Recent Developments In Electron Pulse Compression

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Outline

• Applications of ultra-short electron beams
• Schemes for ultra-short beam creation
• Physics issues in compression: collective effects
• Review of experimental progress and measurement techniques
• Near future plans
Applications of Compressed Electron Beams: Wakefield Accelerators

- Beam used as power source for driving high frequency waves
- Need high frequency content in beam:
  - Short bunches
  - Modulated bunches
  - Ramped bunches
- Cerenkov scaling (nearly) holds for linear/nonlinear systems

Simulated GeV/m Cerenkov wakes for FFTB parameters

\[ W \propto N_b \kappa_{\text{max}} \propto N_b \sigma_z^2 \]

Frontier: \( Q \sim nC \sim 50 \text{ fs} \)

Requirements on \( \varepsilon \) relaxed
Creation of compressed, ramped beams for high XFMR ratios

- Slow ramp, fast fall (sub-100 fs)
- Negative $R_{56}$ gives correct ramp
- Challenge in measuring time domain features.

Optimum profile

Phase space

Current profile

Wakes in 1E16/cc plasma, from PIC simulation
Optical Accelerators

- Laser-based accelerators
- Resonant wakefield accelerators
- Characterized by pulse trains (microbunching)
- Few microns/fs scales
- Charge/bunch
  - Small for laser accelerator
  - Large for wakefield accelerator
- Relatively small emittance
  - Apertures in laser accelerator
Applications of Sub-picosecond Beams: Sub-picosecond Radiation Sources

X-ray SASE Free-Electron Lasers
A fast growing beam-radiation instability; needs cold, dense “lasing media”
High energy (>10 GeV), low energy spread

- Very high current (>kA)
- Excellent emittance (~ mm-mrad)

Short pulse (<100 fsec) beams

Inverse Compton Scattering Sources
Ultra-short $\lambda$ from collision of short pulse lasers and electron beams; needs “luminosity”

- Low energy! (~20-200 MeV)
- Very high current (>kA)
- Focusability, good emittance

Short pulse (<100 fsec) beams, sub-psec timing

Needs highest brightness beams for gain...

$B_e = \frac{2I}{\epsilon^2}$
Chicane Compression

- Negative chirp applied to beam (forward of crest in linac). Positive $R_{56}$ then compresses beam

$$R_{56} \approx 4 R(\theta_b - \sin \theta_b)$$

- Compression in middle dipoles
- Final current profile limited by
  - rf curvature
  - dynamical nonlinearities
  - Collective effects
- Final current has sharp rise, long tail
- Space charge and wakes degrade compression

Schematic for chicane compression

Simulated longitudinal phase space and current profile from chicane compression at TTF
IFEL: chicane compression for bunch trains

- Compression with continuous application of chirping (nonlinear) and magnetic path length difference
- Popular for prebunching!
  - STELLA (done)
  - LEAP (soon)
  - Neptune (proposed)

Simulation of proposed Neptune THz IFEL Prebuncher (Tochitsky/Musumeci)
Dogleg compression

- Negative $R_{56}$ beamline
  - Correctly ramped beams
  - Match dispersion with quadrupoles

- Very nonlinear
  - Extremely large $T_{566}$
  - Experience at BNL ATF
  - Sextupole correction needed

- Newly implemented at Neptune
- Planned for ORION

Equation:

$$R_{56} = 2R\left(\theta_b - \tan \theta_b \right)$$

Dogleg sections at (a) ATF-VISA, (b) UCLA Neptune, and (c) ORION-SLAC. Sextupoles indicated in red.
Longitudinal phase space transport linearization with sextupoles

- Correction of $T_{566}$ gives desired linearized transformation in longitudinal phase space (ELEGANT simulation)
- Also helps with nonlinear emittance growth
Velocity Bunching

- Proposed by Serafini, Ferrario; avoids magnetic compression
  - Large energy spreads at low energy
- Inject emittance-compensated beam at 5-7 MeV into linac near zero-crossing
- Perform one-quarter of synchrotron oscillation to compress beam
  - Alternative: ballistic compression (gun or linac)
- Similar to thermionic injector bunchers, but with high phase space density
- Must simultaneously control emittance
  - Continuous emittance compensation

