# The CLIC Beam Delivery System

R. Assmann, CERN-SL/AP

For the SL/AP-CLIC team and collaborators:

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Based on Talks of F. Zimmermann & R. Assmann

# Outline

1 Introduction

2 Optics & Tools

3 Performance

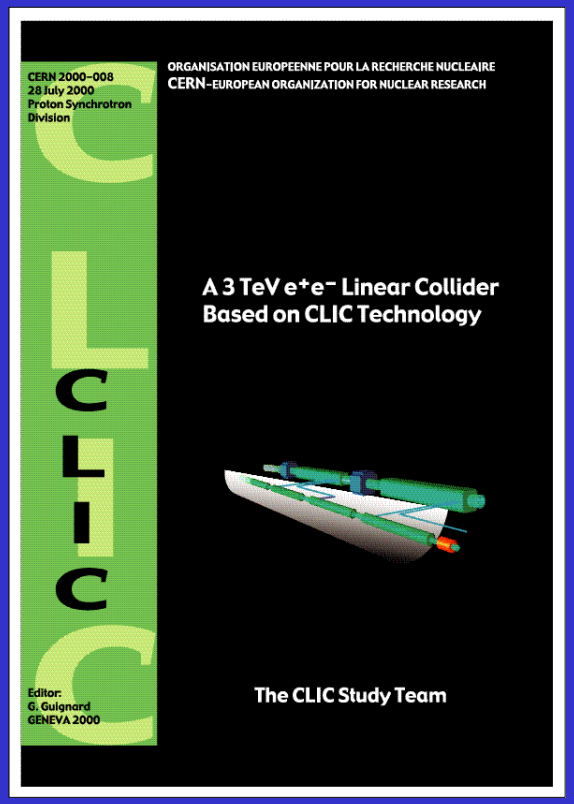
4 Collimation Issues

5 Stability Issues in the IP

6 Conclusions

# The Compact LInear Collider (CLIC) study at CERN:

Goal: **Study a 3 TeV e+e- linear collider as an option for CERN's long-term future with innovative two beam acceleration scheme (high gradient, no klystrons for main beam)**




Collaborations with:

CEA/CESTA, Le Barp (France)
IHEP, Protvino (Russia)
LBL, Berkeley (USA)
SLAC, San Francisco (USA)
Stockholm University (Sweden)
Technische Universität, Berlin (Germany)
LAL, Orsay (France)
LLNL, Livermore
INFN, Frascati (Italy)
JINR, Dubna (Russia)
KEK, Tsukuba (Japan)

*The CLIC team:*

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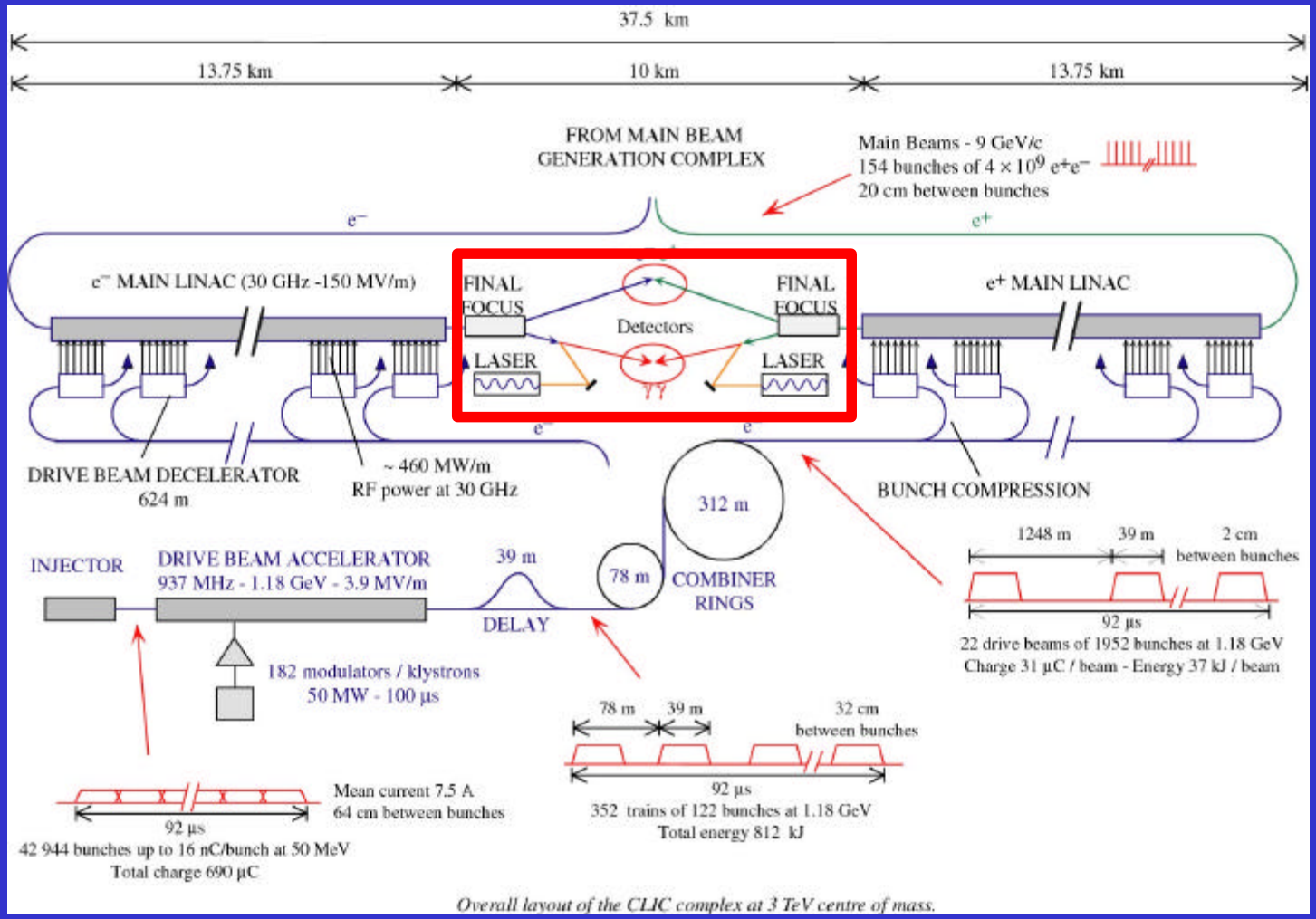
# The CLIC Complex




*Overall layout of the CLIC complex at 3 TeV centre of mass.*

Innovative two beam scheme

High gradient & energy reach

Elegant RF power generation and distribution (only few klystrons)

R&D ongoing

Accelerator Physics group in the SPS-LHC division responsible for:

**Design and study of damping ring, collimation, beam delivery! Help in CTF3.**

# Parameters

| parameter | symbol | SLC | NLC | CLIC |
|---|---|---|---|---|
| **c.m. energy [TeV]** | E | **0.1** | 1 | **3** |
| **luminosity [$10^{34}$ cm$^{-2}$ s$^{-1}$]** | $L$ | **0.0002** | 1.3 | **10** |
| **IP hor. emittance [$\mu$m]** | $\gamma\epsilon_x$ | **50** | 4.5 | **0.68** |
| **IP vert. emittance [$\mu$m]** | $\gamma\epsilon_y$ | **8** | 0.1 | **0.02** |
| hor. beta [mm] | $\beta_x^*$ | 2.8 | 12 | 8 |
| vert. beta [mm] | $\beta_y^*$ | 1.5 | 0.15 | 0.15 |
| **hor. spot size [nm]** | $\sigma_x^*$ | **1700**$^\dagger$ | 235 | **43** |
| **vert. spot size [nm]** | $\sigma_y^*$ | **900**$^\dagger$ | 4 | **1.0** |
| bunch length [mm] | $\sigma_z$ | 1 | 0.12 | 0.03 |

$^\dagger$ 1998 average value, $\sim$ 60 nm at FFTB

1 nm is the size of a water molecule!

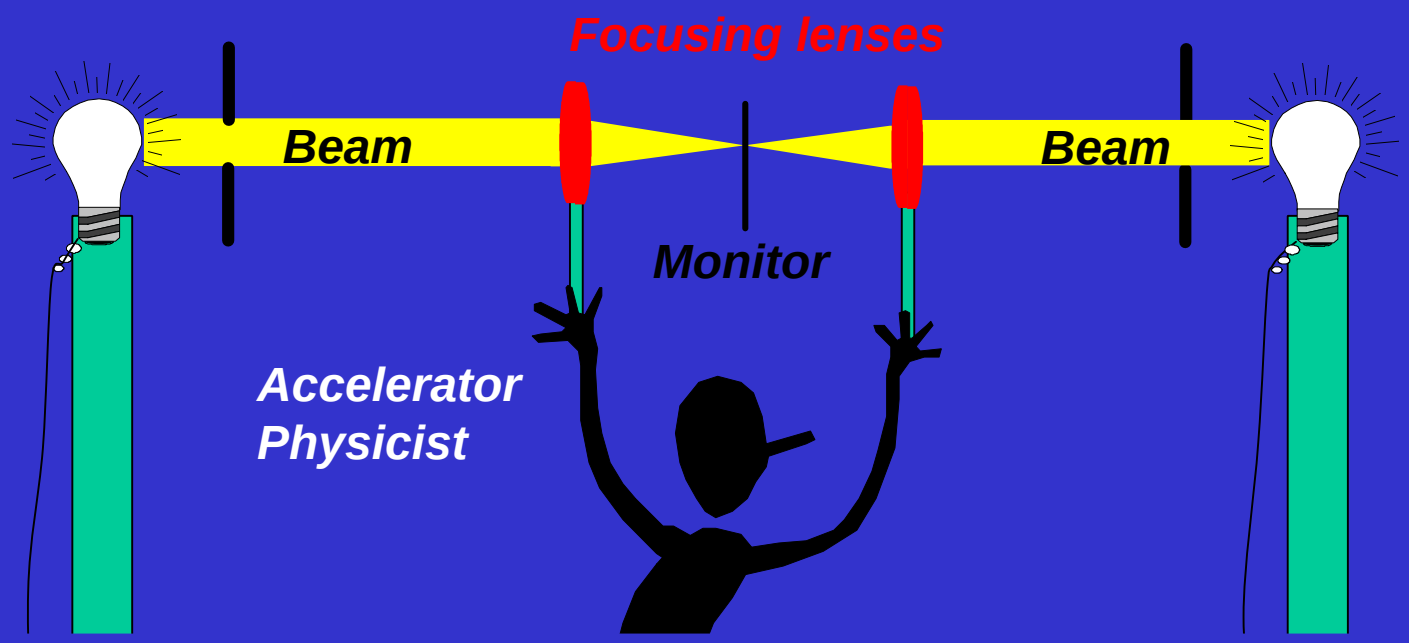
Other LC's: < 5 nm

Major challenges: High energy

Small spot size
High beam power

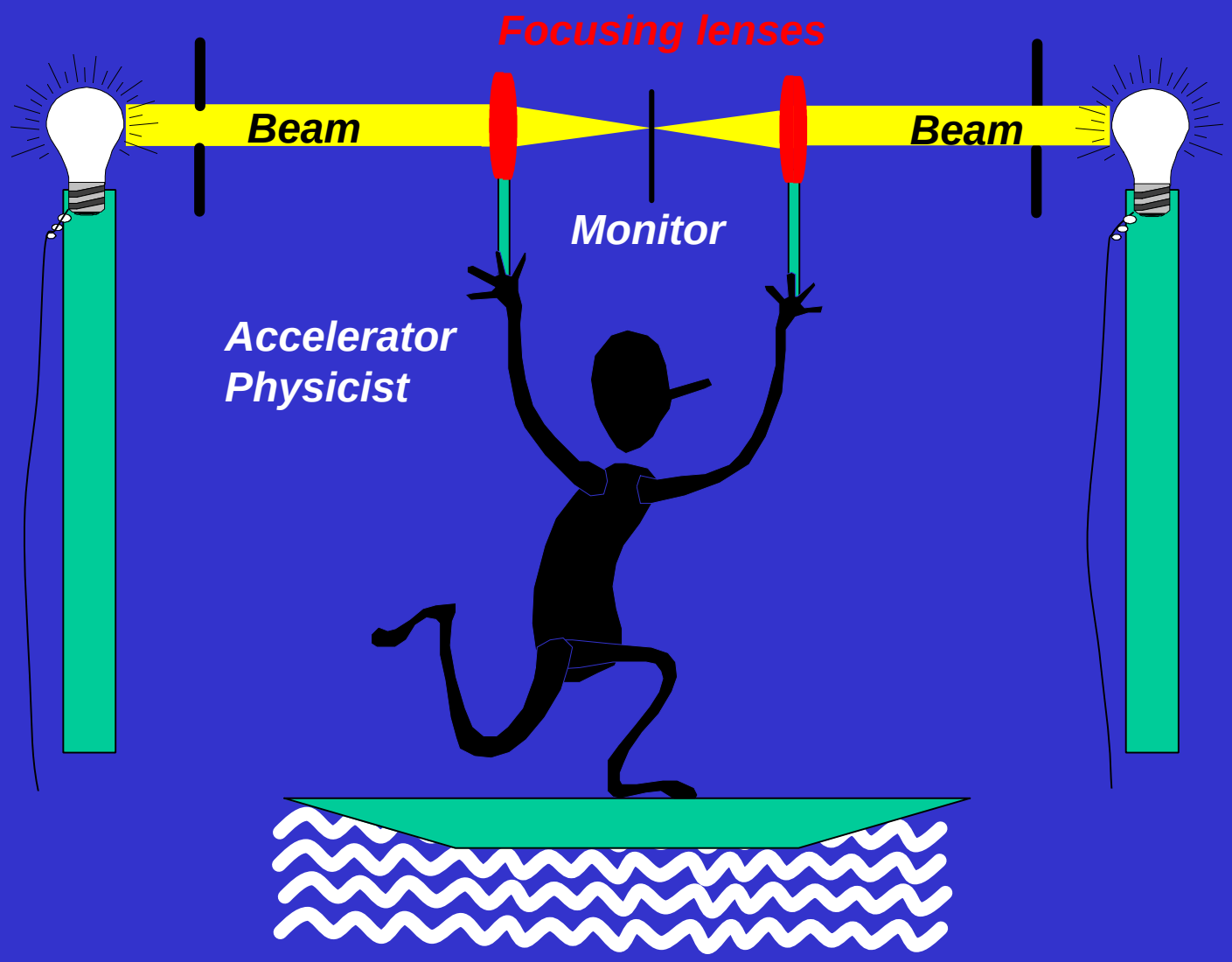
*Prepare design and show feasibility in real environment!*

Poor Physicist's Final-Focus Experiment: Understanding the challenge!



