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Understanding 1D to 3D Coherent Synchrotron Radiation Effects

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Free Electron Laser Conference

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Outline

- Introduction
- Theory of CSR
- Inclusion of transient effects
- Simulations
- Effect on electron beam
- Experimental measurements
- Conclusion

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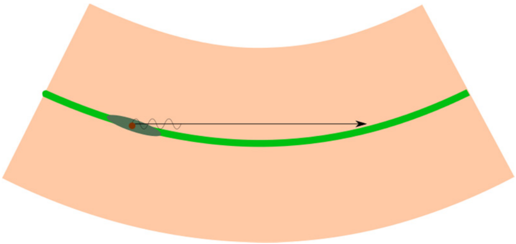
Motivation

Coherent Synchrotron Radiation (CSR)

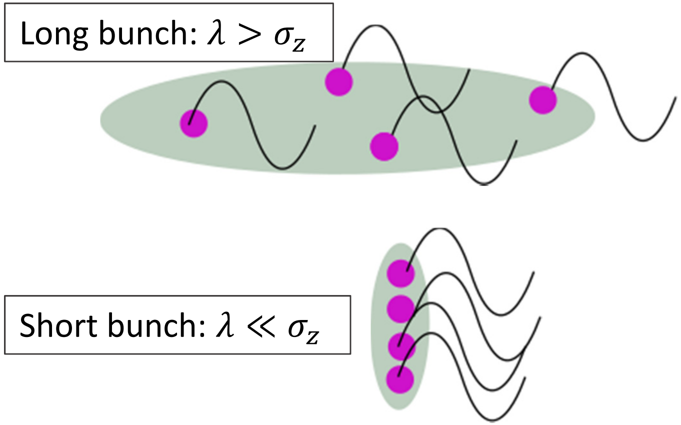


- Particles on a curved trajectory emit synchrotron radiation.

- Radiation due to a bunch of electrons in a dipole causes a wakefield which can interact with particles at the head of the bunch, causing a loss in energy and emittance growth.

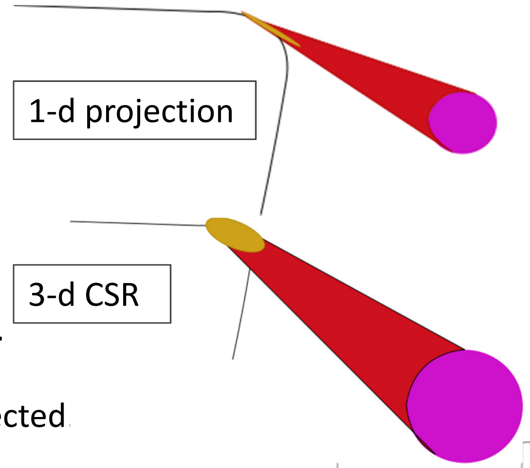
- Overtaking length: $L \sim (24\sigma_z R^2)^{1/3}$

- Power radiated causes an energy loss in the bunch: $P \propto N^2$ - CSR is a problem for short bunches!



Motivation

Calculations of CSR

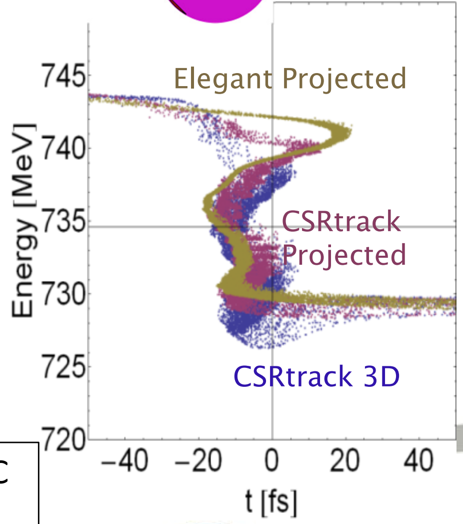


- Many codes simulate CSR energy loss in the 1-d approximation.
  - The bunch distribution is projected onto the nominal axis.
  - Any change in longitudinal distribution due to CSR is neglected.
  - Ultrarelativistic approximation.
  - Assumes infinitely long drifts before and after the dipole.

- A bunch with larger transverse size has a larger radiation cone -> possible miscalculation of CSR wake and error in convolving the wake with the bunch distribution.

- Need to validate codes and test their region of applicability (particularly 1D), and compare with experiment.

- 1D codes: Elegant, Impact-Z, ……..
- 2D/3D codes: CSRTrack, GPT v3, …



[1] Williams et al, EPAC '08, MOPC034 (2008)