Longitudinal phase space schematic for velocity bunching
Physics issues in compression

- Nonlinear effects in transport
- Velocity fields
  - Longitudinal space charge. Energy change can fight or help compression!
  - Transverse space-charge
  - Produces dispersion mismatch
- Acceleration fields
  - Coherent synchrotron radiation (CSR)
  - Produces energy changes forward in bunch
  - New type of instability, *spontaneous microbunching*, cousin of FEL

BNL SDL zero-phasing measurement of microbunching?
Modeling Tools

- Many commonly used programs; all have notable limitations
- PARMELA
  - Electrostatic approximation
  - Only for velocity bunching
- ELEGANT
  - No velocity fields
  - Rudimentary CSR model
- TREDI
  - Free-space Lienard-Wiechert
  - Far-field calculations
- TRAFIC4
  - 3D charge-based model
  - Cond. boundary conditions
- KEK code
  - Mesh based, boundary conditions
  - No velocity field

Frequency spectrum from 1000 particle TREDI simulation of coherent edge radiation (far field) for UCLA/BNL compressor
Chicane compression at FNAL A0: Initial use of compressed beam for PWFA

- Streak camera and coherent transition radiation diagnosis
- Compressed beam at A0 has 1.6 kA in 2 psec rms
  - Beam matched with plasma blowout ion focusing
  - Very large relative acceleration/deceleration

Compression of 8nC bunches at FNAL A0 Photoinjector (OTR streak data)

Beam deceleration; almost stops in 7 cm.

Acceleration to > 24.3 MeV (~130 MeV/m), 60% gain.
Neptune chicane compression: Transverse phase space bifurcation

- 12 MeV, 300 pC bunches compressed to 0.6 ps rms
- Slit-based reconstruction of transverse phase space
- Modeling indicates that velocity fields dominate
- Configuration space folding during final magnet splits phase space

Measured uncompressed horizontal phase space

Compressed, bifurcated horizontal phase space
Testing the limits of CTR Martin-Puplett interferometer

- Velocity bunched beams at Neptune and LLNL produce very short beams
  - Compression limited by RF nonlinearities
  - 0.3-0.4 ps (~100 μm)
- Polarizing beam splitter has 100 μm wire spacing
- @ limit of resolution
- Much tougher at SLAC

CTR interferogram of velocity bunched beam at Neptune
Michelson (amplitude splitting) Interferometer for CTR Bunch Length Measurement

- Need to measure much shorter (20 micron) beams
- Substitute Mylar amplitude beam splitters for polarizers

M. Hogan (SLAC)
P. Muggli (USC)
First Measurement of SLAC Ultra-short Bunch Length!

M. Hogan (SLAC)  
P. Muggli (USC)

Reconstruction:
\[ \sigma_z \approx 18 \, \mu m \]

- Take into account Fabry-Perot resonances: \( \lambda = 2d/nm, \; m=1,2,\ldots \)
- Expected effect of frequency notches (9 micron autocorrelation)
- Very large wakes, of course!
- Need to measure even better
**Bunching and Spontaneous Microbunching DUVFEL Accelerator**

T. Shaftan, et al., BNL

- For energy/time domain measurements we use CCD camera (Num. 14) located after 72° spectrometer dipole.
- “Zero-phasing” method of the bunch length measurement:
  a) single-shot
  b) gives high time resolution (~10 fs)

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Curious “microbunching” observations

• “Zero-phasing” images from the spectrometer dipole revealed spiky structure with sub-picosecond period in the chirped beam energy spectrum.

• Assuming that the chirped bunch energy spectrum represents longitudinal density distribution → spikes could be treated as spikes in the longitudinal bunch density (peak current).

• Similar effect has been observed at Tesla Test Facility.

