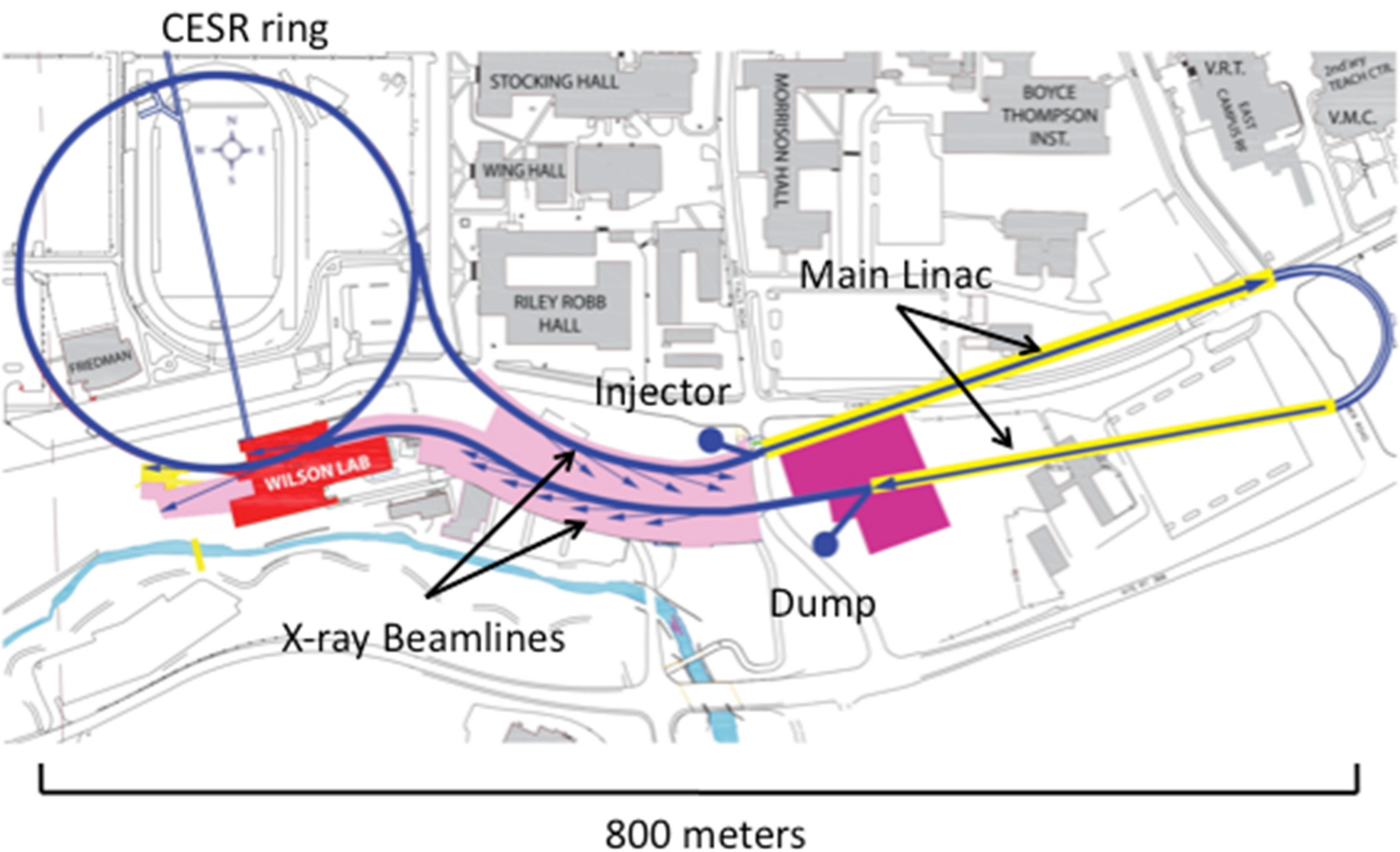
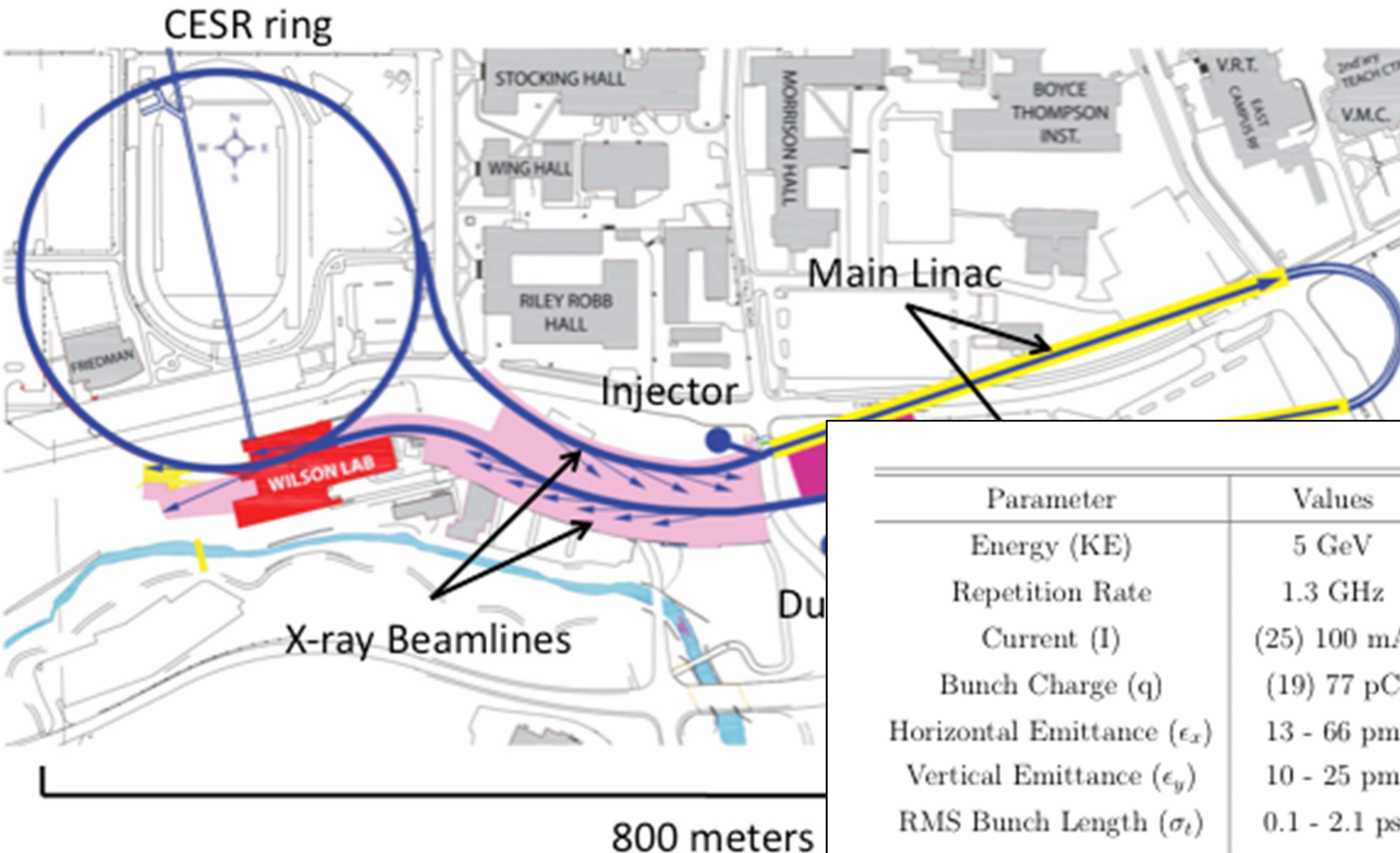
Low Emittance Measurements in the Cornell ERL Injector

Colwyn Gulliford
For the Cornell University ERL Team

The Cornell ERL



The Cornell ERL



Parameter	Values
Energy (KE)	5 GeV
Repetition Rate	1.3 GHz
Current (I)	(25) 100 mA
Bunch Charge (q)	(19) 77 pC
Horizontal Emittance (ϵ_x)	13 - 66 pm
Vertical Emittance (ϵ_y)	10 - 25 pm
RMS Bunch Length (σ_t)	0.1 - 2.1 ps
RMS Energy Spread (σ_δ)	0.009 - 0.09 %

Requires a state-of-the-art electron source!

Parameter Specifications for the Injector

Cornell 5 GeV ERL X-ray Facility

Parameter	Values
Energy (KE)	5 GeV
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Current (I)	(25) 100 mA
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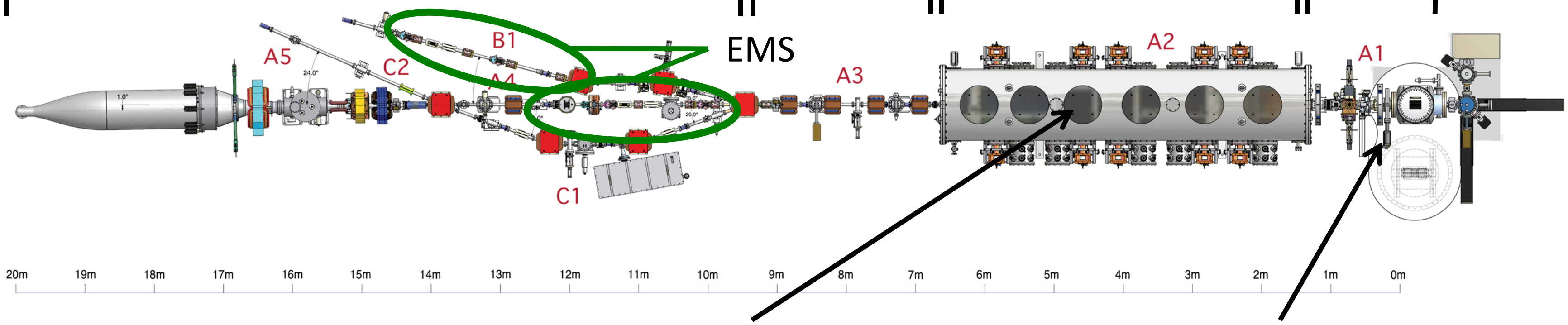
Horizontal Emittance (ϵ_x)	13 - 66 pm
Vertical Emittance (ϵ_y)	10 - 25 pm
RMS Bunch Length (σ_t)	0.1 - 2.1 ps
RMS Energy Spread (σ_δ)	0.009 - 0.09 %

