# Machine Protection for FLASH and FERMI@Elettra

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# Overview

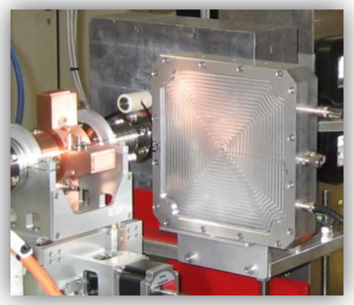
- Machine Protection
- FLASH
  - Transport of dark current from the gun
- FERMI@Elettra
  - Demagnetization of permanent magnets
  - MPS instrumentation
  - RADFET online dosimetry
  - Beam loss position monitors (Cherenkov fibers)

# Machine Protection

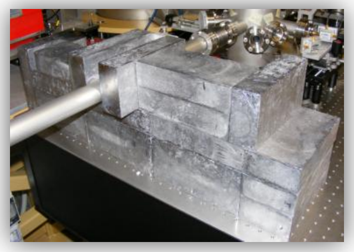
# What is Machine Protection?

**Machine protection is the sum of all measures that protect an accelerator and its infrastructure from the beam.**

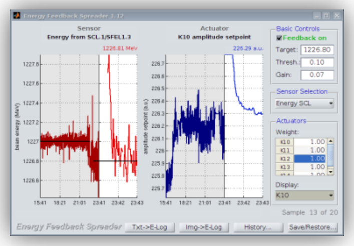
- Machine Protection System
  - Interlock on components (magnets, screens, ...)
  - Monitoring of the beam (beam loss monitors, charge monitors, BPMs, ...)
  - Mitigation (inform the operator, reduce repetition rate, fire abort kickers, stop beam production, ...)



- Collimators, absorbers
- Shielding



- Physics (matching, collective effects, ...)
- Robust systems+software (feedbacks, LLRF, controls, ...)
- Safe procedures (switch on, change beam energy, ramp to full power, ...)



# Average Electron Beam Powers

Photo: Michael J. Linden

## Normal conducting

| | | | |
|---|---|---|---|
| FERMI@Elettra | 1.3 GeV | 10-50 Hz | 7-60 W |
| SACLA | 7 GeV | 10-60 Hz | 18-140 W |
| LCLS | 15 GeV | 120 Hz | 8-440 W |

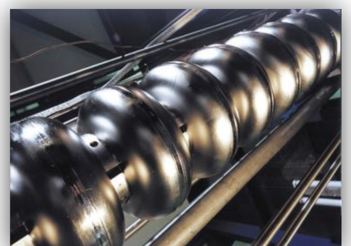
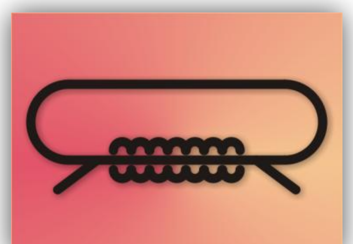


Photo: DESY

## Superconducting

| | | | |
|---|---|---|---|
| FLASH | 1.3 GeV | 1-3 MHz pulsed | 10 W – 22 kW |
| European XFEL | 17.5 GeV | 4.5 MHz pulsed | >500 kW |
| Berkeley NGLS | 2 GeV | 1 MHz CW | 600 kW |



## Energy recovery linacs

| | | | |
|---|---|---|---|
| NovoFEL | 12 MeV | 5.6-22 MHz CW | 15-60 kW |
| Jlab FEL | 200 MeV | 75 MHz CW | >1 MW |
| Future ERLs | 5 GeV | 1.3 GHz CW | 500 MW |

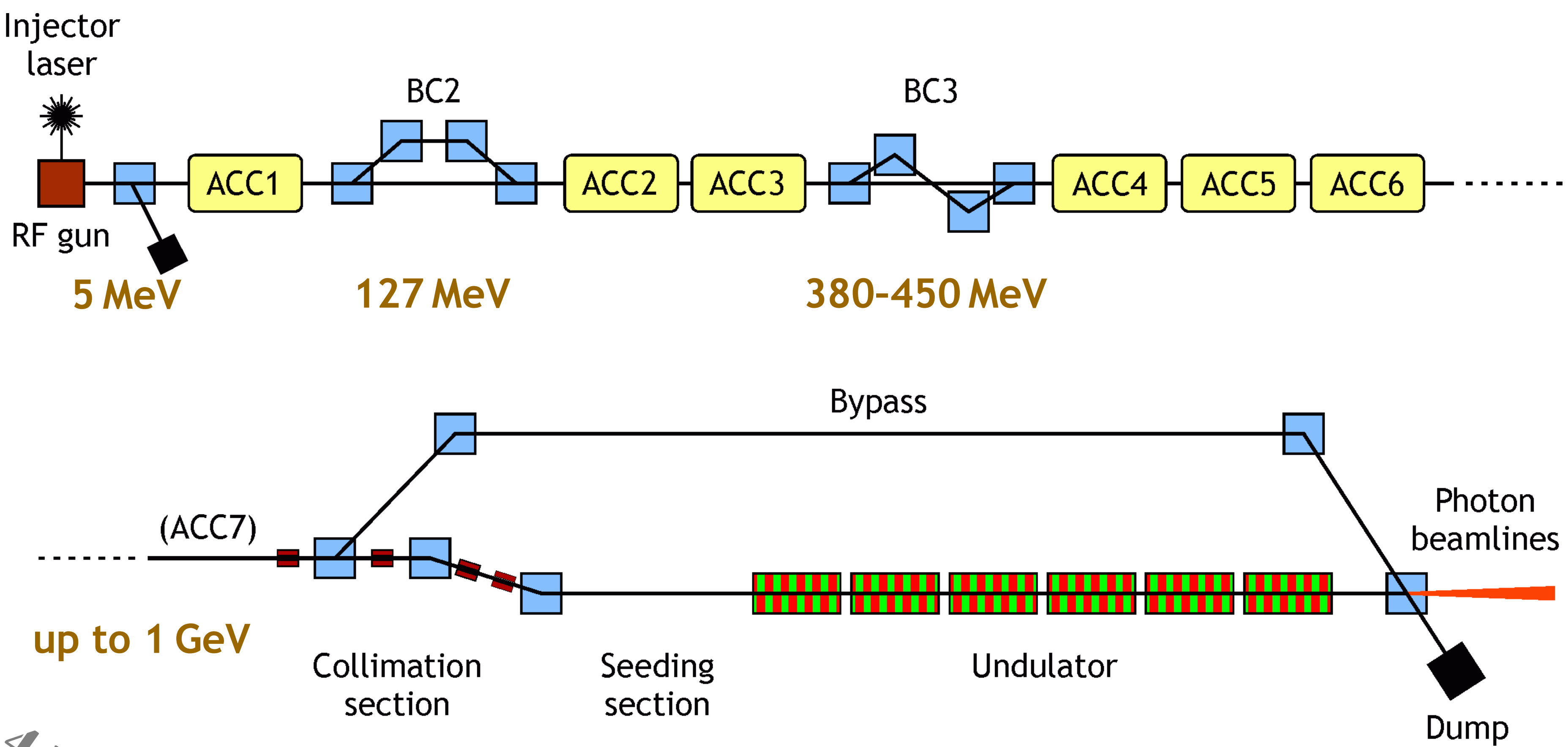
# Hazards

| Local loss power (W) | Effects |
|---|---|
| 100 – 1000 | Thermal/mechanical damage |
| 10 – 100 | Mechanical failure of flange connections |
| 1 – 100 | Activation of components |
| 1 – 100 | Radiation damage to electronics, optical components, &c. |
| 1 – 10 | Excessive cryogenic load, quenches |
| 0.01 – 0.1 | Demagnetization of permanent magnets |


# FLASH

Dark Current Transport

# FLASH — Free-Electron Laser in Hamburg



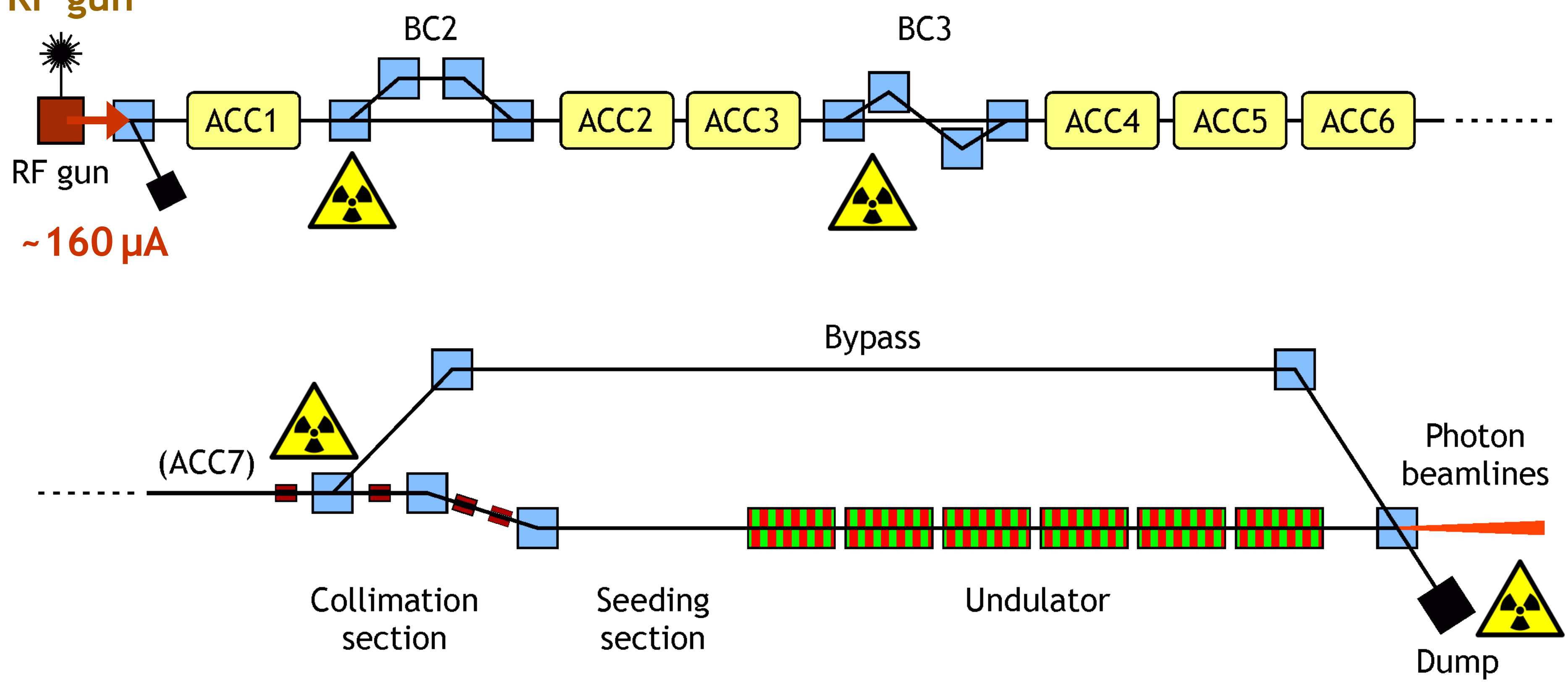

SASE free-electron laser, down to 6.5 nm

4 YEARS AGO

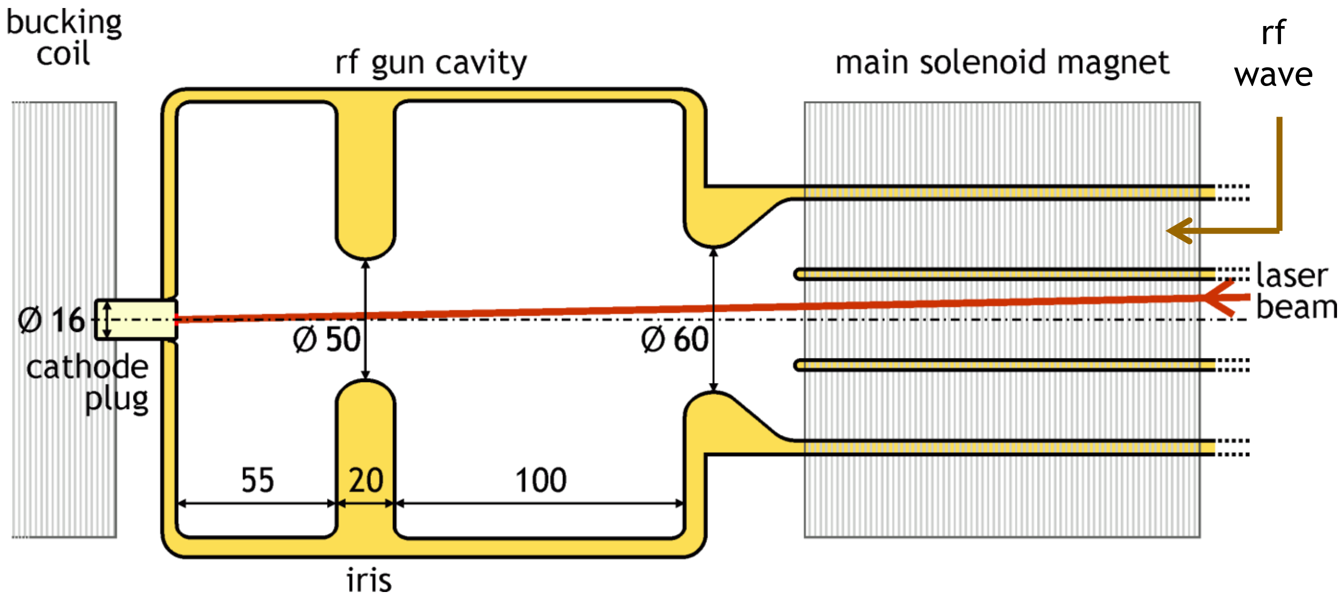
# Radioactivation by Dark Current

**Dark current:** all charge carriers emitted from a device or structure *unintentionally*
→ by field emission from cavities

