Linear Colliders
Lecture 3
Subsystems II

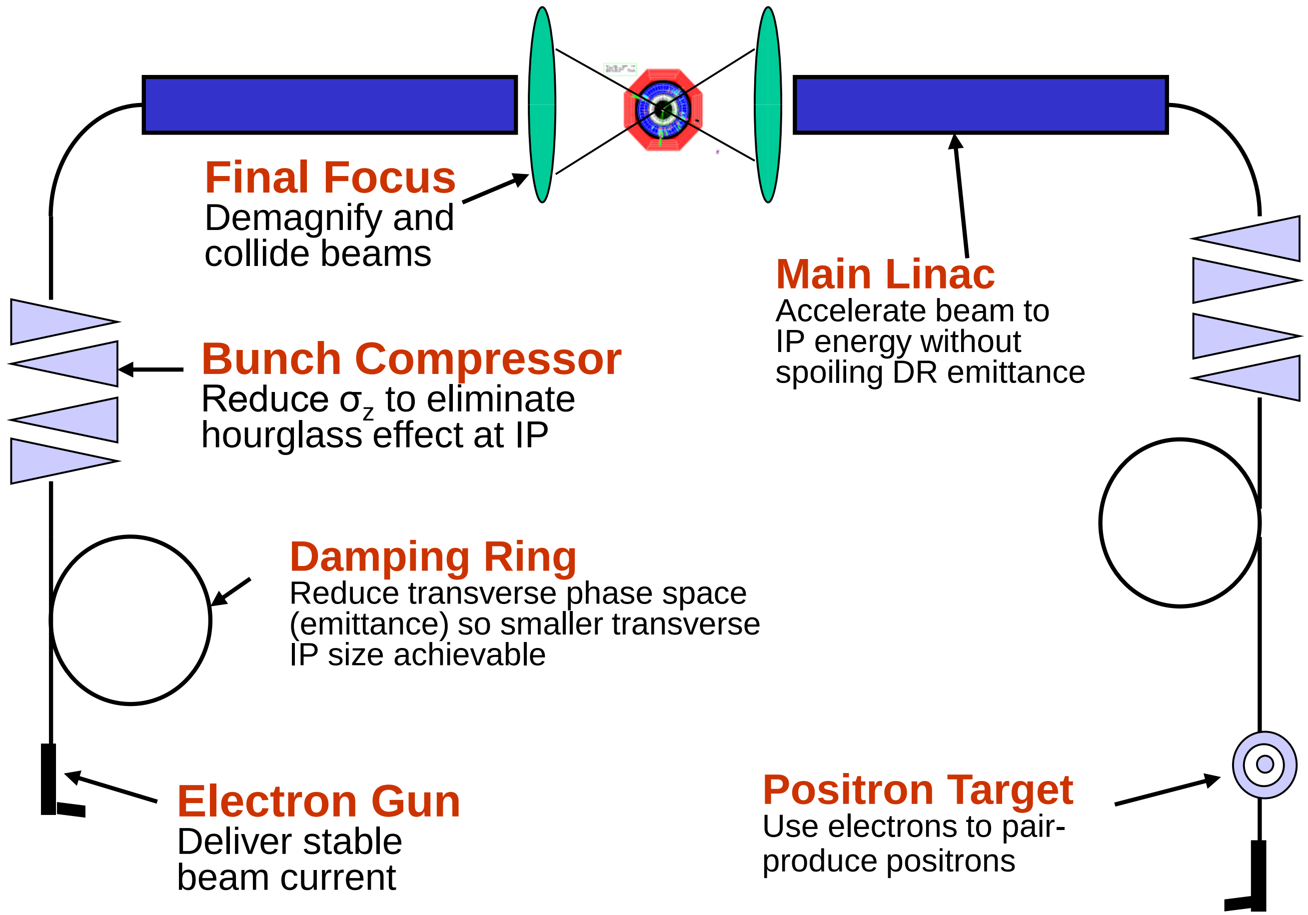
Frank Tecker – CERN

- Main Linac (cont.)
  - RF system and technology
  - Accelerating gradient
- Beam Delivery System
- Alignment and Stabilization

Last Lecture

- Particle production
- Damping rings with wiggler magnets
- Bunch compressor with magnetic chicane

⇒ small, short bunches to be accelerated w/o emittance blowup



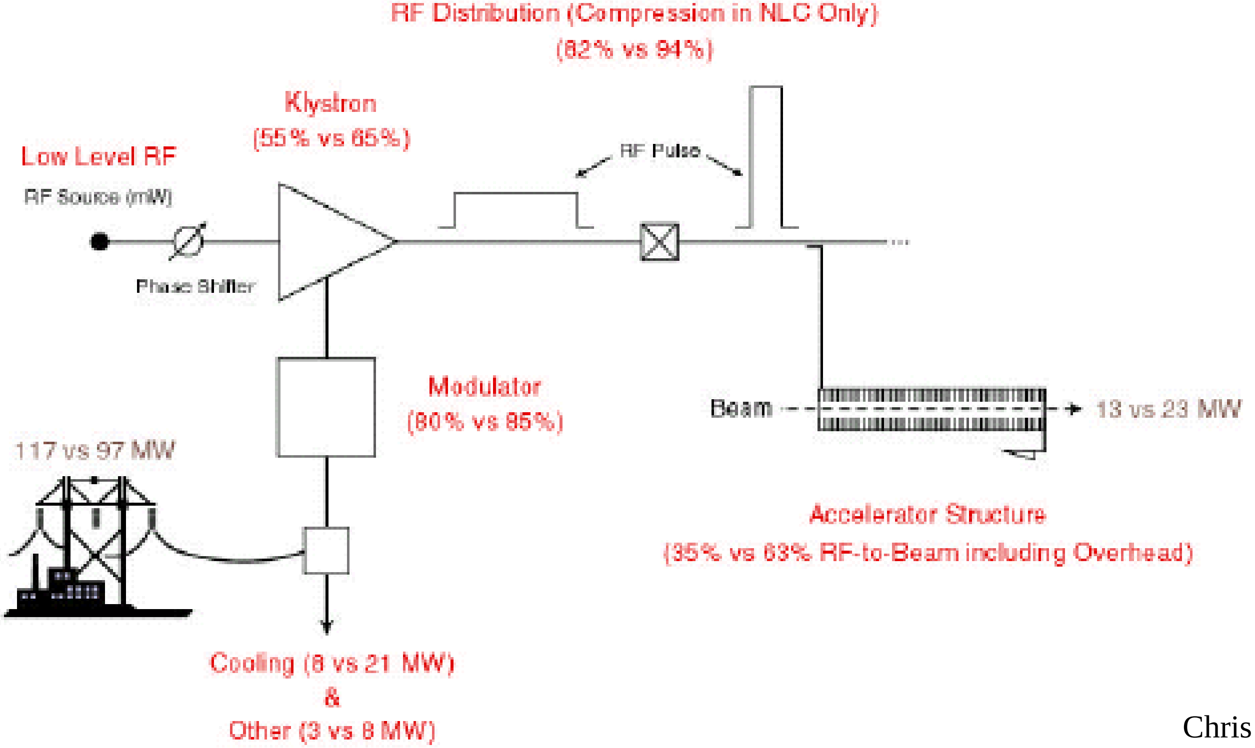
- Main linac: longitudinal wakefields cause energy spread

  => Chromatic effects

- Long-range (multi-bunch) wakefields are minimized by structure design

RF systems

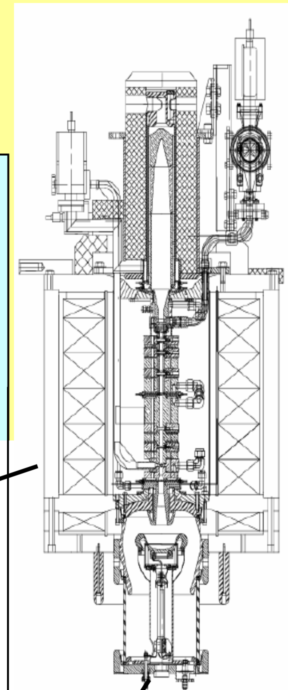
- Need efficient acceleration in main linac
- 4 primary components:
  - Modulators: convert line AC → pulsed DC for klystrons
  - Klystrons: convert DC → RF at given frequency
  - RF distribution: transport RF power → accelerating structures evtl. RF pulse compression
  - Accelerating structures: transfer RF power → beam



Chris Adolphsen

RF systems

Klystron



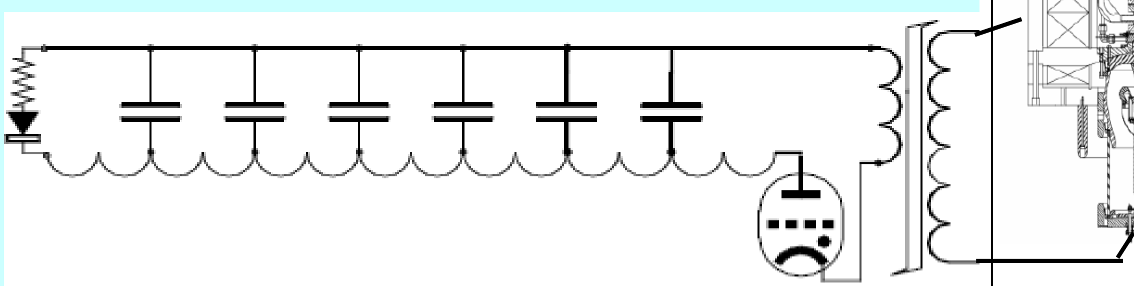
U 150 -500 kV
I 100 -500 A
f 0.2 -20 GHz

