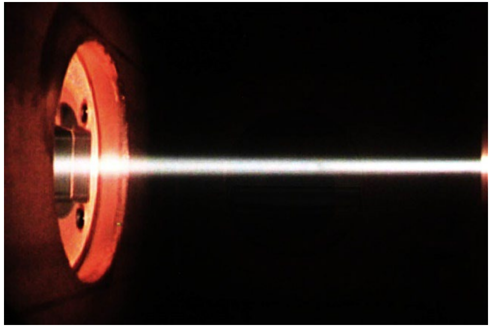
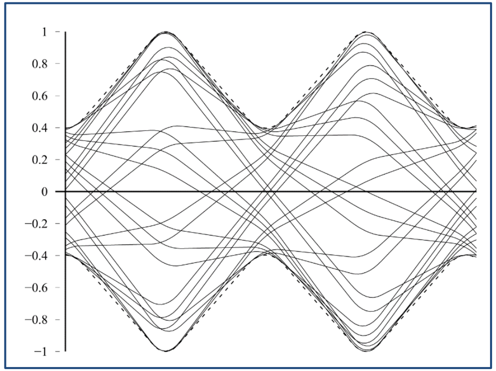




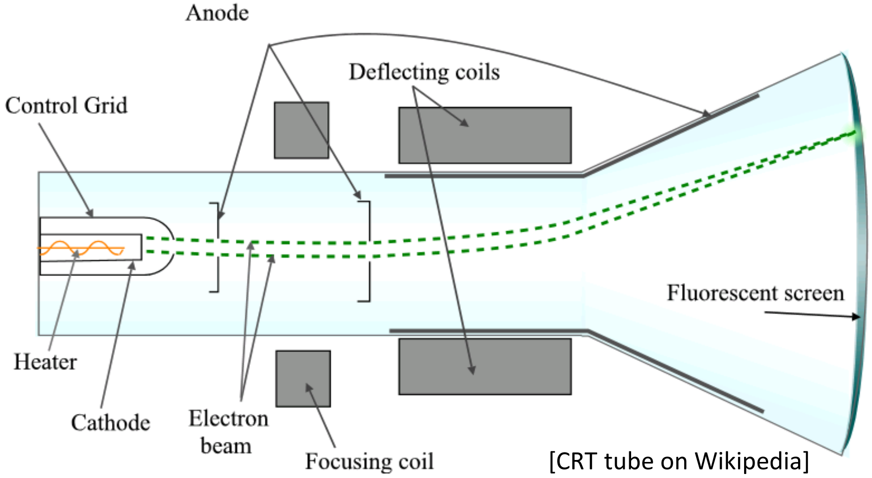
Particle Accelerators, Tools for Basic Research

L aboratory
P article
A ccelerator
P hysics

EPFL

Mike Seidel
EPFL / PSI

Particle Accelerator



[CRT tube on Wikipedia]

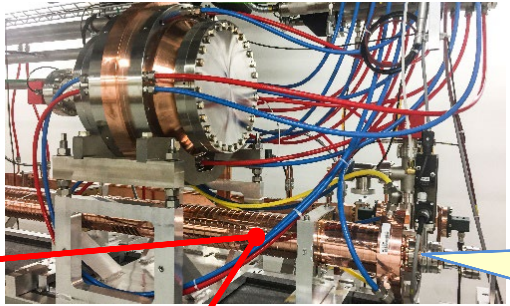
main operating principles

- acceleration in electric fields
- steering in magnetic fields
- focusing in magnetic fields

particle energy, for example: $U = 20\ \text{kV} \rightarrow E_k = e \times U = 20\ \text{keV}$

Accelerating Things and Particles

	Acceleration	Velocity
Motorcycle (300 kg)	1 g	0.085 km/s
Bullet (0.004 kg)	10^5 g	1 km/s
Electron (10^{-30} kg)	2×10^{16} g	299‘780 km/s (99.996 % × c)



one SwissFEL accelerator structure:

56 MV over 2m length

→ particles quickly become «relativistic», approach speed of light

→ instead of getting faster they become «heavier»

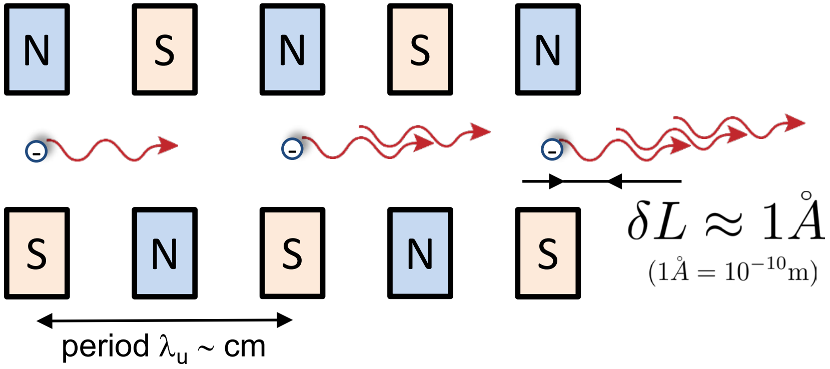
$$\gamma = \frac{E_{\text{tot}}}{mc^2} = 110$$

Amazing Properties of Accelerators:
Extreme relativistic speed of electrons

particles approach the speed of light very closely

for example: $E = 6\,\mathrm{GeV}, \quad \frac{\delta v}{v} \approx \frac{1}{2\gamma^2} = 3.6 \cdot 10^{-9}$

constructive interference of X-ray radiation in undulator magnet (time delay & path lengthening are relevant)



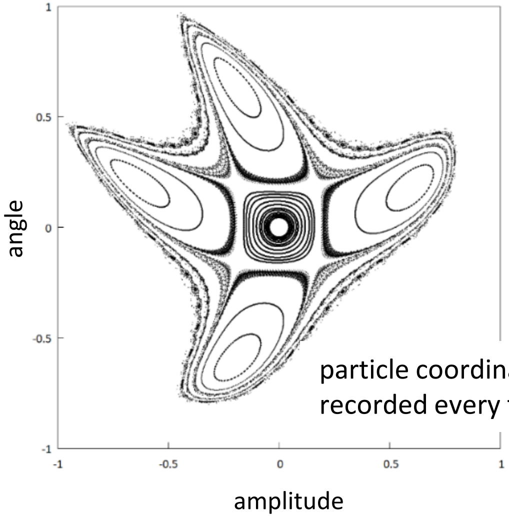
Amazing Properties of Accelerators
“Frictionless Motion” and Nonlinear Dynamics

solar system:
$\tau_{earth} \sim 4.5\times10^9$ years or cycles

accelerator long term dynamics:
e.g. storage time in a proton ring
$\tau_{beam} \sim 20\text{h} \approx 10^{10}$ cycles

