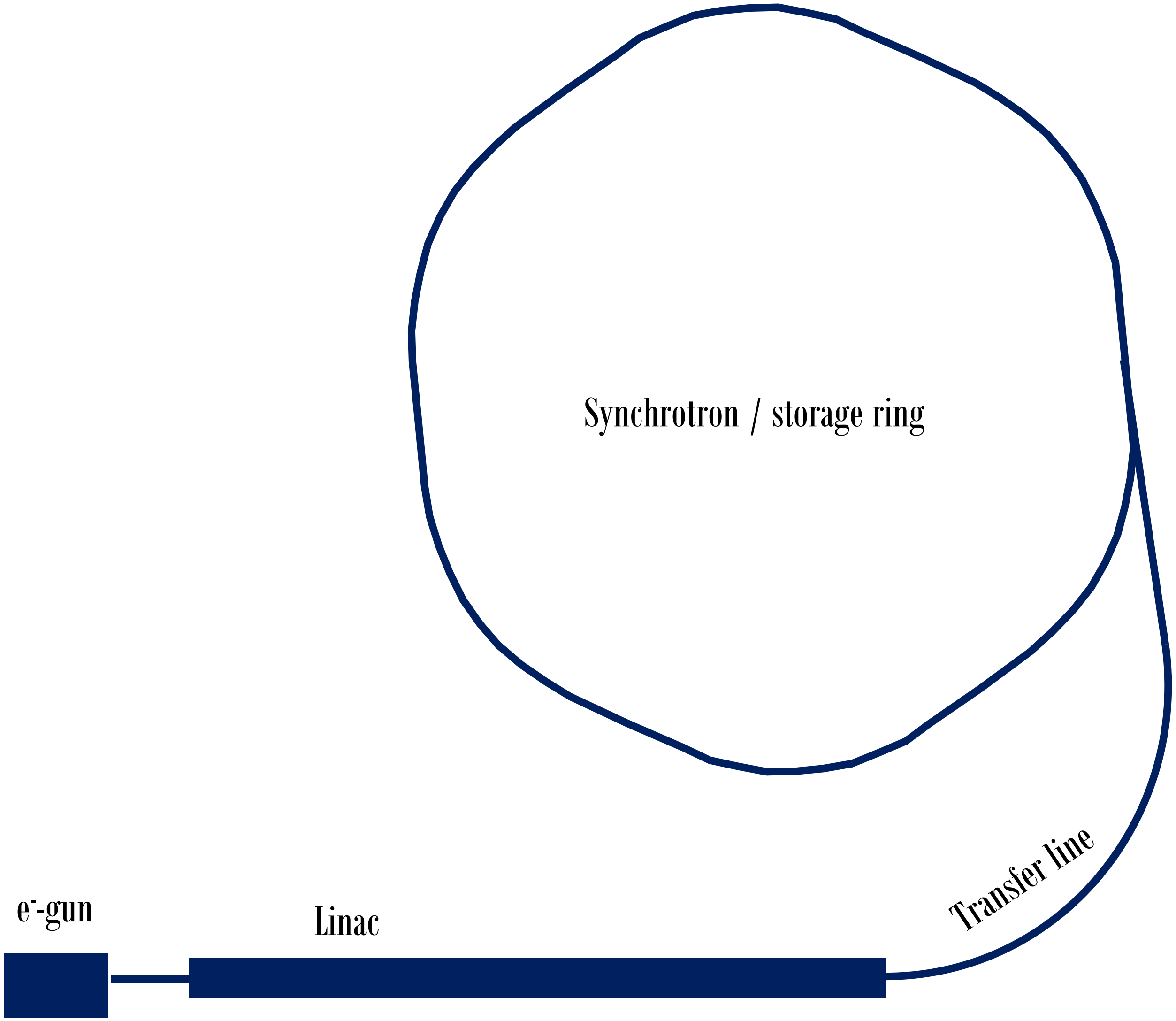
Between Model and Reality, part I

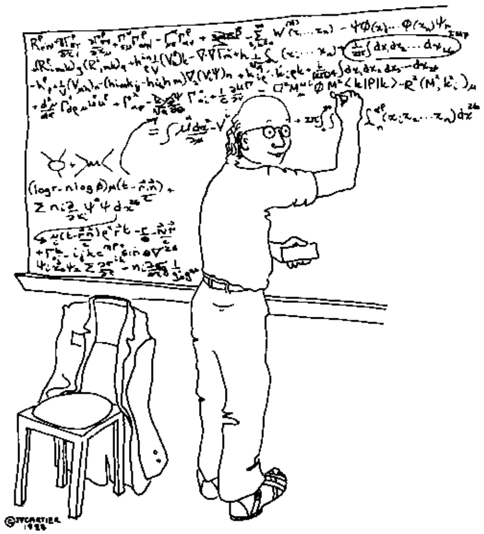
- *Why don't accelerators behave as designed ?*
- *Why do we need beam diagnostics ?*
- *Why is diagnostics getting more demanding ?*

Hans Braun / CERN

Example accelerator complex



Accelerator design relies on well established physics !



Magnets, RF cavities

Maxwell's equations

$$\vec{\nabla}\cdot\vec{D} = 4\pi\rho$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{H} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial\vec{D}}{\partial t}$$

Beam dynamics

Lorentz Force

$$\vec{F} = e\left(\vec{E} + \vec{\beta}\,c\times\vec{B}\right)$$

Newton's 2nd law
+ special relativity

$$\frac{d}{dt}\left(\frac{m c\vec{\beta}}{\sqrt{1-\vec{\beta}^2}}\right) = \vec{F}$$

...tron / storage ring

Synchrotron radiation

Lienard-Wiechert potentials and Planck's energy quanta

$$\phi(t) = \frac{e}{4\pi\varepsilon_0}\left\{\frac{1}{r\left(1-\hat{n}\cdot\vec{\beta}\right)}\right\}_{ret}$$

$$\vec{A}(t) = \frac{\mu_0 e}{4\pi}\left\{\frac{\vec{\beta}\,c}{r\left(1-\hat{n}\cdot\vec{\beta}\right)}\right\}_{ret}$$

