Beam Diagnostic Requirements Overview

Gero Kube

DESY (Hamburg)

- Measurement Principles
- Specific Diagnostics Needs for Hadron Accelerators
- Specific Diagnostics Needs for Electron Accelerators

Reminder: Lepton Properties

- properties of electrons/positrons
  - simple point objects
  - small rest mass

$$m_e c^2 = 0.511\ \text{MeV}$$

- consequences
  - particles are relativistic already at a few MeV

→ typically at first accelerating section

  - particle produce strong electromagnetic field

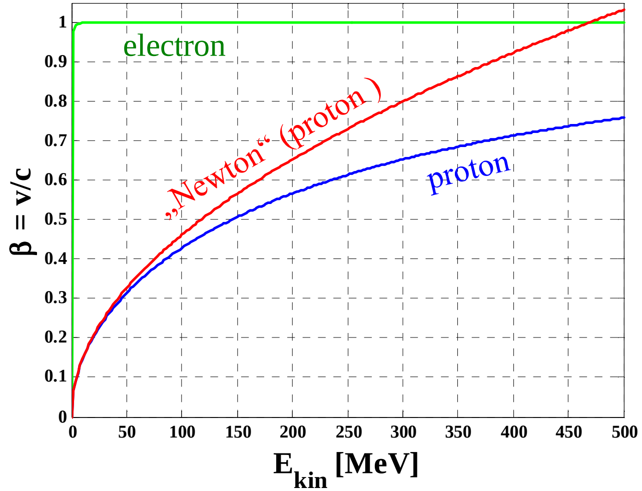
Lorentz factor: $$\gamma = E/m_e c^2$$

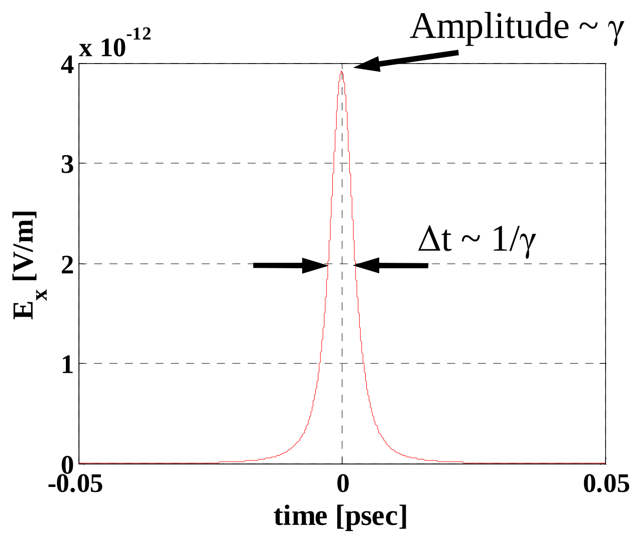
→ long range of transverse non-propagating fields

→ emission of synchrotron radiation (bend motion)

➡ influence on particle dynamics
impact on beam diagnostics

…discussion in context with different accelerator types





non-propagating transverse el. field

Electron Collider

- Comments on Synchrotron Radiation
- Injector Chain
- Storage Ring

HELSINKI INSTITUTE OF PHYSICS

Tuusula (Finland), 2-15 June 2018

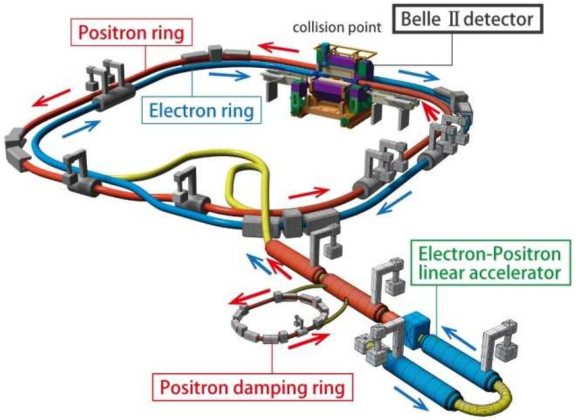
DESY.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Lepton Collider (Storage Ring)

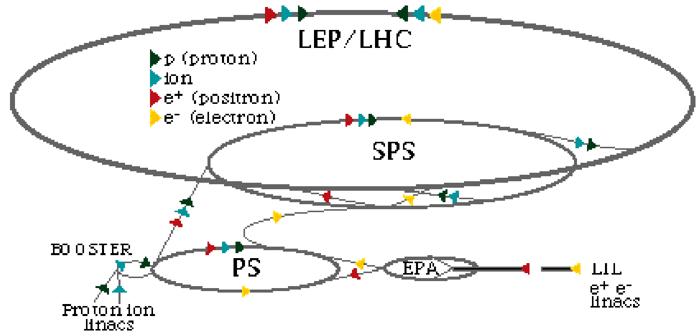
BEBC II @ IHEP (Beijing)
1 - 2.1 GeV e^+/e^-

Super KEKB @ KEK (Tsukuba)
4 GeV e^+/ 7 GeV e^-

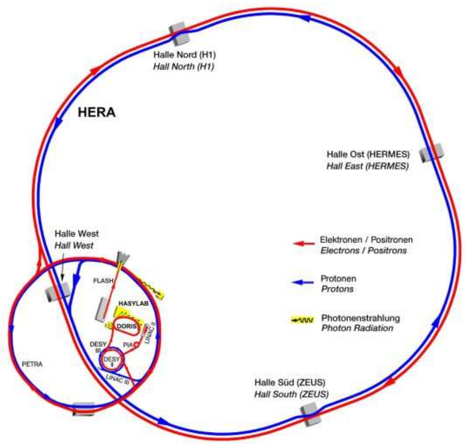


➡ first collisions: 26th April 2018

LEP @ CERN
100 GeV e^+/e^-



HERA @ DESY
27.5 GeV $e^+(e^-)$ / 920 GeV p



- general comments on lepton colliders (storage rings)
  - standard, normal conducting dipole magnets
    → sufficient to achieve final energies
  - long injector chain with different beam properties
    → ***relaxed requirements, particle dynamics with radiation***

SR Emission in circular Accelerators

- emitted power

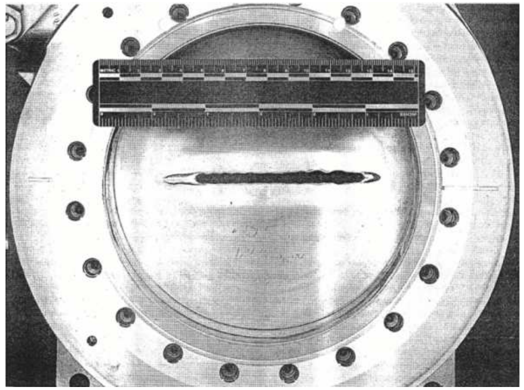
$$P_\gamma[\mathrm{MW}] = 8.85 \times 10^{-2} \frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{m}]} I[\mathrm{A}]$$

› HERA e (I=50 mA, E=27.5 GeV, ρ=550 m): **P_γ = 4.6 MW**

protect accelerator components from

direct SR illumination !

power is real!



L.Rivkin (PSI), CAS 2004

damaged front end gate valve; incident power about 1 kW for time estimated to 2-10 min.

- energy loss per turn

$$\Delta E[\mathrm{keV}] = 88.5 \frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{m}]}$$

› HERA e (E=27.5 GeV): **ΔE = 92 MeV**

→ average radiated power restored by RF

cavity provides voltage to accelerate particles back to nominal energy

➡ requires typically a large number of cavities

<u>HERA e:</u> 98 cavities, grouped in 8 sections; 8 transmitter stations, each with 1.4 MW nominal power, fed by 2 Klystrons.

Consequences of SR Emission

- large number of cavities
  - cavity represents ***high impedance*** → excitation of (multibunch) ***instabilities***

    ➡ need for feedback systems

- high SR power
  - heat load critical ➡ protection of machine and instrumentation, necessity of cooling

- high total cavity voltage V_r for loss compensation & lifetime
  - rms bunch length

    $$\sigma_t = \frac{\alpha_c - 1/\gamma^2}{2\pi f_s}\sigma_\delta \propto {}^{1}\!/\!\sqrt{V_r}$$

    (above transition energy)

    ➡ smaller bunch lengths → beam spectrum with higher frequencies

- beam emittance
  - formation of ***equilibrium emittances*** in all 3 planes

    → ***radiation damping*** and ***quantum fluctuations*** (random excitation of oscillations)

    ➡ emittance determined by storage ring itself

    ➡ emittance blow-up not critical, relaxed requirements for injector chain

e± Injector Complex @ DESY

- thermionic gun

  150 keV, 3 µsec long pulses @ 50 Hz
- chopper and collimator

  shortening of long gun pulses (60/20 nsec for e+/e-)
- pre-buncher

  single cell cavity, matching to linac RF
- Linac sections

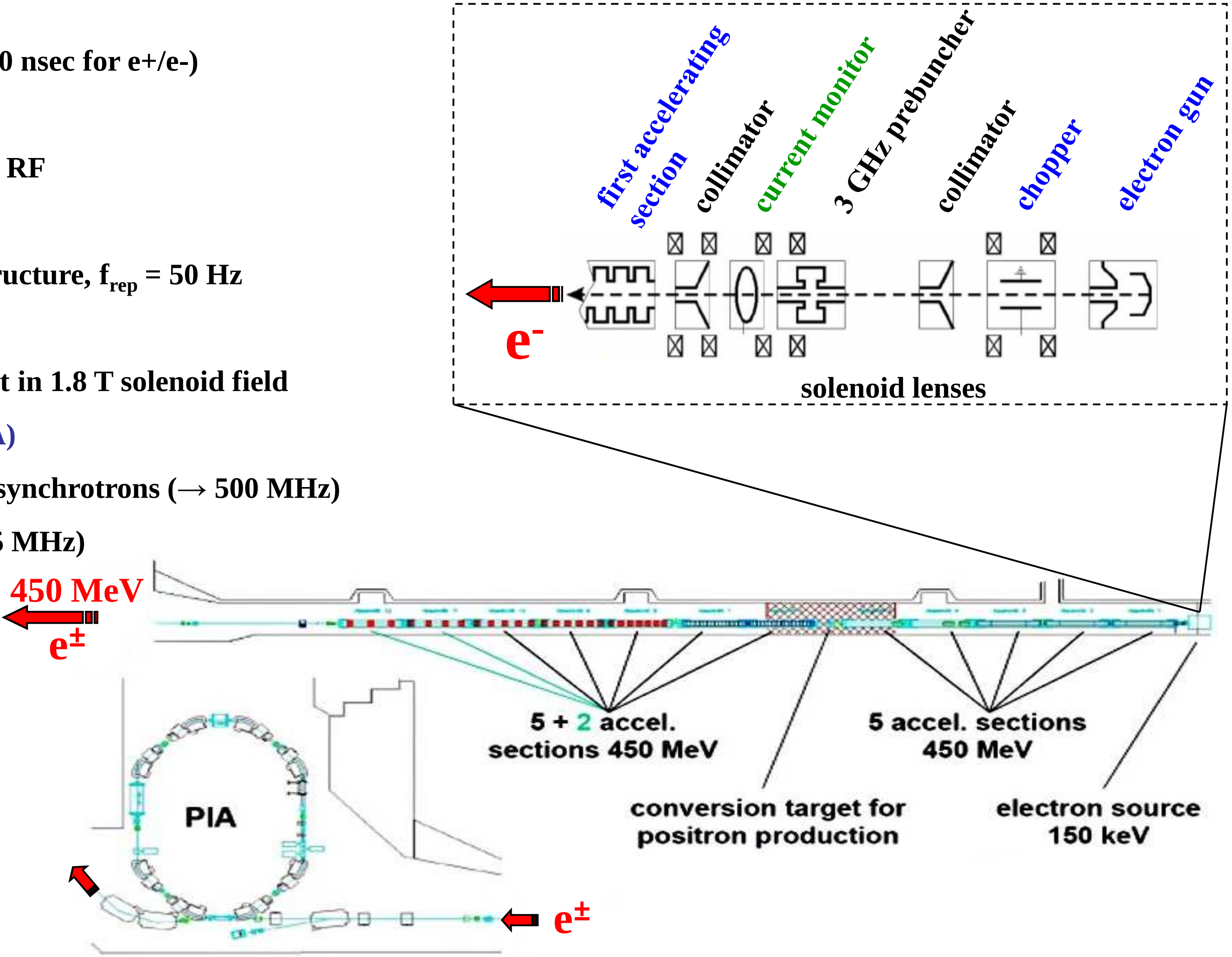
  3 GHz (S-band) travelling wave structure, f_{rep} = 50 Hz
- converter for e^+ production