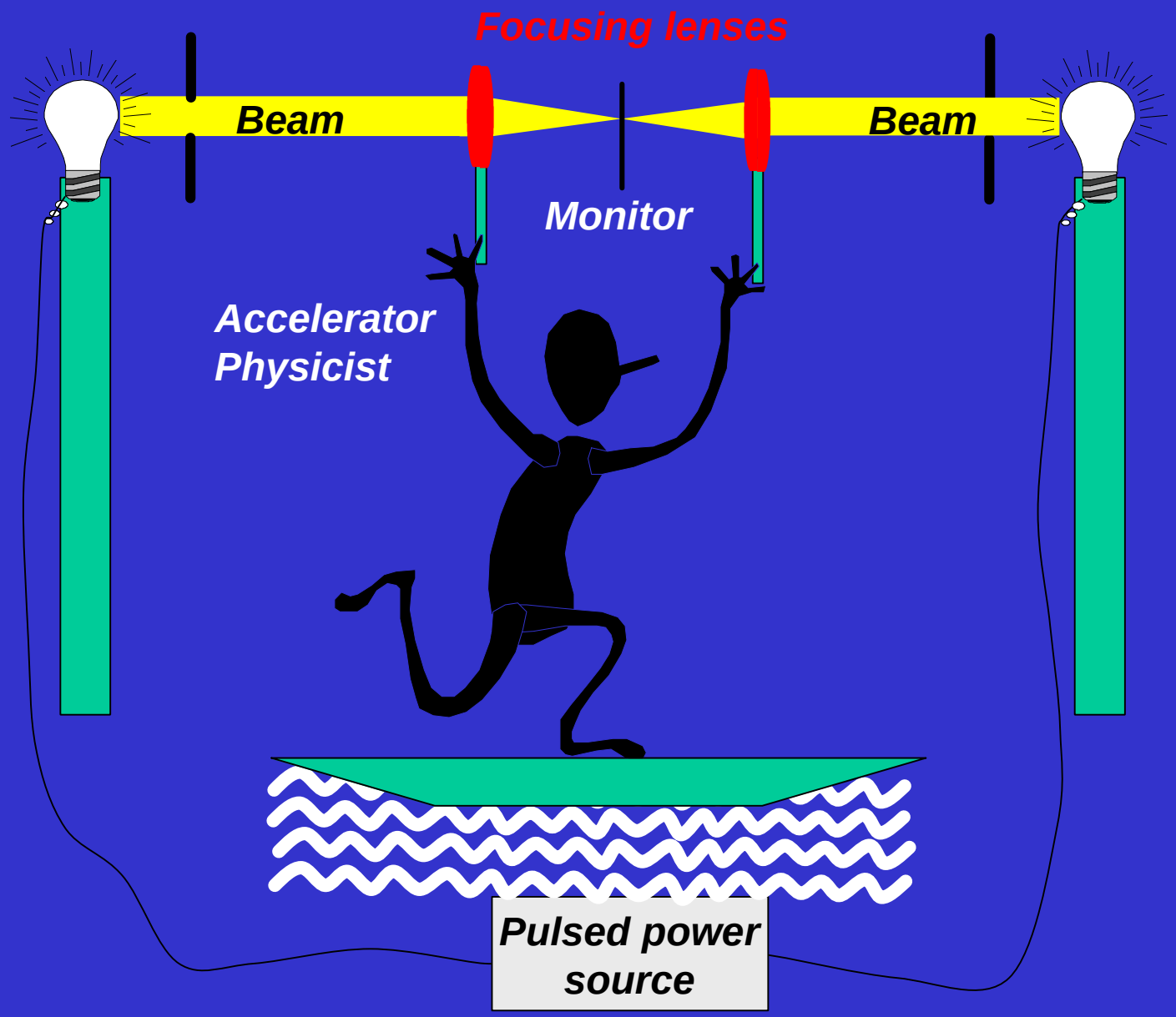

**Too easy?**

# Poor Physicist's Final-Focus Experiment: Understanding the challenge!

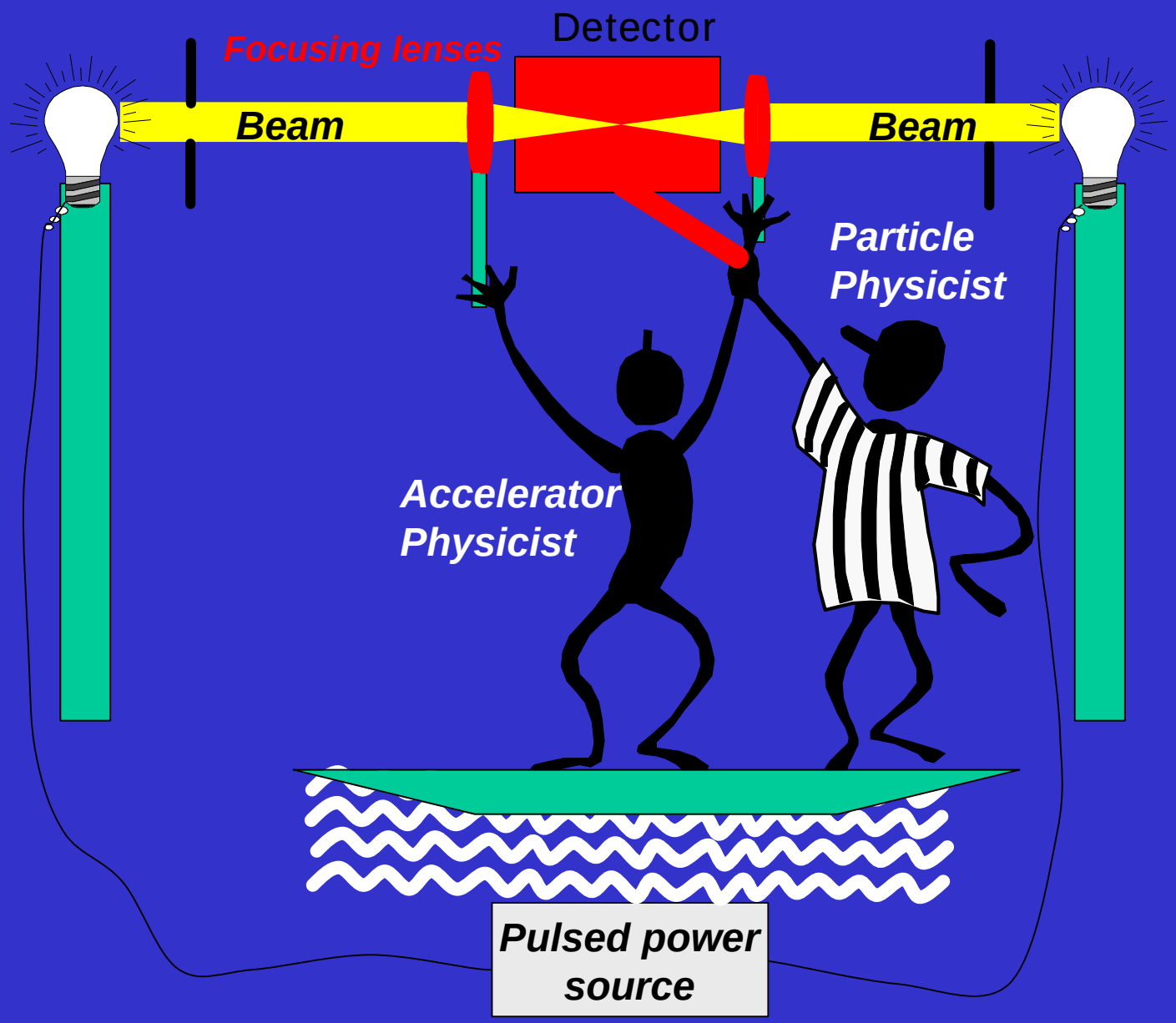



**Still too easy?**

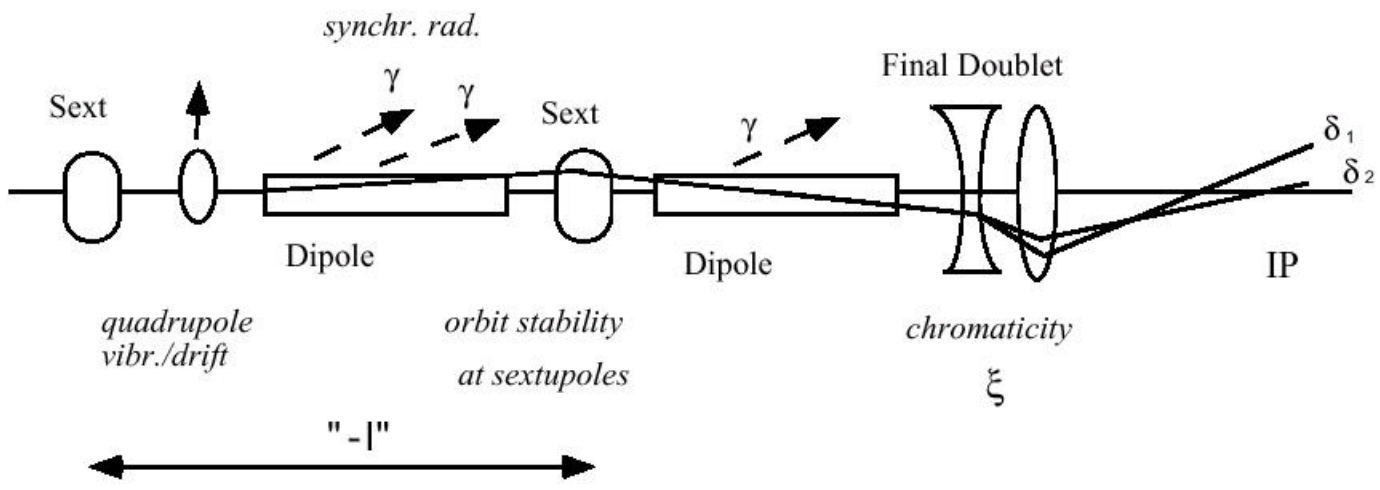
# Poor Physicist's Final-Focus Experiment: Understanding the challenge!



## Poor Physicist's Final-Focus Experiment: Understanding the challenge!



# Final Focus Layout




Schematic of a conventional final focus.

Used: Dipole, Quadrupole, Sextupole, (Octupole)

Design: Position, magnetic field.

Performance: Design emittance growth.
Imperfections (vibration, alignment, field errors, beam loss induced, ...)

# Design Constraints

- chromaticity: $\Delta\sigma/\sigma = \xi\delta_{\rm rms}$, with $\xi \approx \int \beta K \mathrm{d}s$.
- limited quadrupole strengths, $\rightarrow \xi$.
- synchrotron radiation in bending magnets, $\delta_{\rm rms} \propto \gamma^{5/2}\theta_B^{3/2}/l_B$, $\rightarrow l_B$.
- synchrotron radiation in final quadrupole (Oide effect),

$$\frac{\Delta\sigma_y}{\sigma_y} \propto \gamma^{5/2} F(K, L_Q, l^*)\ \frac{\epsilon^{3/4}}{{\beta_y^*}^{7/4}};$$

  $F$ smallest if $l^* \ll L_Q$; also $L_Q$ should be small to confine $\xi$; $\rightarrow \xi$.
- higher order aberrations, from chromatic breakdown of linear transformations between sextupoles, and between sextupoles and final doublet.

Unfavorable length scaling…

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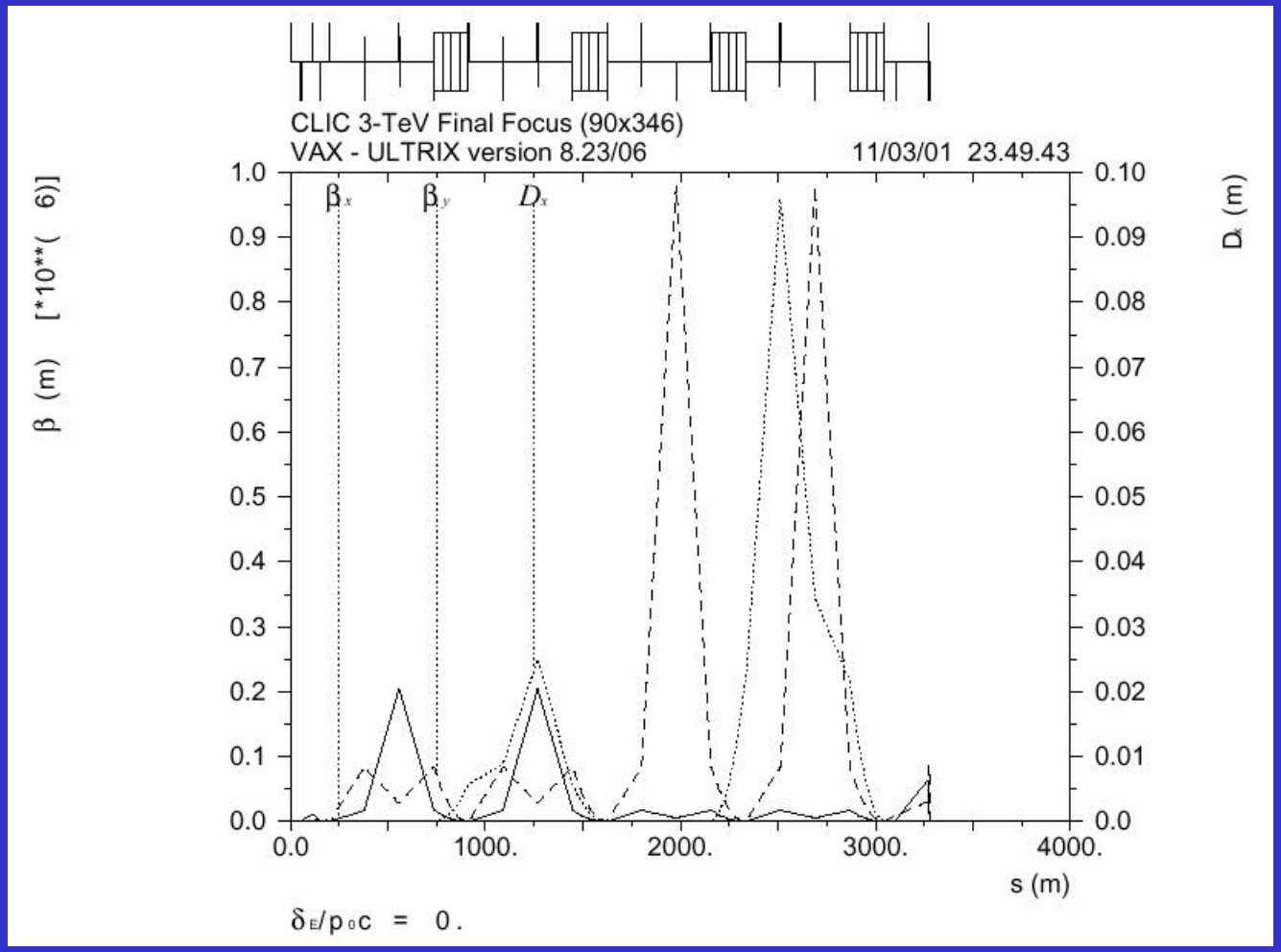
# Optics and Tools

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Baseline final-focus optics; modular design, odd-dispersion function a la Oide. Total length 3.3 km.

