Linear Colliders with Examples
From the SLC & the NLC

Lecture # 12

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Linear Colliders with examples from SLC and NLC

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SLAC

• Introduction
• IP issues
• Parameters
• Sources
• Polarization
• Damping rings
• Bunch compressors
• Linac beam dynamics
• Rf generation
• Collimation
• Final focus
• Advanced ideas
Acceleration Structures

- Two types of structures: standing wave and traveling wave

- Standing wave structures fill uniformly – all power feeds into beam but filling is difficult because couplers are mismatched — typically used with long pulse (storage rings)

- Traveling wave structures fill from one end and power travels to a load at the other end – typically used in (short) pulsed linacs (SLAC)

- In traveling wave structures, need phase velocity = c for synchronism – slow with irises or other impedance
**Constant Gradient/Impedance**

- In traveling wave structures, power is lost due to attenuation – if all cells are the same (constant impedance structure)
  \[ E_z(z) \sim e^{-z\omega/2Qv_g} \]
  where \( v_g \) is the group velocity

- Constant gradient structures slow group velocity along the structure to obtain constant \( E_z(z) - v_g \sim a^3 \) thus large variation for small changes in iris radii

- Constant gradient structures also have detuned dipole modes – NLC has designed gaussian detuned dipole modes \( \Rightarrow \) quasi-constant gradient structure

\[ V_{cell} = \sqrt{R_s LP_i (1 - e^{-2z})} \]
\[ R_s = \text{Short Imp./length} \]
\[ P_i = \text{Input Power} \]
X-Band Detuned Structure

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<th>R: 21.0%</th>
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Efficiency and Freq. Scaling

- Choose structure parameters for large power transfer to beam – longer structures or lower group velocity for lower beam currents

- Described by \( \tau \equiv \omega L / 2Q\bar{v}_g \quad P_L = P_0 e^{-2\tau} \)

*Fig. A4: RF to beam efficiency as a function of the field attenuation of the structures*

- Operational limitation on efficiency due to beam loading – makes operation difficult

- High group velocity for lower wakefields \( W_\perp \sim 1/a^3 \) and \( v_g \sim a^3 \)

- For constant \( \tau \Rightarrow T_{fill} = L/\bar{v}_g \sim f^{-3/2} \)
RF Power (Klystrons)

- DC beam from cathode using (pulsed) DC power source
- Velocity modulate the DC beam with low level rf
- Use additional unpowered cavities to improve bunching and gain
- Extract rf power with extraction cavity: $P_{rf} = IV\eta$
- Effect of beam self fields are characterized by the perveance: $K_\mu = I/V^{3/2}$ and this has strong effect on the efficiency
RF Power Source (Klystrons)

- Self fields oppose bunching and cause beam to diverge – solenoidal focusing with $r_b \sim \sqrt{K_\mu / B_0}$
- Want $r_b < 0.1\lambda$ for good coupling to the rf cavities
- Makes high frequency klystrons more difficult!
Collector for spent beam

Flower-petal mode converter from TE_{10} rectangular waveguide to TE_{01} circular waveguide

Collector ion pump

RF output coupler

RF input coupler

Anode

Gun ion pump

Cathode & heater

High voltage ceramic insulator

1.7 m

Interaction cavities & focusing structure

Samarium cobalt permanent magnet rings

Magnetic field

RF cavity

Pole pieces

Spacer
RF Pulse Compression

- Klystrons need high voltage/current during the rf pulse

- Generated with modulators: capacitors/charged transmission line and high power switch — long rise/fall

- High frequency linacs have require short rf pulses — two problems modulator efficiency and peak power

- Compress rf pulse: SLED-I, SLED-II, Binary Pulse Compression (BPC), Delay Line Distribution System (DLDS)
SLED-II / BPC

- SLED-II like SLED-I but store energy in delay line rather than cavity to get uniform rf pulse

- Delay line length $= ct_{\text{pulse}}/2$ long! Impractical at low rf frequency with long fill times

- At high frequency, attenuation of rf is large $\Rightarrow$ use over-moded waveguide with $TE_{01}$ circular mode — no field on walls and loss is about 1000 time smaller than normal rectangular $TE_{10}$

- Both SLED-I and SLED-II have intrinsic efficiencies $<1$ because some power is lost during filling — BPC and DLDS have intrinsic efficiencies equal to 1

\[ \alpha \sim \frac{c}{f}^{3/2} \]
RF Sources (TBA)

- Maybe generate rf also using Two Beam Accelerator (TBA)

- Two choices: generate short beam pulses using magnetic DC pulse compression (induction linac - LBL/LLNL TBA) or use low frequency rf linac and separate beam into shorter trains by manipulating beams rather than rf (CLIC TBA)

- Especially relevent at high frequencies, ie. CLIC (30 GHz) where conventional rf sources are hard to make
Schematic Layout of the CLIC complex at 1 TeV c.m.