$$E = \hbar\omega$$

Cathode

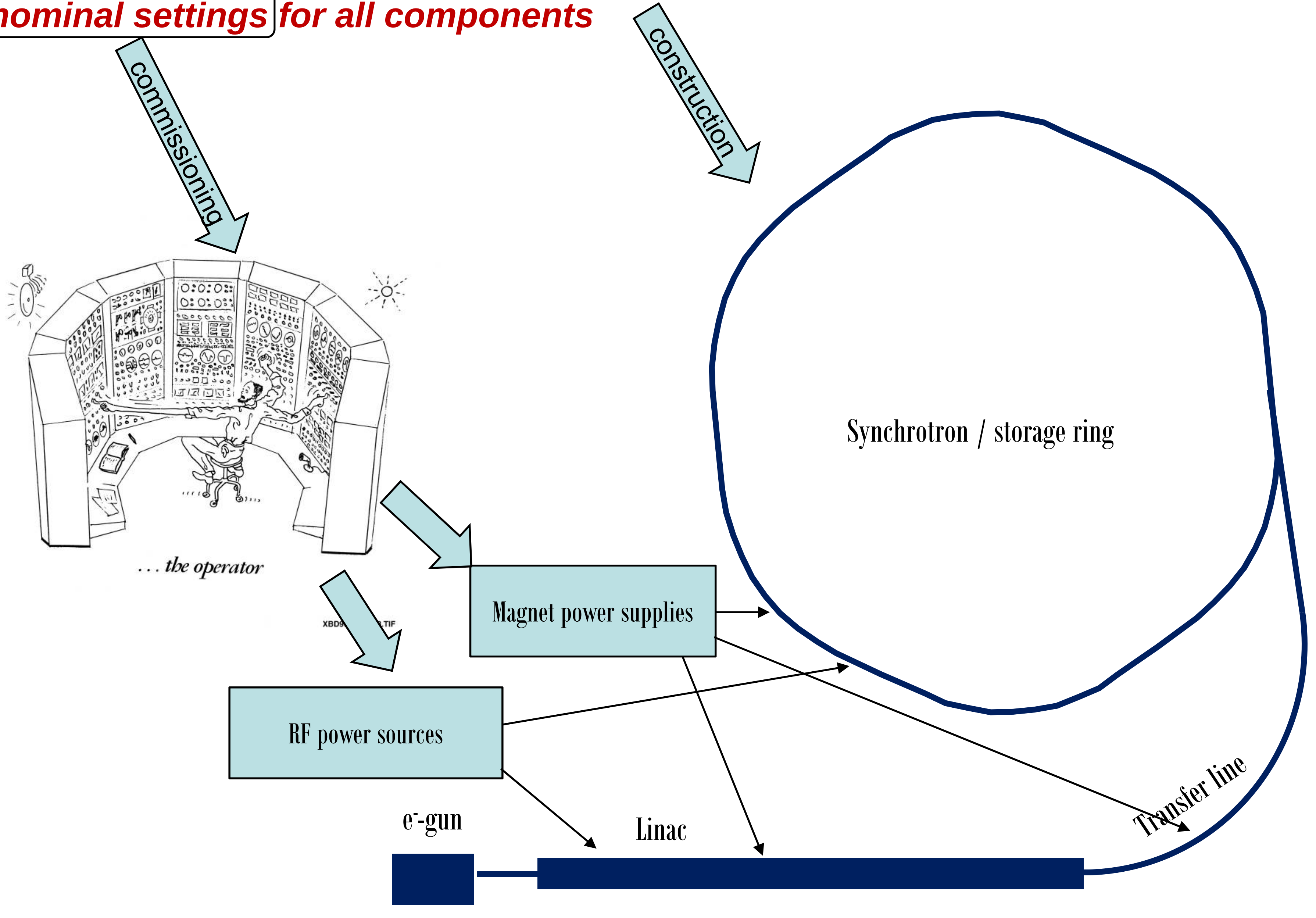
Richardson-Dushman equation

$$J = CT^2 e^{\frac{-\Phi}{kT}}$$

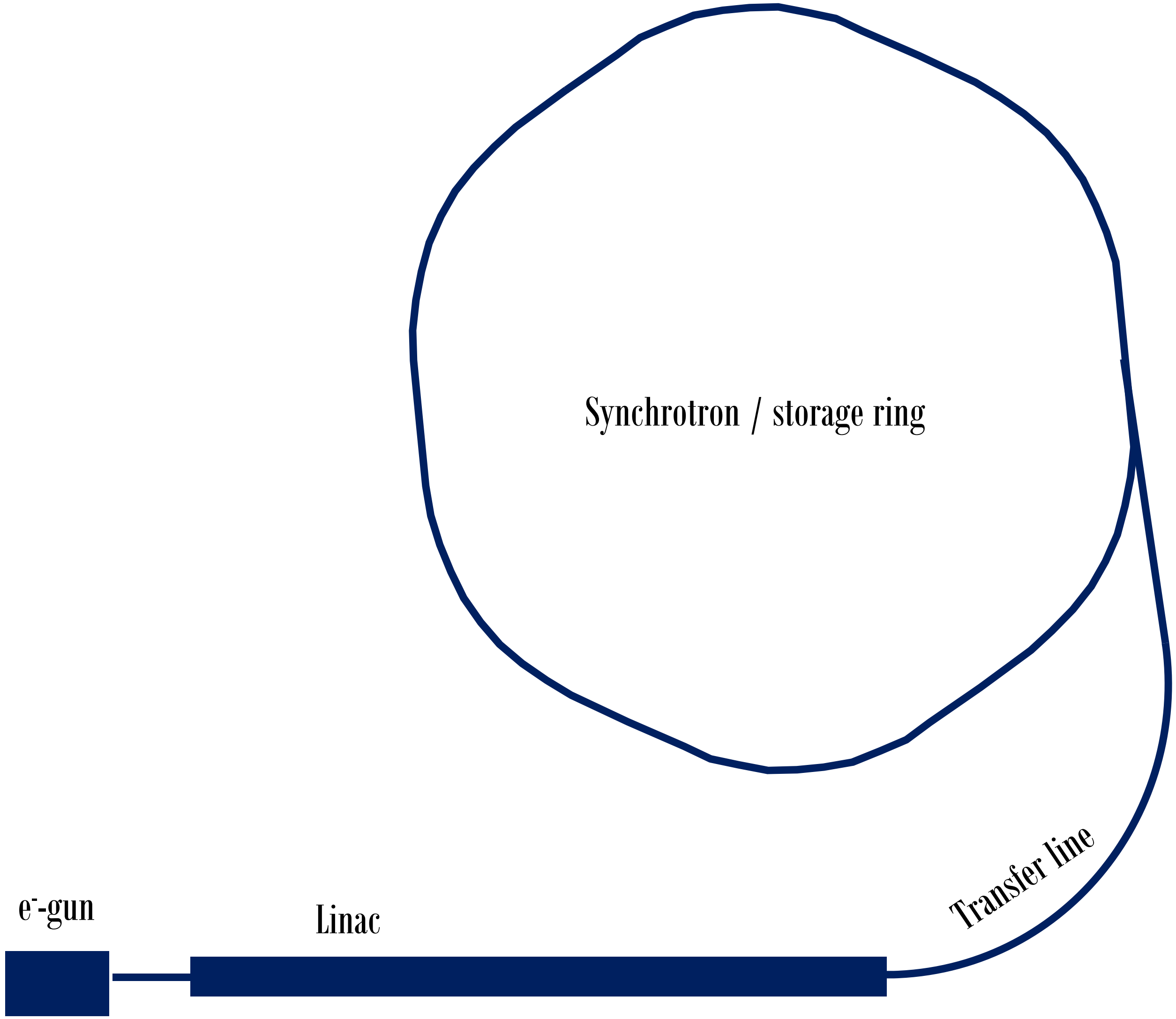
e$^-$-gun

Linac

Machine design provides specifications and nominal settings for all components



So, why do we need beam diagnostics here?



