New Electron Source for Energy Recovery Linacs

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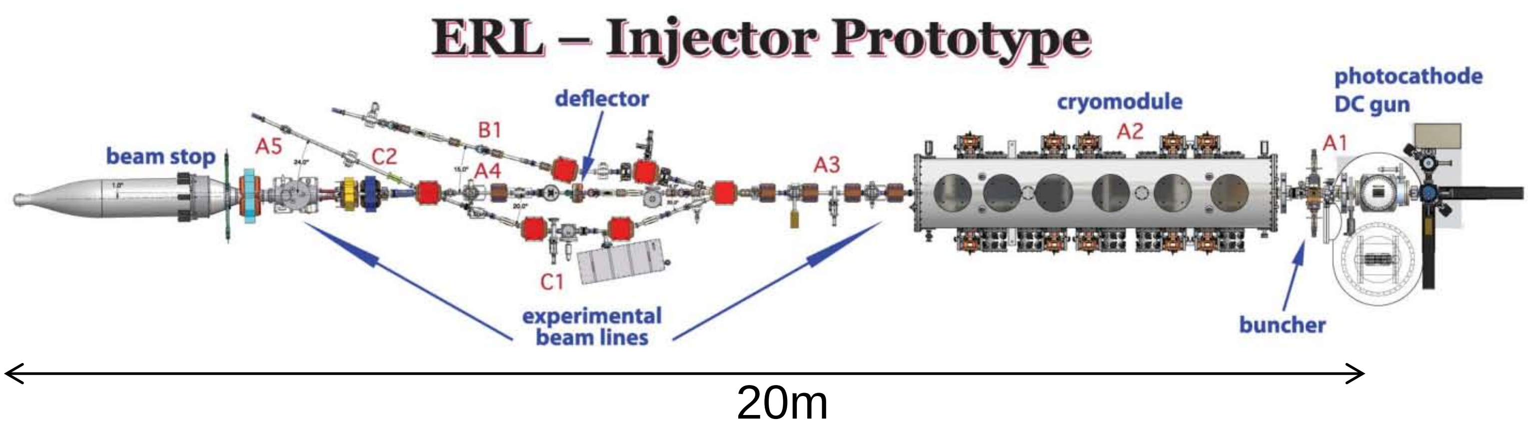
Cornell University



Cornell's photoinjector: world's brightest electron source

Outline

- **Uses of high brightness electron beams**
- **Physics of brightness**
- **High brightness high current photoinjectors**
- **Cornell photoinjector for Energy Recovery Linac**

Acknowledgements: our team & NSF for funding

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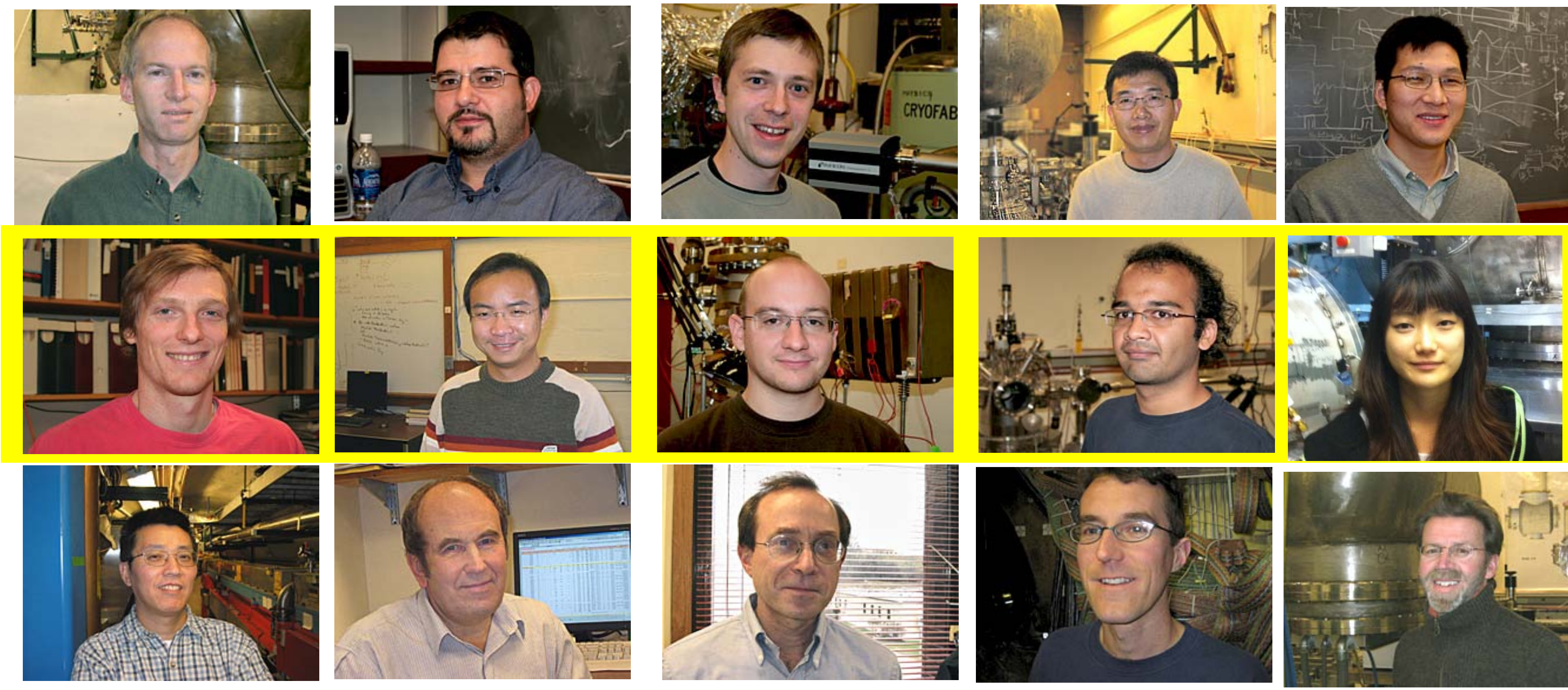
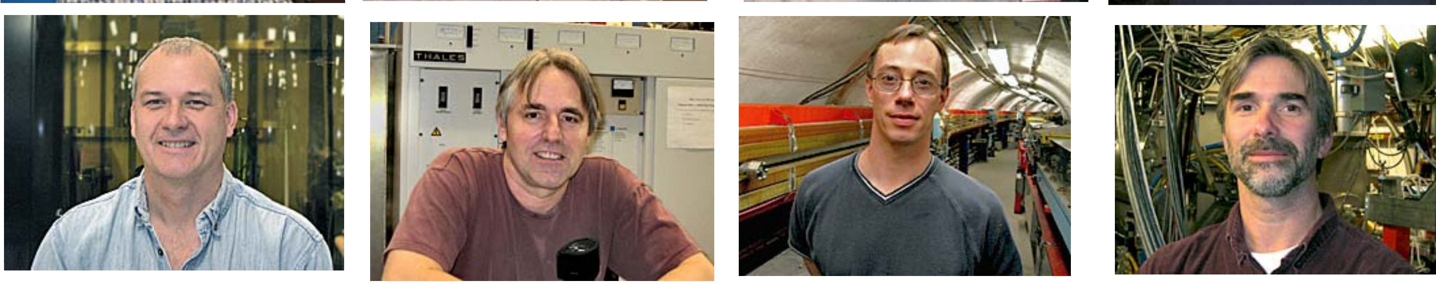


