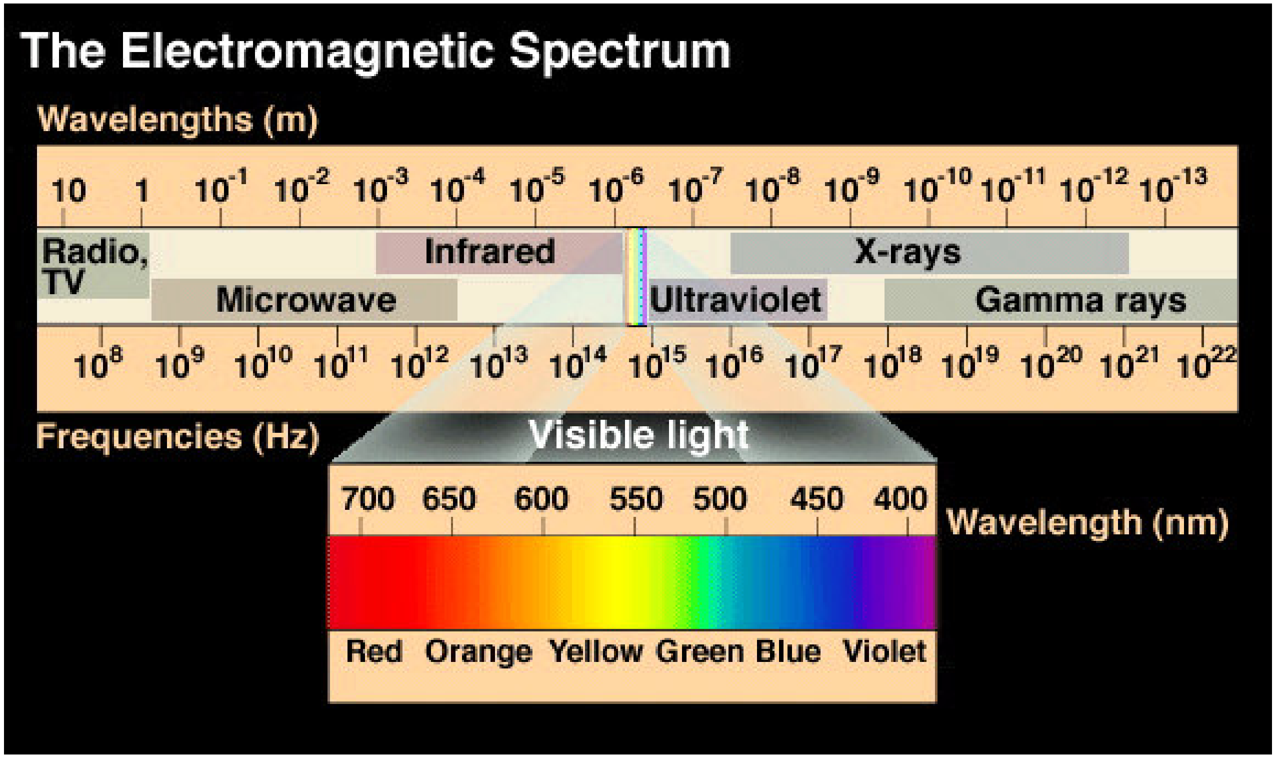
Linac-based light sources

Ivan Bazarov
Cornell University

Talking points

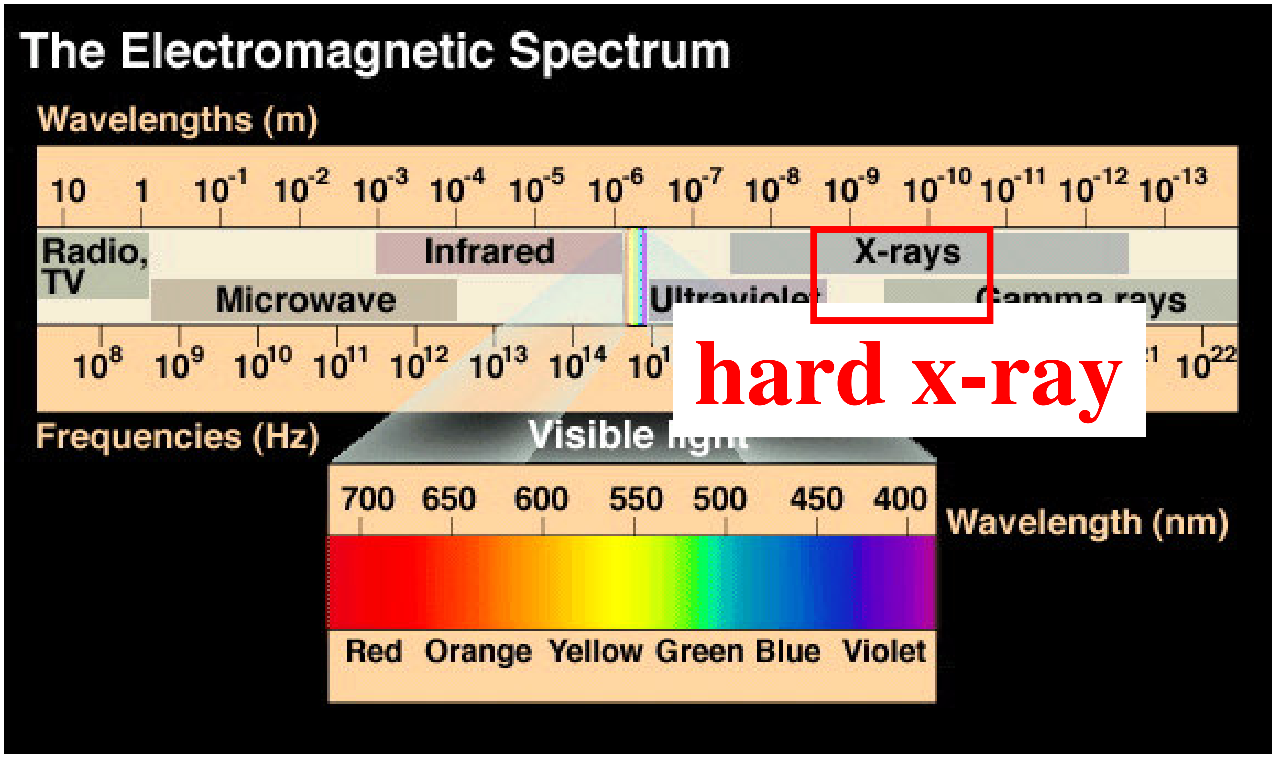
- Synchrotron radiation sources of today
- Motivation for a linac based source
- Physics of high-brightness electron injectors
- Energy Recovery Linac (ERL) Phase 1
- Summary

Free e^- as medium



- Relativistic free electrons – the only medium for tunable light production in widest spectral range
- Hard x-ray range is the subject of this talk

Free e^- as medium



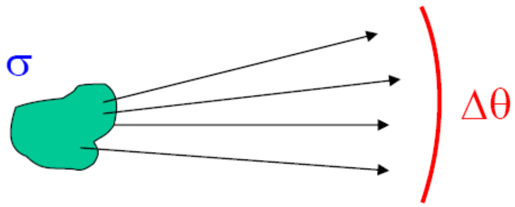
- Relativistic free electrons – the only medium for tunable light production in widest spectral range
- Hard x-ray range is the subject of this talk

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

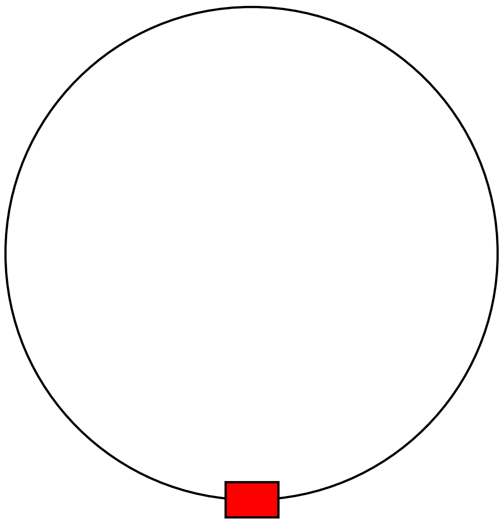
$$F_c = B_{avg}\left(\frac{\lambda}{2}\right)^2$$

- **Peak brightness:** proportional to the number of photons per coherence volume ≡ the photon degeneracy

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

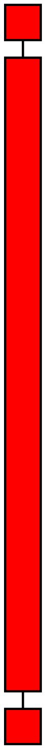
SR/XFEL/ERL

SR



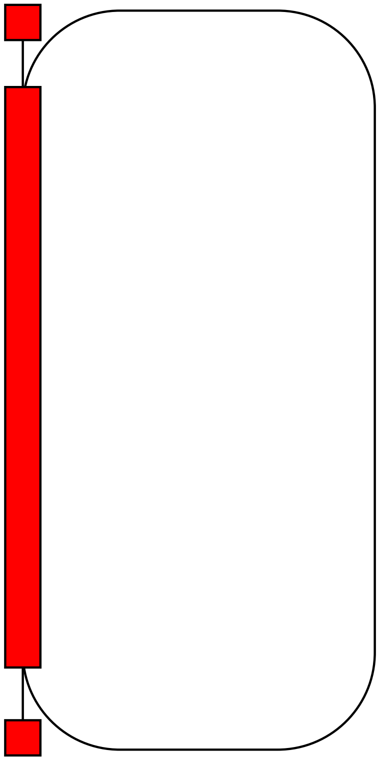
- efficient
- avg. brightness
- workhorse technology

XFEL



- peak brightness
- short pulse
- new user-base

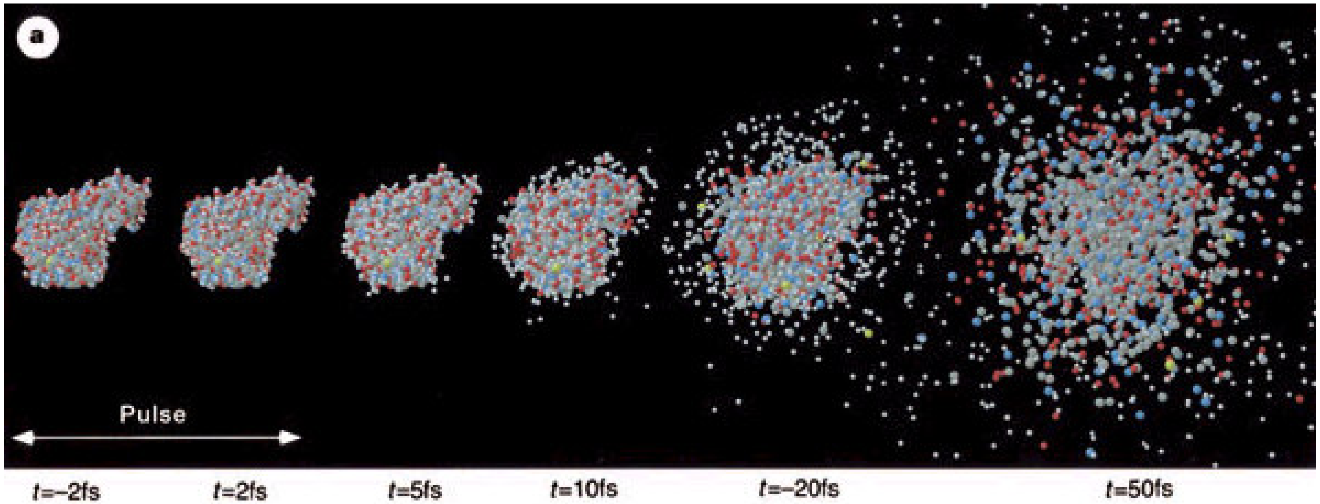
ERL



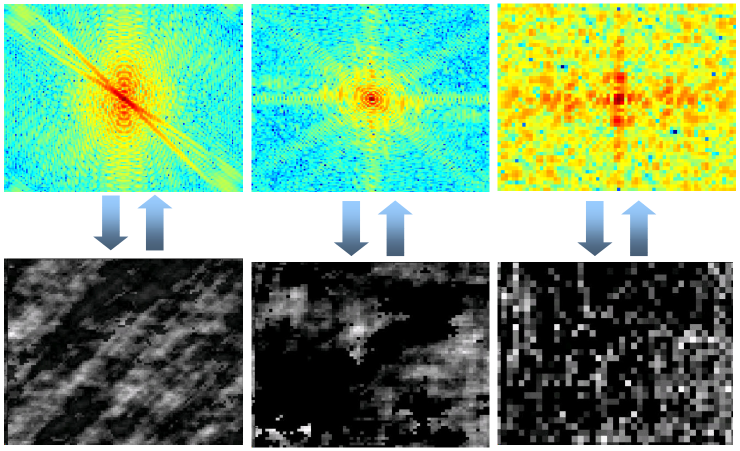
- avg. brightness
- existing user-base
- XFEL as a subset
- short pulse

Exp1: diff. imaging of proteins

R. Neutze, et al., *Nature*, **406**, 752 (2000)



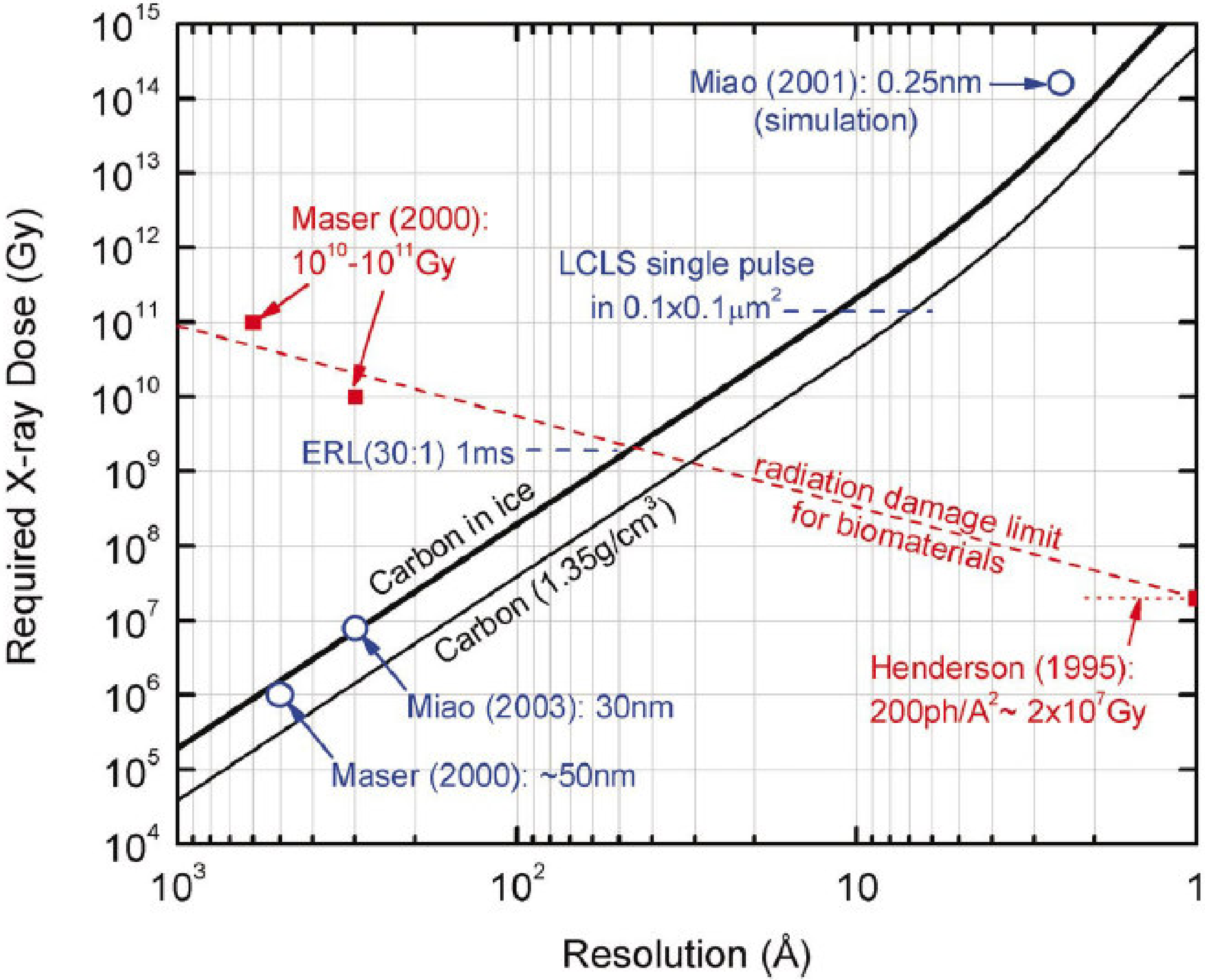
Fienup's algorithm



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: coherent x-rays

Radiation damage: biomaterials

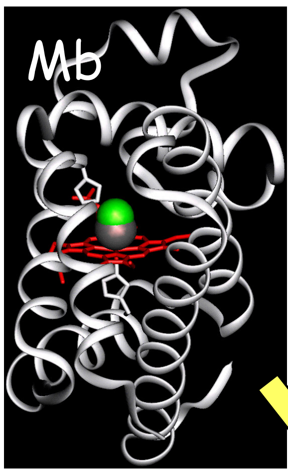


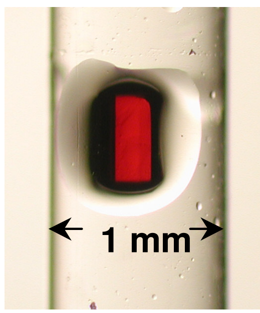
Shen, Bazarov, Thibault, J. Sync. Rad., Vol. 11 (2004) 432

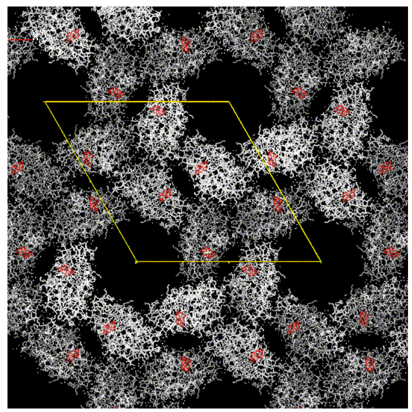
Exp2: fs chem. reaction movie

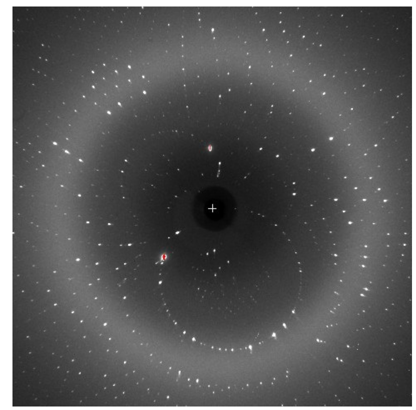
Broad class of pump-probe experiments providing structural (core e$^-$'s) conformational changes in the initial stages (mol. vibrational timescale 10's fs) of photo-induced reactions

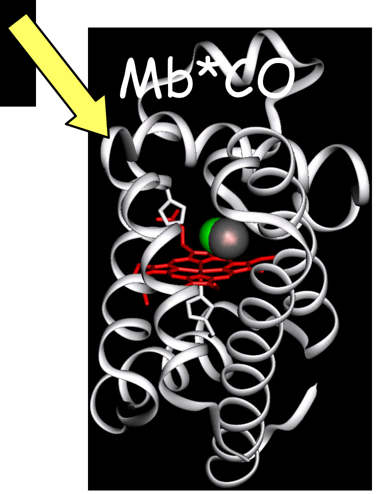
Time-resolved Laue Crystallography (Phil Anfinrud, NIH)

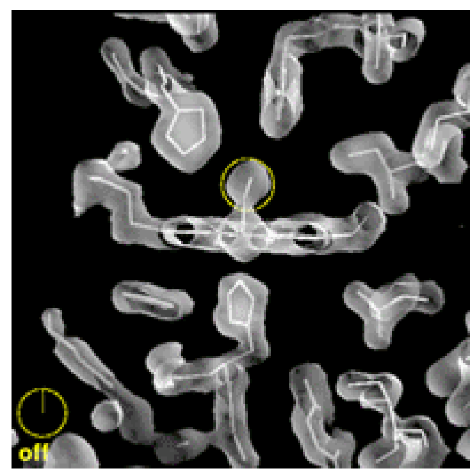






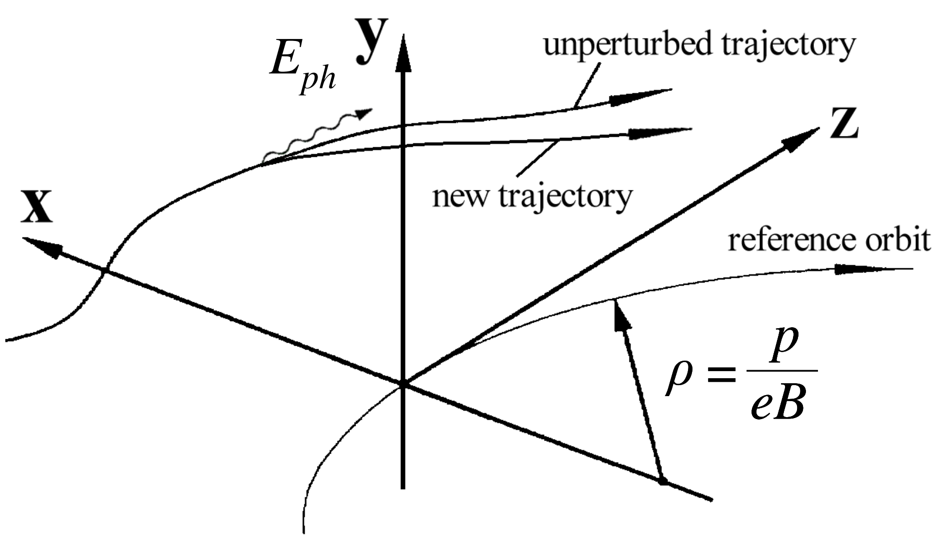


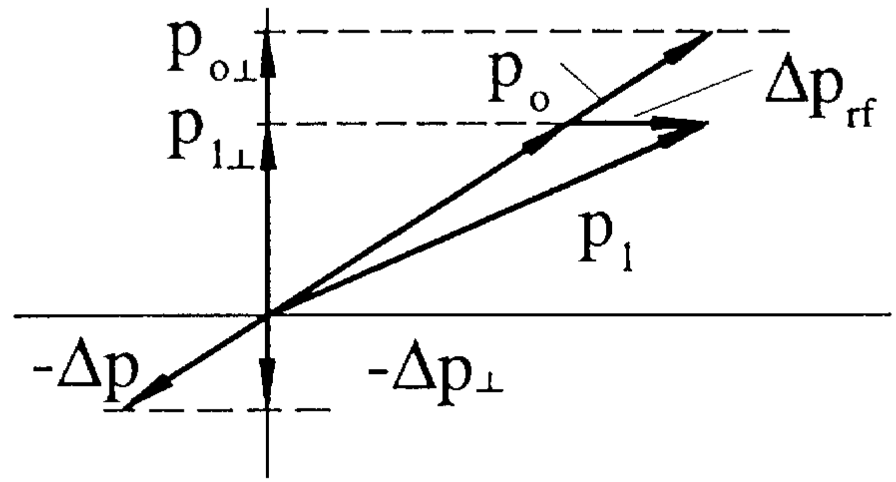




Equilibrium

Quantum Excitation **vs.** Radiative Damping





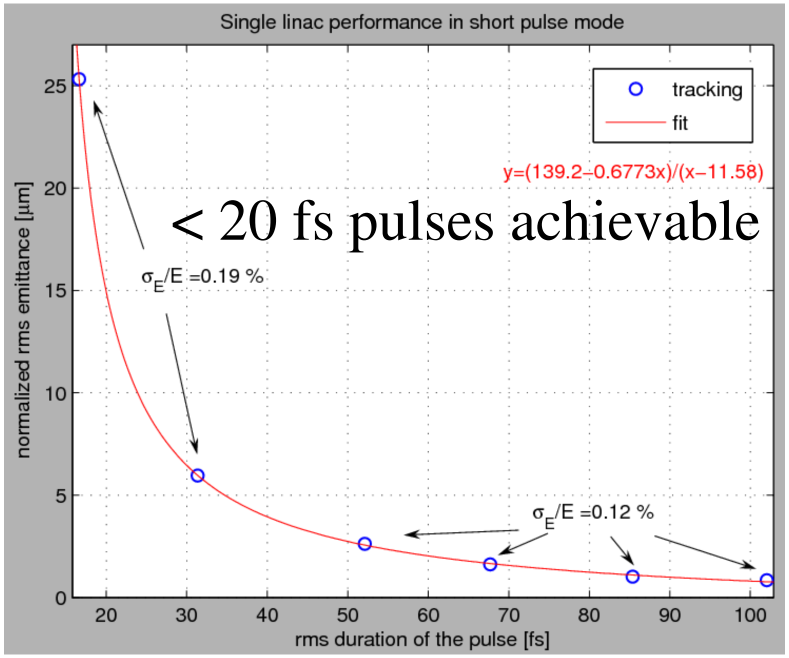
$$\frac{d\sigma_E^2}{dt} \sim \dot{N}_{ph} E_{ph}^2$$

Emittance (hor.), Energy Spread, Bunch Length

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

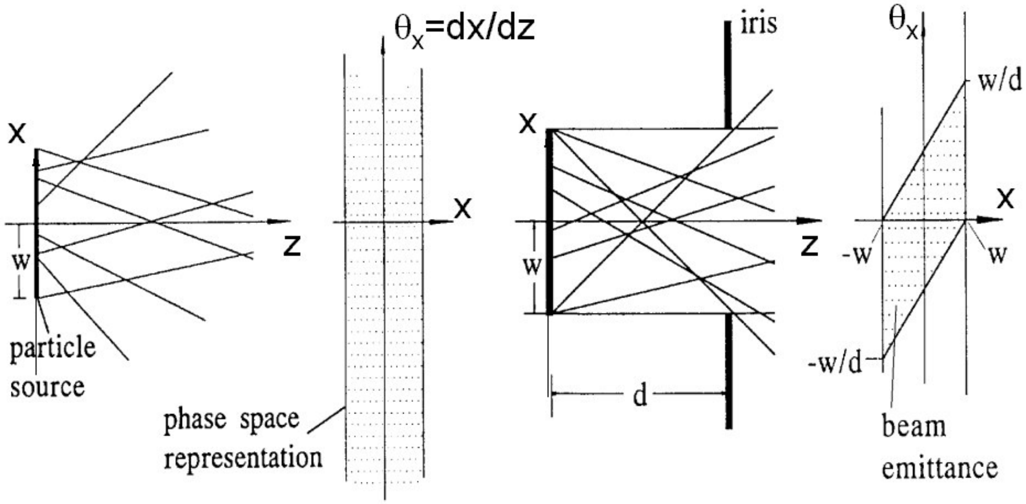
Why linac?