6 good reasons for beam diagnostics

- *Stupid things*
- *Component tolerances and related random errors*
- *Environmental effects*
- *Equipment fault*
- *Equipment set-up*
- *Performance tuning and preservation* ⇒ Laurent Nadolki's lecture tomorrow

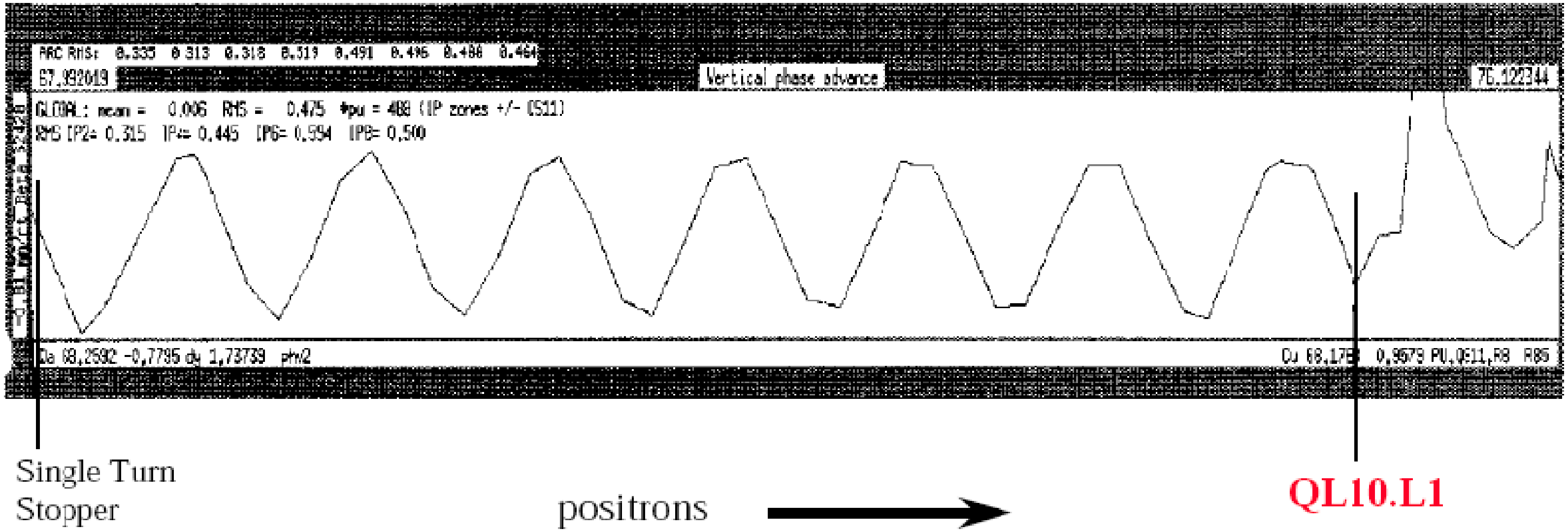
Stupid things

- ☹ magnets connected with wrong polarity
- ☹ cables connected to wrong equipment
- ☹ wrong entries in control system database
- ☹ calibration values mixed up
- ☹ “nominal settings” from wrong optics file
- ☹ kicker mounted in wrong direction
- ☹ somebody stepped on beampipe to change neon tube
- ☹ beer bottles in vacuum chamber
- ☹ …

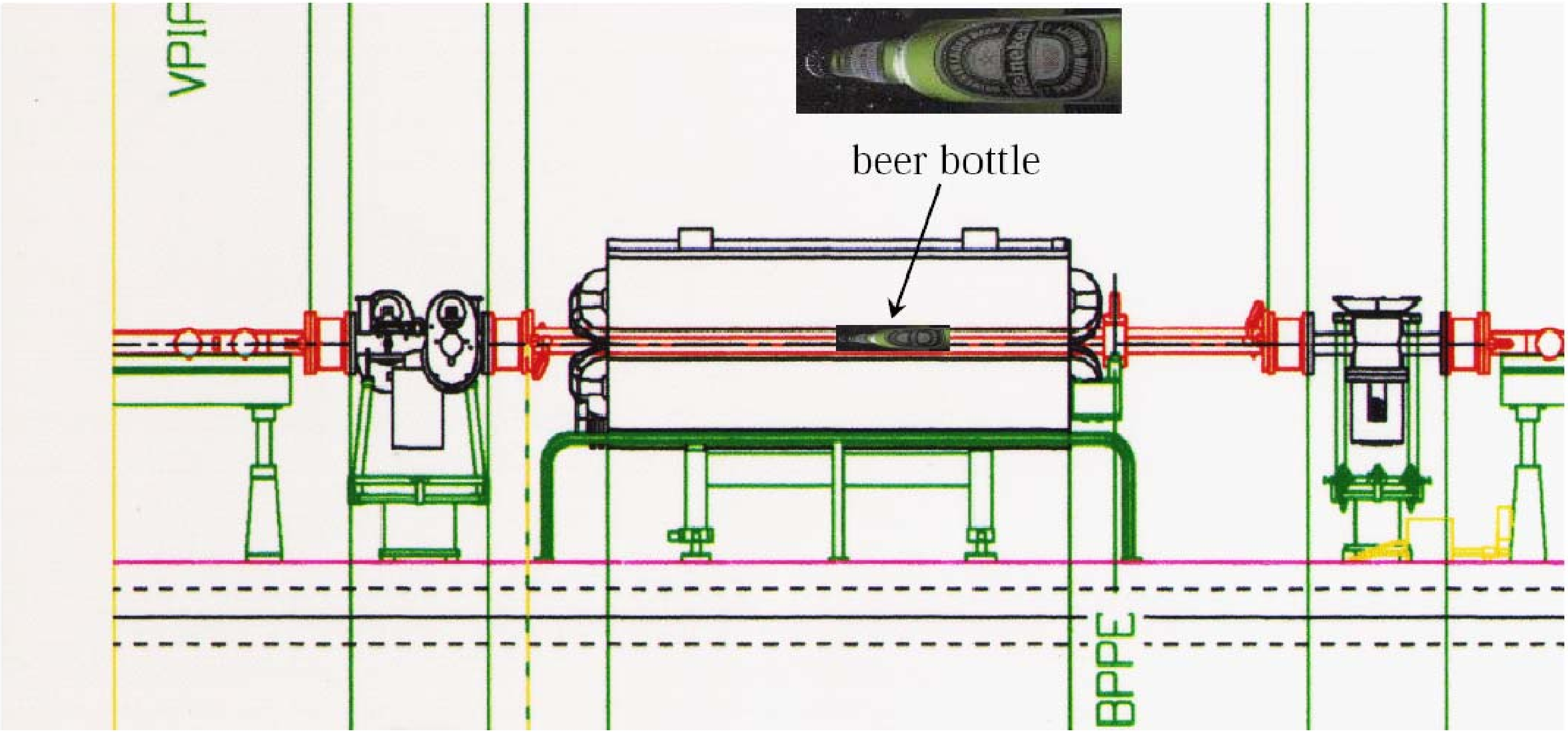
"PARTICLES, PARTICLES, PARTICLES

Some really unexpected events

Could not get the beam to circulate more than 15 turns even with large bumps all around the ring. Use single turn orbit system and normalised the measurement.