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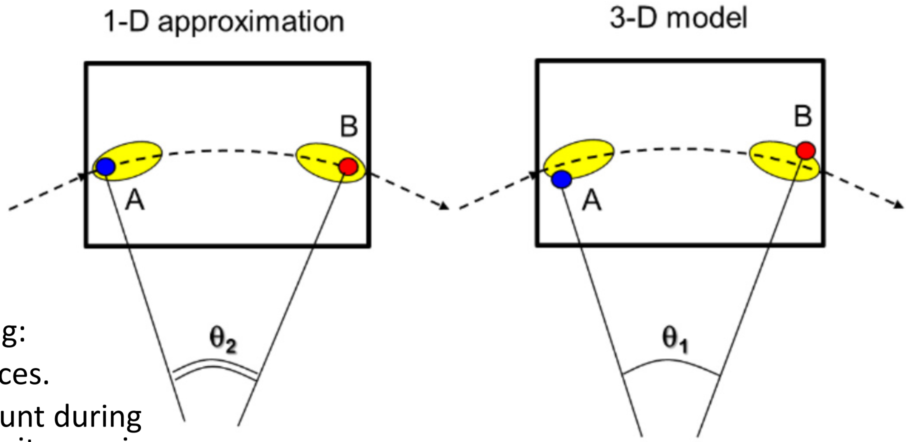
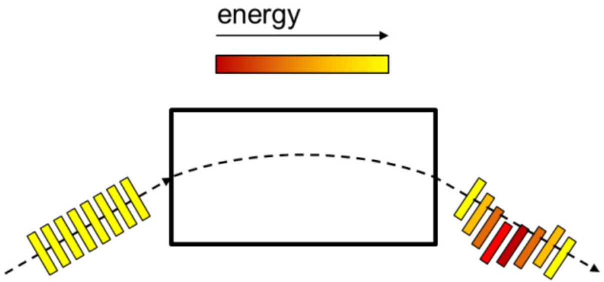
Motivation

Calculations of CSR

- A full 3D simulation of CSR needs to achieve the following:
  - Accounting for both longitudinal and transverse forces.
  - Taking the transverse extent of the bunch into account during emission, rather than assuming that all electrons emit on-axis.
  - Doing the same for the particles that experience the field from the emitters.
  - Self-consistently solving for the trajectory during emission rather than neglecting deviations from the nominal trajectory.
  - Taking the full Liénard-Wiechert field into account rather than only the term which arises during acceleration.
  - Including stochastic effects due to the long-range interaction between a discrete number of radiation cones.
  - Not assuming that the charge density distribution moves rigidly along the nominal trajectory.
  - Inclusion of shielding effects.





1D Theory

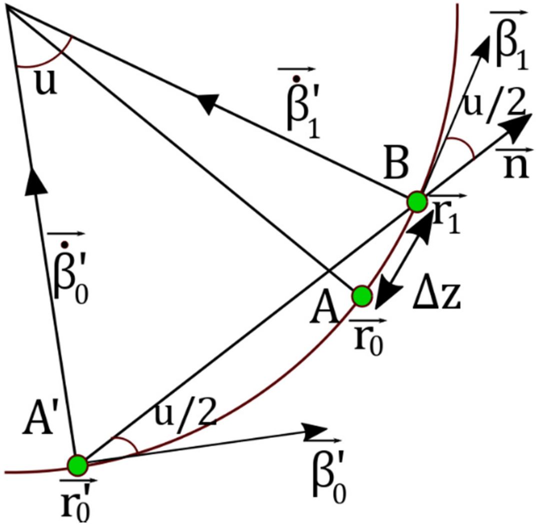
[2] Saldin et al (NIM A 398.373) (1997) distinguished 3 regimes: steady-state, entrance and exit transient

CSR Force

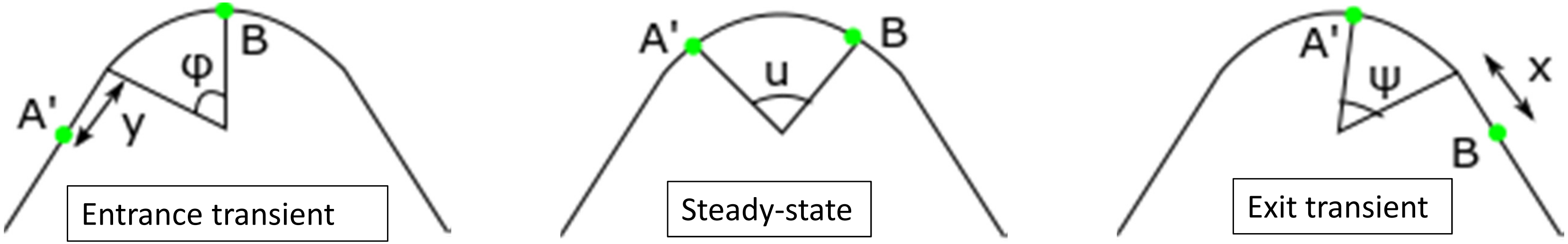
- We begin with the Liénard-Wiechert field between two particles:

'Coulomb' field — 'Acceleration' field

$$\underline{E}(\underline{r},t)=\frac{e}{4\pi\epsilon_0}\left[\frac{\underline{n}-\underline{\beta}'}{\gamma^2\left(1-\underline{n}\cdot\underline{\beta}'\right)\rho^2}+\frac{\underline{n}\times\left(\left(\underline{n}-\underline{\beta}'\right)\times\underline{\dot{\beta}}'\right)}{c\left(1-\underline{n}\cdot\underline{\beta}'\right)^3\rho}\right]$$



- The electric field experienced by a particle in front of an emitter is then dependent on the geometry of the lattice and the particle trajectory.



