U.S. Particle Accelerator School
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VUV and X-ray Free-Electron Lasers

Optimization and Beam Shaping

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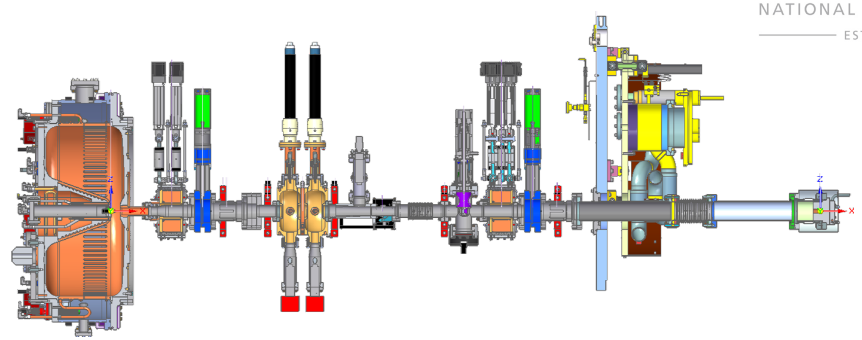
Photoinjector Optimization

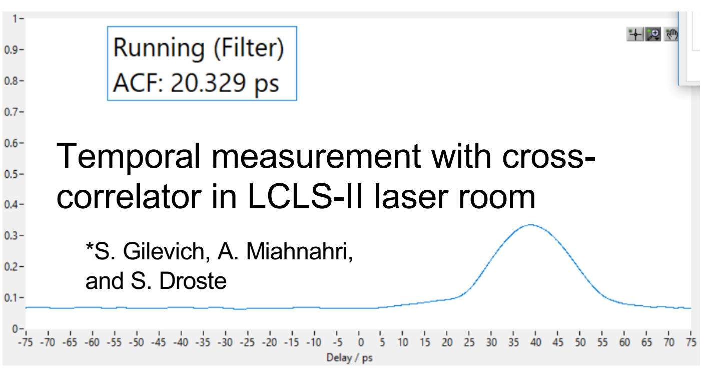
Laser shaping:



Operations baseline:

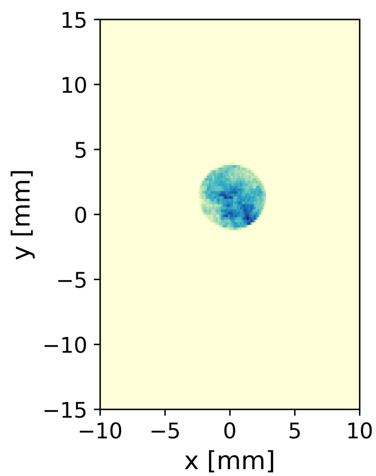
- Gaussian longitudinal profile
- Uniform or truncated gaussian in transverse
  - Feng, et al.
  - Single pulse: 10-30 ps FWHM
- Radius options:
  - Determined by pre-defined/installed iris wheel with cut outs

Parameter	Value
Charge	100 pC
Laser radius	0.5 mm
Laser FWHM	20 ps
Gun phase	Max energy gain
Field on cathode	20 MV/m
Buncher	on
Solenoid strength	0.06 T



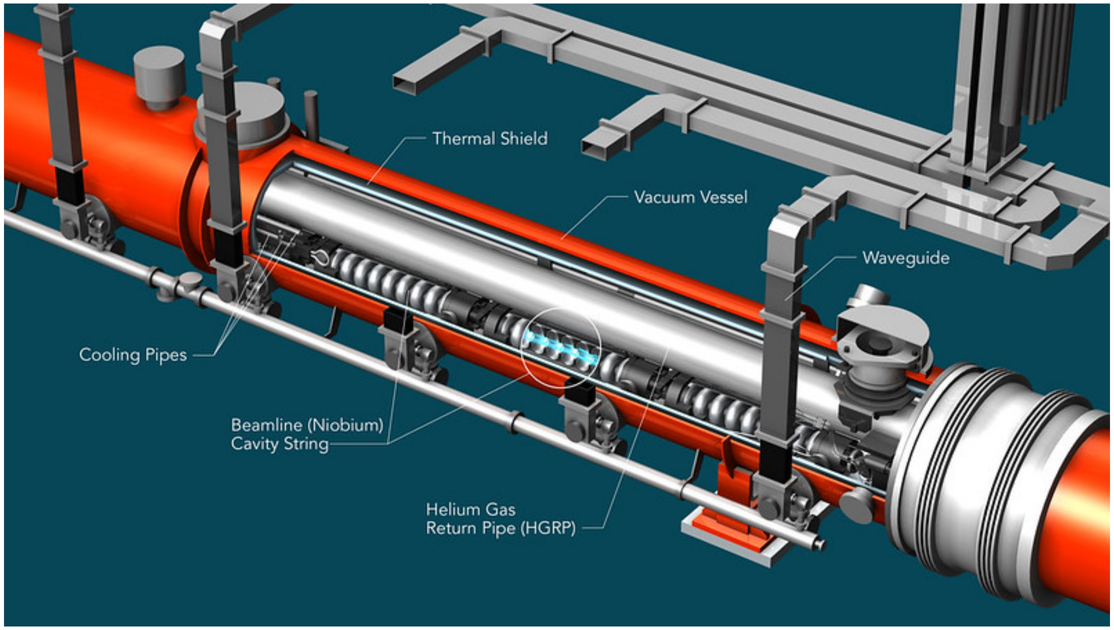
Temporal measurement with cross-correlator in LCLS-II laser room

*S. Gilevich, A. Miahnahri, and S. Droste



Superconducting cryomodule

- SRF niobium cavities
- 8 cavities per cryomodule
    - Standing wave, 1.3 GHz
- Total 37 cryomodules
- Installation location decided based on design simulations w/ flattop profile in longitudinal



Parameters	Value
Cavity phases	+/-40 deg
Cavity gradients (on axis)	32 MV/m

Optimization Vocabulary

- **Design variables:** knobs
- **Objectives:** goals of the simulation/experiment
  - usually emittance & bunch length for injectors
- Photoinjector MOGA optimization

- **Pareto front:** set of 'best' points given trade off between two parameters.
  - Region where you can not improve one parameter w/o 'hurting' the other.
  - Examples on next slide

Constant Design Variables

Variable	Value	Unit
Gun Gradient	20	MV/m
Buncher Gradient	~2	MV/m
Cavity 5-8 Gradient	32	MV/m
Cavity 5-8 Phase	max energy	Degrees
Laser radius	0.5	mm
Laser FWHM	20	ps

