Particle Accelerators - Part 4

DESY Summer Student Lectures 2025

Michaela Schaumann
DESY, Accelerators (M) Department, MPY, PETRA III Operations
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HELMHOLTZ

DESY.

4 Lectures

Yesterday

Part 1: General introduction:

- What are particle accelerators?
- Why and where do we need them?
- What types do exist?

Part 2: Accelerator Technology (Gregor Loisch)

Today

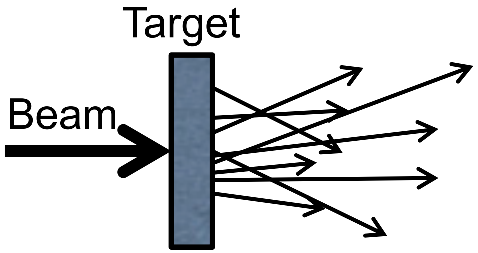
Part 3: How to build a particle accelerator

Part 4: What Users need and how to deliver

Experimental Application

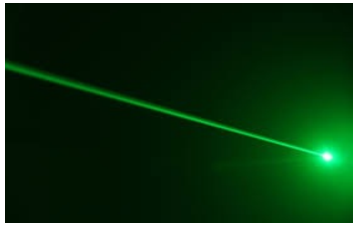
Each accelerator and experiment requires specific beam properties. Fundamentally different are:

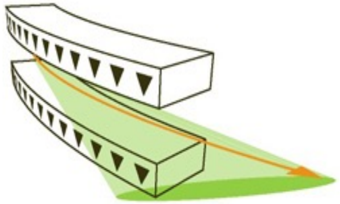
Fixed Target:



Secondary particles

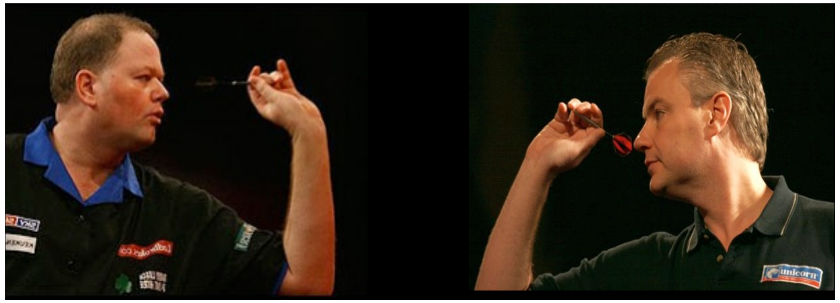
Light Sources:

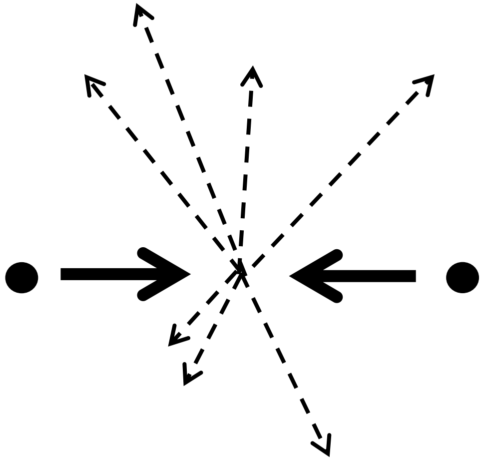




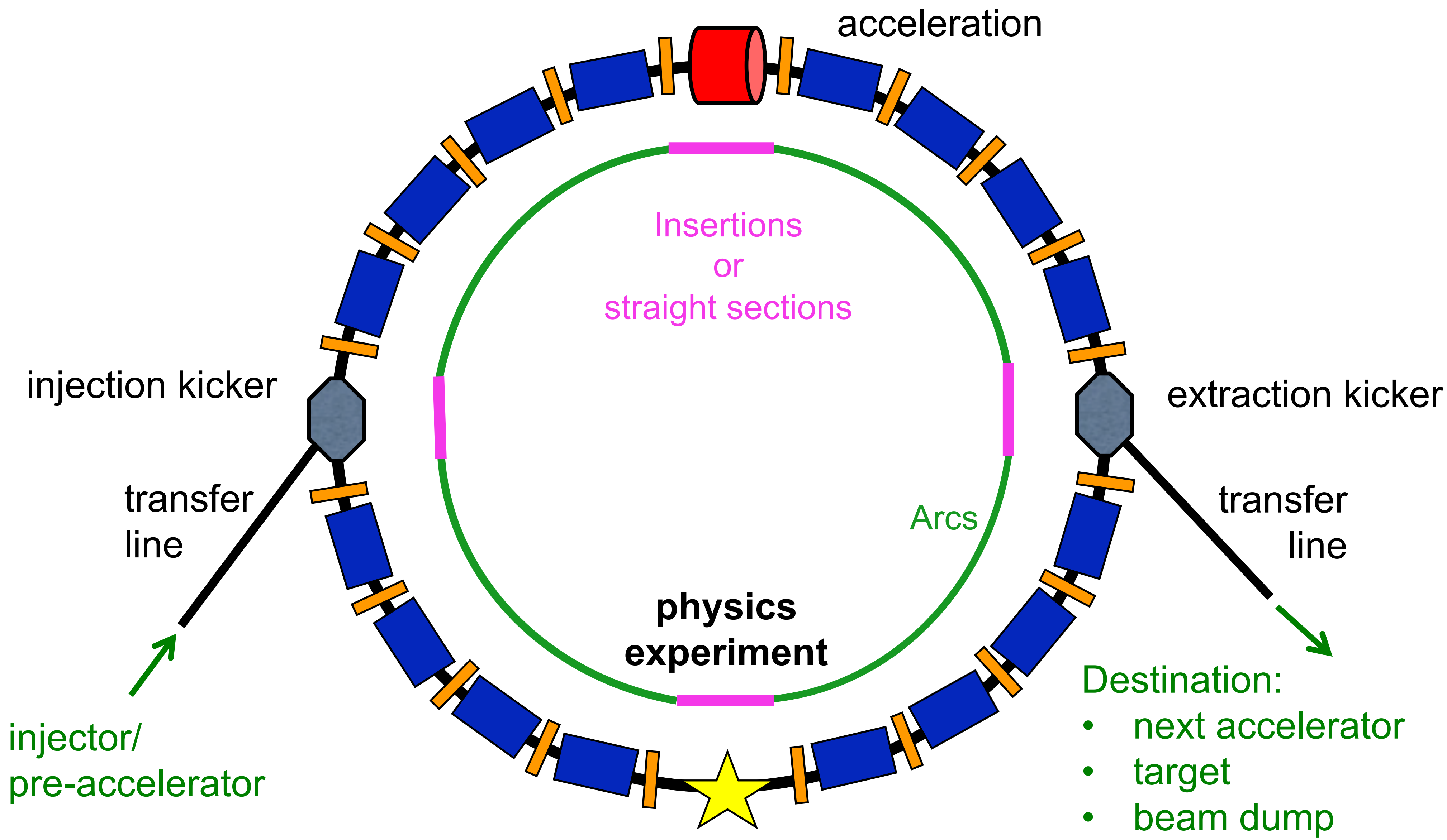
Particles that are bent to a circular orbit emit energy/light.

Collider:





Collider Experiments and Luminosity



Destination:
- next accelerator
- target
- beam dump

Particle Collisions

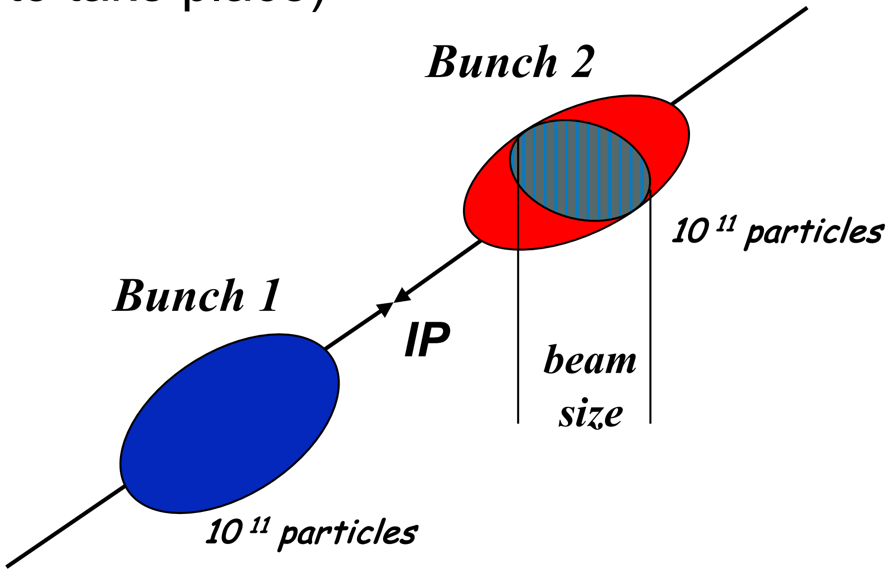
Experiments are interested in maximum number of interactions per second.
The event rate in an experiment is proportional to the luminosity.

$$\frac{dR}{dt} = L \times \sigma_p$$

Interaction Cross-section
(= constant probability for the given interaction to take place)

Luminosity

Event rate
(= number of collisions per time)



“Quality Factor” of a Collider

The most important measure to describe the potential of a collider is the Luminosity.

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

Defined by the injectors

N….. No. particles per bunch
k…… No. bunches
f……. revolution freq.
g…… rel. gamma
β^*…. beta-function at IPs
ε…... norm. trans. emit

Limitation:
“Collective effects” cause beam instabilities for too high bunch intensities, too small bunch spacing, too “bright” beams.

Overall Goal of an Collider: Maximizing Luminosity!

→ Many particles (N, k)
→ In a small transverse cross-section (ε, β)

Performance depends on the injectors:

→ Production of large N and small ε
→ Preservation of these parameters until collisions.

Optimizing Luminosity

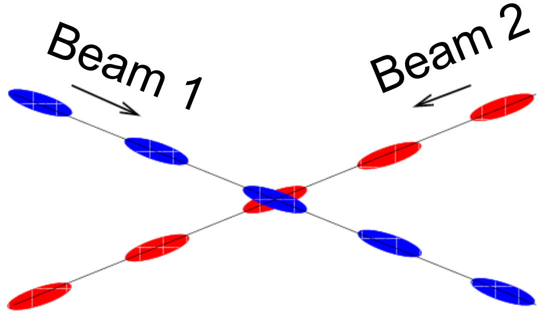
Bunch properties (N & ϵ) are defined in the injectors. But what can we do in the Collider?

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

N….. No. particles per bunch
k…… No. bunches
f……. revolution freq.
g…… rel. gamma
β^*…. beta-function at IPs
ε…... norm. trans. emit

f_{rev}, γ: defined by the design of the accelerator

F [0,1]: When colliding with many bunches, a **crossing angle is needed** to avoid unwanted collisions. However this ***reduces the beam overlap*** and therefore the luminosity. Keep as *small as possible*!
→Limited by beam-beam effects.



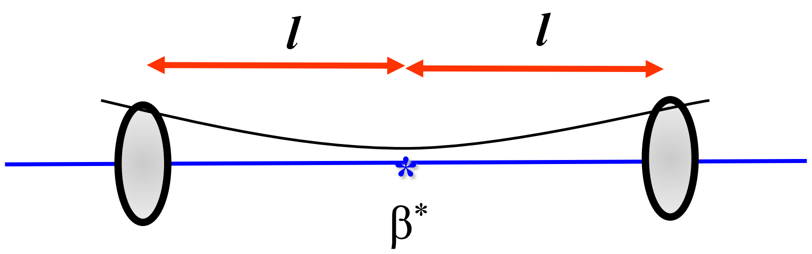
k: Optimize filling scheme and bunch spacing.

$\boldsymbol{\beta^*}$: Can be optimized by focusing!

Mini-Beta Insertions

Squeezing the beams to the smallest beam size possible

Mini-beta insertion is a ***symmetric drift space*** with a ***waist of the β-function*** in the center of the insertion.



$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

On each side of the symmetry point a quadrupole **doublet** or **triplet** is used to generate the waist.

They are not part of the regular lattice.

Collider experiments are located in mini-beta insertions: **smallest beam size possible** for the colliding beam to increase probability of collisions.

There is a price to pay: **The smaller β^*, the larger β at the triplet.**

Example: Mini-Beta Insertion at LHC

Example of the LHC (design report values):

At the interaction point:

$\beta^* = 0.55$ m

$\sigma^* = 16\ \mu$m

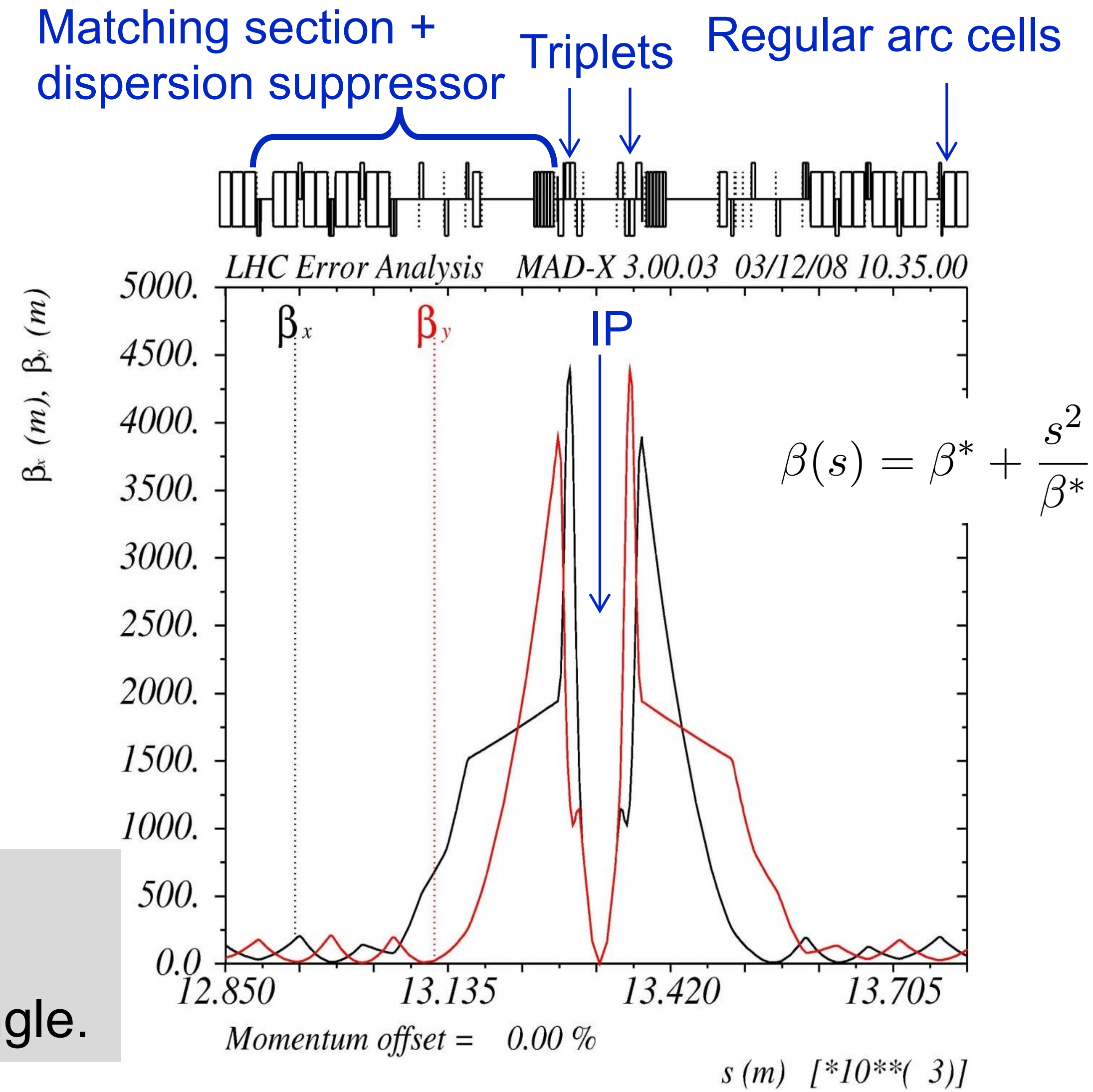
That's smaller than a hair's diameter!

At the triplet:

$\beta = 4500$ m

$\sigma = 1.5$ mm $= 1500\ \mu$m

Largest beams size in the lattice!

