Linear Colliders
Lecture 3
Subsystems II

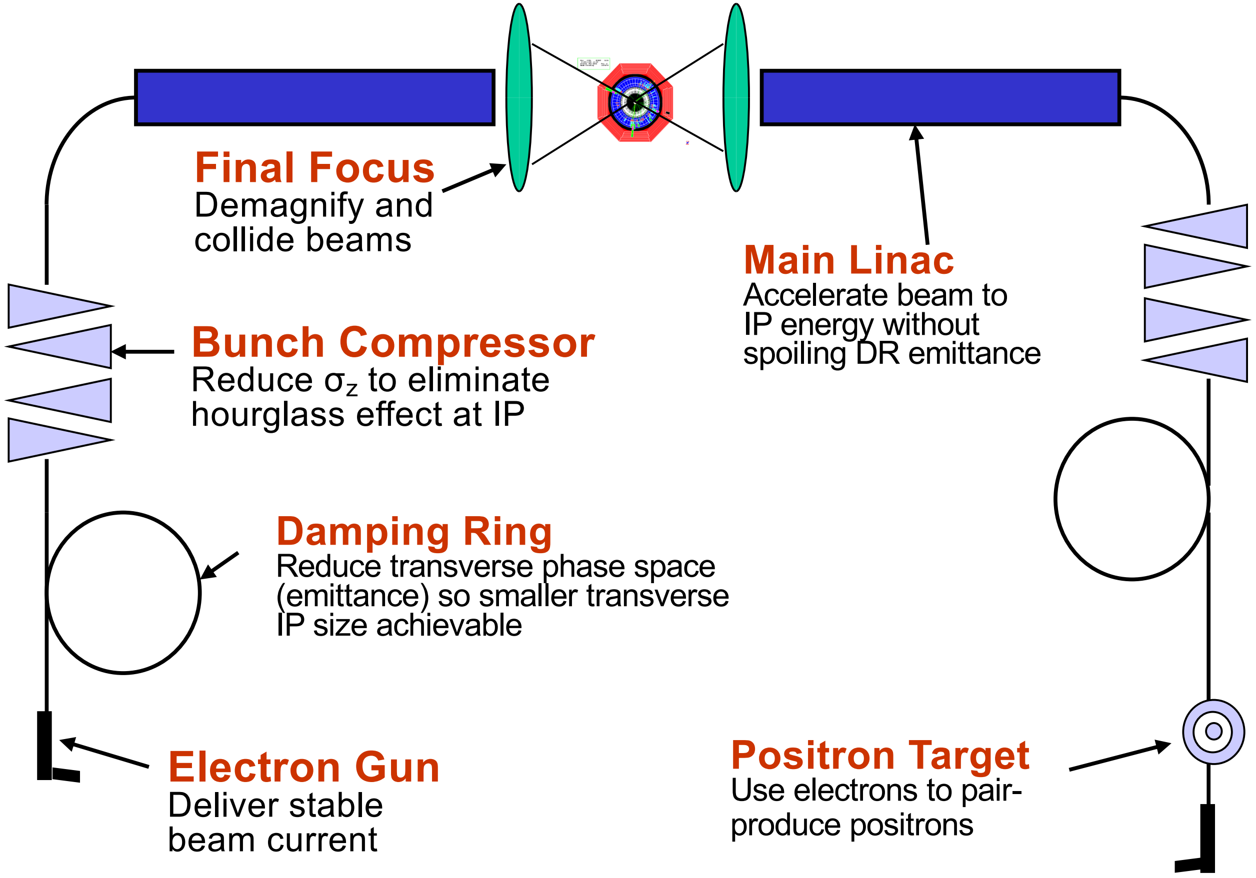
Frank Tecker – CERN

- Main Linac (cont.)
  - Accelerating gradient – NC/SC
- Beam / bunch structure
- Beam Delivery System
- Alignment and Stabilization
- Damping rings
- NC/SC driven differences

Previous Lecture

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

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



Final Focus
Demagnify and collide beams

Main Linac
Accelerate beam to IP energy without spoiling DR emittance

Bunch Compressor
Reduce σ_z to eliminate hourglass effect at IP

Damping Ring
Reduce transverse phase space (emittance) so smaller transverse IP size achievable

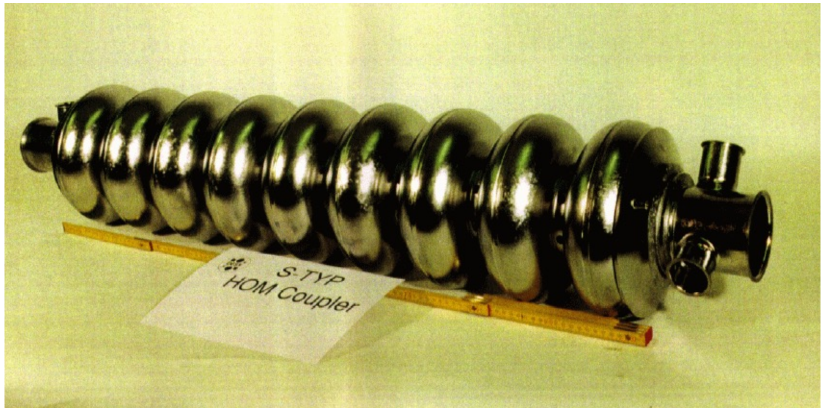
Electron Gun
Deliver stable beam current

Positron Target
Use electrons to pair-produce positrons

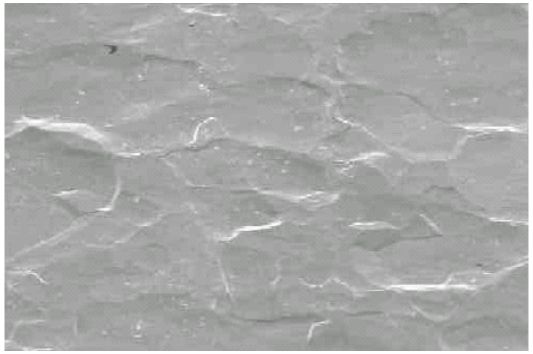
- Main linac:
  - longitudinal wakefields => energy spread, chromatic effects
  - Transverse wakefields, minimized by structure design
- Now: Acceleration in the linac

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 H_{crit} above which no superconductivity exists