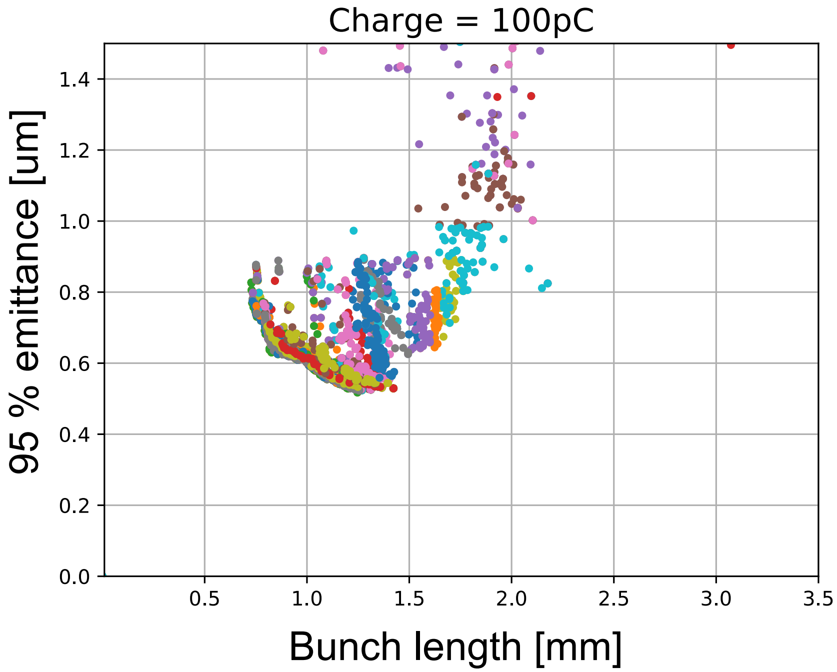
Flexible design Variables

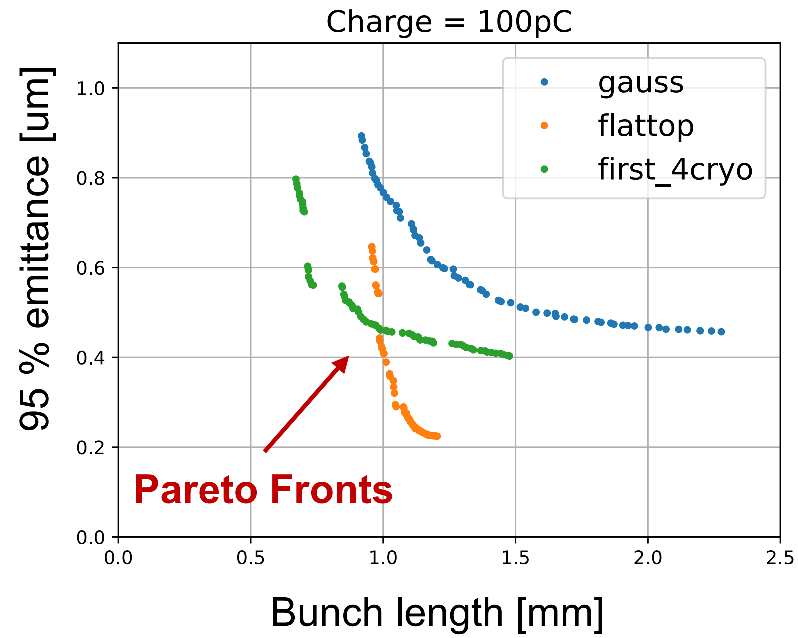
Variable	Min	Max	Unit
Sol 1	0	0.075	T
Sol 2	0	0.075	T
Gun Phase	-10	10	Degrees
Buncher Phase	-90	-40	Degrees
Cavity Phases (4)	-20	20	Degrees
Cavity Gradients (4)	0	32	MV/m

Baseline injector optimization results

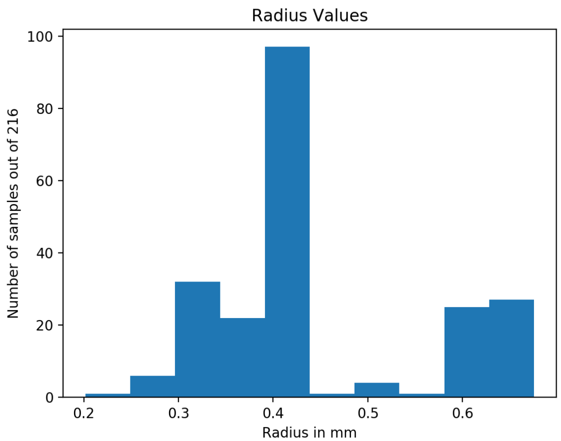
- First 4 cryo = varied gun, buncher, solenoids, and first 4 cavities of cryomodule

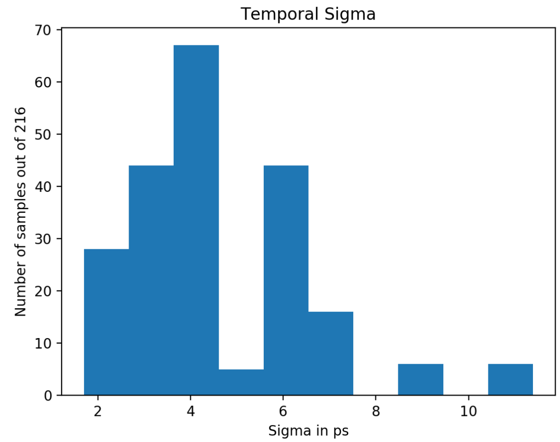
- **Flattop**
  - Cryomodule at commissioning baseline
- **Gauss**
  - Cryomodule at commissioning baseline
- **First_4cryo**
  - First 4 cryomodule cavity phases and gradients

