Machine Protection for FLASH and the European XFEL

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Universität Hamburg

HELMHOLTZ ASSOCIATION

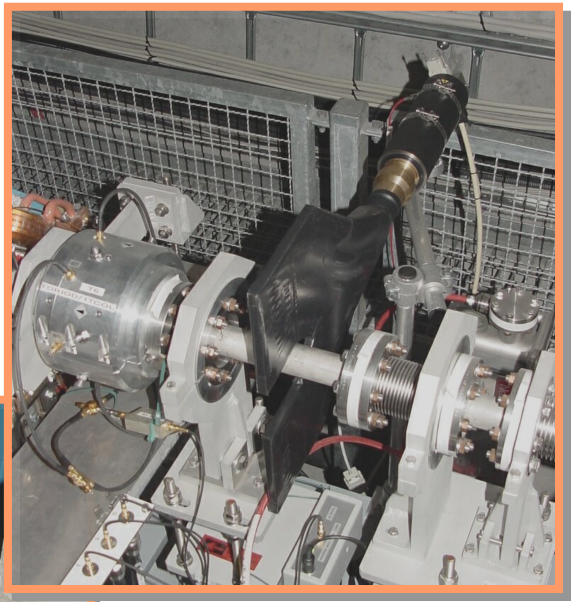
DESY

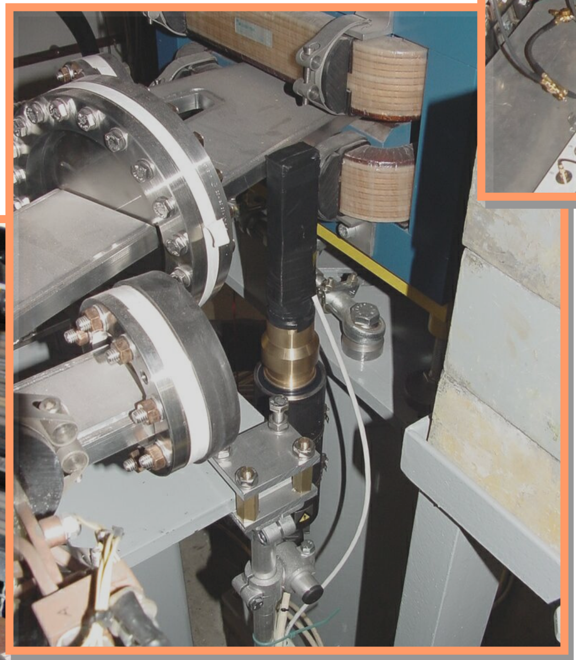
FLASH

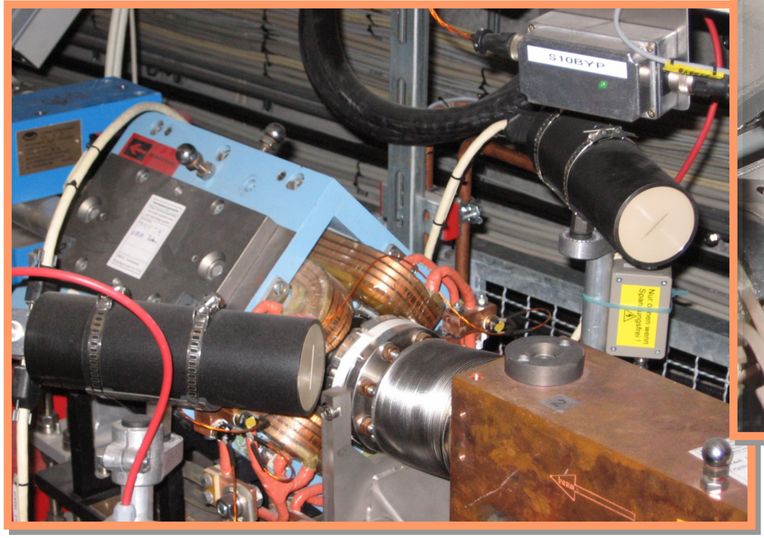
Overview

Machine Protection for FLASH and the European XFEL

- Introduction
- Dark current transport at FLASH
- Undulator Damage
- Machine protection system for FLASH
- Machine protection system for the European XFEL







What is Machine Protection?

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

What is it not?

- Personnel or radiological protection—protecting people from harm.
- Technical interlock—protecting devices from damage by arbitrary malfunctions.

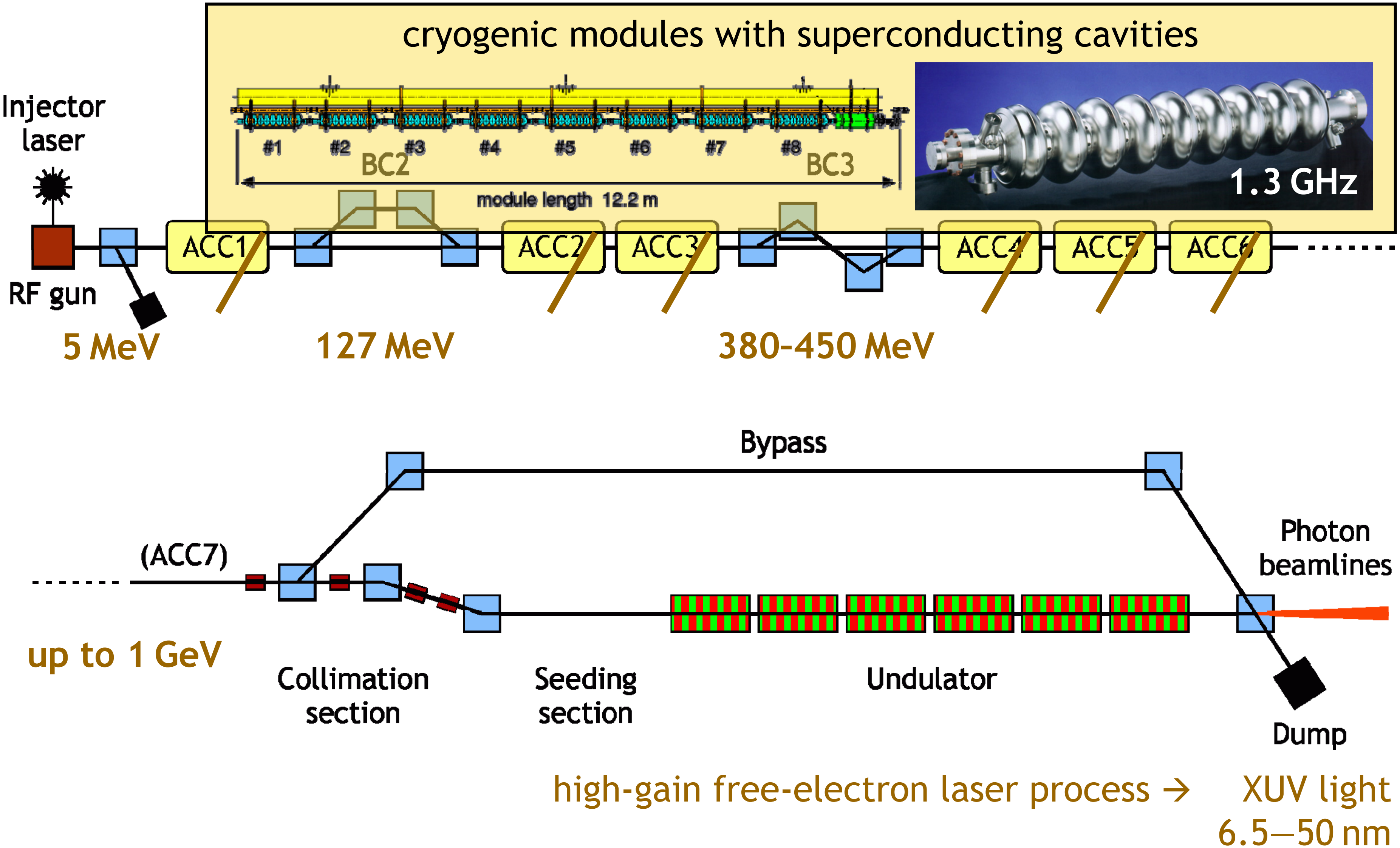
Why do we need it?

- High stored energy in circular accelerators:
  Tevatron 1.3 MJ, HERA 2 MJ, LHC 362 MJ
- High average power in linear accelerators:
  FLASH 90 kW, European XFEL 600 kW,
  SNS 1.4 MW, JLab FEL 1.5 MW, ILC 11 MW

Energy stored in LHC beams can melt 1 ton of copper.

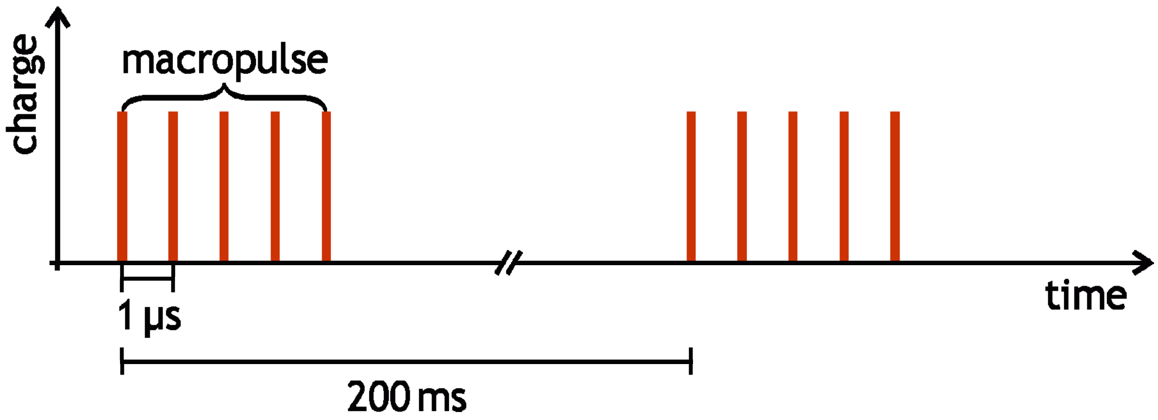
Power used for electron beam welding: 5-100 kW

FLASH — Free-Electron Laser in Hamburg



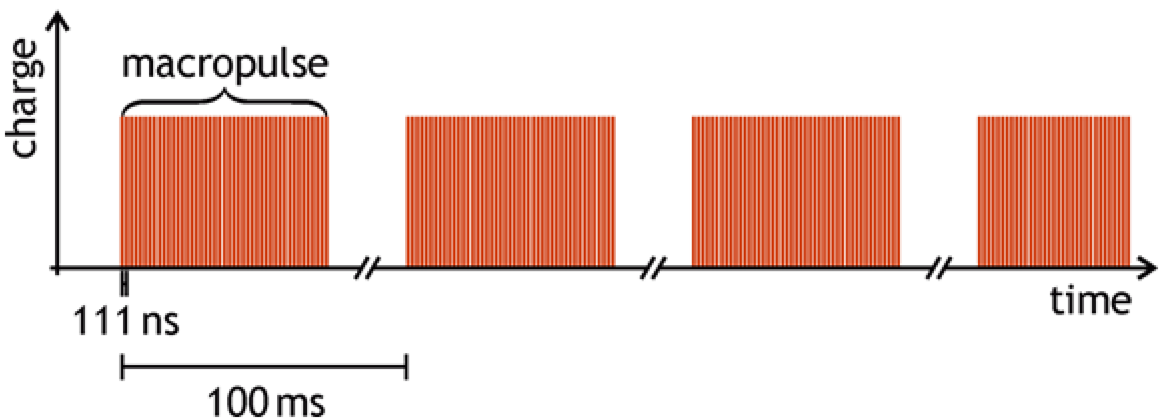
Time Structure of the FLASH Electron Beam

bunch charge: ~1 nC
macropulse length: ≤ 800 μs



Current parameters

repetition rate: 5 Hz
bunch frequency: ≤ 1 MHz
→bunches per pulse: ≤ 800
→average power: ≤ 5 kW



