Transverse-to-Longitudinal Emittance Exchanger at Fermilab's Advanced Superconducting Test Accelerator (ASTA)

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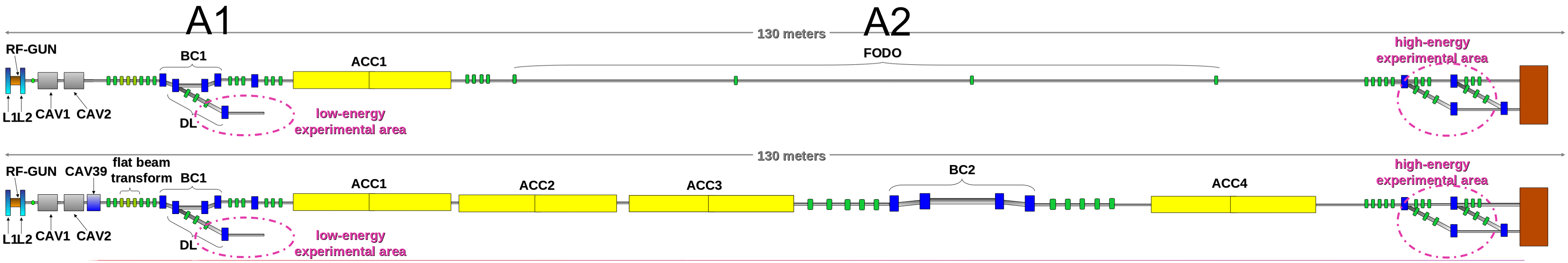
ASTA

- Electron linac for Advanced Accelerator R&D being built at Fermilab.
- Construction in stages:
  - 50 MeV injector
  - 1~4 cryomodules, for energies ranging from 300 MeV to ~1 GeV
  - Room for user-experiments at two energies

parameter	nominal value	range	units
energy exp. A1	50	[5,50]	MeV
energy exp. A2	~ 300 (stage 1)	[50,820]	MeV
bunch charge Q	3.2	[0.02,20]	nC
bunch frequency f_b	3	see $^{(a)}$	MHz
macropulse duration τ	1	≤ 1	ms
macropulse frequency f_{mac}	5	[0.5, 1, 5]	Hz
num. bunch per macro. N_b	3000	$[1,3000]^{(b)}$	–
trans. emittance$^{(b)}$	$\varepsilon_\perp \simeq 2.11Q^{0.69}$	[0.1, 100]	μm
long. emittance$^{(b)}$	$\varepsilon_{\|\|} \simeq 30.05Q^{0.84}$	[5, 500]	μm
peak current $\hat{I}$ $^{(c)}$	~ 3	≤ 10	kA

Source: P. Piot, FERMILAB-CONF-13-086-AD-APC (2013)

Source: J. Leibfritz, Proceedings of IPAC2012, p. 58

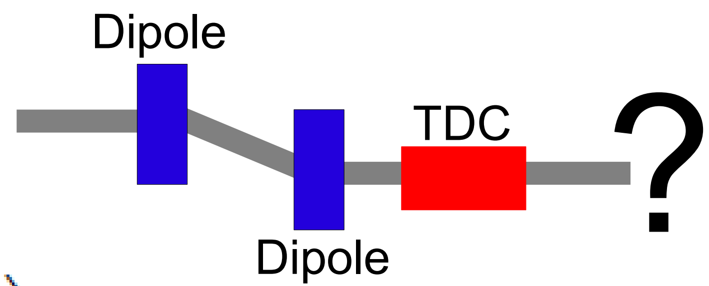


Why an Emittance Exchanger?

- Emittances (longitudinal (L), horizontal (H), and vertical (V)) generally distinct
- Emittance partition depends on applications
    - Different experiments at ASTA have varying requirements for each of the three emittances
    - Emittances evolve independently in each degree of freedom:
        - Coherent Synchrotron Radiation -> L,H
        - Transverse Space Charge -> H,V
        - Longitudinal Space Charge -> L
- Shaping current profiles is hard...
    - No ballistic bunching
    - Acceleration follows RF fields, needs magnetic compression to create spatial change.
- ... but shaping transverse distributions is much easier!
    - Masks, quadrupoles, laser spot, etc..