$\rightarrow$ nonlinear dynamics becomes relevant for long term stability

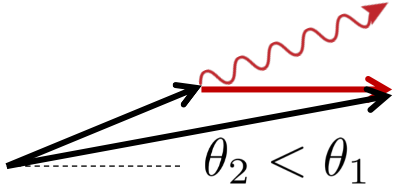
quadratic map, tune near fourth-order resonance



particle coordinates
recorded every turn

Amazing Properties of Accelerators
Quantum Effects in Electron Storage Rings

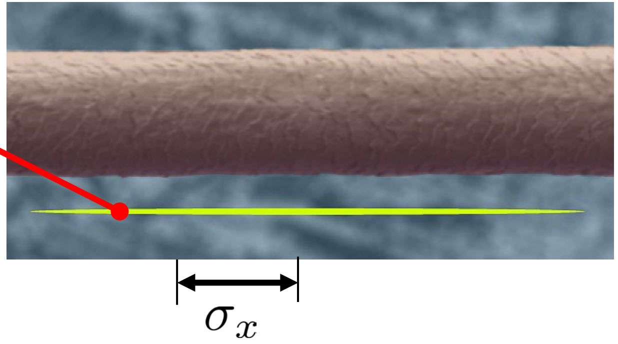
radiation damping by replacing lost momentum ⟷ statistical equilibrium ⟷ **excitation by emission of individual photons**



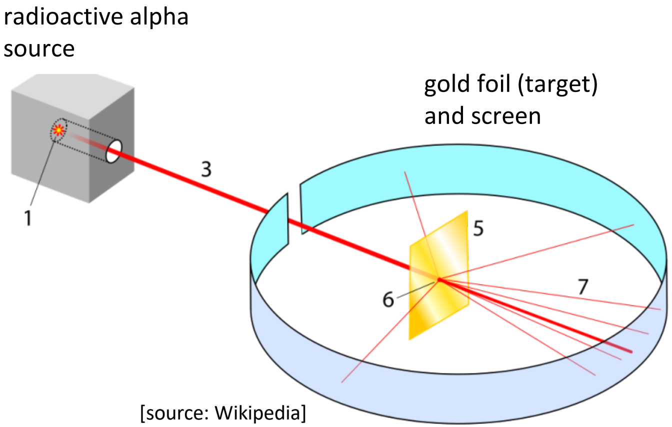
human hair and SLS beam cross section

beam size depends **on Planck's quantum**

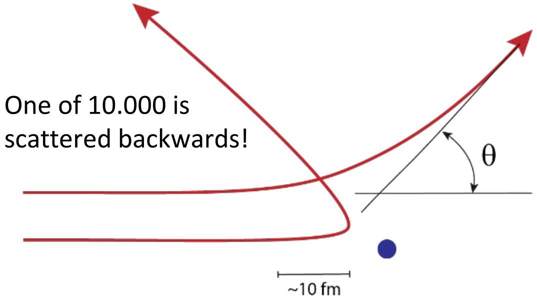
simple lattice: $\sigma_x^2 \approx \frac{55}{32\sqrt{3}} \frac{\hbar c}{m_0 c^2} \frac{\beta_x R}{J_x \rho} \frac{\gamma^2}{Q_x^3}$



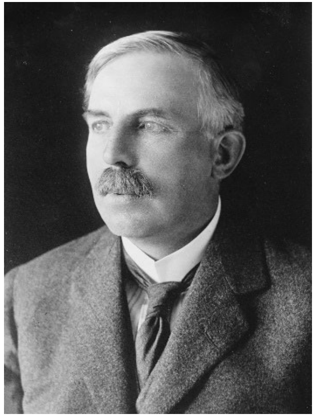
Rutherford Scattering
- an early model for **accelerator research applications**



[source: Wikipedia]



de Brogli wavelength (resolution): $\lambda = \frac{h}{p}$

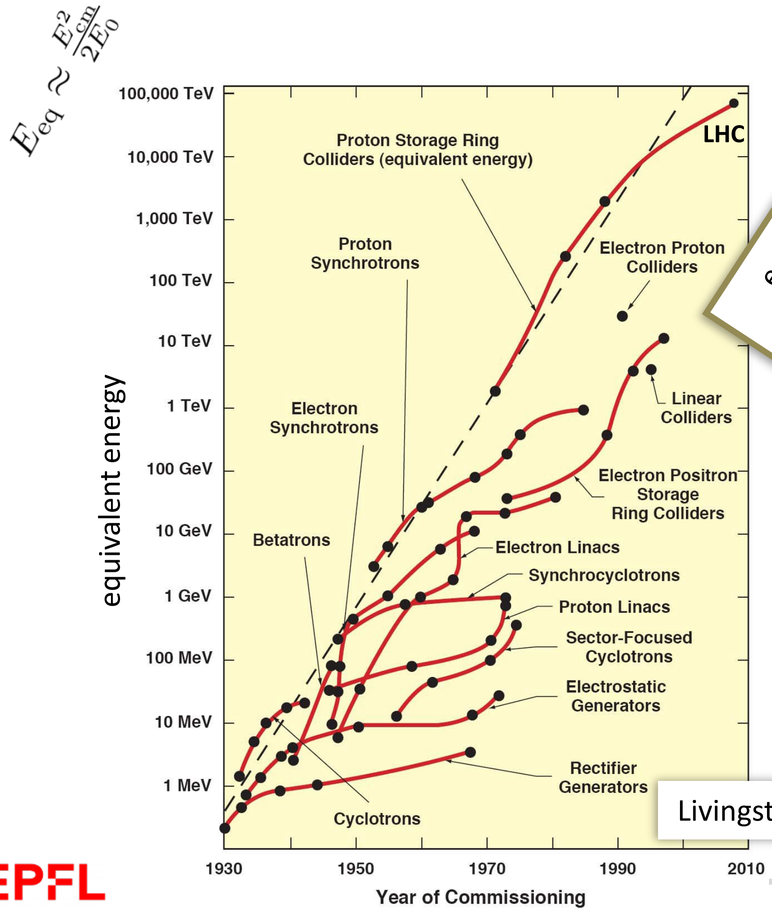


[Ernest Rutherford, Nobel Prize 1908]

Lord Rutherford (1927 @ Royal Society):

“I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances.”

Accelerator Development



Livingston Chart

energy frontier, FCC/LC studies

particle colliders

condensed matter, biology, medicine, materials

precision physics

synchrotron light sources

free electron laser

neutron sources

particle therapy

muon, neutrino sources, UCNs etc.