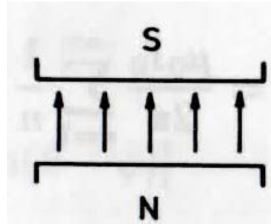
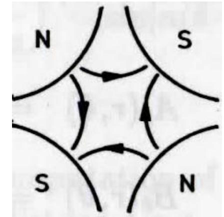
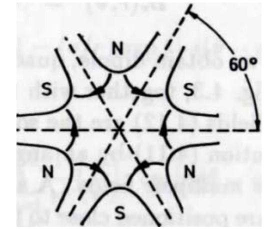


Zoom sur Quadrupole



Component tolerances and related random errors

- Finite precision of survey and alignment
- Finite accuracy of power supplies
- Ripple of power supply
- Finite accuracy of magnet field measurement
- Ripple of RF Amplitude
- RF phase noise
- Drifts (temperature, humidity, aging of component)

	Dipole 	Quadrupole 	Sextupole 
purpose	beam deflection & sometimes focusing	beam focusing	chromatic correction
unwanted, but somehow predictable side effects	sextupole component modifies chromaticity reduces acceptance	dodecapole component (usually negligible)	limits dynamic acceptance
effect of excitation errors and ripple	generates orbit errors and chromaticity deviations	generate tune errors	generate chromaticity errors
most critical alignment issues	roll angle generates vertical orbit excursions and spurious vertical dispersion	transverse shifts generate orbit excursions and spurious dispersion roll angle generates x, y coupling vertical shift destroys beam polarisation	vertical displacement generates x,y coupling horizonal displacement generates tuneshift

Some typical values

A good survey and alignment team adjust magnets within $\pm$150 μm of nominal position and $\pm$100 μrad of nominal angle.

Active alignment systems can measure and correct position of accelerator components relative to a laser or stretched wire reference within 1 μm.

Machining with precision turning lathe and milling cutter can be done with a few μm precision

Typical technical materials have thermal coefficient of expansion in range $5 \cdot 10^{-6}$-$25 \cdot 10^{-6}$
a ΔT of 1^o C of a 1m size object will therefore change it's dimensions by 5-25 μm

Rapid (>1 Hz) seismic movements $\approx$10-50 nm

Displacement of one quadrupole in a storage ring by 1 μm will result in a change of mean orbit amplitude of typically 1-10 μm.

In a new building or tunnel floor moves in some cases several mm per year

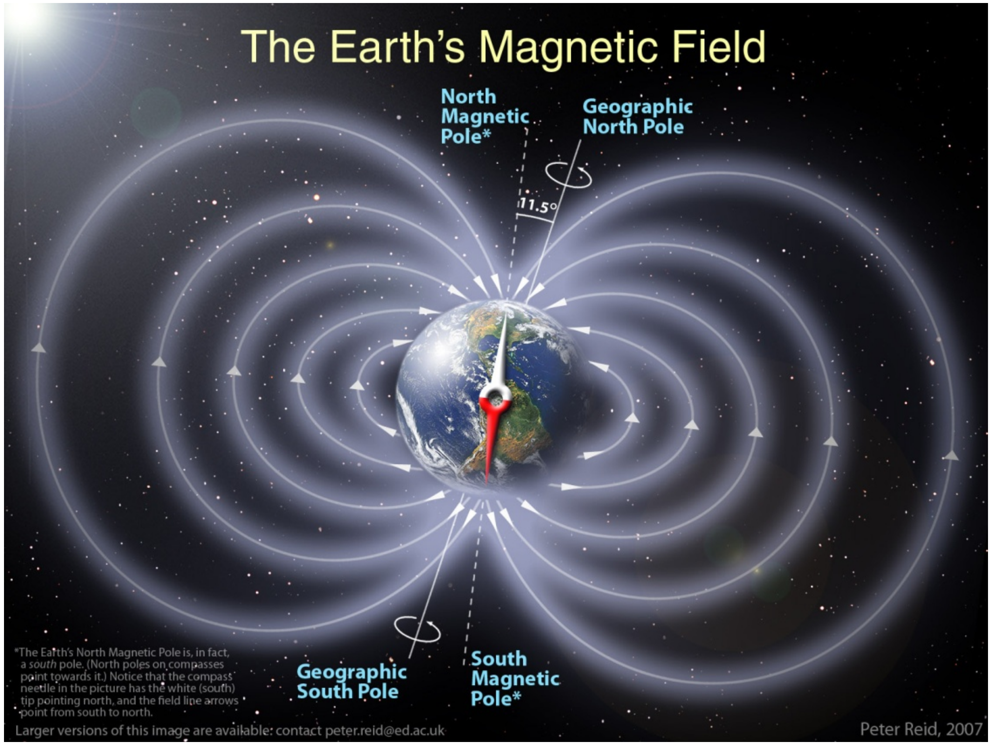
A 30^0 horizontal bending dipole with a roll error of 1 mrad will give 0.5 mrad of vertical deflection.

Magnet power supplies have residual ripples & drifts ranging from 10^{-3}-10^{-6}.
A 10^{-4} ripple on a 30^0 horizontal bending dipole produces a jitter on beam angle of 50μrad corresponding to 50 μm position jitters one meter downstream.

Environmental effects

- Subsiding of building/tunnel foundation
- Mechanical vibrations induced by water flow, vacuum pumps, water pumps, ventilation
- Mechanical vibrations from nearby traffic or construction work
- Seismic vibrations
- Earth magnetic field
- Magnetic fields from electric currents induced on vacuum chamber
- Stray fields from permanent magnets in vacuum pumps and vacuum gauges
- Field distortions from magnetic materials in support structures, building and equipment
- Magnetic stray field from cables

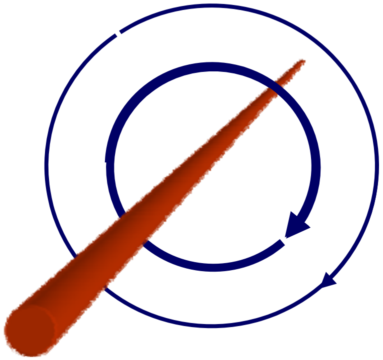
Disturbing fields I



$B_{earth} \approx 70\ \mu T$,
deflects a 100 MeV electron beam over a 10m long drift by one 1cm.

In accelerator environment direction and strength of B_{earth} may vary considerably due to ferromagnetic support structures and steel in concrete.

Disturbing fields II



$$B = \frac{\mu_0 I}{2\pi R}$$

Stray field from a cable with a current of 350 A in a cable tray 1m from beam pipe will have same strength as earth magnetic field. Therefore both power leads for a magnets should always be pulled together at close distance to compensate strayfields.
For arrangements with several magnets in series this is not always feasible.