Cornell DC Photoinjector

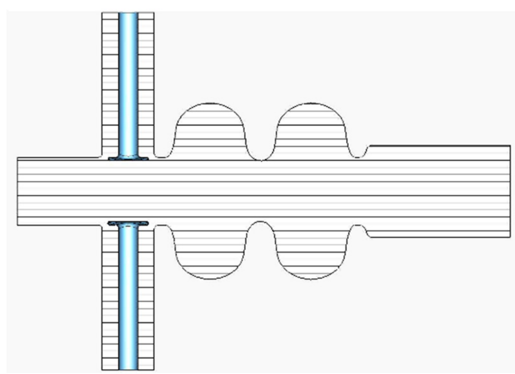
Parameter	Specification
Energy (E)	5 - 15 MeV
Repetition Rate	1.3 GHz
Current (I)	(25) 100 mA
Bunch Charge (q)	(19) 77 pC
Norm. Emittance (ε_n)	≤ 0.3 µm
RMS Bunch Length (σ_t)	≤ 3 ps
RMS Energy Spread (σ_δ)	~ 10^{-3}

The Cornell ERL Injector

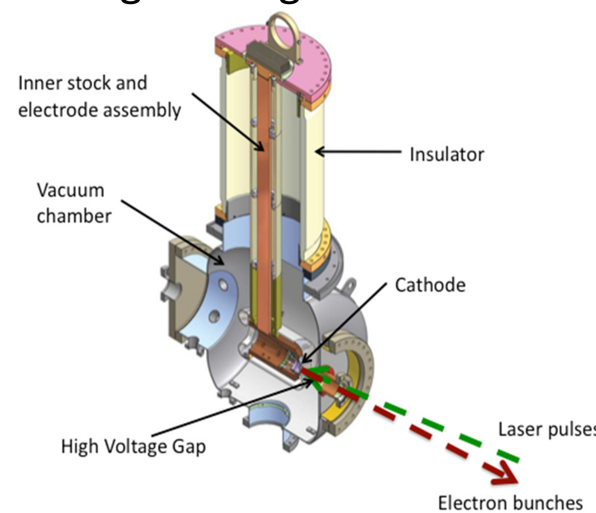
6 Dimensional Phase Space Diagnostics + Merger Section + High Power Beam Dump | Focusing | Main Acceleration 5 – 15 MeV | Source (350 keV) + Bunching/Focusing



Superconducting RF Cavities (niobium)



High Voltage DC Gun



Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

The Cornell ERL Injector

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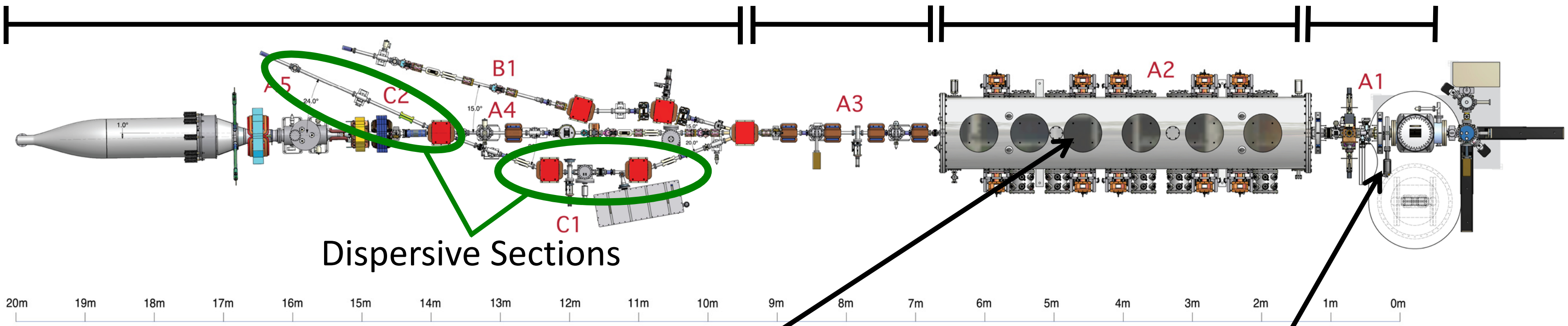

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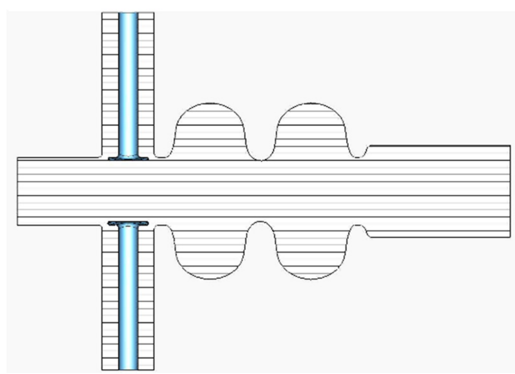

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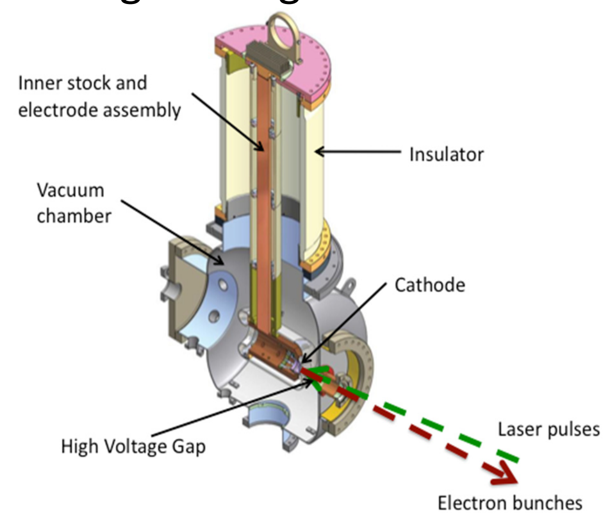


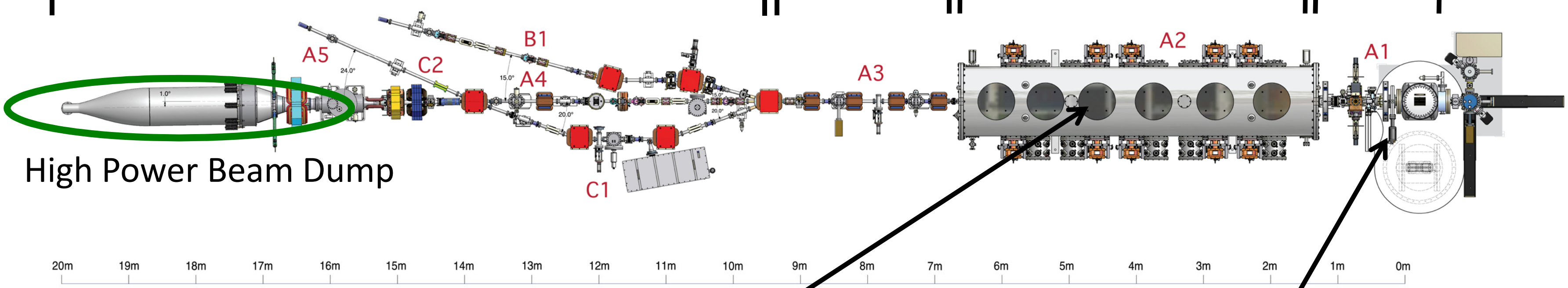
The Cornell ERL Injector

6 Dimensional Phase Space Diagnostics + Merger Section + High Power Beam Dump

Focusing

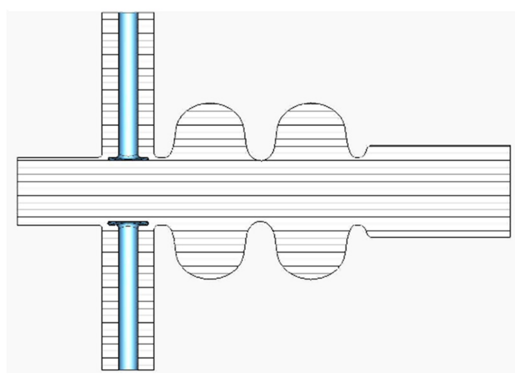
Main Acceleration 5 – 15 MeV

Source (350 keV) + Bunching/Focusing



High Power Beam Dump

Superconducting RF Cavities (niobium)



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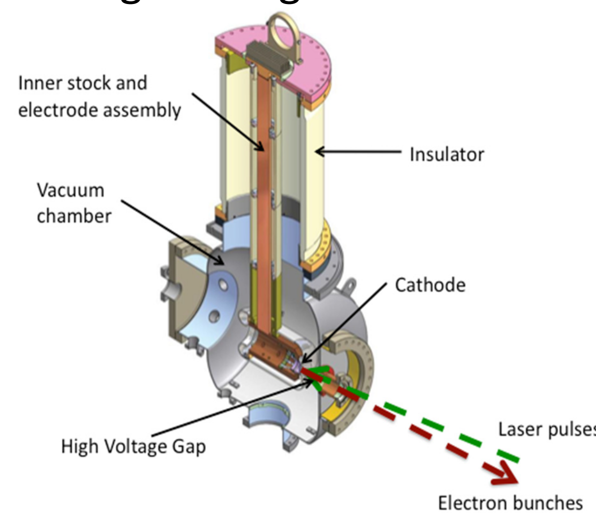

