Longitudinal Shaping of Relativistic Electron Bunches with Applications to the Plasma Wakefield Accelerator

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Introduction: The RF Photoinjector

- Acceleration from rest to relativistic energies (~1 to 10 MeV)
- Temporal structure of electron beam reflects that of laser pulse on the cathode.
- Capable of producing low-emittance beams.
- Emittance: figure of merit; measure of area occupied by beam distribution in transverse phase space.

\[ \varepsilon_{x,N} = \frac{1}{mc} \sqrt{\langle p_x^2 x^2 \rangle - \langle p_x x \rangle^2} \approx \sqrt{\varepsilon_{x,th}^2 + \varepsilon_{x,rf}^2 + \varepsilon_{x,sc}^2} \]

thermal emittance: \( \varepsilon_{x,th} \propto \sigma_x \)

RF emittance: \( \varepsilon_{x,rf} \propto \sigma_x^2 \sigma_z^2 \)

space charge emittance: \( \varepsilon_{x,sc} \propto \frac{1}{\sigma_z} \)

- Trade-off between rf and sc components
- Implies optimal pulse length \( \sigma_z \)
- Generally determined by photoinjector codes (e.g. PARMELA, HOMDYN)
- Typical \( \sigma_z \sim 10 \) degrees of RF phase
- For S-Band (2.856 GHz) 10 deg \( \sim 10 \) ps
Beam Brightness

\[ B_\perp = \frac{I}{\varepsilon_{x,N}^2} \quad I \propto \frac{Q}{\sigma_z} \]

\[ Q_{\text{max}} \approx \frac{2}{5} \pi \sigma_x^2 \varepsilon_0 E_0 \]

- “brightness”: measure of density of particles in transverse phase space.
- Emittance constrained by photoinjector: \( \varepsilon_N > 1 \mu m \)
- \( \sigma_z \) constrained (\( \sim 10 \) deg of RF phase) to minimize \( \varepsilon_N \)
- \( Q \) constrained by cathode image charge limit


Optimal photoinjector brightness

- To obtain higher brightness beams, require compression techniques

\[ B_{\perp,\text{opt}} = 16(2\pi)^{9/2} \alpha k \frac{I_A[1 + \frac{3}{5} A]^2}{\sigma_z A^2} \]

\( \alpha=1.5; \lambda=10\text{cm}; A=1; I_A=16\text{kA}; \sigma_z=3\text{mm} \)

\[ B_{\perp,\text{opt}} = 80 \text{ } \text{A}/\mu\text{m}^2 \]
Bunch Compression Techniques

RF Techniques

Phase Space Rotation

Ballistic Compression

Magnetic Techniques

Chicane

Other Nonisochronous Devices (e.g. dogleg compressor)
Applications for High Brightness Beams

Free electron laser

- high gain regime
- minimize the gain length $L_g$

$$L_g = \frac{\lambda_u}{2\sqrt{3}\pi \rho} \quad \rho \propto \omega_p^{2/3} \propto n_e^{1/3}$$

Inverse Compton Scattering

- beam + laser (hv) \rightarrow higher hv' photons
- shortness of scattered pulse limited by shortest of beam, laser

$$N_{ph} = \mathcal{L} \sigma_T \quad \mathcal{L} \propto \frac{N_e}{A_{int}}$$

Plasma Wakefield Accelerator:

- beam + plasma \rightarrow high-gradient wakes
- beam density, time profile important

$$E_{\text{max}} = E_0 1.3 \Lambda \ln(1 / \sqrt{\Lambda / 10}) \quad n_{\text{beam}} \gg n_0$$

$$\Lambda = (n_{\text{beam}} / n_0) k_p^2 \sigma_r^2$$
Optimal Drive Beam Profile for Blowout Regime of PWFA

- PWFA: plasma wakefield accelerator
- electron beam-driven plasma waves
- acc. fields on order of multi-GeV/m
- acceleration of drive tail or witness bunch

Transformer Ratio:

\[ E_+ = acc.\ field; E_- = decc.\ field \]

\[ R = \frac{E_+}{E_-} = k_p L_z \]

\[ R > 2 \quad \text{if} \quad L_z > 2k_p \]
Focus of this Talk

- Generation of electron beam with ramped current profile
- Temporal diagnostic with sub-ps resolution
  - transverse deflecting mode cavity
- Experimental verification of ramping mechanism
How Does a Dogleg Compress the Beam?