# Alternative Compact Optics

- Derives from NLC 1-TeV final focus, developed by Raimondi and Seryi.
- To limit the impact of synchrotron radiation, sextupole strengths were increased by a factor 3.4 and all bending angles reduced accordingly.
- Upstream quadrupoles, sextupoles, and bending angles have been empirically fine-tuned for maximum luminosity, using a Monte-Carlo optimization

# Optimization with Sixtrack

procedure:

(1) call minuit from fortran,

(2) minuit changes parameters and calls script `run minuit' [see picture],

(3) rematch linear optics using new parameters with MAD

(4) produce MAD twiss tape le `TWISS2'

(5) convert this into Sixtrack90 input le [executable xsb],

(6) track with Sixtrack90 `pointer',

(7) compute luminosity on a grid [`run track2'],

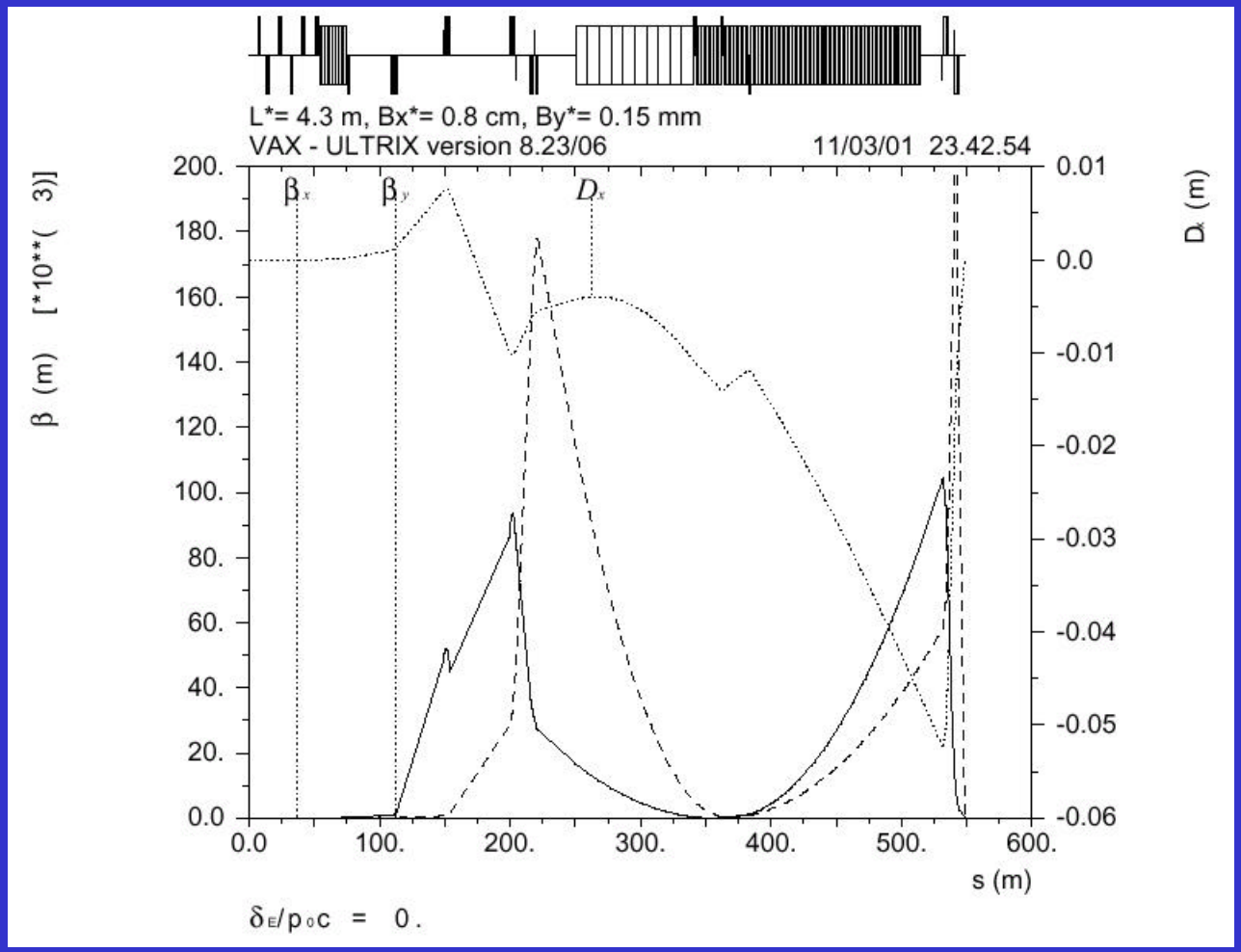
(8) read luminosity value back into minuit,

(9) iterate

```
run_track2



[slapb01] /local/work/frankz/clic/tmp2/SIX90/MAPS/six
track > more run_minuit
rm fort.7_clic
mad < clicshorttrack.mad
mv TWISS2 twiss
xsb > fort.7_clic
pointer < pointer.input
rm lum.data
run_track2



[slapb01] /local/work/frankz/clic/tmp2/SIX90/MAPS/sixtrack >
```

F. Zimmermann
F. Schmidt

# Compact Final Focus

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Compact final focus scaled from the NLC design by Raimondi & Seryi; not modular; dispersion across the final doublet; linear and nonlimear optics are mixed. Total length 600 m.

# Comparison I

| optics | baseline | compact |
|---|---|---|
| beam energy | 1.5 TeV | |
| no. of bunches per second | 15400 | |
| bunch population | $4 \times 10^9$ | |
| ideal luminosity w/o pinch | $4.56 \times 10^{34}$ cm$^{-2}$s$^{-1}$ | |
| IP beta functions | 8.0 (x), 0.15 (y) mm | |
| IP normalized emittances | 0.68(x), 0.02 (y) $\mu$m | |
| full-width momentum spread | 0.8–1.0% | |
| demagnification factor | 90 (x), 346 (y) | |
| peak vertical beta function | 1000 km | 200 km |
| peak dispersion | 10 cm | 5 cm |
| total length | 3282 m | 548 m |

# Comparison II

| optics | baseline | compact |
|---|---|---|
| total bending length | 705 m | 276 m |
| total bending angle $\sum \lvert\theta_i\rvert$ | 586 $\mu$rad | 363 $\mu$rad |
| gradient of last quadrupole | 450 T/m | 388 T/m |
| gradient of 2nd last quadr. | 184 T/m | 135 T/m |
| strength of SD sextupole | 1.29 $m^{-3}$ | 20.1 $m^{-3}$ |
| strength of SF sextupole | 2.70 $m^{-3}$ | 5.6 $m^{-3}$ |
| free length from IP $l^*$ | 2 m | 4.3 m |

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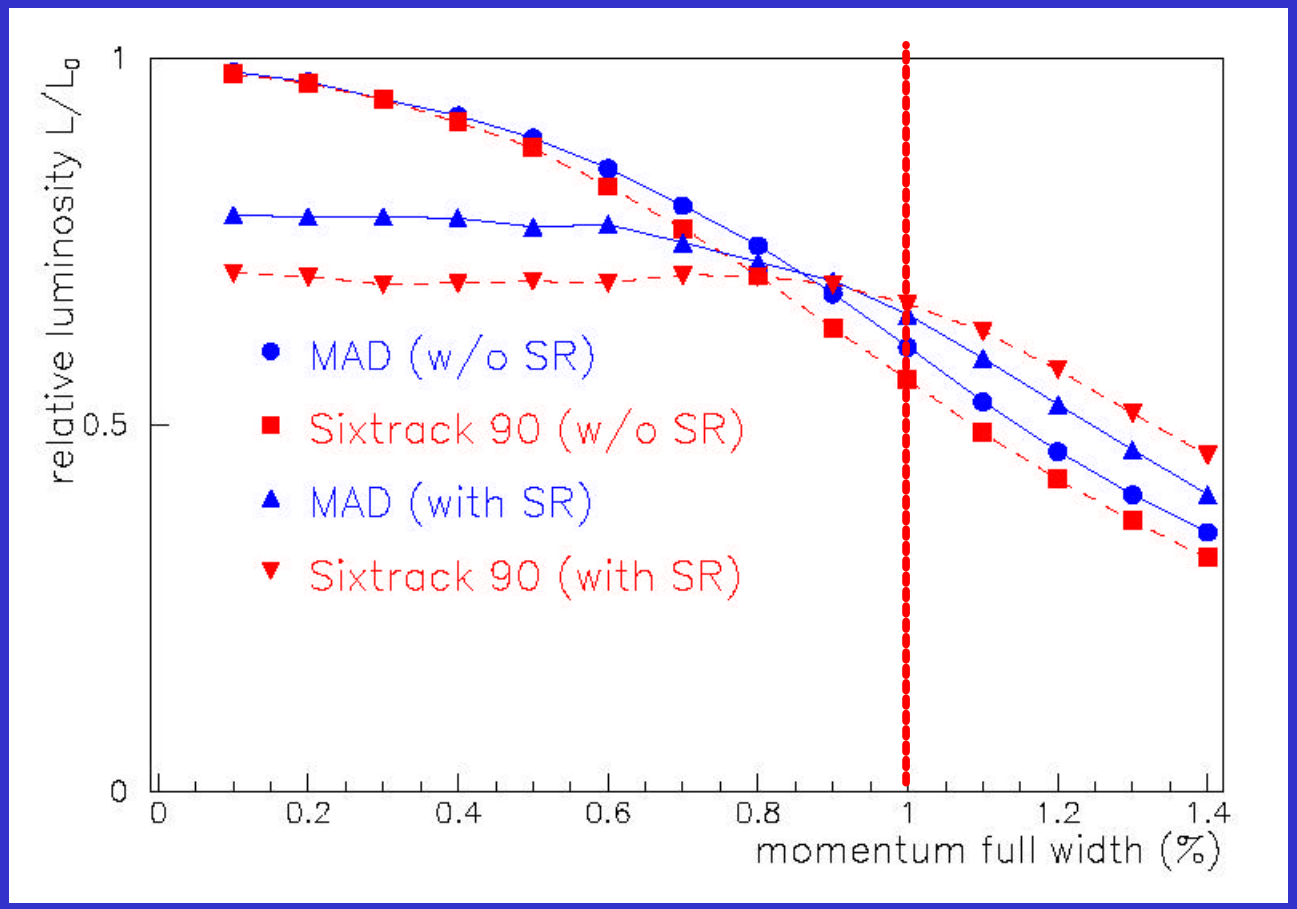
# Performance

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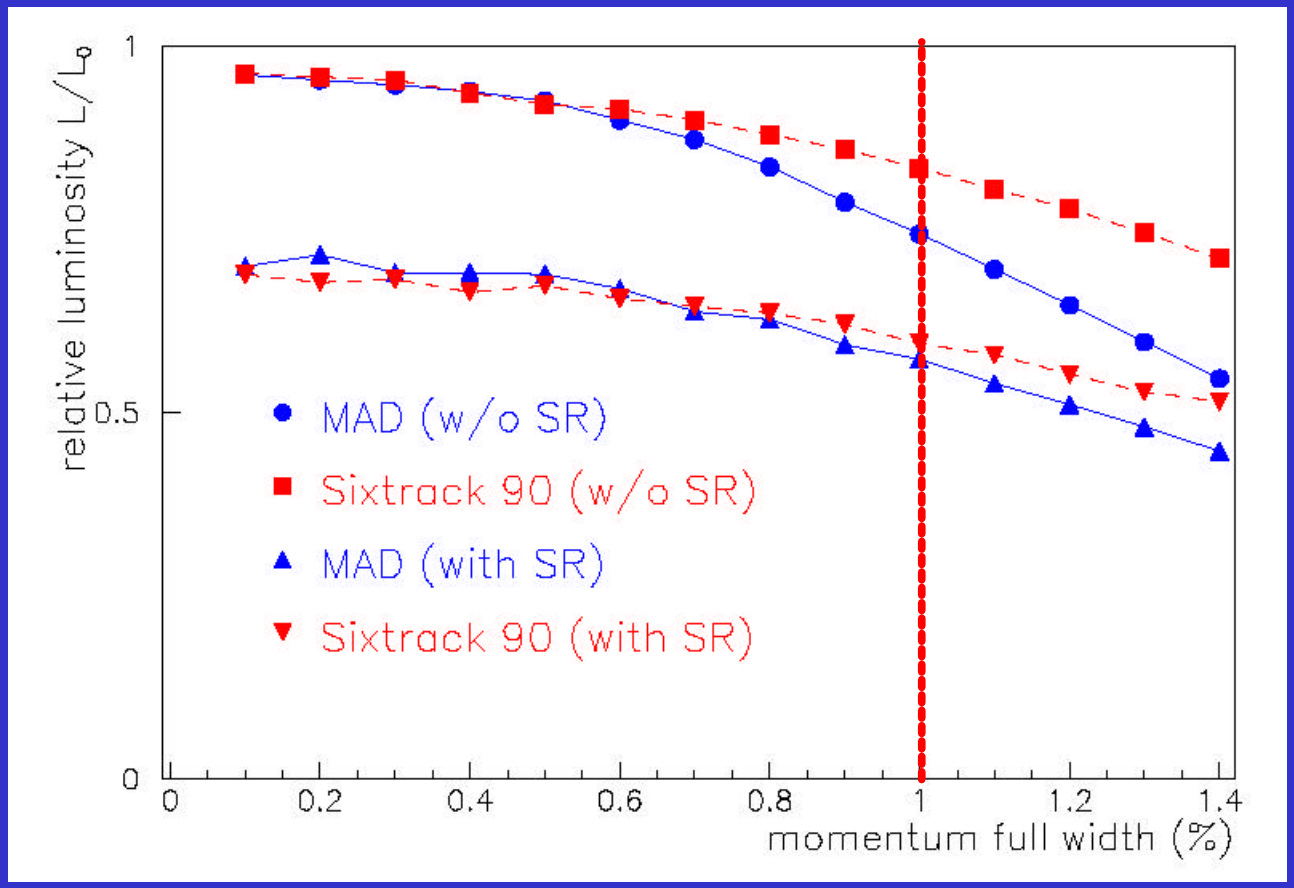
Luminosity, in units of the ideal geometric luminosity $L_0$, vs. the full-width momentum spread for the baseline optics, as simulated by MAD and Sixtrack90 with and without synchrotron radiation.

