The Birth of a Future Light Source in Wilson Basement

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LEPP/CHESS

Talking points

- Light sources today and tomorrow
- 'Holy grail' x-ray experiments
- Physics of SR/XFELs/ERLs
- ERL Phase1a
- Future X-ray source at Cornell

Prelude

"Basement Conjecture": successful experimental physics ∝ basement area

Clark basement

Newman basement

⇐ Wilson:
'solely' basement

Future light source

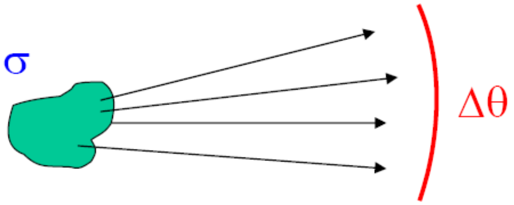
?

X-ray brightness

Brilliance / Spectral Brightness

$$\frac{\text{FLUX OF PHOTONS IN UNIT SPECTRAL RANGE}}{\text{(SOURCE AREA) X (BEAM DIVERGENCE)}}$$

Units: Photons/s/mm^2/mrad^2/0.1% bandwidth



$$B = \frac{\Phi}{\sigma\, \Delta\theta_h\, \Delta\theta_v}$$

- **Average brightness:** measure of transversely coherent flux

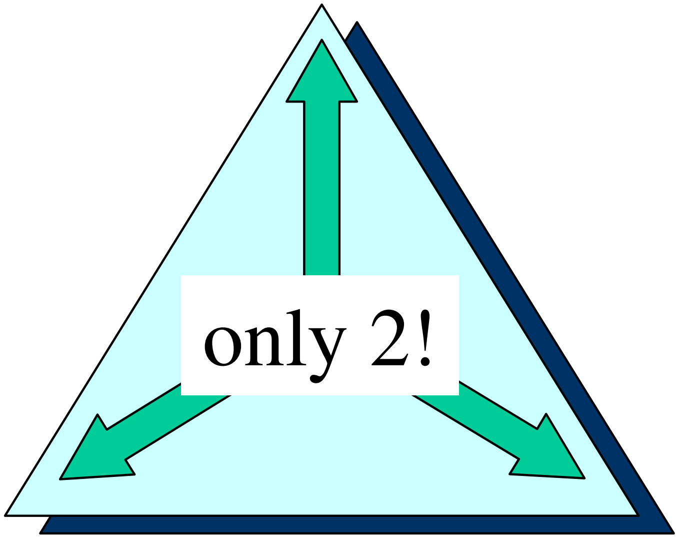
$$F_c = B_{avg} \left(\frac{\lambda}{2}\right)^2$$

- **Peak brightness:** proportional to the number of photons per coherence volume in 6D phase space ≡ the photon degeneracy

$$\Delta_c = B_{peak} \left(\frac{\lambda}{2}\right)^3 \frac{\Delta\lambda}{\lambda} \frac{1}{c}$$

Three frontiers in source dev.

- Avg. brightness
- Short pulses (< ps) & peak brightness
- Compactness

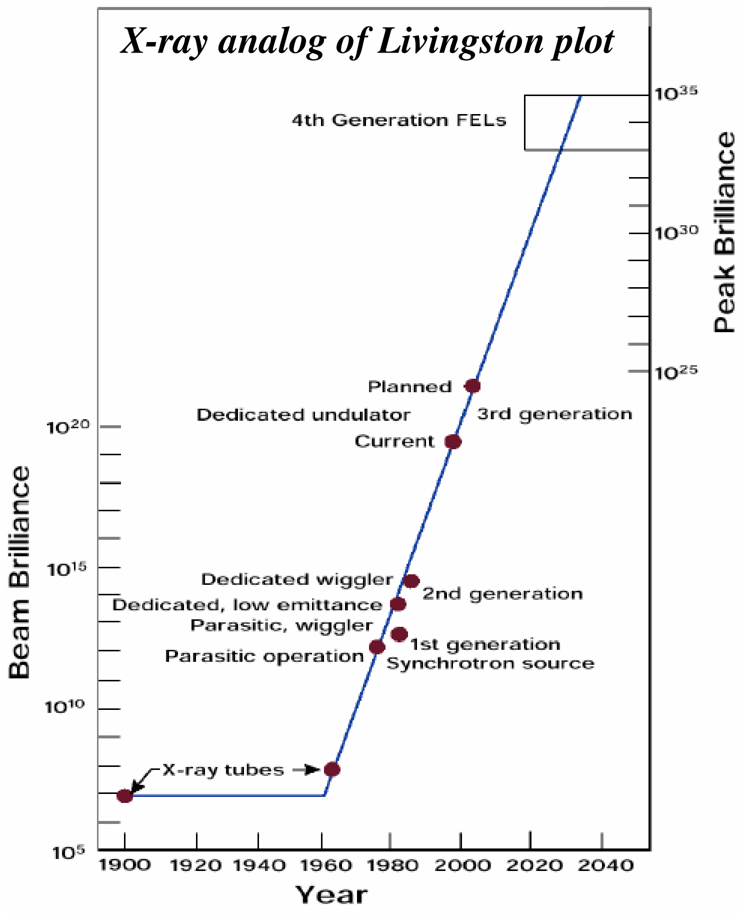


Compact

only 2!

Hard x-rays

Brightness

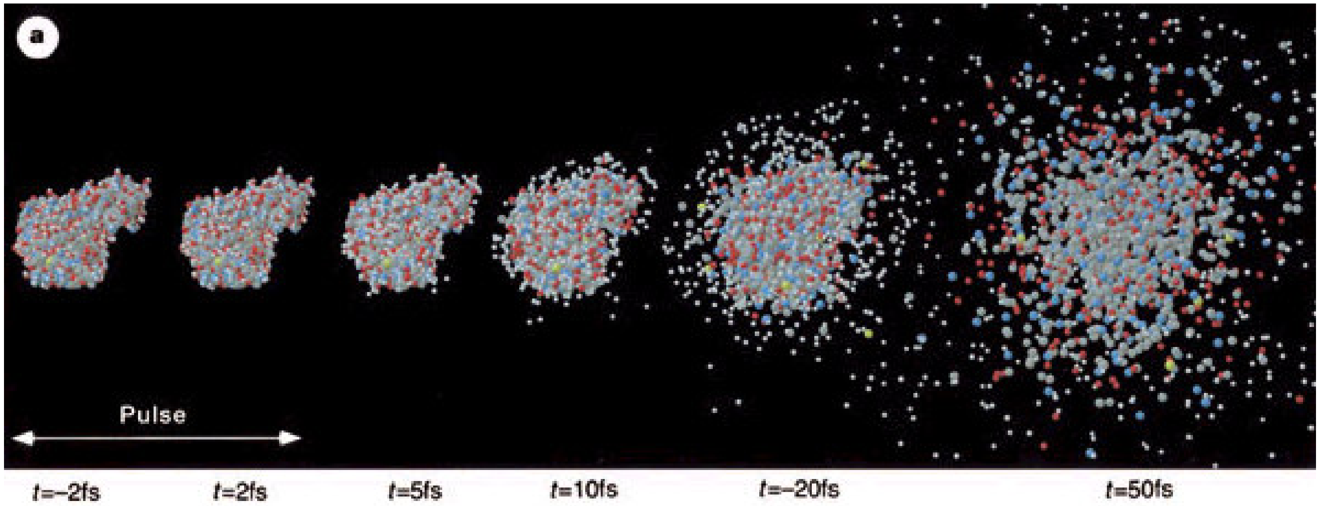


Light sources worldwide

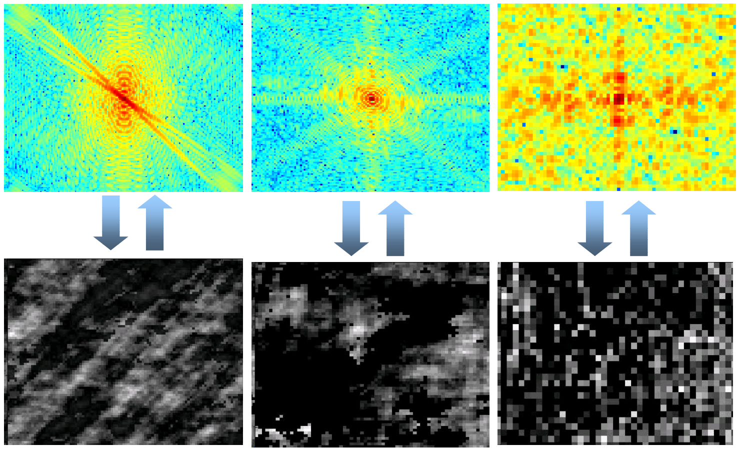
- About 70 light sources worldwide based on **storage ring** technology (**VUV to hard X-rays**), new ones are being built / designed
- 22 **FELs** operational, some as scientific research instruments (**far IR to VUV**)
- 3 **XFELs** in construction / committed to, plus half a dozen in CDR or earlier stages (**soft to hard X-rays**)
- 3 labs seriously consider building **ERL** as a **hard X-ray** light source

Exp1: ‘explosive’ proteins

R. Neutze, et al., *Nature*, **406**, 752



Fienup’s algorithm



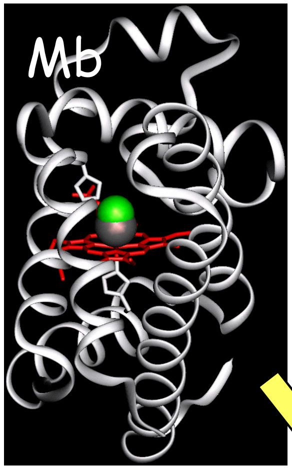
Briefly: calculations were done for T4 lysozyme (diameter 32 Å, N_C ~ 1000);
flux 4×10^6 X-rays/Å^2 with ~ 2000 primary ionization events;
elastically scattered ~ 200 photons.
If pulse is sufficiently short (<10 fs), 5×5×5 lysozyme nanocrystal will scatter to <2Å resolution.

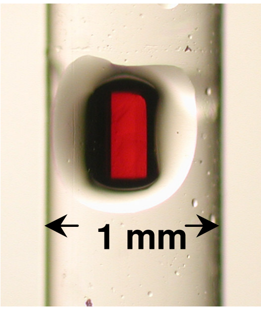
Key feature: sufficiently short X-ray pulse can beat Henderson’s limit of radiation damage (200 x-ray photons /A^2*)*

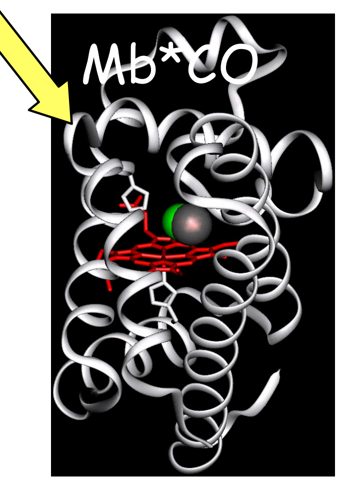
Exp2: fs chem. reaction movie

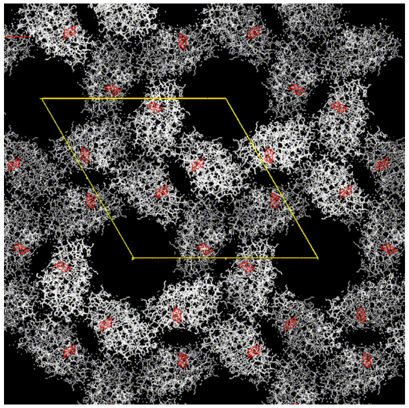
Broad class of pump-probe experiments providing structural (core e^-'s) conformational changes in the initial stages (mol. vibrational timescale 10's fs) of photo-induced reactions

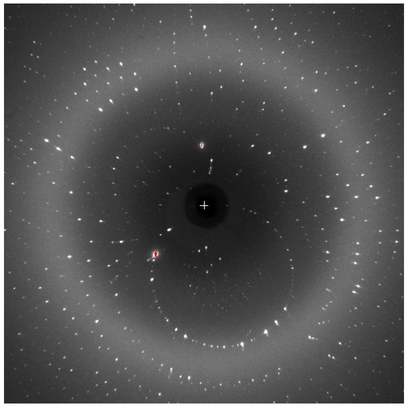
Time-resolved Laue Crystallography (Phil Anfinrud)

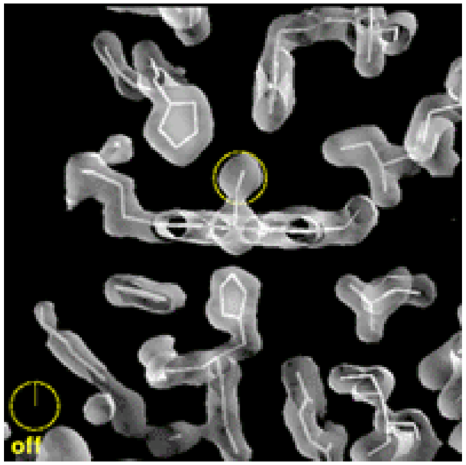






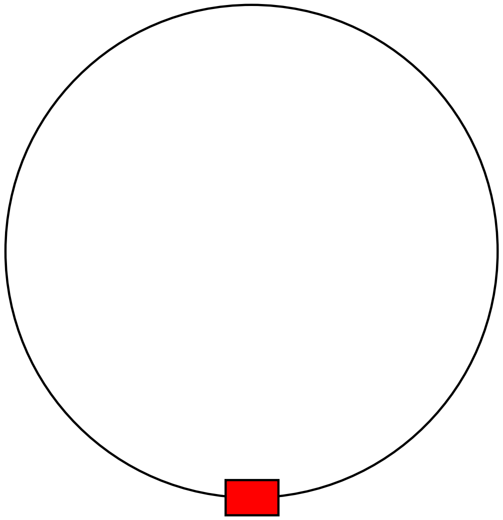






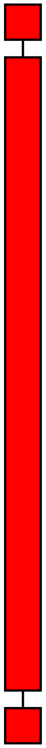
SR/XFEL/ERL

SR



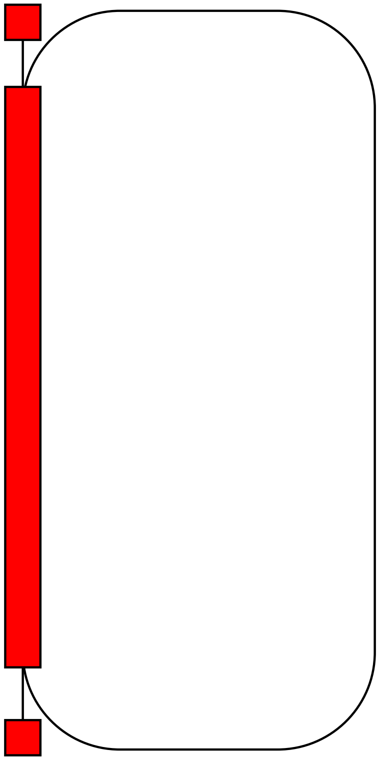
- efficient
- avg. brightness
- many beamlines
- workhorse technology