Bridging CERN, PSI and EPFL in Switzerland

CERN

- Large Hadron Collider + upgrade
- FCC studies (hh, ee, eh)
- CLIC linear collider study

- various accelerator technology R&D

PSI

- Synchrotron Light Source
- Free Electron Laser
- High Intensity Proton Accelerator
- Proton Therapy

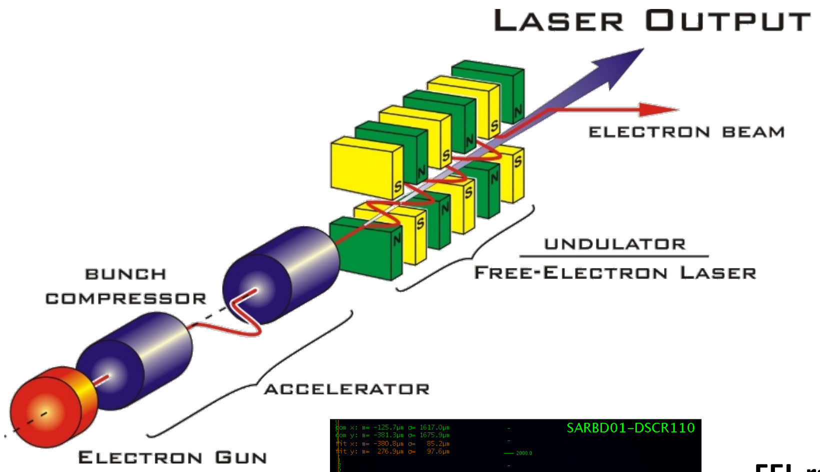
- various diagnostic methods at RIs

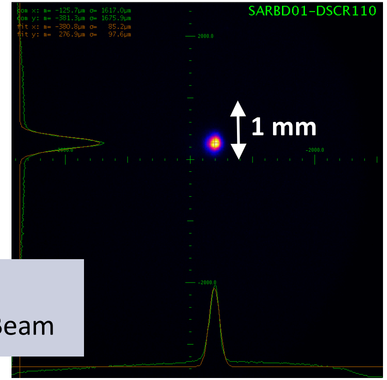
EPFL Laboratory for Particle Accelerator Physics

- Accelerator research at the forefront of the field.
- Themes aligned with development projects of CERN and PSI.
- Education of accelerator scientists and engineers.

LPAP Project Examples

Generating Intense Radiation Pulses by a Free Electron Laser





SwissFEL Photon-Beam

SwissFEL@PSI with L = 0.8km, E_e = 5.8 GeV

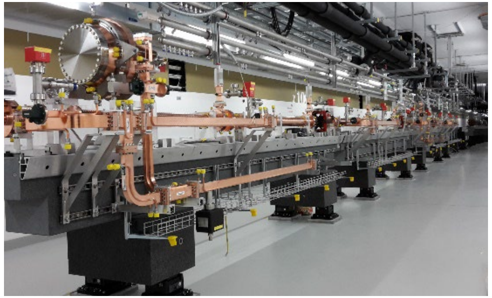
SwissFEL, since 2017

FEL radiation:
$\lambda \approx 0.5 .. 500$ Å
$\tau \approx 1 .. 1000$ fs

extreme brightness of photon beam:

- high peak power, eg. 50 GW
- eq. radiation from sun on 8km x 8km area (!)

400m linear accelerator, 28MV/m



Attosecond X-Ray FEL Pulses

EPFL/PSI PhD project, **Longdi Zhu**, PSI supervisor: S.Reiche

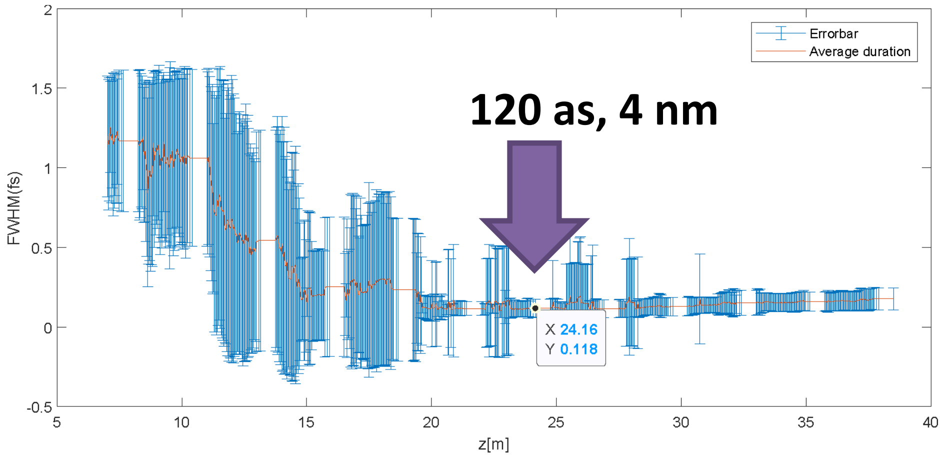
Method:
- manipulation of particle distribution to enhance lasing of a short sub-section of the bunch
- energy modulation by a conventional laser (800nm), delay chicanes between undulators, longitudinal taper of undulator strength

Application:
- e.g. study of molecular reactions at their natural time scale (electron dynamics)

light travels 300nm during 100as !

Simulation Result:

Average FWHM photon pulse duration along undulator



L.Zhu, E.Ferrari, S.Reiche, FEL2022

EPFL PSI

A positron source demonstrator for future colliders

LPAP/PSI/CERN PhD project, **Nicolas Vallis**, PSI supervisor: P.Craievich

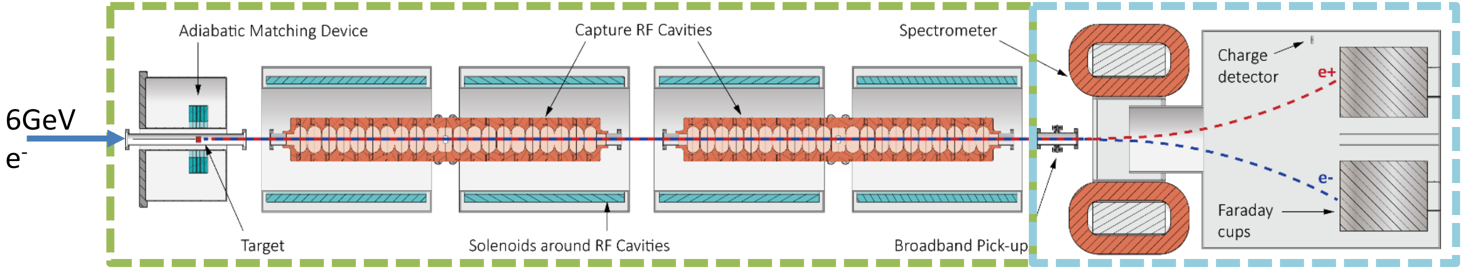
positron source concept:

high energy electrons → target → e^+,e^-,γ → quick acceleration → e^+ separation

A new type of positron source is to be developed for a future CERN collider

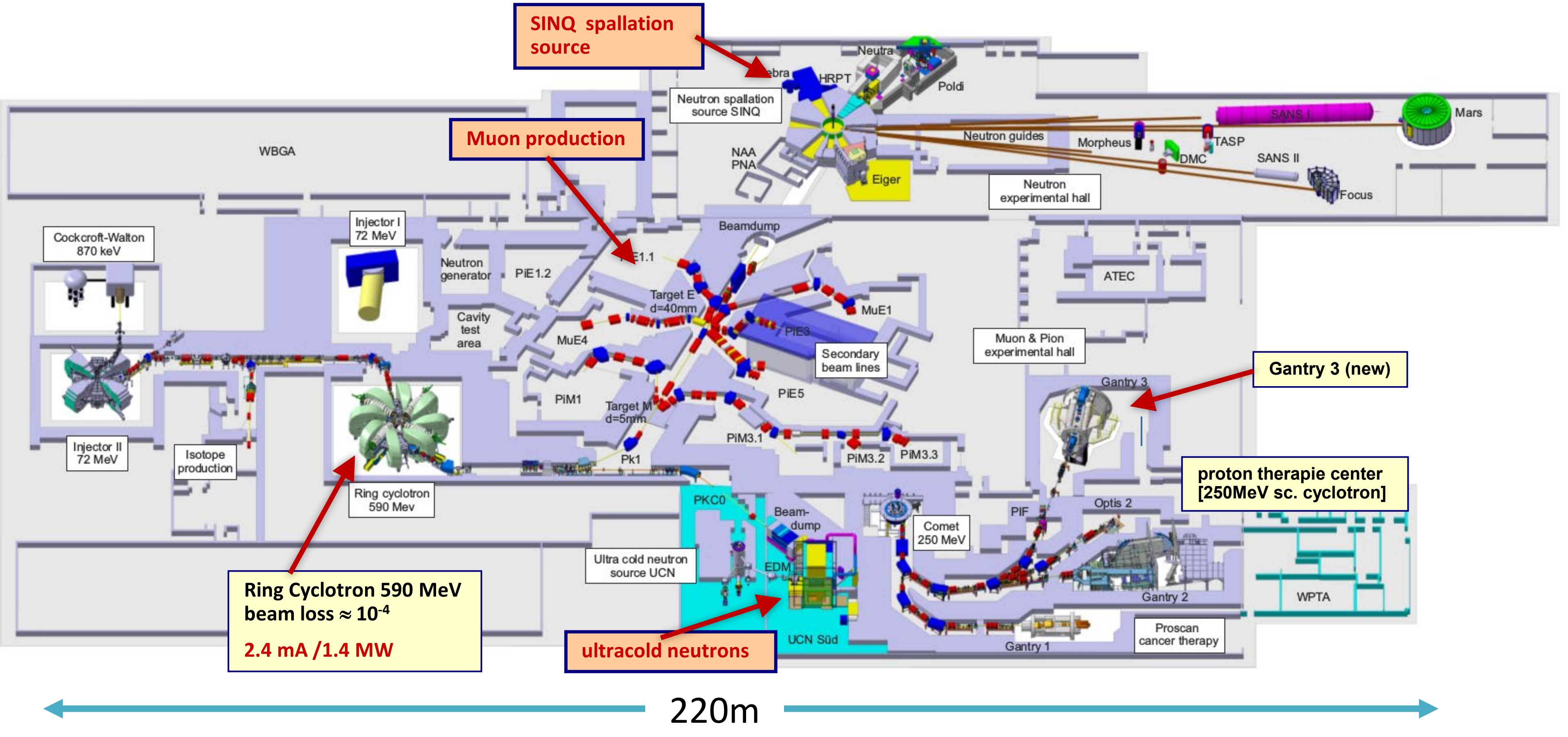
- state of art, KEKB/Japan: $N_{e+}/N_{e-} \approx 0.5$
- aim of PSI project: $N_{e+}/N_{e-} \approx 1..5$
- option high temperature s.c. solenoid

P^3 = prototype of FCC-ee e+ source + beam diagnostics



Setup for experimental test at SwissFEL/PSI

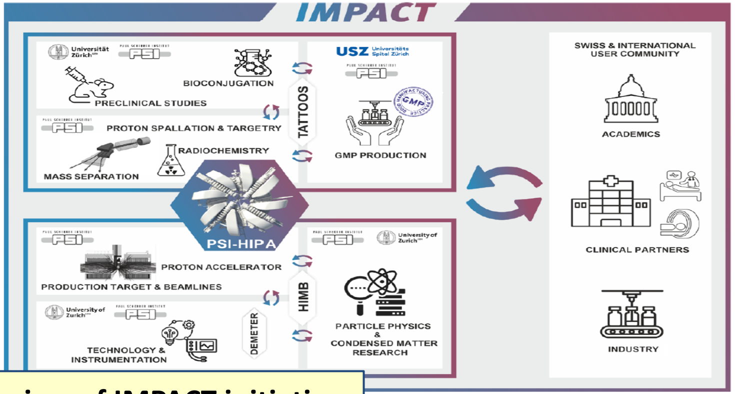
PSI's High Intensity Proton Accelerator HIPA



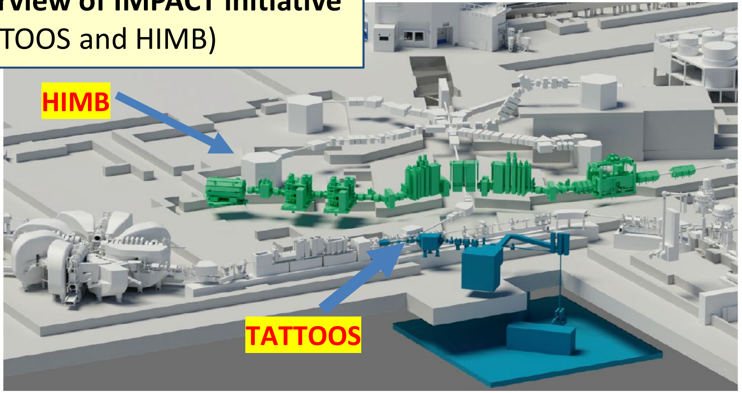
Design of a High Intensity Proton Beamline for Isotope Production