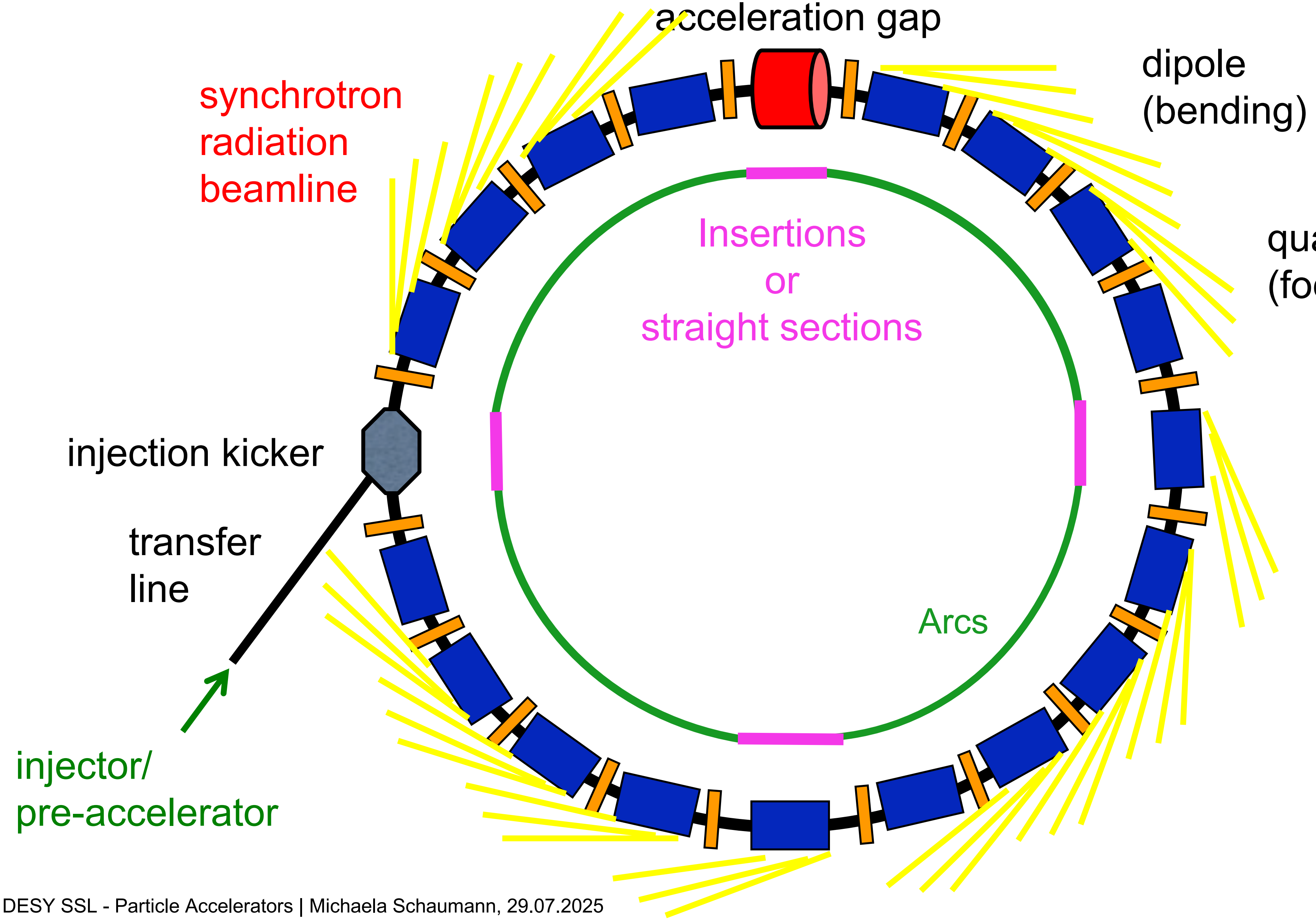


$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

Limitations:

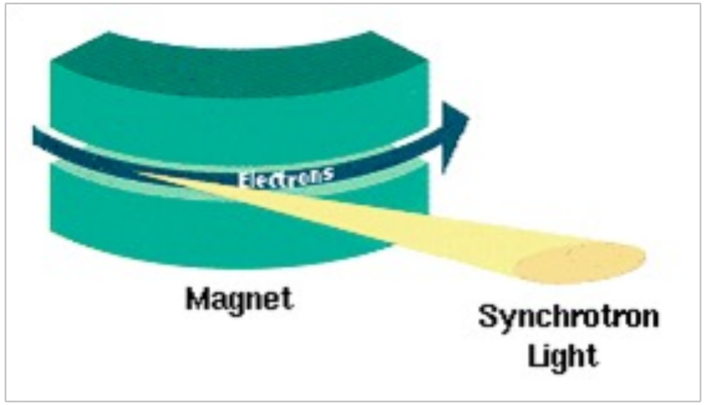
- Tighter tolerances on field errors
- Triplet aperture limits β^* together with crossing angle.

Synchrotron Light Source



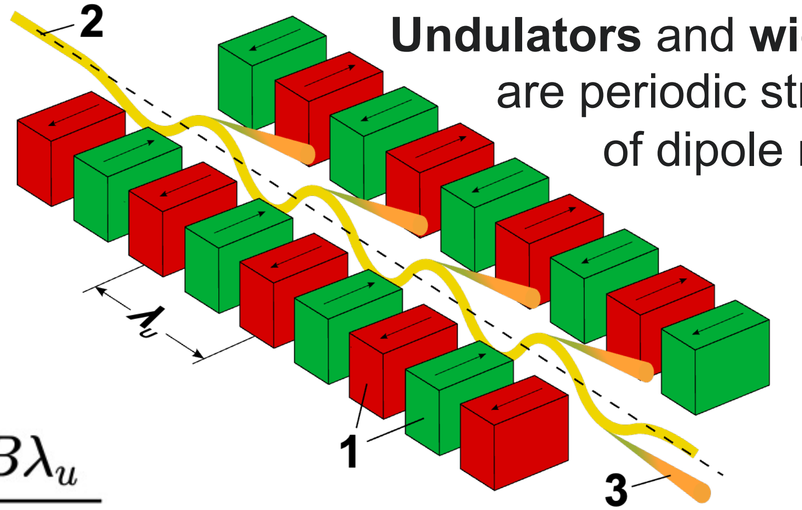
Undulators to control synchrotron light yield

Particles radiate when bent on a circular orbit



Particles emit synchrotron radiation when radially accelerated.

Light emission is spread over fan-like region through the dipole passage.



Undulators and **wigglers** are periodic structures of dipole magnets.

Undulator strength parameter:

$$K = \frac{eB\lambda_u}{2\pi m_e c}$$

Undulators: K<<1, small oscillation amplitude, interference of radiation leads to narrow energy bands and **coherent radiation**.

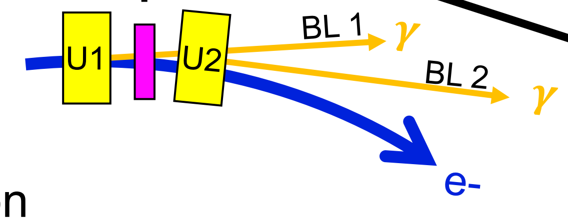
Wigglers: K>>1, bigger oscillation amplitude, radiation from each field period sum up independently, leading to a **broad energy spectrum.** → **provides additional radiation damping to reach desired emittance.**

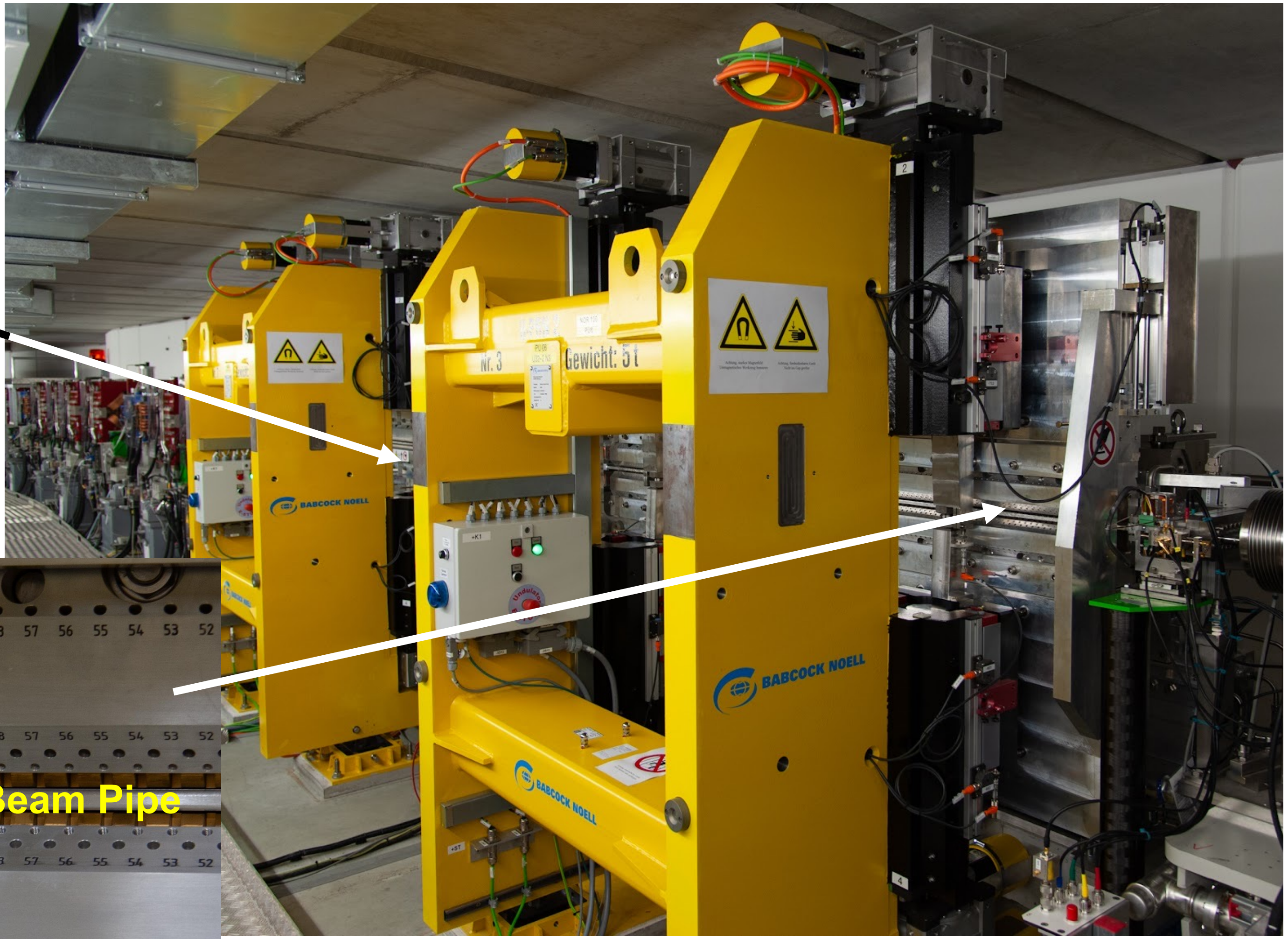
Source graphs: Wikipedia

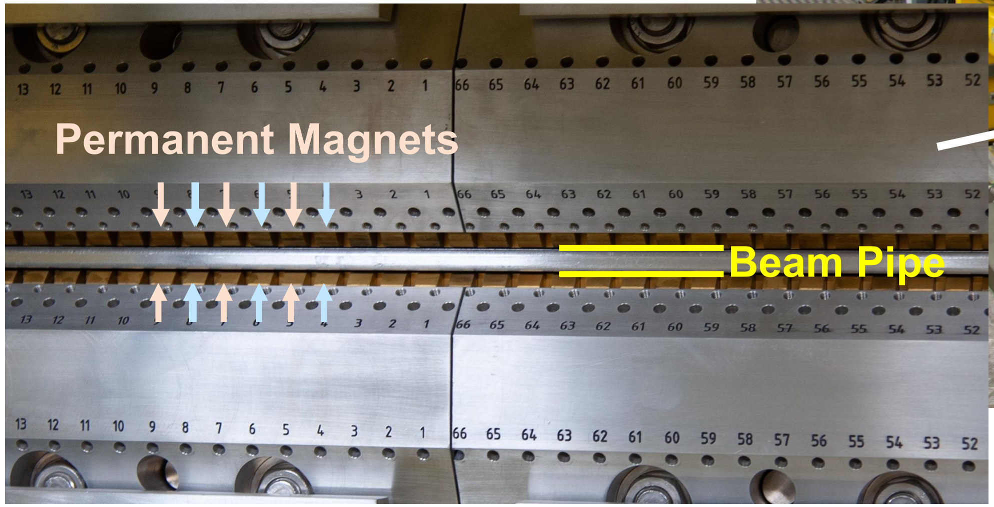
Each beamline needs their own undulator

Undulators of different types and length, provide photons with varying properties

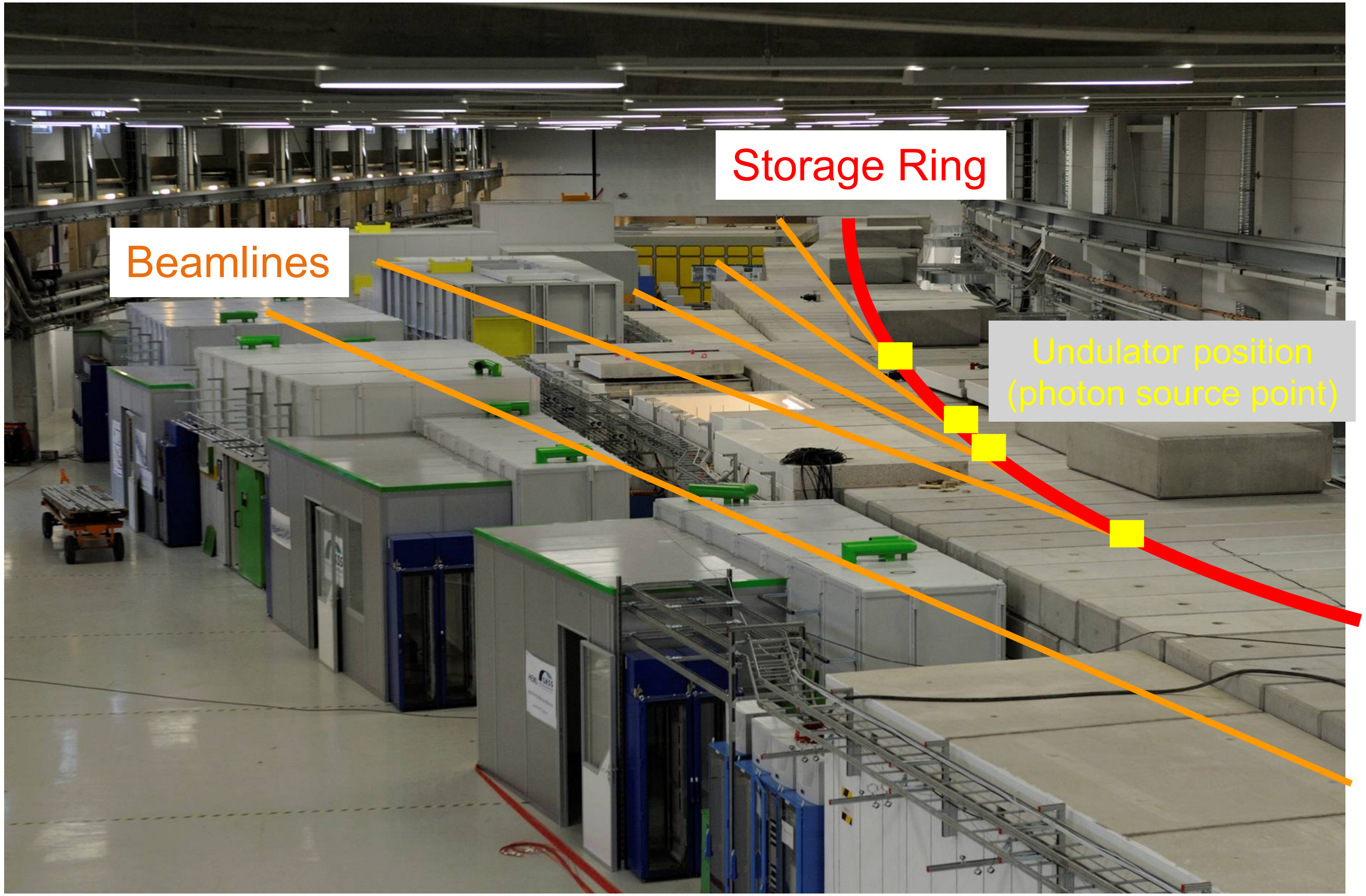
Canting dipole
separating photon beams from two undulators in the same straight section