  7 mm (2 rad. length) thick W target in 1.8 T solenoid field
- Positron Intensity Accumulator (PIA)

  re-formation of time structure for synchrotrons (→ 500 MHz)

  two RF systems (10.4 MHz and 125 MHz)

Linac front-end



3 GHz Linac section

Injector Complex Instrumentation

- key devices for
  - adjusting beam transport through injector sections
  - tuning the RF system
  - indicating operating status

in principle same than for hadron machines

- overview: standard instrumentation and their tasks

transfer efficiency

→ current transformers

beam position for beam steering

→ screens (low energy deposition)

→ BPMs (sensitivity for long linac bunch trains)

beam profiles for beam optics matching

→ scintillating/OTR screens (in straight section)

→ synchrotron light (accumulator ring)

transverse emittance

→ multi-screen method or quadrupole scans (in straight section)

→ synchrotron light (accumulator ring)

longitudinal plane

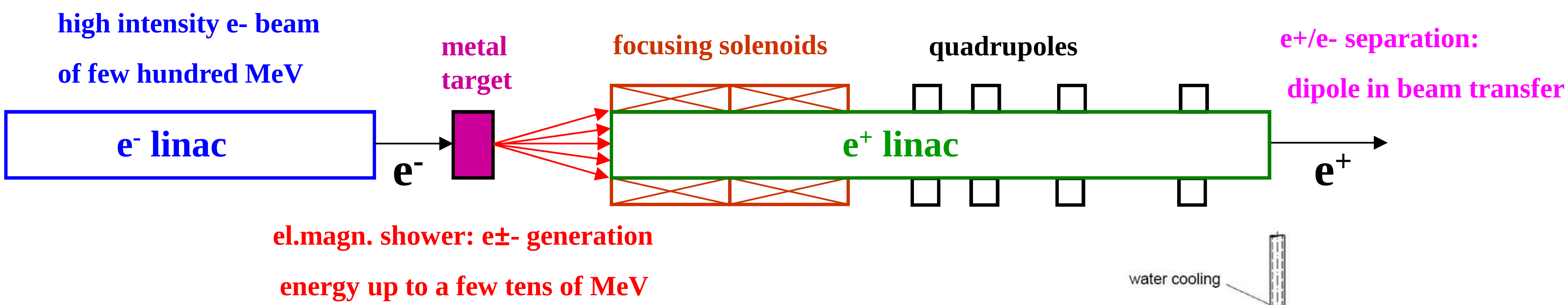
→ magnet spectrometer for energy (-spread) (diagnostics beamline)

→ time structure via RF deflector, wall current monitor, coh. radiation diagnostics

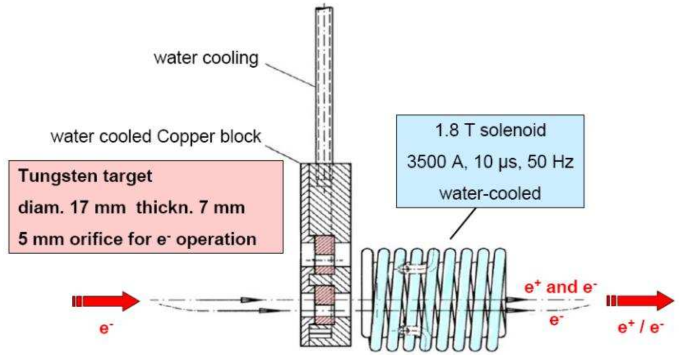
Comment: e^+ Production

- principle of positron production

K.Hübner, Hyperfine Interactions 44 (1988) 167



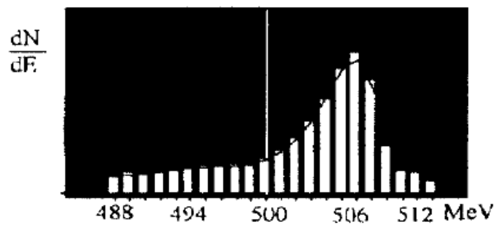
- conversion target in harming radiation environment
  - → only radiation resistive diagnostics close to target



conversion target @ DESY Linac II

- high e^+ yield: focus at converter
  - → profile measurement close to target desirable
  - → ***secondary emission monitors*** (no screens because of degradation)

C.Bourat et al., Proc. EPAC 94, p.704



- matching the energy acceptance ($\Delta E/E$) of accumulator ring
  - → i) spread from conversion process, ii) microbunch length
  - → ***precise measurements of energy spread and bunch length***

Storage Ring Diagnostics: Remarks

- „walk" along injector chain to storage ring / collider
  - no fundamental difference in requirements compared to hadron machines
  - no fundamental difference in instrumentation between e-linac and storage ring
    - → ***direct descripton of needs for storage ring diagnostics***

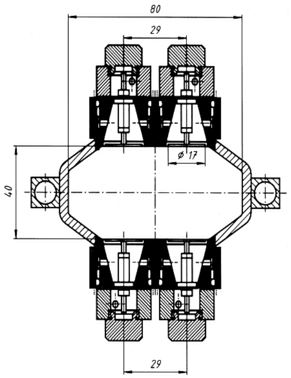
- diagnostics system of storage ring / collider
  - current monitors (AC and DC) → bunch charge, stored dc current
  - BPMs → orbit
  - tune measurement → working point
  - feedback system → stabilization
  - synchrotron light diagnostics → beam profile, emittance
  - energy measurement → cms energy for particle production
  - luminosity monitors → collider key parameter, optimization
    simple point objects, i.e. absolute luminosity
  - beam loss monitors → control losses, optimization
    not only protection, also for machine physics
  - machine protection system → temperature control,…
    protection of sensitive components (heat load)

Storage Ring Diagnostics (1)

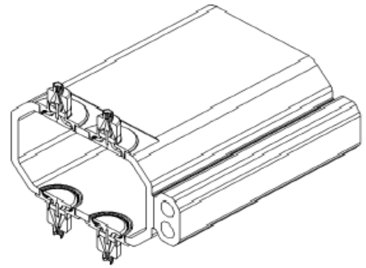
- beam position monitors (BPMs)
  - short electron bunches (10 - 100 psec)
    - → use of ***button pickups***
  - synchrotron radiation emission
    - → pickups mounted ***out of orbit plane***
  - vacuum chamber profile not rotational-symmetric
    - → ***horizontal emittance » vertical emittance***
    - (SR emission in horizontal plane)
    - → ***injection oscillations due to off-axis injection***
    - (allows intensity accumulation)

Super KEKB

H. Fukuma (KEK), Proc. eeFACT 2016, WET1H3

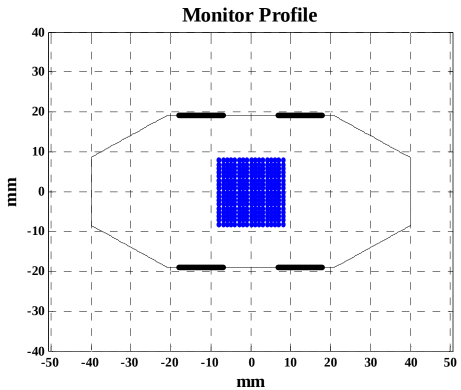


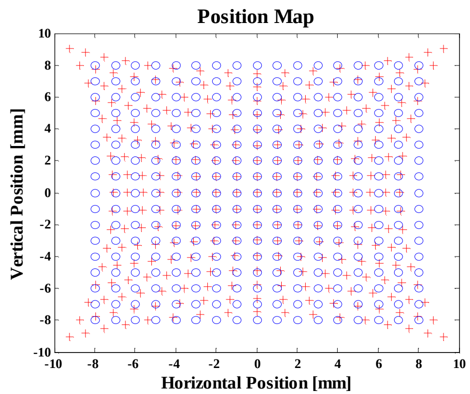
HERA e



PEP II

→ correction of non-linearities in beam position

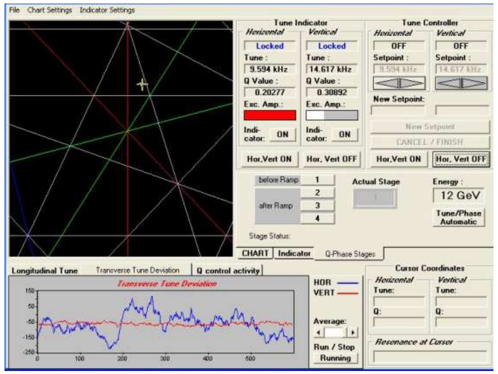




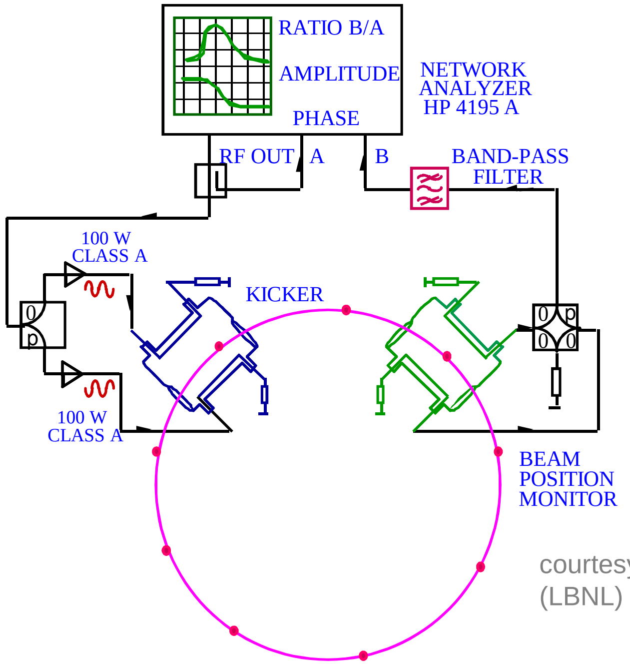
Storage Ring Diagnostics (2)