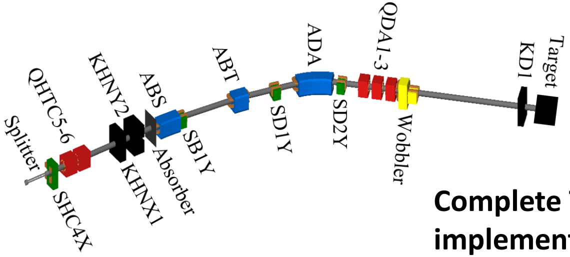
LPAP/PSI PhD project, **Marco Hartmann**, PSI supervisor: Jochem Snuverink

- new beamline to produce **terbium radionuclides** for therapeutic and diagnostic purposes. (**TATTOOS**)
- intensity – **100 µA (60kW power)** → requires splitting of main HIPA beam via electrostatic beam splitter.
- challenges:
  - beam optics design and tolerances
  - survival of beam splitter and target
  - control of low beam losses and resulting activation



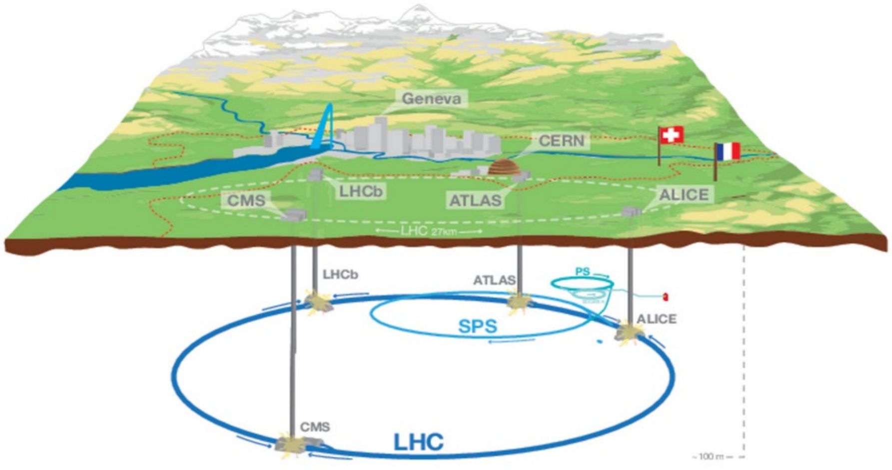
Overview of IMPACT initiative (TATTOOS and HIMB)



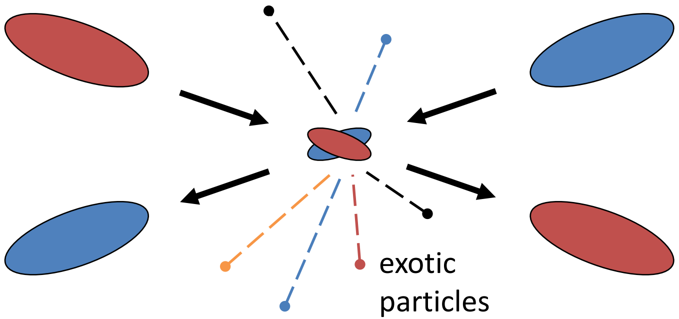


Complete TATTOOS beamline implemented in BDSIM

Particle Collisions at Extreme Energies



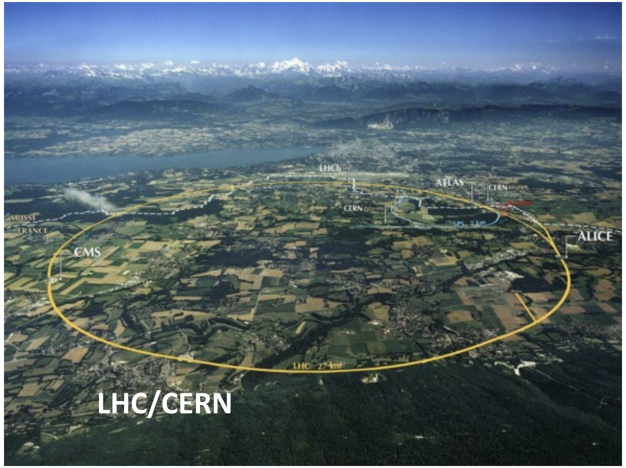
LHC with protons: E_{cm} = 13.6 TeV, C = 27km



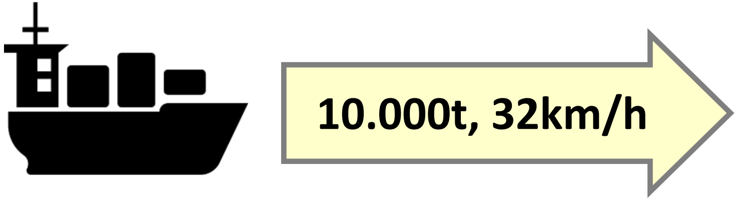
luminosity: $L = 2 \cdot 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.
proton collisions: ≈ 1.5 billion / sec
Higgs particles: ≈ 1 / sec

circulating beam power: ≈ 4 TW
beam size at interact. point: 10..20 μm

Energetic Beam in LHC – a Challenge



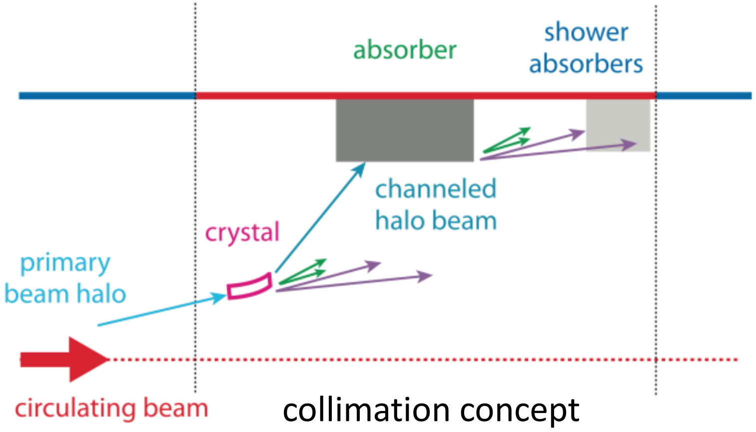
beam energy: **E_{tot} = 400MJ**
acceptable loss power: **0.5 MW over 10 sec**
acceptable deposition in superconducting magnets: **Quench: ~ 30mW/cm³.**