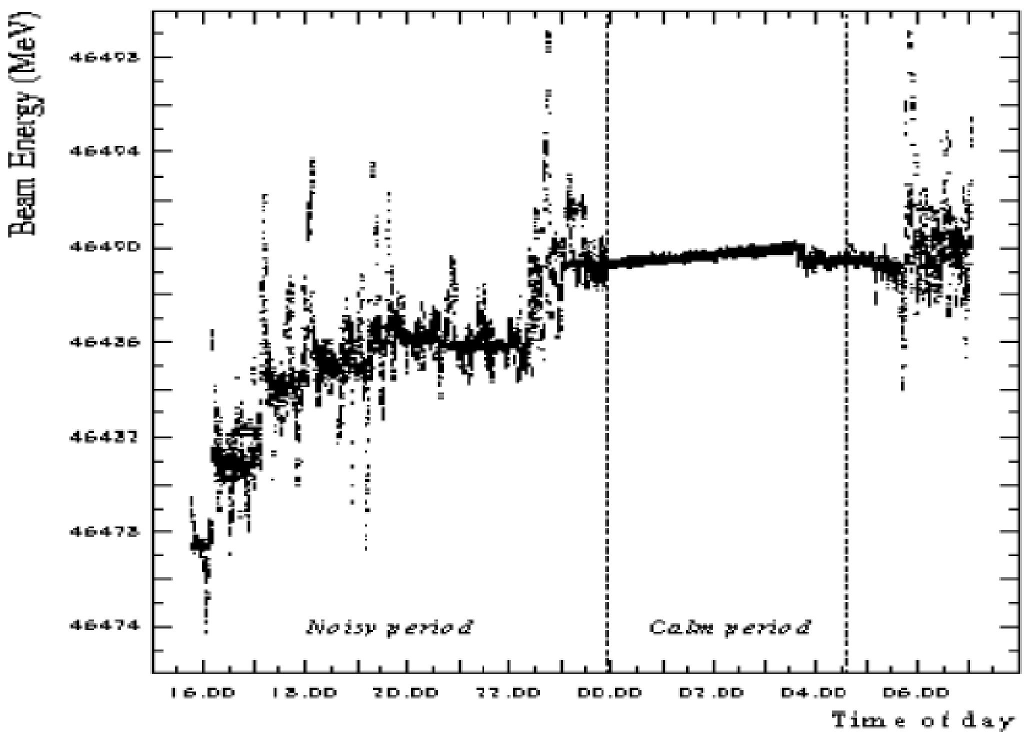
Strong permanent magnets are used in ion pumps and vacuum gauges. Make sure that their stray field in the beampipe is sufficinently low !

The effect of stray fields from injection / extraction line magnets and septa is often a nuisance.

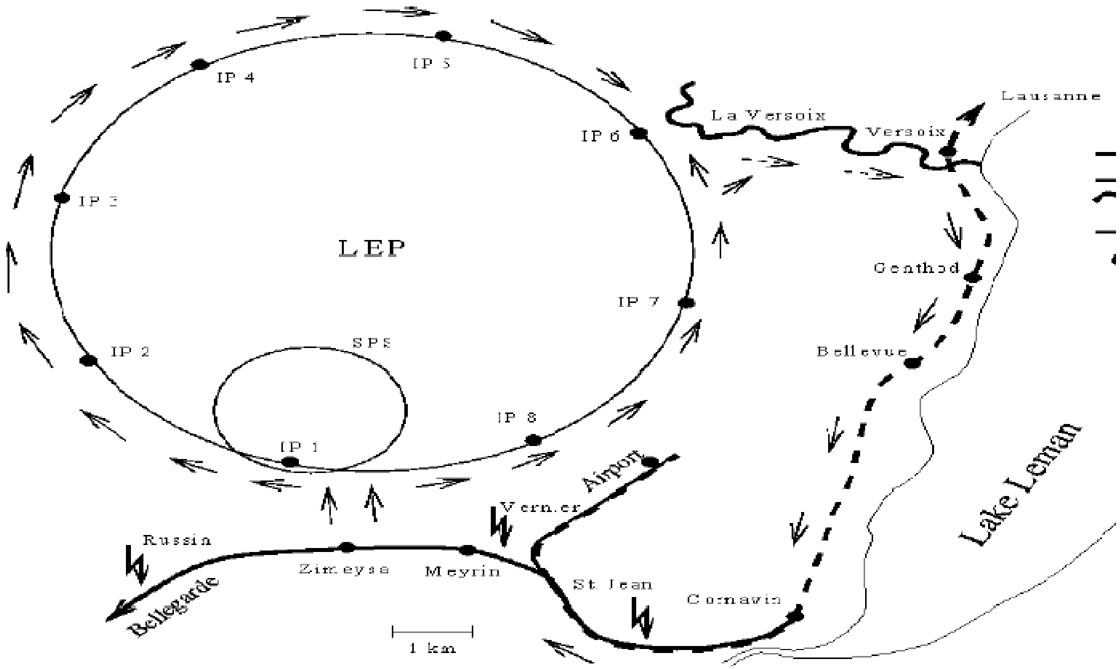
Make sure that ferrits in beam monitors are not affecting / or affected by field from accelerator magnets !

Stray fields effects can be mitigated with compensation coils or shielding by thin sheets of μ-metal.

Noise on the Beam Energy



TGV induces current in LEP vacuum chamber



Equipment faults

- Major faults of equipment are usually trivial to detect (main RF, dipole,…)

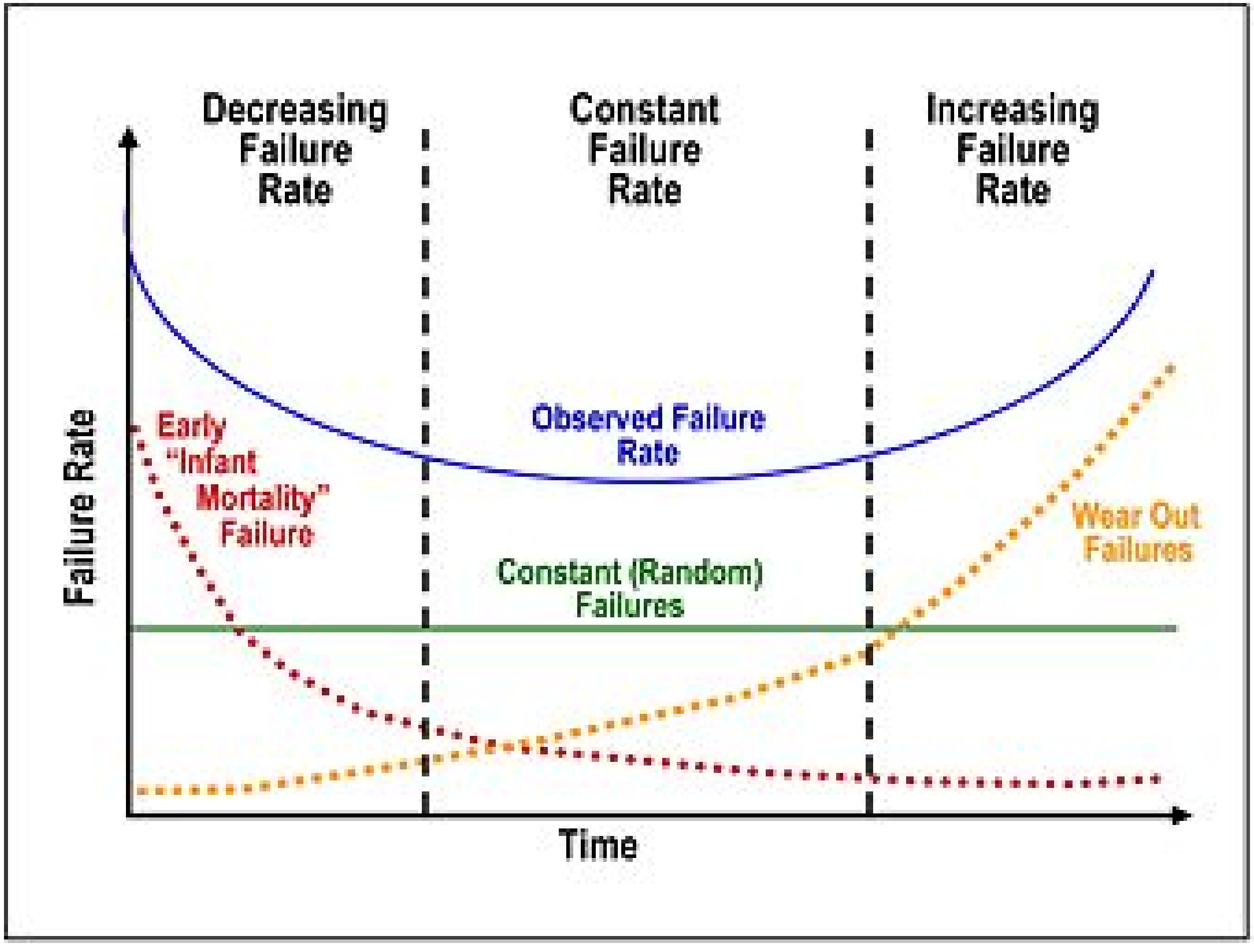
- Small and/or intermittent faults can be extremely difficult to diagnose and a real headache. Signal can for example be step change in orbit, a transient beam loss or intermittent beam position jitters.