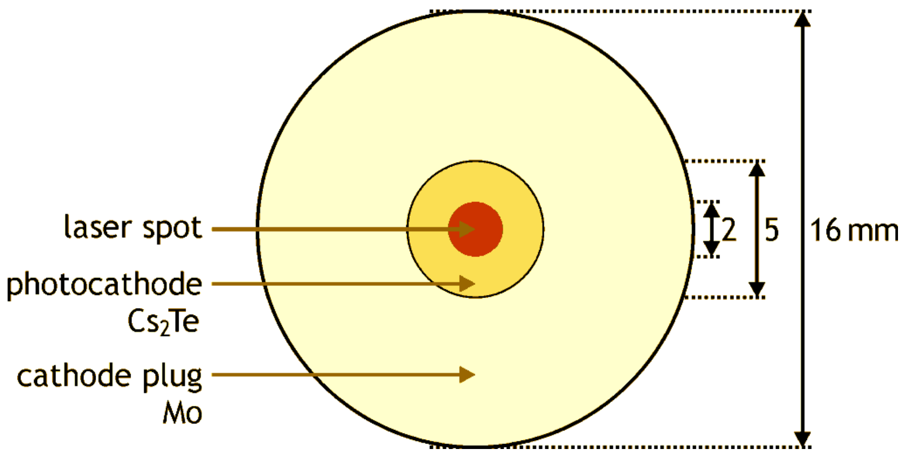
**main source at FLASH: RF gun**



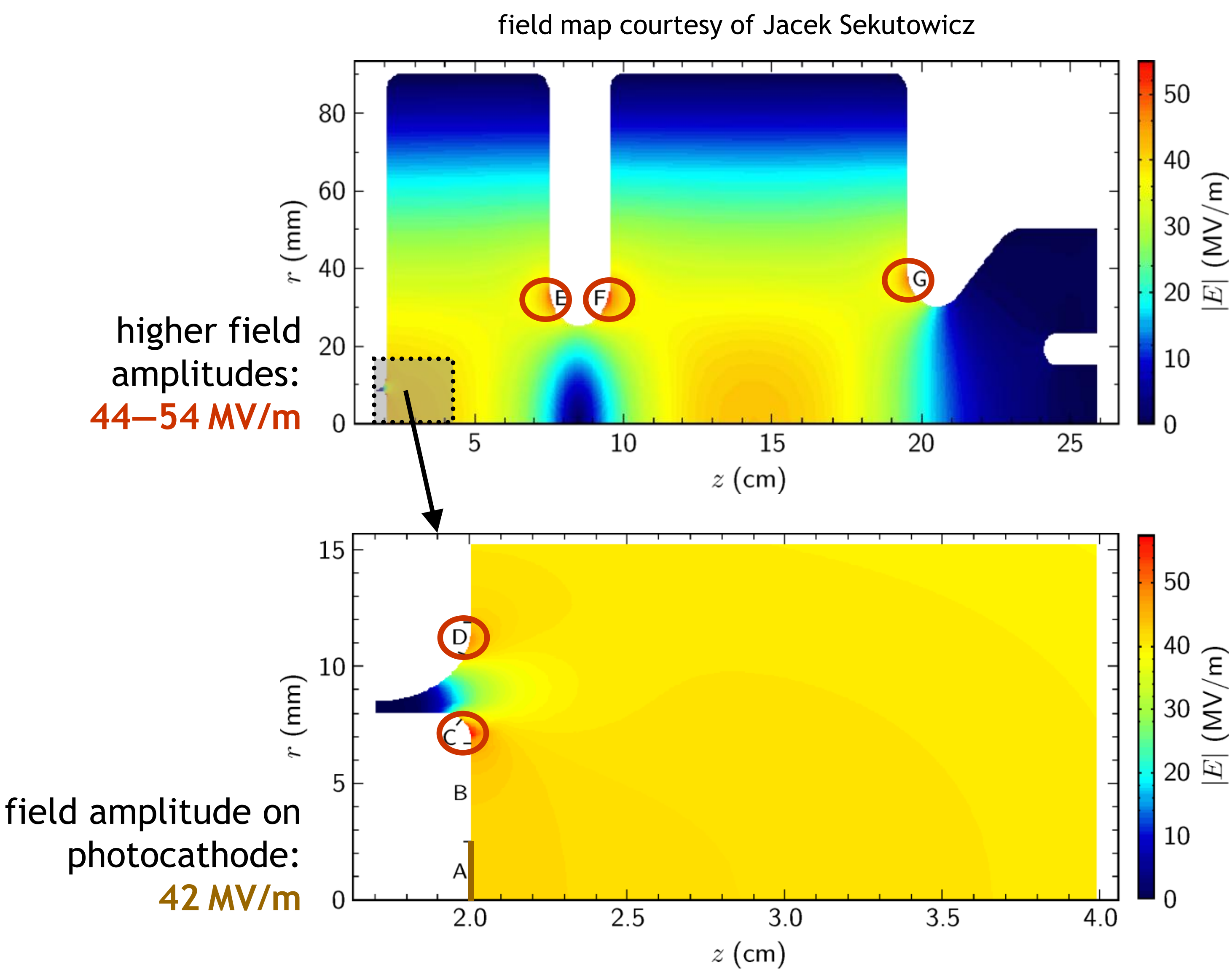
# The FLASH RF Gun




- Normal conducting 1½ cell copper cavity
- Exchangeable photocathode with high quantum efficiency

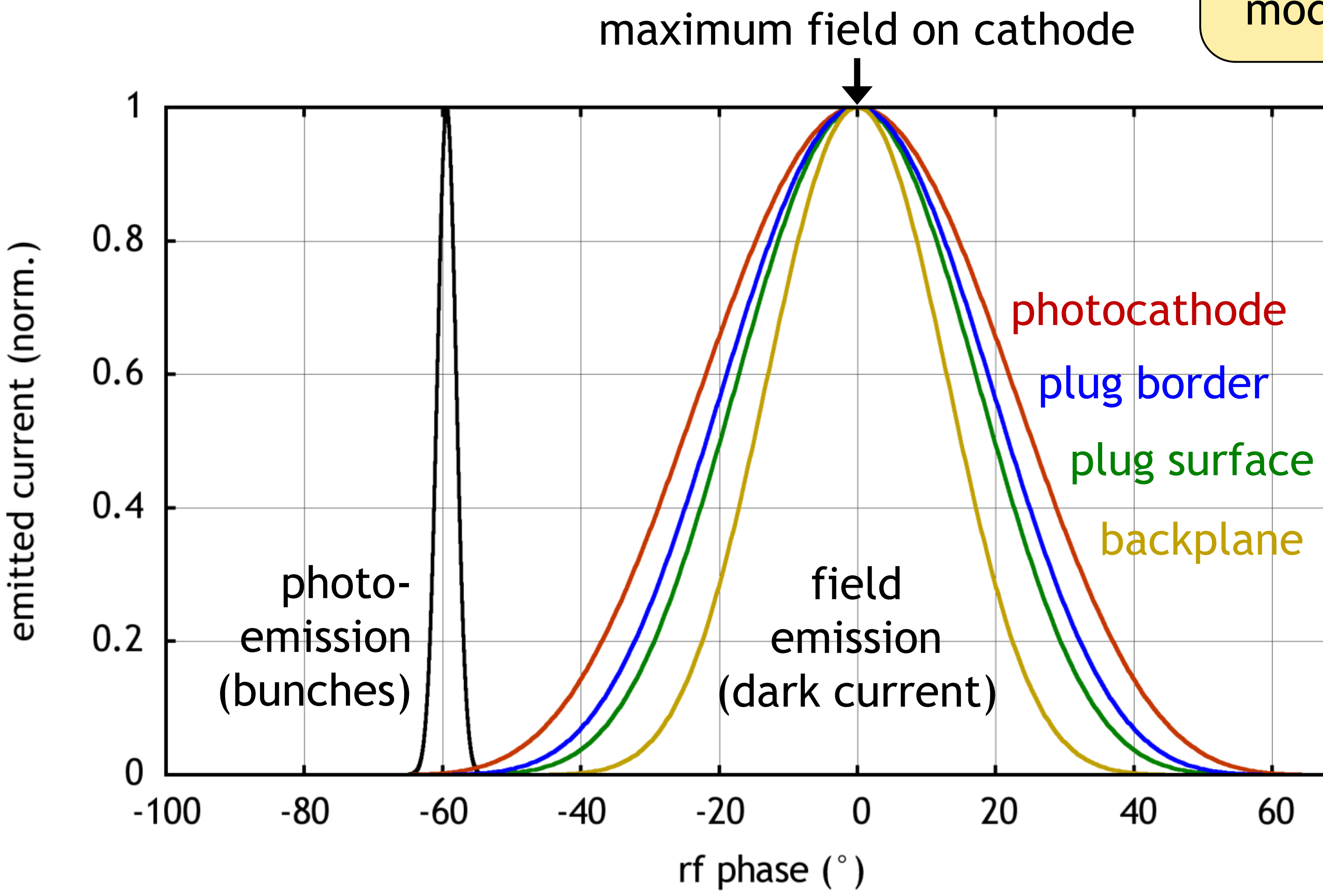


# Field Emitters in the RF Gun Cavity



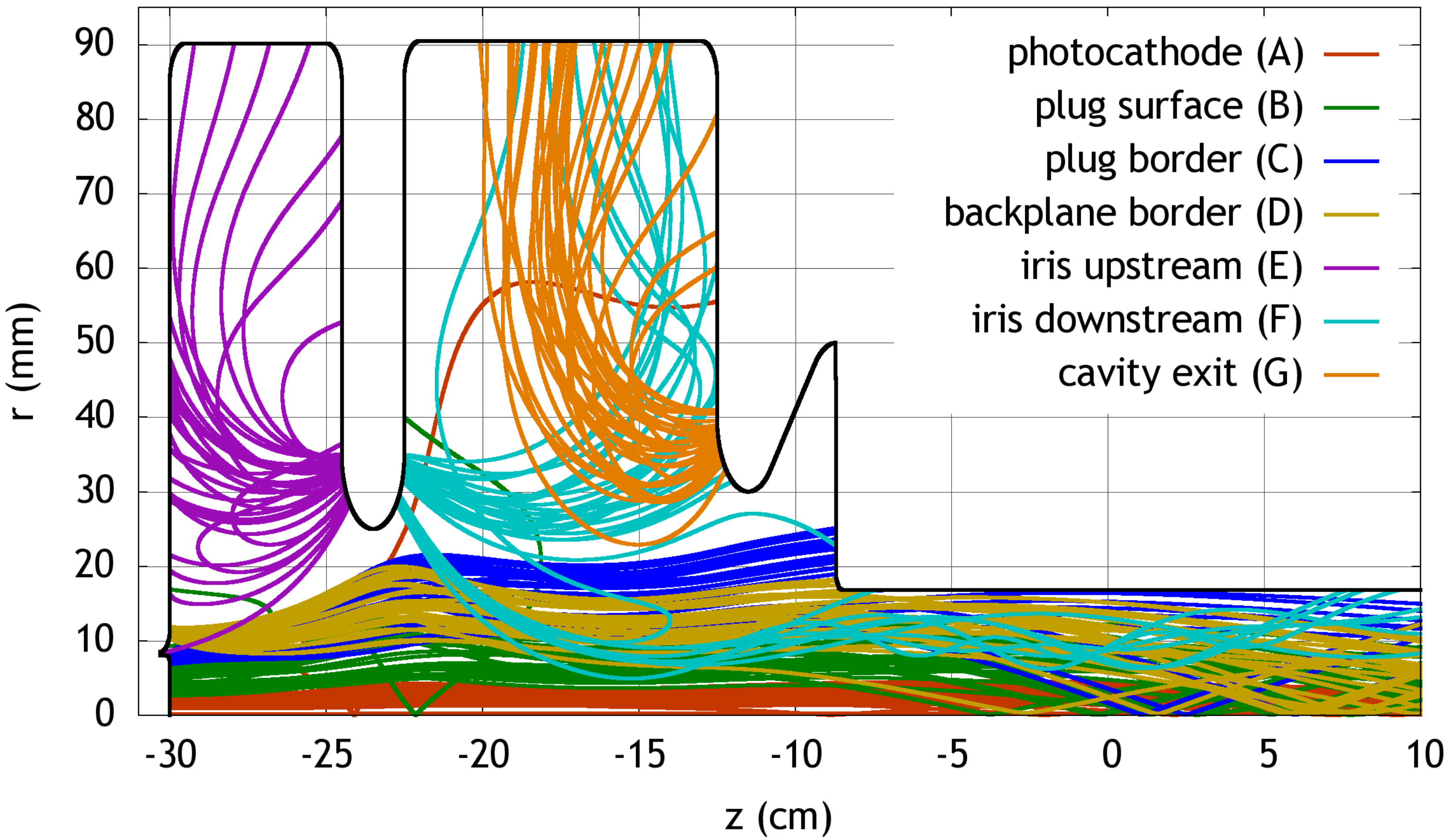
# Modelling of Dark Current Emission

Fowler-Nordheim field emission model

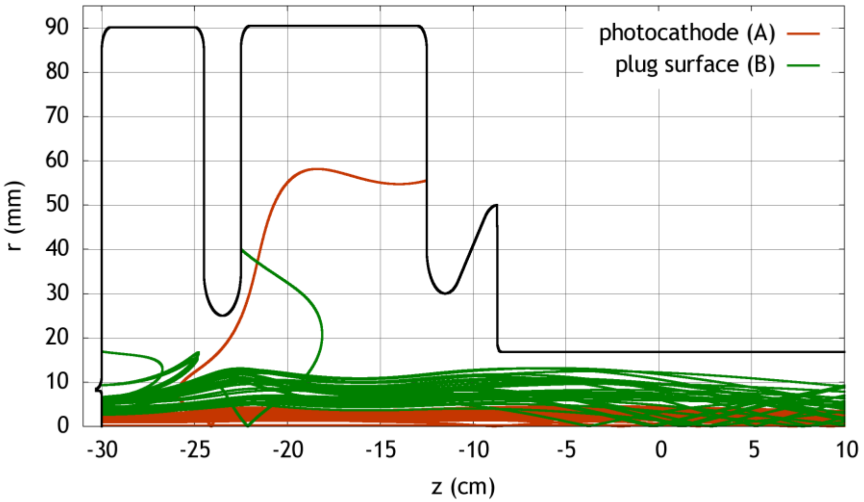


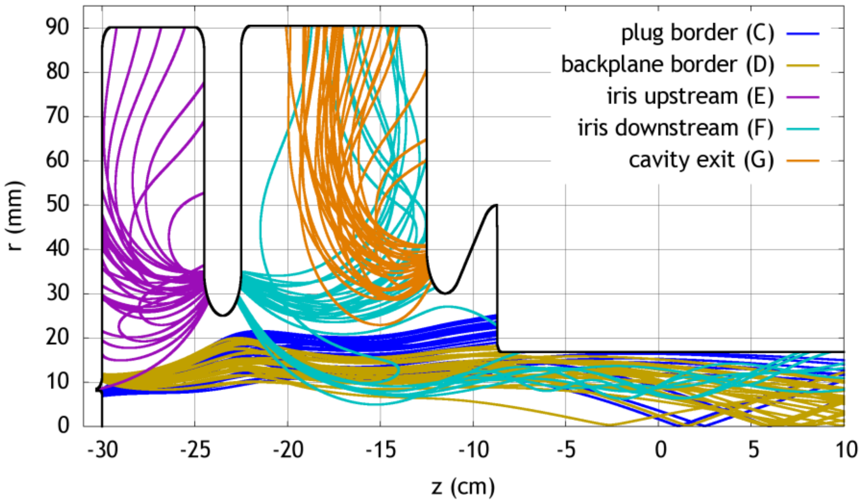
# Dark Current Transport in the RF Gun Cavity