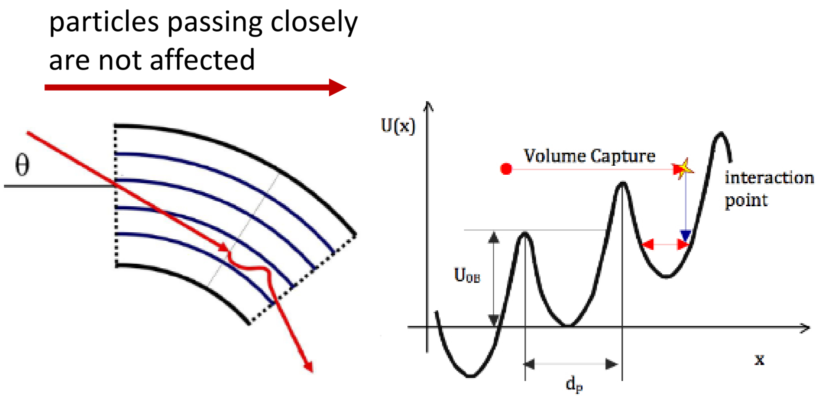


400 MJ concentrated in a sub-mm beam
→ need collimation system to localize losses

Extract Halo Particles in LHC using a Bent Crystal

LPAP/CERN PhD Project, **Maria Cai**, CERN supervisor Roderik Bruce





the beant crystal acts like an ideal septum to remove halo ions from the beam:

- positioned very close but does not affect circulating beam (closely passing ions)
- equivalent bending strength of several 100T

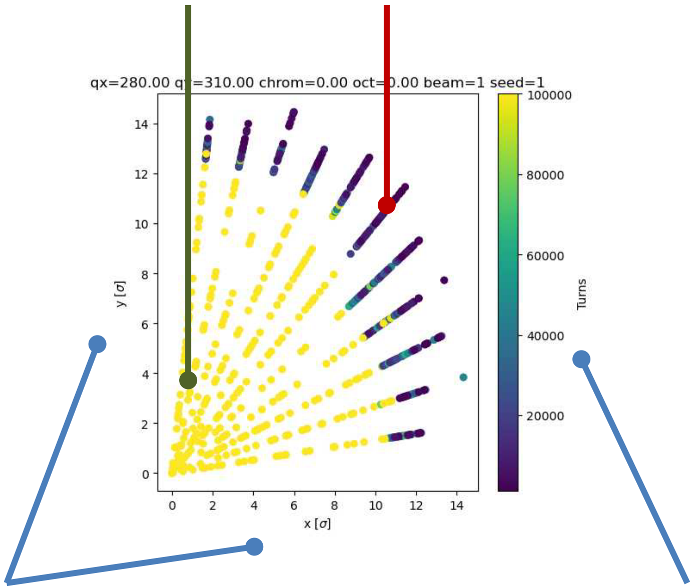
Application of Machine Learning for Hadron Ring Design

D.di Groce, F. van der Veken (CERN), E.Krymova, Y. El Bachir (EPFL SDSC) et al.

an SDSC co-funded project of LPAP - „ML4FCC“

- nonlinearities cause chaotic motion, loss of particles
- LHC ring: ≈ **1600 main magnets, ≈ 4000 correctors**
- parameters to be optimized: **now 6, planned 13** (e.g.: tunes, chromaticity etc)
- active learning mechanism through ML, smart sampling in chaotic regions
- machine configuration scan using ML model will last **few hours**, full tracking simulation: **few months**

stable vs. chaotic region



deviation from beam center (hor./vert.)

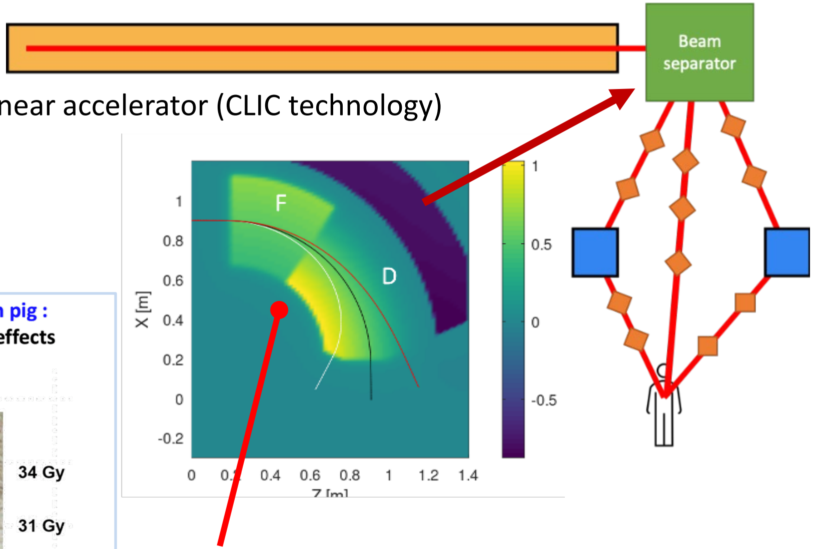
color code: number of survived turns

Beam Separator for FLASH Therapy

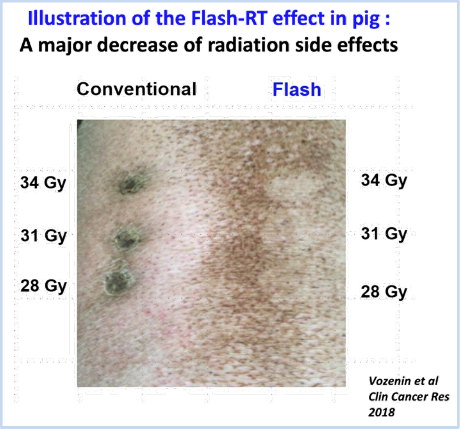
LPAP/CERN PhD Project, **Vera Korchevnyuk**, CERN supervisor: Davide Tommasini

FLASH therapy:

- consists of delivering the **full treatment dose** in a very **small time window → FLASH effect**
- effect **spares the healthy tissues**, while still destroying the tumour cells.
- ***several beams target the tumour*** from varying directions
- prototype at **CHUV/Lausanne**



Separator magnet: splitting beams at different energies while maintaining beam quality



Towards a next Generation Collider

Lepton Ring Collider (FCC-ee: Z, WW, HZ, ttbar)

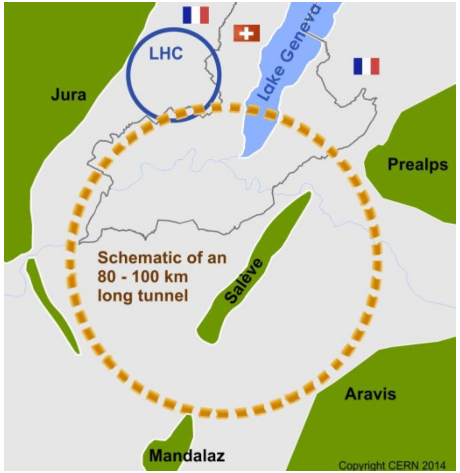
strong beam-beam effect, injector concepts (top-up injection), positron source, crab waist collision, beam polarisation, energy efficiency & management

