# Absorbed Radiation Doses on the EuXFEL Undulator Systems During Early User Experiments

**Frederik Wolff-Fabris**

Undulator Systems – EuXFEL

FEL’19, Hamburg, August 28th, 2019

# Joint collaboration between

- **DESY** (F. Schmidt-Föhre, W. Decking, D. Noelle, A. Leuschner, S. Liu, and accelerator coordinators and operators)
  - Online Dosimetry system
  - Accelerator studies, operation, and simulations

- **Stockholm University** (F. Hellberg, A. Hedqvist, N. Bassler)
  - In-kind contribution
  - Dosimeter sensors and calibration

- **EuXFEL** (H. Sinn, F. Preisskorn, M. Bagha-Shanjani, J. Pflüger, Optics, Diagnostics, and Undulator groups)
  - Overview, Analysis
  - Magnetic Measurements

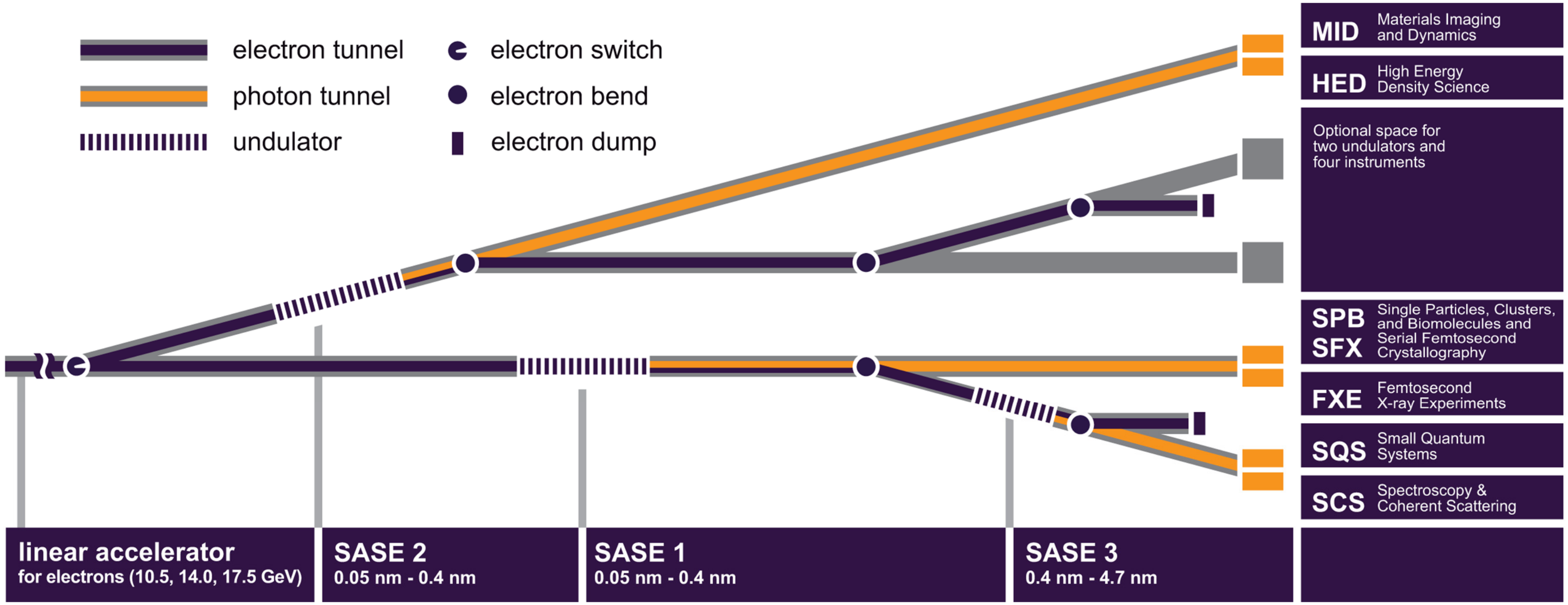
# Outline

- 1. Introduction
- 2. Absorbed doses: commissioning phase vs user operation
- 3. Dose per transmitted charge rate in user experiments
- 4. Energy-dependent radiation profile and demagnetization monitoring
- 5. Summary

# The European XFEL GmbH

- The EuXFEL is a new user facility that uses high-intensity X-ray light and receives worldwide users since 2017
  - DESY and European XFEL are strong partners on construction, commissioning, and operation of X-ray free-electron laser
  - Supported by 12 countries

# Photon tunnels, Parameters and Timeline



electron tunnel
photon tunnel
undulator
electron switch
electron bend
electron dump

**MID** Materials Imaging and Dynamics
**HED** High Energy Density Science
Optional space for two undulators and four instruments
**SPB SFX** Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography
**FXE** Femtosecond X-ray Experiments
**SQS** Small Quantum Systems
**SCS** Spectroscopy & Coherent Scattering

**linear accelerator**
**for electrons (10.5, 14.0, 17.5 GeV)**

**SASE 2**
**0.05 nm - 0.4 nm**

**SASE 1**
**0.05 nm - 0.4 nm**

**SASE 3**
**0.4 nm - 4.7 nm**

| | SASE1/2 | SASE3 |
|---|---|---|
| **$\lambda_0$ [mm]** | 40 | 68 |
| **Operational Gap Range [mm]** | 10-20 | 10-25 |
| **K-Range** | 3.9–1.65 | 9.0-4 |
| **# of Segments** | 35 | 21 |
| **System Length [m]** | 213.5 | 128.1 |

| | SASE1 | SASE2 | SASE3 |
|---|---|---|---|
| **1st beam transmission** | 27.04.2017 | 13.03.2018 | 27.04.2017 |
| **1st lasing** | 02.05.2017 | 01.05.2018 | 08.02.2018 |
| **1st Early user exp.** | **14.09.2017** | **20.03.2019** | **28.11.2018** |
| **Typical user e-beam parameter** | 14 GeV<br>250 pC<br>2000 bps | 14 GeV<br>250 pC<br>4000 bps | 14 GeV<br>250 pC<br>2000 bps |
| **Typical user photon energies** | 6-14keV | 6-14keV | 0.7-1.6keV |

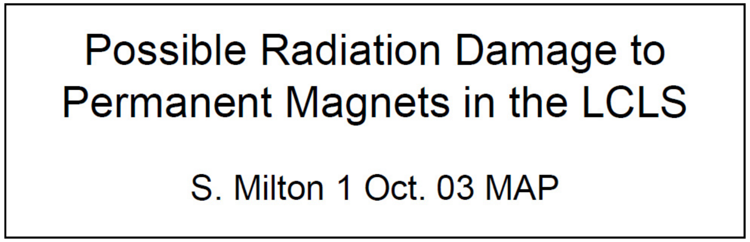
# Undulator Systems

We run 91 Undulator Segments and Intersections consisting of $Nd_2Fe_{14}B$ permanent magnets for producing FEL to experiments.

# Undulator Systems: What do we need to keep in mind?

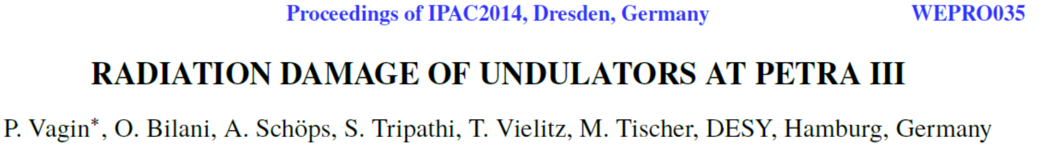
Interaction of Beam and Matter: radiation damage to the permanent magnets was expected

(FLASH, LCLS, PETRA III, APS, SACLA, EuXFEL) → demagnetization



Possible Radiation Damage to Permanent Magnets in the LCLS

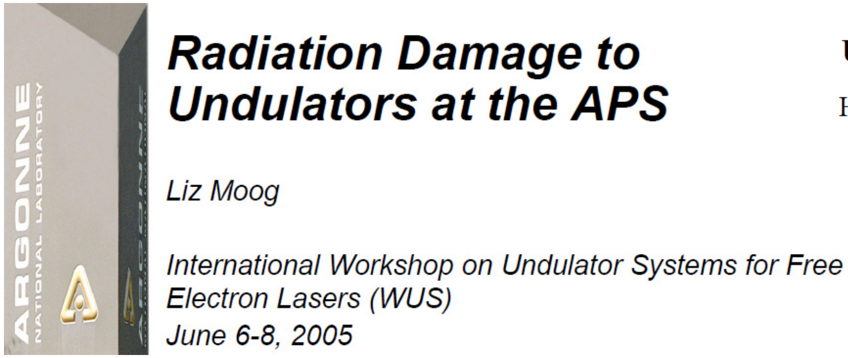
S. Milton 1 Oct. 03 MAP



Proceedings of IPAC2014, Dresden, Germany WEPRO035

RADIATION DAMAGE OF UNDULATORS AT PETRA III

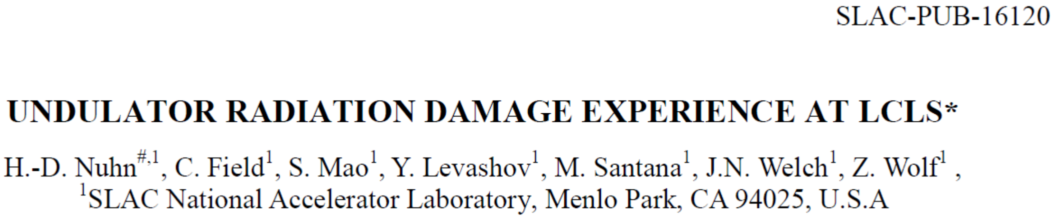
P. Vagin*, O. Bilani, A. Schöps, S. Tripathi, T. Vielitz, M. Tischer, DESY, Hamburg, Germany



*Radiation Damage to Undulators at the APS*

*Liz Moog*

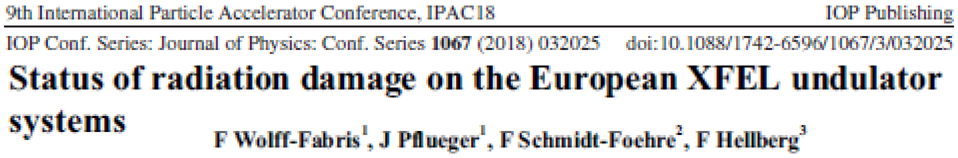
*International Workshop on Undulator Systems for Free Electron Lasers (WUS)*
*June 6-8, 2005*