Tracking of dark current from emitter surfaces
(with enhanced **Astra** code for complex 3D geometries)



# Transmission to ACC1

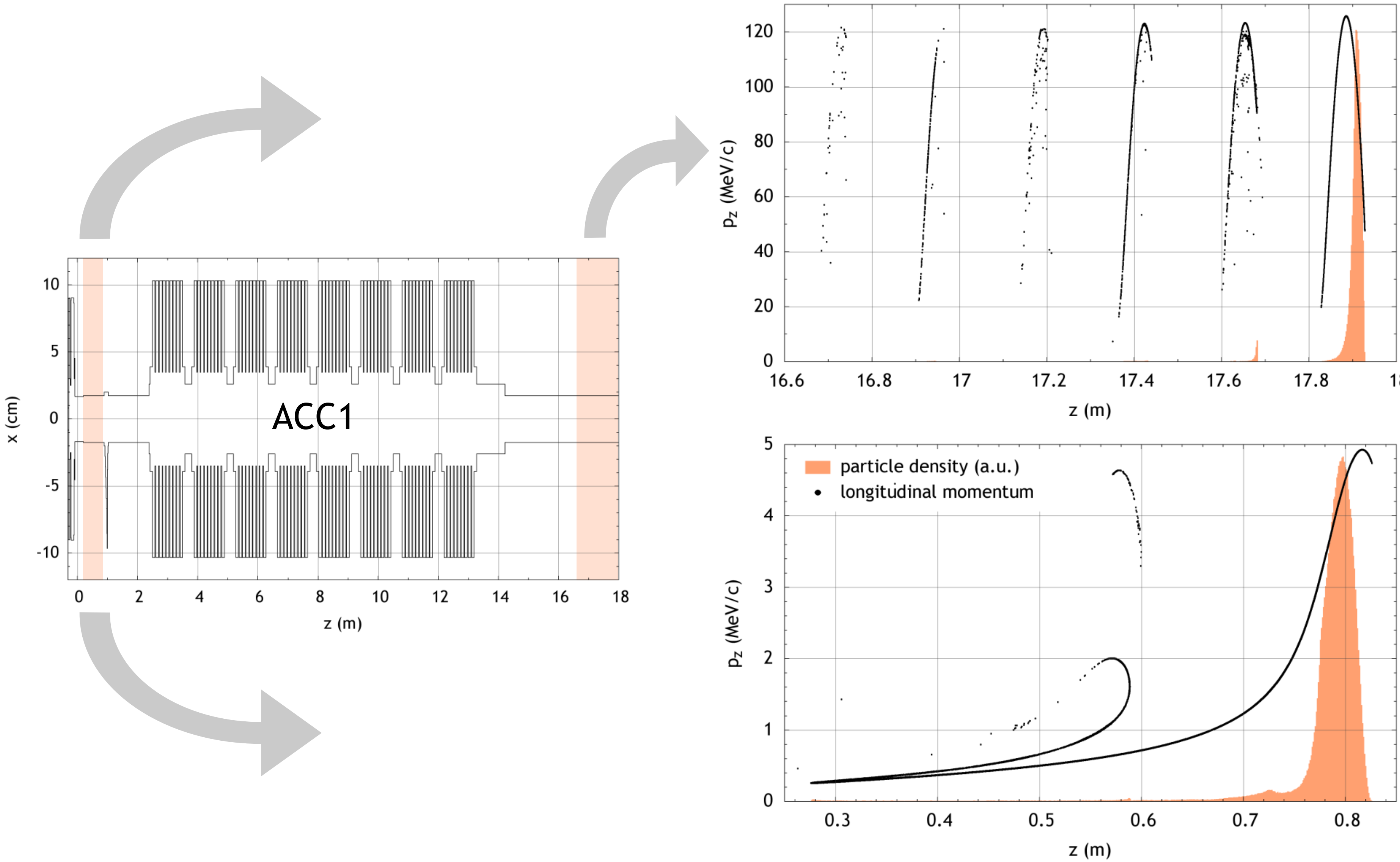


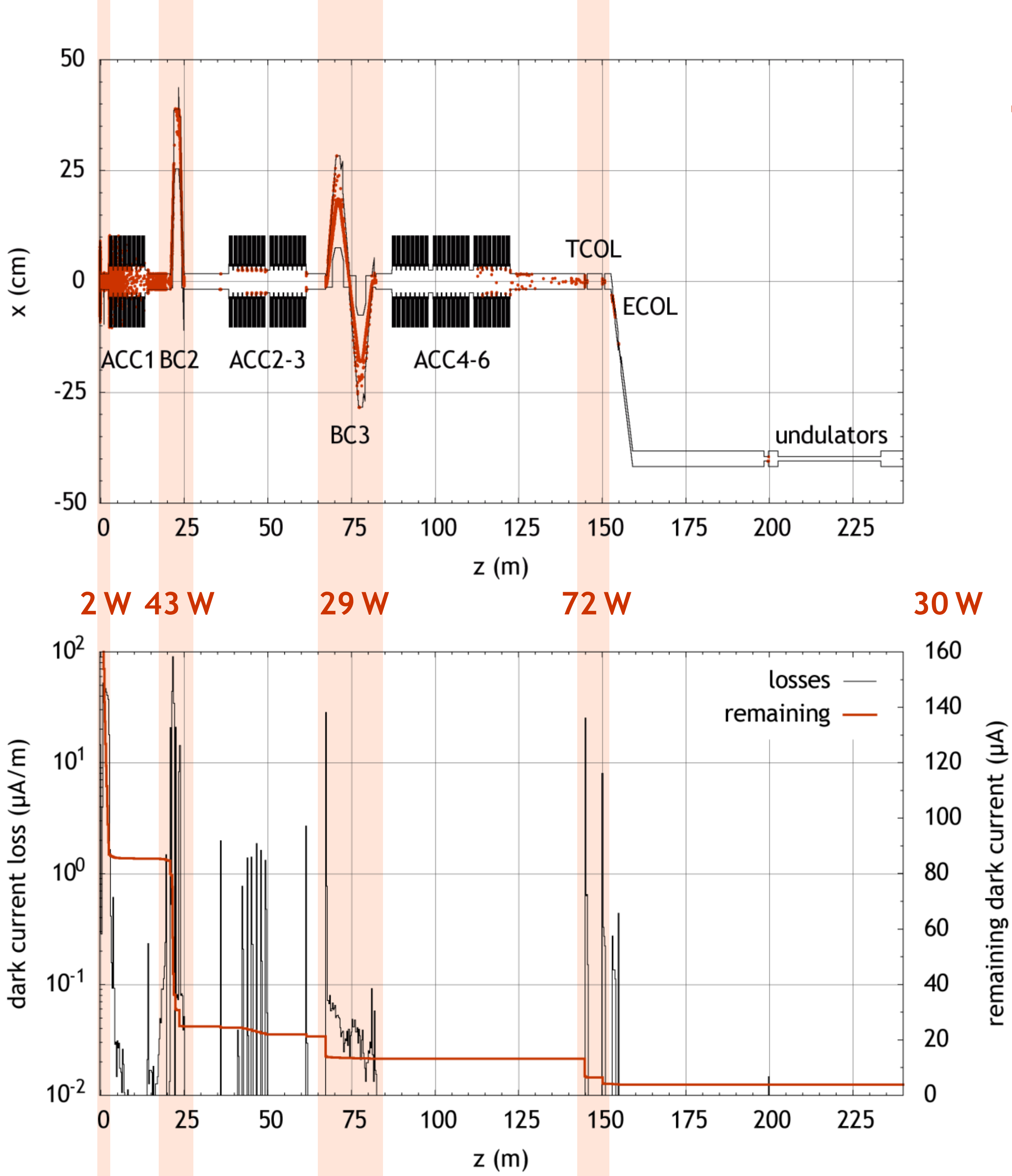

**Percentage of particles transported to ACC1 (2.6 m from cathode)**

| | Emitter | all | ≥ 1 MeV/c | ≥ 2 MeV/c |
|---|---|---|---|---|
| A | Photocathode | 20.99 | 20.64 | 19.61 |
| B | Plug surface | 1.17 | 0.85 | << 0.01 |
| C | Plug border | 0.07 | 0 | 0 |
| D | Backplane border | 0.41 | 0 | 0 |
| E | Iris upstream | 0 | 0 | 0 |
| F | Iris downstream | 0 | 0 | 0 |
| G | Cavity exit | 0 | 0 | 0 |

# Before & After ACC1



# Overview




Location of major dark current losses:

- behind rf gun
- bunch compressor 2
- bunch compressor 3
- transverse collimators

**dark current power deposition (10 Hz, 800 μs pulse length)**

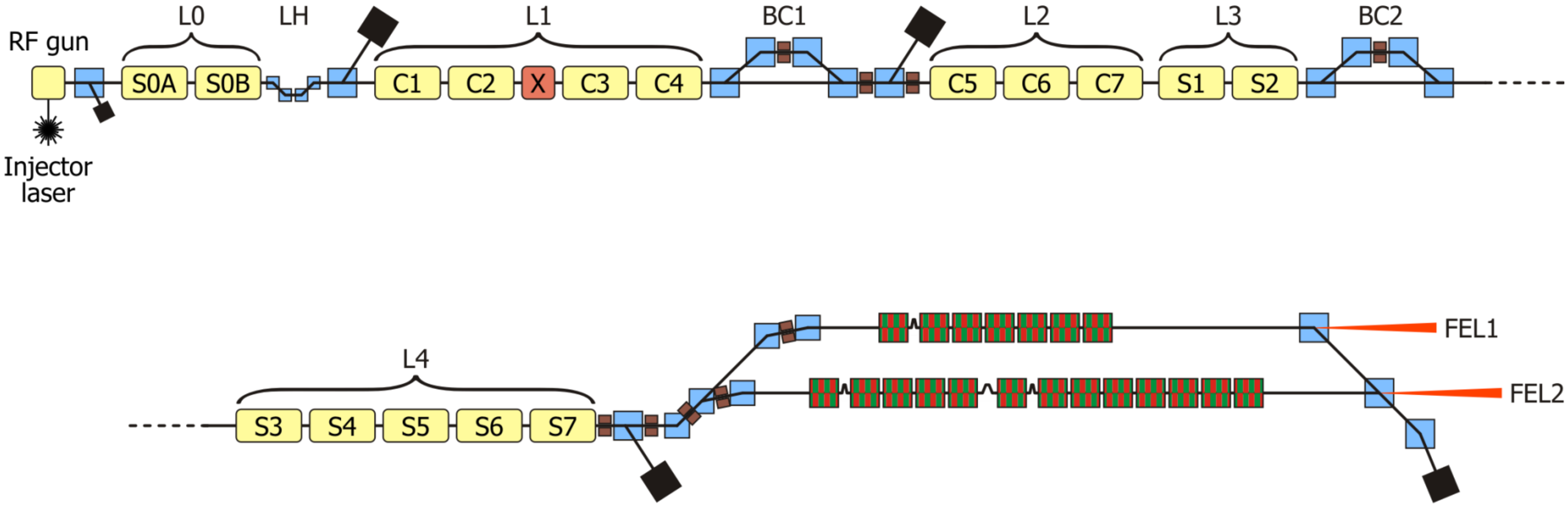
Simulation parameters:

- final beam energy: 980 MeV
- ACC1 rf phase: 8 off-crest
- ACC2—3 rf phase: 20 off-crest

# FERMI@Elettra

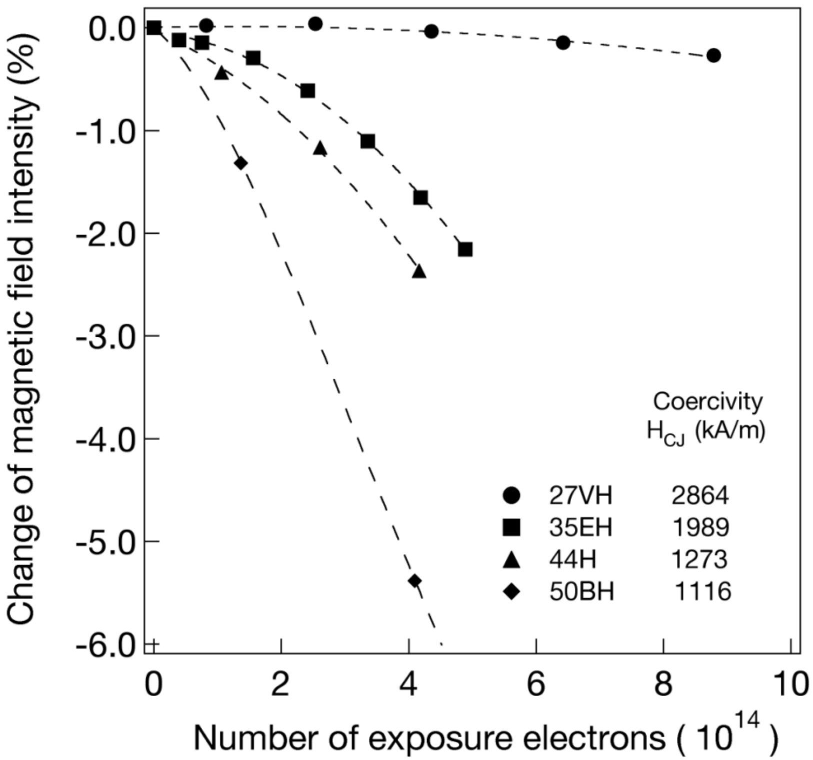
Undulator Protection

# FERMI@Elettra




| | Energy | Bunch Charge | Repetition Rate | Beam Power |
|---|---|---|---|---|
| Typical | 1.2 GeV | 500 pC | 10 Hz | 6 W |
| Design | 1.5 GeV | 1 nC | 50 Hz | 75 W |

