ERL injector prototype project at Cornell University

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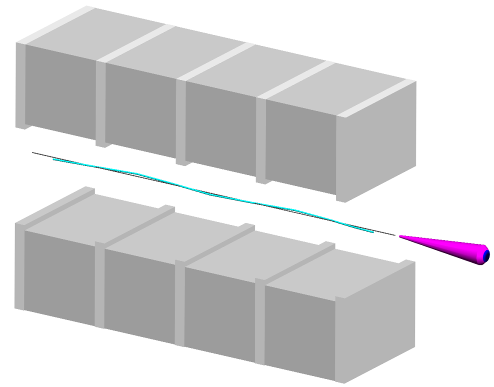
Talking points

- Intro to ERL as an x-ray light source
- Overall injector layout
- Injector optimizations (without the merger)
- DC gun & photocathode & laser issues for beam brightness
- Matching to the main linac & merger
- Beam physics experimental program

Future hard x-ray source

?

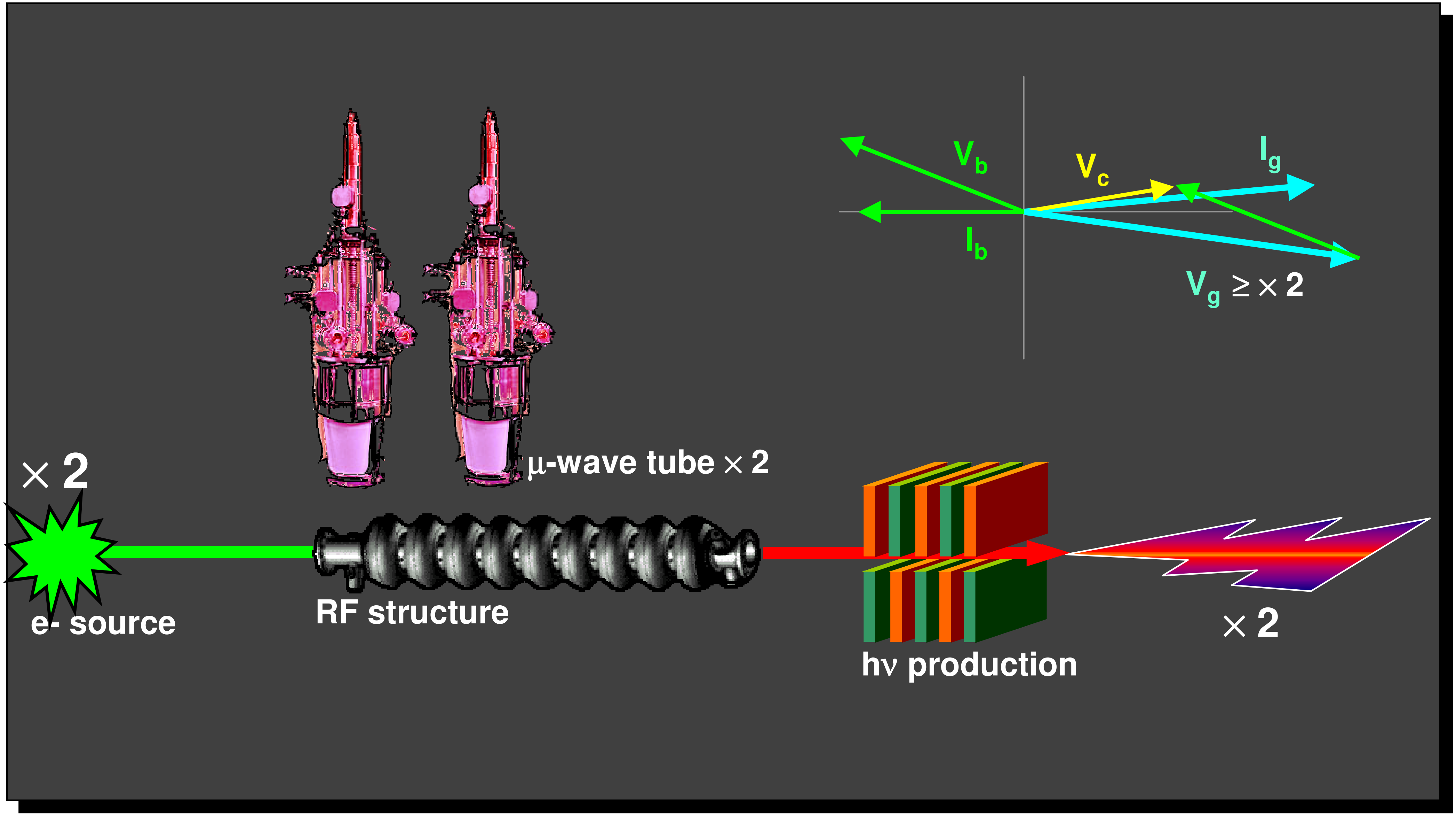
X-ray characteristics needed



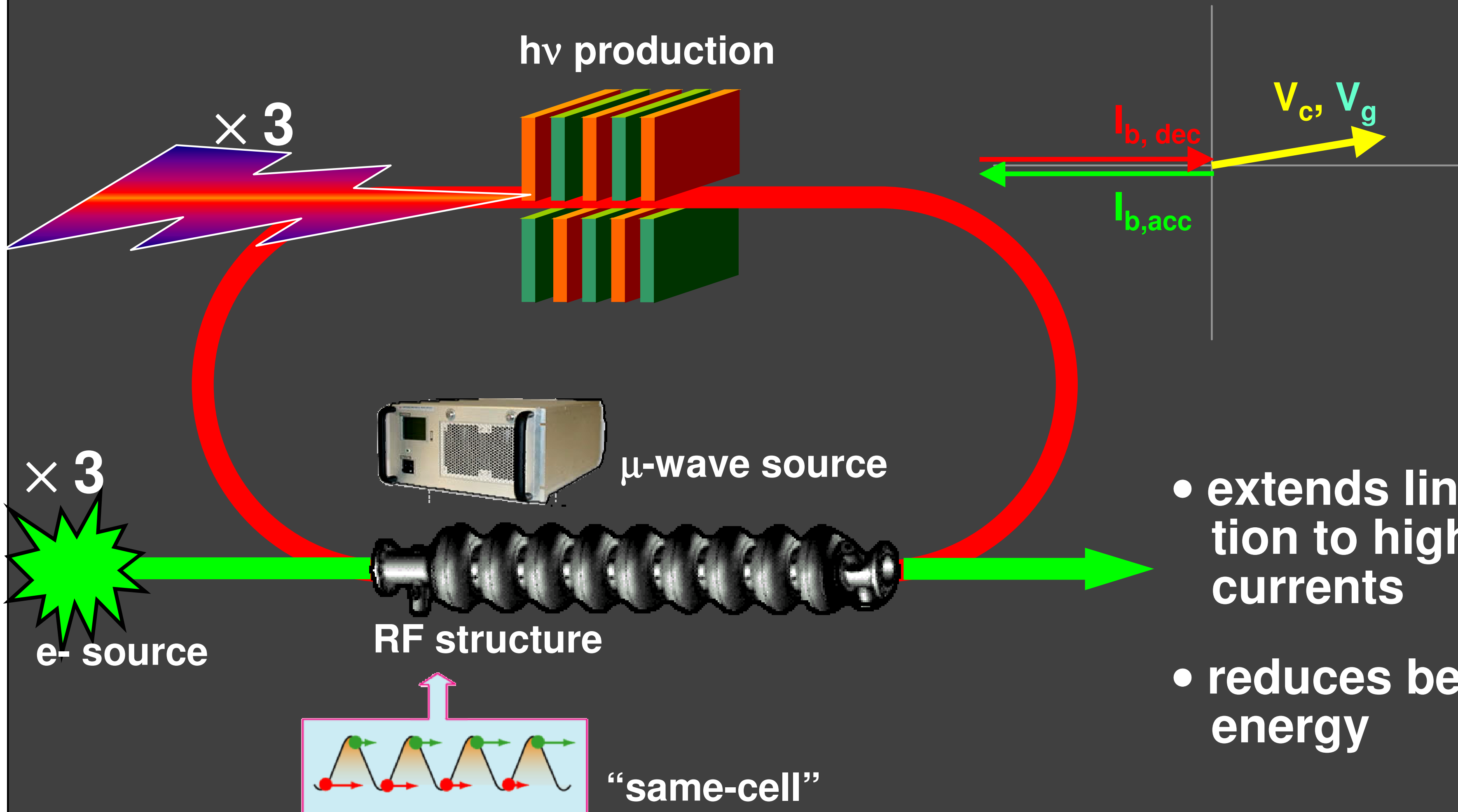
- For a properly tuned undulator (non-SASE): x-ray phase space is a replica from electron bunch + convolution with the diffraction limit
- ideally, one wants the phase space to be diffraction limited (i.e. full transverse coherence), e.g. $\varepsilon_{\perp,rms} = \lambda/4\pi$, or 0.1 Å for 8 keV x-rays (Cu K_α), or $\varepsilon_{\perp n,rms}$ = **0.1 μm** normalized at 5 GeV

Flux	ph/s/0.1%bw
Brightness	ph/s/mrad^2/0.1%bw
Brilliance	**ph/s/mm^2/mrad^2/0.1%bw**