Basics of Emittance Exchangers

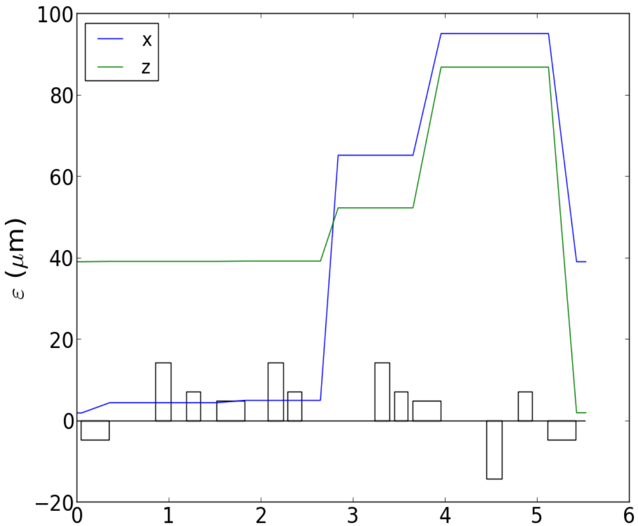
- A transverse deflecting cavity (TDC) in dispersive region allows exchange of longitudinal and transverse phase spaces (P. Emma, et. al, PRSTAB 9, 100702 (2006))



$$R_{EEX} = \begin{pmatrix} 0 & 0 & R_{15} & R_{16} \\ 0 & 0 & R_{25} & R_{26} \\ R_{51} & R_{52} & 0 & 0 \\ R_{61} & R_{62} & 0 & 0 \end{pmatrix}$$

- 4x4 transfer matrix must be block-anti-diagonal.

- Can map specific transverse shaping into current profiles via laser masking, flat beam transformations (TUPWO 060), collimation, quadrupoles, etc...
    - Triangular Hole → Ramped Bunch
    - Slits → Bunch Train
    - Big Hole & Little Hole → Drive Bunch & Witness Bunch

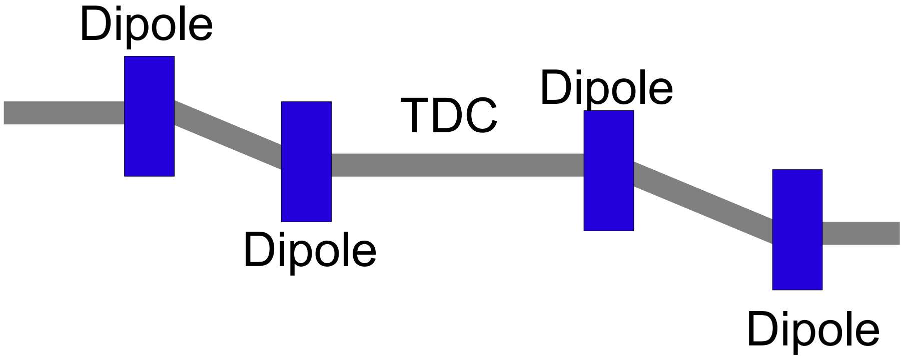


Requirements for Perfect Exchange

- Block-anti-diagonality has several key requirements:
  - TDC strength inverse of dispersion
  - Many choices for downstream line

$$\kappa \equiv \frac{eV_x}{pc}\frac{2\pi}{\lambda} = -\frac{1}{\eta_x}$$

    - Identical Dogleg- used in proof of concept experiment at Fermilab's A0 photoinjector (J. Ruan, et. al, Phys. Rev. Lett. **106**, 244801 (2011), Y.-E. Sun, et. al, Phys. Rev. Lett. **105**, 234801 (2010))
    - Chicane with extra quadrupoles (variable R_{56}, dispersion)
    - "Boost" dispersion to larger values, reduce TDC field strength and power/cooling requirements!