# Demagnetization of Permanent Magnets

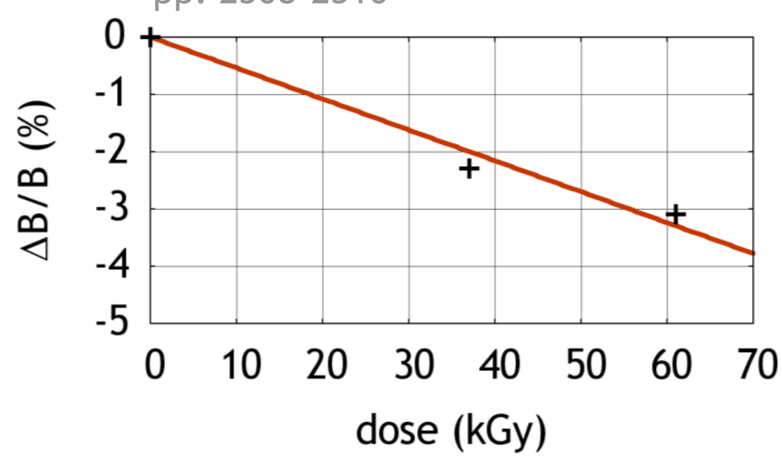



($Nd_2Fe_{14}B$ magnets, 2 GeV electrons)

Teruhiko Bizen – “Brief Review of the Approaches to Elucidate the Mechanism of the Radiation-induced Demagnetization” (ERL workshop 2011, Tsukuba, Japan)

- FELs rely on precision magnetic fields
- Permanent magnets lose magnetic field under irradiation with high energy electron beams
- Various magnetic materials behave differently

Skupin et al., “Undulator demagnetization due to radiation losses at FLASH”, Proc. EPAC 2008, pp. 2308–2310

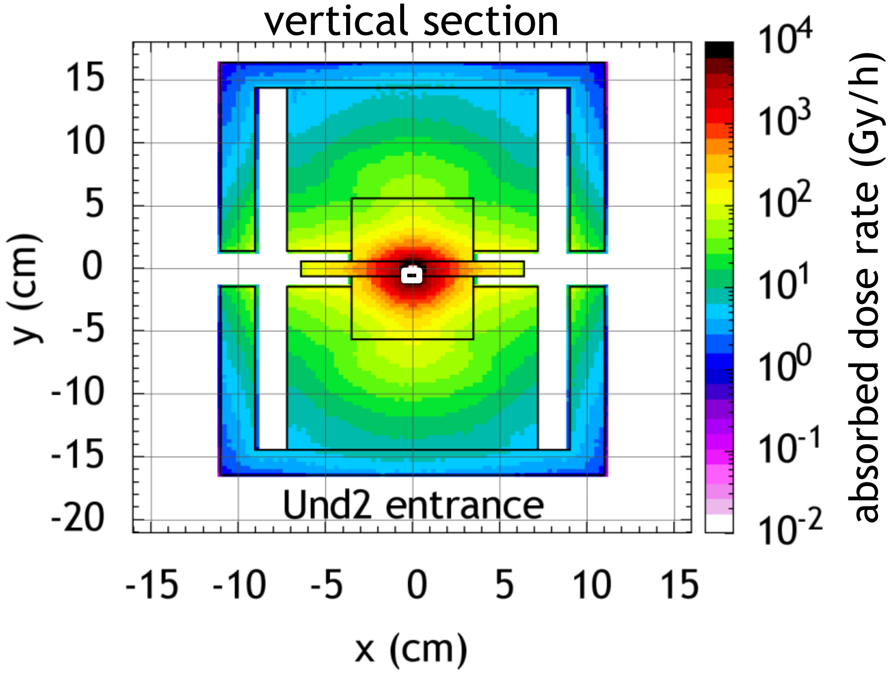


# Demagnetization of Permanent Magnets

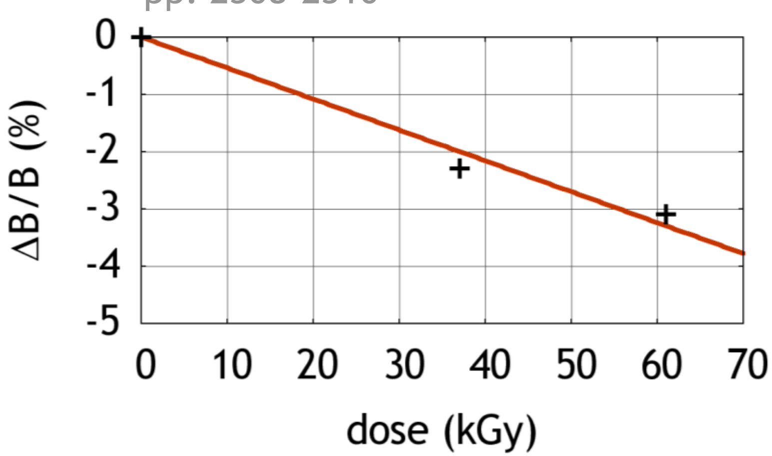
Can demagnetization be compensated by undulator tuning (opening gaps)?

- FELs rely on precision magnetic fields
- Permanent magnets lose magnetic field under irradiation with high energy electron beams
- Various magnetic materials behave differently

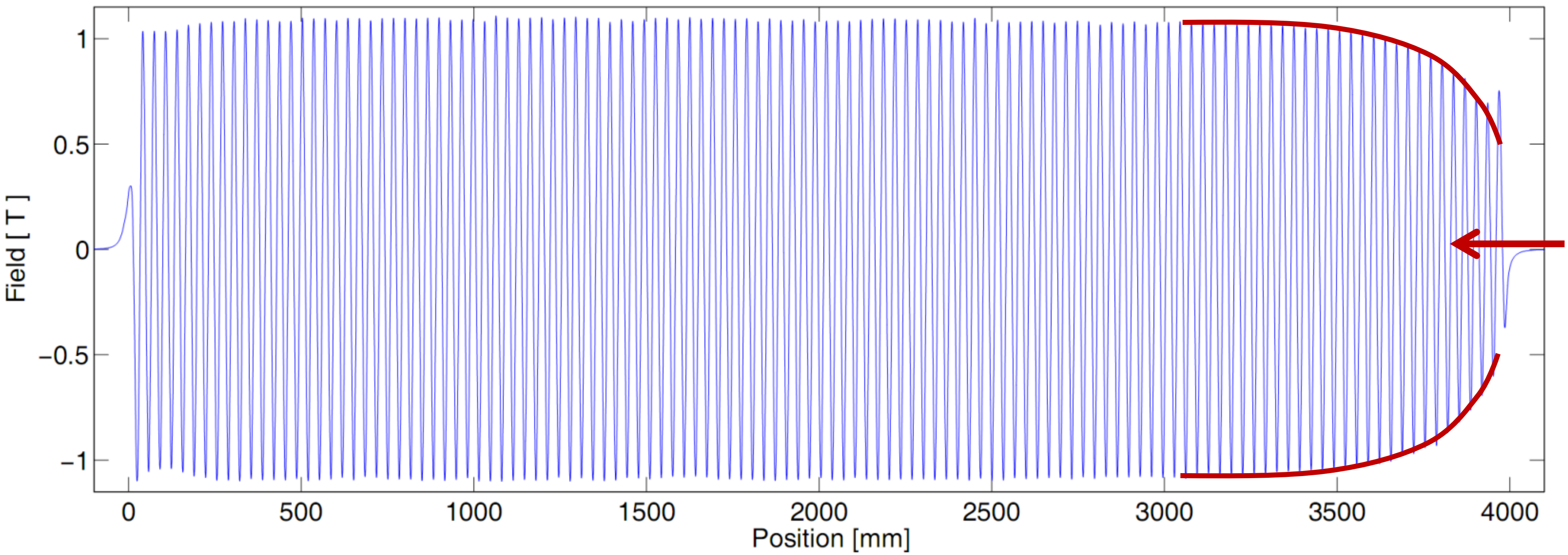
**FLUKA beam loss simulation**
(FLASH, 1 bunch, 10 Hz)




Skupin et al., "Undulator demagnetization due to radiation losses at FLASH", Proc. EPAC 2008, pp. 2308–2310



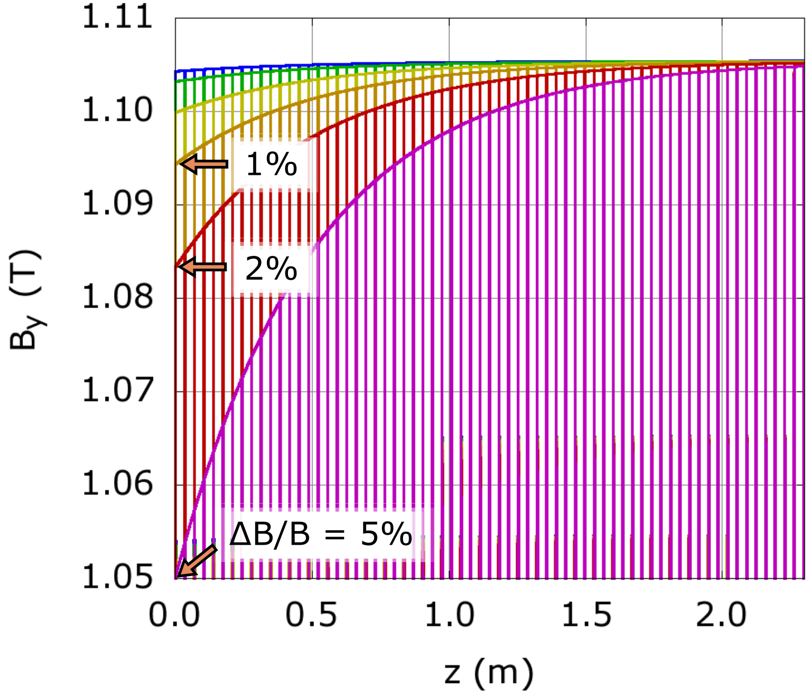
# Field Loss of a PETRA-II Undulator



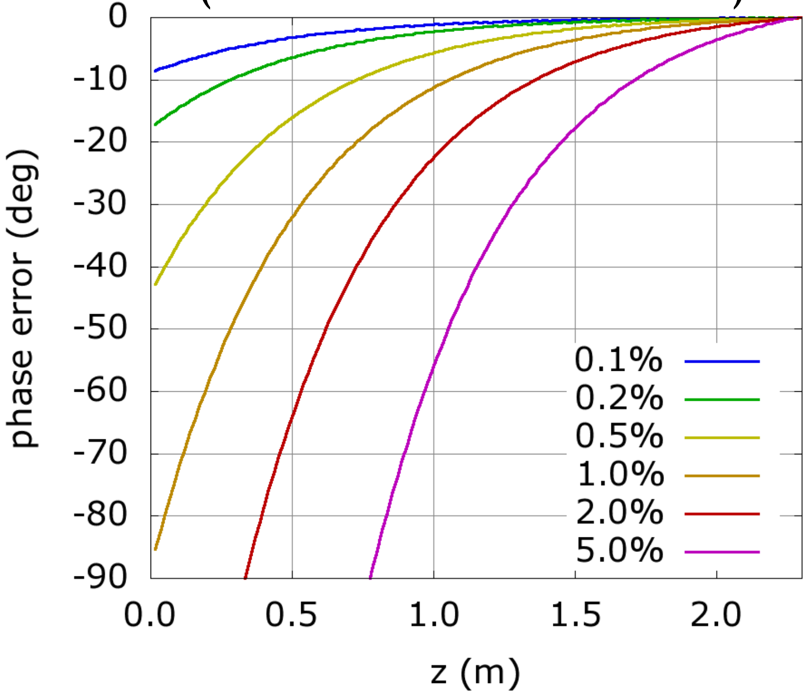

P. Vagin et al., “Commissioning experience with insertion devices at PETRA III”, SR2010, Novosibirsk, Russia.

# Demagnetization and Phase Error

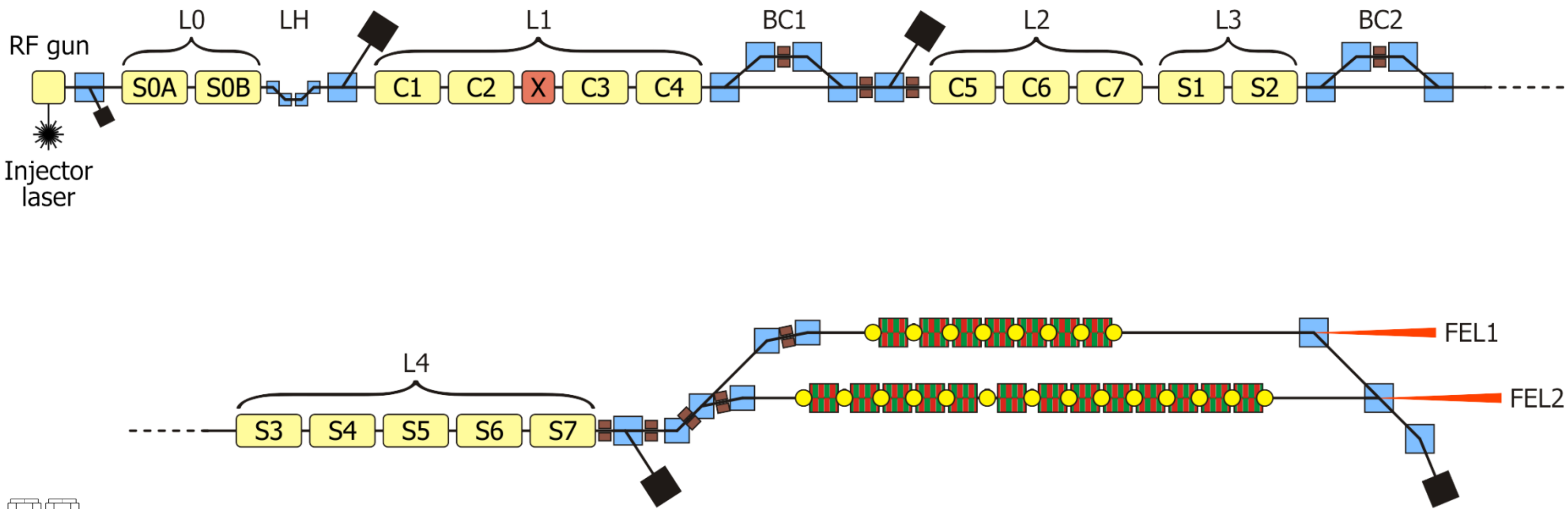
Undulator Field

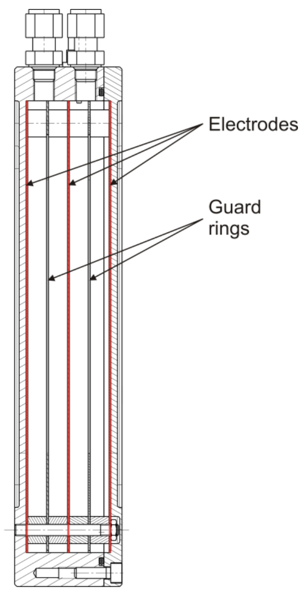



Phase Error
(Electrons—FEL radiation)