Hadron Ring Collider (FCC-hh: 100TeV)

collimation & beam handling, intensity limiting effects / stability, beam-beam with radiation damping, IR design, optimized injector concept, eh options: e.g. ERL scheme, energy efficiency & management

Muon Collider (H, up to 14TeV)

long term, Mu generation, emittance cooling, RCS efficiency, maximizing L



Swiss Accelerator Research & Technology Program (CHART)

CHART Partners: **PSI, CERN, EPFL, ETHZ, Uni Geneva**
Timeline CHART-II: **2019…2024**
Collaborative funding: CERN, SERI, partners, **total: 40MFr**

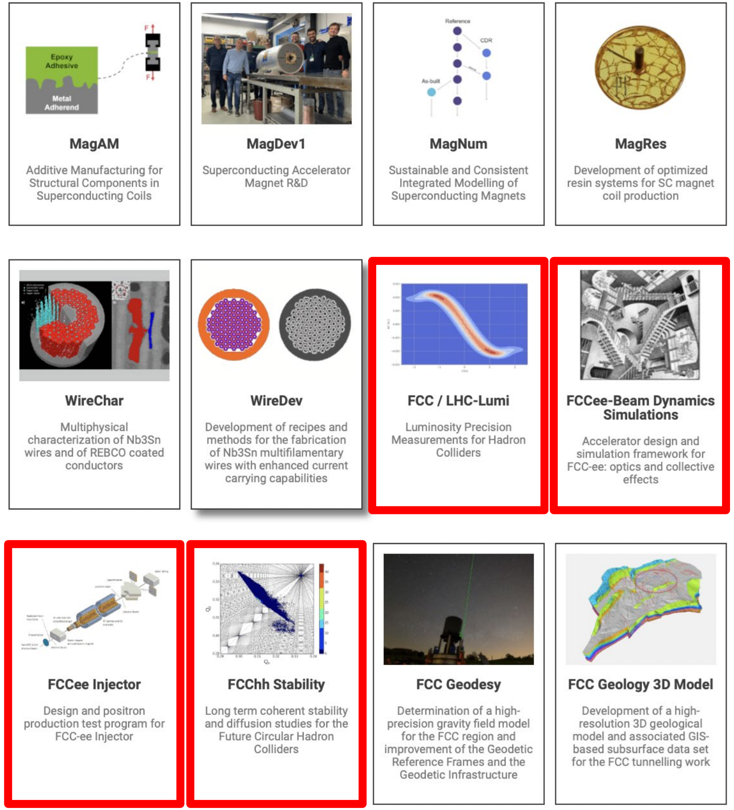
High field magnet R&D at PSI: 16..20T (Nb_3Sn/HTS)

Particle collider design, research projects at EPFL/CERN

other topics (<10%), e.g. THz diagnostics SwissFEL

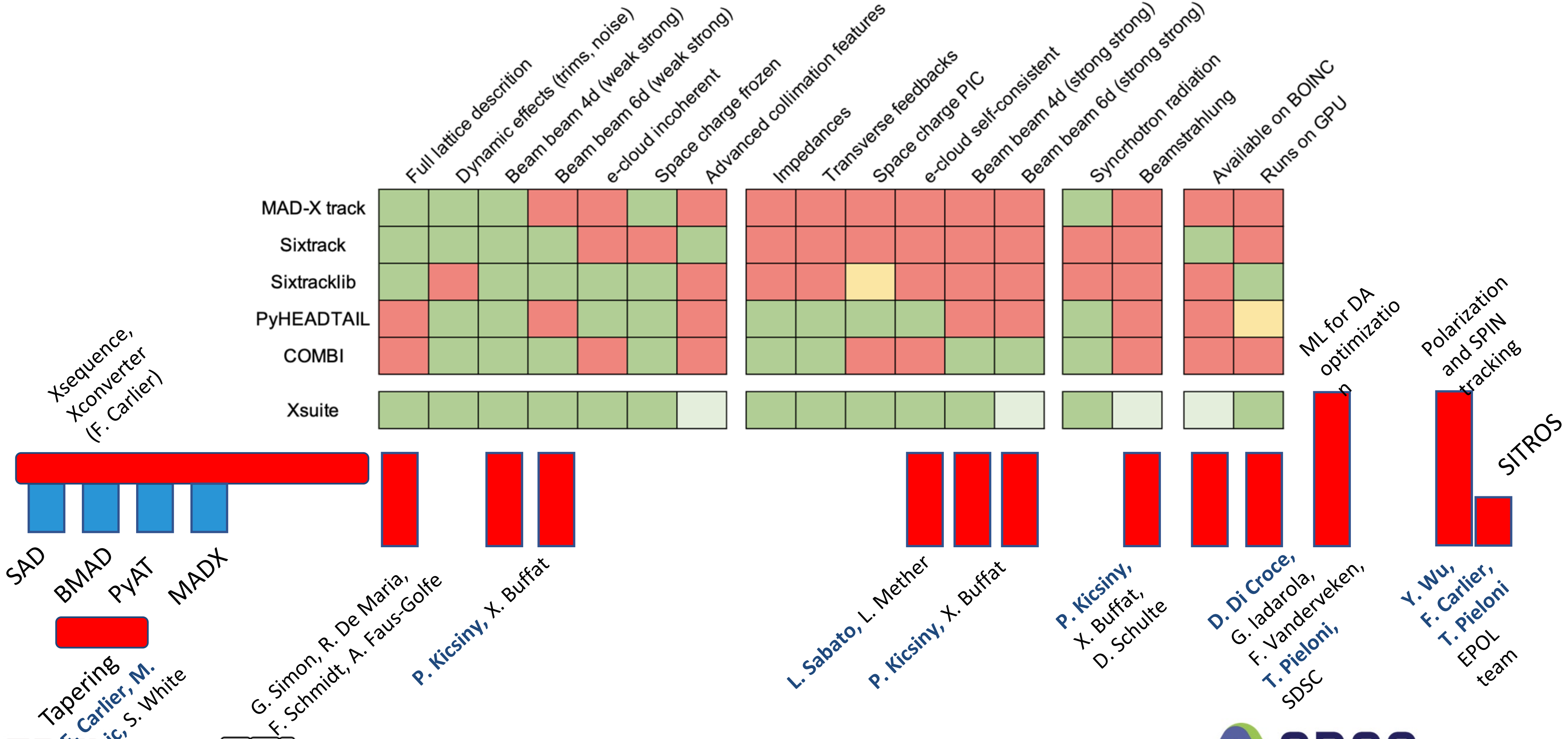
EPFL/LPAP activities:

- simulation framework components
- stability project : electron cloud studies
- ML4FCC project with Suisse Data Science Center SDSC
- recently approved polarization project (E calibration)
- positron source – test at SwissFEL



www.chart.ch

LPAP CHART Project: simulation framework



LPAP Opportunities for Students

Today´s particle accelerators are **highly specialized** research tools with a wide field of physics and technology aspects.