Imperfections in the Exchange

- Finite-thickness of TDC introduces spurious diagonal terms in EEX
  - Can be compensated with accelerating cavity (Zholents, PAC11)
- Collective effects- mutual forces between electrons
  - Space charge (SC)
  - Coherent Synchrotron Radiation (CSR)
- Second Order Effects

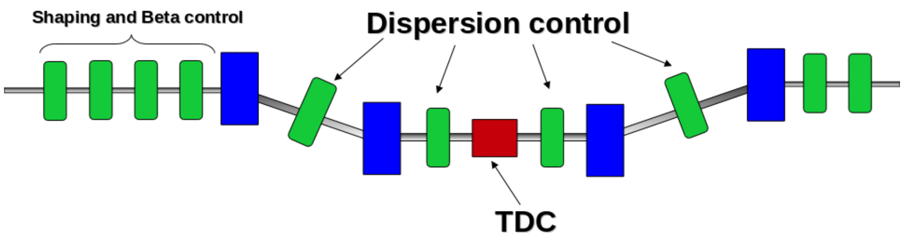
$$\kappa \equiv \frac{eV_x}{pc}\frac{2\pi}{\lambda}$$

$$R_{TDC} = \begin{pmatrix} 1 & \frac{\lambda}{2} & \kappa\frac{\lambda}{4} & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & \kappa\frac{\lambda}{4} & \boxed{\kappa^2\frac{\lambda}{8}} & 1 \end{pmatrix}$$

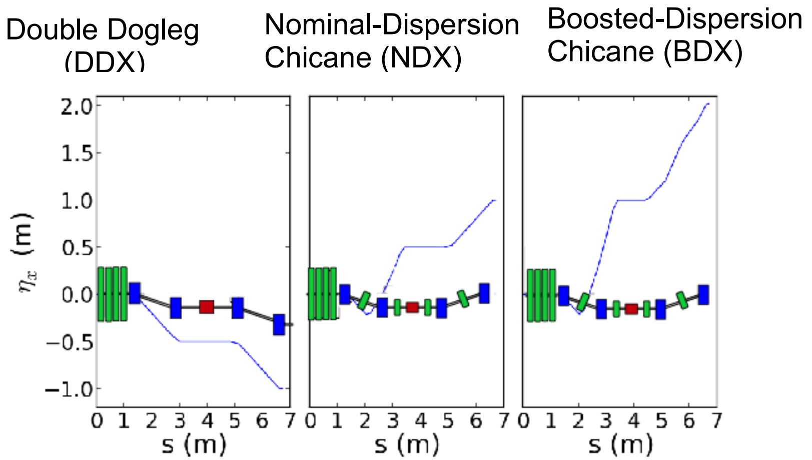
Next-Generation In-line EEX Design

- In-line Chicane EEX has several benefits.
- Remains in-line with initial beam.
  - Similar doglegs, flipped angles.
- Dispersion is controlled, and potentially boosted.
  - Can aim to arbitrarily high values, but...
- Additional quads shape final distribution, controlling R_{51} and R_{52}. Accurately converts horizontal phase space into current profile, with scaling.
  - Slits, masks, collimation may also be used for custom shaping.
- R_{65} of TDC canceled by accelerating mode cavity.
- Dispersion can be "boosted" to larger values (here, nominal=0.5m). Requires weaker field, less power/cooling.
  - Strong quads in chicane make shaping/fitting more difficult.
- Simulations performed in Elegant, and Impact-Z for SC+CSR

$$\kappa \equiv \frac{eV_x}{pc}\frac{2\pi}{\lambda} = -\frac{1}{\eta_x}$$



$$R_{EEX} = \begin{pmatrix} 0 & 0 & R_{15} & R_{16} \\ 0 & 0 & R_{25} & R_{26} \\ R_{51} & R_{52} & 0 & 0 \\ R_{61} & R_{62} & 0 & 0 \end{pmatrix}$$



