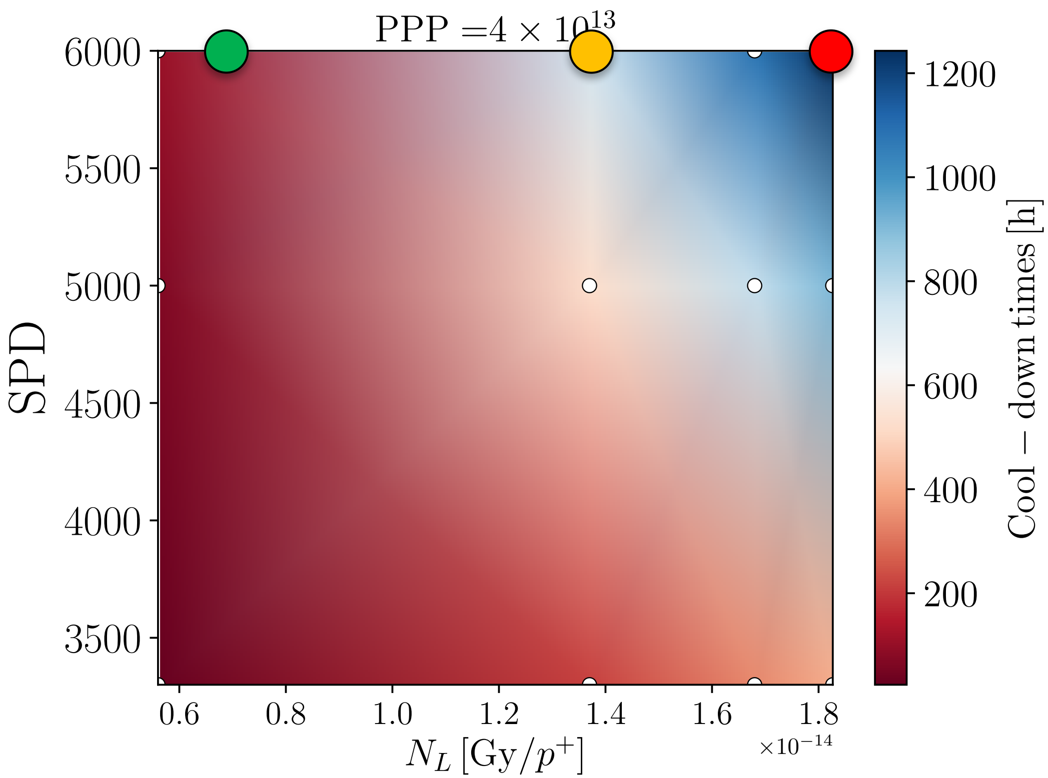

Key	Extraction efficiency (specific loss) N_L [Gy/10^{14} p^+]	Cool-down time
🔴	As in 2015: 1.8	~7 weeks
🟡	As in 2017: 1.4	~4 weeks
🟢	< 2017/2: 0.7	< 1 week

We found the cooldown times to be roughly quadratic with intensity or specific loss:

$$t_{\text{cooldown, 5 mSv}} \sim N_L^2, \text{SPD}^2, \text{PPP}^2$$

Conclusions

- An empirical relationship has been exploited to model the build-up and cool-down of slow extraction induced radioactivity of the SPS
- A software toolkit was developed in python to exploit the empirical relationship and to fit logged data:
  - Only 3 fit constants are required to give reasonable predictions over the timescales fitted (~10%)
  - Cool-down times for a simple case study (ZS exchange) were predicted for YETS 2017 and for future SPS BDF operation
  - As longer time periods are fitted, one expects the prediction of the build-up of longer-lived isotopes will improve: to be studied
- The cool-down following a year of operation scale quadratically with intensity or extraction inefficiency:

$$t_{\text{cooldown}} \sim N_L^2, \text{SPD}^2, \text{PPP}^2$$

- The model offers the possibility to predict cool-down times online and alert the operations team to anomalies: development possible

Thank you!

- Any questions?