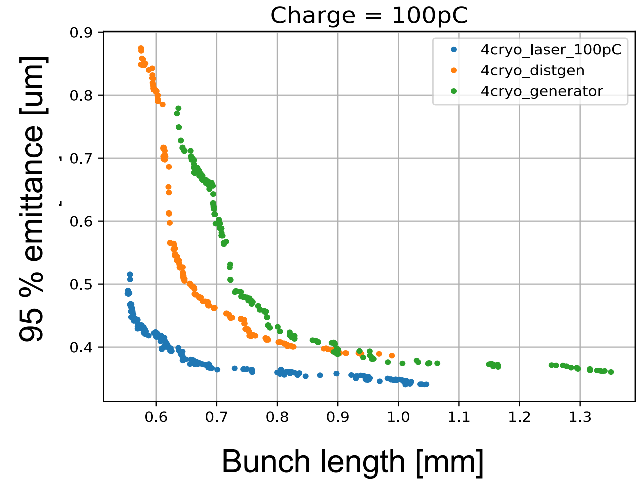




Varied Laser and Gun Energy

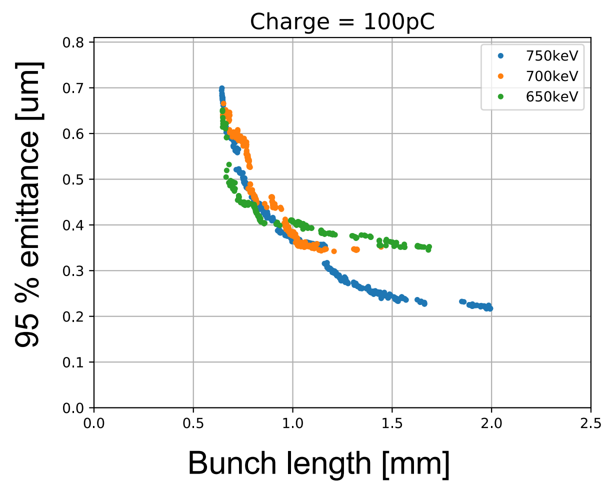






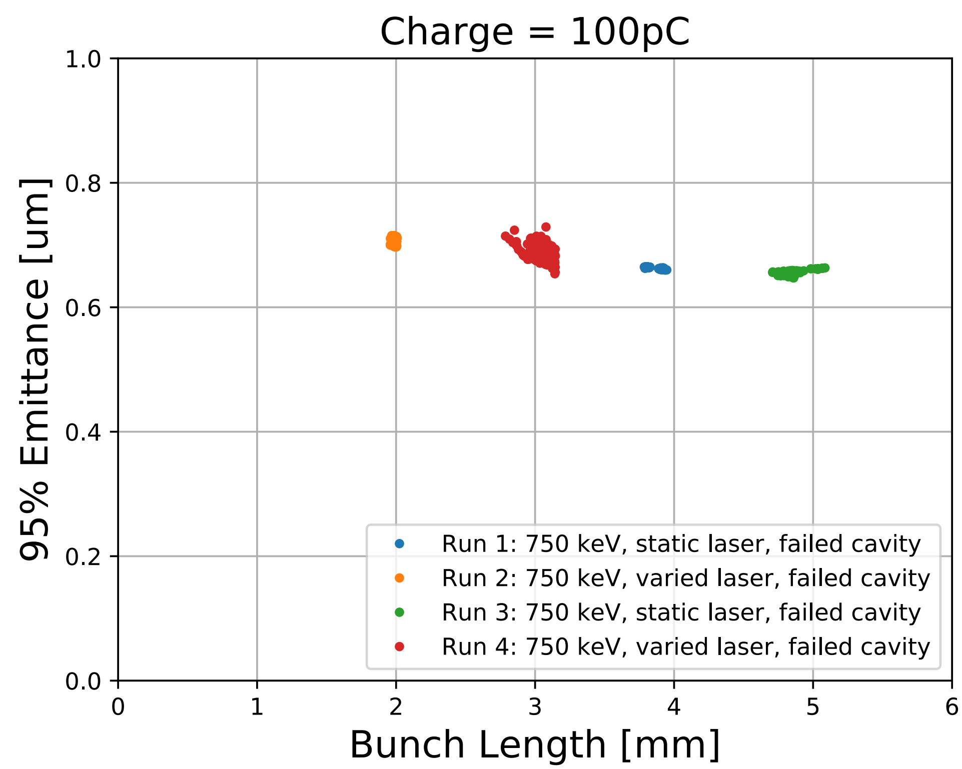
- Requirements:
- Final energy >90 MeV
- Energy spread < 0.5 MeV

- Laser radius and FWHM has large impact on results
- Gun gradient set to produce:
    - 700 keV or 650 keV



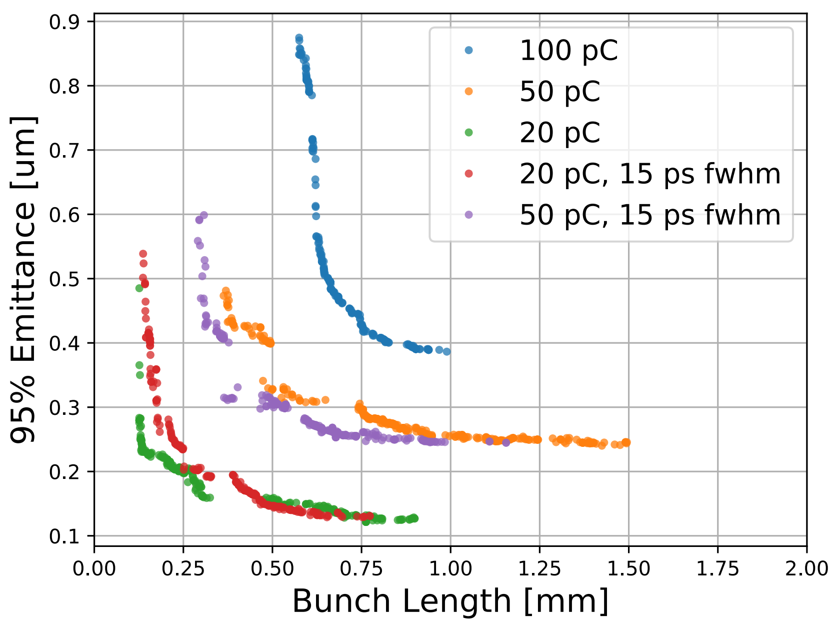
Optimizations with one cavity failure:

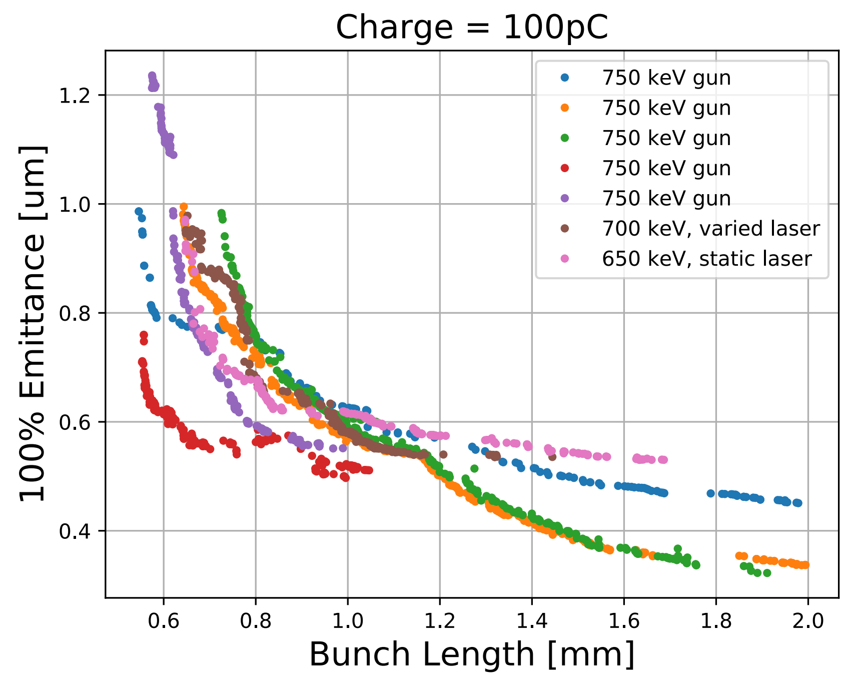
- Run 1 & 3:
  - Laser FWHM = 20ps
  - Laser radius = 1.0 mm
  - Cavity 1 gradient = 0 MV/m
- Run 2 & 4:
  - Laser radius and FWHM variable
  - Cavity 1 gradient = 0 MV/m
- All runs:
  - Cavity 2-4 allowed to vary
  - Cavity 5-8 gradient = 32 MV/m
    - Peak field on axis*