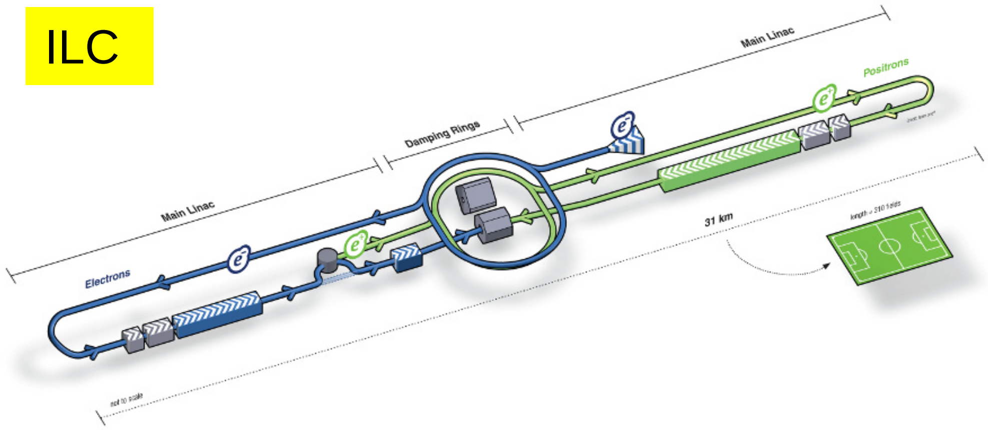


and more …

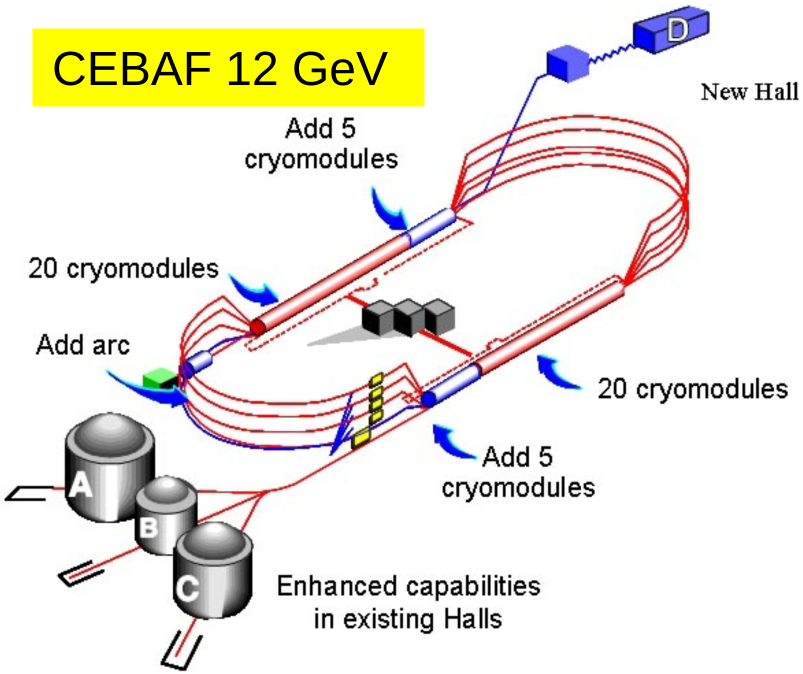
Need for high brightness beams

- **Powerful probes of matter**
  - **Colliders, fixed target experiments**

ILC



CEBAF 12 GeV



Need for high brightness beams

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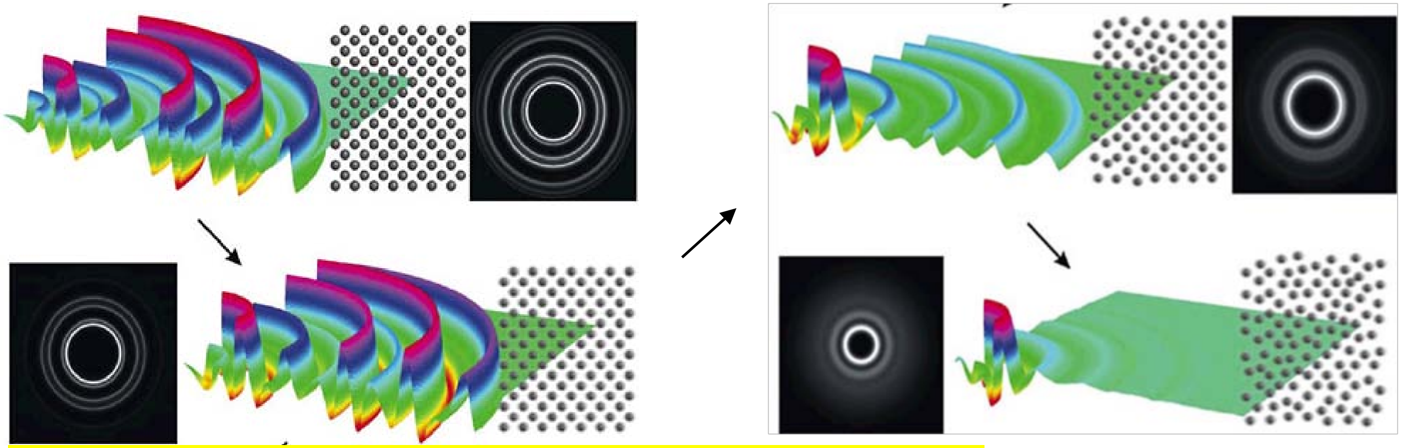
  - **Small lab scale probes (e.g. ultrafast electron diffraction)**



600 fs snapshots of Al melting, Dwayne Miller, U Toronto

Need for high brightness beams

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- **Sources of secondary beams**
  - **Synchrotron radiation sources: storage rings, free electron lasers, energy recovery linacs**

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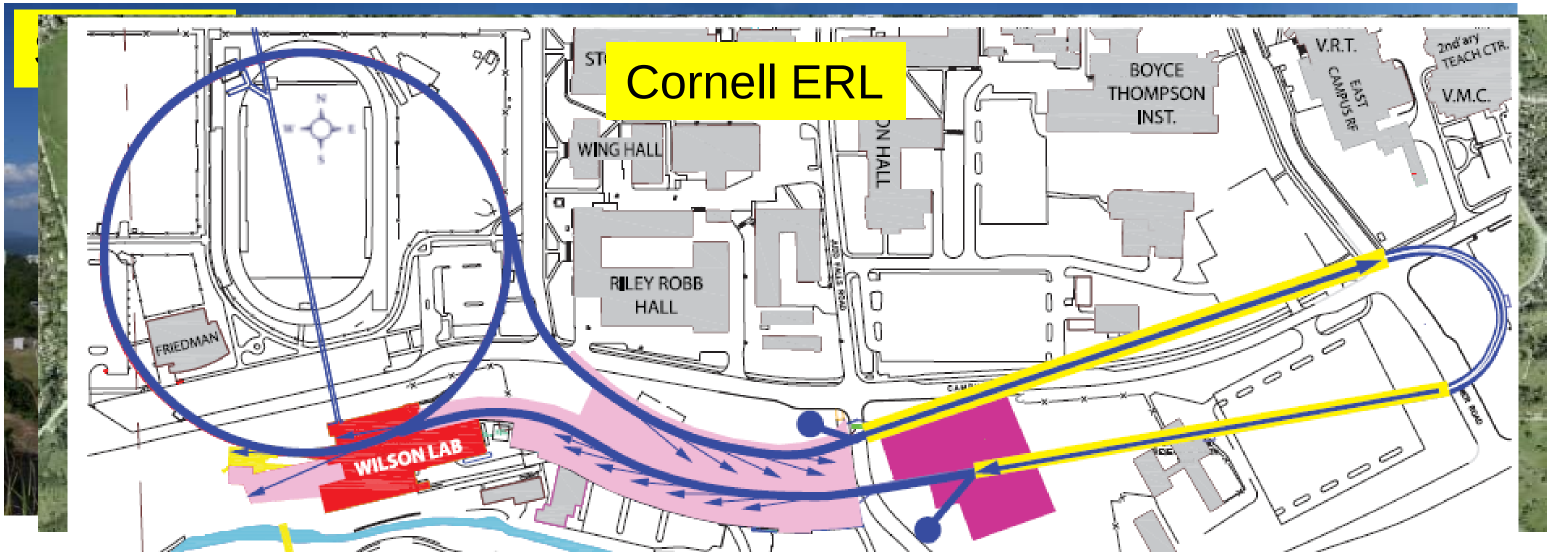

Need for high brightness beams

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- Powerful probes of matter
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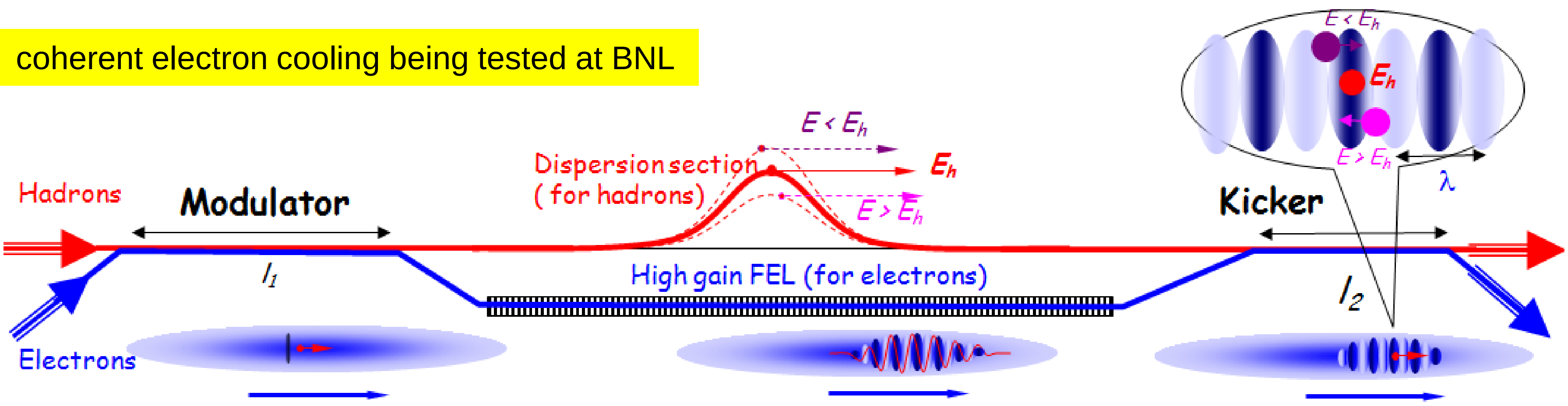
- Cooling of hadron beams

coherent electron cooling being tested at BNL



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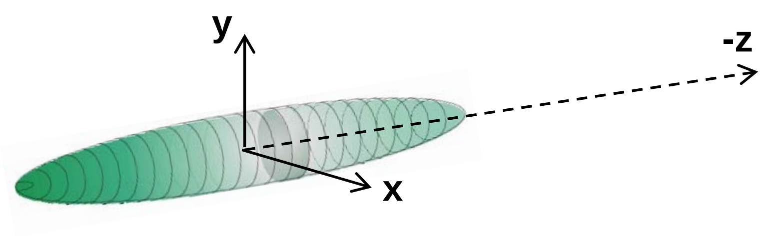
What is brightness?