Design parameters

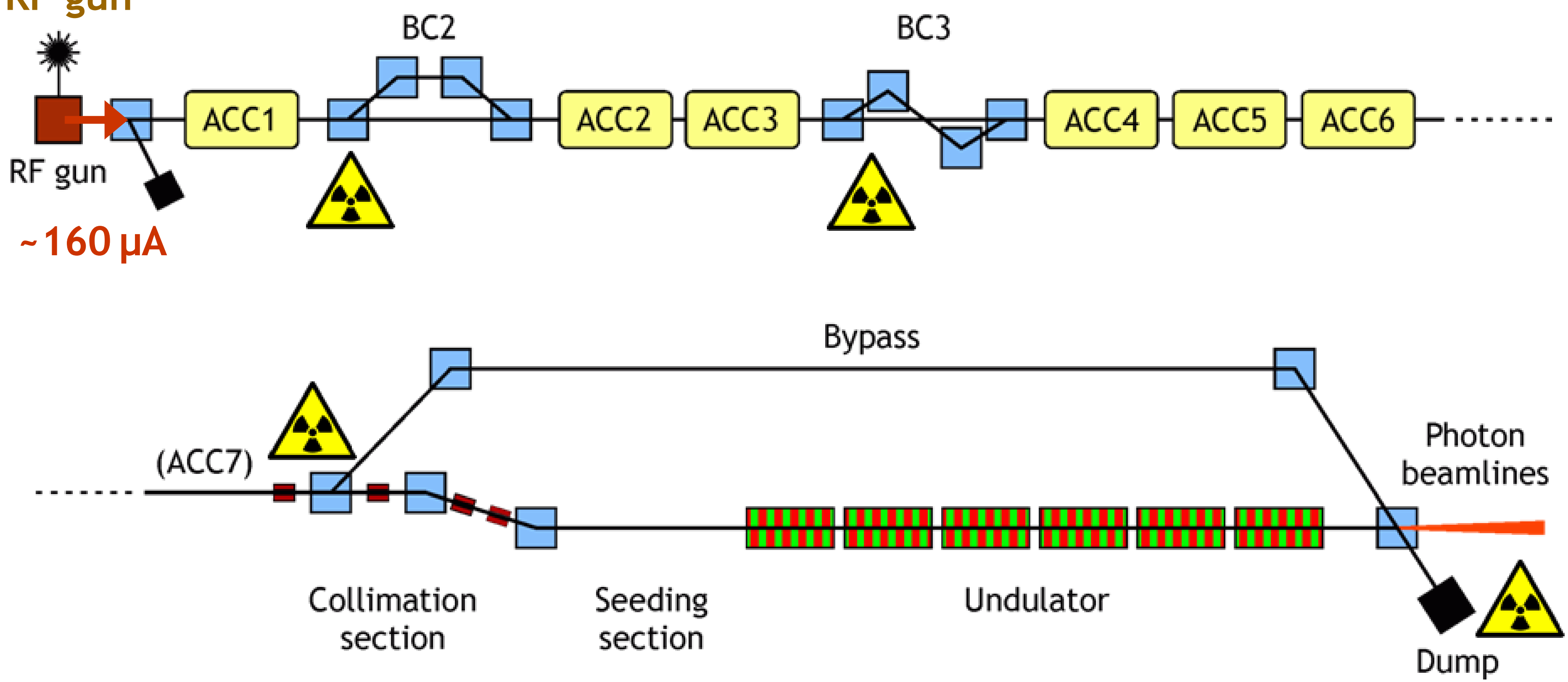
repetition rate: 10 Hz
bunch frequency: 9 MHz
→bunches per pulse: ≤ 7200
→average power: ≤ 90 kW