- Beam never in equilibrium – 6D phase space (x,p_x,y,p_y,E,t) defined by the electron source
- Longitudinal phase space (E,t) “gymnastics”: exchange momentum spread for shorter bunches (3 orders of magnitude)
- ‘Colder’ intense beams (transverse coherence)



Emittance basics

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

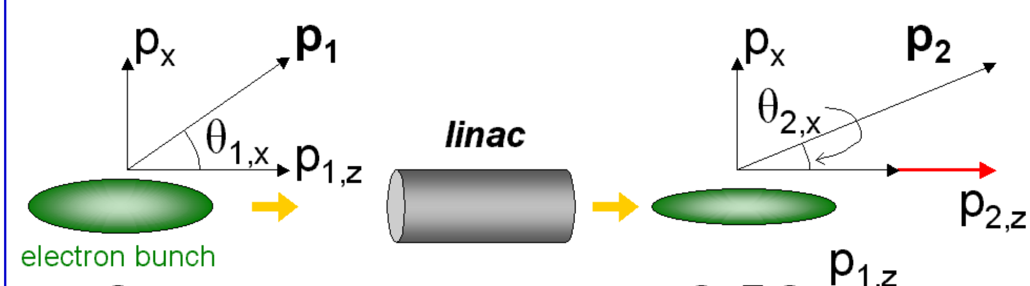


Liouville's Theorem: phase space volume is "incompressible fluid"

What exactly is emittance?
(2D projected)

E.g. rms emittance of laser Gaussian beam
$\varepsilon = \lambda/4\pi$ *(diffraction limit)*

"Adiabatic damping"
of geometric emittance



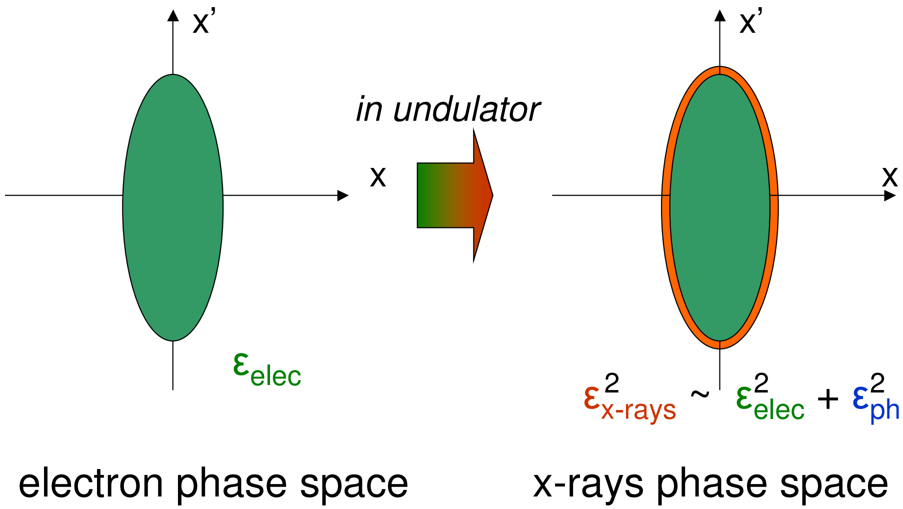
$$\varepsilon_2 = \varepsilon_1 \frac{p_{1,z}}{p_{2,z}}$$

geometric $\{x, \theta_x\}$ — $\varepsilon = \dfrac{\varepsilon_n}{\beta\gamma}$ — normalized $\{x, \dfrac{p_x}{mc^2}\}$

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

Diffraction limited e-beam

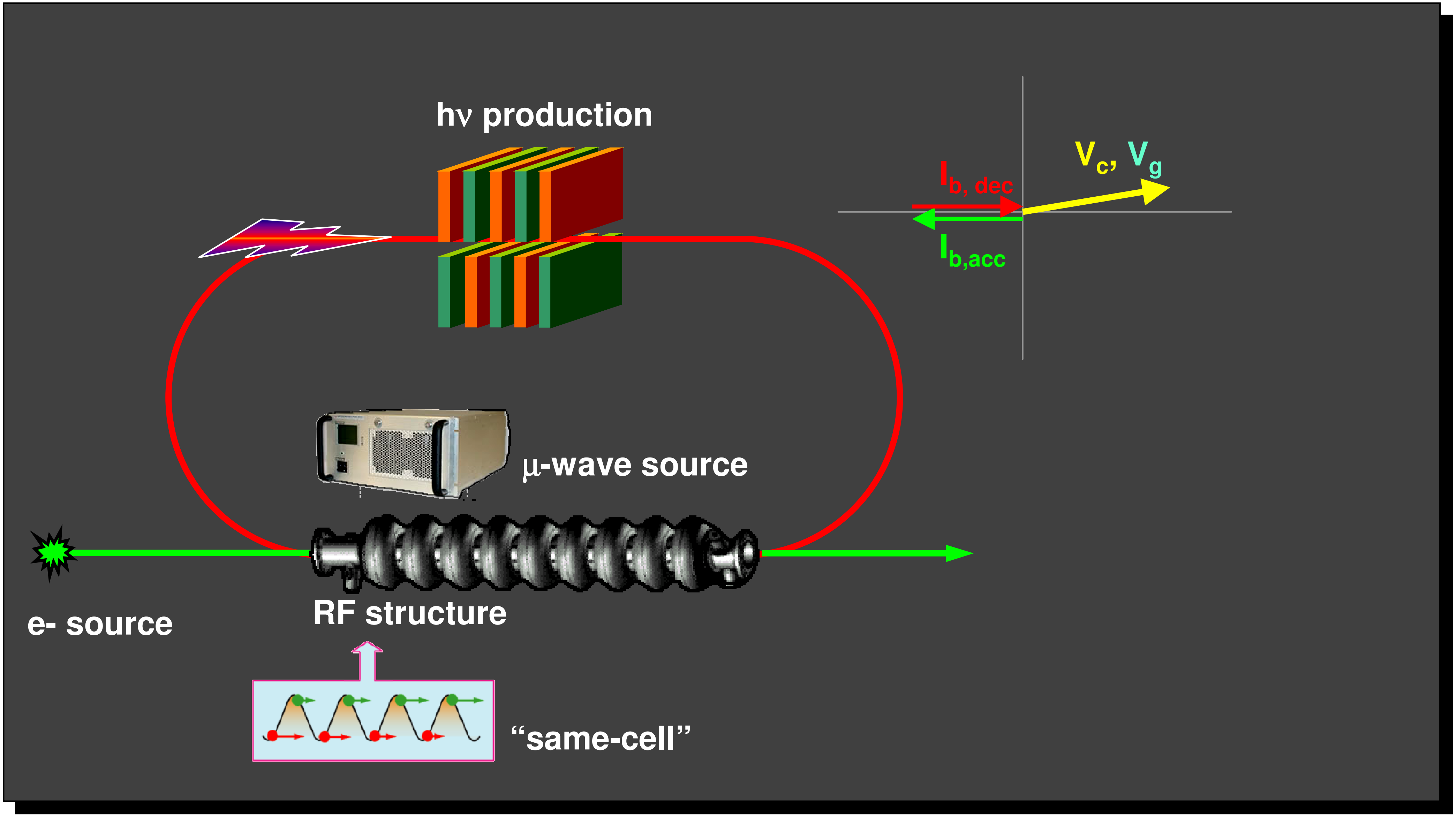
- In properly tuned undulator x-ray phase space is convolution of e-beam with diff. limit



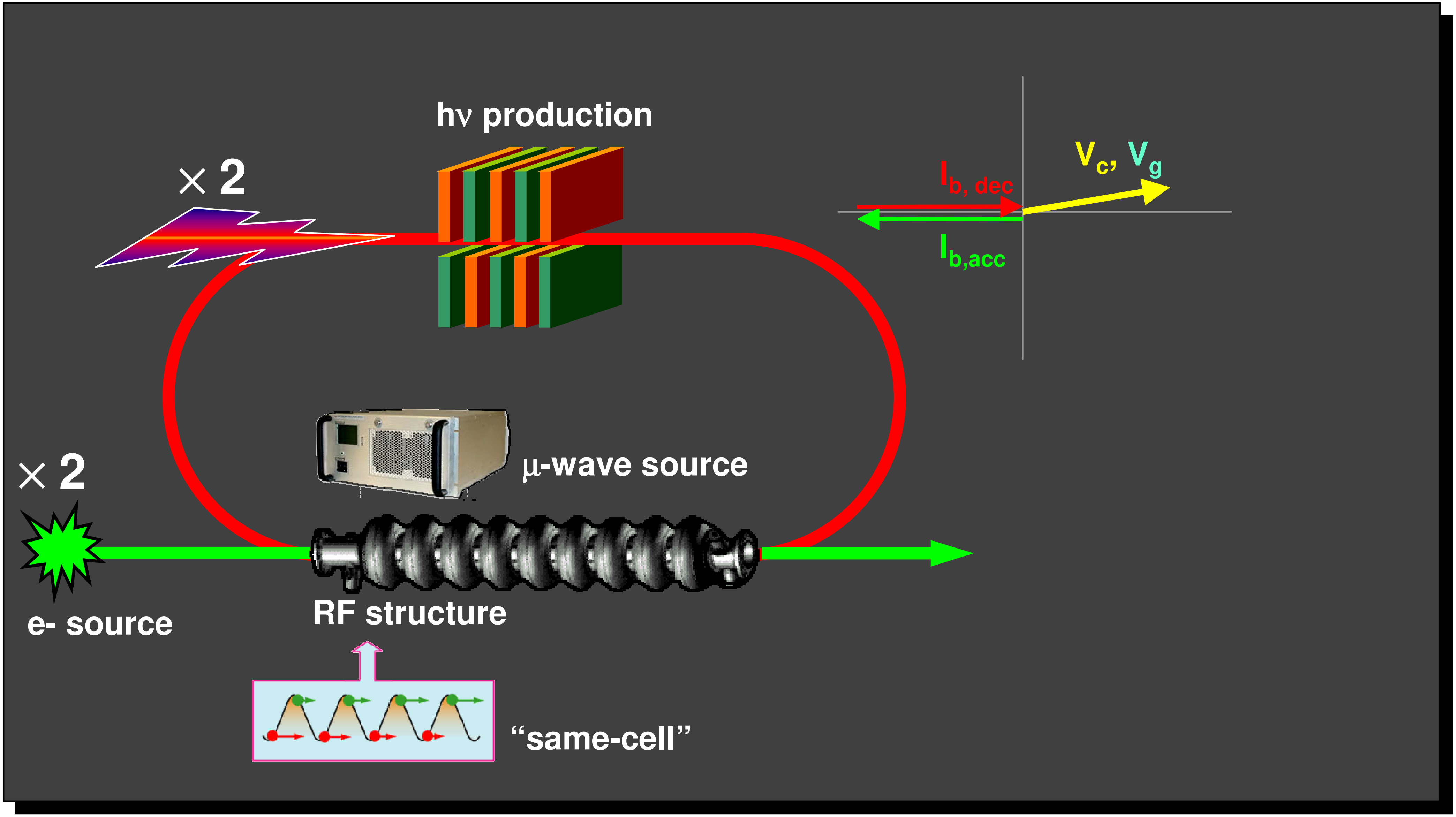
- **Goal**: for 1 Angstrom → $\varepsilon_x \sim \lambda/4\pi = 8$ pm geometric, or $\varepsilon_{nx} = 0.08$ μm if energy is 5GeV

- E.g. best storage ring performance as of today: $\varepsilon_x / \varepsilon_y = 3000 / 15$ pm

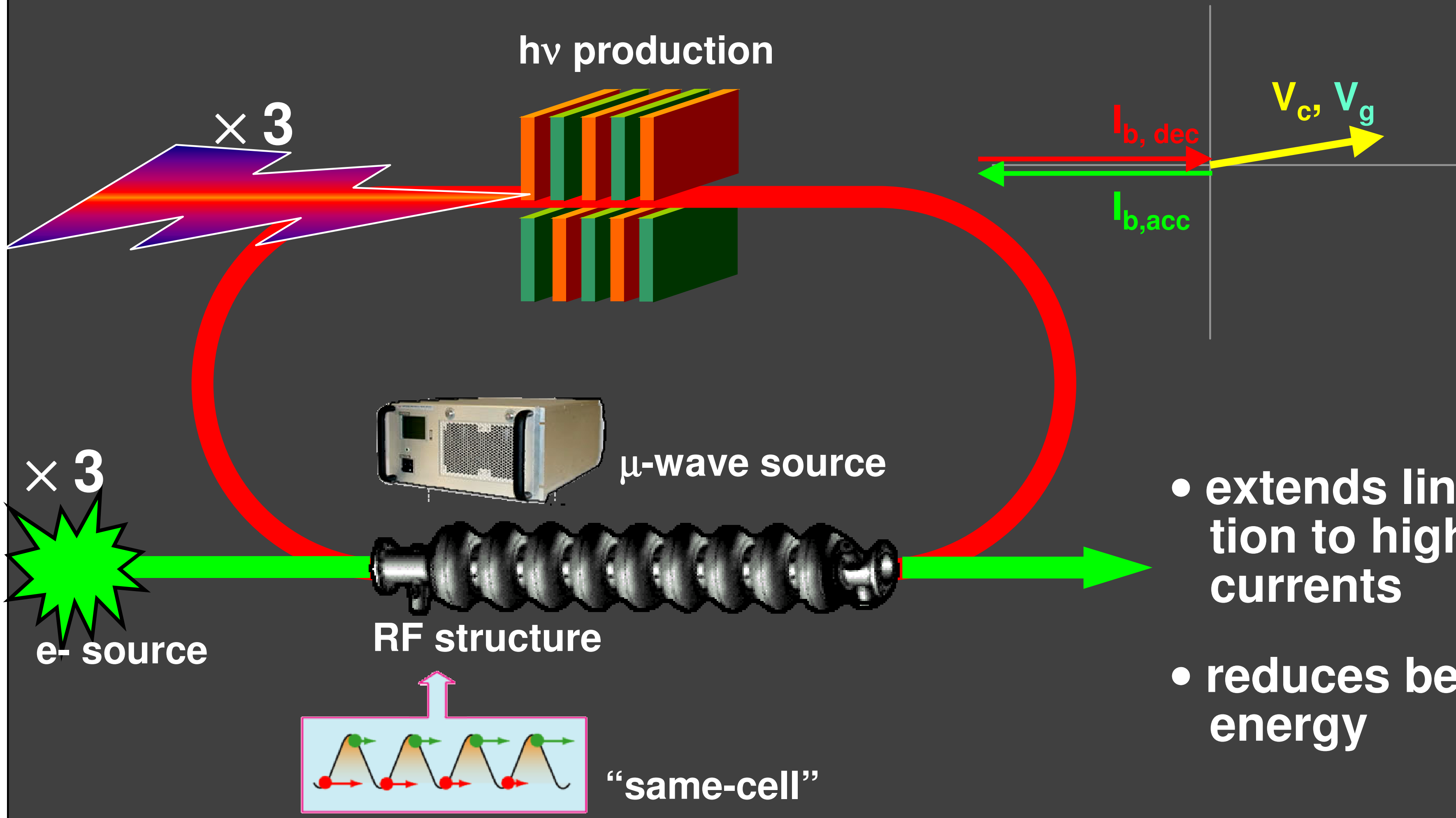
Energy recovery concept



Energy recovery concept



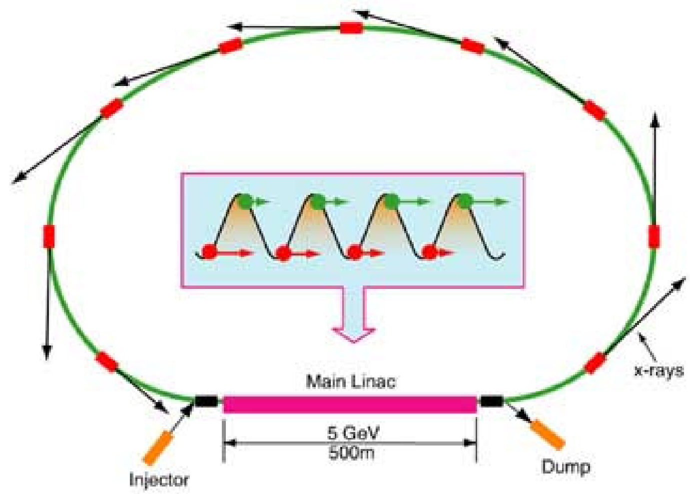
Energy recovery concept



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

ERL: e-source limited

$$\frac{I}{(\varepsilon_x + \lambda / 4\pi)(\varepsilon_y + \lambda / 4\pi)}$$



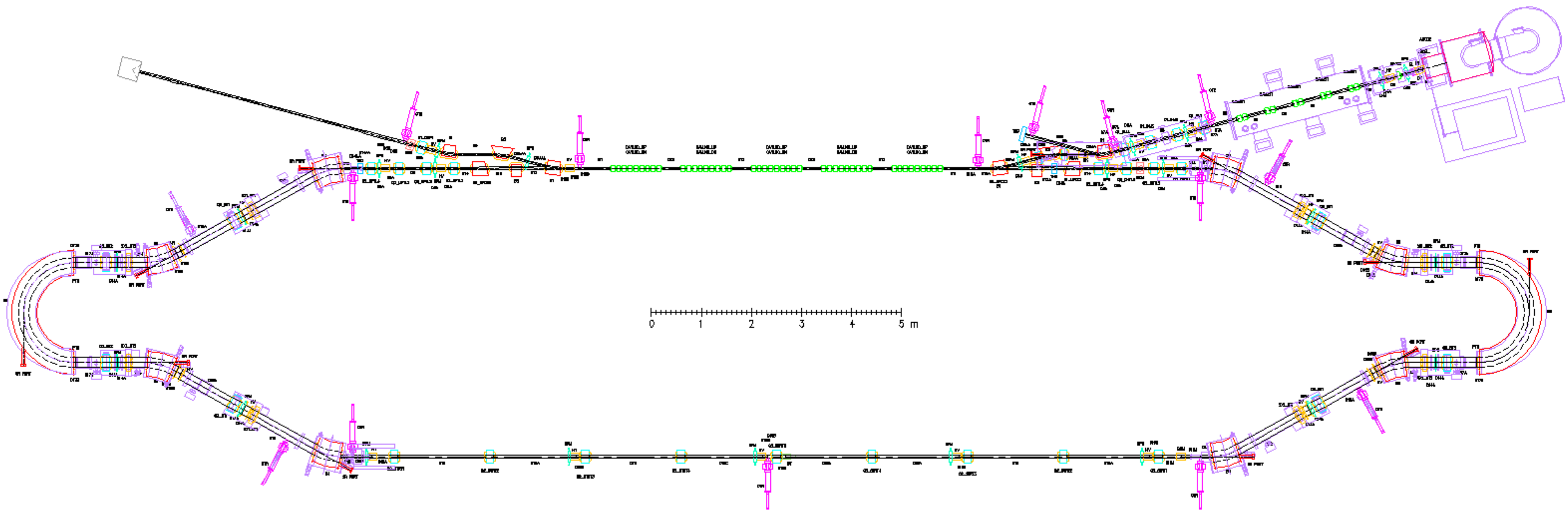
- E.g. ESRF I_{avg} = 200 mA, $\varepsilon_{x,y}$ = 4 nm / 0.02 nm

- ERL I_{avg} = 100 mA, $\varepsilon_{x,y}$ = 0.1 nm ($\varepsilon_{nx,y}$ = 1 µm if 5GeV) is superior + bonus short bunches

Caveat: state-of-the-art in high brightness injectors $I_{avg} \leq 10$ mA; $\varepsilon_n \geq 10$ µm ($\varepsilon_n \sim 2$ µm for pulsed)