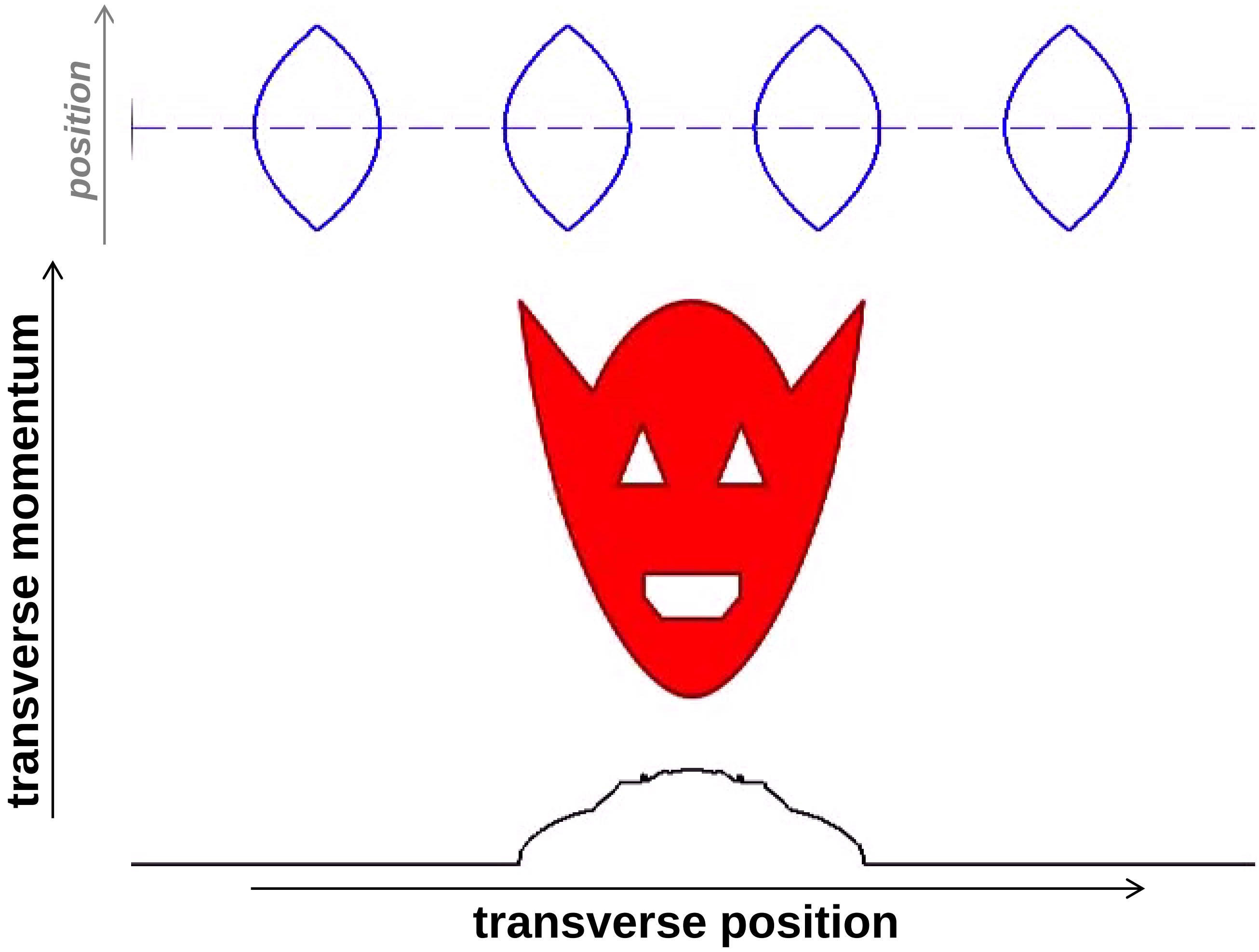
- **6D phase space**
  - **$\{x, p_x, y, p_y, E, t\}$**



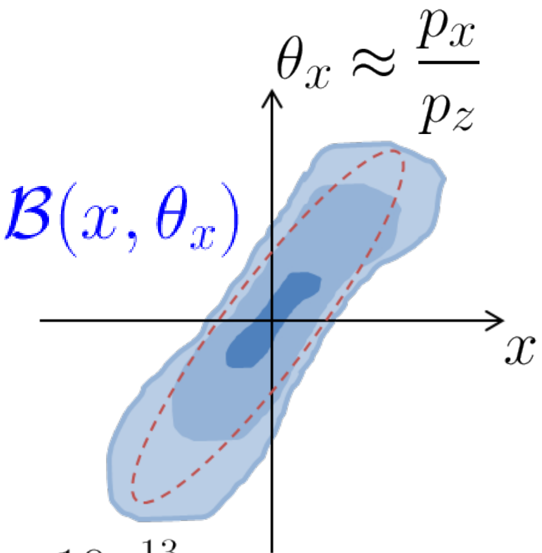
- $$\mathcal{B}_{4D} = \frac{\text{flux or current}}{\text{4D phase space volume}}$$

- **Connection to:**
  - **Liouville theorem, beam temperature, entropy, coherence**

Example: linear optics beamline of non-interacting particles



Some definitions

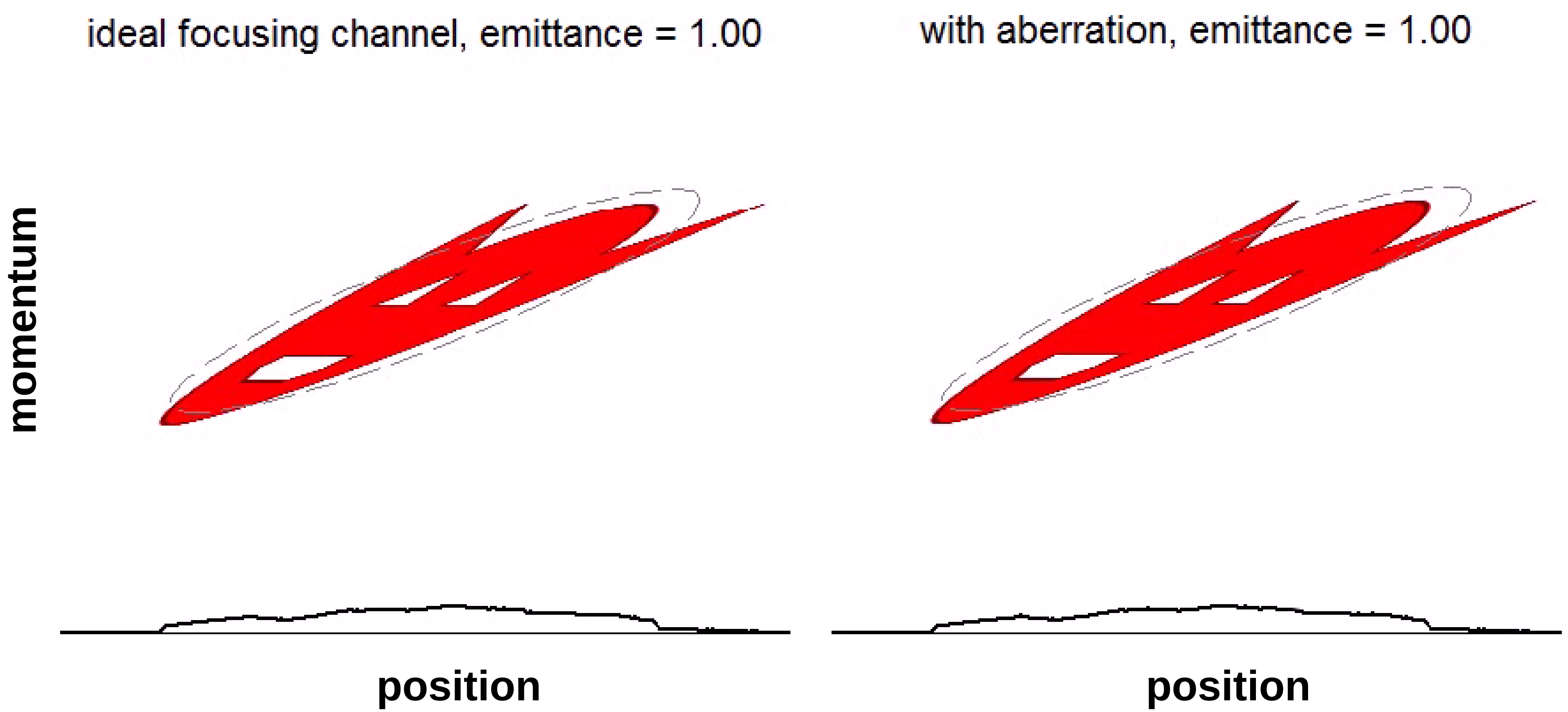


- **Micro-brightness**: $\mathcal{B}_{\rm 2D}(x,p)$
  - **Flux:** $\mathcal{F} = \iint \mathcal{B}\, dx dp$
- **Normalized emittance (phase space area)**:

$$\epsilon_{\rm norm} = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2}$$

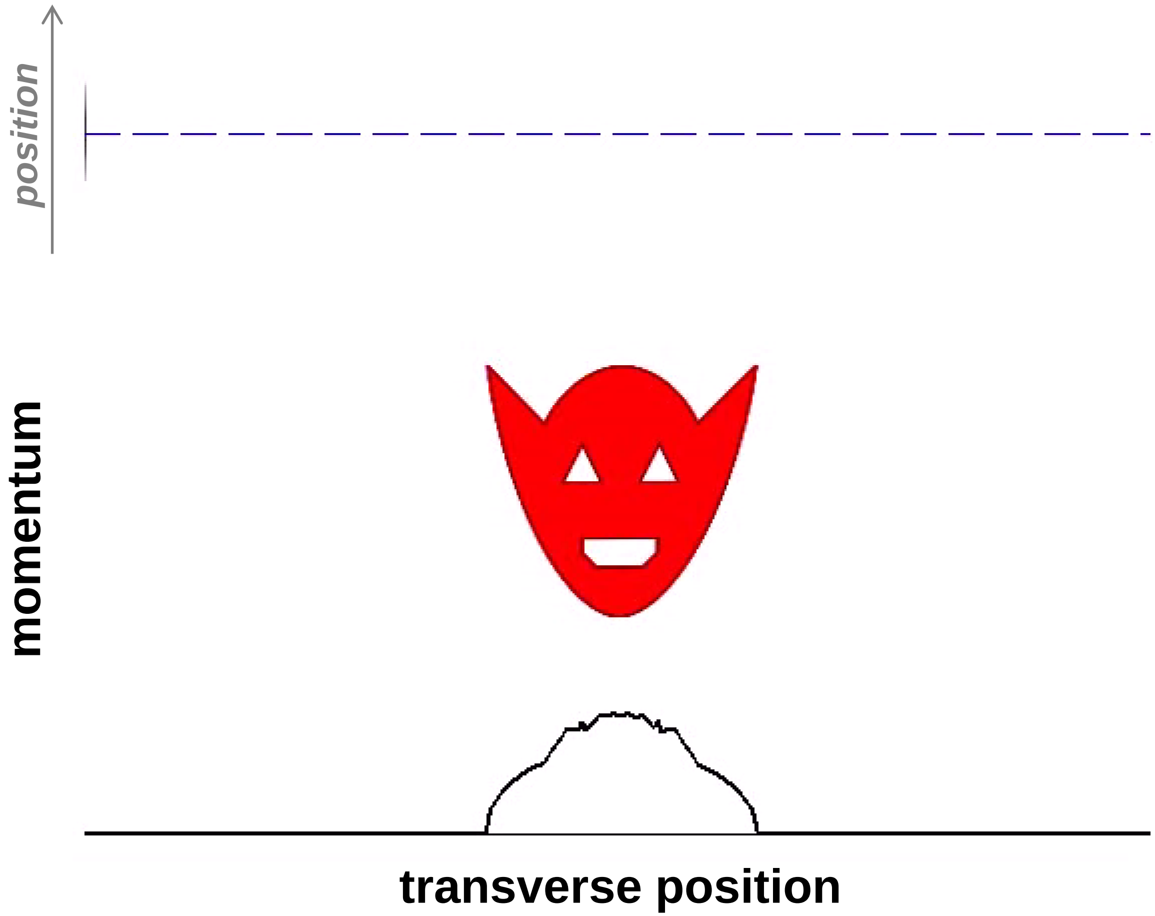
  - **e.g. quantum limit for e⁻:** $\epsilon_{\rm norm} = \frac{\hbar/2}{m_e c} = 1.93\times 10^{-13}\,{\rm m}$
  - **geometric emittance**: $\epsilon_{\rm geom} = \sqrt{\langle x^2\rangle\langle \theta_x^2\rangle - \langle x\theta_x\rangle^2} = \epsilon_{\rm norm}/(\beta\gamma)$
- **Alternative definition of phase space area (volume)**
  - **"Liouville's emittance"**: $\epsilon_{\rm Liouville} = \left[\frac{4\pi}{mc}\iint\left(\frac{\mathcal{B}}{\mathcal{F}}\right)^2 dx\, dp\right]^{-1}$

Linear and non-linear motion (continuous focusing channel)