SLAC-PUB-16120

UNDULATOR RADIATION DAMAGE EXPERIENCE AT LCLS*

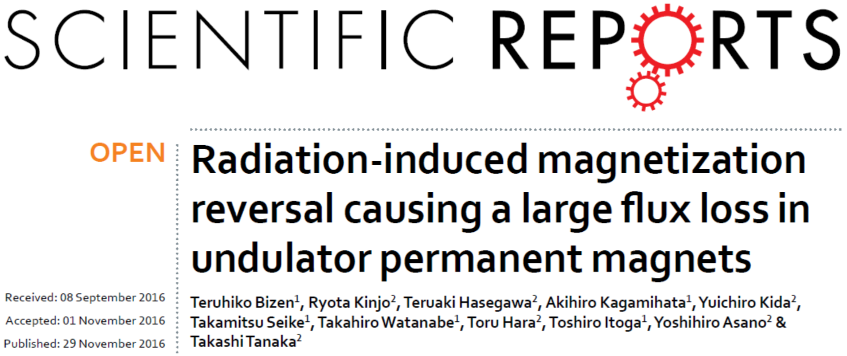
H.-D. Nuhn[#,1], C. Field[1], S. Mao[1], Y. Levashov[1], M. Santana[1], J.N. Welch[1], Z. Wolf[1] ,
[1]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, U.S.A



9th International Particle Accelerator Conference, IPAC18 IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **1067** (2018) 032025 doi:10.1088/1742-6596/1067/3/032025

**Status of radiation damage on the European XFEL undulator systems**

**F Wolff-Fabris[1], J Pflueger[1], F Schmidt-Foehre[2], F Hellberg[3]**



SCIENTIFIC REPORTS

OPEN

**Radiation-induced magnetization reversal causing a large flux loss in undulator permanent magnets**

Received: 08 September 2016
Accepted: 01 November 2016
Published: 29 November 2016

Teruhiko Bizen[1], Ryota Kinjo[2], Teruaki Hasegawa[2], Akihiro Kagamihata[1], Yuichiro Kida[2], Takamitsu Seike[1], Takahiro Watanabe[1], Toru Hara[2], Toshiro Itoga[1], Yoshihiro Asano[2] & Takashi Tanaka[2]

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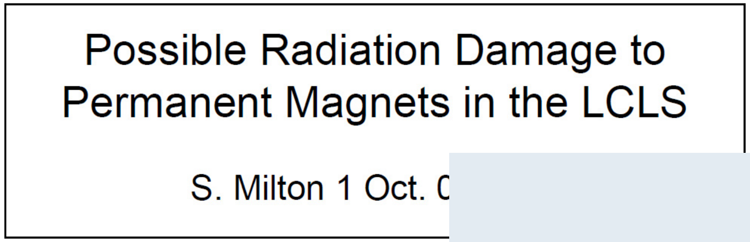

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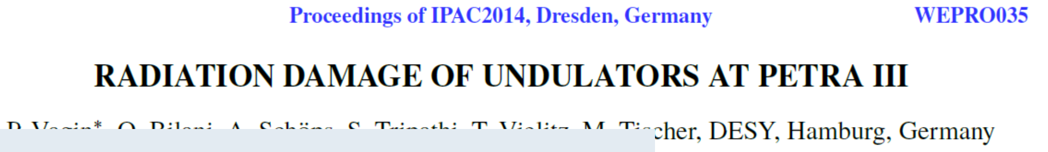

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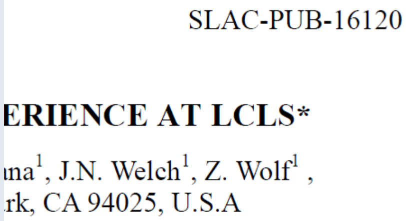


SLAC-PUB-16120

ERIENCE AT LCLS*

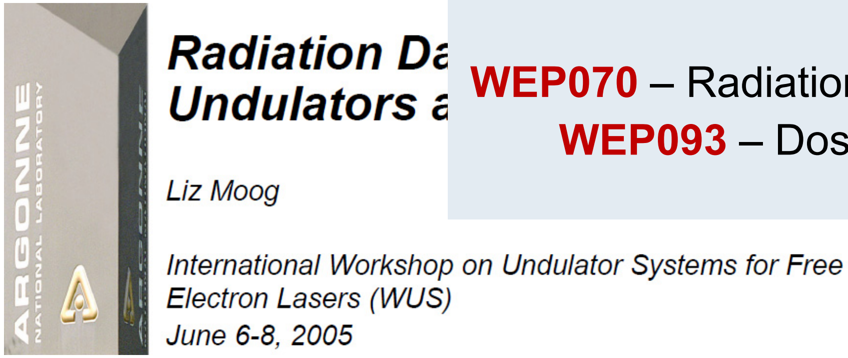
na[1], J.N. Welch[1], Z. Wolf[1] ,

rk, CA 94025, U.S.A

**@FEL2019:**

**WEP070** – Radiation on undulators at FLASH-DESY

**WEP093** – Dose monitoring at PAL (Korea)



*Radiation Da*

*Undulators a*

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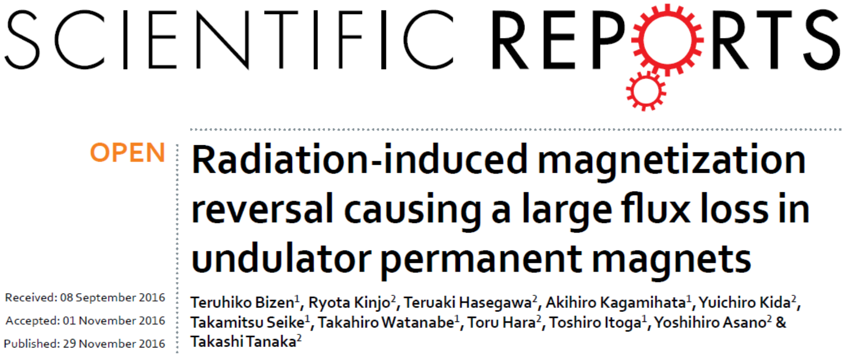

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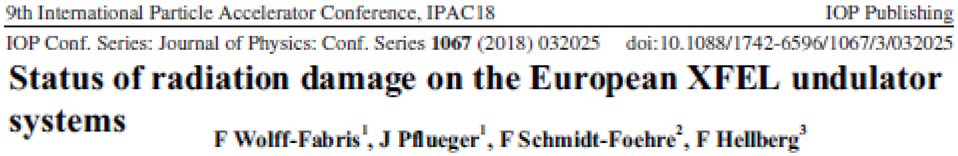


9th International Particle Accelerator Conference, IPAC18 IOP Publishing

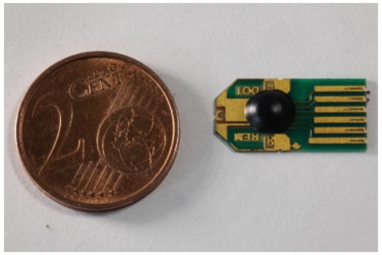
IOP Conf. Series: Journal of Physics: Conf. Series **1067** (2018) 032025 doi:10.1088/1742-6596/1067/3/032025

**Status of radiation damage on the European XFEL undulator systems**

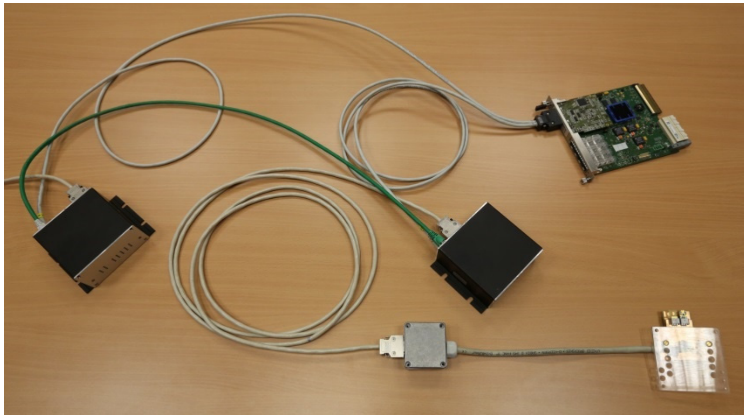
F Wolff-Fabris[1], J Pflueger[1], F Schmidt-Foehre[2], F Hellberg[3]

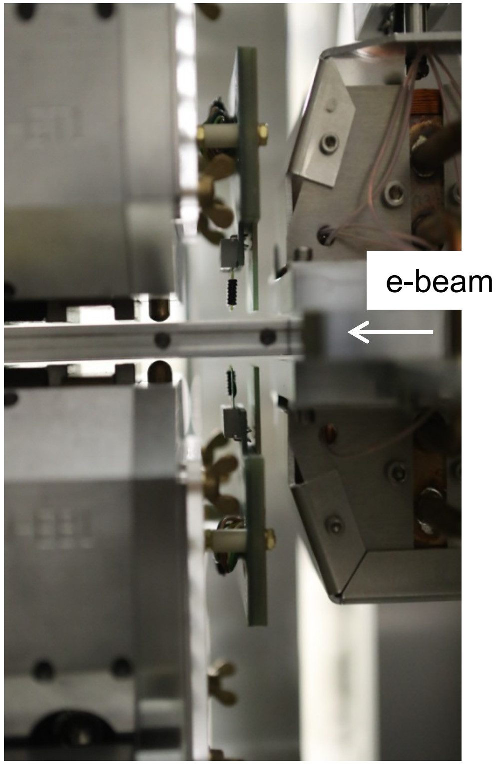
# Evaluating Radiation Damage: Dosimeters

- **Radfet System:** implemented as an FMC module; Permits on-line dose readings; 2 Radfets installed at the entrance of each Undulator; Cross-calibrated with TLD-800.