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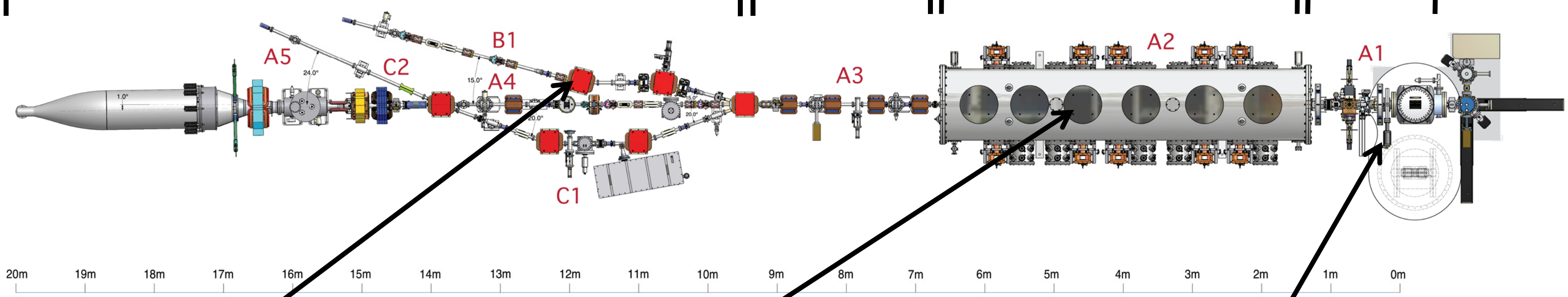
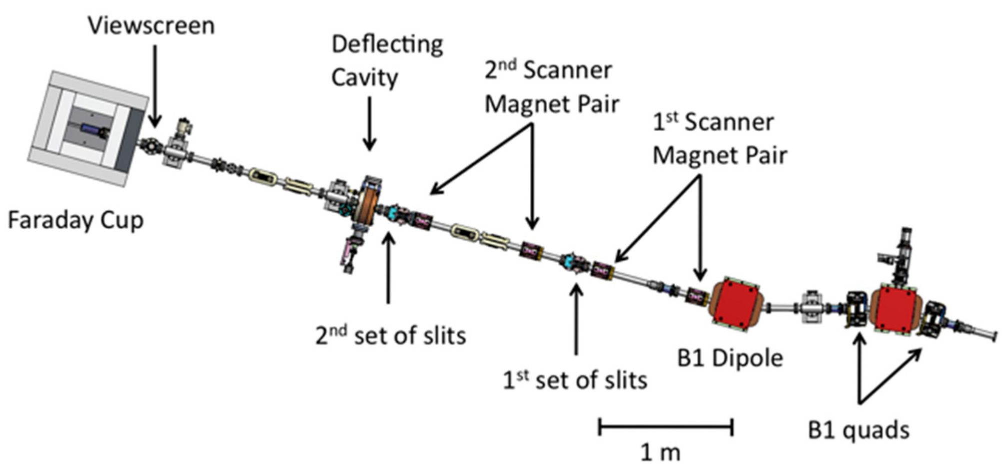
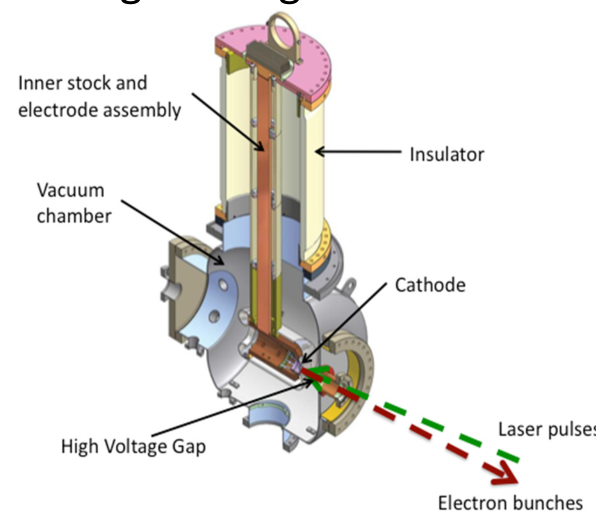


B1 Merger Section

Superconducting RF Cavities (niobium)

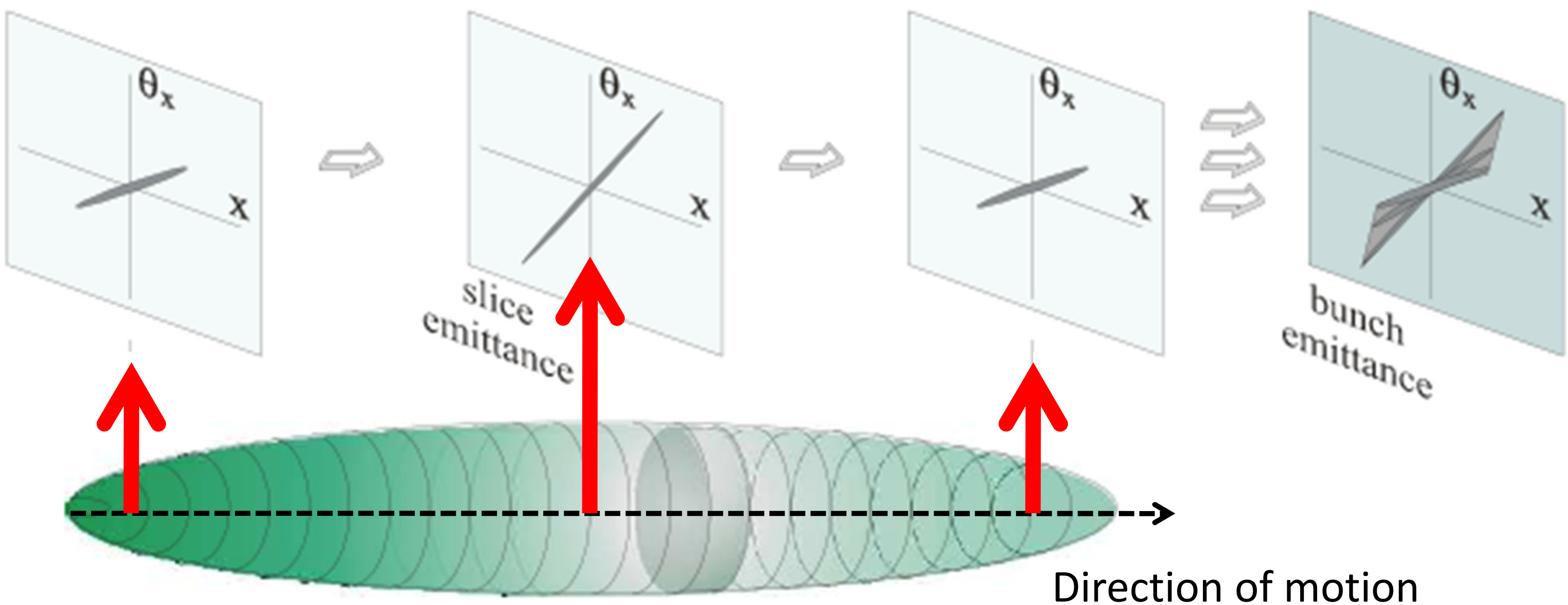
High Voltage DC Gun





Low Emittance Experiments

Sources of Emittance Degradation	Remedy
1. Non-linear fields (aberrations, space charge)	1. Beam alignment, Laser shaping
2. Longitudinally dependent focusing (RF fields, space charge)	2. Emittance Compensation (detailed simulations)

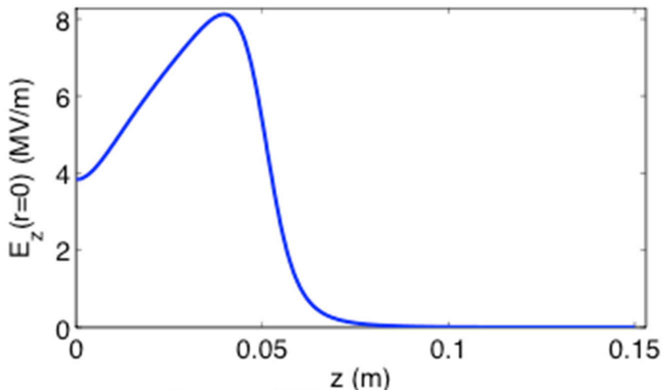


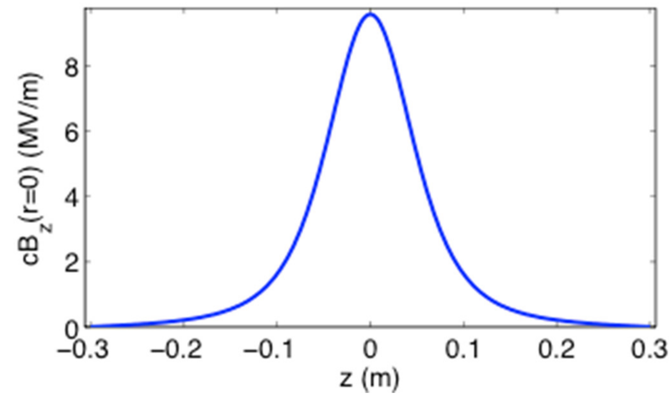
GPT Injector Model

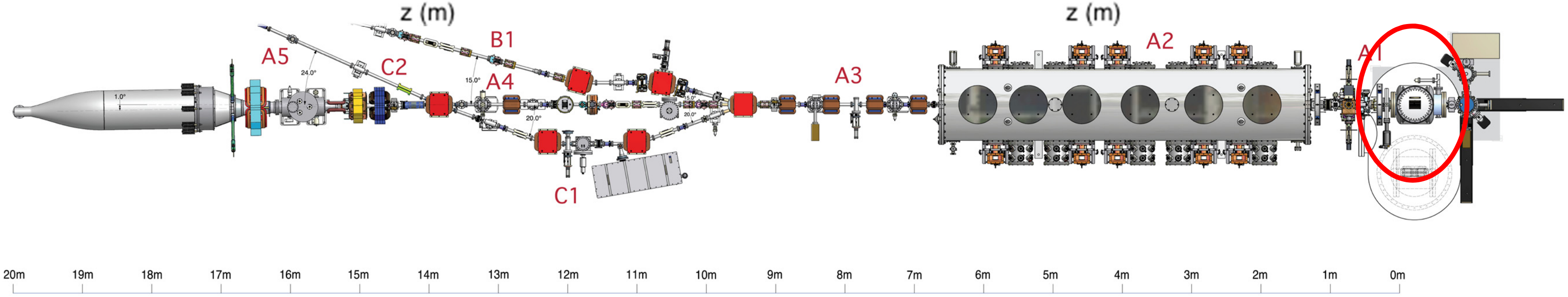
Code of choice for this work: General Particle Tracer