View from the Tunnel Roof in the Max von Laue Hall

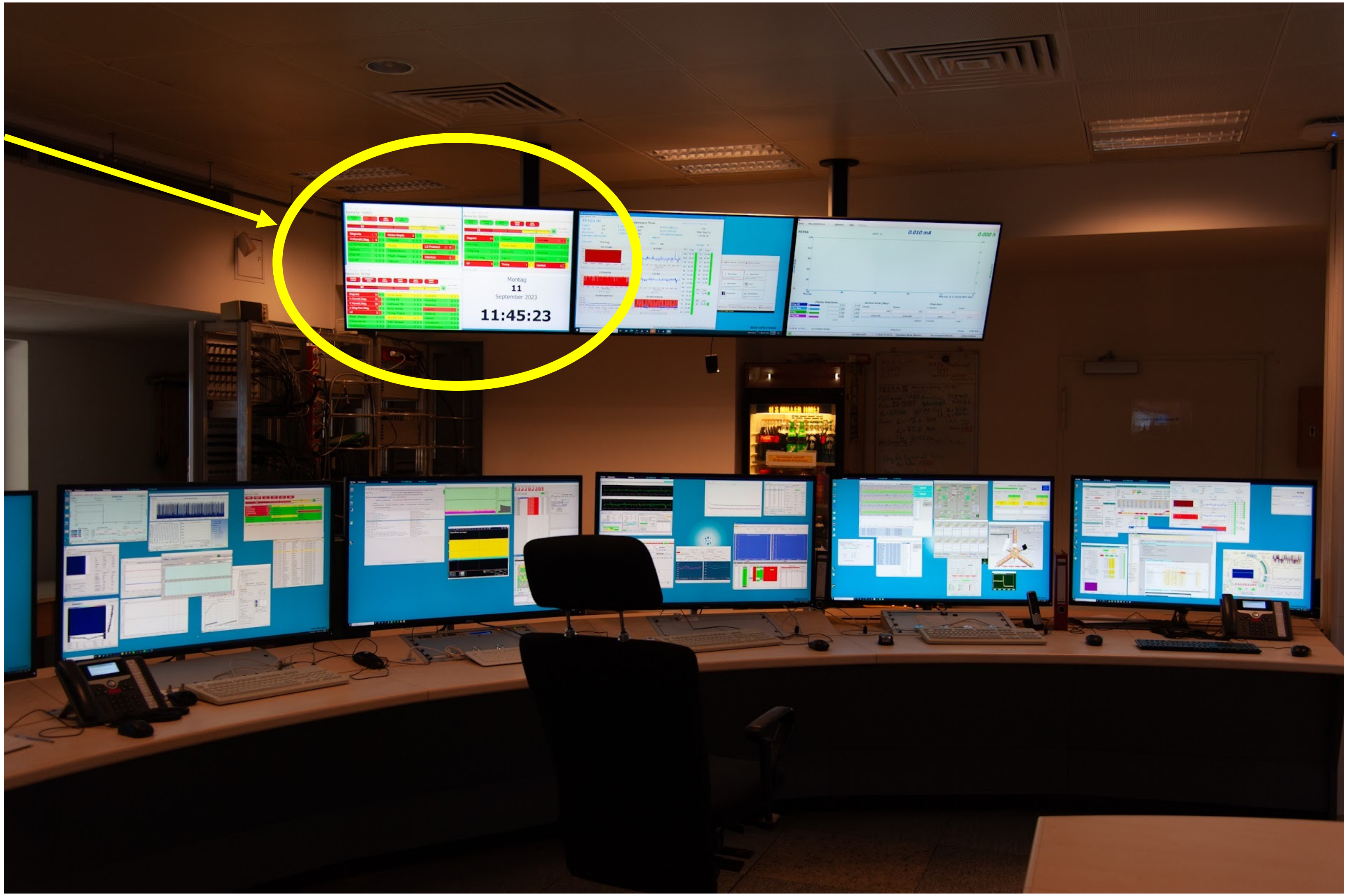


Taking PETRA III back in operation

A day as an operator in the accelerator control room

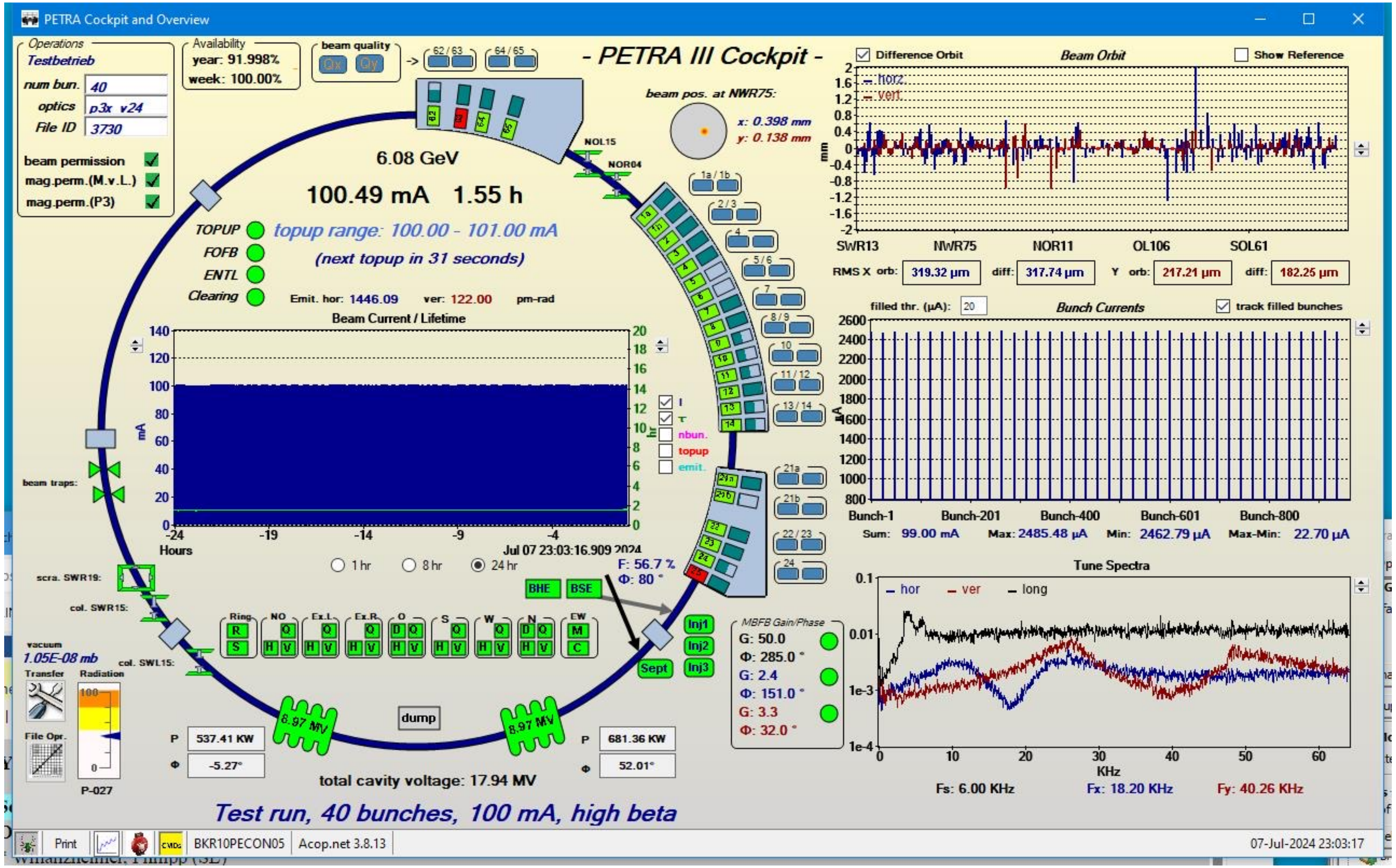
Red is never good for operation

PETRA is off



PETRA III Accelerator Cockpit

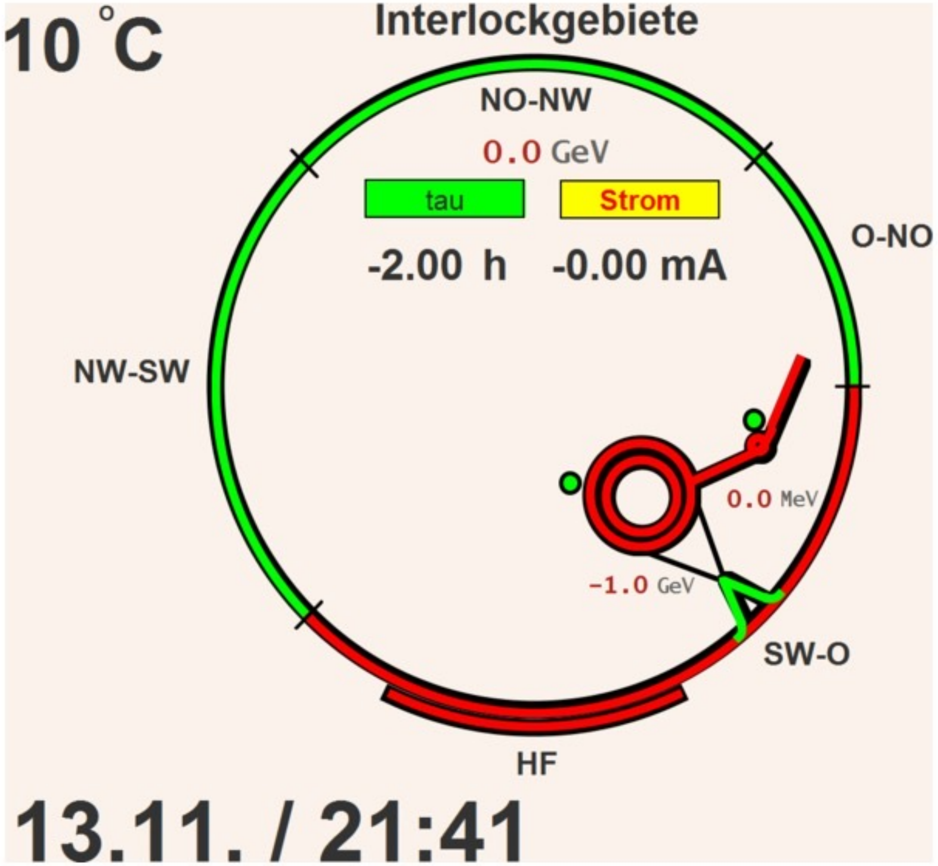
Lets grab a chair – hope in the cockpit – and start the engine



Patrol the Tunnel and Set the Interlock

Make sure the machine operation is radiation safe for all persons

Take a 2.3 km long walk around the PETRA tunnel and check every corner, niche, place for remaining people before circulating beam.



Switch on all Systems and Cycle the Magnets

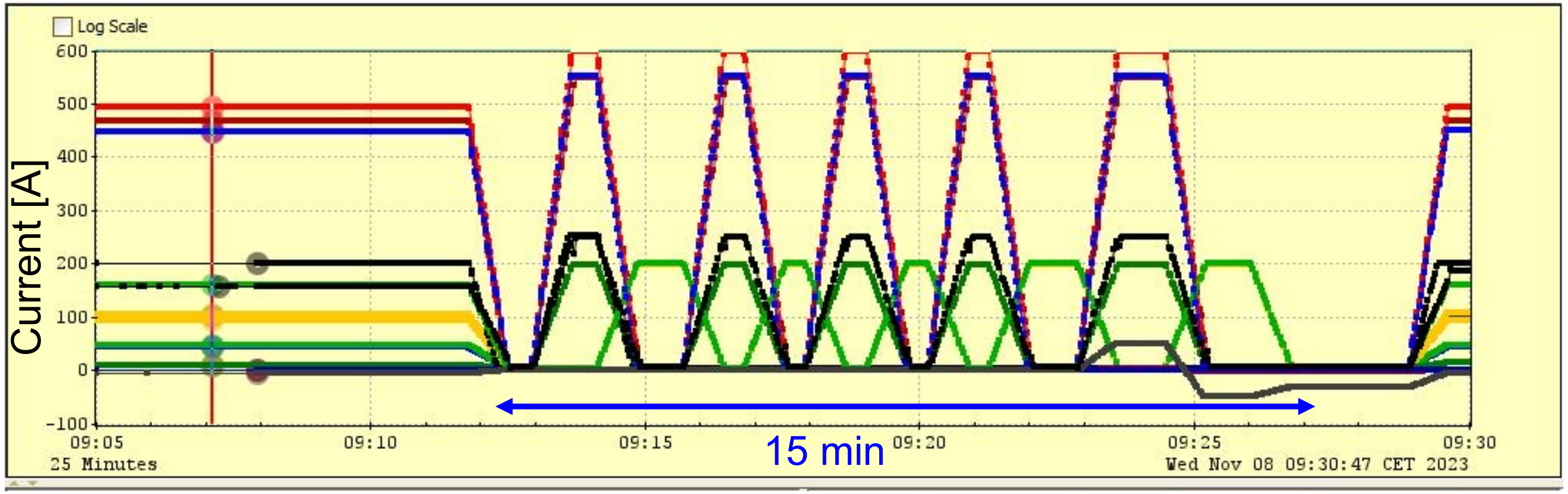
Magnet Power Supply control

Kreis	PS	Status	Soll	Ist-Soll
28610	PCV_SWR_13	Ein	-0.0257	0.0000
28611	PCVM_SWR_31	Ein	-0.0425	0.0001
28253	PKVSU_SWR_46	Ein	-6.8815	-0.0005
28254	PKVSU_SWR_60	Ein	4.5829	0.0013
28255	PKVSX_SWR_75	Ein	-1.8893	0.0002
28256	PKVSX_SWR_89	Ein	-5.7353	-0.0014
28257	PKVSX_SWR_104	Ein	-2.9472	-0.0006
28258	PKVSX_SWR_118	Ein	-5.2963	0.0013
28259	PKVSX_SWR_132	Ein	1.0014	-0.0009
28265	PKVSX_WL_140	Ein	-4.9276	-0.0009
28264	PKVSX_WL_125	Ein	5.2494	0.0008
28263	PKVSX_WL_111	Ein	0.6223	0.0005
28262	PKVSX_WL_96	Ein	-2.1819	0.0000
28261	PKVSX_WL_82	Ein	10.5201	-0.0005
28260	PKVSU_WL_68	Ein	1.1515	-0.0006
28612	PCVM_WL_52	Ein	-0.2714	0.0001
28613	PCV_WL_40	Ein	0.0241	0.0001
28407	PKVW_WL_25	Ein	-0.7292	0.0001
28409	PKVW_WL_13	Ein	1.0708	0.0000
28411	PKVW_WL_1	Ein	0.6370	0.0000
28413	PKVW_WR_12	Ein	1.5030	0.0001
28415	PKVW_WR_24	Ein	1.4060	0.0001
28618	PCV_WR_38	Ein	-0.0542	0.0000
28619	PKVW_WR_54	Ein	-0.3311	0.0001
28266	PKVSU_WR_68	Ein	4.5715	0.0006
28267	PKVSX_WR_82	Ein	-4.0972	-0.0006
28268	PKVSX_WR_96	Ein	-5.8339	-0.0011
28269	PKVSX_WR_111	Ein	-4.8853	-0.0003
28270	PKVSX_WR_125	Ein	0.1553	0.0003
28271	PKVSX_WR_140	Ein	-5.1922	-0.0002
28278	PKVSX_NWL_132	Ein	3.1577	0.0010
28277	PKVSX_NWL_118	Ein	-1.5184	-0.0003
28276	PKVSX_NWL_104	Ein	2.0466	0.0005
28275	PKVSX_NWL_89	Ein	-1.3204	0.0001
28274	PKVSX_NWL_75	Ein	1.4168	-0.0002

The magnet currents need to be cycled a few times up-down

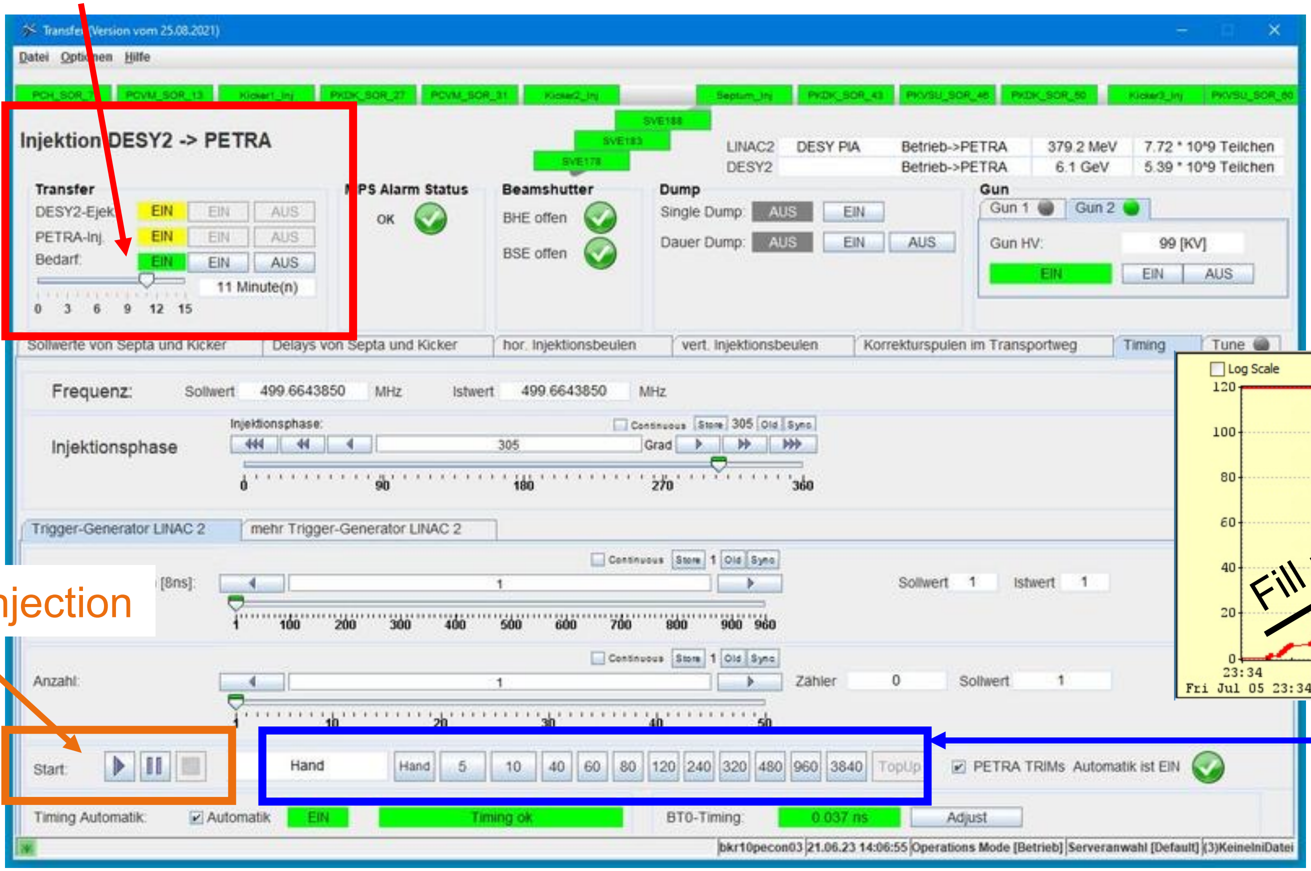
→ **Reset the remanence** of the iron core

→ We need a highly reliable magnetic field strength for high beam quality



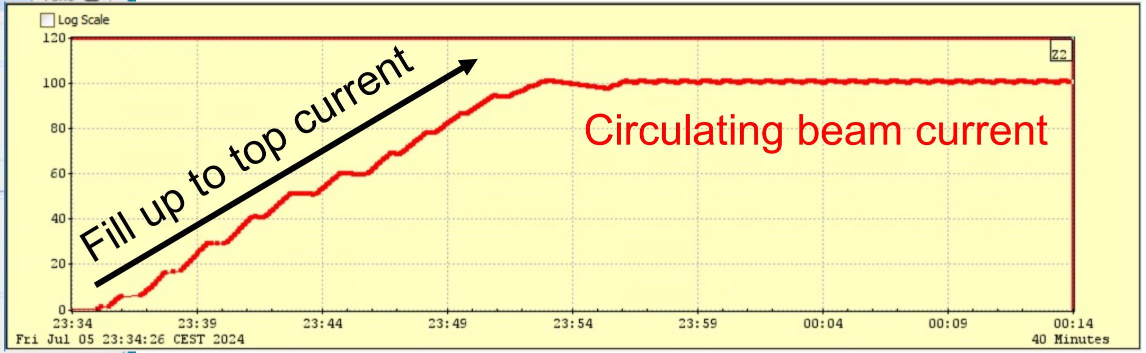
Request Beam from the Injectors - Fill up to Top Current