F. Schmidt-Föhre et al,
IBIC´15, WECLA02

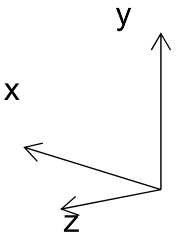




- **Gafchromic films** (Univ. Stockholm)**:** spatial distribution and doses (“more doses” = “darker”)

# Evaluating Radiation Damage: Diagnostic Undulator (DU)

- U40 type (mini) undulator;
- Placed in front of each Undulator System;
- Easy to handle and transport to mag. lab;
- Allows a preview on expected radiation damage.



| DU XFEL U40 | |
|---|---|
| **Period length** | **40 mm** |
| **Gap** | **12 mm, fixed** |
| **Peak Field** | **0.916 T** |
| **K** | **3.28** |
| **Number of Poles** | **8** |
| **Total length** | **≈ 350mm** |
| **Weight** | **≈ 47 Kg** |

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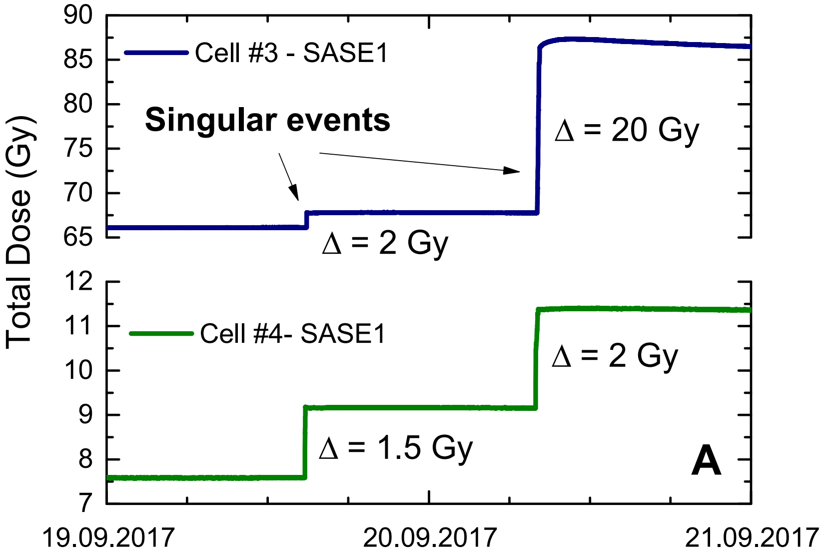
# Importance of online Dosimetry System

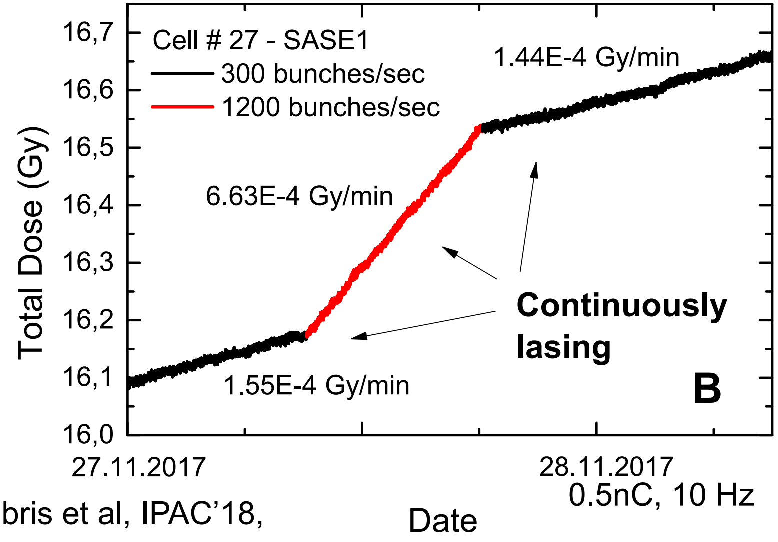
## Singular Events

- Step-like dose increase in short time;
- Due to e-beam steering, changes on quads and air coils settings, e-beam energy change during BBA, opening/closing undulators;
- Mainly seen as beam losses.



## Stable Lasing

- Slow and steady dose rise as function of time;
- Seen while continuously lasing in the course of user operation.



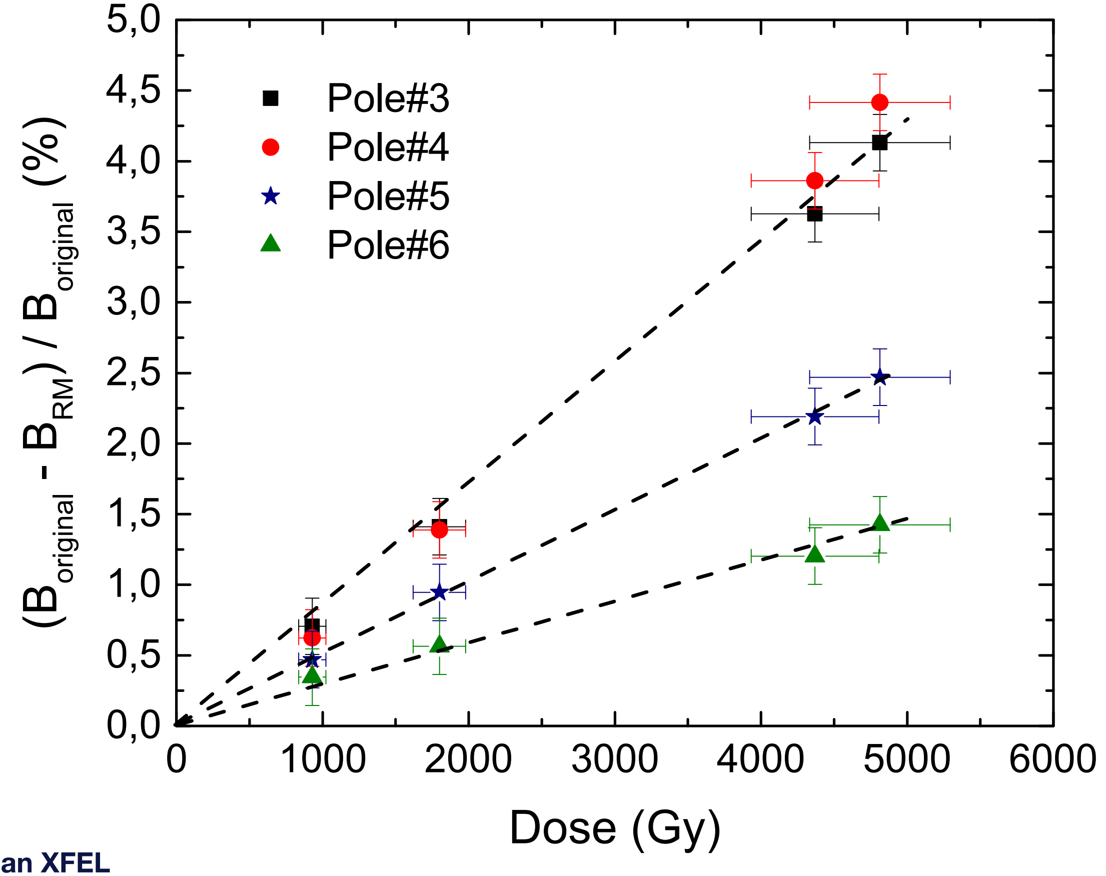
0.5nC, 10 Hz

F. Wolff-Fabris et al, IPAC'18, talk/paper WEYGBD2 (2018)

# Commissioning phase – Magnetic field degradation

We have measured magnetic field reduction on the DUs;

A wideband dose limit of **55 Gy** for the 5-m undulators can be estimated based on a change of $\frac{\Delta B}{B} = 4.10^{-4}$.

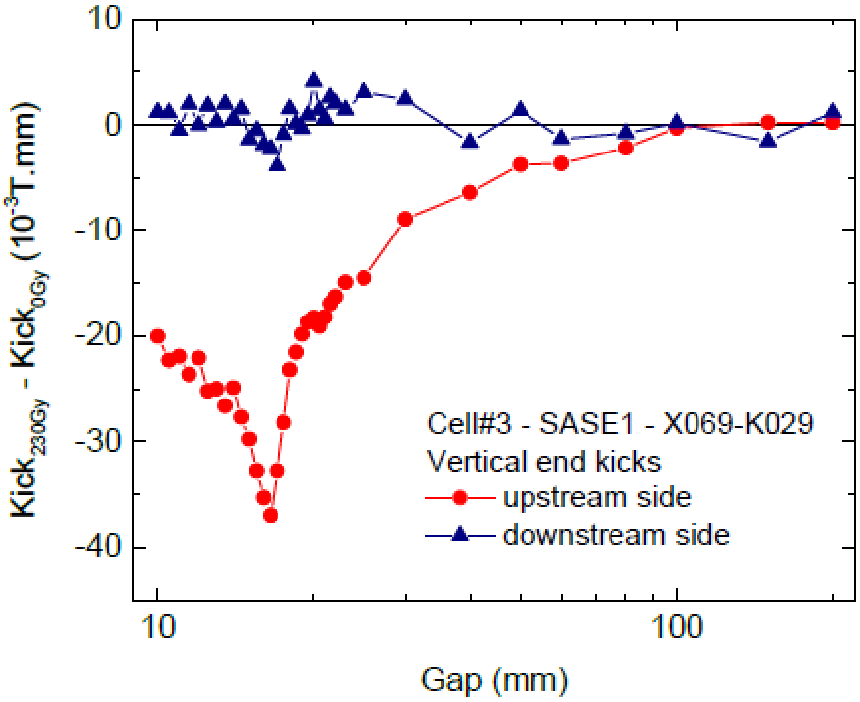


# Commissioning phase – Magnetic field degradation

- **5-m SASE1/Cell#3 Undulator after 230 Gy:**

- Differences up to 30-40 G.cm in the entrance kick $K_{1(y)}$ (stretched wire measurements)

$$K_{1(y,x)} = \frac{I_{1(y,x)}}{2} - \frac{F_{2(y,x)}}{L} \qquad K_{2(y,x)} = \frac{I_{1(y,x)}}{2} + \frac{F_{2(y,x)}}{L}$$