- Has a 3D Space Charge algorithm
- Realistic Initial Particle Distribution
- Ability to overlap field maps and position them in 3D space
- Customizable (define new beamline elements)

Used realistic field maps for all beam line elements







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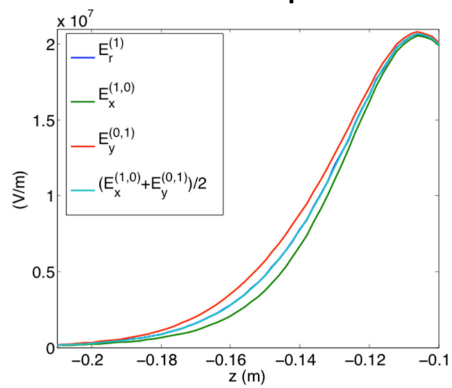
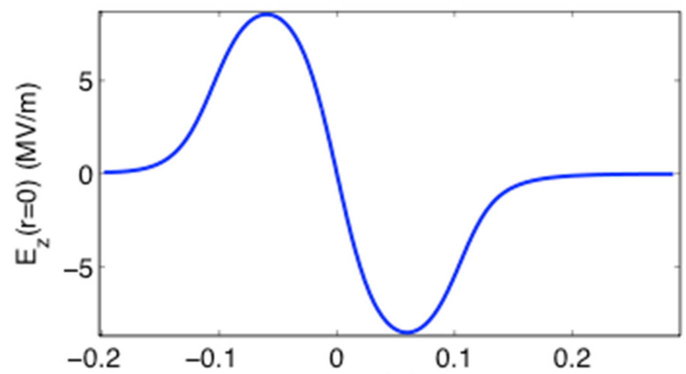
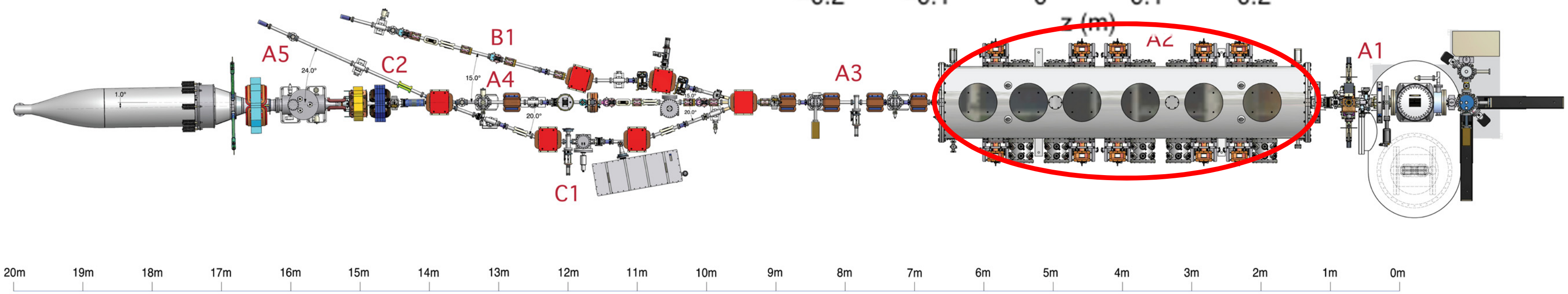
Includes 3D complex RF Field Maps w/coupler fields







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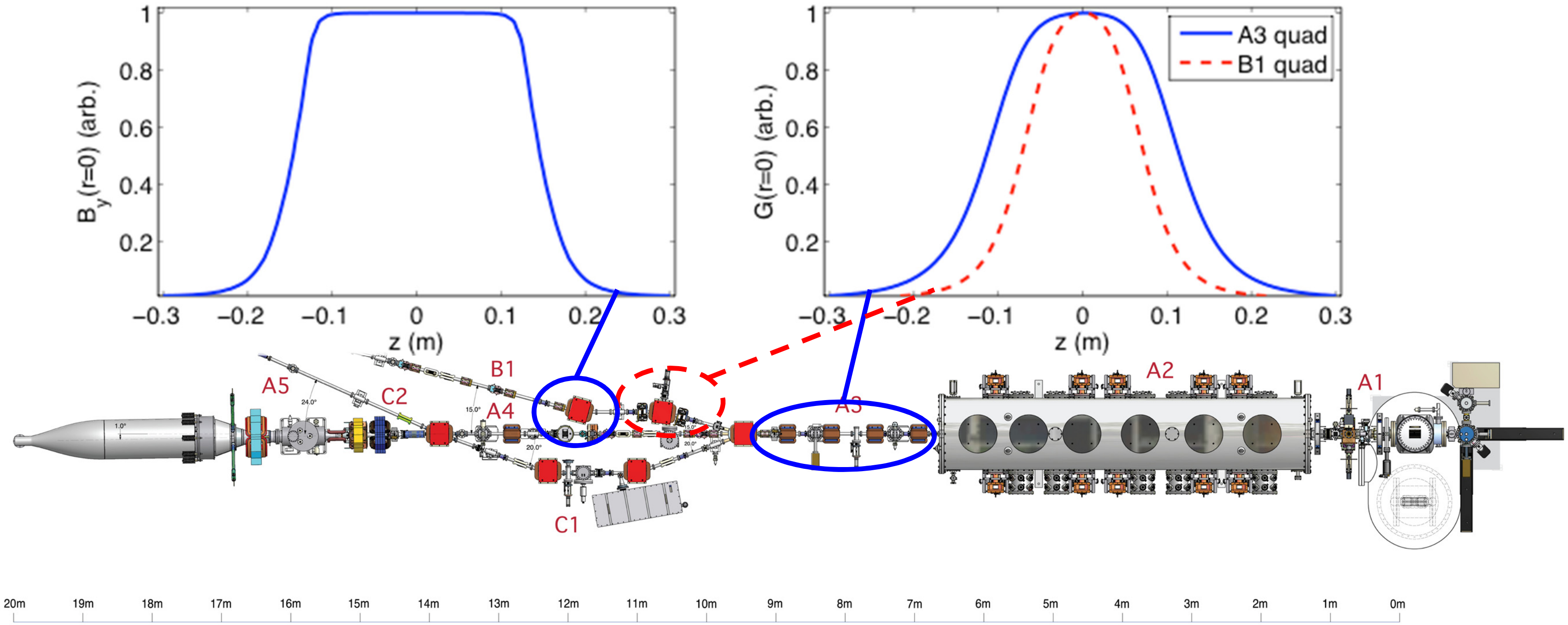
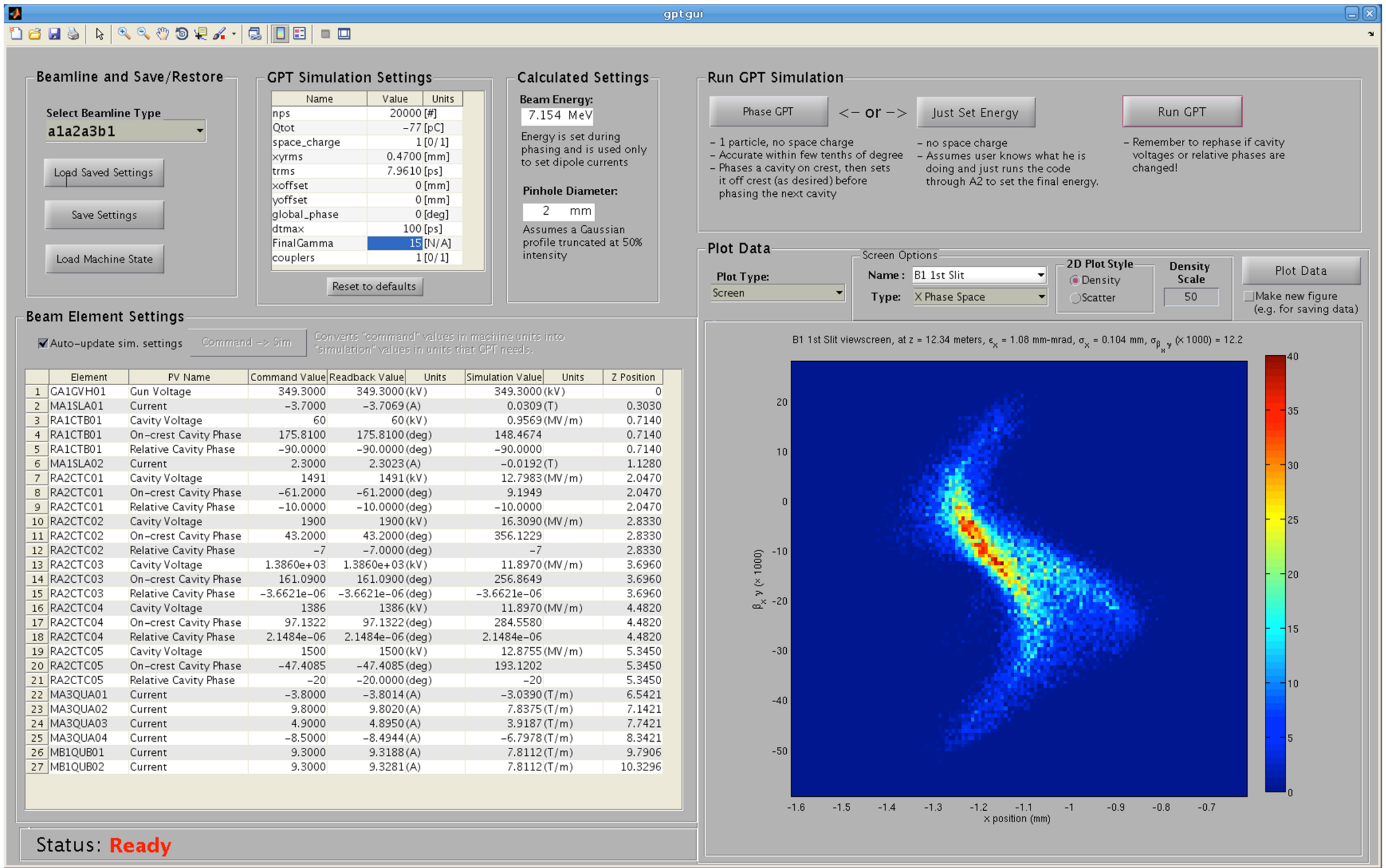
Customized quadrupole and dipole elements with fields computed from an on-axis field map