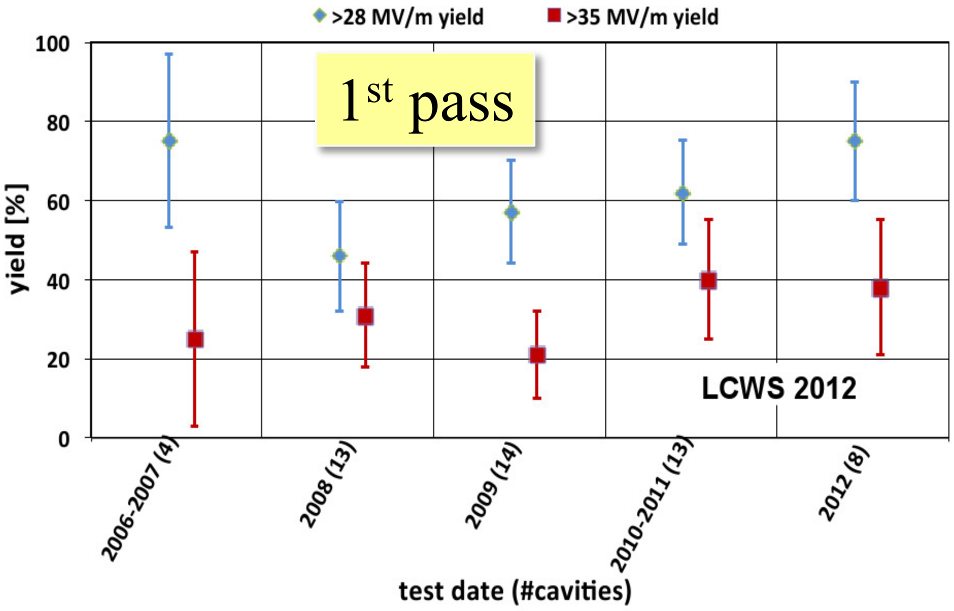
Chemical polish

=>

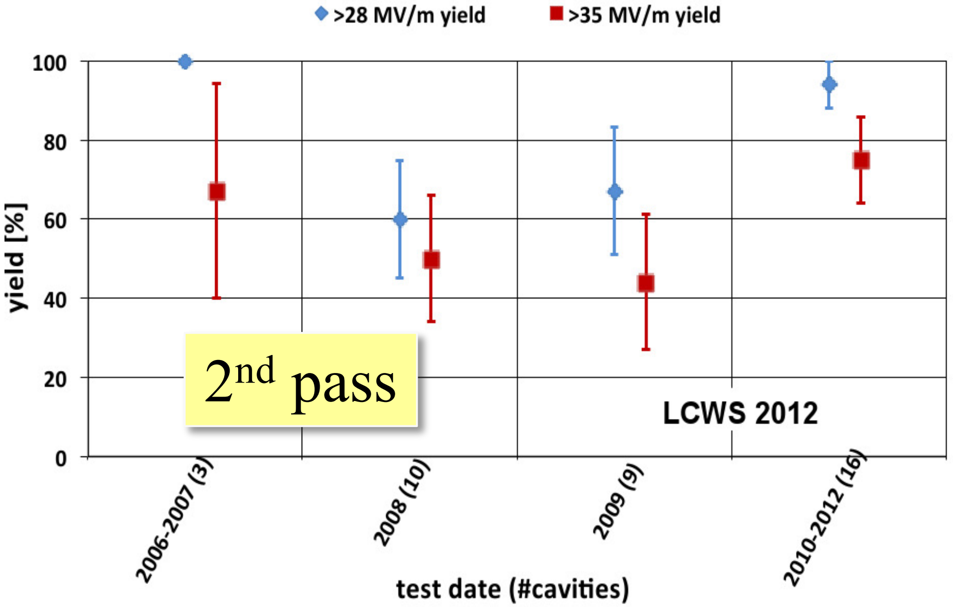
Electropolishing

Achieved SC accelerating gradients

- Large 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 (H_{crit})
- X-FEL running with 23.6 MV/m