As built optimizations

- Operations study for low charge commissioning
- Fixed FWHM at 15 ps, for 20 and 50 pC





Laser shaping

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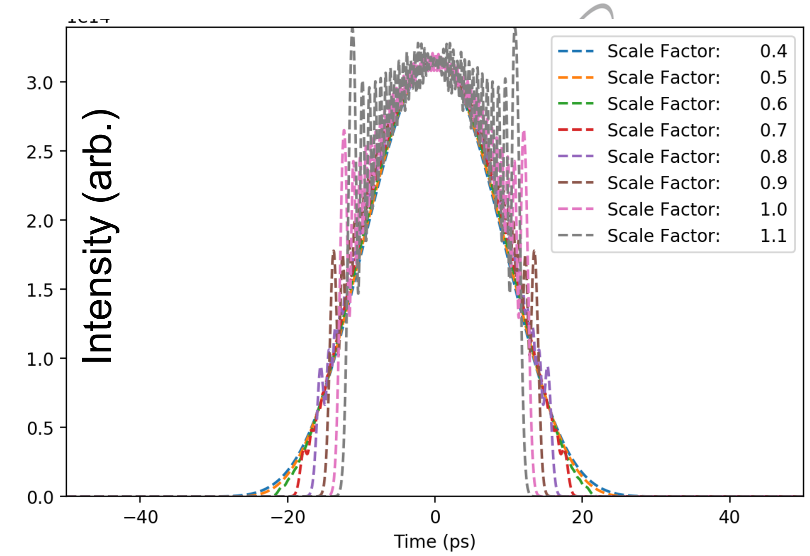
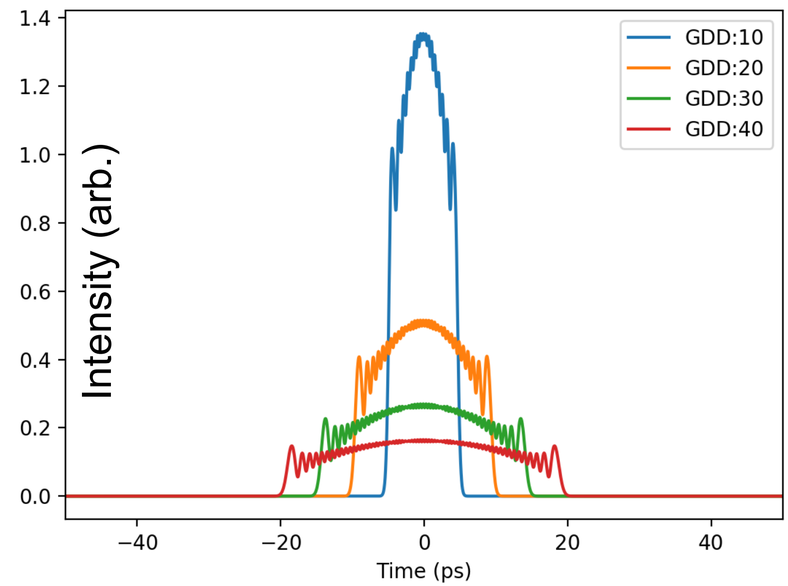
Sum Frequency Generation (SFG)

- Ongoing R&D by the laser group + ARD
  - R. Lemons, S. Carbajo, J. Duris, et al.
  - Same transverse/radius options as gaussian pulse
  - Wide range of longitudinal profiles from Gaussian to puesdo-square pulses

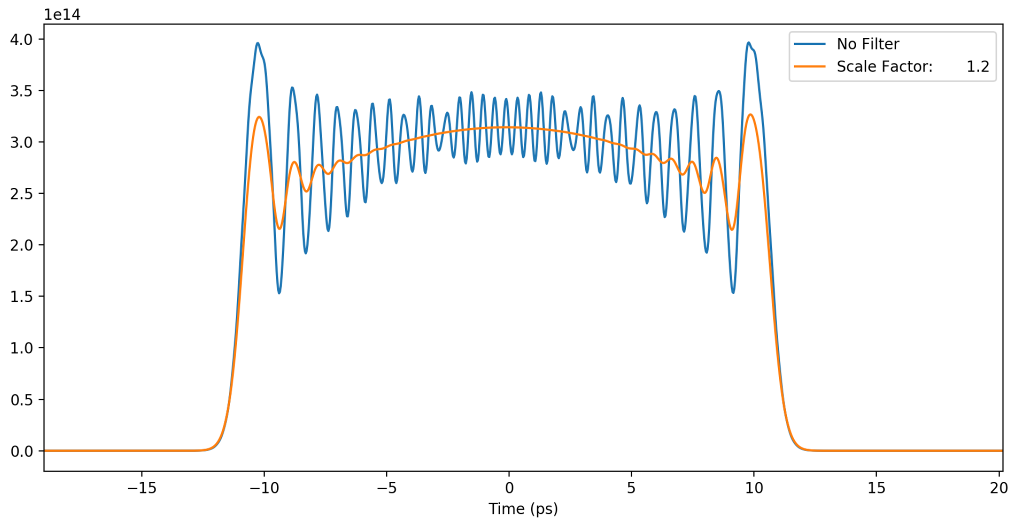
- Generation of non-gaussian temporal profiles
- **Flexible FWHM (GDD)**
  - Group delay dispersion
- **'Rounding'**
  - Scale factor (SF) between Taylor coefficients