Request the production of beam



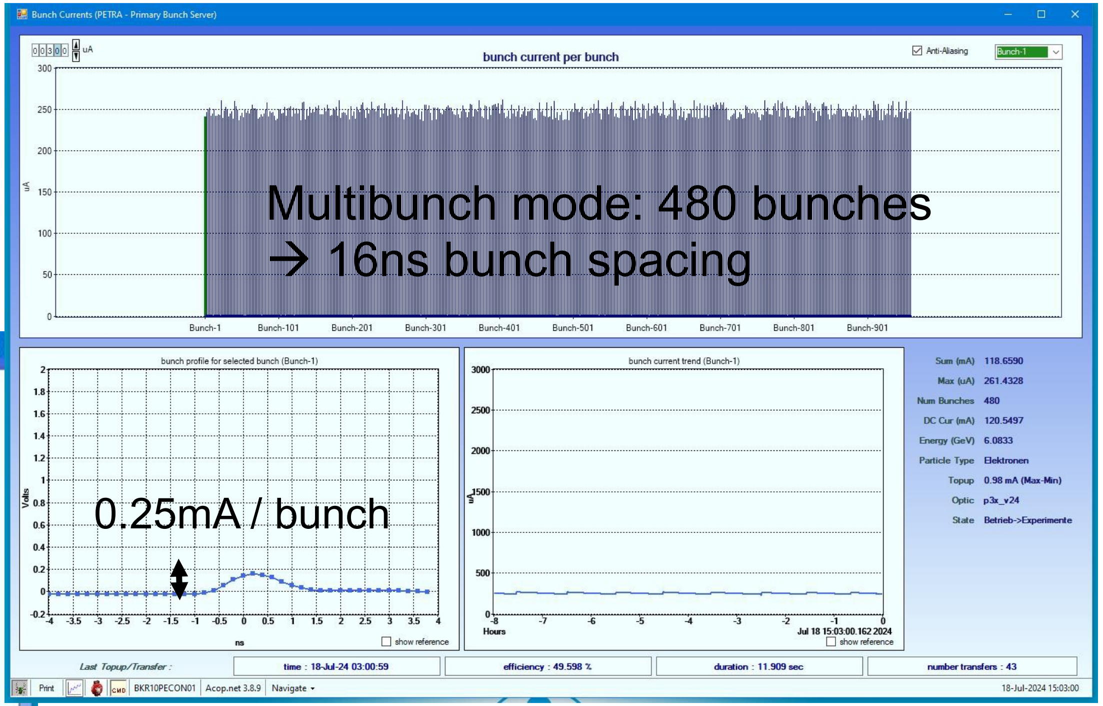
Start injection

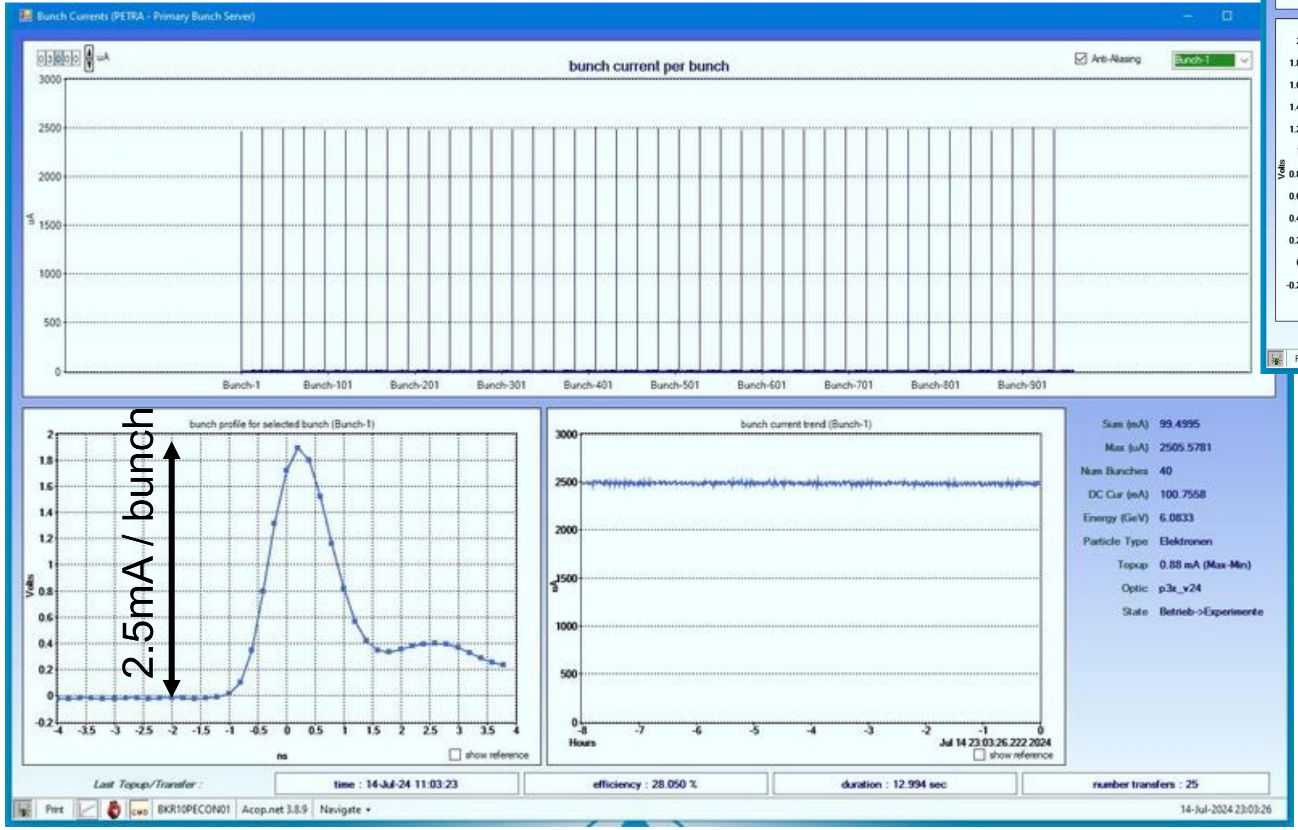
Choose filling pattern



Choose your filling pattern

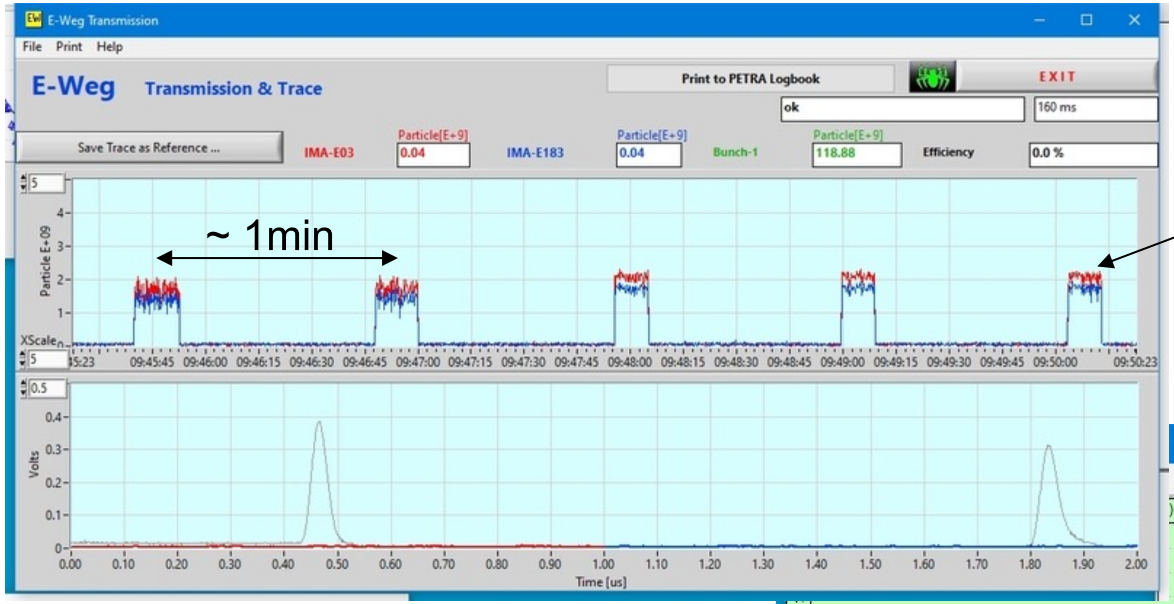
Timing mode: 40 bunches
→ 192ns bunch spacing
→ Time resolved measurements





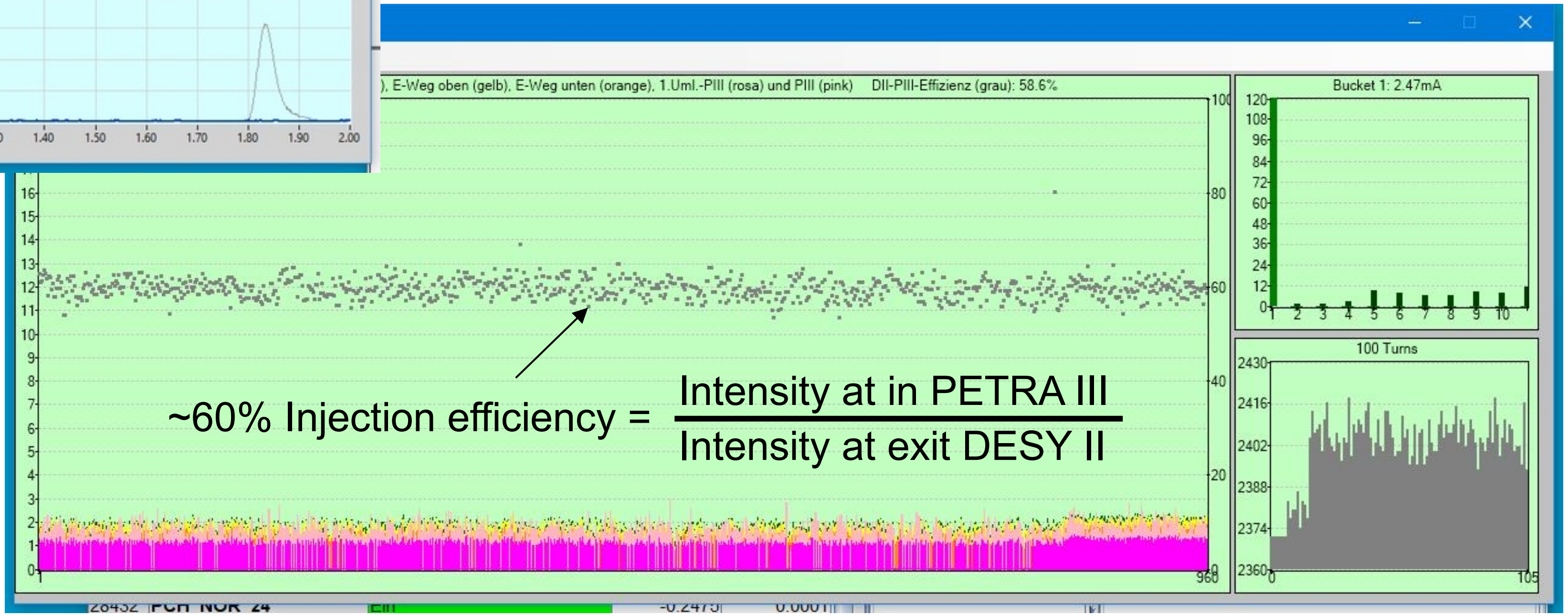
Total beam current of either 100mA or 120mA is distributed over the number of bunches

How is the beam arriving in PETRA?



On PETRA's request electron bunches are produced in the injector chain → 1 bunch every 160ms

Injection of XX individual bunches
Intensity measurement while passing through the transfer line



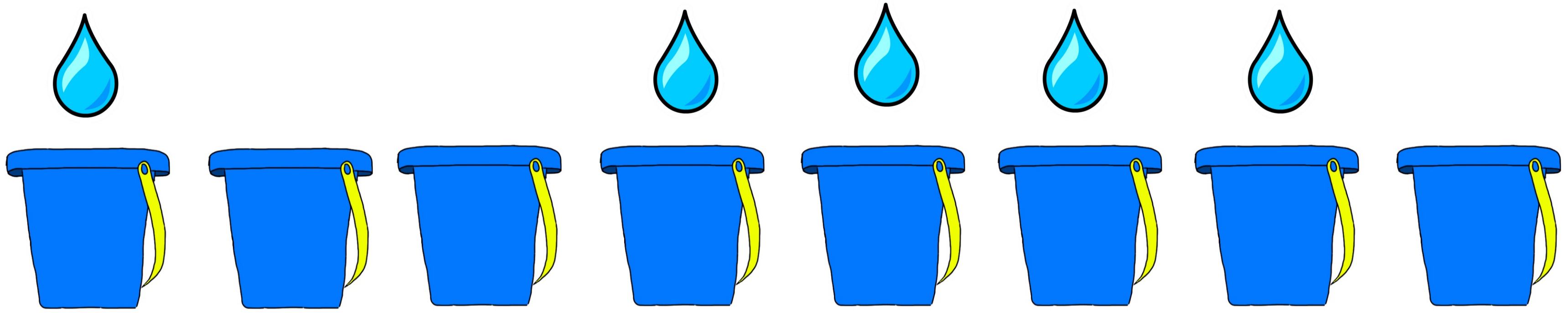
~60% Injection efficiency = $\frac{\text{Intensity at in PETRA III}}{\text{Intensity at exit DESY II}}$

Switch on continuous Top-Up Injection

Keeping the total circulating beam current constant within 1%

A sequencer constantly checks: Beam current is above 99% of top current?

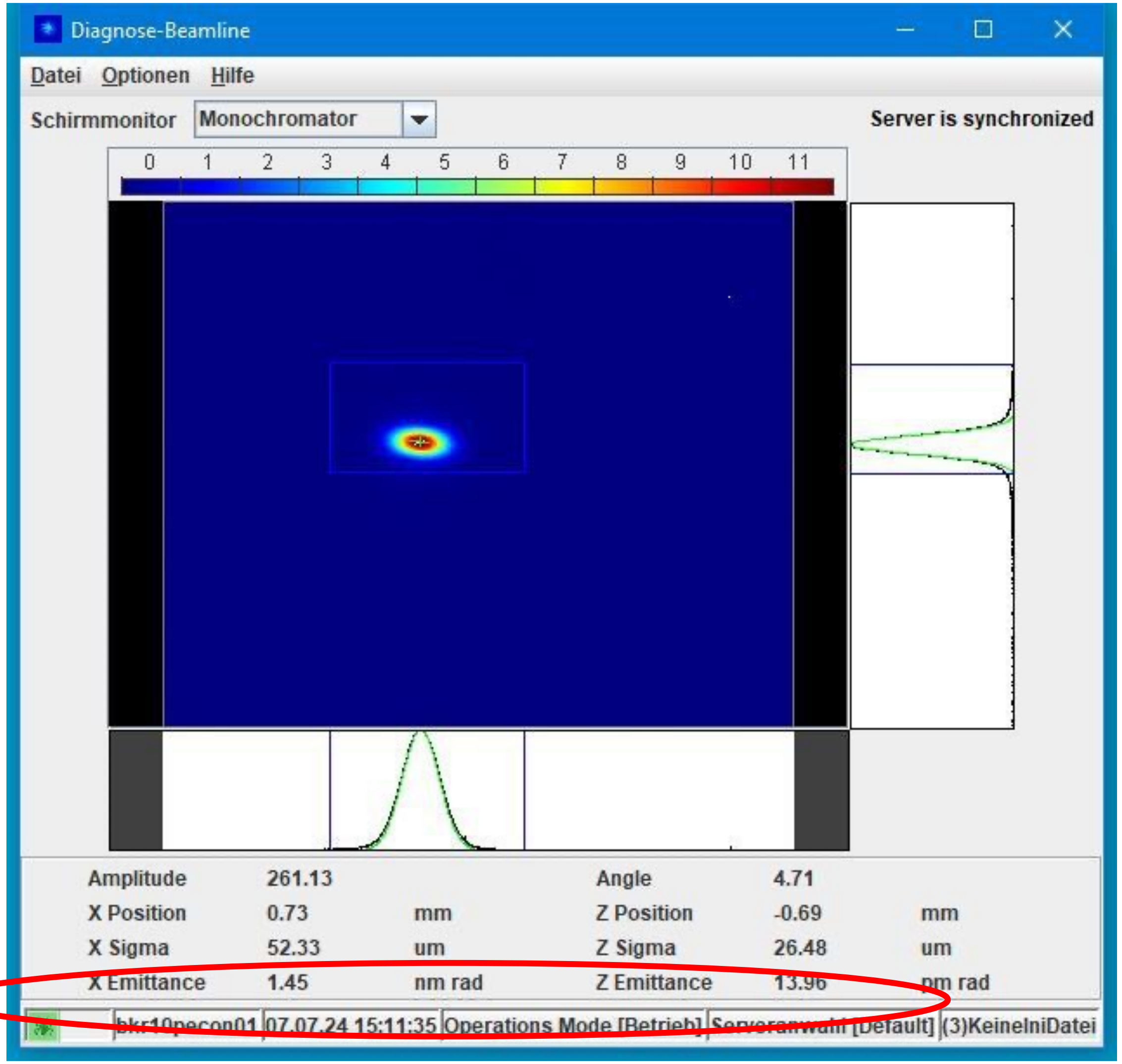
While (decay > 1%){
→ Look for the smallest bunches
→ Estimate how many are needed to fill up to top current
→ Set timing to selected bunches
→ Request bunch production at source
→ Fill new bunch **on top of circulating one (merge)**
}



Graphics from clipart-library.com

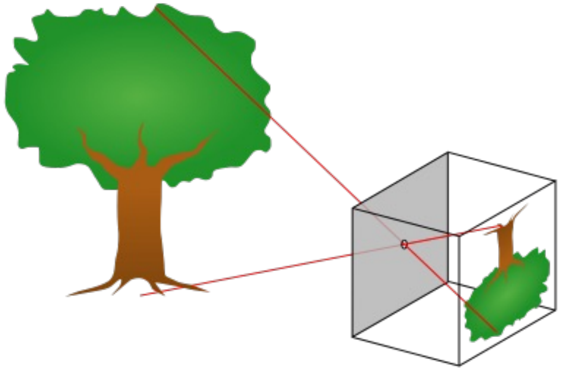
Is the emittance at the target value?

Measure the electron beam emittance by looking at the emitted synchrotron radiation



In contrast to hadron operation, the electron emittance is mainly defined by the machine design rather than the injector performance, due to strong radiation damping.