Linac based approach

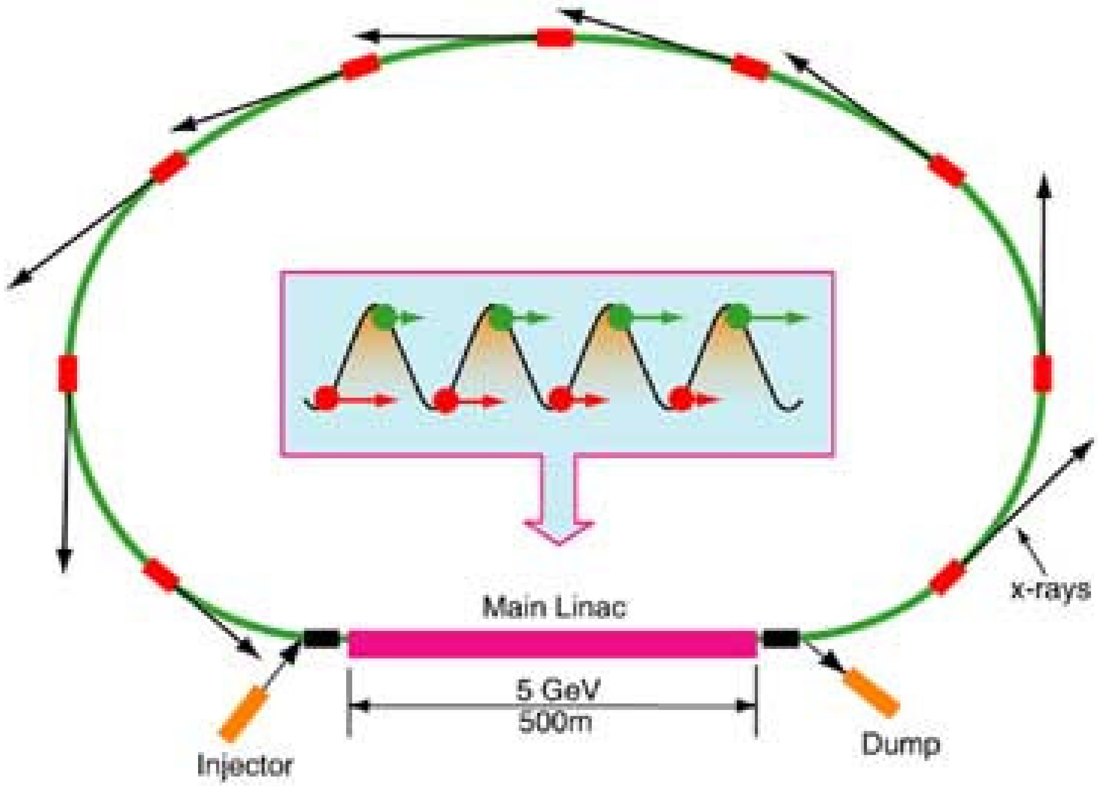


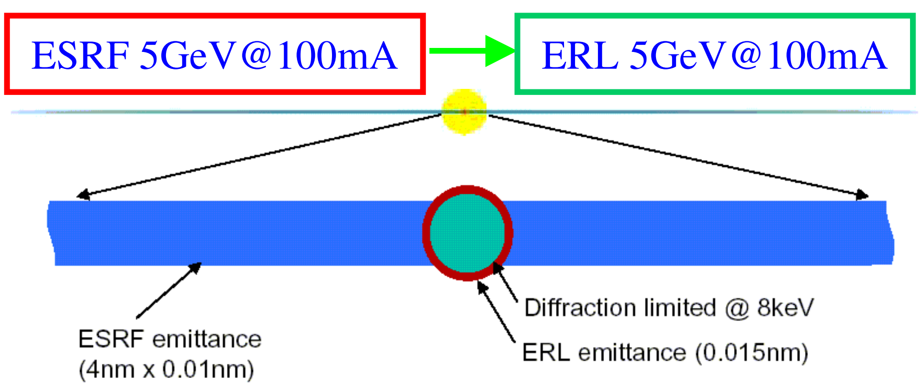
Energy recovery concept

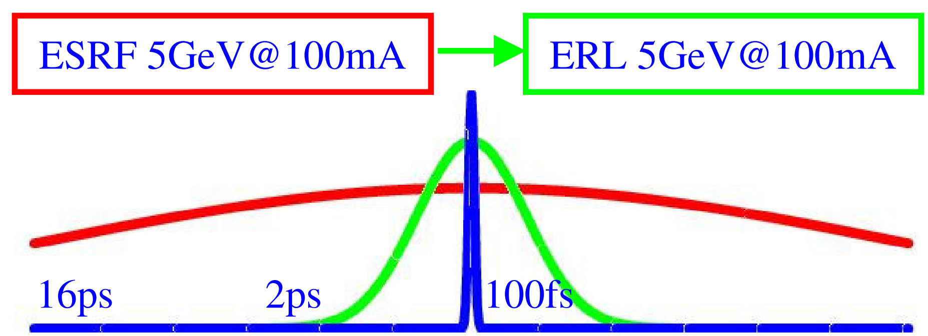


- extends linac operation to high average currents
- reduces beam dump energy

ERL promise



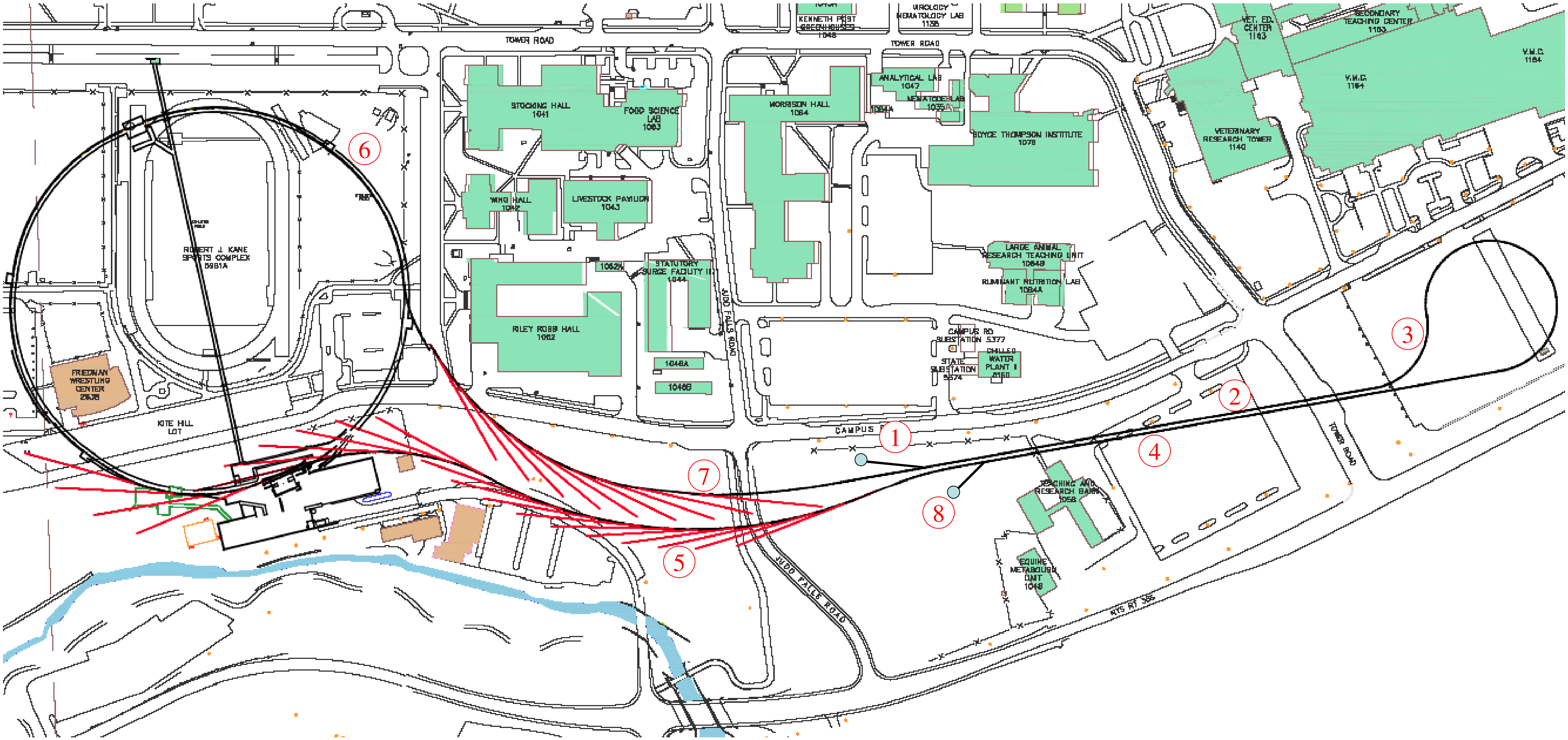




Much smaller (×100) horizontal emittance

Much shorter (×100) pulses

Cornell plans



ERL vs. SR

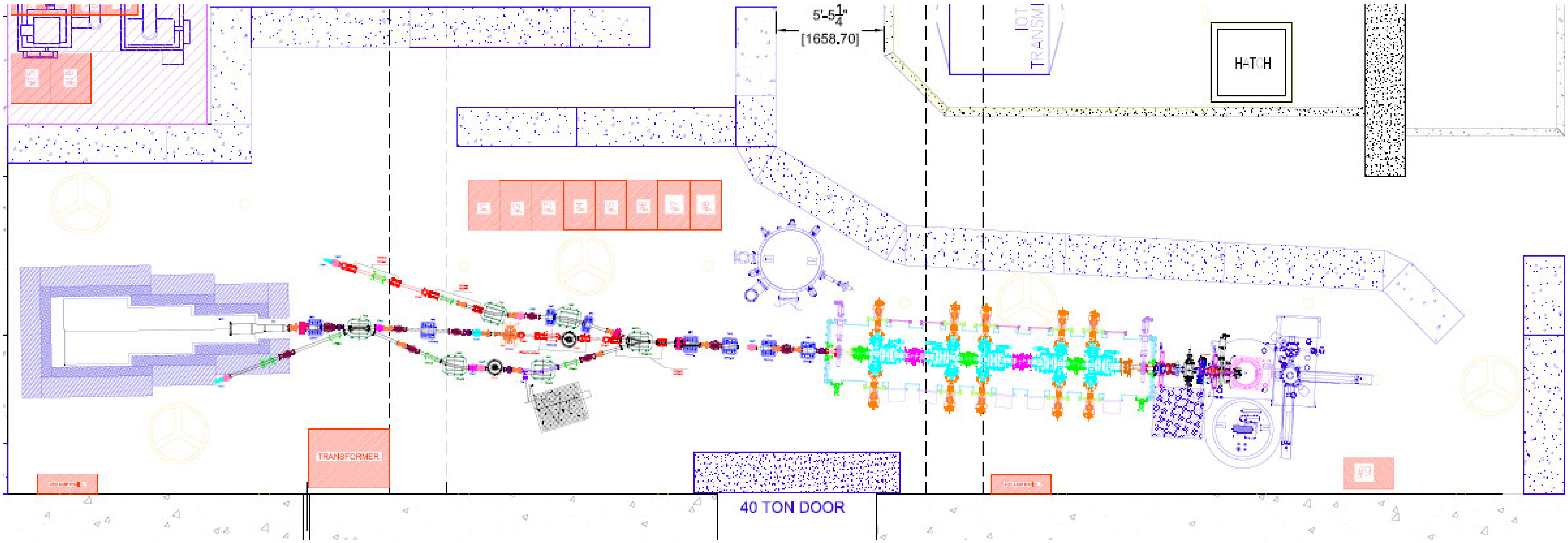
- Brightness figure of merit (FOM) $\frac{I}{(\varepsilon_x + \lambda/4\pi)(\varepsilon_y + \lambda/4\pi)}$ for 1Å

Light source	I (A)	ε_x (nm-rad)	ε_y (nm-rad)	FOM (A/nm^2/rad^2)
ESRF	0.2	3.7	0.010	3.0
Petra-III	0.1	1.0	0.010	5.5
NSLS-II*	0.5	1.54	0.008	20.24
UHXS(ESRF)	0.5	0.2	0.005	185.6

- 5 GeV ERL to achieve the same brightness per m of ID as Petra-III / NSLS-II / UHXS(ESRF) needs **1.3 / 0.6 / 0.15 μm** rms normalized emittance for 77 pC bunch (100 mA average current at 1.3 GHz bunch rep rate) assuming no emittance degradation downstream

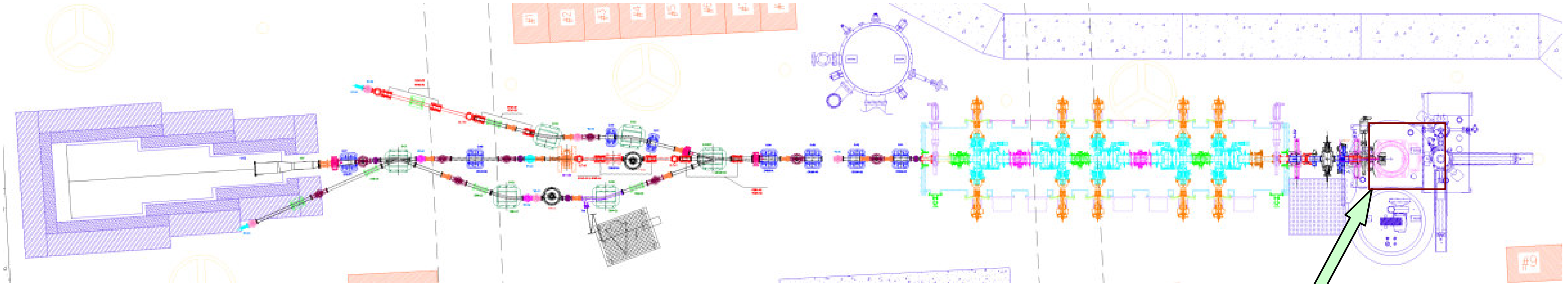
* without use of damping wigglers

ERL injector prototype



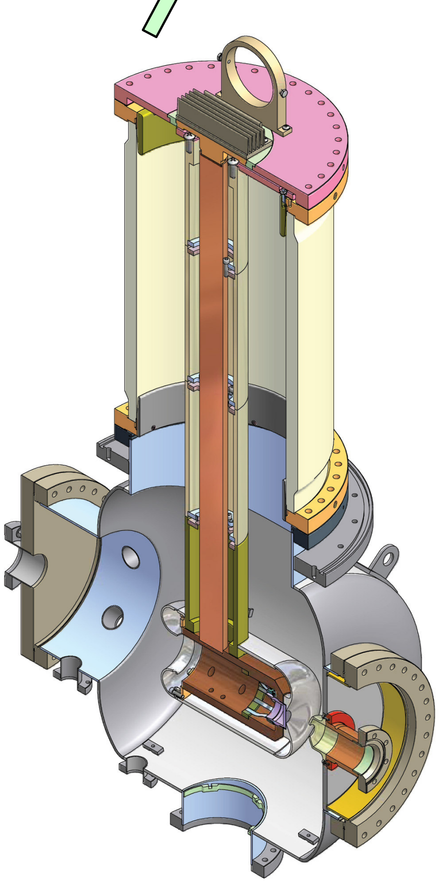
- HV DC gun based photoinjector
- up to **100 mA** average current, **5-15 MeV** beam energy
- norm. rms emittance **≤1 μm** at **77 pC**/bunch
- rms bunch length **0.6 mm**, energy spread **0.1%**

ERL injector components

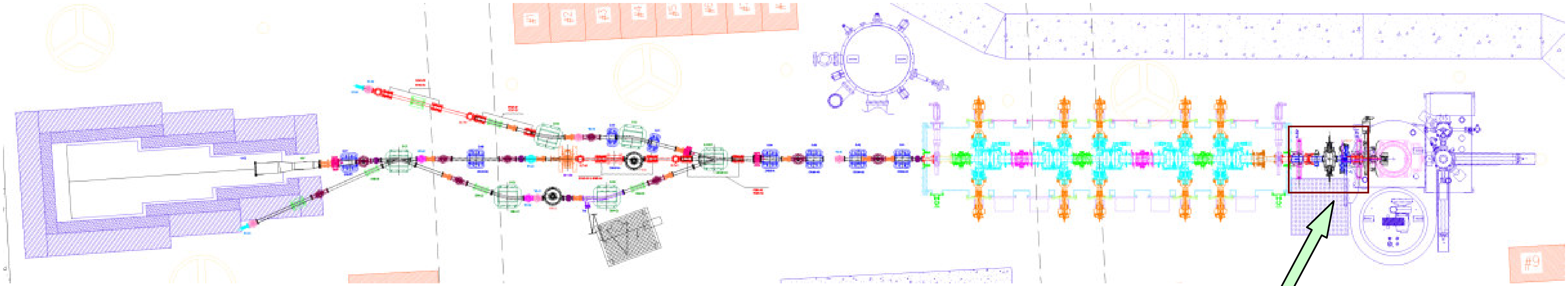


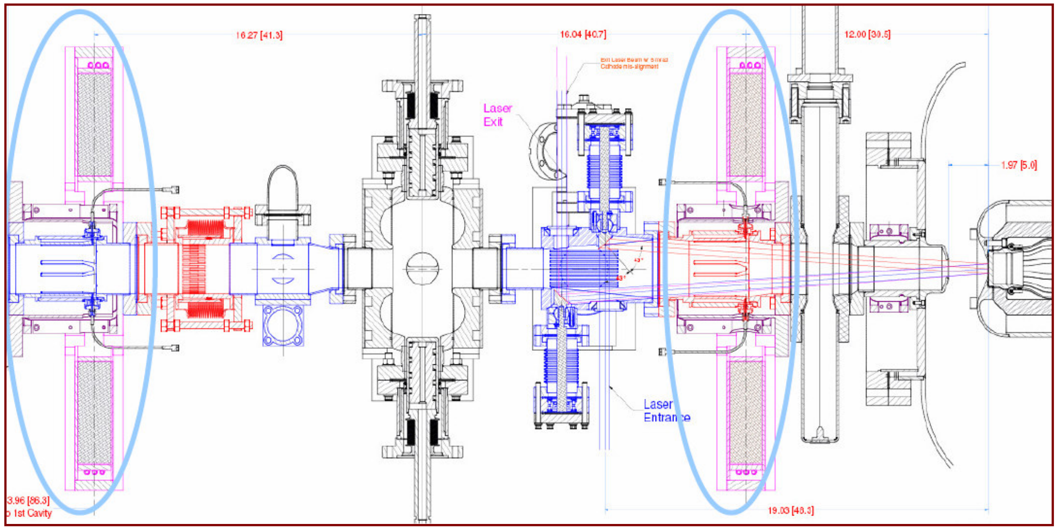
DC gun

- Designed & built for 750 kV max voltage
- Cathode preparation chamber with load-lock for cathode transport into the gun
- Excellent vacuum in the low 10^{-12} Torr range (essential for good lifetime of NEA photocathodes) by reduction of outgassing (H) via 400 C air-bake, 20000 l/s NEG pumping capacity and 400 l/s ion pump



ERL injector components

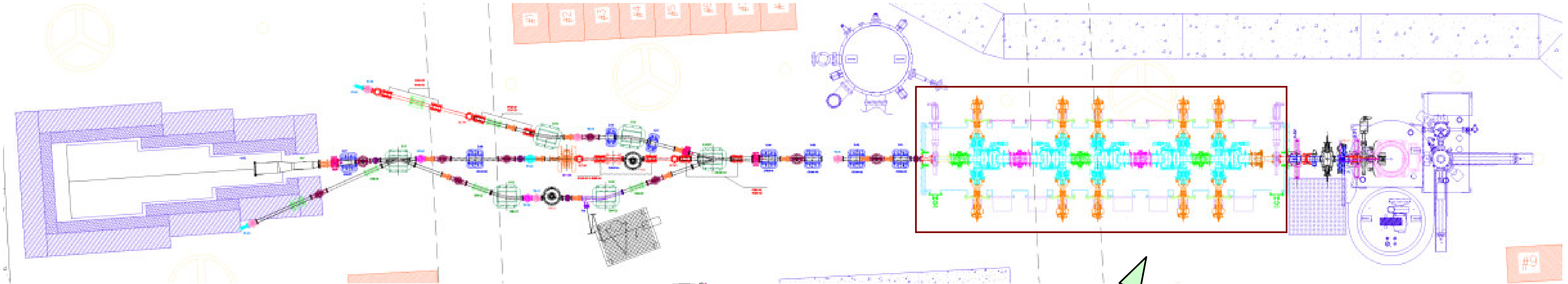


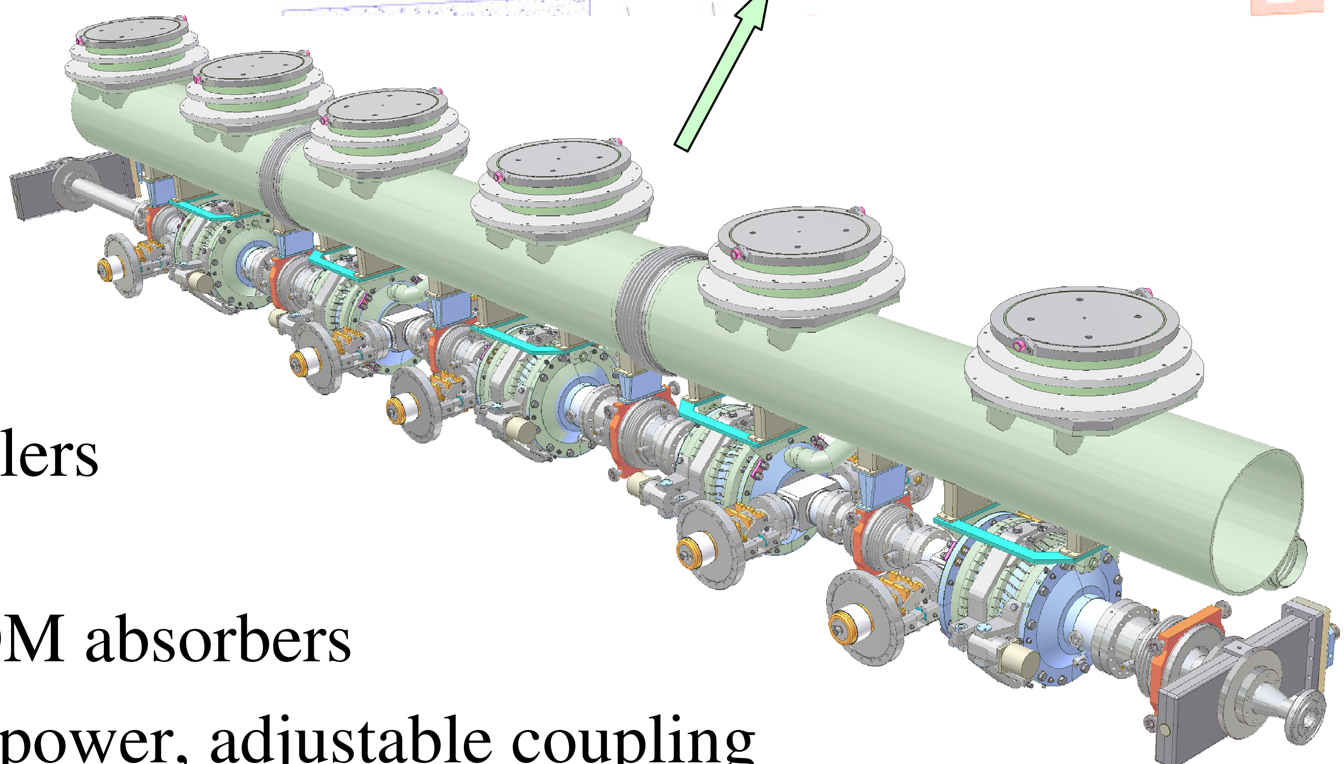


Injector front end

- Two solenoids for emittance compensation and matching into the injector's linac
- Copper buncher cavity with max bunching voltage of 200 kV