P_{ave} < 1.5 MW
P_{peak} < 150 MW

efficiency 40-70%

Modulator

Energy storage in capacitors
charged up to 20-50 kV (between pulses)



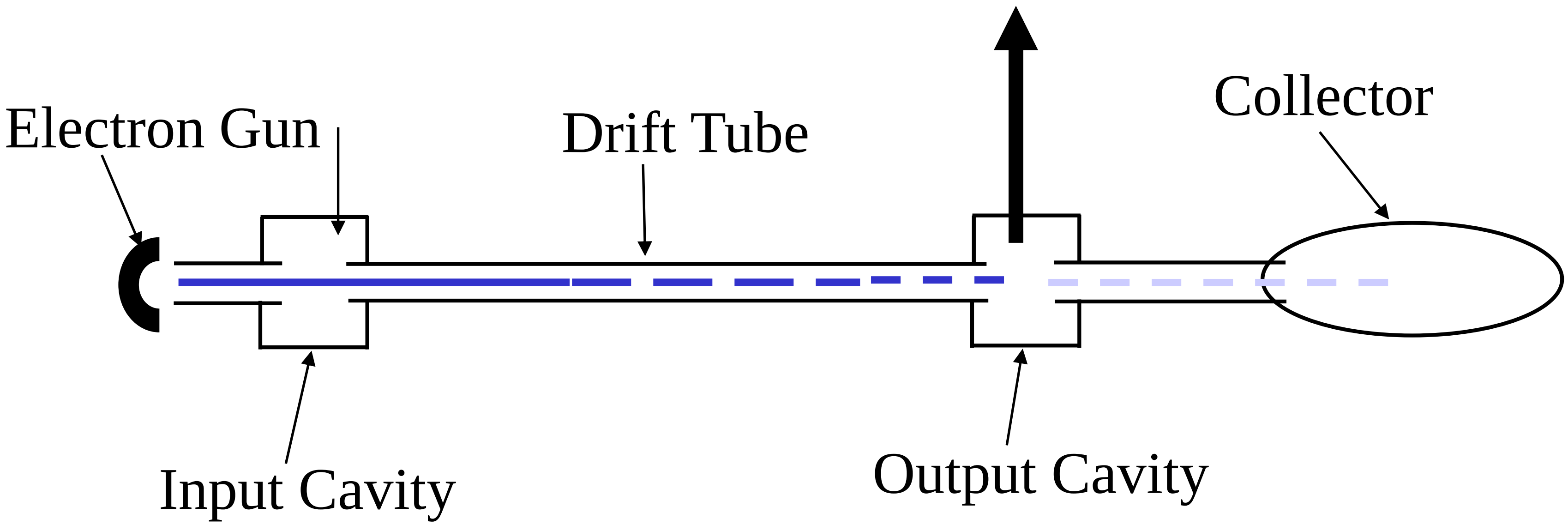
High voltage switching and
voltage transformer
rise time > 300 ns

Or solid state device

=> ***for power efficient operation***
pulse length t_P >> 300 ns favourable

Klystrons

- narrow-band vacuum-tube amplifier at microwave frequencies (an electron-beam device).
- low-power signal at the design frequency excites input cavity
- Velocity modulation becomes time modulation in the drift tube
- Bunched beam excites output cavity



RF efficiency: cavities

- Fields established after cavity filling time
- Only then the beam pulse can start
- Steady state: power to
  beam, cavity losses, and (for TW) output coupler

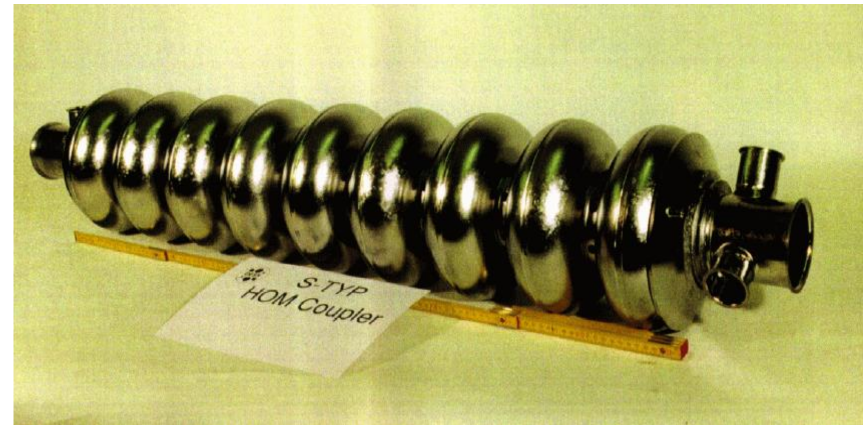
- Efficiency:

$$\eta_{RF \to beam} = \underbrace{\frac{P_{beam}}{P_{beam} + P_{loss} + P_{out}}}_{\approx 1 \text{ for SC SW cavities}} \frac{T_{beam}}{T_{fill} + T_{beam}}$$

- NC TW cavities have smaller fill time T_{fill}

SC Technology

- In the past, SC gradient typically 5 MV/m and expensive cryogenic equipment
- TESLA development: new material specs, new cleaning and fabrication techniques, new processing techniques
- Significant cost reduction
- Gradient substantially increased
- Electropolishing technique has reached ~35 MV/m in 9-cell cavities
- 31.5 MV/m ILC baseline
- limited by critical magnetic field, above which no superconductivity exists



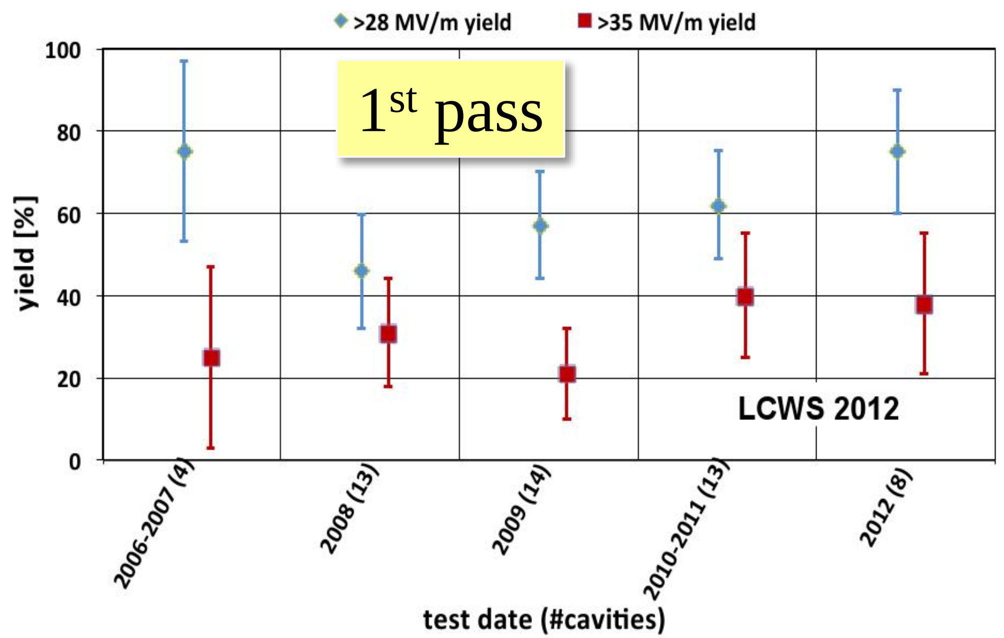
Chemical polish

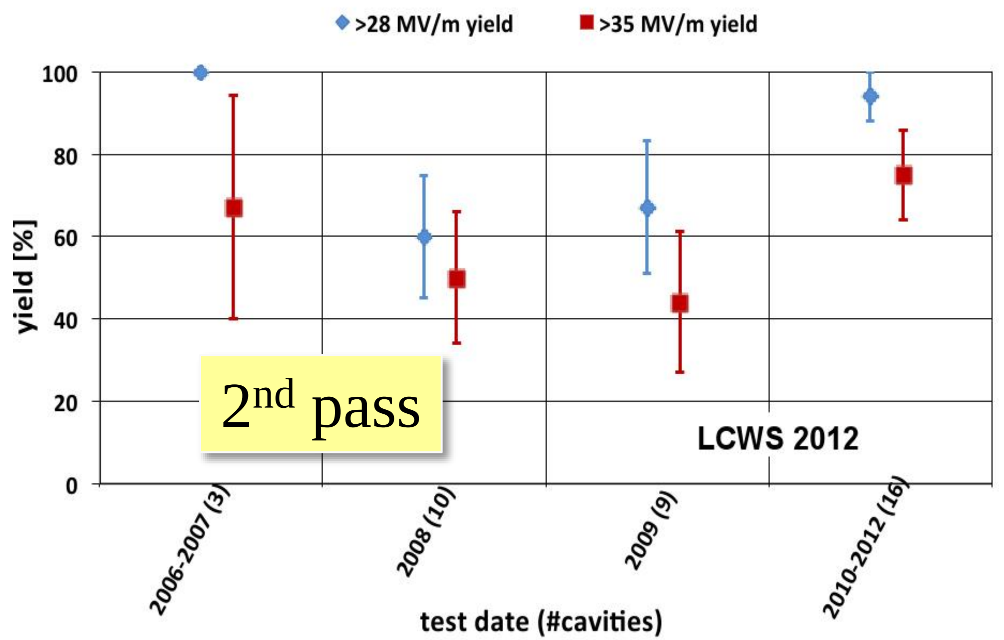
=>

Electropolishing

Achieved SC accelerating gradients

- Recent progress by R&D program to systematically understand and set procedures for the production process
- reached goal for a 50% yield at 35 MV/m by the end of 2010
- 90% yield at 28 MV/m exceeded in 2012
- Tests for higher gradient ongoing
- limited certainly below 50 MV/m