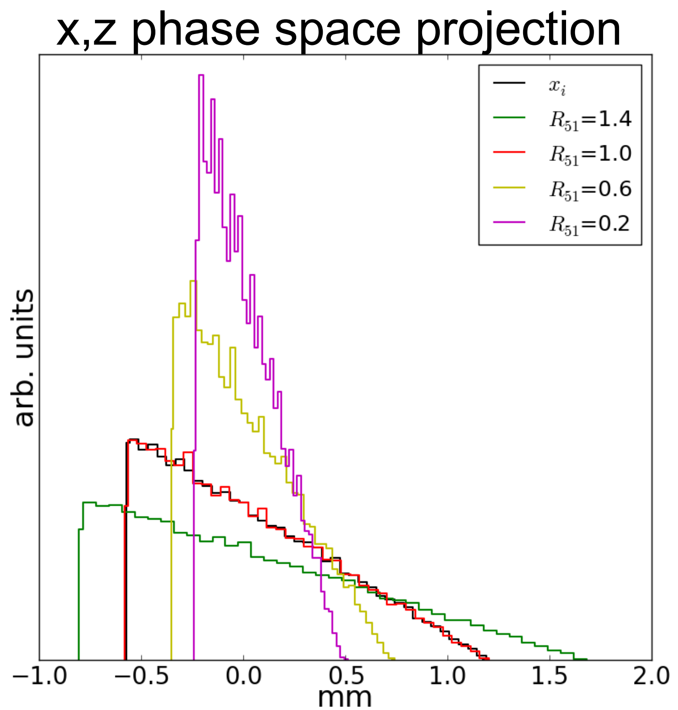
Performance and Shaping of Nominal-Dispersion Chicane

- Two criteria for discussing the quality of the emittance exchange.
  - Quantitative: Numeric exchange of the transverse and longitudinal emittances.

$$\mathcal{F}_{zx} \equiv \frac{\varepsilon_{zf}}{\varepsilon_{xi}} \qquad \mathcal{F}_{xz} = \frac{\varepsilon_{xf}}{\varepsilon_{zi}}$$

  - Qualitative: Preservation of the transverse shaping in to the longitudinal plane.

R_{51}	R_{52}	F_{xz}	F_{zx}
0.21	-0.025	1.04	1.27
0.6	0.0	1.03	1.25
1.0	0.0	1.16	1.66
1.4	0.0	1.28	2.134



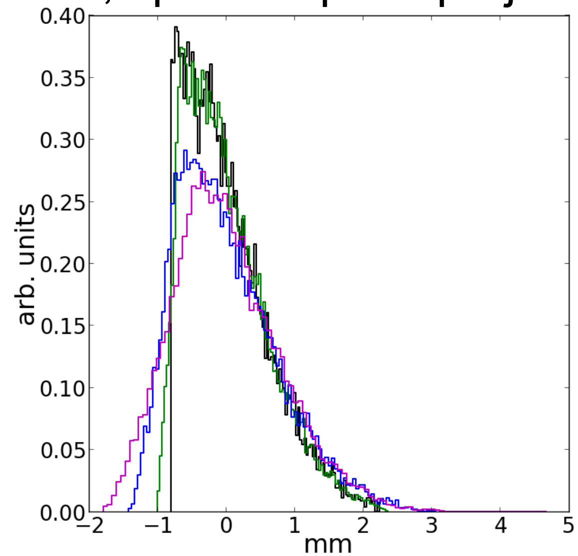
Collective Effects & Boosting

- Both SC and CSR are important, particularly when aiming for compression.
- Overall shape may be retained (here, horizontal Gaussian cut in half as quick approximation of ramped bunch) C. Prokop, NIM A,719, pp 17–28
- Finer structures may become washed out.
- Boosting-dispersion (BDX) makes shaping more difficult than non-boosted (NDX, DDX)