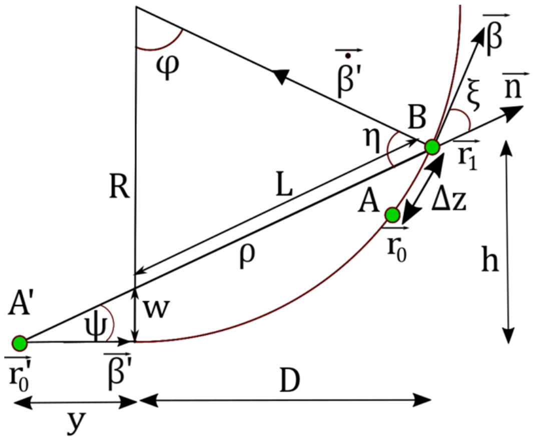
1D Theory

Entrance Transient

- For the entrance transient case, a portion of the electrons have not yet entered the dipole field, and so their contribution to the CSR field comes from the Coulomb term. [3]

- There is a partial cancellation between the two terms of the L-W field.
  - But without using the small-angle approximation, and taking the distance y to be small, there is a spike in the field experienced by the observer.

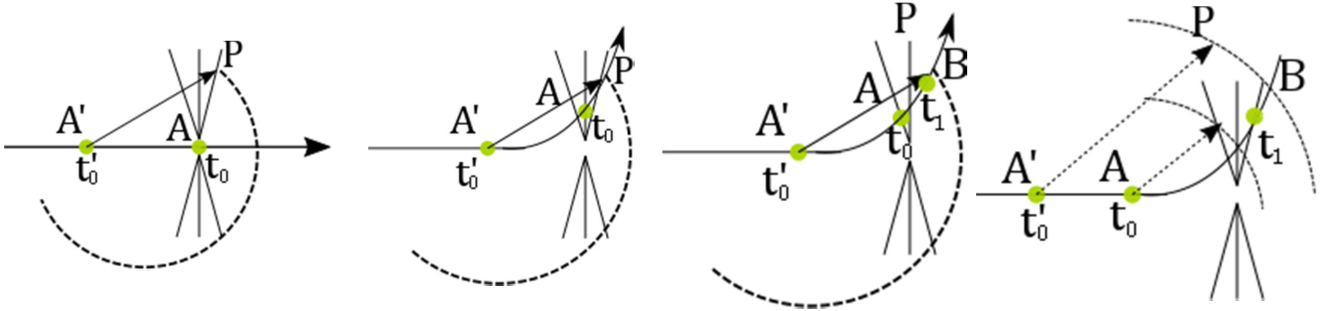
- It turns out that the Coulomb field can have a significant impact on the CSR field in the “entrance transient” regime, and so this should not be neglected in simulation.



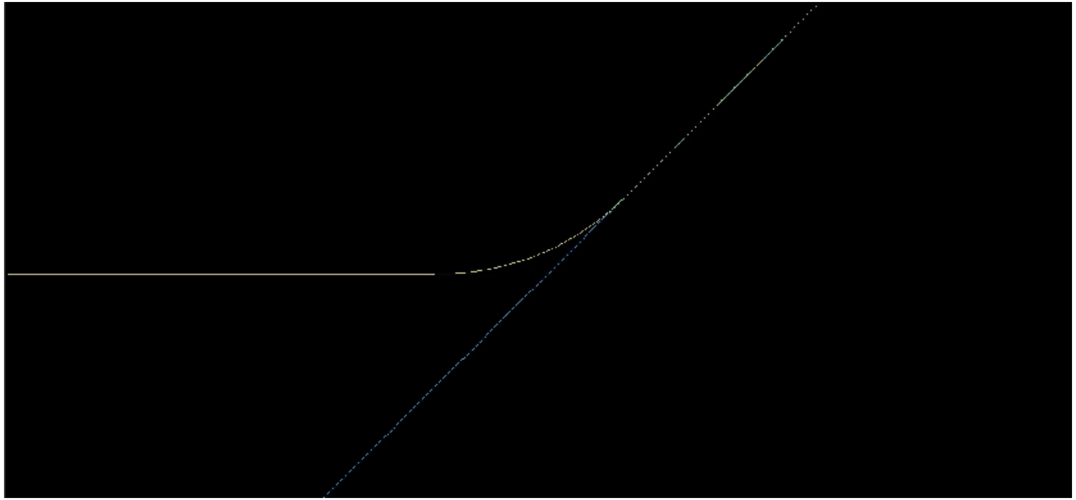
[3] Stupakov, SLAC-PUB-9242 (2002)
[4] Brynes et al, New J Phys 20.073035 (2018)

1D Theory

Entrance Transient



- Since the Coulomb field continues to travel along the straight trajectory, it moves in front of the emitting particle as it enters the bend, producing a spike in the field observed at the head of the bunch.