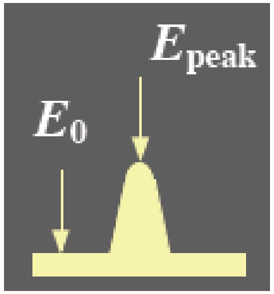
Limitations of Gradient E_{acc}

- Surface magnetic field
  - SC structures become normal conducting above H_{crit}
  - NC: Pulsed surface heating => material fatigue => cracks
- Field emission due to surface electric field
  - Vacuum arcs - RF break downs
  - Break down rate => Operation efficiency
  - Local plasma triggered by field emission => Erosion of surface
  - Dark current capture
    => Efficiency reduction, activation, detector backgrounds
- RF power flow
  - RF power flow and/or iris aperture apparently have a strong impact on achievable E_{acc} and on surface erosion. Mechanism not fully understood

NC Structure conditioning

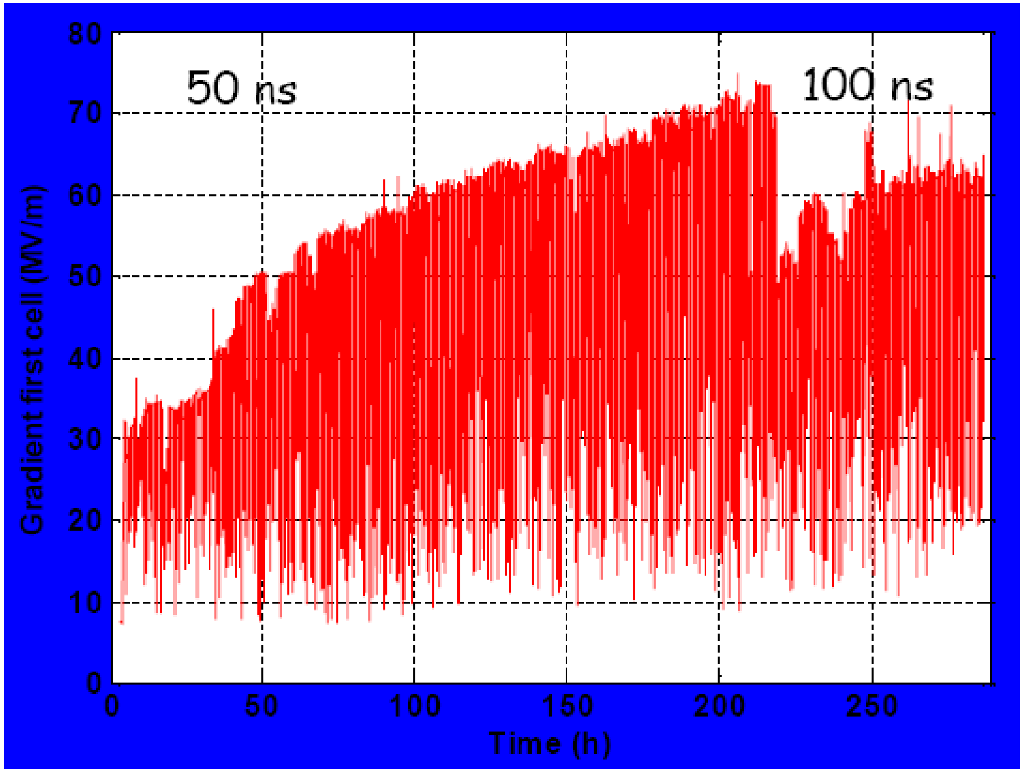
- Material surface has some intrinsic roughness (from machining)
- Leads to field enhancement
  β field enhancement factor

$$E_{\mathrm{peak}} = \beta E_0$$



- Need conditioning to reach ultimate gradient
  RF power gradually increased with time
- RF processing can melt
  field emission points
  - Surface becomes smoother
  - field enhancement reduced
  - => higher fields
    less breakdowns
- More energy: Molten surface splatters and generates new field emission points!
- Excessive fields can also damage the structures