XFEL



- peak brightness
- short pulse
- few beamlines
- new user-base

ERL

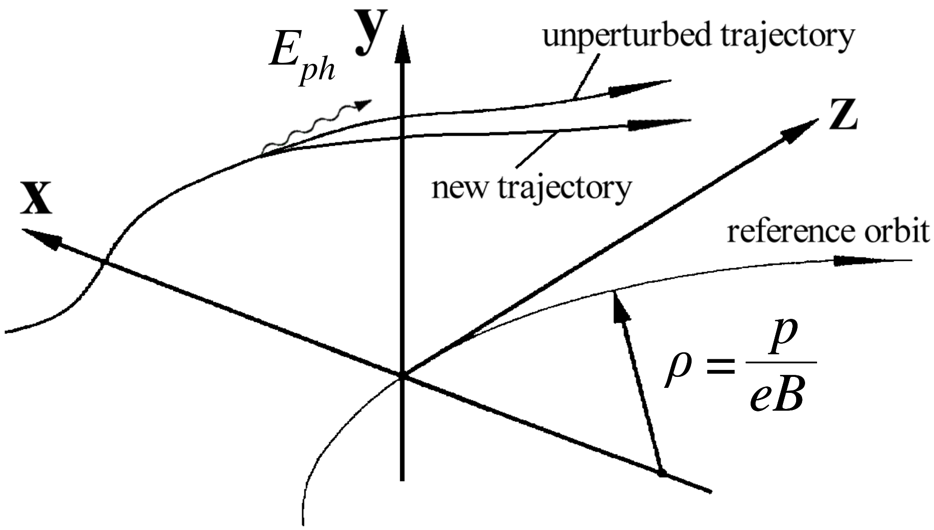


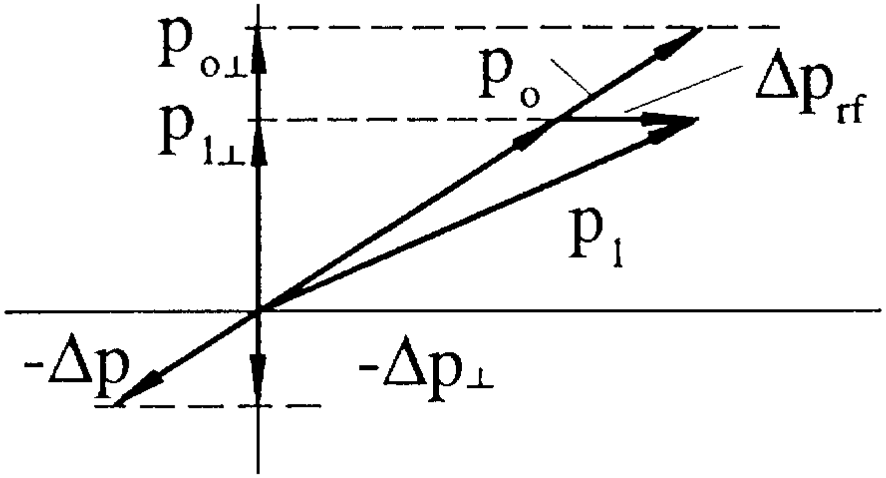
- avg. brightness
- short pulse
- many beamlines
- existing user-base

Storage ring

Equilibrium

Quantum Excitation **vs.** Radiative Damping



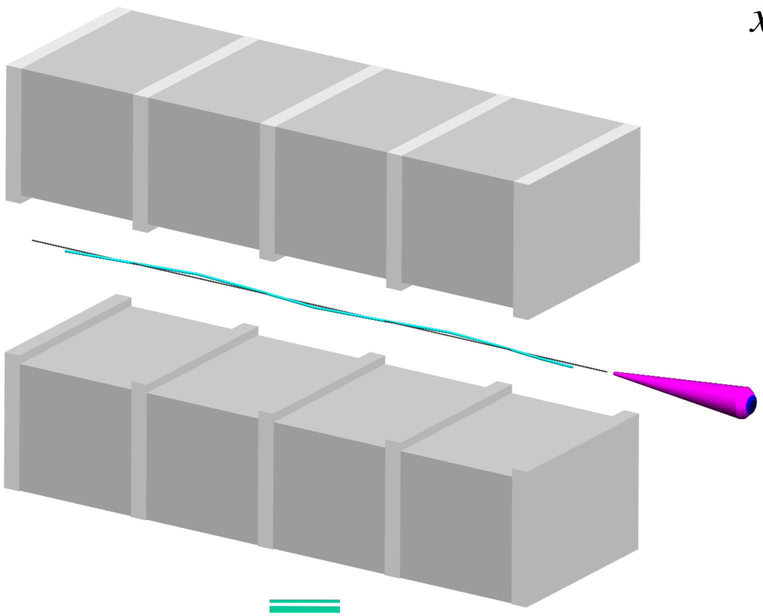


$$\frac{d\sigma_E^2}{dt} \sim \dot{N}_{ph} E_{ph}^2$$

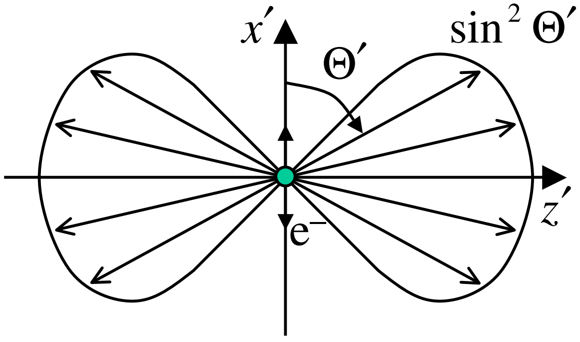
Emittance (hor.), Energy Spread, Bunch Length

Tighter focusing (higher tune) → stronger 6-poles for chromaticity correction → smaller dynamic aperture & lifetime

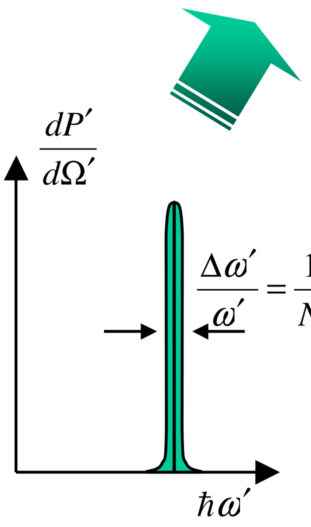
Basics of sync. rad. production

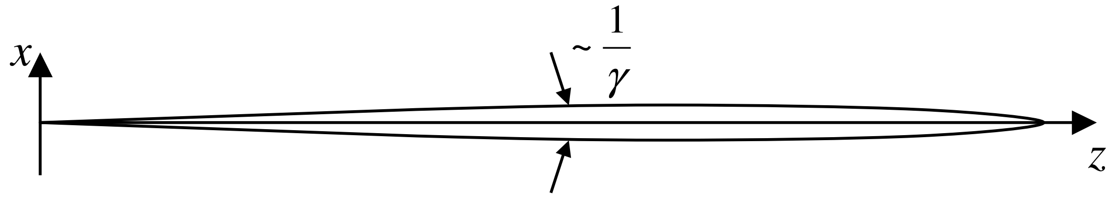


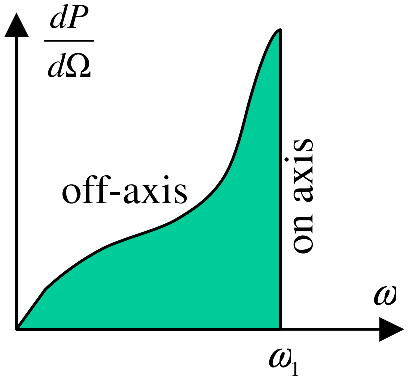
$$\lambda_p' = \lambda_p / \bar{\gamma}$$



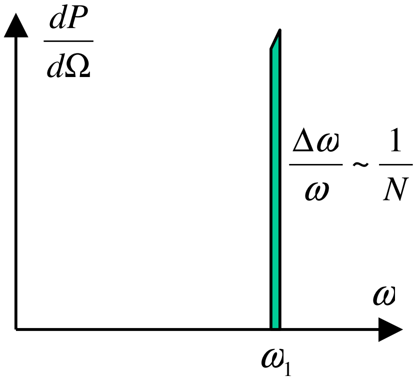
in e⁻ frame







back to lab frame



after pin-hole aperture

$$\boxed{\lambda_n = \frac{\lambda_p}{2\gamma^2 n}\left(1+\tfrac{1}{2}K^2+\gamma^2\theta^2\right)}$$

$$\boxed{\frac{\Delta\lambda}{\lambda_n} \sim \frac{1}{nN_p}}$$

(for fixed θ only!)

Coherent enhancement

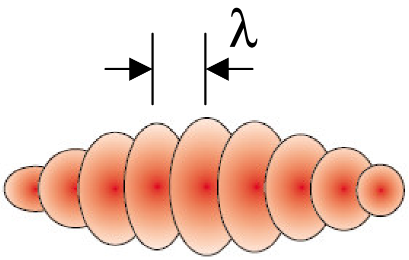
E.g. **5 m** undulator ($K = 1.5$, $\lambda_p = 2$ cm) @ **5 GeV** → converts only **10^{-8}** e^--beam energy fraction into X-rays with desired narrow bandwidth (0.1%) & small divergence

Radiation field from a single k^{th} electron in a bunch:

$$E_k = E_0 \exp(i\omega t_k)$$

Radiation field from the whole bunch ∝ bunching factor (*b.f.*)

$$b.f. = \frac{1}{N_e}\sum_{k=1}^{N_e} \exp(i\omega t_k)$$



Radiation Intensity:

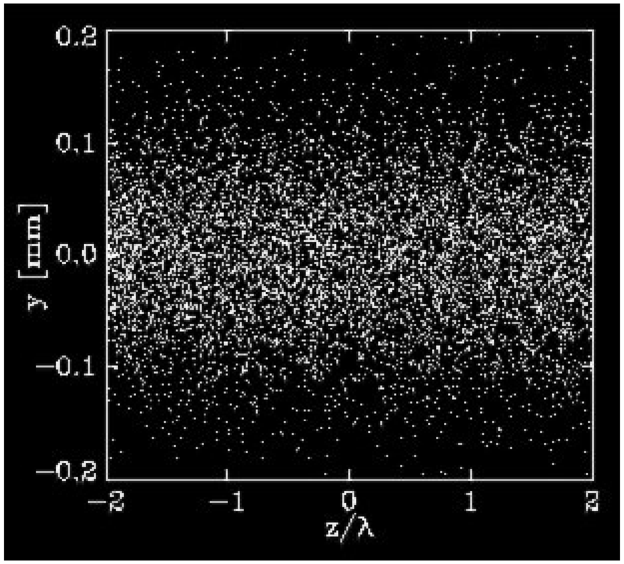
$$\boxed{I = I_0 |b.f.|^2 N_e^2}$$

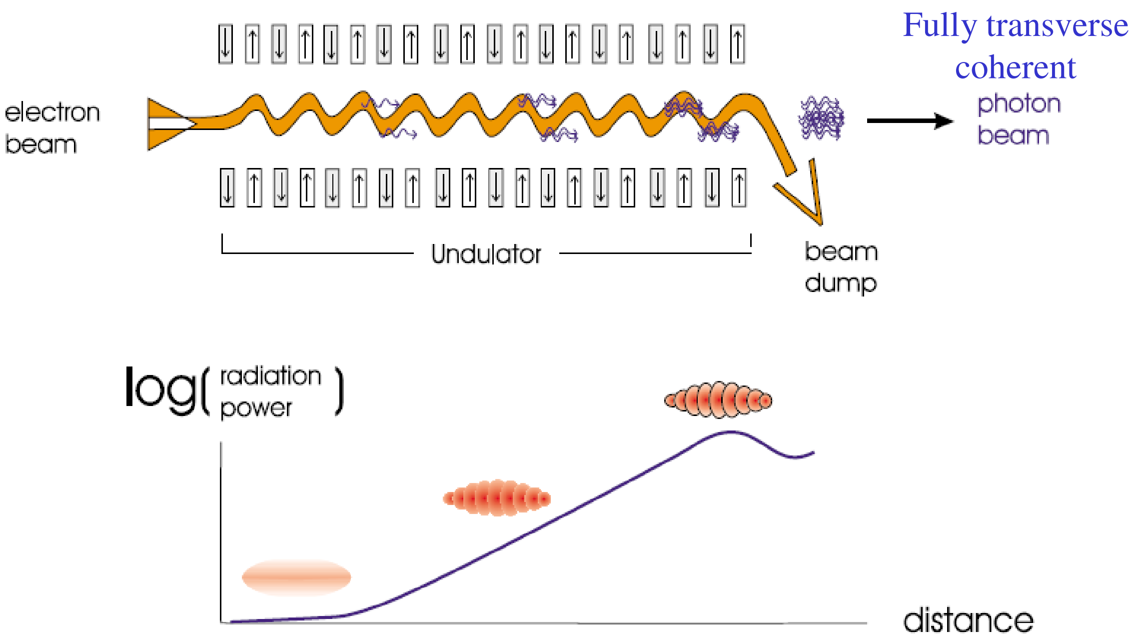
single electron

1) "long bunch": $|b.f.|^2 \sim 1/N_e \quad \Rightarrow I = I_0 N_e$ *incoherent (conventional) sync.rad*

2) "short bunch" or μ-bunching: $|b.f.| \leq 1 \quad \Rightarrow I \sim I_0 N_e^2$ *coherent (FELs) sync.rad*

XFEL





Fully transverse coherent

Prerequisites for e⁻-bunch:

diffraction-limited emittance

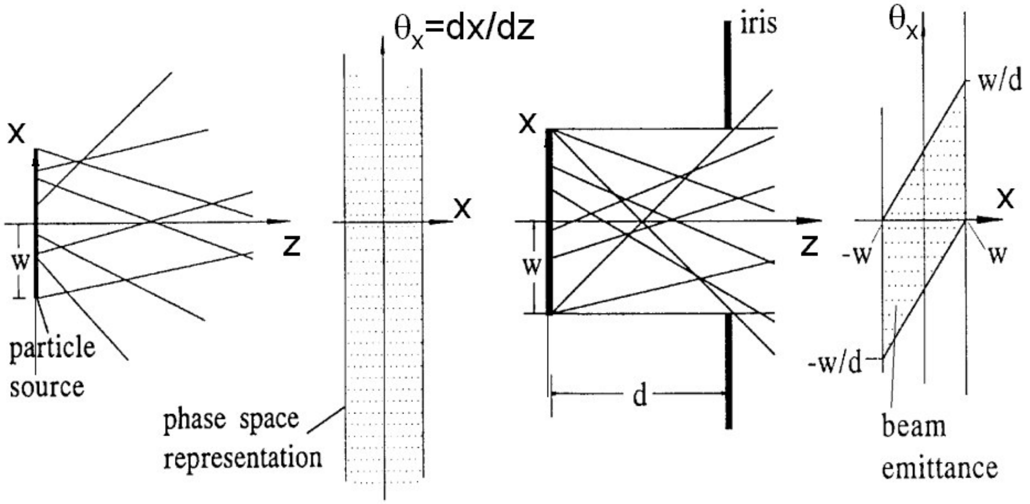
peak current 3-5 kA

energy spread 10^{-4}

Intense relativistic electron bunch becomes effective gain medium (e.g. use seed / amplifier setup)

