Instrumentation Requirements for Different Accelerator Types

Bernhard Holzer, CERN

Instrumentation Requirements for Different Accelerator Types

Bernhard Holzer, CERN

high energy proton machines
LHC, Tevatron, HERA, RHIC
synchrotron light sources
ESRF, PETRA 3, SLS ...
therapy machines
HIT, Proscan ...
sase FEL´s

ILC / CLIC

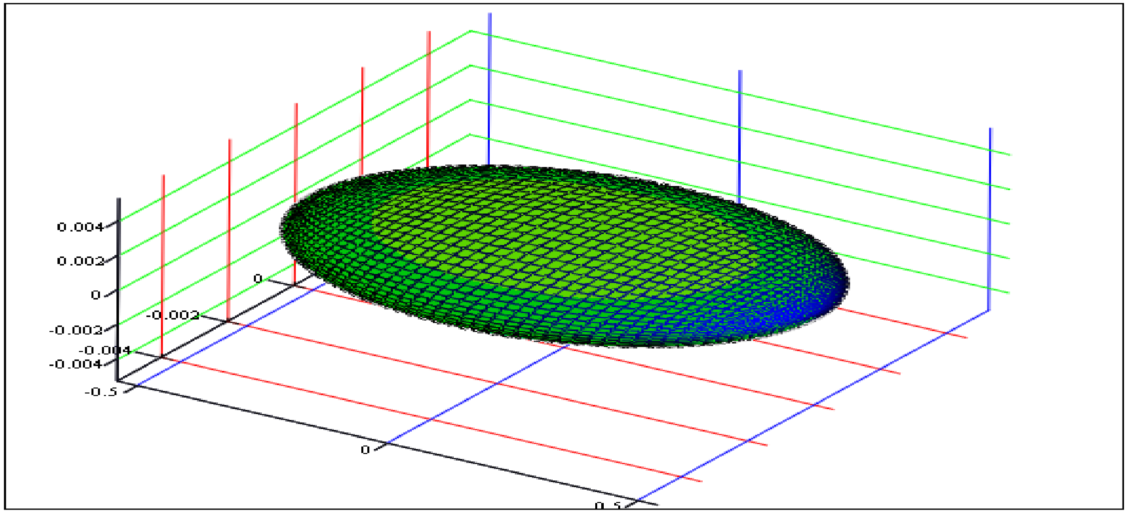
... cyclotrons, betatrons, proton linacs
el. static machines, heavy ion storage rings ...

I. (s.c.) High Energy Proton Machines

SPS & LHC at CERN

LHC parameters

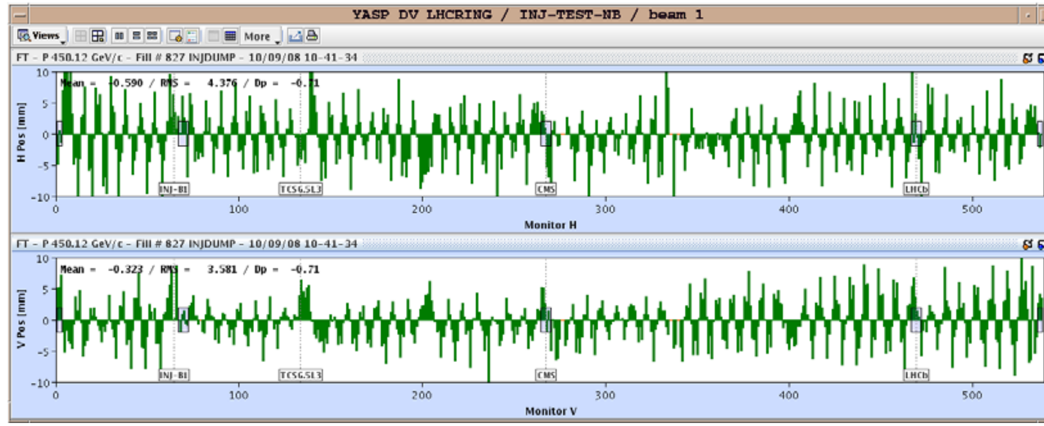
proton energy	*7 TeV*
particles per bunch	*1.2*10 11*
number of bunches	*2808*
beam current	*0.582 A*
stored beam energy	*362 MJ*
bunch length	*≈ 8 cm*
beam size (arc)	*1.2mm ... 0.3 mm*



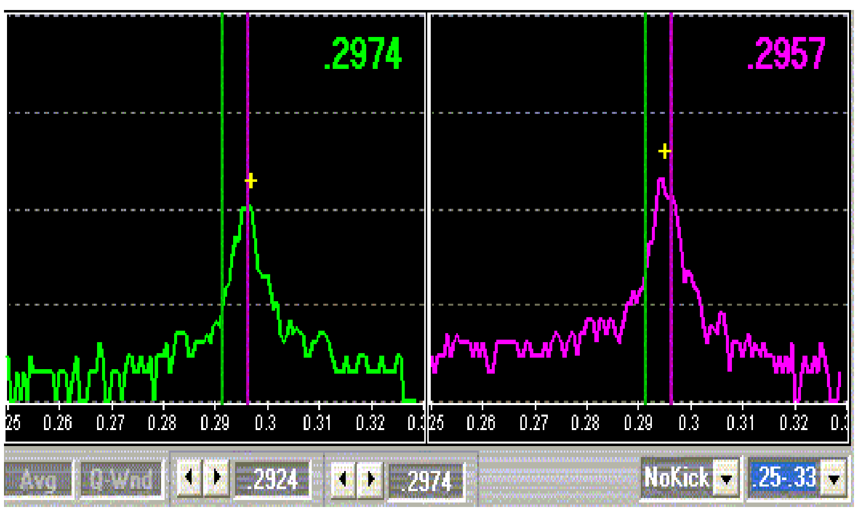
(Z , X , Y)