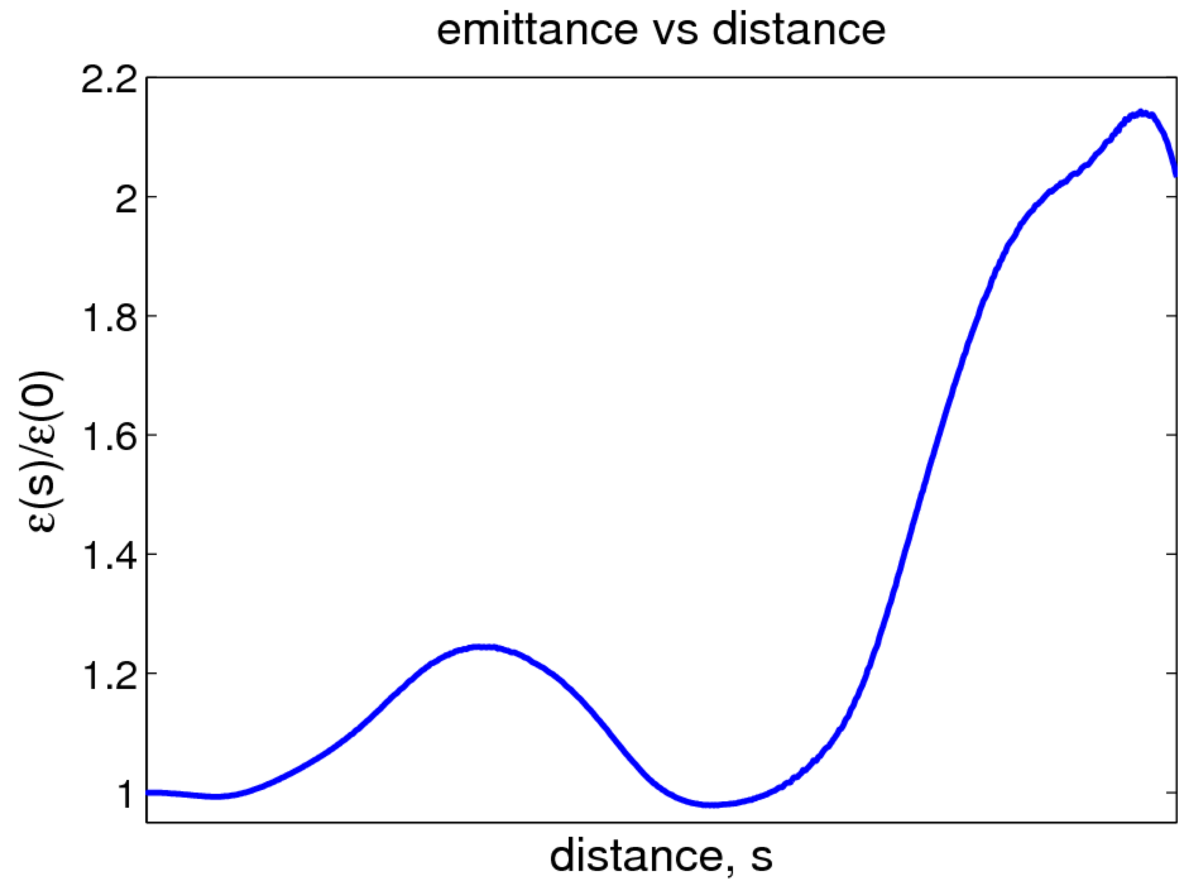


- **Liouville's emittance: const in both cases**

Space charge in a continuous focusing channel



Space charge in a continuous focusing channel



- **But Liouville's emittance stays const**

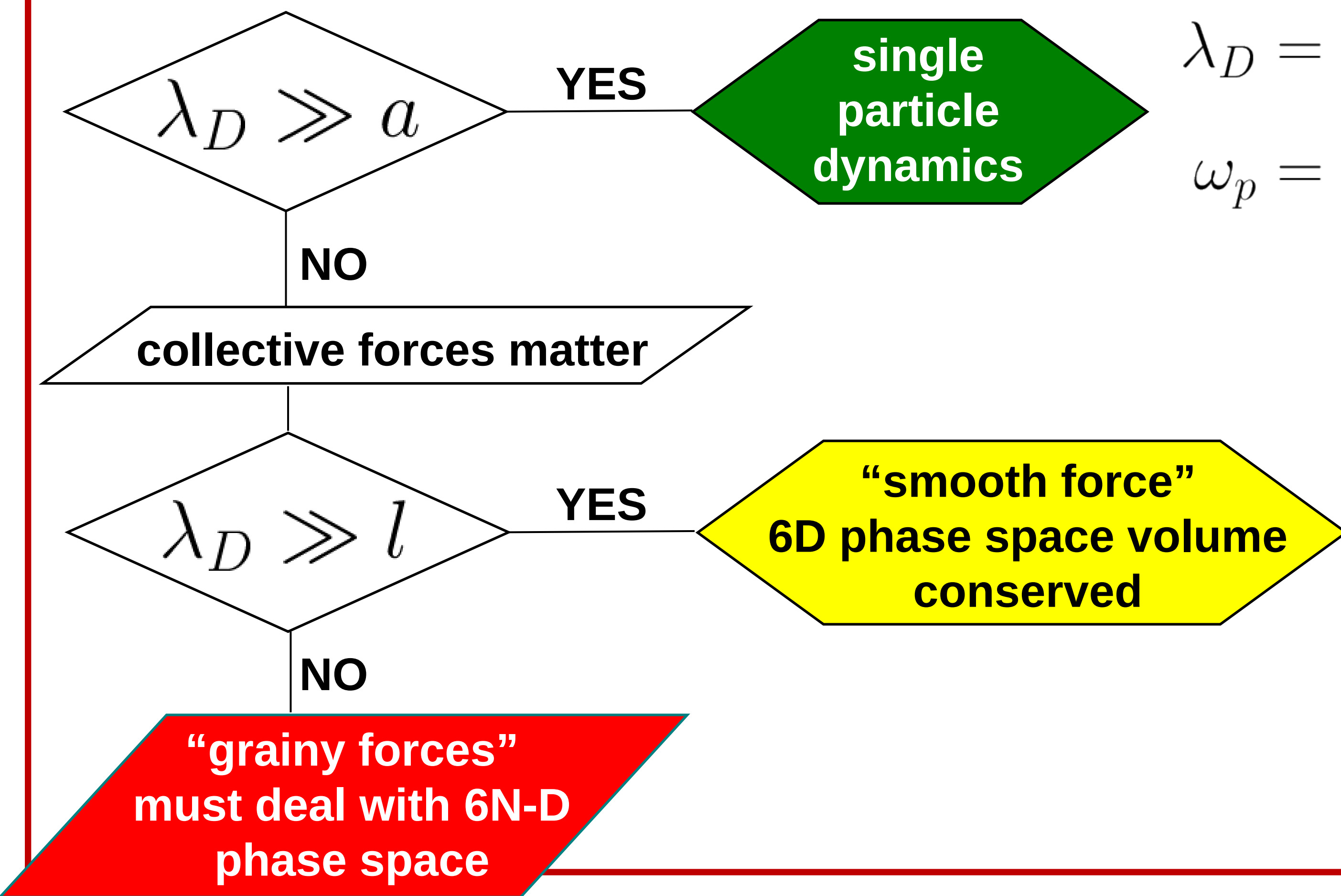
Tricky space charge

- **Beam as non-neutral plasma: 3 characteristic lengths**

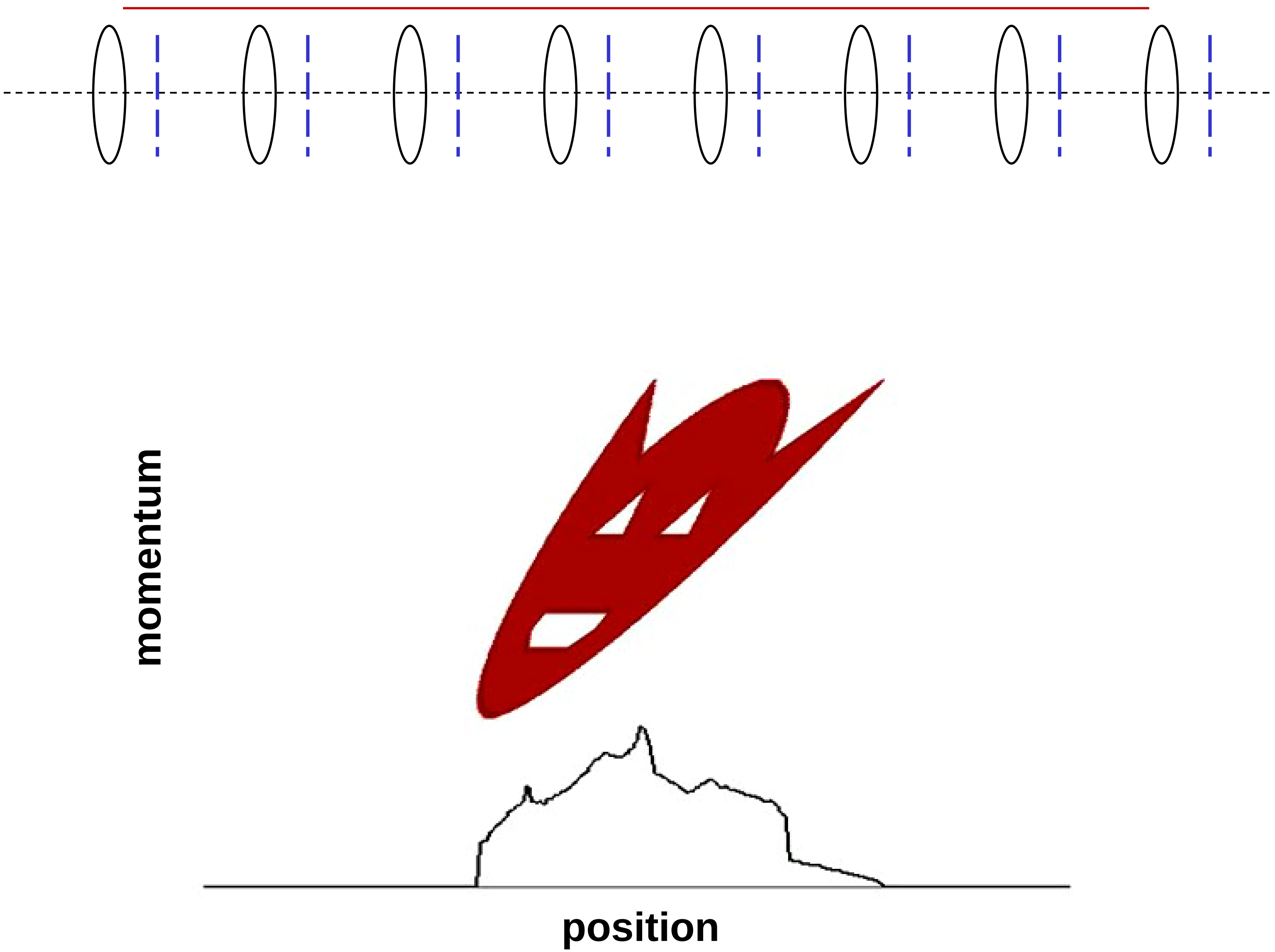
  a **beam diameter;** l **inter-particle distance;** λ_D **Debye length**

$$\lambda_D = \frac{\sigma_{v_\perp}}{\omega_p} = \frac{\sqrt{k_B T_\perp / \gamma m}}{\omega_p}$$

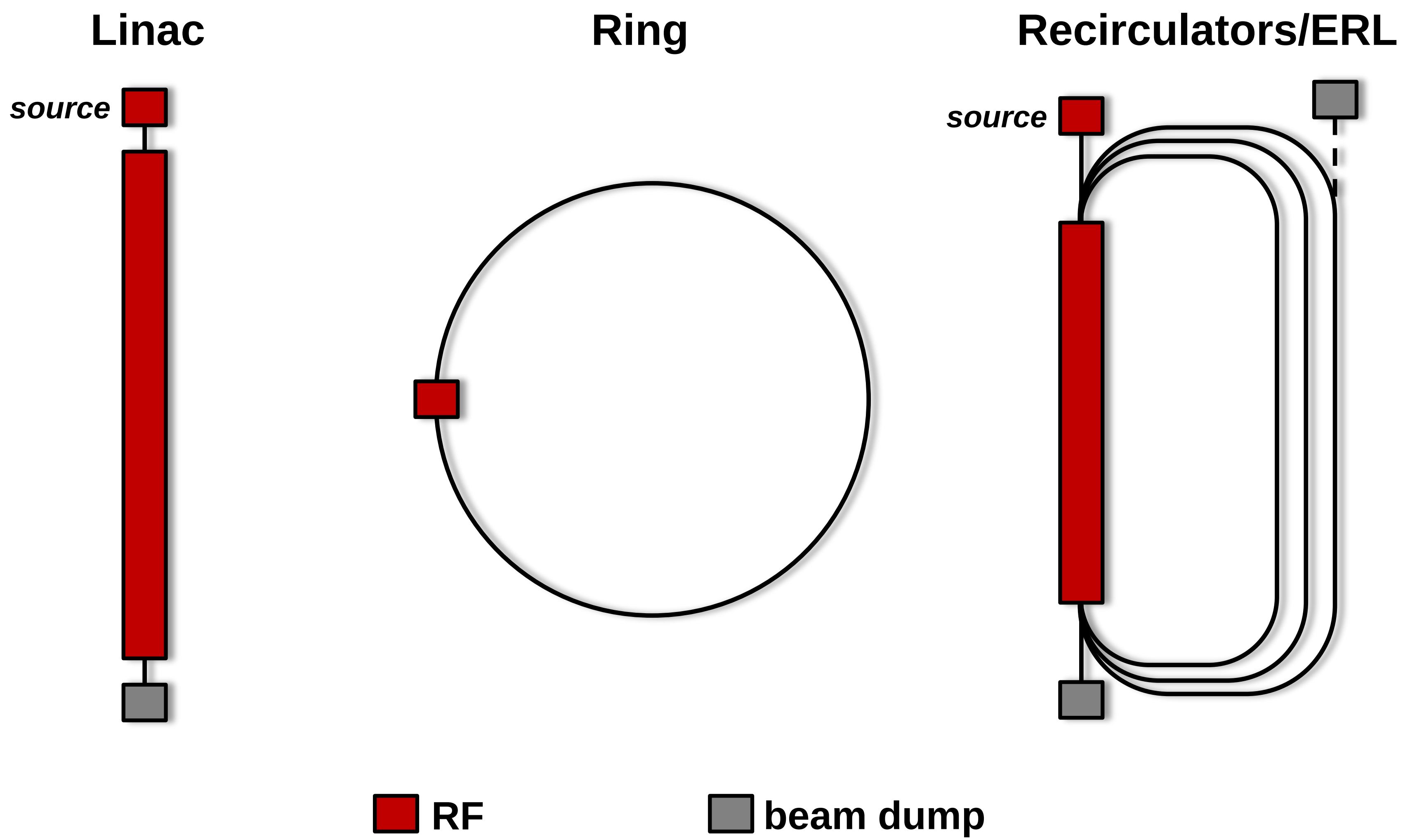
$$\omega_p = \sqrt{\frac{e^2 n}{\epsilon_0 m \gamma^3}}$$