Emittance basics

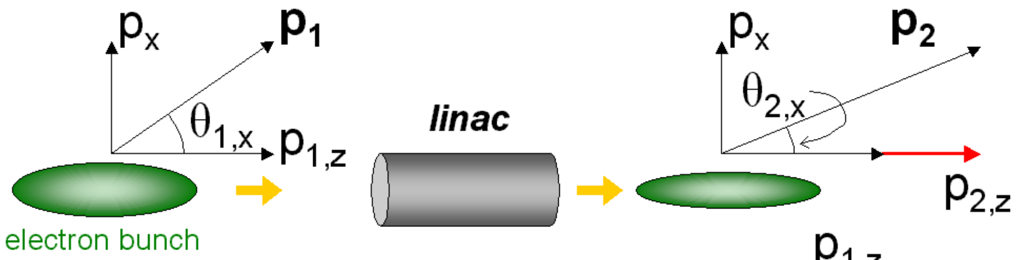
R.M.S. definition: $\varepsilon_x = \sqrt{\langle x^2 \rangle \langle \theta_x^2 \rangle - \langle x\theta_x \rangle^2}$



Liouville's Theorem: phase space volume is "incompressible fluid"

What exactly is emittance?
(2D projected)

"Adiabatic damping"
of geometric emittance



$$\varepsilon_2 = \varepsilon_1 \frac{p_{1,z}}{p_{2,z}}$$

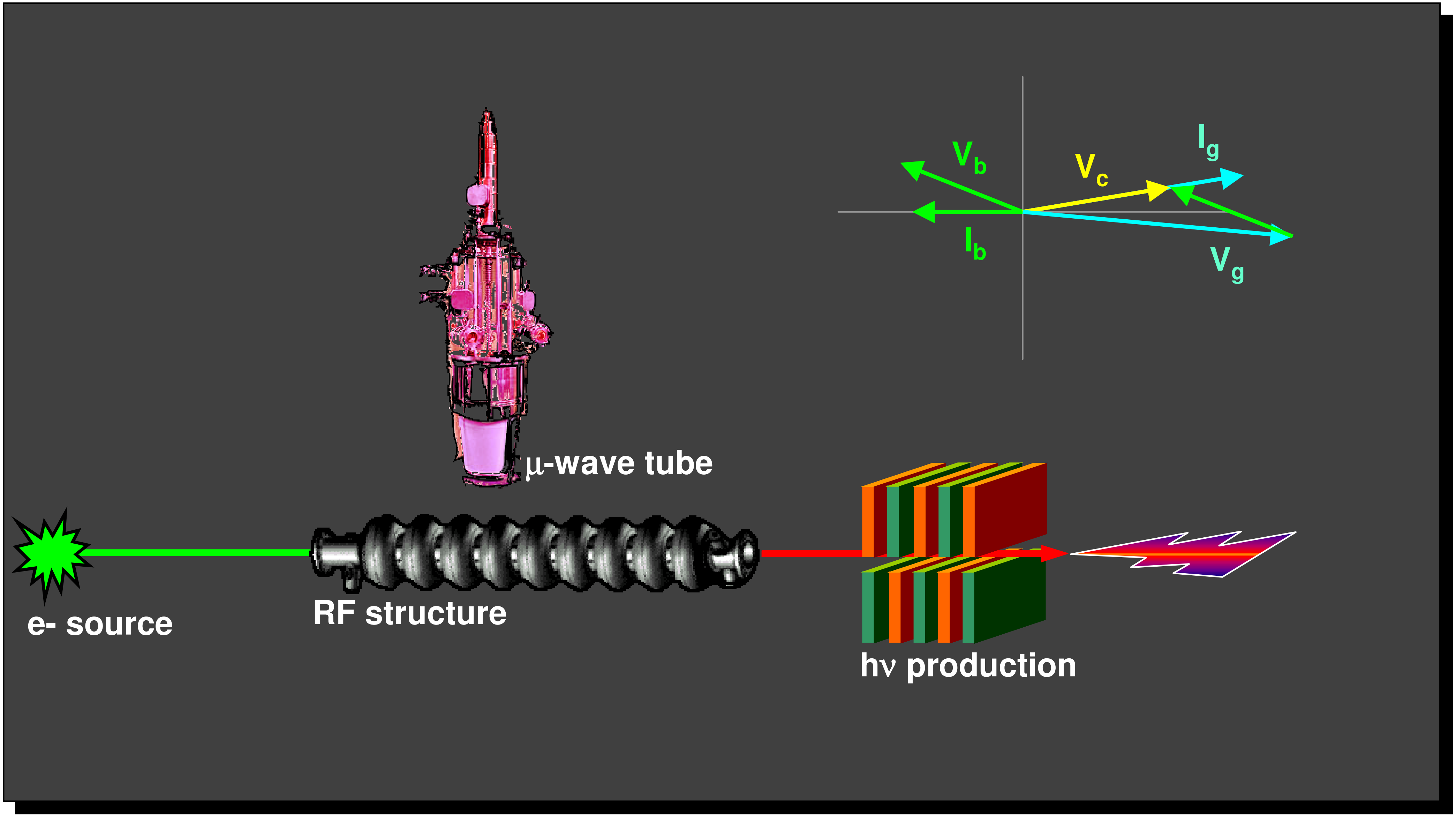
geometric $\{x, \theta_x\}$

$$\boxed{\varepsilon = \frac{\varepsilon_n}{\beta\gamma}}$$

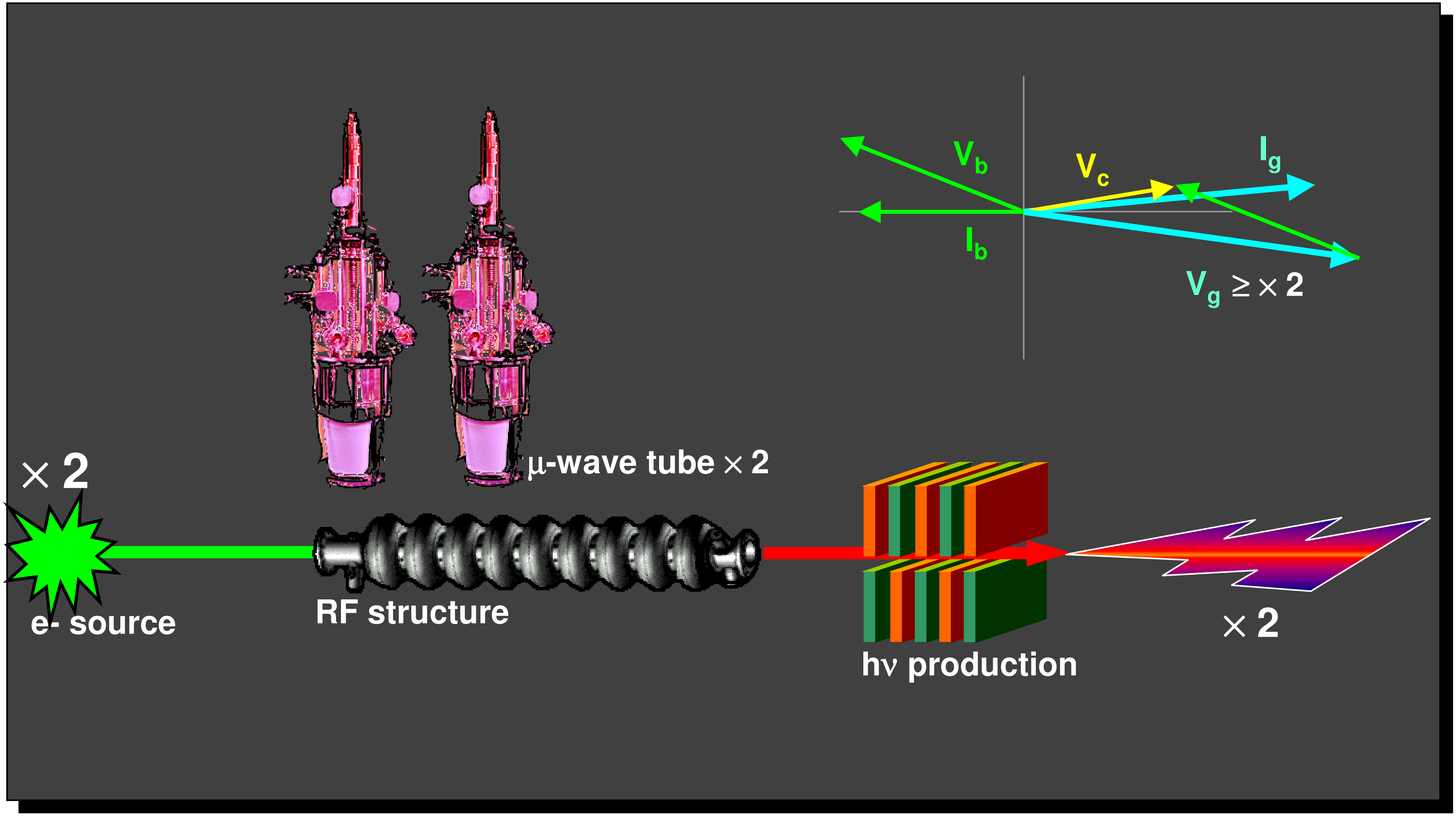
normalized $\{x, \frac{p_x}{mc^2}\}$

ε_n is invariant since
$\{x;\ p_x = mc^2\beta\gamma\cdot\theta_x\}$ form canonically conjugate variables