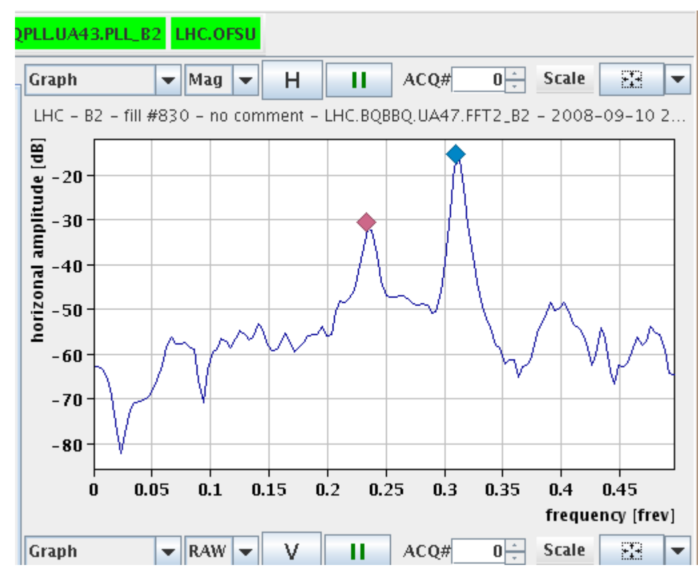
beam parameters ... the standards

orbit



tune, chromaticity, coupling



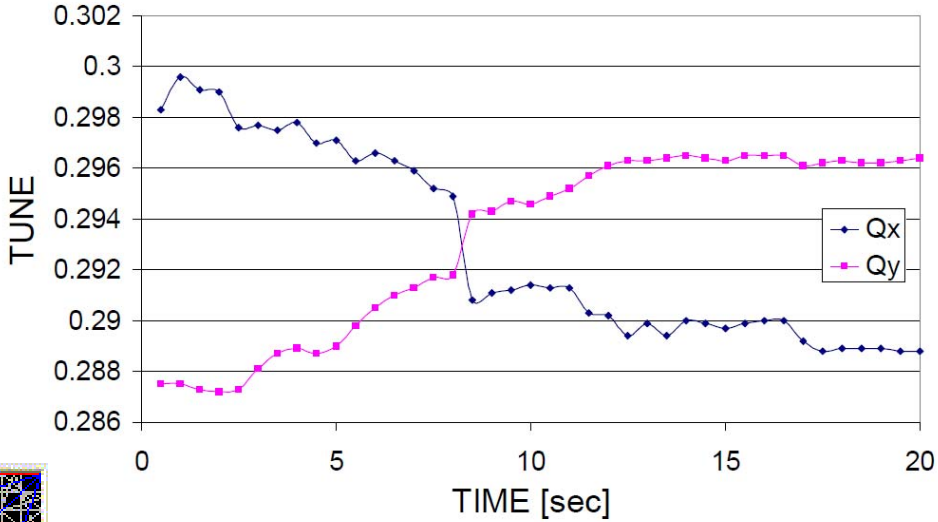


the non standards: ***keep these values constant during ramp***

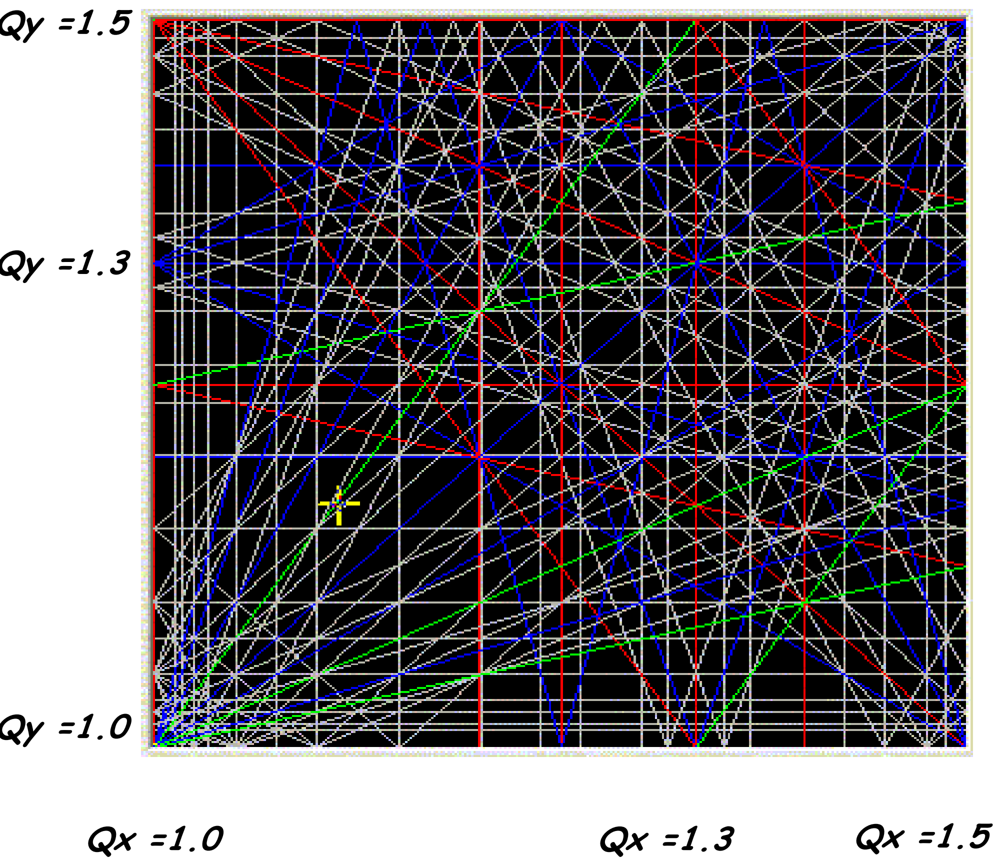
"snapback"

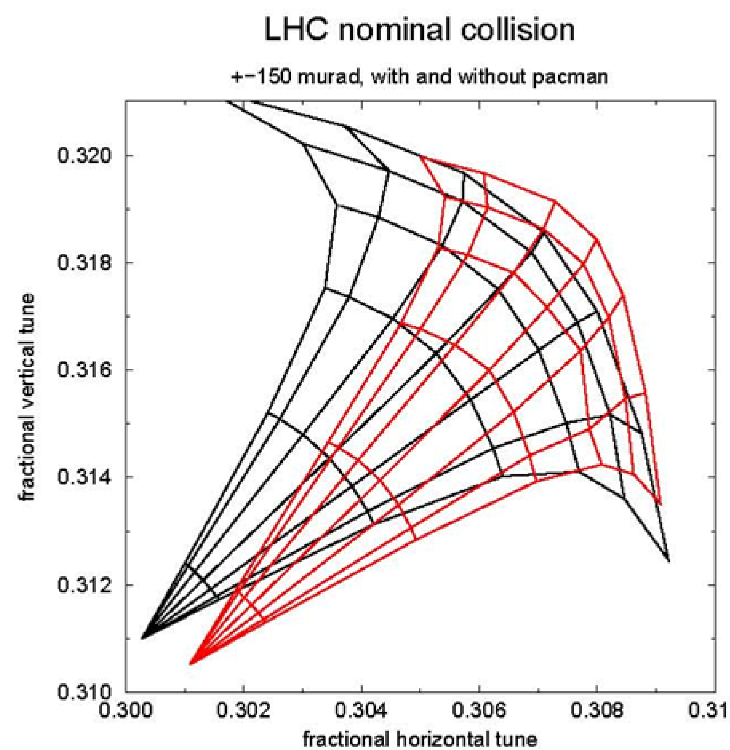
Tune and Resonances

$m*Q_x+n*Q_y+l*Q_s$ = integer



HERA p Tune diagram up to 7th order

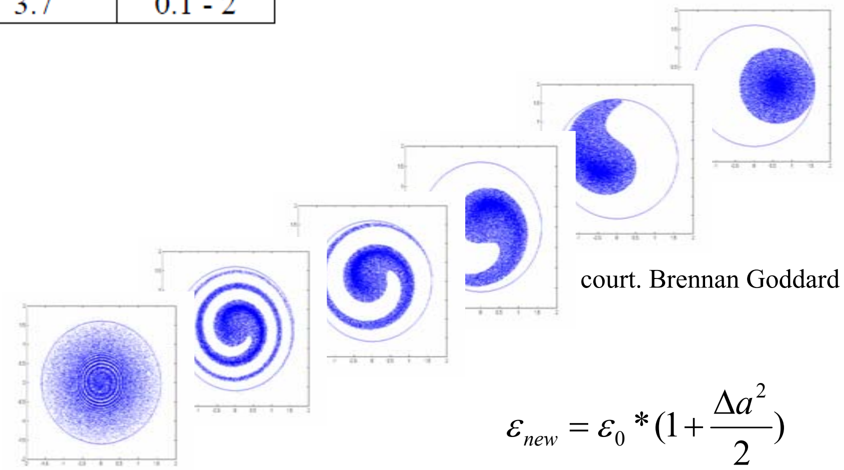




Beam Emittance

	E_k [GeV]	ε* [π μm]	σ [mm]
LINAC	0.0001 – 0.05	~1.0	
BOOSTER	0.05 – 1.4	2.5	0.3 – 6.5
PS	1.4 - 26	3.0	0.3 – 15
SPS	26 - 450	3.5	0.1 – 6
LHC	450 - 7000	3.7	0.1 - 2

tight emittance budget for beam transfer & accleration



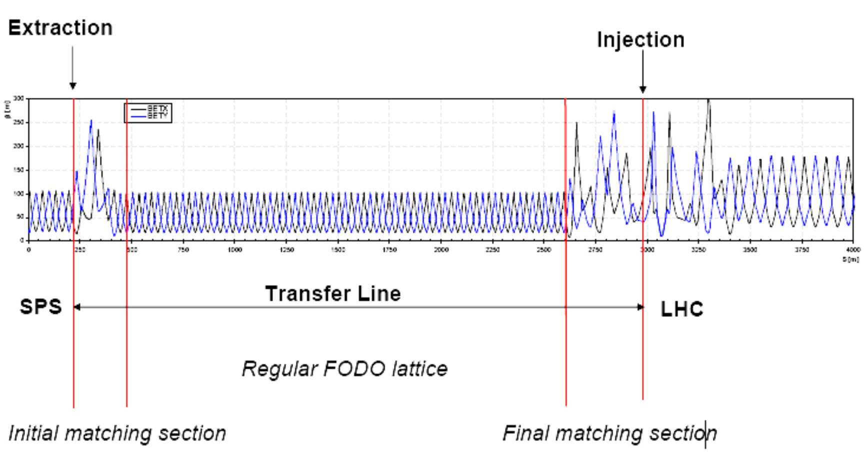
court. Brennan Goddard

$$\varepsilon_{new} = \varepsilon_0 * (1+\frac{\Delta a^2}{2})$$

emittance dilution due to offset at injection

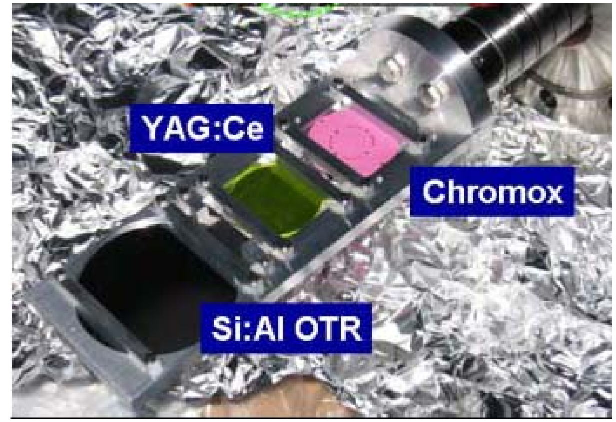
measure: position & angle at injection
optics mismatch between
transfer lines and storage ring