Information loss in phase space



Accelerator topologies

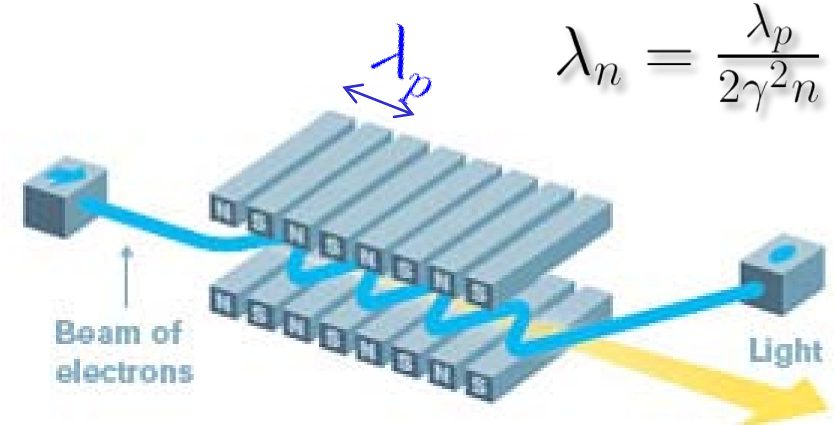


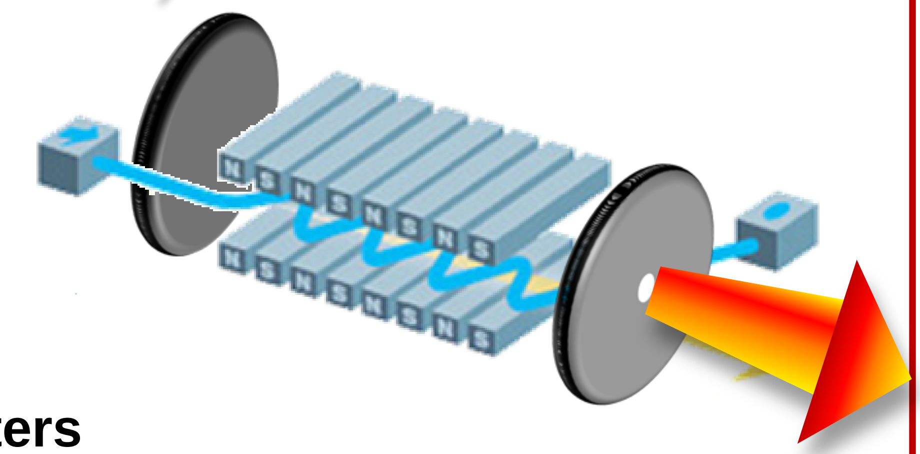
Synchrotron radiation sources

- **Some approaches to light production**

undulators (spontaneous emission) ***Free-electron-laser (oscillator)***

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





- **Desired electron beam parameters**
  - **Transverse phase space area (emittance) ~ wavelength**
  - **Energy spread ~ 1/#periods**
  - **Short pulses (~ picosecond and less)**

Storage rings for hard x-rays

CLASSE

APS: circumference 1.1 km, emittance 3 nm

ESRF: circumference 0.84 km, emittance 4 nm

Spring-8: circumference 1.4 km, emittance 3 nm

PETRAIII: circumference 2.3 km, emittance 1 nm

Storage rings for hard x-rays

APS: circumference 1.1 km, emittance 3 nm

ESRF: circumference 0.84 km, emittance 4 nm

For transverse coherence at 1Å require

$$\epsilon_{\text{geom}} = \frac{\lambda}{4\pi} \approx 0.01\,\text{nm}$$

Spring-8: circumference 1.4 km, e

e 2.3 km, emittance 1 nm

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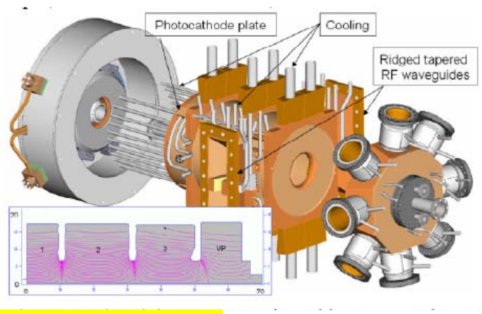
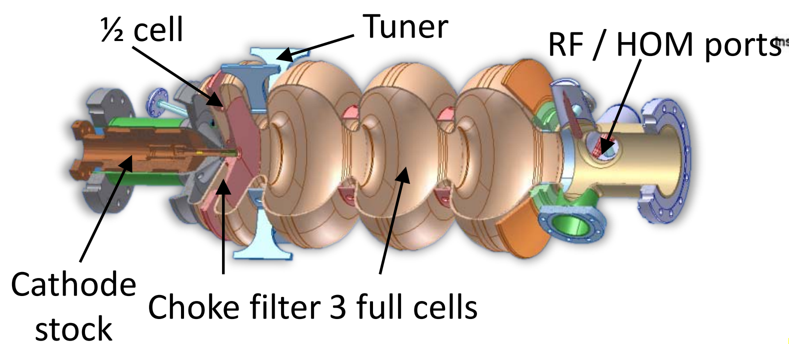
Photoinjectors = marriage of physics and technology

normal conducting RF gun



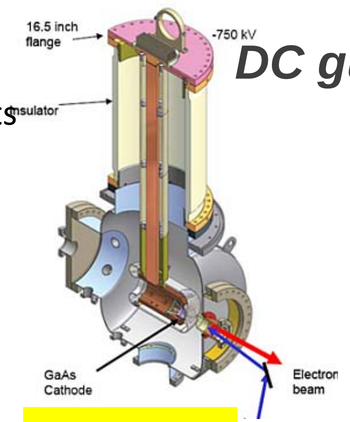
LANL RF gun

SRF gun



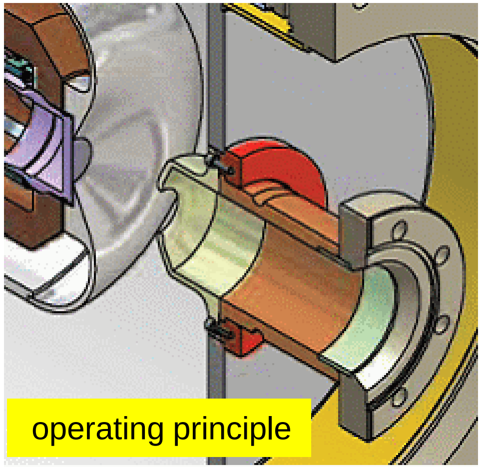
ELBE SRF gun

DC gun



Cornell gun

plus variants…

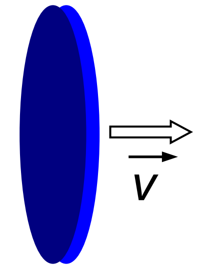


operating principle

- **CW operation: max cathode fields: (DC ≤10 MV/m), NCRF (≤ 20 MV/m), best promise for SRF (≤ 30 MV/m)**

Physics 101: basic limit to beam brightness from photoinjectors

- **Each electron bunch assumes a 'pan-cake' shape near the photocathode for short ($\leq$ 10ps) laser pulses**



- **Maximum charge density determined by the electric field:**

$$dq/dA = \varepsilon_0 E_{cath}$$

- **Angular spread set by mean transverse energy (MTE) of photoelectrons**

$$\Delta p_\perp \sim (m \times MTE)^{1/2}$$

$$\left.\frac{B_n}{f}\right|_{max} = \frac{\varepsilon_0 mc^2}{2\pi} \frac{E_{cath}}{MTE} \qquad \epsilon_{n\perp} = \sqrt{\frac{3}{10\pi\varepsilon_0 mc^2} q \frac{MTE}{E_{cath}}}$$