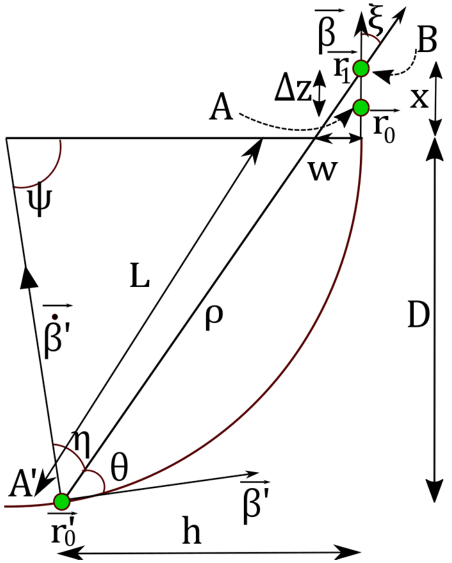


[5] Shintake, Radiation2D code (2003)

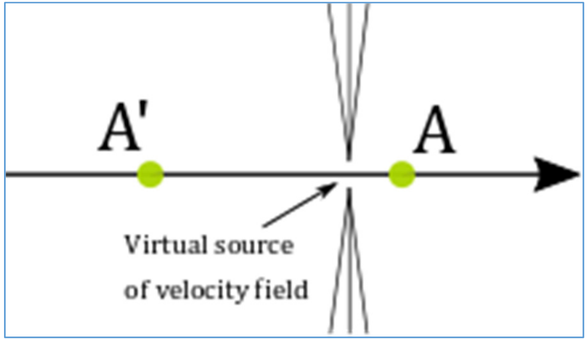
1D Theory

Exit Transient

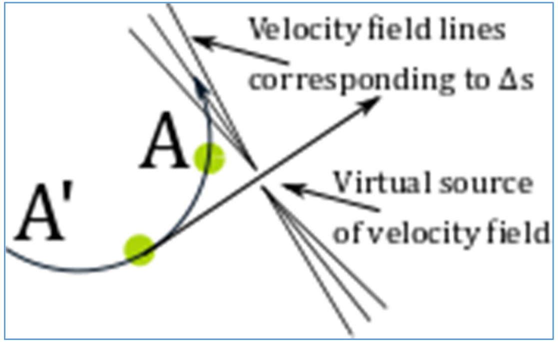
- The field lines corresponding to the velocity field of a relativistic particle are confined in a very flat pancake perpendicular to the direction of motion.
- At the end of the arc, the geometry must pass from a situation with field lines in front of the observer to a situation with field lines behind the observer, giving a spike of CSR force.



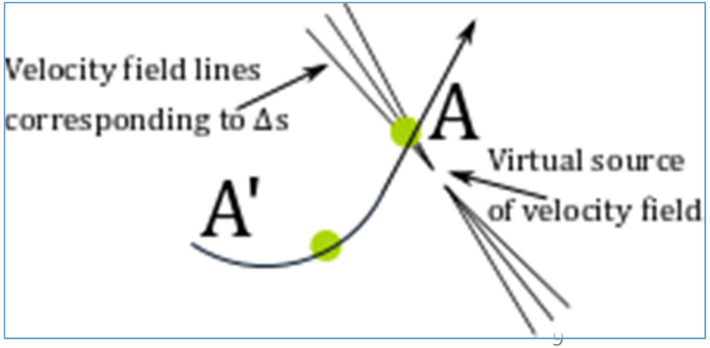
Rectilinear motion



Both particles on arc

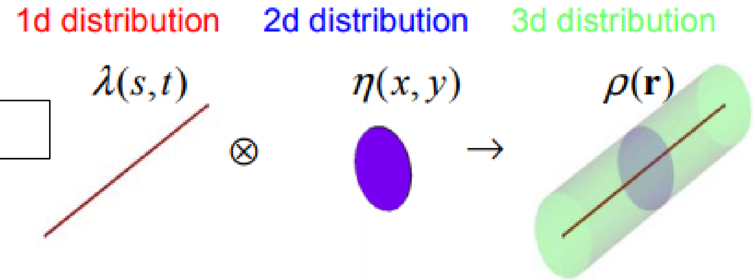


Exit transient



Simulation

[6] CSRTrack



Simulation of CSR

- Elegant: based on 1-d model of Saldin et al [2]. Good agreement with experimental results [8].

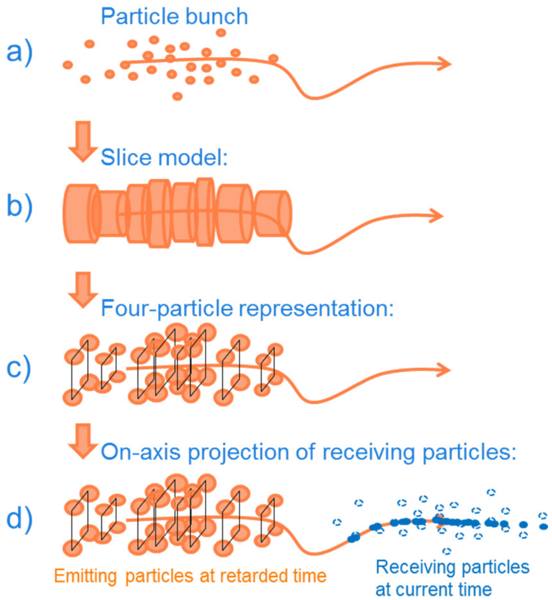
- CSRTrack: 2-d and 3-d models based on sub-bunches. Neglects vertical forces. CSR field calculated directly from retarded potentials. Good agreement with experiment [9].

