Update on Beam Dynamics Studies for the E Linac

Guidelines set in earlier meetings (March-April)

- Common design for different modes of operation
- Candidate capture configurations identified for study
- Diagnostics/tuning needs taken into account

Main lines of design study

- Seek common solution for different modes of operation
  - Low bunch charge (16 pC) and high bunch charge (100 pC)
  - Dictated by beam quality targets at 10 MeV and 50 MeV
- Cases studied using Parmela (**Marco**) and Track (**Sophia**) with variations.

  $\Rightarrow$ Performance in the same ball park
- Capture configurations
  - Three capture section prototypes identified for optimization (March 26 meeting):
    - Two 1-cell β=1.0 captures (A)
    - One 1-cell β=0.7 and one 1-cell β=1.0 capture (B)
    - A two-cell β=0.7 capture (C)
  - Other configurations examined for completeness & clarification:
    - One 1-cell β=0.7 and one 1-cell β=0.85 capture (D- **Siddhu**)
    - One 1-cell β=0.6 and one 1-cell β=1.0 capture (E)
    - Two 1-cell β=0.7 captures (F)

Distribution from Gun:

Kinetic E: 100 keV
Momentum: 335 keV
Bunch charge: 16 pC

Transverse:

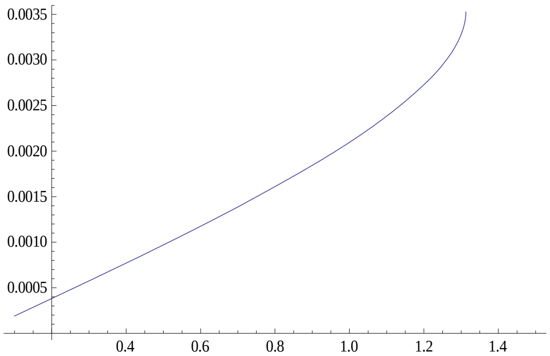
- Cylindrically symmetric
- X & Y - 4 × Normalized Emittance = 30 µm (2σ × 2σ uncorrelated, 86% of beam)
- Normalized RMS Emittance = 7.5 µm
- Scenario A: In each dimension (no correlation):
  - X: $\sigma_x \approx$ 6 mm; ± 6 mm contains 68%; 2 $\sigma_x \approx$ 12 mm; ± 12 mm contains 95%
  - X': $\sigma_{x'} \approx$ 1.25 mrad; ± 1.25 mrad contains 68%; 2 $\sigma_{x'} \approx$ 2.5 mrad; ± 2.5 mrad contains 95%
- Scenario B: In each dimension (no correlation):
  - X: $\sigma_x \approx$ 3 mm; ± 3 mm contains 68%; 2 $\sigma_x \approx$ 6 mm; ± 6 mm contains 95%
  - X': $\sigma_{x'} \approx$ 2.5 mrad; ± 2.5 mrad contains 68%; 2 $\sigma_{x'} \approx$ 5 mrad; ± 5 mrad contains 95%
- Scenario C: In each dimension (no correlation):
  - X: $\sigma_x \approx$ 1.5 mm; ± 1.5 mm contains 68%; 2 $\sigma_x \approx$ 3 mm; ± 3 mm contains 95%
  - X': $\sigma_{x'} \approx$ 5 mrad; ± 5 mrad contains 68%; 2 $\sigma_{x'} \approx$ 10 mrad; ± 10 mrad contains 95%
- Un-normalized: Multiply emittance by 1.52554. Multiply linear dimensions by 1.23513.
- All % values are derived from Gaussian distribution, and refer to distribution projected onto the 1D coordinate X or X'. Use the % anyway for other distributions even if the σ number is off. For example in Scenario C, 95% of beam should be inside the ± 3 mm boundary in the beam distribution histogram in X, and 95% of beam should be inside the ± 10 mrad boundary in the beam distribution histogram in X', regardless of distribution.
- We may need to further limit the "scenario" specs later on.