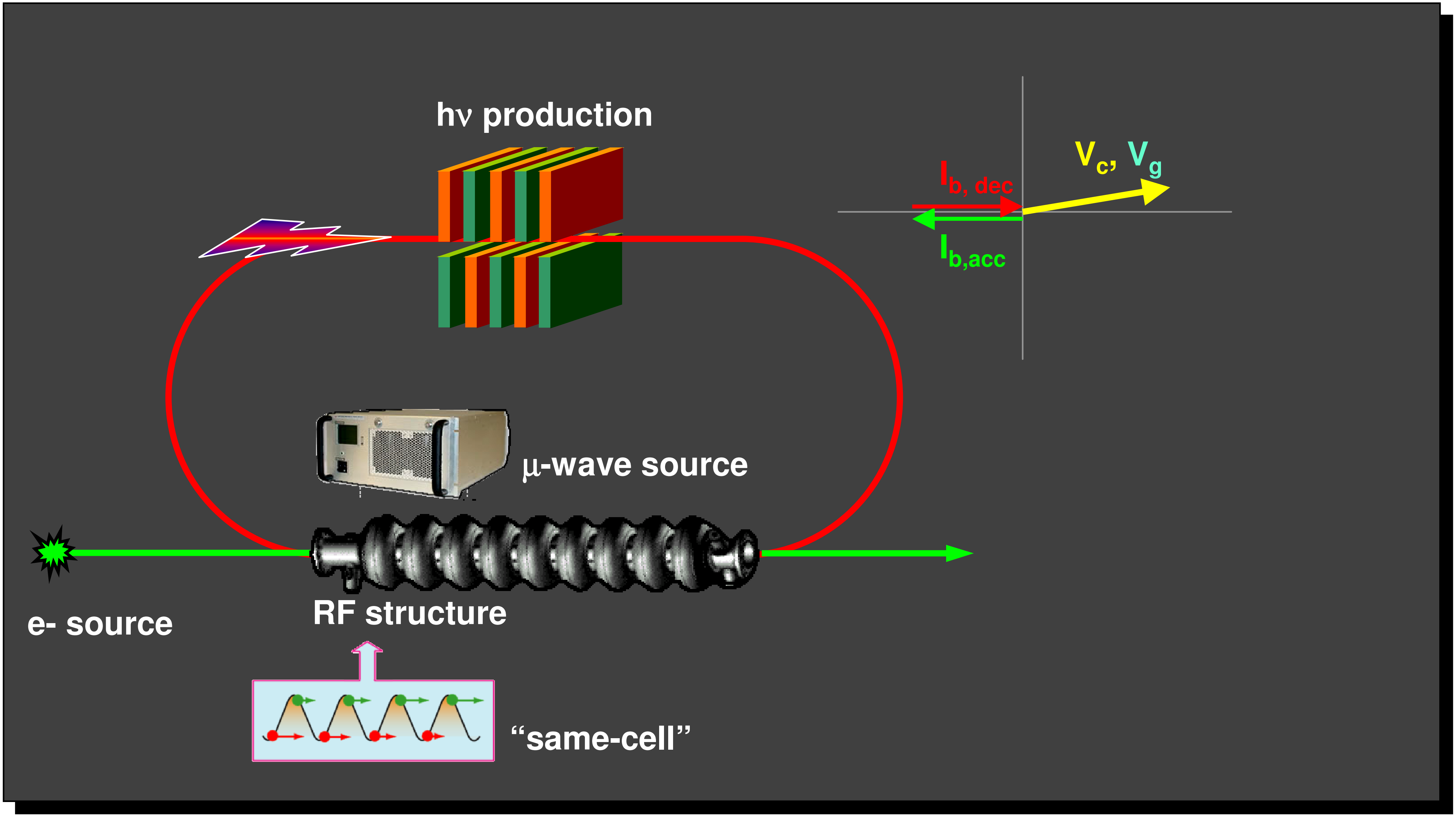
Linac based approach



Linac based approach



Energy recovery concept



hν production

V_c, V_g

$I_{b,\ dec}$

$I_{b,acc}$

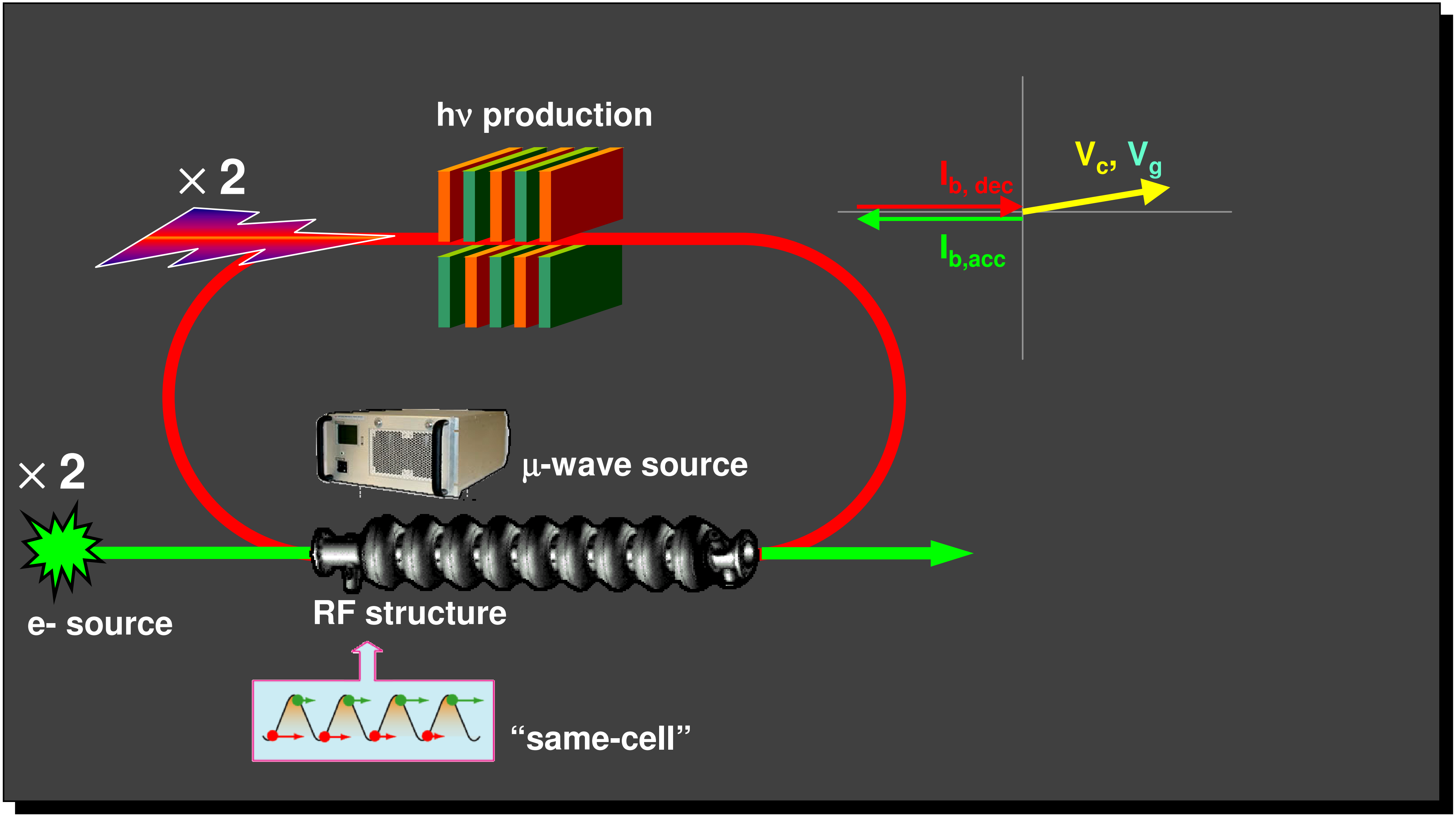
μ-wave source

e- source

RF structure

“same-cell”

Energy recovery concept



hν production

× 2

$I_{b,\ dec}$

V_c, V_g

$I_{b,acc}$

× 2

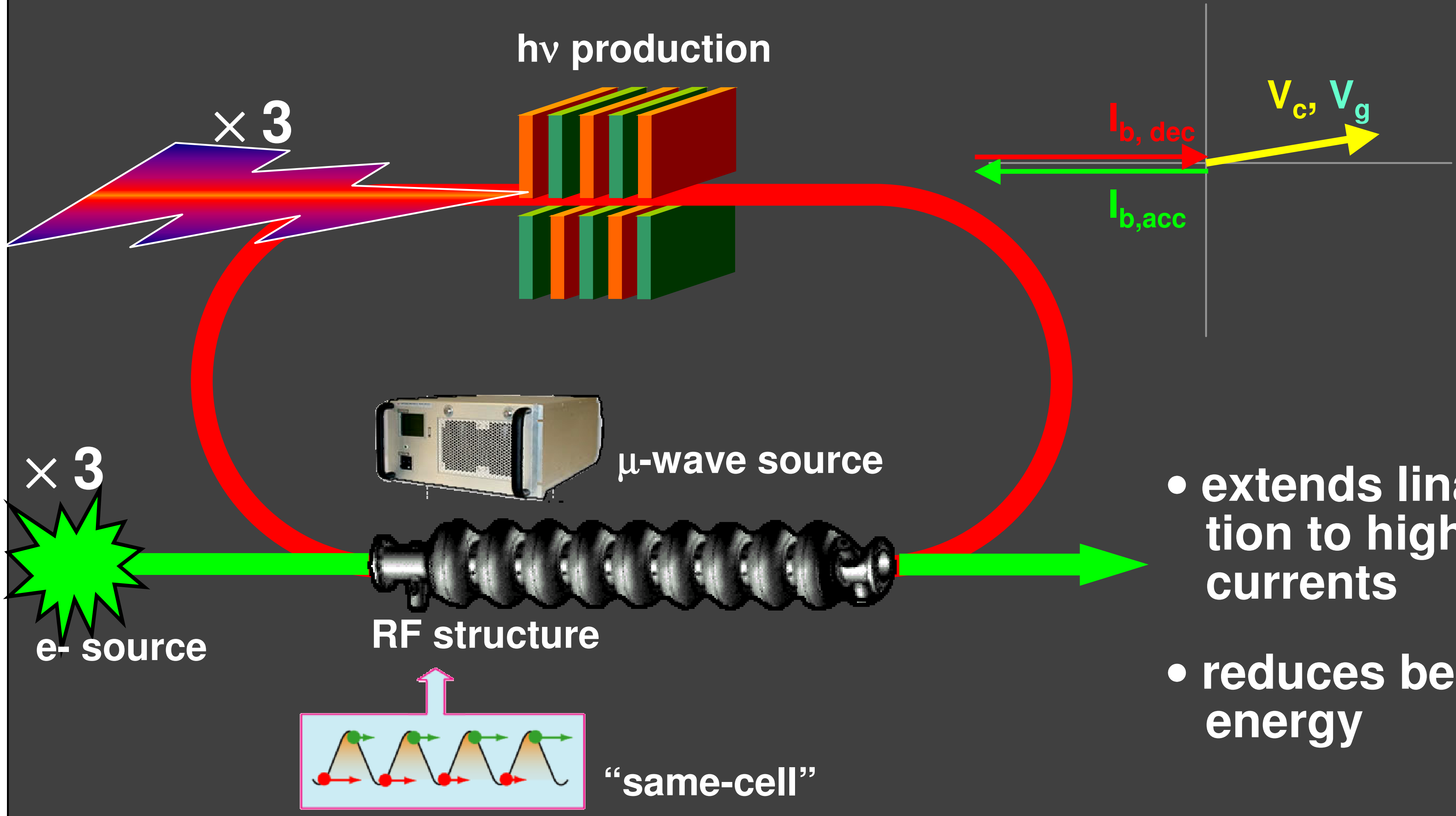
μ-wave source

e- source

RF structure

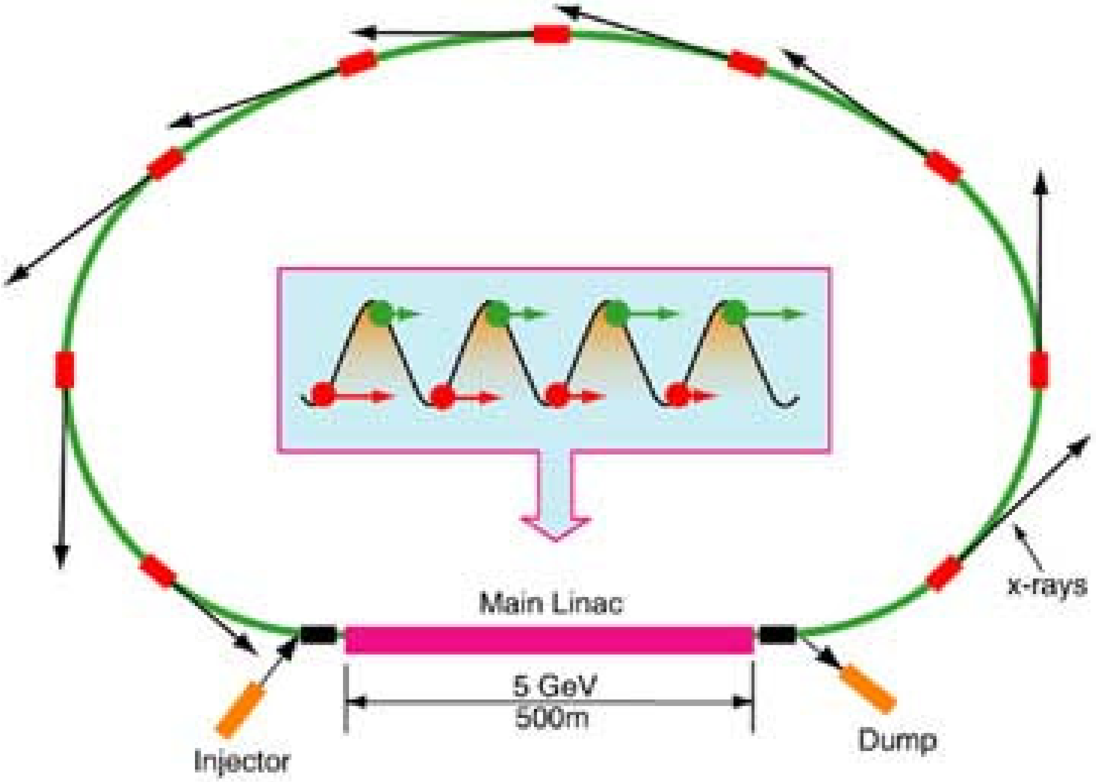
“same-cell”

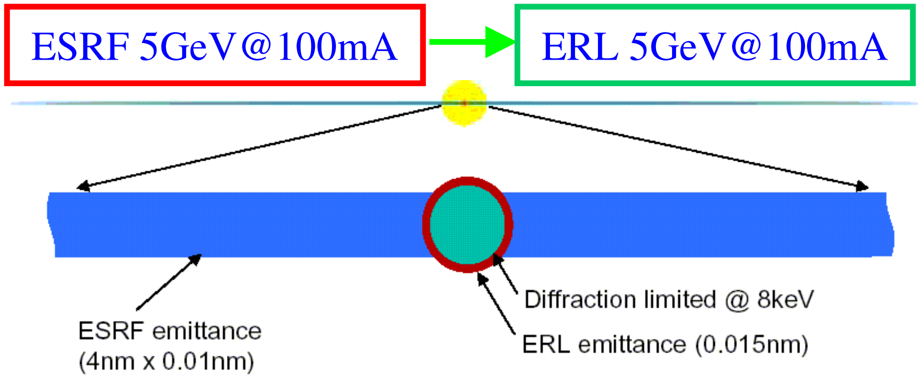
Energy recovery concept

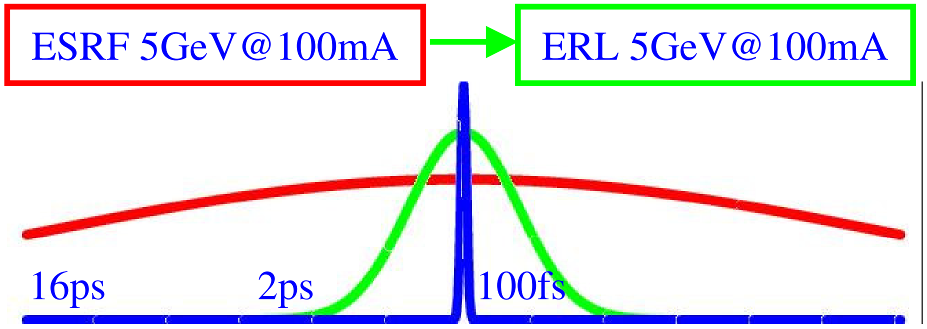


- extends linac operation to high average currents
- reduces beam dump energy

ERL promise







Much smaller (×100) horizontal emittance

Much shorter (×100) pulses

Source-limited: ERL vs. future 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 **80 pC** bunch (0.1 A average current at 1.3 GHz bunch rep rate) assuming no emittance degradation downstream
- Comparison: ILC norm. emit. $\sqrt{\varepsilon_{nx}\varepsilon_{ny}}$ = **0.6 µm** for **3.2 nC**

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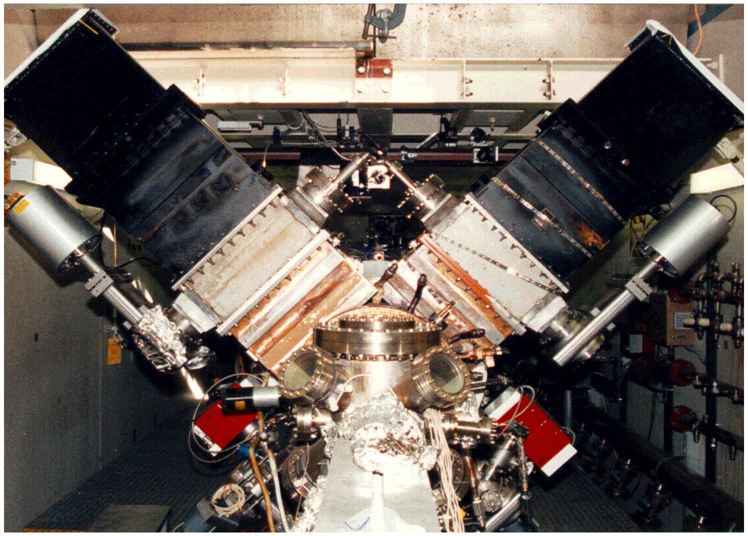
* without use of damping wigglers