- **tune**
  - radiation damping due to SR emission

    → permanent excitation, online tune control



HERA e tune controller



courtesy: F.Sannibale (LBNL)

- **feedback**
  - long-range electromagnetic fields and short bunch lengths (→ broad beam spectrum)

    → fields act back on beam itself via environment

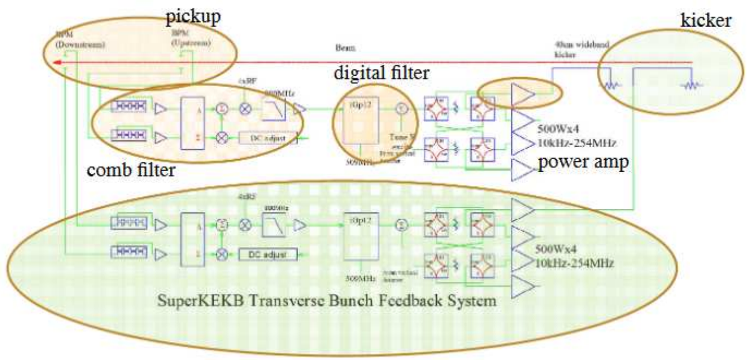
    → excitation of ***coupled bunch instability***

  - feedback system for instability damping

    i) detection system to measure beam oscillations

    ii) signal processing unit to derive correction signal

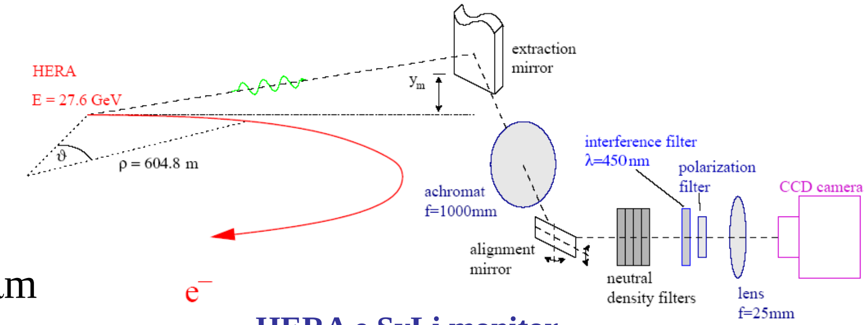
    iii) broad band amplifier and beam deflector to act on beam



H. Fukuma (KEK), Proc. eeFACT 2016, WET1H3

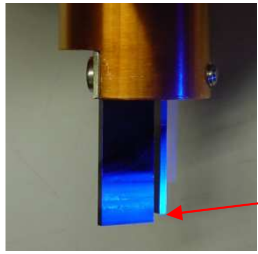
Storage Ring Diagnostics (3)

- transverse profile / emittance
  - imaging with ***synchrotron radiation*** (SR)
    - → non-destructive profile diagnostics
  - HERA e beam sizes: σ_h = 1200 μm, σ_v = 250 μm
    - → resolution with ***optical SR*** sufficient



HERA e SyLi monitor

  - problem: ***heat load*** on ***extraction mirror*** (X-ray part of SR)
    - → material with low absorption coefficient (Be)
    - → cooling of extraction mirror
    - → not sufficient to prevent image distortion…

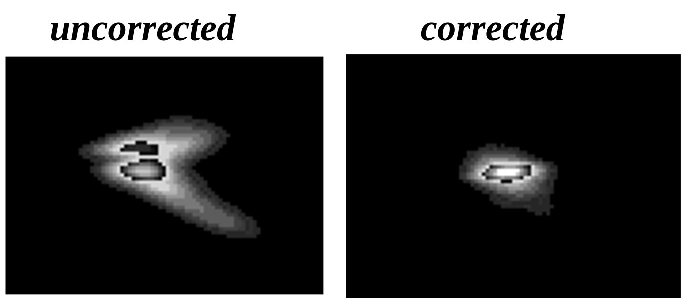


  - solutions:

HERA e:
observation out of orbit plane

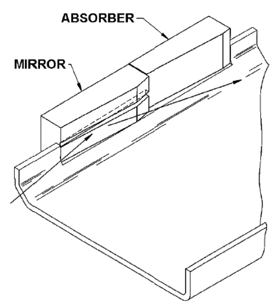
G. Kube *et al*., Proc. DIPAC 2005, Lyon, France (2005), p.202

Photon Factory, LEP: adaptive optics



courtesy: T.Mitsuhashi (KEK)

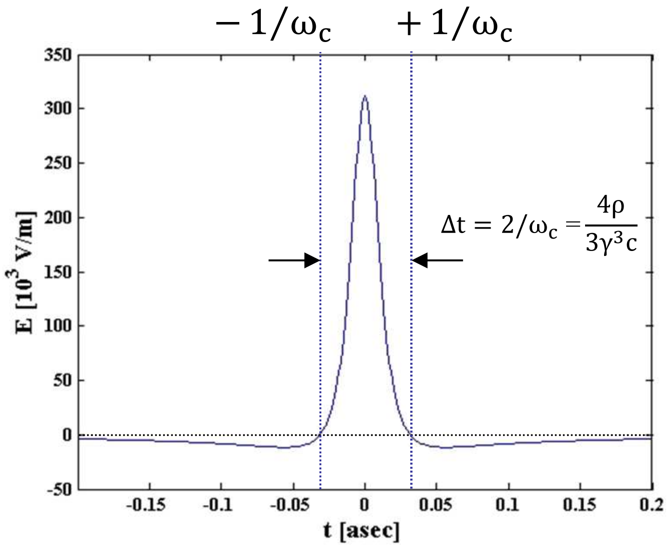
PEP II: slotted mirror



A.S.Fisher *et al*., Proc. EPAC 1996, TUP098L

Storage Ring Diagnostics (4)

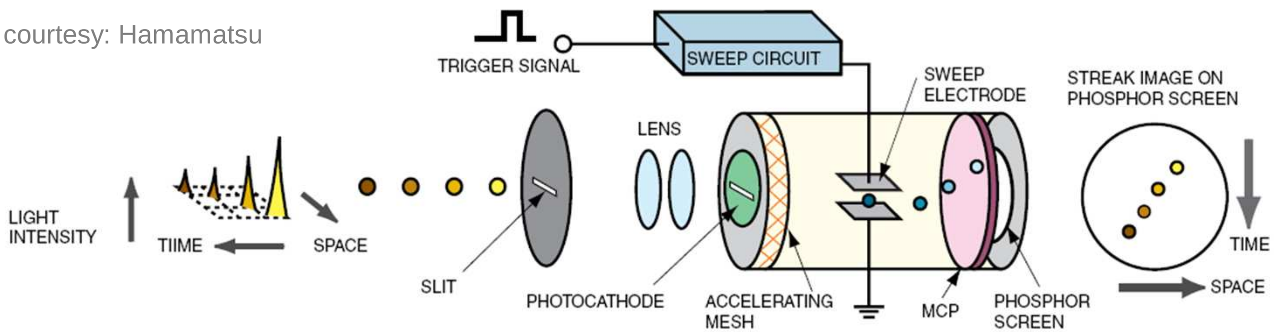
- longitudinal profile
  - SR single particle time structure
    - → calculation for 6 GeV electron, electric field vector in orbit plane

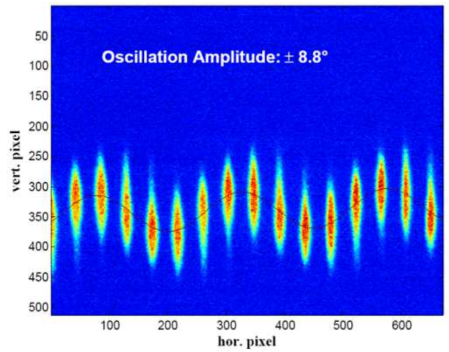


➡ time structure of SR suitable to resolve ***psec*** longitudinal profiles (and even less)

  - streak camera
    - → time resolution ~ 1 psec

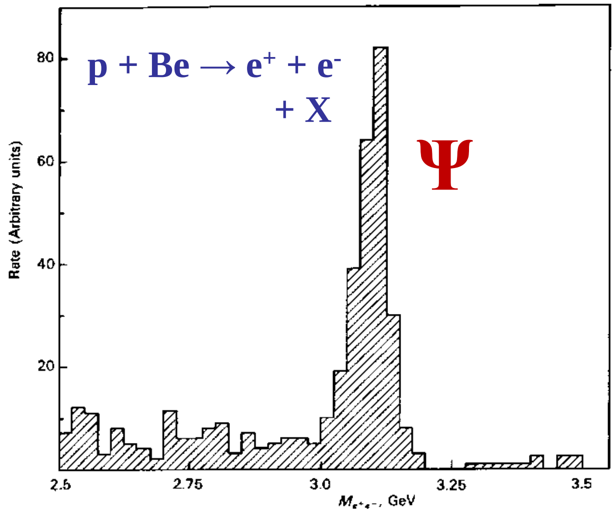
courtesy: Hamamatsu





Storage Ring Diagnostics (5)

- beam energy: $e^{\pm}$ are point objects, i.e. reaction energy directly related to beam energy

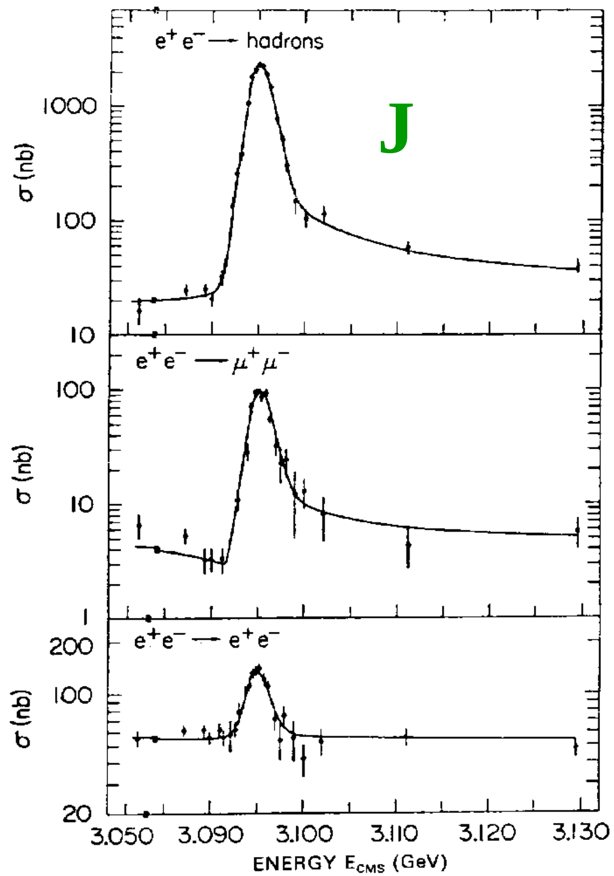


fixed target

AGS (BNL)