ERL injector components

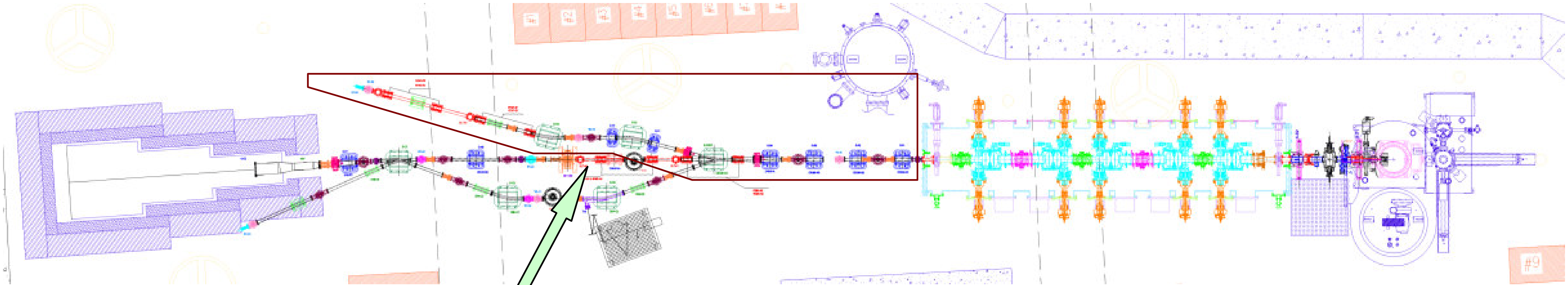


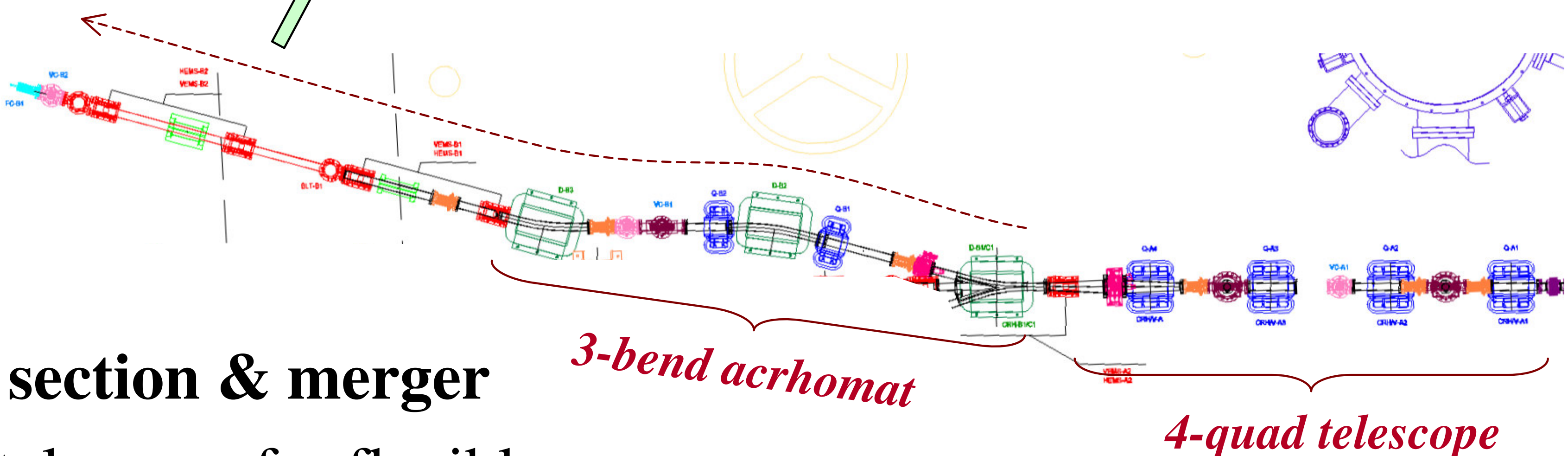


Injector cryomodule

- 5 SRF cavities with symmetric input couplers to avoid RF kick
- Broadband ferrite HOM absorbers
- 0.5 MW installed RF power, adjustable coupling
- Energy gain per cavity 1-3 MeV

ERL injector components

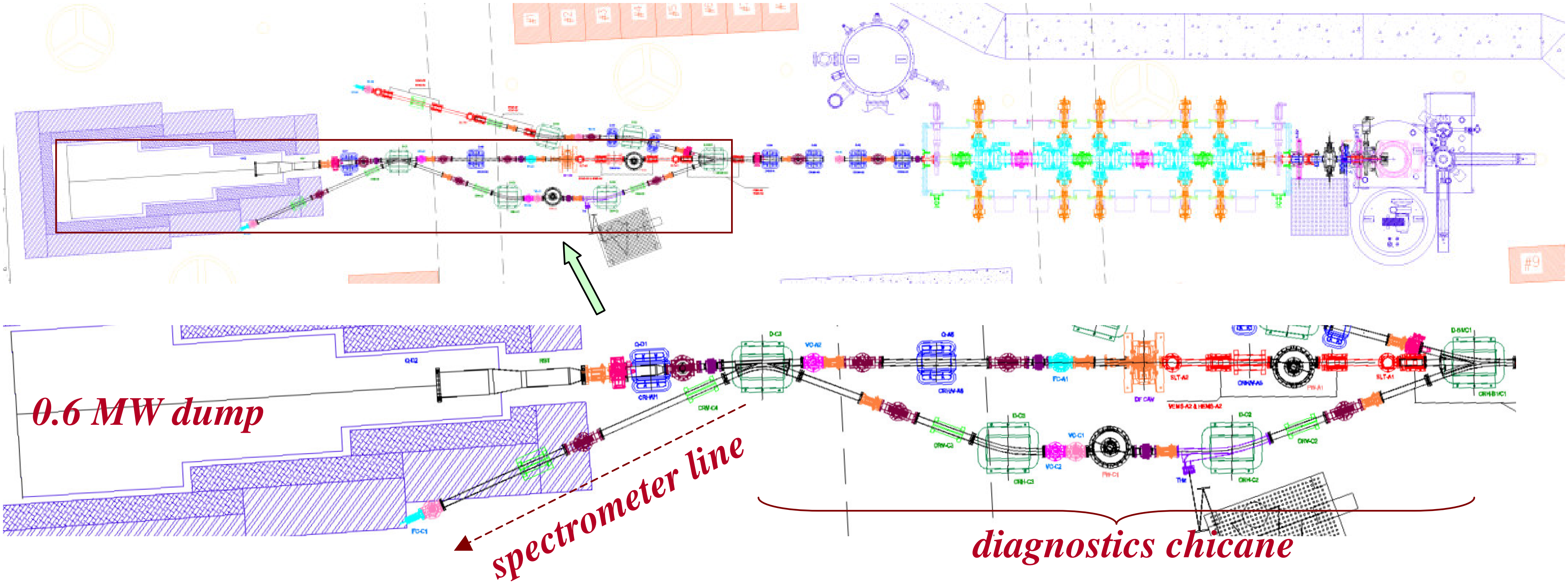




Matching section & merger

- 4-quad telescope for flexible matching into merger & main linac
- 15° 3-bend acrhomat followed by diagnostics section designed to take low beam power (~ 100 μA average current)

ERL injector components



Diagnostics line & how power dump

- chicane and straight-ahead beamline which handles average beam current of up to 100 mA
- Interceptive and non-interceptive diagnostics for characterization of single bunch and intra-bunch effects

S.c. compensation concept

Serafini PRE **55**, 7565

$$\sigma'' + K_r\sigma = \frac{I}{2I_0(\beta\gamma)^3\sigma} + \cancel{\frac{\epsilon_{n,\text{th}}^2}{(\beta\gamma)^2\sigma^3}}. \qquad \epsilon_{n,\text{th}}(\zeta) \equiv \frac{\beta\gamma}{2}\sqrt{\langle r^2\rangle_\zeta \langle r'^2\rangle_\zeta - \langle rr'\rangle_\zeta^2}$$

focusing s.c. ~~emittance~~

Needle beam: $I \rightarrow Ig(\zeta)$

linearize

$$\sigma_{\text{eq}}(g(\zeta)) = \left(\frac{Ig(\zeta)}{2I_0(\beta\gamma)^3 K_r}\right)^{1/2}$$ equilibrium flow condition for slice

$$\delta\sigma''(\zeta) + \left[K_r + \frac{Ig(\zeta)}{2I_0(\beta\gamma)^3\sigma_{\text{eq}}^2 g(\zeta)}\right]\delta\sigma(\zeta) = 0 \quad \text{or}$$

oscillation frequency current independent

$$\delta\sigma''(\zeta) + 2K_r\delta\sigma(\zeta) = 0,$$

Design approaches

- Cut the number of decision variables to some reasonable number (2-4) perhaps by using a simplified theoretical model to guide you in this choice
- **Large regions of parameter space remain unexplored**
- Optimize the injector varying the remaining variables with the help of a space-charge code to meet a fixed set of beam parameters (e.g. emittance at a certain bunch charge and a certain length)
- **One ends up with a *single-point* design without capitalizing on beneficial trade-offs that are present in the system**

Primary challenge in exploring the full parameter space is computational speed

Doing it faster

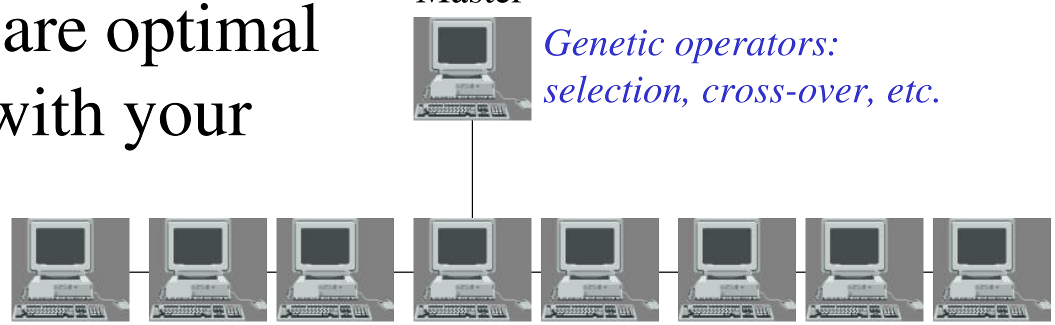
- work harder
- work smarter
- get help

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

***M**ulti**O**bjective **G**enetic **A**lgorithm*

- throw in all your design variables
- map out whole Pareto front, i.e. obtain multiple designs all of which are optimal
- use realistic injector model with your favorite space charge code



Multi-objective optimization

$$\left.\begin{array}{lll} \text{maximize} & f_m(x_1, x_2, \ldots, x_n), & m = 1, 2, \ldots, M; \\ \text{subject to} & g_j(x_1, x_2, \ldots, x_n) \geq 0, & j = 1, 2, \ldots, J; \\ & x_i^{(\mathrm{L})} \leq x_i \leq x_i^{(\mathrm{U})}, & i = 1, 2, \ldots, n. \end{array}\right\}$$

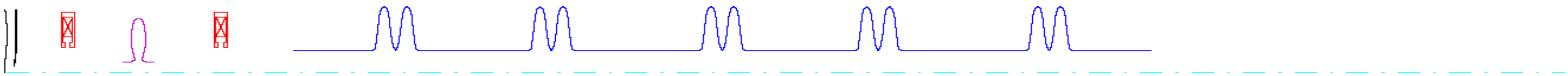
Definition 1. *A solution $\boldsymbol{x}_a$ is said to dominate the other solution $\boldsymbol{x}_b$ if the solution $\boldsymbol{x}_a$ is not worse than $\boldsymbol{x}_b$ in all objectives and $\boldsymbol{x}_a$ is strictly better than $\boldsymbol{x}_b$ in at least one objective. In other words, $\forall m \in 1, 2, \ldots, M$: $f_m(\boldsymbol{x}_a) \geq f_m(\boldsymbol{x}_b)$ and $\exists m' \in 1, 2, \ldots, M$: $f_{m'}(\boldsymbol{x}_a) > f_{m'}(\boldsymbol{x}_b)$.*

Definition 2. *Among a set of solutions $\mathcal{P}$, the nondominated subset of solutions $\mathcal{P}'$ are those that are not dominated by any member of the set $\mathcal{P}$.*

When the set $\mathcal{P}$ is the entire search space resulting nondominated set is called the *Pareto-optimal set.*

Vilfredo Pareto, 1848-1923

Injector decision variables



Fields:
DC Gun Voltage (300-900 kV)
2 Solenoids
Buncher
SRF Cavities Gradient (5-13 MV/m)
SRF Cavities Phase

Positions:
2 Solenoids
Buncher
Cryomodule

Bunch & Photocathode:
$E_{thermal}$
Charge

Laser Distribution:
Spot size
Pulse duration (10-30 ps rms)
{tail, dip, ellipticity} $\times$ 2

Total: 22-24 dimensional parameter space to explore

Optimization results

Takes some 10^5 simulations

E_{therm} = 35 meV (aka GaAs @ 780 nm)