Overall missing ≥ 3 orders of magnitude in beam brightness

ERL Phase1

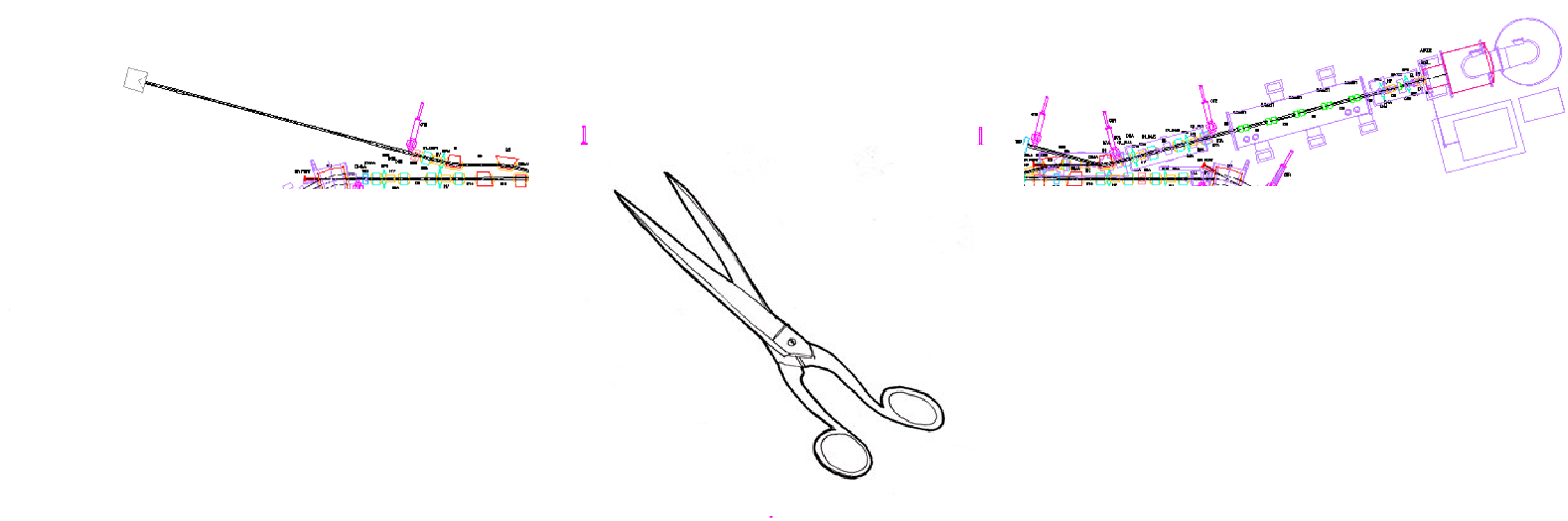


ERL PROTOTYPE

Energy	**100 MeV**	**Injection Energy**	**5 – 15 MeV**
Max Avg. Current	**100 mA**	**E_{acc} @ Q_0**	**20 MeV/m @ 10^{10}**
Charge / bunch	**1 – 400 pC**	**Bunch Length**	**2 – 0.1 ps**
Emittance (norm.)	**≤ 2 μm@77 pC**		

***Eds. Gruner, Tigner*; Bazarov, Belomestnykh, Bilderback, Finkelstein, Fontes, Krafft, Merminga, Padamsee, Shen, Rogers, Sinclair, Talman, ERL prototype proposal to the NSF, 2001**

ERL Phase ~~1~~ 1a



ERL PROTOTYPE

Injection Energy 5 – 15 MeV

Max Avg. Current 100 mA

Charge / bunch 1 – 400 pC

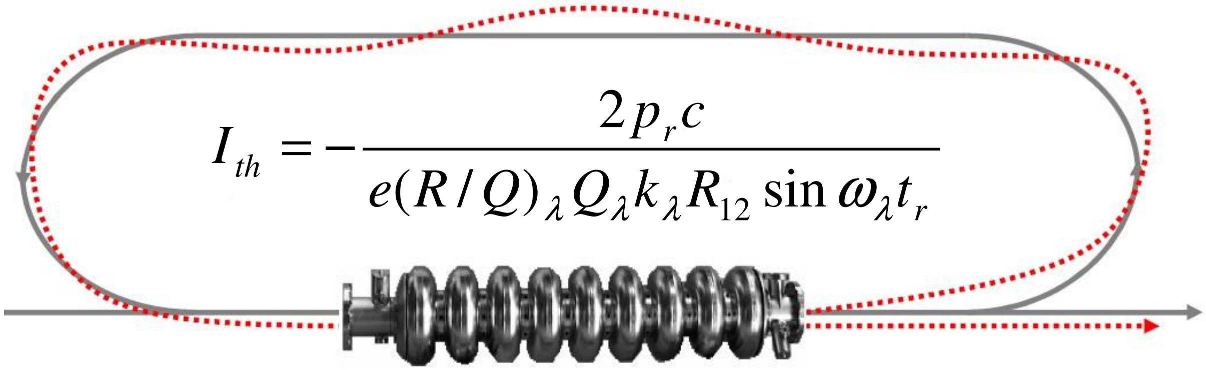
Bunch Length 2 ps

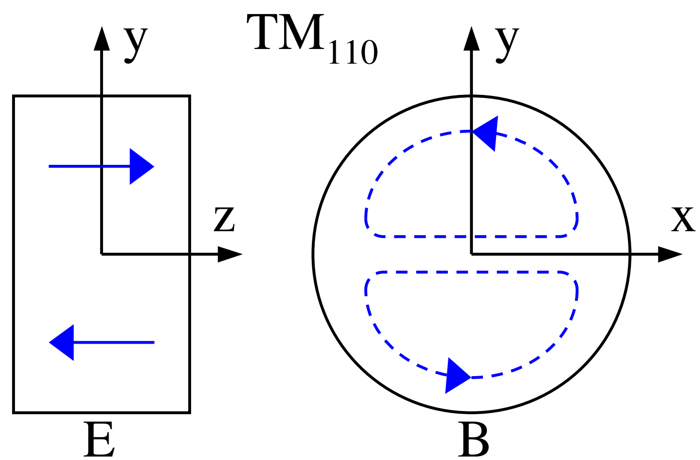
Emittance (norm.) ≤ 2 μm@77 pC

***Eds. Gruner, Tigner*; Bazarov, Belomestnykh, Bilderback, Finkelstein, Fontes, Krafft, Merminga, Padamsee, Shen, Rogers, Sinclair, Talman, ERL prototype proposal to the NSF, 2001**

Beam breakup: challenge

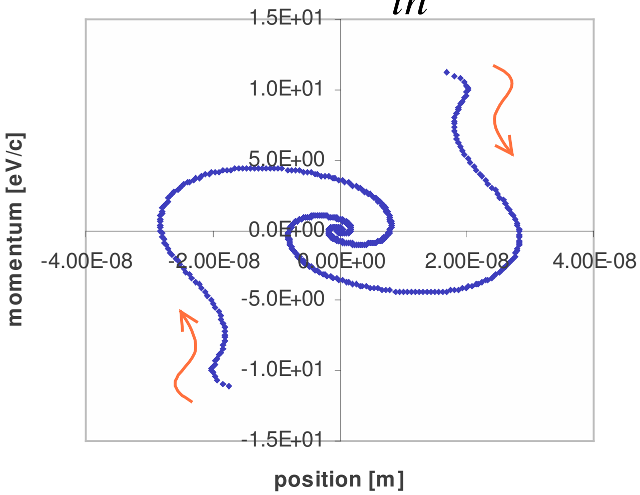
$$I_{th} = -\frac{2 p_r c}{e(R/Q)_\lambda Q_\lambda k_\lambda R_{12} \sin \omega_\lambda t_r}$$



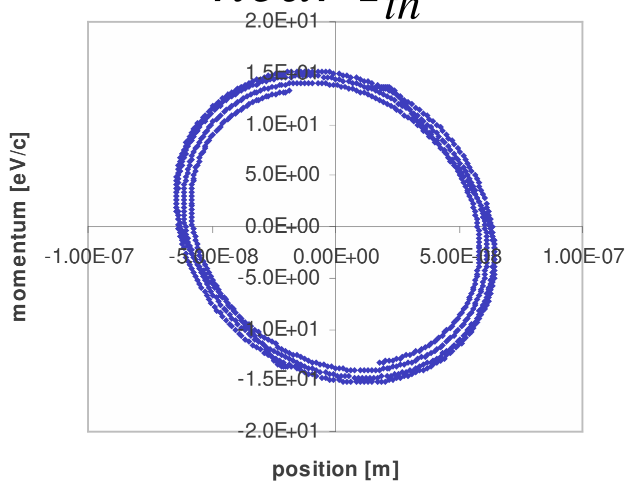


Bazarov, Krafft, Merminga, PAC (2001) 3347

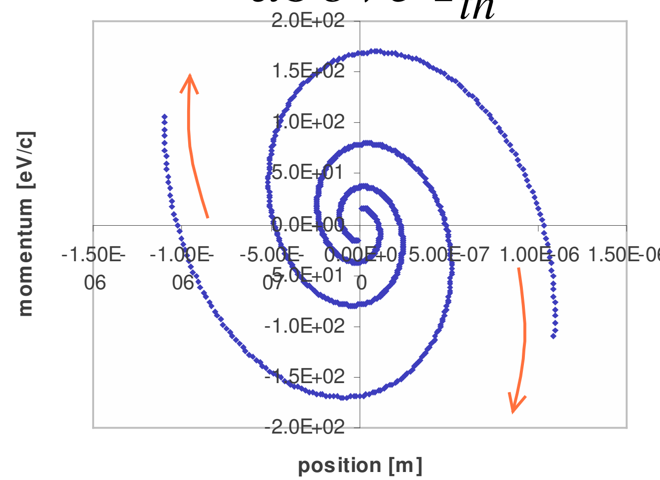
below I_{th}



near I_{th}



above I_{th}



Highest current recirculated in SRF linac was ***4.5 mA*** *in year 2001*

Beam breakup: figured out

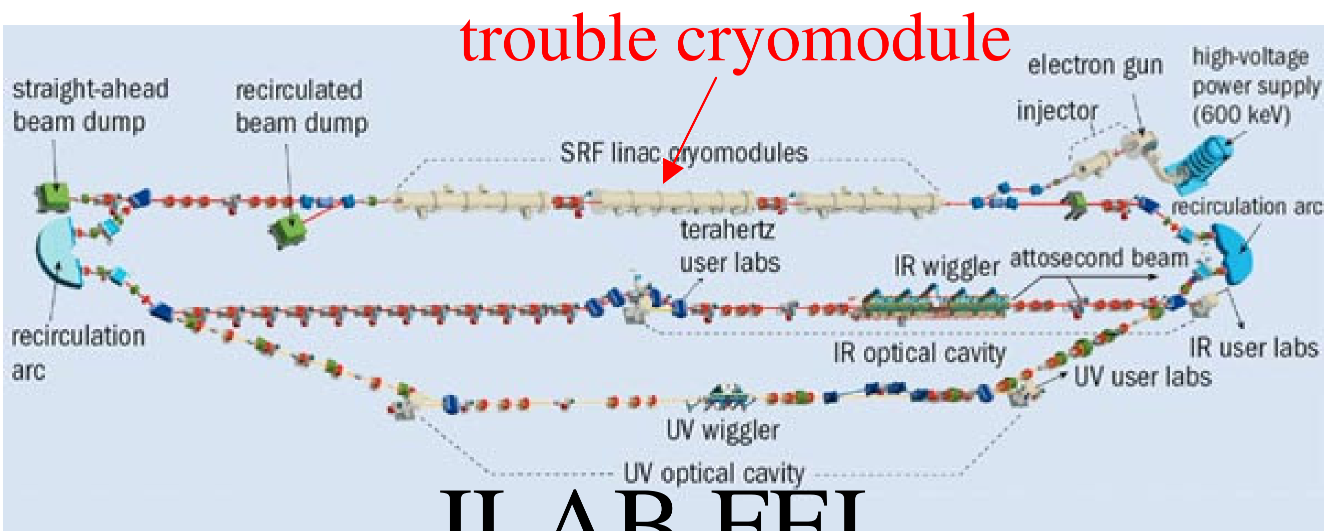
- BBU code & theory developed for ERLs

Bazarov, Hoffstaetter, EPAC (2004) 2194
Hoffstaetter, Bazarov, Phys. Rev. ST: AB 7, 054401 (2004)

- Benchmarked with good accuracy in JLAB FEL

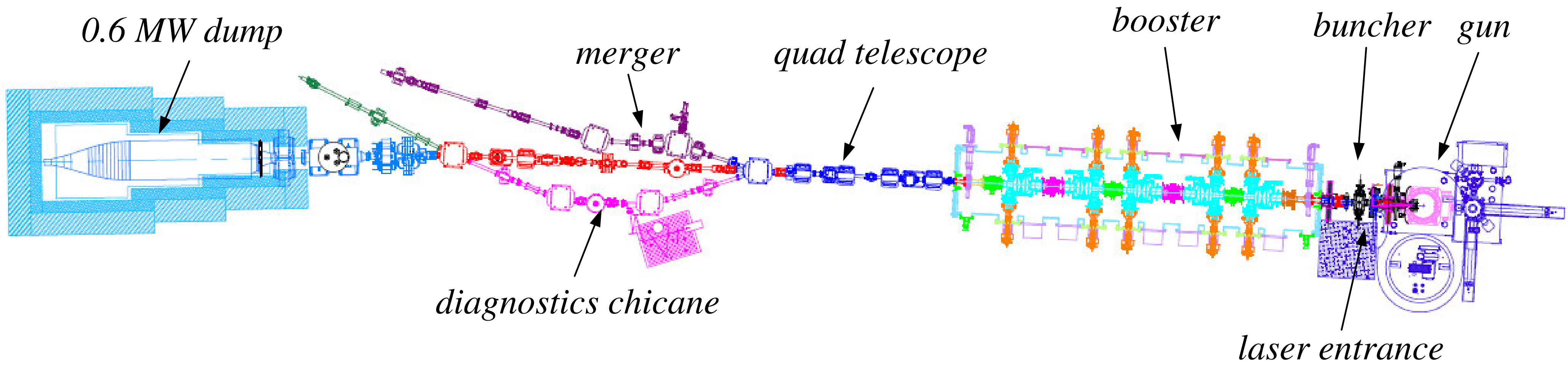
Douglas, Jordan, Merminga, Pozdeyev, Tennant, Wang, Smith, Simrock, Bazarov, Hoffstaetter, Phys. Rev. ST: AB 9, 064403 (2006)

- Various suppression techniques successfully tested



JLAB FEL

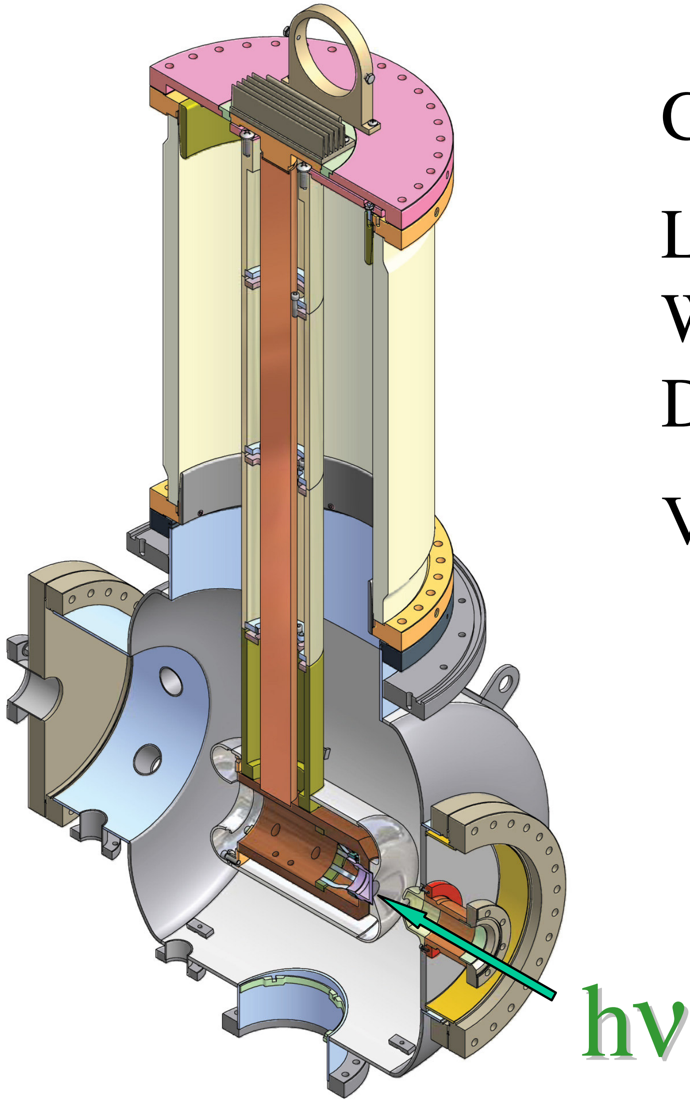
Phase 1a



- **HV DC gun** based **photo**-injector
- 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%**

Bazarov, Sinclair, PAC2003, IEEE 0-7803-7739-9 (2003) 2062

Photo-gun



goal: 750 kV

Cathode	Cs:GaAs
Laser rep. rate	1.3 GHz
Wavelength	520 nm
Duration (rms)	10 ps
Vacuum	$<10^{-12}$ Torr

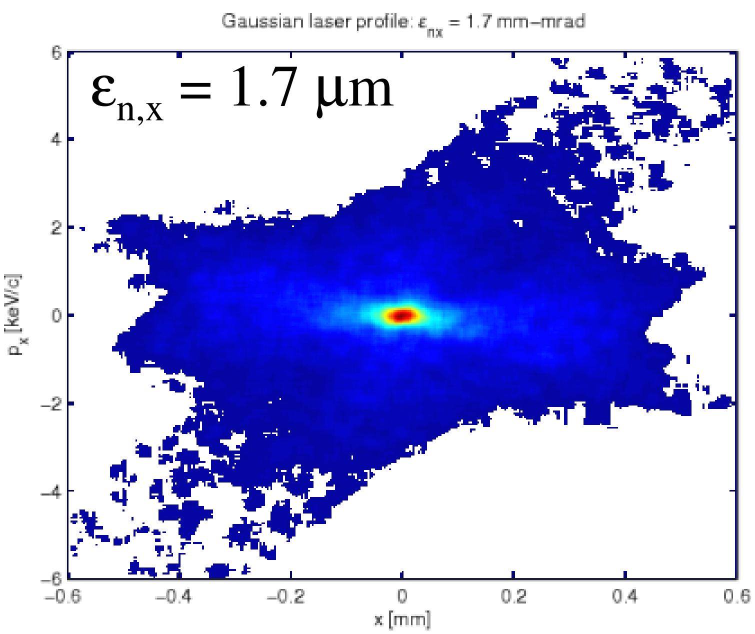
space charge limit → q, *cathode field* → E_{cath}, *laser spot* → σ_x^2

$$q = 4\pi\varepsilon_0 E_{cath}\sigma_x^2$$

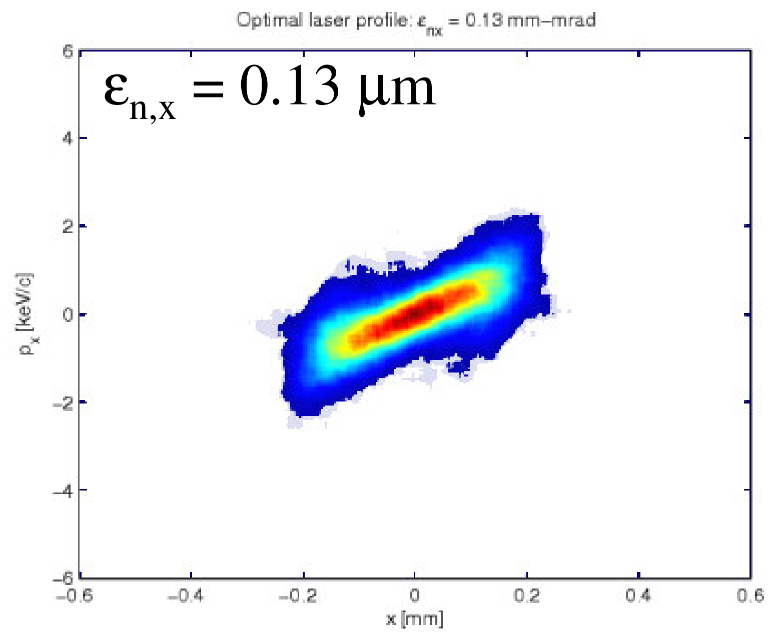
Two main limiting mechanisms:

- Phase space scrambling due to nonlinear space charge

3D Gaussian initial distribution



Optimal initial distribution

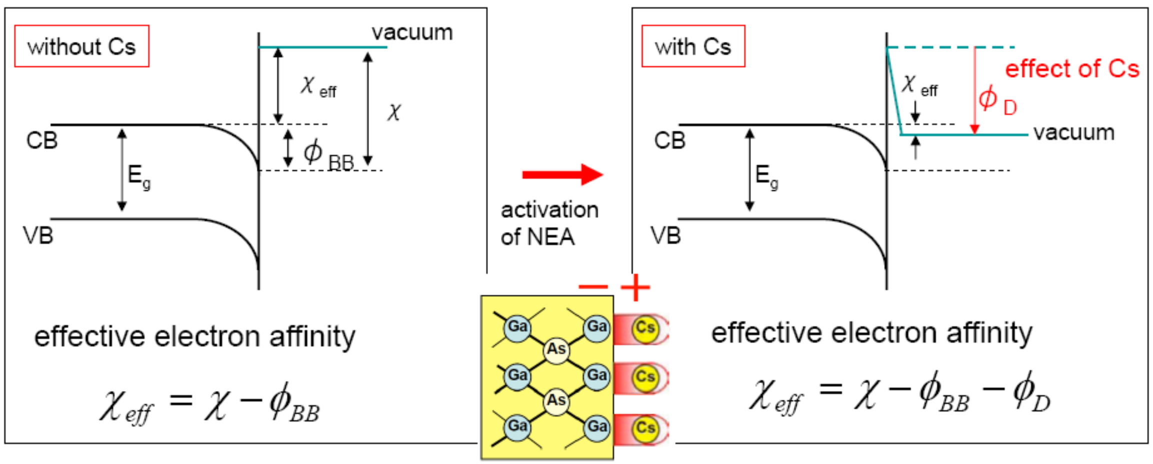


- Photocathode thermal emittance

transverse temperature of photoemitted electrons

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

Photocathode requirements



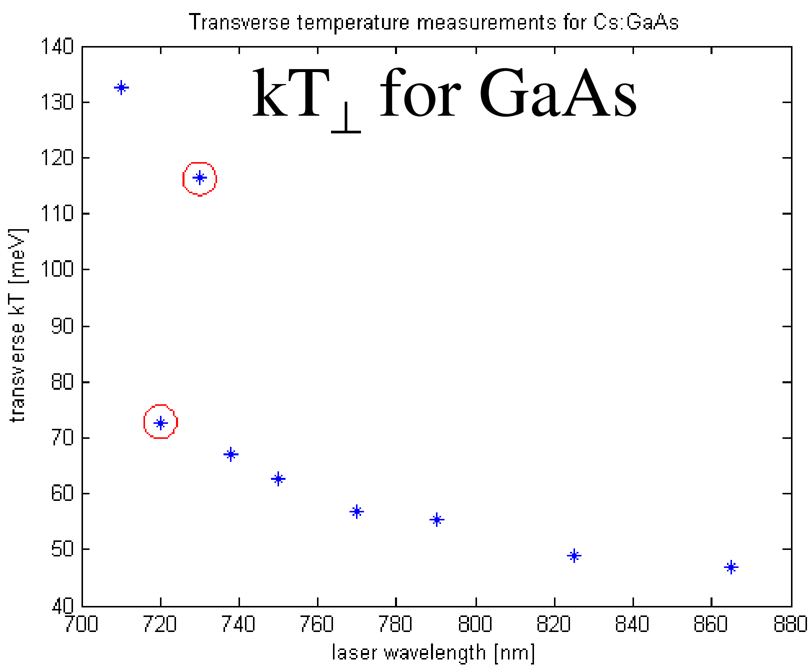
(1) photon excites electron to a higher-energy state;