W.S. Graves, et al., PAC 2001, p. 2860

M. Huning et al., NIM A 475 (2001) p. 348
Explanation: Space-charge-induced distortion of bunch energy spectrum

- Modulation of beam energy spectrum by longitudinal space charge
- Initial temporal modulation of drive laser/injected beam
- Density modulation converted to energy modulation
- Microbunching is diminished
- Not CSR instability!
Neptune dogleg compression: first results

- Sextupole correction parametrically tested
- Beam size and bunch length systematics v. sextupole strength
- Must measure better! X-band RF deflector...
- J. England reports here

UCLA sextupole at Neptune
Velocity bunching optimization and implementation

- Long slow-wave structure from tuning $\omega$ (new source) or $k$ (structure)?
  - Mimic with short linac sections (LLNL)
- Alternative: use very short bunching section to split functions of bunching and acceleration
- Emittance compensation
  - Tailored solenoid focusing

Bunch length in ORION case

PARMELA simulation of ORION bunching emittance compensation
Velocity bunching experiments at BNL DUV-FEL

- Direct test of Serafini-Ferrario proposal
- Bunching measured with zero-phasing, CTR amplitude
- Modest bunching observed (~3)
- No emittance compensation
Velocity bunching experiments at LLNL PLEIADES ICS

- Very short beams
  - 0.3 ps (UCLA CTR)
  - ~15 times compression
- Emittance growth limited to <50% by use of solenoids around TW linacs
- Used to enhance X-ray brightness by ~4
  - S. Anderson talk
- Experimental improvements needed
  - INFN SPARC project

Single shot, false-color X-ray beam images measured by the CCD for the (a) uncompressed and (b) compressed electron beams
Microbunch train creation at STELLA

- Excellent microbunching measured by trapping and acceleration efficiency
- Good agreement with model

Kimura, et al.
Microbunching from radiation measurements at VISA

- Measure harmonic gain in FEL (coherent undulator radiation)
- Harmonics give additional information
- CTR harmonics as well...

Wavelength spectrum of saturated VISA FEL signal: fundamental, 2nd and 3rd harmonics.

Second harmonic CTR as a function of SASE signal at VISA FEL
Some future directions

- Measurement techniques
  - fs RF sweeping diagnostics
- Collective physics
  - Coherent edge radiation
Deflecting Mode Cavity
Longitudinal Diagnostic

Lowest dipole mode is $T_{M10}$
Zero electric field on-axis (in pillbox approx.)
Deflection is purely magnetic
Polarization selection requires asymmetry

\[ x' = \frac{\pi f_R L_B \sqrt{2P_{RF}R_s}}{cE/e} \]

\[ x_B = \frac{\pi f_R L_B \sqrt{2P_{RF}R_s}}{cE/e} \]

- Old idea from SLAC, LLNL, etc.
- Revived by X. Wang for LCLS proposal
- New implementation at SLAC
- New development at low energy, high frequency at INFN-LNF, UCLA Neptuen
Neptune X-band Profile Measurement System

ELEGANT Simulation Results

9.59 GHz cold test at Neptune

Initial Current Profile

- $V_0 = 0; P = 0$
- $V_0 = 272$ kV; $P = 12$ kW
- $V_0 = 545$ kV; $P = 48$ kW
- $V_0 = 609$ kV; $P = 61$ kW
More advanced diagnostics

- Longitudinal phase space (with dipole)
- Slice emittance (with quad scan)

Simulated longitudinal phase space at SPARC

Simulated spatial signal from longitudinal phase space diagnostic
ATF Chicane CER experiment

- UCLA/ATF chicane
- Coherent edge radiation (CER) output port

20 micron beams!
CER Spectrum

ER v. SR wavelength spectrum

Signal at output window in BNL ATF chicane

- Long wavelengths look like transition radiation in angle
- Easier to detect wavelength signature
- Experiment now in commissioning stage
Conclusions

• Ultra-short pulse generation, manipulation and measurement are critical to advanced accelerator and FEL development

• Concepts theoretically, computationally, and now experimentally, mature

• Some of what were once experiments are now tools

• Next few years should yield a wealth of results in compression, and applications of compressed beams