Table 1: Emittance Exchange Values with IMPACT-Z

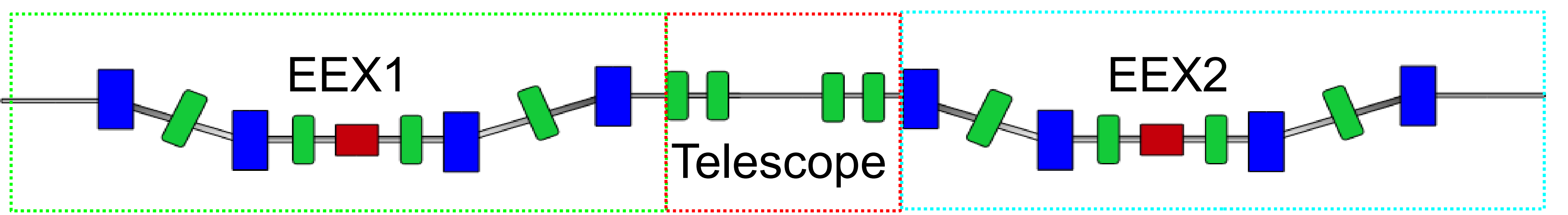
Des.	Q (nC)	η_x	R_{51}	R_{52}	$\mathcal{F}_{zx}$	$\mathcal{F}_{xz}$
DDX	0.0	0.5	-0.339	-0.259	1.33	1.00
DDX	1.6	0.5	-0.339	-0.259	5.51	1.65
NDX	0.0	0.5	1.00	-0.013	1.25	1.01
NDX	1.6	0.5	1.00	-0.013	4.24	1.67
BDX	0.0	1.0	1.17	-0.385	1.55	1.01
BDX	1.6	1.0	1.17	-0.385	5.09	1.63
BDX	0.0	1.5	1.04	-0.810	5.76	1.13
BDX	1.6	1.5	1.04	-0.810	8.85	1.50

x,z phase space projection



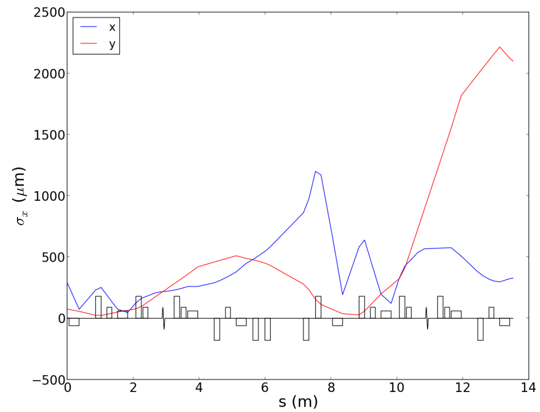
Double Emittance Exchanger

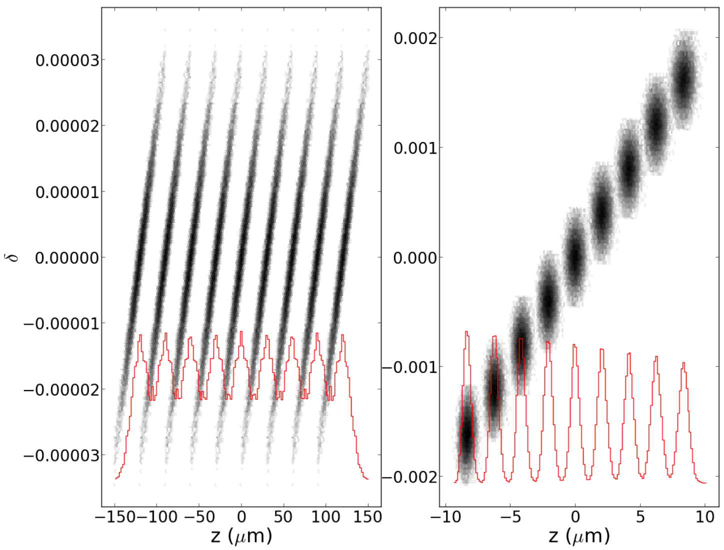
- Two EEXs placed in sequence, multiple uses and designs.
  - Bunch compressor without initial energy chirp!
- Three part process: (Zholents & Zolotorev, ANL/APS/LS-327 (2011))
  - EEX Longitudinal Modulation -> Transverse Beamlets
  - "Focus" the Transverse Modulation
  - EEX Transverse Beamlets -> Compressed Longitudinal Modulation
- Simplified Design
  - No Pre/Post quads for R_{51} and R_{52} control. We use innate values of basic EEX. Set C-S parameters at EEX1 start.
  - Linked with telescope that matches several requirements at entrance of EEX2...