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

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

Ideal photocathode:

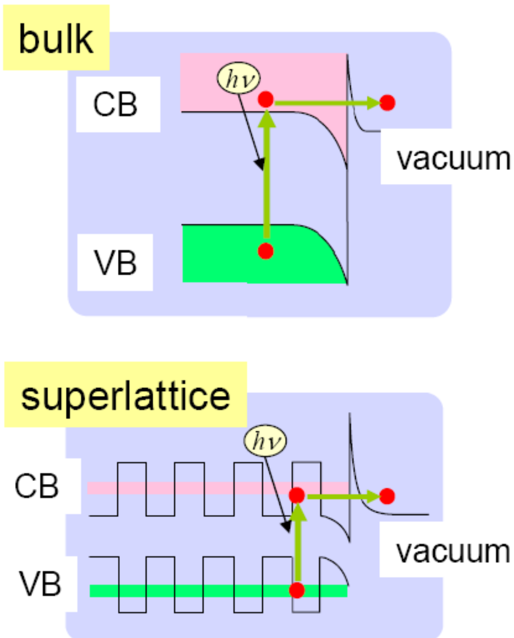
- $E_{th} \rightarrow kT \leq 25$ **meV**
- **response time ≤ 1 ps**
- **high QE ≥ 10%**

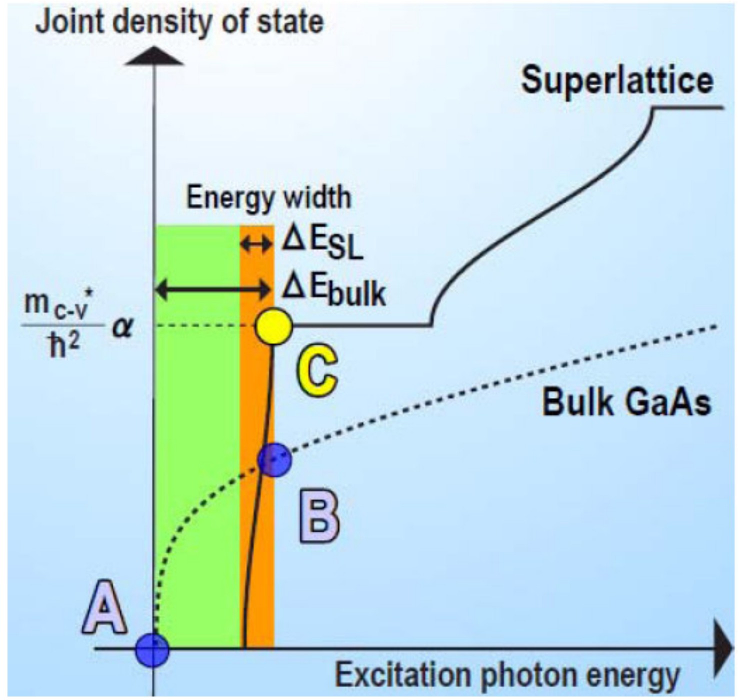


General trend

- λ↑ Q.E.↓ kT↓ τ↑

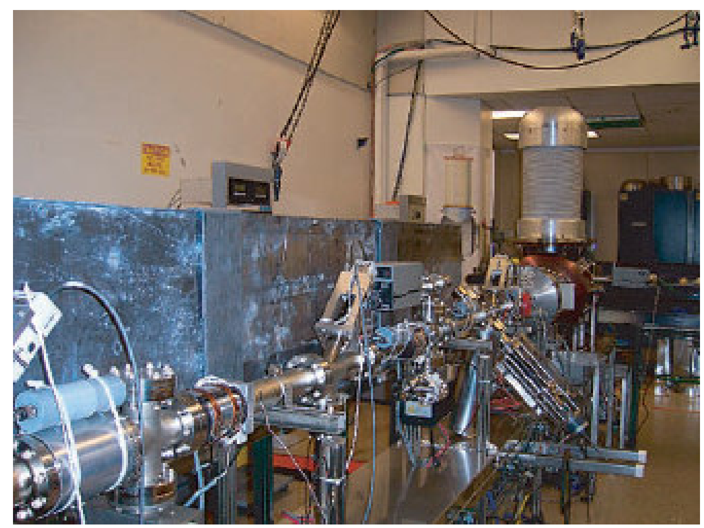
Superlattice photocathode?





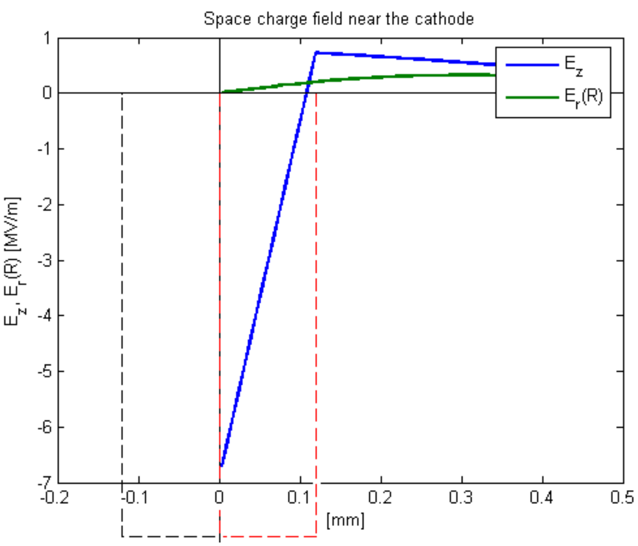
	Q.E.	kT
A	small	*small*
B	*large*	large
C	***large***	***small***

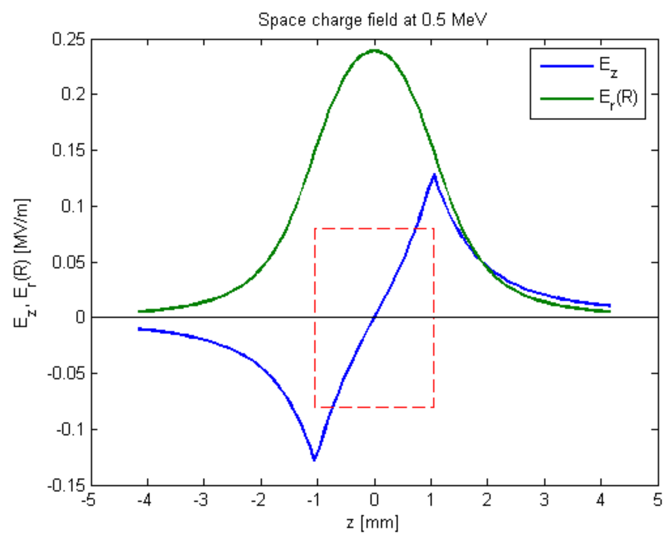
- equipped to accurately (~meV) measure transverse temp. of e⁻ at different wavelengths
- photoemission temporal response resolution (~ps)

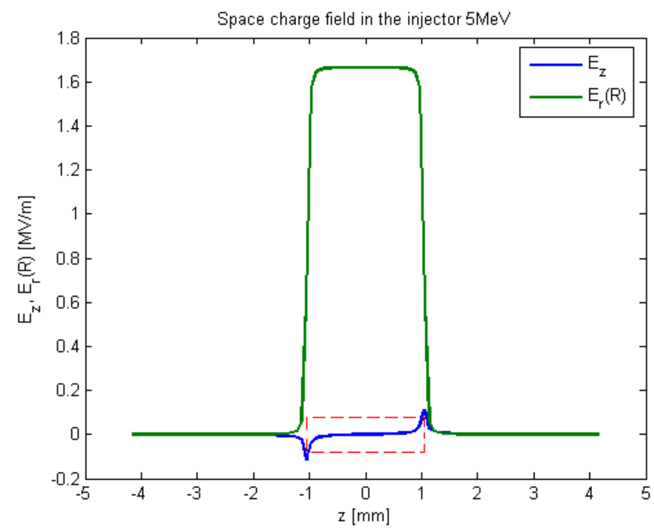


Gun development lab in Wilson

Space charge basics







Beam envelope equation:

$$\ddot{R} + K_f R = \underbrace{\frac{e}{m\gamma}[E_r^{s.c.} - \beta c B_\theta^{s.c.}]}_{} + \left(\frac{4\varepsilon_n^{th} c}{\gamma}\right)^2 \frac{1}{R^3}$$

$$\frac{e}{m\gamma^3} E_r^{s.c.}(R) = \frac{1}{2}\omega_p^2 R$$

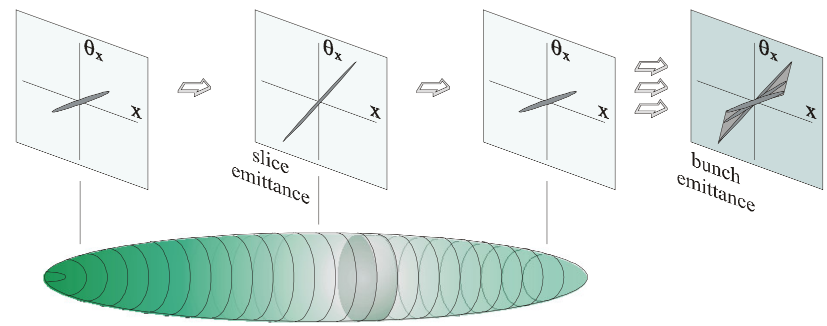
$$\omega_p^2 = \frac{e^2 n}{\varepsilon_0 \gamma^3 m}$$

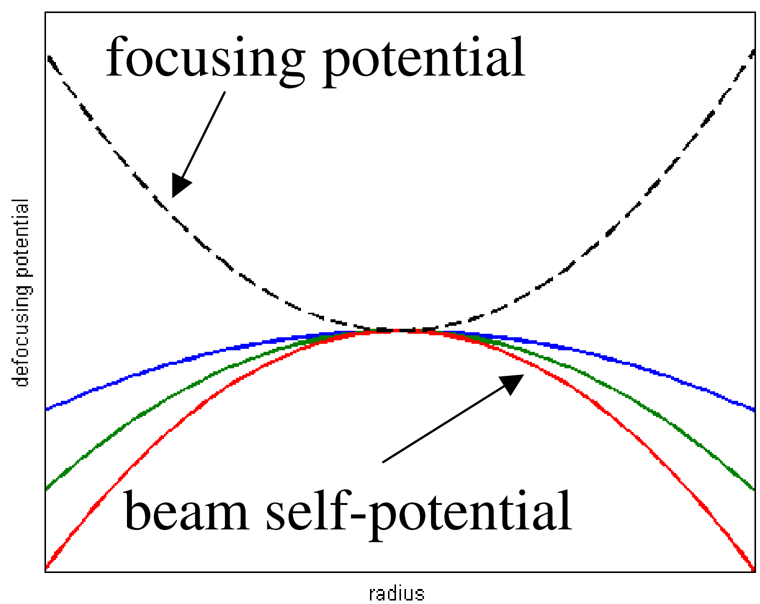
Beam temperature

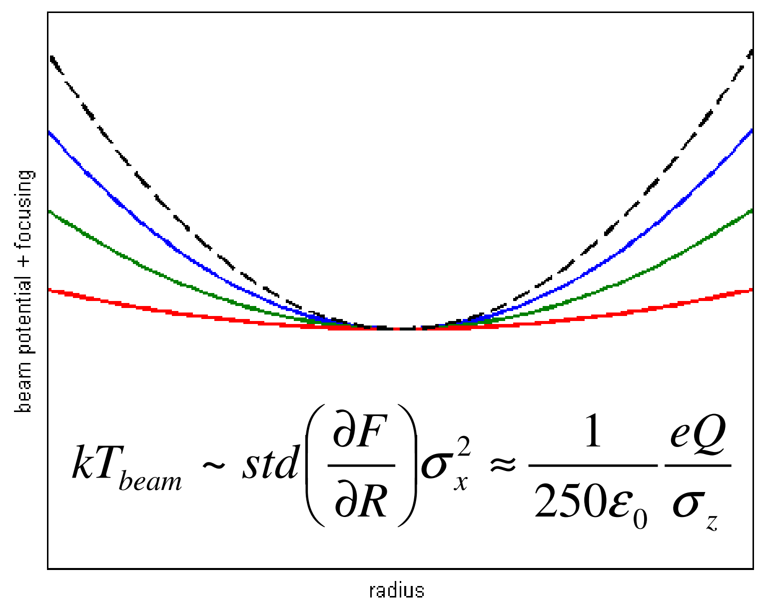
Diffraction limited beam at 1Å → ε_x = 8pm at 5GeV → ε_{nx} = 0.08 μm

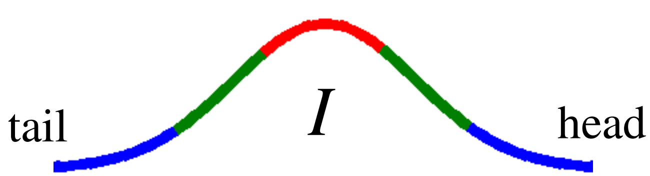
10 MV/m gradient → σ_{laser} = 0.3 mm

Transverse temp. needed ***kT = 25 meV***









Equilibrium ***kT$_{beam}$ ~ 100 eV!!***

S.c. compensation concept

Serafini PRE **55**, 7565

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

focusing s.c. emittance

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

linearize

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

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

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

oscillation frequency current independent

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

S.c. compensation concept

Serafini PRE **55**, 7565

$\sigma'' + K_r \sigma = \frac{}{2I}$ … $\overline{{}^2\rangle_\zeta - \langle r r' \rangle_\zeta^2}$

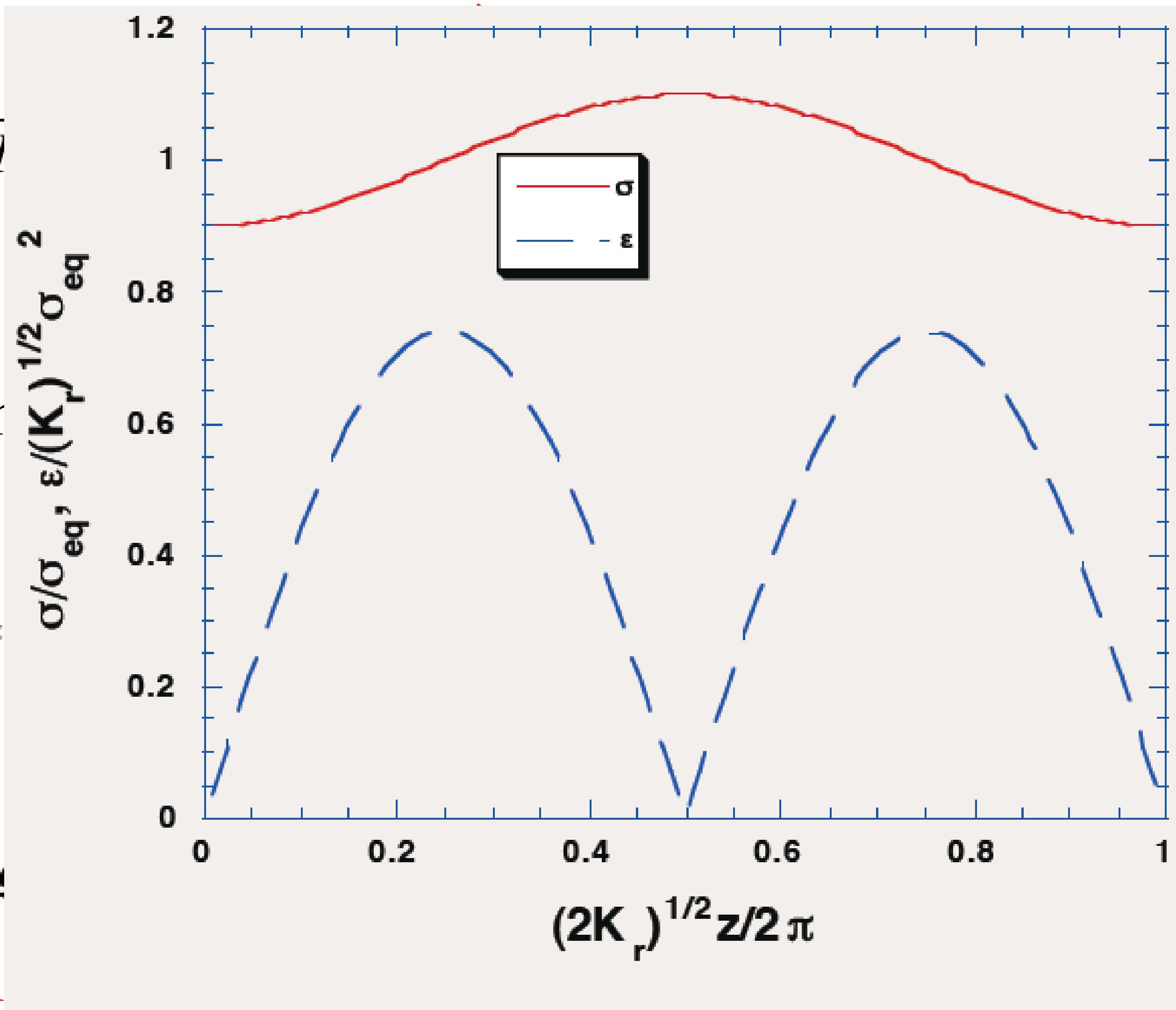
focusing

Needle beam

$\sigma_{eq}(g(\zeta)) =$ … for slice

$\delta\sigma''($ …

osci…



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

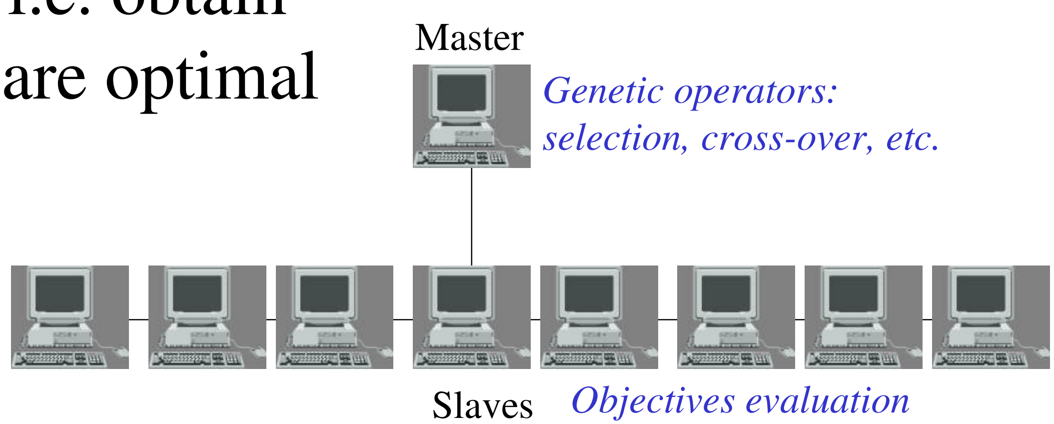
→

- processor speed
- algorithms
- parallel processing

Solution: use parallel MOGA

***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 mode



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

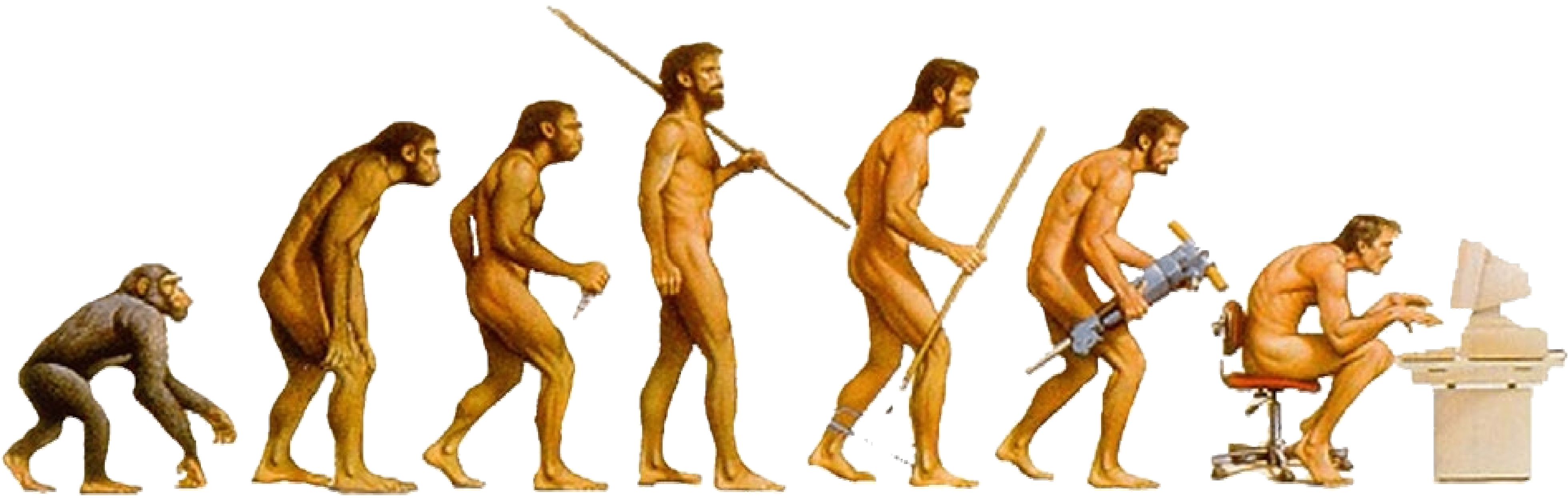
Definition 2. *Among a set of solutions $\mathcal{P}$, the nondominated subset of solutions $\mathcal{P}'$ are those that are not dominated by any member of the set $\mathcal{P}$.*

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

Vilfredo Pareto, 1848-1923

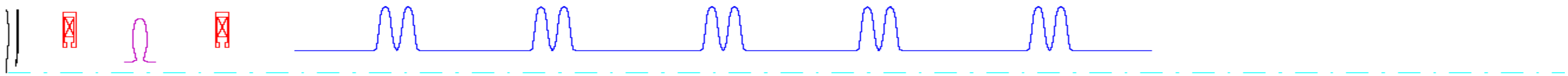
Bazarov, Sinclair, Phys. Rev. ST:AB 8, 034202 (2005)
Bazarov, Padamsee, PAC (2005) 2188