Measurement is taken with a pin-hole camera

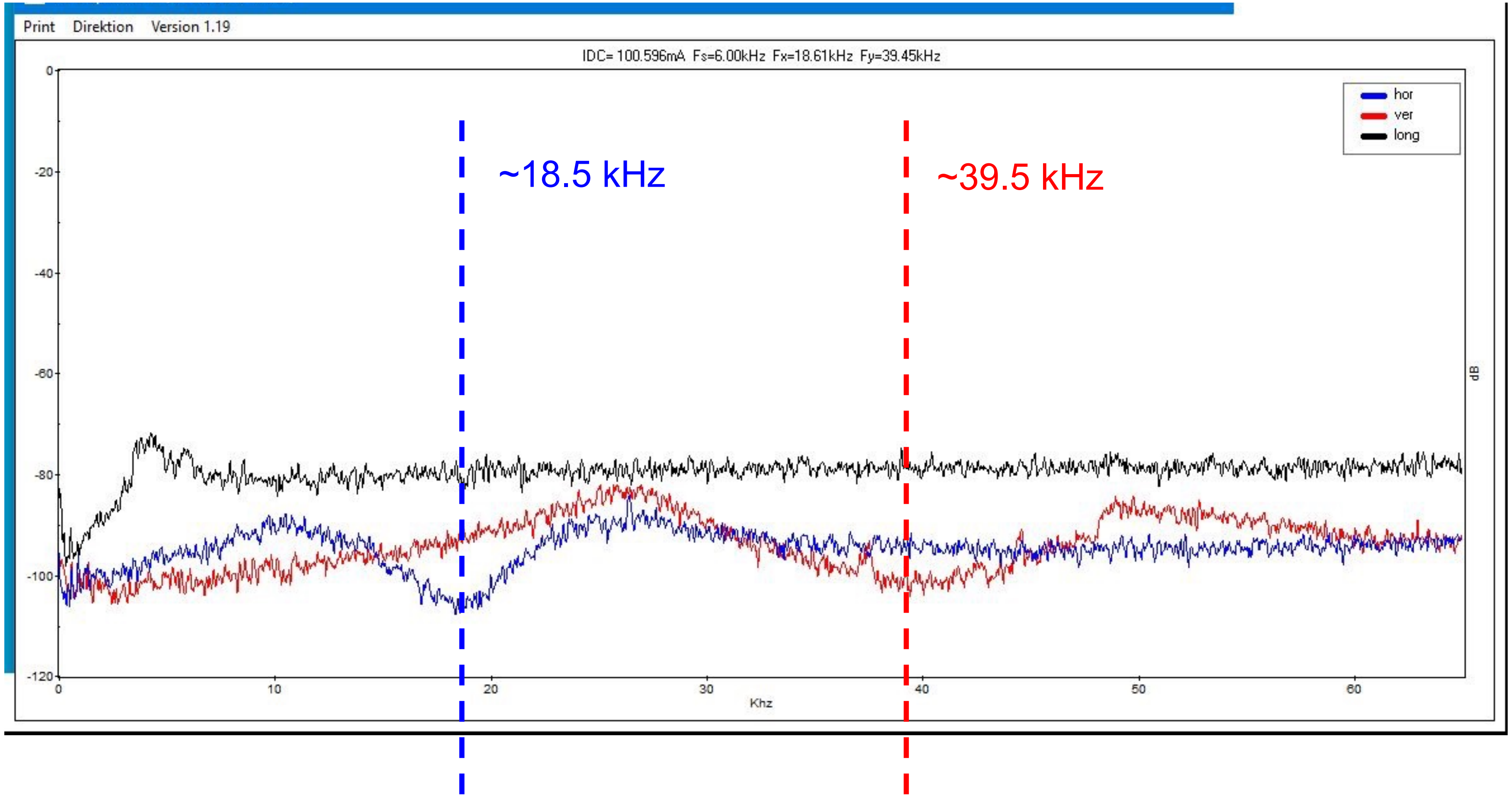


PETRA III emittance:
1.3 nmrad in horizontal

1% of that in vertical

Are the tunes set correctly?

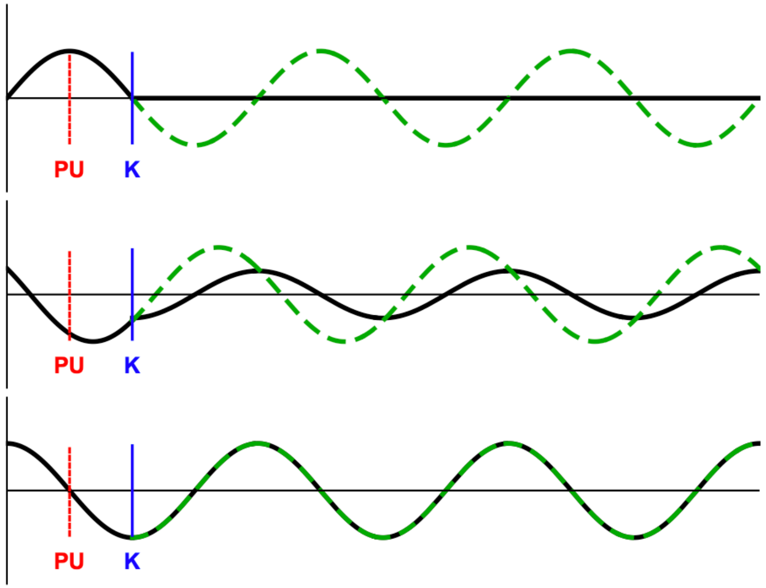
Tunes are measured by the Multi-bunch Feedback



Multi Bunch Feedback to reach design current

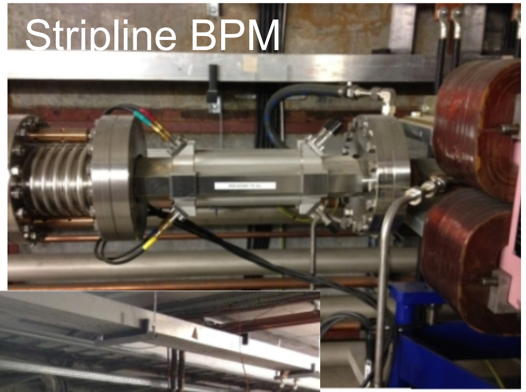
Without MBFB, coupled bunch instabilities limit beam current < 15mA

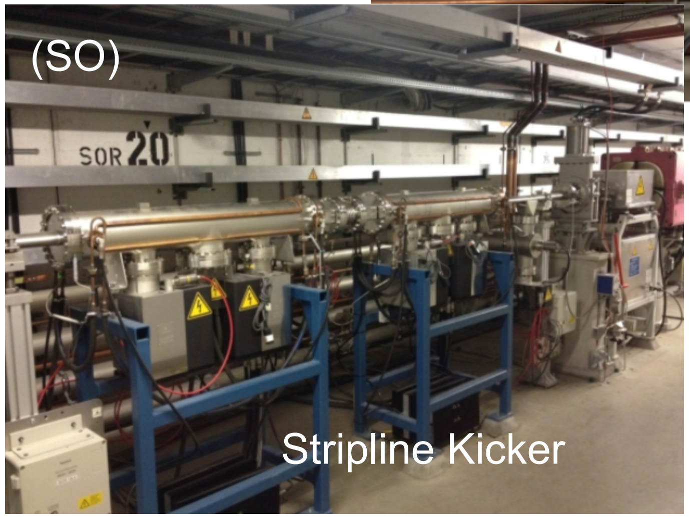
Measure bunch position with BPM - correct with kicker



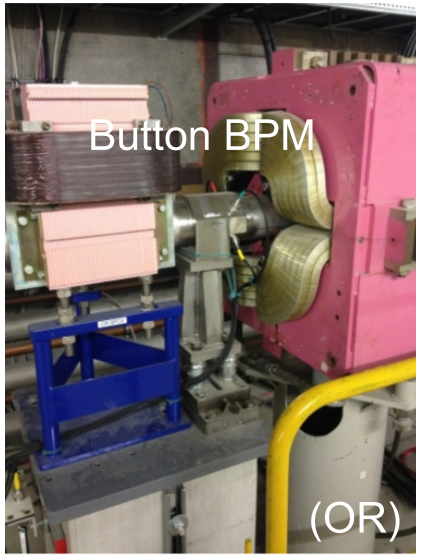
Amplitude → Angle (Kick)

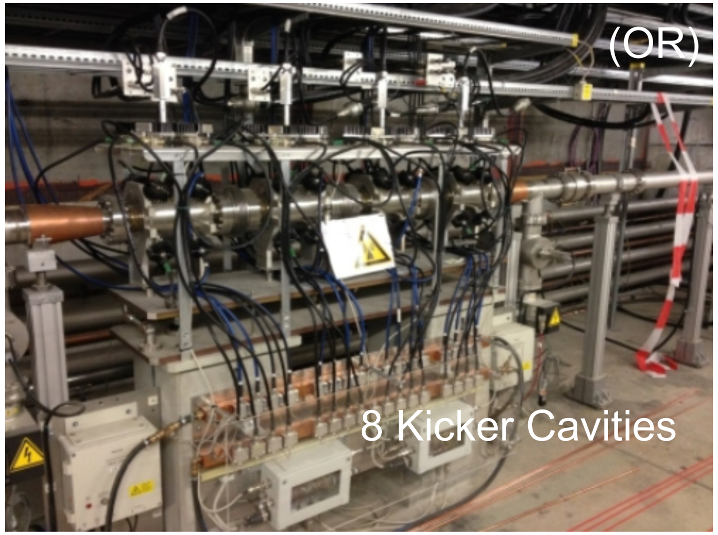
Transverse System





Longitudinal System





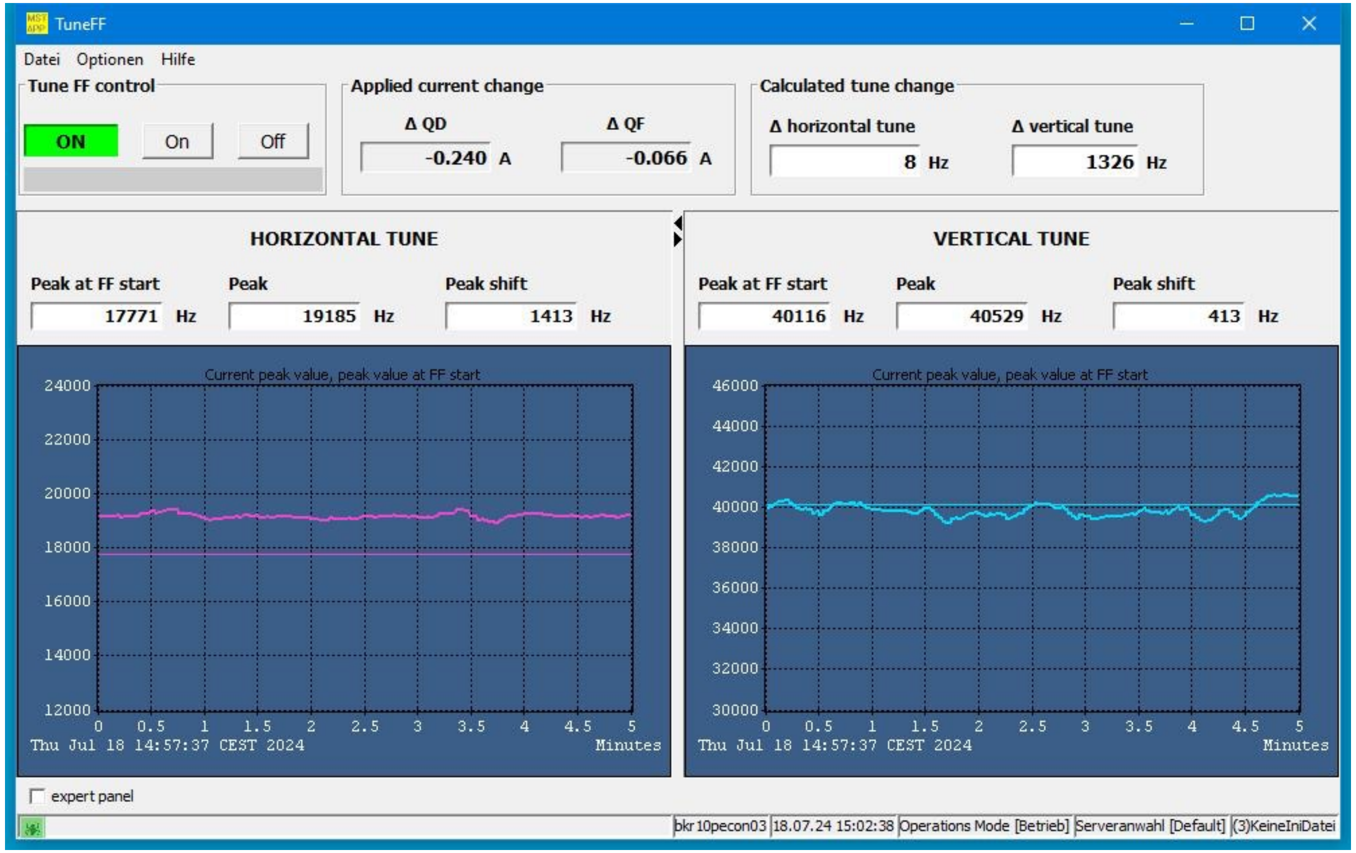
Measures the position of each bunch turn-by-turn, shift the signal by 90° in phase and feed back to the according bunch.

Switch on Tune Feedforward

Anticipation of predictable tune changes

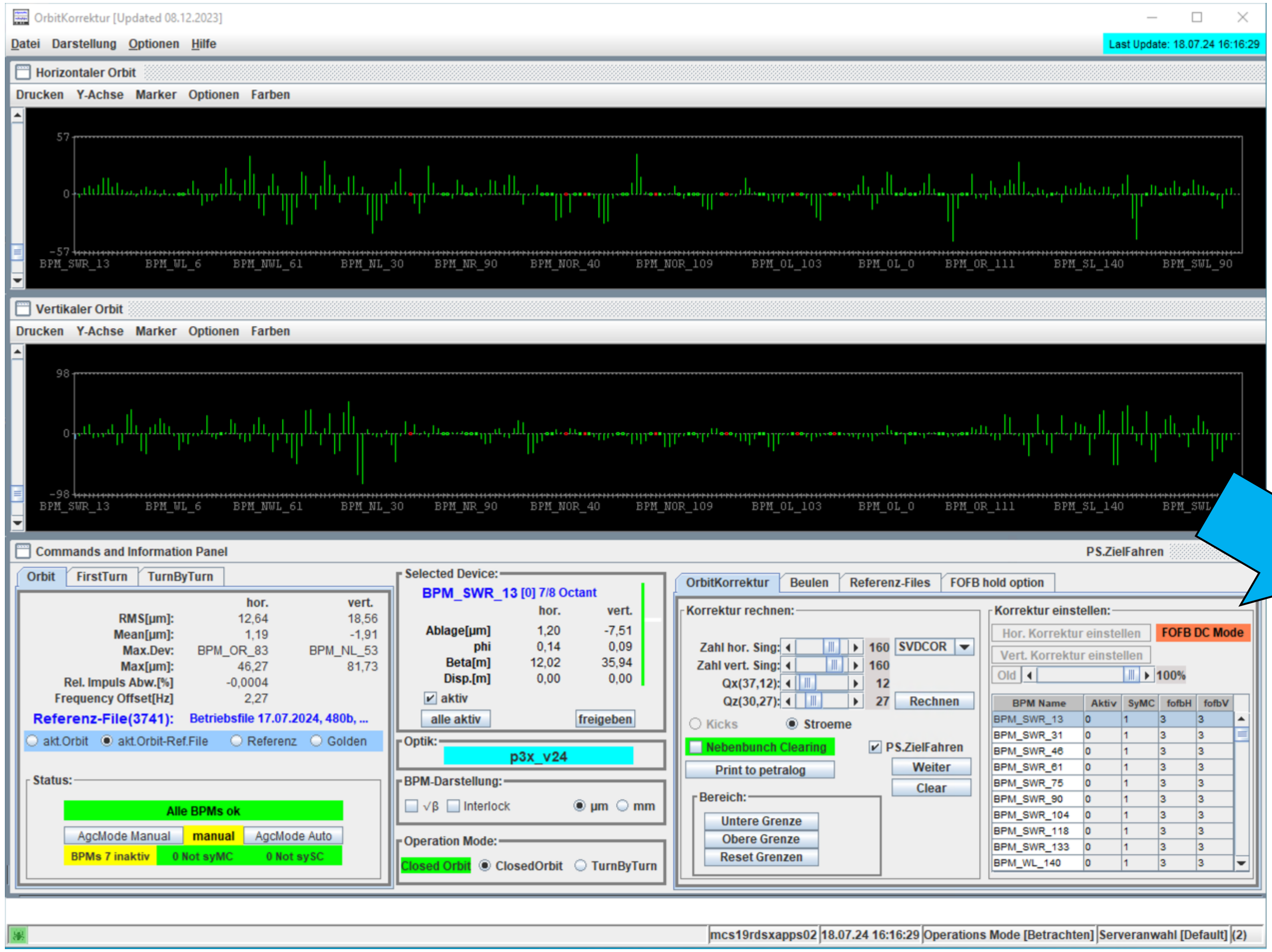
A **predictable tune shift** is introduced by
- Increasing the **bunch current**
- Changing the **undulator gaps**

The feedforward recognises these changes and adjusts the tune accordingly.