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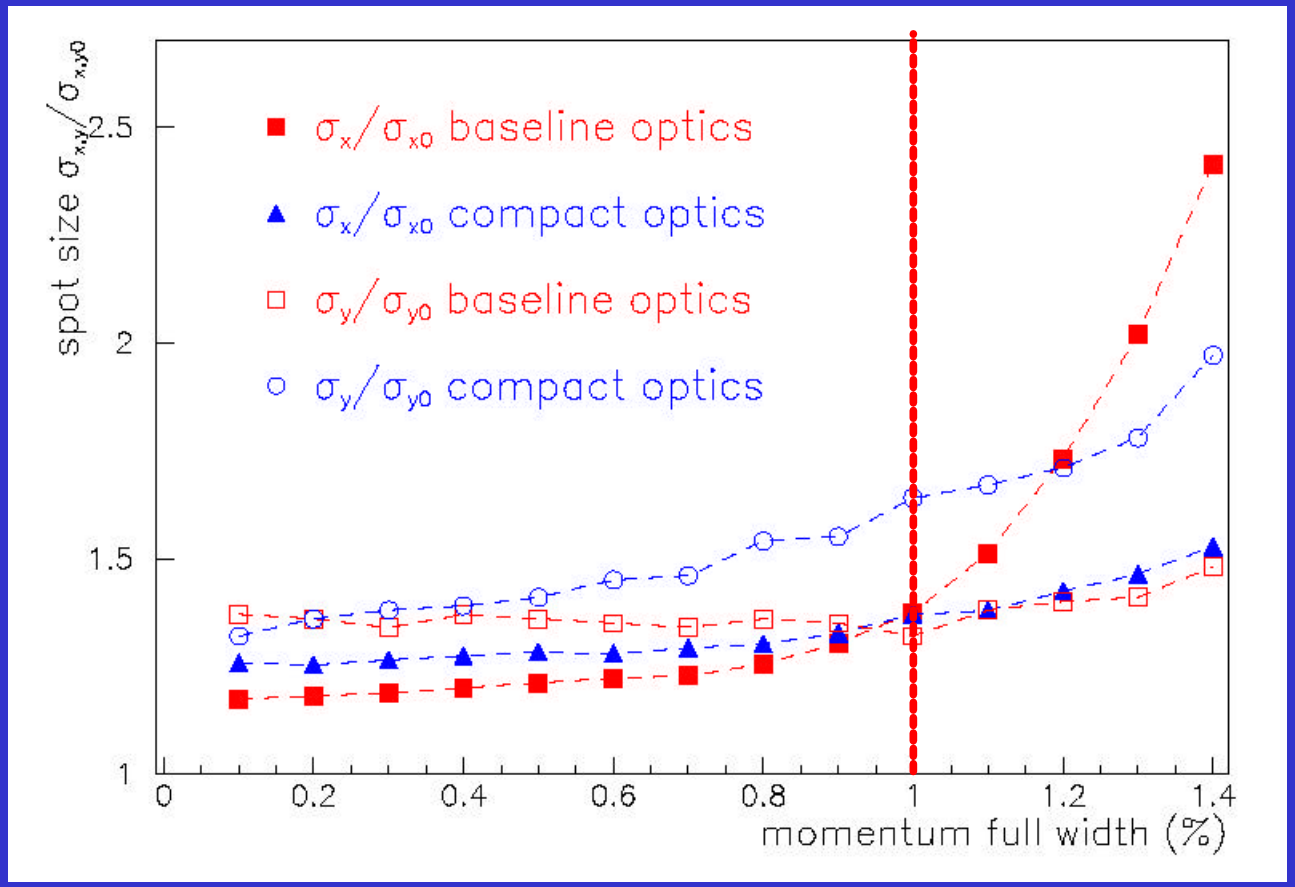
Luminosity, in units of the ideal geometric luminosity L 0 , vs. the full-width momentum spread for the compact optics, as simulated by MAD and Sixtrack90, including random energy fluctuations due to synchrotron radiation.

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Horizontal and vertical rms beam sizes simulated by Sixtrack90 including synchrotron radiation vs. the full-width momentum spread for the two optics.

# Non-linear analysis using Sixtrack90

procedure: (1) get Taylor map from Sixtrack90 [left] (2) evaluate the relative spot-size increase caused by each term [right]

```
ETALL      , NO =    5, NV =    8, INA =  257
**********************************************

   I  COEFFICIENT          ORDER   EXPONENTS
   1  0.20887222105301E-02    1     1 0  0 0  0 0  0 0
 2.0887222105301 36E-003
   2  0.70821388254612        1     0 1  0 0  0 0  0 0
 0.708213882546119
   3  0.65892815880532E-07    1     0 0  0 0  1 0  0 0
 6.589281588053242E-008
   4  -.12734163263917E-04    2     2 0  0 0  0 0  0 0
-1.273416326391663E-005
   5  0.11455766978413E-02    2     1 1  0 0  0 0  0 0
 1.145576697841266E-003
   6  -.12310901975950E-01    2     0 2  0 0  0 0  0 0
-1.231090197595019E-002
   7  -.18727710325114E-04    2     0 0  2 0  0 0  0 0
-1.872771032511433E-005
   8  -.44812942090644E-03    2     0 0  1 1  0 0  0 0
-4.481294209064401E-004
   9  -.26374055536724E-02    2     0 0  0 2  0 0  0 0
-2.637405553672423E-003
  10  -.15256123165149E-02    2     1 0  0 0  1 0  0 0
-1.525612316514935E-003
  11  0.32141854513310E-01    2     0 1  0 0  1 0  0 0
 3.214185451331009E-002
  12  0.51743310892225E-05    2     0 0  0 0  2 0  0 0
 5.174331089222514E-006
  13   4.7047725288583        3     3 0  0 0  0 0  0 0
 4.70477252885829
[slapb01] /local/work/frankz/clic/tmp2/SIX90/MAPS >
```

```
  1.100838
0.86434820234270          0 0  0 1  0
0.50289565852774          0 0  1 0  0
0.35253134286725          0 0  1 0  2
0.20563676043902          0 0  0 1  2
0.13606763426147          1 0  1 0  2
0.11190947276114          0 0  1 0  3
0.78914076450678E-01      1 0  0 1  2
0.65101374243060E-01      0 0  0 1  3
0.43621756716093E-01      0 0  1 0  1
0.26170930369196E-01      0 1  1 0  2
0.21149281593259E-01      0 0  0 1  1
0.15175184142091E-01      0 1  0 1  2
0.13149902561461E-01      0 0  3 0  1
0.10230315575670E-01      0 0  2 1  1
0.79768185713078E-02      1 0  1 0  3
yspot.dat (12%)
```

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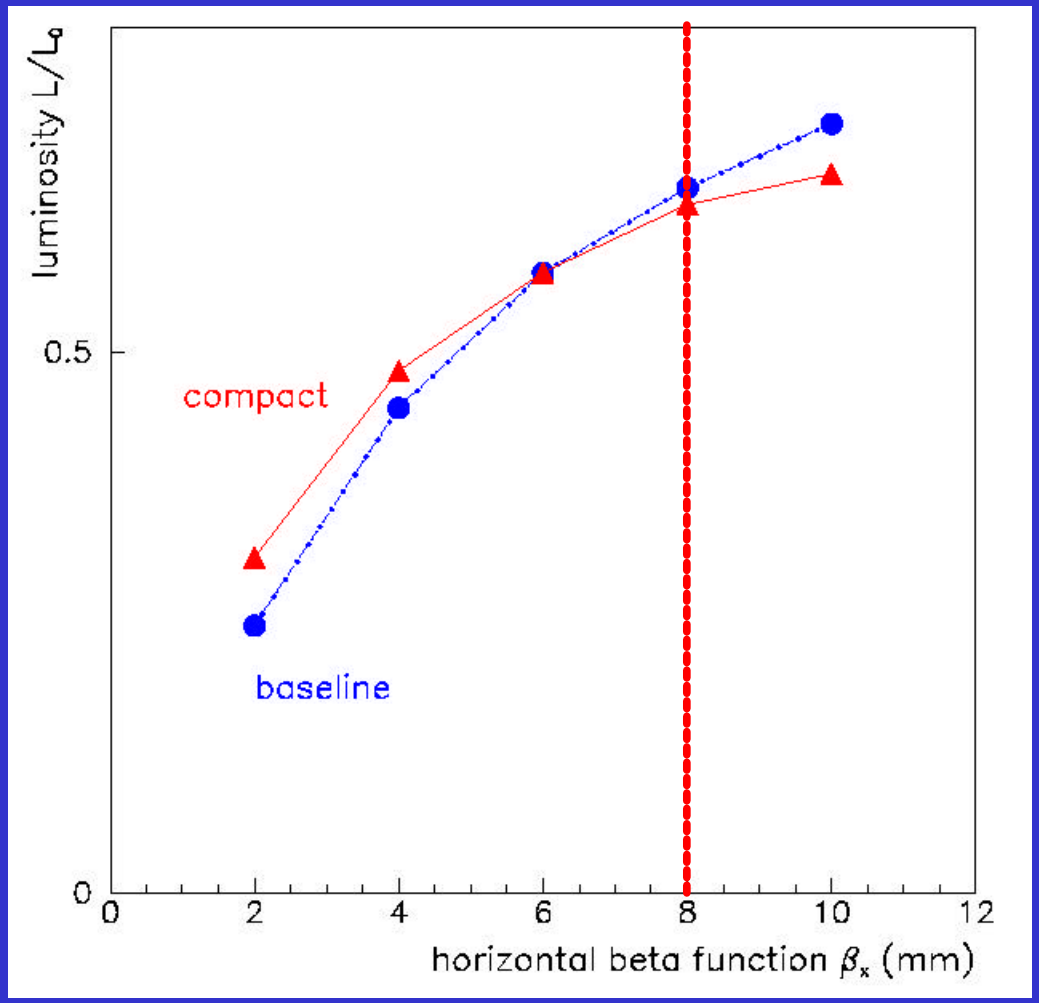
# Residual aberrations

Residual aberrations $\Delta\sigma_{x(y)}/\sigma_{y(x),0}$, which are added in quadrature to the linear spot sizes $\sigma_{y(x),0}$, inferred from Sixtrack90.

| | Lie gen. | $\Delta\sigma_x/\sigma_{x0}$ | Lie gen. | $\Delta\sigma_y/\sigma_{y0}$ |
|---|---|---|---|---|
| baseline | $x'^4\delta$ | 0.70 | $y'^2\delta^2$ | 0.41 |
| | $x'^2\delta^3$ | 0.43 | $x'y'^2\delta^2$ | 0.15 |
| | $x'^2\delta^2$ | 0.40 | $y'^2\delta^3$ | 0.12 |
| compact | $x'\delta^2$ | 0.42 | $y'^2\delta$ | 0.91 |
| | $x'^2\delta$ | 0.41 | $x'^2y'^2\delta$ | 0.31 |

This table provides guidance for further improvements!

# Reduction of $\beta_x^*$

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Luminosity in units of ideal luminosity vs. horizontal IP beta function.
Two schemes are comparable.