J.J.Aubert et al., Phys. Rev. Lett. 33 (1974) 1404

e+/e- collider SPEAR (SLAC)



J.-E.Augustin et al., Phys. Rev. Lett. 33 (1974) 1406

- Nobel Price  (1976)
  - discovery of **J/Ψ** for Samuel Ting & Burt Richter

- measurement techniques
  - determination via dipole current not sufficient

    → ***resonant depolarization*** or ***Compton backscattering***

3^{rd} Generation Light Source

- Storage Ring based Light Source

HELSINKI INSTITUTE OF PHYSICS

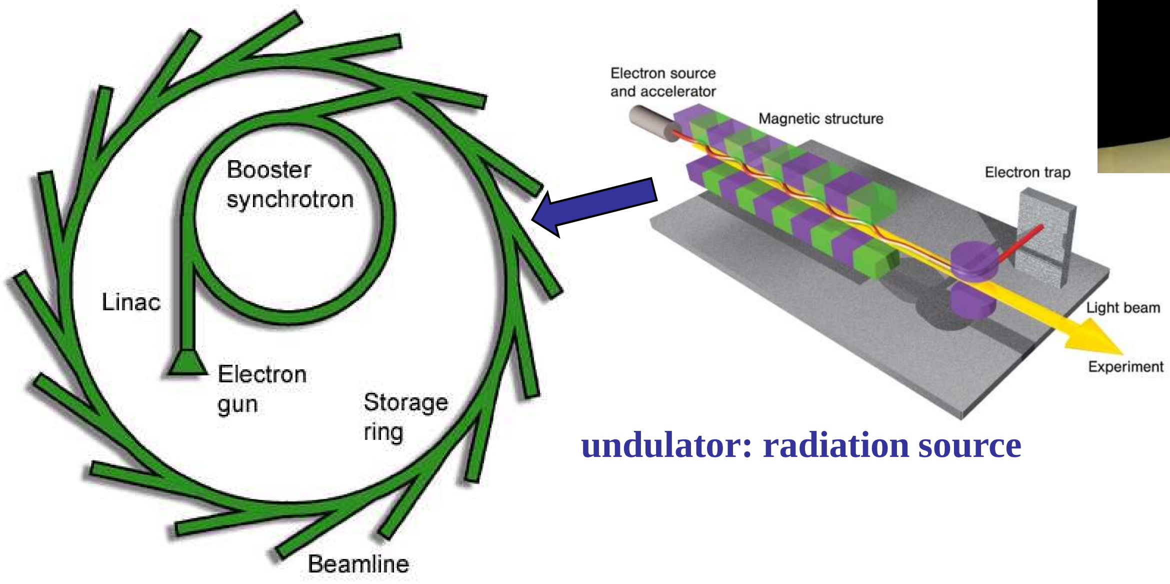
Tuusula (Finland), 2-15 June 2018

DESY.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Storage Ring based Light Sources

- storage ring based 3rd generation light source

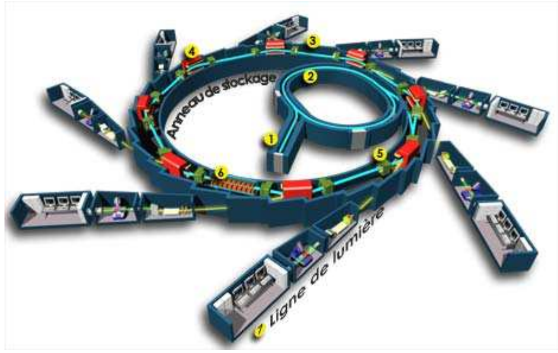


undulator: radiation source

http://www.diamond.ac.uk/AboutDiamond/Diamondstep-by-step/default.htm

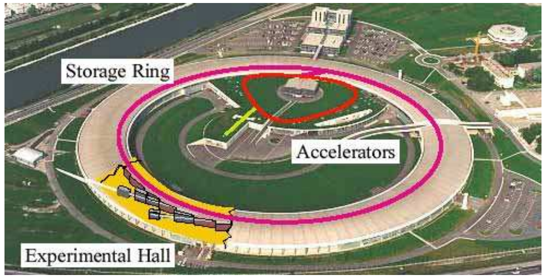
undulator: Petra3 @ DESY

SOLEIL
2.75 GeV / C = 354 m



- storage ring: energy 1 – 8 GeV, circumference ca. 100 - 2300m
  - → insertion devices integrated part of storage ring (straight sections)
  - → user experiments at end of beamlines (~50-100m away from source)
- short injector chain
  - → standard instrumentation

ESRF
6 GeV / C = 844 m



Light Sources: Remarks

- key parameter: spectral brilliance
  - measure for phase space density of photon flux

$$B = \frac{\text{number of photons}}{[\text{sec}][\text{mm}^2][\text{mrad}^2][0.1\%\ \text{bandwidth}]}$$

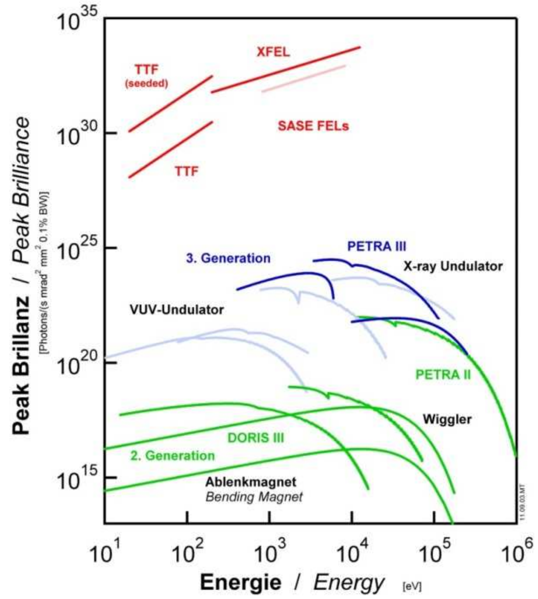
  - user requirement: high brilliance

    → lot of monochromatic photons on sample

  - connection to machine parameters

$$B \propto \frac{N_\gamma}{\sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} \propto \frac{I_{beam}}{\varepsilon_x \varepsilon_y}$$

comparison:
2nd, 3rd and 4th generation light sources



  - requirements for storage ring and diagnostics

i) high beam current

→ achieve high currents

→ cope with high heat load (stability)

ii) small beam emittance

→ achieve small emittance (task of lattice designer)

→ measure small emittance

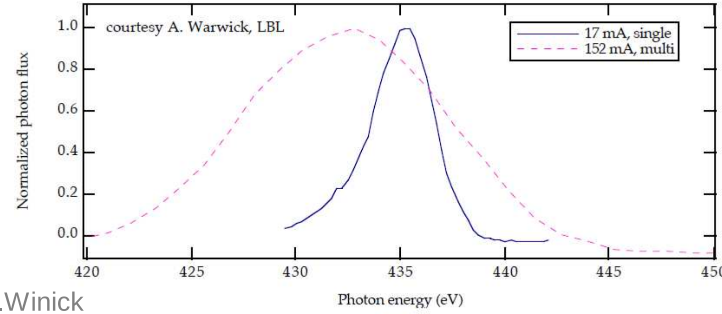
→ preserve emittance (stability)

➡ stability is critical issue

Light Sources: Stability

- energy stability, suppression of energy widening effects
  - cause: (long.) multibunch instabilities
  - shift of radiation harmonics from undulator
    → intensity fluctuation, line broadening
  - longitudinal **multibunch feedback systems (MBFS)**

undulator radiation (3rd harmonic) @ ALS

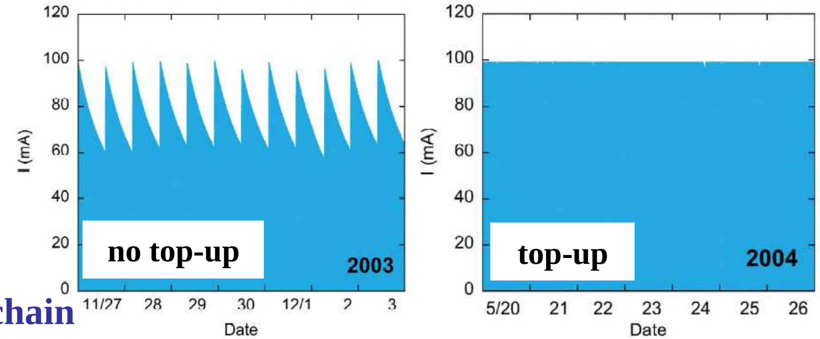


Synchrotron Radiation Sources – A Primer, ed. H.Winick

- intensity stability
  - change in background conditions and thermal load on beamline and machine components
    → position stability!
  - transverse multibunch instabilities → **transverse MBFS**
  - operation in top-up mode (passive stabilization)
    → loss compensation by refill small amount of charges in short time intervals

  vast dynamic range for instruments, starting from injector chain

stored current (1 week) @ Spring8



H.Tanaka et al., J. Synchrotron Rad. 13 (2006) 378

- position stability
  - intensity fluctuations, emittance dilution → reduction of brilliance
  - **orbit feedback systems** including **high resolution e-BPMs** and **photon-BPMs** in beamlines

Light Sources: BPMs

- high resolution e-BPMs
  - typical stability tolerance: ***20% emittance growth*** $\frac{\Delta\varepsilon}{\varepsilon} = 2\frac{\Delta\sigma}{\sigma}$ → ***10% of the (1σ) beam size***

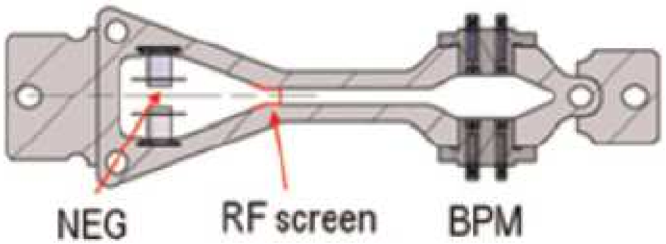
    → example: ***average*** position stability at IDs for PETRA III @ DESY $\Delta\sigma_{hor} = 2\,\mu m$, $\Delta\sigma_{vert} = 0.3\,\mu m$

  - typical example: ***NSLS-II BPM chamber***

    → asymmetric chamber profiles

    (pumping channel, avoid heat load, …)