1st pass



2nd pass

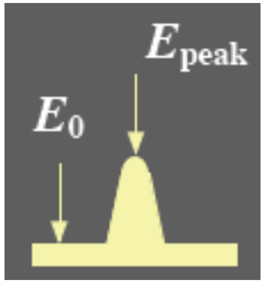
Limitations of Gradient E_{acc}

- 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

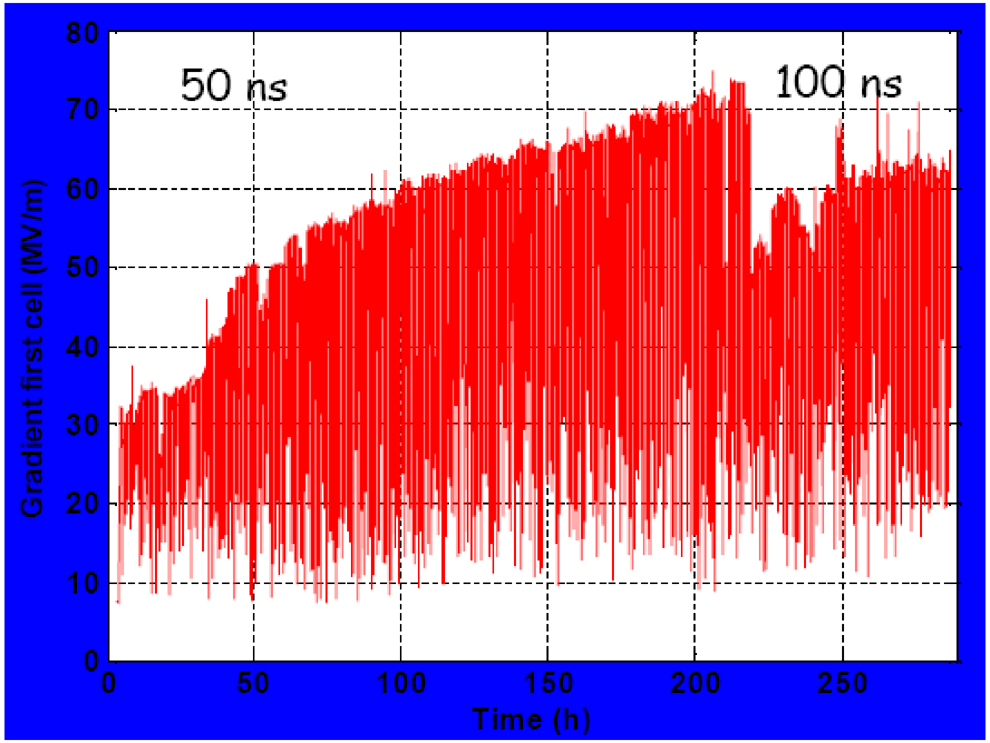
NC Structure conditioning

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

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



- 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



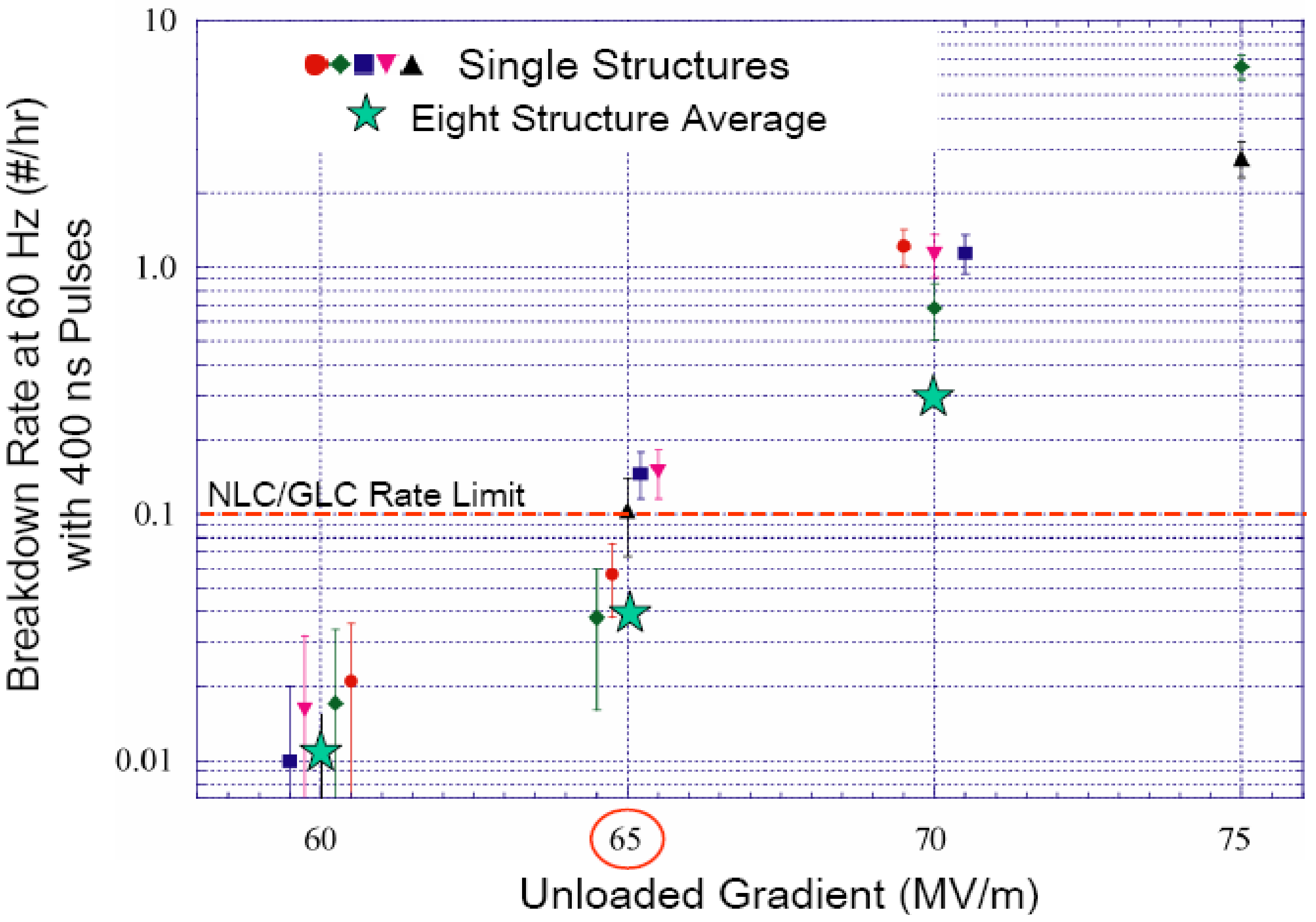
from S.Doebert

Breakdown-rate vs gradient

- Strong increase of breakdown rate for higher gradient

High Gradient Performance

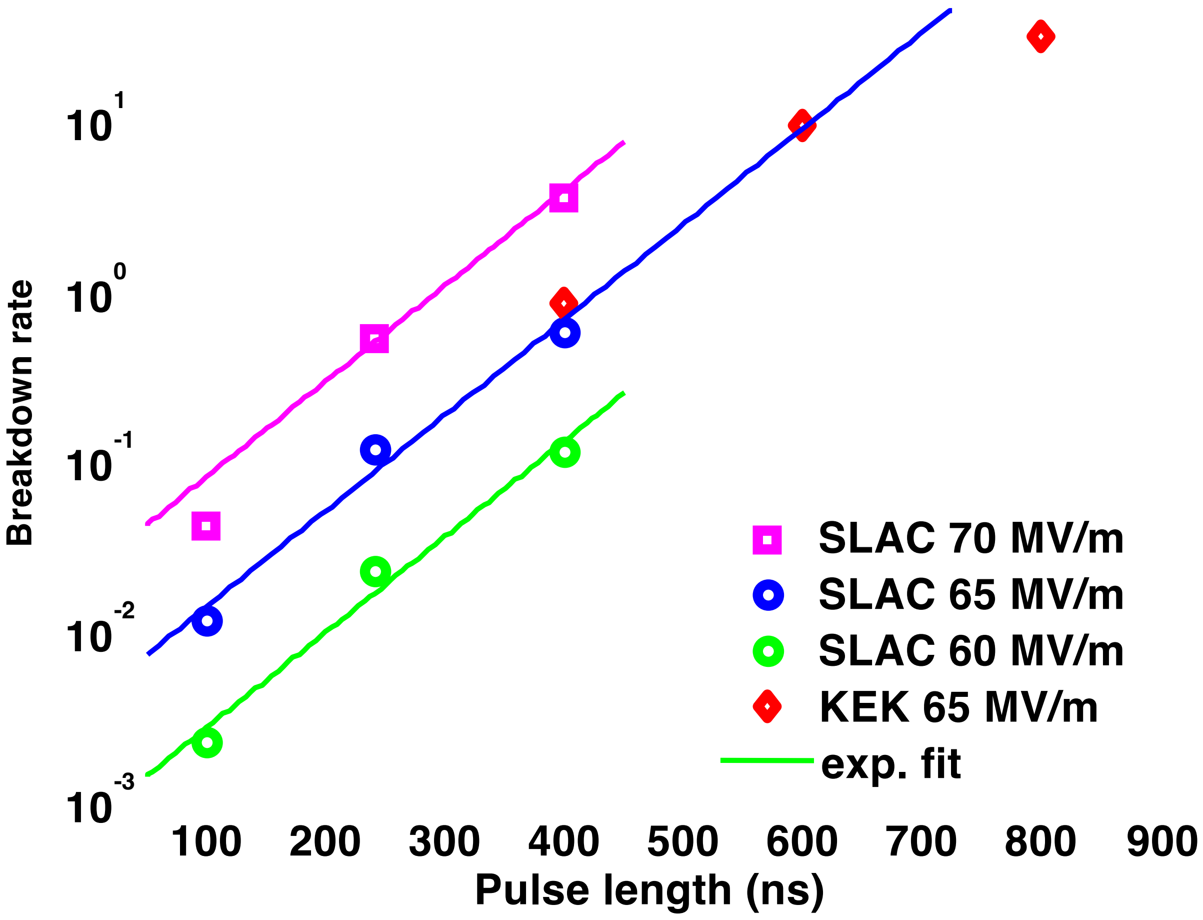
5 Structures after ~ 500 hr of Operation and
8 Structure Average after > 1500 hr of Operation