from S.Doebert

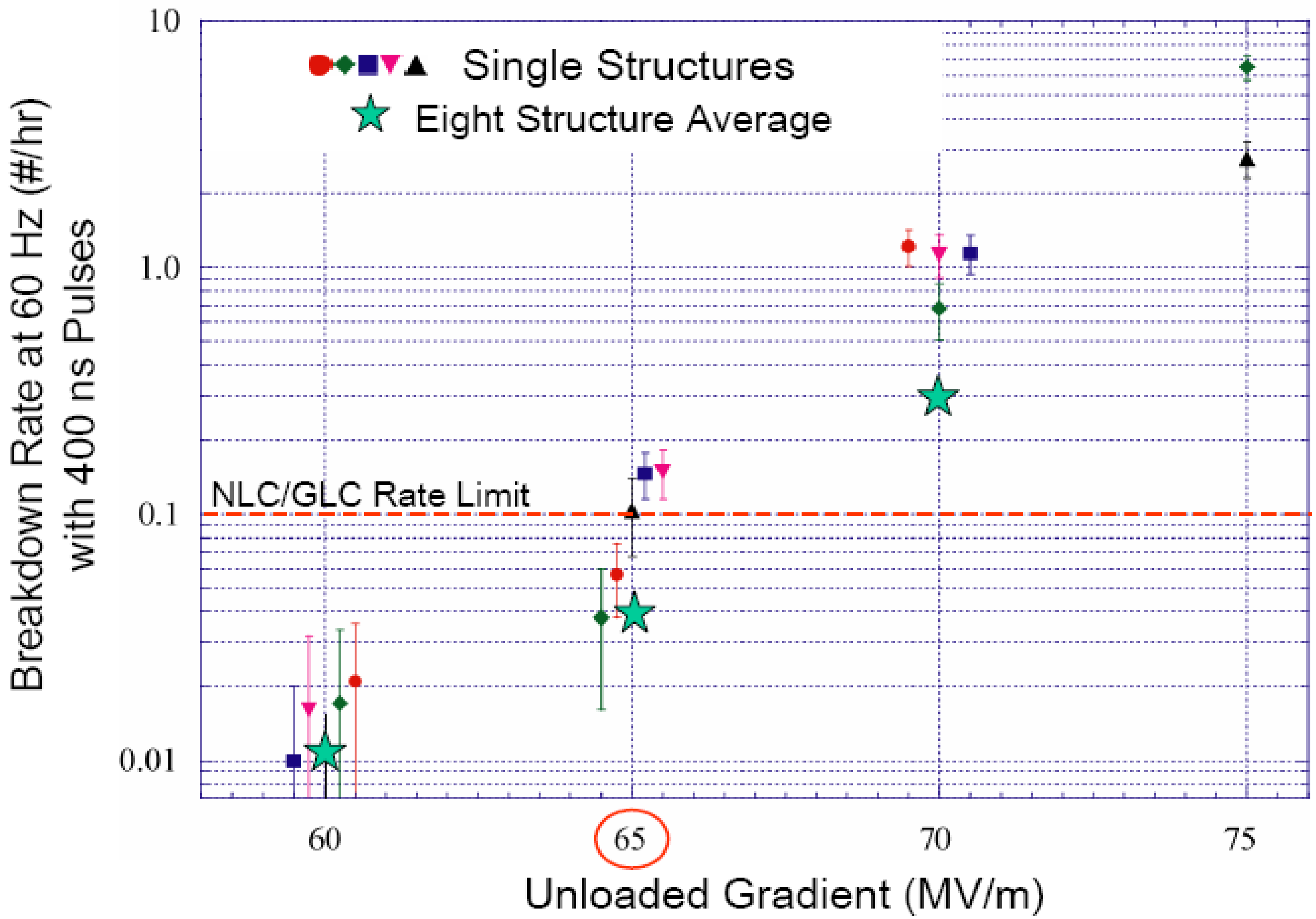


Breakdown-rate vs gradient

- Strong increase of breakdown rate for higher gradient

High Gradient Performance

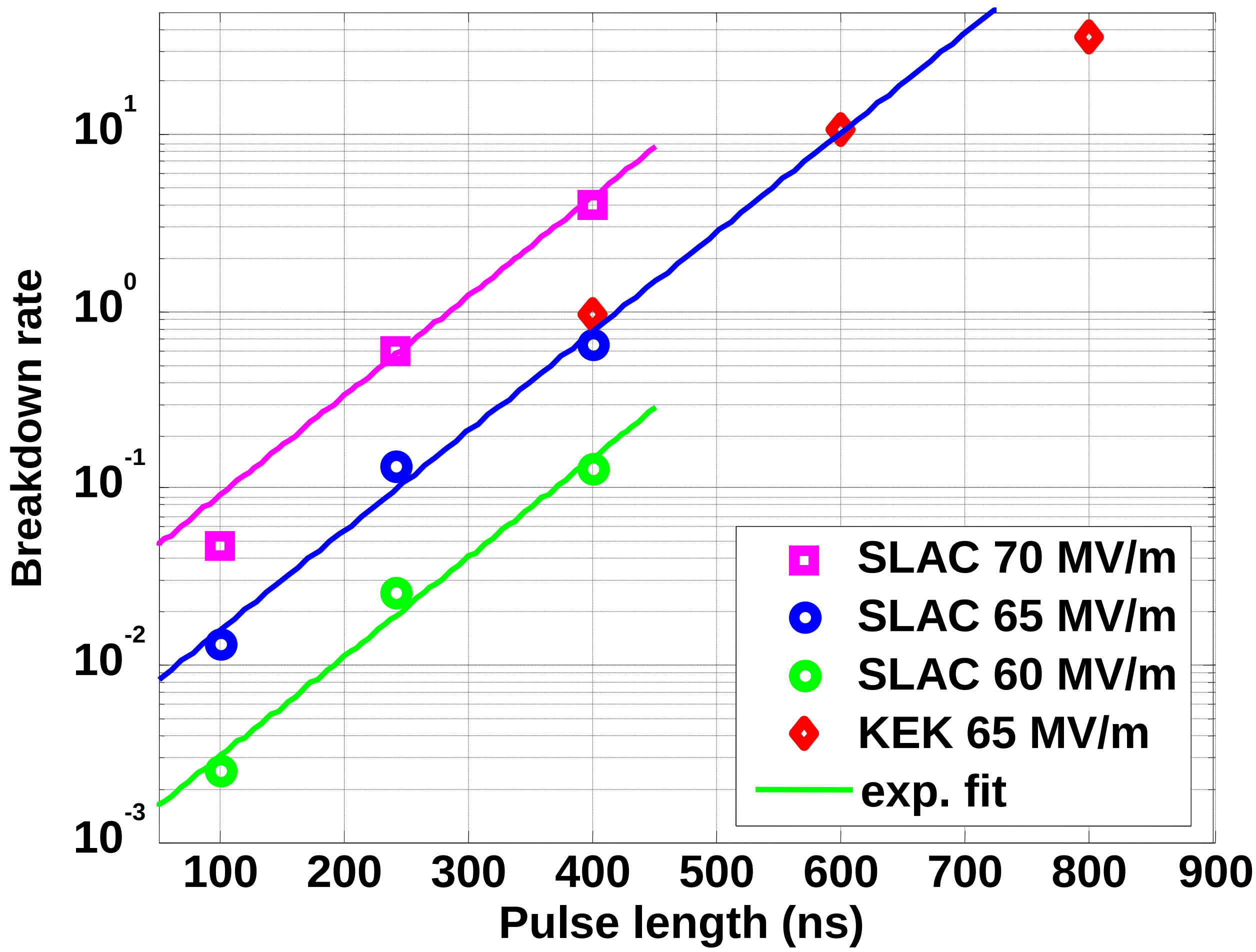
5 Structures after ~ 500 hr of Operation and
8 Structure Average after > 1500 hr of Operation



C. Adolphsen /SLAC

Breakdown-rate vs pulse length

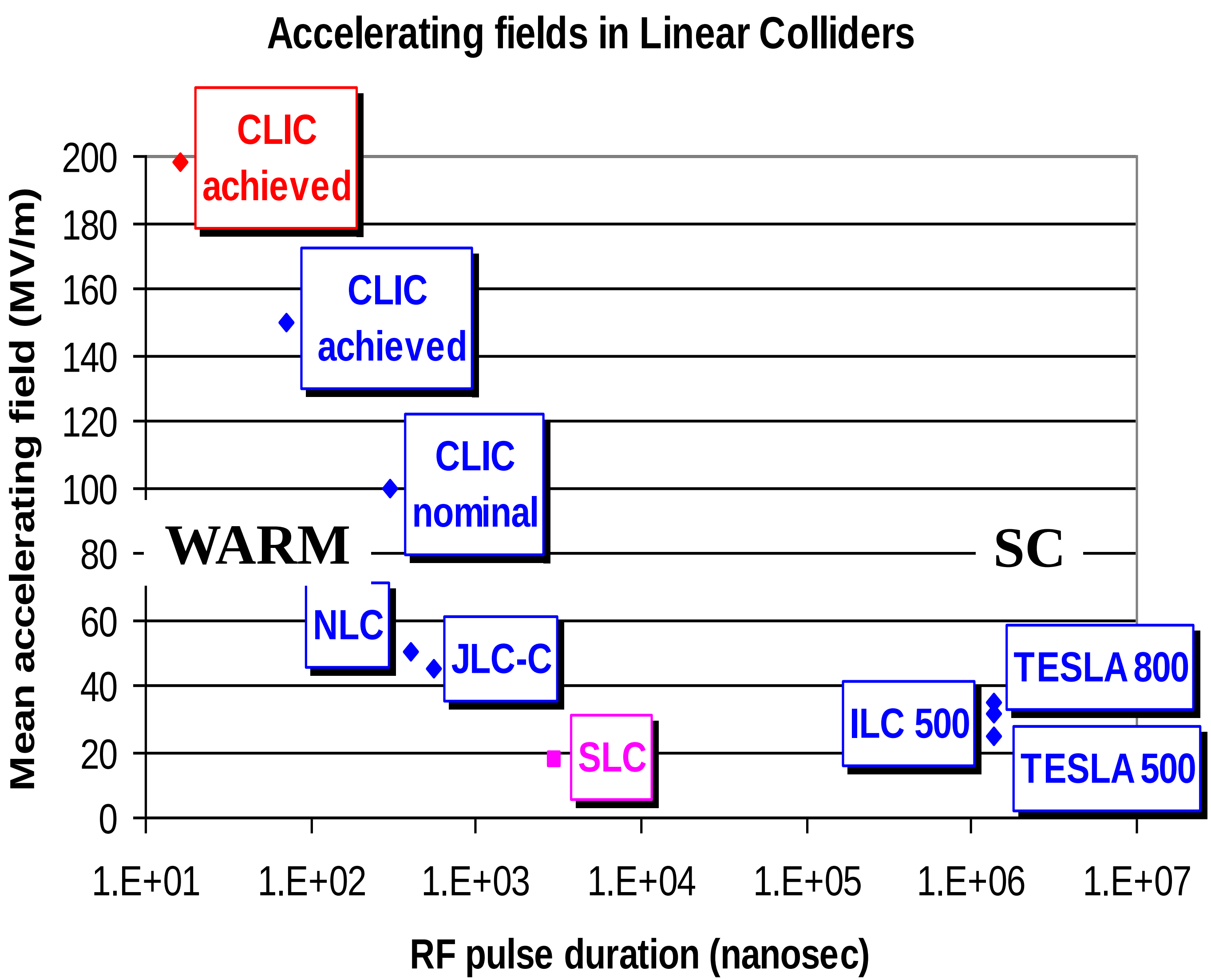
- Higher breakdown rate for longer RF pulses