**Chicane**

- Higher-energy particles travel a shorter path

\[ R_{56} = \frac{\partial z}{\partial \delta} > 0 \]  
“Positive longitudinal dispersion”

**Dogleg**

- Higher-energy particles travel a longer path

\[ R_{56} = \frac{\partial z}{\partial \delta} < 0 \]  
“Negative longitudinal dispersion”
Ramped Beam Mechanism

Artificial mathematical manipulation of a chirped particle distribution

\[
R_{56} = \frac{\partial z}{\partial \delta} < 0
\]

**non linear transformation:** \( z_f = z_0 + R_{56} \delta + T_{566} \delta^2 \)

\( T_{566} \) arises from chromatic focusing errors in horizontally focusing quads and then grows in the subsequent drift sections (2nd order x-z correlation).
Solution: sextupole corrector magnets near the horizontally focusing quads.
Neptune Dogleg Compressor
S-Bahn Compressor

- Is a “dogleg” or dispersionless translating section.
- Half-chicane with focusing elements between the bends.
- Can be operated in a nondispersive mode with symmetric beta function and 2π betatron advance.
- Like a chicane, may be used as a bunch-length compressor.
- Nominal first order temporal dispersion ($R_{56} = -5$cm) is suitable for beam-shaping.
- Sextupoles required to compensate 2nd order longitudinal dispersion.
Neptune Dogleg Compressor
PARMELA Simulation Results: 1000 particles, 300pC

- 2D PIC Simulation
- 5 GeV/m gradients
- 6 nC drive beam w/ n₀=2e16 cm⁻³
The UCLA Neptune Laboratory

Beam Charge: 100pC --> 500pC
Beam energy: up to 15 MeV
Emittance: \( \varepsilon_N = 4 \text{ mm mrad} \)
Power Source: 18 MW Klystron
RF Frequency: 2.856 GHz
Cathode laser: 60 \( \mu \text{J at } \lambda = 266 \text{ nm} \)
Laser pulse length: 5-7 ps RMS
Simulations predict “ramped” beam occurs near point of maximum compression ($\kappa=1094 \text{ m}^{-3}$).


Empirical analysis assumes a gaussian profile, which is not necessarily the case here.

Theoretical curve obtained from PARMELA + ELEGANT simulation, with autocorrelation algorithm.

- Martin-Puplett CTR Interferometer
- Bunch length measurement by autocorrelation.
- Sub-picosecond resolution obtainable.

PARMELA gun and linac 5000 macroparticles

ELEGANT prefocus and s-bahn 60% collimation

MATHEMATICA
1. interferogram reconstruction
2. triple-gaussian fit procedure
CTR Measurements of Compression

- Martin-Puplett CTR Interferometer
- Bunch length measurement by autocorrelation.
- Sub-picosecond resolution obtainable.

\[ \sigma_f(\text{ps}) = 0 \text{ m}^{-3} \]
\[ \sigma_f(\text{ps}) = 1094 \text{ m}^{-3} \]
\[ \sigma_f(\text{ps}) = 1641 \text{ m}^{-3} \]
\[ \sigma_f(\text{ps}) = 2735 \text{ m}^{-3} \]
A Better Temporal Diagnostic
Deflecting Mode Cavity