References

[1] R.L. Keizer et al., *High intensity running and radiation problems during the 1995 physics run*, SL-Note-96-05-MS, Geneva, CERN

[2] R.L. Keizer et al., *High intensity running and radiation problems*, SL-Note-95-14-BT, Geneva, CERN, 1995

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[8] J. Borburgh, *Activation reduction due to different septum tank materials*, SLAWG meeting #7, 28 September 2016, Geneva, CERN: https://indico.cern.ch/event/570165/

[9] M.A. Fraser et al., Modelling the radioactivtiy induced by slow extraction losses in the CERN SPS, Proc. IPAC'17, Copnehagen, Denmark, paper TUPIK086, 2017

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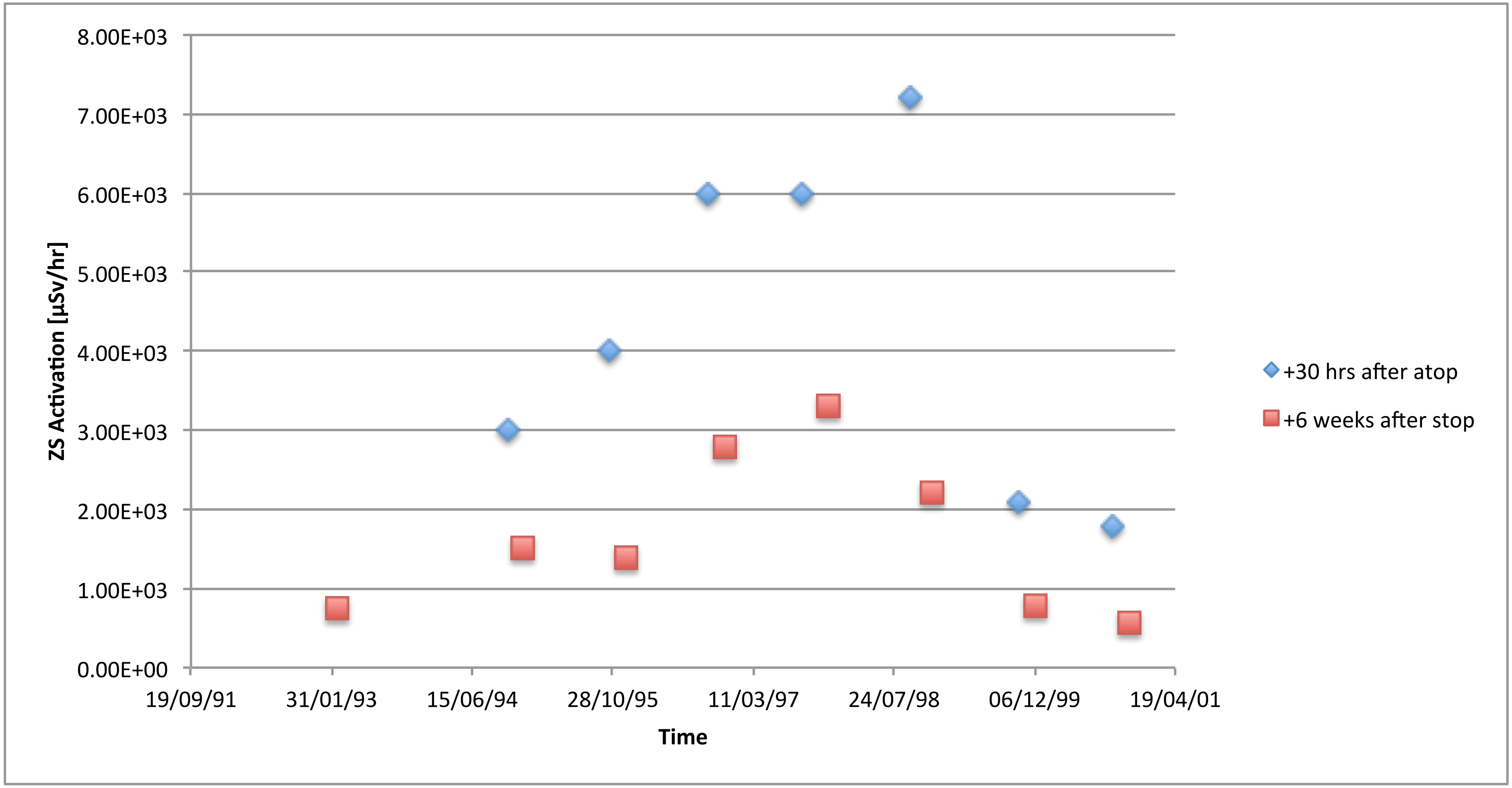
Extra slides

Build-up of IR in LSS6 during WANF

- Surveys made before, during and after the WANF period in LSS6 show the heating and cooling of LSS6. Measurements made 30 hours and again a few weeks later after operation was halted. Background recovers a year or two after WANF ceased.