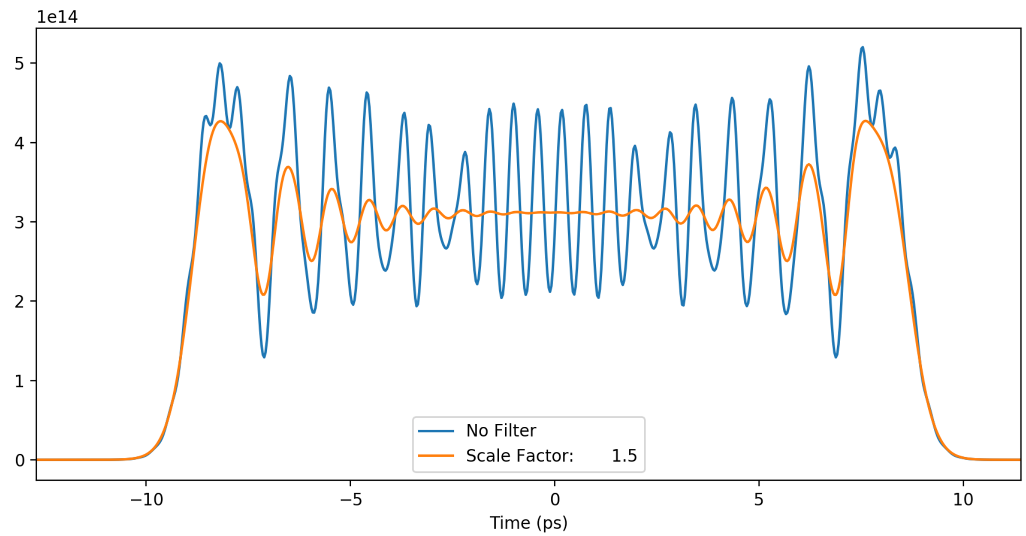




Filtered profiles

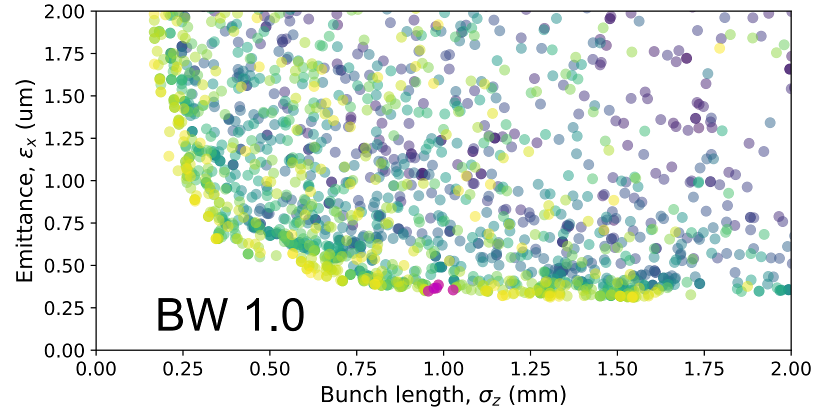
- Filter removes large ripples
  - Filter choice was static for each optimization
  - Varied from 1, 0.7, 0.5 nm
- GDD and SF added as optimization variables
  - These are tunable in the laser room

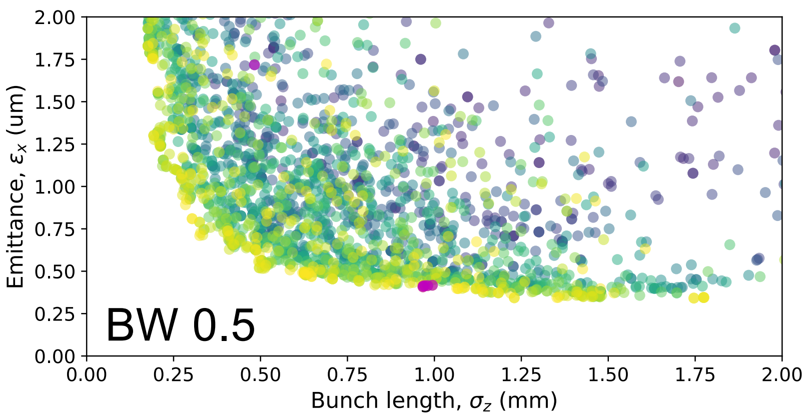


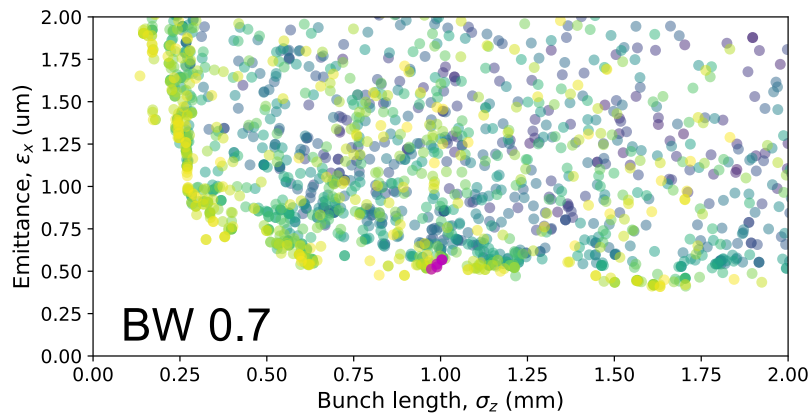


Preliminary SFG laser shaping

- Results shown here are 15 meters:
  - 100 pC
  - After first cryomodule
  - SSNL BW = 1, 0.7, 0.5
- Magenta = best emittance values near 1 (mm) bunch length







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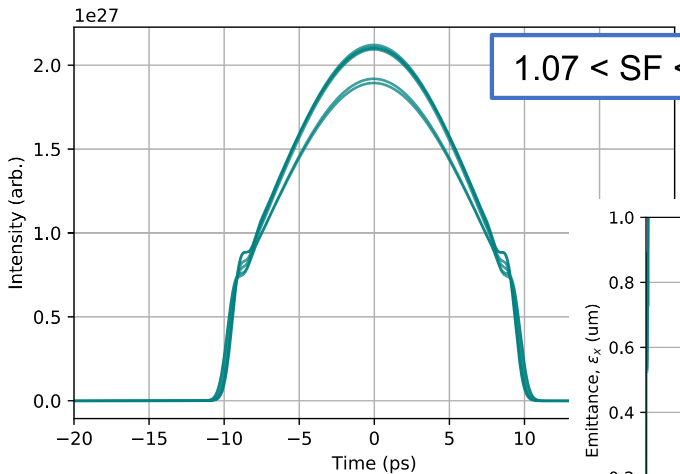
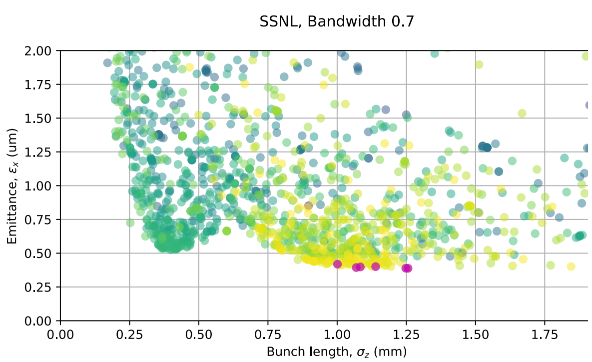
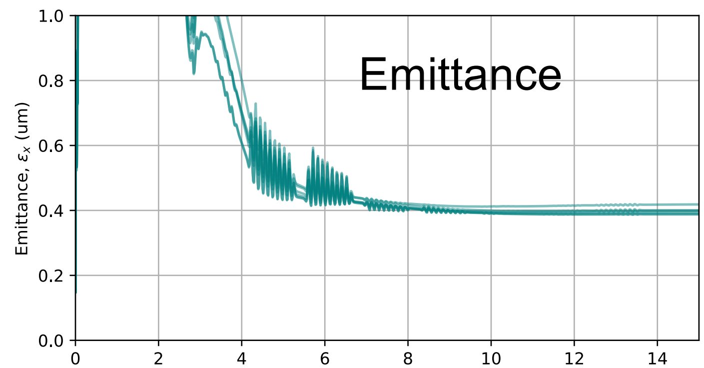
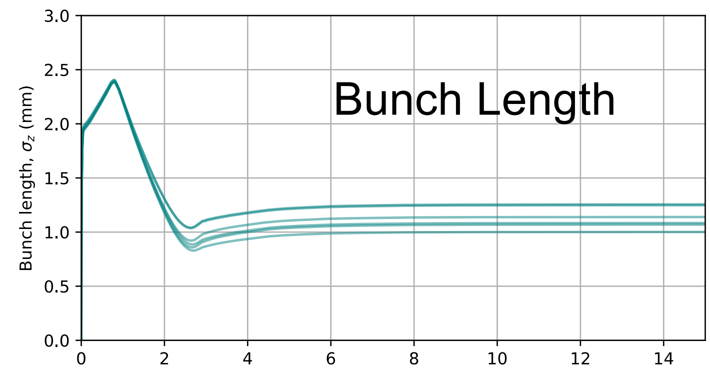
SSNL Bandwidth 0.7 nm