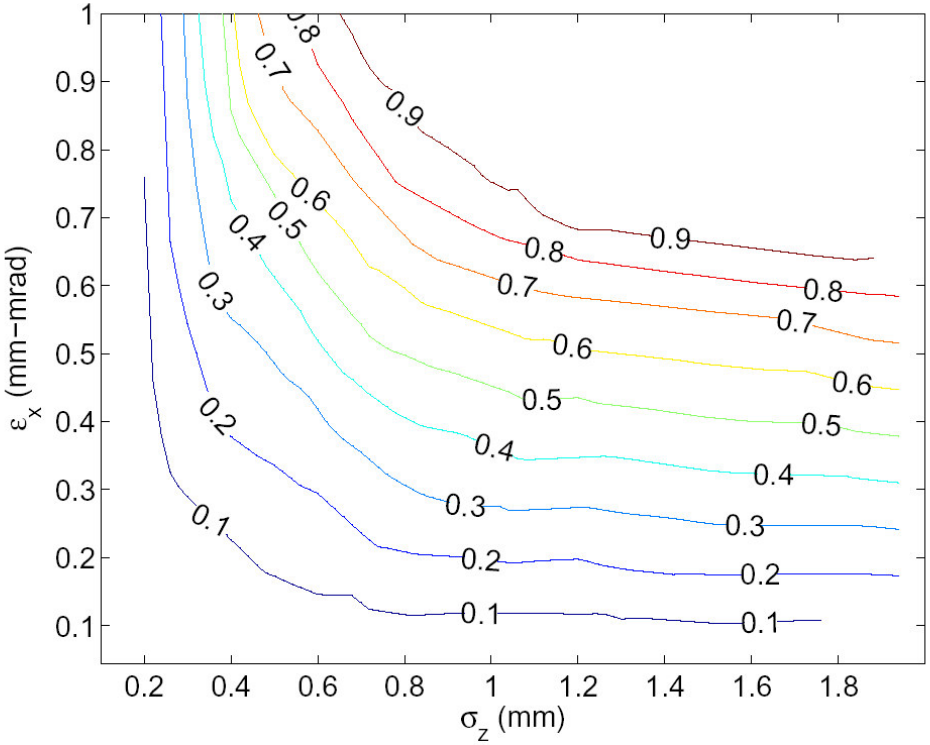


FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

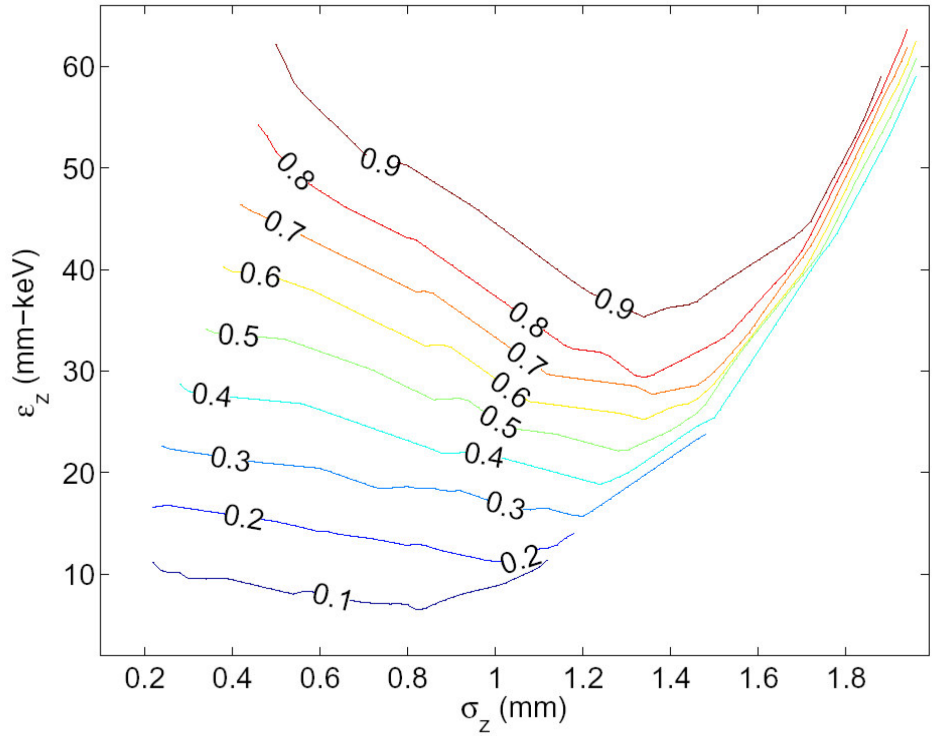
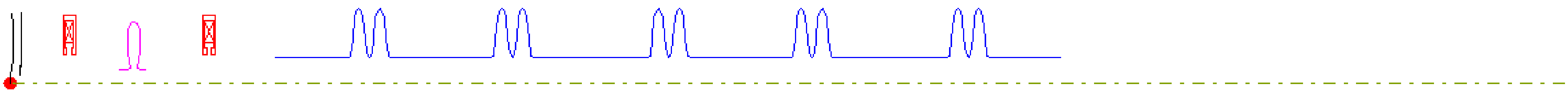
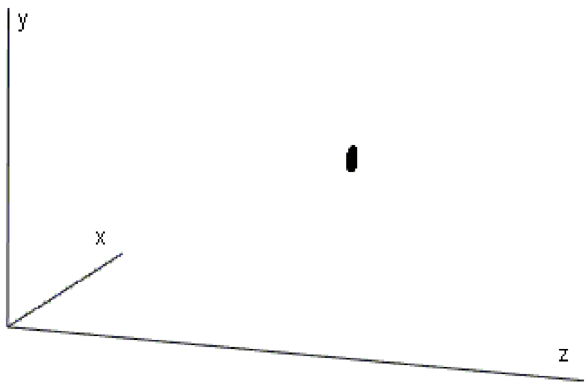


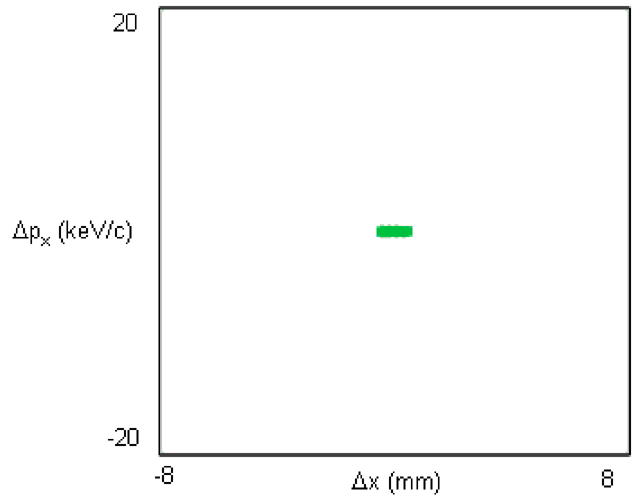
FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

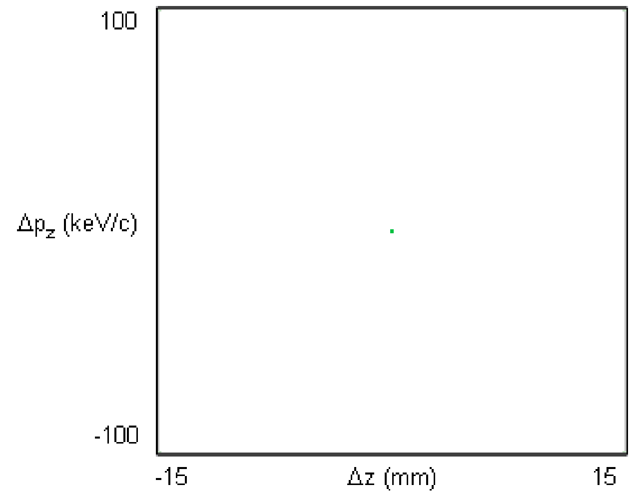
MOO problem:
- minimize emittance
- minimize bunch length
- maximize bunch charge

Closer look: 80 pC







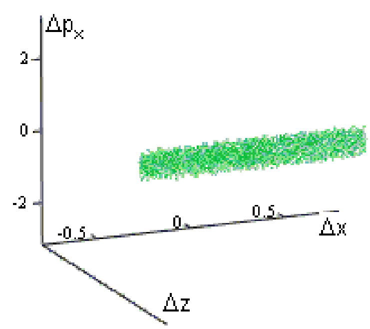


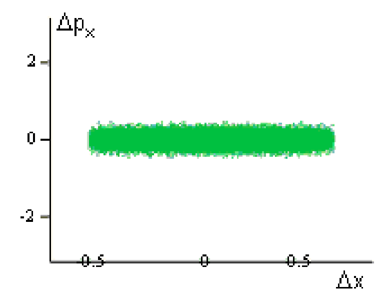
z = 0.000 m

p_z = 0.000 MeV/c

σ_x = 0.294 mm $\quad$ ε_x = 0.077 mm-mrad

σ_z = 0.000 mm $\quad$ ε_z = 0.000 mm-keV





Envelopes

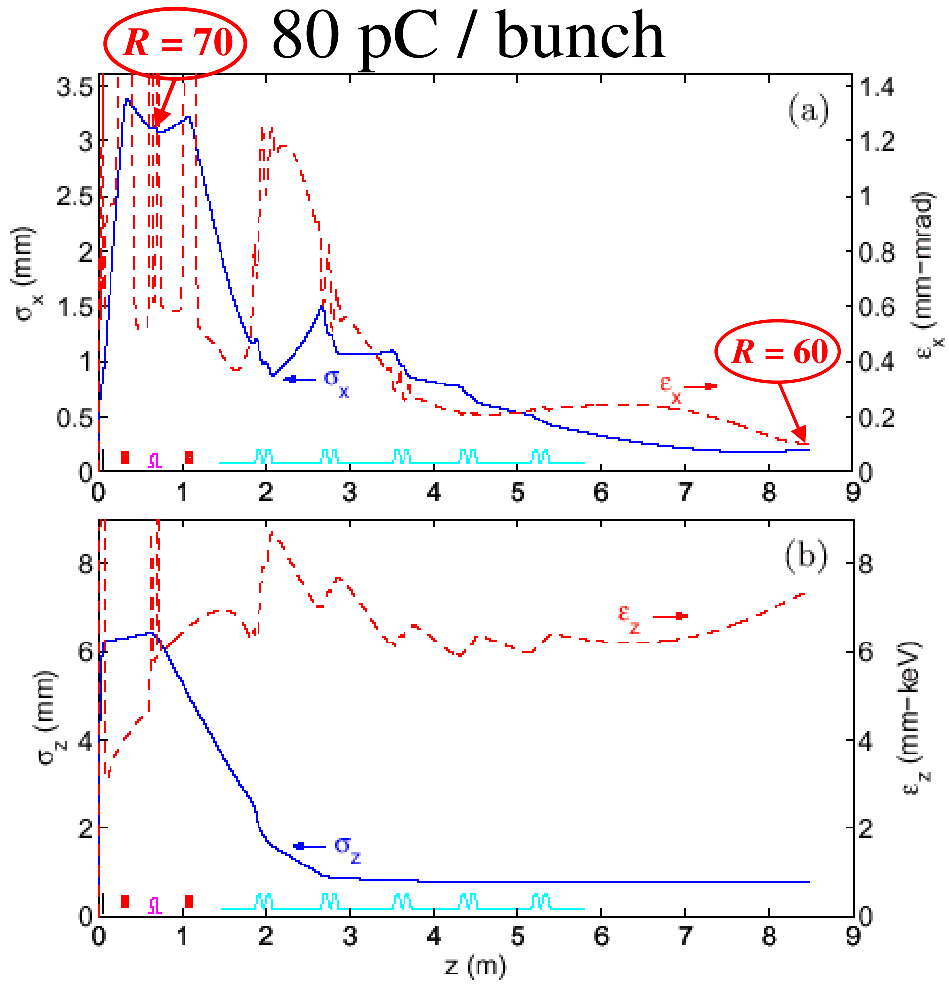


FIG. 3: Beam evolution in the injector for 80 pC bunch charge: transverse (a) and longitudinal (b) emittances (dashed) and sizes (solid) vs. position in the injector.

$$R \equiv \frac{I}{I_0 \beta\gamma} \frac{\sigma_x^3}{(\sigma_x + \sigma_y)\varepsilon_{n,x}^2}$$

emittance dominated beam if $R << 1$

Beam in optimized injector is space charge dominated even at > 10 MeV

Optimizations

- Parallel multi-objective optimizations is a powerful tool to explore limits of the system
- Is not meant to substitute but rather complement analytical & intuitive picture of what's going on
- Not a substitute for accurate model of the physics of what's going on (i.e. 'garbage in, garbage out')

Contributors to emittance

Thermal (cathode) ⟷ RF-induced

Space charge

- Low thermal energy photocathodes
- Min laser spot size
- Max gun voltage

- Rapid acceleration
- ‘adiabatic’ focusing and bunching
- Transverse laser shaping
- Temporal pulse shaping (fast emission photocathodes)

- short bunch length
- tight focus
- reduced field gradient

■ helps here, neutral elsewhere

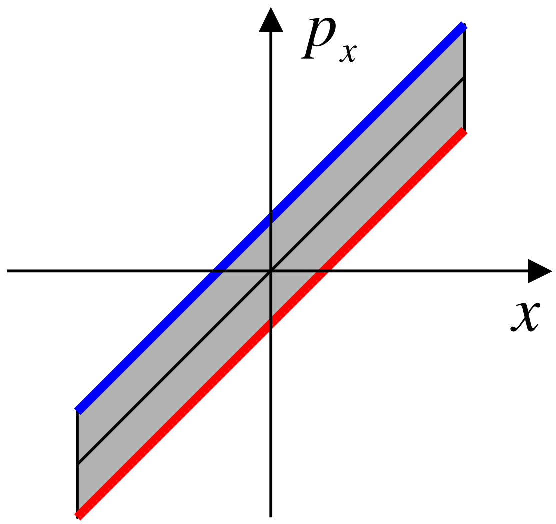
■ helps here, may harm elsewhere

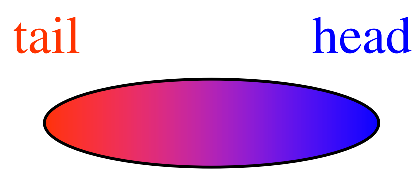
RF-induced emittance

$$\varepsilon_n = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}$$

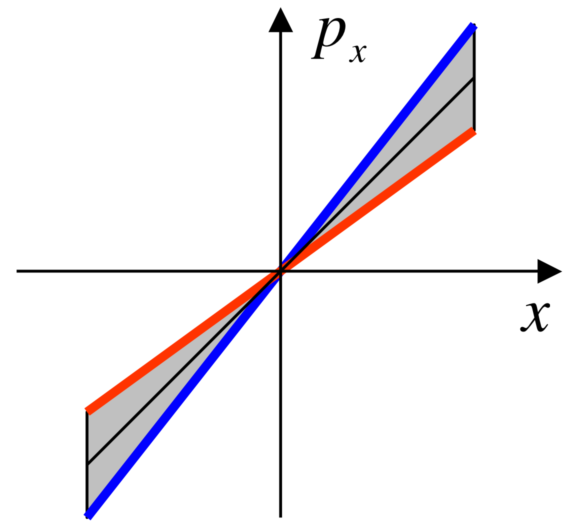
$$p_x(x,z) = p_x(0,0) + \frac{\partial p_x}{\partial x}x + \underbrace{\frac{\partial p_x}{\partial z}}_{kick} z + \underbrace{\frac{\partial^2 p_x}{\partial x \partial z}}_{focusing} xz + \ldots$$

kick





focusing



$$\varepsilon_{kick} = \frac{1}{mc}\left|\frac{\partial p_x}{\partial z}\right|\sigma_x\sigma_z$$

$$\varepsilon_{focus} = \frac{1}{mc}\left|\frac{\partial^2 p_x}{\partial z \partial x}\right|\sigma_x{}^2\sigma_z$$

Thermal & RF contribution

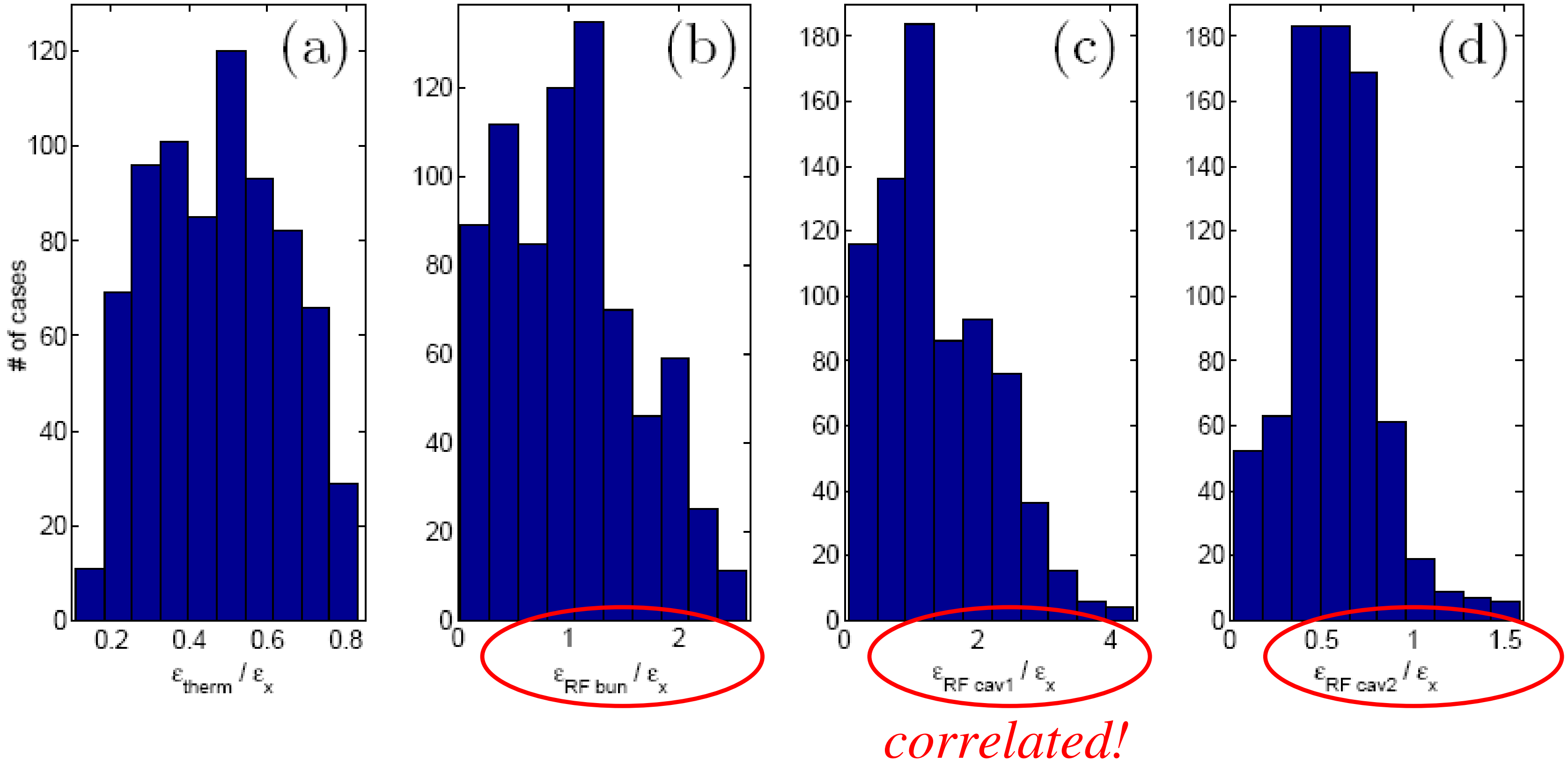
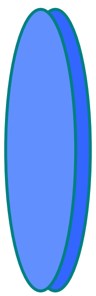


FIG. 12: Histogram showing (a) thermal emittance and estimated RF correlated emittances due to (b) the buncher and the first two SRF cavities (c,d) relative to the final transverse emittance for optimized injector settings with the bunch charge between 10 pC and 1 nC.