Deriving the effective half-life of IR(t)

- Differentiating (using the chain rule) the empirical ansatz:

$$\mathrm{IR}(t) \propto \exp\left(-k_1 \ln(t)^{k_2}\right),$$

one can write:

$$\frac{d\mathrm{IR}(t)}{dt} = -\frac{k_1 k_2 \ln(t)^{k_2-1}}{t}\mathrm{IR}(t)$$

- This a linear ODE which resembles our exponential law for radioactive decay with a time-dependent effective decay constant:

$$\frac{d\mathrm{IR}(t)}{dt} = -\lambda(\mathrm{t})\mathrm{IR}(t)$$

where by inspection the effective half-life can be written:

$$t_{1/2}(t) = \frac{\ln(2)}{\lambda(t)} = \frac{t}{k_1 k_2 \ln(t)^{k_2-1}}\ln(2)$$

ALARA III at CERN

https://edms.cern.ch/document/1296520/1

Waiving of the ALARA committee meeting

Circumstances

- Repetitive intervention
  - A **procedure** has been worked out under which circumstances a waiving of the ALARA committee meeting could be possible
  - Generic DIMRs should be worked out and approved a priori in an ALARA committee meeting.
- Urgent maintenance/repair
  - 'Urgent ALARA committee' decision
  - No 'formal (physical)' ALARA committee meeting required
  - Generic DIMRs for standard maintenance/repair should be worked out and approved a priori in an ALARA committee meeting.

new

CRITÈRE DE DOSE INDIVIDUELLE **hard limits**

Équivalent de dose prévisionnel individuel (H_i) pour l'intervention, ou pour l'ensemble des interventions de même nature lorsque celles-ci sont répétées plusieurs fois sur une année :

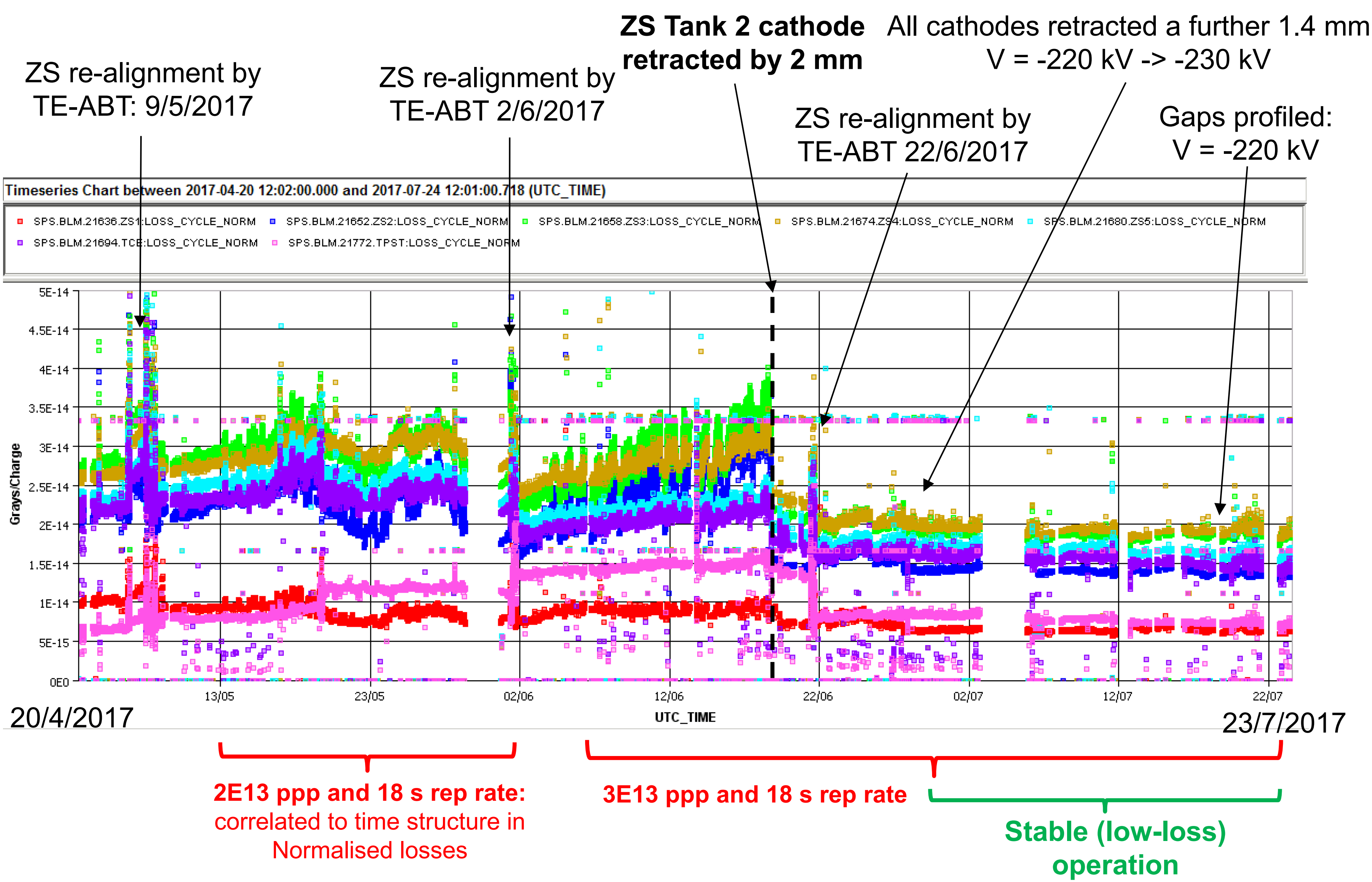
niveau I	niveau II	niveau III
< 100 µSv	100 µSv – 1 mSv	> 1 mSv