- SPS to LHC transfer line TI 8 – beta functions

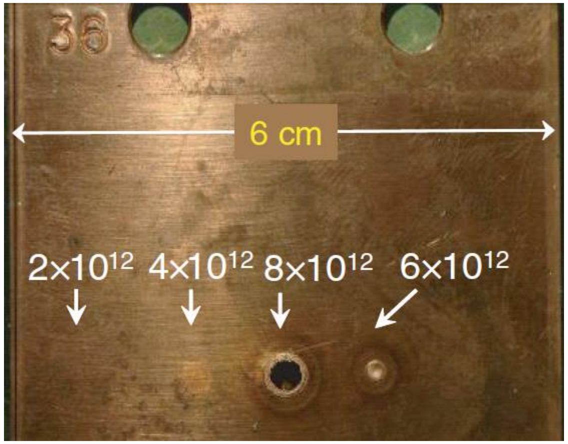


... (OTR) screens, wire scanners,
residual gas monitors etc

minor detail: beam energy = 360 MJ



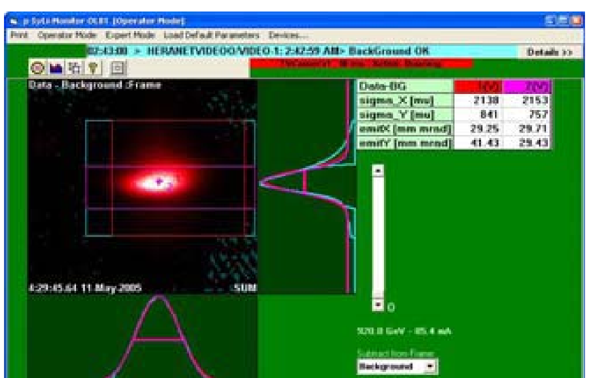
OTR & scintilltion screens at ELETTRA (Trieste) DIPAC 2007



beam dump tests of a 450 GeV SPS beam on a target

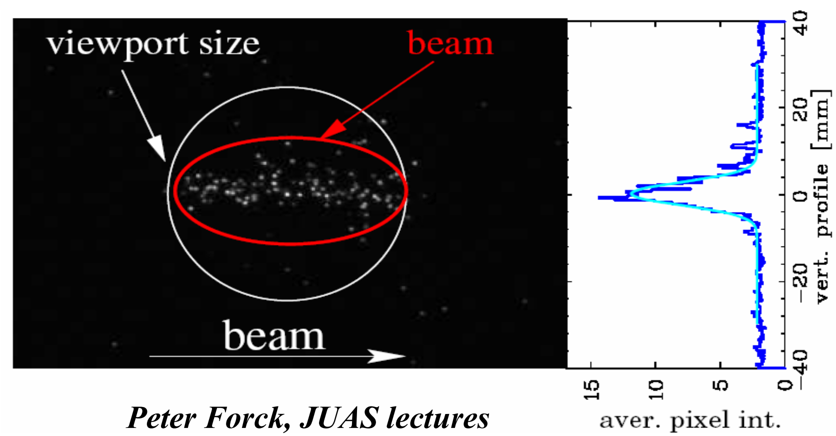
possible solutions: don't touch

synchrotron light monitors for proton beams



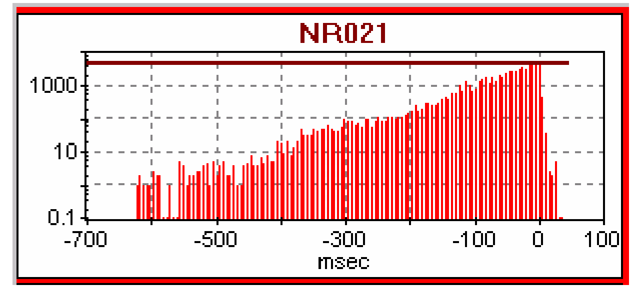
Gero Kube, CAS lectures 2008

residual gas monitors



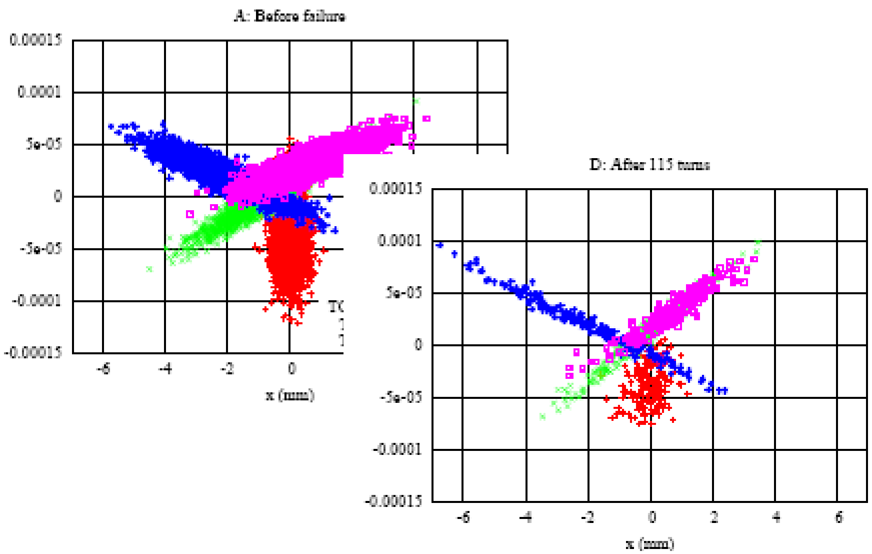
Peter Forck, JUAS lectures

Machine safety: Detection of Beam Losses



1 bin = 250 turns

beam losses in HERA -p seen by a single BLM
failure of standard magnet (dipole /quadrupole)



A. Gomez: Error analysis in LHC, Phase space deformation in case of failure of RQ4.LR7

Short Summary of the studies:

quench in sc. arc dipoles: τ_{loss} *=20 - 30 ms*
BLM system reacts in time, QPS is not fast enough

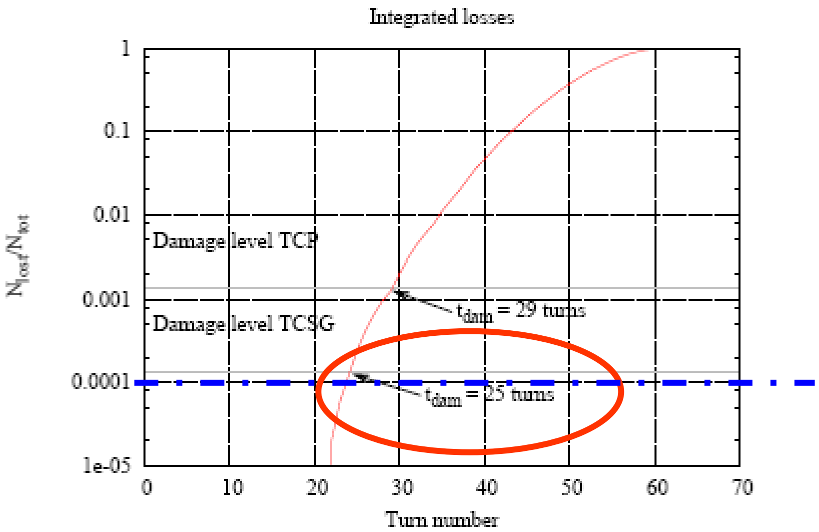
quench in sc. arc quadrupoles: τ_{loss} *=200 ms*
BLM & QPS react in time

failure of nc. quadrupoles: τ_{det} *= 6 ms*
τ_{damage} *= 6.4 ms*

failure of nc. dipole: τ_{damage} *= 2 ms*

→ FMCM installed

Analysis of fast beam losses (A. Gómez)



worst case: nc. dipole magnets: RD1.LR1 / LR5

simulaion of beam losses due to failure of RD1

damage level reached after 25 turns

$\tau_{BLM\ react.} \approx \tau_{damage}$

FMCM installed *(M. Werner et al)*

... but redundancy does not really exist

... does it make sense to contemplate about a fast AC beam current monitor in LHC ???
(M. Werner et al)

experience is excellent:
combination of fast FMCM and AC-BM installed at HERA in 2003/2004

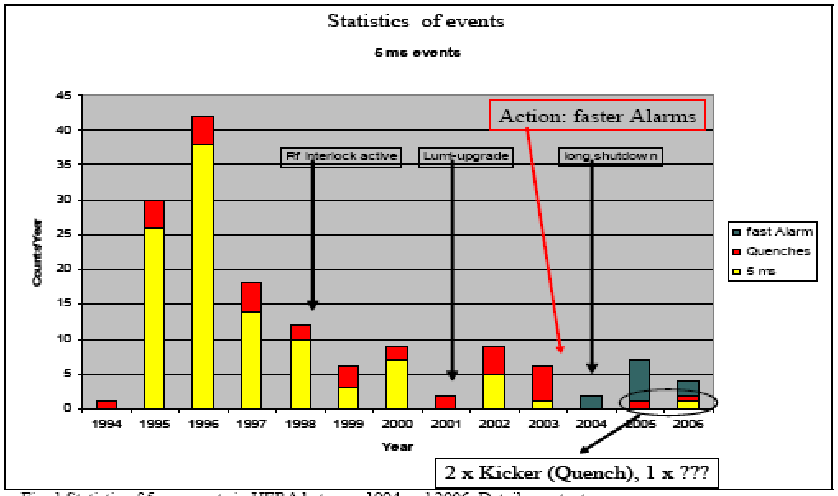
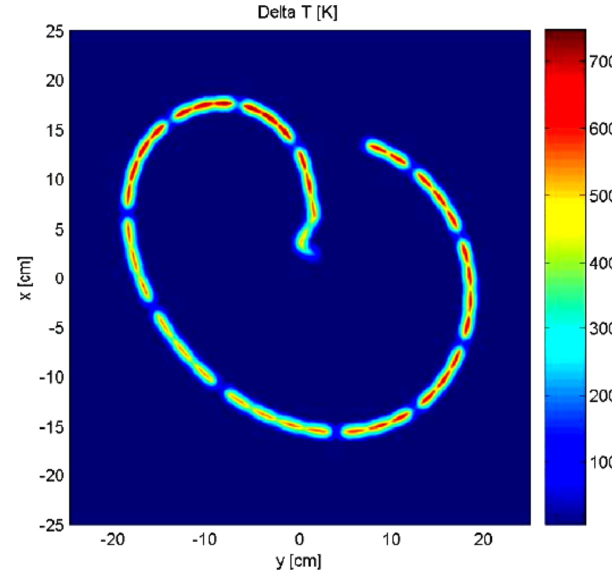
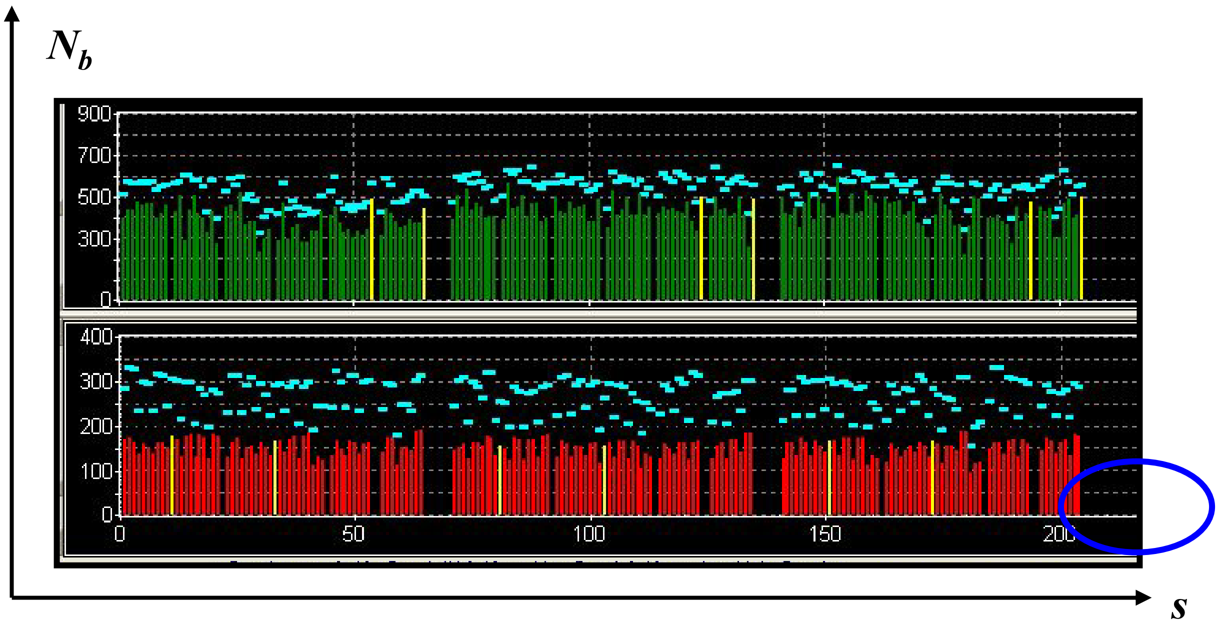