Thermal & cathode field

More often than not A >> 1 in photoinjectors, i.e. the bunch looks like a pancake near the cathode (!).



From PHYS101 (note a factor of 2 due to image charge)

$$E_{s.c.} = \frac{\sigma}{\varepsilon_0} \rightarrow \quad q = 4\pi\varepsilon_0 E_{cath}\sigma_x^2$$

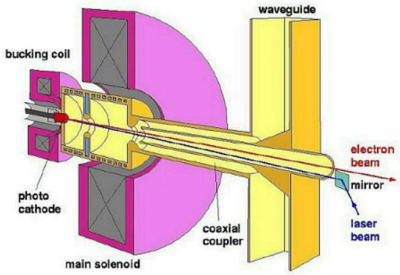
$$= 0.11 \times E_{cath}[\mathrm{MV/m}]\sigma_x[\mathrm{mm}]^2 \ \mathrm{nC}$$

Lower limit on emittance due to cathode and available field:

$$\varepsilon_n[\mathrm{mm\text{-}mrad}] \approx 4\sqrt{q[\mathrm{nC}]\frac{E_{th}[\mathrm{eV}]}{E_{cath}[\mathrm{MV/m}]}}$$

Gun & cathode package

NCRF

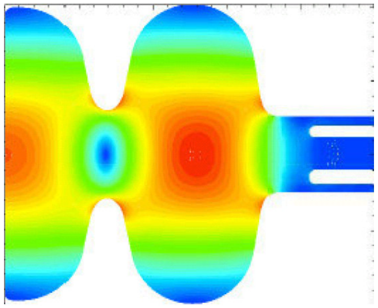


pulsed!

E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

$\tau_{laser} \rightarrow z$ = 0.08 mm

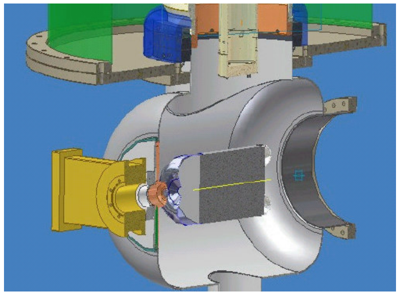
SRF



E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

DC

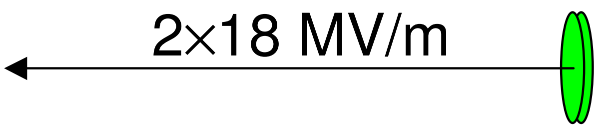


E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

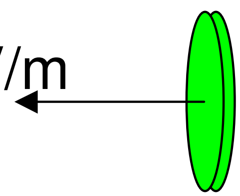
$\tau_{laser} \rightarrow z$ = 0.12 mm

1 nC

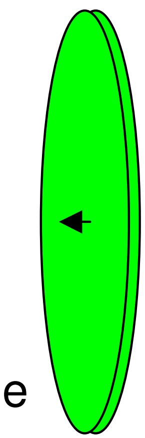
2×18 MV/m



2×6 MV/m



2×1 MV/m



$E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$

same simulated emittance

Gun technology choice

Emittance compensation can be achieved despite reduced flexibility in solenoid positioning

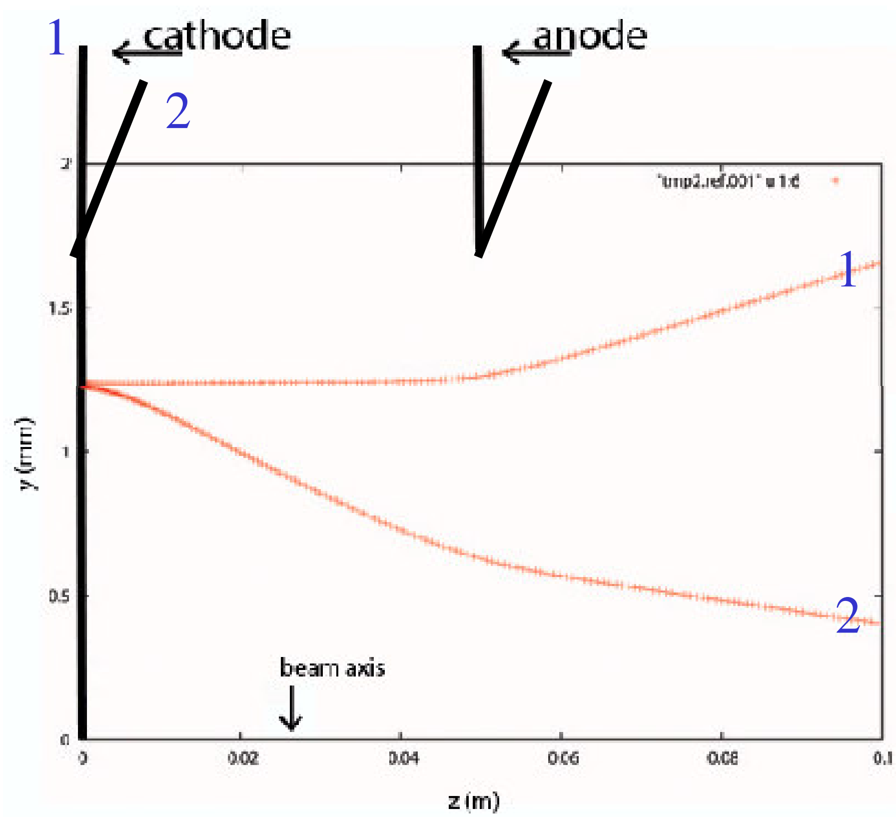
	Q [nC]	Rms bunch Length (compressed)	Ex [mm-mrad]	Cathode material(&)	Band Peak field
RF	1 / 0.2	2.8 ps / 1.7 ps	0.72 / 0.3 (**)	Copper, 700 meV	S-Band [120 MV/m]
DC	1/ 0.1	3ps / 3ps	0.8 / 0.14 (**)	GaAs 35 meV	[15 MV/m] (Average)
SRF	1 / 0.1(*)	5.7 ps/ 2.7 ps	0.8 / 0.23 (**)	"metallic" 184 meV	L-Band [60MV/m]

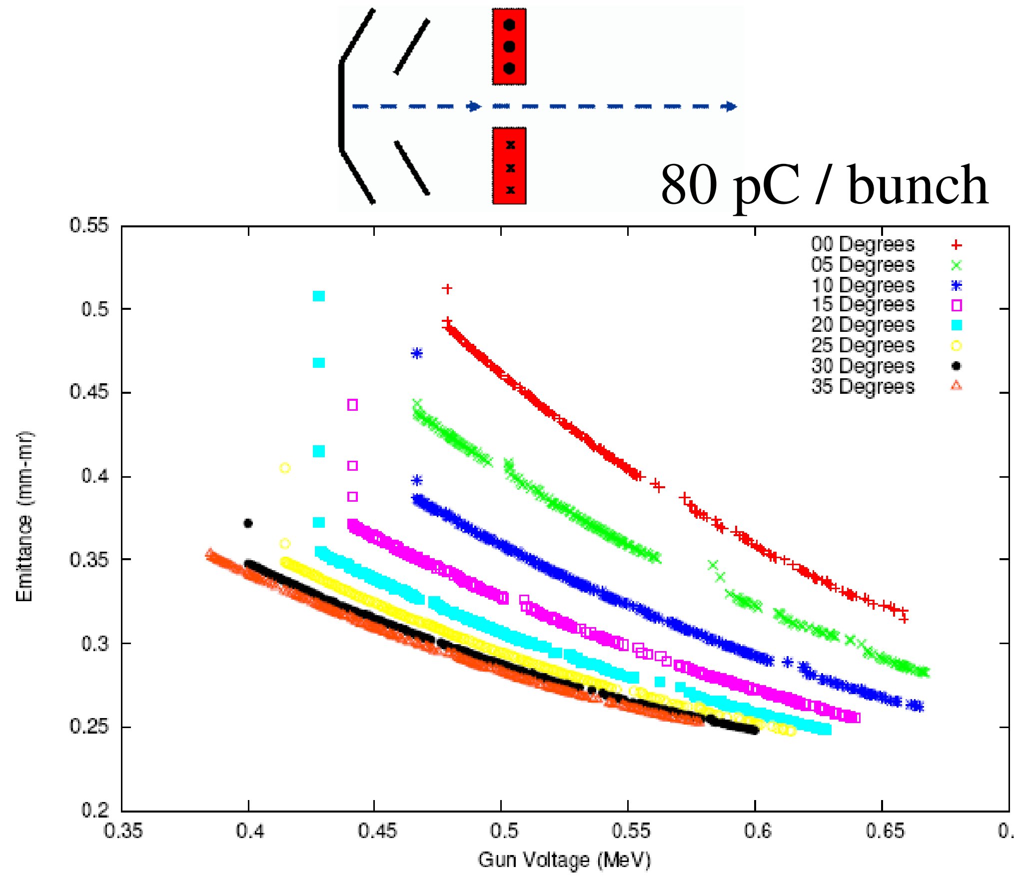
(*) scaled
(**) limited by thermal emittance
(&) Copper and GaAs use measured values, but SRF gun uses generic metallic cathode number for thermal emittance (0.3 mm-mrad per 1 mm full radius)

$$\varepsilon_n[\text{mm-mrad}] \approx 4\sqrt{q[\text{nC}]\frac{E_{th}[\text{eV}]}{E_{cath}[\text{MV/m}]}}$$

RF and DC guns computations are based on optimum emission pulse "3D-ellipsoid", whereas SRF gun computation uses "beer can"

DC gun focusing





- Focusing at the cathode is achieved through electrode shaping (25° angle), brings emittance down by a factor of ~2
- The drawback is increased aberrations from the gun (an issue when scanning laser spot on the cathode to increase re-Cs interval)

Extremely high gun voltage?

Distance to 1st SRF cavity

1.25 m

2.3 m

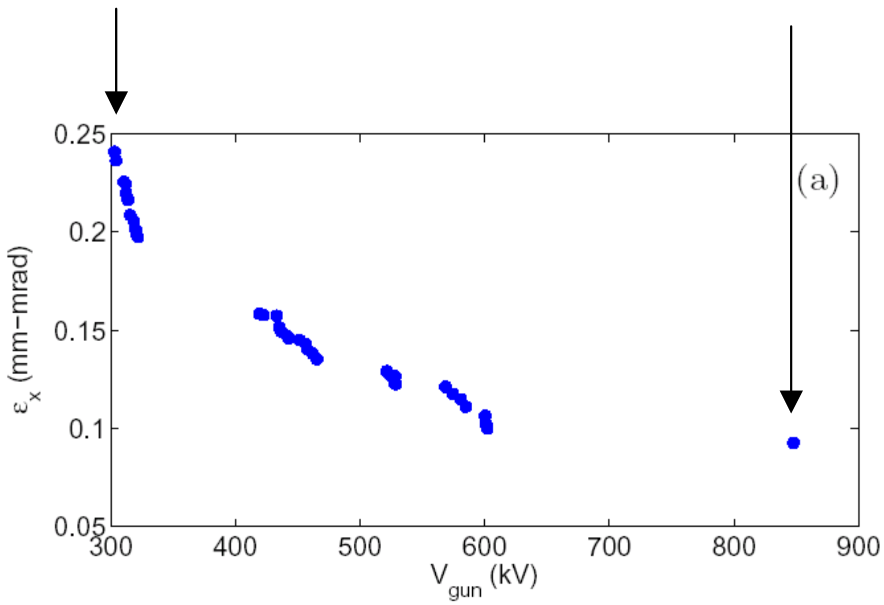
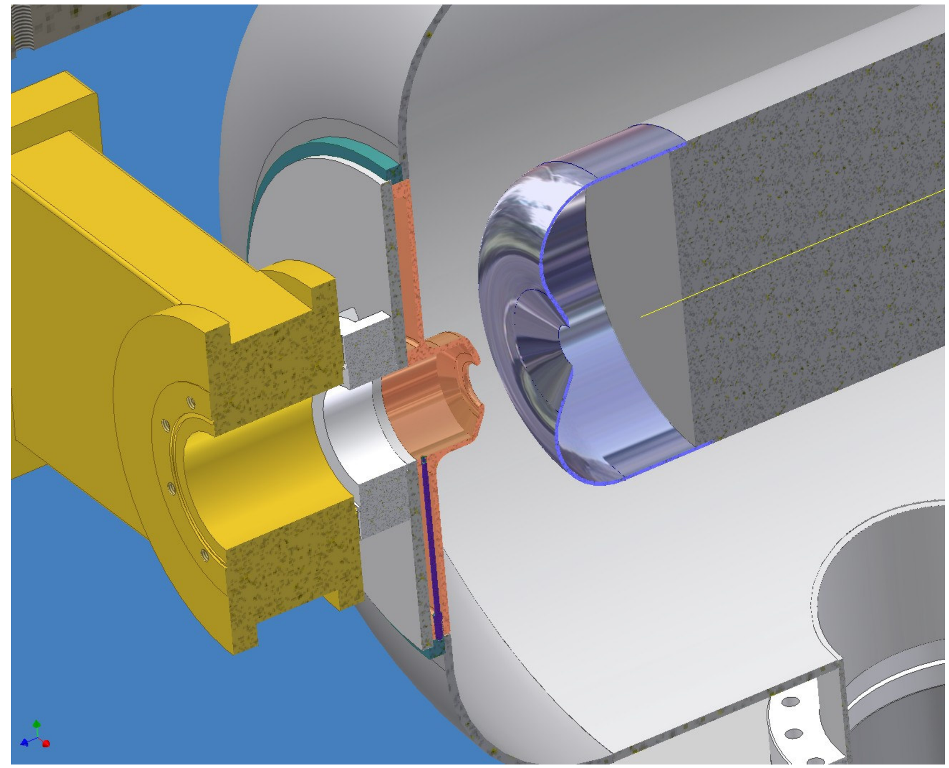


FIG. 5: Emittance vs. voltage in the gun for (a) 80 pC and (b) 0.8 nC bunch charges. The average bunch length corresponding to these calculations was (a) 0.8 mm and (b) 0.9 mm.