Integration into the Control System

GPT Virtual Accelerator GUI: load machine settings, load optimizer settings, save/restore, independently simulate machine in (near) real time

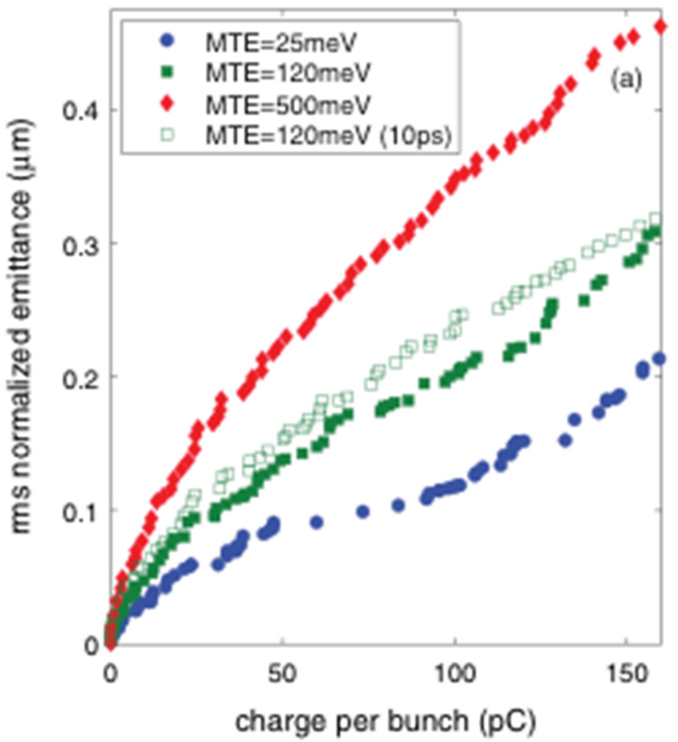


Name	Value	Units
nps	20000	[#]
Qtot	-77	[pC]
space_charge	1	[0/1]
xyrms	0.4700	[mm]
trms	7.9610	[ps]
xoffset	0	[mm]
yoffset	0	[mm]
global_phase	0	[deg]
dtmax	100	[ps]
FinalGamma	15	[N/A]
couplers	1	[0/1]

	Element	PV Name	Command Value	Readback Value	Units	Simulation Value	Units	Z Position
1	GA1GVH01	Gun Voltage	349.3000	349.3000	(kV)	349.3000	(kV)	0
2	MA1SLA01	Current	-3.7000	-3.7069	(A)	0.0309	(T)	0.3030
3	RA1CTB01	Cavity Voltage	60	60	(kV)	0.9569	(MV/m)	0.7140
4	RA1CTB01	On-crest Cavity Phase	175.8100	175.8100	(deg)	148.4674		0.7140
5	RA1CTB01	Relative Cavity Phase	-90.0000	-90.0000	(deg)	-90.0000		0.7140
6	MA1SLA02	Current	2.3000	2.3023	(A)	-0.0192	(T)	1.1280
7	RA2CTC01	Cavity Voltage	1491	1491	(kV)	12.7983	(MV/m)	2.0470
8	RA2CTC01	On-crest Cavity Phase	-61.2000	-61.2000	(deg)	9.1949		2.0470
9	RA2CTC01	Relative Cavity Phase	-10.0000	-10.0000	(deg)	-10.0000		2.0470
10	RA2CTC02	Cavity Voltage	1900	1900	(kV)	16.3090	(MV/m)	2.8330
11	RA2CTC02	On-crest Cavity Phase	43.2000	43.2000	(deg)	356.1229		2.8330
12	RA2CTC02	Relative Cavity Phase	-7	-7.0000	(deg)	-7		2.8330
13	RA2CTC03	Cavity Voltage	1.3860e+03	1.3860e+03	(kV)	11.8970	(MV/m)	3.6960
14	RA2CTC03	On-crest Cavity Phase	161.0900	161.0900	(deg)	256.8649		3.6960
15	RA2CTC03	Relative Cavity Phase	-3.6621e-06	-3.6621e-06	(deg)	-3.6621e-06		3.6960
16	RA2CTC04	Cavity Voltage	1386	1386	(kV)	11.8970	(MV/m)	4.4820
17	RA2CTC04	On-crest Cavity Phase	97.1322	97.1322	(deg)	284.5580		4.4820
18	RA2CTC04	Relative Cavity Phase	2.1484e-06	2.1484e-06	(deg)	2.1484e-06		4.4820
19	RA2CTC05	Cavity Voltage	1500	1500	(kV)	12.8755	(MV/m)	5.3450
20	RA2CTC05	On-crest Cavity Phase	-47.4085	-47.4085	(deg)	193.1202		5.3450
21	RA2CTC05	Relative Cavity Phase	-20	-20.0000	(deg)	-20		5.3450
22	MA3QUA01	Current	-3.8000	-3.8014	(A)	-3.0390	(T/m)	6.5421
23	MA3QUA02	Current	9.8000	9.8020	(A)	7.8375	(T/m)	7.1421
24	MA3QUA03	Current	4.9000	4.8950	(A)	3.9187	(T/m)	7.7421
25	MA3QUA04	Current	-8.5000	-8.4944	(A)	-6.7978	(T/m)	8.3421
26	MB1QUB01	Current	9.3000	9.3188	(A)	7.8112	(T/m)	9.7906
27	MB1QUB02	Current	9.3000	9.3281	(A)	7.8112	(T/m)	10.3296

Goals for Experiment

- Measure low emittances at the end of the merger
  - Emittances ≤ 0.3 micron
  - Bunch Length ≤ 3 ps
  - Energy Spread ~ 1e-3
- Demonstrate $\varepsilon_{n,x} \propto \sqrt{q}$, take 19 pC and 77 pC data, corresponds to 25 and 100 mA if operating at full repetition rate.
- Demonstrate agreement between measurement and simulation



Optimizations of the Injector Model

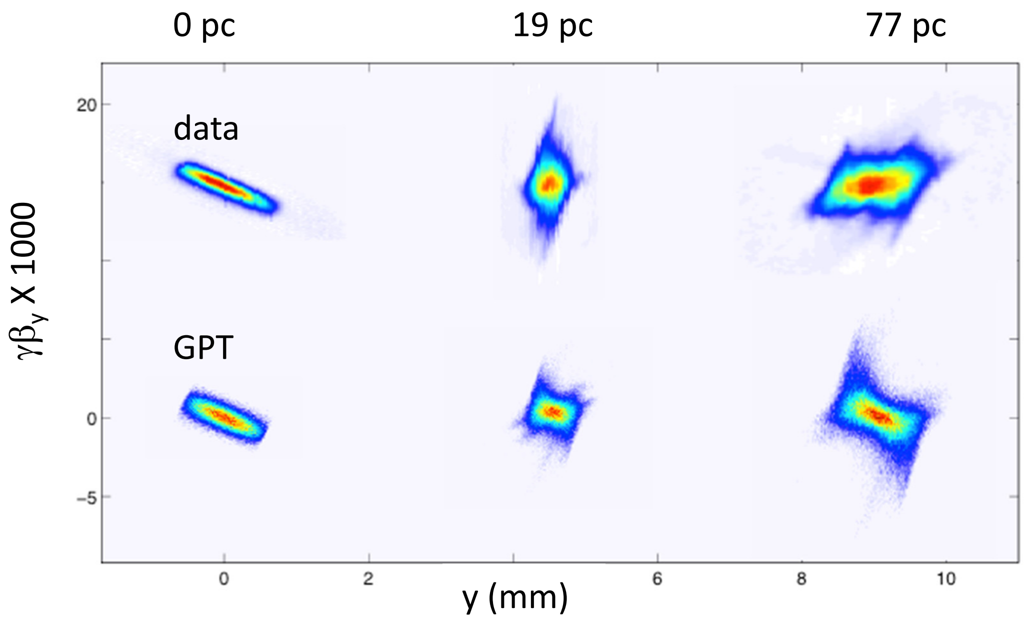
Used a multi-objective genetic optimization algorithm to find machine settings to load into the injector.