C. Adolphsen /SLAC

Breakdown-rate vs pulse length

- Higher breakdown rate for longer RF pulses

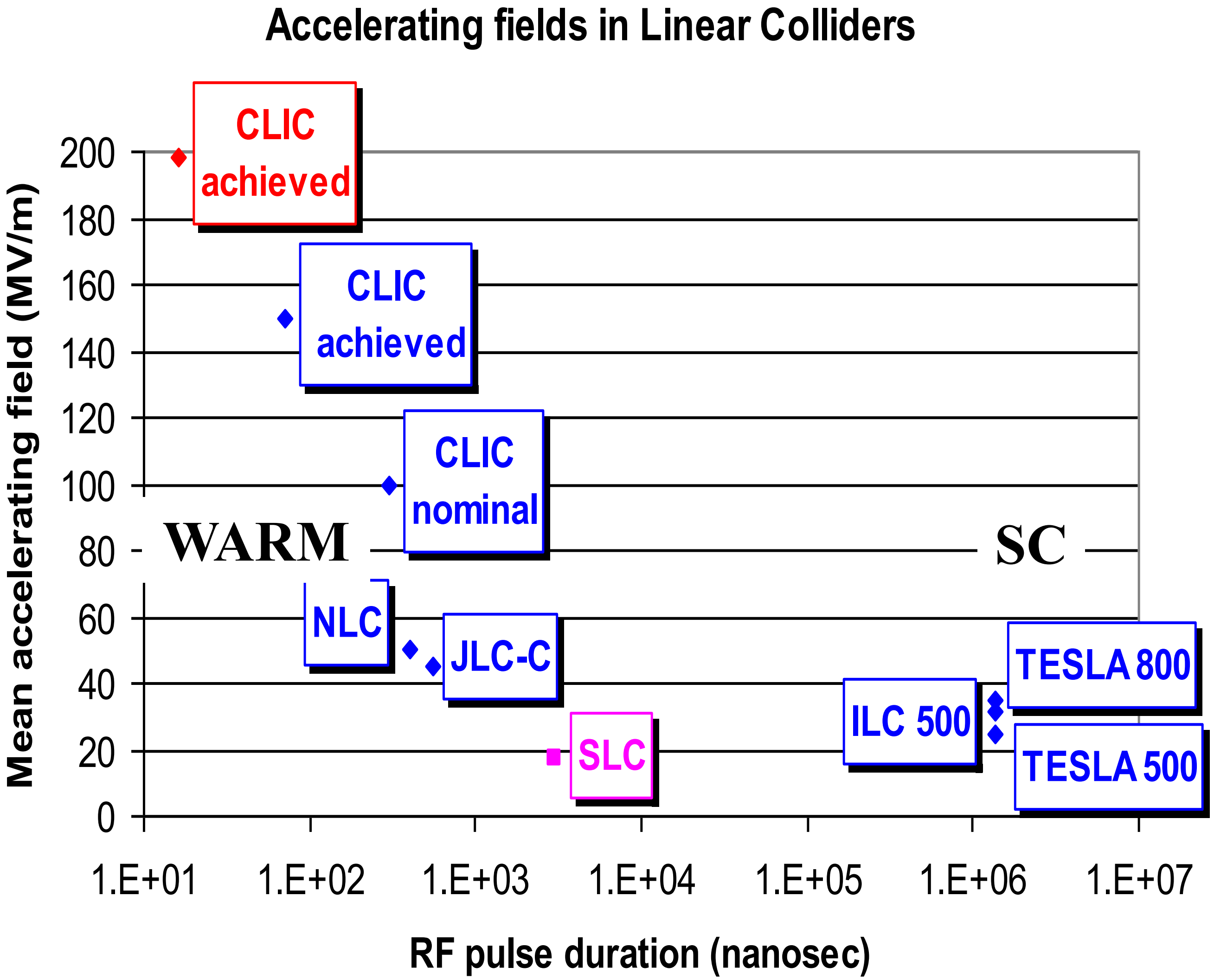


- Summary: breakdown rate limits pulse length and gradient

Accelerating gradient

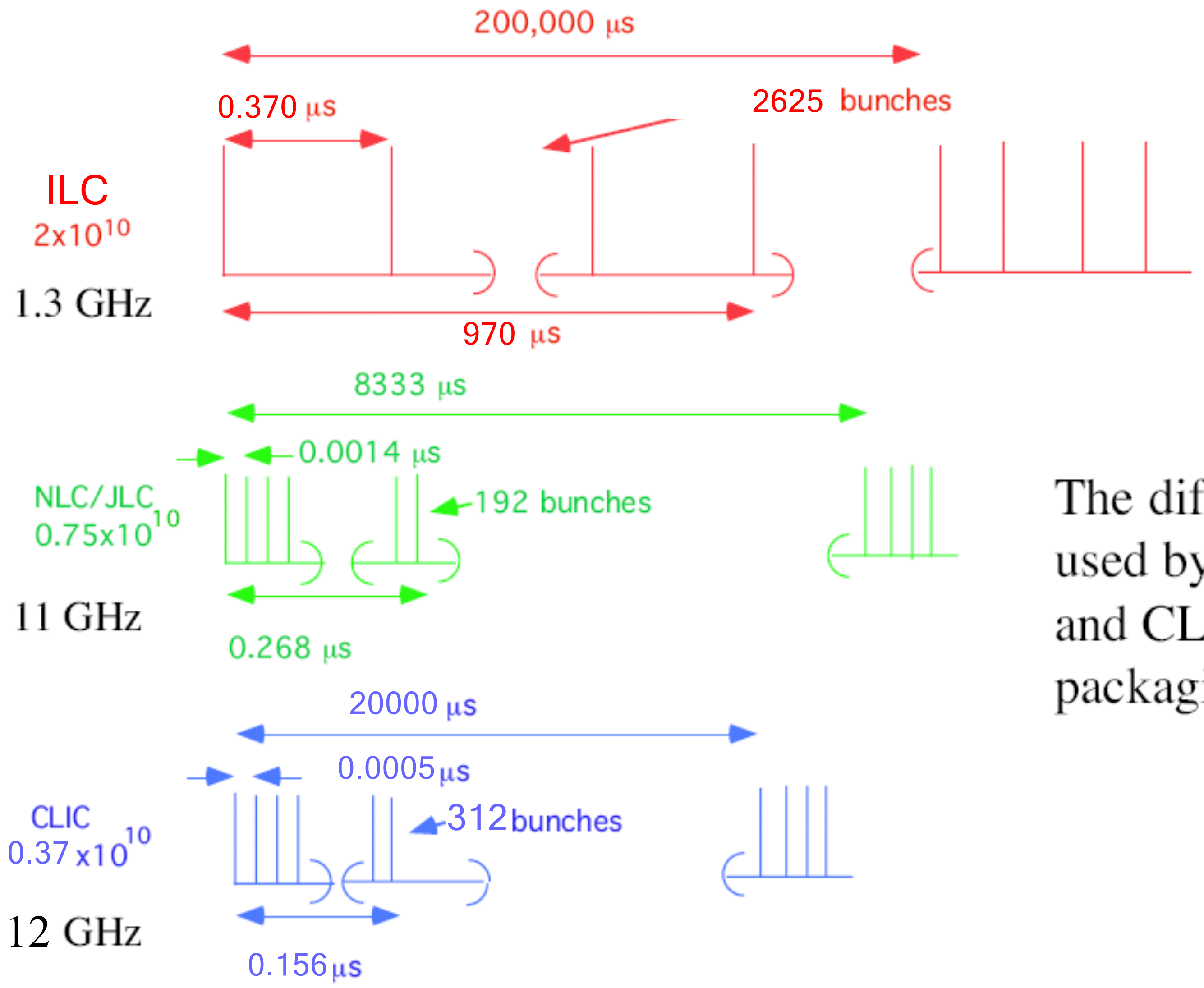
- Normal conducting cavities have higher gradient with shorter RF pulse length

- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse



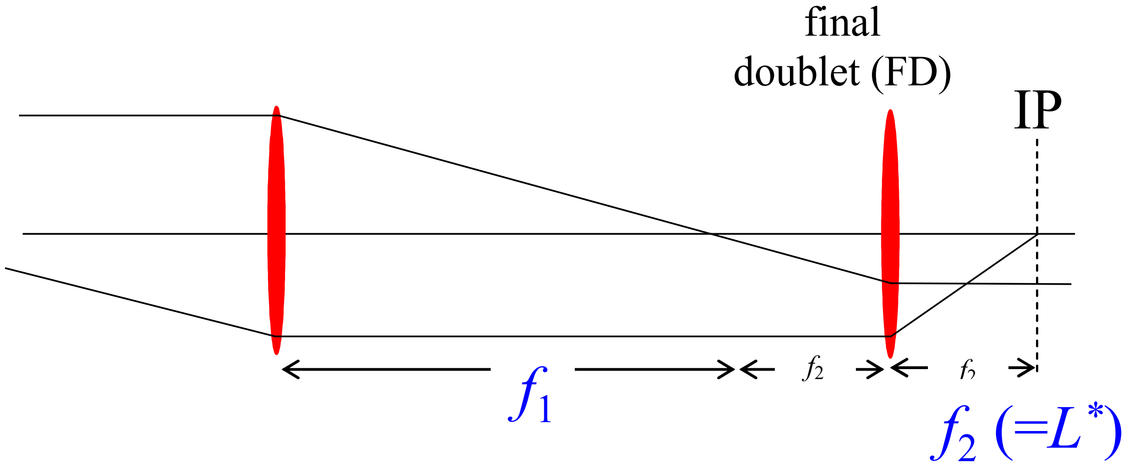
Bunch structure

- 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



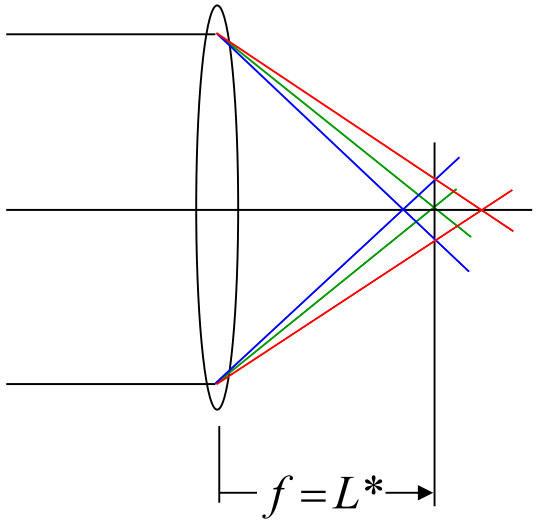
- Need large demagnification of the (mainly vertical) beam size

$$M = \sqrt{\beta_{linac} / \beta_y^*} = f_1 / f_2 \quad \text{typical value} \approx 300$$

- 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: $$\left\langle \Delta y_{IP}^2 \right\rangle = \left\langle y_{quad}^2 \right\rangle \left\langle \delta^2 \right\rangle = \beta_{quad}\varepsilon_y \delta_{\mathrm{rms}}^2$$

Final focus: Chromaticity

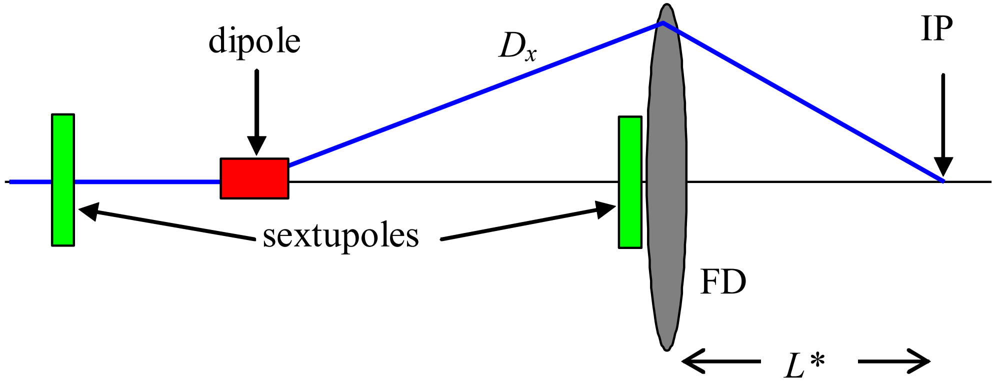
- Small β* => β_{FD} very large (~ 100 km)
- for δ_{rms} ~ 0.3%

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

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

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

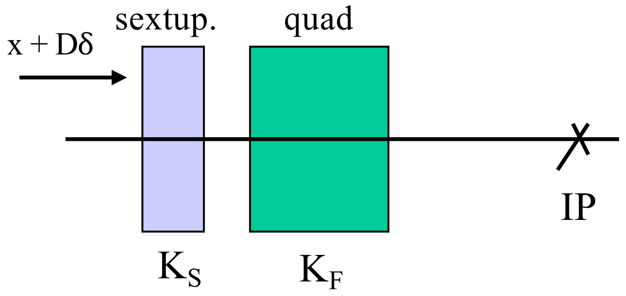
$$B_y = \frac{1}{2} s\left(x^2 + y^2\right)$$



- 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

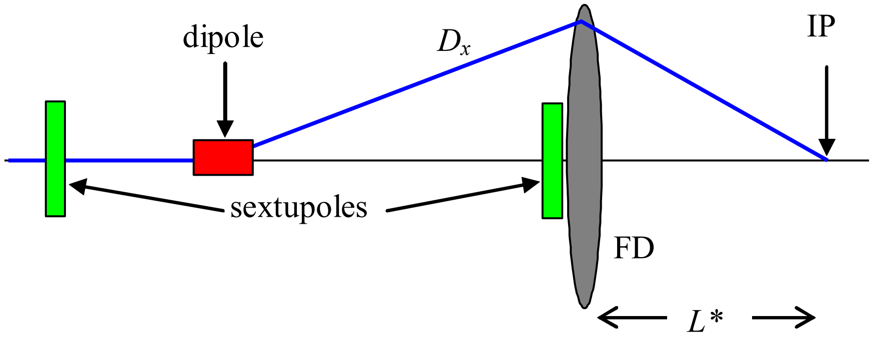
$$\Delta x' = \frac{K_F}{(1+\delta)}(x+D\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)}x \Rightarrow 2K_F(-\delta x - \frac{D\delta^2}{2})$$