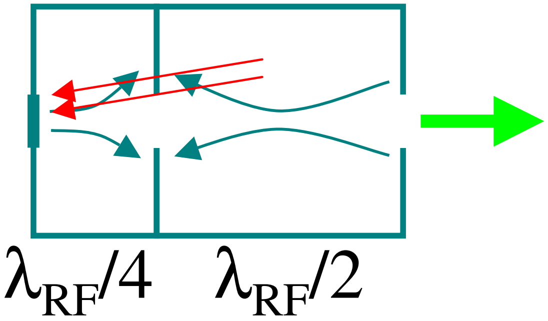
State-of-the-art: BOEING gun

Photocathode Performance:	
Photosensitive Material:	**K_2CsSb Multialkali**
Quantum Efficiency:	5% to 12%
Peak Current:	45 to 132 amperes
Cathode Lifetime:	1 to 10 hours
Angle of Incidence:	near normal incidence
Gun Parameters:	
Cathode Gradient:	26 MV/meter
Cavity Type:	Water-cooled copper
Number of cells:	4
RF Frequency:	433 $\times 10^6$ Hertz
Final Energy:	5 MeV(4-cells)
RF Power:	600 $\times 10^3$ Watts
Duty Factor:	25%, 30 Hertz and 8.3 ms
Laser Parameters:	
Micropulse Length:	53 ps, FWHM
Micropulse Frequency:	27 $\times 10^6$ Hertz
Macropulse Length:	10 ms
Macropulse frequency:	30 Hertz
Wavelength:	527 nm
Cathode Spot Size:	3-5 mm FWHM
Temporal and Transverse Distribution:	gaussian, gaussian
Micropulse Energy:	0.47 microjoule
Energy Stability:	1% to 5%
Pulse-to-pulse separation:	37 ns
Micropulse Frequency:	27 $\times 10^6$ Hertz
Gun Performance:	
Emittance (microns, RMS):	**5 to 10 for 1 to 7 nCoulomb**
Charge:	1 to 7 nCoulomb
Energy:	5 MeV
Energy Spread:	100 to 150 keV

433 MHz RF Gun



32 mA avg. current

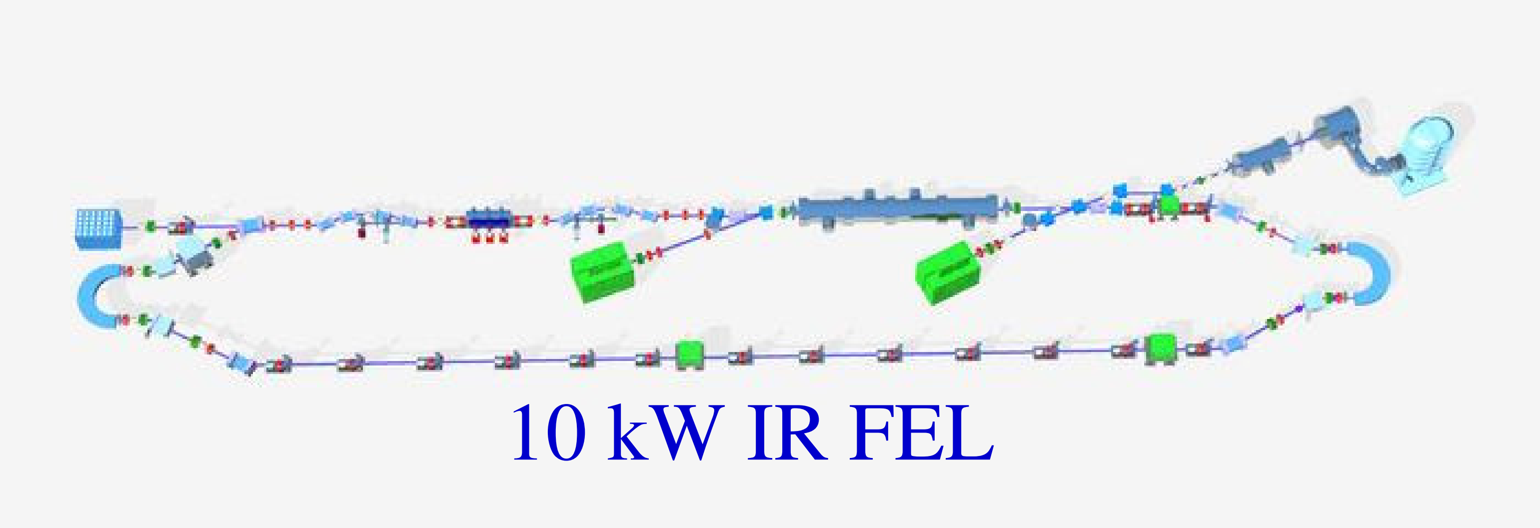


State-of-the-art: JLAB FEL inj.

500 kV (350) DC gun

9.1 mA avg. current

- Cs:GaAs photocatode
- max current 9.1 mA, routine 5 mA
- best simulated emittance 5 µm, measured ×2 larger at 60 pC
- work on 100 mA gun underway to drive high power IR FEL

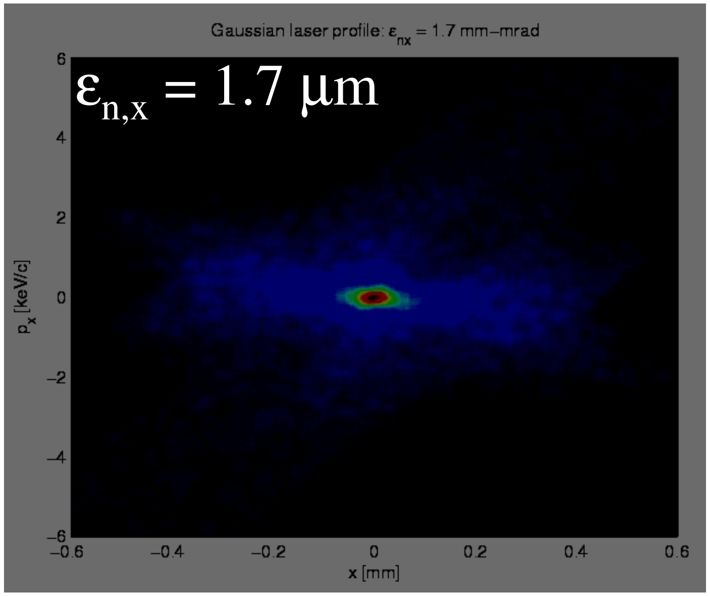


10 kW IR FEL

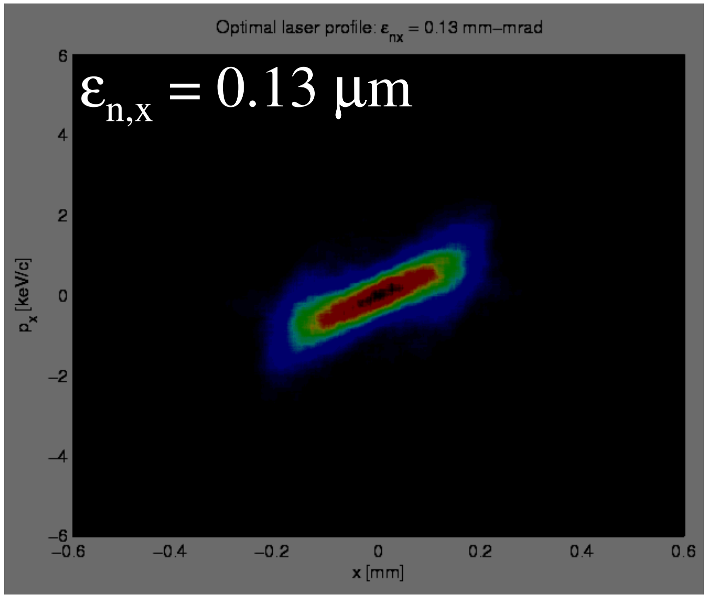
Two main limiting mechanisms:

- Phase space scrambling due to nonlinear space charge

3D Gaussian initial distribution



Optimal initial distribution

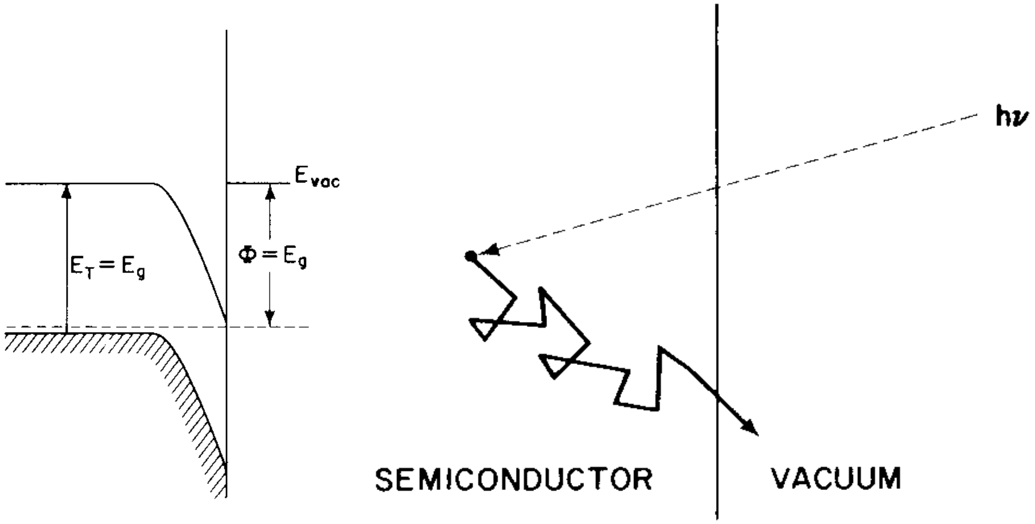


- Photocathode thermal emittance

transverse temperature of photoemitted electrons

$$\varepsilon_{n,th} = \sigma_{x,y}\sqrt{\frac{E_{th}}{mc^2}}$$

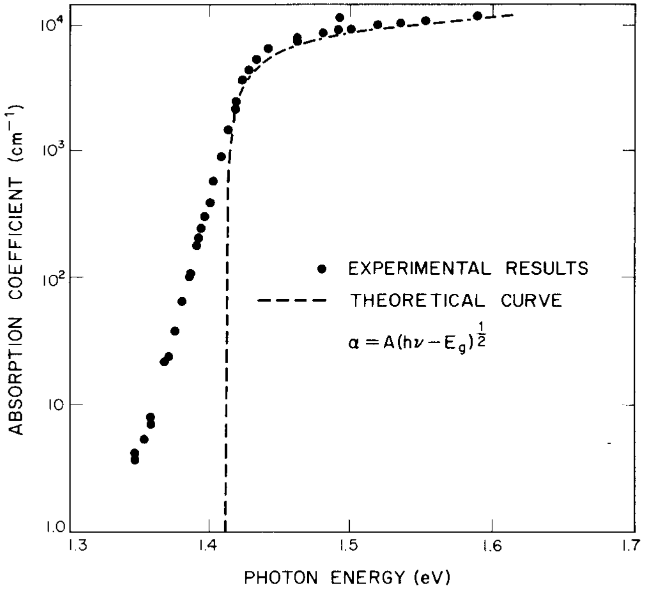
Photocathode requirements



(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.

Ideal photocathode:

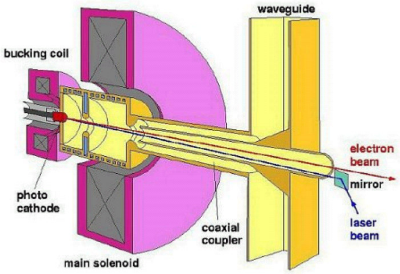
- $E_{th} \rightarrow kT \leq 25$ **meV**
- **response time ≤ 1 ps**
- **high QE ≥ 10%**
- **robust**

No ideal photocathode exists. NEA:GaAs has small thermal energy but slow response time (~10 ps)

Cathode Field ← E_{th} cathode

1 nC

NCRF

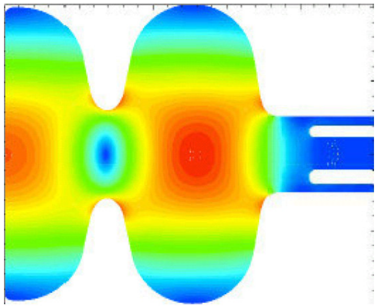


pulsed!

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

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

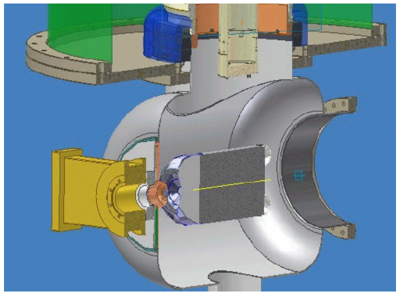
SRF



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

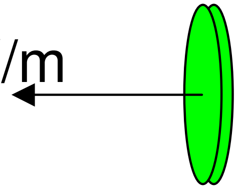


E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

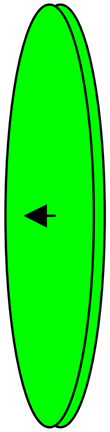
$\tau_{laser} \rightarrow z$ = 0.12 mm

2×18 MV/m

2×6 MV/m



2×1 MV/m

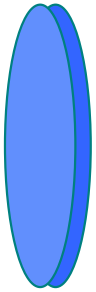


$E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$

same simulated emittance

Thermal emit. & cathode field

Near the photocathode, the bunch typically has a pancake shape:

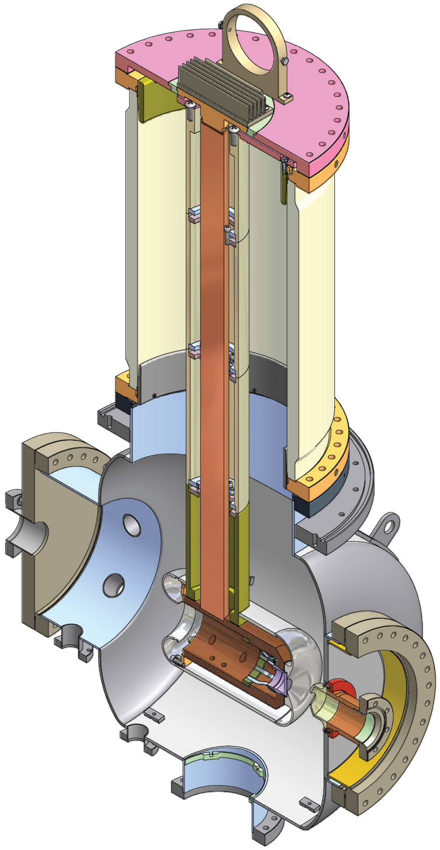


space charge limit

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

Lower limit to the achievable emittance

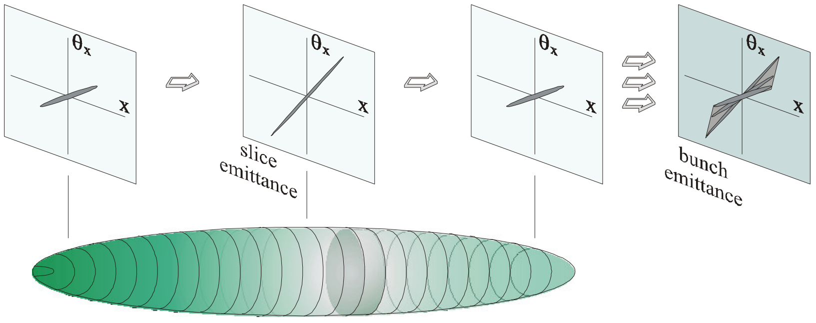
$$\varepsilon_n[\text{mm-mrad}] \geq 4\sqrt{\frac{q[\text{nC}]E_{th}[\text{eV}]}{E_{cath}[\text{MV/m}]}}$$