Longitudinal:

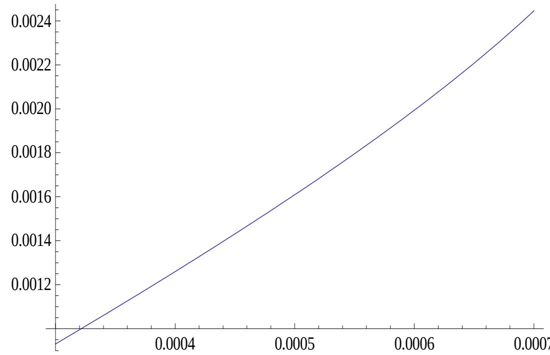
- Uncorrelated
- Bunch = ±20 deg. of 650 MHz waveform at 100 keV
- 1.7094×10^{-10} second total bunch length or 2.8094 cm total bunch length
- Energy spread = ±0.5 keV (However, **±1 keV** is used in Parmela & Track now)

- Geometry/element location optimization
    - Initially dictated by high bunch charge transport
    - Further modification (resulting in length increase) accounting for tuning/diagnostics needs
    - Baseline geometry (6.0 m Gun to 2nd cryo-module) supports decent solutions for high bunch charge (200-300 keV, 1 mm-mrad norm. transverse emittance)
    - Baseline is not optimal for low bunch charge longitudinal matching.

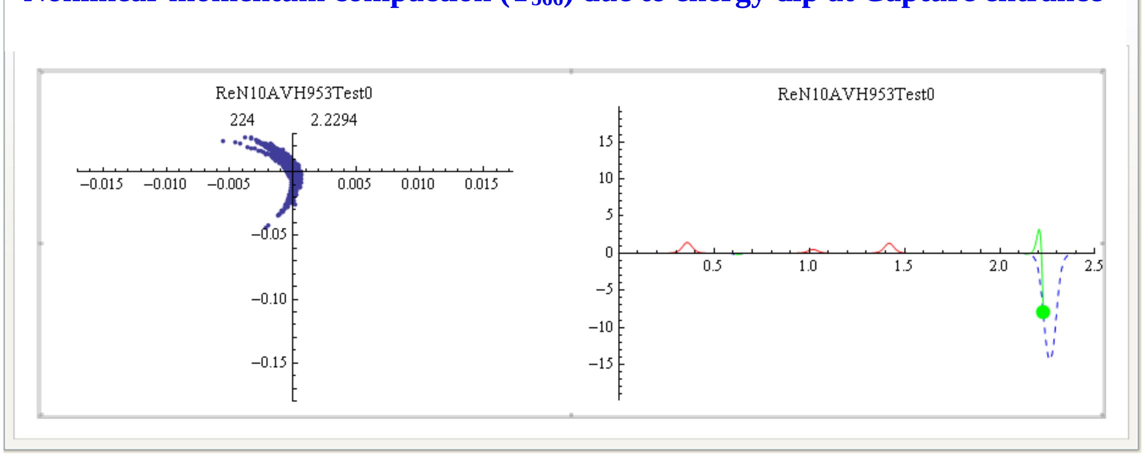
Bunch length at Capture vs Buncher-Capture distance



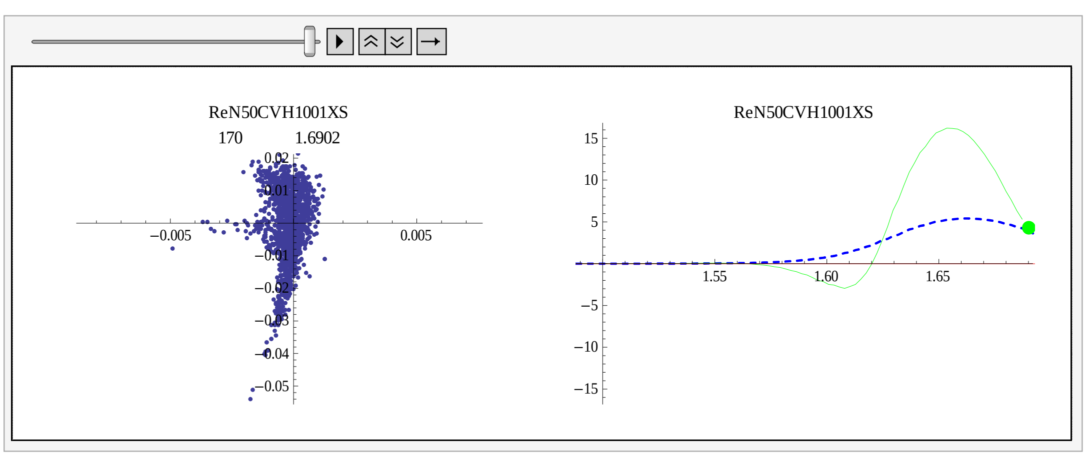
Bunch length at Capture vs Energy spread at Buncher