Lowest dipole mode is TM_{110}
Zero electric field on-axis (in pillbox approx.)
Deflection is purely magnetic
Polarization selection requires asymmetry

\[
x' = \frac{\pi f_{RF} L_B \sqrt{2 P_{RF} R_\perp}}{c E/e}
\]

\[
x_B = \frac{\pi f_{RF} L_B \sqrt{2 P_{RF} R_\perp}}{c E/e}
\]

Pillbox Fields

\[
E_z = E_0 J_1(\kappa r)e^{i\phi};
\]

\[
B_r = B_0 \frac{J_1(\kappa r)}{\kappa r} e^{i\phi};
\]

\[
B_\phi = iB_0 J'_1(\kappa r)e^{i\phi};
\]

on axis
\(\kappa r = 0\)

\[
E_z = 0;
\]

\[
B_x = \frac{B_0}{2};
\]

\[
B_y = i\frac{B_0}{2};
\]

Courtesy of D. Alesini
J.D. Fuerst, et. al., DESY Report CDR98, 1998
Deflecting Mode Cavity
Power and Resolution

\[ \sigma_{x,f} = \sqrt{\sigma_0^2 + \sigma_{\text{def}}^2} \]
\[ \sigma_{\text{def}} = 2\sigma_z L \frac{\pi V_{\perp} f}{cU/e} \]

\[ V_{\perp} \gg V_{\text{min}} = \frac{\sigma_{x,0} U/e}{L\pi \sigma_t f} \]
\[ \sigma_{t,\text{min}} = \frac{\sigma_{x,0} U/e}{L\pi V_{\perp} f} \]

\[ V_{\perp,\text{design}} = 3V_{\text{min}} = 545 \text{kV} \quad \sigma_{t,\text{min}} = 545 \text{fs} \]

\( \Delta t = \frac{\sigma_0 U/e}{L\pi f R_{\perp}^{1/2} \sqrt{nP_{\text{in}}}} \)

\( \begin{align*}
\sigma_{x,f} &= \text{beam size at screen with deflector on;} \\
\sigma_0 &= 0.3 \text{mm} = \text{beam size at screen with deflector off;} \\
L &= 43 \text{cm} = \text{drift from deflector to screen;} \\
f &= 9.6 \text{GHz} = \text{RF frequency;} \\
V_{\perp} &= \text{deflecting voltage;} \\
R_{\perp} &= 820 \text{k}\Omega = \text{transverse shunt impedance per cell;} \\
P_{\text{in}} &= \text{input RF power;} \\
U &= 12 \text{MeV} = \text{electron beam energy;} \\
\varphi_0 &= \text{deflector injection phase} = 0; \\
\sigma_{t,\text{min}} &= \text{minimum resolvable rms bunch length;} \\
\Delta x &= 30 \mu\text{m} = \text{spatial resolution of screen \& optics;} \\
\Delta t &= \text{effective temporal resolution of deflector;} \\
\end{align*} \)

9 cells; 50 kW; 400 fs resolution
Overview of Design Process

2004

- Cold test prototype
  - Aluminum 9-cell
  - 9.3 GHz
  - Cold-test only
  - Clamped
  - No polarization separation

2005

- Steel prototype
  - Steel with Cu coating 9-cell
  - 9.5 GHz
  - Cold-test only
  - Cflange design
  - No polarization separation

2006

- Final design
  - GlidCop Al-15 9-cell
  - 9.59616 GHz
  - Tested up to 50kW peak pwr
  - Cconfalt flange design
  - EDM’ed polarization holes
Deflecting Cavity Animations

H-field complex magnitude

H-field vector plot
Deflecting Cavity: Polarization Separation

- **Rods** give larger mode separation but shift the desired mode too much.
- **Holes** give less mode separation but don’t perturb the desired mode.
- In final design, holes used with radius reduced to 1 mm, giving a mode separation of 1 MHz.

