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

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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:

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

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

\[ R > 2 \quad \text{if} \quad L_z > 2k_p \]

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

![Diagram of chicane]

higher-energy particles travel a shorter path

$$R_{56} = \frac{\partial z}{\partial \delta} > 0 \quad \text{“positive longitudinal dispersion”}$$

dogleg

![Diagram of dogleg]

higher-energy particles travel a longer path

$$R_{56} = \frac{\partial z}{\partial \delta} < 0 \quad \text{“negative longitudinal dispersion”}$$
Ramped Beam Mechanism

Artificial mathematical manipulation of a chirped particle distribution

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

linear transformation: $z_f = z_0 + R_{56}\delta$

$T_{566}$ 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.
Ramped Beam Mechanism

Artificial mathematical manipulation of a chirped particle distribution

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

\( T_{566} \) 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.
- 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 $2\pi$ betatron advance.
- Like a chicane, may be used as a bunch-length compressor.
- Nominal first order temporal dispersion ($R_{56} = -5\text{cm}$) is suitable for beam-shaping.
- Sextupoles required to compensate 2nd order longitudinal dispersion.
Neptune Dogleg Compressor
PARMELA Simulation Results: 1000 particles, 300pC

Initial

Final: Sextupoles Off

Final: Sextupoles On

- 2D PIC Simulation
- 5 GeV/m gradients
- 6 nC drive beam w/ n_0=2e16 cm⁻³
Neptune Dogleg Compressor
PARMELA Simulation Results: 1000 particles, 300pC

\[ \Delta \varepsilon_{x,N} = 9.9 \, \mu m + 12.7 \, \mu m = 22.6 \, \mu m \]

\[ \varepsilon_{x,N} \text{(initial)} = 4.9 \, \mu m \]

Initial

Final: Sextupoles Off

Final: Sextupoles On

GUN PWT Pre-Focus sextupoles Final Focus
The UCLA Neptune Laboratory

Beam Charge: $100\text{pC} \rightarrow 500\text{pC}$

Beam energy: up to $15\text{ MeV}$

Emittance: $\varepsilon_N = 4\text{ mm mrad}$

Power Source: $18\text{ MW Klystron}$

RF Frequency: $2.856\text{ GHz}$

Cathode laser: $60\mu\text{J at } \lambda = 266\text{ nm}$

Laser pulse length: $5-7\text{ ps RMS}$
Simulations predict “ramped” beam occurs near point of maximum compression ($\kappa$=1094 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
Coherent Transition Radiation Measurements of Compression

\[ \sigma_T(\text{ps}) \]

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

\[ \kappa = 0 \text{ m}^{-3} \quad \kappa = 1094 \text{ m}^{-3} \quad \kappa = 1641 \text{ m}^{-3} \quad \kappa = 2735 \text{ m}^{-3} \]
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

\[
\begin{align*}
E_z &= E_0 J_1(\kappa r)e^{i\phi}; \\
B_r &= B_0 \frac{J_1(\kappa r)}{\kappa r} e^{i\phi}; \\
B_\phi &= iB_0 J'_1(\kappa r)e^{i\phi};
\end{align*}
\]

\[
\begin{align*}
x' &= \frac{\pi f_{RF} L_B \sqrt{2P_{RF} R_\perp}}{cE/e} \\
x_B &= \frac{\pi f_{RF} LL_B \sqrt{2P_{RF} R_\perp}}{cE/e}
\end{align*}
\]

Pillbox Fields

on axis
\[\kappa r = 0\]

\[
\begin{align*}
E_z &= 0; \\
B_x &= \frac{B_0}{2}; \\
B_y &= i\frac{B_0}{2};
\end{align*}
\]
Deflecting Mode Cavity
Power and Resolution

Screen deflection: $\sigma_{x,f} = \sqrt{\sigma_0^2 + \sigma_{\text{def}}^2}$
$\sigma_{\text{def}} = 2\sigma_z L \frac{\pi V_{\perp} f}{c U / e}$

$V_{\perp} >> V_{\text{min}} = \frac{\sigma_{x,0} U / e}{L \pi \sigma_{t,f}}$
$\sigma_{t,\text{min}} = \frac{\sigma_{x,0} U / e}{L \pi V_{\perp} f}$