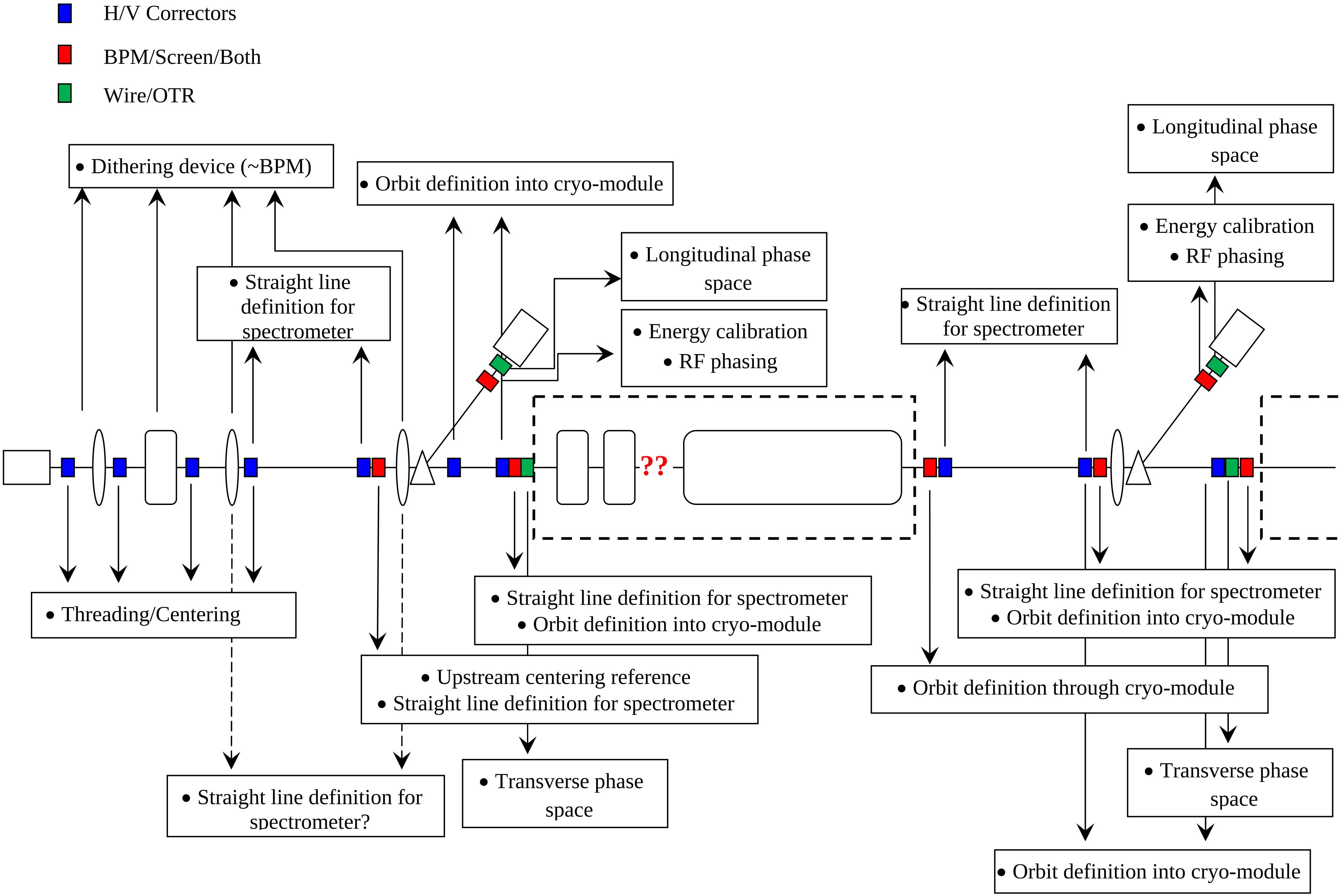
Nonlinear momentum compaction (T_{566}) due to energy dip at Capture entrance



- Better matching can be achieved by reducing distance, at expense of diagnostics
    - 5.6 m Gun to 2nd cryo-module → Some compromise
    - 5.4 m Gun to 2nd cryo-module → More compromise