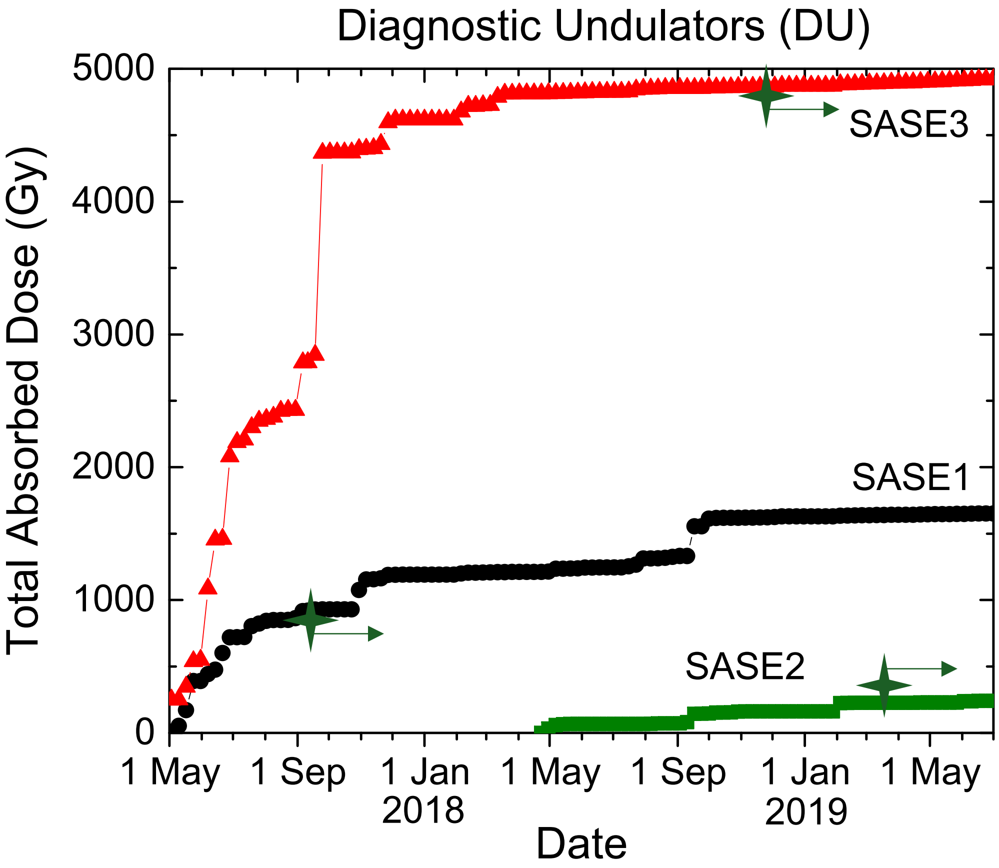
- Mag. Field change on entrance magnets (Hall probe):

$$\frac{\Delta B}{B} = -5 \times 10^{-4}$$

Indicate different degradation rate

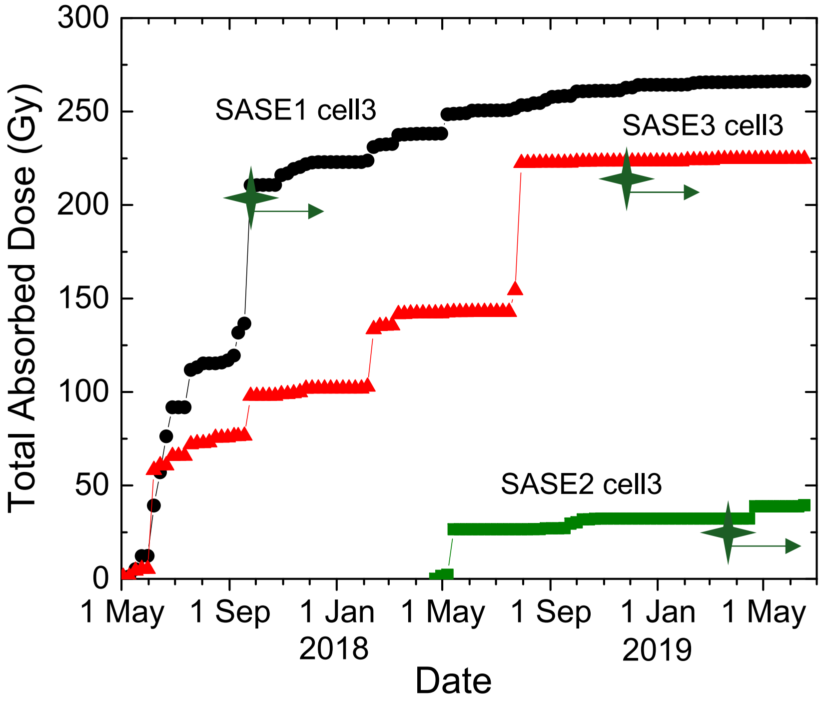
# Absorbed Doses since start of operation - DUs

- Total dose increase in the DUs has reduced as compared to the commissioning phase
- Setup days during user experiment phase also do not produce doses
- Losses have been minimized!

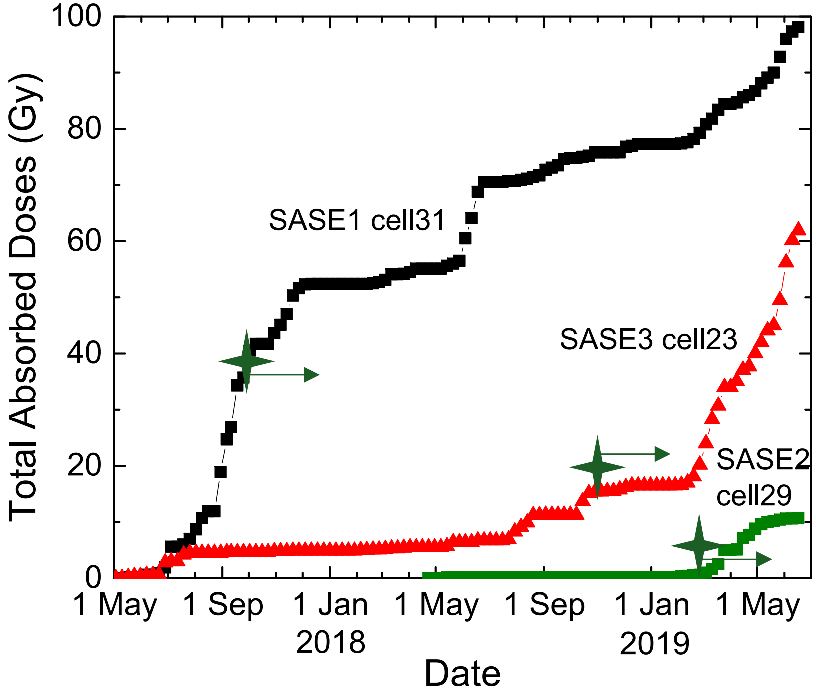


# Absorbed Doses since start of operation – 5-m undulators

- Upstream segments have similar behaviour as the DUs



- Downstream segments show increase in dose rate starting with user experiments



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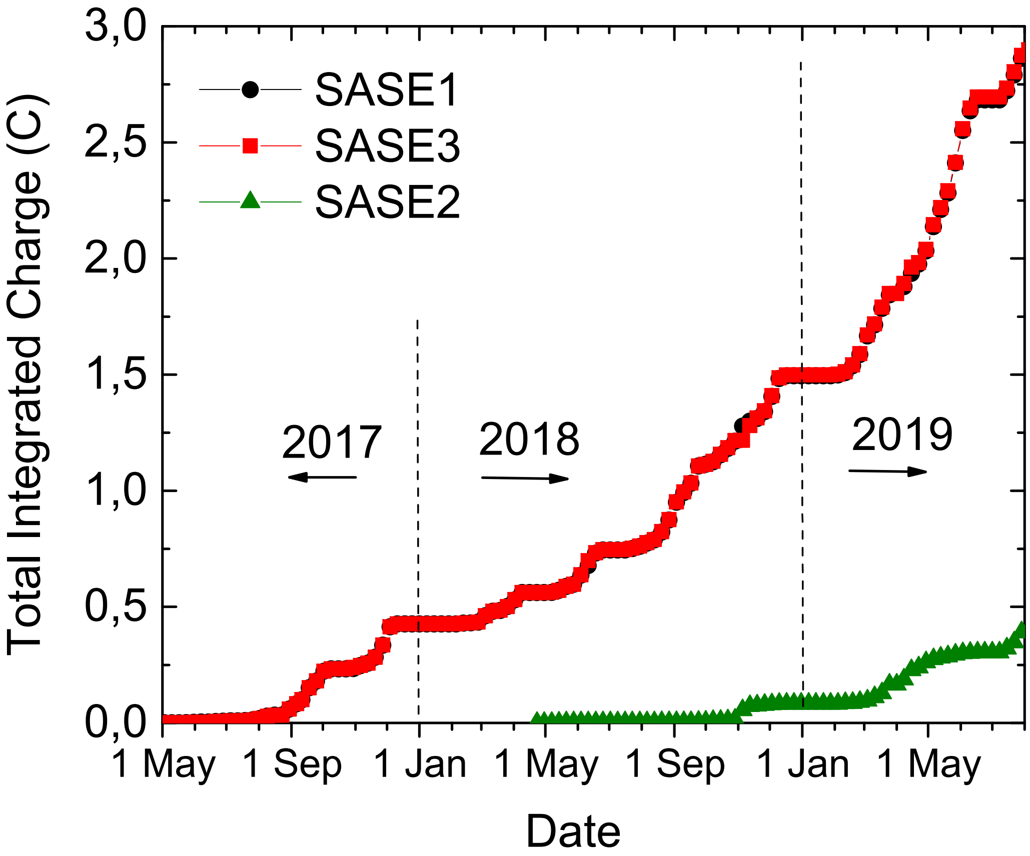
# Total transmitted charge

- Current user operation up to 400 bunches per train (at 10Hz = 4000 bps) at 0.25nC
- Charge rate will increase with higher operational modes

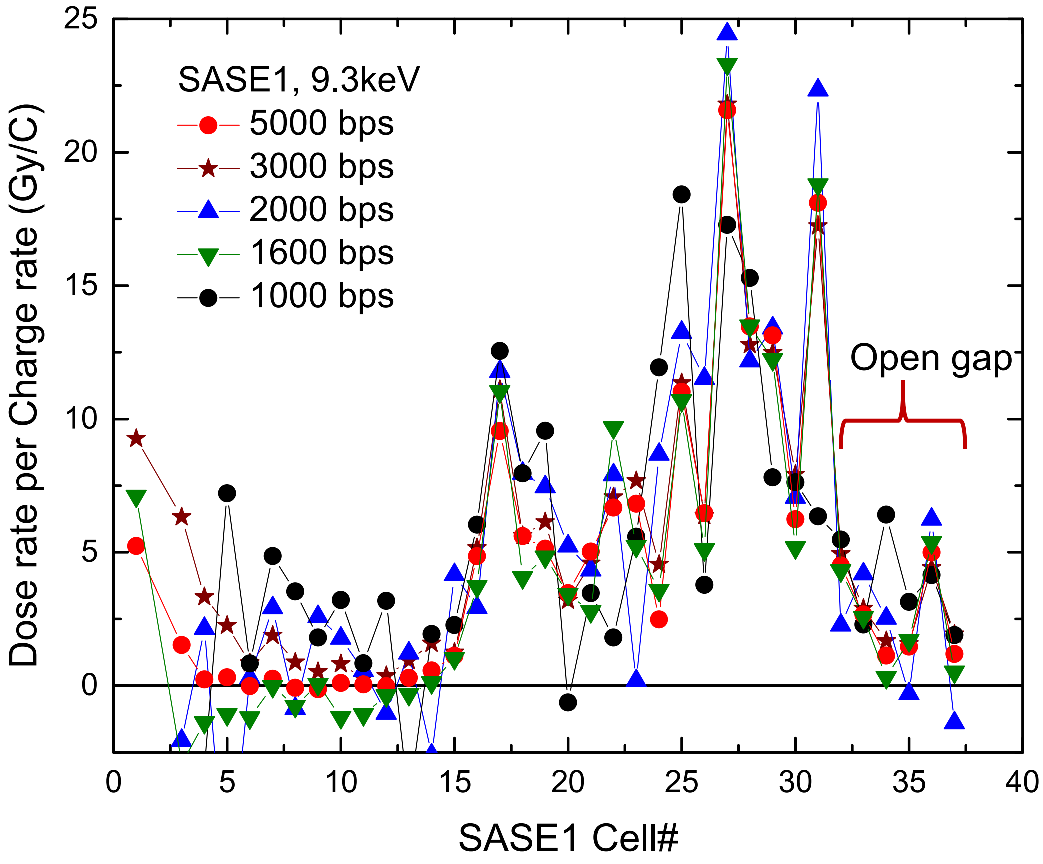


**!!! Comparison:
LCLS: ~ 2.5C
in 10 years !!!**

# Dose per transmitted charge rate

- At fixed gap (photon energy) and changing e-beam repetition rate:

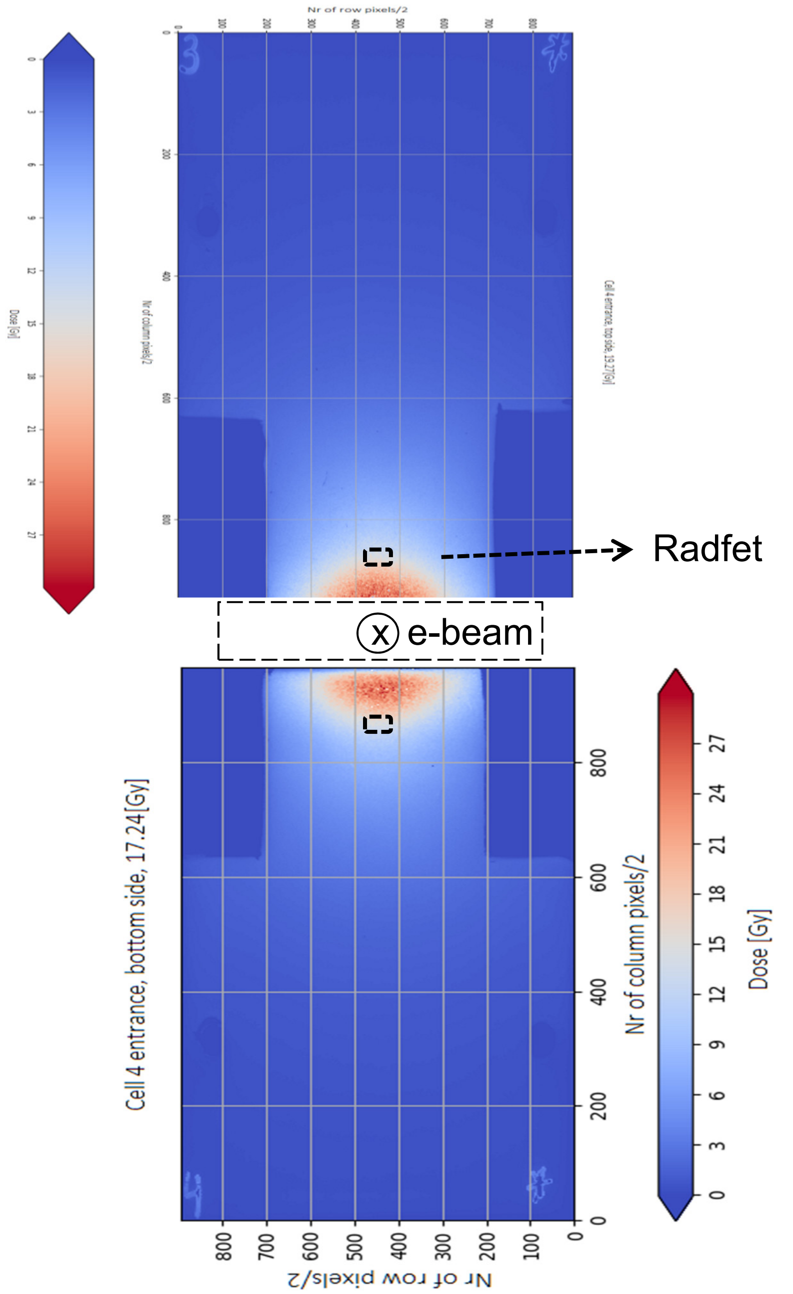
- Dose rate at each segment is proportional to the transmitted charge at fixed photon energies (fixed undulator gaps)
- Downstream segments with higher dose per charge rate



# Dose per transmitted charge rate

- Changing gaps (photon energy) and fixed e-beam repetition rate:

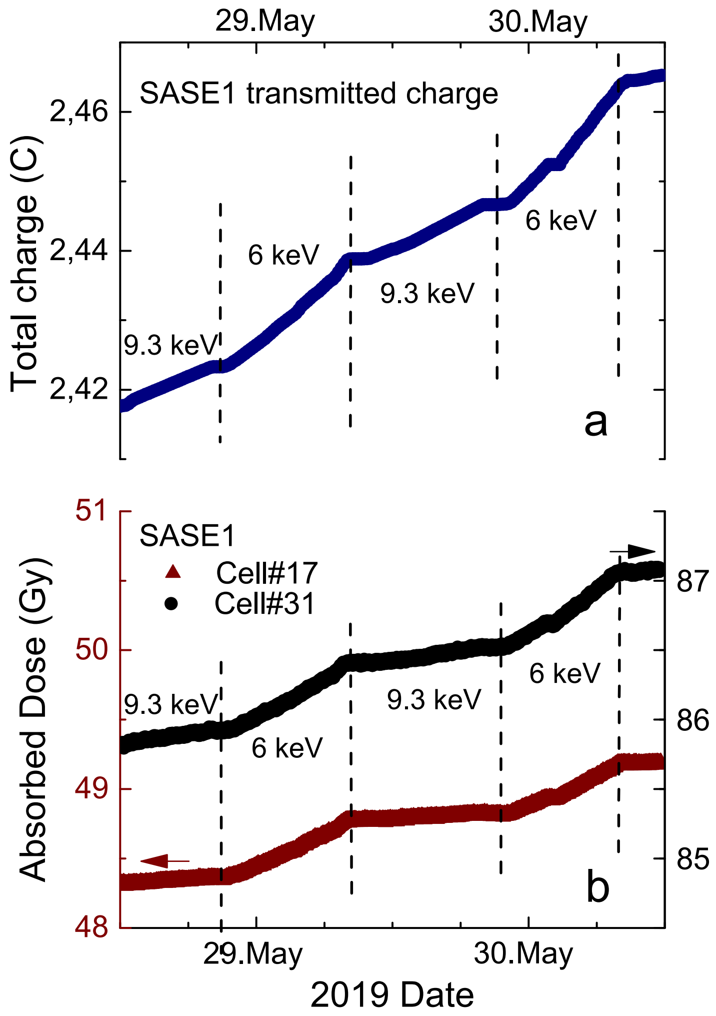
- Gafchromic films and Radfets showed equivalent doses at same position
- Gafchromic films have indicated higher doses when near to vacuum chamber



# Dose per transmitted charge rate

- Changing photon energy and fixed e-beam repetition rate:

- Increase in dose rate when SASE1 close from 13.7 to 10.7mm (B=0.782 T to B =1.036 T)



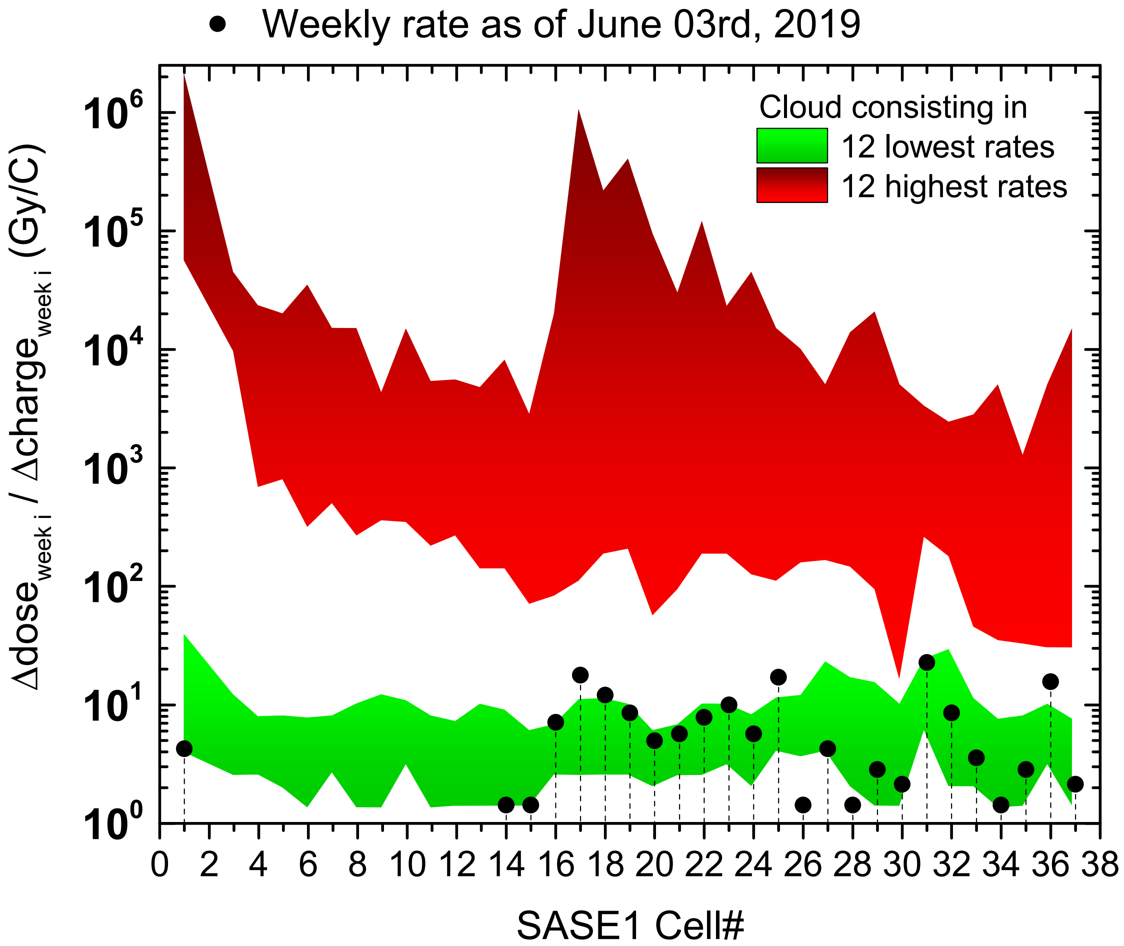
- Dose per charge rate increases by factor 2 to 3-4 if closing undulators to 6keV

| Photon Energy (keV) | SASE1 – cell 17 (Gy/C) | SASE1 – cell 31 (Gy/C) |
|---|---|---|
| 9.3 | 8.2 | 17.4 |
| 9.3 | 6.2 | 14.9 |
| 9.3 | 4.9 | 15.9 |
| 6.0 | 27.1 | 31.7 |
| 6.0 | 21.0 | 29.0 |
| 6.0 | 21.7 | 31.8 |

Cell#31 at 200mm in both cases!