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} $\times$ 2

Total: 22-24 dimensional parameter space to explore

Optimization results

Takes ~10^5 simulations

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

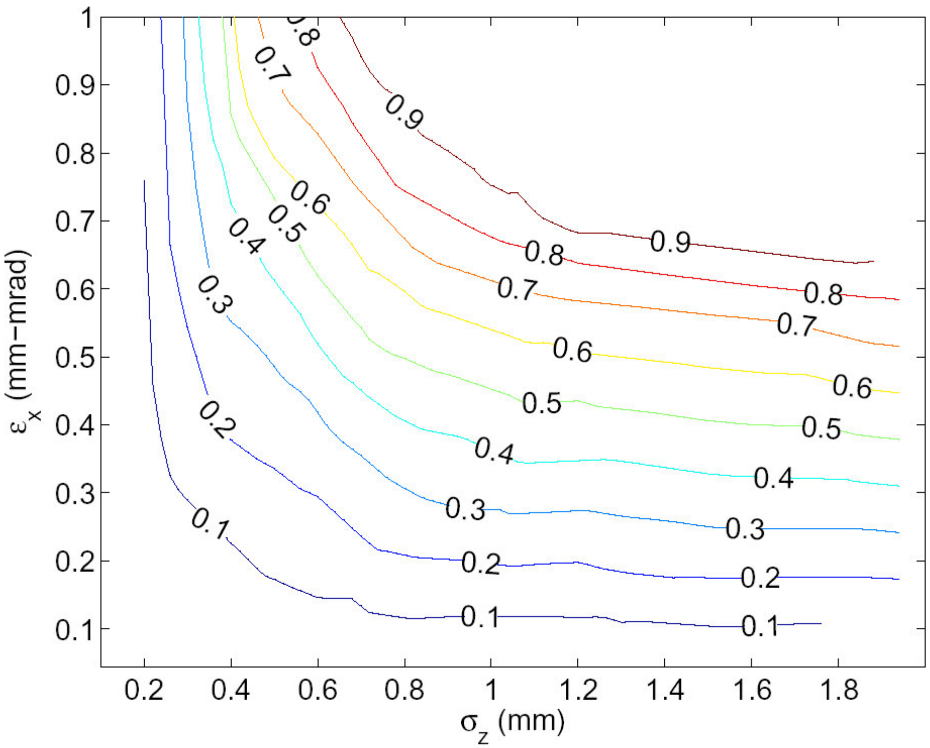


FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

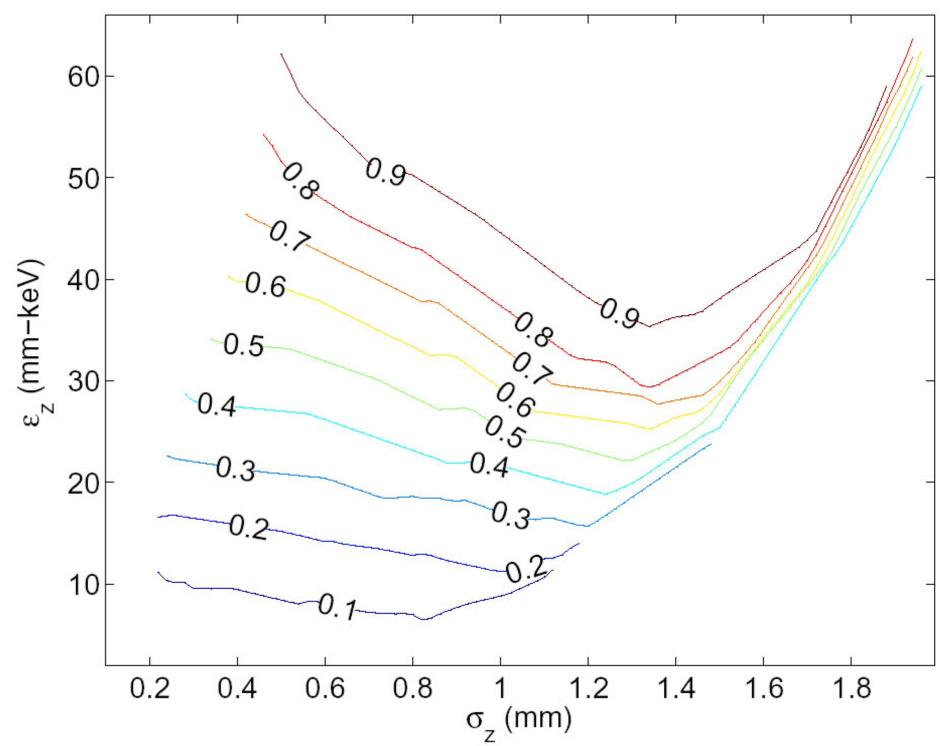
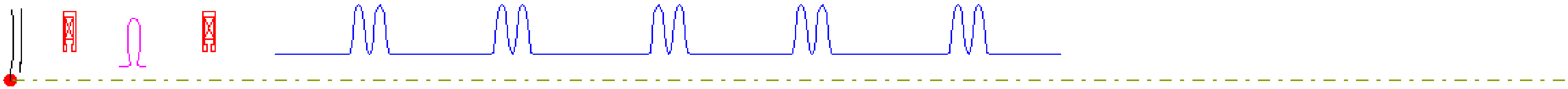
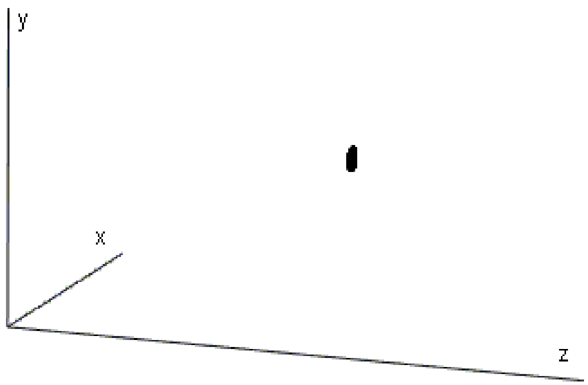


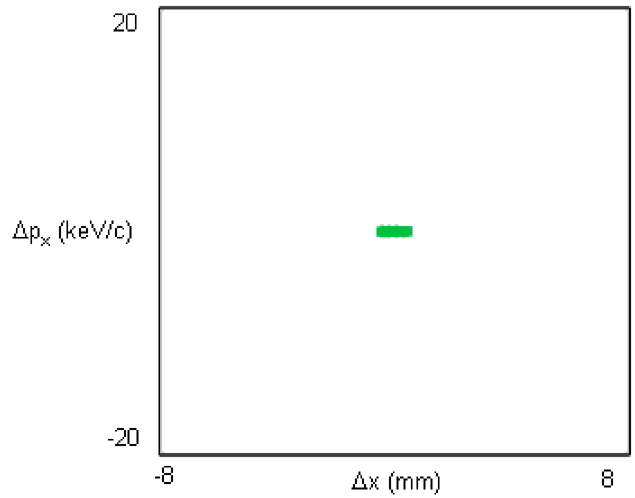
FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

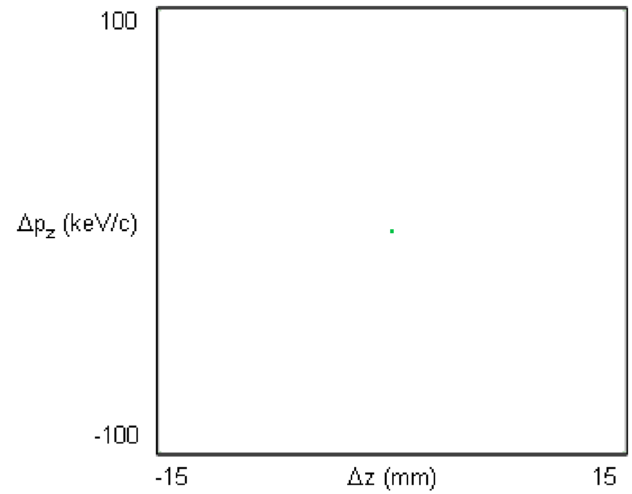
optimization problem:
- minimize emittance
- minimize bunch length
- maximize bunch charge

Closer look: 80 pC







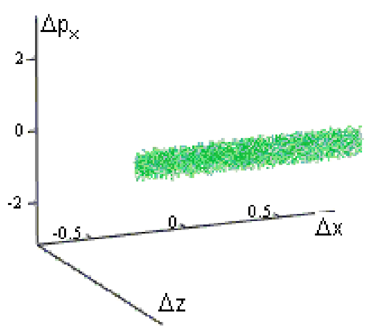


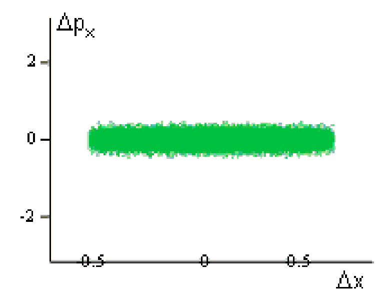
$z = 0.000$ m

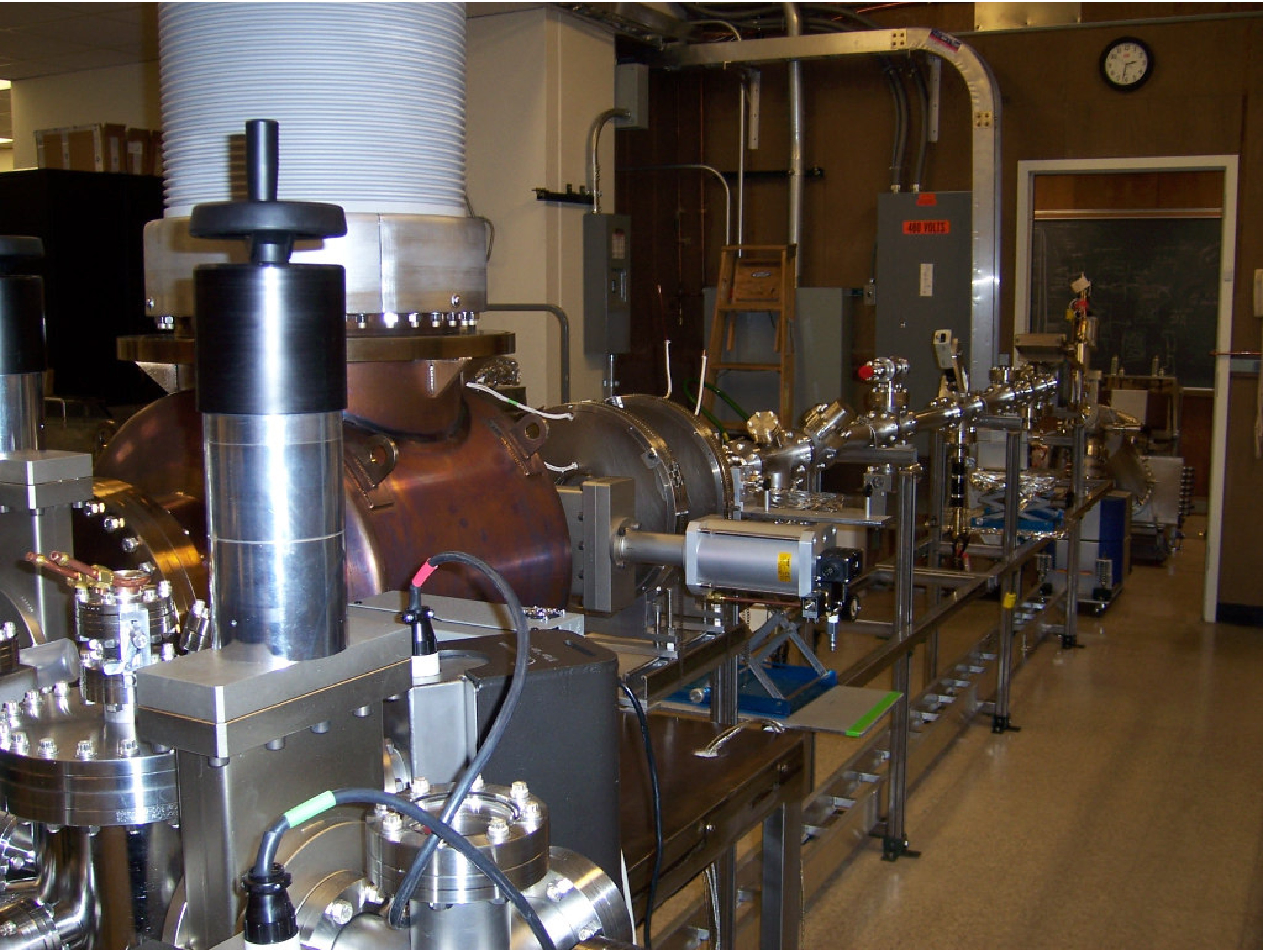
$p_z = 0.000$ MeV/c

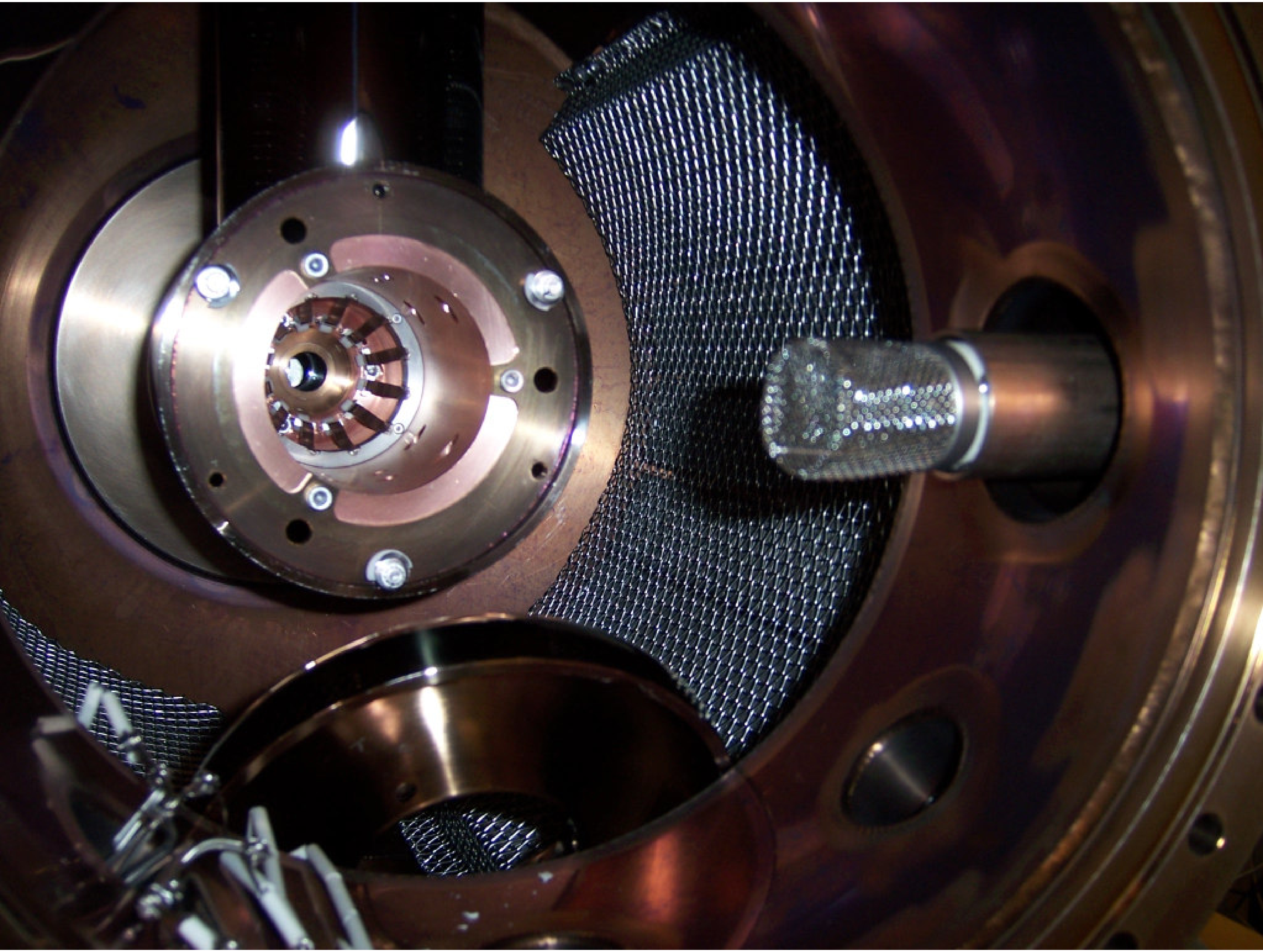
$\sigma_x = 0.294$ mm $\quad \varepsilon_x = 0.077$ mm-mrad

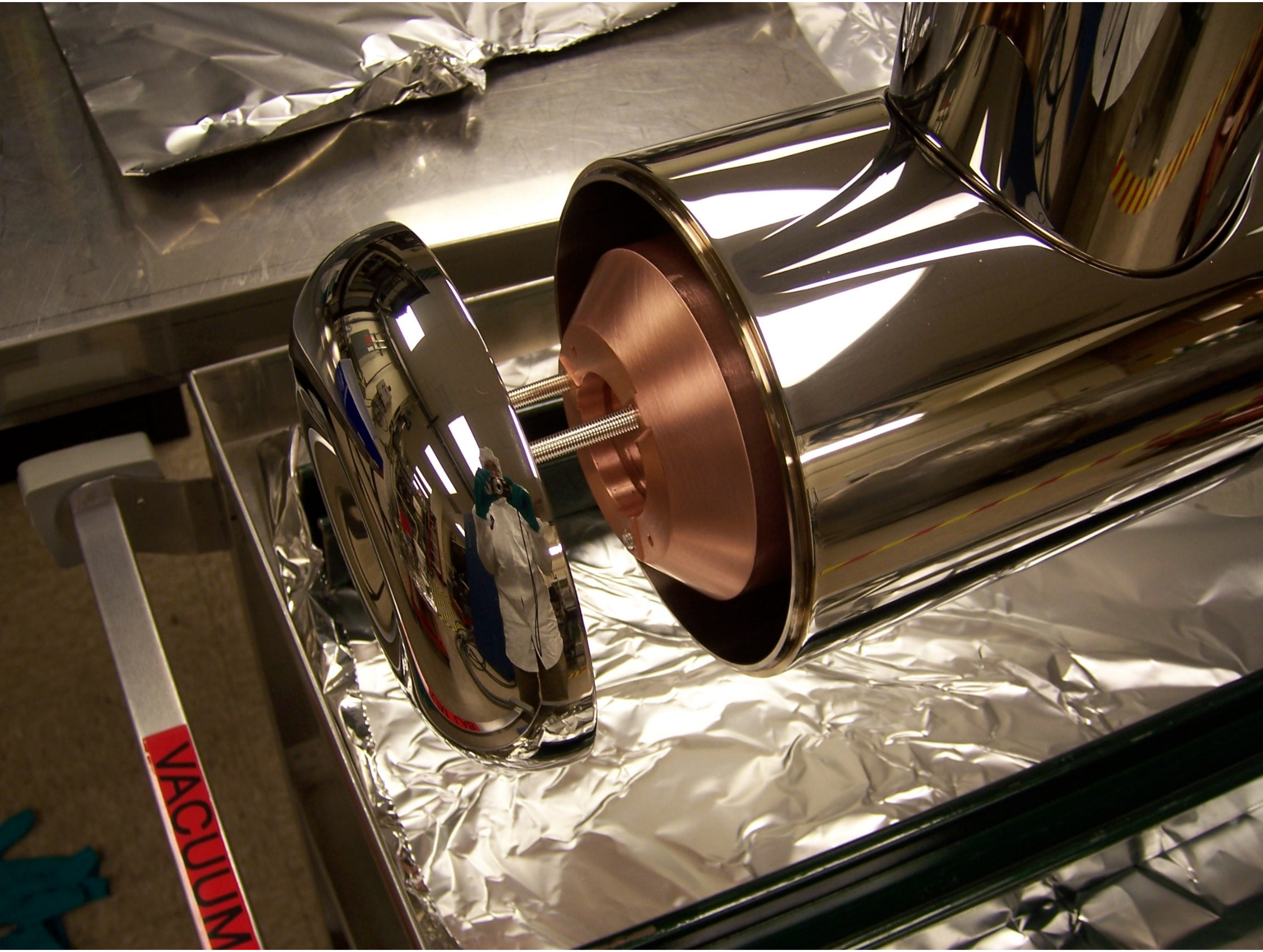
$\sigma_z = 0.000$ mm $\quad \varepsilon_z = 0.000$ mm-keV

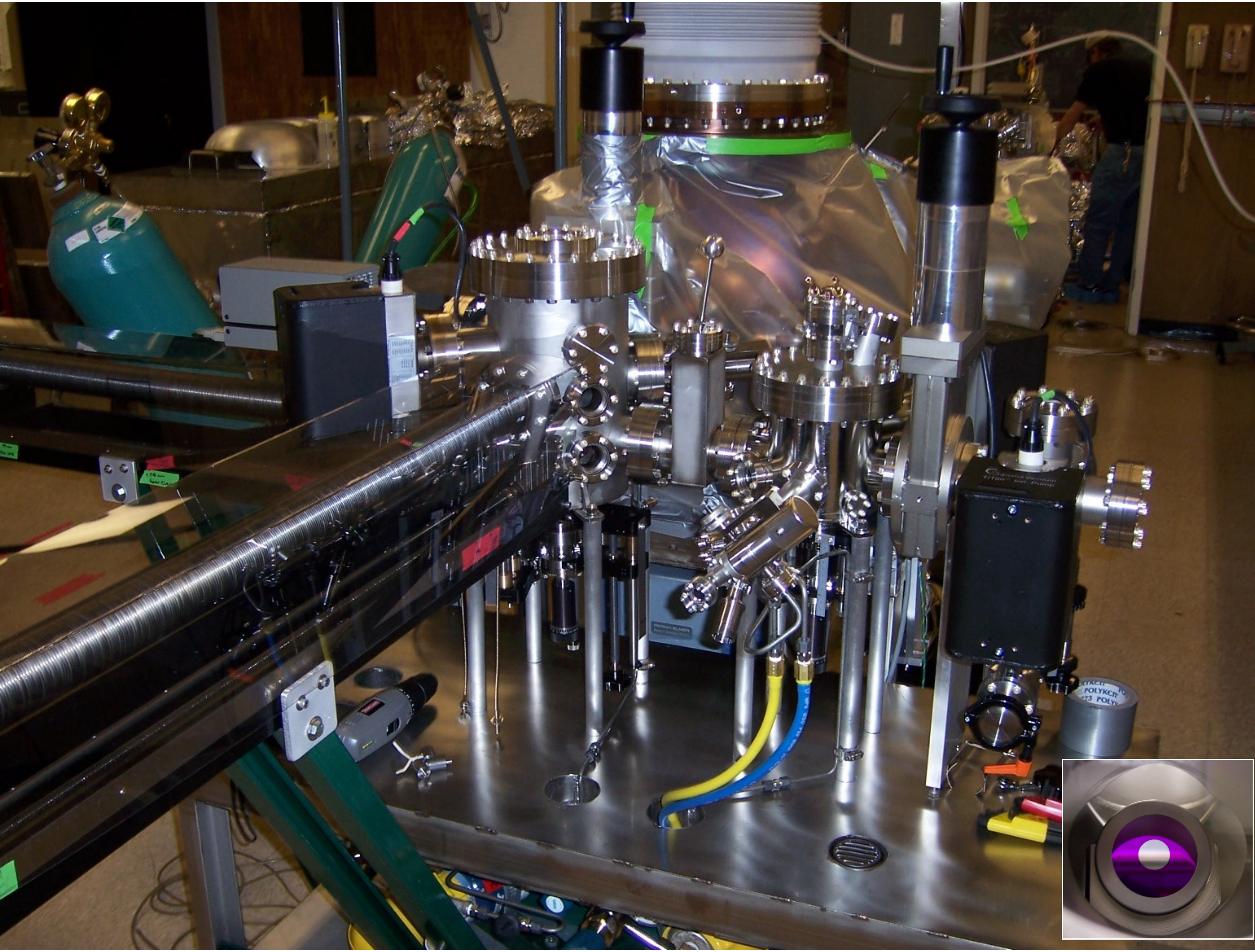





480 VOLTS




VACUUM


POLYKEN

Summary

- Linac-based source to put Cornell on the forefronts of synchrotron radiation science for many years to come (both spontaneous and stimulated SR)
- Key to feasibility of ERL is the very high current, high brightness electron source (in the works)
- Plenty of opportunities for interdisciplinary exchange (photocathodes, surface science, laser technology, beam diagnostics & instrumentation)