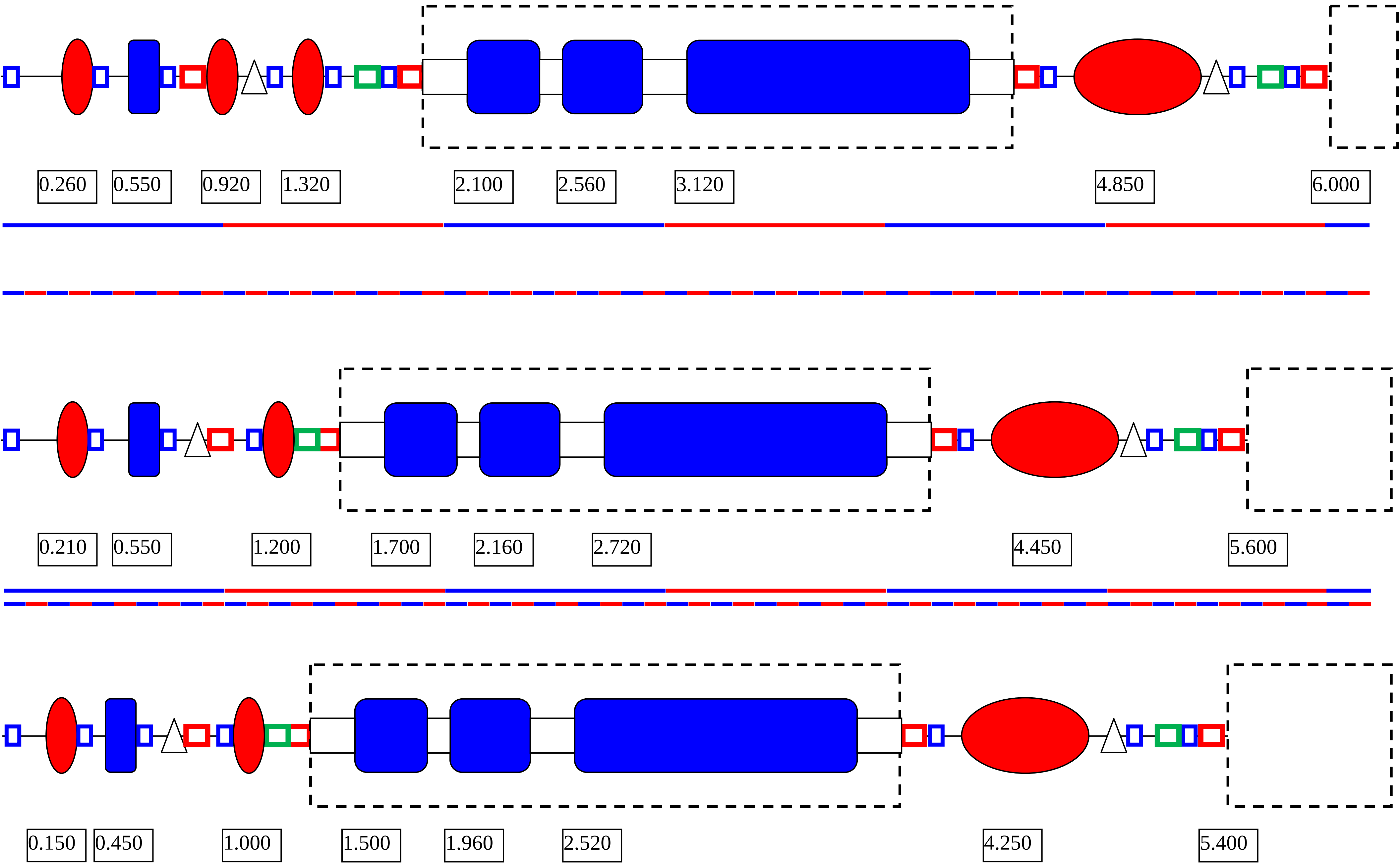


A possible diagnostics scheme (March 26)



- **Beam current?**
- **Bunch length?**
- **Arrival time?**

Geometries A-B-C (Exact scale; Exact cryomodule dimensions)



Optimization strategy

- Optimized solution depends on what we set as objectives and constraints
  - Use different sets of objectives / constraints to compare versatility of different configurations
  - Which configuration can respond better to a wide range of input beams?