    ➡ correction of strong position non-linearities



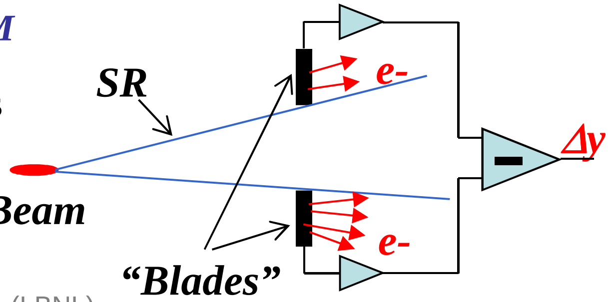
S. Sharma et al., Proc. MEDSI-6 2011, DLS Proceedings Vol. 1 e63

- photon BPM
  - location in user beamlines: two monitors (per plane) → correction of position and angle

„blade“ type BPM

sensitive for tails

of distribution

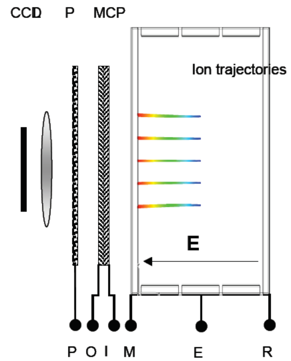


courtesy: F.Sannibale (LBNL)

residual gas XBPM

sensitive also for

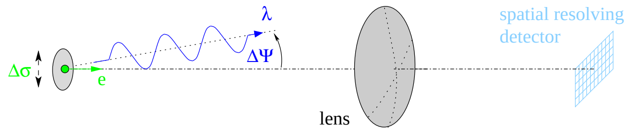
distribution core



courtesy: P.Ilinski (BNL)

Light Sources: Emittance Diagnostics (1)

- emittance: typical values **ε_x = 1-5 nm.rad and 1% emittance coupling**
  - example: σ_h = 40 μm, σ_v = 20 μm (PETRA III @ DESY)



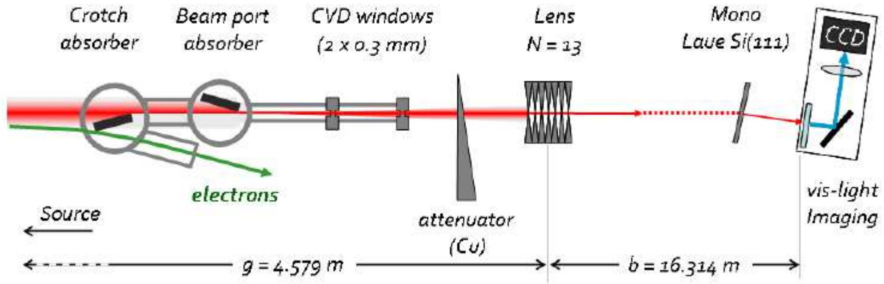
fundamental resolution limit (uncertainty principle)

$$\Delta\sigma \approx \frac{\lambda}{2\Delta\Psi}$$

optical imaging @ PETRA: λ = 500 nm and $\Delta\Psi_v$ = 1.7 mrad ⇒ $\Delta\sigma_v$ = 145 μm diffraction limited

- imaging at smaller wavelengths: ***X-ray imaging with focusing optics***
  - reflective optics: Kirkpatrick-Baez mirrors,…
  - diffractive optics: Fresnel zone plates,…
  - refractive optics: Compound Refractive Lenses (CRL)

CRL monitor @ ESRF (32 keV)



F. Ewald et al., Proc. IBIC 2013, Oxford, UK (2013) 833

X-ray imaging with non-focusing optics

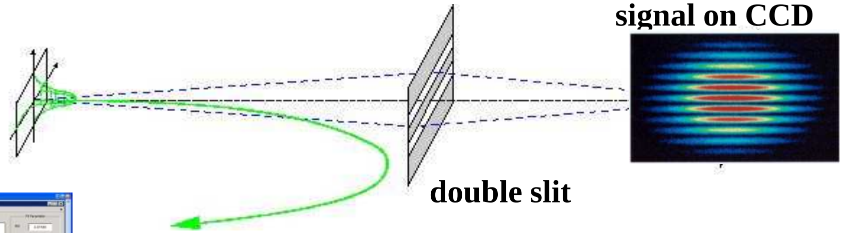
- pinhole camera — example: Diamond Light Source

C. Thomas et al., Phys. Rev. ST Accel. Beams **13** (2010) 022805

Light Sources: Emittance Diagnostics (2)

- exploit coherence properties
  - Synchrotron Radiation Interferometer (SRI)

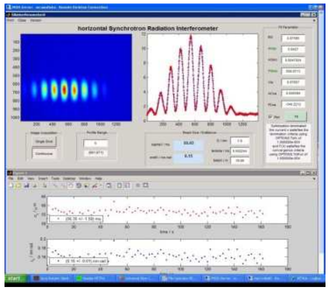
    T. Mitsuhashi, Proc. of BIW 2004 Knoxville, Tennessee, p.3



  - example: SRI @ PETRA III

    USR studies at PETRA III (DESY):

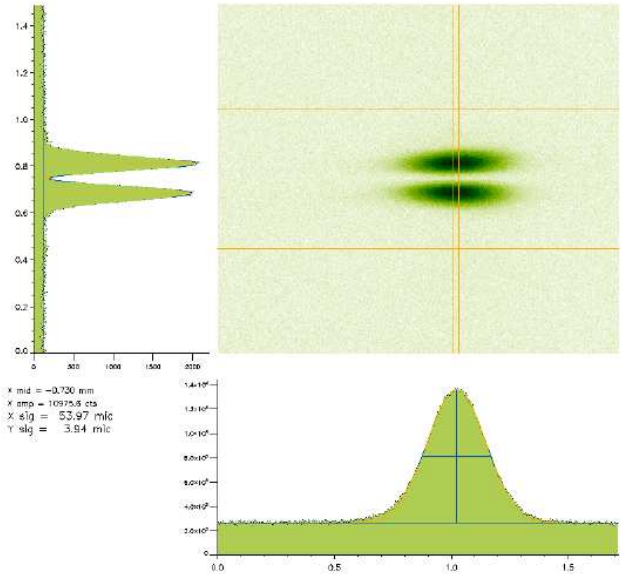
    ε_x = 160 pm.rad @ 3 GeV



- exploit Point Spread Function (PSF)
  - π-polarization imaging

    V. Schlott et al., Proc. IBIC 2013, Oxford, UK (2013) 519

    widely applied @ SLS



- coded aperture imaging

  R.H. Dicke, Astrophys. Journal 153, L101, (1968)

  J.W. Flanagan et al., Proc. DIPAC 2011, Hamburg, Germany (2011) 561

  C. Bloomer, „Coded Aperture @ DLS“, TUCZB2

4^{th} Generation Light Source

- Linac based Light Source

  → Free Electron Laser (FEL)

HELSINKI INSTITUTE OF PHYSICS

Tuusula (Finland), 2-15 June 2018

DESY.

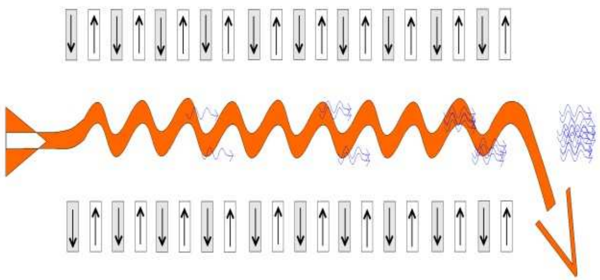
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

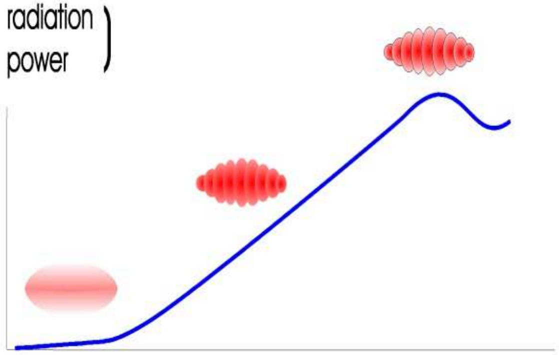
Free Electron Lasers (FELs)

- linac (single pass) based 4th generation light sources

Linac based Self Amplification of Spontaneous Emission (SASE) FELs

(→ no matter for diagnostics which FEL type)





Electron bunch modulated with its own synchrotron radiation field

- micro-bunching
- more and more electrons radiate in phase until saturation is reached
- beam energy defines photon wavelength λ_r

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

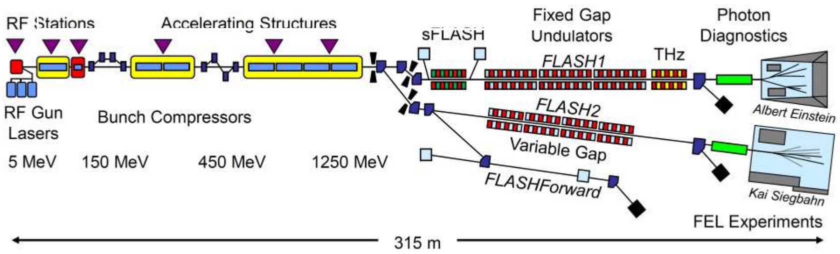
λ_u : undulator period
K : undulator parameter (measure for B field)

Free Electron Lasers (FELs)

- linac-based European X-ray FELs

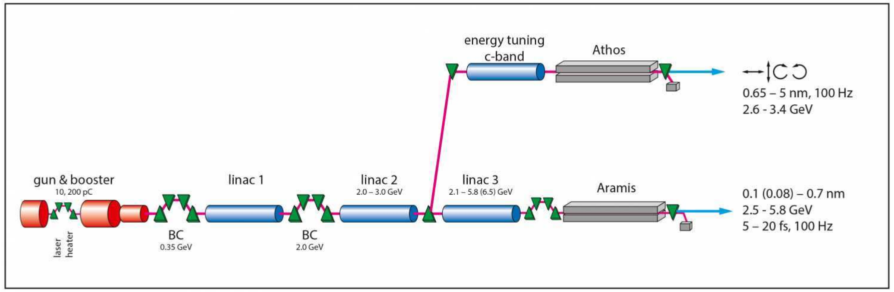
FLASH @ DESY (Hamburg)

E_{max} = 1.25 GeV, λ = 4 – 90 nm



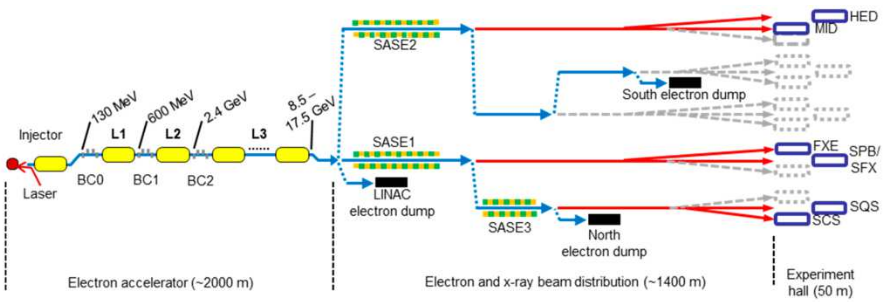
SwissFEL @ PSI (Villigen)