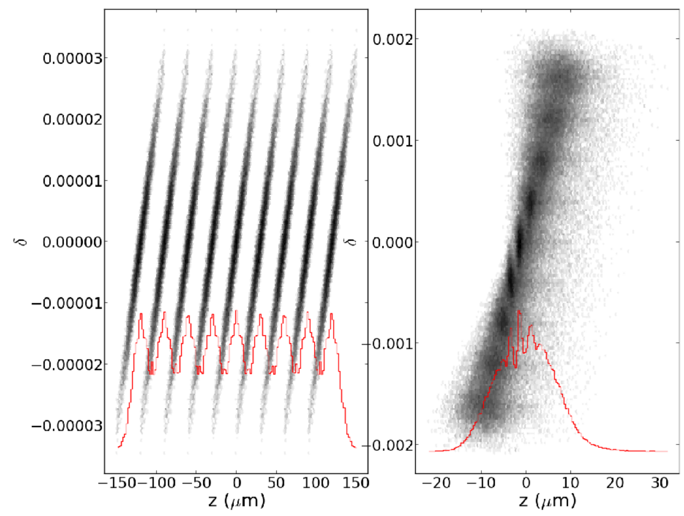
Double EEX results

- We match for C-S parameters of single beamlet, then track the full train through the same quadrupole settings.
- Aim to shape in horizontal to create upright bunches
    - Keep vertical constrained.
- “Flat” beam emittances to mitigate vertical beam size
- Poor fit, 15x compression, still much room for improvement.





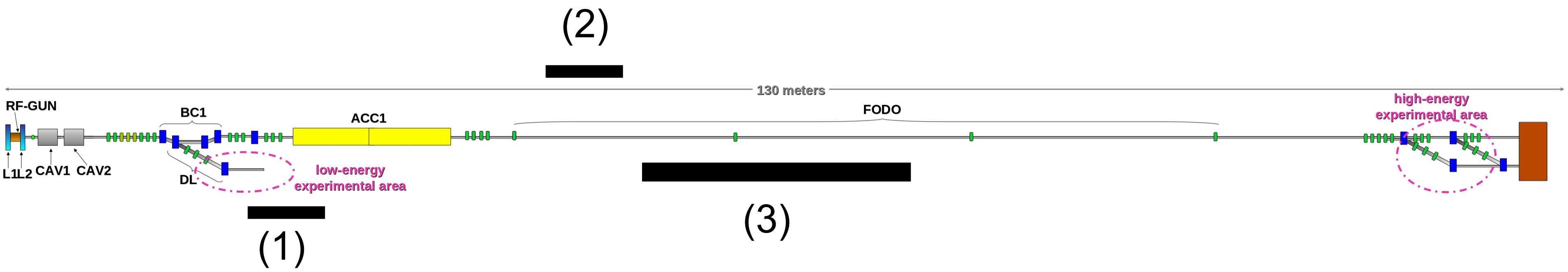
1st Order, >15x compression



Full 2nd Order (transverse size in EEX#2 very large)

Implementation at ASTA

- (1) Low-energy experimental line (50 MeV)
  - Would be first-ever chicane EEX.
- (2) Use same basic design at 300+ MeV after CM1.
  - Could be used as first stage of dielectric wakefield “energy doubler” (F. Lemery, this conference)
- (3) Potential Double EEX
  - Still many designs to consider.



Summary

- Design of in-line Chicane Emittance Exchanger
    - Advanced Longitudinal Shaping (Control of R_{51} and R_{52})
    - Boosted Dispersion → lower TDC requirements.
    - Collective Effects reduce quality of exchange and wash-out details.
- Early design and simulation for a double emittance exchanger.
- Eventual implementation at ASTA.