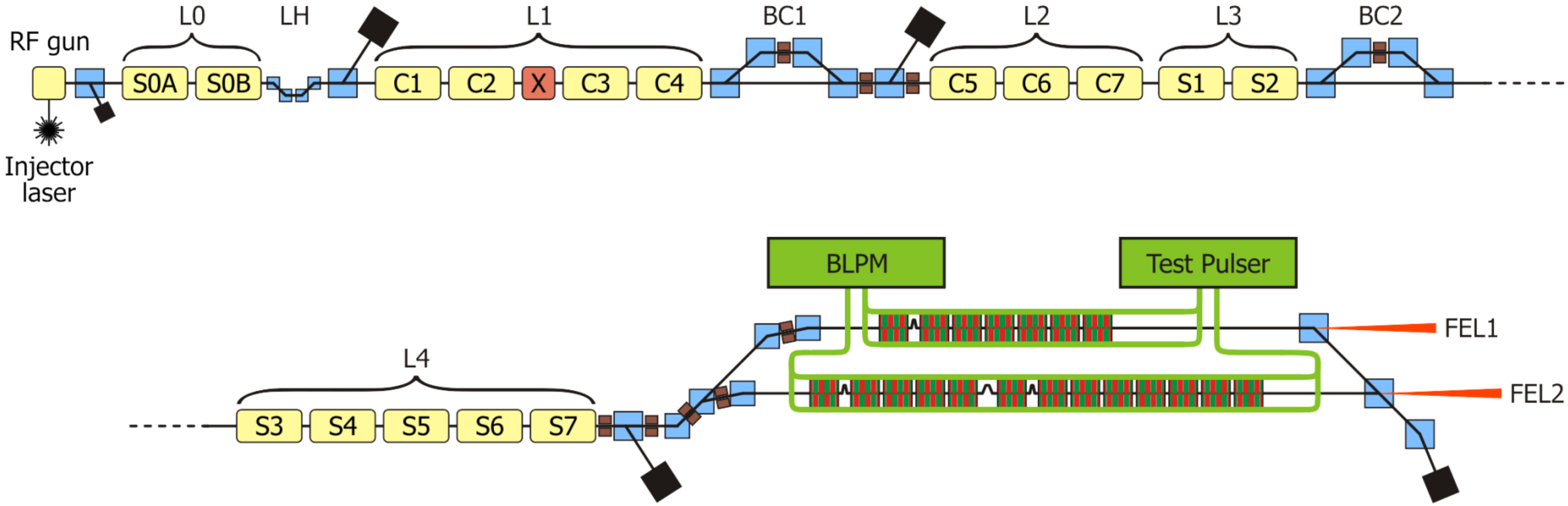



Example: FERMI@Elettra FEL-2, second stage radiator
66 periods of 3.48 cm

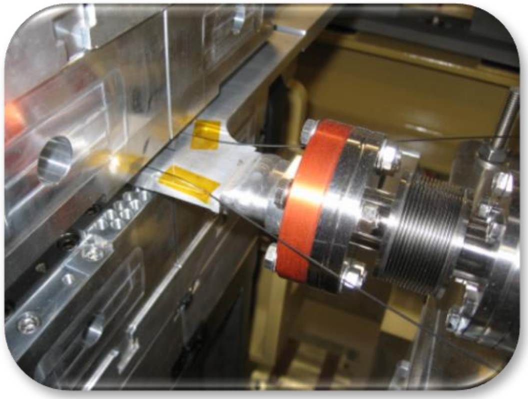


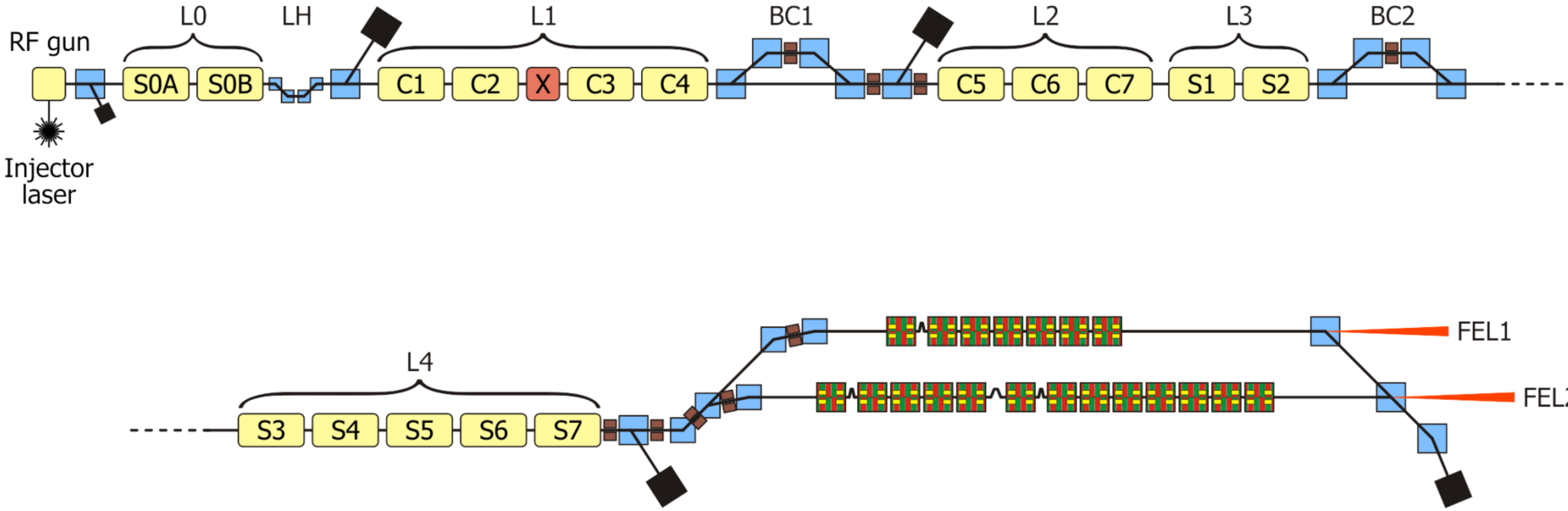

Ionization Chamber
Beam Loss Monitors (BLMs)

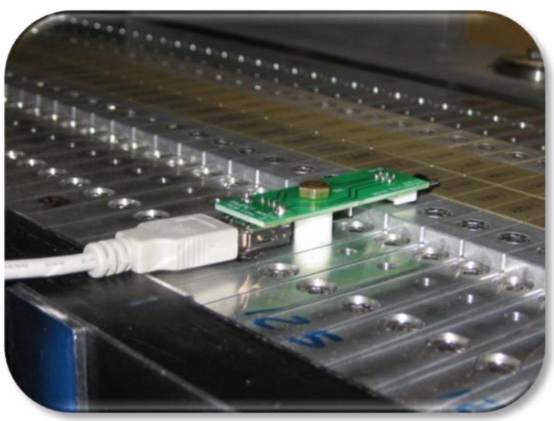



Cherenkov Fiber Beam Loss Position Monitors (BLPMs)



# FERMI@Elettra



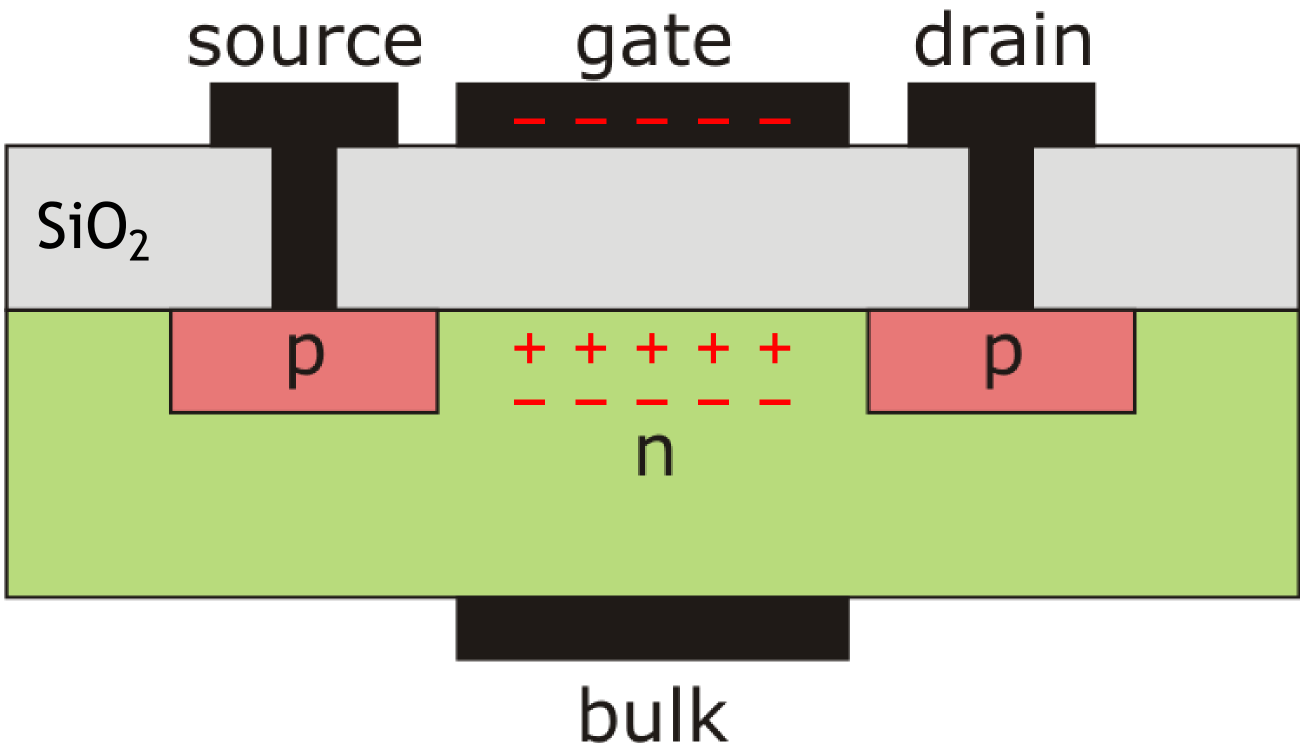



RADFET Online Dosimetry System

# Online Solid-State Dosimetry

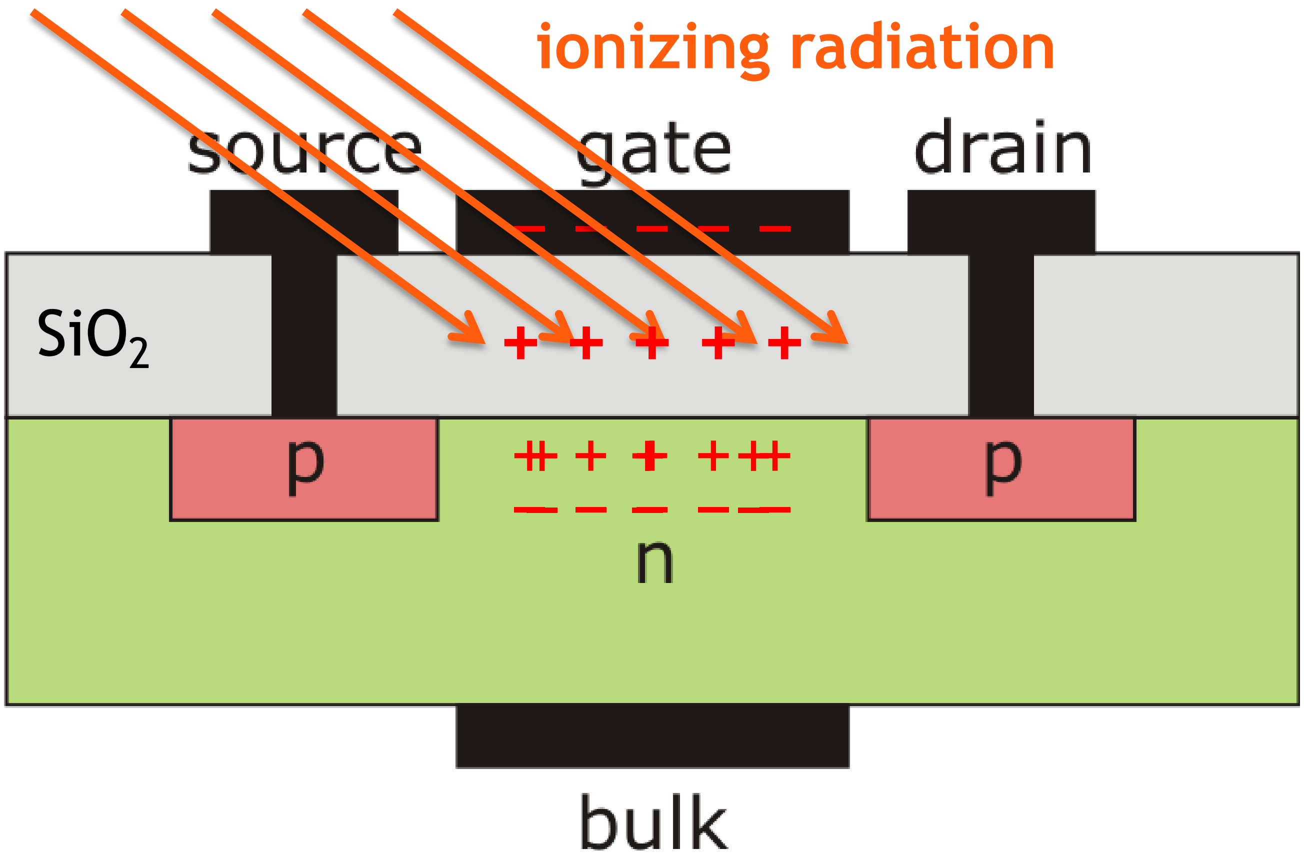
L. Fröhlich, K. Casarin, E. Quai, et al., “Online monitoring of absorbed dose in undulator magnets with RADFET dosimeters at FERMI@Elettra”, Nucl. Instr. & Meth. A (2012), http://dx.doi.org/10.1016/j.nima.2012.11.021