- Longitudinal distribution
  - Use more generic (uncorrelated) distributions
  - No bias in phase space orientation for starter

- Input beam emittance set by Freidhelm's numbers
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εx^N (mm-mrad)	2.50
εy^N (mm-mrad)	2.50
εz^N (m-eV/c)	2.95

Objectives:

A	εx^N, 95% εz^N
B	εx^N, εz^N, σz, σE
C	εx^N, Max(Δz), Max(ΔE)

Constraints:

Energy

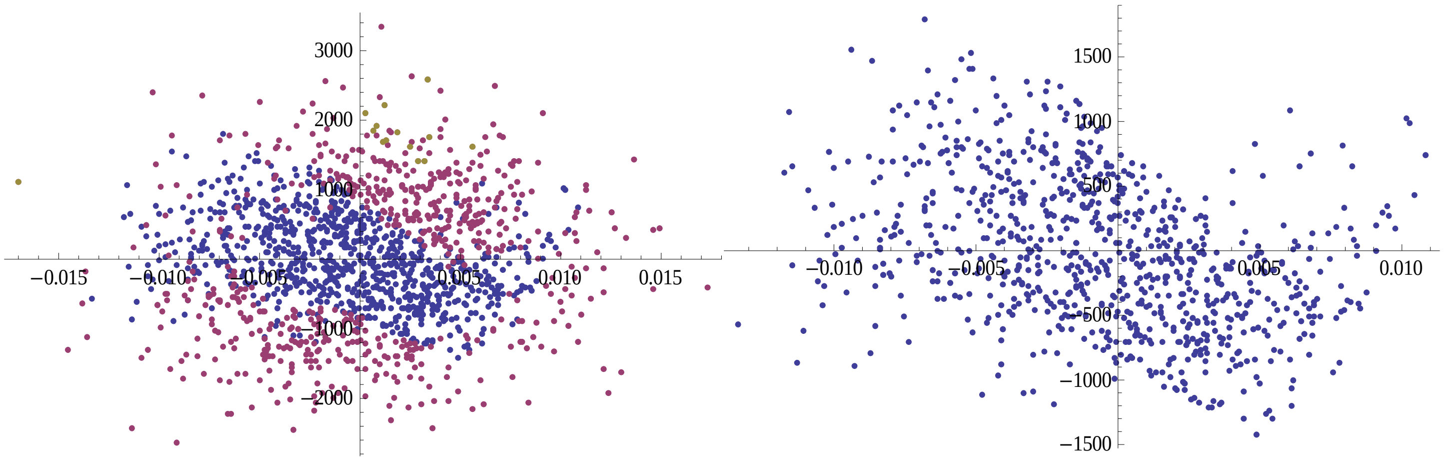
Final σx

Max(σx)

Backward Particles

Lost Particles

Longitudinal "Acceptance" defined by energy tails at 10 MeV



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$\sigma_z = 4.5\ mm$ $\qquad \sigma_p = 571.3\ eV$ $\qquad \dfrac{\langle Z \cdot P_z \rangle}{\sigma_z \cdot \sigma_p} = -0.3741$

What has been accomplished so far?

- A streamlined, debugged process to obtain optimized solutions under a wide range of user defined objectives and constraints
  - Well tested Astra mode
  - Reasonably established Track mode
  - XML scheme for interchangeable runs, including initial distribution generation
- 100’s of runs
  - Optimization under given condition
  - Configuration comparison
  - Clarifying beam dynamics issues
  - Exploratory
- At this point, β=0.7 + 1.0 captures with 6.0 m geometry can produce solutions satisfying diverse beam property objectives for low bunch charge at 10 MeV and 50 MeV.
- This configuration already proved adequate for high bunch charge case
- Close competition from β=0.7 + 0.85, and β=0.7 + 0.7.
  - β=0.7 + 1.0 holds slight edge over β=0.7 + 0.7 in latitude in solution space
  - Possibly even thinner edge over β=0.7 + 0.85
  - Clearly superior to all other configurations
  - Due to fringe field, capture β exactly matched to 100 keV does not help much in eliminating the energy dip.
- Preliminary GPT generated input beam resulted in much better performance due to smaller energy spread. This is under evaluation.

This preliminary baseline is versatile enough to handle a diverse range of input and output conditions

$\Rightarrow$ Still need to ask the robustness question

Some Examples:

- Simultaneous bunching and cancellation of nonlinearities (T_{655} from RF waveform + T_{566} from non-relativistic momentum compaction)
  - Buncher performs some acceleration
  - Captures perform matching to cancel nonlinearity

50 MeV Solution

10 MeV Solution

- Using GPT time distribution (dP vs T)

GPT Input

- Using GPT Z distribution (dP vs Z)
  - Objective set C:

εx^N	4.6 mm-mrad
Max(Δz)	3.8 mm
Max(ΔE)	40 keV

- Almost 0 field in last solenoid!