Fig. 1 Statistic of 5 ms events in HERA between 1994 and 2006. Details see text.

Dump-Gap Monitoring: AC / DC Monitors



pattern of the LHC bunch train at the dump absorber screen



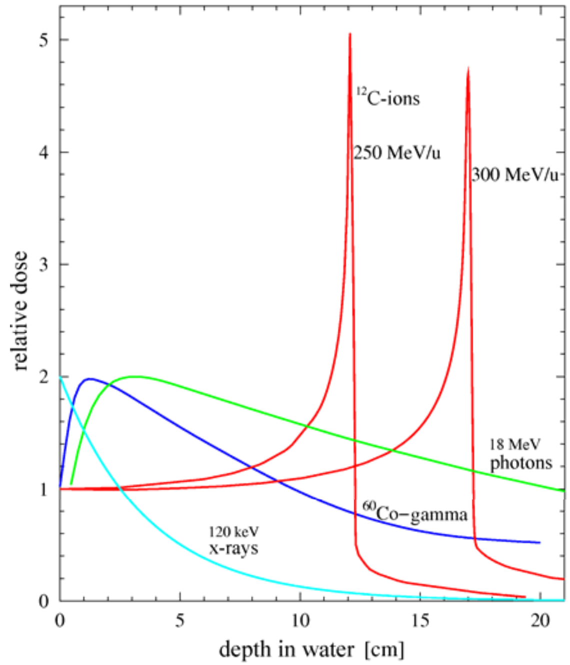
HERA Bunch Pattern:
C_0 = 6335m
nb = 180
bunch distance = 96 ns

LHC abort gap: 3µs ≈ 900m
Quench limit for gap population at 7 TeV:
$2 * 10^6$ p/m or $5*10^{-6}$ of overall current
or 3.2 µA DC

LHC parameters:
C_0 = 26660 m
nb = 2808
bunch distance = 25 ns !!!

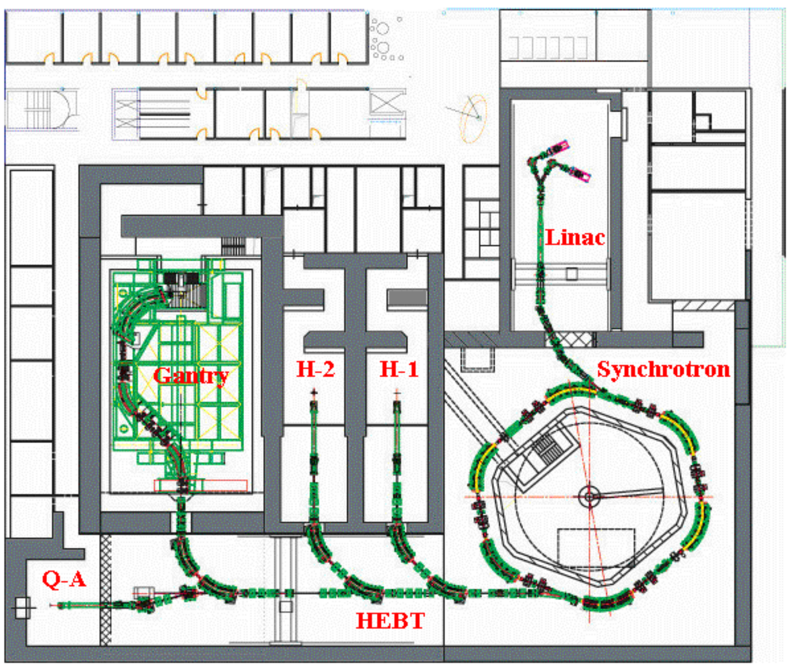
II. Hadron Therapy Machines

the standards: beam energy, intensity, tunes, orbits
not really a problem



control of penetration depth / Bragg peak via beam energy

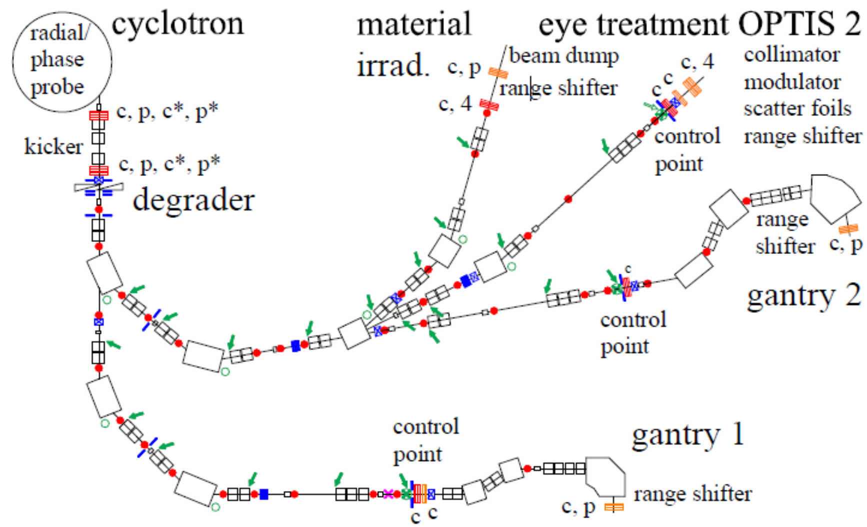
Example: parameters of the HIT project in Heidelberg:



particles:	*p, C, He, O*
beam energy	*50 - 430 MeV/u*
beam size	*4-10 mm*
extraction time	*1-10 s*
extraction intensity	*10^6 - $4*10^{10}$ ions / spill*
beam power	*360 W dc power*

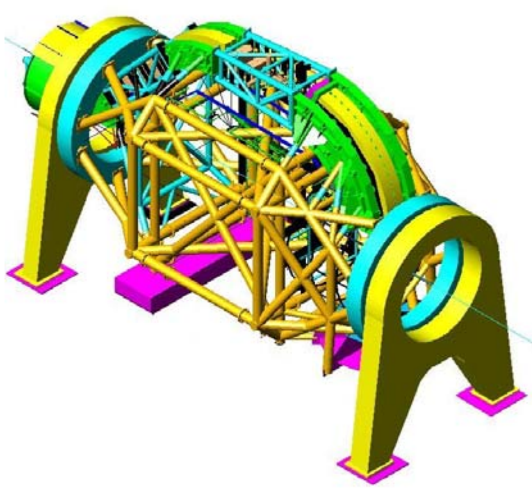
The challenge: Stability

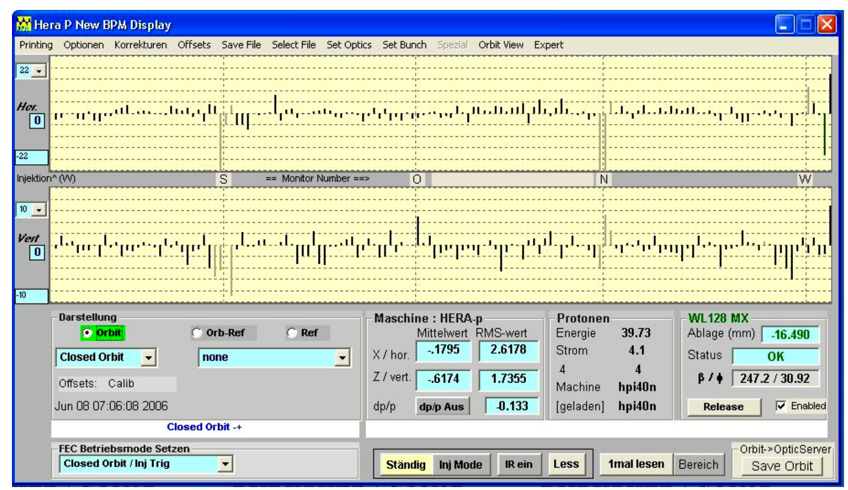
Example: PSI proscan project



37 multistrip ionisation chambers
5 faraday cups
6 thin current monitors
4 bpms
22 halo monitors
7 extr. loss monitors