Examples:

insulation fault between two coil turns of a quadrupole.
Change in magnet resistivity often not detectable
consequences are a small change in quadrupole strength
and a field asymmetry leading to beam deflection.

Intermittent instability of a power supply.

The Bathtub Curve



Equipment set-up

☺ Beam diagnostics often provides the most sensitive signals to adjust equipment parameters to their operational values.

Examples:

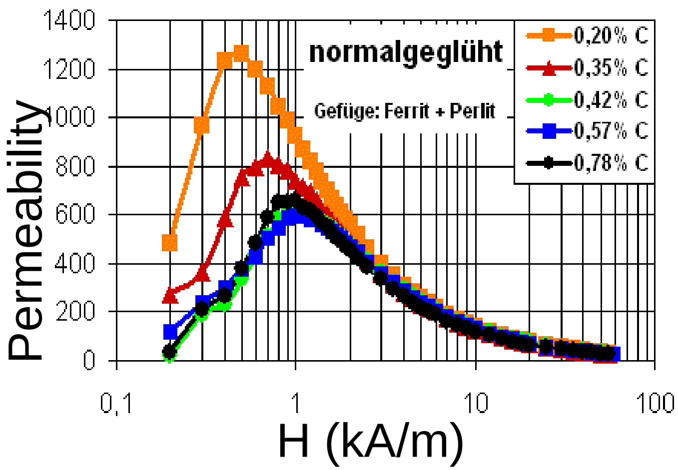
- Setting of RF phases between different cavities in a linac with RF measurements only would be very difficult, because very precise characterisation of all cables, connectors etc. required.
  With beam phasing of cavities is straight forward and precision better that $<1^0$ can be readily obtained just by optimising beam energy at end of linac.
- Tune and chromaticities settings more precisely with beam than with predictions from magnet measurement.
  One reason:
  Magnets have no “easy” power supply current $\Rightarrow$ field mapping
- In electron storage ring the polarisation method allows an extremely precise measurement of beam energy, better than any magnetic field calibration.

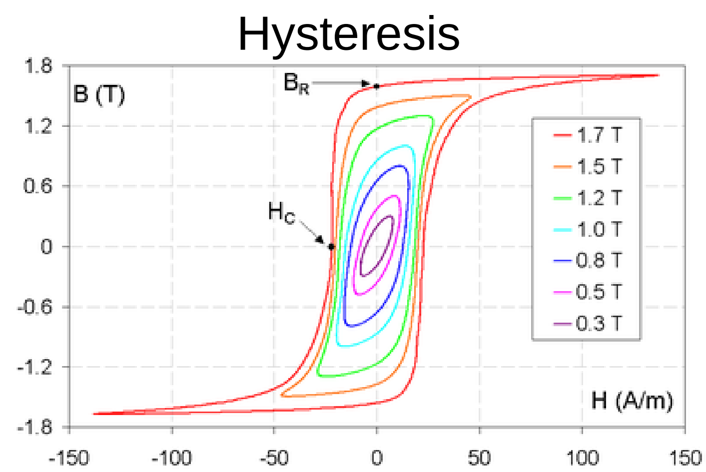
Warm magnets

Relation between magnet current and field neither linear nor unique

Moreover does field distribution (the relative strength of multipole coefficients) vary with excitation.

In most existing storage rings magnet model is derived from a combination of magnetic field measurments and beam measurements.





Properties of soft magnetic materials

Material	μ	B_S (T)	B_{OPT} (T)	H_C (A.m^{-1})	T_C (°C)	ρ (μΩ/cm)	Price (CHF/kg)
80%Ni-Fe	10^5-10^6	0.8	0.7	1	460	15	70-150
50%Ni-Fe	10^4-10^5	1.6	1.0	5-10	500	35	30-60
3%Si-Fe	5.10^3-10^4	2.0	1.3	30-50	750	47	2-5
Very low-C steel	10^3-8.10^3	2.18	1.5	40-80	770	10	1
Amorphous	10^4-5.10^4	0.8	0.5	<1	350	130	
Soft ferrite	1400	0.25		0.8	110	10^8	

Superconducting magnets

Even worse, nonlinearities from permeability of iron yoke
+ persistent currents

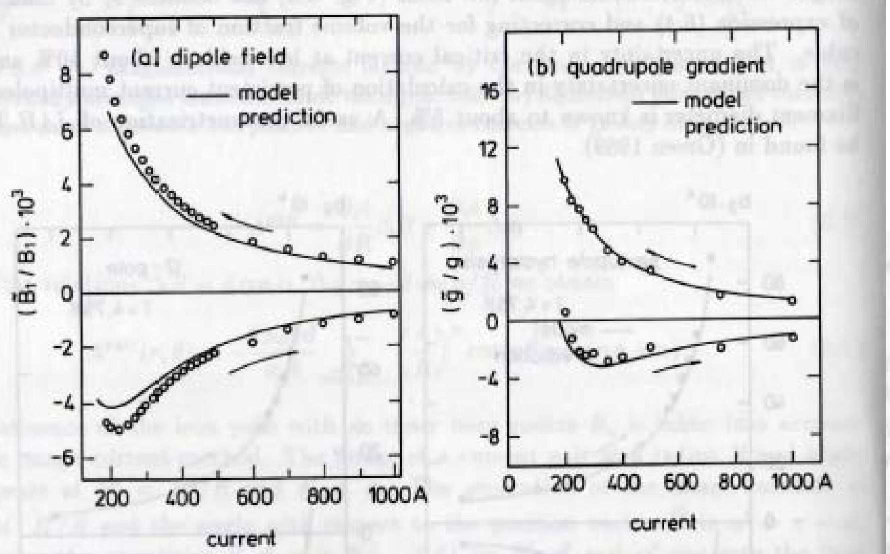


Figure 6.6: (a) The relative contribution $\bar{B}_1/B_1$ of the persistent currents to the main dipole field. (b) Relative contribution $\bar{g}/g$ to the main quadrupole gradient. Solid curves: model prediction.