# Dose per transmitted charge rate

- SASE1 Regular user operation weeks at 9.3keV show rates lower than 20 Gy/C



| Bunches per sec (0.25 nC) | Dose (Gy) | Time (weeks) |
|---|---|---|
| 5000 | 230 | 38-77 |
| 5000 | 1000 | 169-337 |
| 27000 | 230 | 7.2-14.4 |
| 27000 | 1000 | 31.2-62.4 |

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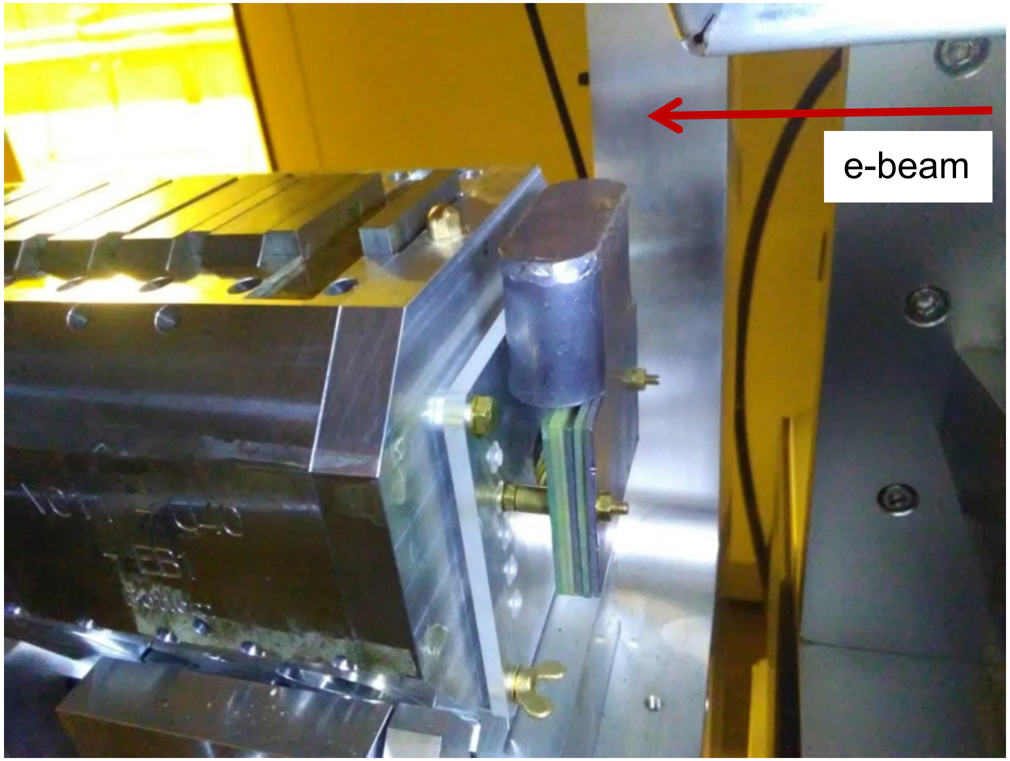
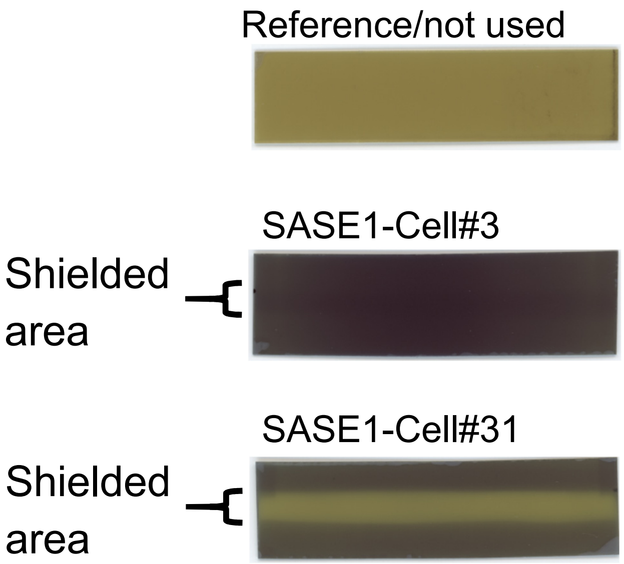
# Depicting high and low energy radiation doses

- 4mm Pb shield on lower Radfets



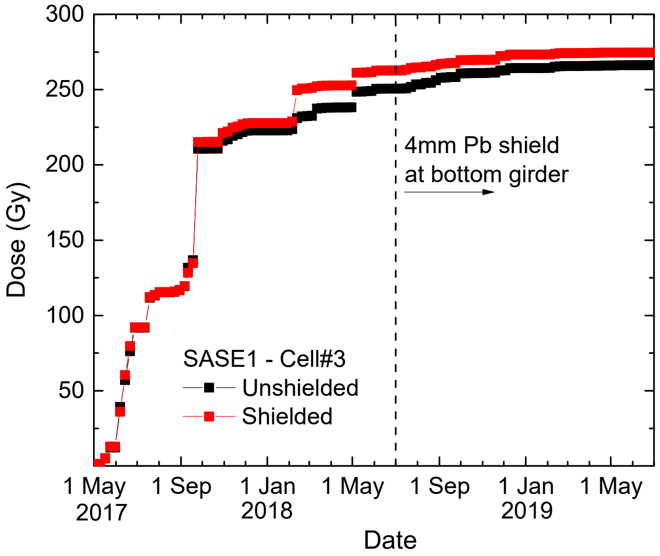
Courtesy by F. Schmidt-Foehre

- Gafchromic films with 2mm Pb shield

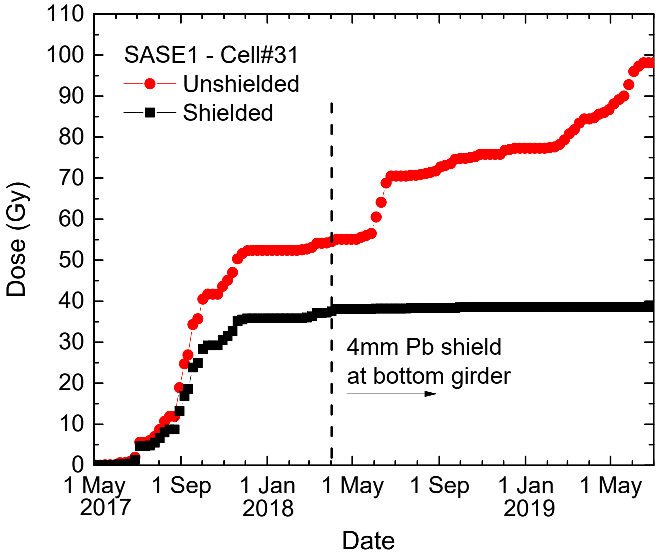


# Depicting high and low energy radiation doses

- SASE1-Cell#3: shielded Radfet measure dose increases;



- SASE1-Cell#31: shielded Radfet does not measure dose increases.



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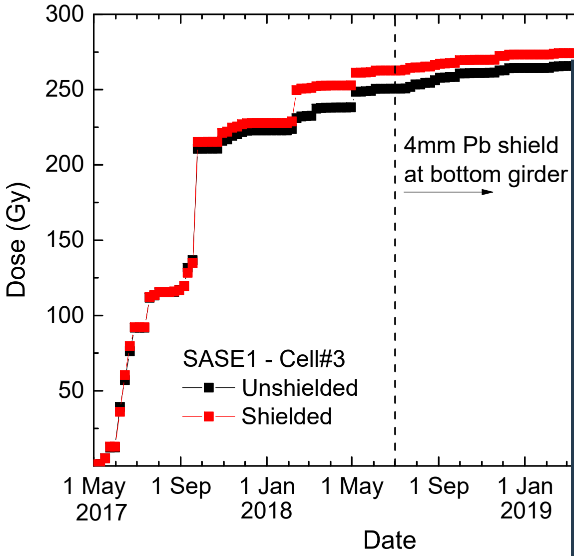

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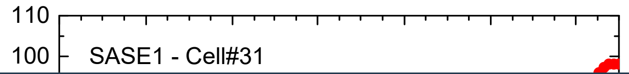
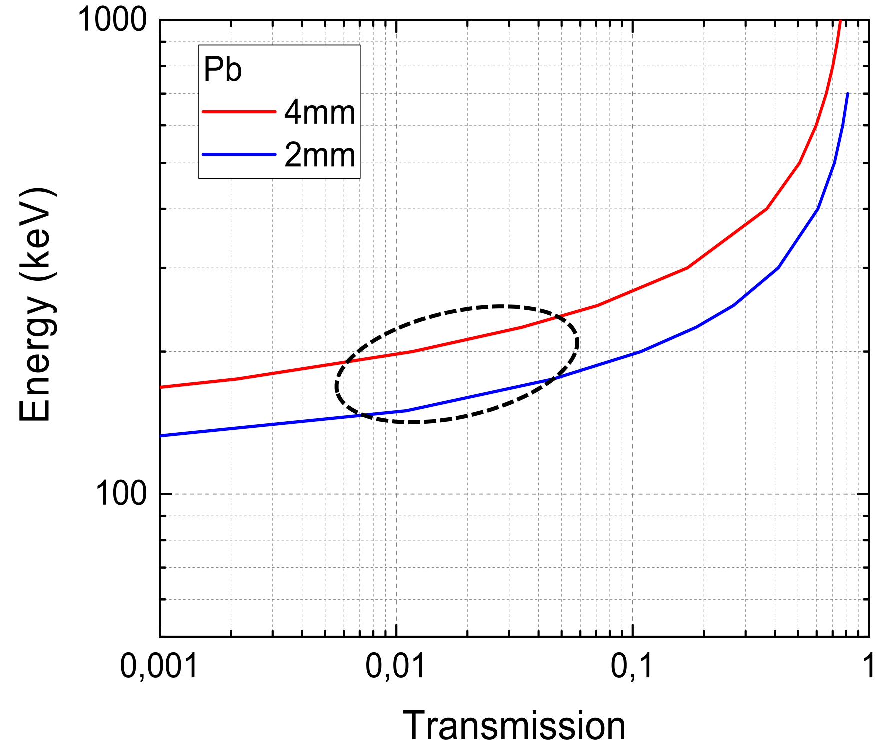