# P-channel MOSFET



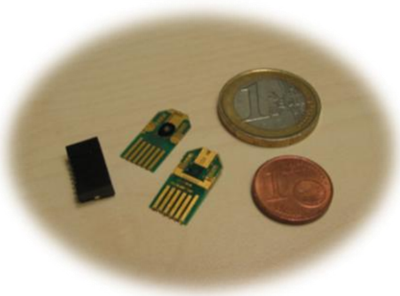

negative gate potential → conductive inversion layer

# P-channel MOSFET



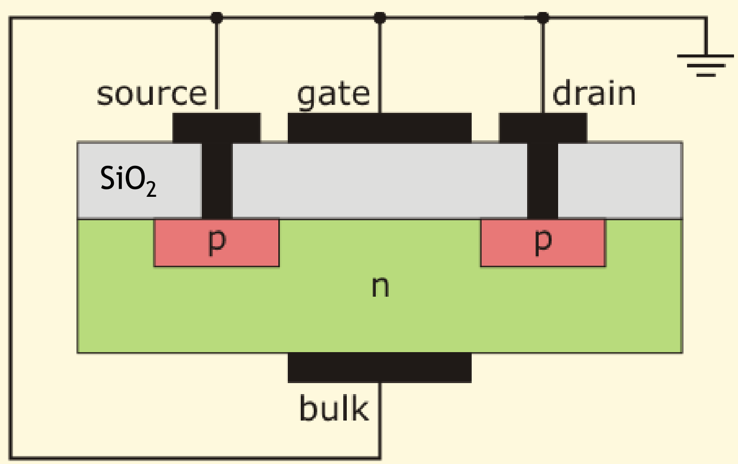

ionizing radiation → stationary charges in insulation layer

# RADFET Dosimeters

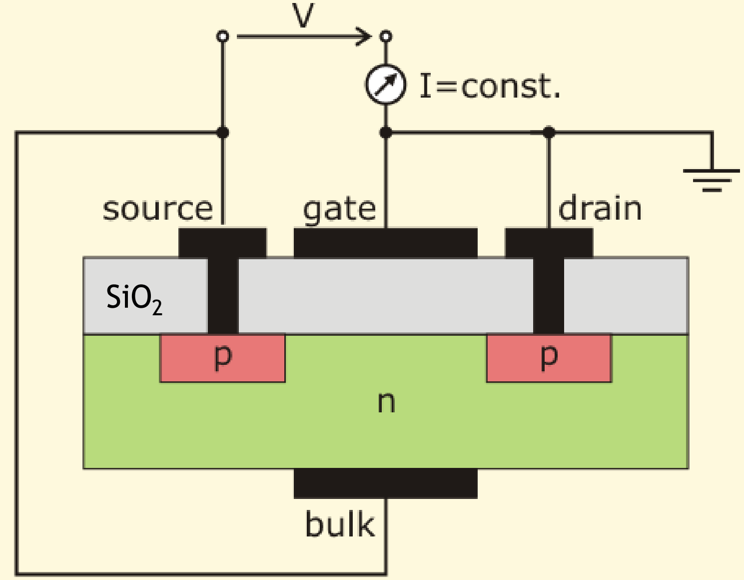


- REM Oxford Ltd. RADFET RFT-300-CC10G1
- Chip contains 2 p-channel MOSFETs with 300 nm insulator layer

exposure
"zero bias"

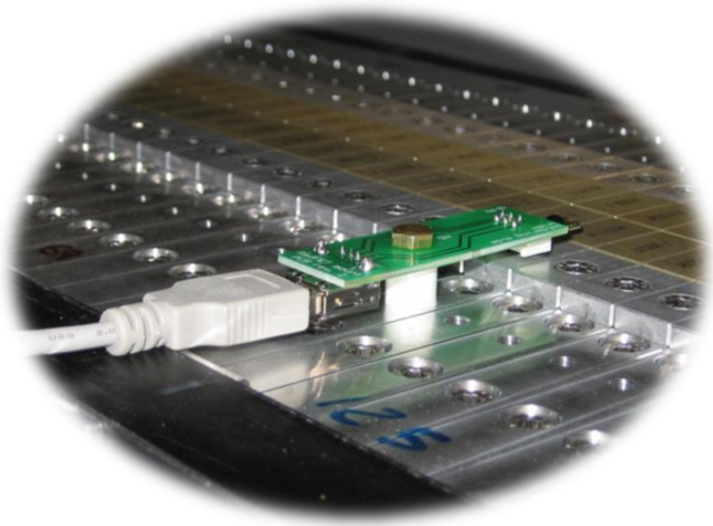



read-out




Track voltage for constant current (490 μA) between source and drain

# Dosimeter Reader



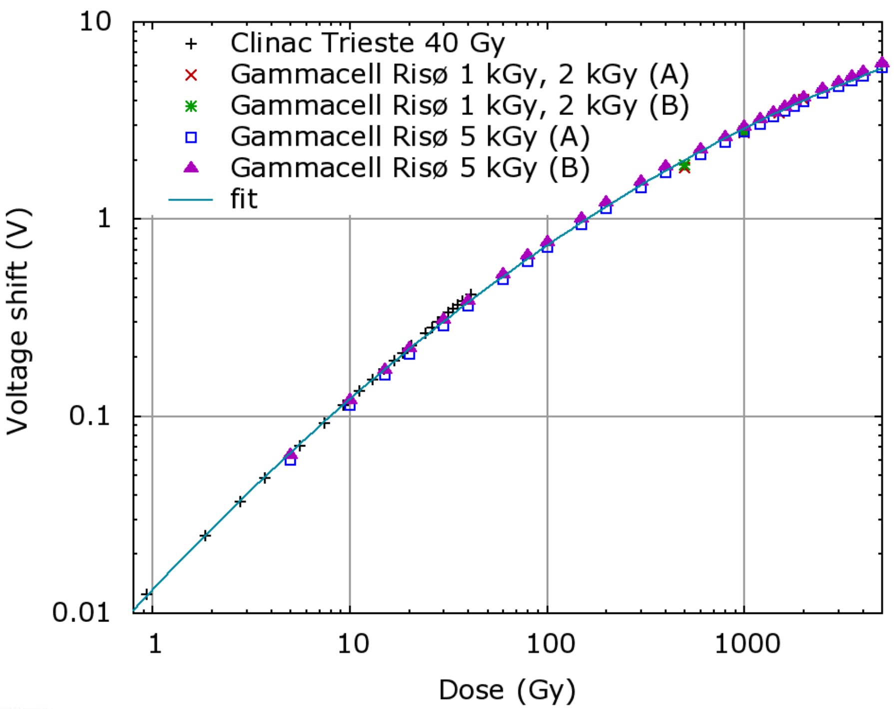
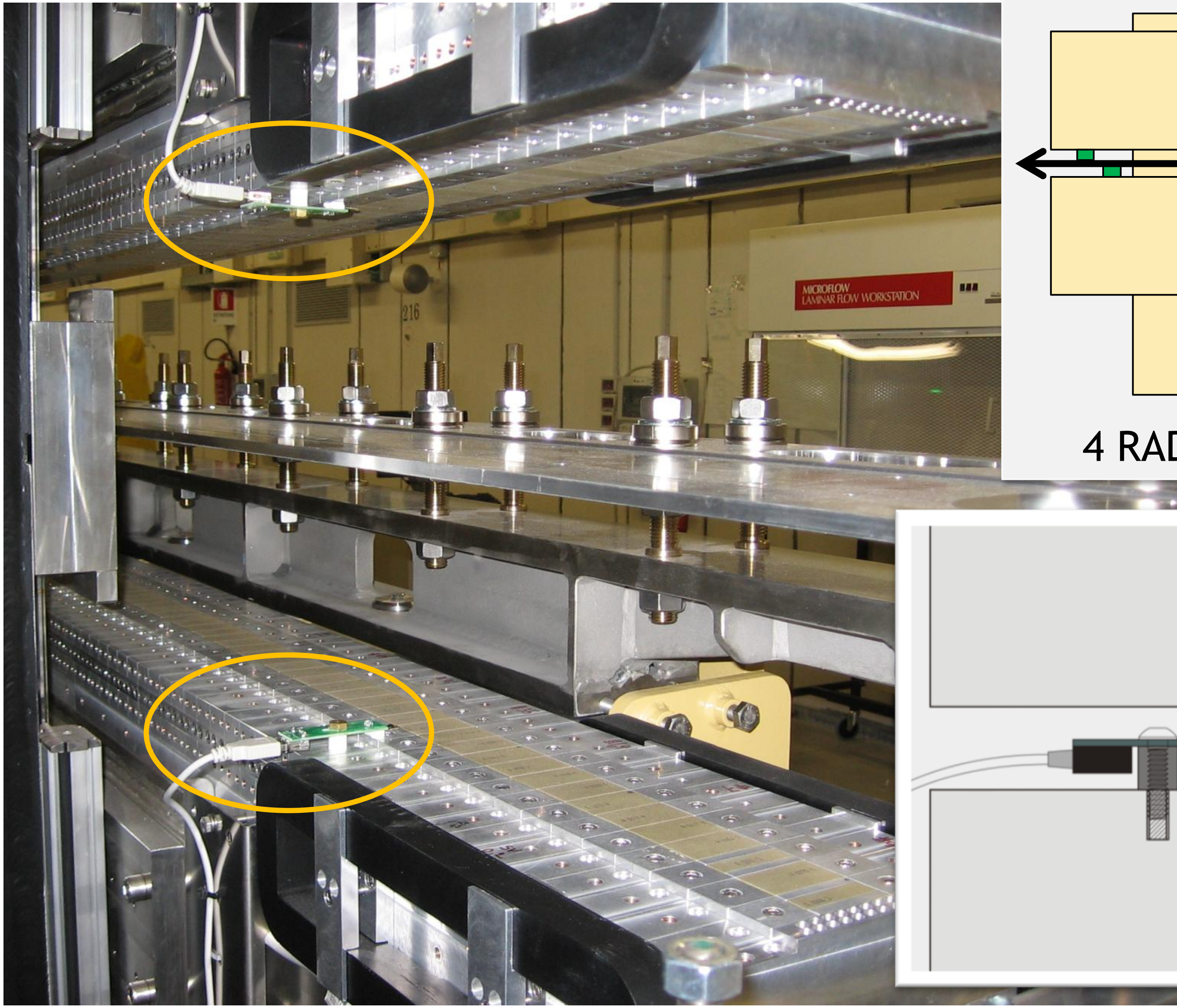