Dark Current Transport at FLASH

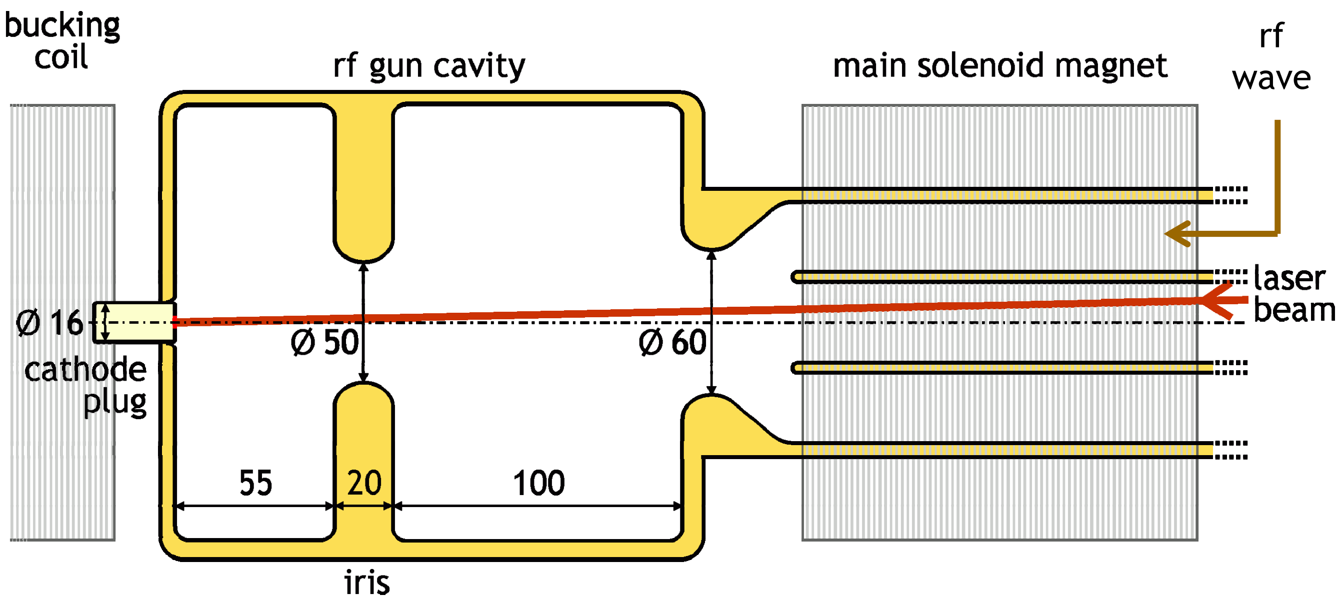
Radioactivation by Dark Current

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

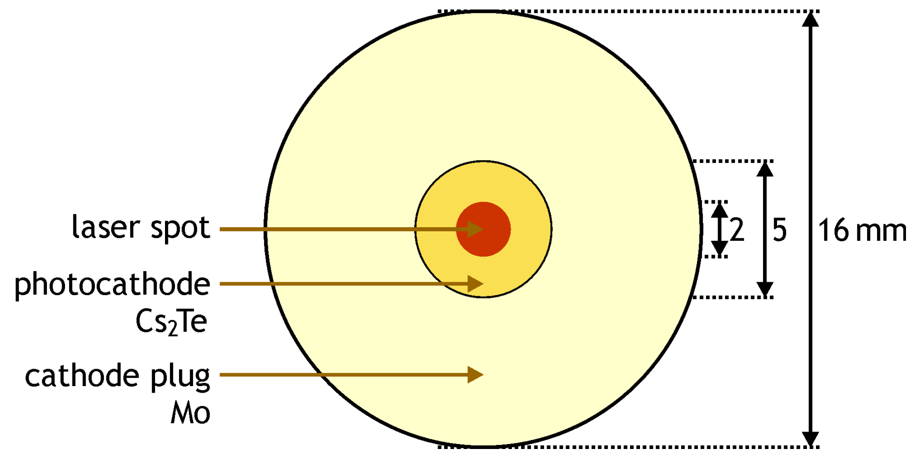
main source at FLASH: RF gun



The FLASH RF Gun



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

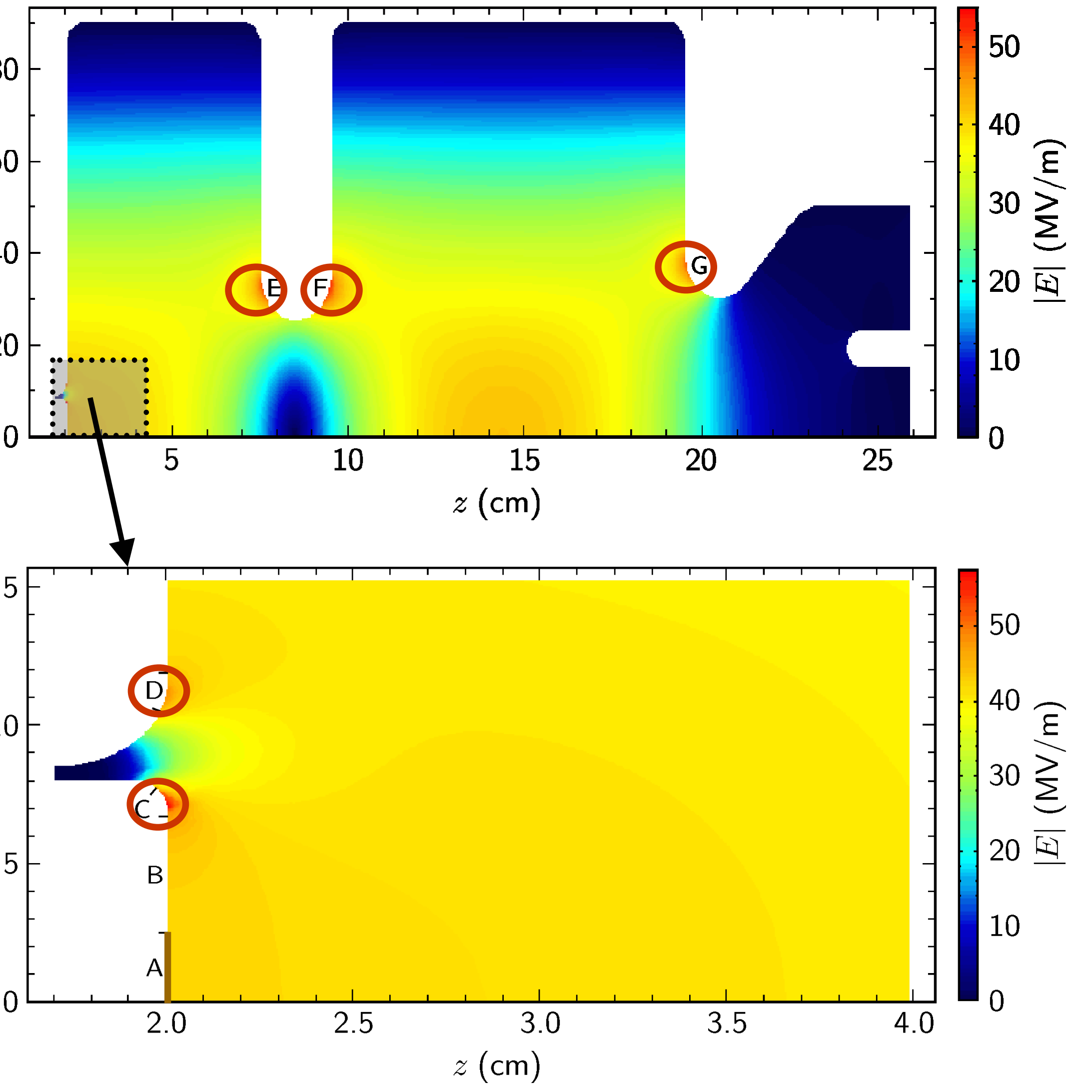


Field Emitters in the RF Gun Cavity

field map courtesy of Jacek Sekutowicz

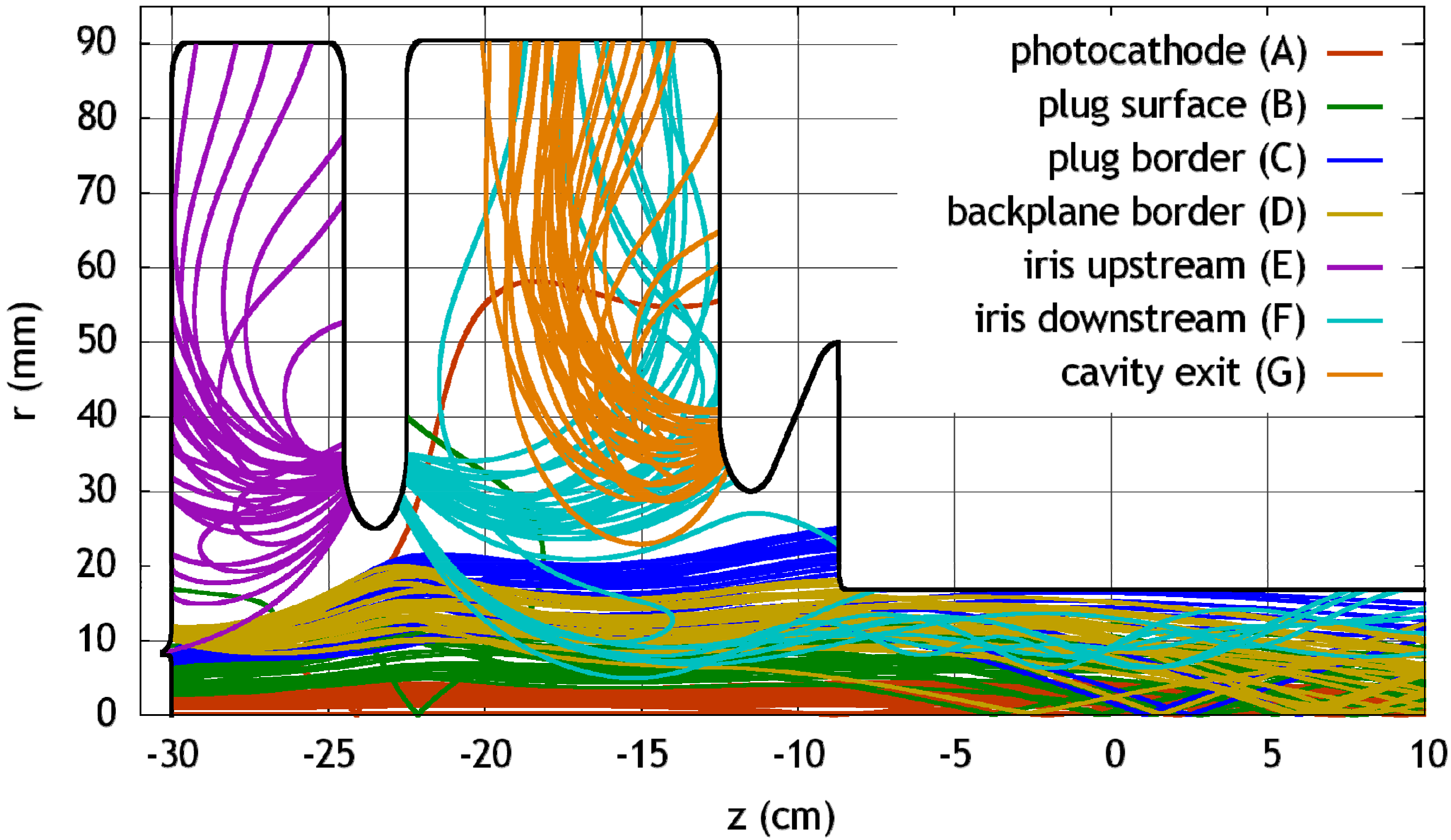
higher field amplitudes: **44—54 MV/m**

field amplitude on photocathode: **42 MV/m**

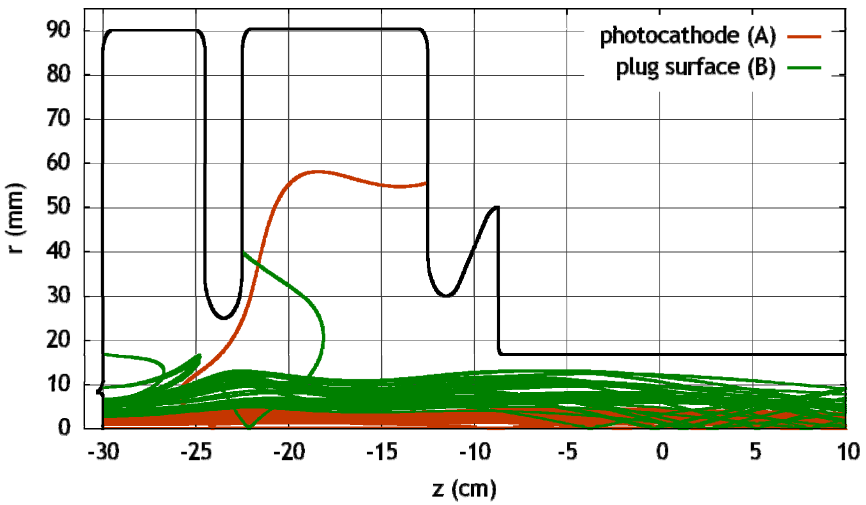


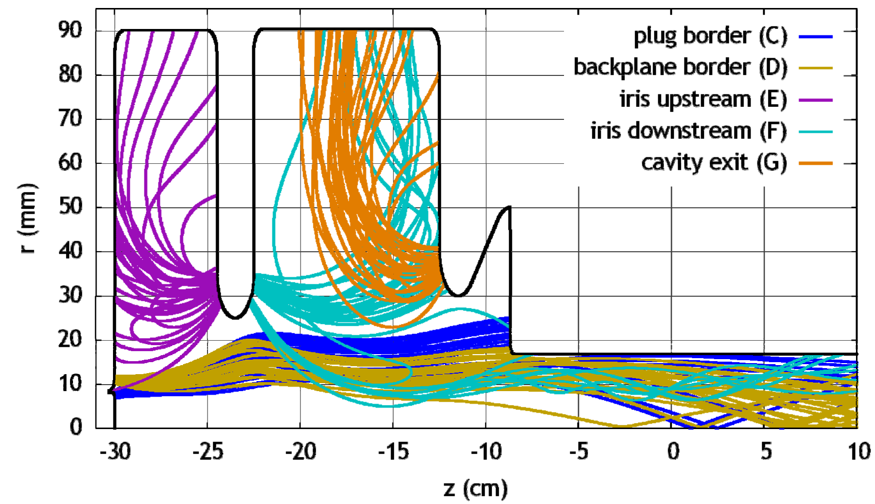
Dark Current Transport in the RF Gun Cavity

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



Transmission to ACC1

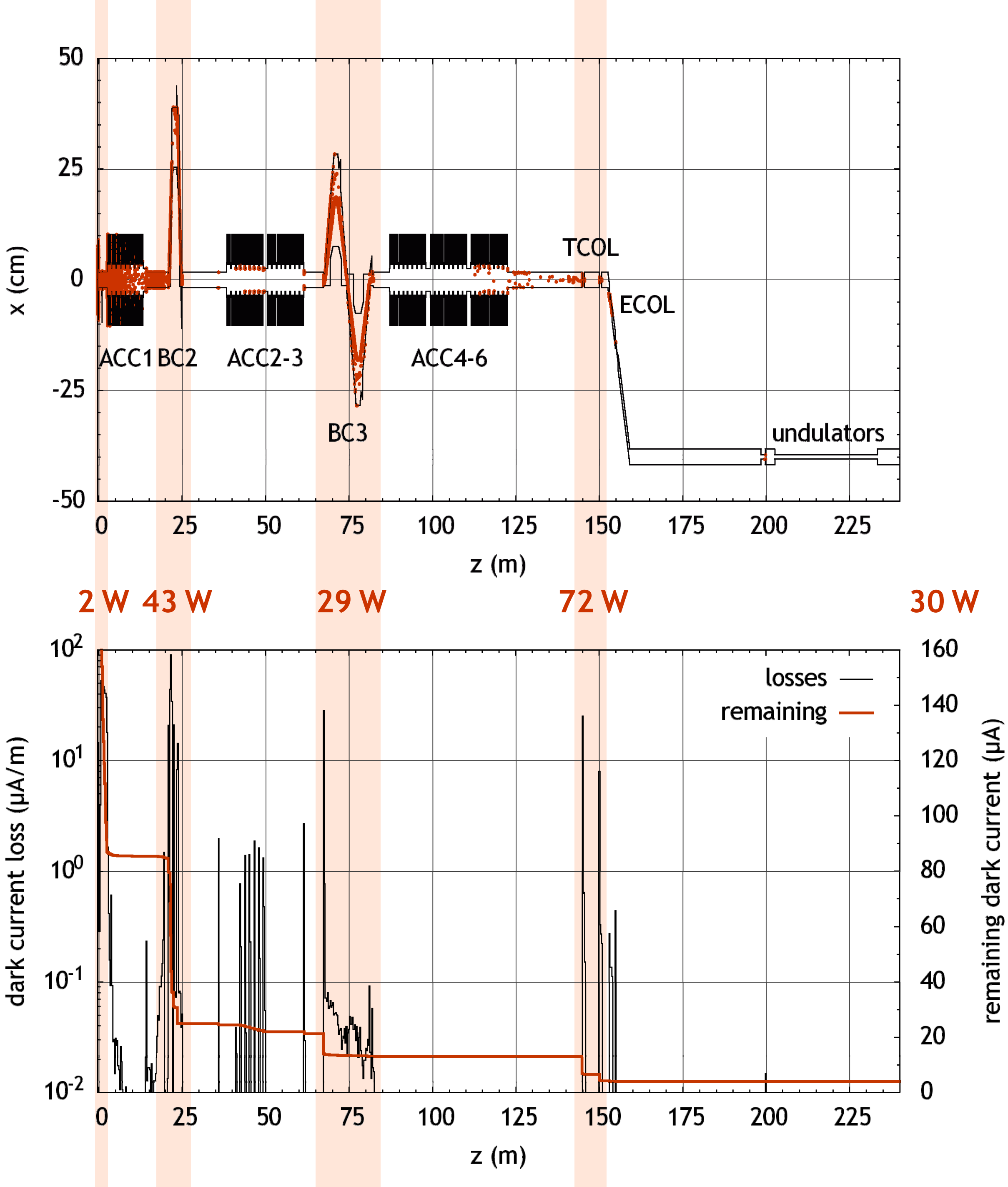




Percentage of particles transported to ACC1 (2.6 m from cathode)

	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

Overview



Location of major dark current losses:

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

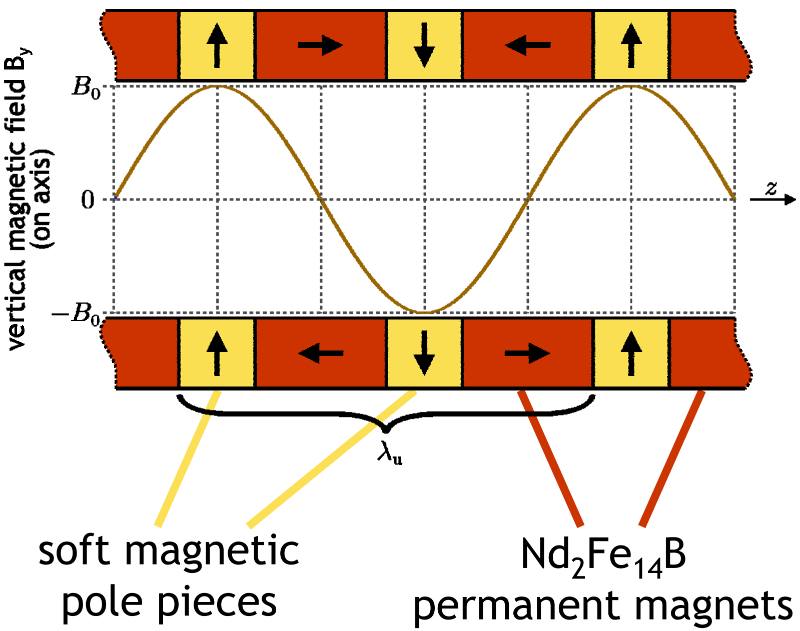
dark current power deposition (10 Hz, 800 µs pulse length)

Simulation parameters:

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

Undulator Damage

Radiation Damage to Undulator Magnets

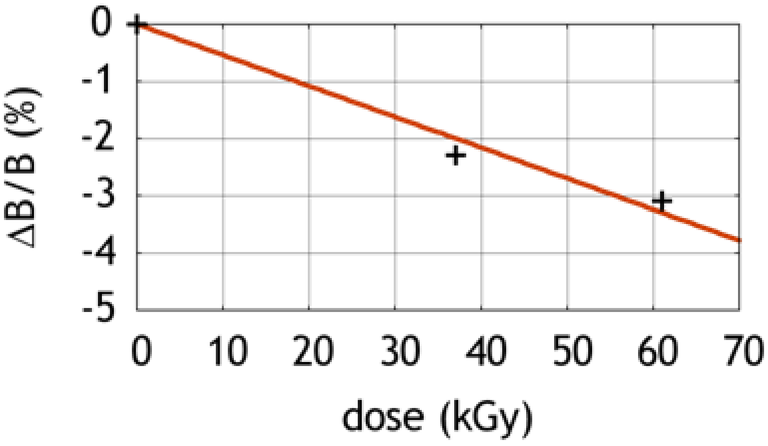


- $Nd_2Fe_{14}B$ magnets lose magnetization when irradiated
- literature: relative demagnetization rate 10^{-8}/Gy (gammas) — 10^{-4}/Gy (fast neutrons)

Measurements at FLASH

- Relative demagnetization: **$5 \cdot 10^{-7}$/Gy**

	Dose (kGy)	ΔB/B (%)
2004-08-13	0	0
2006-03-21	37	−2.3
2007-09-29	61	−3.1



Simulations indicate

10% FEL power loss

for

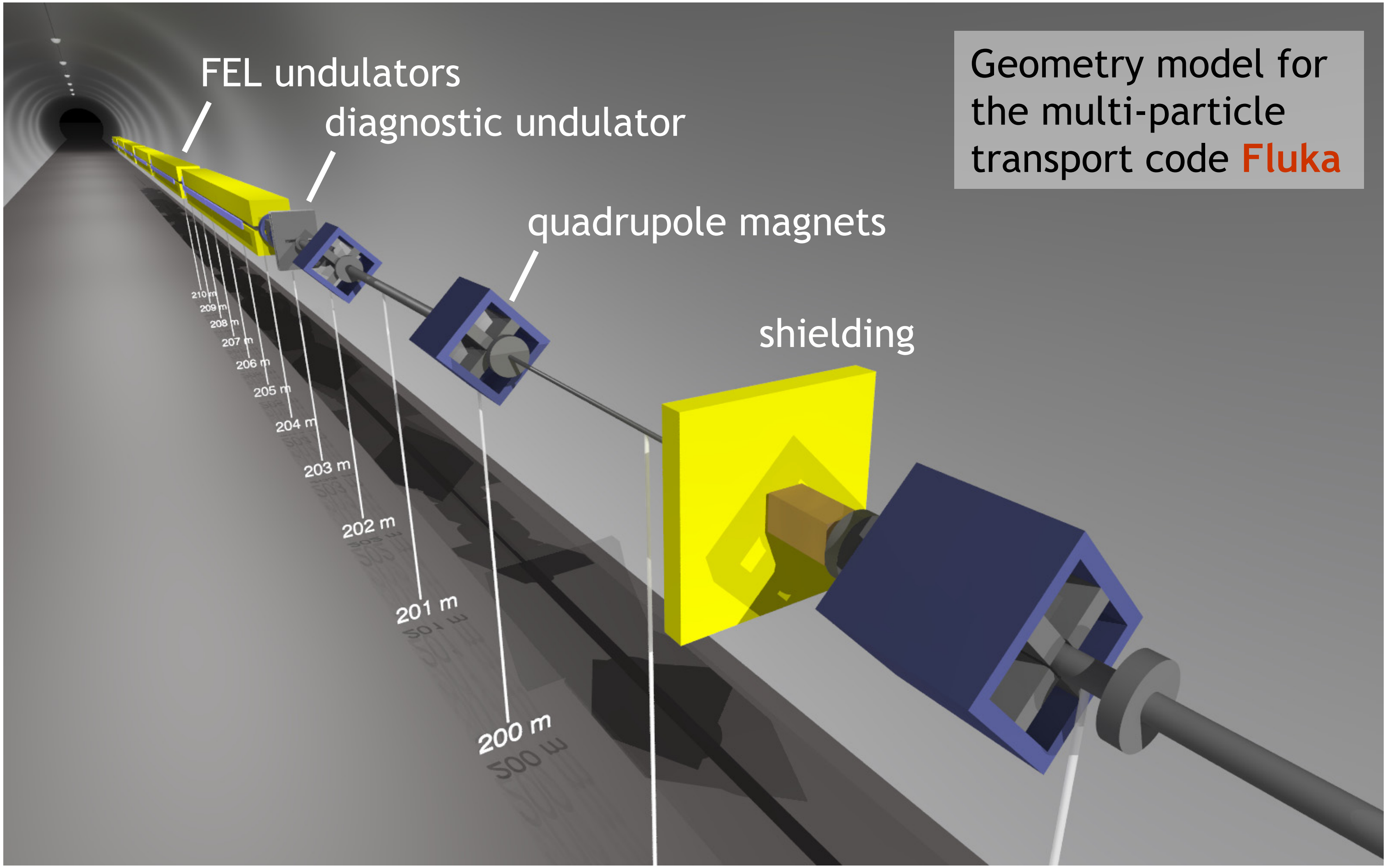
0.5% (periodic) field loss

For 10 years undulator lifetime:

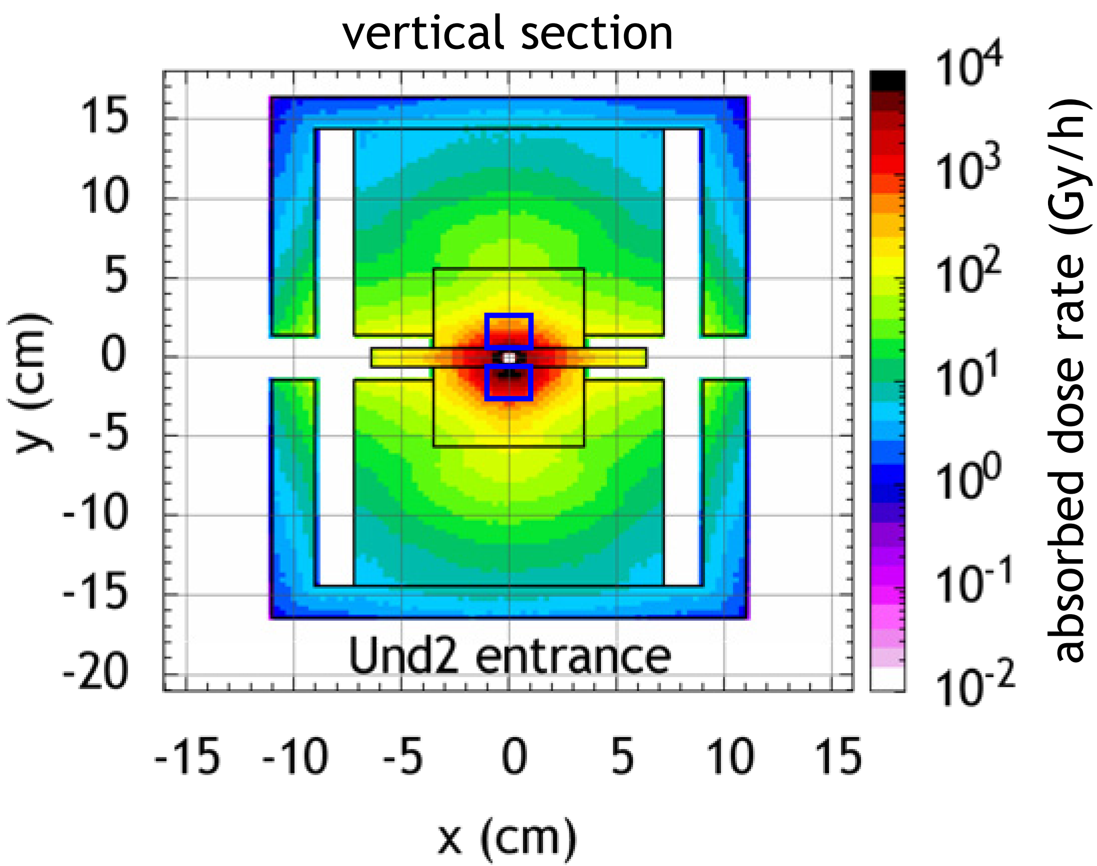
5 Gy/d dose budget

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

Undulator Beamline Model



Beam Loss in the Undulator



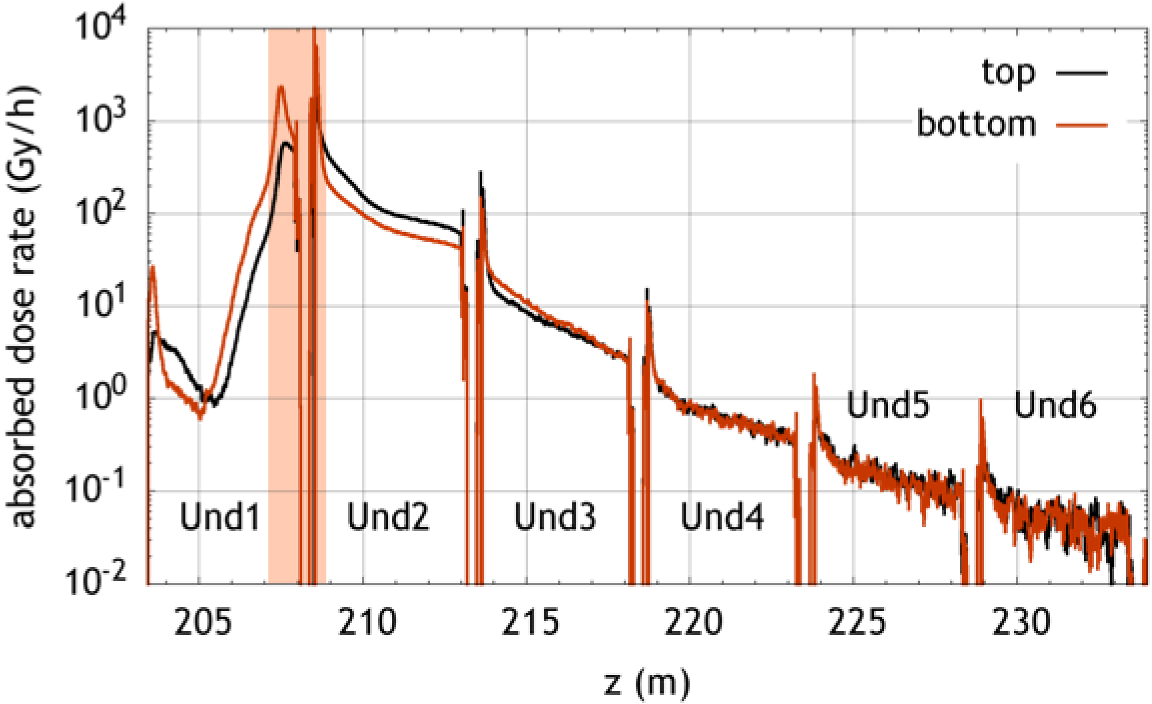
Worst case scenario:

- Loss of a bunch at the exit of undulator 1
- Bunch strikes the bottom of the vacuum chamber

Parameters:

- 1 GeV
- 1 nC/bunch
- 1 bunch/macropulse
- 10 Hz

Beam Loss in the Undulator



- Dose rate around **1 kGy/h** in an extended range (1 bunch, 10 Hz)
- FLASH design parameters: 7200 bunches, 10 Hz → **2 kGy/s**

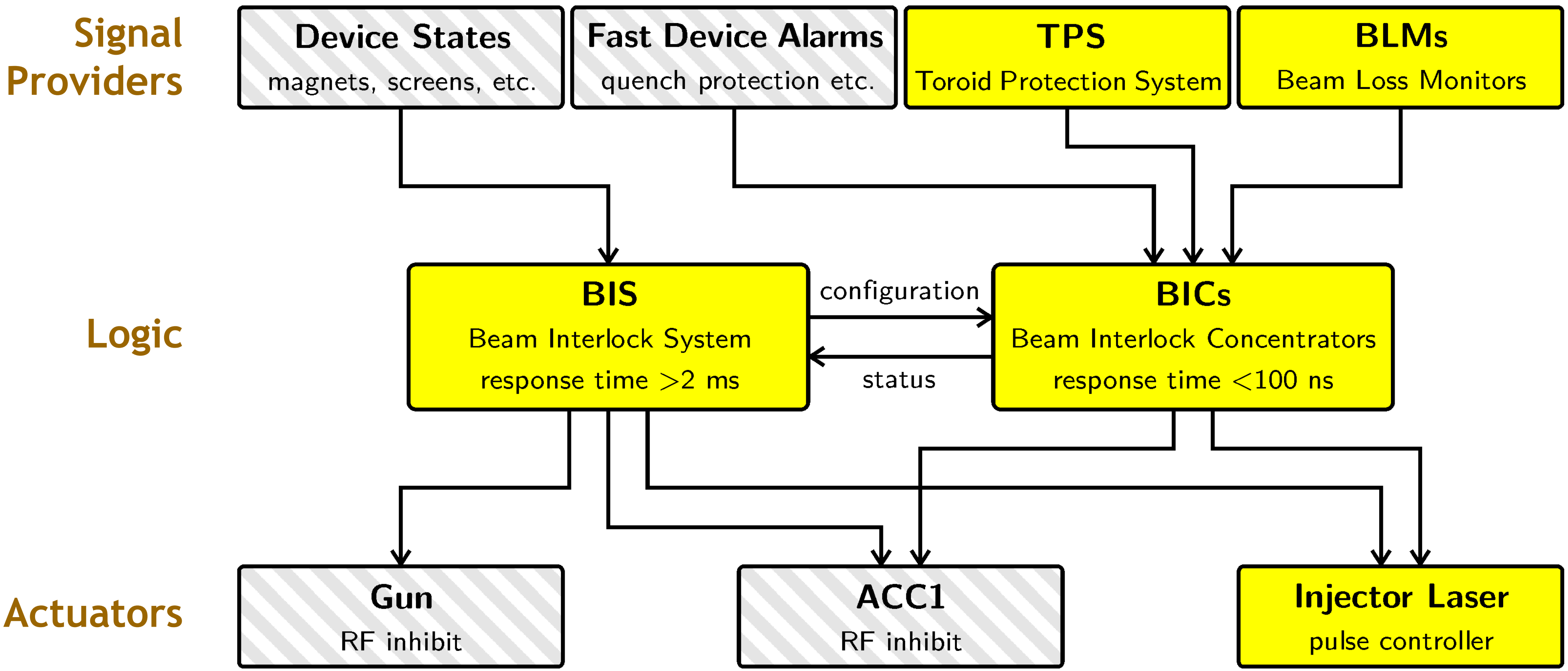
To stay within 5 Gy/d with 7200 bunches, local beam loss has to be limited to

$3 \cdot 10^{-8}$ (relative)

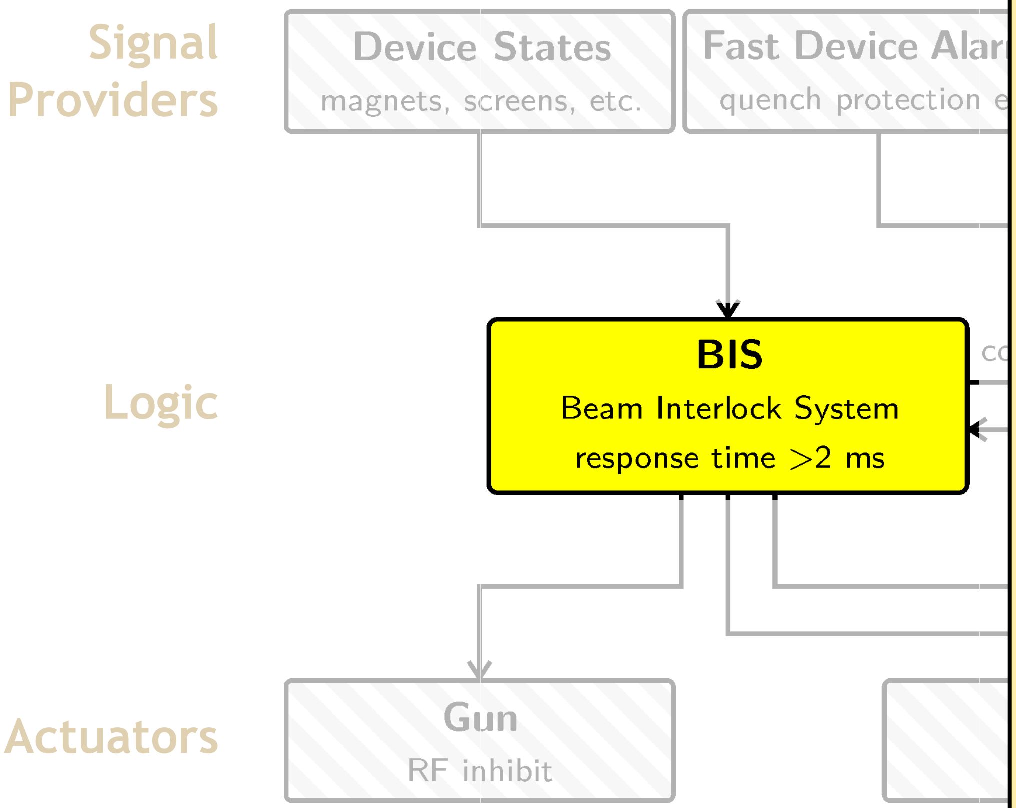
180 electrons per bunch

FLASH Machine Protection System

Machine Protection System Overview



Beam Interlock System (BIS)