X-ray light source dev. team

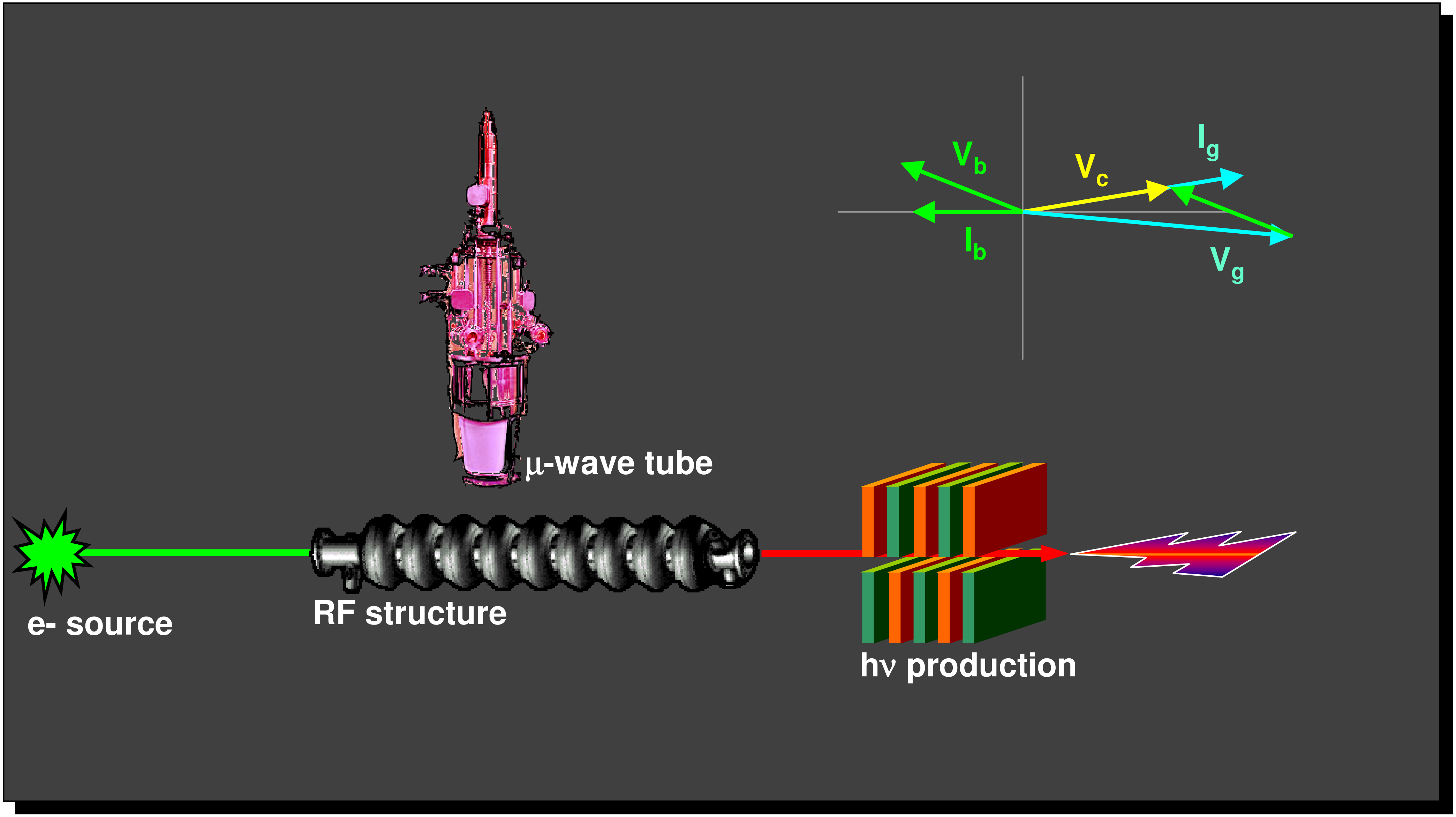
Thank you!

Backup slides

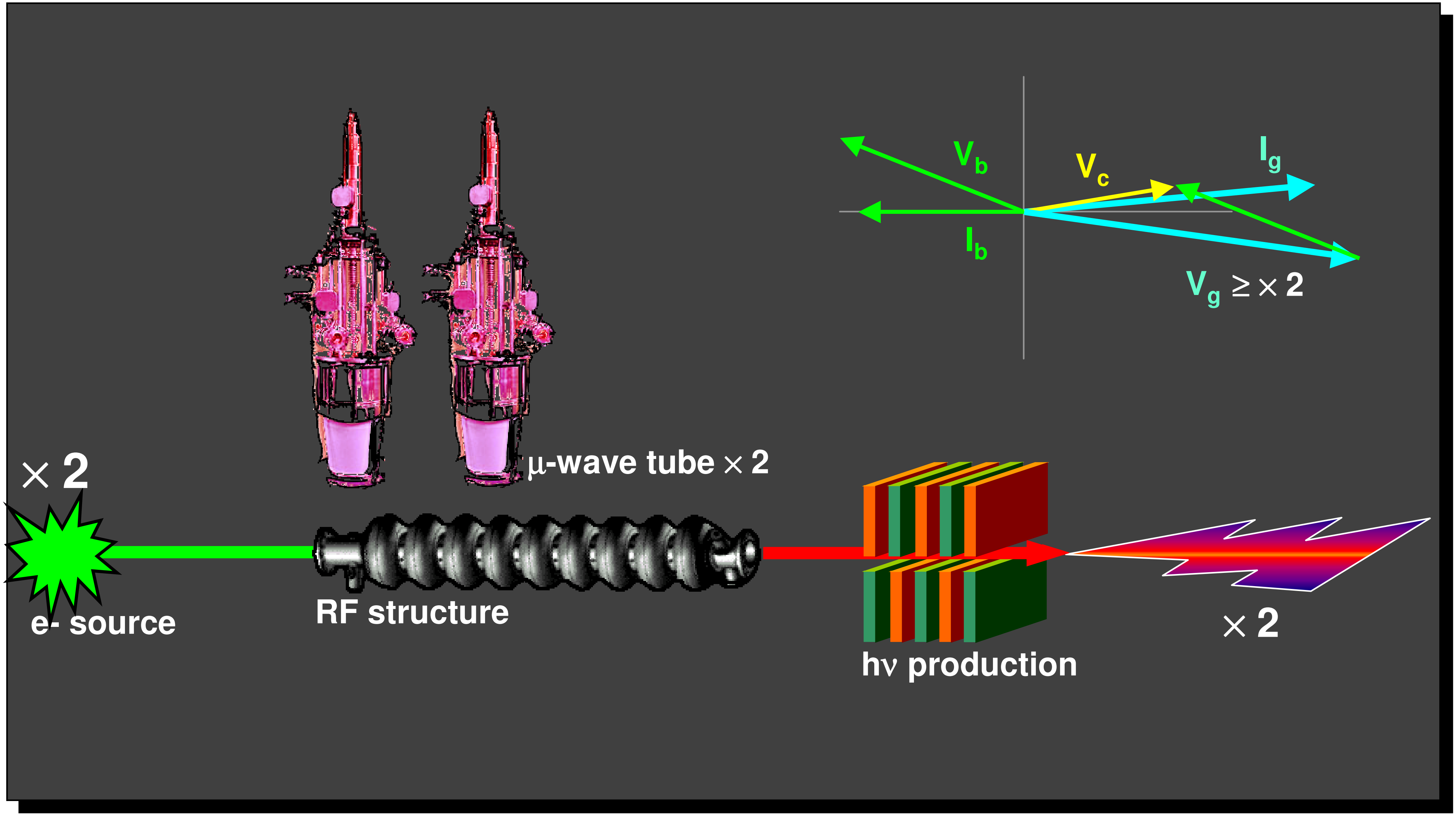
Light sources worldwide

- About 70 light sources worldwide based on **storage ring** technology (**VUV to <u>hard X-rays</u>**), new ones are being built / designed
- >20 (small) **FELs** operational (**far IR to VUV**)
- 3 **XFELs** in construction / committed to, plus half a dozen in earlier stages of planning (**soft to <u>hard X-rays</u>**)
- 3 labs seriously consider building **ERL** as a **<u>hard X-ray</u>** light source

Linac based approach



Linac based approach



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

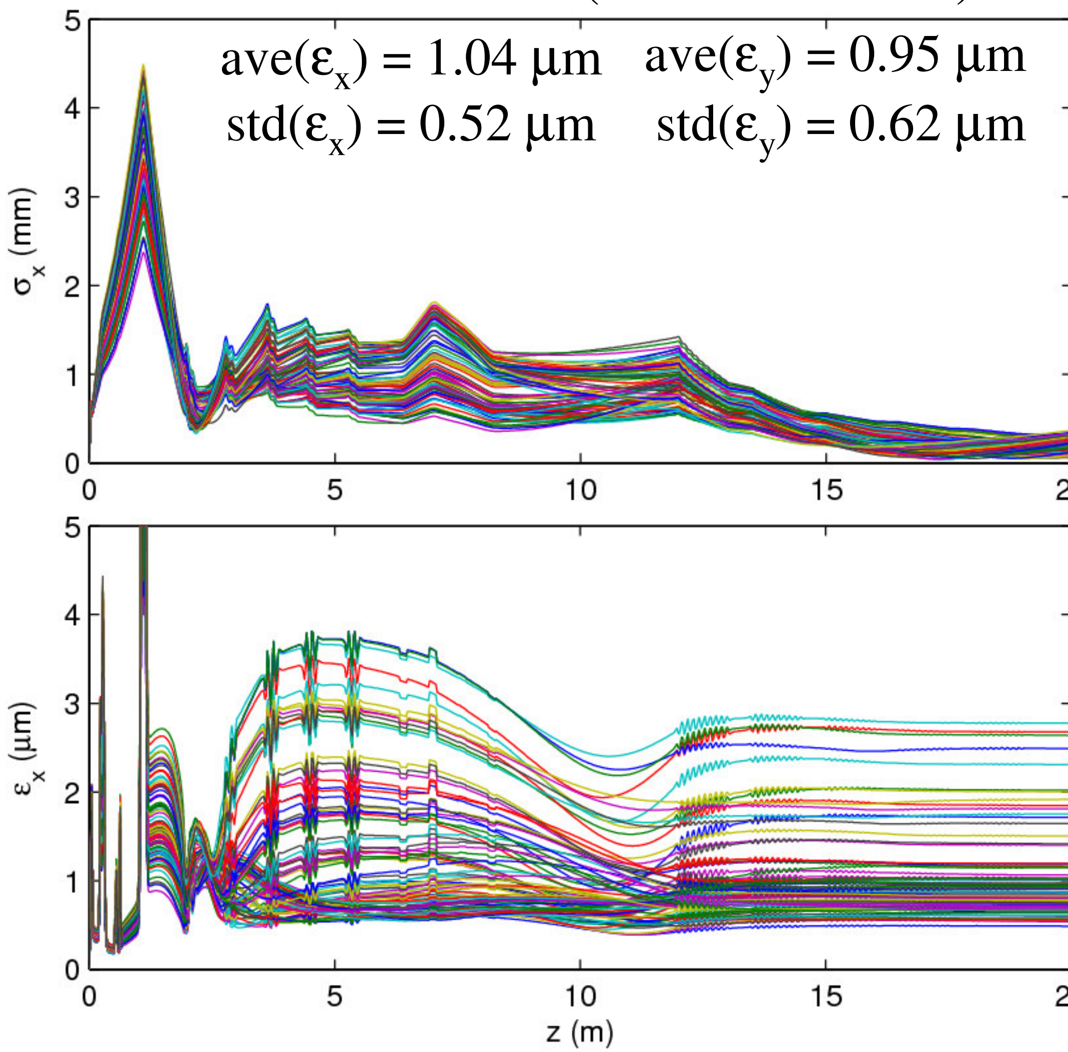
■ helps here, may harm elsewhere

Optima steepness

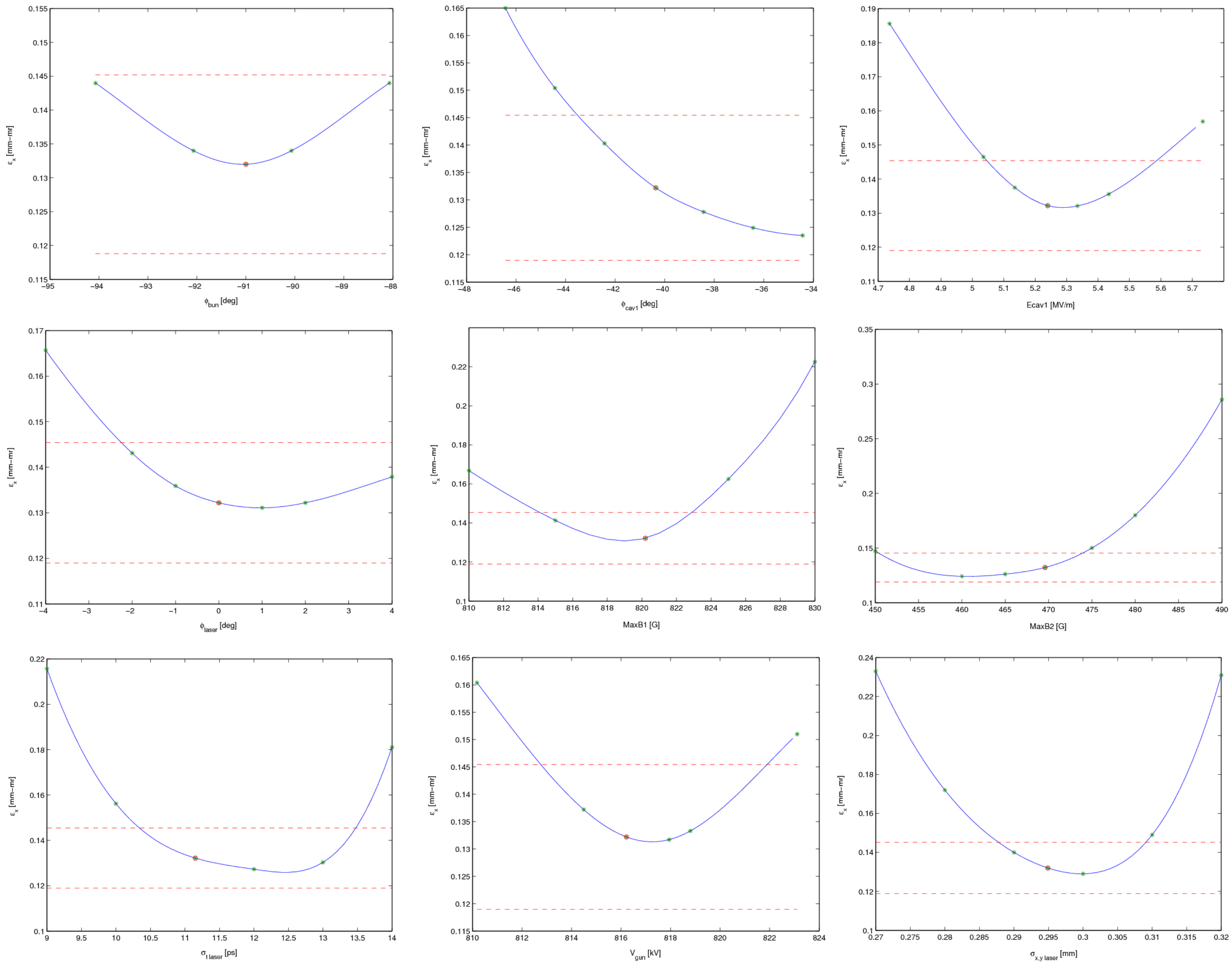
- Virtual injector allows absolute control of parameters, real system with a dozen of sensitive parameters will not

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)



Tolerances for optimum

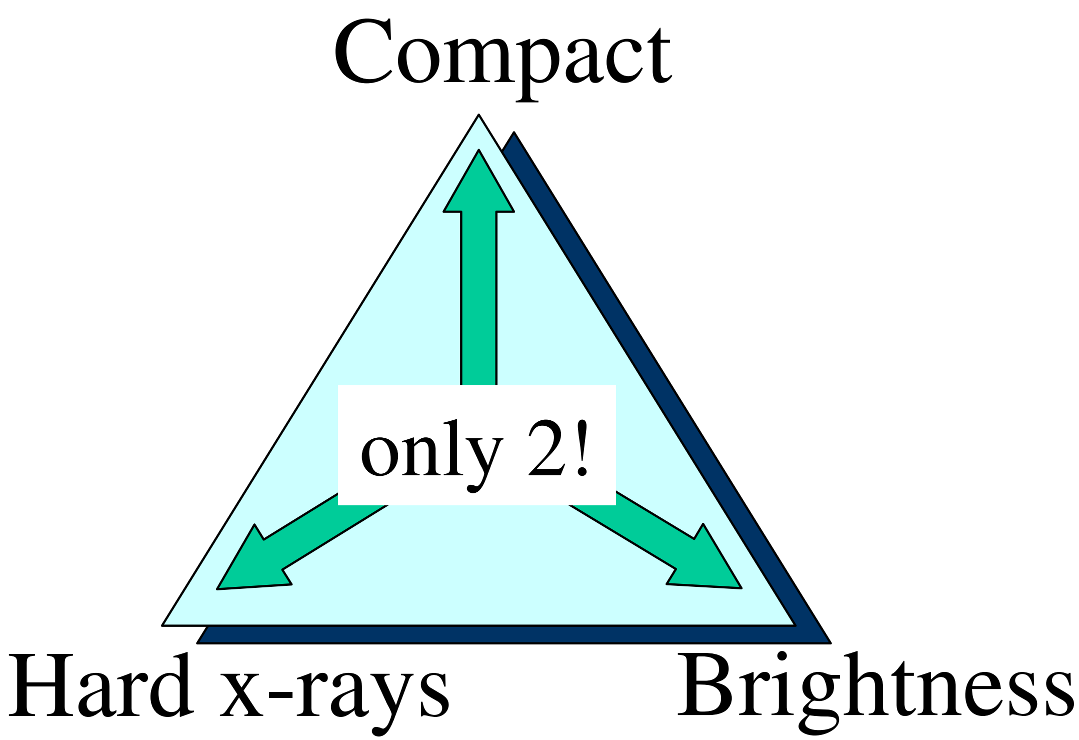


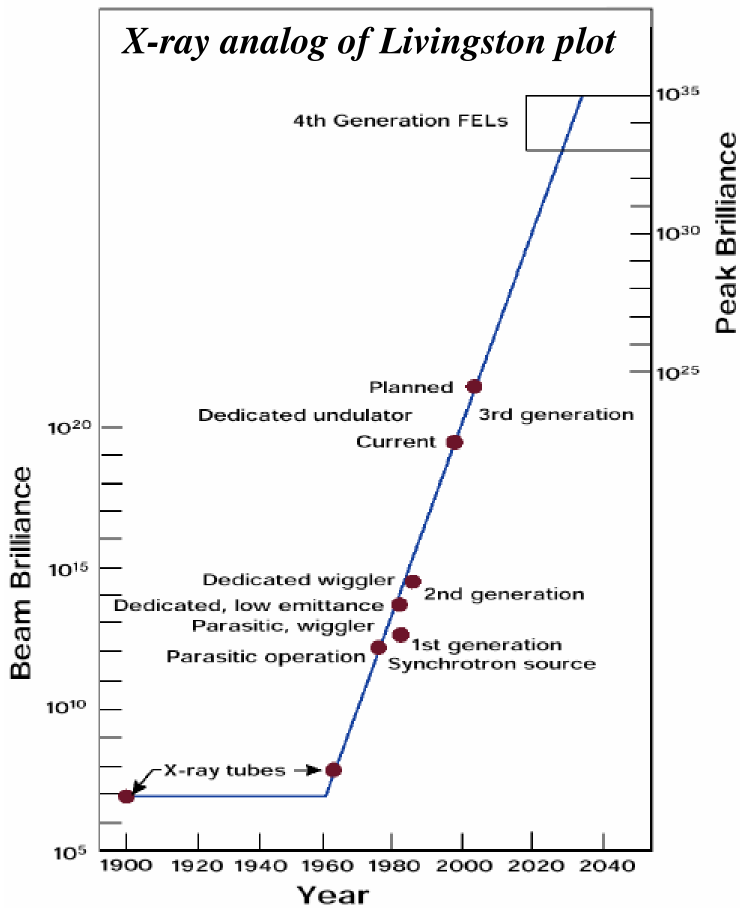
10% increase in emittance (p-t-p)

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%

Three frontiers in source dev.

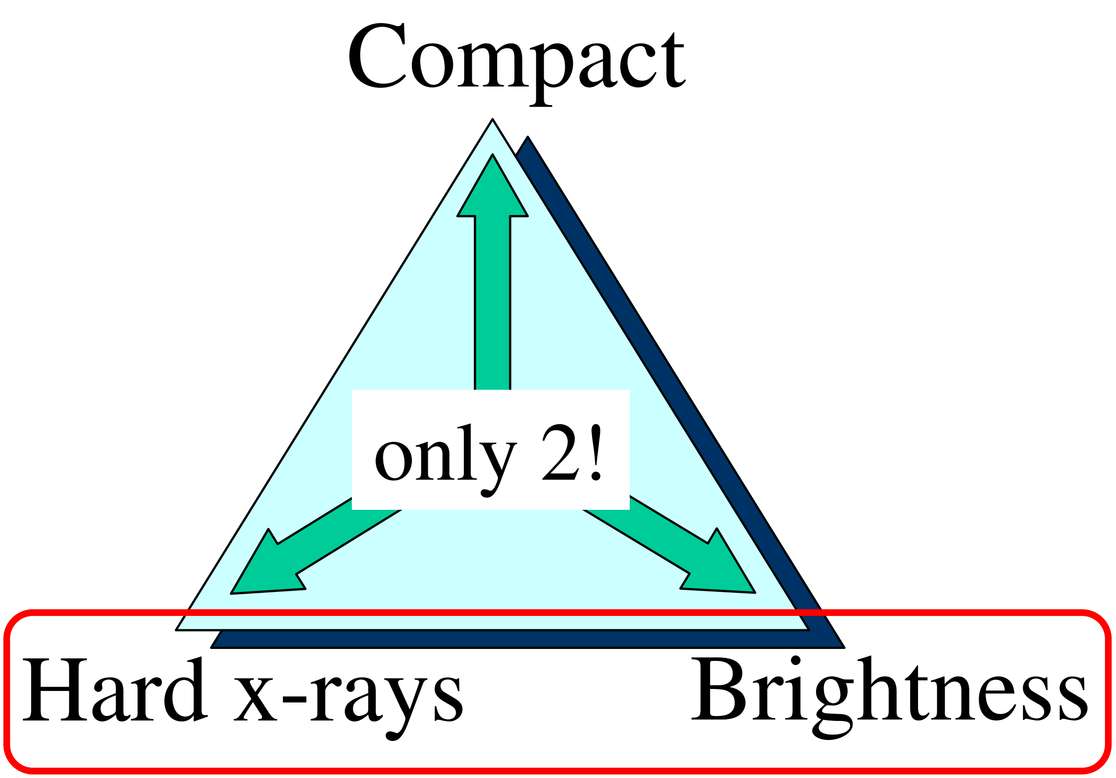
- Avg. brightness
- Short pulses (< ps) & peak brightness
- Compactness

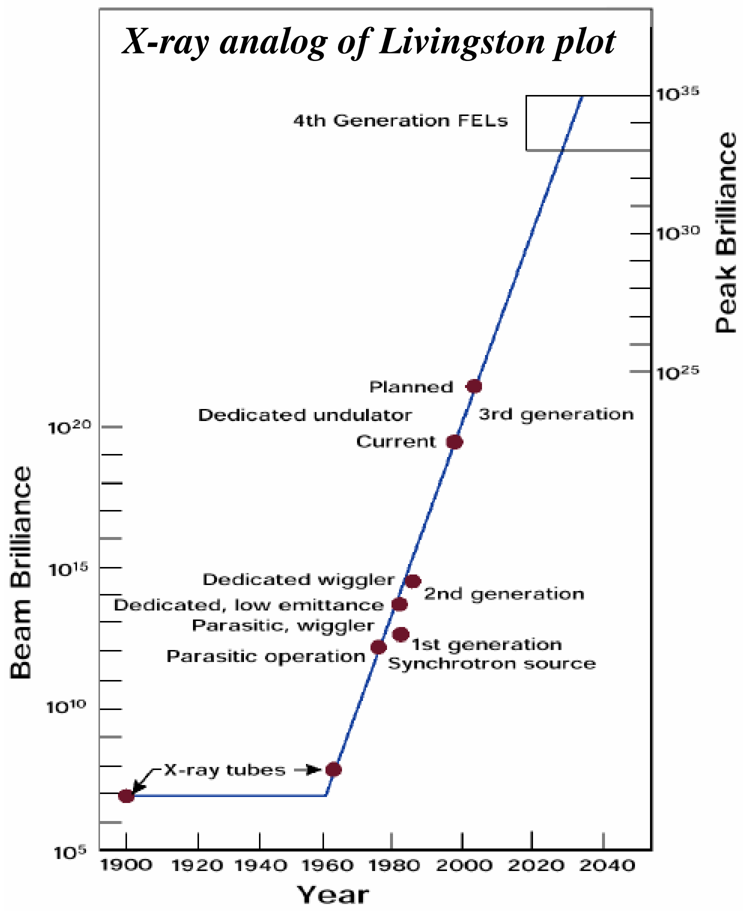




Three frontiers in source dev.