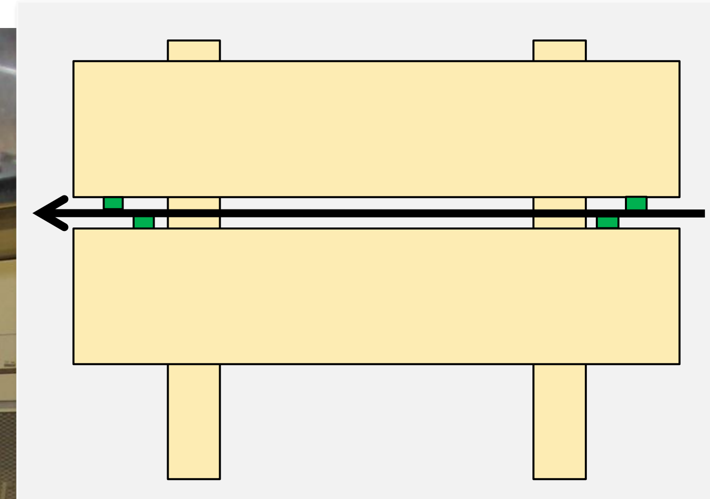


Photo: M. Peloi

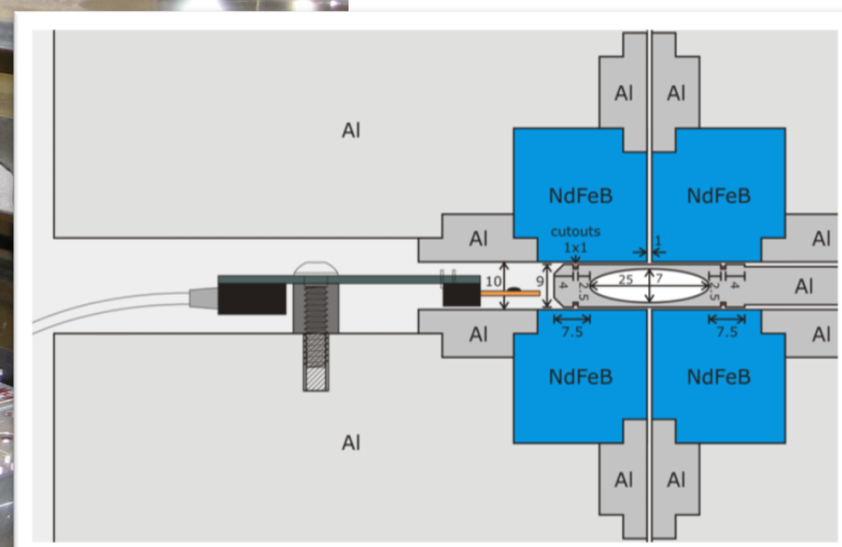
DOSFET-L01

# Installation Overview

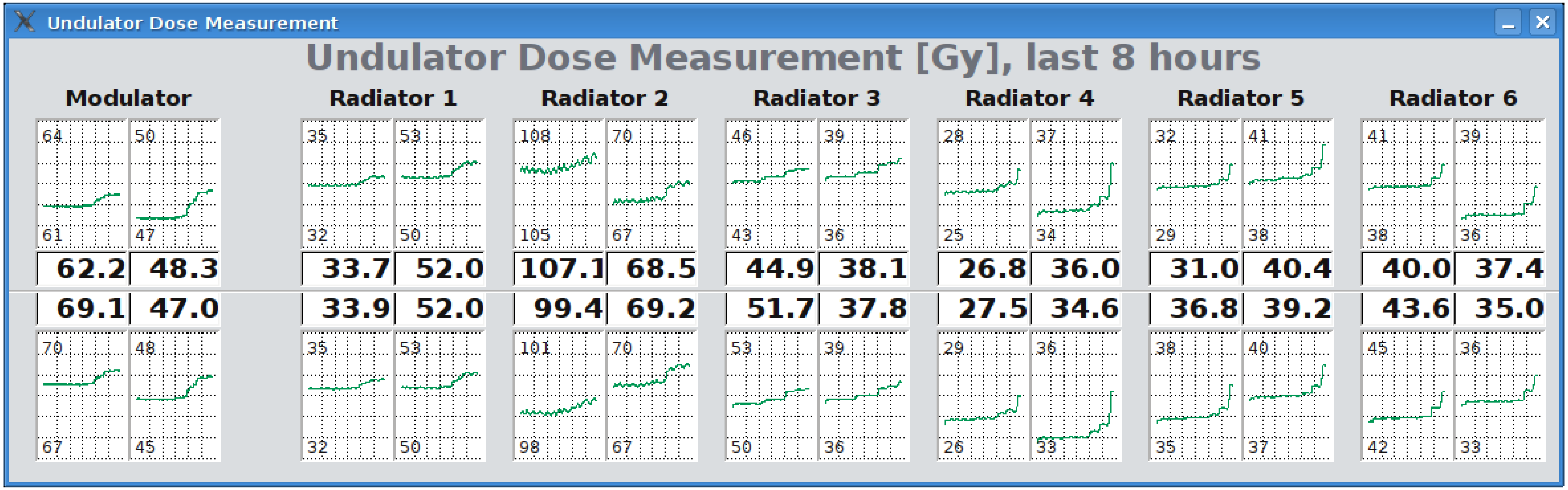


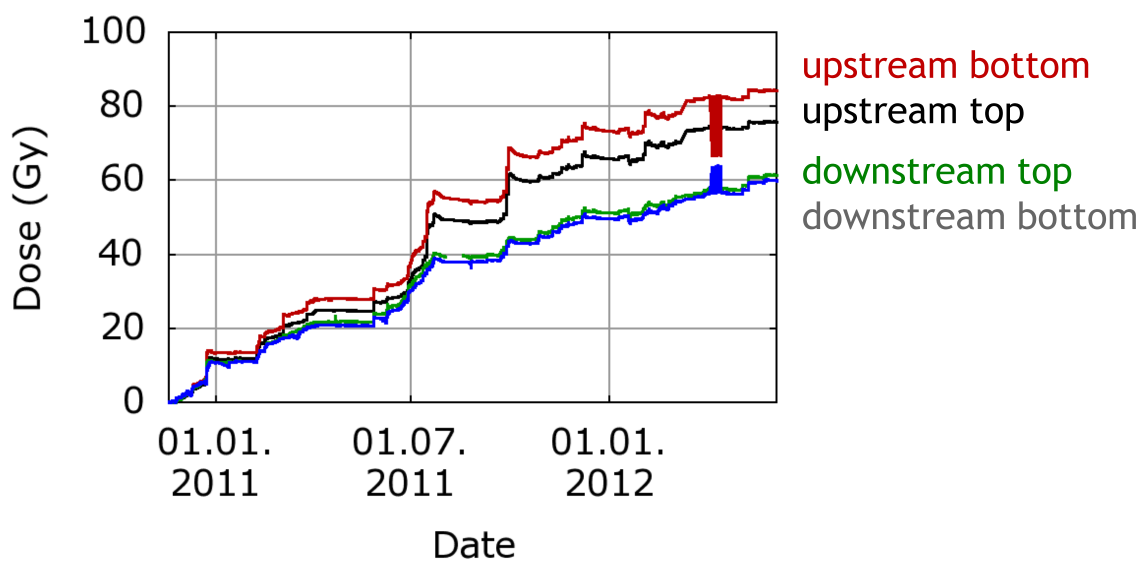
4 RADFETs per undulator



# Dose Histories




First undulator of FEL-1:



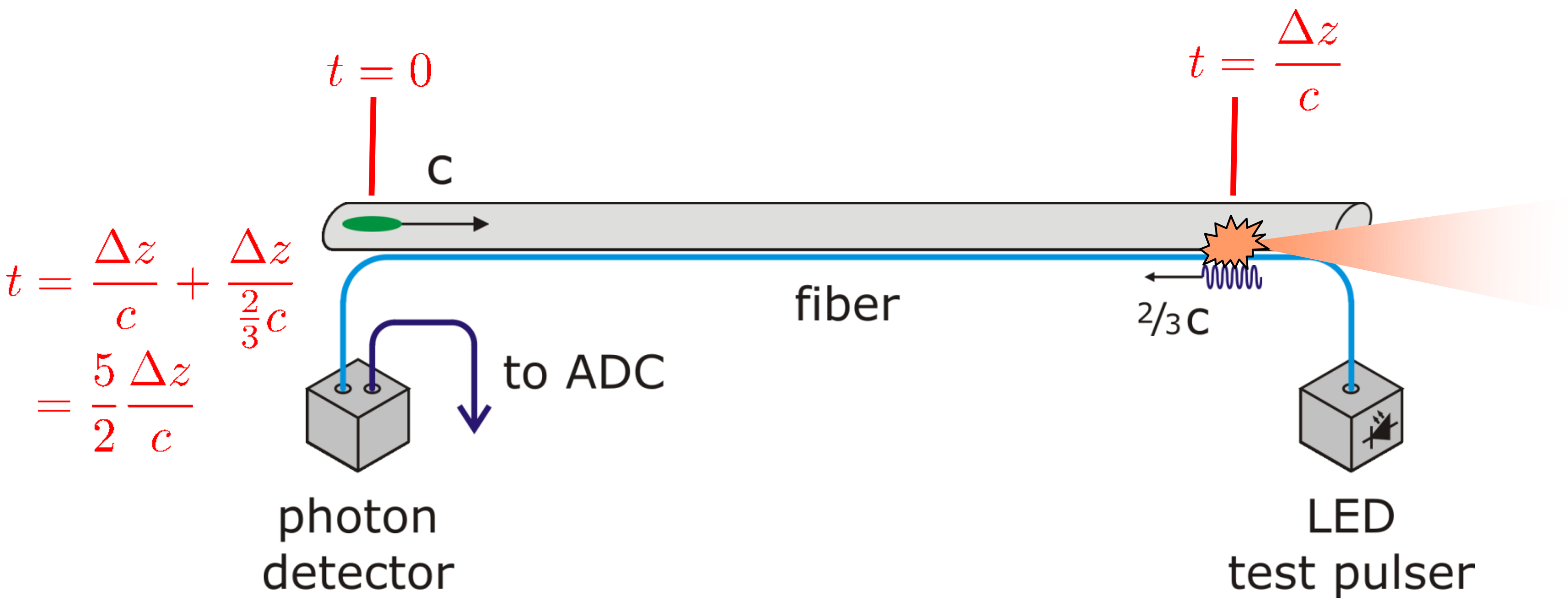
# Beam Loss Position Monitor

"Cherenkov Fiber"

D. Di Giovenale, L. Catani, L. Fröhlich, "A read-out system for online monitoring of intensity and position of beam losses in electron linacs", Nucl. Instr. & Meth. A, 665 (2011), 33–39.

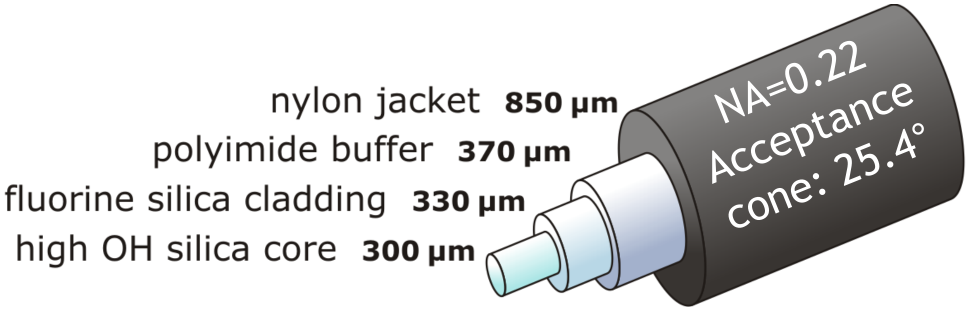
# Beam Loss Position Monitor (BLPM)

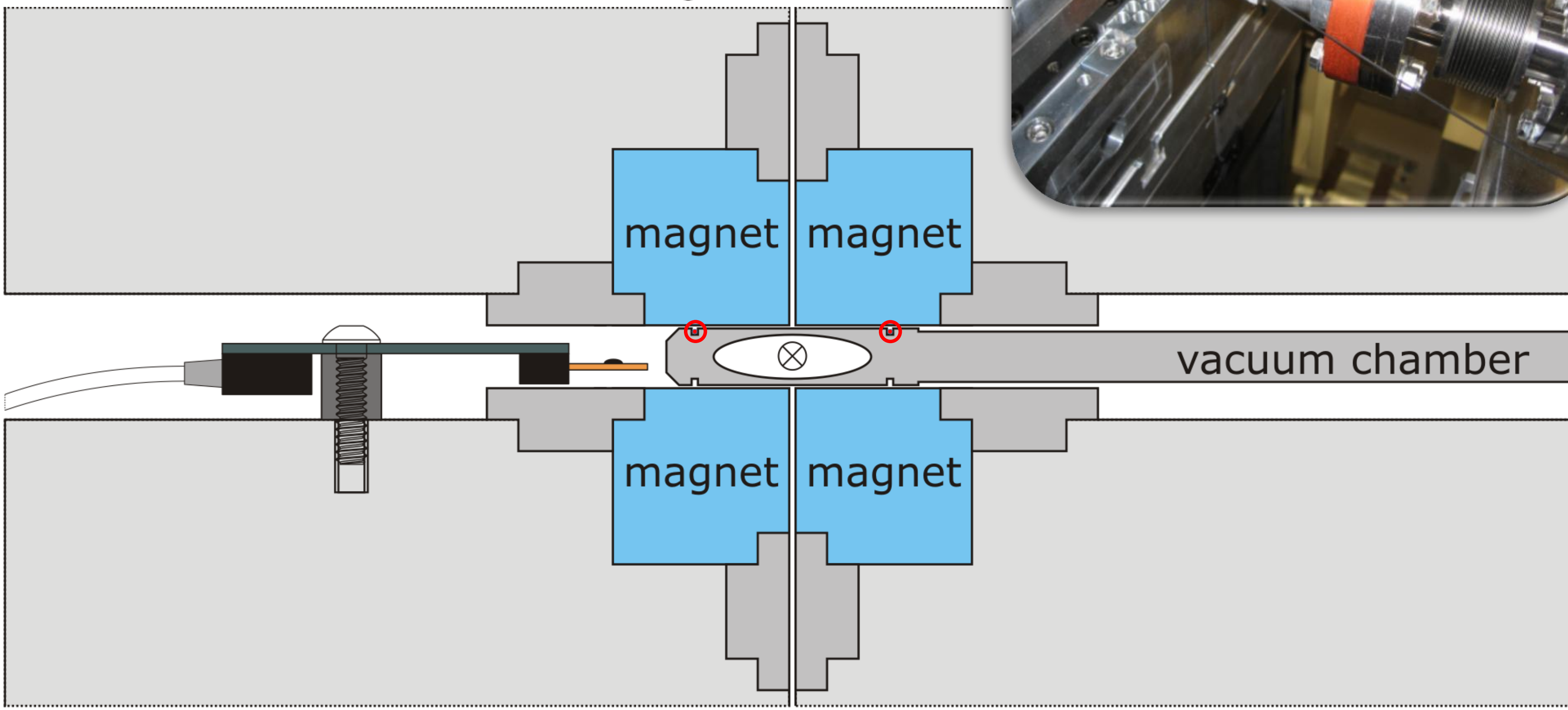
"Cherenkov Fiber"