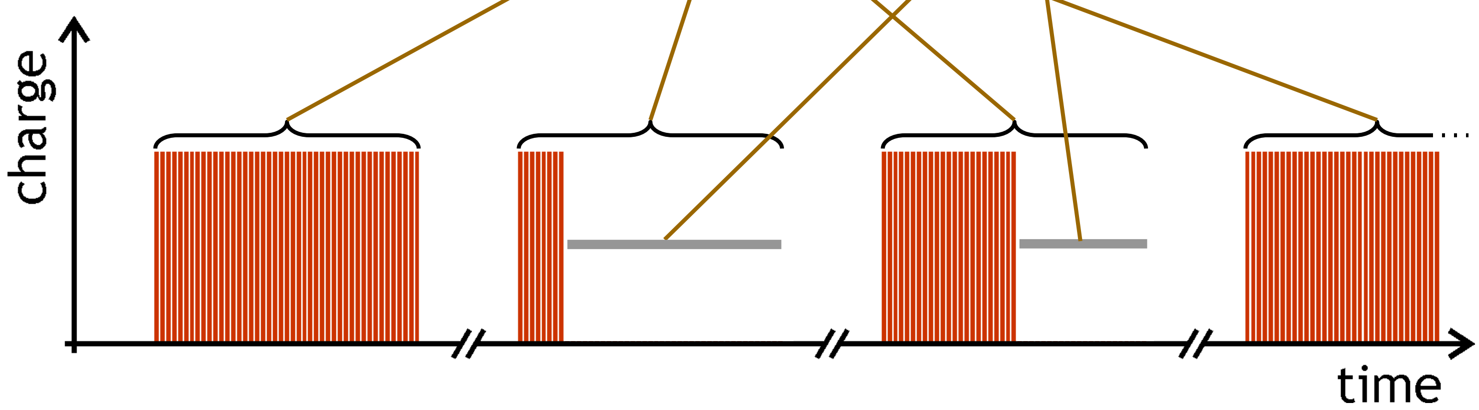
- Programmable logic controller (PLC)
- Monitors ~400 status signals from vital or potentially hazardous devices
- Defines the **beam mode**

Beam Interlock System: Beam Mode

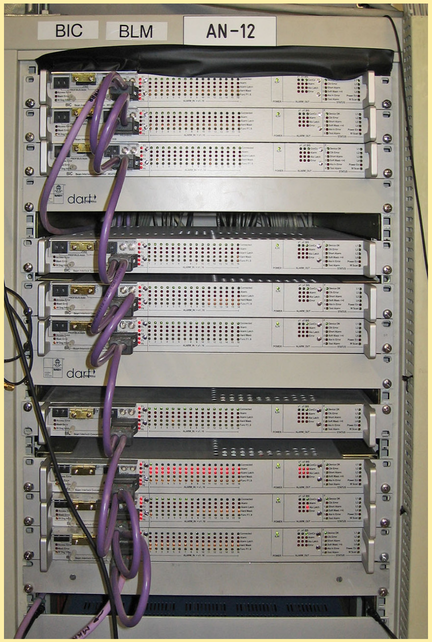
BIS **limits to**

operator **chooses**

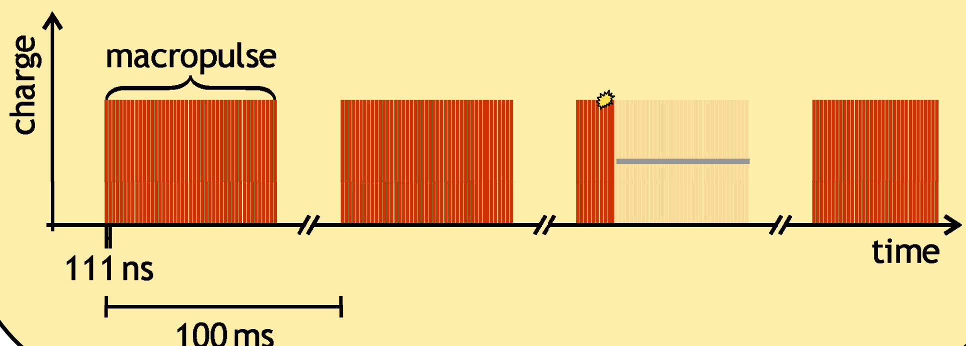
	bunch limit	fast intra-train protection
single	2	✘
short	30	✘
long	∞	✓

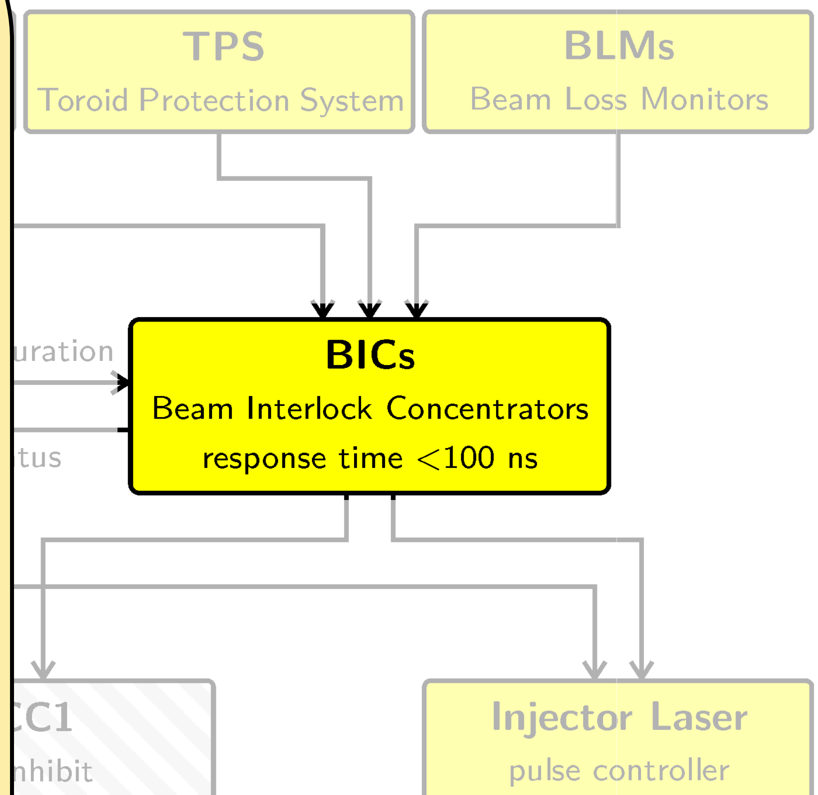


Beam Interlock Concentrators (BICs)

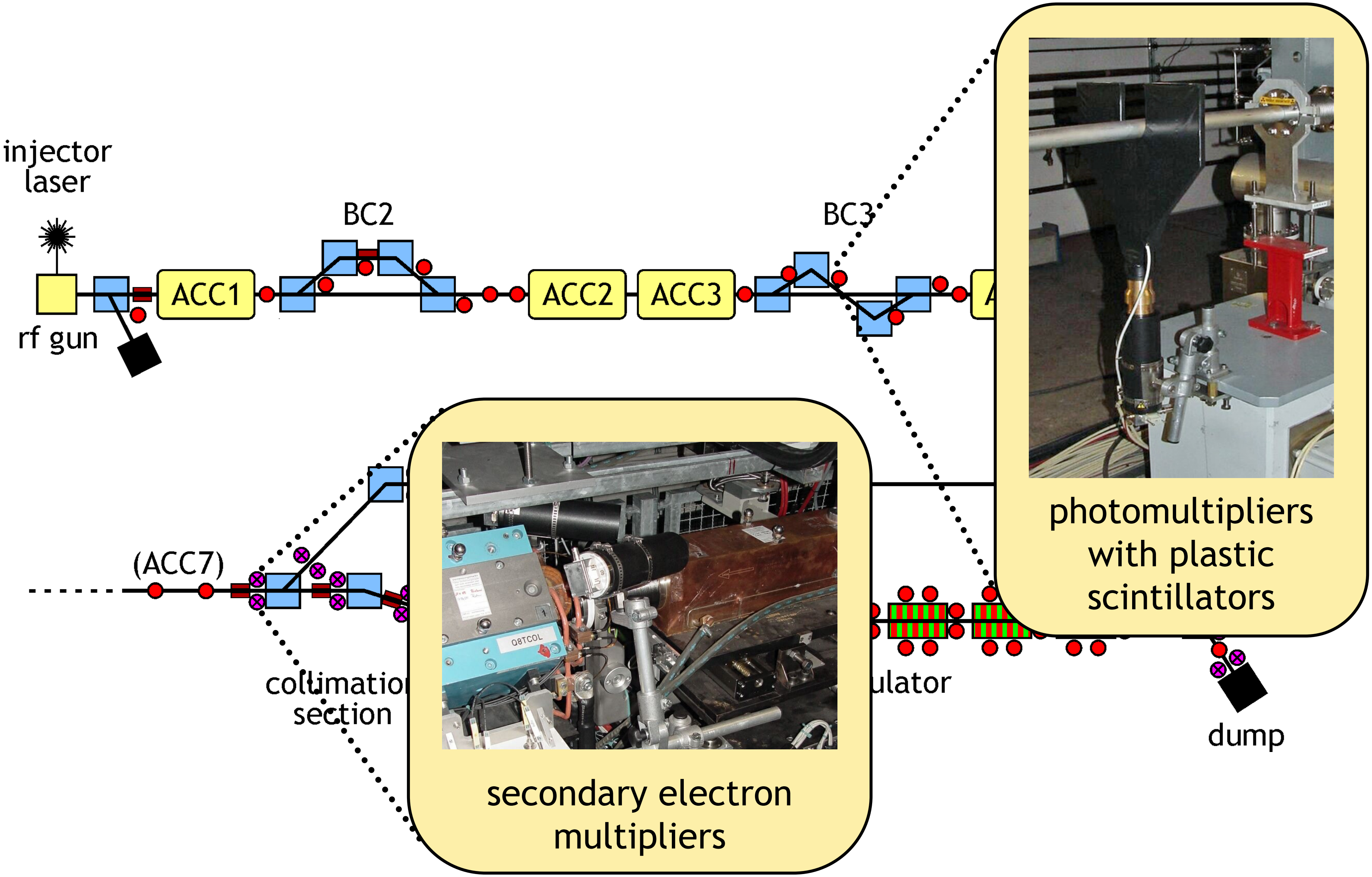


- Custom FPGA-controlled devices
- Function: logical OR for alarm signals
- Interruption of bunch production within the current macropulse



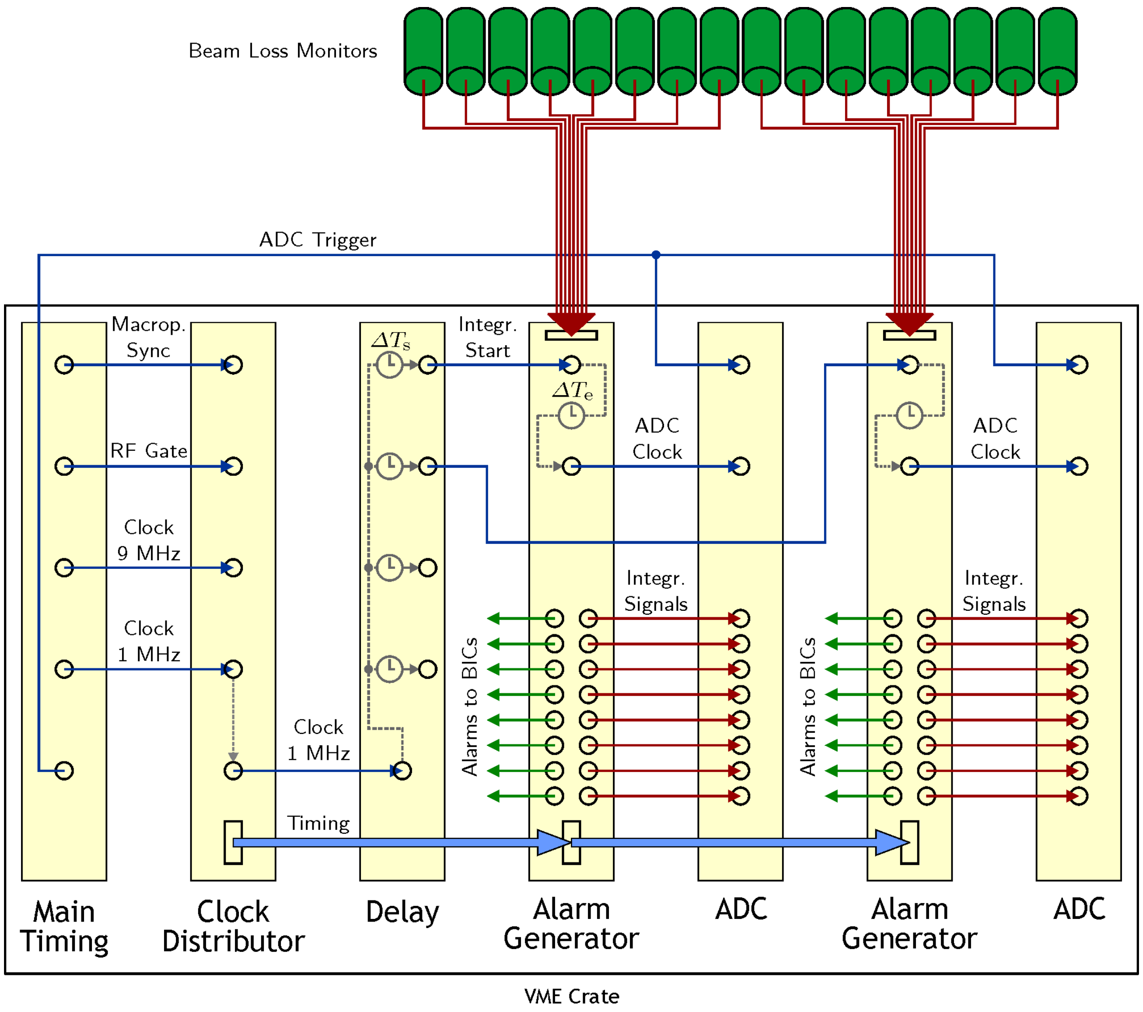


Beam Loss Monitors (BLMs)