E_{max} = 5.8 GeV, λ = 0.1 – 5 nm



European XFEL @ XFEL GmbH/DESY (Hamburg)

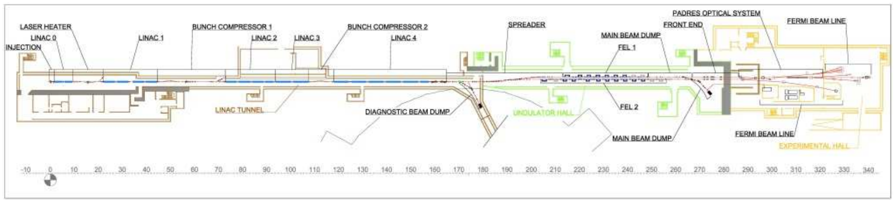
E_{max} = 17.5 GeV, λ = 0.05 – 4.7 nm



Th. Tschentscher *et al.*, Appl. Sci. **2017**, 7(6), 592

FERMI @ Elettra (Trieste)

E_{max} = 1.5 GeV, λ = 4 – 65 nm



seeded FEL (no SASE)

FEL Beam Properties (1)

- single or few bunches, typically with large separation

  ➡ requires single bunch measurements

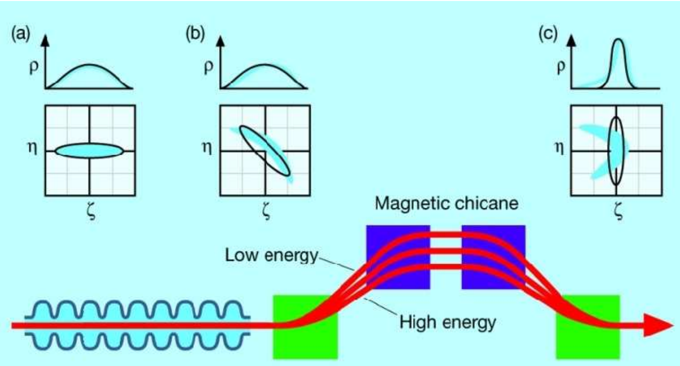
- high current density
  - sufficient energy transfer from electron beam to radiation field
  - natural scale: ***number of electrons per wavelength***

$$N_{e,\lambda} = \frac{I\lambda}{ec}$$

$$N_{e,\lambda} = 1 \quad \Longrightarrow \quad I = \begin{cases} 0.5\ \mu\mathrm{A} & (\lambda = 100\ \mu\mathrm{m}) \\ 0.5\ \mathrm{A} & (\lambda = 0.1\ \mathrm{nm}) \end{cases}$$

➡ requires additional bunch compression in order to increase current density

➡ extremely short bunch lengths: 10-100 fsec



- charge per bunch: pCb up to about nCb
  - new trend: short pulse operation, requires lower and lower charges…

    → ***signal to noise problems*** at low charge, even for kA peak currents

    → ***high dynamic range*** for diagnostic devices

FEL Beam Properties (2)

- high quality electron beam
  - energy spread

$$\frac{\sigma_E}{E} \approx 10^{-4}$$

  - transverse emittance

$$\varepsilon \leq \frac{\lambda}{4\pi}, \qquad \varepsilon = \varepsilon_N / \beta\gamma$$

(→ high energy helps)

for resonant energy exchange and good overlap with radiation field

➡ high demands on 6-dimensional phase space

- ***longitudinal phase space***

→ short bunches require complicate longitudinal diagnostics
→ new methods required to verify pulse lengths of electron and laser bunch

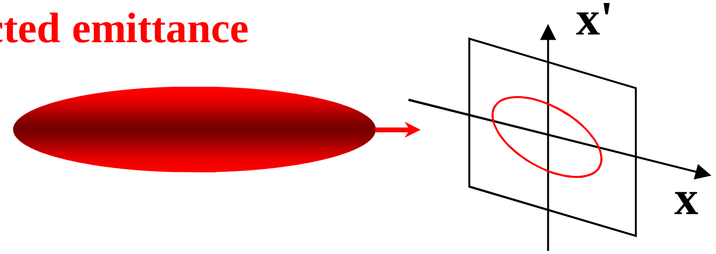
- ***transverse phase space***

→ beam gets extremely small, often weird shape
→ emittance is no equilibrium property, many effects can spoil it
→ optics errors propagate through entire machine (linac is open loop system)
→ coherent effects due to short pulses and instabilities

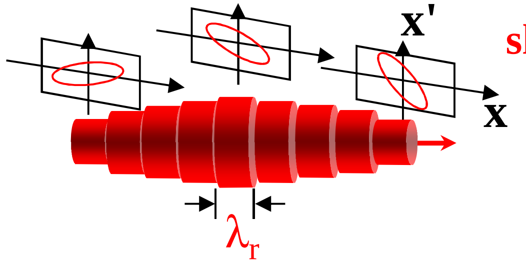
FEL Beam Properties (3)

- comment: transverse emittance
  - electrons ***slip back in phase*** with respect to photons by λ_r each undulator period
  - FEL integrates over slippage length → **slice emittance** of importance

projected emittance



slice emittance



- stability
  - energy stability → wavelength stability $$\frac{\Delta\lambda}{\lambda} = -2\frac{\Delta E}{E}$$
  - arrival time stability **(fsec)** → pump probe experiments
  - position stability
    → overlap between beam and radiation in undulators

LLRF feedback

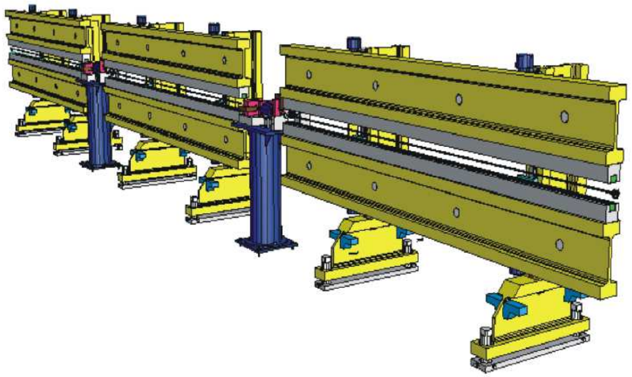
high level synchronisation

high resolution BPMs, orbit feedback

example: XFEL @ DESY

- length of undulator section: 100-150 m
- BPM position resolution:

1 µm (single bunch), **100 nm** (average over bunch train)



FELs: Comments

- linac-based FEL
  - no radiation damping → beam quality determined already from the gun

    ➡ careful diagnostics and control of beam parameters

    SASE FEL is not forgiving – instead of reduced brightness, power nearly switches **OFF**

- accelerating structures
  - part of SASE FELs use superconducting RF cavities

    ➡ part of diagnostics (BPMs) in cold vacuum

    particle free environment

9 cell, 1.3 GHz Nb TESLA cavity

- SASE FELs: FLASH and XFEL @ DESY

FEL Diagnostics: Overview

- standard electron beam diagnostics to operate the linac

  instrumentation to measure

  - electron beam orbit ⬅
  - bunch charge
  - beam size
  - beam phase
  - energy and energy spread

  fast protection system to shut-off the beam in case of high losses

  - prevent damage on undulator (demagnetization) and vacuum system (leakage)

- diagnostics needed to control and optimize the FEL

  - **beam size / transverse emittance** ⬅
    → OTR/wire-scanner stations, resolution < 10 μm
  - **bunch length / longitudinal profile** ⬅
    → bunch length < 100 fsec, reconstruction of bunch shape
  - **slice emittance** ⬅
  - **bunch compression** → online signal for optimization of SASE process

- diagnostics needed for user experiments

  - characterization of radiation pulse (energy, spectral distribution)
  - synchronisation & stability (time-resolved experiments → fsec)

Standard FEL Diagnostics @ FLASH

		FLASH1	FLASH2
Charge	Toroids	12	5
	Dark Current Monitor	1	
	Faraday Cups	3	
	BPMs	6	33
Transverse Size	OTR-Screens	~30	
	Scintillating-Screens	1	7
	Wire scanners (MDI)	10	
	Wire scanners (Zeuthen)	9	
Transverse Position	Button-BPMs	26	12
	Stripline-BPMs	33	4
	Cold Cavity BPMs	6	
	Cavity BPMs		17
	HOM-based monitors	39	
Beam Loss	BLMs	>70	~55
	Cherenkov Fibers	2	1
	Beam Halo Monitors	1x4	1x4
	Ionization Chambers	4	4

about ~ 400 monitors

and a lot of additional special diagnostics…

Standard FEL Diagnostics @ E-XFEL

Monitor (Standard Diagnostics Only)	Number
BPMs (cold)	120
BPMs (Striplines, Pickups)	250
Undulator BPMs (Cavity, 1µm Resolution)	140
Charge Monitors (Toroids, Faraday Cups)	40
Beam Size: OTR, Wirescanners	77
Dark Current	10
Loss Monitors (PM Systems, Fibers)	320
Phase	15
Other	about 50
Total	**about 1000**

and a lot of additional special diagnostics…

Beam Position Monitors

- short version of E-XFEL BPM specification

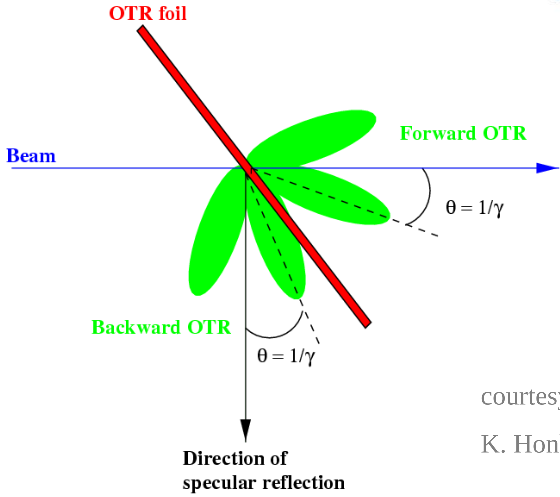
specified charge range: 0.1 – 1nC	Number	Beam Pipe	Length	Type	Single Bunch Resolution (RMS)	Train Averaged Resolution (RMS)	Optimum Resolution Range	Relaxed Resolution Range	x/y Crosstalk	Bunch to Bunch Crosstalk	Trans. Alignment Tolerance (RMS)
		mm	mm		µm	µm	mm	mm	%	µm	**µm**
Standard BPM	219	40.5	200/ 100	Button	50	10	± 3.0	± 10	1	10	**200**
Cold BPM	102	78	170	Button/ Re-entrant	50	10	± 3.0	± 10	1	10	**300**
Cavity BPM Beam Transfer Line	12	40.5	255	Cavity	10	1	± 1.0	± 2	1	1	**200**
Cavity BPM Undulator	117	10	100	Cavity	1	0.1	± 0.5	± 2	1	0.1	**50**
IBFB	**4**	**40.5**	**255**	**Cavity**	**1**	**0.1**	**± 1.0**	**± 2**	**1**	**0.1**	**200**