- GPT v3: bunch is sliced longitudinally and coherent force simulated from four transverse points in each slice. Needs benchmarking!

- Other codes exist! (e.g. IMPACT, BMAD, CSR3D) – Not used for this study

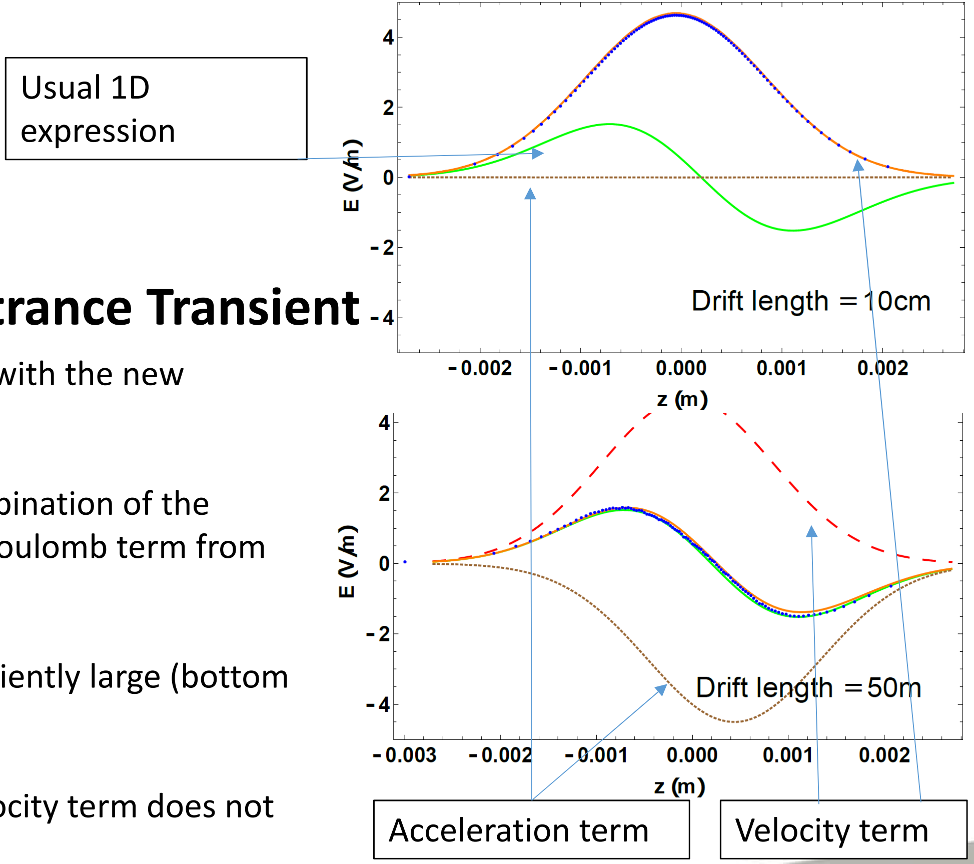
[2] Saldin et al, NIM A 398.373
[8] Bane et al, PRSTAB 12.030704
[9] Bettoni et al, PRSTAB 19.034402

[7] GPT



Simulation

Validation of GPT-CSR model – Entrance Transient



- Firstly we used a test case for 1 dipole to compare with the new expressions for transients.
- The full entrance transient field results from a combination of the radiative term from particles in the bend and the Coulomb term from particles on the straight trajectory.
- These partially cancel out if the drift length is sufficiently large (bottom plot).
- But this is not the case if the drift is small – the velocity term does not contribute to the overall CSR field.
- This is important when considering multi-bend systems!