gantry: 3 dipoles 8 quads ... all in all 570 t

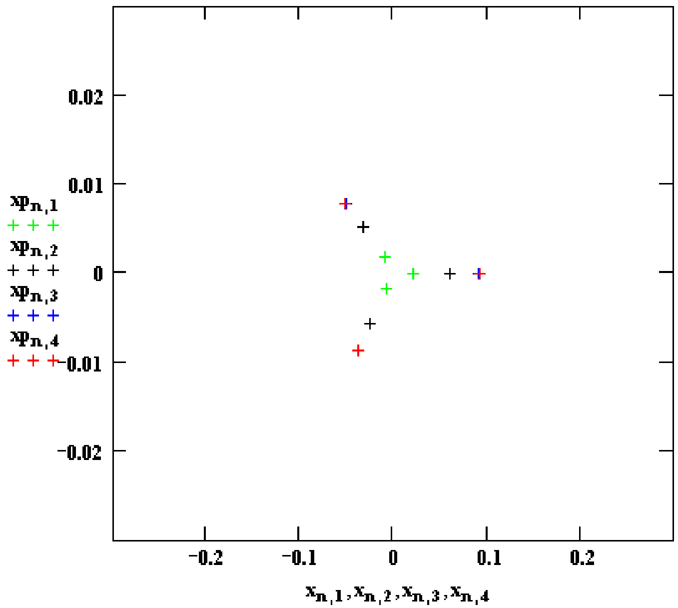


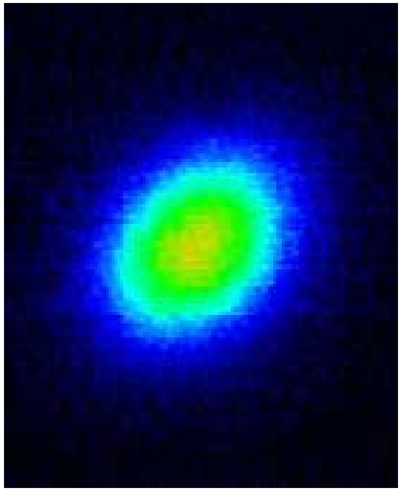


so sorry: Example how not to do it
the old & rusty HERA-p BPM system

The Challenge: Slow Extraction

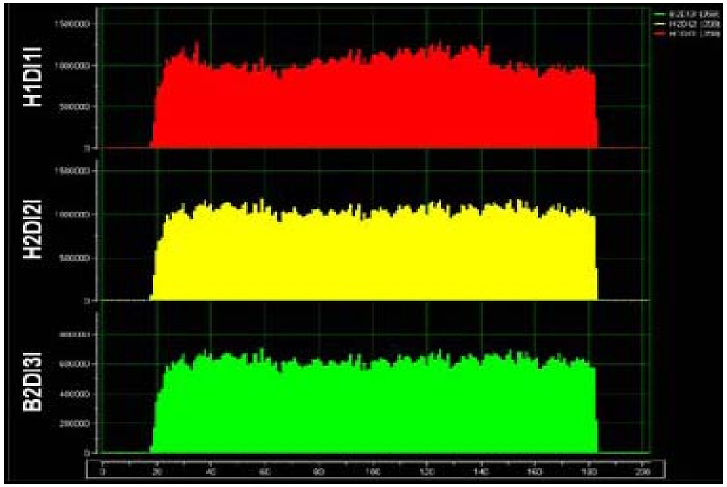
3 order resonance extraction
dedicated & well controlled excitation of the beam
be conservativ, ... & ... stable
aim: constant spill intensity





transverse beam profile

$$\frac{10^{10}\,p}{10\,s} = \frac{10^{9} * 1.6 * 10^{-19}\,Cb}{s} = 1.6 * 10^{-10}\,A$$



spill intensity diagnostics: 1% accuracy
non destructive measurement of fraction of nA
in single pass !!!
keyword: secondary emission monitors

The challenge: Slow Extraction

3 order resonance extraction
dedicated & well controlled excitation of the beam
be conservativ, ... & ... stable
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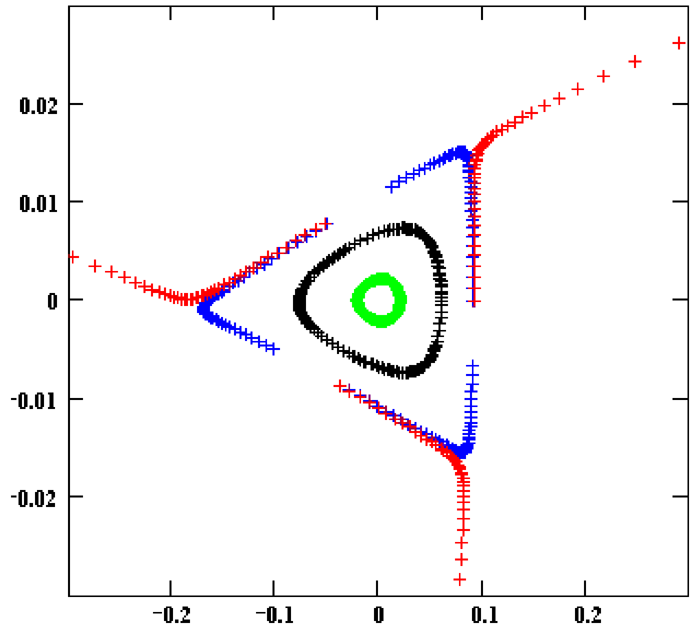
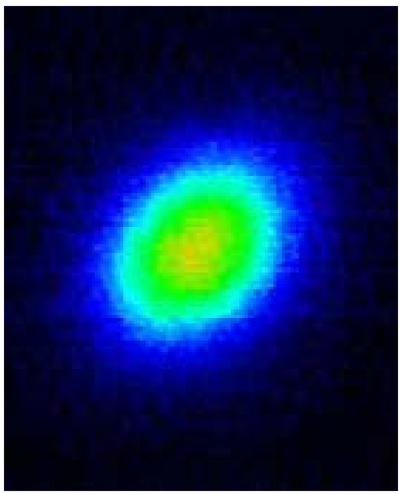
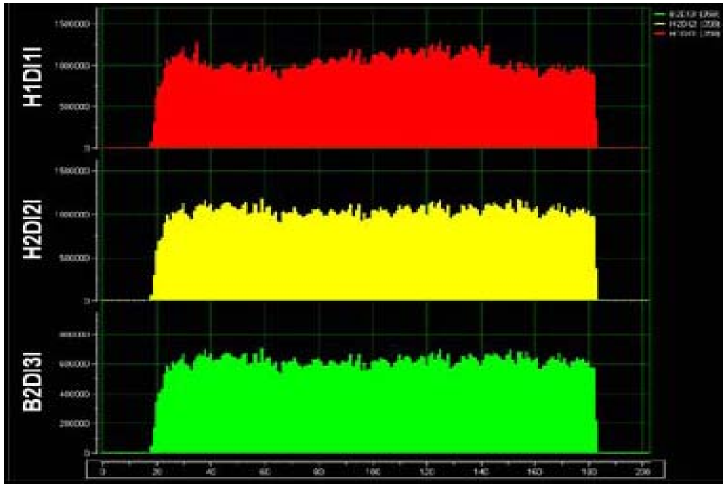




transverse beam profile



$$\frac{10^{10}\,\boldsymbol{p}}{10\boldsymbol{s}} = \frac{10^{9} * 1.6 * 10^{-19}\,\boldsymbol{Cb}}{\boldsymbol{s}} = 1.6 * 10^{-10}\,\boldsymbol{A}$$

spill intensity diagnostics: 1% accuracy
non destructive measurement of fraction of nA
in single pass !!!
keyword: secondary emission monitors

III. Light Sources

The Standards: beam energy, intensity, tunes etc ... not really a problem

BUT measurement & control of beam size & beam orbits is a real challenge

photon flux $$F = \frac{number\ of\ photons}{s * 0.1\% BW * A}$$

brilliance $$B = \frac{F}{4\pi^2 \varepsilon_x \varepsilon_y}$$

emittanz ≈ 1 nm rad (PETRA 3)

$$\varepsilon_y \approx 1\%\ \varepsilon_x$$

	ϵ_x [nmrad]	E [GeV]	ϵ_x/E^2		ϵ_x [nmrad]	E [GeV]	ϵ_x/E^2
USR	0.3	7	0.006	SLS	4.4	2.4	0.763
PETRA III	1	6	0.027	ELETTRA	7	2.4	1.215
SPring-8	3.4	8	0.053	BESSY II	6	1.9	1.66
APS	3	7	0.061	Spear III	18	3	2
ESRF	3.9	6	0.108	MAX II	9	1.5	4
Diamond	2.5	3	0.2	ANKA	41	2.5	6.56
Soleil	3	2.5	0.48	DORIS III	450	4.5	22.2