Adopted distance to the 1st SRF cavity 2 m

Laser shaping

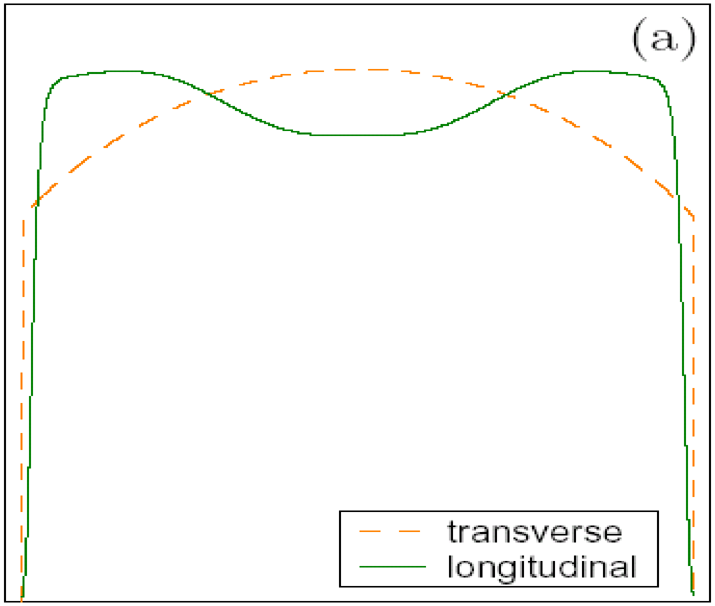


FIG. 6: Initial distribution profiles corresponding to minimal emittance at the end of the injector for (a) 80 pC and (b) 0.8 nC cases.

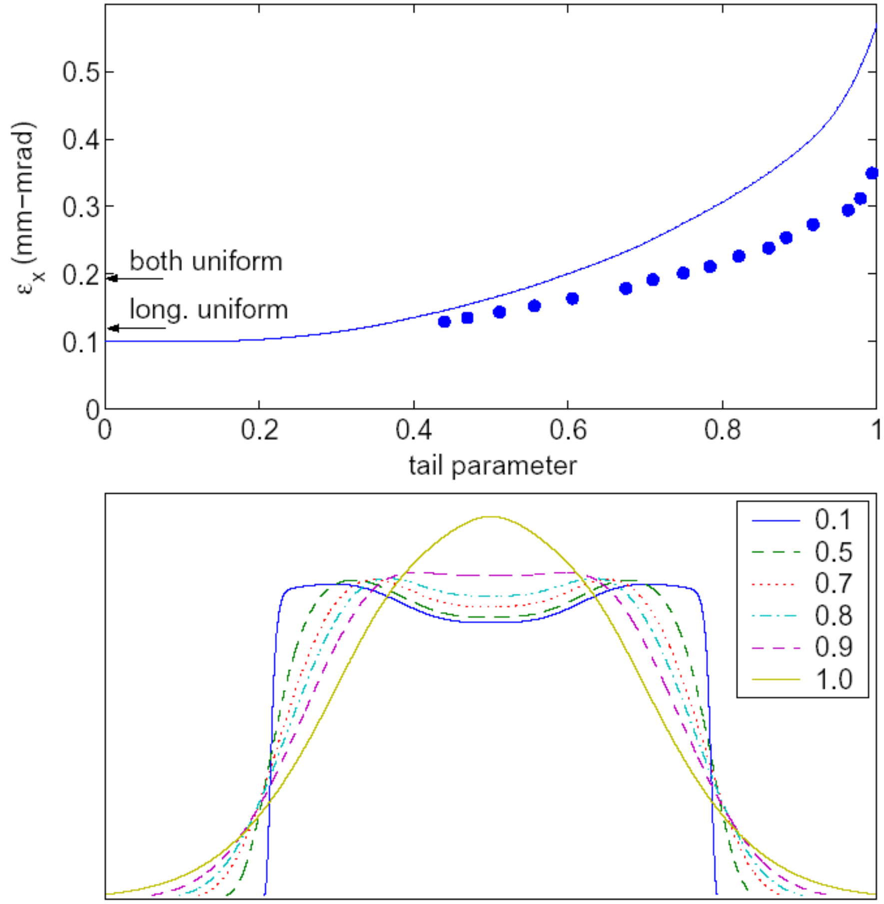


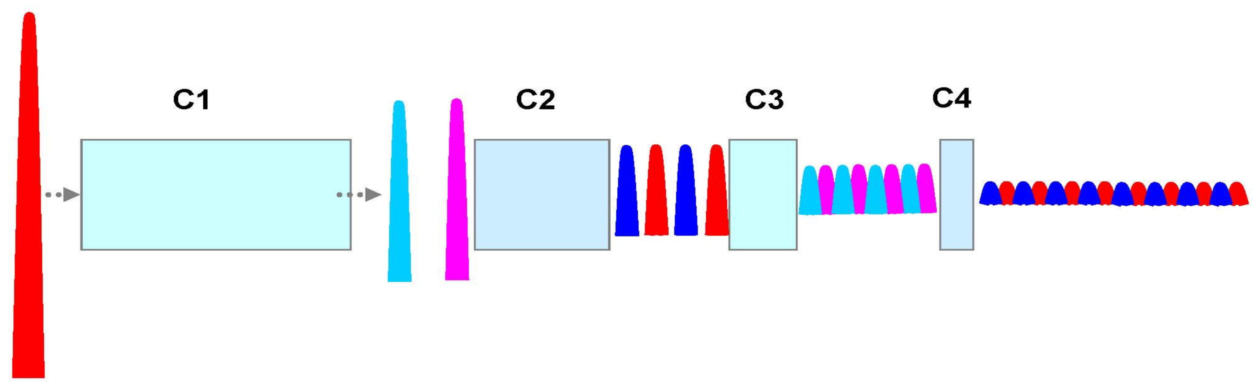
FIG. 7: 80 pC: emittance sensitivity (solid curve) to the longitudinal profile changes (top) and the corresponding profile shapes (bottom).

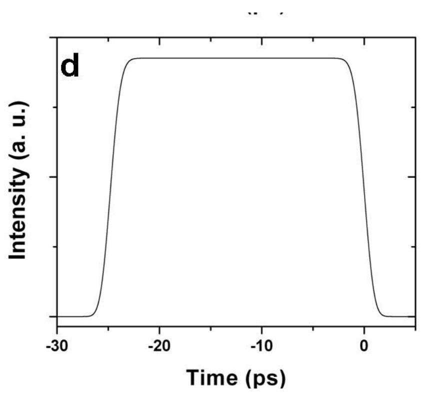
- Large factor (~5) in emittance is expected from proper transverse and longitudinal pulse shaping

Shaping approaches

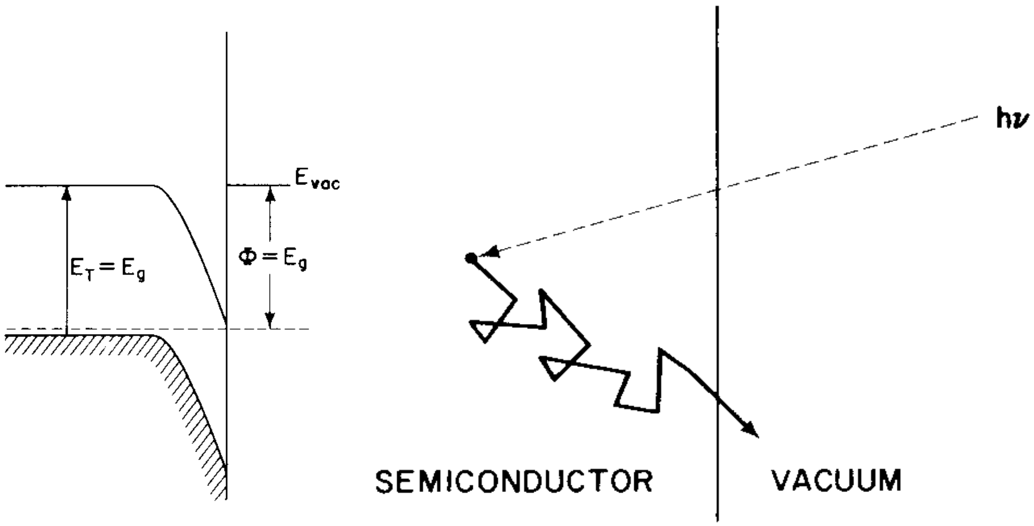
- Refractive beam shaper from Newport for transverse

- Birefringent crystal set pulse stacker for temporal





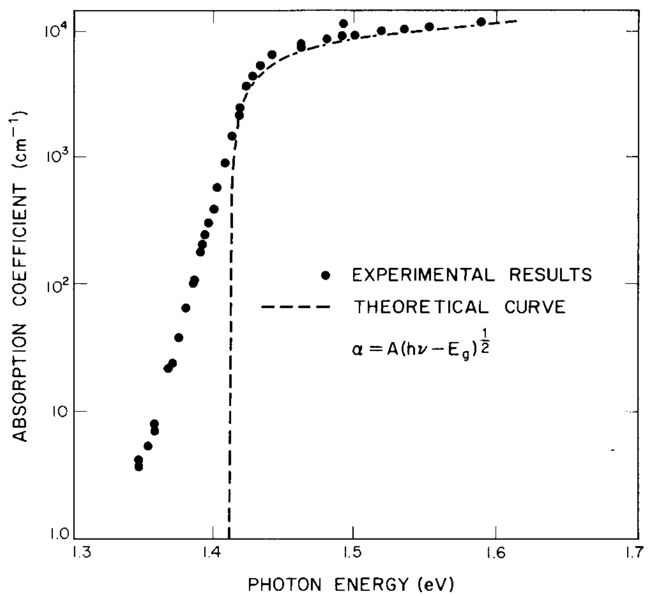
NEA:GaAs response time



(1) photon excites electron to a higher-energy state;

(2) electron-phonon scattering (~0.05 eV lost per collision);

(3) escape with kinetic energy in excess to E_{vac}

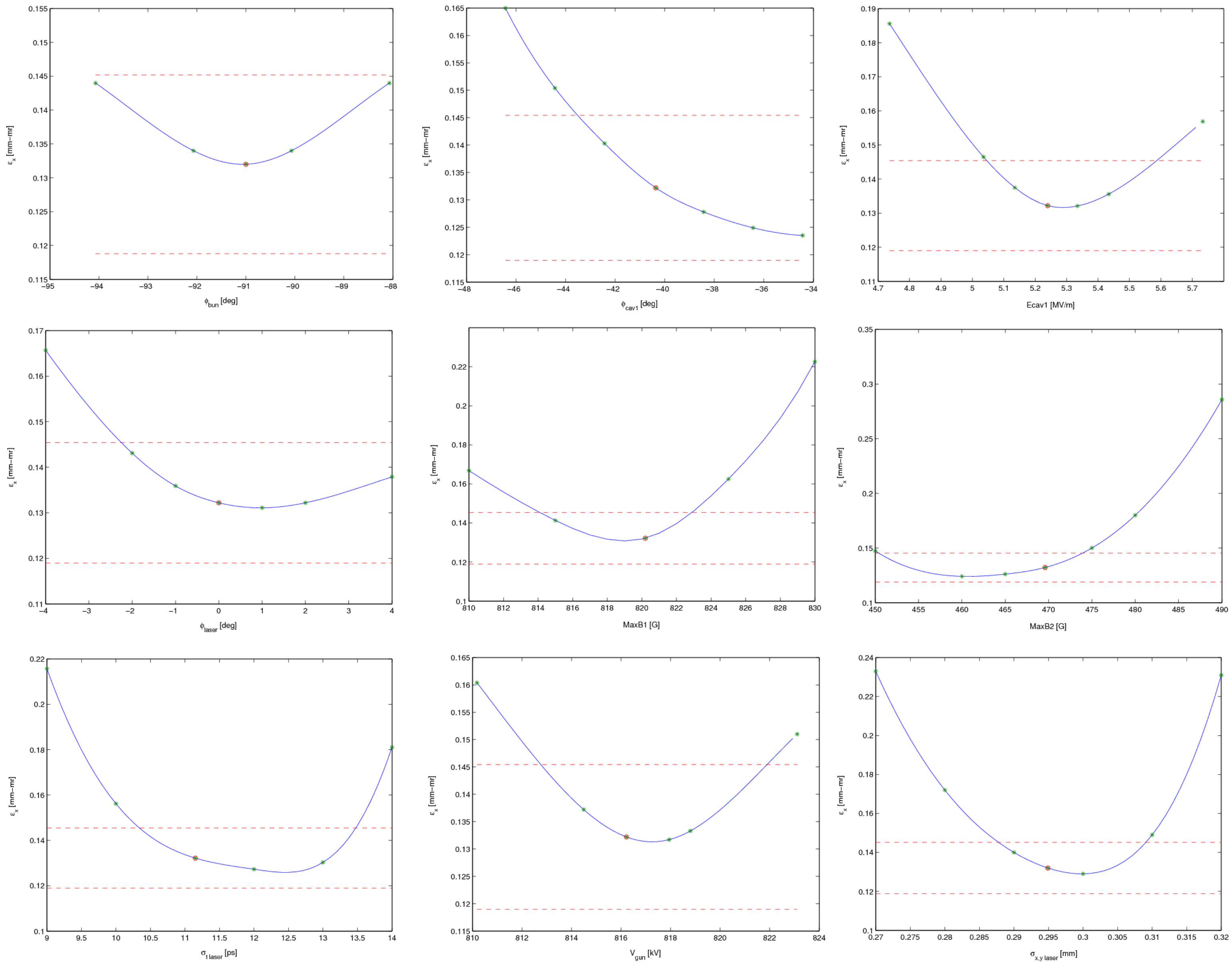


Absorption edge of GaAs at room temperature.

In GaAs the escape depth is sufficiently long so that photo-excited electrons are *thermalized* to the bottom of the conduction band before they escape.