Create as much chromaticity as FD upstream

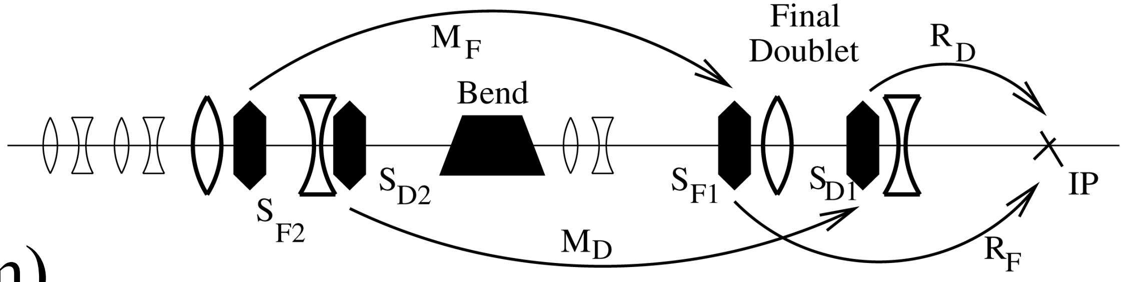
=> second order dispersion corrected

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

Final Focus: Chromatic Correction

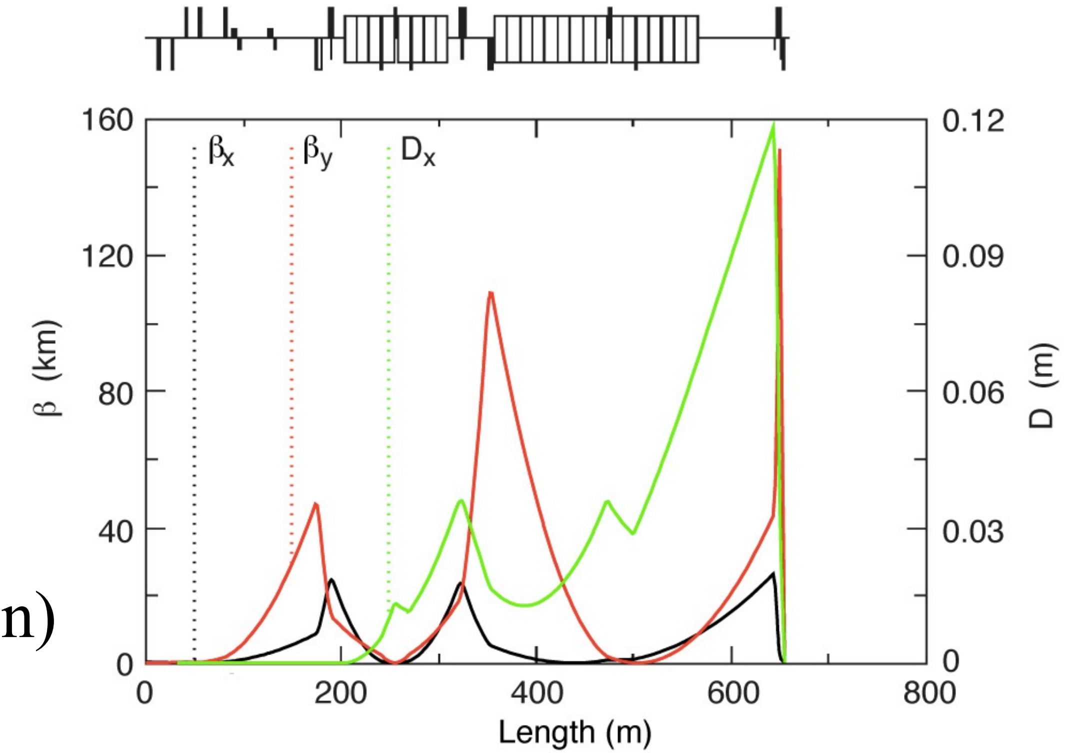


Correction in both planes



- 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)



“2001 Report on the Next Linear Collider”, SLAC-R-0571

Final focus: fundamental limits

- From the hour-glass effect: $\beta_y \cong \sigma_z$
- 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 $F \sim 7$ (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
- Any quadrupole misalignment $\Delta y_{Q,i}$ and jitter will cause orbit oscillations and displacement at the IP (designated by *)

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

$k_{Q,I}$ quad. strength
γ rel. gamma
β opt. beta funct.
$\Delta\phi_i$ opt. phase adv.

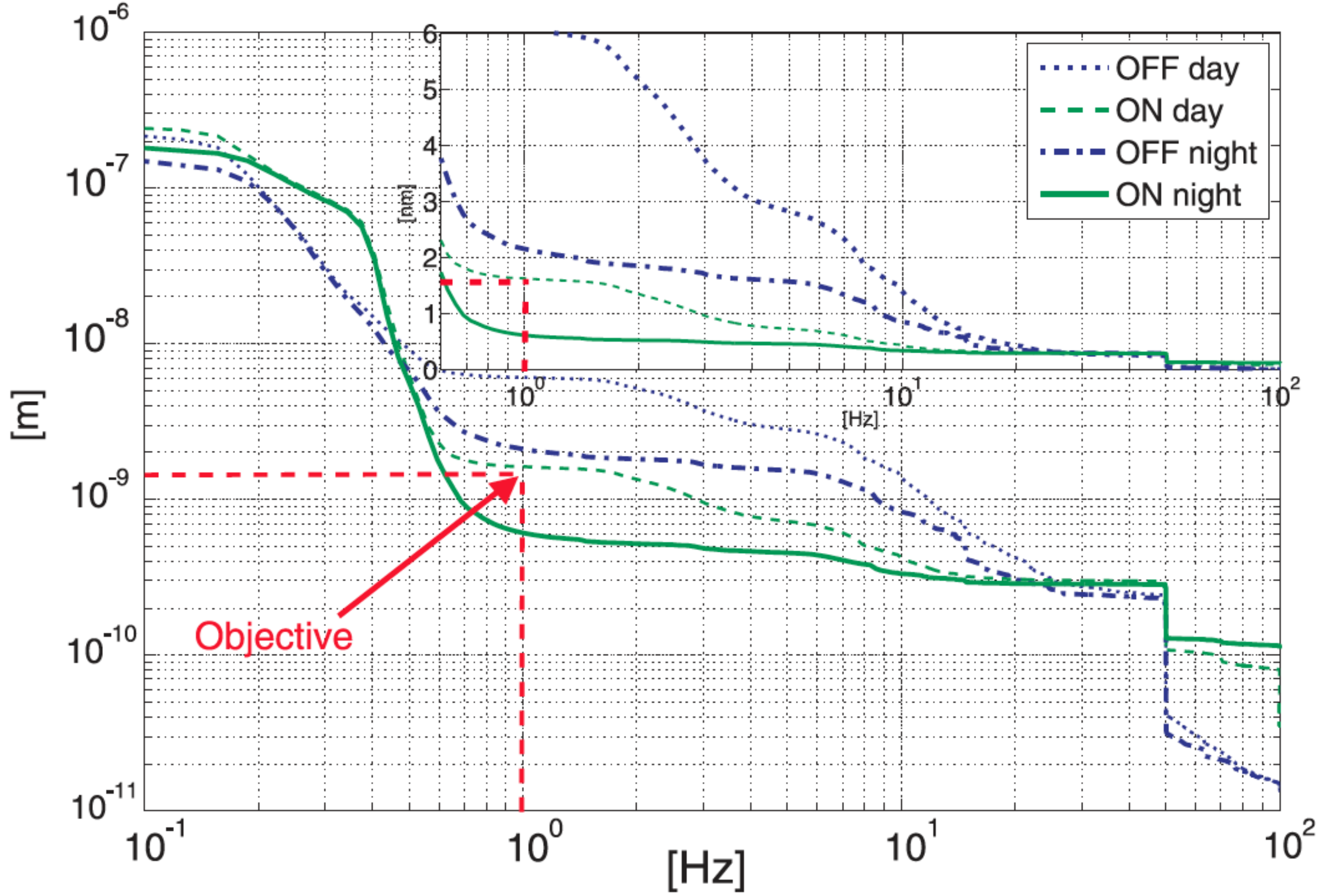
- => Tight component tolerances
  - Field quality
  - Alignment
- Vibration and Ground Motion issues
- Active stabilisation
- Feedback systems

- 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 !!!