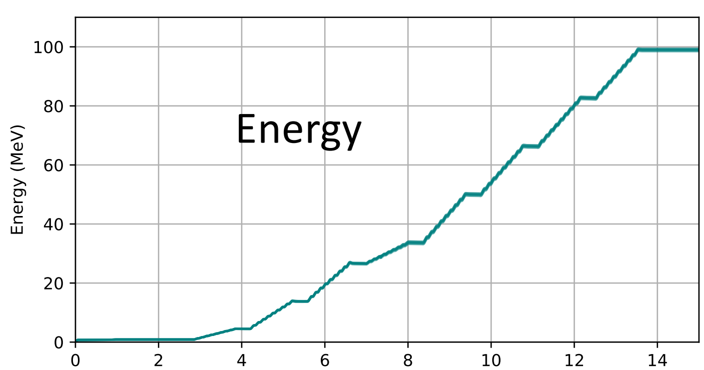
1.07 < SF < 1.1

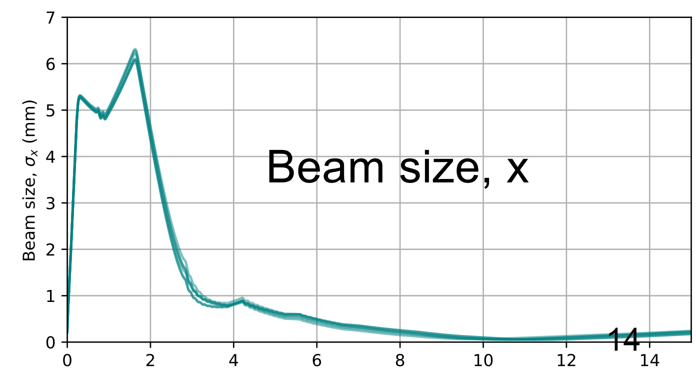




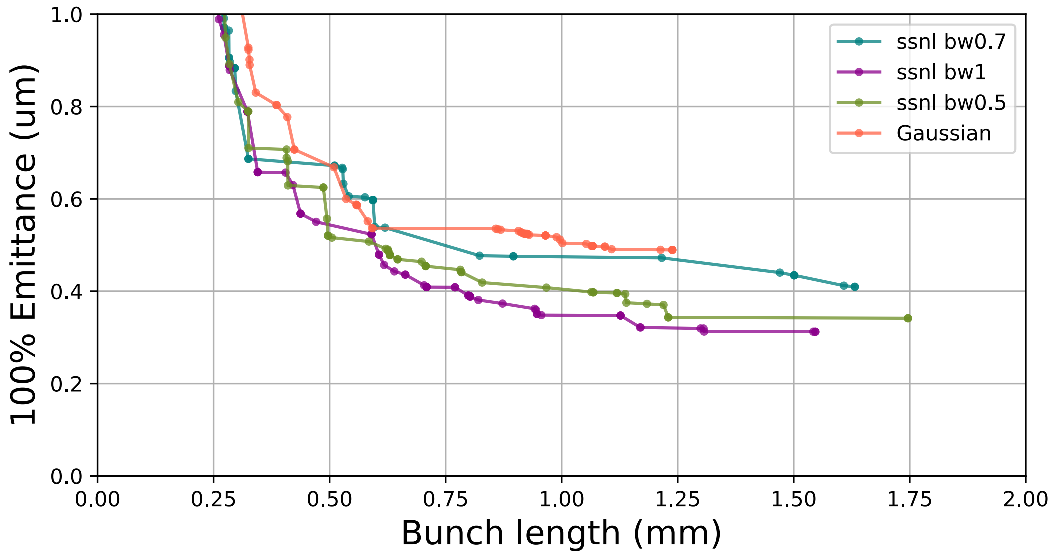


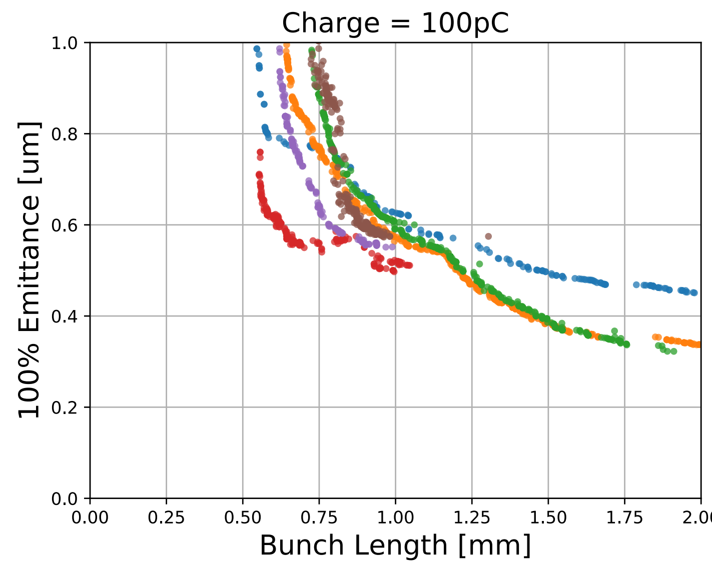


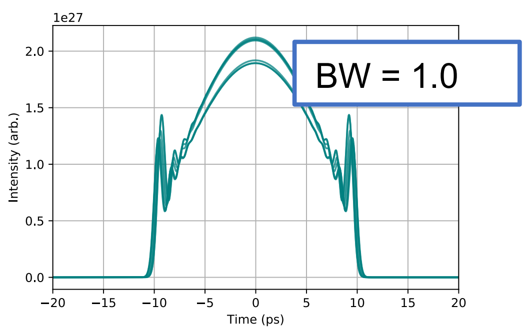


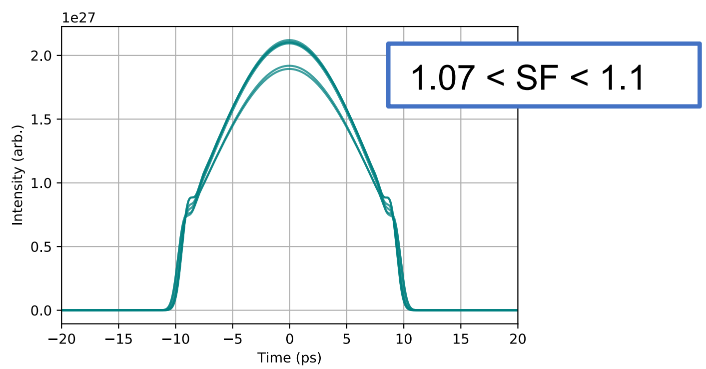


Preliminary SFG results



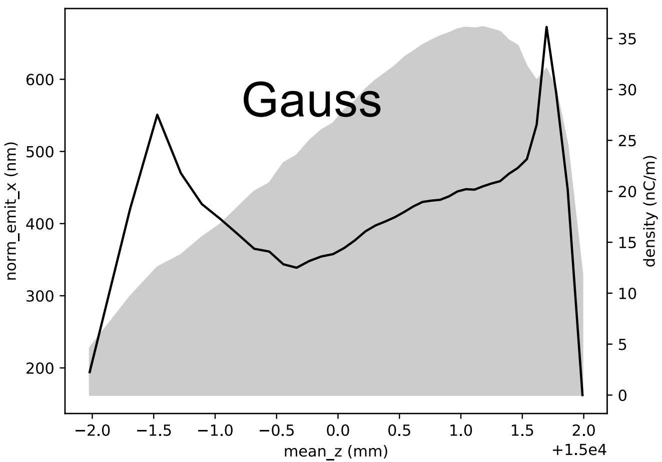


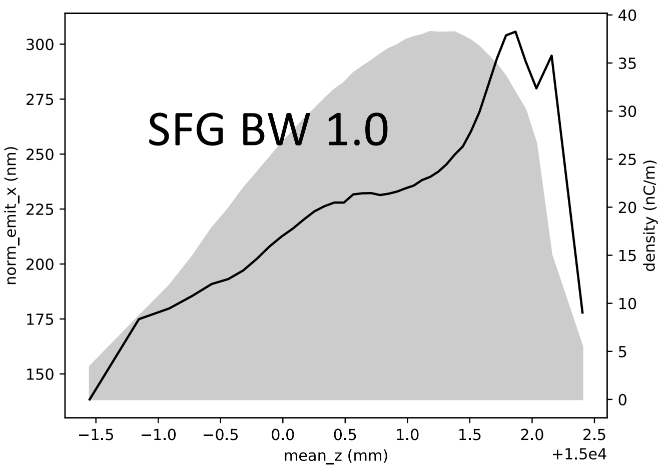




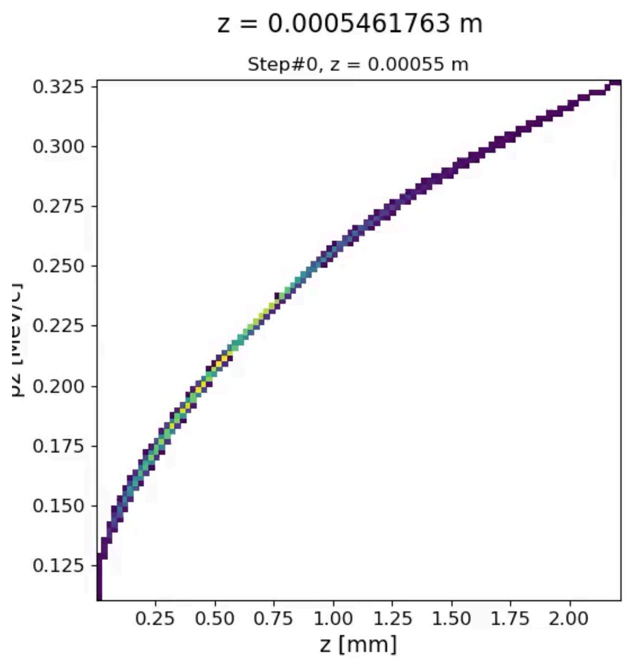
- 100 pC astra optimizations to date have not reached ~0.4 um at 1 mm bunch length

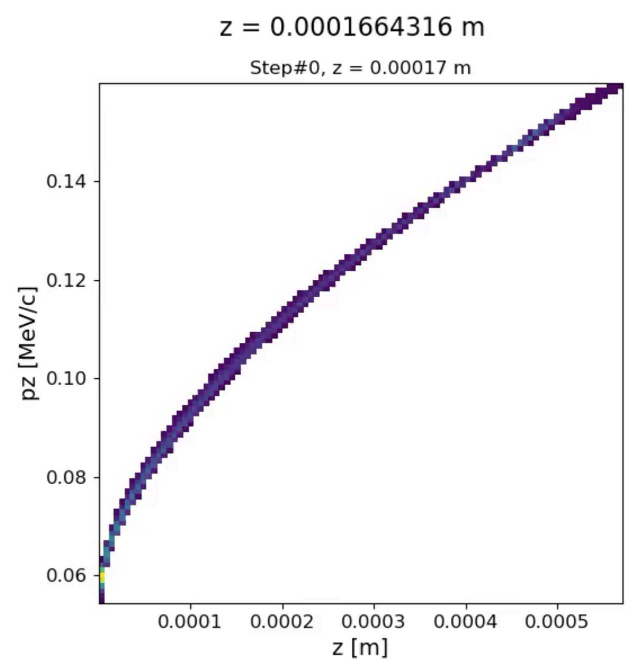
Gauss vs. SFG BW 1.0





- About 20% difference in 100% emittance
- Folded tails are mitigated by SFG shaping





Summary:

- Optimization helps improve, understand, and estimate machine performance
- Beam emittance is sensitive to parameters in gun and first accelerating cavties
- Flexible laser radius and FWHM is helpful for mitigating space charge forces
- Small deviations in gun energy does not degrade performance dramatically
  - 700keV or 650 keV vs. 750 keV
- A failed cavity in the first cryomodule can be a showstopper
- New laser shaping techniques can help mitigate emittance growth by reducing ‘tails’ of the beam