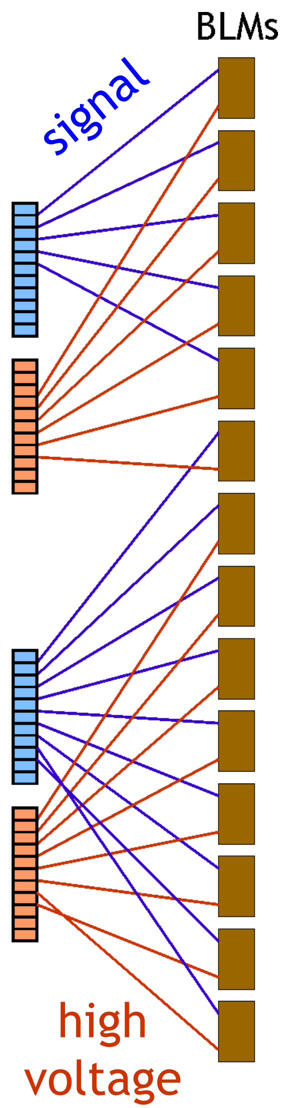


Algorithms for the Setup of the BLM System

- Passive configuration plausibility check
- **Active cable test**
- Input offset setup
- ADC sampling point setup
- Integrator timing setup
- ADC offset setup
- BLM calibration by induced beam loss
- **BLM calibration by wirescan**
- &c.



Verification of BLM Cabling



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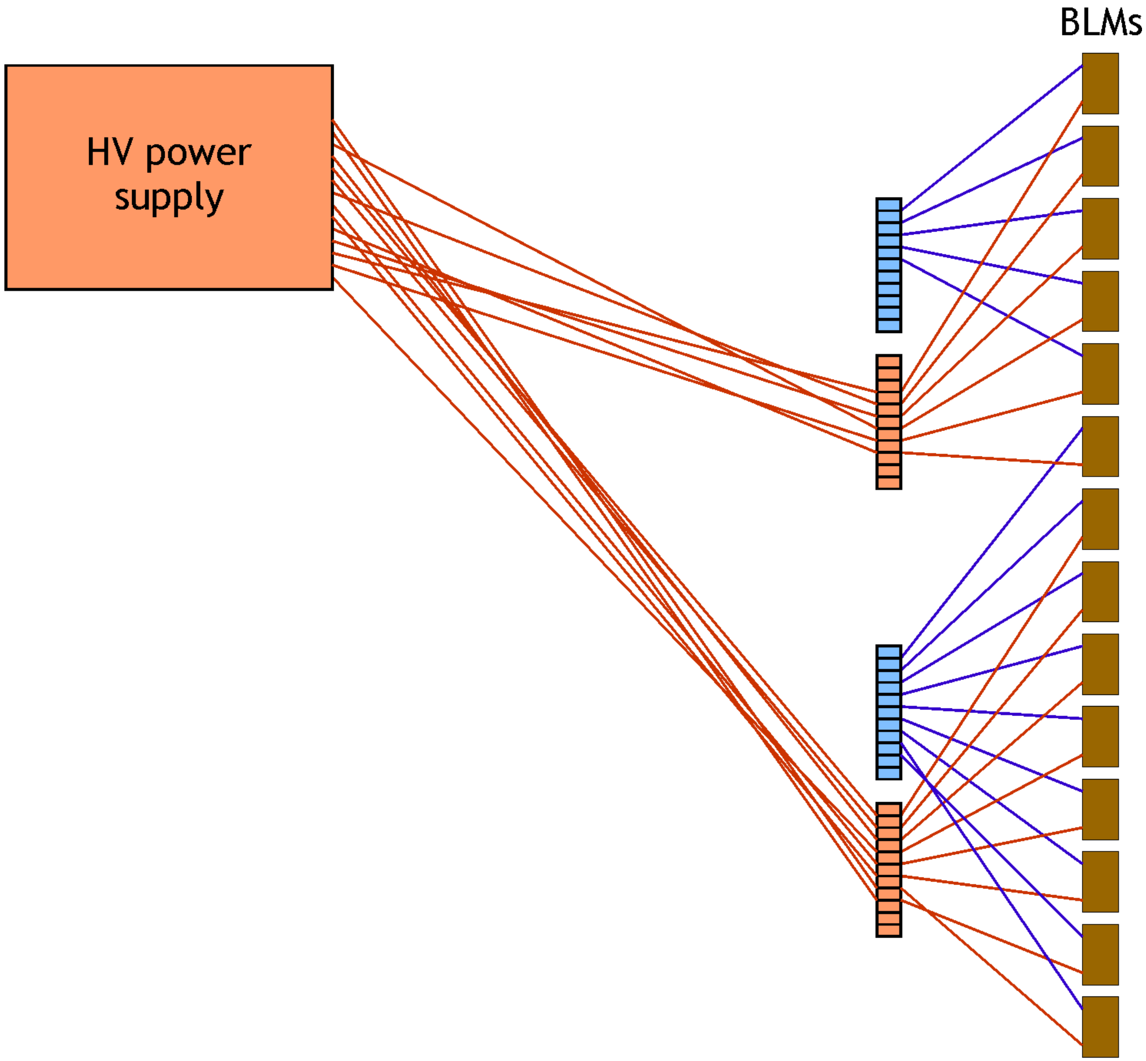

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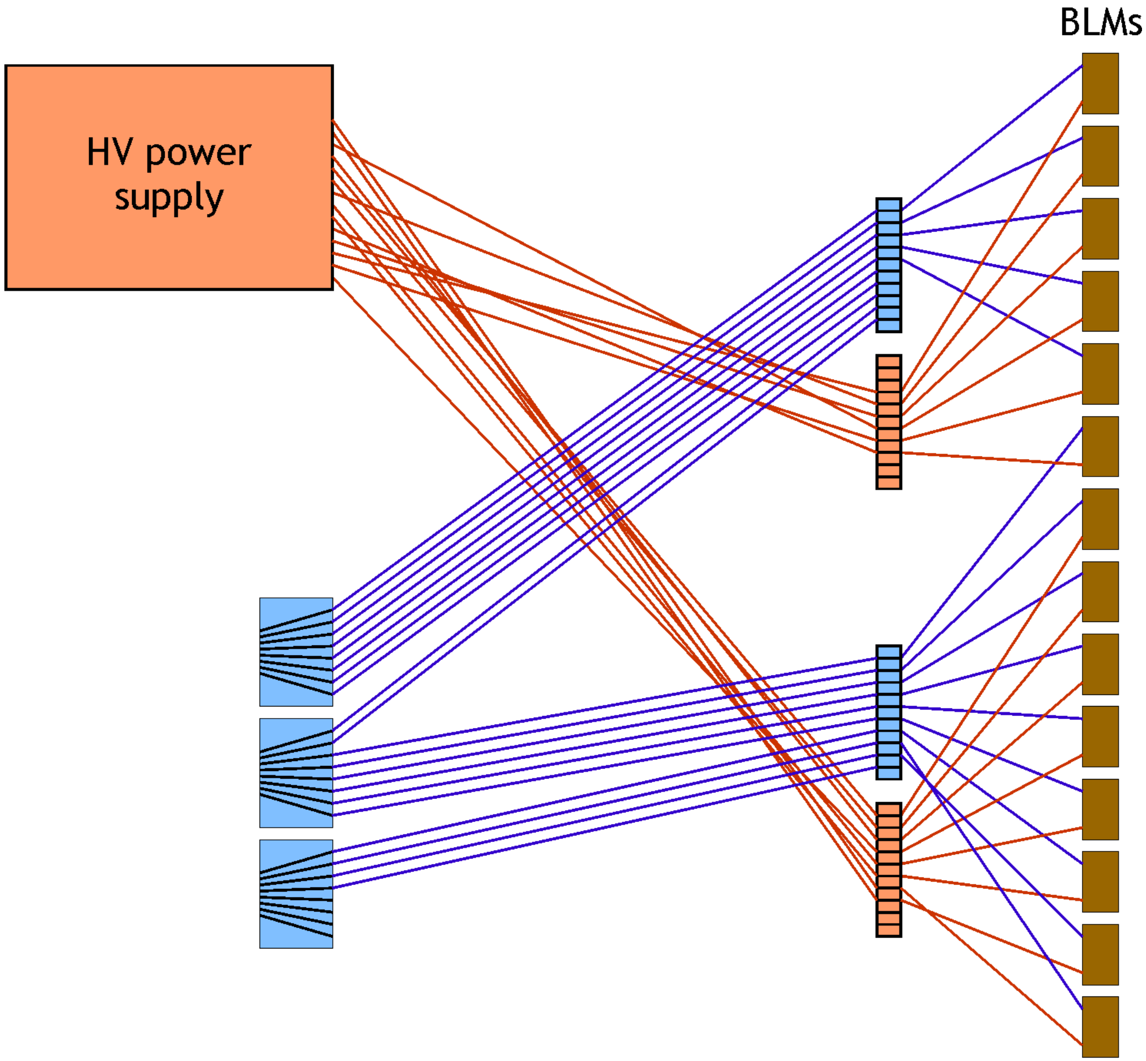

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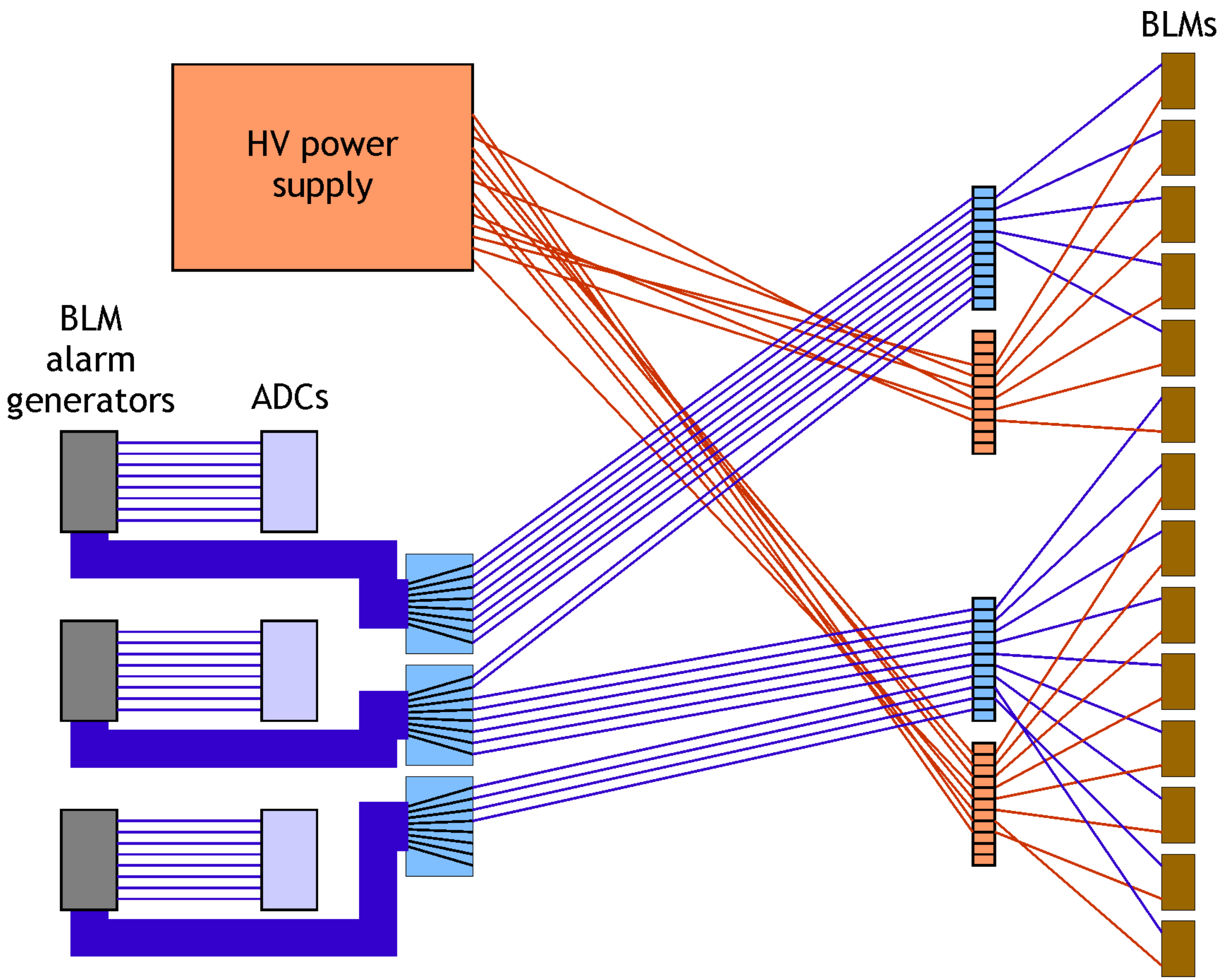