- Summary: breakdown rate limits pulse length and gradient

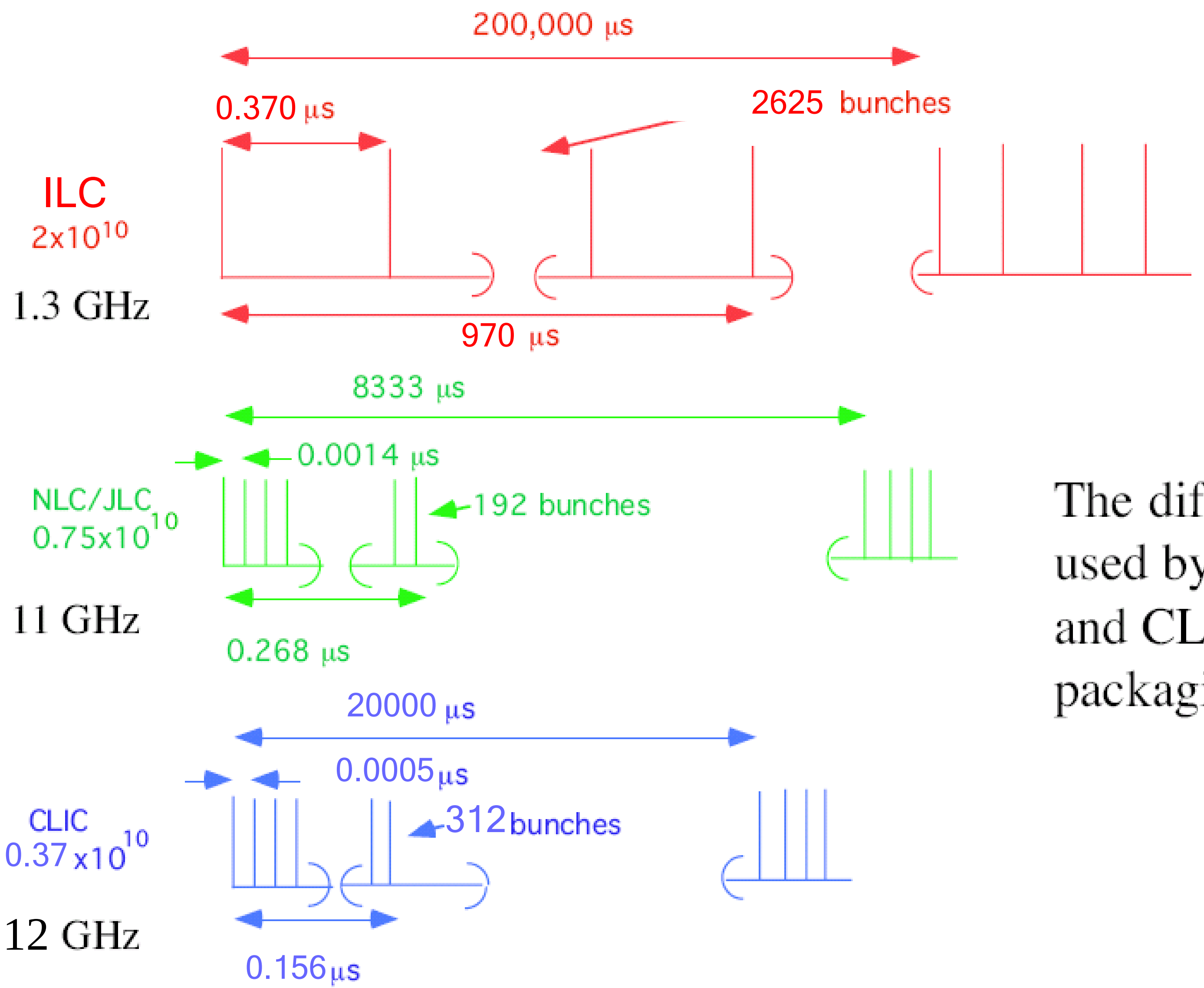
Accelerating gradient

- Normal conducting cavities have higher gradient with shorter RF pulse length
- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse



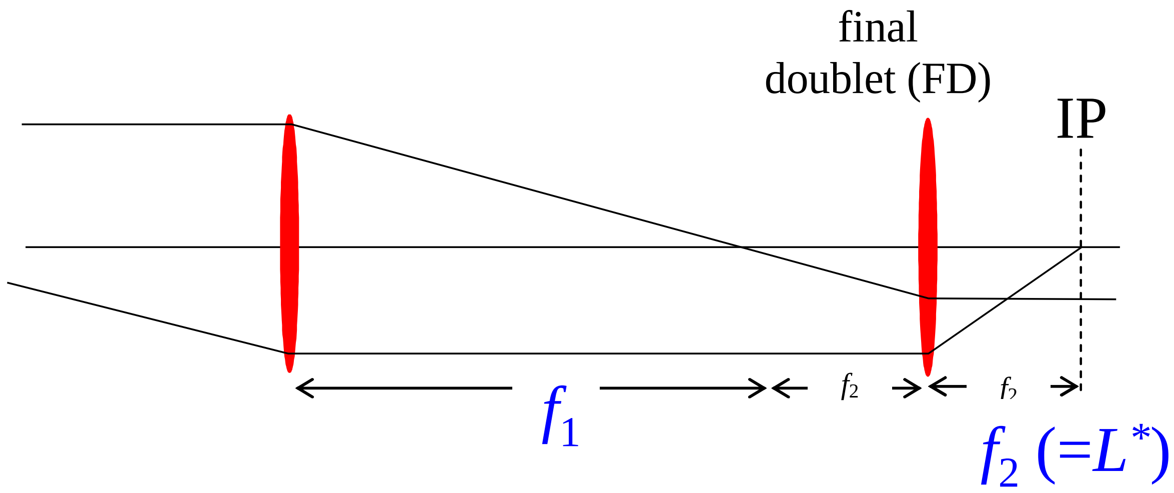
Bunch structure

- SC allows long pulse, NC needs short pulse with smaller bunch charge



The different RF technologies used by ILC, NLC/JLC and CLIC require different packaging for the beam power

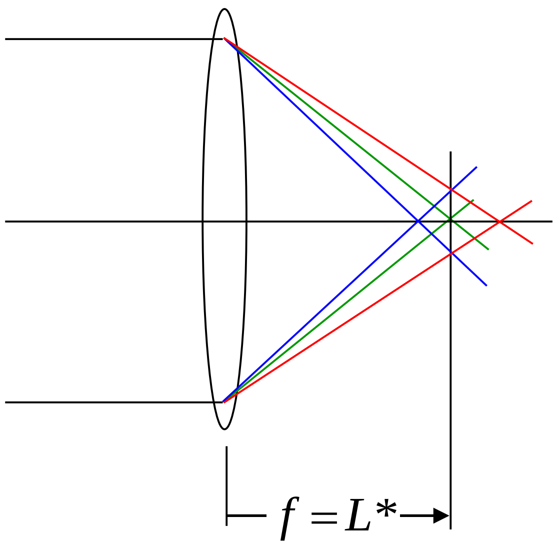
Beam Delivery: Final Focus



- Need large demagnification of the (mainly vertical) beam size
  $$M = \sqrt{\beta_{linac} / \beta_y^*} = f_1 / f_2 \quad \text{typical value} \approx 300$$
- β_y^* of the order of the bunch length σ_z (hour-glass effect)
- Need free space around the IP for physics detector
- Assume $f_2 = 2$ m => $f_1 \approx 600$ m
- Can make shorter design but this roughly sets the length scale

Final Focus: chromaticity

- Need strong quadrupole magnets for the final doublet
- Typically hundreds of Tesla/m
- Get strong chromatic aberations



for a *thin-lens* of length *l*: $$\frac{1}{f} \approx k_1 l$$

change in deflection: $$\Delta y'_{quad} \approx -k_1 l\, y_{quad} \frac{\delta}{1+\delta} \approx -k_1 l\, y_{quad}\, \delta$$

change in IP position: $$\Delta y_{IP} \approx f \Delta y'_{quad} = y_{quad}\, \delta$$

RMS spot size: $$\langle \Delta y_{IP}^2 \rangle = \langle y_{quad}^2 \rangle \langle \delta^2 \rangle = \beta_{quad}\, \varepsilon_y\, \delta_{\mathrm{rms}}^2$$

Final focus: Chromaticity

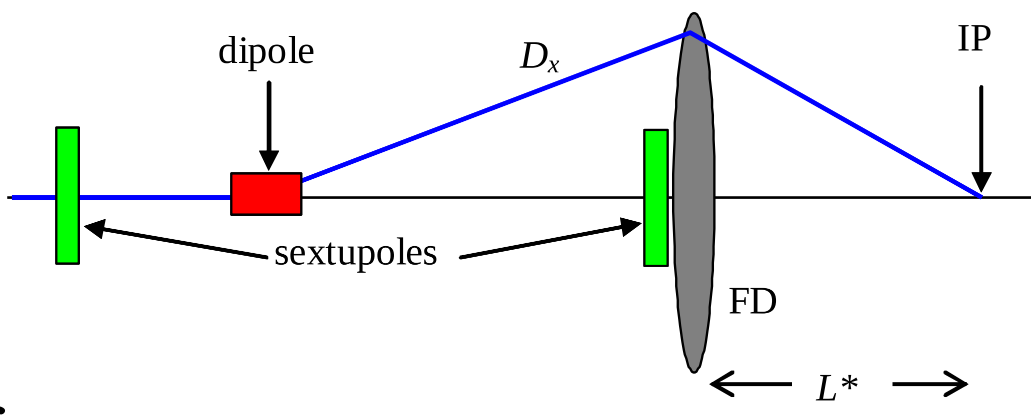
- Small β* => β_{FD} very large (~ 100 km)
- for $^{TM}_{\mathrm{rms}}$ ~ 0.3%

$$\sqrt{\left\langle \Delta y_{IP}^2 \right\rangle} \approx 20-40\ \mathrm{nm}$$

- Definitely much too large
- We need to correct chromatic effects
- => introduce sextupole magnets

$$B_x = s\,x\,y$$

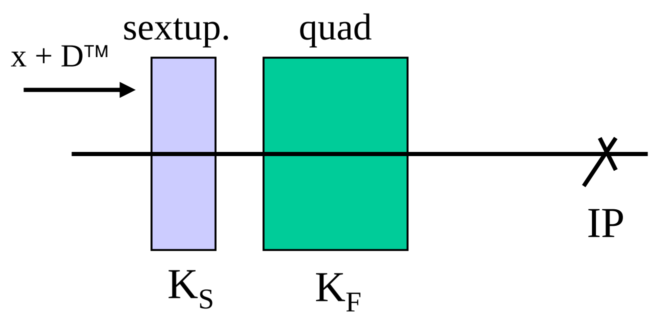
$$B_y = \frac{1}{2} s\left(x^2 + y^2\right)$$