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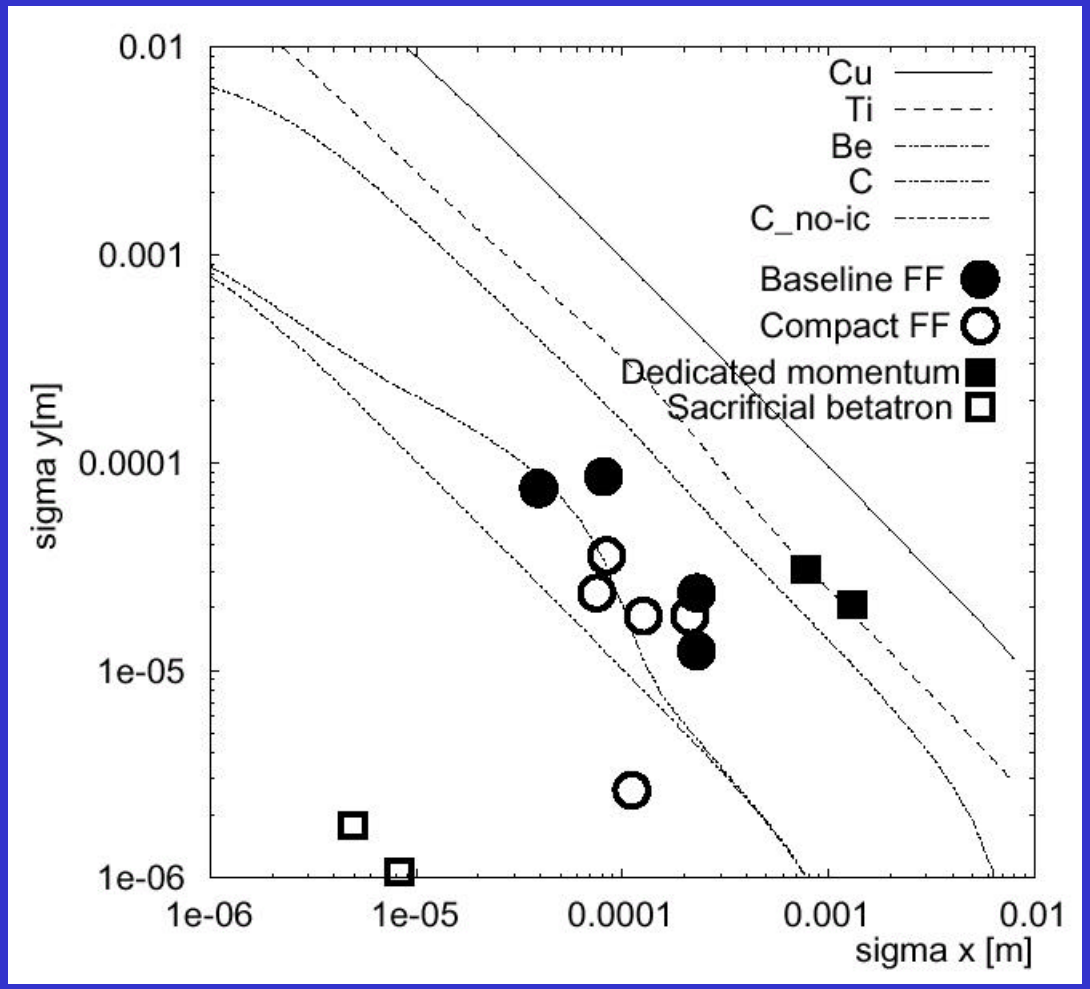
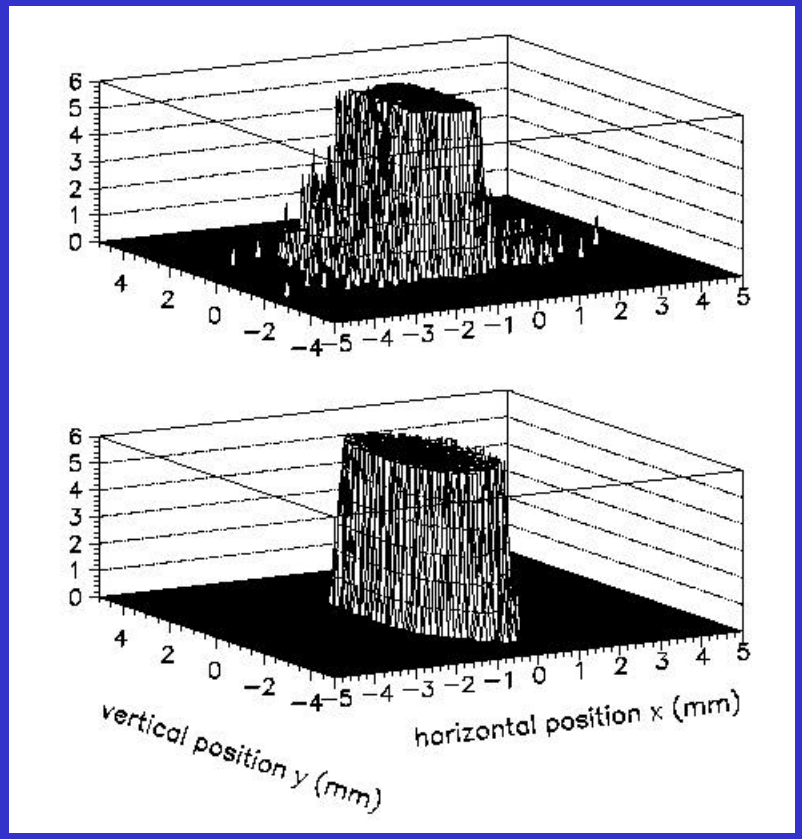
# Collimation Issues




S. Fartoukh
J.B. Jeanneret
J. Pancin

Vertical vs. horizontal beam sizes required for spoiler survival and values at spoiler locations.

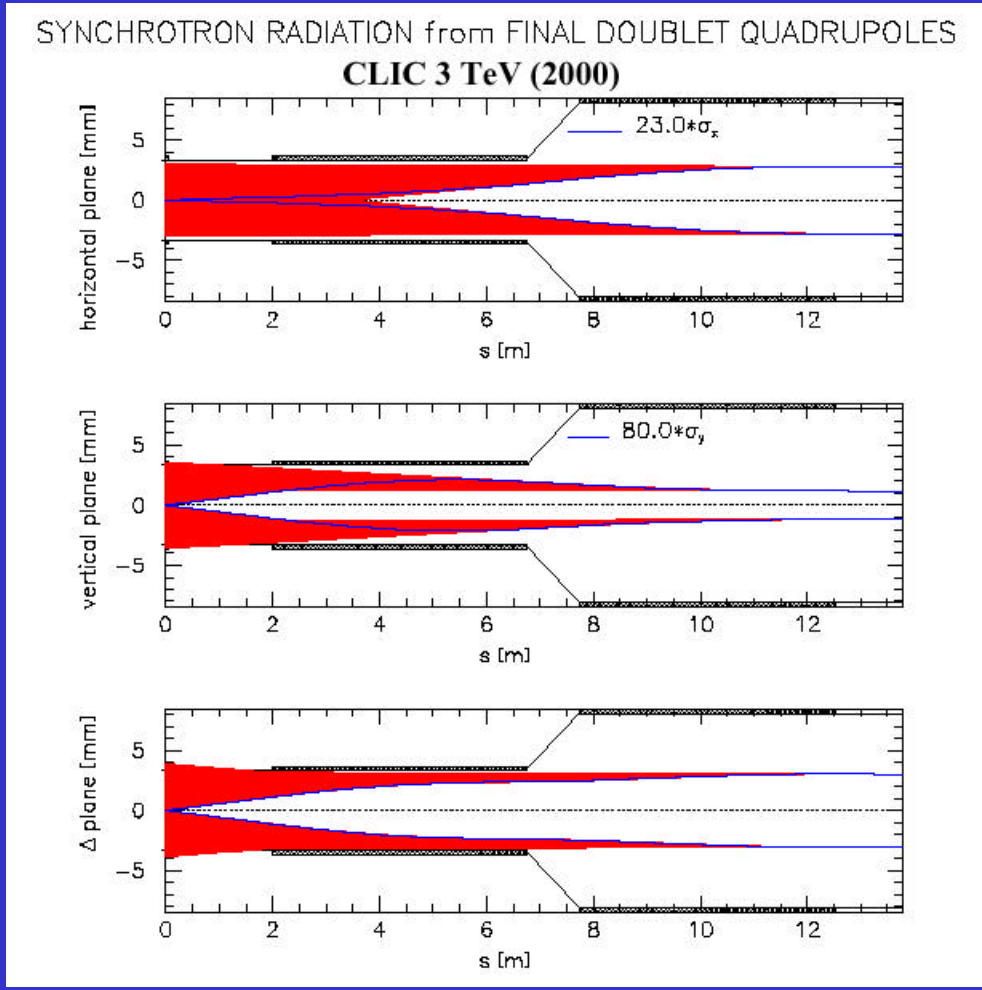
# Tails




F. Zimmermann
et al

Beam halo at final-quadrupole entrance for baseline (top) and compact optics (bottom). The initial (uniform) distribution extends up to $\pm 15\ \sigma_x$ , $\pm\ 70\ \sigma_y$ , and $\pm$ 4%.

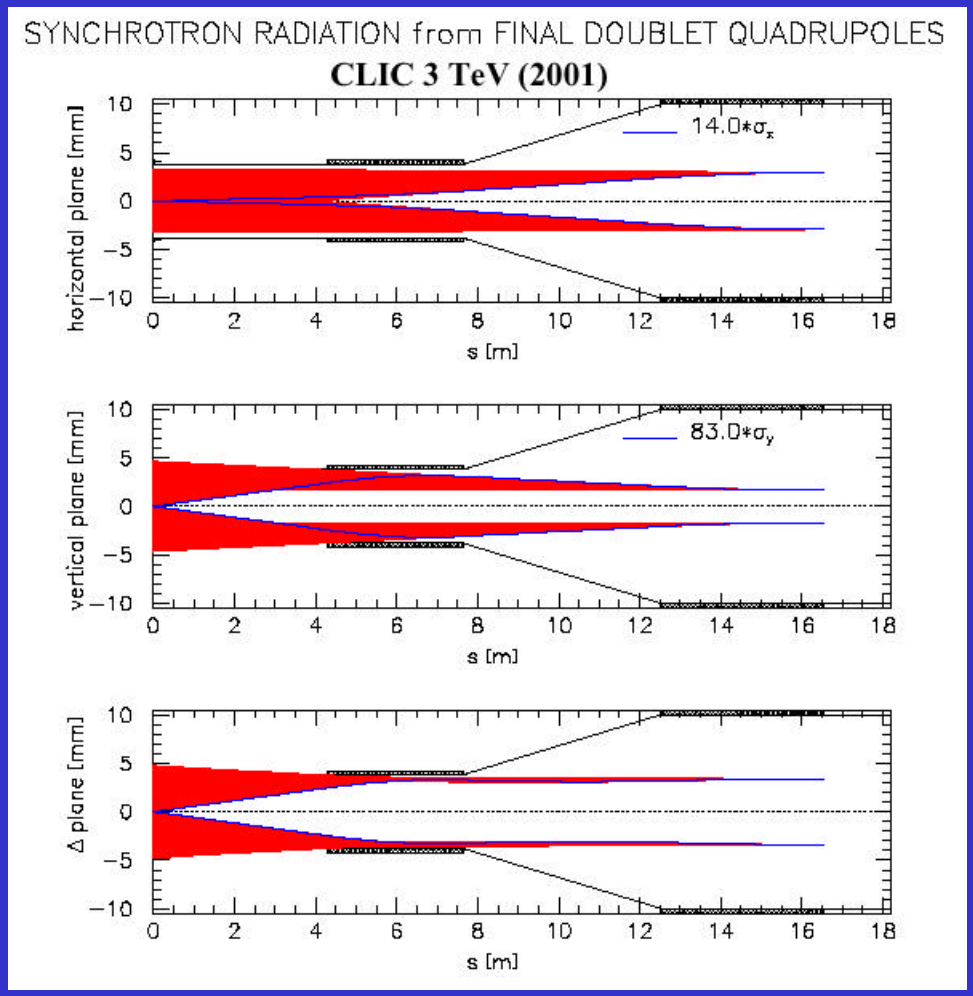
# Synchrotron radiation I




O. Napoly

Synchrotron radiation fans across the final doublet for the baseline optics with beam envelopes of 23 $\sigma_x$ and 80 $\sigma_y$ . Pictures refer to horizontal (top), vertical (center) and 45$^o$ plane (bottom).

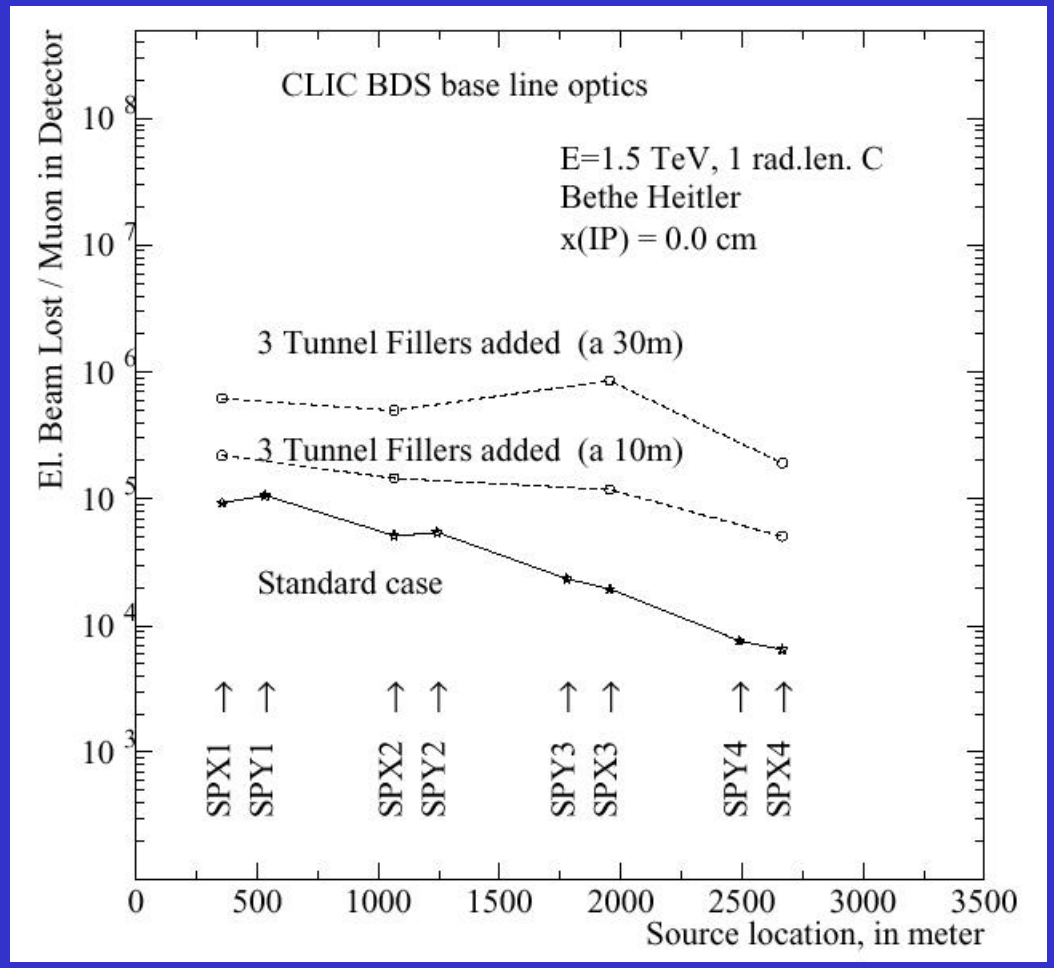
# Synchrotron radiation II




O. Napoly

Synchrotron radiation fans for the compact optics with beam envelopes of 14 $\sigma_x$ and 83 $\sigma_y$ .