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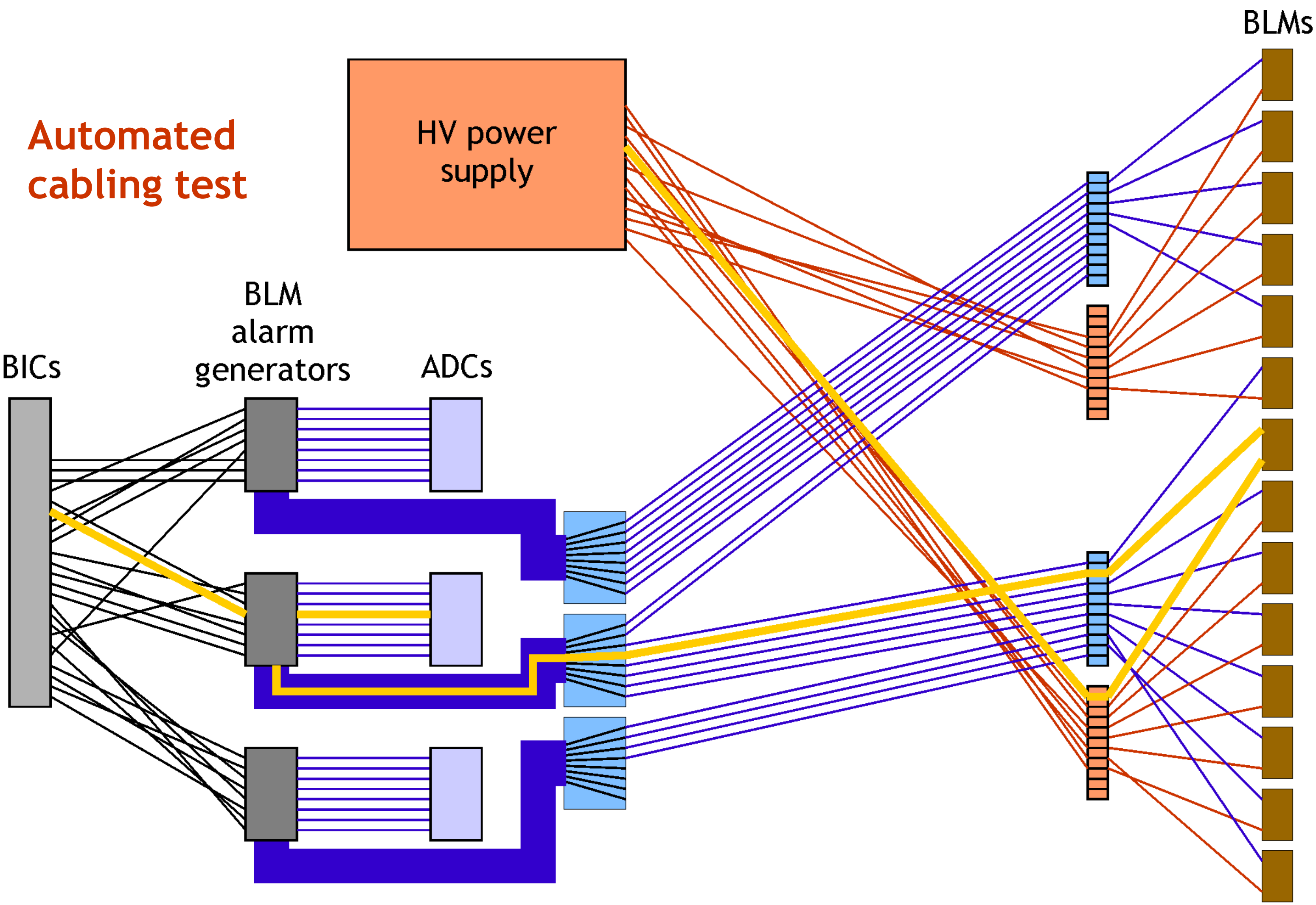


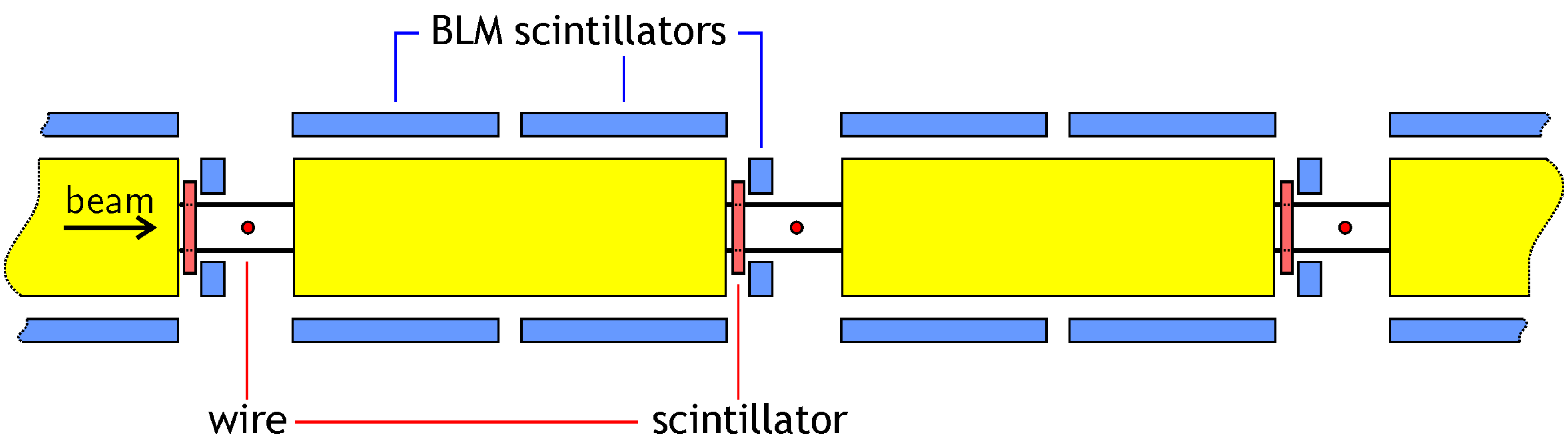
small fraction of HV
added to BLM signal

BLM Calibration by Wirescan

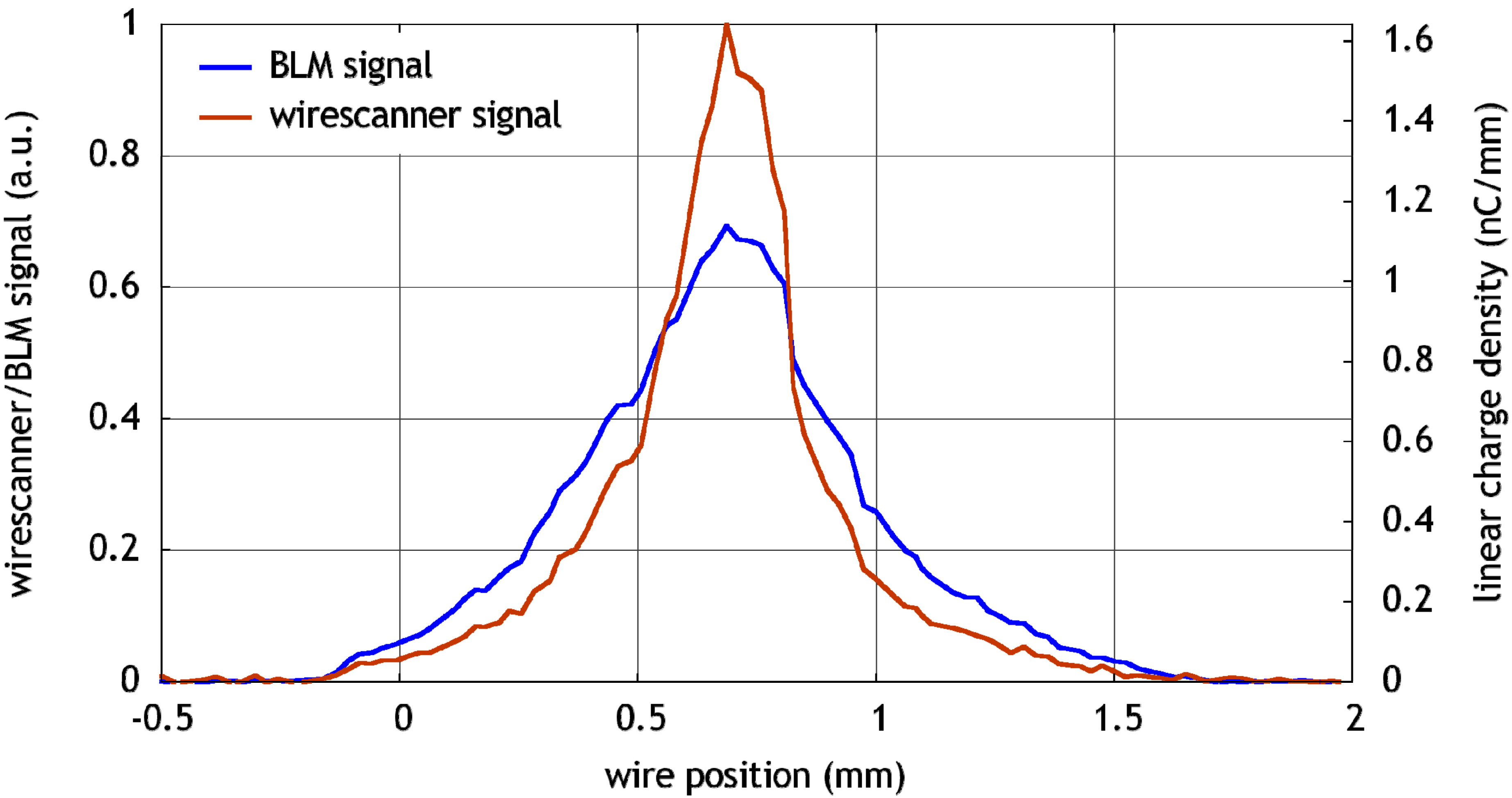
Goals:

- Make readings comparable between left and right beam loss monitors
- Make readings comparable between BLMs in different undulator segments