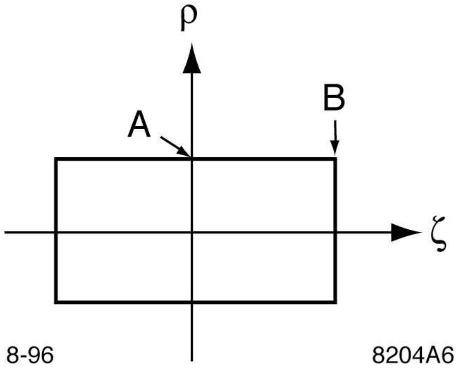
In reality cathode field (gun voltage) matters much more due to nonlinear space charge.

goal: 750 kV

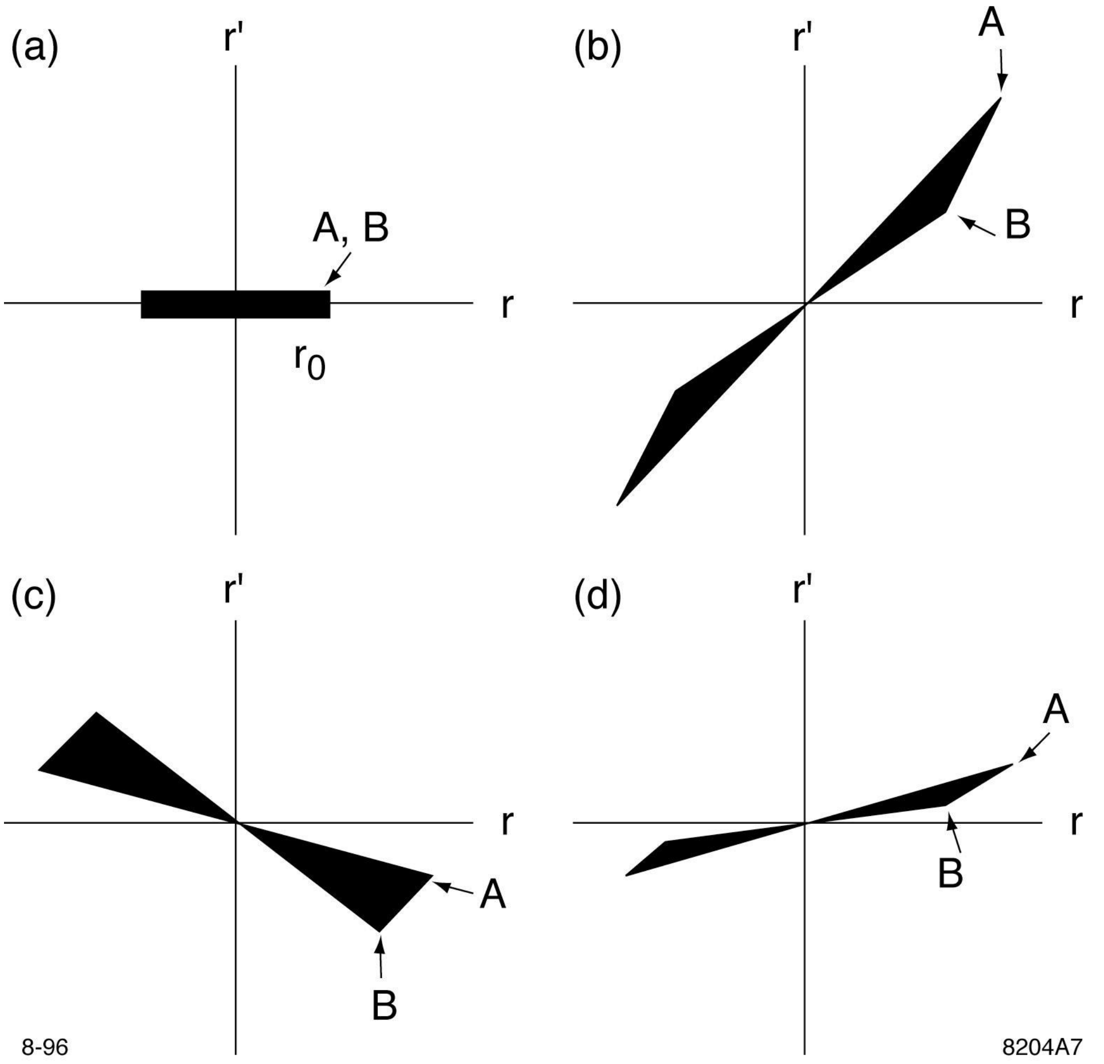
Emittance compensation



Axial cross section of bunch charge at cathode



Very sensitive on optics & bunch distribution details; Need computer modeling



Transverse phase space plots: (a) at cathode; (b) after drift; (c) after lens; (d) more drift

S.c. compensation concept

Serafini PRE **55**, 7565

$$\sigma'' + K_r\sigma = \frac{I}{2I_0(\beta\gamma)^3\sigma} + \cancel{\frac{\epsilon_{n,\mathrm{th}}^2}{(\beta\gamma)^2\sigma^3}}.$$

focusing s.c. ~~emittance~~

$$\epsilon_{n,\mathrm{th}}(\zeta) \equiv \frac{\beta\gamma}{2}\sqrt{\langle r^2\rangle_\zeta\langle r'^2\rangle_\zeta - \langle rr'\rangle_\zeta^2}$$

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

linearize

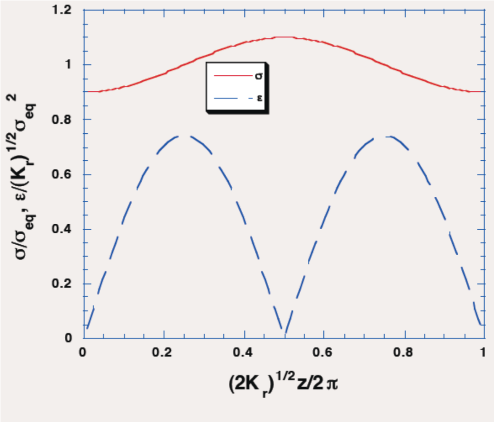
$$\sigma_{\mathrm{eq}}(g(\zeta)) = \left(\frac{Ig(\zeta)}{2I_0(\beta\gamma)^3K_r}\right)^{1/2}$$

equilibrium flow condition for slice

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

oscillation frequency current independent

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



Small amplitude oscillation model

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

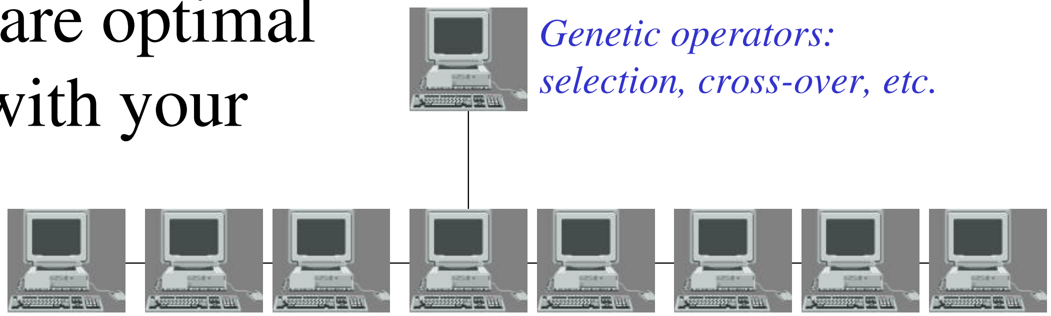
→

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

Multi***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



Master

Genetic operators: selection, cross-over, etc.

Slaves *Objectives evaluation*

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* $\exists m' \in 1, 2, \ldots, M : f_{m'}(\boldsymbol{x}_a) > f_{m'}(\boldsymbol{x}_b)$.

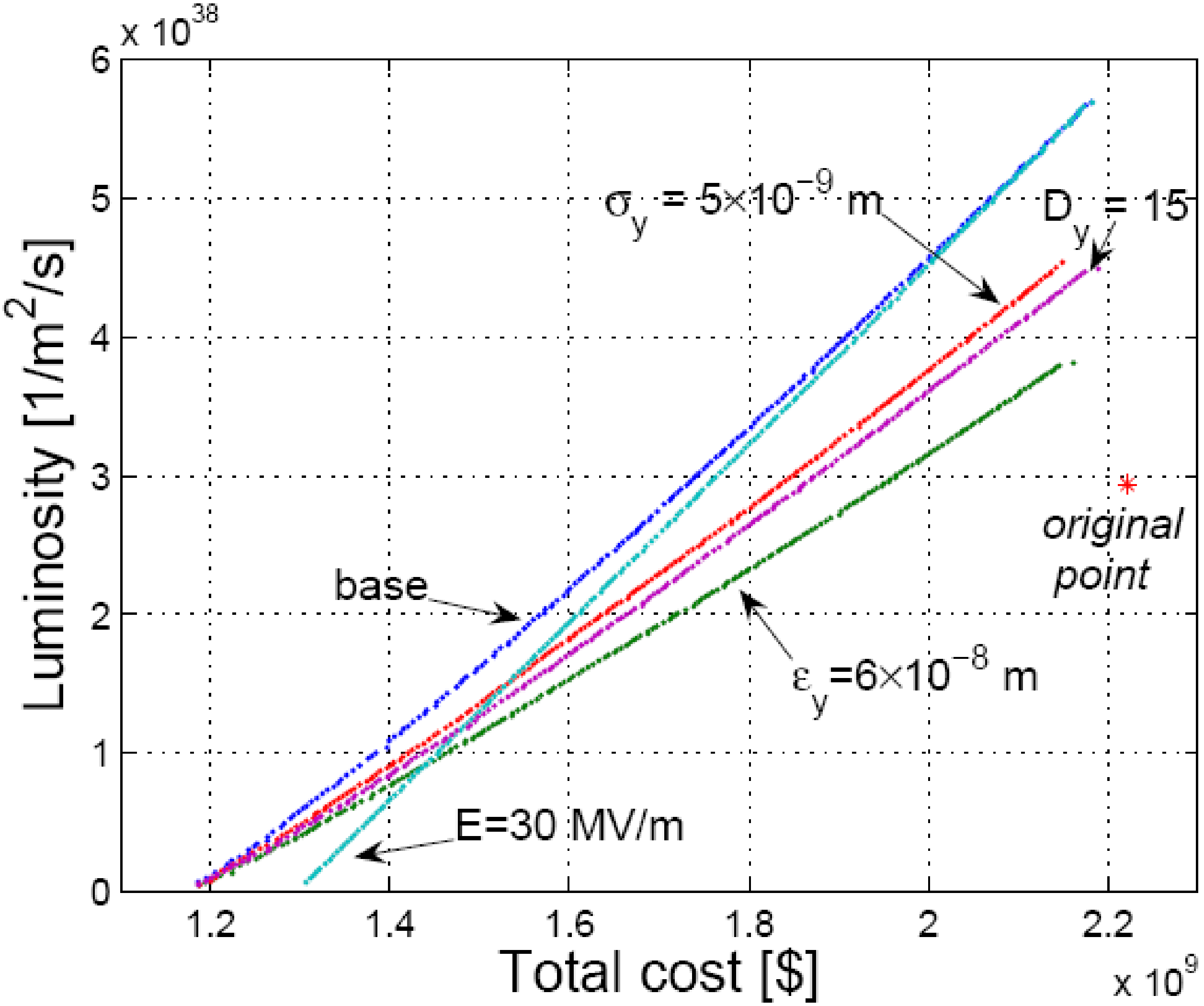
Definition 2. *Among a set of solutions $\mathcal{P}$, the nondominated subset of solutions $\mathcal{P}'$ are those that are not dominated by any member of the set $\mathcal{P}$.*