**Hole/rod radius = 2 mm**

- Undesired +1358 MHz
- Desired +53 MHz
- Undesired -7 MHz
- Desired -2 MHz
Final Cavity Design

- 9-cell standing wave structure
- center-fed input RF
- reconditioned VA-24G klystron
- no brazing between cells
- cells are stacked CF vacuum flanges

x-band klystron (50 kW peak)

CAD drawing of stacked cells

one cell with polarization holes
S-Band/X-Band frequencies are multiples of modelocker freq of drive laser

Ensures phase stability of gun, linac, laser, and deflector
Bead Pull Results

- Bead pull using aluminum bead
- Data proportional to $|E|^2$ and $|H|^2$
- Field flatness $\sim \pm 5\%$
- Data taken at room temp (24°C)

After brazing input coupler

Field flatness $\sim 10\%$

\[ f_0 = 9.60084 \text{ GHz} \ ; \Delta f = 1.5 \text{ MHz} \]
\[ \beta = 0.870 \ ; \text{VSWR} = 1.15 \]
\[ Q_L = 6359 \ ; Q_0 = 11889 \ ; Q_e = 13672 \]
Temperature Tuning

Frequency vs. Temperature

- using heater tape and thermocouple
- PID temperature feedback control
- dots are measured data
- solid lines are linear fits
- $\frac{df}{dT} = -179$ kHz/°C

Reflectance vs. Temperature

- dots are measured data
- solid lines are interpolations
- at optimal freq in vacuum (9.59616 GHz), cavity is slightly overcoupled (-35 dB @ 62 C)
- therefore operating $\beta = 1.036$ in vacuum
High Power RF Measurements

- oscilloscope traces for several attenuation settings
- measured on deflecting cavity waveguide power coupler
- maximum forward power level is 50 kW
Experimental Setup

- pop-in faraday cup / 1” YAG
- YAG = ytrium aluminum garnet
Deflection vs. RF Phase

- Solid curve = sine function fit
- Amplitude = $eV_0L/p_0c = 5.5 \text{ mm}$

$$y_{cen} = \frac{eV_0L}{p_0c} \sin(\phi_0)$$

<table>
<thead>
<tr>
<th>Method</th>
<th>Forward Power (kW)</th>
<th>$V_0$ (kV)</th>
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<tbody>
<tr>
<td>Phase Scan</td>
<td>9.6 kW</td>
<td>232</td>
</tr>
<tr>
<td>RF (50 $\Omega$ termination)</td>
<td>12.75</td>
<td>267</td>
</tr>
<tr>
<td>RF (1 M$\Omega$ termination)</td>
<td>12.15</td>
<td>261</td>
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- Comparison with RF values
- Calibrated crystal detector
- Assumption: shunt impedance = 5.6 M$\Omega$ (sim. value)
Deflecting Cavity: Uncompressed Beam

- beam is on-crest in linac (no chirp)
- therefore not compressed in dogleg
- beam appears asymmetrical
- somewhat long pulse
- a lot of structure in the tail
- in some streaks, it is more pronounced
- structure related to nonlinear xtals (?)

\[ \sigma_t = 5.9 \text{ ps} \]

---

IR drive laser autocorrelation

\[ \text{FWHM} = 28.8 \text{ ps} \quad \text{(IR)} \]

Doubling xtals
(factor of 2)

\[ \text{FWHM} = 14.4 \text{ ps} \quad \text{(UV)} \]

\[ \sigma_{\text{rms}} \sim 7 \text{ ps} \]
Deflecting Cavity: Compressed Beam

- chirped 20° in linac, 234 pC of charge at 11.8 MeV with $V_0 = 400$ kV
- residual horizontal dispersion produces pseudo-phase space reconstruction
- combination of linear and nonlinear effects ($R_{16}$ & $T_{166}$)
- ramping mechanism clearly visible
- due to asymmetry of initial pulse, overcompensation with sextupoles needed

ELEGANT Simulation

“streak” in x, y, z phase space current profile

sextupoles: 0 m$^3$
sextupoles: 602 m$^3$
sextupoles: 903 m$^3$
sextupoles: 1204 m$^3$
Gaussian beam

sextupoles: 1094 m$^3$
sextupoles: 1641 m$^3$
sextupoles: 2188 m$^3$
Asymmetric (front-heavy) beam
ELEGANT Simulation