Response time ~ (10^{-4} cm)/(10^7 cm/s) = 10 ps (wavelength dependant) – may preclude use of optimum pulse duration & temporal shaping $\rightarrow$ will use longer pulse

Tolerances for optimum



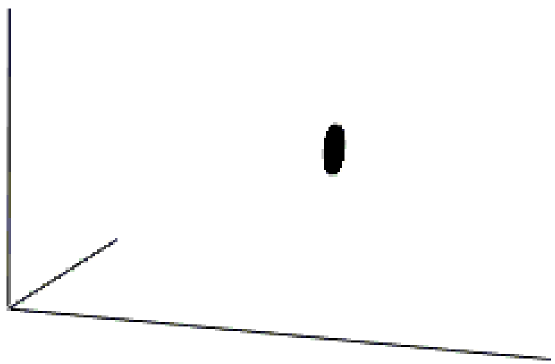
10% increase in emittance (p-t-p)

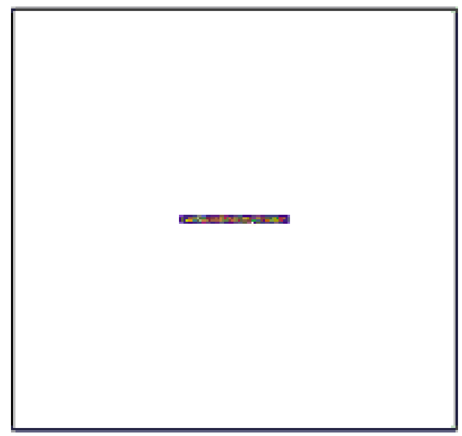
BunPhase	3.5°
Cav1Phase	3.0°
Ecav1	3.8%
Lphase	2.4°
B1	0.37%
B2	0.85%
Qbunch	3.7%
Trms	8.0%
Vgun	0.39%
XYrms	2.4%

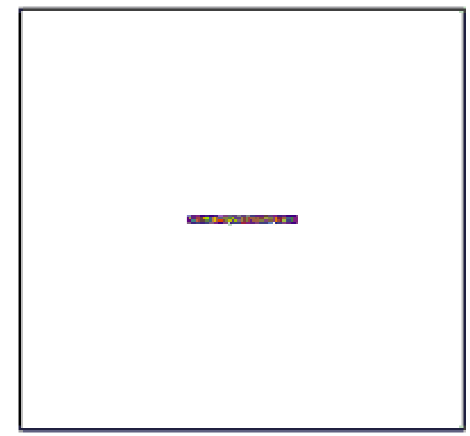
Challenges

- Beam has to be matched into the main linac and taken through the merger while being space-charge dominated $\rightarrow$ work out procedures for space-charge friendly optics tune-up procedures
- Final beam properties are very sensitive to about ten different parameters that need to be 'set right' $\rightarrow$ controls and diagnostics must be up to the task to provide the necessary guidance

Adding quads and main linac







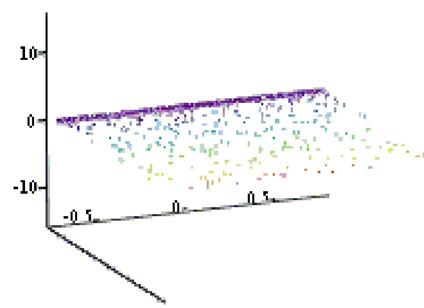
$z = 0.000$ m

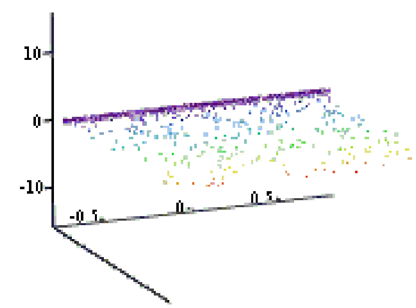
$p_z = 0.000$ MeV/c

$\sigma_x = 0.640$ mm $\varepsilon_x = 0.167$ mm-mrad

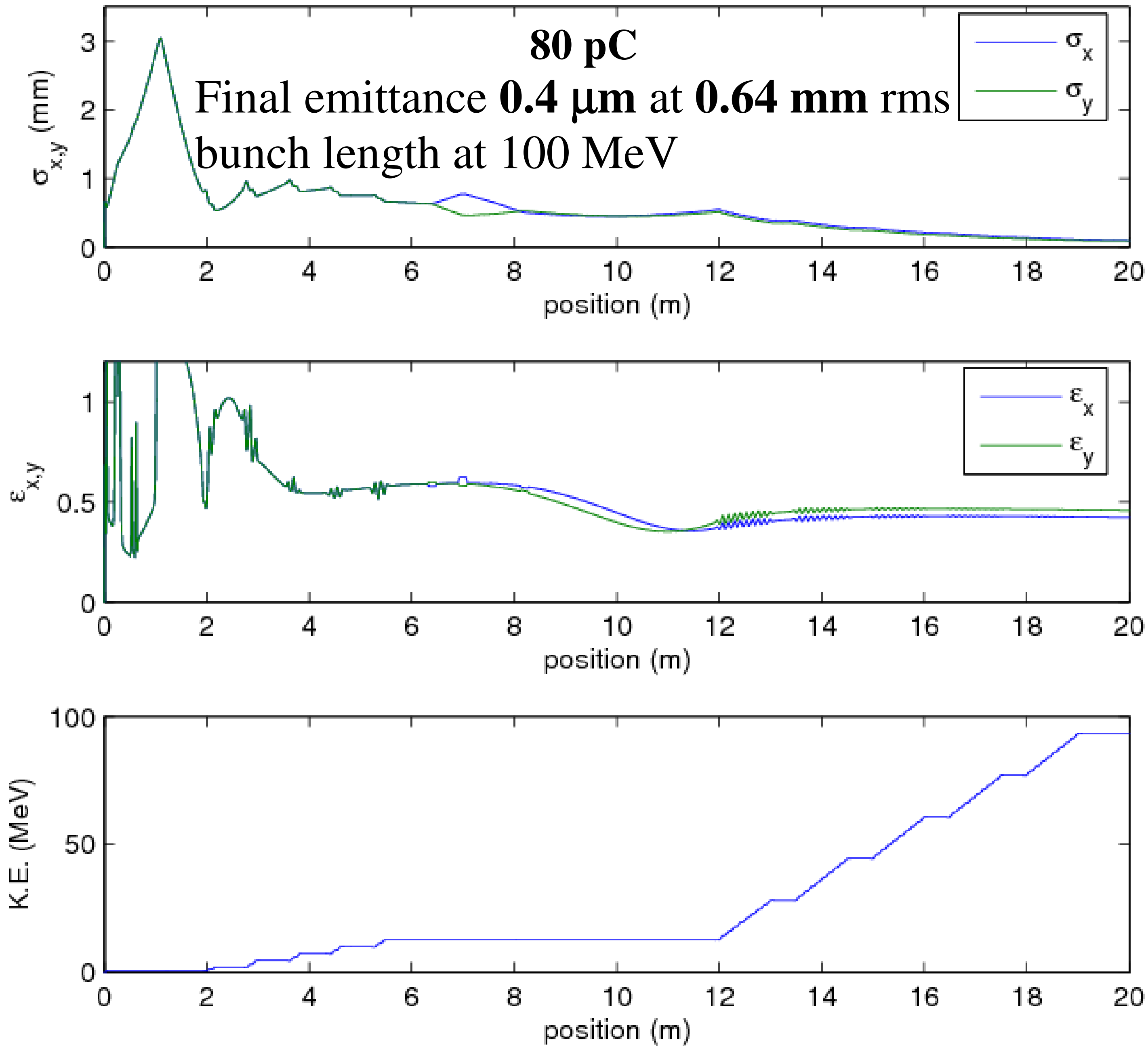
$\sigma_y = 0.640$ mm $\varepsilon_y = 0.167$ mm-mrad

$\sigma_z = 0.000$ mm $\varepsilon_z = 0.000$ mm-keV





Closer look: 80 pC

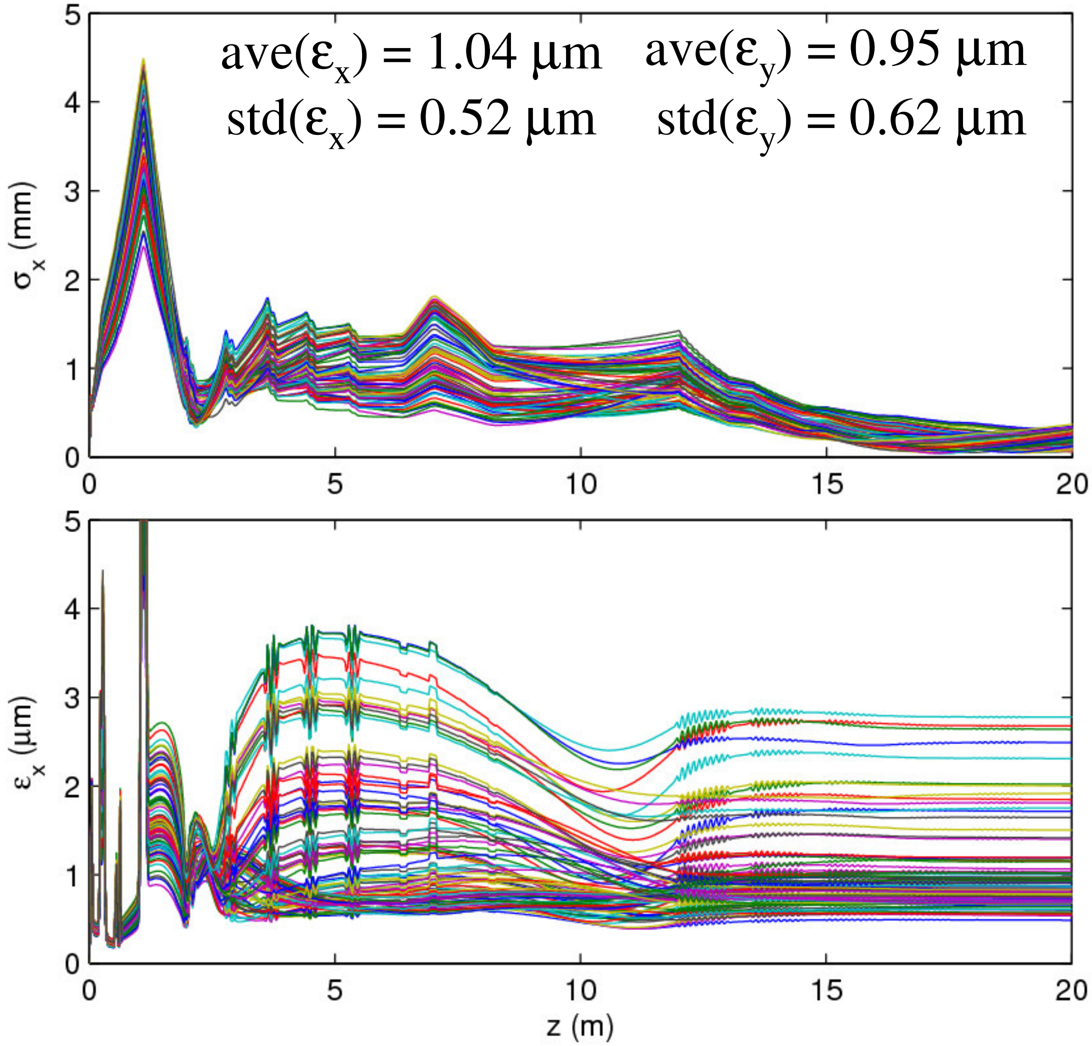


Optima steepness

- Virtual injector allows absolute control of parameters, real system with a dozen of sensitive parameters will not

Pulse duration rms	21.5 ± 1.4 ps
Spot size rms	0.640 ± 0.057 mm
Charge	80 ± 5.8 pC
Solenoid1 Bmax	0.491 ± 0.010 kG
Solenoid2 Bmax	0.532 ± 0.010 kG
Cavity1 phase	-41.6 ± 1.7 deg
Cavity2 phase	-31.9 ± 2.0 deg
Cavity3-5 phase	-25.7 ± 2.0 deg
Buncher Emax	1.73 ± 0.04 MV/m
Cavity1 Emax	15.4 ± 0.3 MV/m
Cavity2 Emax	26.0 ± 0.5 MV/m
Cavity3-5 Emax	27.0 ± 0.5 MV/m
Q1_grad	-0.124 ± 0.002 T/m
Q2_grad	0.184 ± 0.002 T/m
Q3_grad	0.023 ± 0.002 T/m
Q4_grad	-0.100 ± 0.002 T/m

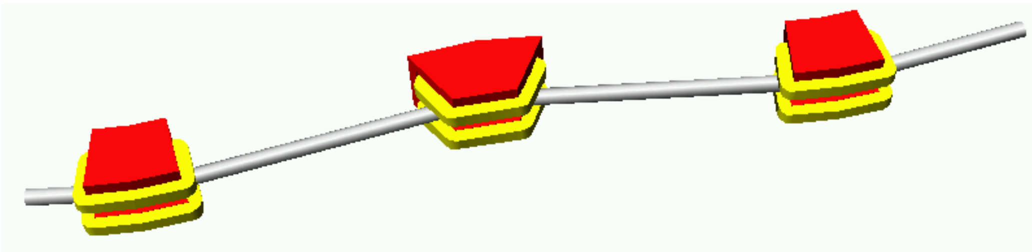
100 random seeds (outliers removed)

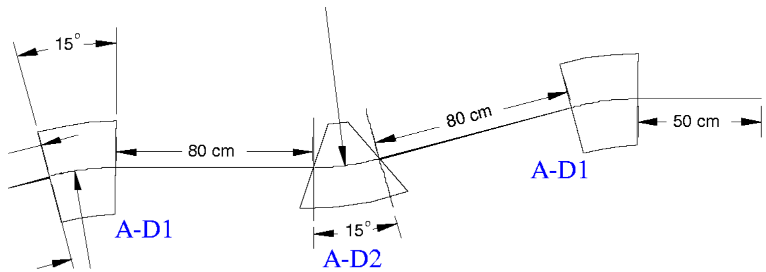


Merger issues

- Asymmetric transport → x-y coupling term in beam envelope equation
- Energy change in non-zero dispersion section (CSR and space charge) → emittance growth