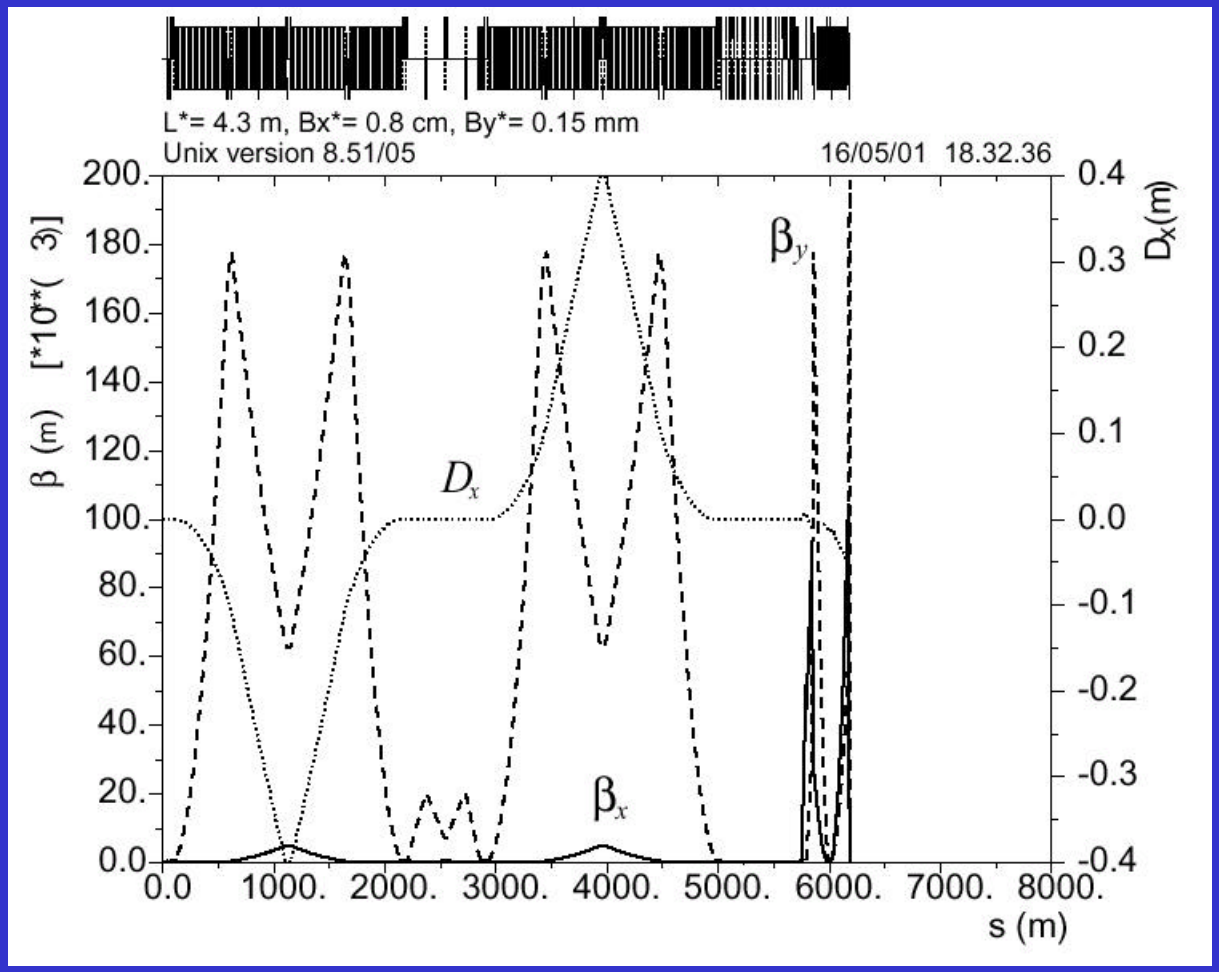
# Generation of Muons




H. Burkhardt
H.-J. Schreiber

Number of lost electrons per muon passing through a detector with 7.5-m radius as a function of position along baseline final focus. Potential collimator locations are indicated.

# Final-Focus and Collimation




~ 6.2 km
total length

T. Risselada

Optics of a 3-TeV CLIC beam delivery system consisting of a 5.6-km long collimation section, scaled from the 2000 NLC design and the 550-m compact final focus.

# Wakefield effects

Centroid deflection by tapered circular collimator [K. Yokoya]:

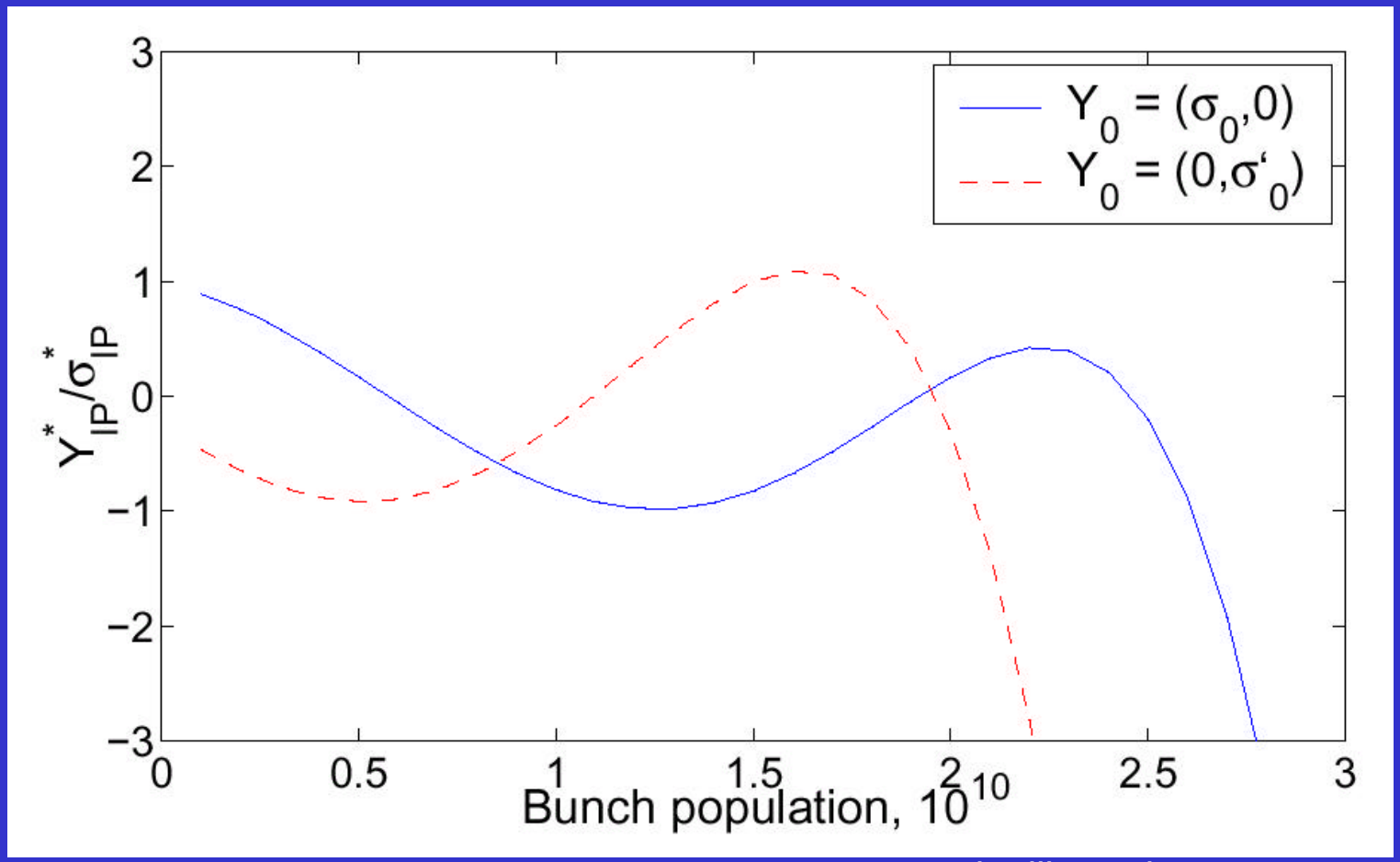
$$\Delta y' = \frac{2N_b r_e}{\gamma \sigma_z}\left[\frac{(4\lambda\sigma_z)^{1/4}}{g^{3/2}} + \frac{L_F(\lambda\sigma_z)^{1/2}}{2\sqrt{\pi}g^3}\right] y$$

where $y$ is the offset from the center of the chamber, $\lambda[\mathrm{m}] = \rho[\Omega\mathrm{m}]\ /(120\pi)$, $L_F$ the length of the collimator flat part, and $g$ the half gap. The taper angle is assumed to be optimally chosen as $\theta_{\mathrm{opt}} \approx 1.1(\lambda\sigma_z/g^2)^{1/4}$ [J. Irwin]

Consider:

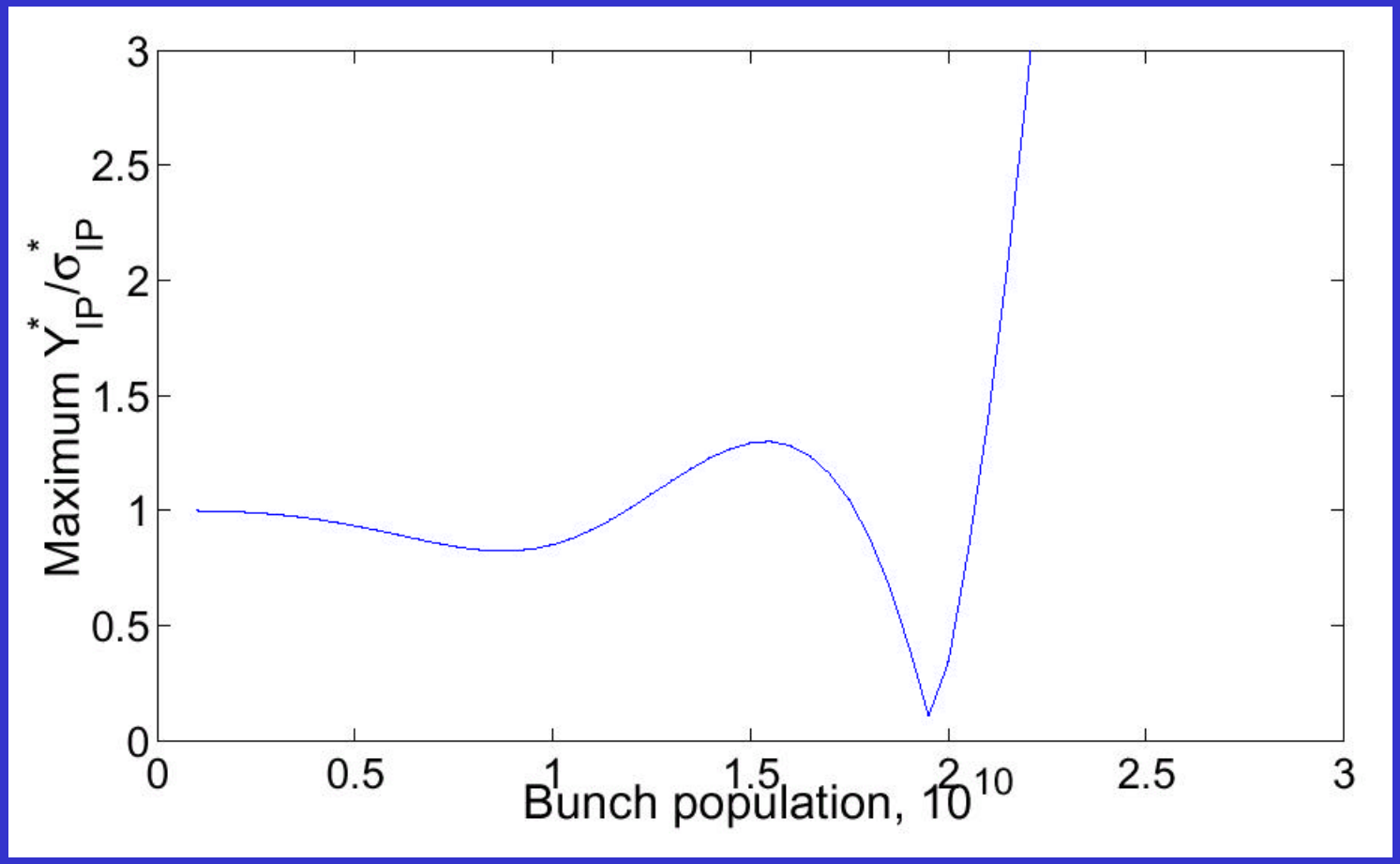
- 4 vertical spoilers, 0.5 r.l. beryllium (177 mm)
- 4 vertical absorbers, 20 r.l. copper coated titanium (712 mm)
- collimation depth set to 80 $\sigma_y$
- compute change of IP displacement for incoming
- betatron oscillations in presence of collimator wakefields

*R. Assmann, S. Redaelli, F. Zimmermann*



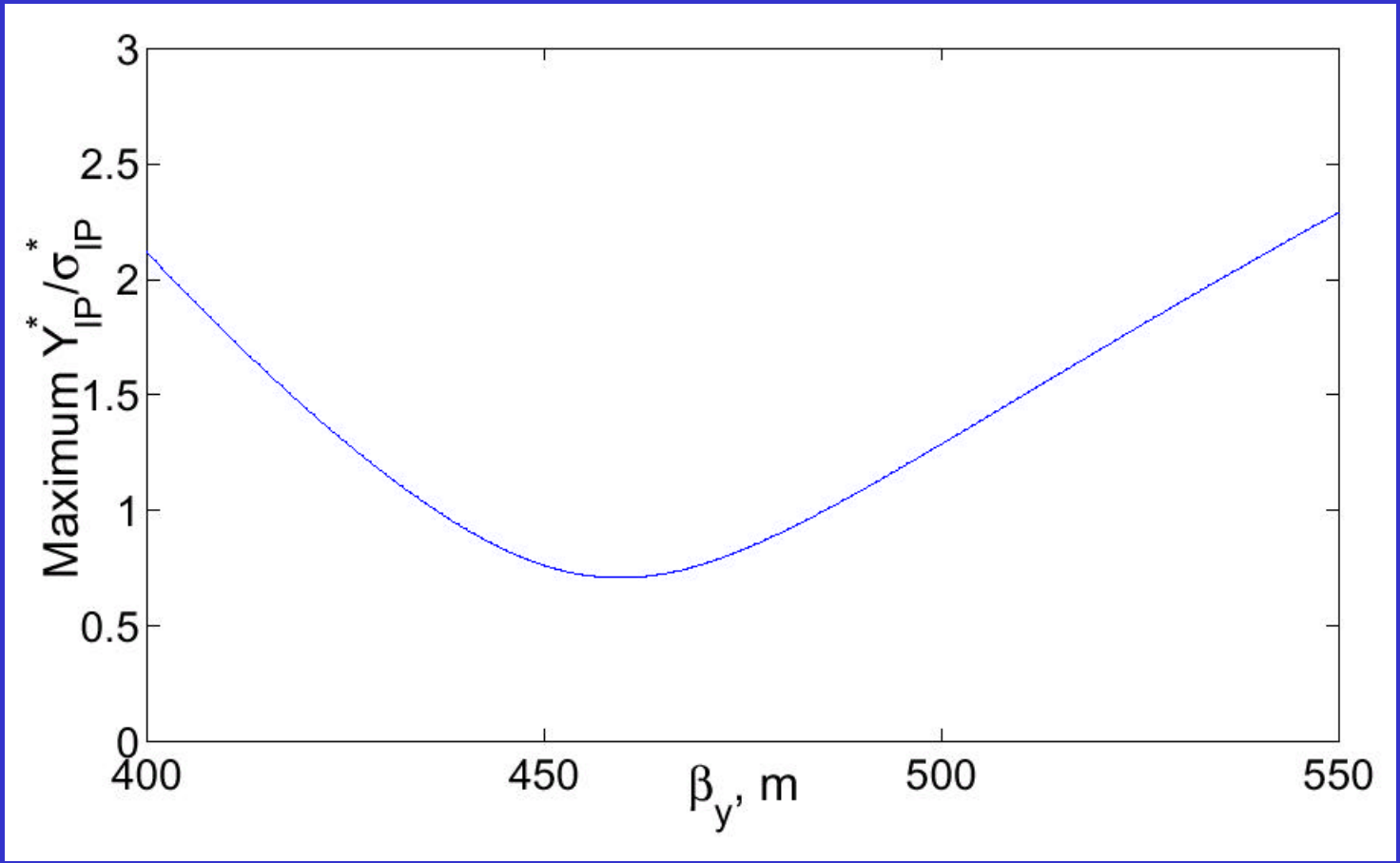

*R. Assmann, S. Redaelli, F. Zimmermann*

IP orbit displacement for a 1s change in incoming beam position or slope (the two curves) as a function of bunch population.