Phys. Rev. Lett. 102 (2009) 104801

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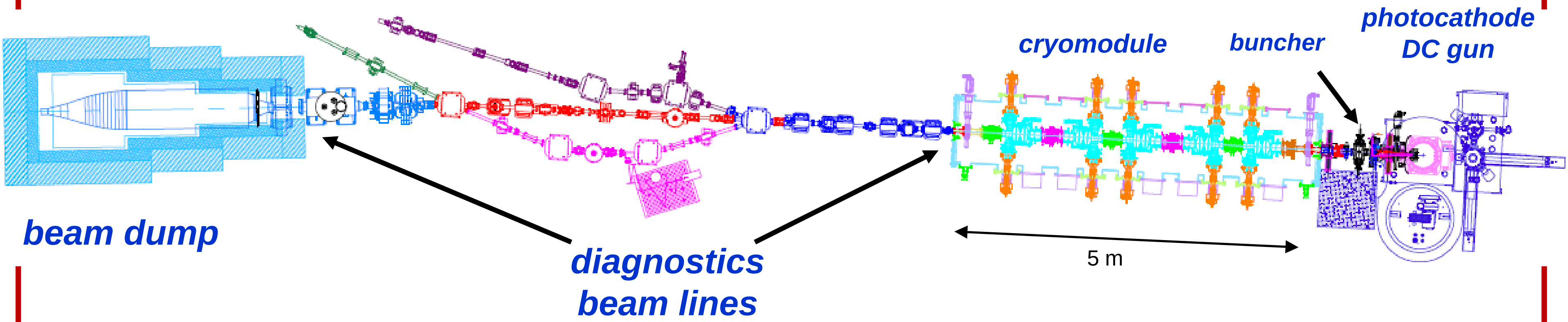
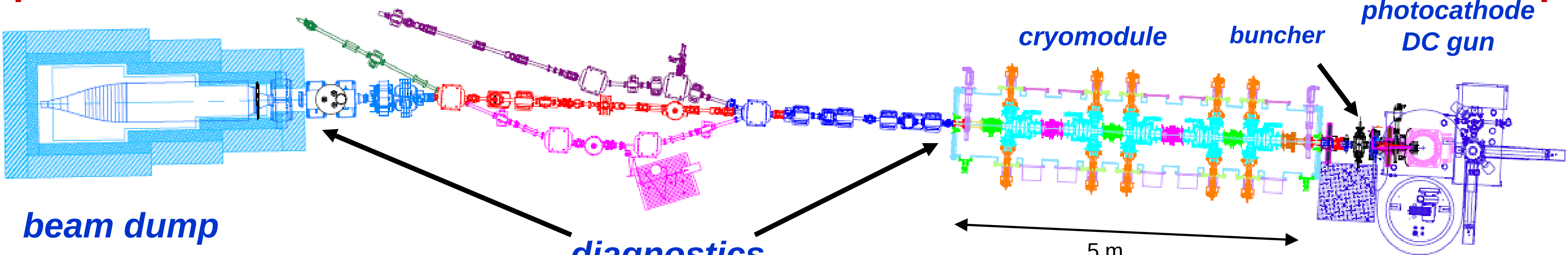
Cornell photoinjector



- **NSF-supported accelerator R&D test-bed, fully beam-operational starting 2010**
  - **Main goals:** **<1 μm normalized rms emittance (to best storage rings)**
    average current 33mA @ 15MeV & 100mA @ 5MeV
    (demonstrate photocathode longevity)
    2-3 ps bunch length

Cornell photoinjector



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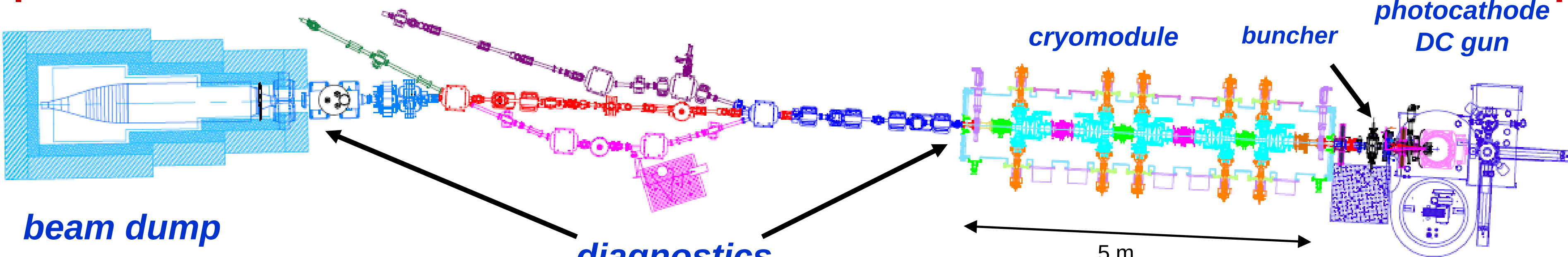

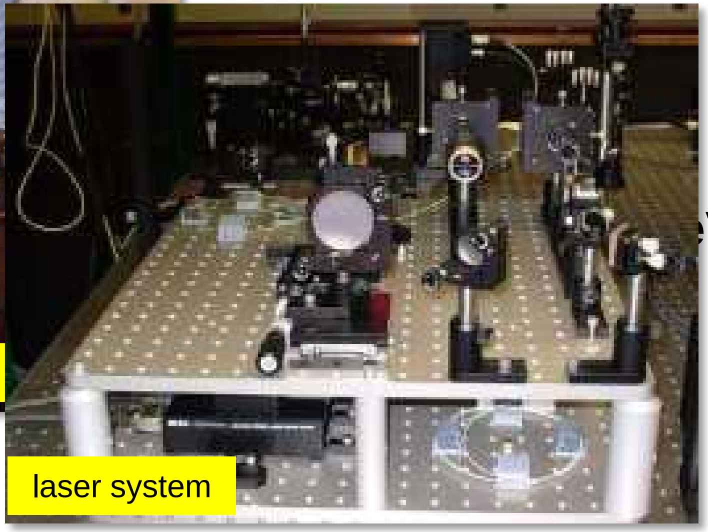

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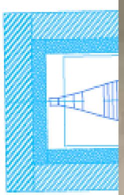

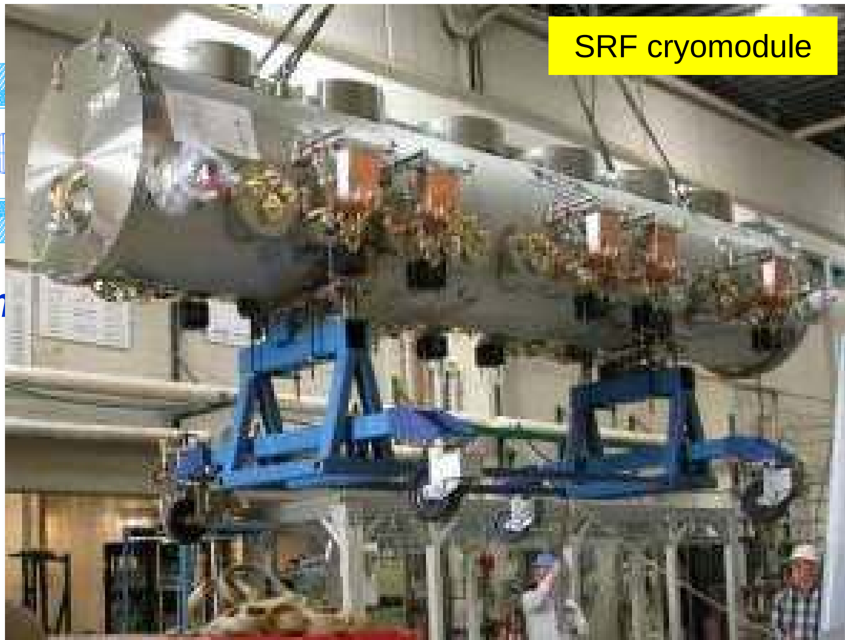

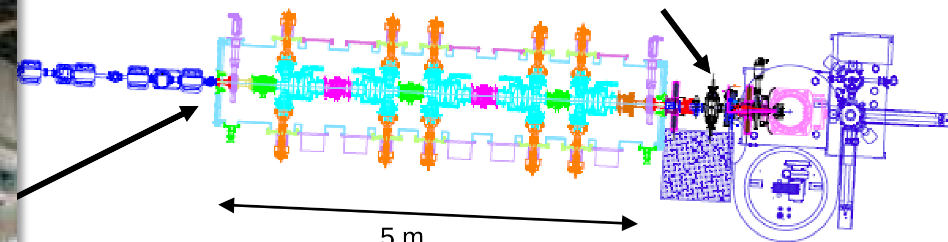

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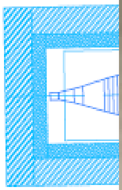
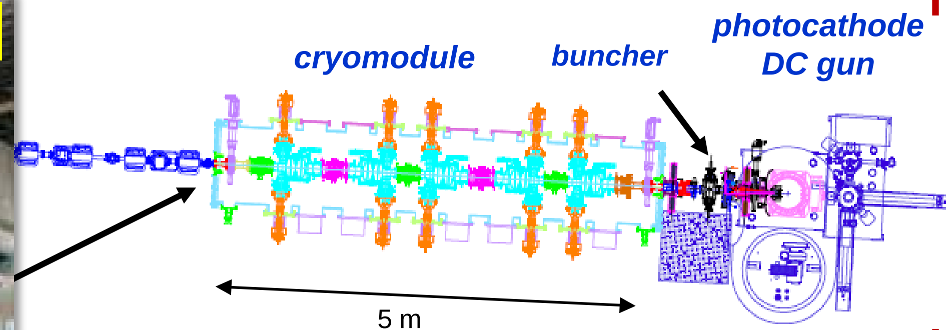