➡ different BPM types to meet different requirements

courtesy: D.Nölle (DESY)

Transverse Beam Profile: Coherent Effects

- standard beam diagnostics: Optical Transition Radiation (OTR)
  - backward OTR: reflection of virtual photons
    - → instantaneous process
  - single shot measurement
  - full transverse (2D) profile information



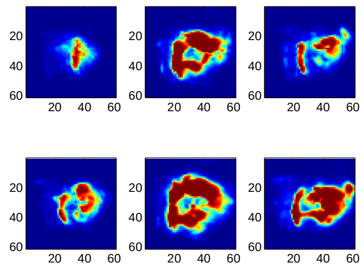
courtesy:
K. Honkavaara (DESY)

- Coherent OTR observation at LCLS (SLAC)

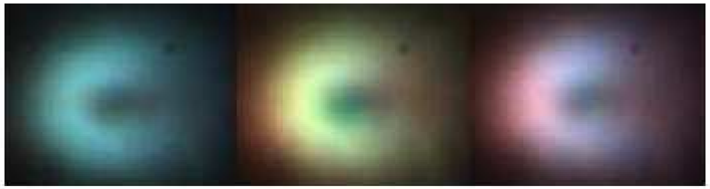
  R. Akre et al., Phys. Rev. ST Accel. Beams **11** (2008) 030703

  H. Loos et al., Proc. FEL 2008, Gyeongju, Korea, p.485.

  - OTR 12



  - OTR 22



  - strong shot-to-shot fluctuations
  - doughnut structure
  - change of spectral contents

→ measured spot is no beam image!

- interpretation of coherent formation in terms of “Microbunching Instability”

  E.L. Saldin et al., NIM **A483** (2002) 516 Z. Huang and K. Kim, Phys. Rev. ST Accel. Beams **5** (2002) 074401

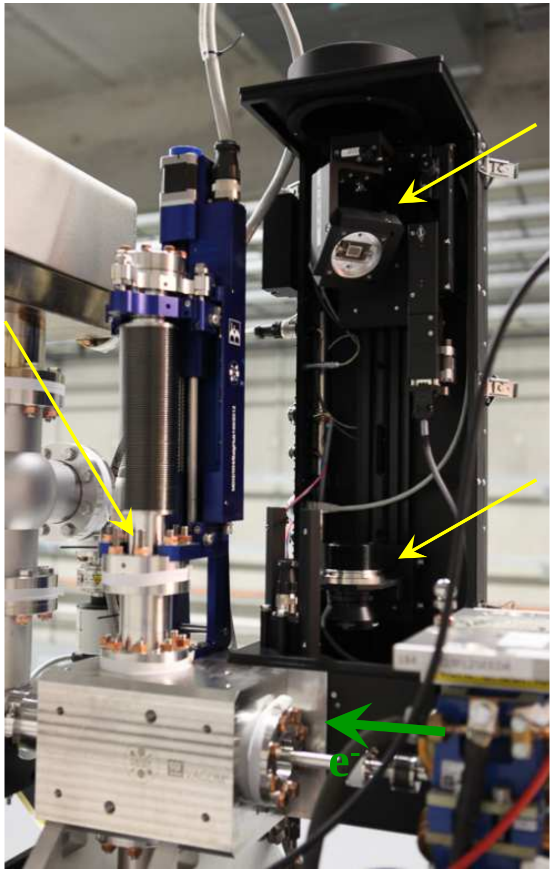
- alternative schemes for beam profile diagnostics
  - wire scanners → bunch trains
  - scintillating screens → single shot

XFEL Screen Monitors

- monitor setup

Ch. Wiebers, M. Holz, G. Kube et al.,

Proc. IBIC 2013, Oxford (UK), WEPF03



→ ~ 70 monitors in operation

- beam profile observation
  - projected emittances larger than expected

injector: ~ 1 mm.mrad

BC1, BC2: > 2 mm.mrad

downstream L3: > 4 mm.mrad

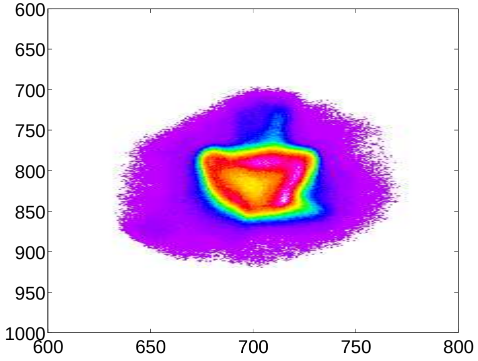
  - 'smoke-ring' shaped beam profiles

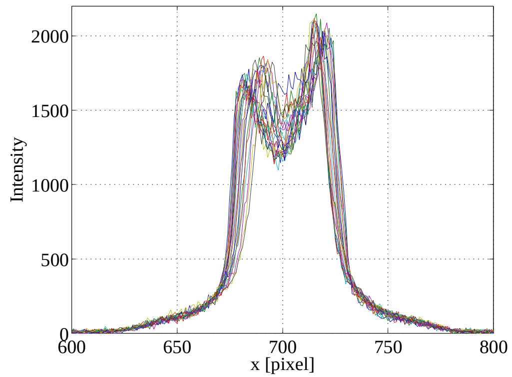
suspicious:

effect of scintillator

→ connected with high Q_{bunch}

→ studies ongoing





courtesy: M. Scholz (DESY)

FEL Diagnostics: Bunch Length/Profile

- coherent radiation diagnostics
  - **principle:** bunch length/shape dependent emission spectrum of coherent radiation

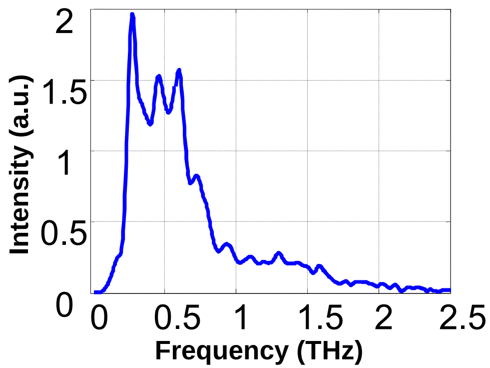
single particle spectrum — bunch form factor

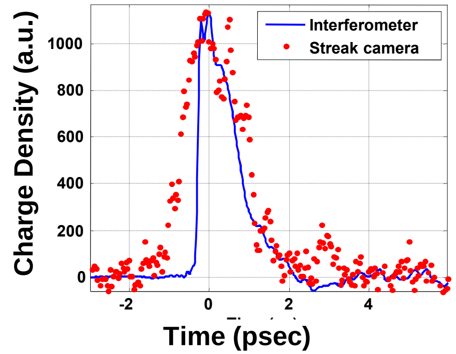
$$\frac{dU}{d\lambda} = \left(\frac{dU}{d\lambda}\right)_1 \left(N + N(N-1)\left|F(\lambda)\right|^2\right) \quad \text{with} \quad F(\lambda) = \int dz\, S(z)\, e^{i\frac{2\pi z}{\lambda}}$$

no. of particles per bunch — bunch profile

  - spectral decomposition and Fourier transform:
    → **bunch length and shape**

source: synchrotron radiation, transition radiation, diffraction radiation, Smith-Purcell radiation,…

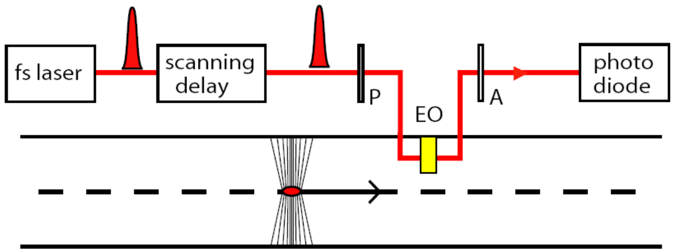




courtesy: O.Grimm (DESY)

- electro optical sampling (EOS)
  - **principle:** Coulomb field induces refractive index change in EO crystal (Pockels effect)
    → effective polarization rotation proportional to Coulomb field
  - Coulomb field converted in opt. intensity variation
    → **laser + polarizer (P) + analyzer (A)**

example: EOS using variable delay (simple scheme)
more sophisticated: temporal, spectral, spatial encoding

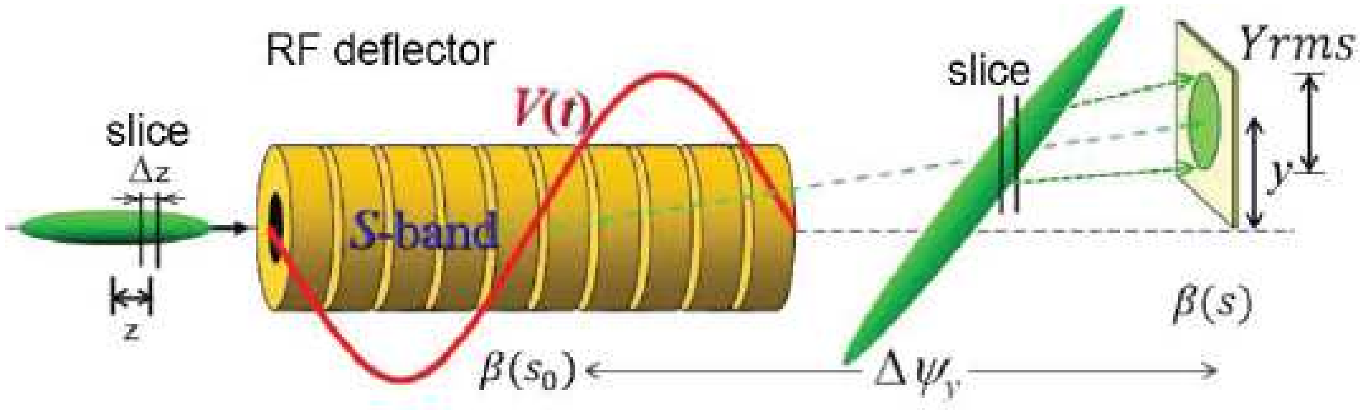


courtesy: B. Steffen (DESY)