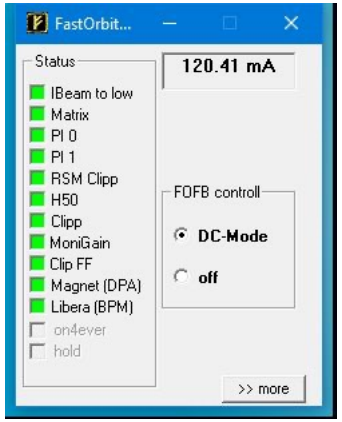


Setting the (optimal) Golden Orbit

And switch on the Fast Orbit Feedback (to keep it stable)

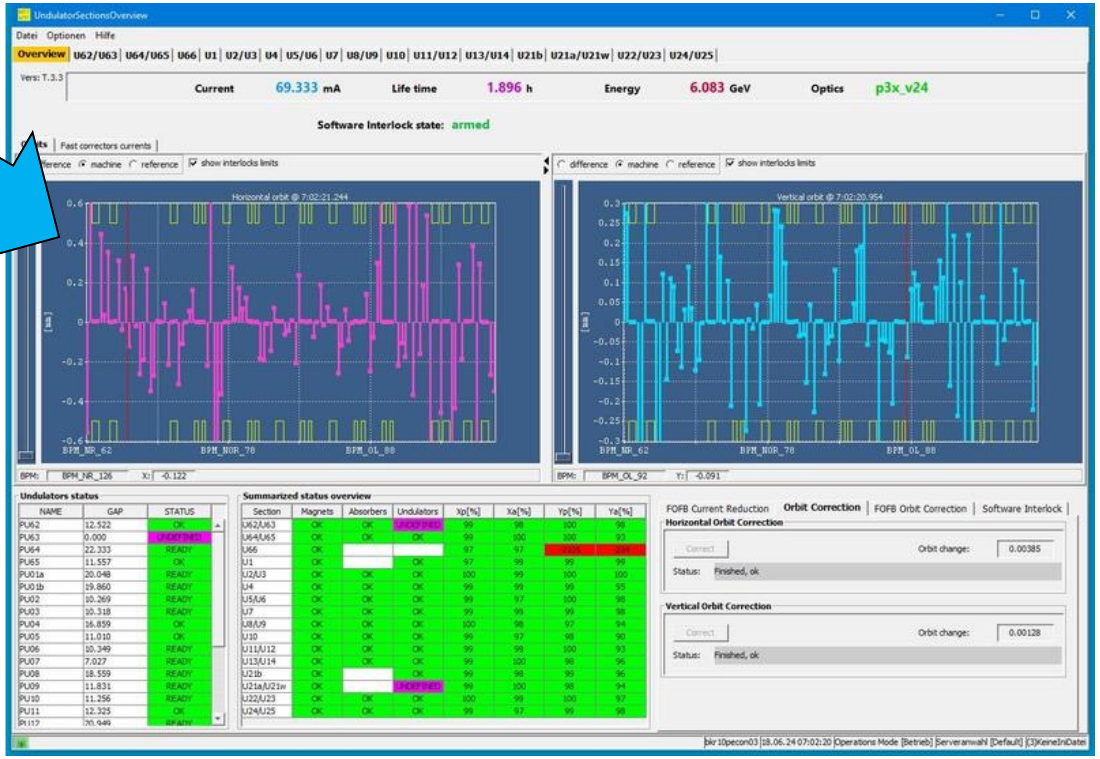


First correct the global orbit around the whole circumference.



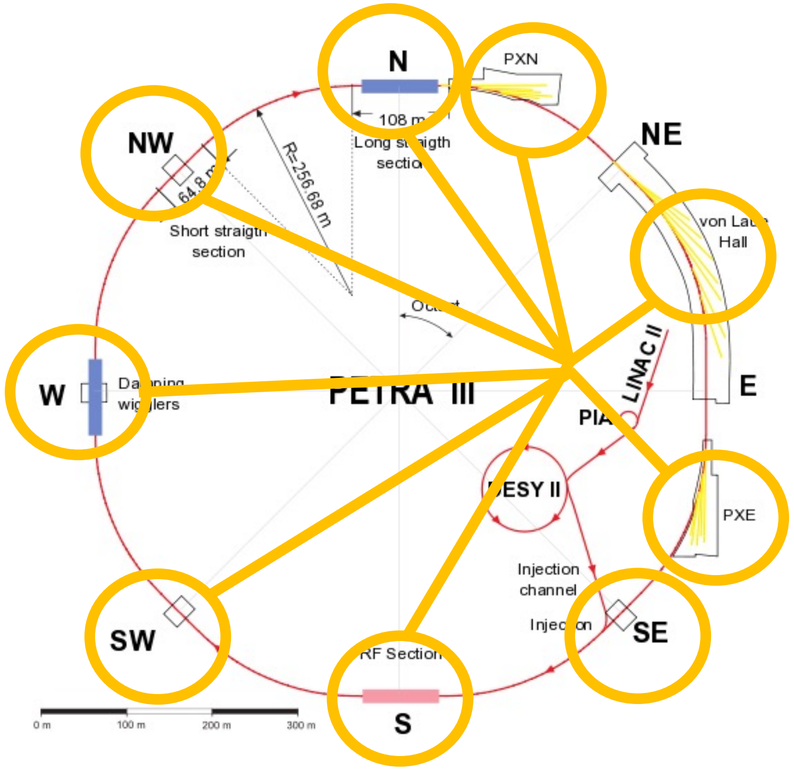
Switch on FOFB

Then do a fine correction for each beamline



Fast Orbit Feedback keeps the beam stable at $\pm 0.5\ \mu m$

Compensates fast orbit distortions from mechanical and electrical noise sources



218 BPMs measure the beam position around the ring

↓

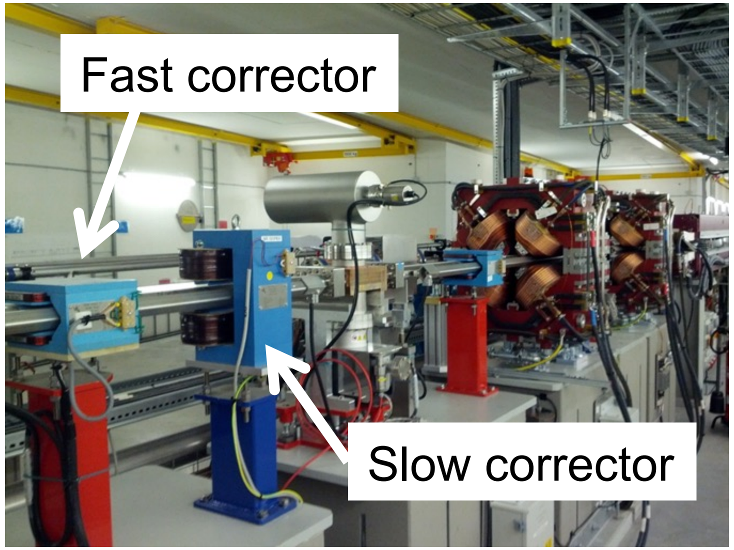
central processing unit

↓

40H+40V Fast air coil magnets apply correction kicks to the beam

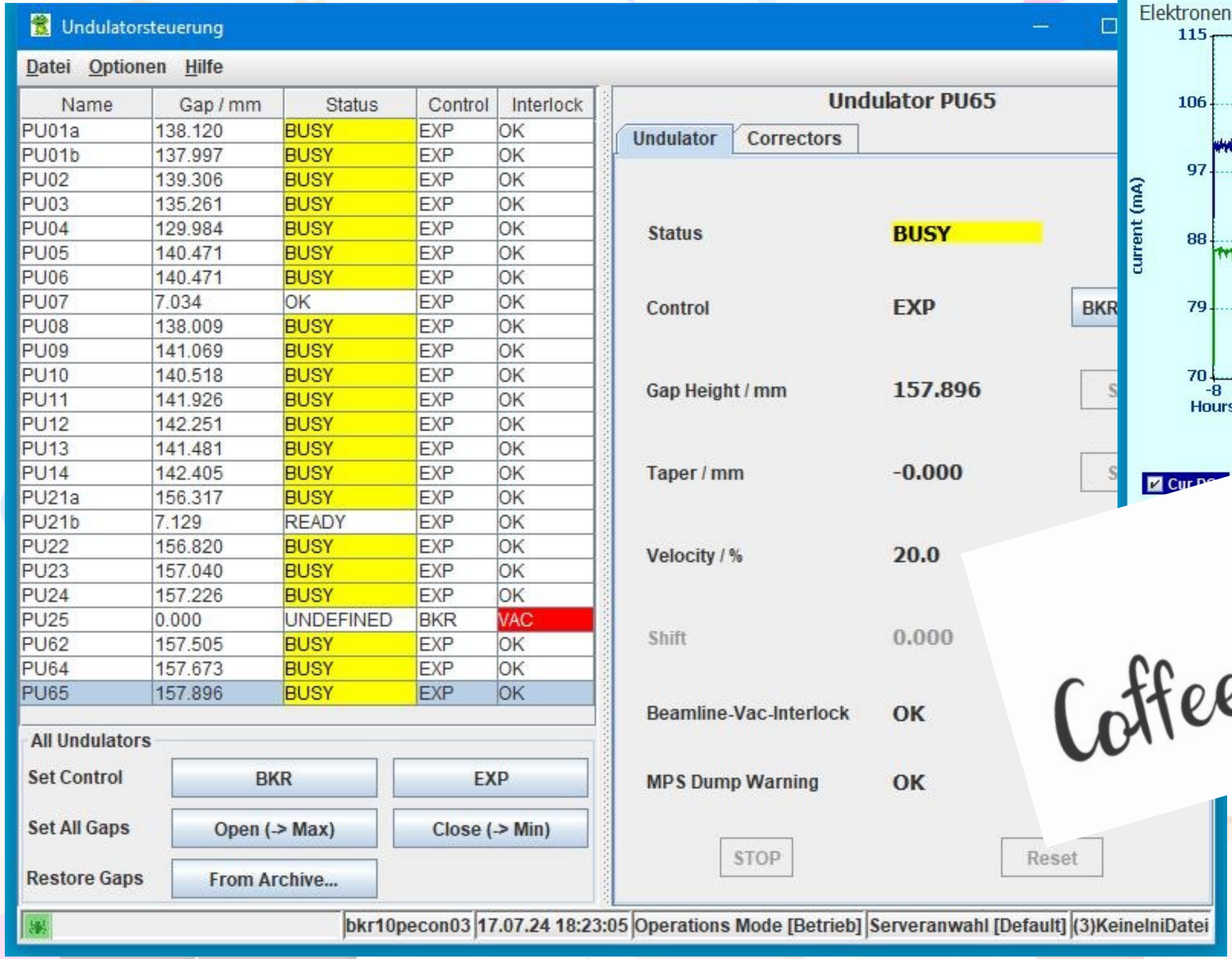
↓

Relaxing air coils to slow corrector magnets when accumulated current passes threshold

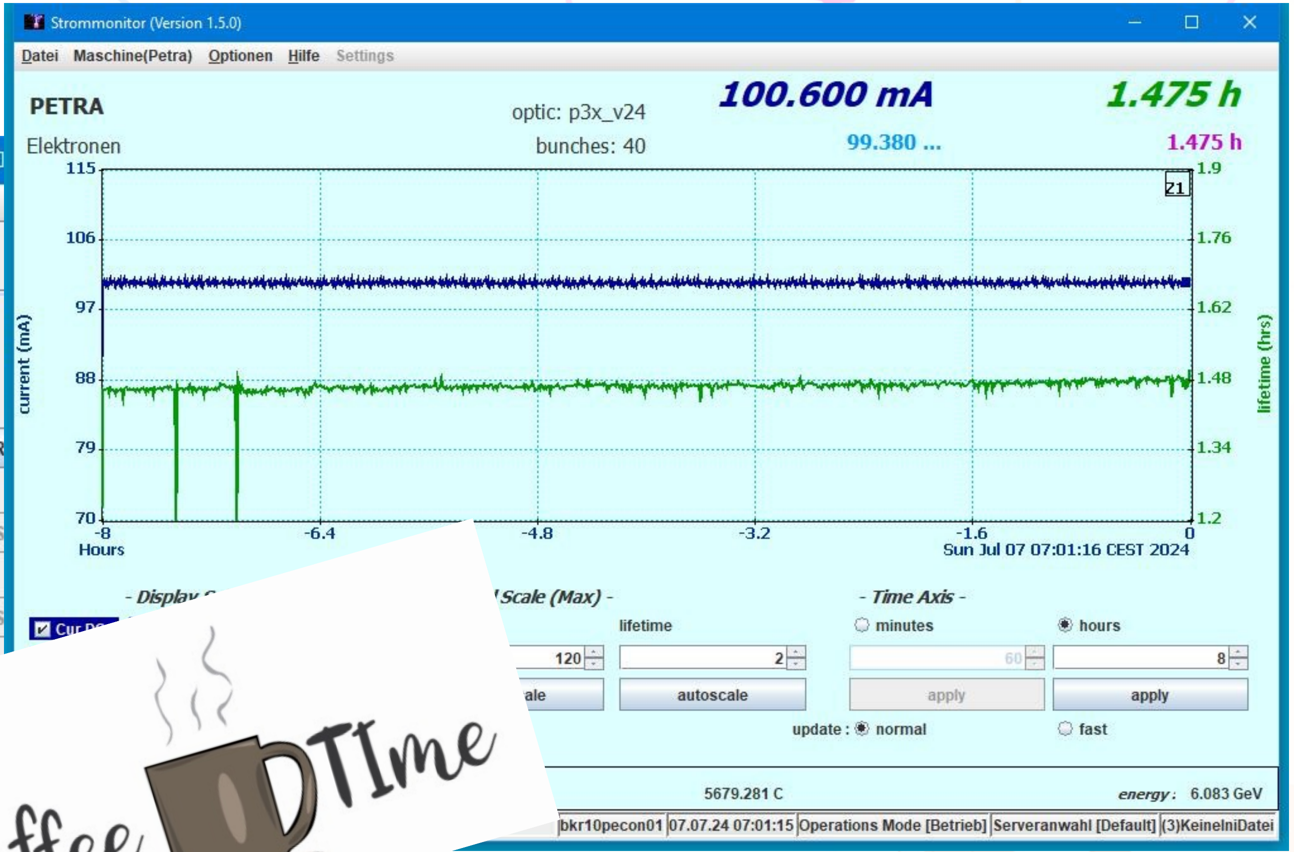


Beam is setup – Last step: Closing all undulators

Ready for User Operation !!!

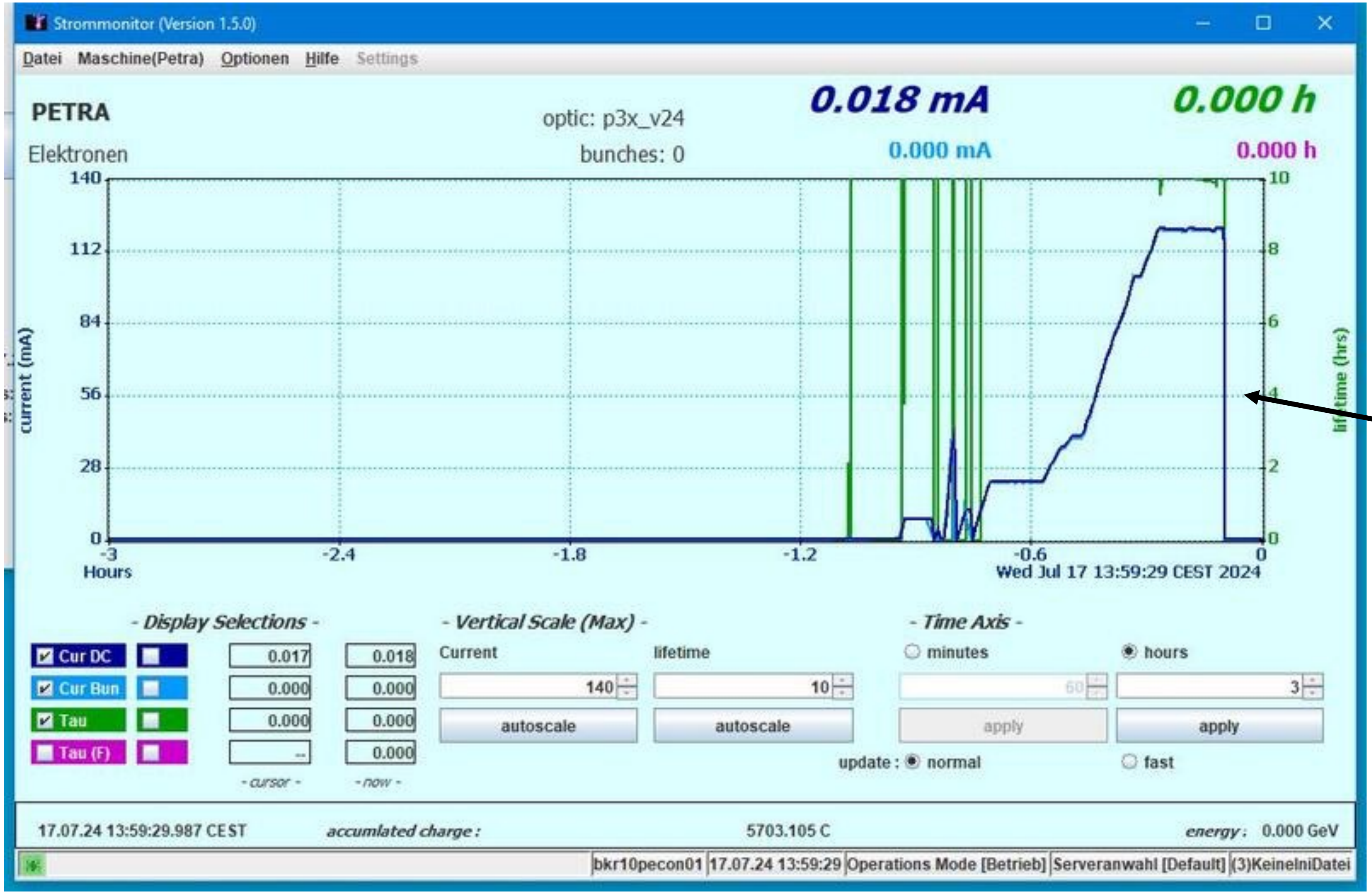


Name	Gap / mm	Status	Control	Interlock
PU01a	138.120	BUSY	EXP	OK
PU01b	137.997	BUSY	EXP	OK
PU02	139.306	BUSY	EXP	OK
PU03	135.261	BUSY	EXP	OK
PU04	129.984	BUSY	EXP	OK
PU05	140.471	BUSY	EXP	OK
PU06	140.471	BUSY	EXP	OK
PU07	7.034	OK	EXP	OK
PU08	138.009	BUSY	EXP	OK
PU09	141.069	BUSY	EXP	OK
PU10	140.518	BUSY	EXP	OK
PU11	141.926	BUSY	EXP	OK
PU12	142.251	BUSY	EXP	OK
PU13	141.481	BUSY	EXP	OK
PU14	142.405	BUSY	EXP	OK
PU21a	156.317	BUSY	EXP	OK
PU21b	7.129	READY	EXP	OK
PU22	156.820	BUSY	EXP	OK
PU23	157.040	BUSY	EXP	OK
PU24	157.226	BUSY	EXP	OK
PU25	0.000	UNDEFINED	BKR	VAC
PU62	157.505	BUSY	EXP	OK
PU64	157.673	BUSY	EXP	OK
PU65	157.896	BUSY	EXP	OK



What could possibly go wrong?