LPAP offers:

- **master course: introduction accelerator physics**
- **doctoral course: advanced acc. concepts (T.Pieloni et al)**
- **forefront research projects** at the **PSI and CERN large scale facilities**
- **TP4- / Master- / PhD projects**

Thanks to **Dr Tatiana Pieloni** (Senior Scientist LPAP) for her tremendous commitment to teaching and coordination.

LPAP scientists, PhD students
lpap.epfl.ch

Thank you for your attention!

Technology Trends for Accelerators

1) specialized concepts

low em. rings, FELs, collider variants, plasma …
→ **specific and deep studies**

2) advanced technologies

s.c. magnets & resonators / HTS, materials, sputtering & coating, fs-synchronization, laser systems, advanced manufacturing …
→ **cross linking to other fields**

3) computer science

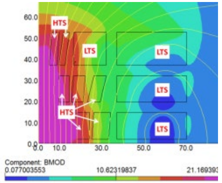
massively parallel simulations, large data volumes for controls, machine learning
→ **utilize possibilities**

4) complexity of operation

e.g. advanced FEL modes, LHC injector complex
→ **automation & efficiency is key**

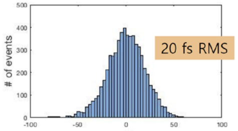
5) energy efficiency

relevant for every project
→ **dedicated R&D required**

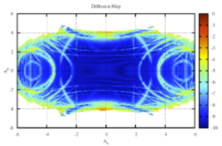


[20T HTS block coil design, R.Gupta, BNL]


[add.manufact. magnet, S.Brooks, BNL]

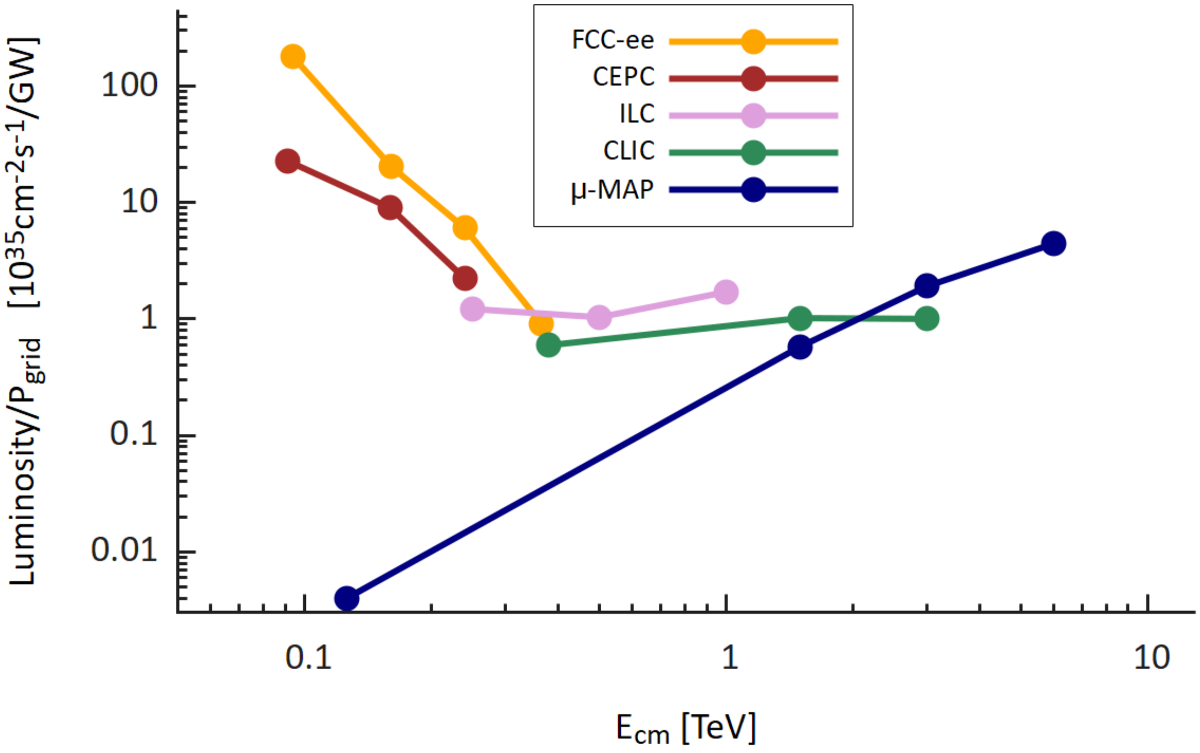


[FEL arrival time jitter, Ch.Kim, PAL]


[SLS2 diffusion map, A.Streun et al, PSI]

Overview Lepton Proposals

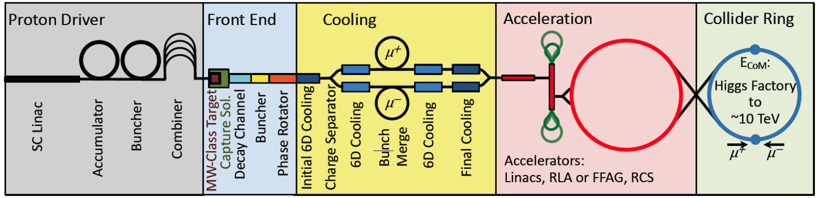
energy specific
luminosity production:



Muon Collider – Efficient at Highest Energies

Muon: E_0 = 106 MeV, τ_μ = 2.2 μs

low SR, low beamstrahlung during collisions!
scaling laws for muon collisions at varying E:



MAP design, see also D.Schulte this conference

$$\frac{\delta E}{E} \approx 10^{-3} \rightarrow \sigma_z \propto \frac{1}{\delta E} \rightarrow \beta^*_{x,y} \propto \sigma_z \rightarrow \beta^*_{x,y} \propto \frac{1}{\gamma}$$

thus L/P is increasing with energy:

$$\mathcal{L} \propto B \frac{N_0}{\varepsilon_n} \gamma P_{\mathrm{beam}}$$

unique for muons

smaller ring → more collisions during τ_μ

not for muons: Beamstrahlung in e+/e- collider