top view on FEL undulator segments

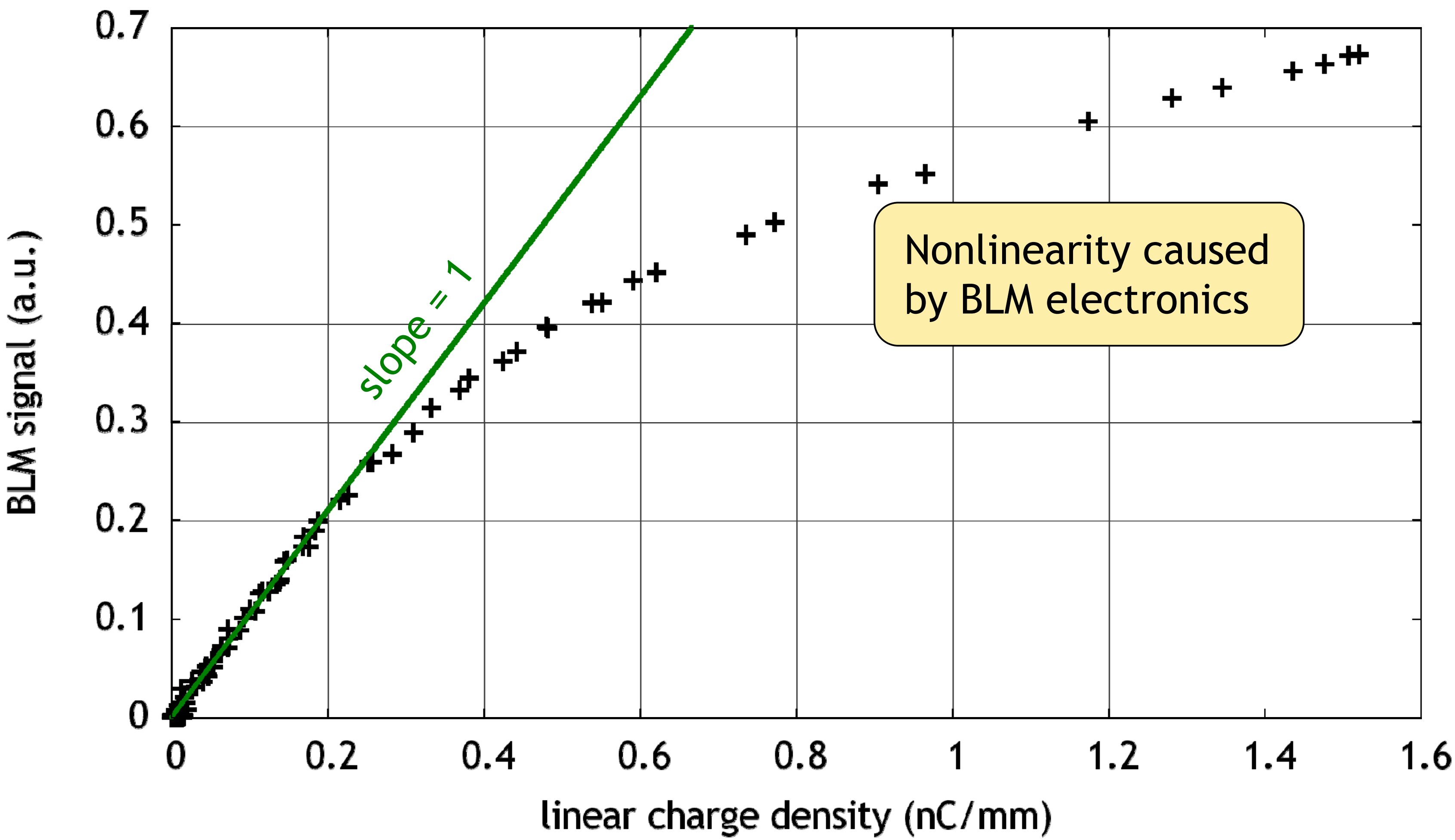


BLM Calibration by Wirescan



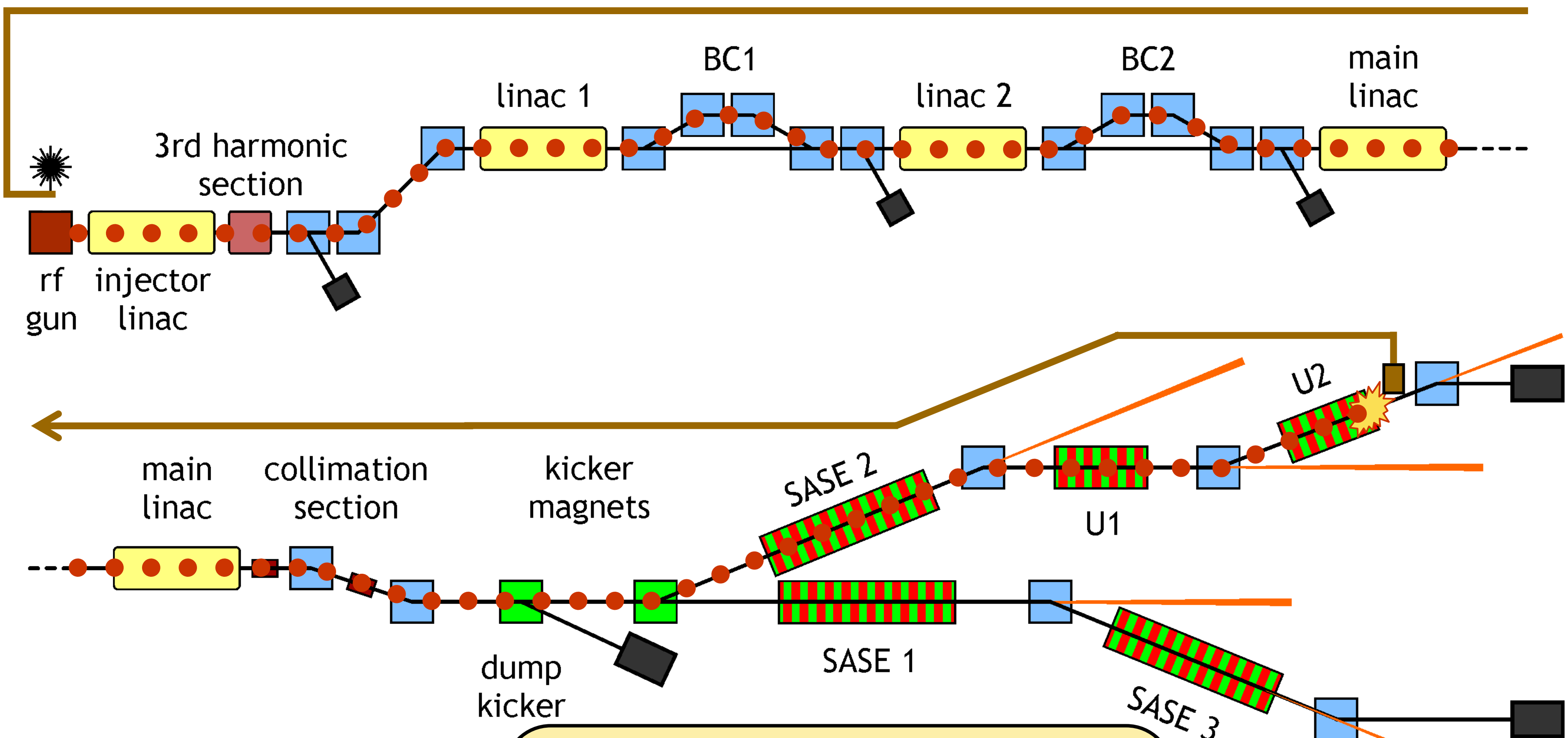
BLM Calibration by Wirescan

Undulator BLMs are calibrated against linear charge density



An MPS for the European XFEL

The European X-Ray Free-Electron Laser (XFEL)



accelerator length: **3 km**
bunch frequency: **5 MHz**
repetition rate: **10 Hz**

50 bunches in the accelerator
75 injected during signal propagation (2/3 c)

125 bunches lost (22 kW)

Monitoring of critical components

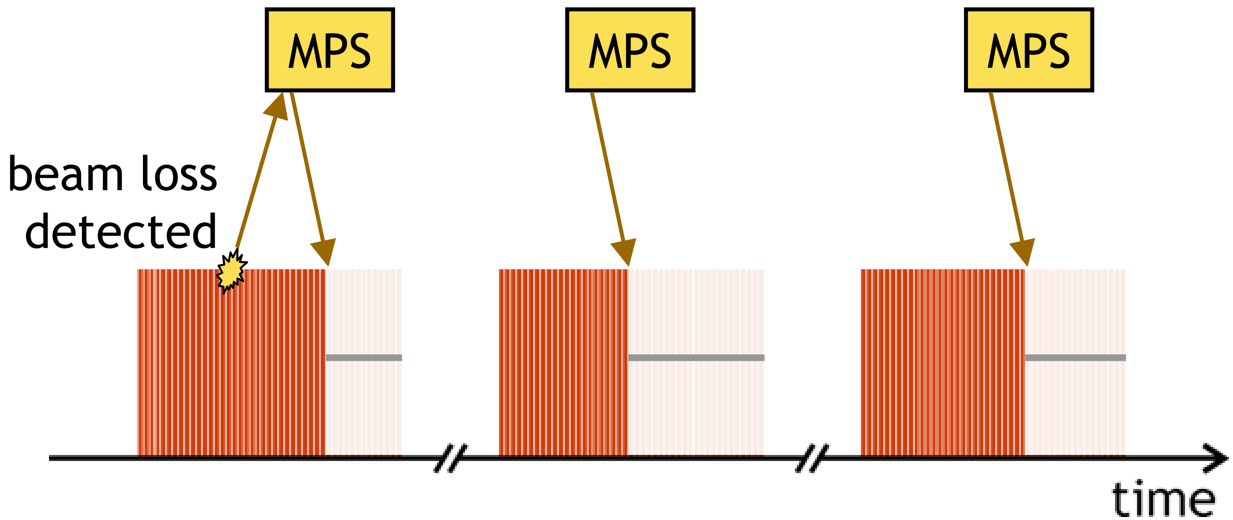
- Ensure that valves and magnets are set up correctly to guide the beam to a dump

Power limits

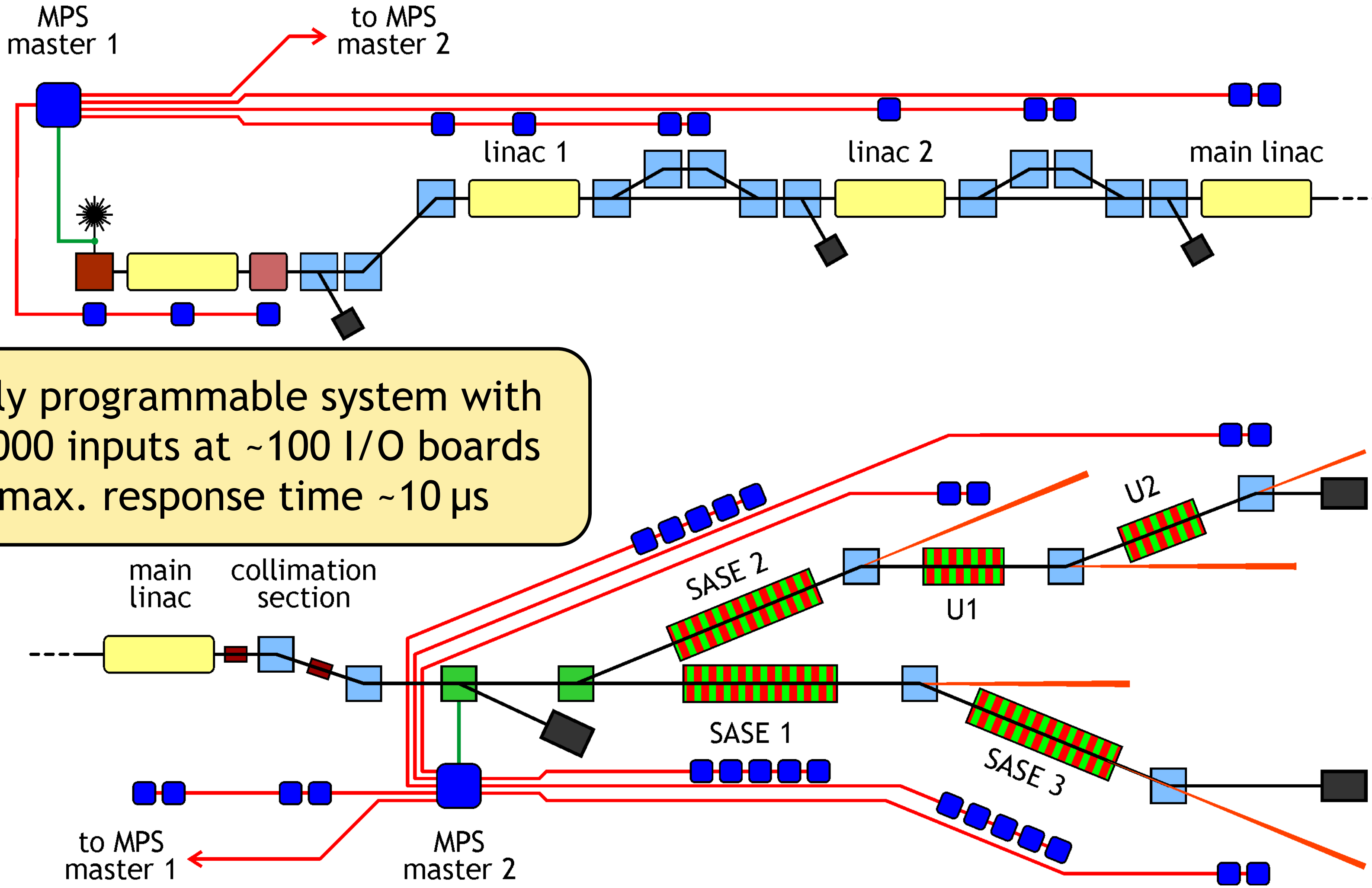
- Limit the number of bunches for startup, to protect screens, ...

Alarm cutoffs

- React immediately to beam losses
  & reduce the number of bunches dynamically for following macropulses



Example Topology



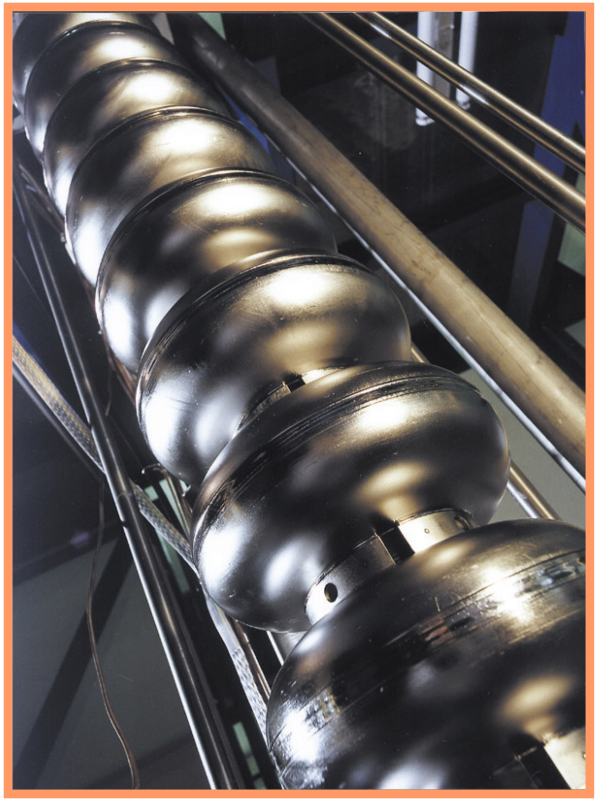
fully programmable system with
>1000 inputs at ~100 I/O boards
max. response time ~10 μs

Conclusion

Conclusion

- Superconducting linacs can transport dangerously powerful beams
- Permanent magnet undulators are among the most vulnerable components
- Beam losses must be controlled tightly (FLASH design: $3 \cdot 10^{-8}$)
- Dark current can be problematic
- Good passive & active protection is required

- FLASH machine protection system is fully functional & reliable
- XFEL machine protection system will be more complex, but concepts & first prototypes are ready



Acknowledgements

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