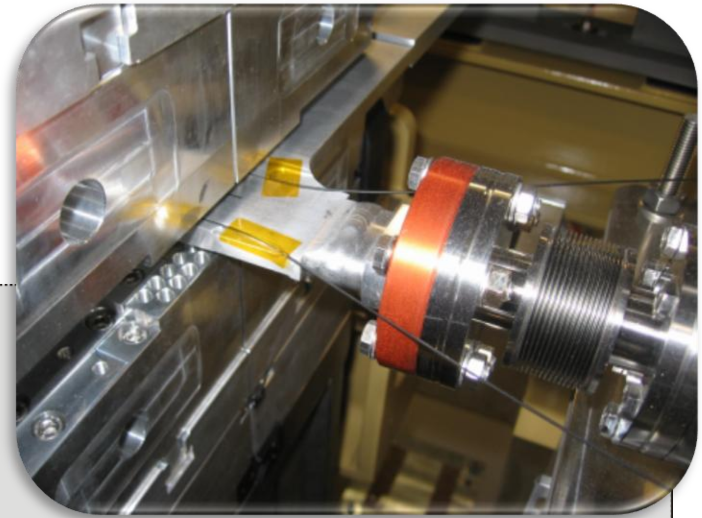



250 MS/s ADC → longitudinal resolution ~50 cm

# Undulator Cross Section

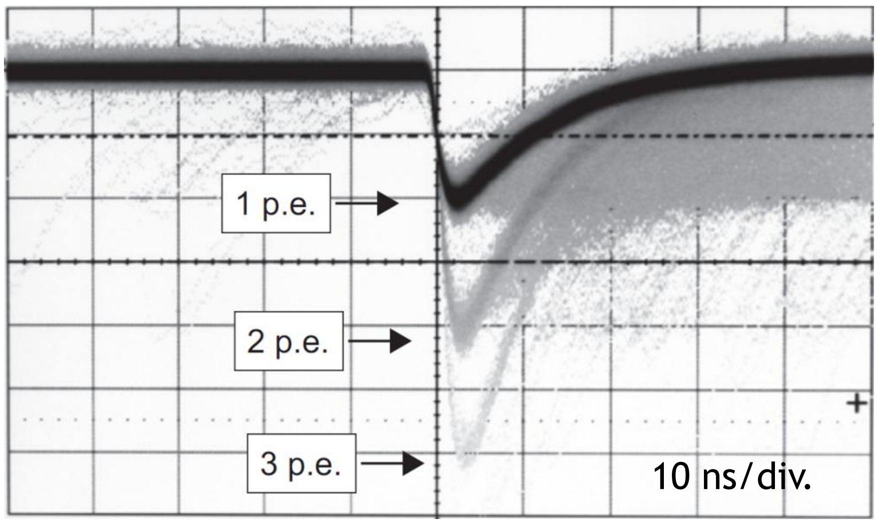


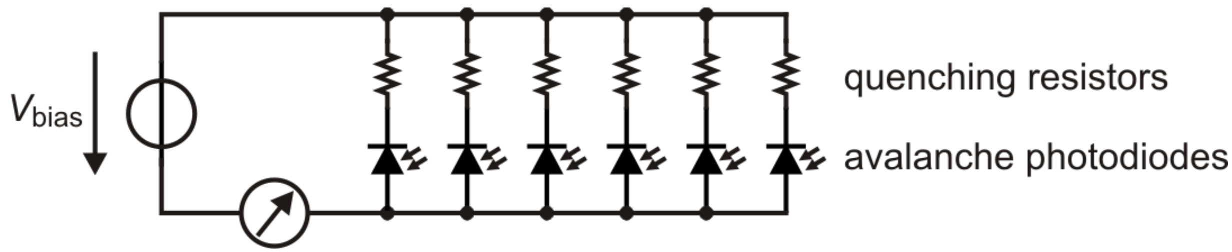



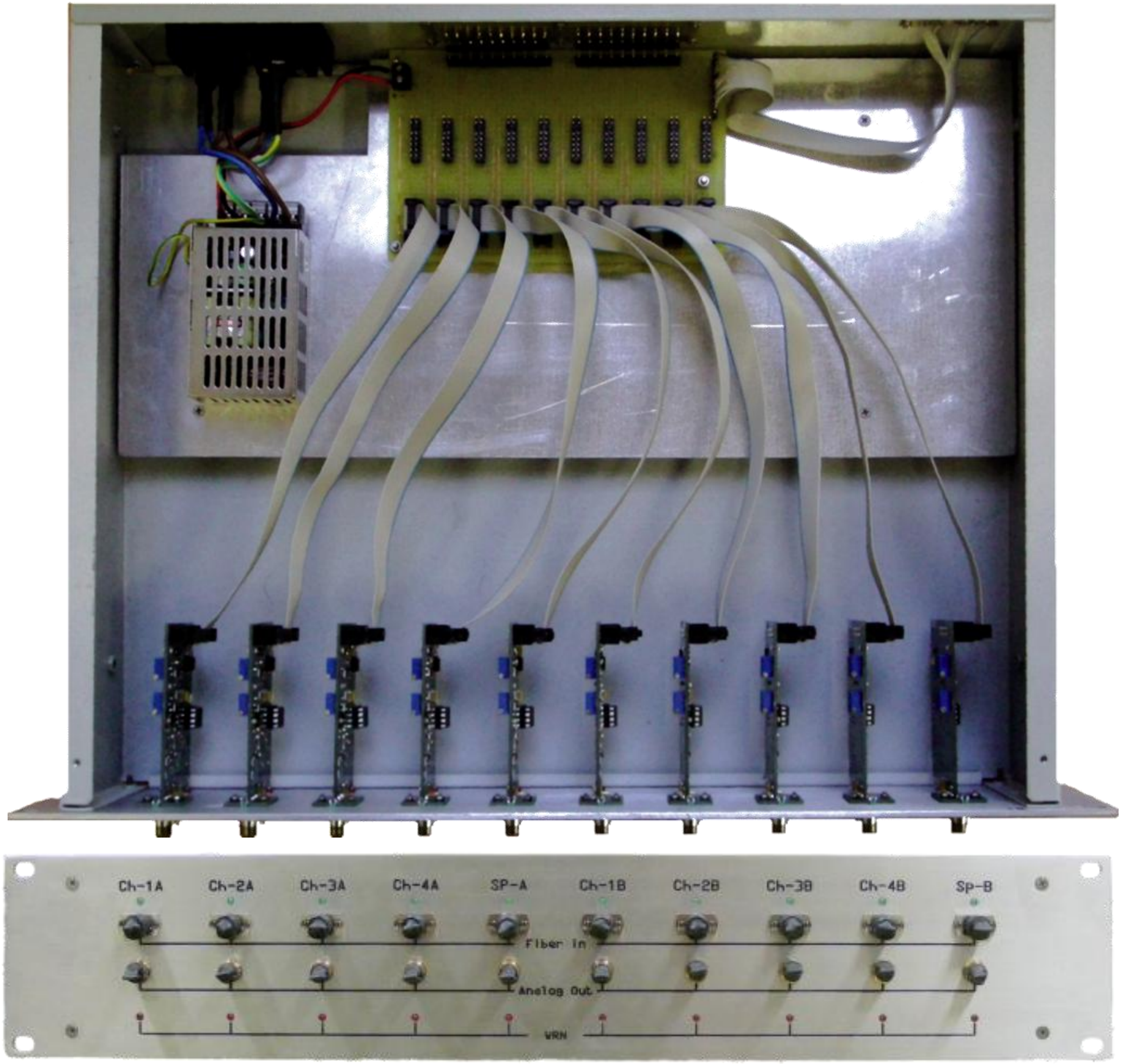
# Multi-pixel Photon Counters (MPPCs)

- Array of avalanche photodiodes (APDs) connected in parallel
- Reverse bias → photon causes APD breakdown
- Photomultiplier-like gain
- Dynamic range limited by number of APDs
- Rise time: some 100 ps
- Hamamatsu S10362-11-050U:
  400 APDs at ~70 V reverse bias

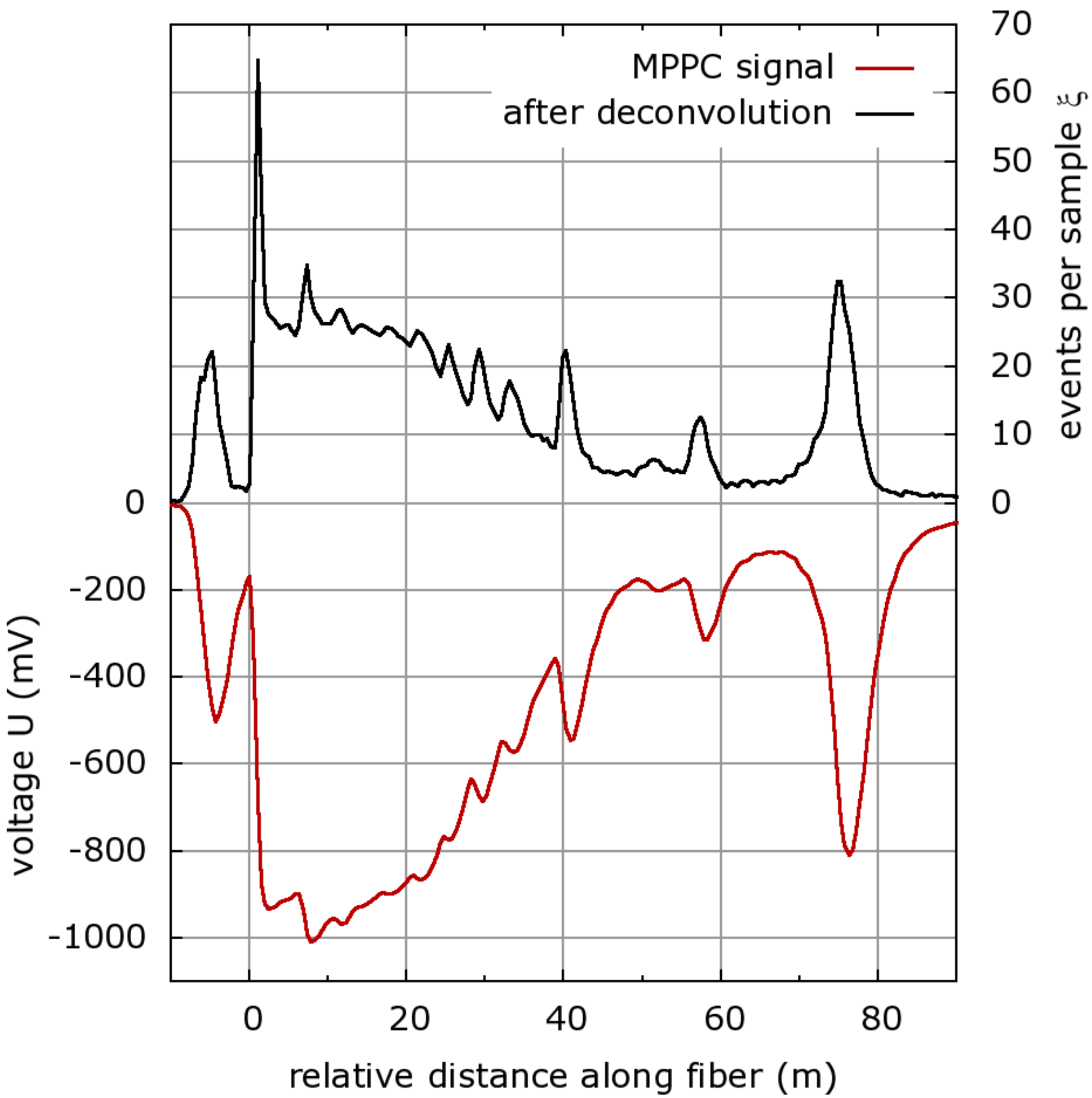


# Modular Frontend Electronics



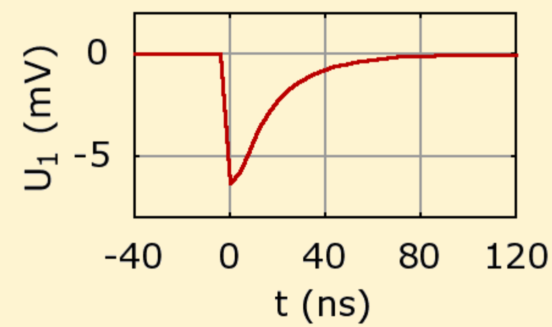
# Signal Processing




number of photodiode breakdowns

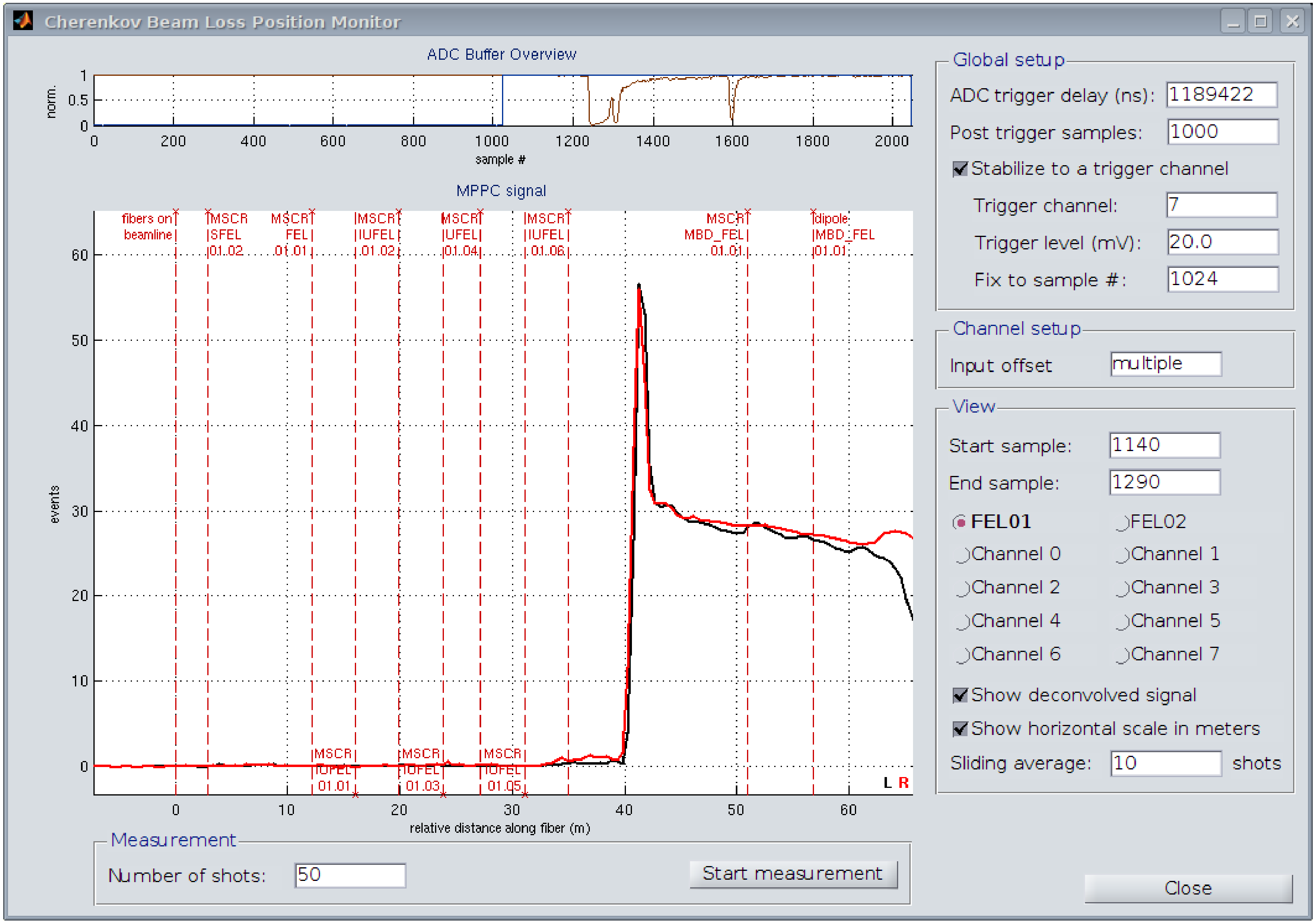
deconvolution

$$\xi(t) = \mathcal{F}_{\nu}^{-1}\left[\frac{\mathcal{F}_t[U(t)]}{\mathcal{F}_t[U_1(t)]}\right]$$




MPPC output signal

# Viewer Application



# Thanks for your interest.