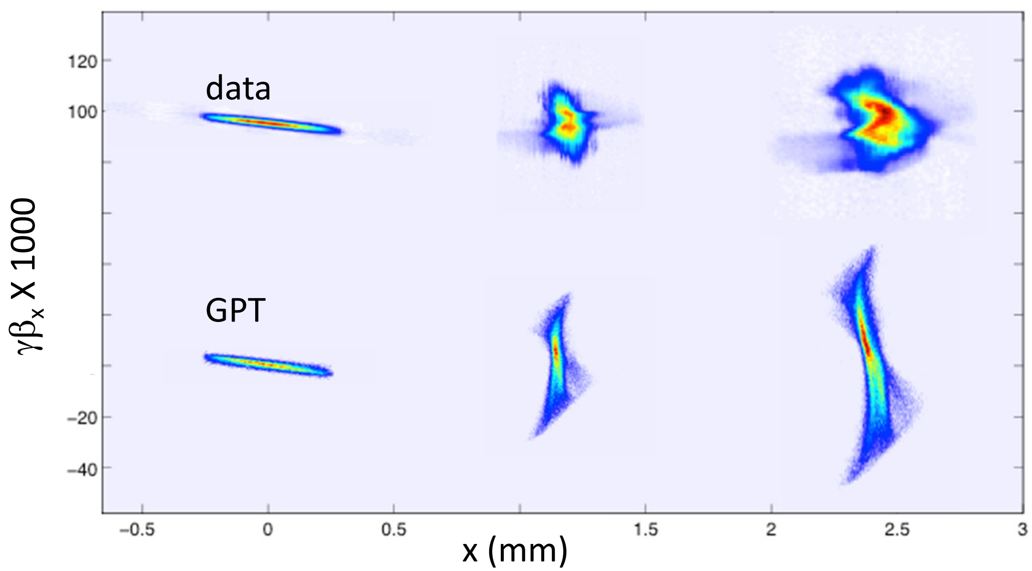
After several rounds of optimizations and emittance measurements, found a solution which we based our 19 pC and 77 pC injector settings.

Injector Parameter	(19) 77 pC settings
Gun High Voltage	(350) 350 kV
Beam Kinetic Energy	(7.5) 7.7 MeV
Laser Pinhole	(1) 2 mm
Laser Pulse Length	(8) 8 ps
Buncher Voltage	(50) 60 kV

Measurements were taken using a chopped 50 MHz laser pulse train, reducing the beam power going into interceptive diagnostics.

Low Emittance Experiments





Projected Emittance for 19 (77) pC:

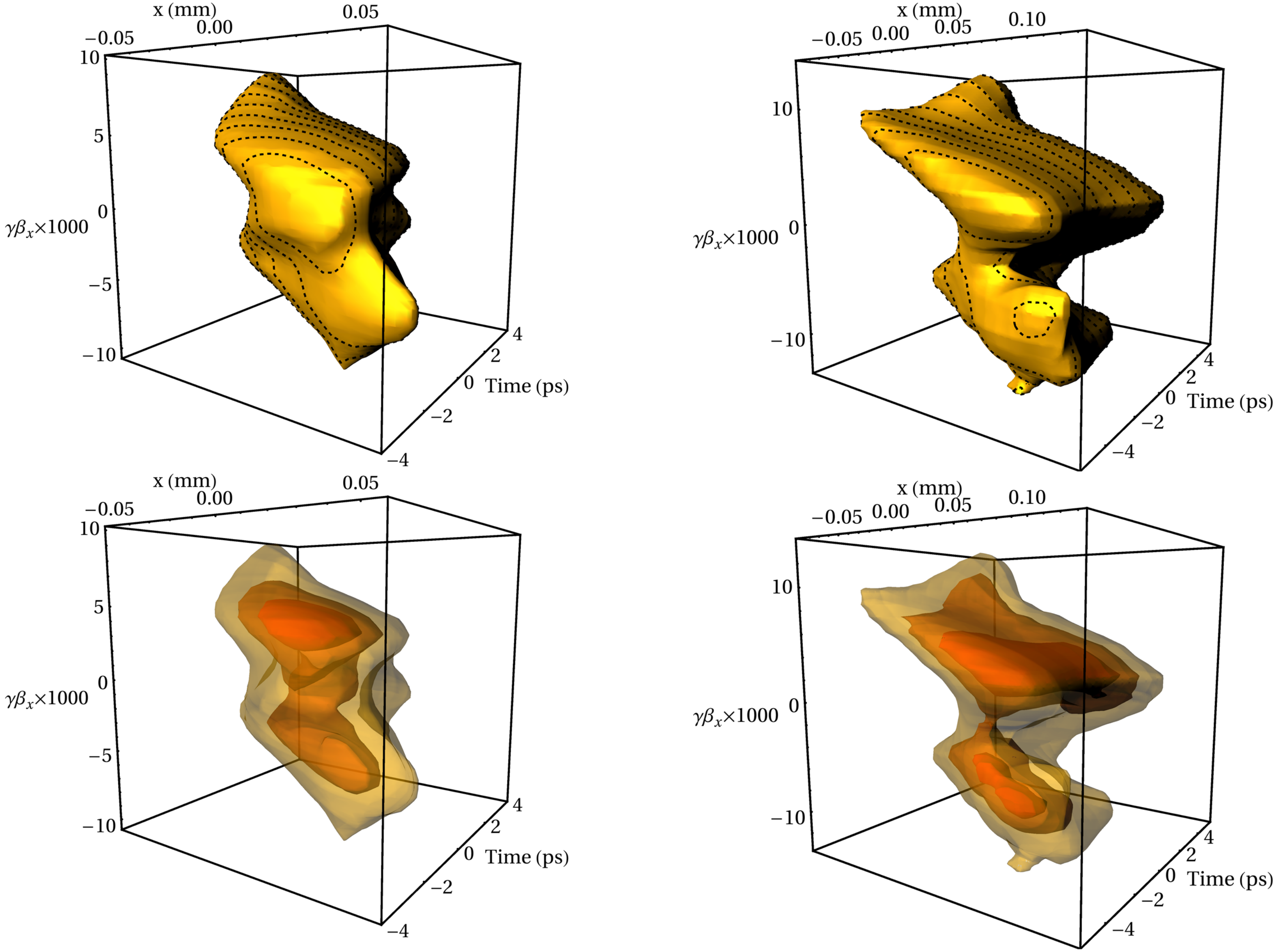
<u>Vertical Phase Space</u>

Data Type	en(100%) [microns]	en(90%) [microns]
P-EMS	0.20 ± 0.01 (0.40 ± 0.03)	0.14 ± 0.01 (0.29 ± 0.02)
GPT	0.16 (0.37)	0.11 (0.25)

<u>Horizontal Phase Space</u>

Data Type	en(100%) [microns]	en(90%) [microns]
P-EMS	0.33 ± 0.02 (0.69 ± 0.05)	0.23 ± 0.02 (0.51 ± 0.04)
GPT	0.31 (0.72)	0.19 (0.44)

Low Emittance Experiments



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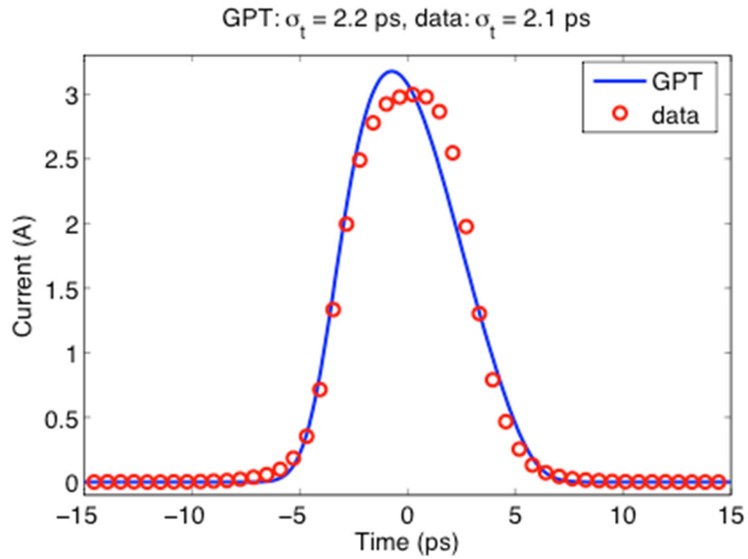

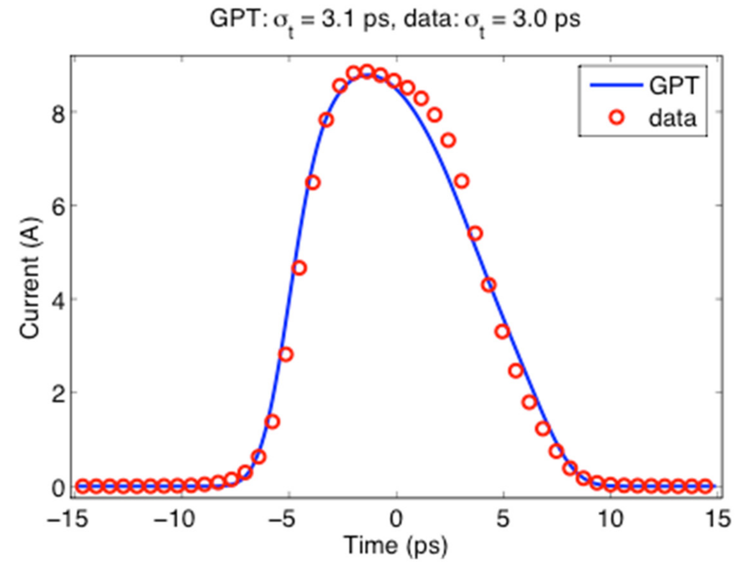

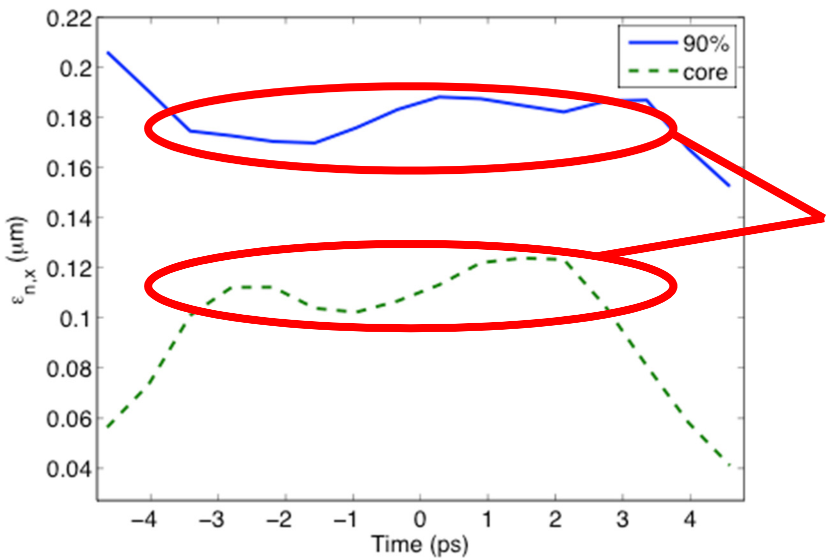

Flat, core dominated by intrinsic emittance (0.12 μm)