*R. Assmann, S. Redaelli, F. Zimmermann*

`Maximum' IP orbit displacement for a 1s change in incoming beam trajectory as a function of bunch population.




*R. Assmann, S. Redaelli, F. Zimmermann*

`Maximum' IP orbit displacement for a 1s change in incoming beam trajectory vs. beta function at the collimator.

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# CLIC Magnet Stability Study

*M. Aleksa, R. Assmann, W. Coosemans, G. Guignard, N. Leros, M. Mayoud, S. Redaelli, F. Ruggiero, S. Russenschuck, D. Schulte, A. Verdier, I. Wilson, F. Zimmermann*

- **CERN: SL, PS, EST, LHC divisions involved**
- CERN test stand on main site (surface, close to road, accelerators, equipment).
- **Collaboration with SLAC/NLC. Contacts with DESY and FNAL.**

Since January 2001 fully approved…

**www.cern.ch/clic-stability**

Goal: *The goal of the proposed study is to show that the present design parameters of CLIC are feasible in a real accelerator environment, using and further developing latest cutting-edge stabilization technology and time-dependent simulation programs.*

Active and passive stabilization technology subject of intense industrial research and development. Applications:

*Chip lithography, electron-transmission microscopy, NMR devices, solid-sate physics, satellites, airplanes, gravitational wave detectors, lasers, …*

E.g. If TEM can achieve 0.05 nm resolution why can't we use this?

*Collaboration with strong effort at SLAC (A. Seryi, J. Frisch, et al)*

# Ph

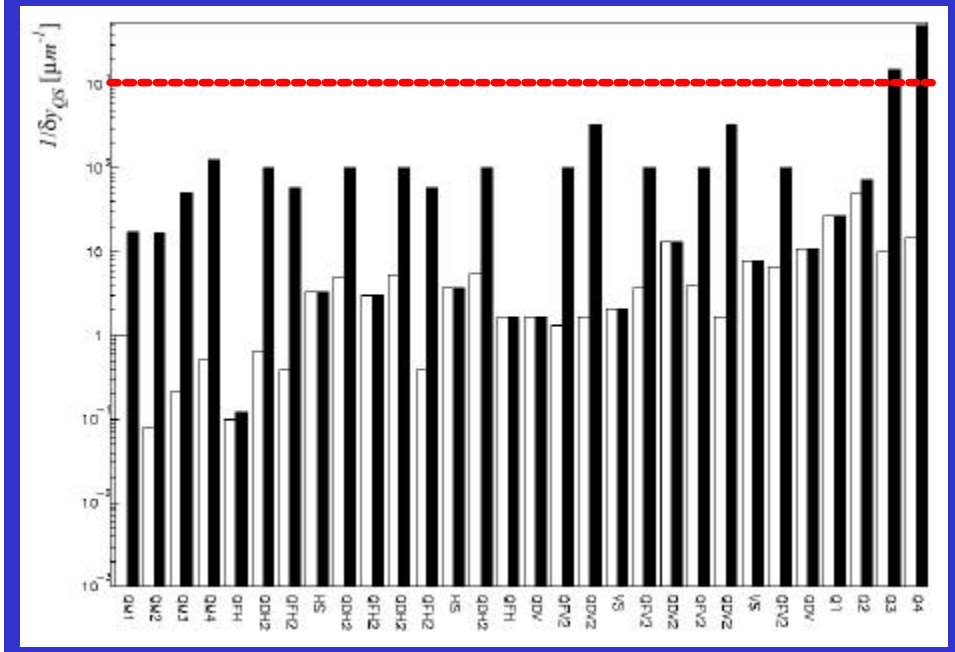
1. **Review of existing measurements and solutions.**
2. **Establish vibration measurements with sub-nm accuracy.**
3. **Test and characterize active and passive stabilization equipment.**
4. **Predict luminosity stability for the CLIC complex.**

*Connected tasks:*

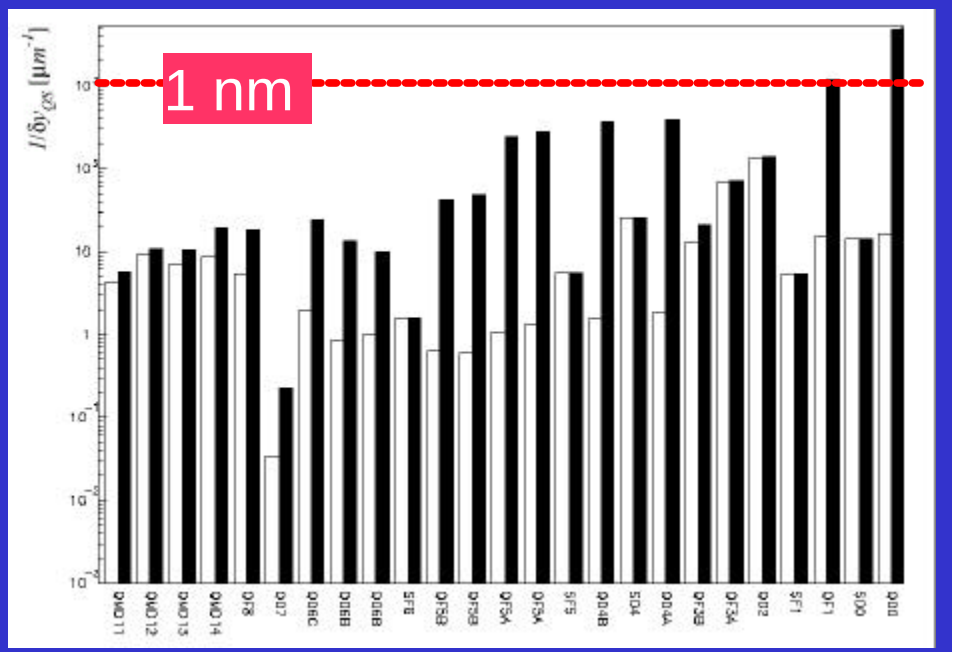
- Adapt solutions to the actual quadrupole designs (help from LHC)
- Test and characterize eventual prototype magnet
- Understand magnetic versus mechanical stability of quadrupole center (help from FNAL)
- Adapt solutions to the requirements of the physics detector (CLIC physics study group)
- Set-up advanced simulation tools for luminosity stability

# Vibration sensitivity

***Baseline optics***




***Compact "Raimondi" optics***



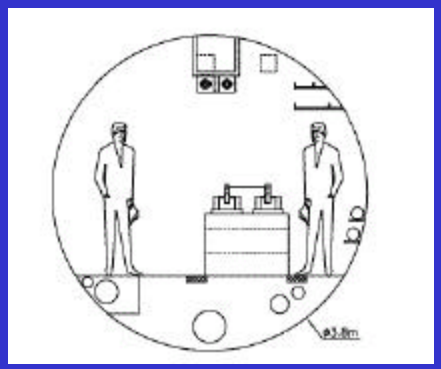

Vertical displacement sensitivities corresponding to a 2% luminosity loss (FFADA, S. Fartoukh)

Full bars: Pulse-to-pulse `jitter' tolerances, due to both the IP orbit motion and IP spot-size increase.

Open bars: `Drift' tolerances referring only to increases in the IP beam size.

# Stabilization requirements

**Two types of quadrupoles in two different sub-systems:**



**Type 1:** **Linac quadrupoles**

Number: 1300 times two

Field: 200 T/m

Transverse size: 0.15 × 0.11 m × height)

Length: 0.46 – 2.08 m

Weight: 69 – 312 kg (+ 20% supports)

Goal: **1.3 nm (vertical)** rms uncorrelated motion **above 4 Hz**

**Type 2:** **Final Focus quadrupoles (short or standard solution)**

Number: 2/4

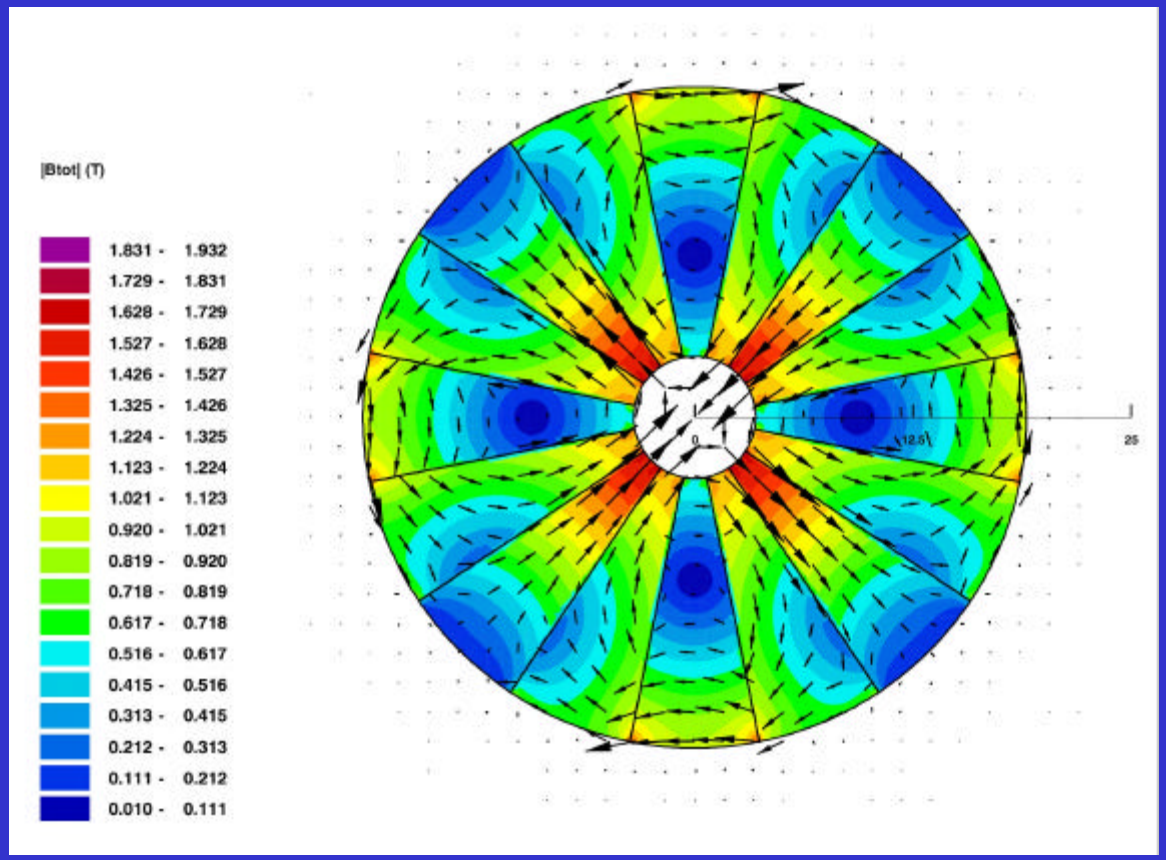
Field: 388 or 450 T/m

Transverse size: 4.3 or 2.0 cm (outer radius)

Length: 3.50 or 4.75 m

Weight: 250 or 50 kg (+ 20% supports)