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

$\sigma_{x,f}$ = beam size at screen with deflector on;
$\sigma_0 = 0.3mm$ = beam size at screen with deflector off;
$L = 43cm$ = drift from deflector to screen;
$f = 9.6GHz$ = RF frequency;
$V_{\perp}$ = deflecting voltage;
$R_{\perp} = 820k\Omega$ = transverse shunt impedance per cell;
$P_{\text{in}}$ = input RF power;
$U = 12MeV$ = electron beam energy;
$\phi_0$ = deflector injection phase = 0;
$\sigma_{t,\text{min}}$ = minimum resolvable rms bunch length;
$\Delta x = 30\mu m$ = spatial resolution of screen & optics;
$\Delta t$ = effective temporal resolution of deflector;

\[ \Delta t = \frac{\sigma_0 U / e}{L \pi f R_{\perp}^{1/2} \sqrt{n P_{\text{in}}}} \]

Resolution vs. Power: 9.6 GHz

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

- **Cold Test Prototype**
  - Aluminum 9-cell
  - 9.3 GHz
  - Cold-test only
  - Clamped
  - No polarization separation

- **Steel Prototype**
  - Steel with Cu coating 9-cell
  - 9.5 GHz
  - Cold-test only
  - Cf flange design
  - No polarization separation

- **Final Design**
  - GlidCop Al-15 9-cell
  - 9.59616 GHz
  - Tested up to 50 kW peak pwr
  - Conflat 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.

- Undesired: +1358 MHz
- Desired: +53 MHz
- Undesired: -7 MHz
- Desired: -2 MHz

hole/rod radius = 2 mm
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 RF System

- S and X-Band frequencies are multiples of modelocker freq of drive laser
- Ensures phase stability of gun, linac, laser, and deflector
Bead Pull Results

After brazing input coupler

- 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)

Field flatness $\sim 10\%$

$f_0 = 9.60084$ GHz; $\Delta f = 1.5$ MHz
$\beta = 0.870$; 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
- \( \frac{df}{dT} = -179 \text{ kHz/}°\text{C} \)

\( f_0 = 9.596 \text{ GHz} ; \Delta f = 1.5 \text{ MHz} \)
\( \beta = 1.036 ; \text{VSWR} = 1.03637 \)
\( Q_L = 6638 ; Q_0 = 13043 ; Q_e = 13517 \)

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 = yttrium aluminum garnet

Faraday Cup Calibration

\[ y = 4.566x + 0.9899 \]
Deflection vs. RF Phase

- Solid curve = sine function fit
- Amplitude = $eV_0 L/p_0 c = 5.5$ mm

$$y_{cen} = \frac{eV_0 L}{p_0 c} \sin(\phi_0)$$

<table>
<thead>
<tr>
<th>Method</th>
<th>Forward Power (kW)</th>
<th>$V_0$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Scan</td>
<td>9.6 kW</td>
<td>232</td>
</tr>
<tr>
<td>RF (50 Ω termination)</td>
<td>12.75</td>
<td>267</td>
</tr>
<tr>
<td>RF (1 MΩ termination)</td>
<td>12.15</td>
<td>261</td>
</tr>
</tbody>
</table>

- Comparison with RF values
- Calibrated crystal detector
- Assumption: shunt impedance = 5.6 MΩ (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 (?)

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

- FWHM = 28.8 ps (IR)
- doubling xtals (factor of 2)
- FWHM = 14.4 ps (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 $V_0 = 400 \text{ kV}$
- 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

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$^{-3}$
ELEGANT Simulation

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

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Gaussian beam

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Future Applications
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

- Witness beam
- Ramped drive beam
Future Applications
Tailored Profiles for FACET?

- dogleg: $R_{56} = -7\text{cm}$
- reduce chicane compression to increase bunch length to $\sim 2\, k_{p}^{-1}$
- collimate to remove low-energy tail
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
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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


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

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

\[ B_{\perp,\text{opt}} = 80 \, \text{A/\mu m}^2 \]
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 $L_g$

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

Inverse Compton Scattering
- beam + laser (hv) ---> higher hv* photons
- shortness of scattered pulse limited by shortest of beam, laser

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

Plasma Wakefield Accelerator:
- beam + plasma --> high-gradient wakes
- beam density, time profile important

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

$$\Lambda = (n_{\text{beam}} / n_0) k_p^2 \sigma_r^2$$
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 λ = 266 nm
Laser pulse length: 50 fs RMS

• observed compression when running off-energy by 0.76%
• however, for negative chirp, dogleg should expand, not compress

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

off energy by \( \Delta = -0.76\% \)

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

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

+18 cm

-0.4 cm -10m (!)

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

PowerTrace 1.08 Simulation

PMQs (110 T/m)

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

$$B \approx \frac{2Q}{\sigma_i} \frac{\varepsilon_{N,x}}{\varepsilon_{N,y}} = 412 mA / \mu m^2$$