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

Vilfredo Pareto, 1848-1923

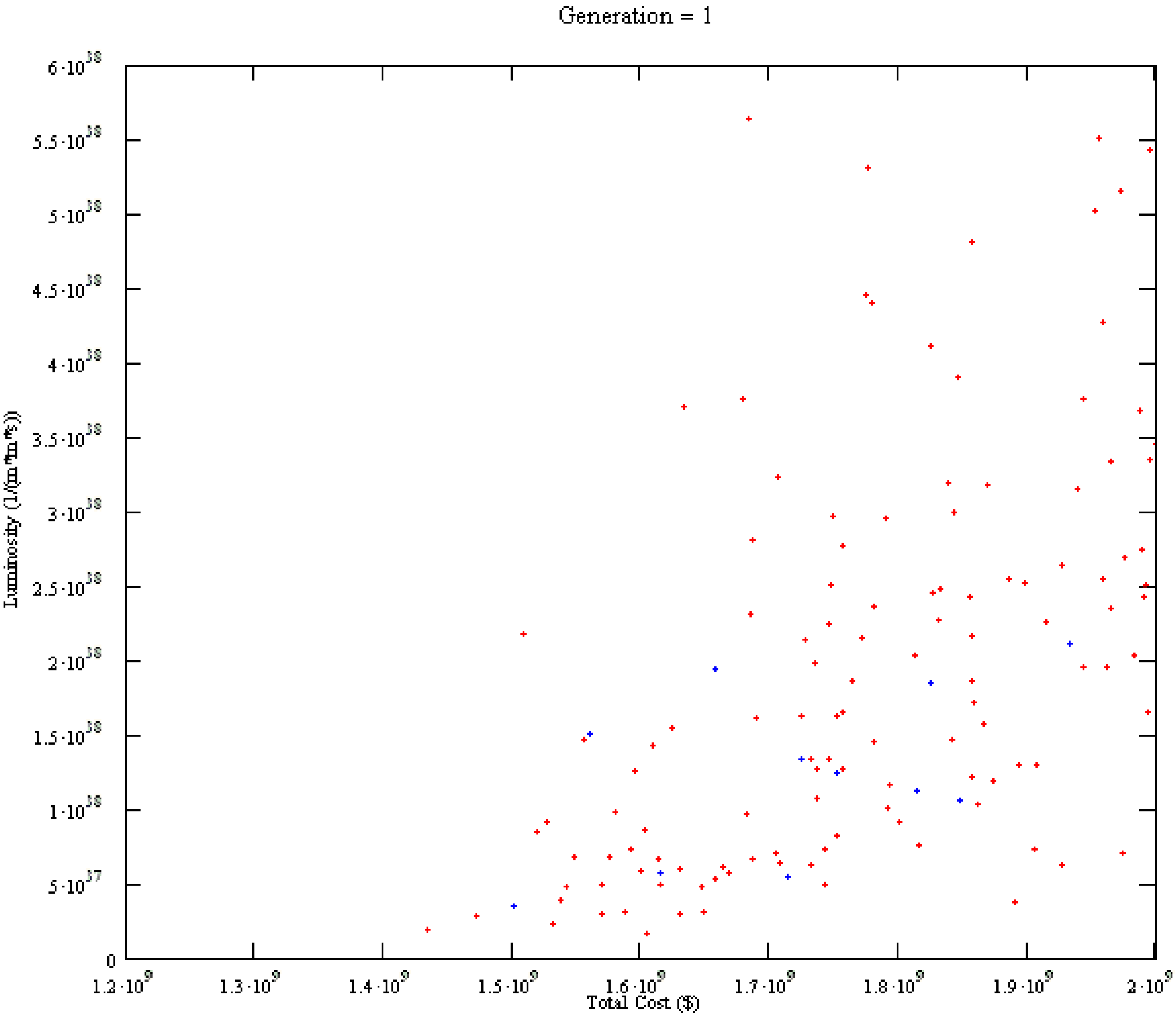
ILC linac optimal front

10 bounded decision variables, 10 constraints



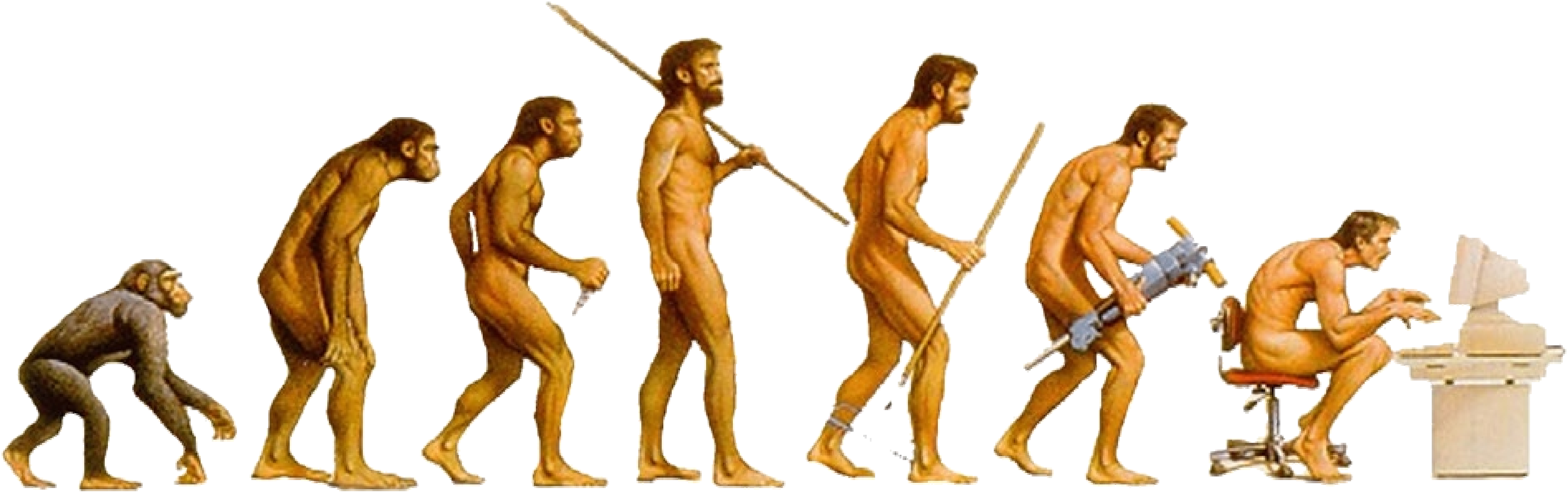
ILC linac optimization

maximize **Luminosity**



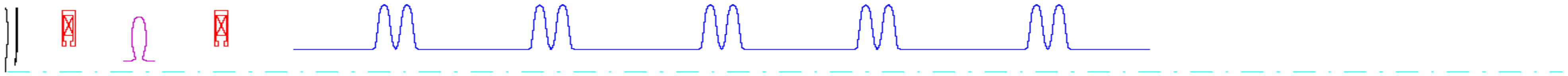
minimize **Total Cost**

Evolving into optimal injector design



Parallel Multiobjective Evolutionary Algorithm

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} × 2

Total: 22-24 dimensional parameter space to explore

Optimization results

Takes some 10^5 simulations

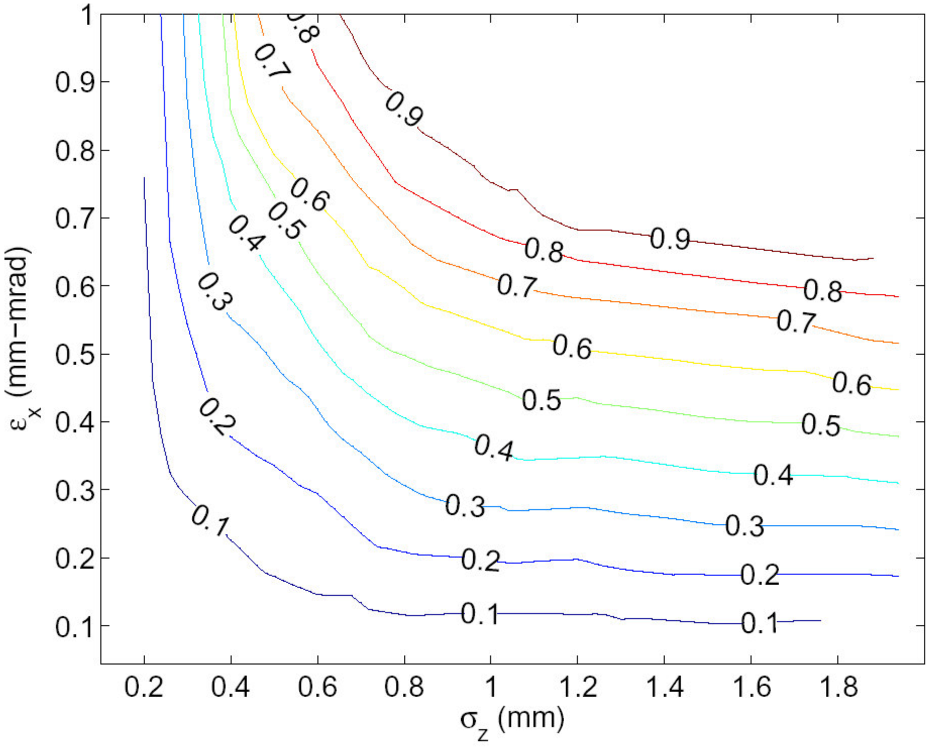


FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

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

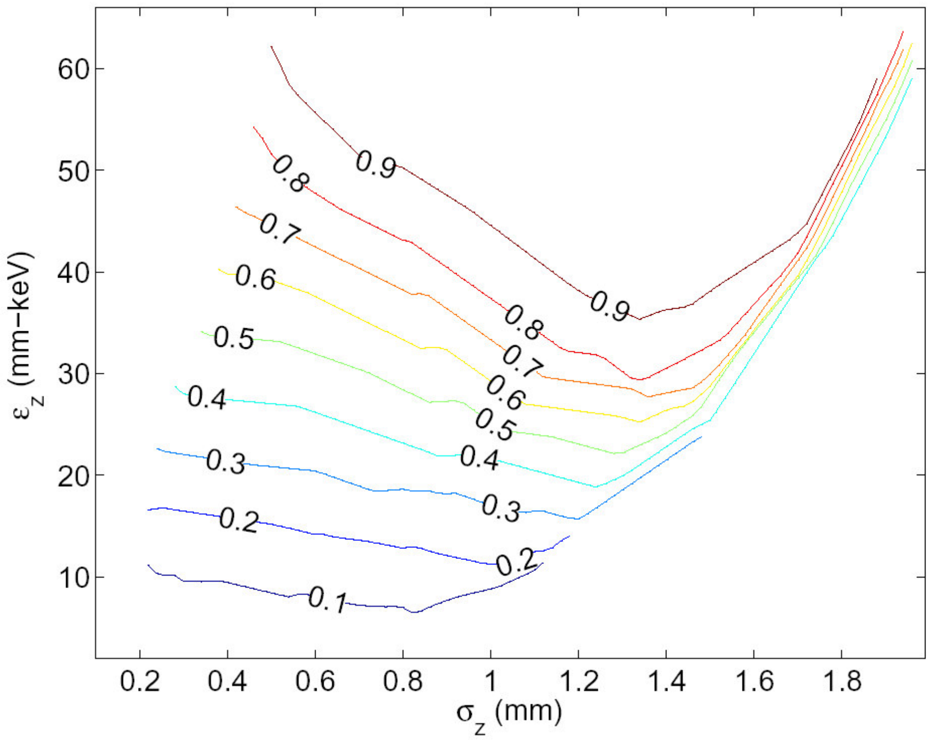
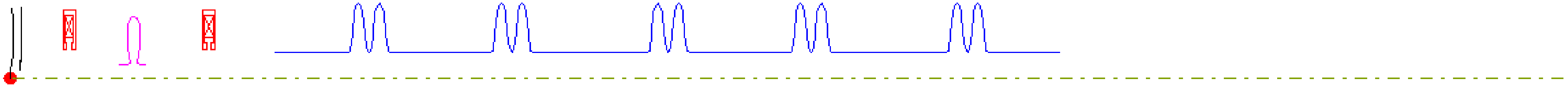
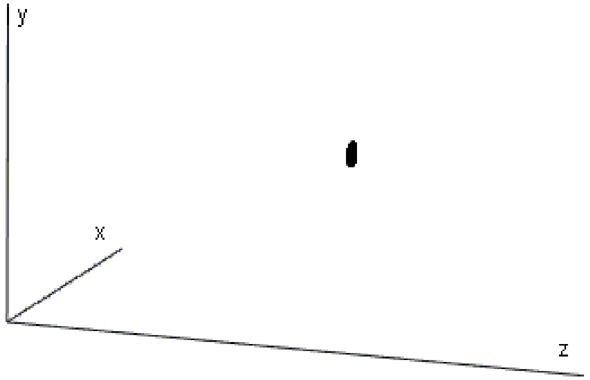


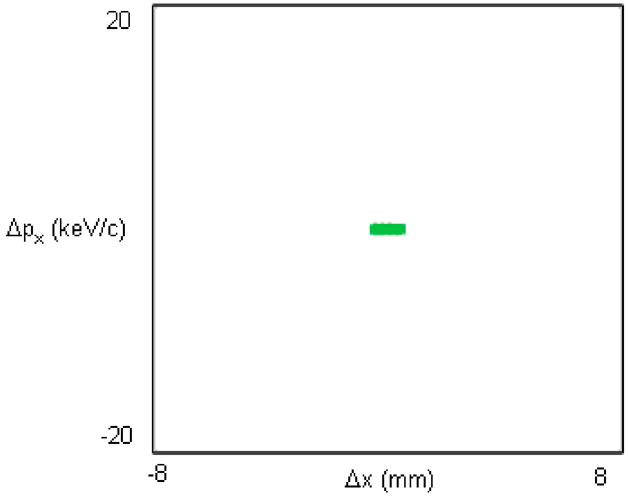
FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

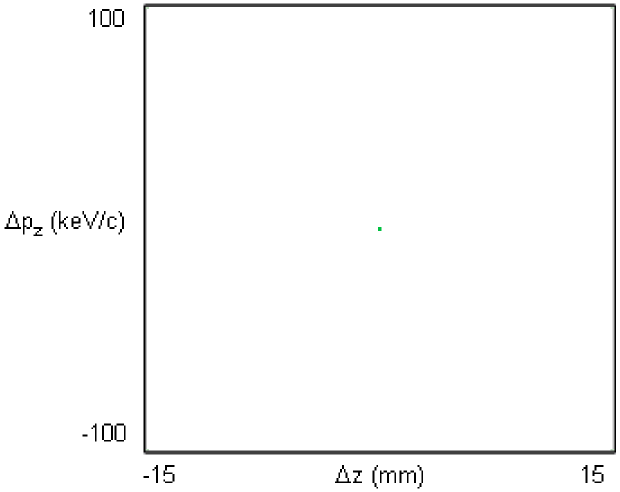
$$\text{MOO problem: } \begin{cases} \text{minimize emittance} \\ \text{minimize bunch length} \\ \text{maximize bunch charge} \end{cases}$$

Closer look: 80 pC







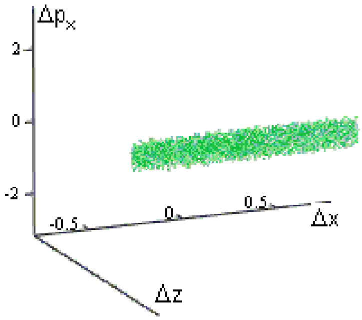


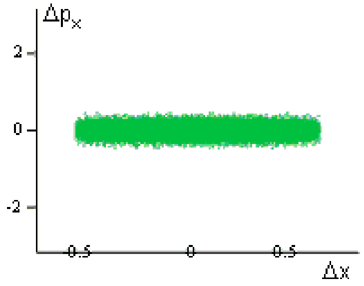
z = 0.000 m

p_z = 0.000 MeV/c

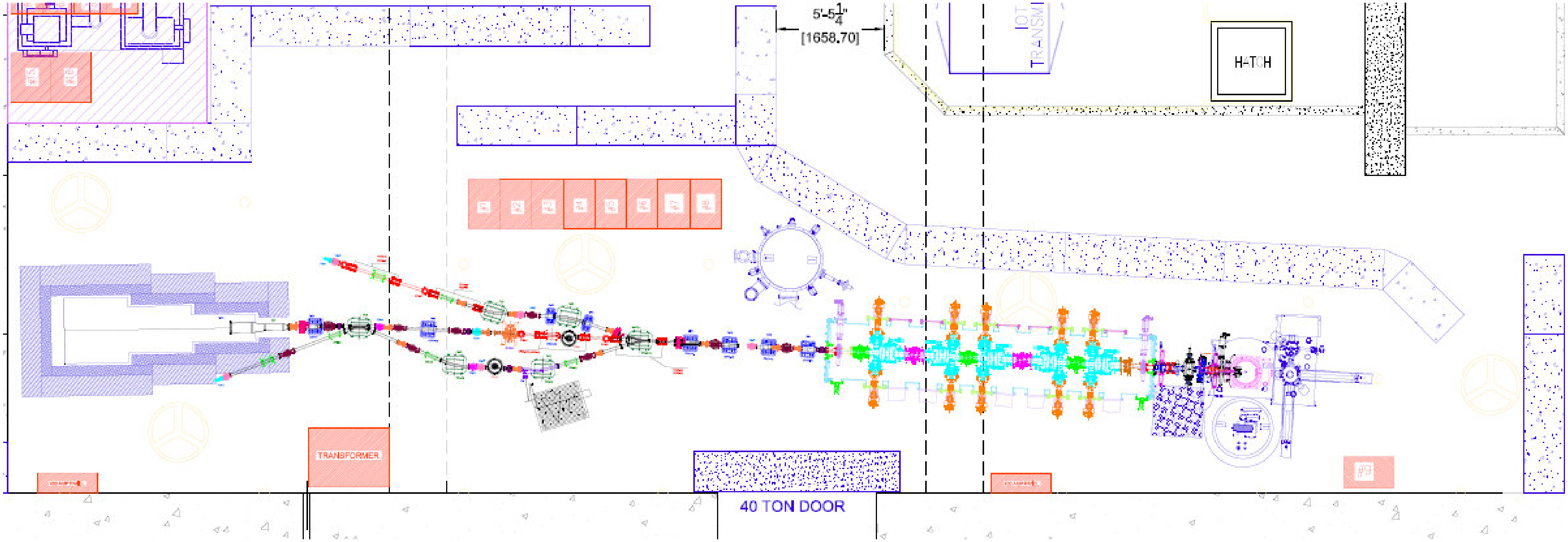
σ_x = 0.294 mm ε_x = 0.077 mm-mrad

σ_z = 0.000 mm ε_z = 0.000 mm-keV



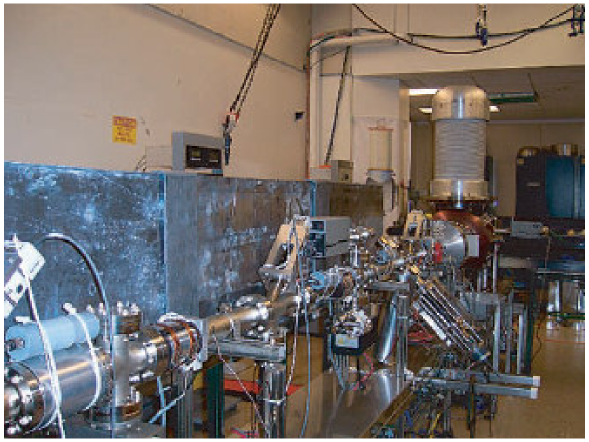


ERL Phase1a



- HV DC gun based photoinjector
- max **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%**