- Use dispersion *D*: $x = x_o + D\delta$

Chromaticity correction

- Combine quadrupole with sextupole and dispersion



y plane straightforward

x plane more tricky

Second order dispersion

Quad: $$\Delta x' = \frac{K_F}{(1+\delta)}(x + D\delta) \Rightarrow K_F(-\delta x - D\delta^2)$$

chromaticity

Sextupole: $$\Delta x' = \frac{K_S}{2}(x + D\delta)^2 \Rightarrow K_S D(\delta x + \frac{D\delta^2}{2})$$

Could require $K_S = K_F/D$

=> ½ of second order dispersion left

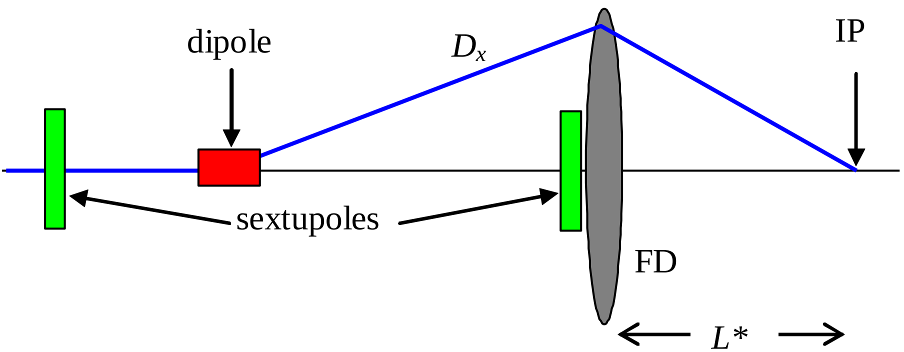
$$\Delta x' = \frac{K_F}{(1+\delta)}(x + D\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)}x \Rightarrow 2K_F(-\delta x - \frac{D\delta^2}{2})$$

Create as much chromaticity as FD upstream

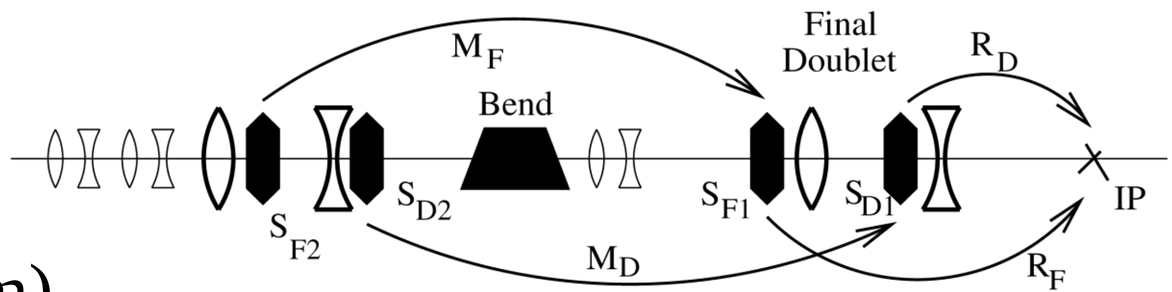
=> second order dispersion corrected

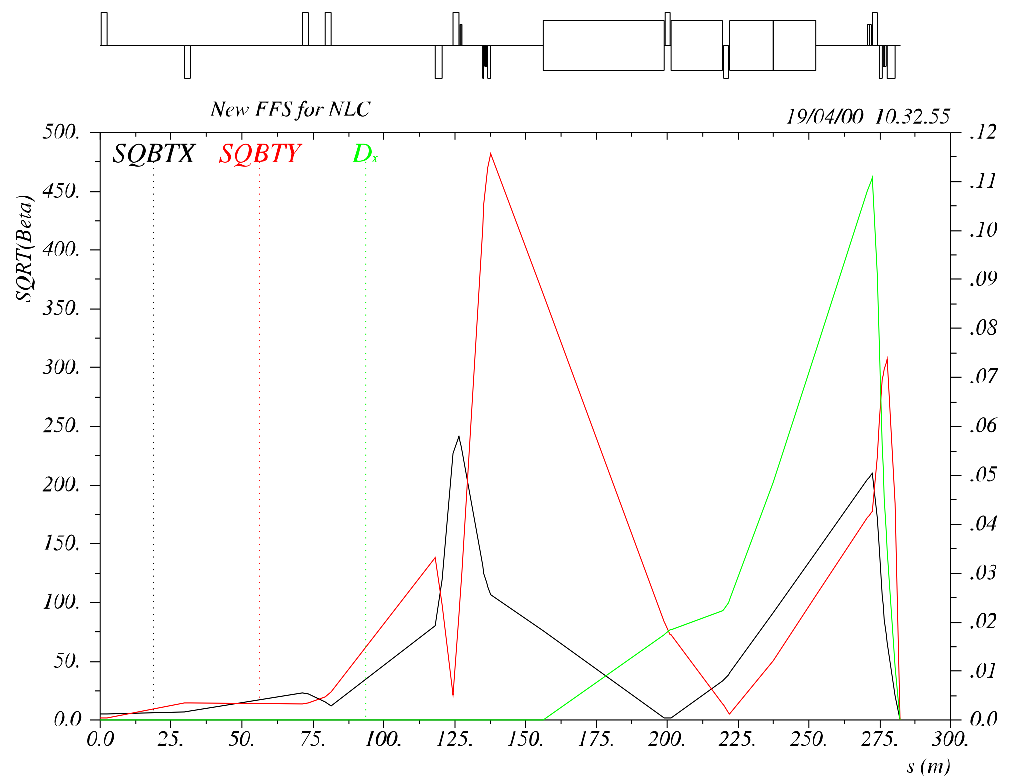
$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{D}$$

Final Focus: Chromatic Correction



Correction in both planes





- Relatively short (few 100 m)
- Local chromaticity correction
- High bandwidth (energy acceptance)

- FF tested at ATF2 (KEK Japan)
  - 44 nm achieved (37 nm design)
  - scales to 6 nm at ILC (5 nm)

Final focus: fundamental limits

- From the hour-glass effect: $\beta_y \approx \sigma_z$
- For highest energies, additional fundamental limit: synchrotron radiation in the final focusing quadrupoles => beamsize growth at the IP
- so-called *Oide Effect*:

minimum beam size: $\sigma \approx 1.83 \left(\frac{r_e \lambda_e}{2\pi} F\right)^{1/7} \varepsilon_n^{5/7}$

- for $\beta \approx 2.39 \left(\frac{r_e \lambda_e}{2\pi} F\right)^{2/7} \varepsilon_n^{3/7}$

λ_e is the Compton wavelength of the electron

F is a function of the focusing optics: typically *F* ~ 7 (minimum value ~0.1)

- $\sigma_{\text{oide}} = 0.85$ nm for 3 TeV CLIC

Stability and Alignment

- Tiny emittance beams, nm vertical beam size at collision
- => Tight component tolerances
  - Field quality
  - Alignment
- Vibration and Ground Motion issues
- Active stabilisation
- Feedback systems

- Some numbers (CLIC):
  - Cavity alignment (RMS) 17 µm
  - Main Beam quad alignment: 14 µm
  - vert. MB quad stability: 1.5 nm @>1 Hz
  - hor. MB quad stability: 5 nm @>1 Hz
  - Final quadrupole: 0.15 nm @>4 Hz !!!