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

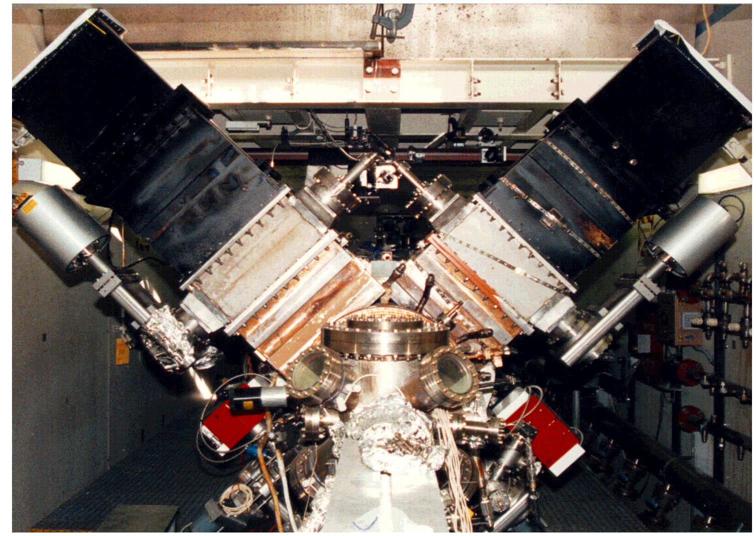




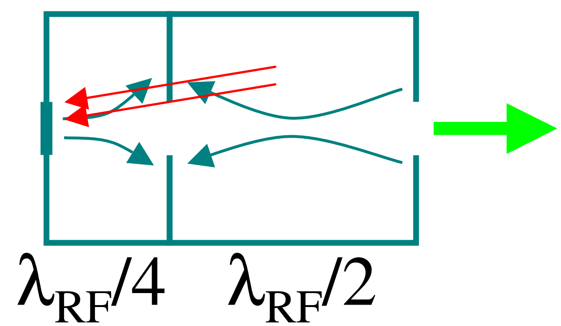
State-of-the-art: BOEING gun

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

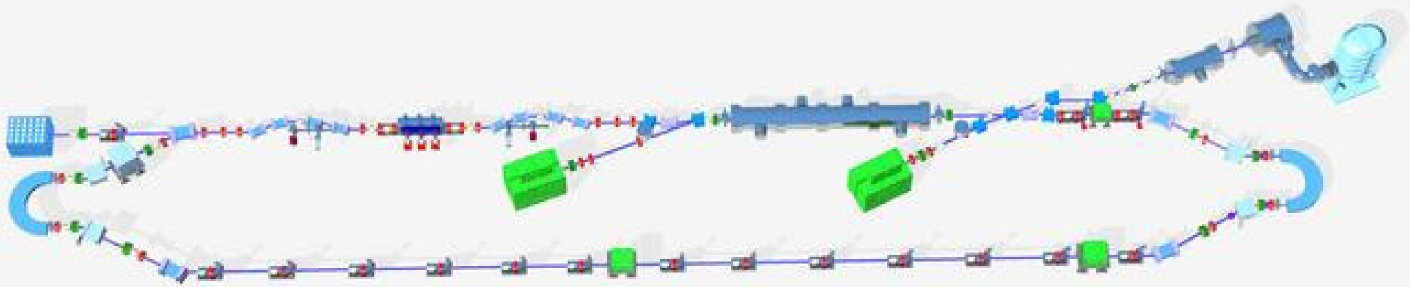


State-of-the-art: JLAB FEL inj.

500 kV (350) DC gun

9.1 mA max avg. current

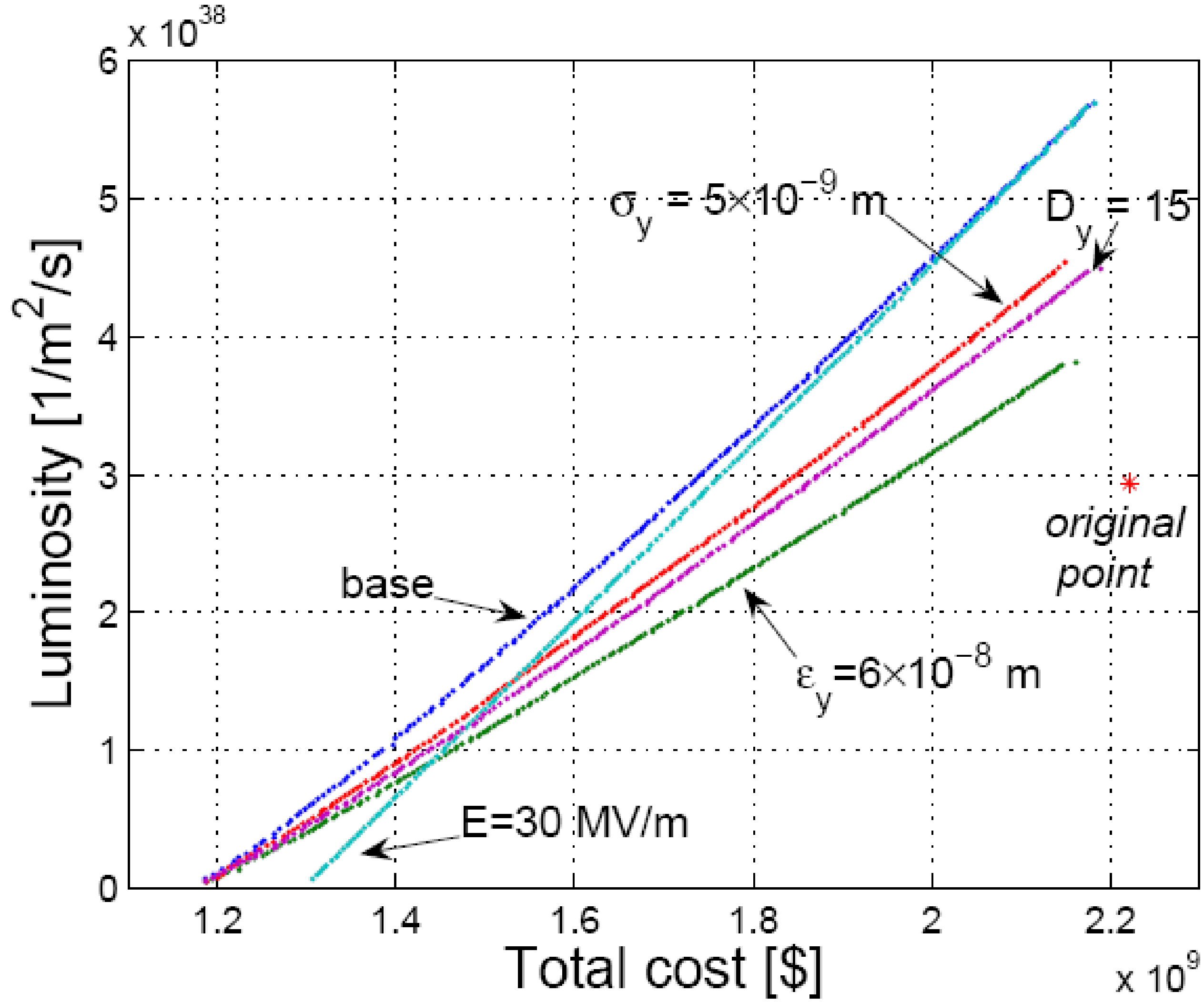
- Cs:GaAs photocatode
- max current 9.1 mA, routine 5 mA
- best simulated normalized emittance 5 μm, measured ≥2 larger at 60 pC



10 kW IR FEL

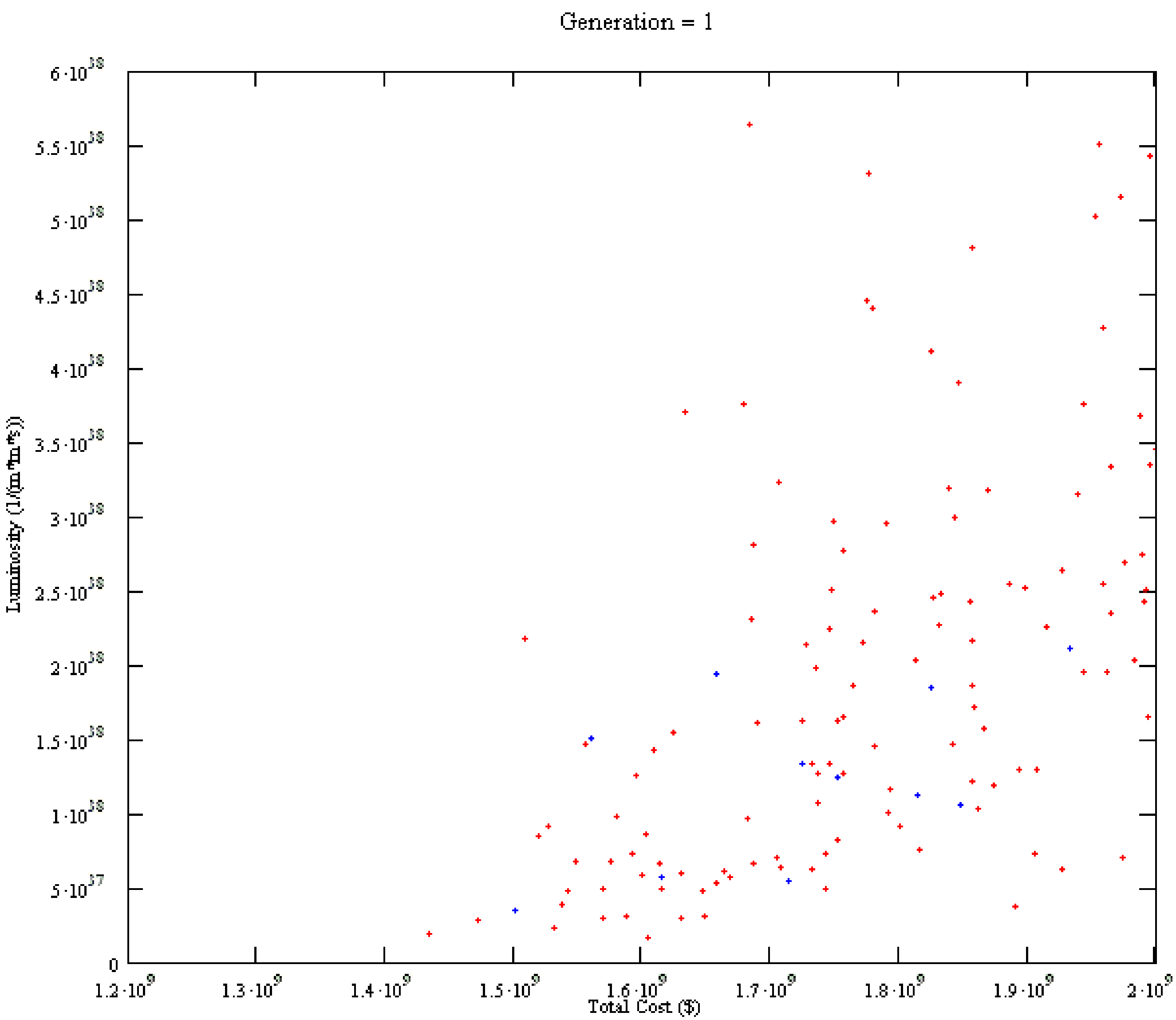
ILC linac optimal front

10 bounded decision variables, 10 constraints



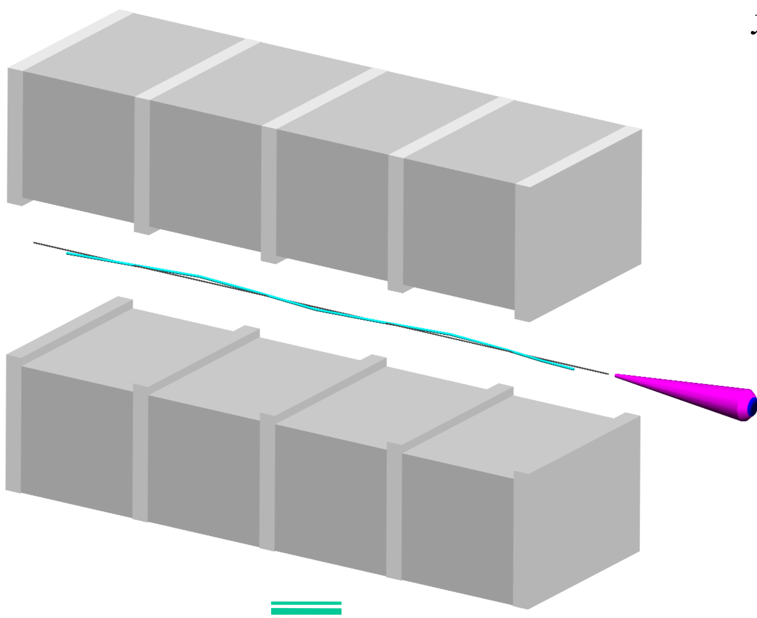
ILC linac optimization

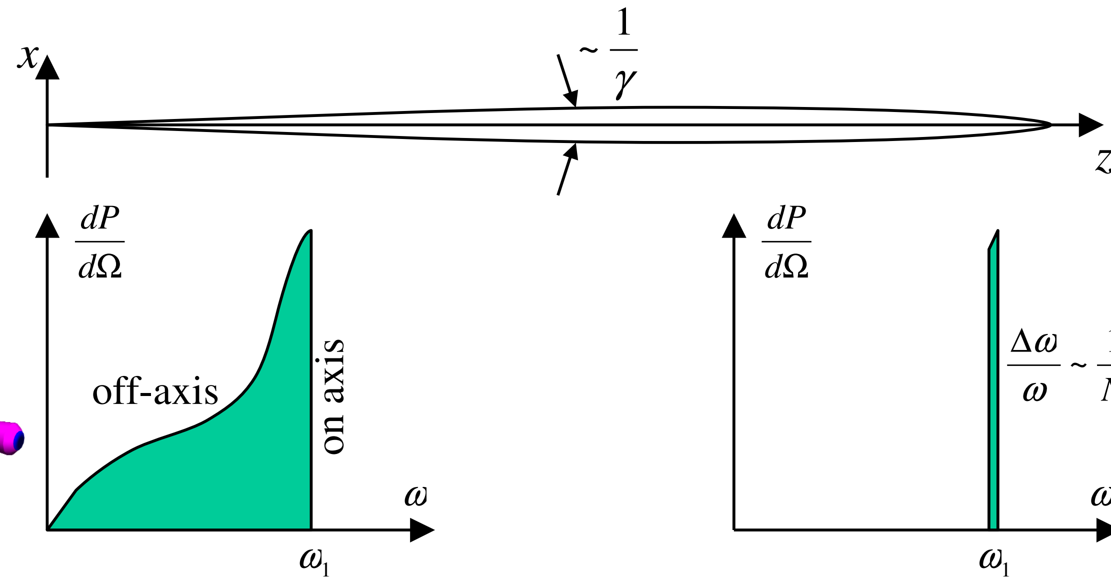
maximize **Luminosity**



minimize **Total Cost**

Basics of sync. rad. production

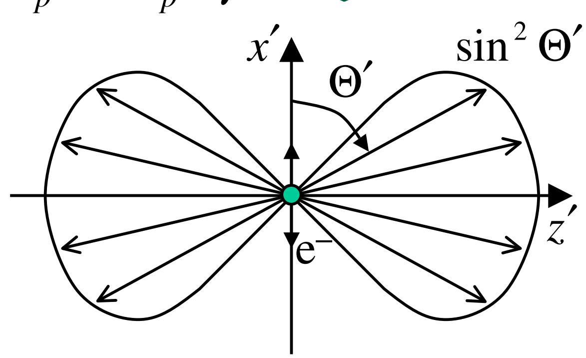




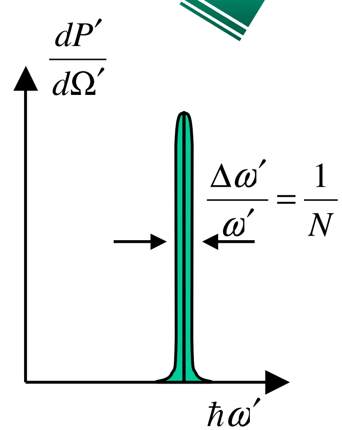
back to lab frame

after a pin-hole

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



in e⁻ frame

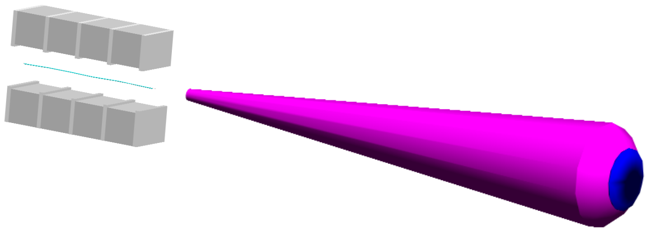


$$\lambda_n = \frac{\lambda_p}{2\gamma^2 n}\left(1 + \tfrac{1}{2}K^2 + \gamma^2\theta^2\right)$$

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

(for fixed θ only!)

Coherent enhancement



Flux in the central cone

$$\dot{N}_{ph}\Big|_n = \pi\alpha N \frac{\Delta\omega}{\omega_n}\frac{I}{e} g_n(K) \le \boxed{\pi\alpha \frac{I}{e}\frac{g_n(K)}{n}}$$

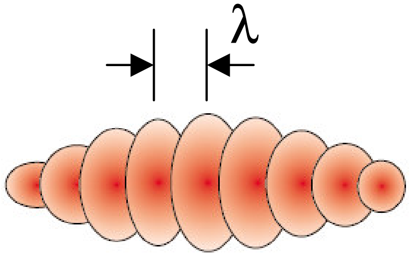
Inefficient! only 10^{-8} e-beam power converted

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.*)

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



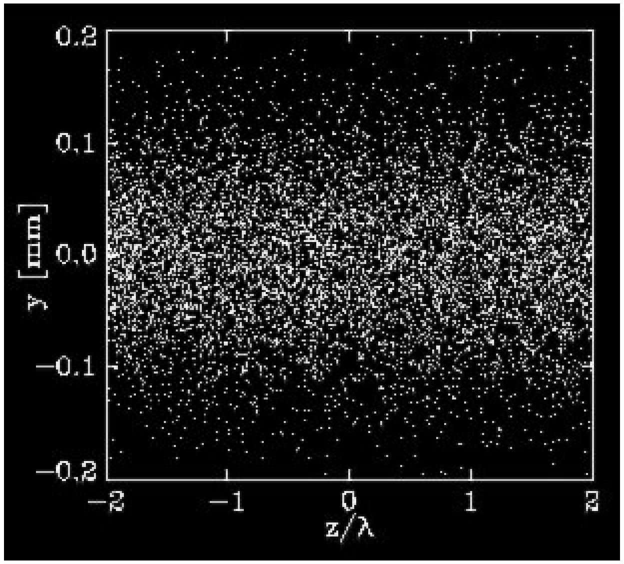
Radiation Intensity: $I = I_0 |b.f.|^2 N_e^2$

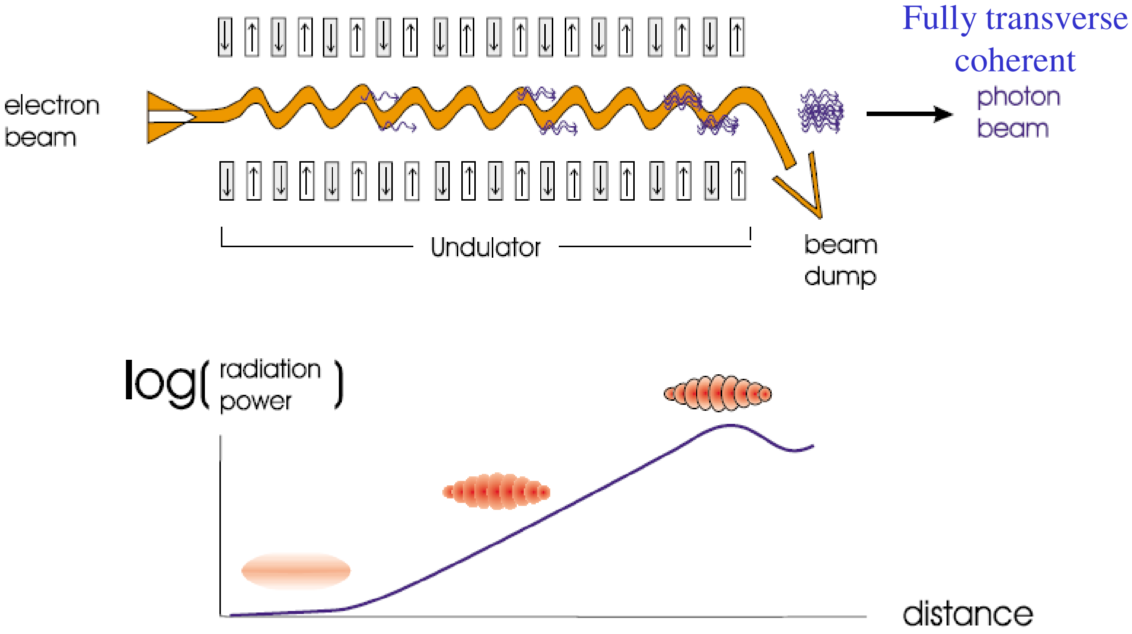
single electron

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

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

XFEL





Prerequisites for e⁻-bunch:

diffraction-limited emittance

peak current 3-5 kA

energy spread 10^{-4}

$$\frac{dE_e}{dt} = -e\vec{v}_e \cdot \vec{E}$$

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

Light brightness

- Geometric optics $B(\vec{x},\vec{\varphi};z) = \dfrac{d^4 F}{d^2\vec{x}d^2\vec{\varphi}}$