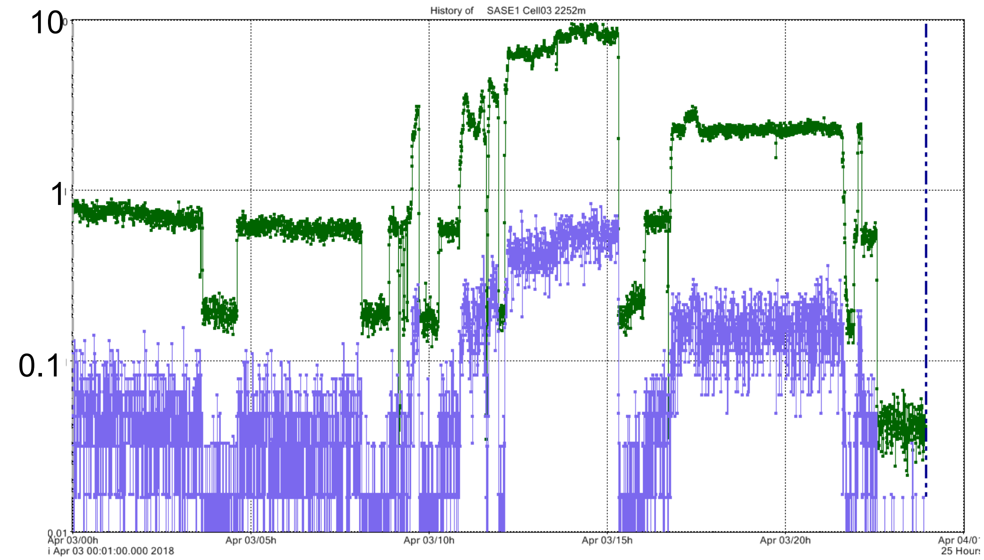


- Downstream undulators mainly absorb radiation lower than 100-200 keV (*X-ray Absorption program – Sean Brennan / SSRL*)

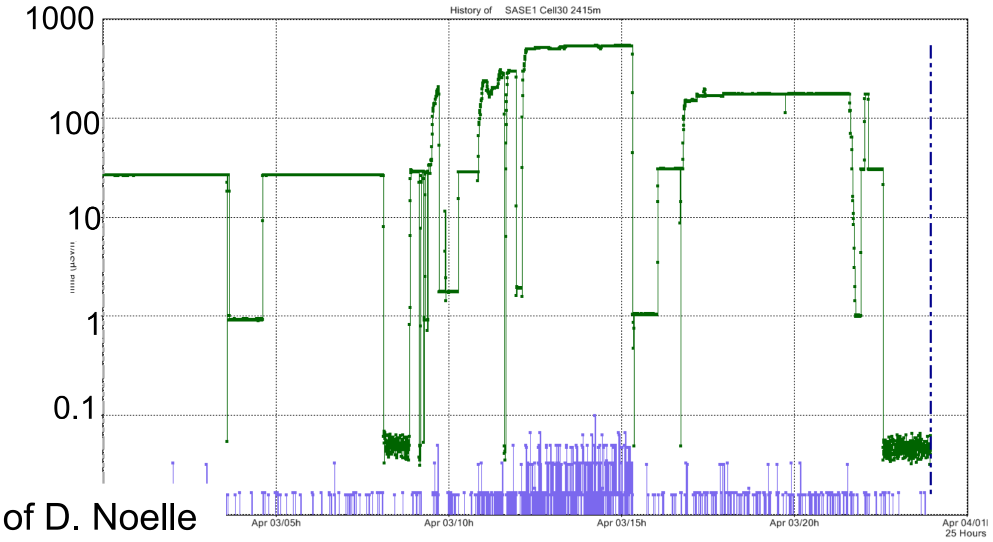
# Depicting high and low energy radiation doses

- *Pandora detector* for neutrons and gamma supported high and low energy depiction

<u>SASE1-cell3</u>: moderate Gamma signal (green), but Neutron signal (purple) significantly higher than noise.



<u>SASE1-cell30</u>: Gamma signal (green) is 3 orders higher than cell#3; Neutron signal (purple) comparable to background;



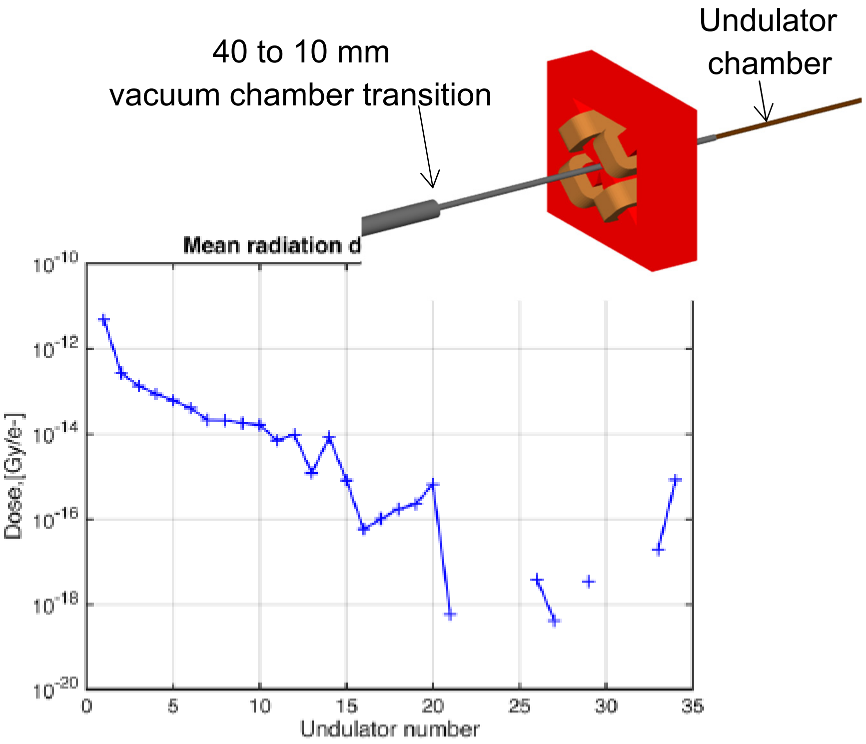
(Courtesy of D. Noelle and A. Leuchner)

# Depicting high and low energy radiation doses

## Wire scanner and mis-steered beam/Halo

Losses generated by the wire scan upstream of SASE system or by mis-steered beam hitting the vacuum chamber mostly at the transition;

Highest dose at the DU followed by decrease



40 to 10 mm vacuum chamber transition

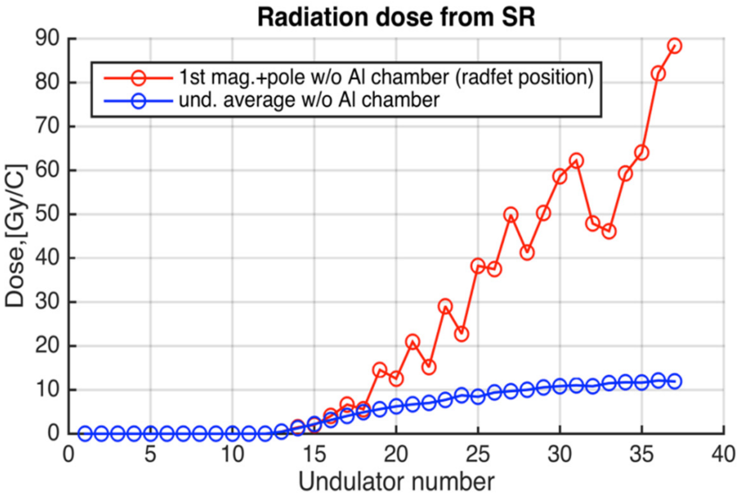
Undulator chamber

Shan Liu, W. Decking and F. Wolff-Fabris, IPAC’18, THPMF022 (2018)

## Simulated Radiation Doses from SR

Tracking code BDSIM is used to track the SR through the whole undulator beam line;

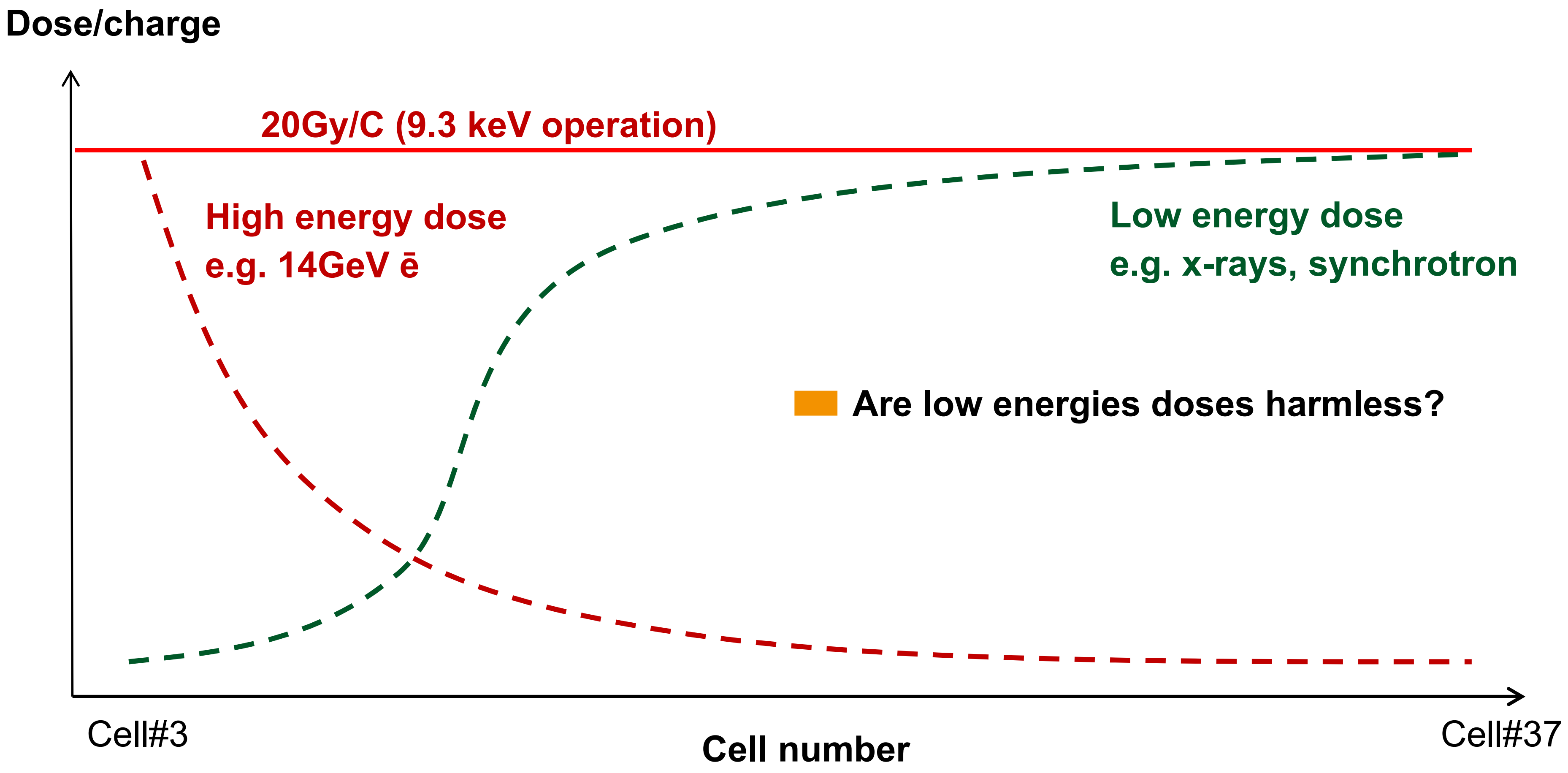
Measurable radiation dose starts to develop at cell 13-16.