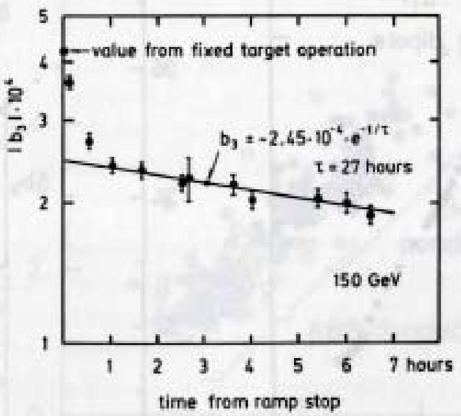


Figure 6.7: Observed sextupole drift in a Tevatron dipole with exponential fit for times above 1 hour. (© 1987 IEEE)

from "Superconducting Accelerator Magnets," K.H. Mess, P. Schmüser, S. Wolff

Yet another effect which is difficult to predict quantitatively:

In synchrotrons $\dot{B}$ induces eddy currents on vacuum chamber.
These currents create a predominantly quadrupolar field,
thus changing the overall focusing in proportion to ramp speed.

Beam diagnostics, what can be measured:

Specific beam diagnostic elements

Beam current
" position
" phase
" energy
" transverse profile
" transverse emittance
" longitudinal profile
" energy profile
" longitudinal emittance
" polarisation
" Schottky noise longitudinal
" Schottky noise transverse
…

But information about beam comes also from

Measurement loops in RF cavities
Vacuum chamber temperature
Residual gas pressure & composition
Activation of vacuum chamber
…

Measurement flavours

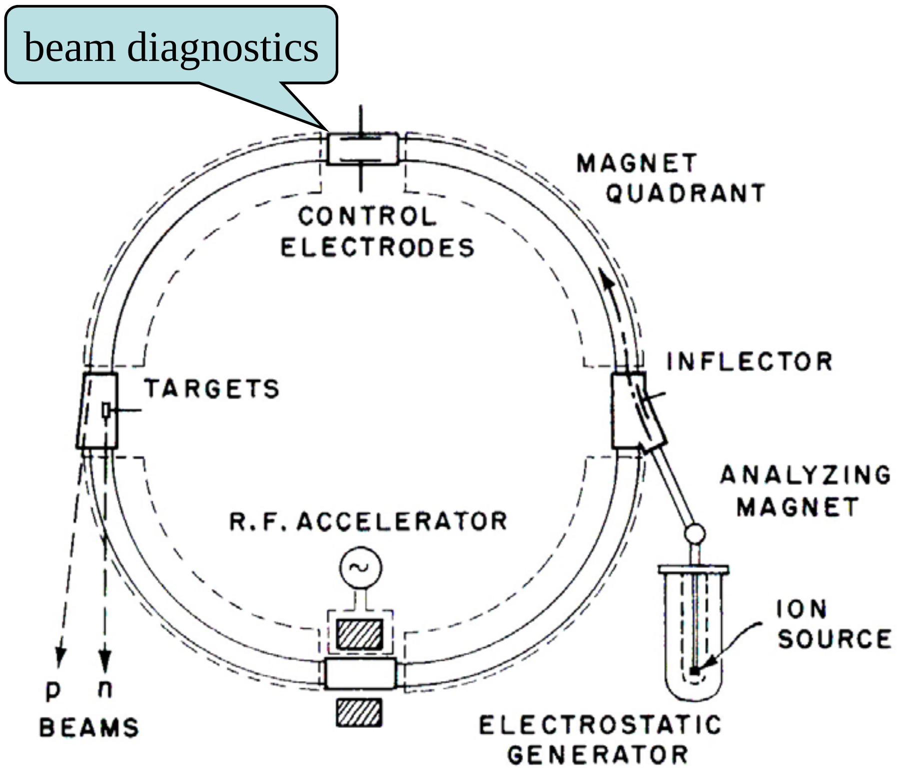
average values
i.e. closed orbit

time resolved
i.e. position of individual bunches in a bunch train

correlations
beam position at different locations
to detect source of a beam jitter.
This requires either real time readout system
or time stamping of signals

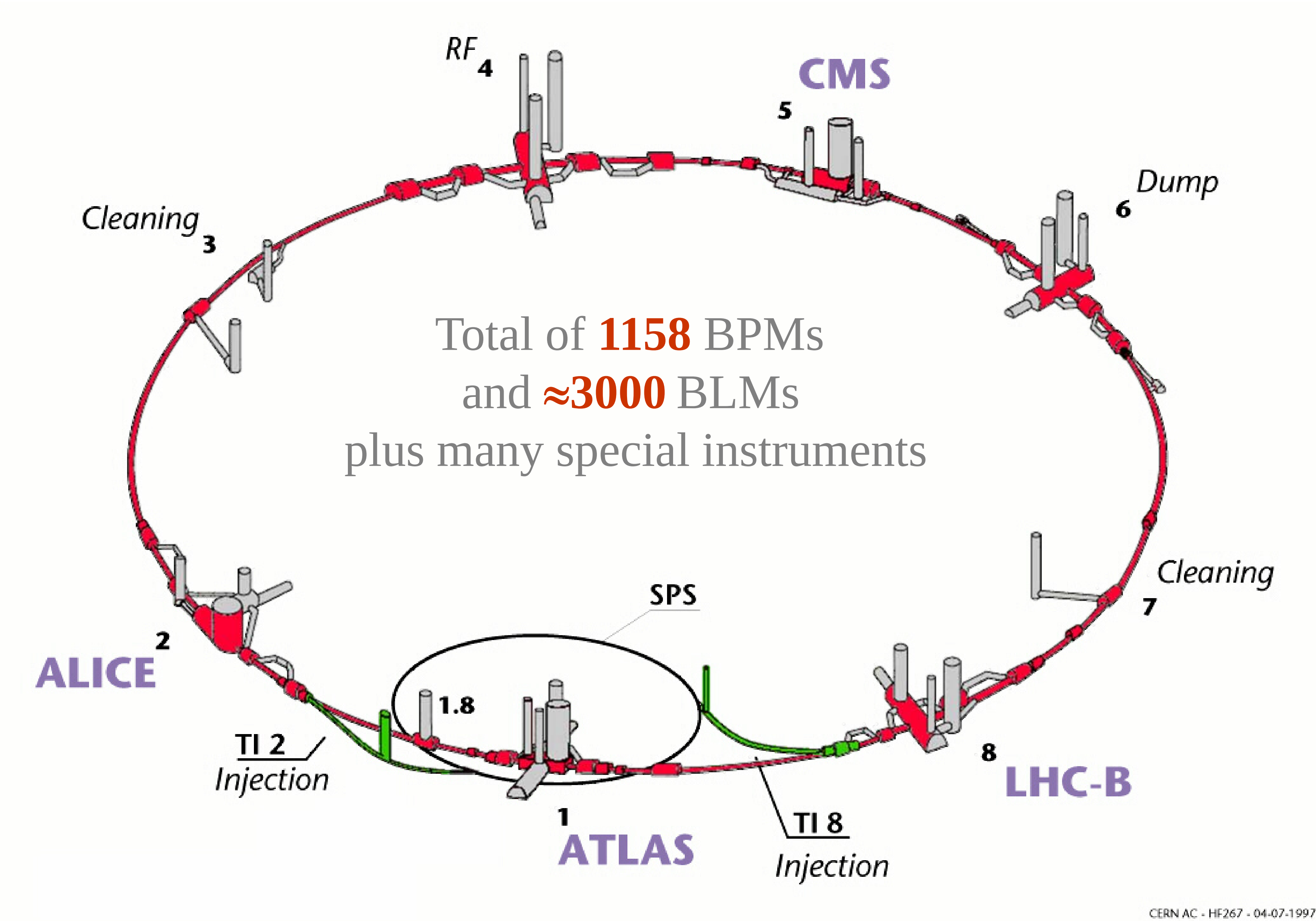
post mortem
complete dump of signal buffer from last seconds
before beam got lost