CRITÈRE DE DOSE COLLECTIVE

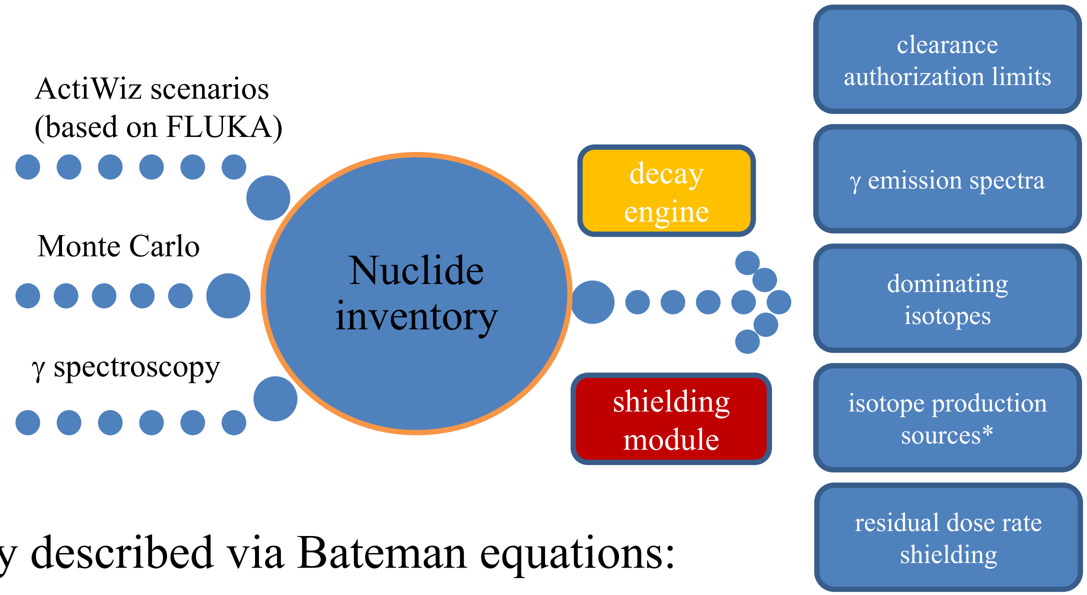
Équivalent de dose prévisionnel collective (H_c) pour l'intervention, ou pour l'ensemble des interventions de même nature lorsque celles-ci sont répétées plusieurs fois sur une année :

niveau I	niveau II	niveau III
< 500 µSv	500 µSv – 5 mSv (~~10 mSv~~)	> 5 mSv

History of ZS normalised losses: 2017



ActiWiz: http://actiwiz.web.cern.ch



Production & decay described via Bateman equations:

$$\frac{\mathrm{d}N_n}{\mathrm{d}t} = P_n + (b_{n-1,n} \cdot \lambda_{n-1} \cdot N_{n-1}) - \lambda_n \cdot N_n$$

N_n … Number of isotope n
P_n … Production rate of isotope n
λ_n … Decay constant of isotope n
b_n … Branching ratio from isotope n-1 into n
k … index of irradiation/cooling cycle

Laplace transform (L)

$$N_n(t) = \sum_{k=1}^{m} \sum_{i=1}^{n} \left[\left(\prod_{j=i}^{n-1} \lambda_{j,j+1} \right) \sum_{j=i}^{n} \left(\underbrace{\frac{N_i^k e^{-\lambda_j (t_{k,irr} + t_{k,cool})}}{\prod_{p=i, p \neq j}^{n} (\lambda_p - \lambda_j)}}_{\text{decay}} + \underbrace{\frac{P_i^k (1 - e^{-\lambda_j t_{k,irr}}) e^{-\lambda_j t_{k,cool}}}{\lambda_j \prod_{p=i, p \neq j}^{n} (\lambda_p - \lambda_j)}}_{\text{build-up}} \right) \right]$$