Shan Liu, Y. Li and F. Wolff-Fabris, IPAC’19, TUPRB021 (2019)

# Depicting high and low energy radiation doses

- SASE1 scheme in user operation mode

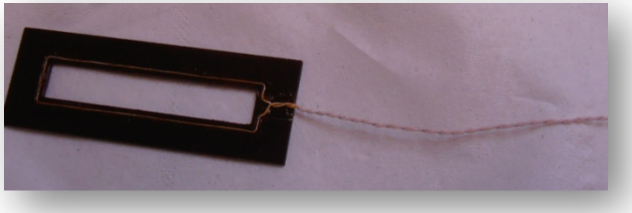


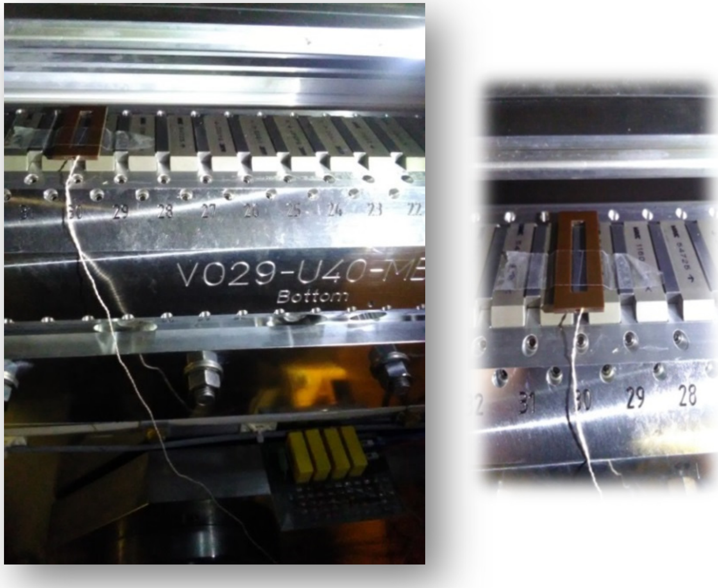
- **Are low energies doses harmless?**

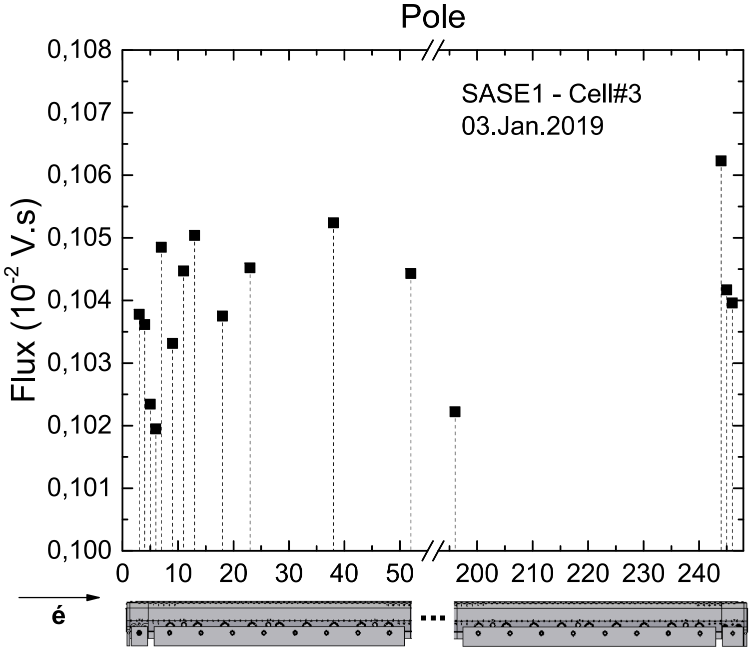
# Development of portable measurement system

- In-situ measurement system based on magnetic flux method: "Flux Coil"
- Reproducibility ~ $\pm 5.10^{-4}$
- A DU can be measured in a temporary access (30-60 min)
- Representative data on 5-m undulator in 2-3 hours

$$\Phi = N \int_{t1}^{t2} V(t)dt$$

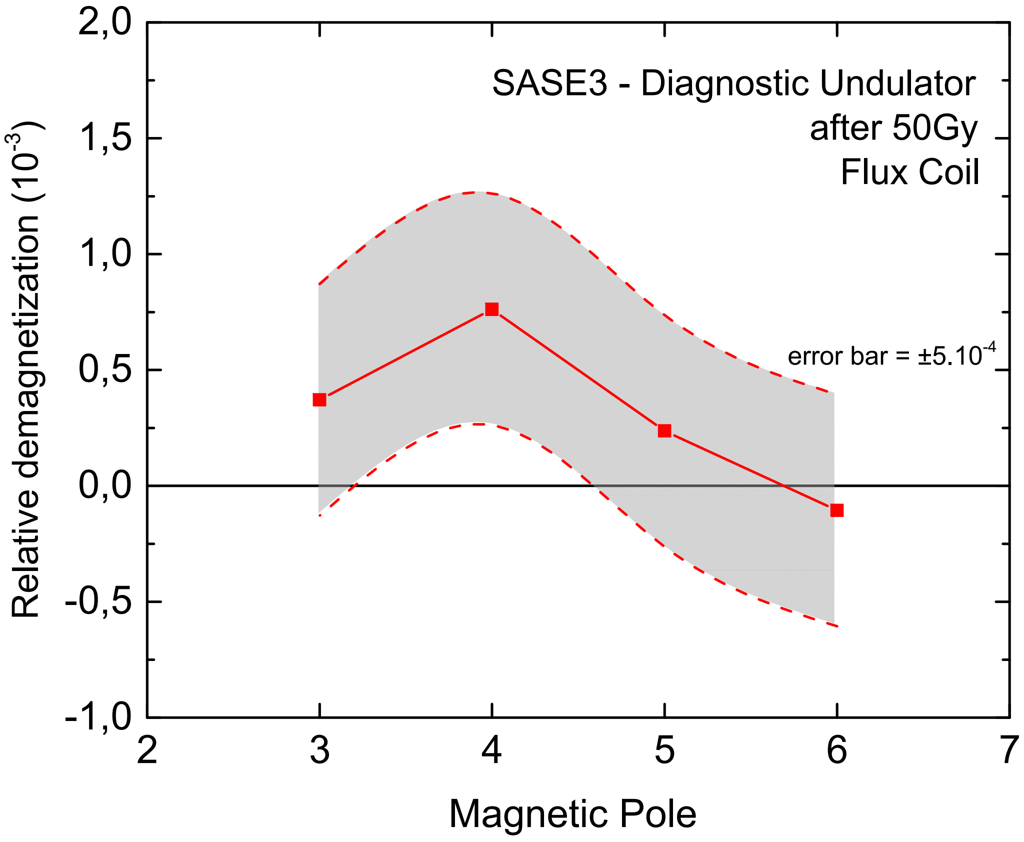


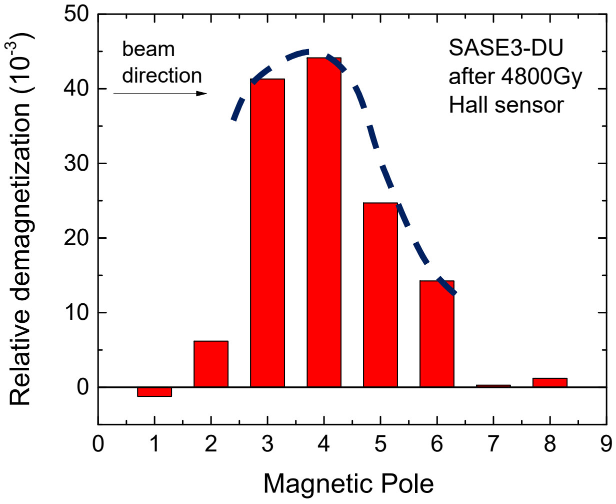




# Development of portable measurements

- Setup shows potential: we measured slightly degradation on SASE3 DU after absorbing 50 Gy with similar behaviour as past Hall sensor measurements.





- Other option: K-mono measurements (W. Freund's later talk)

# Outline

- 1. Introduction
- 2. Absorbed doses: commissioning phase vs user operation
- 3. Dose per transmitted charge rate in user experiments
- 4. Energy-dependent radiation profile and demagnetization monitoring
- **5. Summary**

# Summary

- We demonstrate the importance of radiation monitoring to the Undulators

- Beam protection: Efficient collimation and protection system in place
  - Beam losses were reduced due to improved operation procedures

- Dose rates
  - About maximum 20 Gy/C during user experiments at 9.3 keV (SASE1)
  - Higher dose rates will follow at lower photon energies or at higher repetition rates

- Absorbed dose and energy profile during user experiments
  - Upstream undulators dominated by residual beam losses
  - Further dose reduction at upstream segments seems possible with improvements, e.g., tune-up beam stops in front of SASE systems
  - Downstream undulators are dominated by synchrotron radiation and can´t be protected
  - Portable measurement system allows monitoring of undulator magnetic status

- Based on today´s knowledge and data, 5-m undulator doses > 230 Gy shall not occur within the next 1-2 years (thus answering how much harm low-energy dose may cause).

# THANK YOU FOR YOUR ATTENTION!