- Wave optics (Wigner distribution function)

$$B(\vec{x},\vec{\varphi};z) = \frac{d\omega}{\hbar\omega}\frac{2\varepsilon_0 c}{\lambda^2 T}\int d^2\vec{y}\left\langle E^*_{\omega,x}(\vec{x}+\vec{y}/2;z)E_{\omega,x}(\vec{x}-\vec{y}/2;z)\right\rangle e^{-ik\vec{\varphi}\cdot\vec{y}}$$

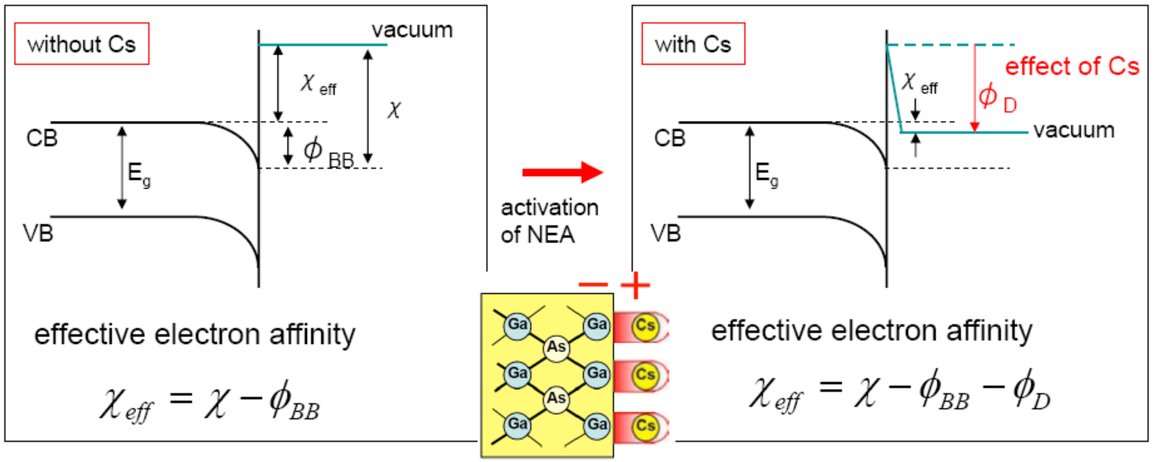
- Gaussian laser beam → $\sigma_x\sigma_{x'} = \lambda/4\pi$

- Or from uncertainty principle (light emittance):

$$std(x)std(p_x) \geq \hbar/2,$$
$$p_x \approx px' = \hbar kx',$$
$$\varepsilon_x = std(x)std(x') \geq 1/2k = \lambda/4\pi$$

$$\boxed{\varepsilon_{x,diff} = \frac{\lambda}{4\pi}}$$

Photocathode requirements



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

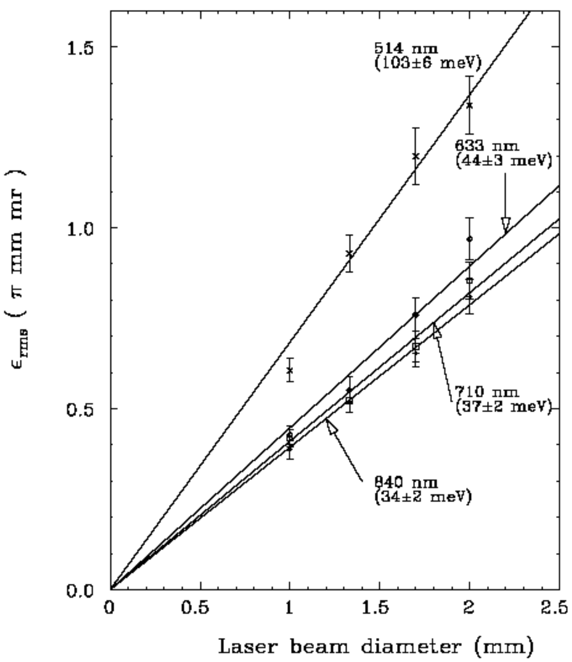
(2) electron-phonon scattering (~0.05 eV lost per collision);

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

Ideal photocathode:

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

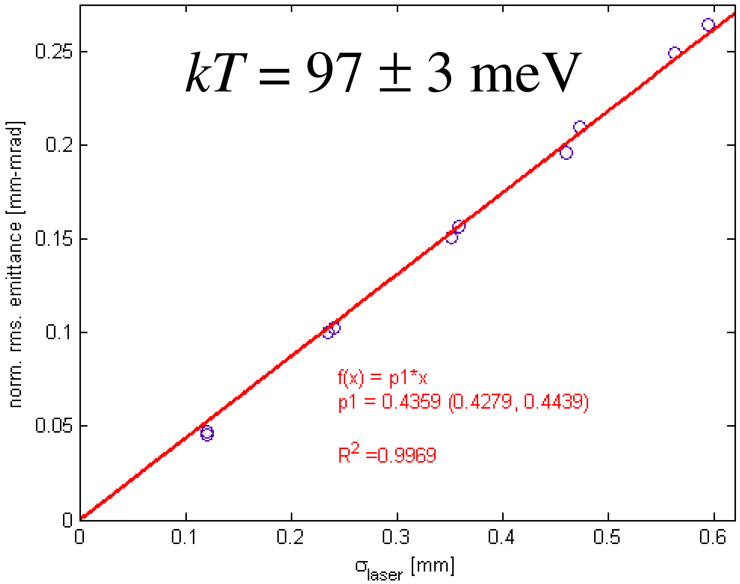
Dunham et al., PAC1995, 1030

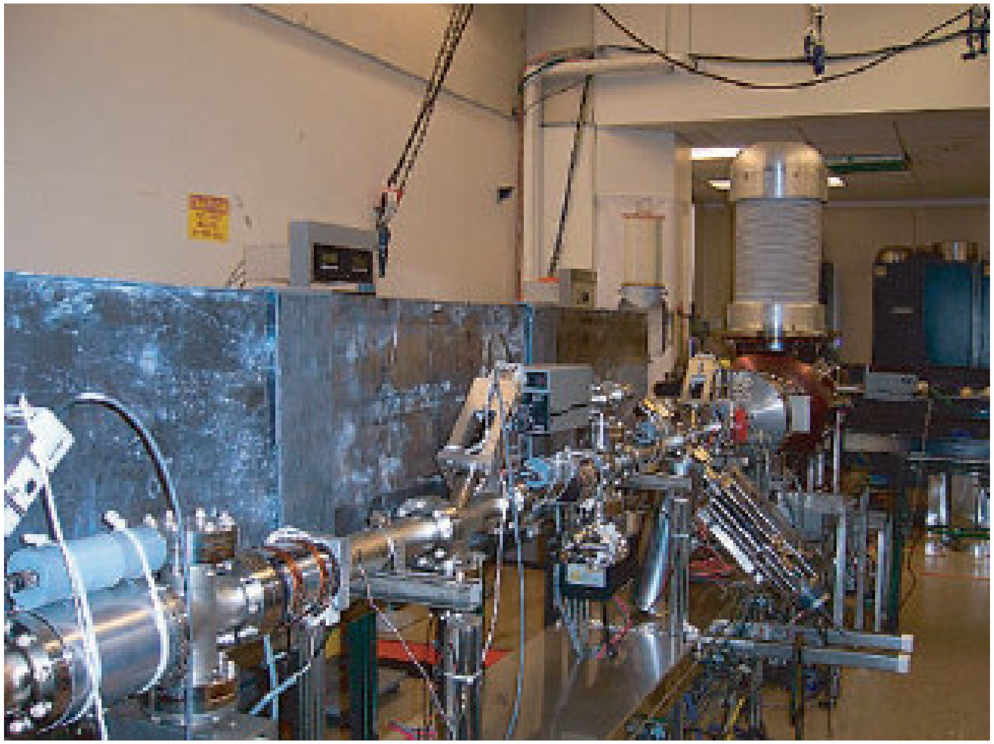


- *hν* close to bandgap – 'cold' electrons, but long response (~10ps), low Q.E.
- currently studying GaAs, GaAsP
- other possibilities GaN, Al-doped GaAs
- dream: superlattice cathode

Photocathode dev. opportunities

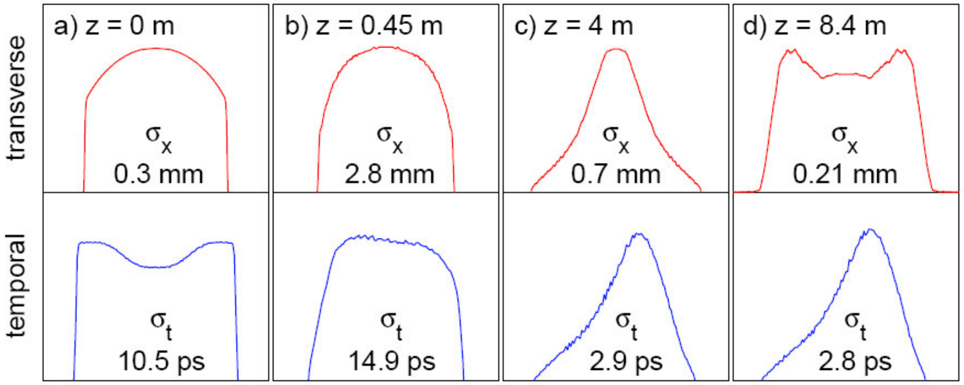
Transverse temp. of e⁻ at different wavelengths





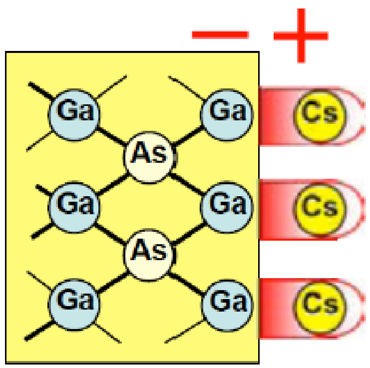
Gun development lab in Wilson

Temporal response with ps resolution

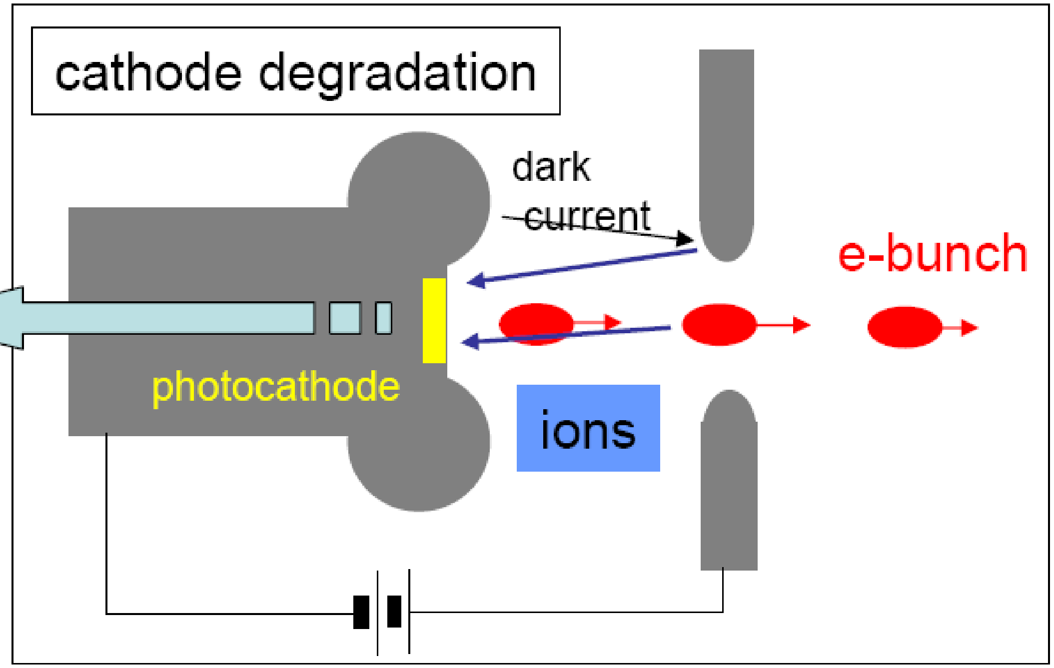


electron shape along the injector corresponding to small emittance

Cathode lifetime



re-cesiation recovers Q.E.
→ damage is only at the surface



- collision, deposition of residual gases
- dark current (and its enhancement)
- ion back bombardment

existing guns

CEBAF polarized gun（100kV, 0.1mA）

life ~ 2 x 10^5 C/cm^2

JLAB-ERL gun（350kV, 9mA）

life ~ 2 x 10^3 C/cm^2

improvement is required

ERL-LS

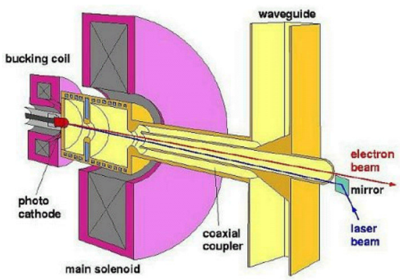
life ~ 10^6 C/cm^2

100mA / ϕ2mm、100 hours

Cathode Field ← E_{th} cathode

1 nC

NCRF

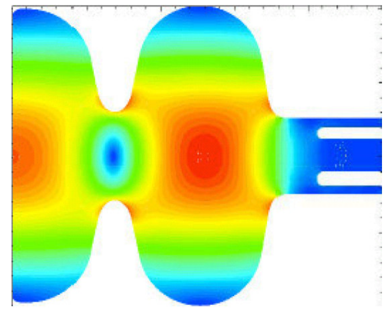


pulsed!

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

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

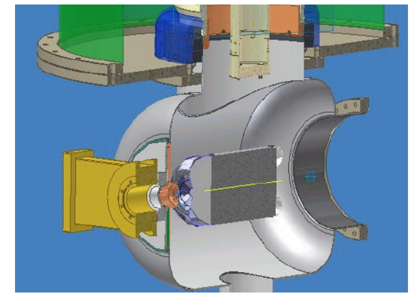
SRF



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

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

DC



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

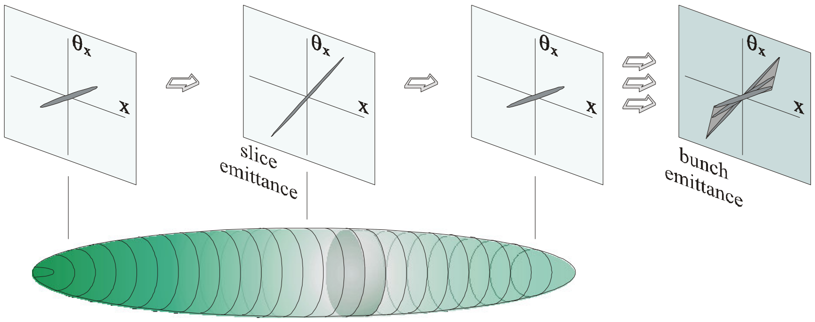
$\tau_{laser} \to z$ = 0.12 mm

2×18 MV/m　　2×6 MV/m　　2×1 MV/m

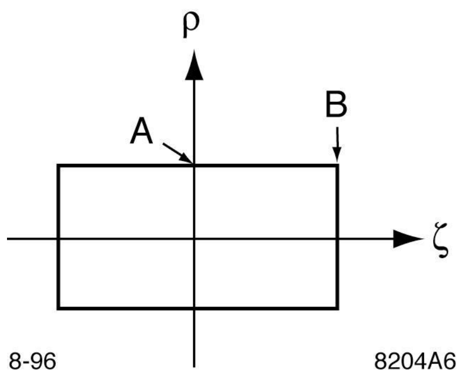
$E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$

same simulated emittance

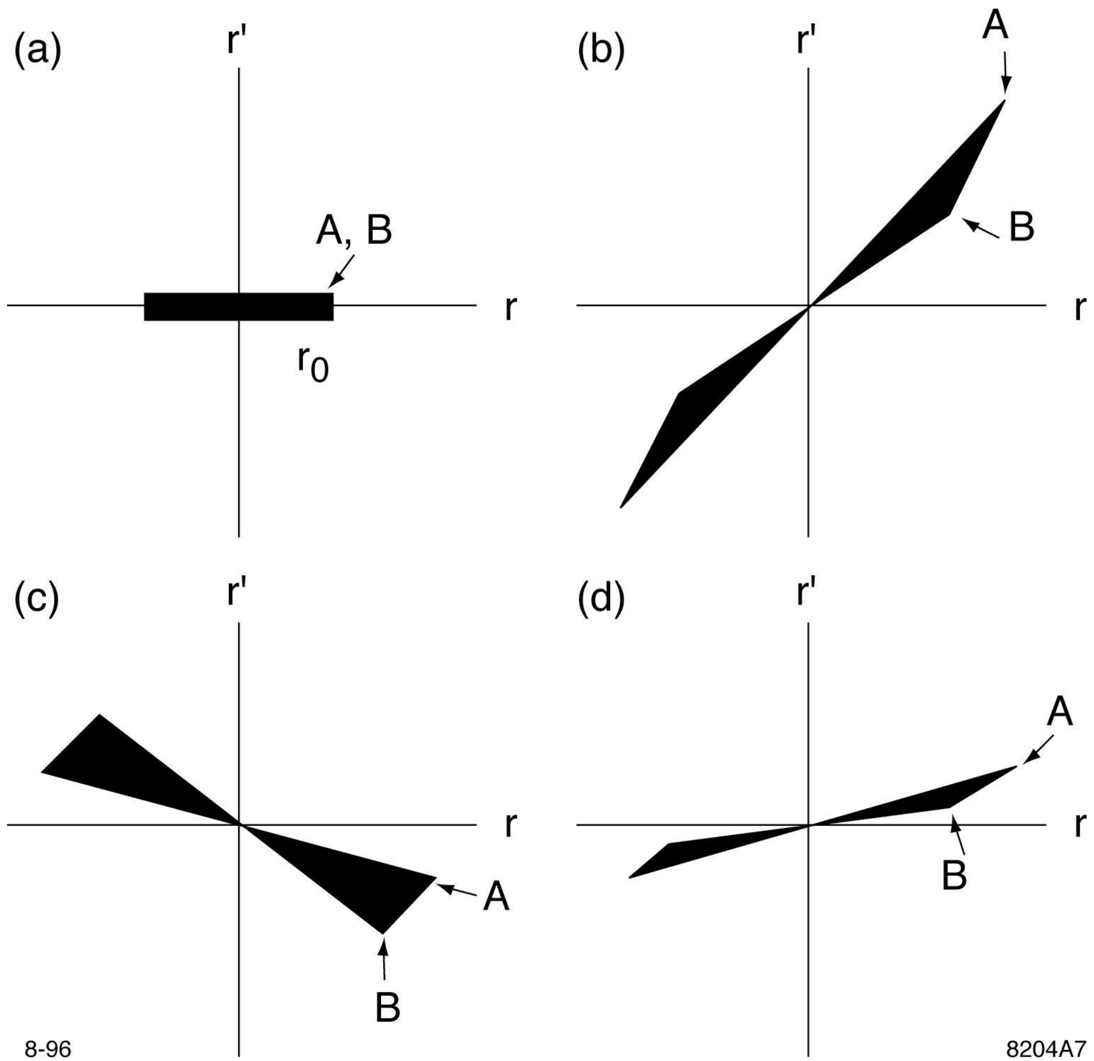
Emittance compensation



Axial cross section of
bunch charge at cathode

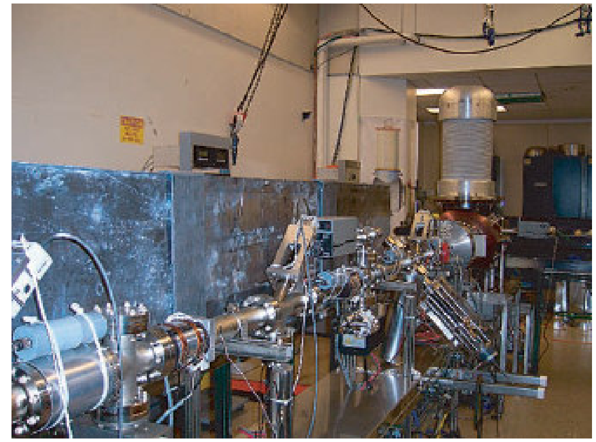


Very sensitive to optics & bunch distribution details; Need computer modeling



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

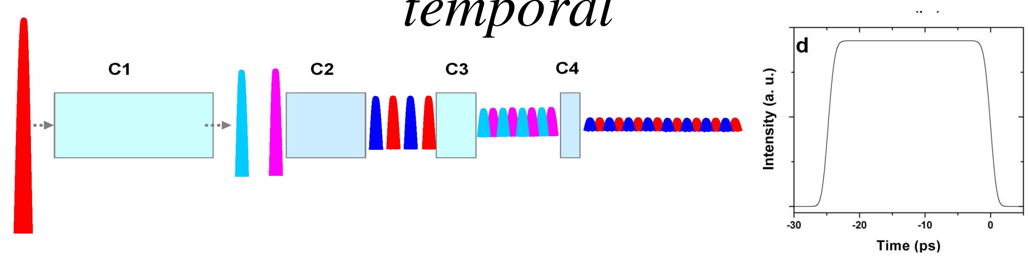
Challenges



- 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

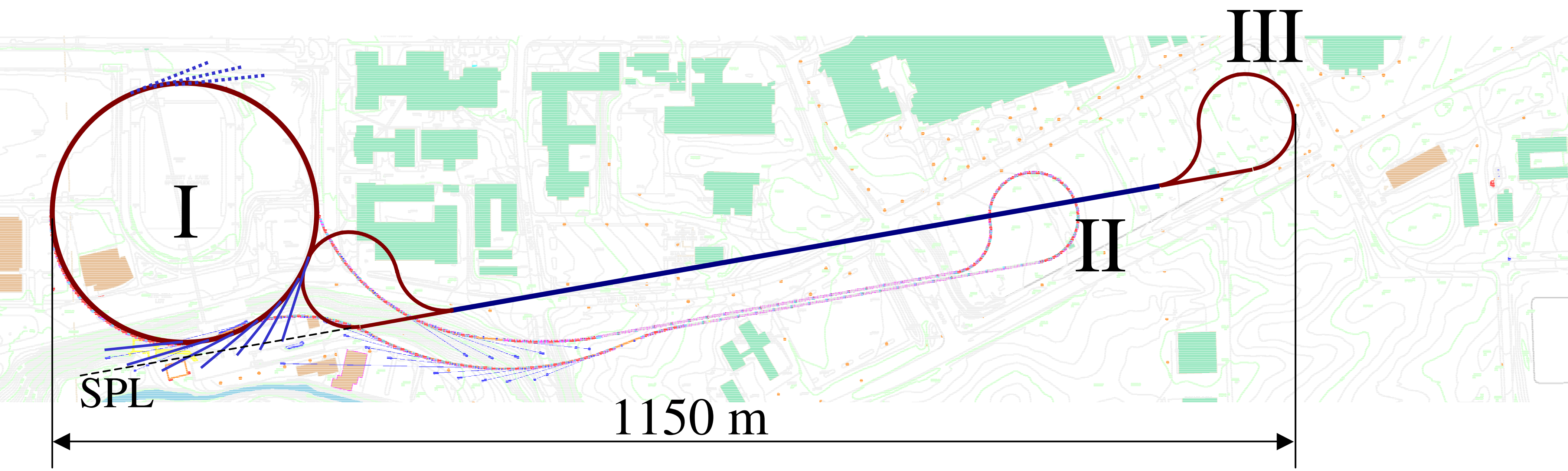


A bigger picture

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