Accelerators are highly complex machines: if one small piece fails the accelerator is out of order!

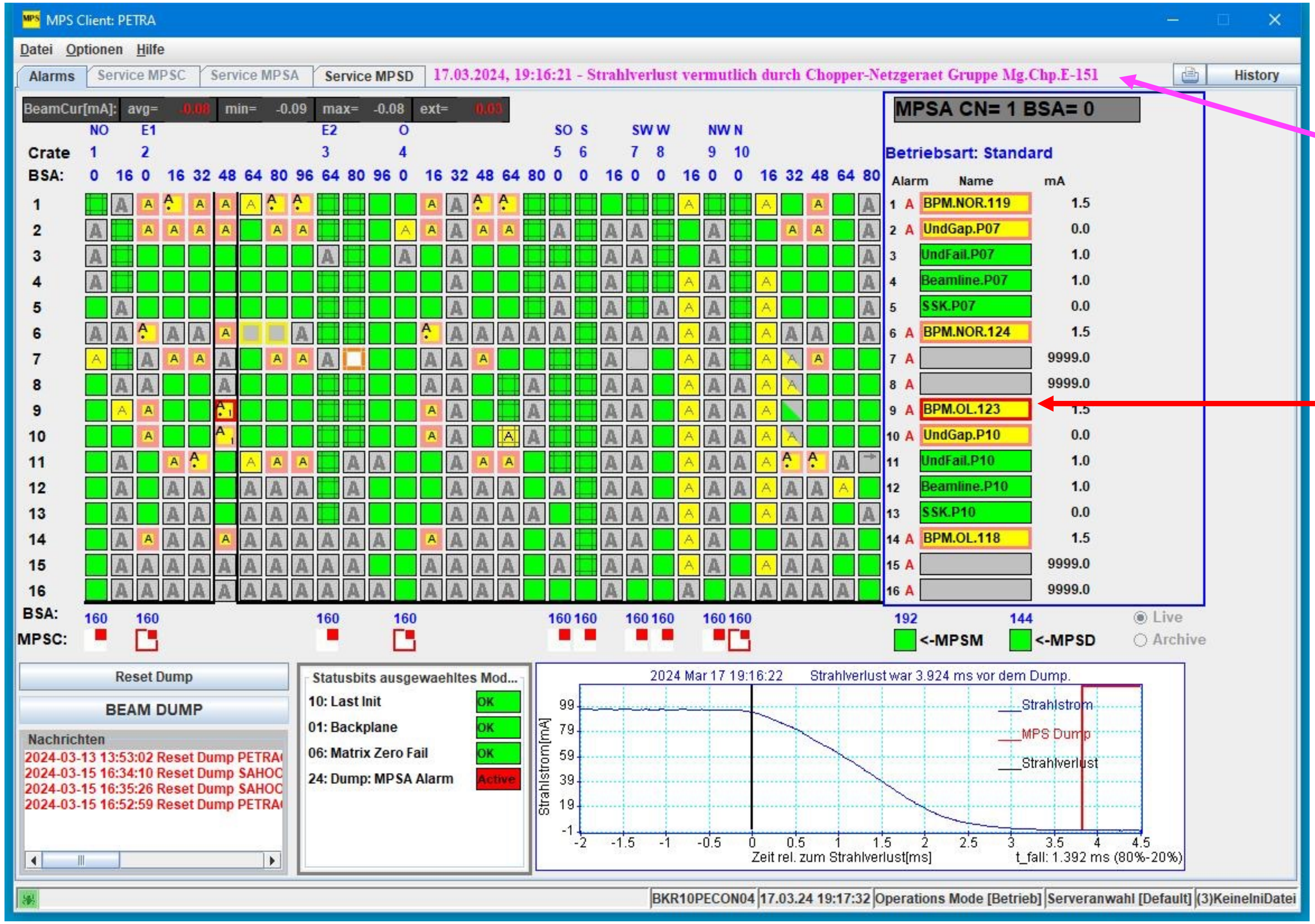


Beam dump!

But why?

What triggered the Beam Dump?

Machine Protection System (MPS) dumps the beam, if a system's interlock is activated



Preliminary root cause analysis:
Dump by power supply fault

Triggered by orbit interlock of BPM

Are there any Alarms?

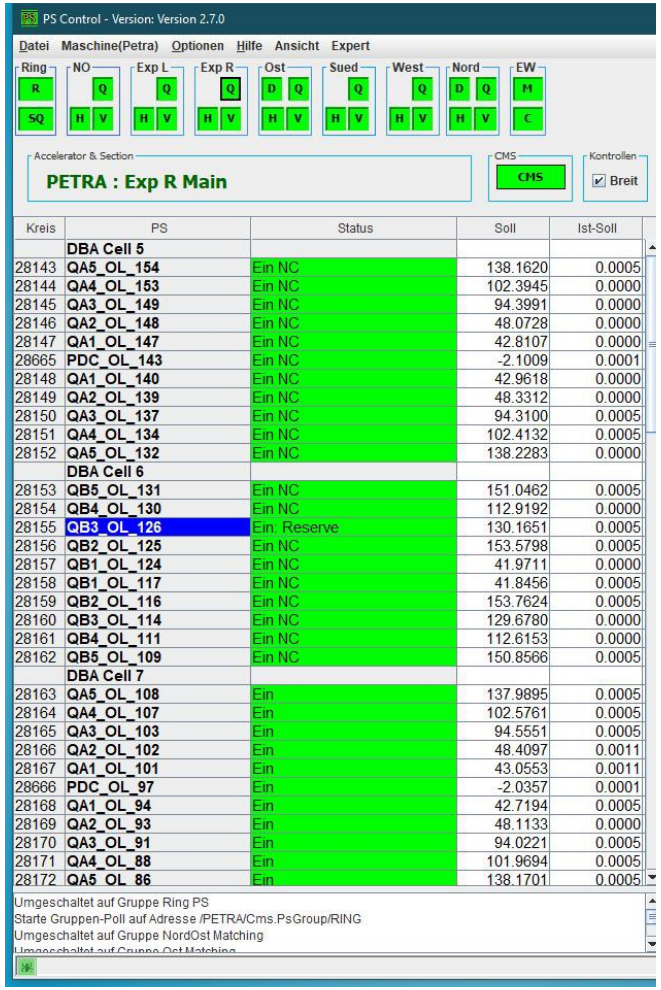
Red alarm on the status of a quadrupole power supply

Are all Power Supplies working?

Error found and fixed

Power supply control panel

Faulty power supply off

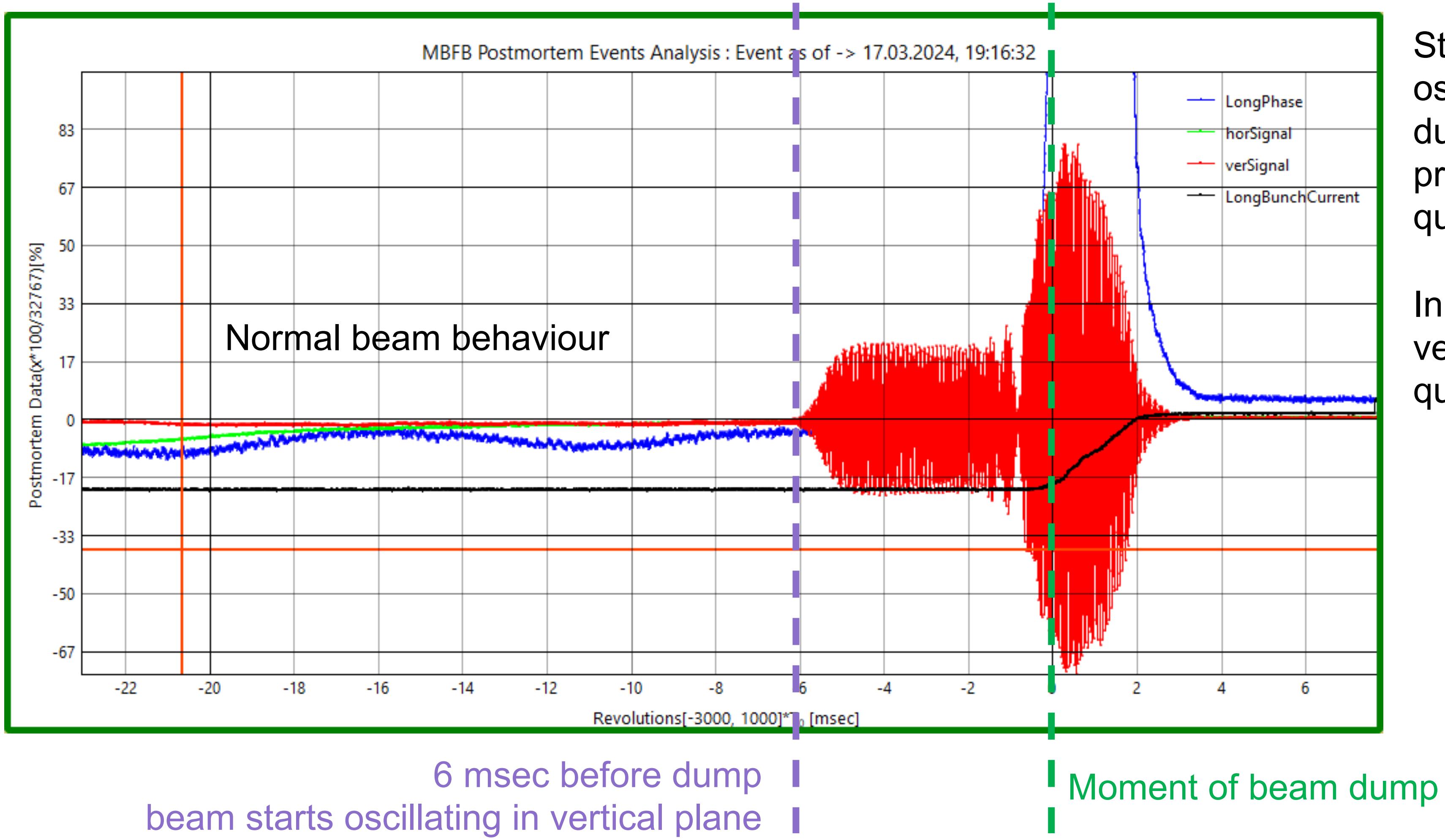


Investigation by PS expert

Switch to reserve PS to quickly continue operation

Repair done on next maintenance day

What does the Post Mortem Data tell me?



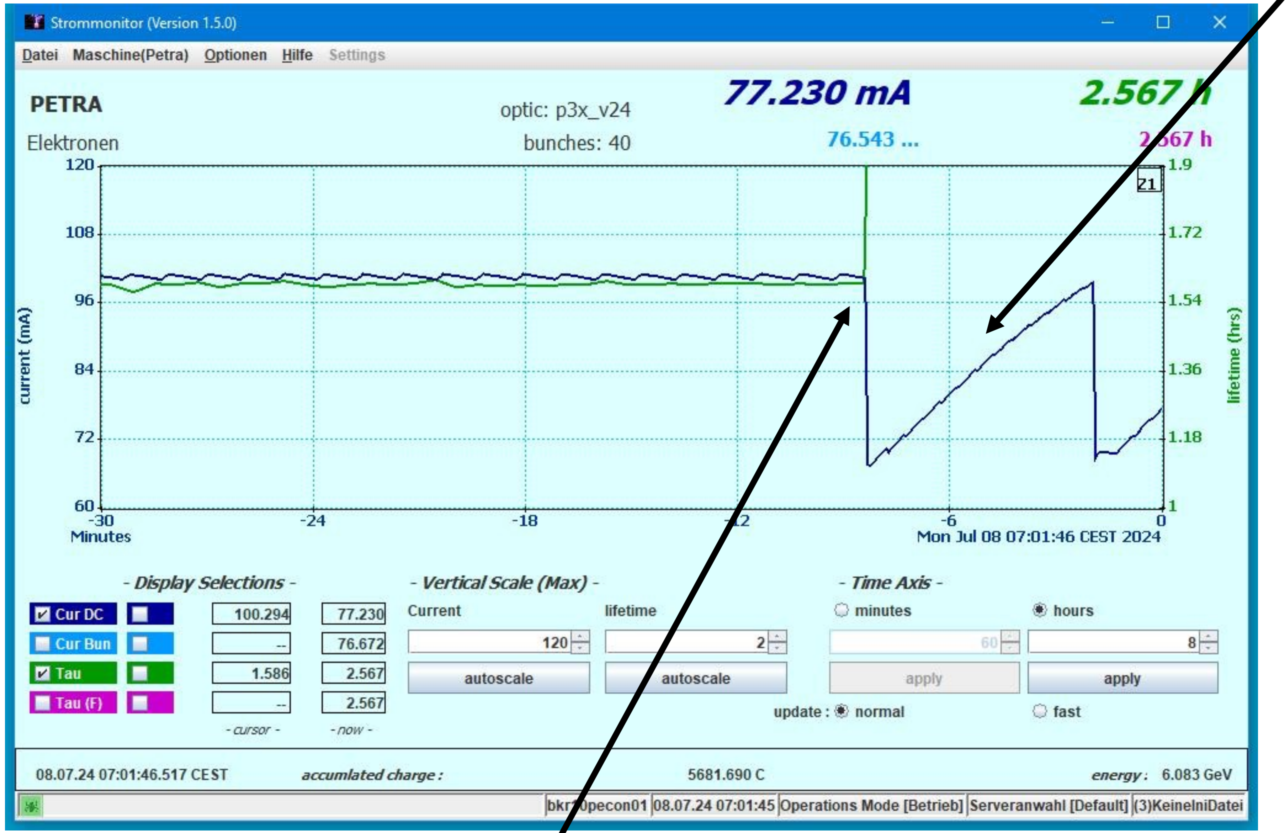
Strong beam oscillation before a dump points to a problem with a quadrupole.

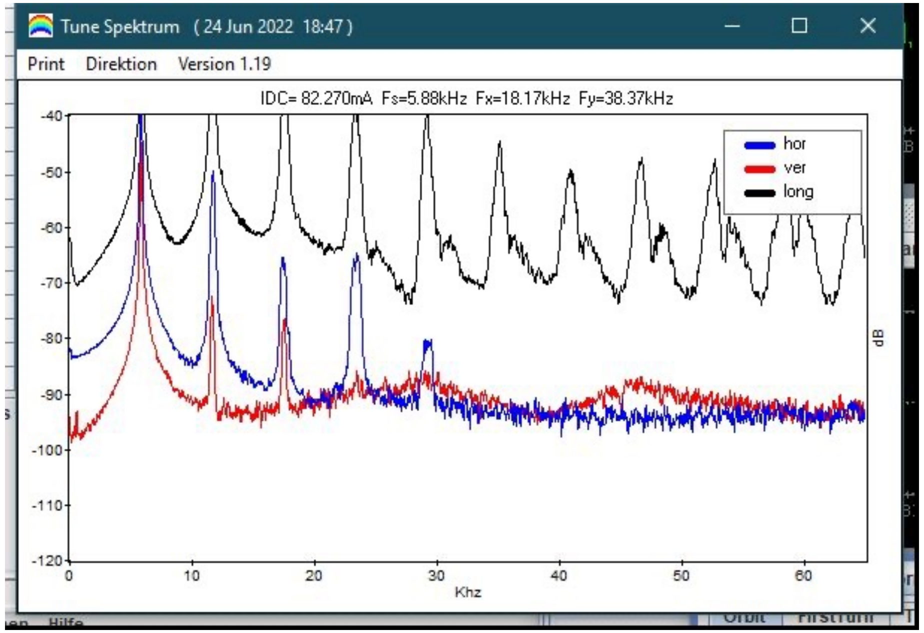
In this case, a vertically focusing quadrupole

Other Symptoms you might observe …

Unstable beam after a power glitch

TopUp recognises too low current and refills, but beam still unstable





Power glitch introduces transient on quadrupole
→ Beam becomes unstable and is partially lost

Feedback tries to counter, but out of range
→ Strong excitation visible on tunes

While beam is still circulating, it is useless for the users and needs to be dumped to reset.

Water Leak Alarm

600l of water went missing from the cooling circuit over the last two days

→ Tunnel access needed for leak search!

New cooling pipe installed along the beam pipe and fixed with clamps.

PETRA Accelerator Tour: Friday Aug 1, 2025, 13:30-14:30

1 August 2025
Universe
Europe/Berlin timezone

Enter your search term

- Overview
- Registration

Contact

michaela.schaumann@...

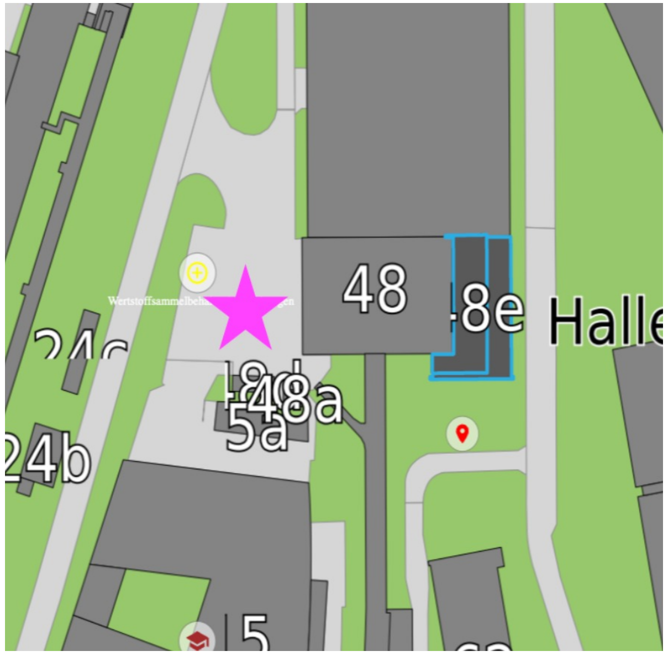
A tour is organised to the PETRA accelerator control room and tunnel on the DESY campus.

The number of participants is limited to 40, to be assigned on a first-come-first-served basis.