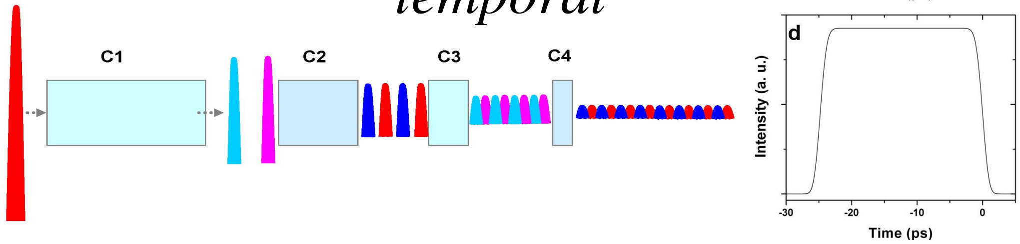
Challenges



- Achieve gun voltage of ≥ 500 kV
- Demonstrate photocathode longevity
- Cleanly couple 0.5 MW RF power into the beam without affecting its transverse emit.
- Control non-linear beam dynamics: over a dozen of sensitive parameters that need to be set ***just right*** to achieve the highest brightness
- Instrumentation and tune-up strategy
- Drive laser profile programming (both temporal and spatial)

spatial

temporal

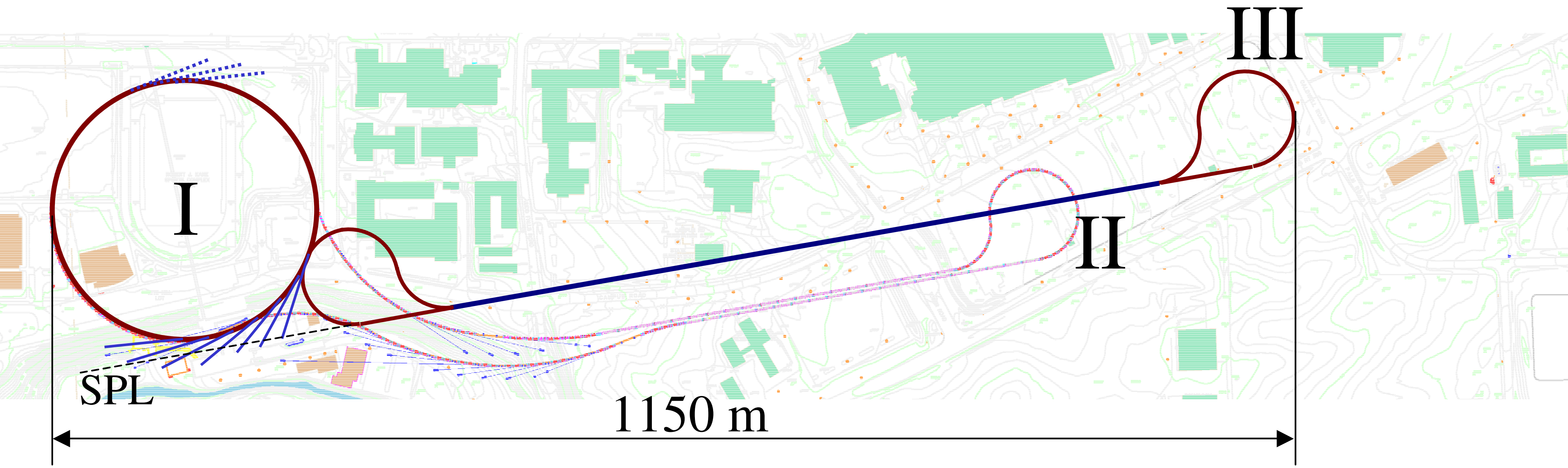


A bigger picture

Mission

- Maintain vibrant/***diverse*** acc. physics program
- Provide ***world-class x-rays*** to CHESS users
- Future light source and new accel. technology ***development***

3-staged approach to ERL



I – upgrade to CESR to put CHESS on the synch. rad. science frontier

II – 5 GeV SRF linac with 10’s fs pulse capability & XFEL friendly

III – diffraction-limited ERL once injector performance is established

More Goliaths on the way

ERL's **cost**
Wall plug **power** required

MUST be brought down!

M. Tigner, "*Does accelerator-based particle physics have a future?*", Physics Today **54** p 36, 2001:

> …Let me put it baldly and simplistically: If the cost of the ill-fated Superconducting Super Collider had been on the order of $1 billion rather than many times that sum, it might well not have been canceled. If the cost of CERN's Large Hadron Collider (LHC), scheduled for completion in 2005, were only of order $1 billion, it might well have been completed by now. If any of the TeV electron-positron linear collider schemes now being studied around the world could be built for something like $1 billion, one or more of them might already be under construction.

Summary

- Birth pains abound but the ‘baby’ has not arrived yet: “Mission Accomplished” when the injector delivers 100 mA, $\varepsilon_{xn} \sim 1\ \mu\text{m}$ (shooting for the end of 2008)
- Future light source at CU is by no means secured; success will require the talents in the lab to come together in unprecedented way
- The adventure continues, so stay tuned…

Thank you!

Backup slides

Contributors to emittance

- 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

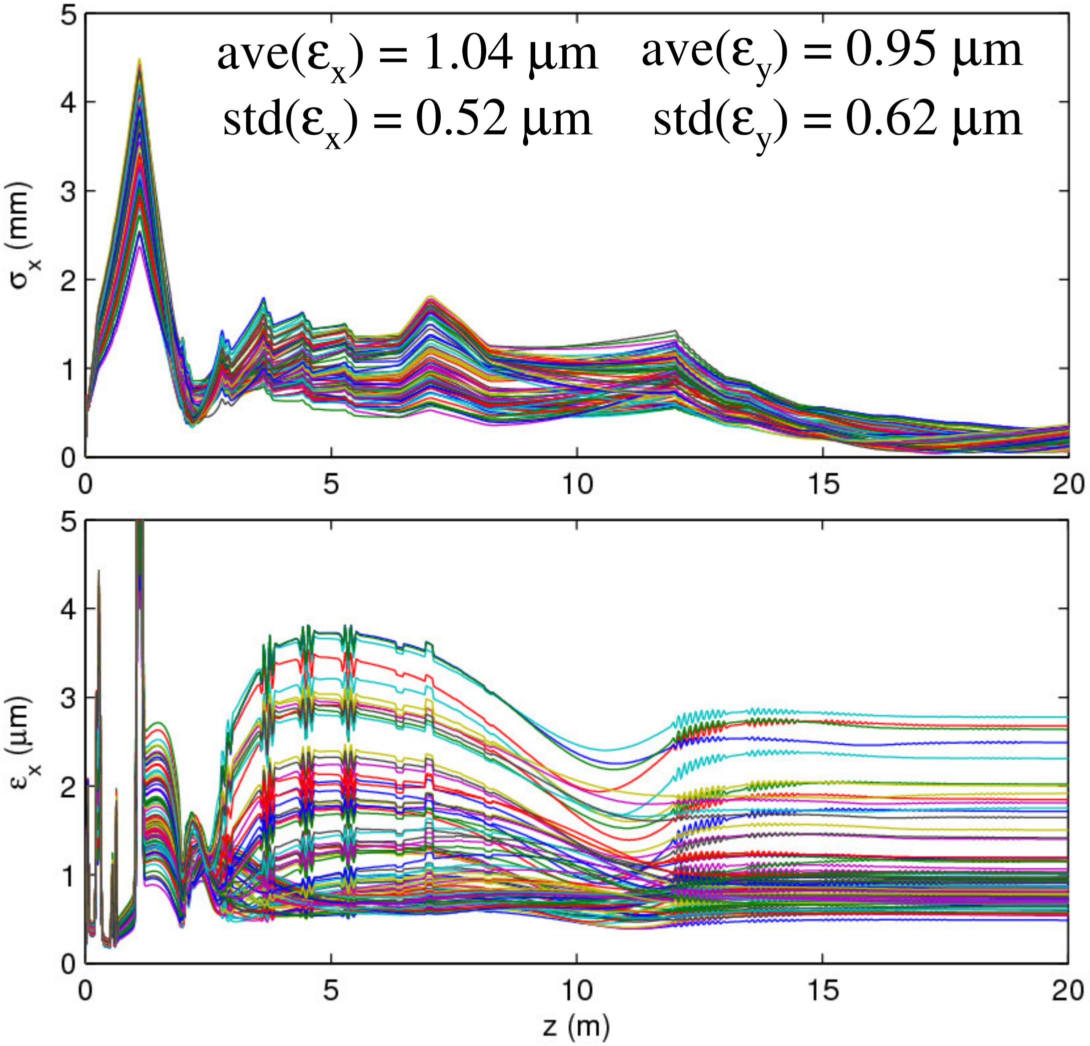
🟥 helps here, may harm elsewhere

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

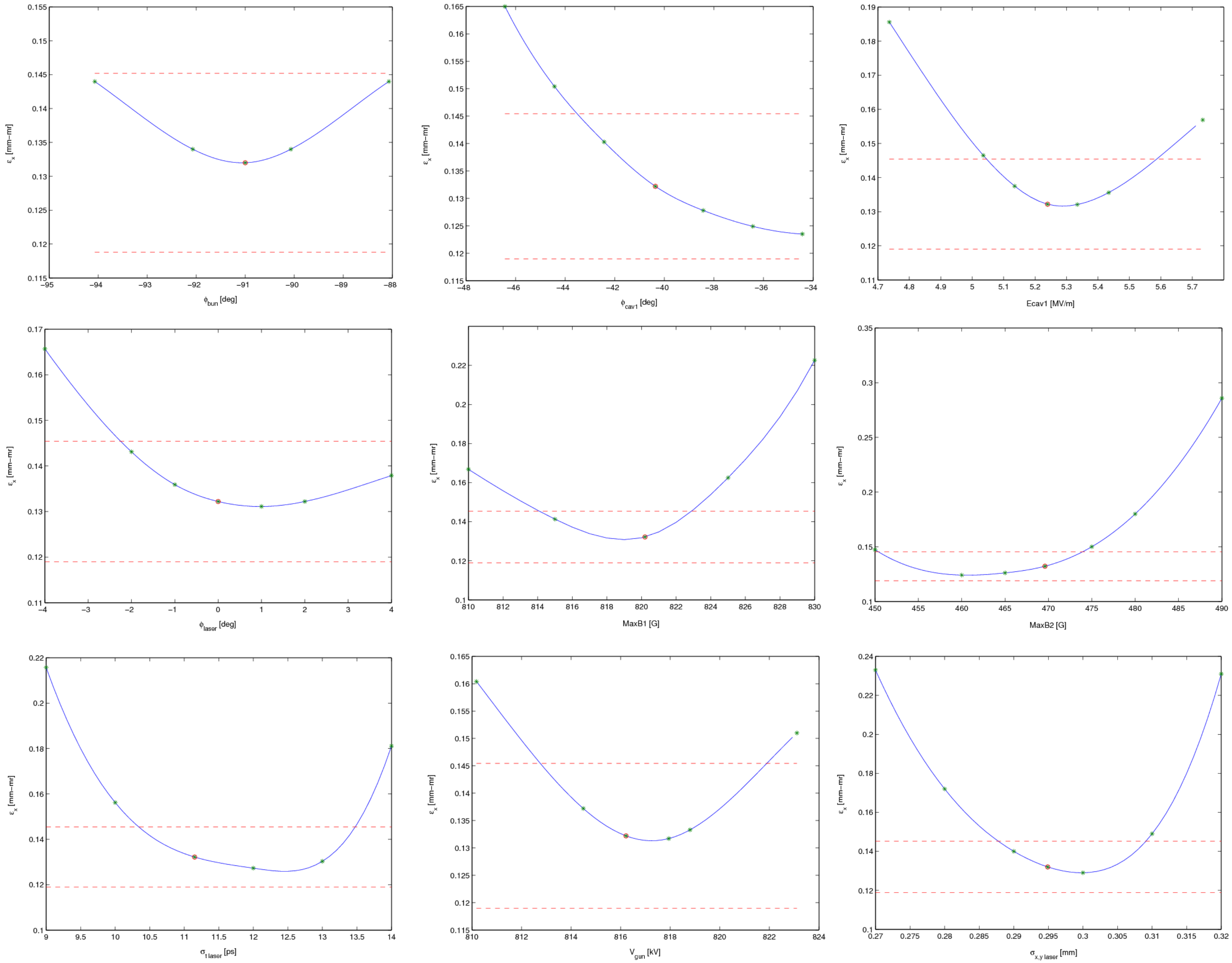
100 random seeds (outliers removed)



ave(ε_x) = 1.04 μm ave(ε_y) = 0.95 μm

std(ε_x) = 0.52 μm std(ε_y) = 0.62 μm

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%