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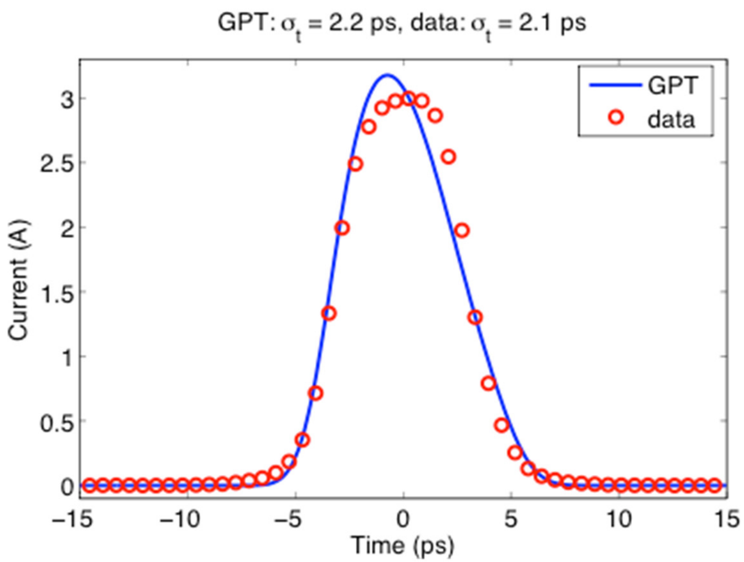
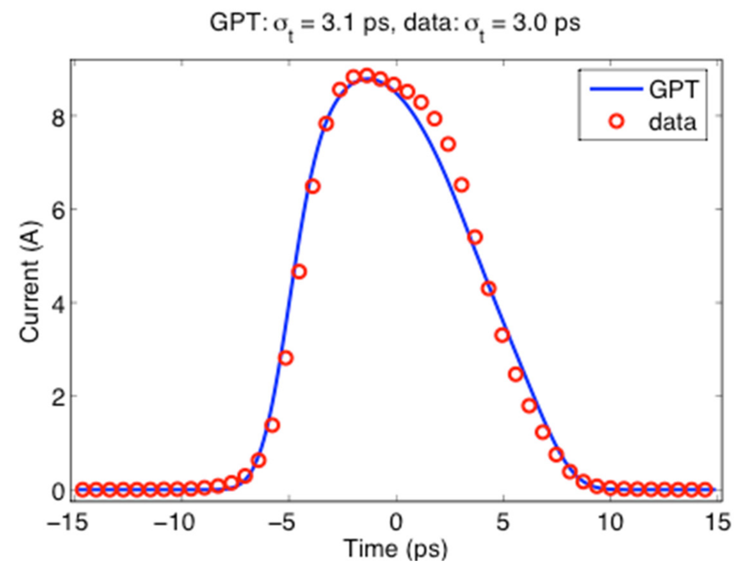
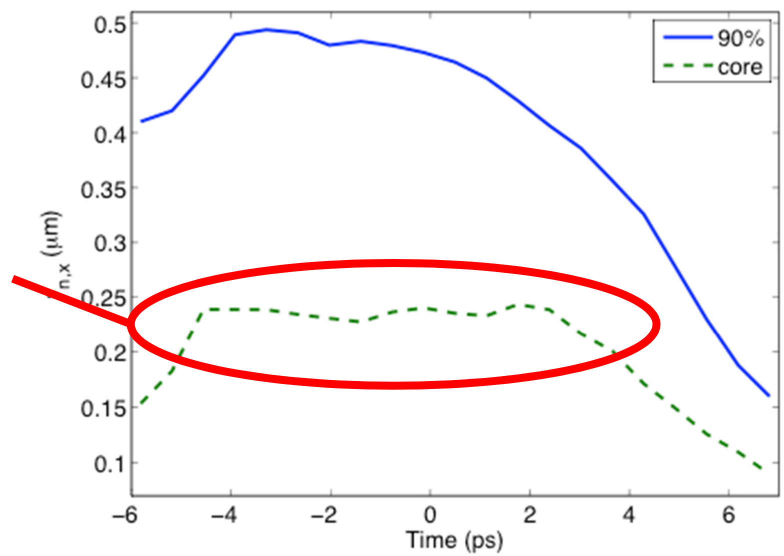
Low Emittance Experiments





Flat, core dominated by intrinsic emittance, (0.24 μm)



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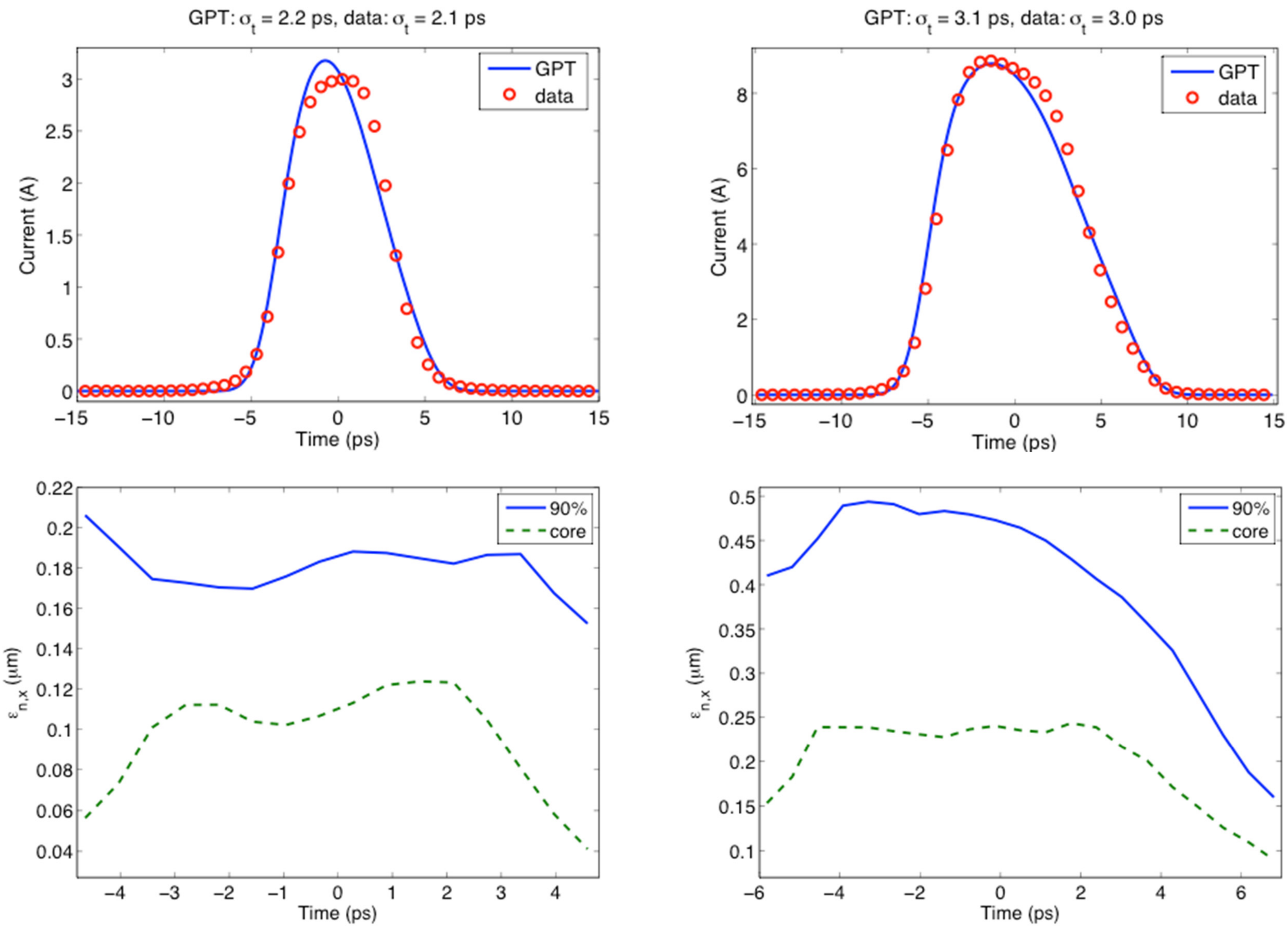


Data Summary

C. Gulliford, et al, Phys. Rev. ST Accel. Beams 16 (Jul, 2013) 073401.

Data Type	Specification for (19) 77 pC	Measured Values for (19) 77 pC
V. Emittance (eff. core*)	≤ (0.3) 0.3 μm	(0.13 ± 0.01) 0.27 ± 0.01 μm
V. Emittance (90%)	≤ (0.3) 0.3 μm	(0.14 ± 0.01) 0.29 ± 0.02 μm
H. Emittance (eff. core*)	≤ (0.3) 0.3 μm	(0.21 ± 0.01) 0.44 ± 0.03 μm
H Emittance (90%)	≤ (0.3) 0.3 μm	(0.23 ± 0.02) 0.51 ± 0.04 μm
RMS Bunch Length	≤ (3) 3 ps	(2.1 ± 0.1) 3.0 ± 0.2 ps
RMS Energy Spread	~ 1e-3	(< 1.4e-3) < 0.26e-3