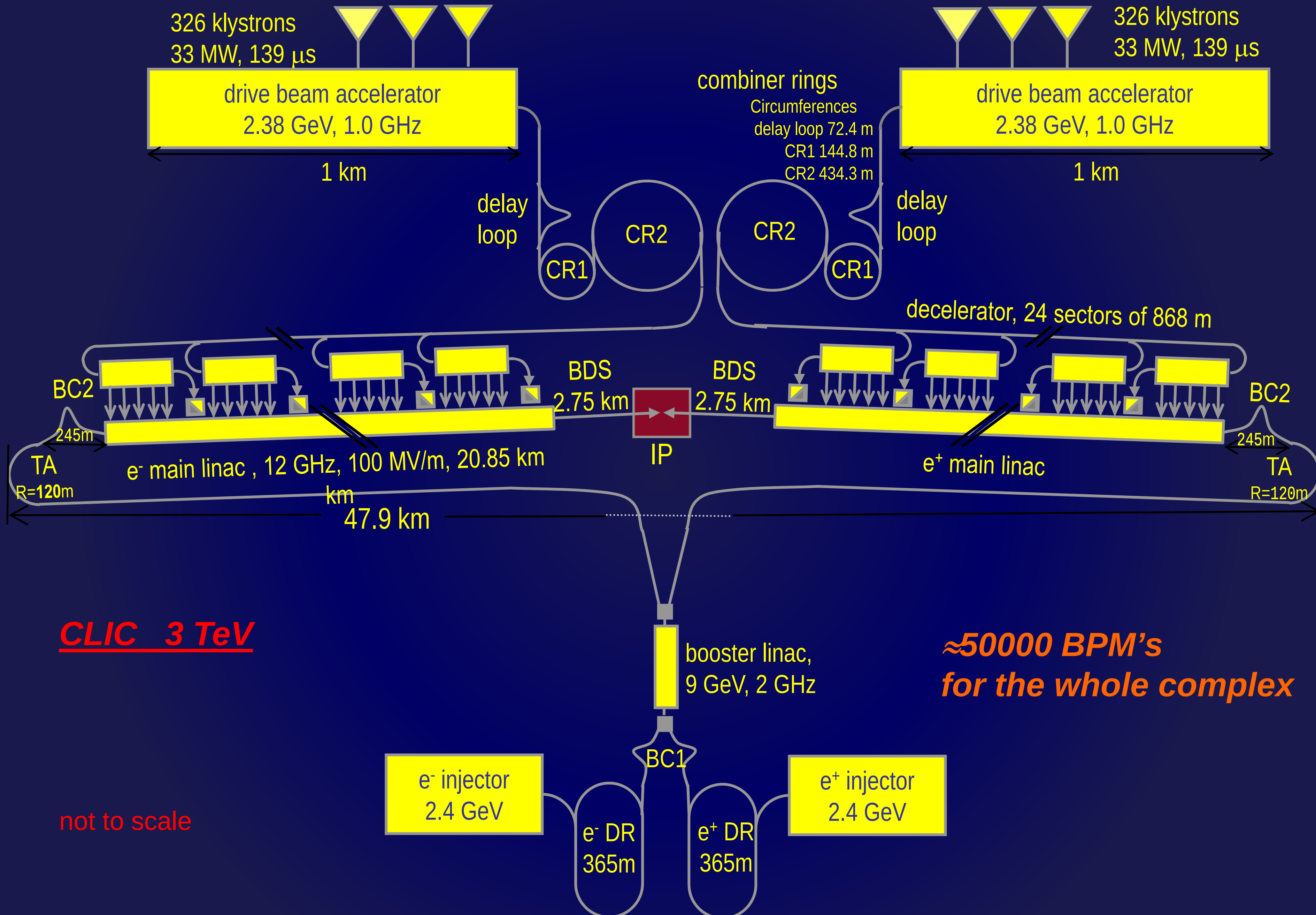
Beam diagnostics, how much ?



Layout of an early proton synchrotron

LHC beam diagnostics




326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
combiner rings
Circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m
delay loop
CR2
CR1
CR2
CR1
delay loop
decelerator, 24 sectors of 868 m
BC2
245m
TA
R=120m
BDS
2.75 km
IP
BDS
2.75 km
BC2
245m
TA
R=120m
e- main linac , 12 GHz, 100 MV/m, 20.85 km
e+ main linac
47.9 km
booster linac,
9 GeV, 2 GHz
BC1
e- injector
2.4 GeV
e- DR
365m
e+ DR
365m
e+ injector
2.4 GeV
CLIC 3 TeV
≈50000 BPM's
for the whole complex
not to scale

What are the present challenges for beam instrumentation ?

Ever higher beam brightness

Comes with ever stronger focusing

Stronger focusing only beneficial and feasible if orbit, tune and chromaticity can be controlled with high resolution

Needs instruments to resolve beams with sub-micron size in all 3 dimensions

Ever higher beam intensity

Higher stored beam energy in storage rings

Higher beam power in synchrotrons and linear accelerators

Beam loss monitoring with very good coverage and reliability

Low noise, large bandwidth beam signals for feedbacks to fight collective instabilities

SR sources
SASE FEL's
ERL's
Linear collider

LHC
spallation neutron sources
ν-beam facilities
ERL linacs
Rare Isotope production
Linear collider

Stored beam energy in LHC vs. other storage rings

Name	Energy GeV	Revolution time or pulse duration μs	Number of Bunches	Number part. / Bunch 10^7	stored energy / beam or pulse MJ
LHC	7000	88.9	2808	11500	**362.1**
HERA p	920	21.1	180	7000	**1.9**
TEVATRON	980	20.9	36	24000	**1.4**
SR source (typical)	2.5	1.0	500	624	**0.0012**

For comparison:

40 T truck with 90 km/h

E_{KIN} **=12.5 MJ**

What diagnostic issue is most important for commissioning of a new accelerator ?

quote from Michel Chanel :
(key player for commissioning of several rings
for protons, antiprotons and ions at CERN)

Orbit and tune diagnostic have to function from day one, hour zero !

Literature

Specialised textbooks

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K. Mess, P. Schmüser, S. Wolff, “Superconducting Accelerator Magnets,” World Scientific, 1996

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K. Wille, “The Physics of Particle Accelerators : An Introduction,” Oxford University Press, 2001

S.Y. Lee, “Accelerator Physics,” World Scientific, 2004

For more accelerator book references http://uspas.fnal.gov/book.html

Thank you for your attention

and

Thanks to Michel Chanel, Tobias Dobers, Giovanni Rumolo,
Piotr Skowronski and Frank Zimmermann for various inputs to this lecture