FEL Diagnostics: Slice Emittance

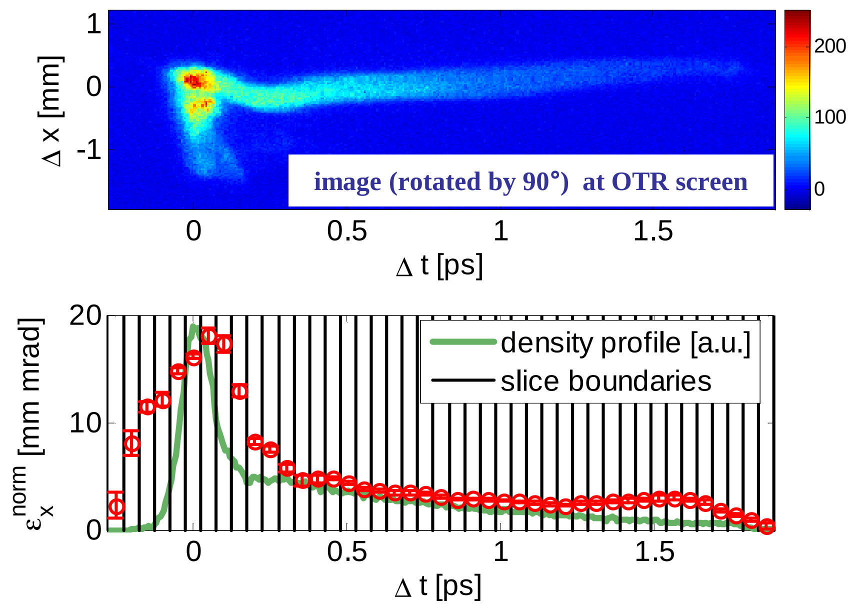
- transverse deflecting structure (TDS)

courtesy: H. Schlarb (DESY)



- 'Intra Beam Streak Camera':
  - → vertical deflecting RF structure (2.856 GHz) operated at zero crossing
- 'parasitical' measurement using kicker and off-axis screen
- vertical size of beam at imaging screen
  - → ***bunch length***
- horizontal size at imaging screen
  - → access to ***slice emittances***

FLASH: slice emittance under SASE conditions @ 13.7 nm



Outlook

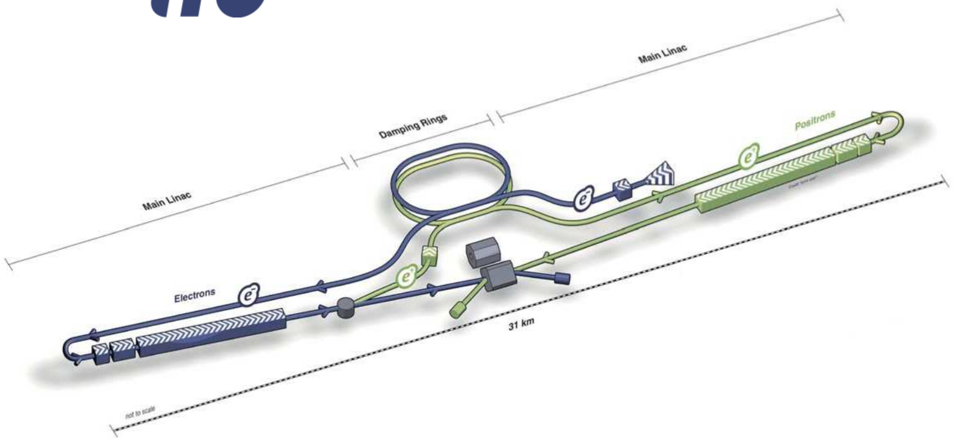
- linear collider
- what is coming next…

Outlook

- putting it all together…
  - injector linac, including e^+ production
  - storage ring with opportunity of radiation damping
  - linac with stringent requirements for 6-dimensional phase space

…and build a linear collider:

superconducting RF
L-band, 1.3 GHz Tesla-Technology

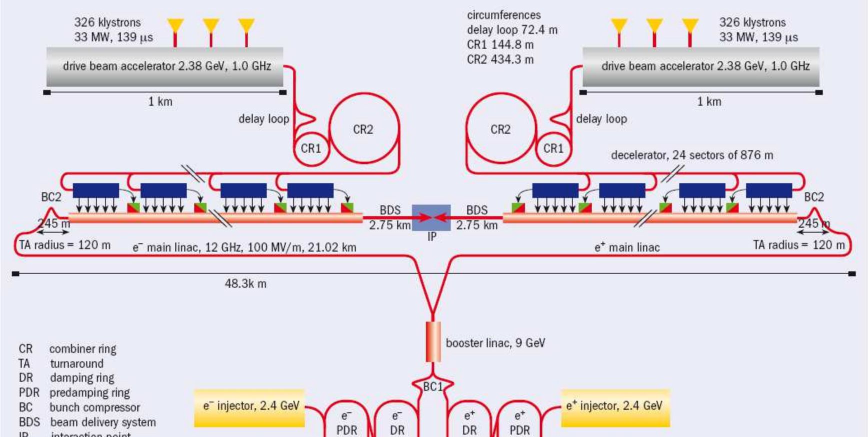


https://www.linearcollider.org/pdf/ILC_Accelerator_bynumbers.pdf

…or the CERN version:

normalconducting RF
X-band, 12 GHz Technology

Compact Linear Collider



CLIC layout 3 TeV

P.Burrows, CLIC Workshop 2016, CERN

International Linear Collider

- key parameters (nominal values)

Beam Parameters	Collision Energy	500 giga-electron-volts (500 GeV = 250 GeV + 250 GeV)
	Luminosity	2×10^{34} cm^{-2} s^{-1}
	Bunch population	2 x 1010
	Number of bunches	1312
	Bunch spacing	554 ns
	Number of collision	6560 s^{-1}
	Number of beam acceleration	5 s^{-1}
	Acceleration gradient	31.5 MV/m
	Beam size at collision point	Width 474 nm
	Number of acceleration cavity unit	Thickness 5.9 nm
Accelerator unit	Number of cryomodules	14742
	Number of klystrons in	1701
	distributed klystron system	378
	Size of cryomodule	1m diameter, 12m length
Cryomodule	Cryomodule type	
	Type 1 Type 2	9 units of 9-cell acceleration cavities 8 units of 9-cell acceleration cavities + 1 unit of superconducting quadrupole magnet
	Frequency of pulsed RF	1.3 GHz
Operation	Power of pulsed RF	190 kW/cavity
	Operation temperature of acceleration cavity	2 K
Size of accelerator	Circumference of Damping ring	3.2 km
	Length of main linac	11 km (electron linac) + 11 km (positron linac)
Collision experiment	Number of Detectors	2 (push-pull alternation)

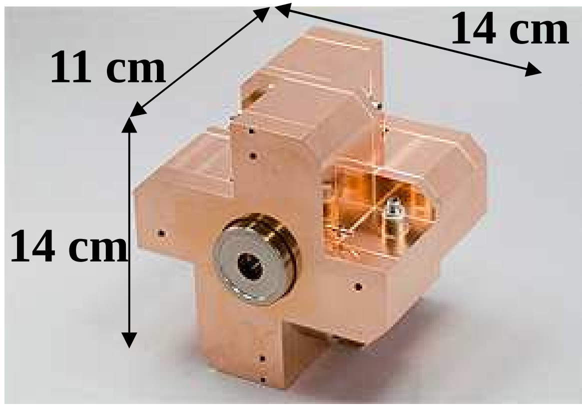
https://www.linearcollider.org/pdf/ILC_Accelerator_bynumbers.pdf

challenges

- ***beam position***
  - → measurement
  - → stability
- ***beam size***
  - → measurement
  - → non-invasive

ILC: Diagnostics

- beam position measurements with sub-μm resolution
  - ***Cavity BPMs*** for higher resolution applications
  - location in cold and warm sections
  - variety of R&D activities for ILC BPMs at different laboratories
  - single bunch position resolution of ~20 nm achieved at ATF (KEK)



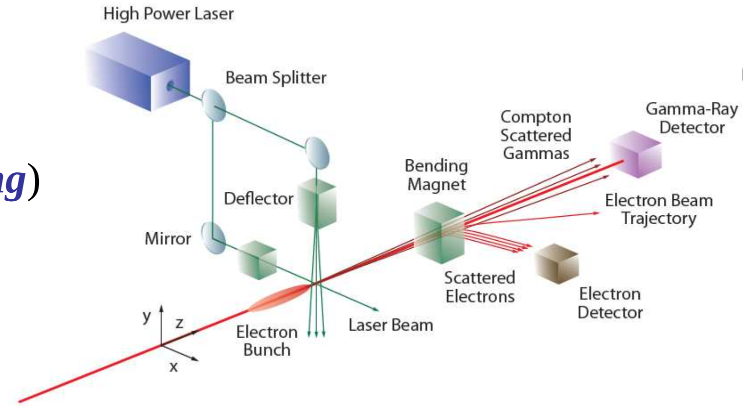
courtesy: T.Nakamura (Tokio University)

high resolution cavity BPM for ILC final focusing system

- non-invasive beam profile monitors
  - laser wire scanner
    - → scanning a finely focussed laser beam across bunches
    - → measure scattered photons (***inverse Compton scattering***) in downstream detector
    - → photon rate as function of relative laser beam position

⮕ ***beam profile***

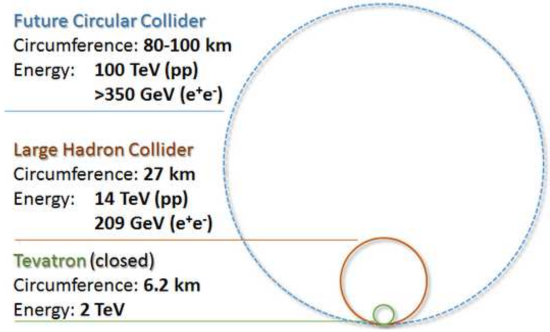
principle of laser wire scanner



ILC Reference Design Report (2007)

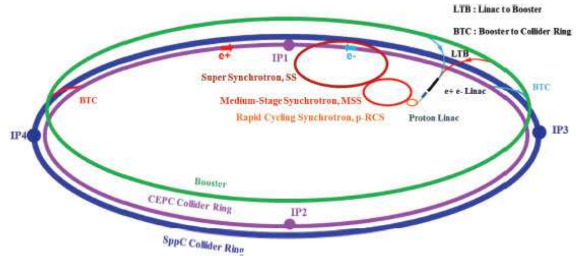
Outlook: New Accelerators

- circular colliders
  - ***Future Circular Collider (FCC)*** @ CERN



https://fcc.web.cern.ch

  - ***Circular e^-e^+ Collider (CEPC)*** @ China
    (Super pp Collider - SppC)



E_{beam} = 120 GeV, C = 54 km /100 km

- light sources
  - circular: ***Ultra Low Emittance Rings***

$$\varepsilon \propto \gamma^2 \theta^3$$

→ Multi Bend Achromat (MBA) scheme, i.e. small bend angle θ

➡ challenging for ***emittance diagnostics***

  - linear: from ***pulsed*** to ***cw*** operation
    low charge operation for ***attosecond photon pulses***

} ➡ challenging for ***all diagnostics***

- plasma wakefield acceleration, dielectric wakefield acceleration, …
  - require new concepts for beam diagnostics