“streak” in x,y z phase space current profile

Gaussian beam

sextupoles: 0 m⁻³

sextupoles: 602 m⁻³

sextupoles: 903 m⁻³

sextupoles: 1204 m⁻³

Asymmetric (front-heavy) beam

sextupoles: 0 m⁻³

sextupoles: 1094 m⁻³

sextupoles: 1641 m⁻³

sextupoles: 2188 m⁻³
observed compression when running off-energy by 0.76%
however, for negative chirp, dogleg should expand, not compress

\[ z_f = z_0 + R_{56} \delta + T_{566} \delta^2 \]

-0.4 cm -10 m (!)

-0.4 cm -10 m (!)

\[ \hat{R}_{56} = R_{56} + 2T_{566} \Delta \]

\[ z_f = z_0 + \hat{R}_{56} \hat{\delta} + \hat{T}_{566} \hat{\delta}^2 \]

sextupoles used to remove \( T_{566} \)

Further Applications: Doglegs
SLAC - ORION Low-E Hall Dogleg

- studies for PWFA / general transport
- large energy spread requires octupole correction

initial beam | no sextupoles | with sextupoles | sext’s + oct’s

Further Applications: Deflecting Cavity
Dynamically Optimized Beam Profiles

Beam Charge: 0 to 50 pC
Beam energy: up to 4 MeV
Power Source: 18 MW Klystron
RF Frequency: 2.856 GHz (S-Band)
Cathode laser: 10 µJ at $\lambda = 266$ nm
Laser pulse length: 50 fs RMS

Future Experiments
Witness Beam Generation

For PWFA application, drive beam needs a witness beam to accelerate.

Region of high dispersion in x
Strong correlation b/w x and z
Insert mask in x to sever beam in z

No mask inserted
Undercorrected with sextupoles to elongate profile

With 1cm mask inserted at above location
Future Experiments
PMQ Focusing

- Hybrid Permanent Magnet and Iron
- Grey cubes are Alnico; M=1.175 T
- Field gradient:
  \[ B' = 110 \text{ T/m}; B'' = -0.002 \text{ T/m}^2 \]
- Bore diameter: 8 mm
- Benefits: cheaper, better field profile
- Downsides: small bore; in-vacuum
ELEGANT Simulation Result

\[ \gamma = 25.7; \quad E = 13.13 \text{ MeV}; \quad Q = 300 \text{ pC} \]

\[ \sigma_x = 130 \mu \text{m}; \quad \varepsilon_x = 41 \text{ mm mrad} \]

\[ \sigma_y = 57 \mu \text{m}; \quad \varepsilon_y = 15 \text{ mm mrad} \]

\[ \sigma_z = 0.51 \text{ mm}; \quad \sigma_\delta = 1.84\% \]

\[ B \approx \frac{2Q}{\varepsilon_{N,x}} \frac{\varepsilon_{N,y}}{\sigma_x} = 412 \text{ mA} / \mu \text{m}^2 \]
Conclusions

• Proposal:
  - ramped beams: improved transformer ratio ($R > 2$) for PWFA applications
  - feasible using dogleg compression with sextupoles
  - deflecting cavity diagnostic (500 fs resolution)

• Deflecting cavity
  - final cavity design finalized in 3-phase process w/ 2 prototypes
  - cavity testing indicates that it operates within the design specifications
  - high power RF testing: no breakdown problems observed

• Experimental tests:
  - unchirped (uncompressed) beam has asymmetric structure
  - chirped beam w/residual dispersion = semi-tomographic reconstruction
  - evidence for ramp-shaped electron beams

• Other Experiments:
  - deflector use for measuring optimized charge distributions
  - dogleg high-brightness focus studies
  - witness bunch generation
## Acknowledgements

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