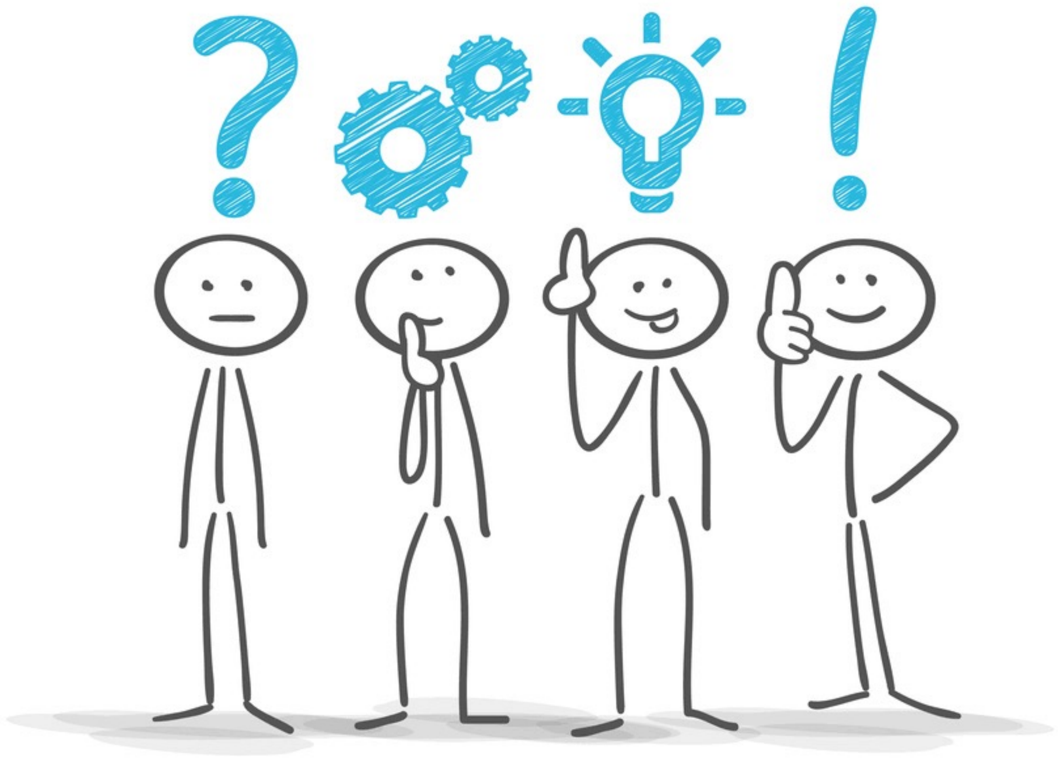
Meeting point is the Bld 48 (PETRA Ost Halle), forecourt to the left of the PETRA ring.

You can find Bld 48 on this map.

The exact meeting place is marked on the map below with a star



Register here:
https://indico.desy.de/event/49913/registrations/7038/



Everything clear! Hmm ….

Excercises

‘Smashing’ Modes and Center-of-Mass Energy

The center-of-mass energy defines the upper limit of the newly created particle’s mass

Fixed Target

$$E \propto \sqrt{E_{beam}}$$

Most of the Energy is lost in the target, only a fraction is transformed into useful secondary particles.

Collider

$$E = E_{beam1} + E_{beam2}$$

All energy is available for the production of new particles.

Exercise 2: Derive center-of-mass energy in fixed target and collider experiment.

Exercise 2: Derive center-of-mass energy in fixed target and collider experiment.

Center-of-mass (CM) frame is defined where sum of all momenta is zero: $\sum \vec{p}_i = \vec{0}$

4-momentum

$$p^\mu = (E/c, \vec{p}) \quad \longrightarrow \quad p^\mu p_\mu = \frac{E^2}{c^2} - \vec{p}^2$$

can be transformed to center-of-mass frame by Lorentz transformation:

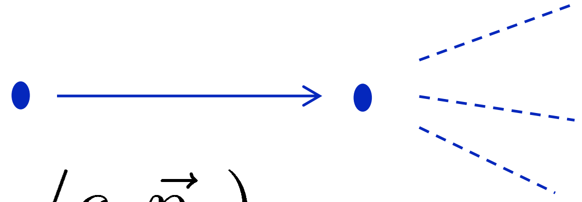
$$p'^\mu = L^\nu_\mu p^\nu$$ Lorentz Transformation

$$p^\mu p_\mu = p'^\mu p'_\mu$$ The norm: is Lorentz invariant

Energy conversation between both frames:

$$\frac{E_{CM}^2}{c^2} - \vec{0}^2 = \frac{E_{tot}^2}{c^2} - \vec{p}_{tot}^2 \quad \longrightarrow \quad \frac{E_{CM}^2}{c^2} = \frac{E_{tot}^2}{c^2} - \vec{p}_{tot}^2$$

Exercise 2 : E_{CM} in Fixed Target Experiment



$$p_2 = (m_2 c, \vec{0})$$

$$p_1 = (E_1/c, \vec{p}_1)$$

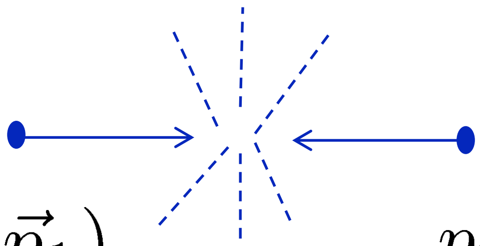
$$p_{tot} = (E_1/c + m_2 c, \vec{p}_1)$$

$$E_{CM}^2 = (m_1^2 + m_2^2)c^4 + 2E_1 m_2 c^2$$

$$E_{CM} \propto \sqrt{E_1}$$

Exercise 2: E_{CM} in Collider Experiment

Laboratory Frame = CM Frame



$$p_1 = (E_1/c, \vec{p}_1) \qquad p_2 = (E_2/c, -\vec{p}_1)$$

$$E_{CM} = E_1 + E_2$$

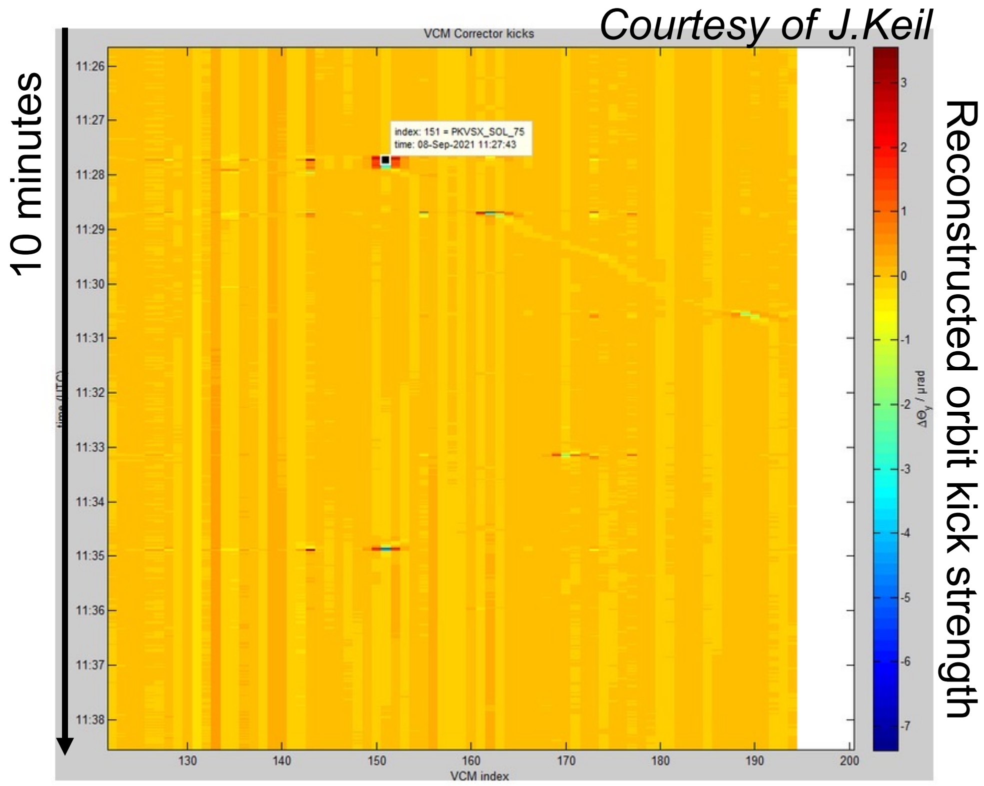
Back-Up Slides

Beam Stability critical for Photon Beam Quality

Car Traffic Impacts Circulating Beam

42 t crane driving on DESY side: crossing or moving along the PETRA III tunnel.

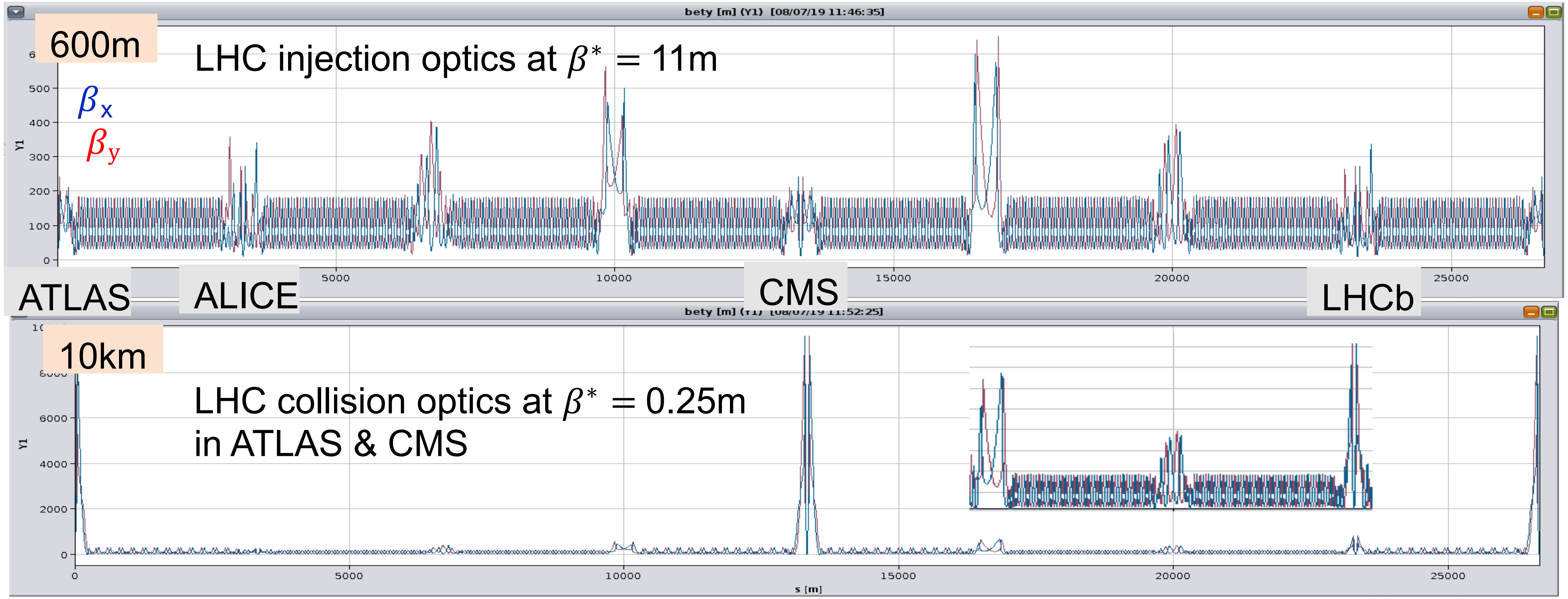
Track of truck over DESY side
☆ Tunnel crossings, ➡ close approaches



Crane route is strongly correlated to the location of reconstructed orbit kicks, which the fast orbit feedback is compensating.

"Beta* - Squeeze" at high beam energies

The β-functions, and thus beam sizes, in the triplet for small β^* is too large at injection energy
→ aperture problems.
→ beam size shrinks with energy $\sigma \propto \sqrt{1/\gamma}$
→ Mini-beta **squeeze** done at top energy when beam size is smaller.



Integrated Luminosity

What counts for the experiments is not peak performance, but total accumulated number of events

$$\sigma_p \cdot \mathcal{L}_{int} = \sigma_p \cdot \int_0^T \mathcal{L} dt$$

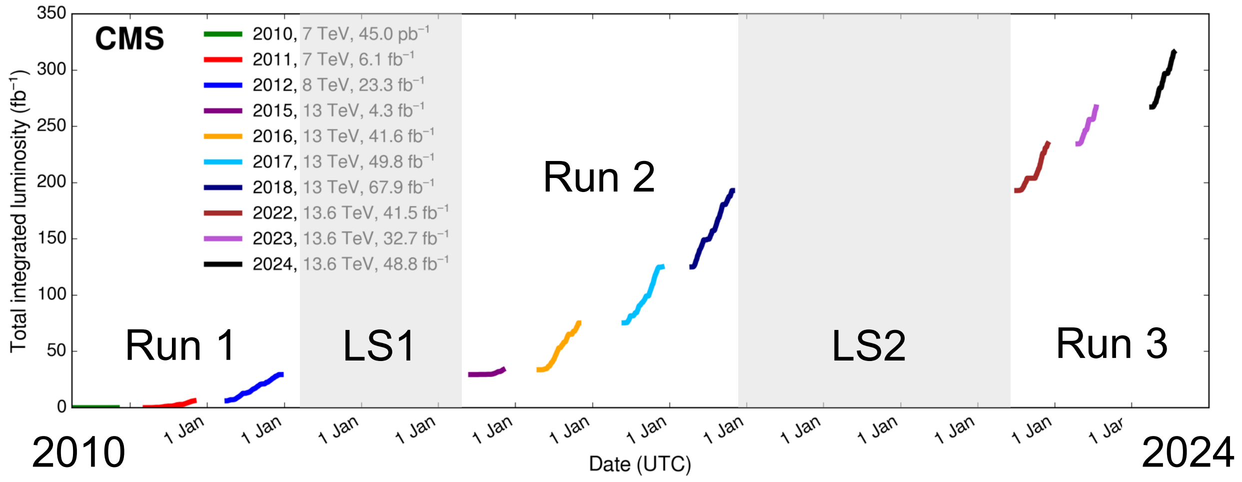
unit "barn" = 10^{-24} cm^2

unit " inverse barn" = 10^{24} cm^{-2}

Common order of magnitude: 1 fb^{-1} = 10^{39} cm^{-2}

For example:
To integrate 1 fb^{-1} it requires 10^7 s at
$\mathcal{L} = 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

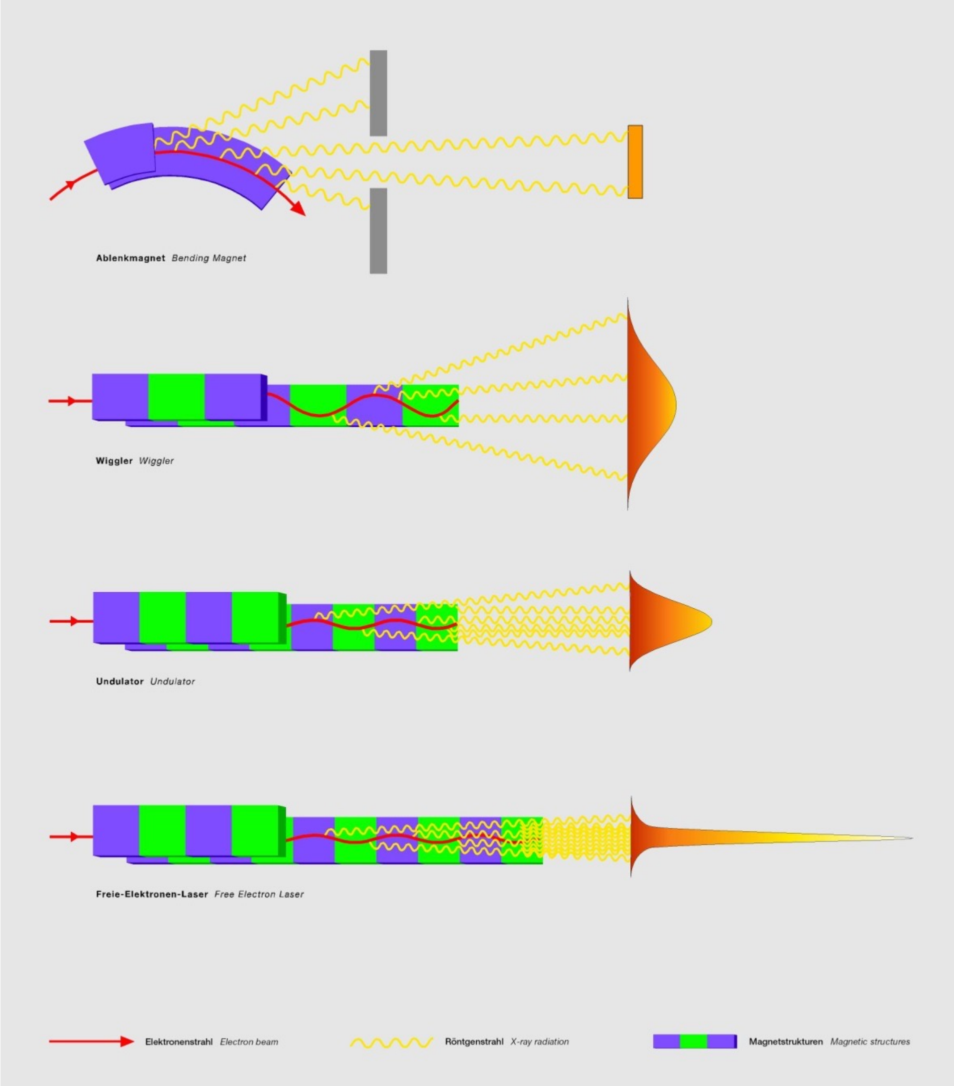
For comparison: a year has about $\pi \times 10^7$ s.



LHC has delivered so far ~350 fb^{-1} to ATLAS/CMS in proton-proton collisions over 10 production years.

Different Ways to produce Synchrotron Radiation

Each charged particle emits electromagnetic radiation when radially accelerated



Storage ring: acceleration towards the ring inside → emission in traveling direction with opening angle $1/\gamma$

Wiggler: slalom path, large opening angle

Undulator: slalom path, small opening angle

Free electron laser: very small opening angle, laser-like amplification

Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Name Surname
Department
E-mail
Phone