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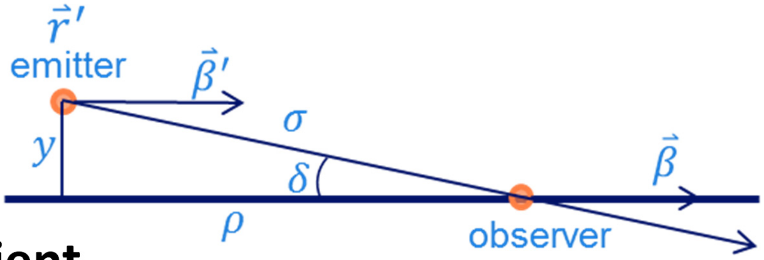
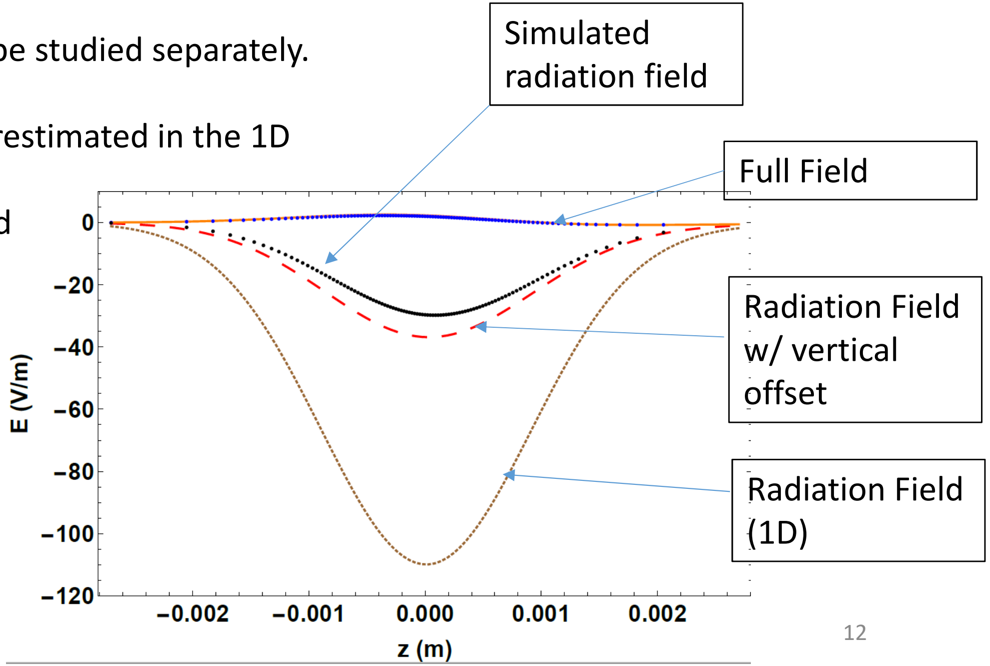
Simulation

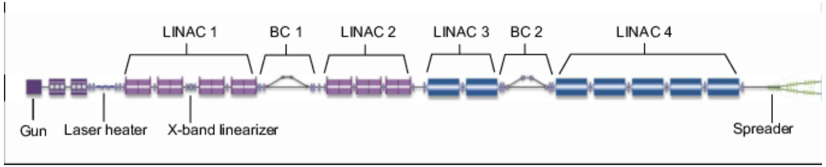


Validation of GPT-CSR model – Exit Transient

- The Coulomb and acceleration terms can also be studied separately.
- The magnitude of the acceleration term is overestimated in the 1D approximation
  - Due to an underestimation of the retarded distance between emitter and observer.
- If we offset the emitter transversely, this effect is corrected.
- However, because of the cancellation between Coulomb and acceleration terms, this 3D effect is masked.



Results



CSR Measurements: Procedure

- Measurements taken at the exit of BC1 in the FERMI FEL
- Maintain "nominal" parameters:
  - BC1 @ 105mrad.
  - Linac 1 on crest.
  - Beam matched @ exit of BC1.
  - Peak current up to 1.5kA.
  - Compression factor 8 – 65.
  - LH at full power (21uJ)
- Scan through each of BC1 angle and L1 phase.
- Measure projected emittance on OTR (and some slice measurements at exit of L4).

Electron beam parameters	Value
Energy (MeV)	300
Charge (pC)	100
Peak current (A)	560
Initial bunch length (ps FW)	1.8
Slice emittance (um-rad, norm)	<1.0
Proj. emittance (um-rad, norm)	<2.0
Uncor. e-spread (keV, rms)	150
Total e-spread (rms)	0.1%
Pulse-to-pulse energy stability	0.1%
Timing jitter (fs, rms)	<150

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[10] Stupakov, SLAC-PUB-8028 (1999)
[11] Cai, PRAB 20.064402 (2017)

Results

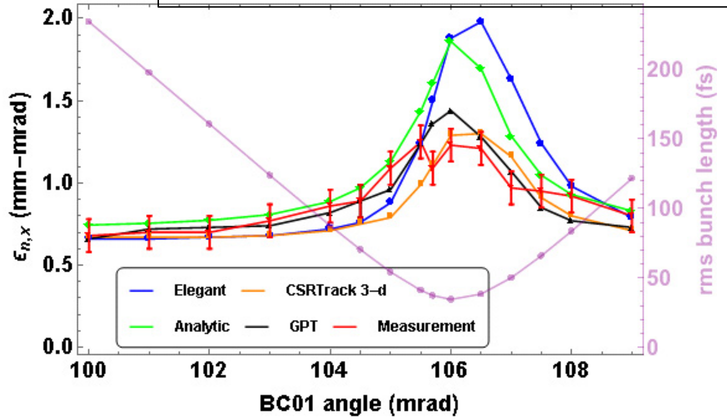
CSR Measurements

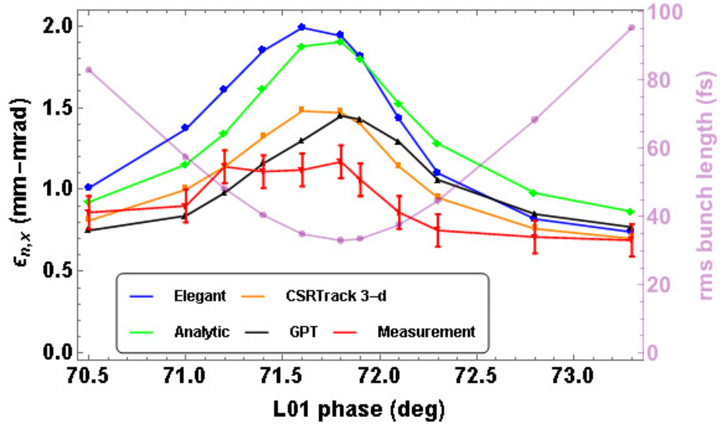
- Projected emittance measured, and compared with Elegant, CSRTrack, GPT and the analytic approximation.
- We estimate the projected emittance growth from the longitudinal and transverse CSR force in each dipole to be [10,11]:

$$\Delta\epsilon_n \approx 7.5\times10^{-3}\frac{\beta}{\gamma}\left(\frac{Nr_eL_b^2}{R^{5/3}\sigma_z^{4/3}}\right)+\frac{-3+2\sqrt{3}}{24\pi}\frac{\beta}{\gamma}\left(\frac{\Lambda Nr_eL_b}{R\sigma_z}\right)^2$$

$$\Lambda = ln\left(\frac{(R\,\sigma_z^2)^{2/3}}{\sigma_x^2}\left(1+\frac{\sigma_x}{\sigma_z}\right)\right)$$

- Good agreement for compression factor (CF) < 40, but the 1D simulation results diverge as we approach maximal compression.
- CSRTrack and GPT manage to capture the trend and the values agree quite well.





[12] Stupakov, arXiv.1901.10745 (2019)

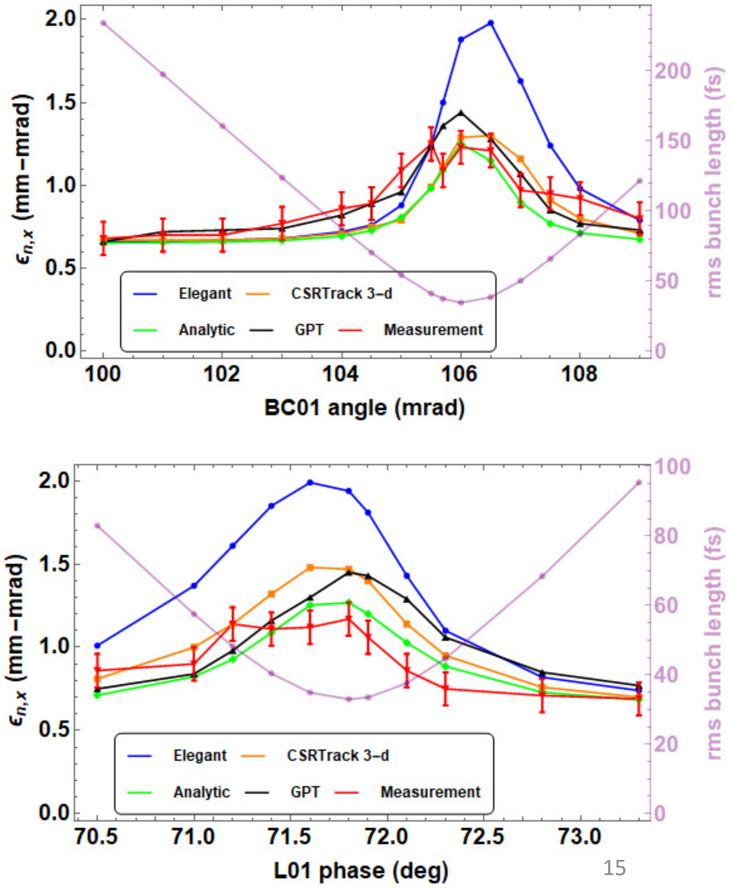
Results

CSR Measurements - Update

- Recently, a new development on the theory of CSR-induced emittance growth was presented.[12]
- It was demonstrated that the transverse CSR kick was much smaller than previously thought, due to a cancellation of the CSR field with the transverse field of the bunch, resulting in the following formula for emittance growth:

$$\Delta\epsilon_n \approx 7.5\times10^{-3}\,\frac{\beta}{\gamma}\left(\frac{Nr_eL_b^2}{R^{5/3}\sigma_z^{4/3}}\right)+2.5\times10^{-2}\,\frac{\beta}{\gamma}\left(\frac{Nr_eL_b}{R\sigma_z}\right)^2$$

- This new analytic estimate (which is valid only in the steady-state regime) produces good agreement with the 3D codes and with the experimental results across all compression factors!



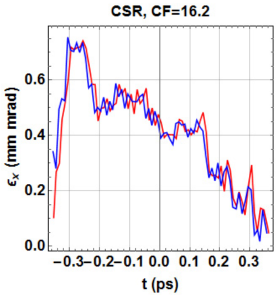
[13]Derbenev et al, TESLA-FEL-1995-05 (1995)

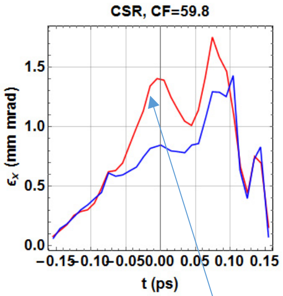
$$D_{par} = \sigma_{\perp}\sigma_z^{-2/3}R^{1/3}$$

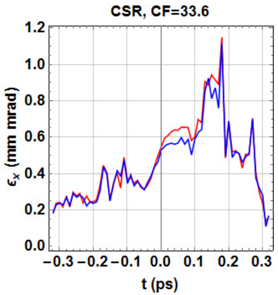
Results

Putting a limit on the 1D approximation

- Looking at the parameter governing the limits of the 1D approximation [13], we can place a limit of around D_{par}~2 at which 1D results for CSR are no longer valid.
- We can also look at the slice emittance as simulated by Elegant and CSRTrack 1D to see where the over-estimation occurs.