17.4 km

7.5 km

2.4 km

7.5 km

12 sections of 625 m each

Main Beams
150 bunches of $4 \times 10^9$ e+ e-

FROM MAIN BEAM GENERATION COMPLEX

e- FINAL FOCUS

Detectors

e- e+ e+ MAIN LINAC
12 Sections of 62.5 GV each (30 GHz - 100 MV/m)

FEL

γ γ

e+ DRIVE LINAC SECTIONS

312 m

COMBINER RINGS

e- DRIVE LINAC SECTIONS

INJECTOR

130 mod/klystrons
29 MW - 50 μsec

1.5 GeV 3.5 MeV/m

DRIVE LINAC
625 MHz
450 m

Delay loop
39 m

Mean current: 3.5 Amp
96 cm between bunches

1 train of 16320 bunches with 4.7 to 11.7 nC/b at 50 MeV
Total charge: 188 microC - Total energy: 9 kJ

50 microsec

192 trains of 85 bunches at 1.1 GeV
Total energy: 205 kJ

50 microsec
CLIC module layout

5 TeV c.m.

(2 CAS + 2 TRS)/module

2 Drive beams with 1024 bunches of 15 nC/bunch

144 cm

DRIVE LINAC 1

BPM

CLIC TRANSFER STRUCTURE

QUAD

8.5 cm 2.5 cm 61 cm

MAIN LINAC

BPM

CAS

CAS

440 MW

5 cm 61 cm 2.5 cm 3.5 cm

DRIVE LINAC 2

BPM

CLIC TRANSFER STRUCTURE

QUAD

5.2 cm 103 cm 3 cm 15 cm 1.5 cm 3.5 cm

THREE BEAM ACCELERATION (TBA) scheme
Collimation

- Can't collimate electrons — just make them angry — cause backgrounds in detector

- Sources of tails: Damping rings (intrabeam scattering, beam gas scattering, nonlinearities), bunch compression (space charge, nonlinearity), linac (beam gas, thermal photons, transverse wakefields), ...

- Problems: survival of collimator / spoiler system and wakefields from the collimators

- In NLC linac typical beam size is 10x1 μm with 10^{12} particles per train — if impacted on copper ⇒ 80 million C°
- To ensure survival of system from single bunch train, use spoiler/absorber scheme with thin Ti spoilers and increase beam size to $(100\mu m)^2$

- Use long drift to let scattered beam increase in size before absorbing

- Problem with large beam sizes (beta functions) is transverse wakefields from the spoiles and absorbers. Use tapered shapes to reduce the geometric wakefield — balance against the resistive wall wakefield from the increased length.
Collimator Transmission and Kick

Transmission (σ_y = 60 um)

Wakefield Kick

Exp.: o

Fit: geo + 3*resi

y/a (a = 0.5 mm)
Collimation Geometry

- Collimate in each plane multiple times because edge-scattered particles repopulate tails

- Separate collimation from IP with “big bend” to reduce muon backgrounds absorbing

- Unfortunately, collimator system length scales as $\gamma$ to protect against single pulse impact – becomes very difficult at higher energies!
Final Focus System

- To attain luminosity, $\sigma_x/\sigma_y \sim 1 \times 0.5\mu m$ in SLC and $\sim 0.3 \times 0.004\mu m$ in NLC.

- To focus beams to very small spot sizes, use final telescope with quadrupole doublet (for flat beams) or quadrupole triplet (for round beams) to demagnify spots $\sigma = \sqrt{\epsilon \beta}$.

- The problem is the chromaticity (energy dependence of focal point) which depends on demagnification and distance to IP:

$$\frac{\Delta \sigma_y}{\sigma_y} = \psi_y \sigma \Delta E/E \quad \psi_y \sim \frac{L^*}{\beta^*}$$

- $\psi_y \sim 6000$ in SLC and $\psi_y \sim 25,000$ in NLC which requires energy spreads less than $10^{-5} \sim 10^{-6}$ without chromatic correction.
Chromatic Correction

- Add (subtract) additional focusing for high (low) energy particles

- Use sextupole magnets in regions of dispersion where high and low energy particles have different X positions – separate sextupoles by $\pi$ in phase advance from the IP

- Large geometric aberrations introduced by sextupoles – place another with the same sign $\pi$ away $\Rightarrow$ geometrics cancel but chromatic effects add

![Diagram]

![Graph]

(b) Uncorrected
Corrected
Linear

$\beta_y^* (\text{mm})$ vs $\sigma_y (\mu\text{m})$
- Separate X and Y chromatic correction sections to reduce 3rd-order sextupole aberrations

- Remaining aberrations are 4th-order — can reduce some of these with additional sextupoles or octupoles
Aberations

- 4th-order aberrations from finite sextupole length and from energy dependence of the $-I$ transformations between sextupoles

- Synchrotron radiation in bends needed to generate dispersion or quadrupole magnets cause emittance growth and increases the energy spread which is not chromatically corrected – this causes the length of the FFS to scale as $\gamma^2$. NLC FF is full of low-field bends

- Oide effect (SR) in final quadrupoles sets a limitation on emittance and final spot size

- All the normal low-order aberrations: beam positions, dispersion, coupling, waist position, ....
Concepts for High Energy

- Above 2 ~ 3 TeV need to consider high Y regime

- Rf breakdown and dark current capture gradient limitations increase roughly as $f$

  ⇒ Higher frequency for higher gradients and shorter linacs — 150 MV/m at 30 GHz or 1 GV/m at 90 GHz

- Plasma and laser accelerators also can achieve very high gradients

- For reasonable parameters, linac tolerances scale as $f^{-1}$

- Conventional FFS and collimation is difficult to go higher in energy than 3 ~ 4 TeV

- Plasma or "dynamic" focusing — or very careful correction of energy spread and eliminate chromatic correction