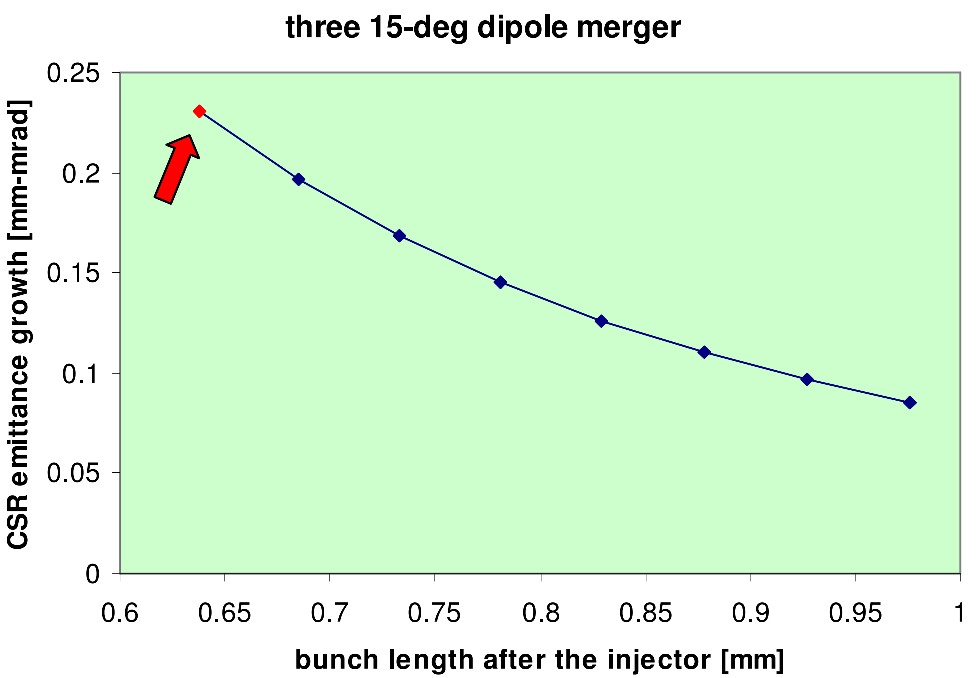
Merger: 1D CSR estimate

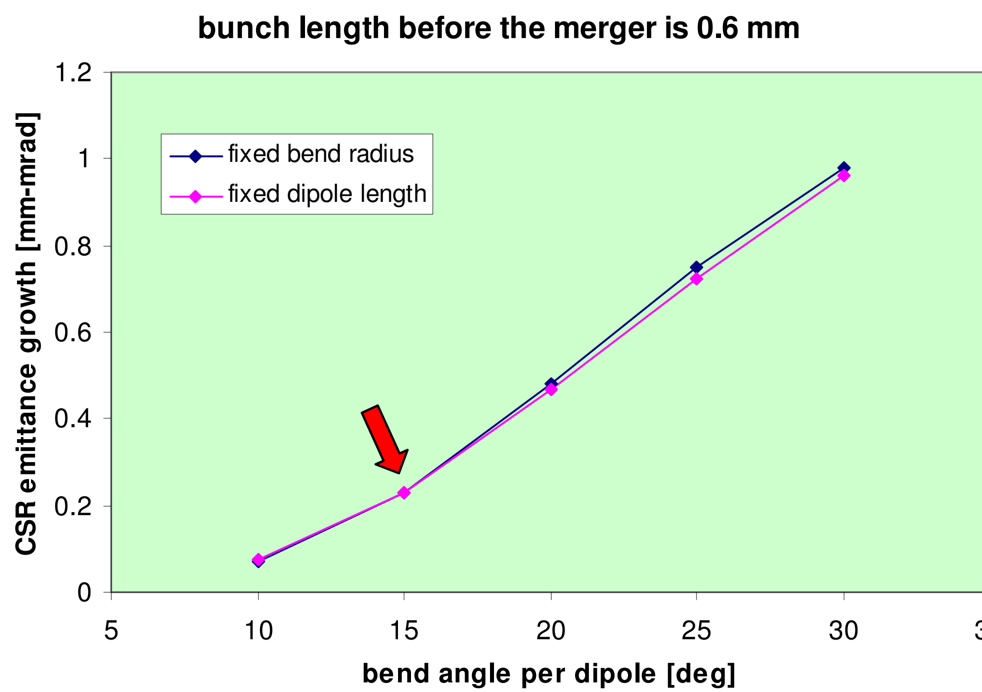




$$\Delta\varepsilon_{x,\mathrm{n,CSR}} \approx 0.2\ \mu\mathrm{m}$$

elegant





Merger: space charge

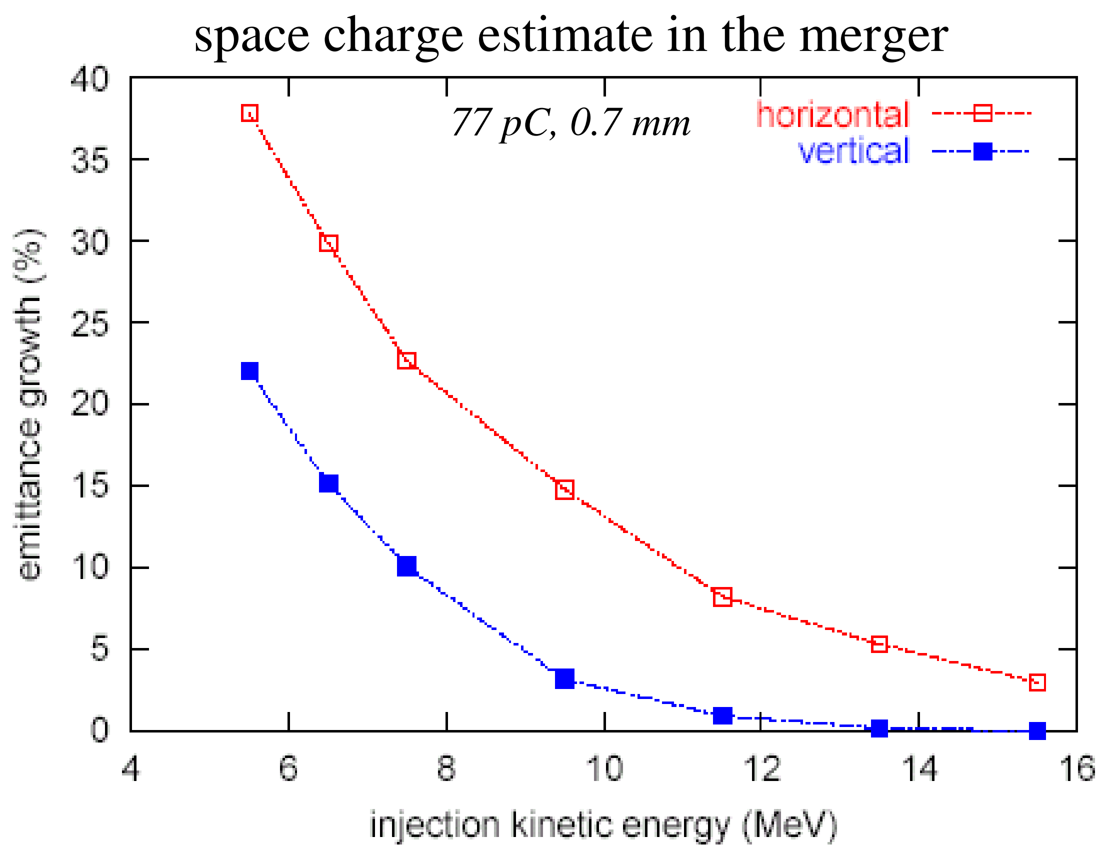
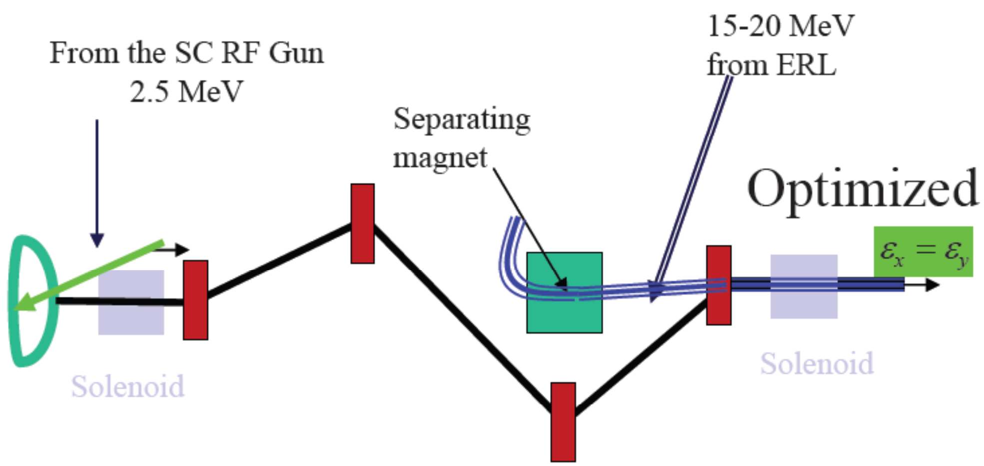


Figure 4: Emittance growth in the merger due to space charge for different injection energies. Initial rms normalized emittance is taken to be 1 mm-mrad.

Alternative merger scenarios

- BNL's "zigzag" merger



$$\delta_i(s) = \delta_{i0} + s \cdot g(\zeta_i) \Rightarrow \quad 4 \text{ "} Achromat\text{" } conditions$$

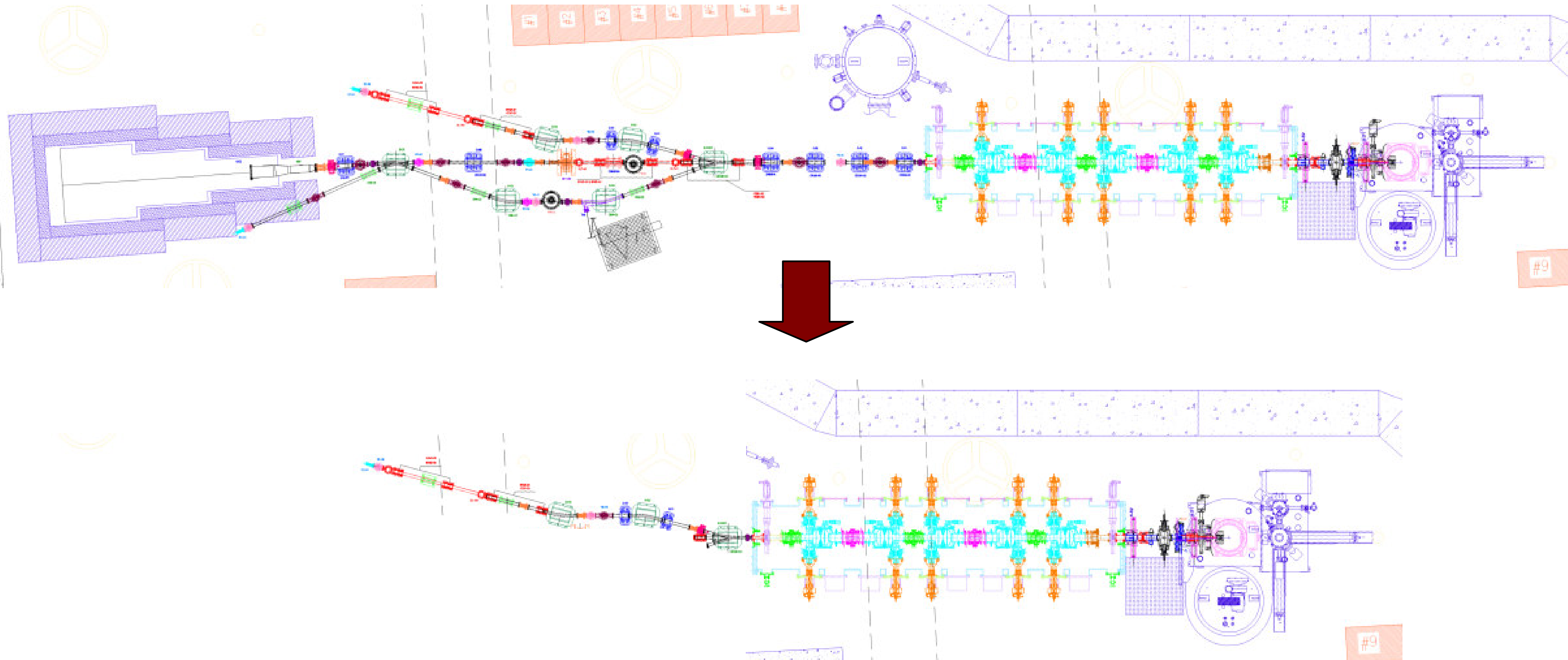
$$\int_0^S K_o(s') \cdot m_{11}(s') ds' = 0; \qquad \int_0^S K_o(s') \cdot s \cdot m_{11}(s') ds' = 0;$$

$$\int_0^S K_o(s') \cdot m_{12}(s') ds' = 0; \qquad \int_0^S K_o(s') \cdot s \cdot m_{12}(s') ds' = 0;$$

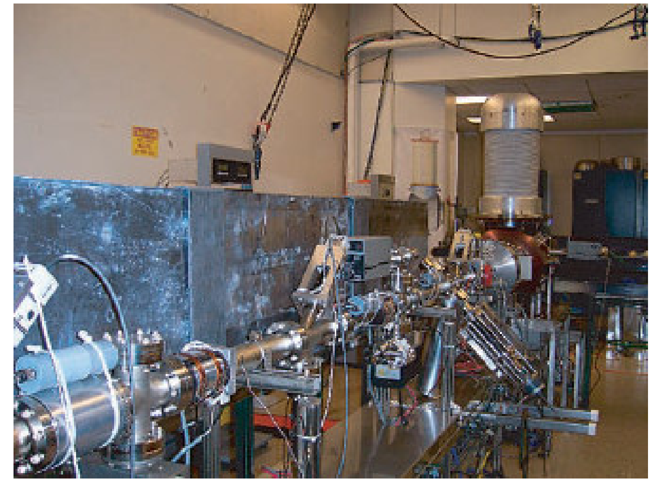
  - Good: emittance growth due to linear correlated energy spread from space charge is canceled to first order
  - Bad: does not separate 2 beams (works for BNL because recirculating energy is only 15-20 MeV)
  - Bad: is longer than Cornell's present 3-bend acrhomat, comparison yielded similar emittance growth for the two

Alternative merger scenarios

- Eliminate quad telescope and move the merger as close as possible to the cryomodule. Rely on RF focusing for beam matching. Live with asymmetry.

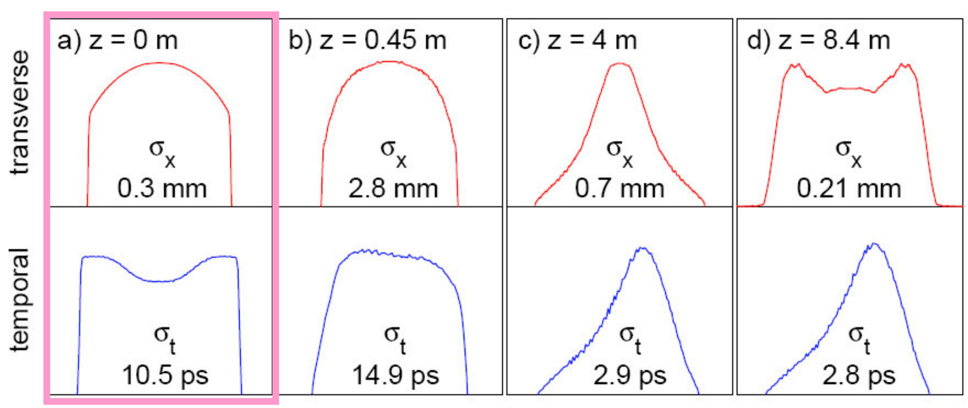


Experimental program



Gun development lab

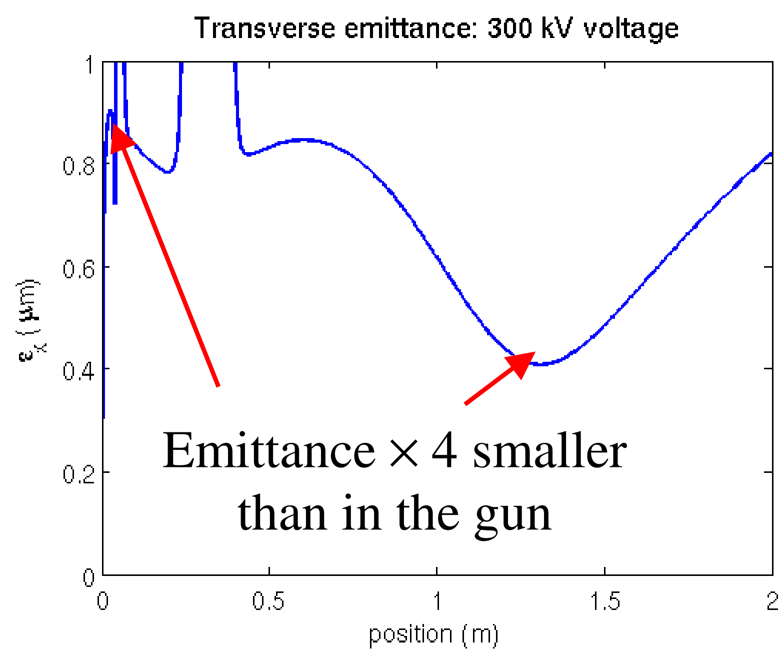
- I. Initial gun/cathode/laser characterization
  - without space charge
    - Laser temporal profile characterization (optical)
    - Gun focusing & aberration study as a function of voltage
    - Thermal emittance characterization of GaAs, GaAsP
    - Photocathode temporal response measurements



electron shape along the injector corresponding to small emittance

Experimental program

- II. Nominal charger per bunch, low rep rate
  - Emittance compensation without bunch compression: gun followed by the solenoid;
  - Benchmarking of existing space charge codes;
  - Solenoid and gun voltage scans; gun aberration study in the presence of the space charge for scanned laser



Experimental program

- III. Full injector layout: setting up of elements with prescribed strength, system debugging
  – Without space charge
    - Beam based alignment in optical elements;
    - Setting RF phases
  – Central orbit fitting to ensure agreement with the model that uses realistic E&M field maps of the elements. Calibration of control signals with descriptors used in the simulations (to be preceded by implementation of computational model to EPICS interface)

Experimental program

- IV. Straight line injector performance (before merger)
  - Nominal bunch charge, low rep rate
    - Use prescribed by simulations element settings. Measure projected emittance after the SRF cryomodule. Compare with extensive simulations done for this case.
    - Stab at online emittance optimization. Quads remain turned off.

Experimental program

- V. Longitudinal issues
  - Nominal bunch charge, low rep rate, to 0.6 MW dump
    - Measurement of slice emittance (slit pair & TM110 cavity), and the bunch length for optimum point found in [IV];
    - Energy spread measurements with a screen in the chicane & energy spread minimization;
    - OTR bunch length measurements, bunch length measurements with RF zero-phase method

Experimental program

- VI. Through the merger
  - Nominal bunch charge, low rep rate
    - Setting of beta-function for space charge dominated beam (quad telescope is employed starting from that stage). Initially, setup the beam with negligible bunch charge and BPMs/betatron phase advance (i.e. quads & merger debugging). Eventually, the nominal charge per bunch is characterized at the location of viewscreens, comparing the spot size with the code's predictions.
    - Series of emittance measurements (both planes) before and after the merger. Study of the emittance growth as a function of Twiss parameters (quads breaking 2D symmetry), bunch length, bunch charge, beam energy.

Experimental program

- VII. High average current
  - Nominal bunch charge, high rep rate
    - Flying wire transverse profile measurements and comparisons with the low rep rate case;
    - Flying wire transverse profile measurements in the chicane for energy spread information, comparison with the low rep rate case;
    - THz non-interceptive diagnostics of bunch length, comparison with the low rep rate case