# Studies on Final Quadrupole



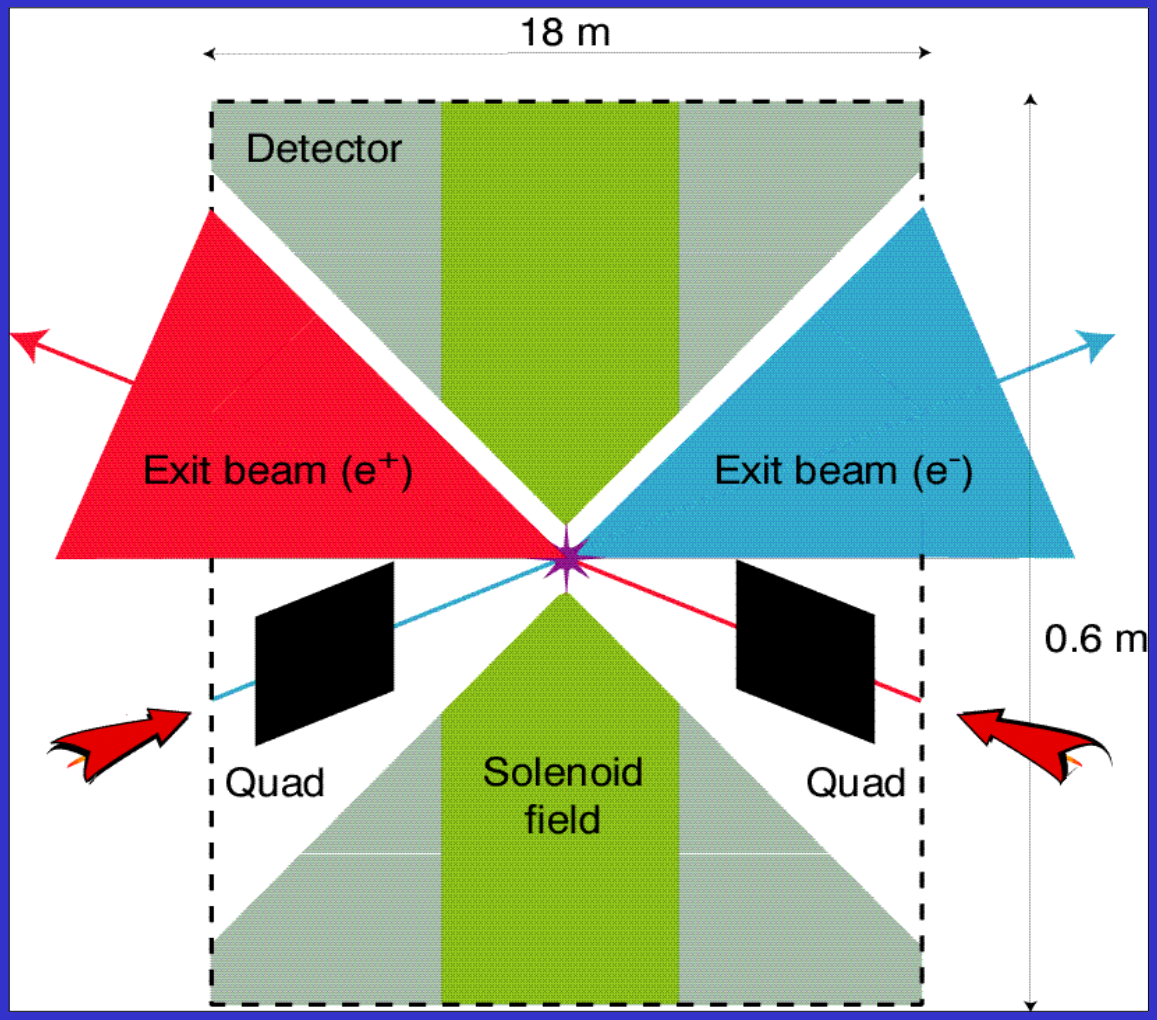

M. Aleksa
S. Russenschuck

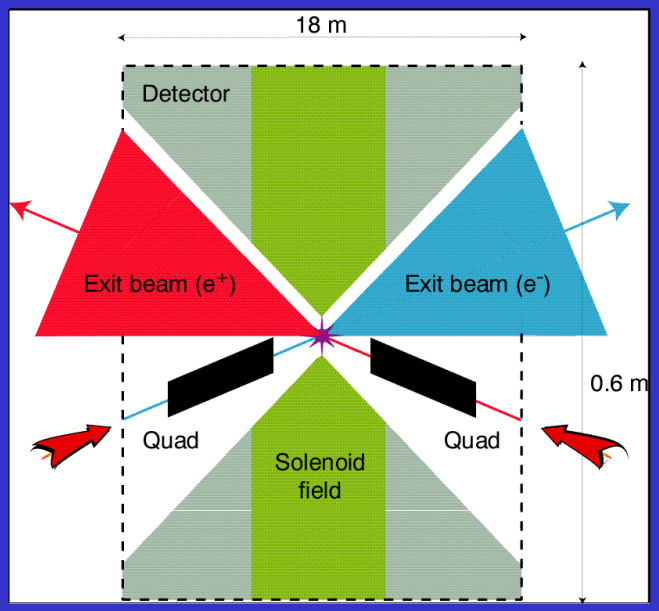
Cross section of the final focusing quadrupole.

G=468 T/m for the permanent magnet material VACOMAX 225HR $Sm_2Co_{17}$ (coercitivity of 820 kA/m).

Issues of radiation, beam loss heating, solenoid are being studied

# IP environment



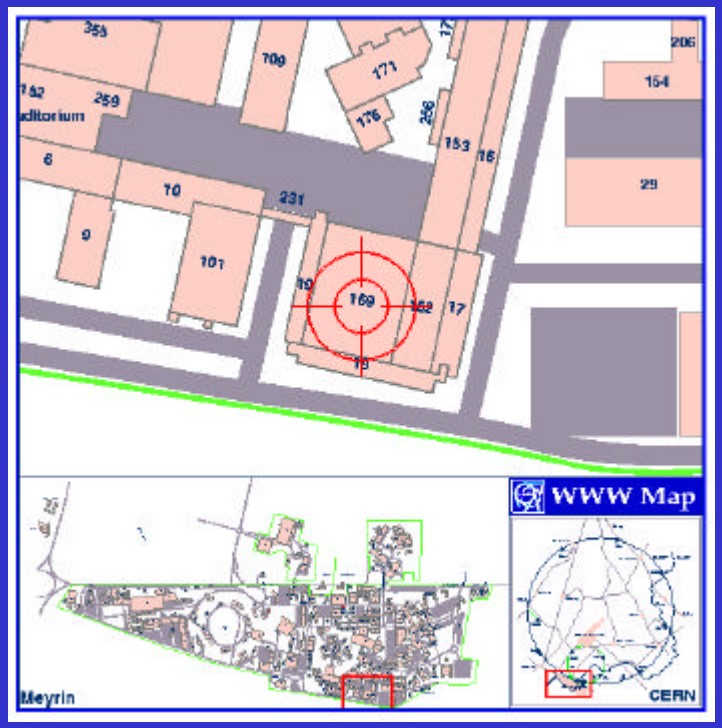

Standard FF

Short FF

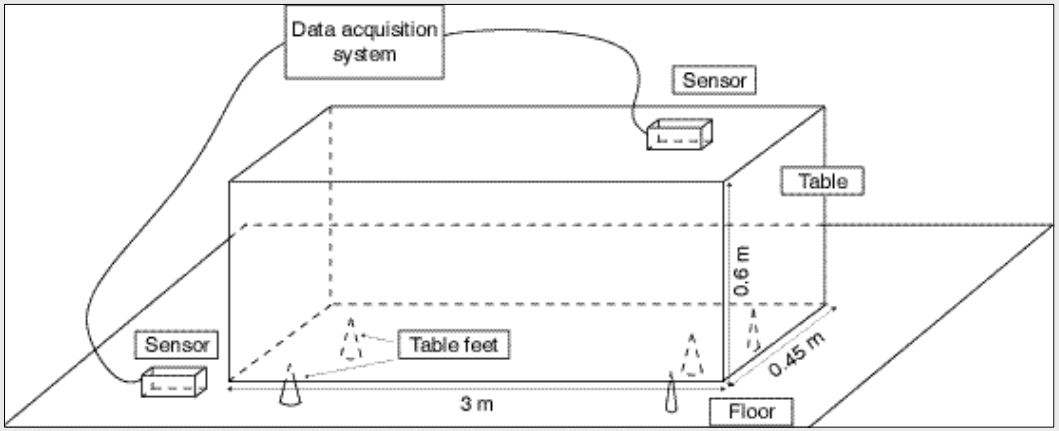
IP issues: Magnet support. Fast Feedback. Crab cavity.

# Vibration measurements with sub-nanometer accuracy

(***S. Redaelli***, *N. Leros, W. Coosemans, R. Assmann)*




## Experimental set-up:

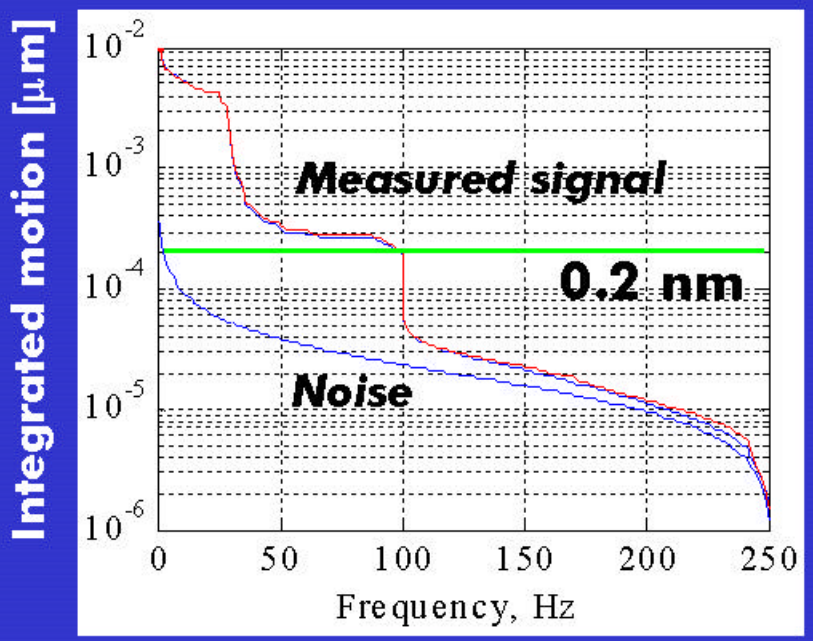


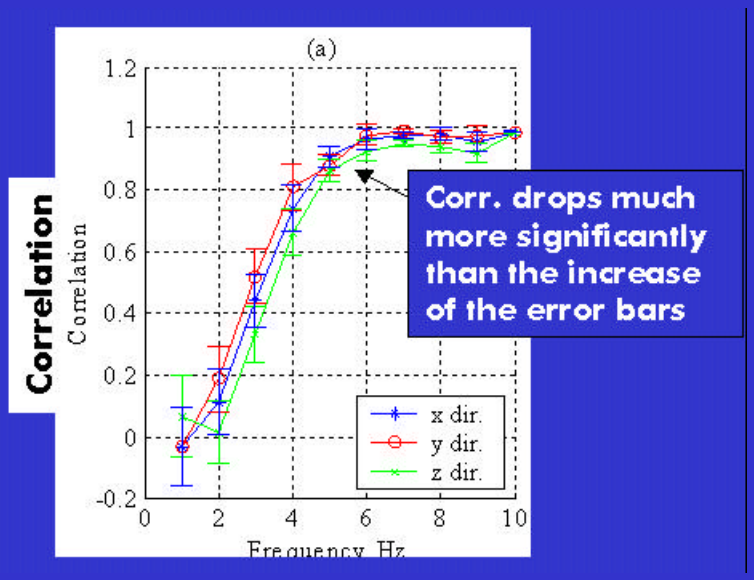

Location:

Not too quiet, not to noisy!

| | |
|---|---|
| Instrument Type: | ***Digital grade long travel geo-phones*** |
| Company: | GeoSig |
| Model: | Velocity sensor GSV-310 |
| Full scale range: | ± 1 mm/s |
| Dynamic Range: | > 96 dB or better |
| Resolution: | 15.3 nm/s |
| Linearity: | < 0.3 % of full scale |
| Cross Axis Sensitivity: | < 0.1 % of full scale |
| Frequency Response: | 1 to 315 Hz |
| Damping: | standard 0.7 |
| Weight: | 0.8 kg |
| Package Size: | 63 x 63 x 140 mm |

# Measurements




*(**S. Redaelli**, N. Leros, W. Coosemans, R. Assmann)*

Analysis tools developed

Measurements taken

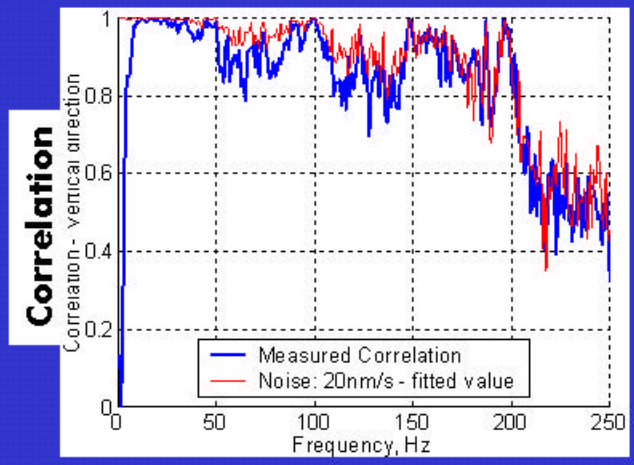
Noise level determined

Noise level ~low enough for sub-nm resolution

Absolute accuracy still to be determined

Measured vibration above tolerance

Work on stabilization at lower frequencies




Now: Starting to get stabilization equipment + work on simulation of luminosity performance

# Outline

1 Introduction

2 Optics & Tools

3 Performance

4 Collimation Issues

5 Stability Issues in the IP

6 Conclusions

# Conclusions

- Two optical solutions (/afs/cern.ch/eng/clic/3tev/OPTICS )
- Sixtrack90 and MAD for tracking. Sixtrack90 computes aberrations of arbitrary order; also SR now treated.
- Compact system (P. Raimondi) provides larger $l^*$, a wider momentum bandwidth, and reduced beam tails.
- Tunability, tolerances and luminosity comparable to baseline.
- Horizontal collimation depth is reduced by about a factor of two due to increased $l^*$ and dispersion across the final doublet.
- First design of 3-TeV CLIC beam delivery system, ~6 km long.
- Wakefields look acceptable.
- Stability requirements reviewed and stability study started. Vibration test stand at CERN. Apply latest stabilization tech.
- Magnet design work started.
- Still many open questions. Work is ongoing...

# 26th Advanced ICFA Beam Dynamics Workshop on Nanometre-Size Colliding Particle Beams

CERN, September 2002

Amongst other topics, address many stability issues!

## Where is the limit?

Hope for input from colleagues in our field and from other fields. Can we give a limit?

Please contact R. Assmann or F. Zimmermann if you have ideas, input, special requests!

Geneva, June 28th, 2001

**The 26th Advanced ICFA Beam Dynamics Workshop on Nanometre-Size Colliding Particle Beams**

***First Announcement:***

The spot size at the interaction points of future linear colliders can approach nanometre values, because the beam-beam limit from circular colliders does not apply for single-passage collisions. The design values for the vertical spot size range from 5 nm for the 500 GeV TESLA design to 1 nm for the 3 TeV CLIC study. Those small spot sizes are a factor 100-1000 beyond the smallest IP spot sizes achieved in previous colliders. Many issues are involved in demonstrating the feasibility of establishing and maintaining collisions of nanometer size beams.

The ICFA workshop on Nanometre-Size Colliding Beams in Future Linear Colliders will review and study the different aspects of the problems involved in demonstrating the feasibility of those small spot sizes. In particular the following *issues* will be discussed:

- Design of appropriate Final Focus Systems and comparison of different design approaches.
- Impact of ground motion, magnet vibration, and field fluctuations on the luminosity performance.
- Design and optimization of required Final-Focus magnets.
- Possible benefits of beam-based feedbacks and modern stabilization technology.
- Design and verification of conventional or advanced collimation sections.
- Estimation of expected background levels and the interface to the physics detector.
- Challenges connected to the handling of the spent beam and beam dump.
- Required beam instrumentation and component alignment.
- Unconventional focusing techniques.

The following *goals* should guide the workshop:

- Describe a path towards proving feasibility of colliding nanometre-size beams.
- Document existing solutions and identify open questions.
- Develop a coherent program for future research and development.
- Strengthen and expand international collaborations for this work.

We plan to organize this workshop in the first week of September 2002 at the European Organization for Nuclear Research, CERN, in Geneva, Switzerland.

Dr. Ralph Assmann and Dr. Frank Zimmermann, CERN