Quadrupole misalignment

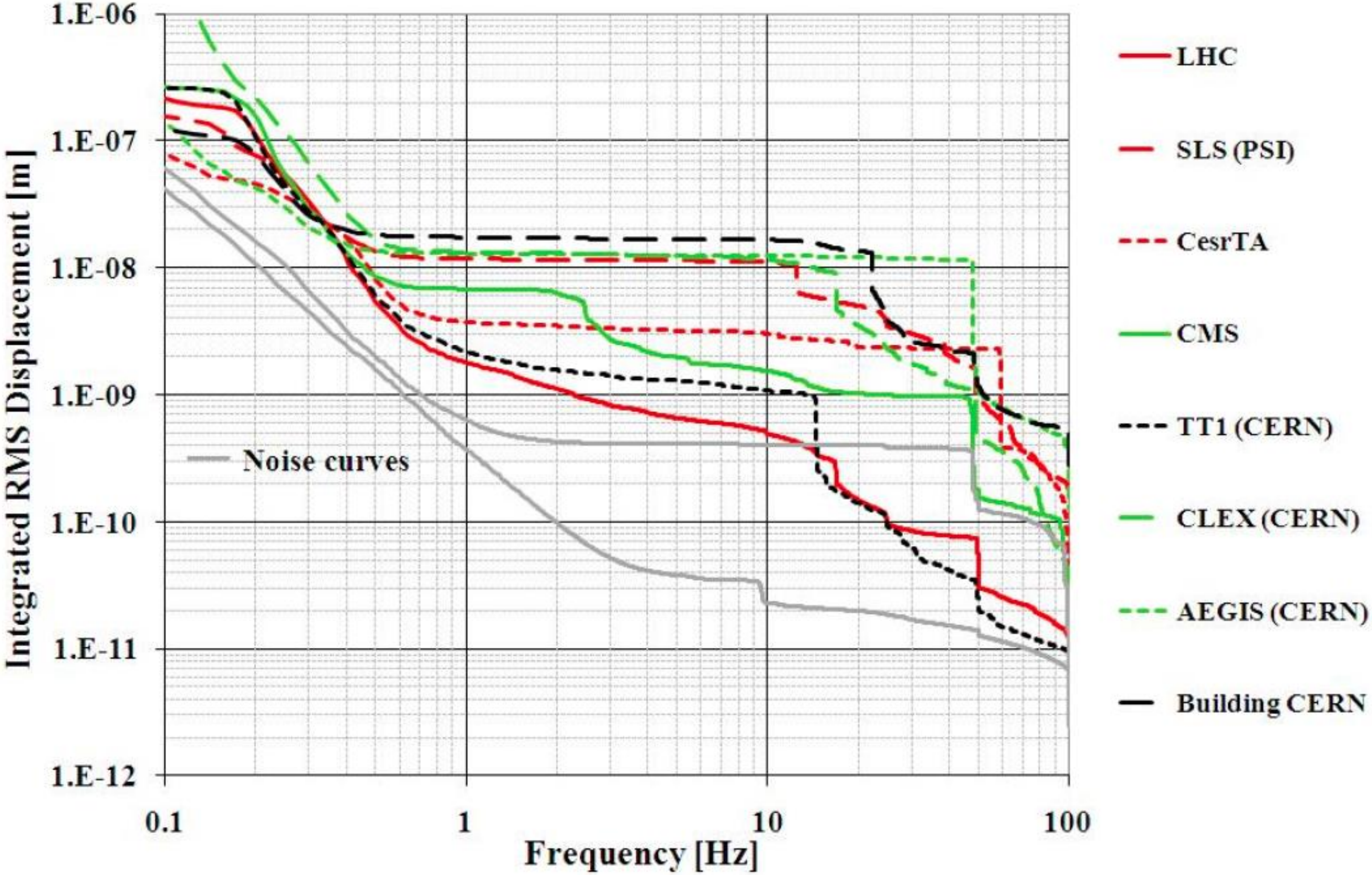
- Any quadrupole misalignment and jitter will cause orbit oscillations and displacement at the IP

$$\Delta y^{*} = \sum_{i}^{Quads} k_{Q,i} \Delta y_{Q,i} \sqrt{\frac{\gamma_i}{\gamma^{*}}} \sqrt{\beta_i \beta^{*}} \sin(\Delta\phi_i)$$

- Precise mechanical alignment not sufficient
- Beam-based alignment
- Dynamic effects of ground motion very important
- Demonstrate Luminosity performance in presence of motion

Ground Motion

- Site dependent ground motion with decreasing amplitude for higher frequencies



Ground motion: ATL law

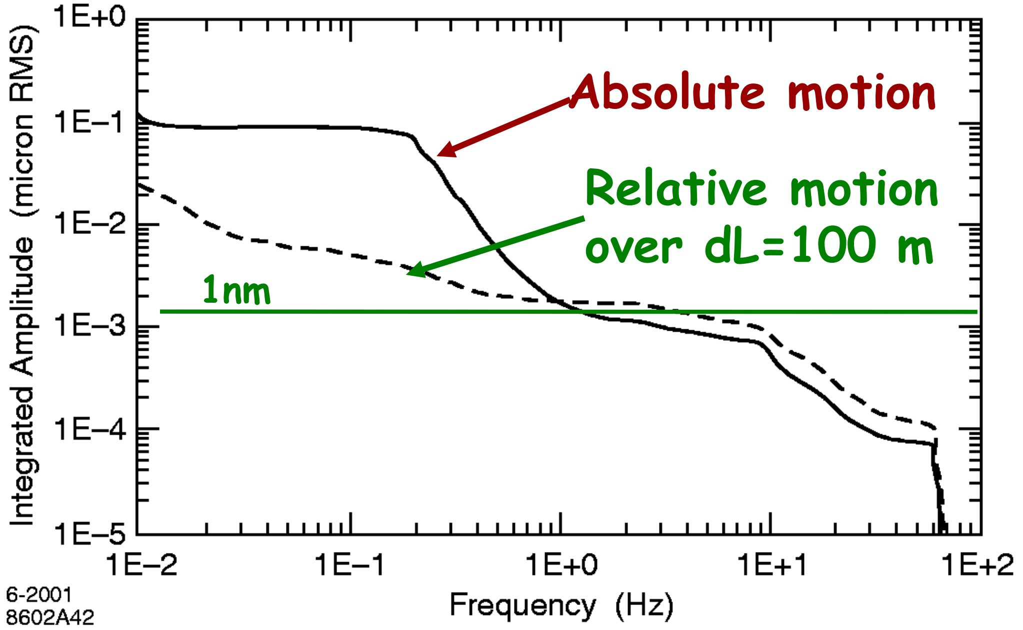
- Need to consider short and long term stability of the collider
- Ground motion model: ATL law

$$\langle \Delta y^2 \rangle = ATL$$

A site dependent constant
T time
L distance

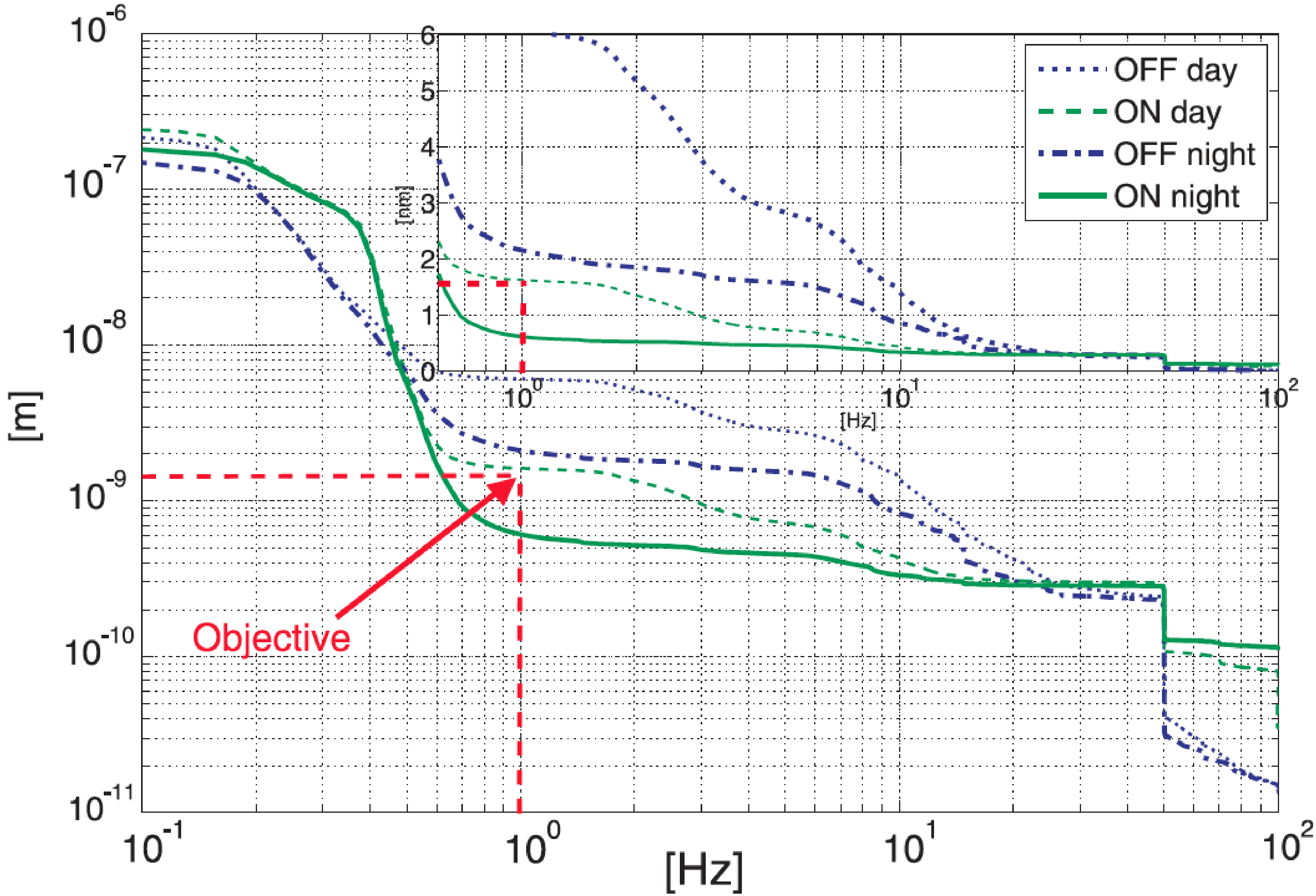
A range 10^{-5} to 10^{-7} μm^2/m/s

- This allows you to simulate ground motion effects
- Relative motion smaller
- Long range motion less disturbing