GPT_Z_Input

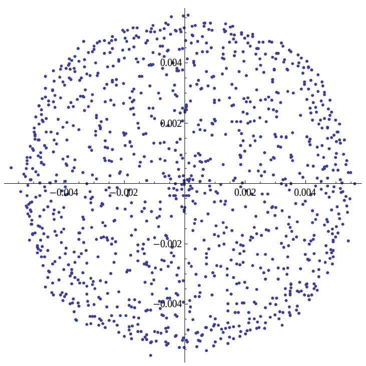
Robustness?

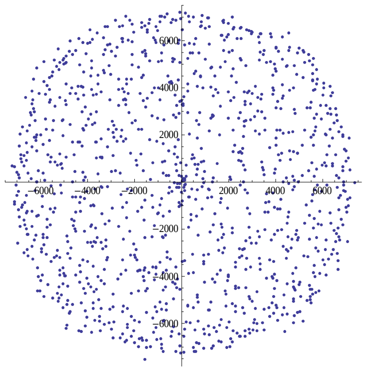
Happening in the mean time ……

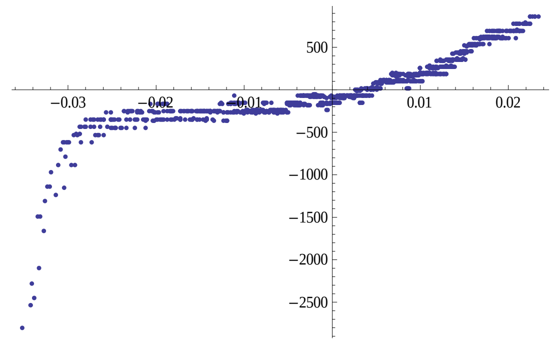
- Benchmarking (**Sophia, Marco, Siddhu, Gabriel**)
  - Rationale
    - Independent confirmation of results
    - Refining Parmela & Track designs with genetic program
  - Good agreement between Astra, Parmela & Track
  - XML platform for interchangeable Astra/Track runs

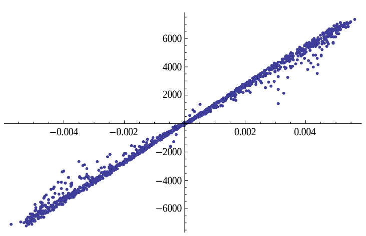
- Ability to include beam parameters as optimization objectives (Astra & Track)
  - Rationale
    - Start-to-end optimization
    - Insight on gun parameter optimization
    - Infrastructure for sensitivity/robustness studies
  - Infrastructure complete and tested.

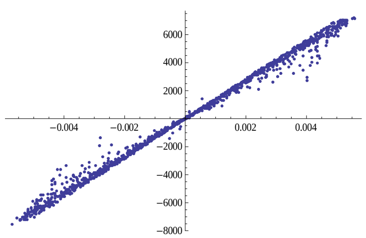
- Gun modeling (Full time domain with space charge - **Siddhu, Friedhelm**)
  - Rationale
    - Realistic input for injector design and optimization – absolutely crucial
    - Start-to-end optimization (a possibility)
  - Some parameter optimization has been performed
  - First cut results are being tested as input to Astra-based optimization
  - Under evaluation











εx^N (mm-mrad)	**2.50**	1.87
εy^N (mm-mrad)	**2.50**	1.91
εz^N (m-eV/c)	**2.95**	1.48

- Sensitivity/Robustness studies
    - Rationale
        - Obvious
    - Built on existing infrastructure of optimization codes
    - Simple sensitivity study to beam parameter or control parameter variation is within computational capability
    - Detailed capture range study may be more resource intensive - depending on how exhaustively we want to comb the parameter space. Needs further thinking.

What's next?

- Firm-up GPT results
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- Next level detail in diagnostics/ tuning
  - Establish start-to-end tuning strategy
  - Numerical simulation and evaluation of feasibility
  - May result in minor iterative design change
- Subject Parmela/Track solutions to optimization
- Sensitivity/Robustness studies
  - Performed on designated baseline configurations
  - May result in minor iterative design change

Resource issues

- Computing power
  - WestGrid availability is unpredictable
  - Either algorithm or computing power improvement is needed to study "capture range" issues.
- Imminent departure of key people (need transition plan)
  - Siddhu
  - Gabriel