- Demonstrate Luminosity performance in presence of motion

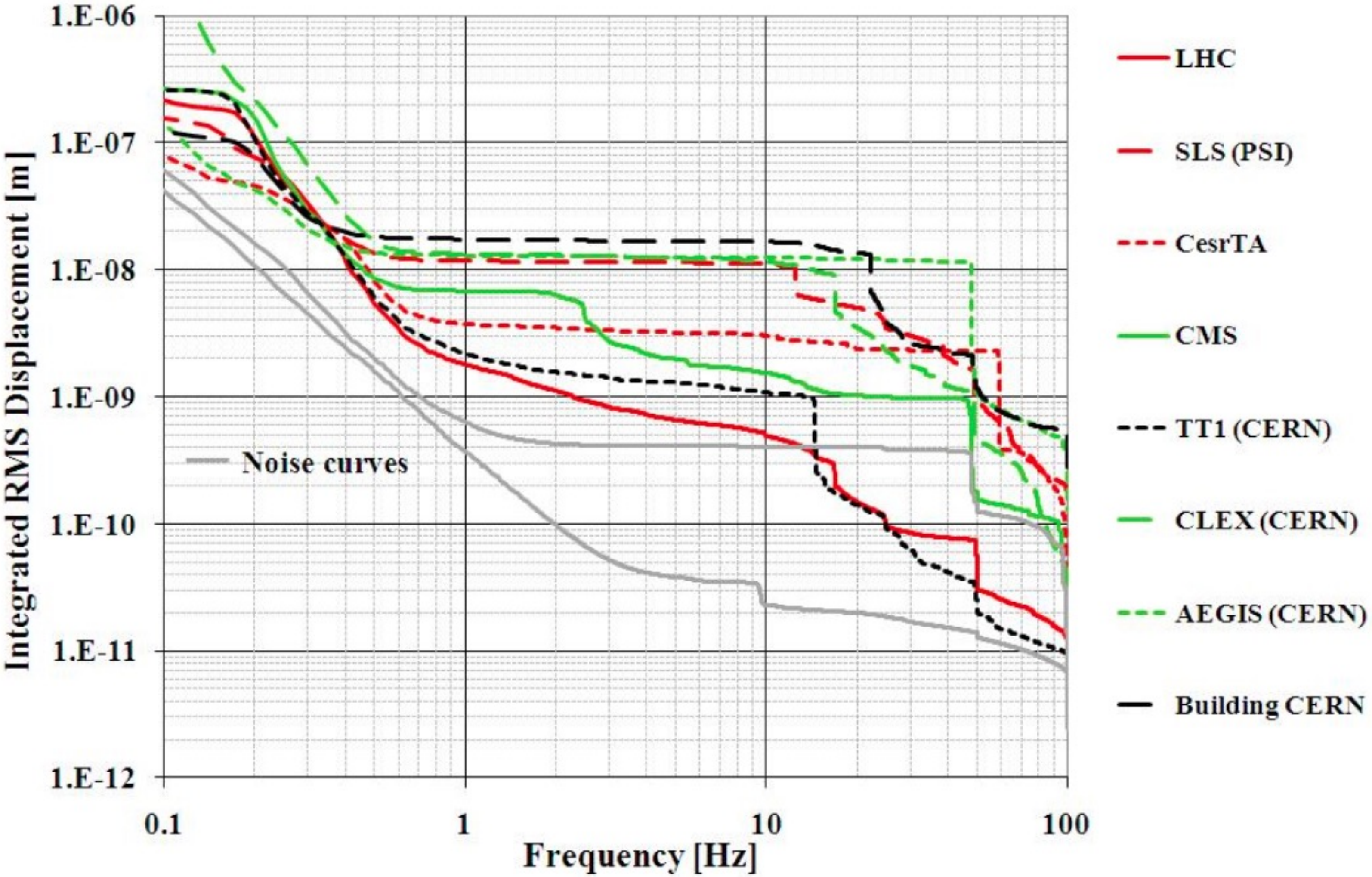
Active stabilization

- Test bench reaches required stability of CLIC MB quadrupole



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

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

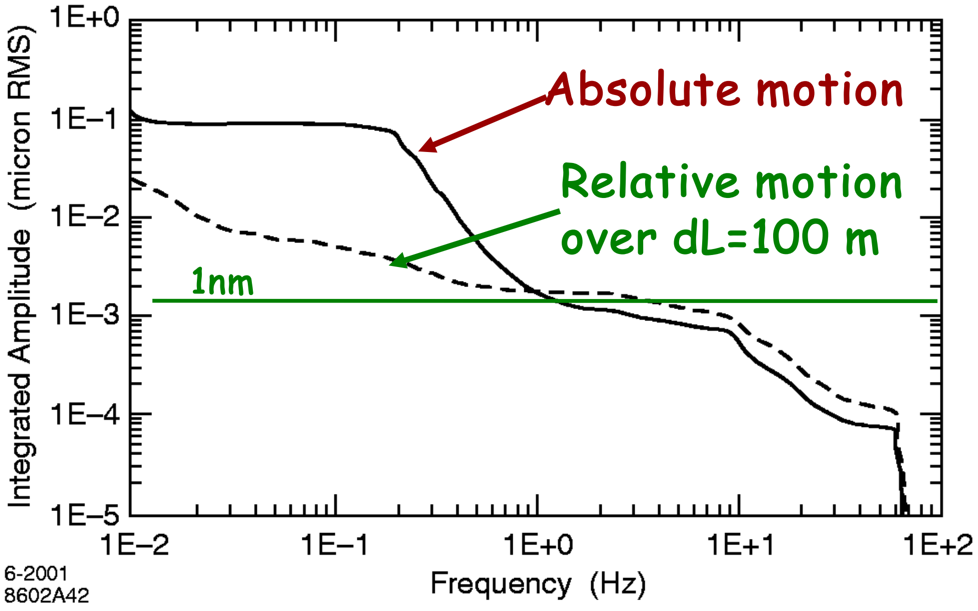
A site dependent constant

T time

L distance

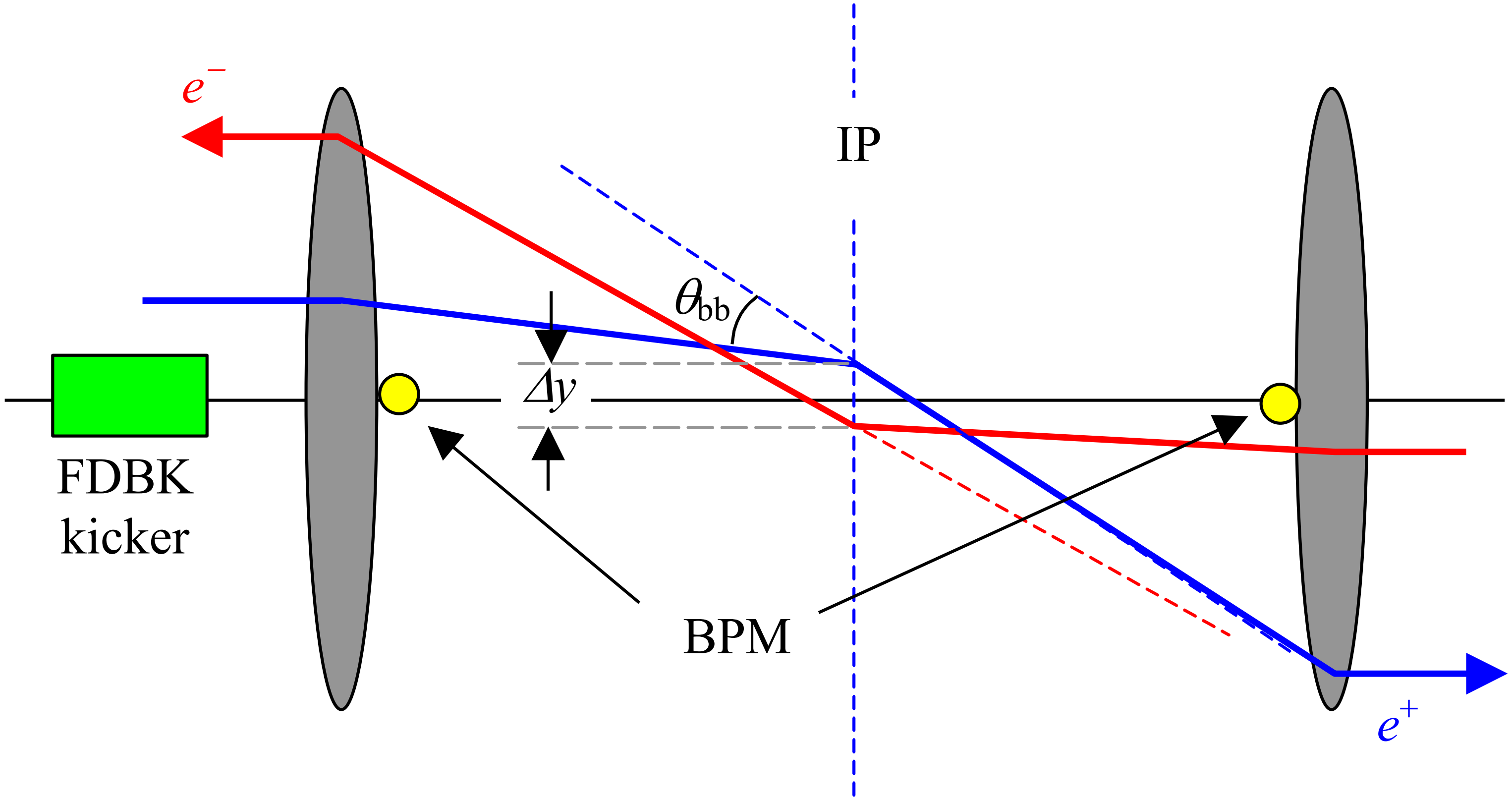
A range 10^{-5} to $10^{-7}\,\mu\text{m}^2/\text{m/s}$