Parameters of some synchrotron light sources

HERA / LEP Emittance: 20 ... 30 nm

Light Sources

requirements for orbit stability: golden rule ≈ 10% σ

→ orbit measurement resolution: ≤ 1 μm

PETRA 3:

220 button BPMs installed,

BPM resolution ≈ 0.3 μm required

	β_x [m]	β_y [m]	σ_{Tx} [μm]	σ_{Ty} [μm]	$\sigma_{Tx'}$ [μrad]	$\sigma_{Ty'}$ [μrad]	ID-length [m]
low-β 5 m	1.3	3	36	6.0	28	3.7	5
high-β 5 m	20	2.4	141	5.5	7.7	3.8	5
low-β 2×2 m	1.4	3	37	5.7	27	5.4	2
high-β 2×2 m	16.2	2.6	127	5.3	9.3	5.5	2
20 m-ID	16	5	126	7.9	8.2	2.7	10
DW-drift	16	16	127	13	8.5	3.3	5
ESRF low-β	0.5	2.73	59	8.3	90	3	5
ESRF high-β	35.2	2.52	402	7.9	10.7	3.2	5
SPring-8	22.6	5.6	277	6.4	13	5	4.5
APS	15.9	5.3	217	12.6	15.3	5.7	4

typical beam sizes

orbit stability required for stable light fan
due to offset in 6poles / quads -> spurious vert. dispersion,
coupling → spoils vert. beam emittance

By the way: diagnostic and control of temperature
coefficient of thermal expansion in steel: 12 *10^-6^

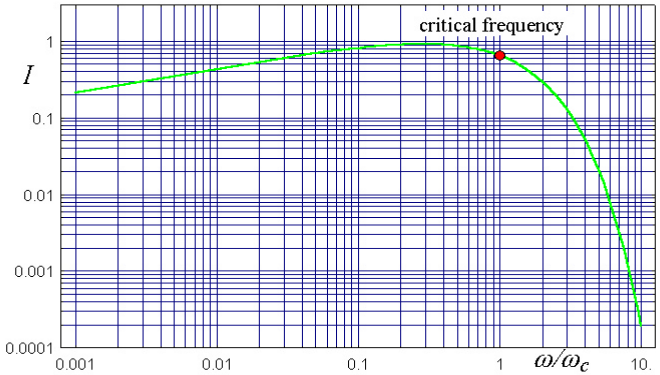
$$\Delta l = 10cm * 12 * 10^{-6} * 1°$$

$$\Delta l = 1.2\mu m \quad \textit{for } \Delta T = 1 \textit{ degree}$$

$$\Delta T = 0.1°$$

temperature stability required

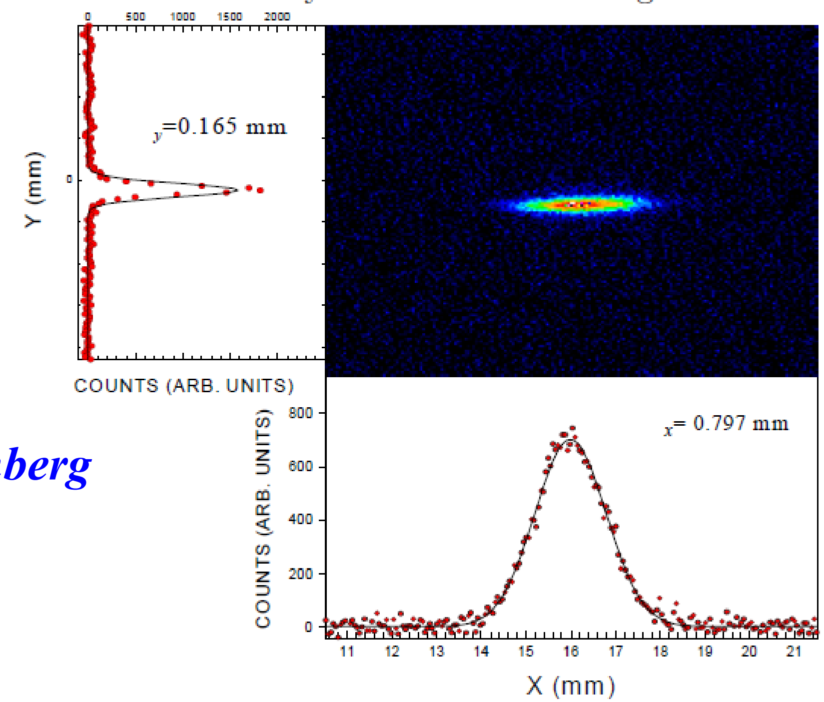
The ideal Diagnostics Tool : ... Sy-Li



1.5 GeV, ρ = 3.3m

Result from synchrotron light monitor

Synchrotron radiation facility APS accumulator ring and blue wavelength:



... and its principle limitation: Werner Heisenberg

diffraction limit ... mainly in vertical plane

$\Delta\sigma = \lambda/2\Delta\Psi$

Example: ***1 GeV electron beam***
λ=500 nm = green-blue
Δψ=1/γ, opening angle of light cone
relativistic factor: $\gamma = E/E_0$, E=1 GeV

completely diffraction limited measurement

$$\Delta\sigma = \frac{\lambda}{2\Delta\psi} = \frac{500nm}{2*0.5mrad} = 500\mu m$$

pinhole cameras
interferometric techniques

III. Sase-FEL's

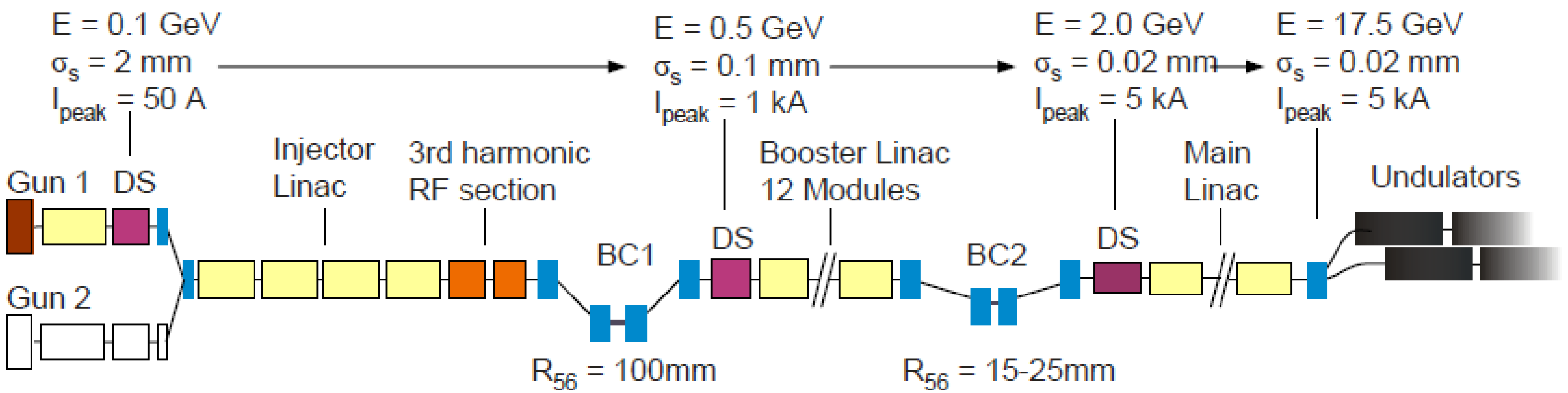
Standards: there are no standards

x-FEL Parameters:

light wavelength	*1 Å*
beam energy	*20 GeV*
norm. emittance	*1.4 mm mrad* → $\varepsilon_0 = 4*10^{-11}$
undulator length	*250m*
beam pulse length	*650 µs*
bunch number	*3250 bunches /pulse*
bunch spacing	*200 ns*
bunch length	*70 fs*
briliance	$5*10^{33} \frac{photons}{0.1\% BW\ s\ mm^2 mrad^2}$

nota bene: HERA / LEP
$\varepsilon_0 = 20 \dots 30$ *nm*

schematic view of the europ. x-FEL



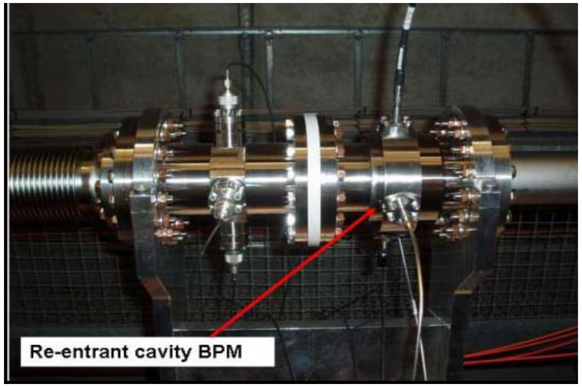
Sase-FEL's: diagnostic requirements

non-destructive
single event (i.e. single pass) diagnostics needed
no periodicity, no averaging over several turns, not even over several bunches.
***intra-bunch-train feedback (IBTF)** → sub μs diagnostics*
***beam size (undulator)** σ ≈ 30 μm*
RMS position stability ≈ 10% of the beam size σ in the undulators
***single bunch orbit resolution ≈** 1 μ m over undulator length (250 m)*
machine safety: average beam power 600kW in Strahl