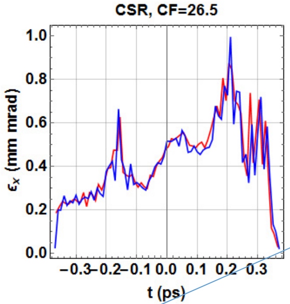


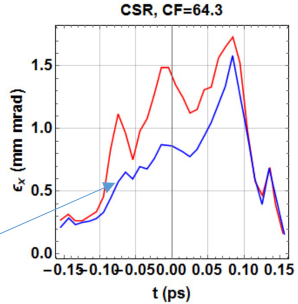


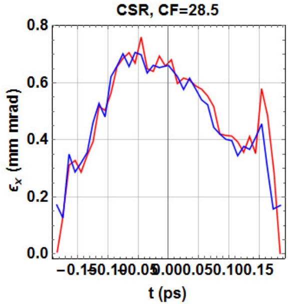


BC01 scan
Elegant (red)
CSRTrack (blue)

L01 scan
Elegant (red)
CSRTrack (blue)







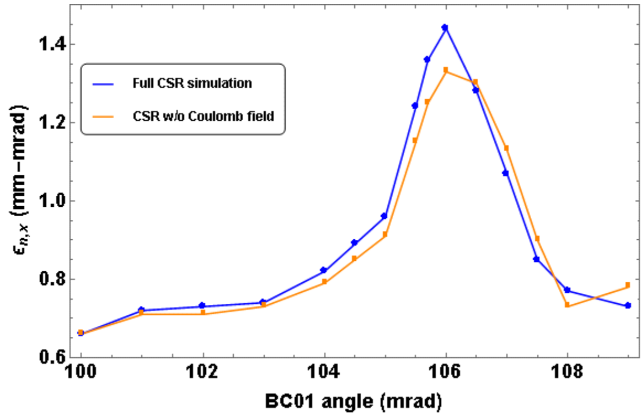
Slice emittance in bunch core ~2x larger!

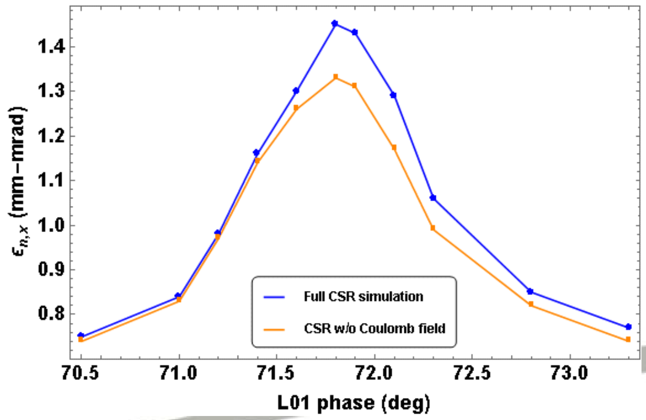
L to R: under-, fully-, over-compressed

Results

Impact of the Coulomb Field

- GPT-CSR has the option to include/exclude the Coulomb field in CSR calculations.
- FERMI parameter scans were simulated with both the full CSR field and with only the radiation field.
- We see an increase of ~10% at full compression when the Coulomb field is included.
- For systems with multiple bends (i.e. ERL arcs), this cannot be neglected even for ultrarelativistic systems!





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Conclusions

- **An extension to the 1D theory of CSR has been developed:**
  - Taking full account of the Lienard-Wiechert field demonstrates the interplay between Coulomb and radiation terms.
    - Neglecting this term can underestimate CSR-induced emittance growth. (Up to ~10% in our case.)
  - The exit and entrance transient effects must take account of the Coulomb term to be fully accurate. (Particularly important for systems involving compressive arcs with many dipoles close together!)
- **Measurements of the CSR-induced emittance growth have been made:**
  - Comparisons with 3D simulation codes show good agreement over the full parameter range.
  - The ratio between transverse and longitudinal bunch size gives an estimate for when 3D simulations are necessary.
- **Agreement between theory, simulation and experiment is good!**

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Thanks

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- Elettra Sincrotrone Trieste: Simone Di Mitri, Giuseppe Penco, Simone Spampinati and all of the FERMI commissioning team
- ASML: Irwan Setija, Peter Smorenburg, Seth Brussaard, Iwan Akkermans
- Pulsar Physics: Bas van der Geer, Marieke de Loos

References

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9. Bettoni et al, PRSTAB 19.034402 (2016)
10. Stupakov, SLAC-PUB-8028 (1999)
11. Cai, PRAB 20.064402 (2017)
12. Stupakov, arXiv.1901.10745 (2019)
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