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



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



Other IP issues

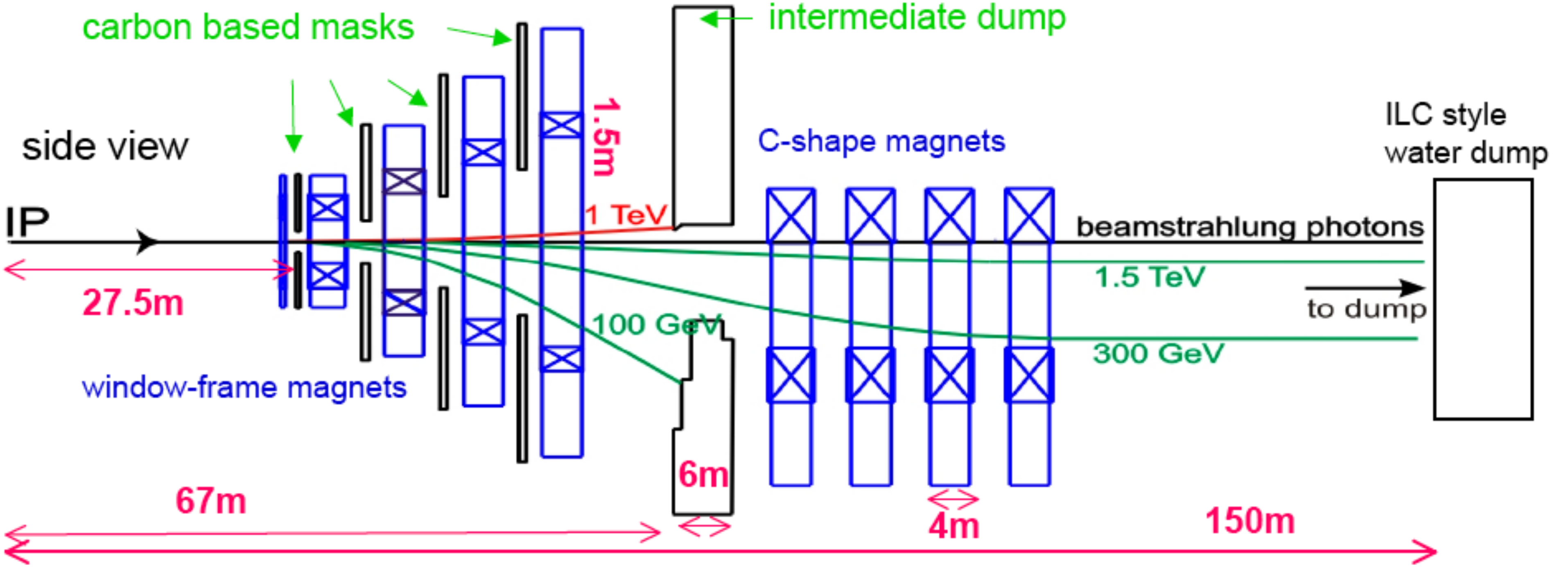
- Collimation:
  - Beam halo will create background in detector
  - Collimation section to eliminate off-energy and off-orbit particle
  - Material and wakefield issues
- Crossing angle:
  - NC small bunch spacing requires crossing angle at IP to avoid parasitic beam-beam deflections
  - Luminosity loss (≈10% when $\theta = \sigma_x/\sigma_z$)
- 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.

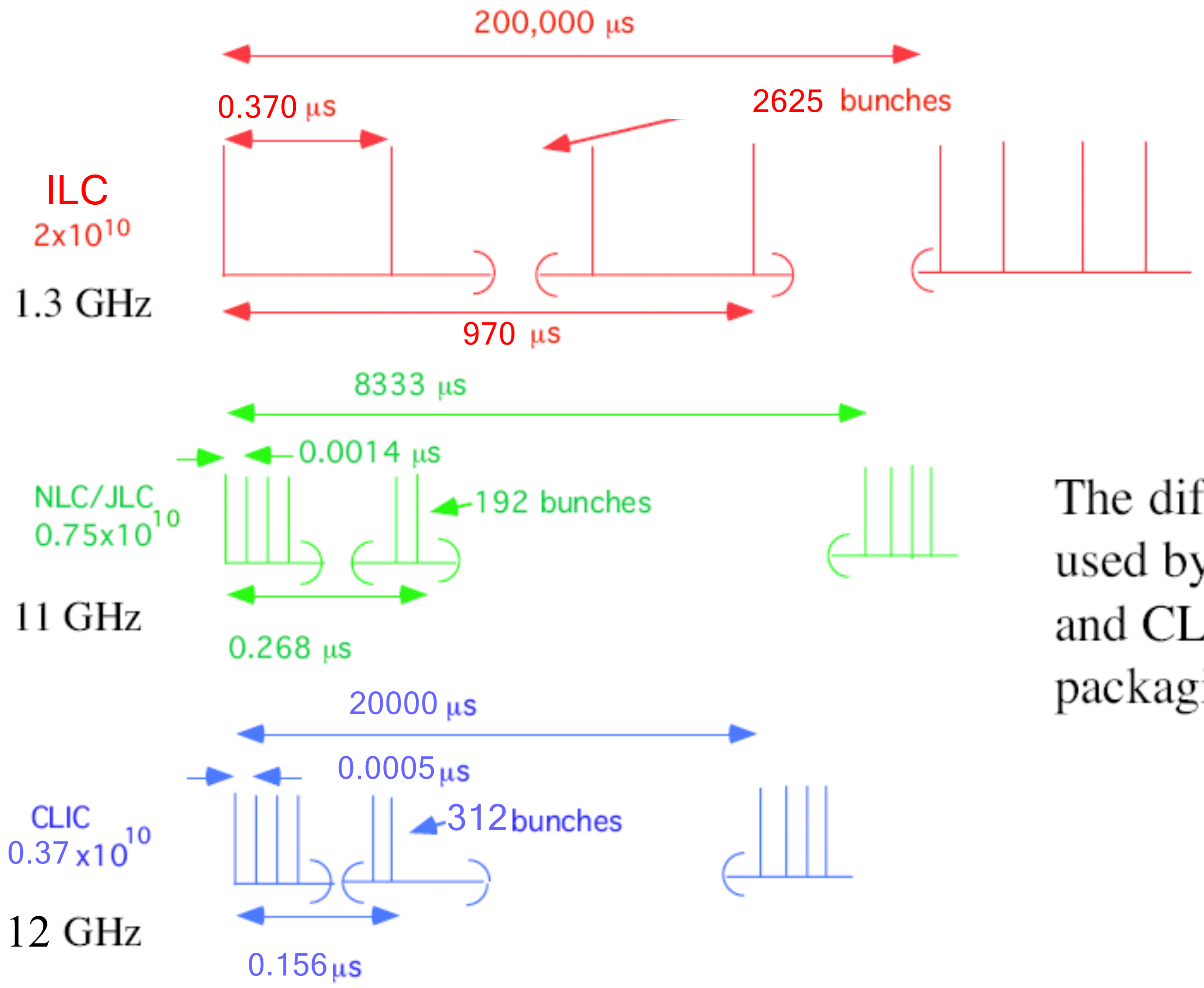
Baseline: vertical chicane with 2x4 dipoles