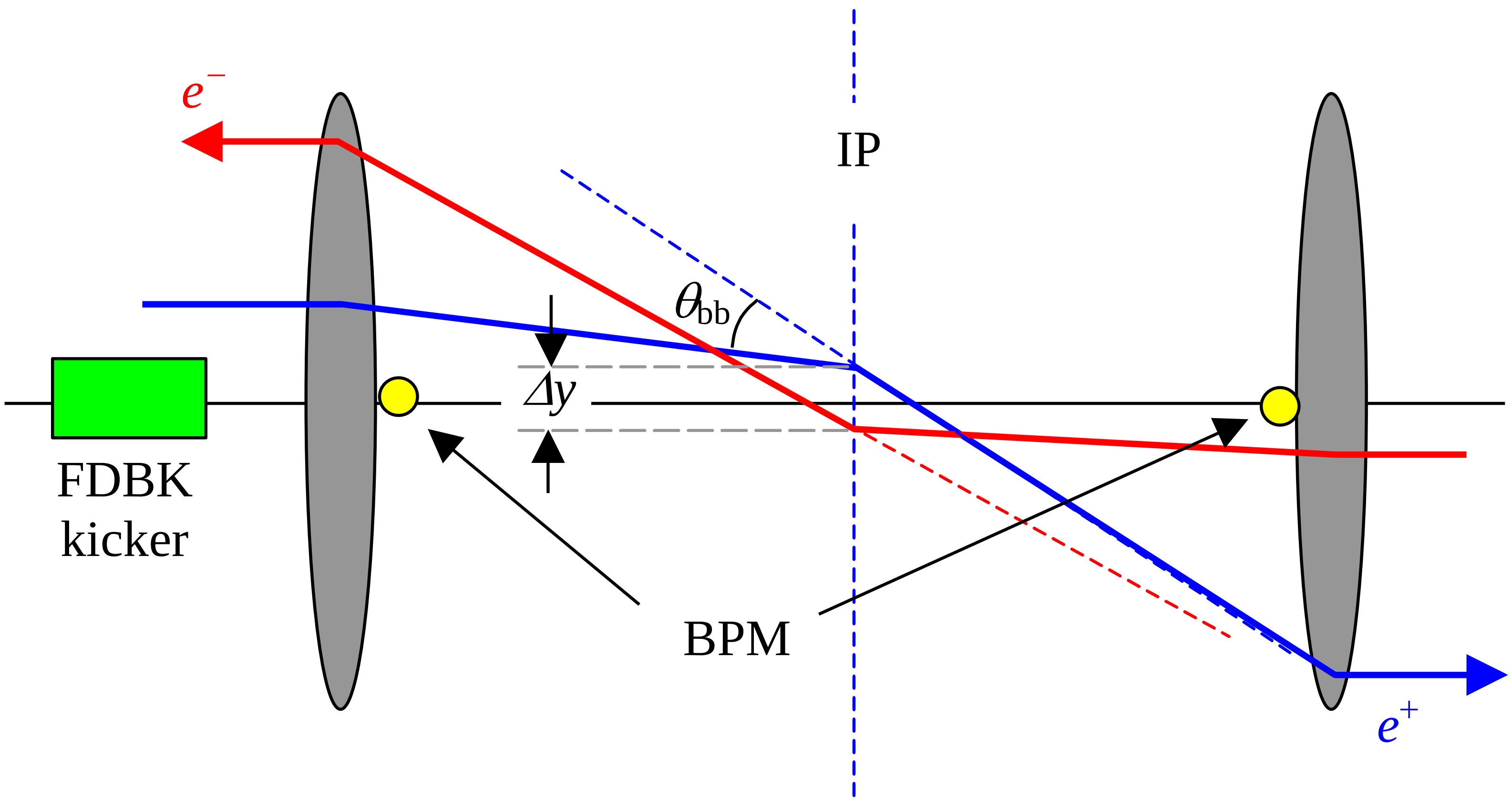
Active stabilization

- Test bench reaches required stability of CLIC MB quadrupole



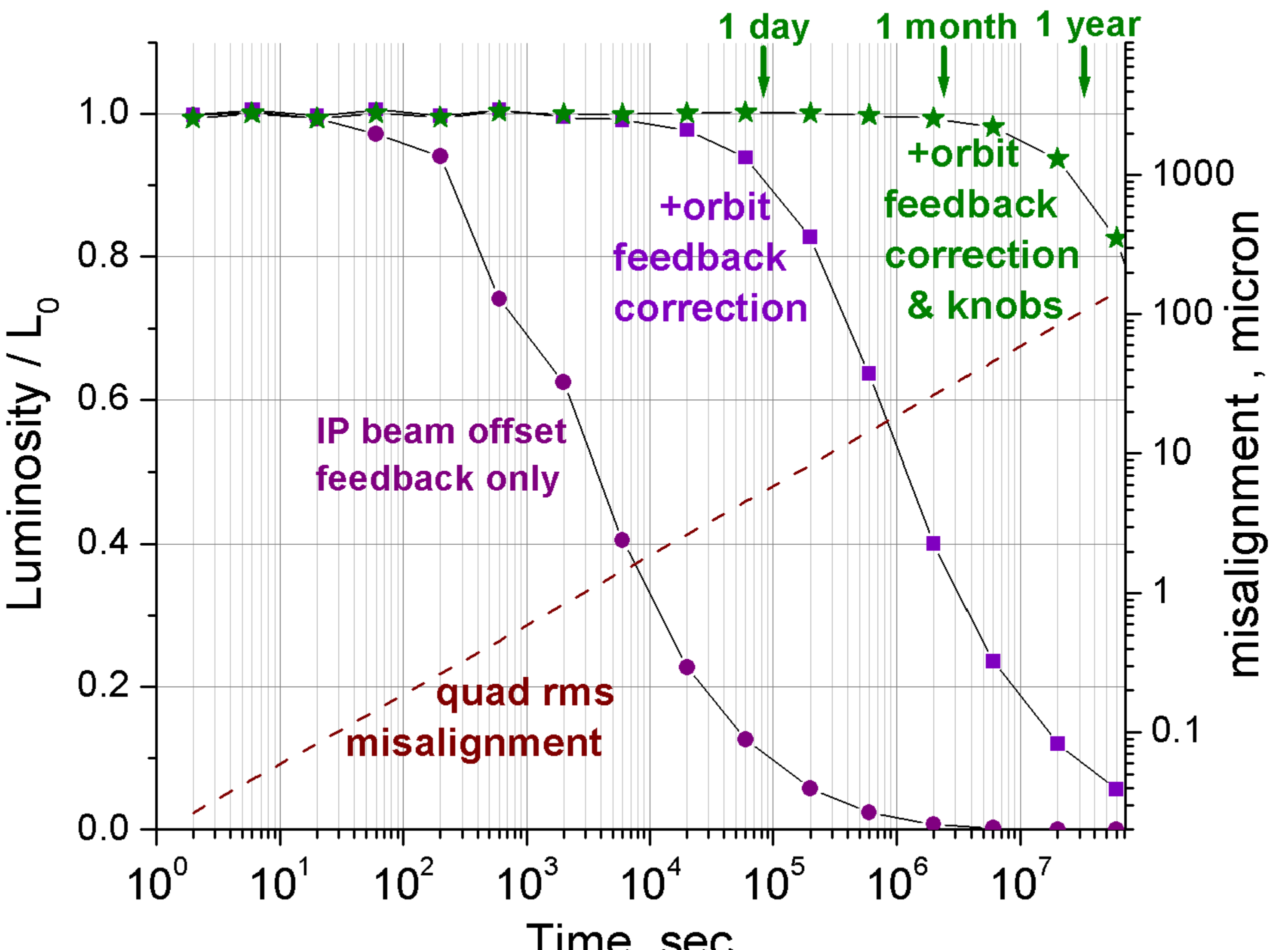
Beam-Beam feedback

- Use the strong beam-beam deflection kick for keeping beams in collision
- Sub-nm offsets at IP cause well detectable offsets (micron scale) a few meters downstream



Dynamic effects corrections

- IP feedback, orbit feedbacks can fight luminosity loss by ground motion



Other IP issues

- Collimation:
  - Beam halo will create background in detector
  - Collimation section to eliminate off-energy and off-orbit particle
  - Material and wakefield issues
- Crossing angle:
  - NC small bunch spacing requires crossing angle at IP to avoid parasitic beam-beam deflections
  - Luminosity loss (≈10% when $(= \int_x / \int_z$)
- Crab cavities
  - Introduce additional time dependent transverse kick to improve collision
- Spent beam
  - Large energy spread after collision
  - Design for spent beam line not easy

Post-Collision Line (CLIC)

R.B. Appleby, A. Ferrari, M.D. Salt and V. Ziemann, Phys. Rev. ST Accel. Beams 12 (2009) 021001.

Baseline: vertical chicane with 2x4 dipoles

1. Separation by dipole magnets of the disrupted beam, beamstrahlung photons and particles with opposite sign from coherent pairs, from low energy tails
   - → Short line to prevent the transverse beam size from growing too much
   - → Intermediate dumps and collimator systems
2. Back-bending region with dipoles to direct the beam onto the final dump
   - → Long line allowing non-colliding beam to grow to acceptable size