Backup

Software Tools

Optimization frameworks:

- Xopt: https://github.com/ChristopherMayes/xopt
  - Astra, GPT
- LibEnsemble: https://github.com/Libensemble/libensemble
  - OPAL

Beam physics:

- Distgen: https://github.com/ColwynGulliford/distgen
- ASTRA: https://www.desy.de/~mpyflo/
- Lume-astra: https://github.com/ChristopherMayes/lume-astra
- OPAL: https://gitlab.psi.ch/OPAL/src/-/wikis/home
- openPMD-beamphysics: https://github.com/ChristopherMayes/openPMD-beamphysics

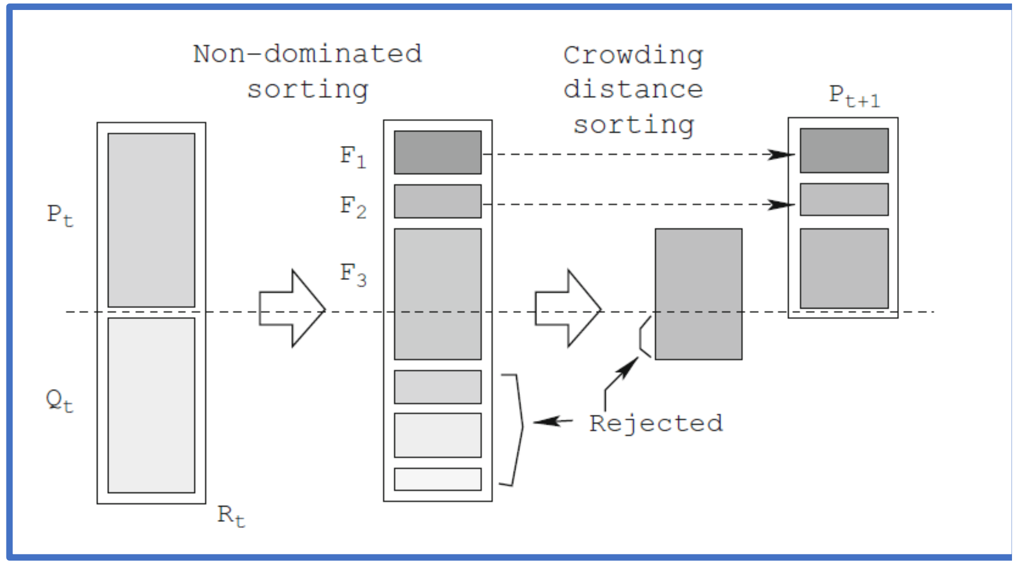
Xopt: Constraints

- Two objectives minimized:
  - 95% emittance
  - bunch length
- Six constraints:
  - Conditions to help optimizer reject bad parameter combinations

Output	Operator	Value
Kinetic Energy	>	90 MeV
Energy Spread	<	200 keV
Bunch Length	<	1.5 mm
95% Emittance	<	90 um
Particle loss	=	0
Higher order dE	<	5 keV

NSGA-II in a nutshell:

1. Do an initial sample
   - parent population, P_0
2. Find the pareto front (F_i) through sorting objectives
   - Pareto front = "nondominated"
3. Calculate crowding distance, and sort to pick new population, P1
4. Use selection, crossover, and mutation to generate children (new population)
5. Evaluate new population (run simulation)
6. Repeat starting at #2.

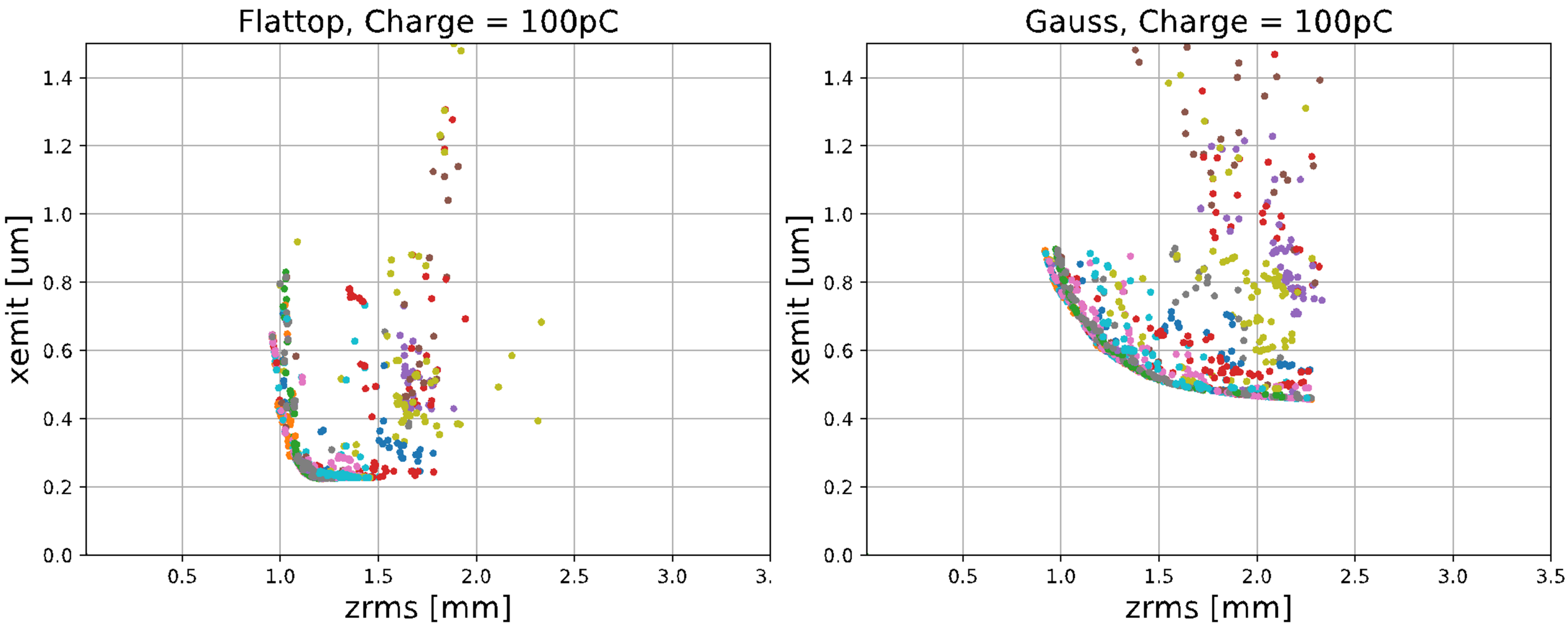


http://oklahomaanalytics.com/data-science-techniques/nsga-ii-explained/

Caveat…ignoring hyperparameter tuning, summer student worked on this

K. Deb, et al. NSGA-II, IEEE Trans. On , 2002

Pareto front evolution, Gauss and Flattop



*95% emittances