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



Bunch structure

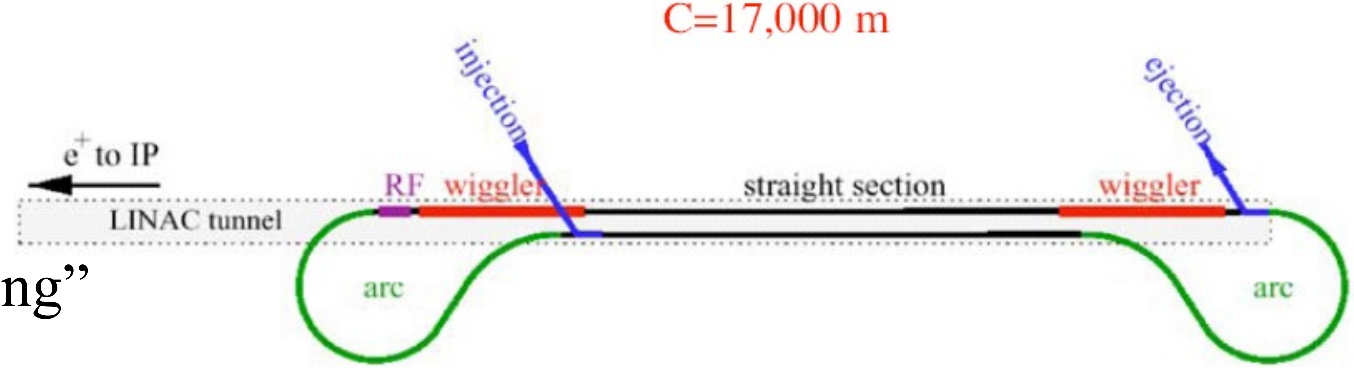
- SC allows long pulse, NC needs short pulse with smaller bunch charge

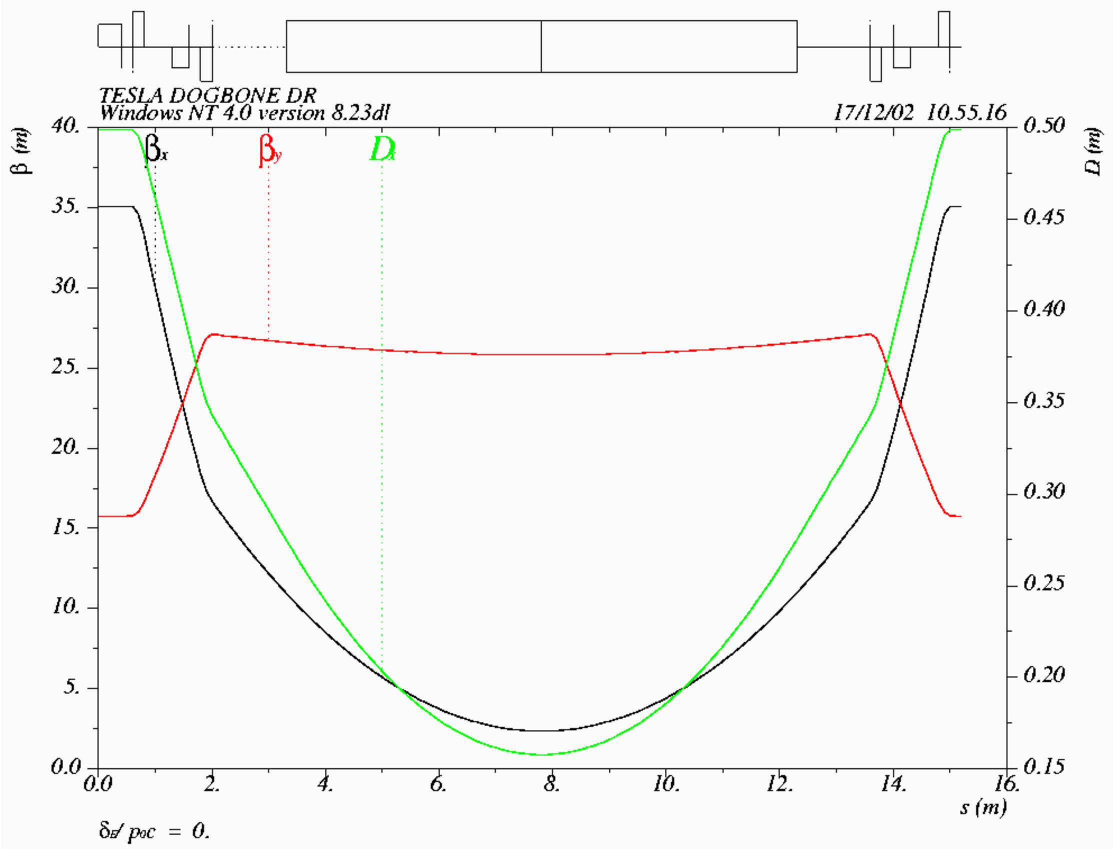


The different RF technologies used by ILC , NLC/JLC and CLIC require different packaging for the beam power

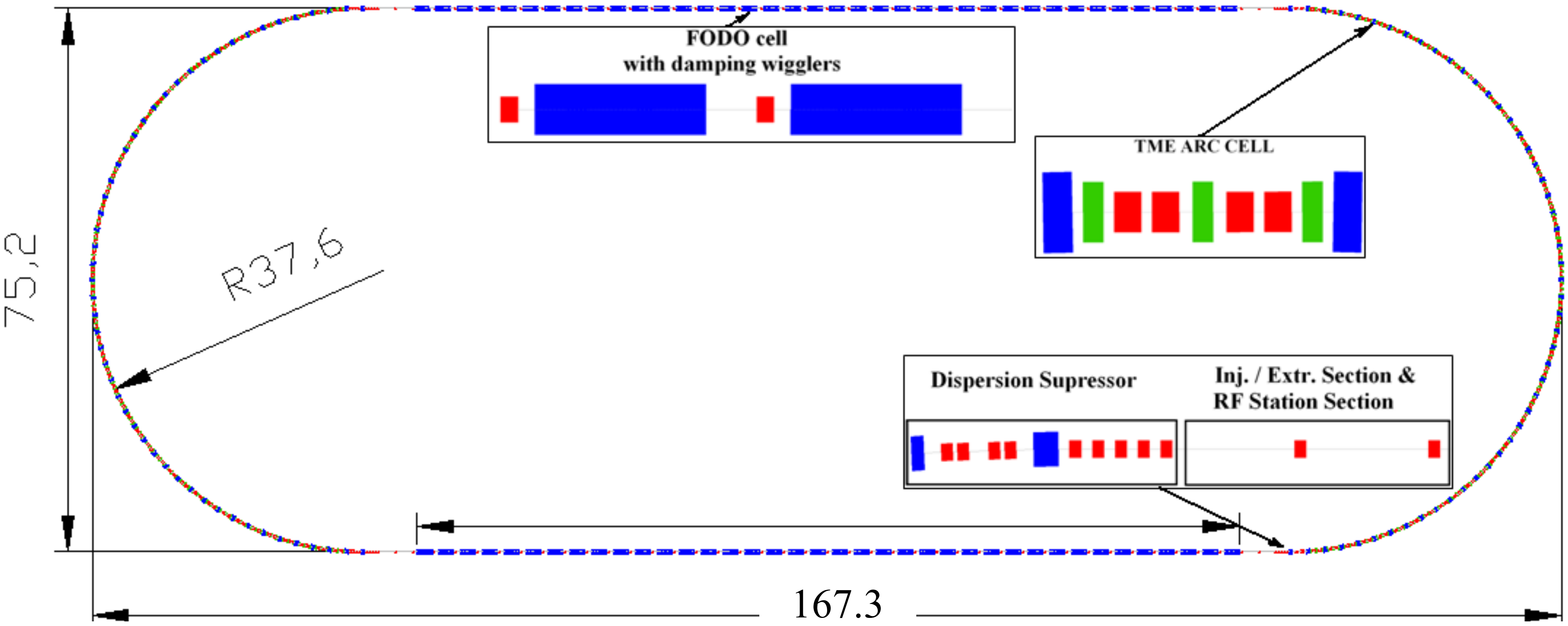
TESLA/ILC damping ring

- Long pulse:
  950µs * c = 285 km!!
- Compress bunch train into 17 km (or less) “ring”
- kick individual bunches
- Min. circumference by ejection/injection kicker speed (≈20 ns)
- “Dog bone” ring with ≈ 400m of 1.67 T wigglers
- 3.2 km circular rings in the baseline ILC design
- Very demanding kicker rise + fall time < 6 ns





CLIC damping ring layout



- Total length 421m (much smaller than ILC), beam pulse only 47m
- Racetrack shape with
- 96 TME arc cells (4 half cells for dispersion suppression)
- 26 Damping wiggler FODO cells in the long straight sections

Warm vs Cold RF Collider

- Normal Conducting
- High gradient => short linac ☺
- High rep. rate => ground motion suppression ☺
- Small structures => strong wakefields ☹
- Generation of high peak RF power ☹
- Small bunch distance ☹

- Superconducting
- long pulse => low peak power ☺
- large structure dimensions => low WF ☺
- very long pulse train => feedback within train ☺
- SC structures => high efficiency ☺
- Gradient limited <40 MV/m => longer linac ☹ (SC material limit ~ 55 MV/m)
- low rep. rate => bad GM suppression (ε_y dilution) ☹
- Large number of e+ per pulse ☹
- very large DR ☹