Transv. IBFB Specifications	**FLASH**	**XFEL**
bunch-by-bunch stability - at location of IBFB - along undulators	$< \sigma/10$ 5 - 15 μm < 5 μm	$< \sigma/10$ 3 - 10 μm < 3 μm
max. beam position offset - at location of the pick-ups	$< 10 \cdot \sigma$ < 1.5 mm	$< 10 \cdot \sigma$ < 1 mm
bunch-by-bunch resolution	≤ 2 μm	≤ 1 μm
system latency	< 1000 ns	< 200 ns

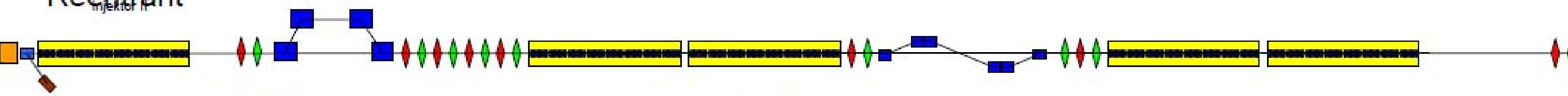
***Keywords:** Resonant Stripline BPMs*
BPM's as reentrant cavity design

Flash, DESY



FEL Diagnostics @ FLASH

Reentrant



GUN:
2 BPM
1 Toroid
3 Screens
3 F-Cups
4 Loss

BC2:
9 BPMs
2 Toroids
6 Screens
4 Wirescanners
2 Phase
1 Resistive
FIR Diagnostics
6 Loss

2 Cavity BPM

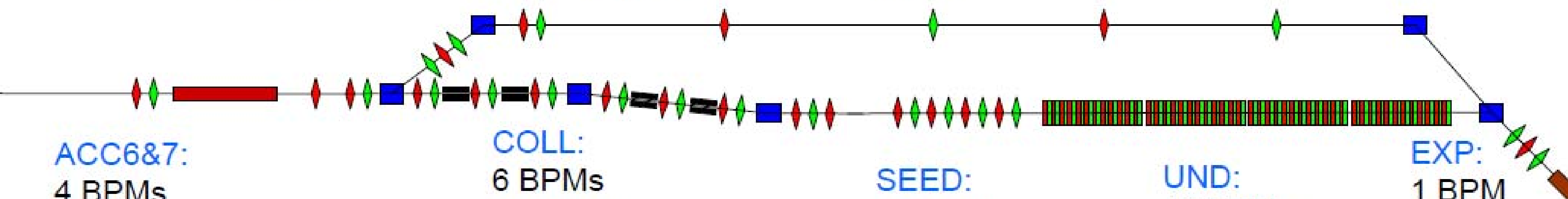
BYP:
7 BPMs
1 Toroid
4 Screens
1 Wirescanner
10 Loss

BC3:
6 BPMs
2 Toroids
4 Screens
1 Wirescanner
1 Phase
1 Resistive
FIR Diagnostics
6 Loss

2 Cavity BPM

&

FEL BL:
Intensity
Spektrum
Position



ACC6&7:
4 BPMs
LOLA
EOS
3 Loss

COLL:
6 BPMs
2 Toroids
1 Phase
1 Resistive
3 Screens
2 Wirescanner
9 Loss

SEED:
4 BPMs
4 Screens
4 Wirescanners
FIR Diagnostics
1 TEO
Optical Replica

UND:
13 BPMs
7 Wirescanners
22 Loss

EXP:
1 BPM
1 Toroid
1 Screen

DUMP:
2 BPM
1 Toroid
1 Screen
4 Loss

courtesy: D. Nölle (DESY)

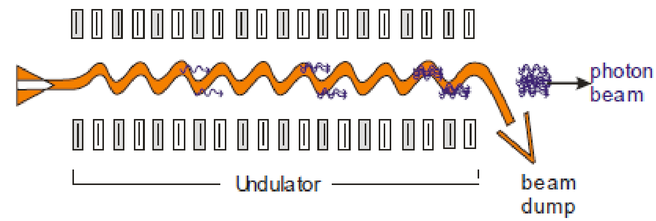
Sase-FEL's: diagnostic requirements

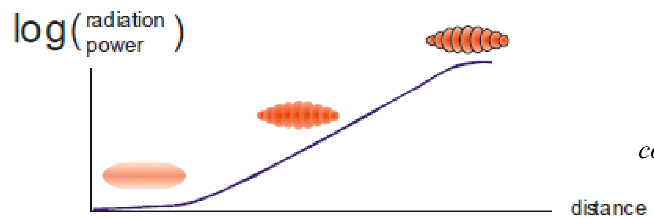
special problem: slice emittance

development of micro bunches

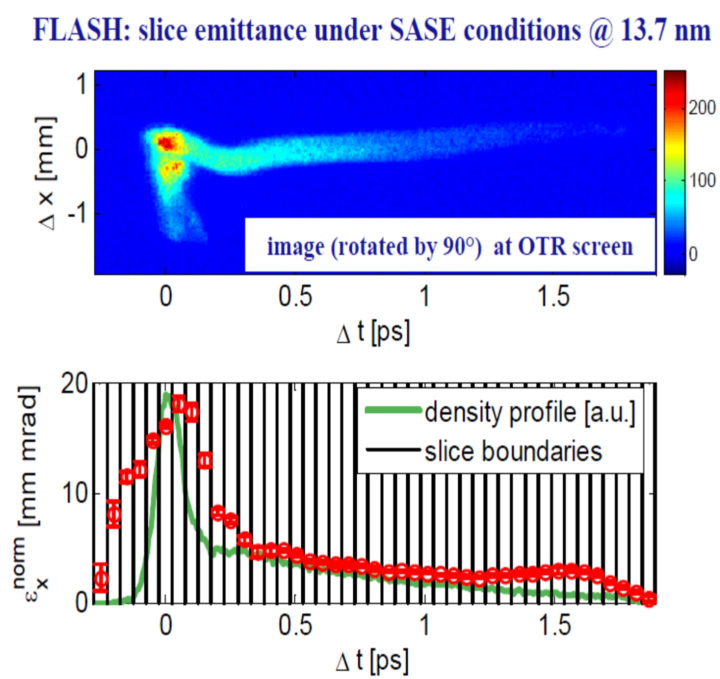
norm. emittance ε_0 = 1.4 mm mrad $\rightarrow \varepsilon_0 = 4*10^{-11}$

Keyword: Transverse Deflecting RF-Structure "LOLA"





court. J. Rossbach



court. H. Schlarb

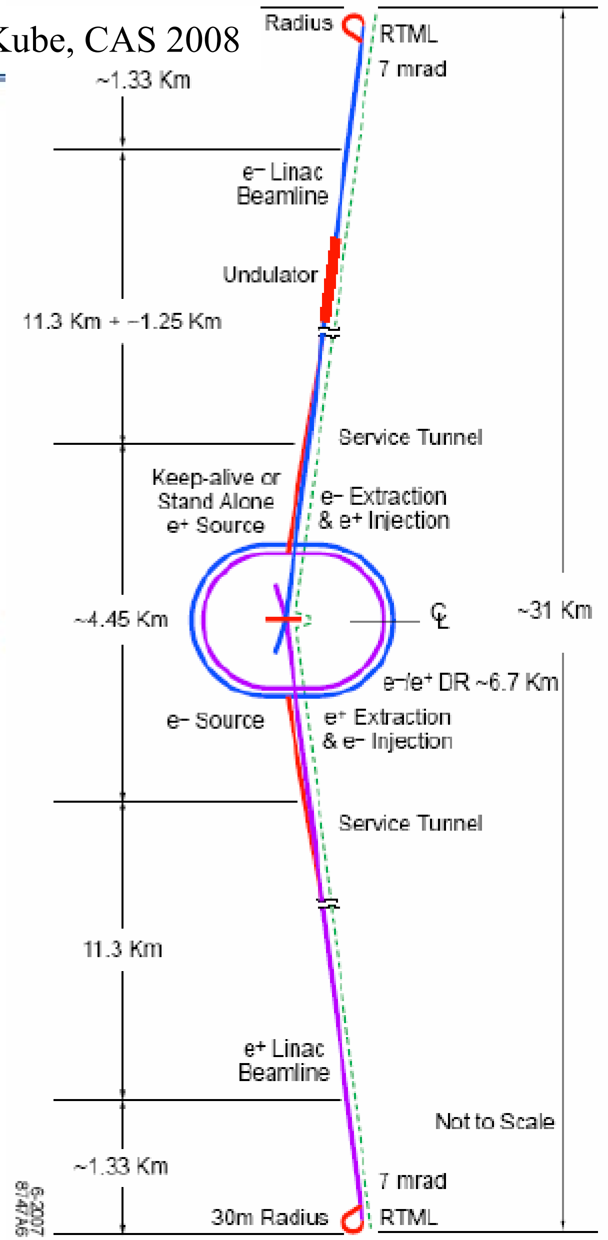
International Linear Collider

court. G. Kube, CAS 2008

- key parameters (nominal values)

train repetition rate / Hz	**5**
bunches per train	**2625**
bunch spacing / nsec	**369.2**
train length / µsec	**~ 970**
particles per bunch / x 10^{10}	**2**
normalized emittance at IP $\gamma\varepsilon_{x,y}$ / mm mrad	**10 / 0.04**
r.m.s. beam size at IP $\sigma_{x,y}$ / nm	**639 / 5.7**
r.m.s. bunch length σ_z / µm	**300**
power per beam at IP / MW	**10.5**
Luminosity $\mathcal{L}$ 10^{34} / cm^2 / sec	**2**