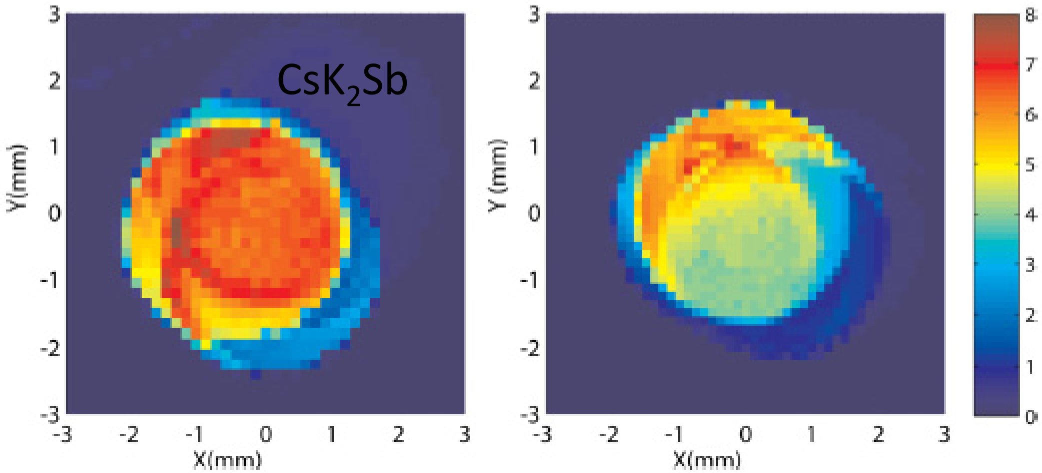
* Effective core emittance = emittance(core fraction) / core fraction

See that for 19 pC the effective core emittance satisfies all injector specifications

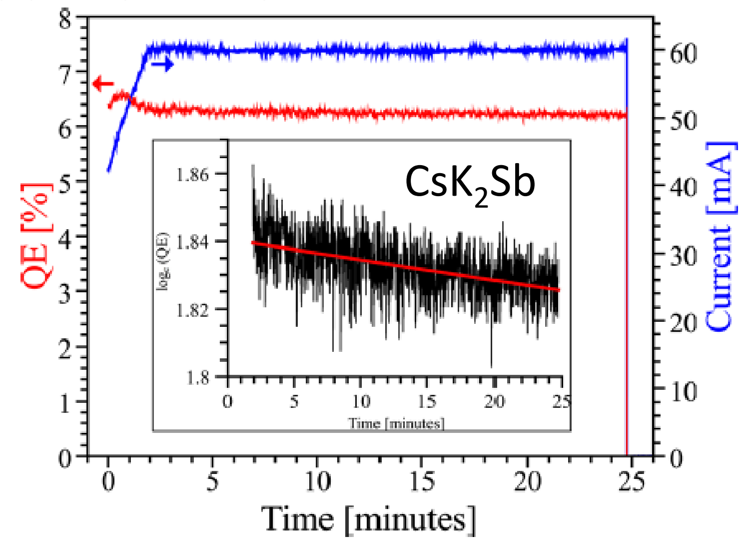
World record photoinjector current!

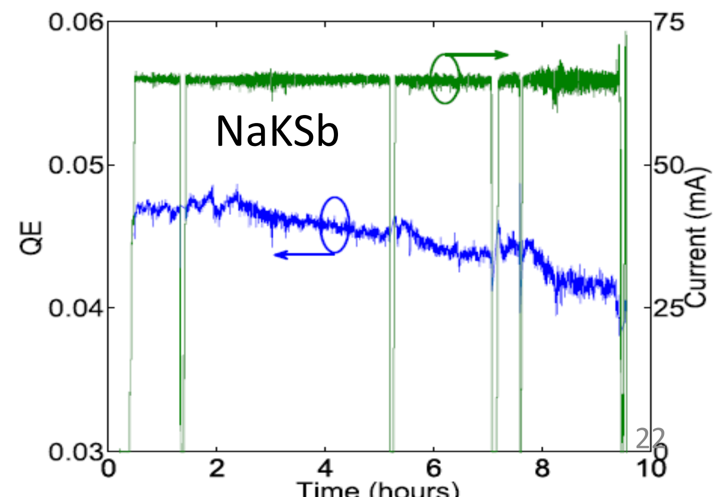
Cultrera et al. APL 103 (2013) 103504, Dunham et al. APL 102, 034105 (2013)

- Using multialkali off center, a robust bulk emitter:



Before use   **After** use





- **60mA run with CsK_2Sb** had ~30 h 1/e lifetime
  - P_{gun}=1.13x10^{-11} torr → 3.0x10^{-11} torr
  - Likely due to beam scraping
- **65mA run with NaKSb** had ~66 h 1/e lifetime

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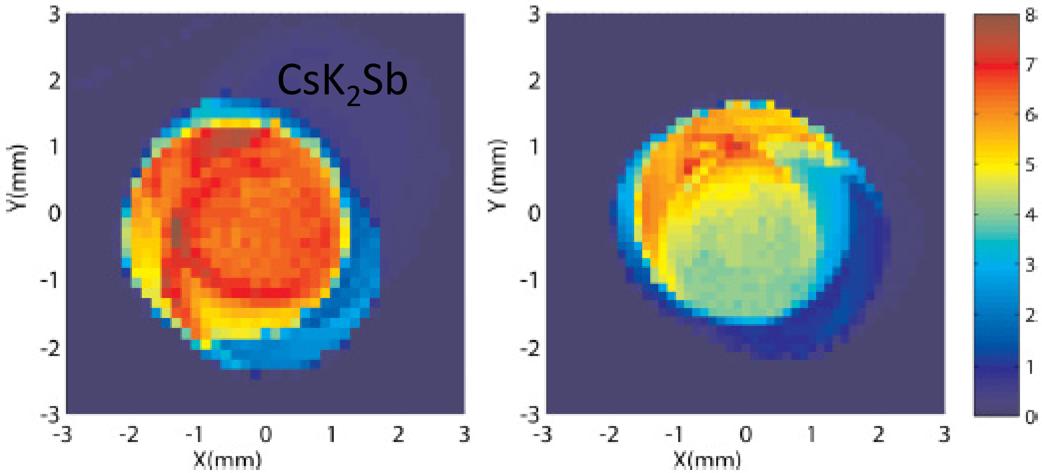

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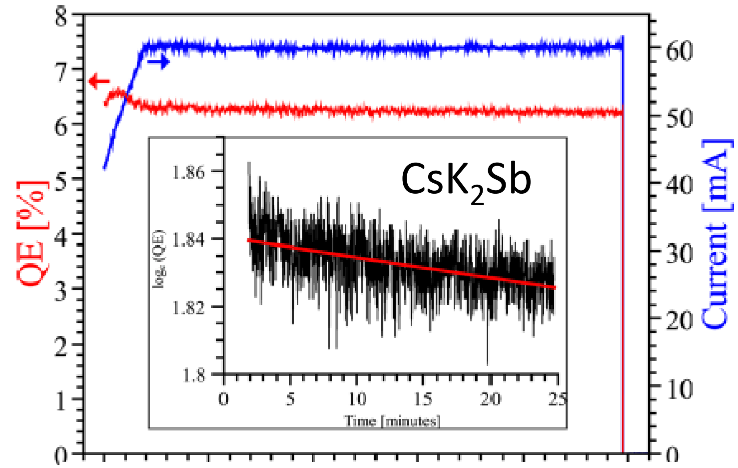

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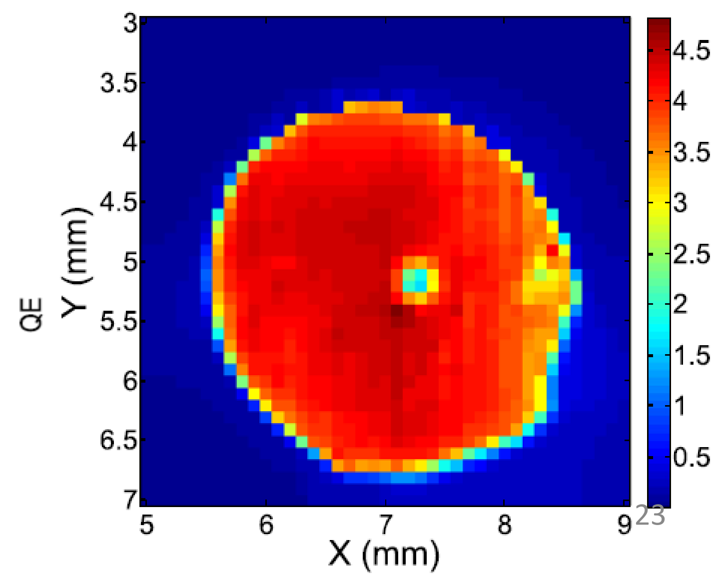

Compare with Storage Rings

- Compare the 19 pC/bunch results (25 mA) to a modern storage ring: PETA III

Data type	H. Emittance (pm)	V. Emittance (pm)	Current (mA)	RMS energy spread (1e-3)
PETRA III	1000	10	100	1
Cornell ERL	14	9	25	0.2

Figure of merit:

$$\underbrace{\left(I \cdot \left. \frac{f_x \cdot f_y}{\epsilon_x(f_x) \cdot \epsilon_y(f_y)} \right|_{\mathrm{core}} \right)}_{\text{Effective Brightness}} \times \frac{1}{\sigma_\delta}$$

← rms energy spread

Roughly 20x the beam quality of the best storage ring!

Conclusions

Significant achievement for the Cornell Project, as well as field of High Brightness Photoinjectors

Further improvements

$$\varepsilon_n \propto \sqrt{\frac{q}{\varepsilon_0 E_{cath}} \frac{MTE}{mc^2}}$$

- Improved cathodes: MTE -> 30 meV
- Improved gun design: Voltage -> 500 kV

} Get half the emittance, and 4x the brightness

- Higher energy: E -> 12 MeV
- Improved laser shaping

} Further reduce emittance

In total, get ~ 5x brightness. Figure of merit then becomes 100x!

Acknowledgements

- Special thanks to my advisor, Ivan Bazarov, as well as the Cornell ERL team!
- This work was supported by the National Science Foundation (Grant No. DMR-0807731)