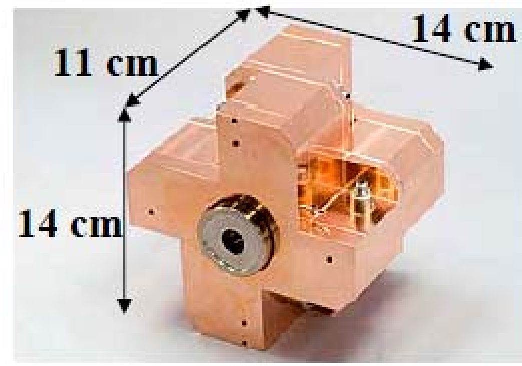
ILC Reference Design Report (2007)



Challenges: ***beam position measurement***
beam stability
beam size
} ***non-invasive***

ILC: Diagnostics court. G. Kube, CAS 2008

- 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)

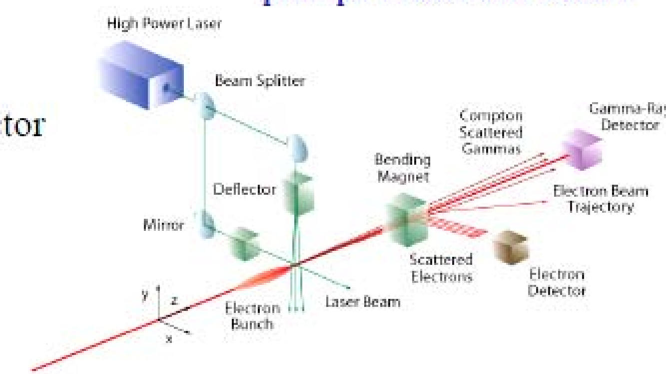


courtesy: T.Nakamura (Tokio University)

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 Compton scattered photons in downstream detector
    - photon rate as function of relative laser beam position
      → beam profile
  - optical diffraction radiation (ODR)
    - diffraction of particle Coulomb field at a slit

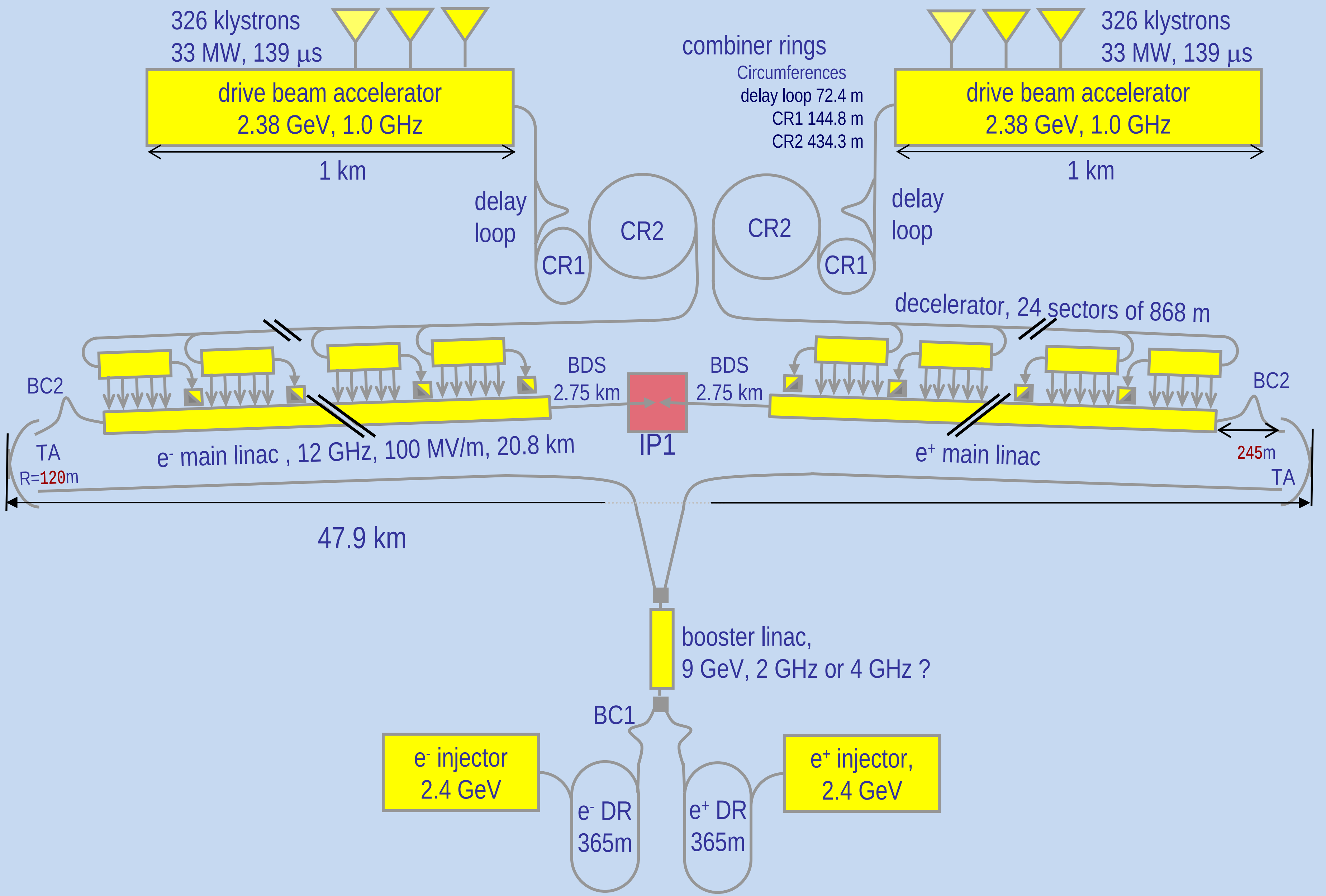
principle of laser wire scanner



ILC Reference Design Report (2007)

CLIC 3TeV

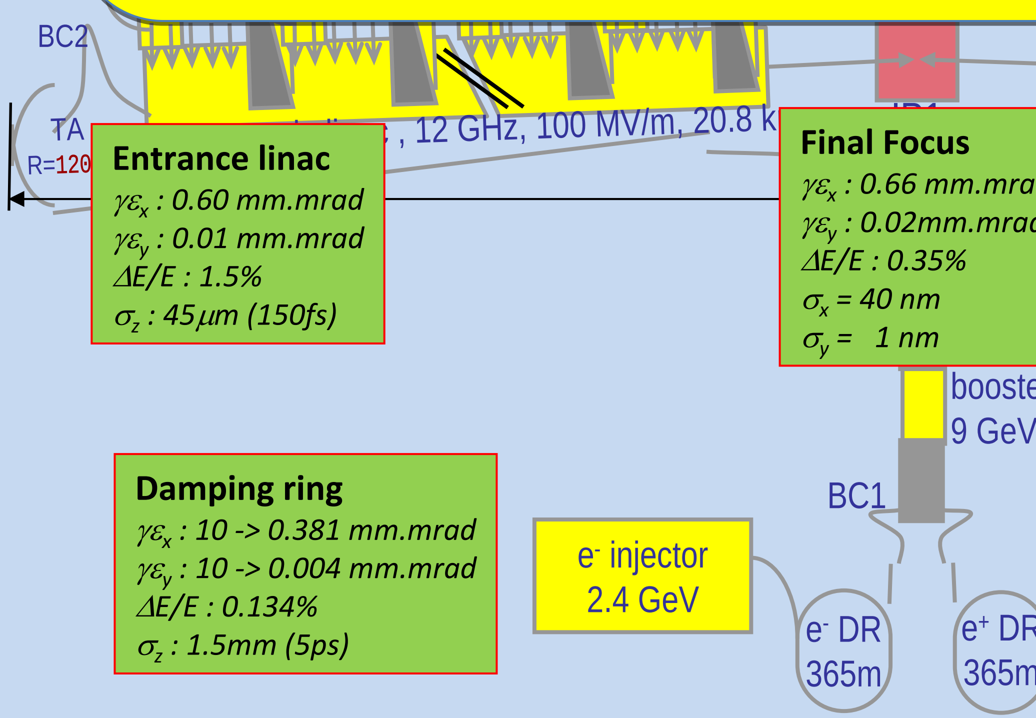
court. D. Schulte et al



CLIC 3TeV : Main Beam

court. D. Schulte et al

- Producing and measuring **small beam emittance**
- Producing and measuring **short Bunches**
- Conserving small beam emittance (very strict tolerances/requirements on the **beam position monitor precision and resolution**)



Entrance linac
$\gamma\varepsilon_x$: 0.60 mm.mrad
$\gamma\varepsilon_y$: 0.01 mm.mrad
$\Delta E/E$: 1.5%
σ_z : 45μm (150fs)

Final Focus
$\gamma\varepsilon_x$: 0.66 mm.mrad
$\gamma\varepsilon_y$: 0.02mm.mrad
$\Delta E/E$: 0.35%
σ_x = 40 nm
σ_y = 1 nm

Damping ring
$\gamma\varepsilon_x$: 10 -> 0.381 mm.mrad
$\gamma\varepsilon_y$: 10 -> 0.004 mm.mrad
$\Delta E/E$: 0.134%
σ_z : 1.5mm (5ps)

Instrument	*Accuracy*	*Resolution*	*How many?*
Intensity	0.1%		48
Position	5µm	**50nm**	**4176**
Beam Size / Emittance	10%	2%	48
Energy	0.10%		48
Beam Phase		**0.1degree**	2
Luminosity		**2%**	**2**
Wakefield monitor	5um	<5um	**142812**