bean



- ully beam-operational
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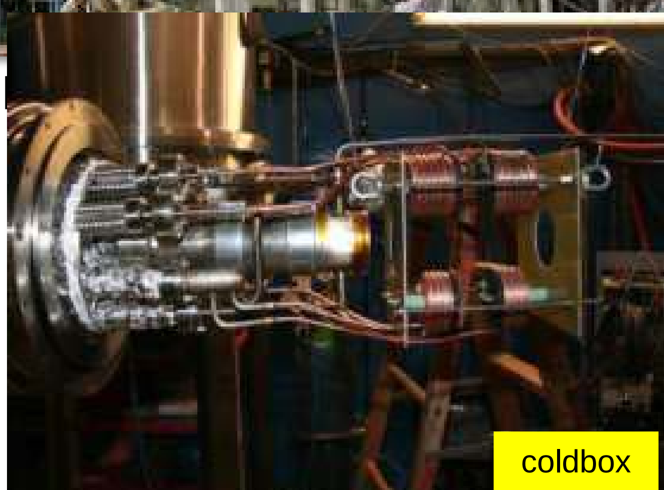
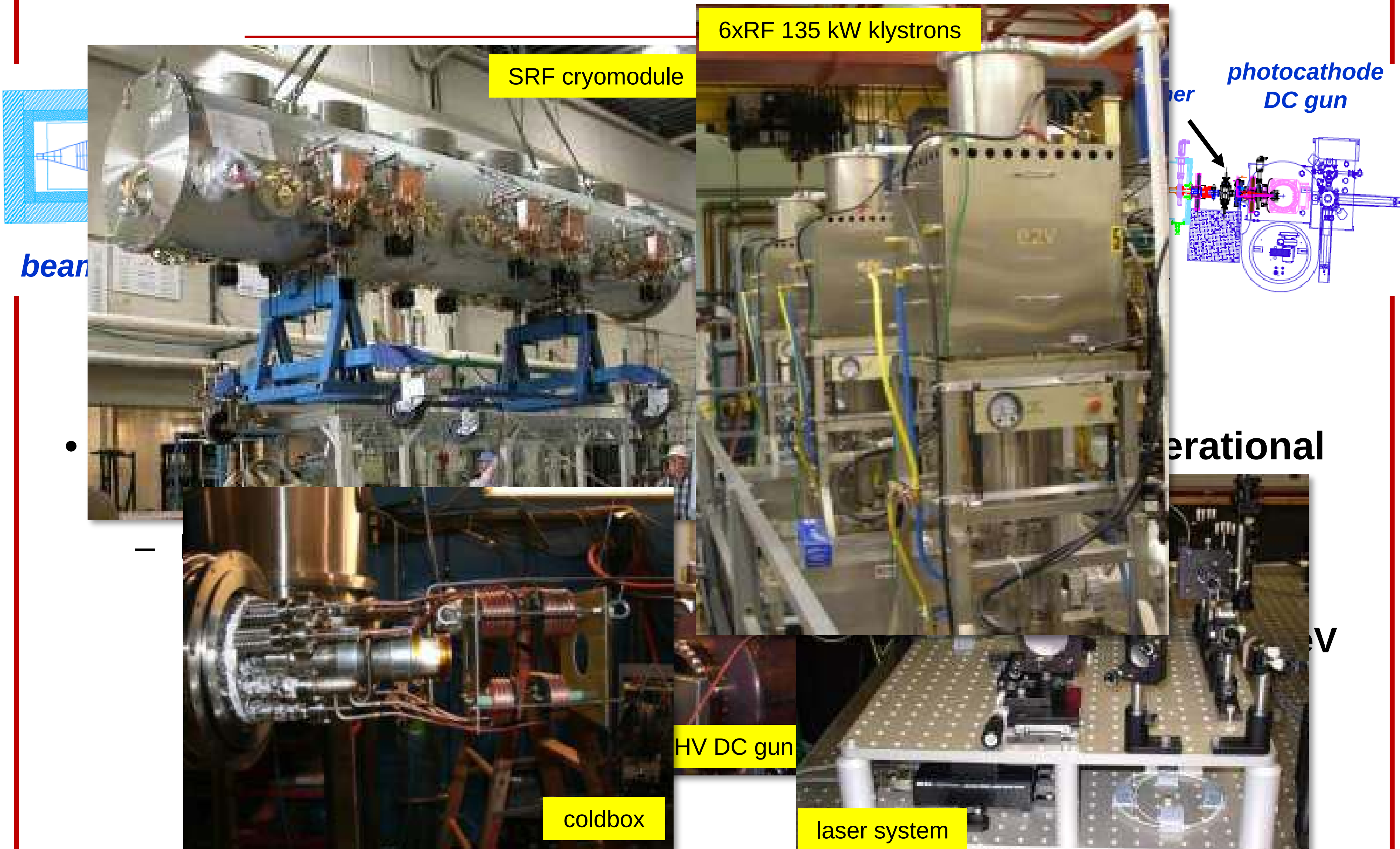
V



Cornell photoinjector



Cornell photoinjector

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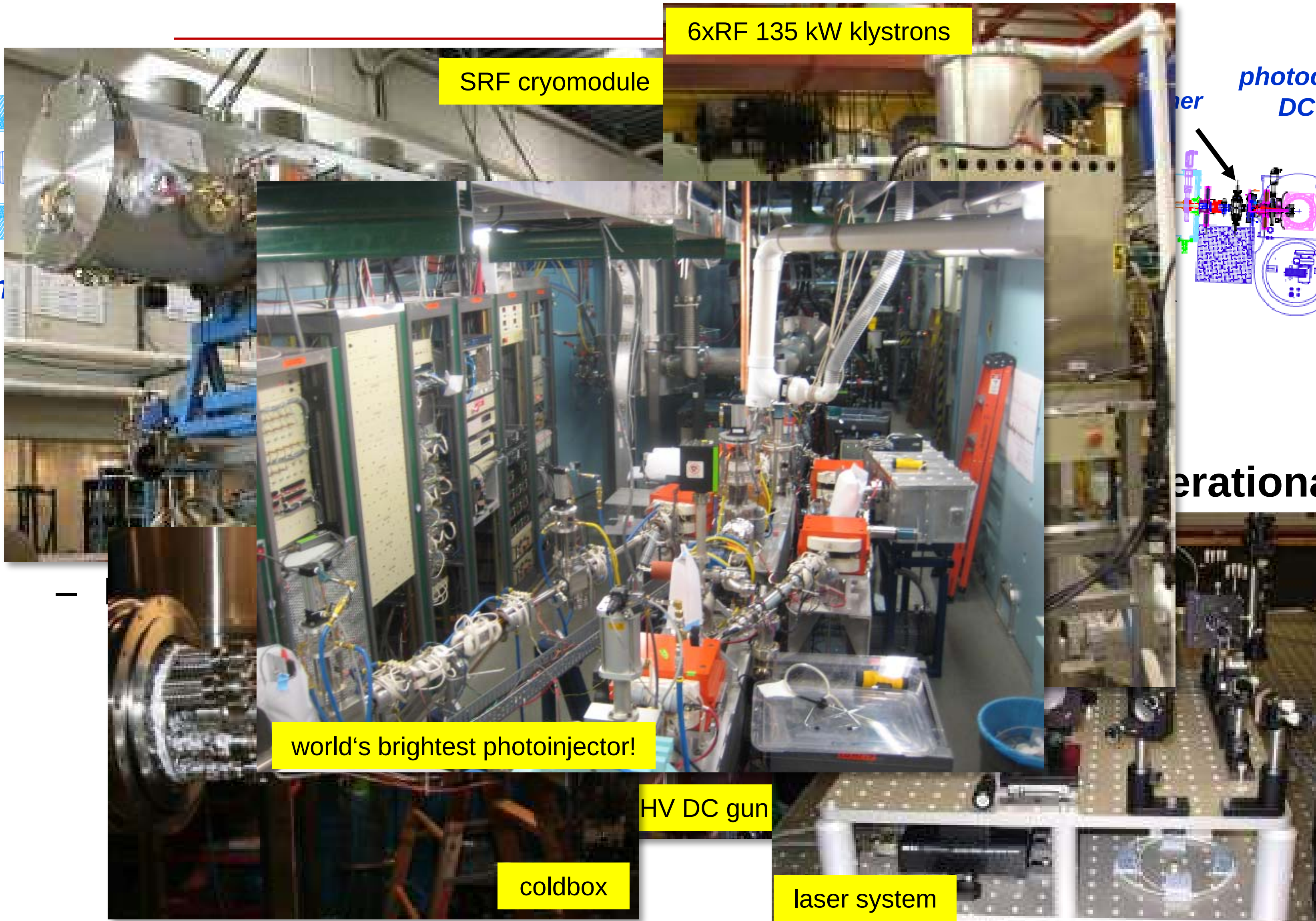
photocathode DC gun

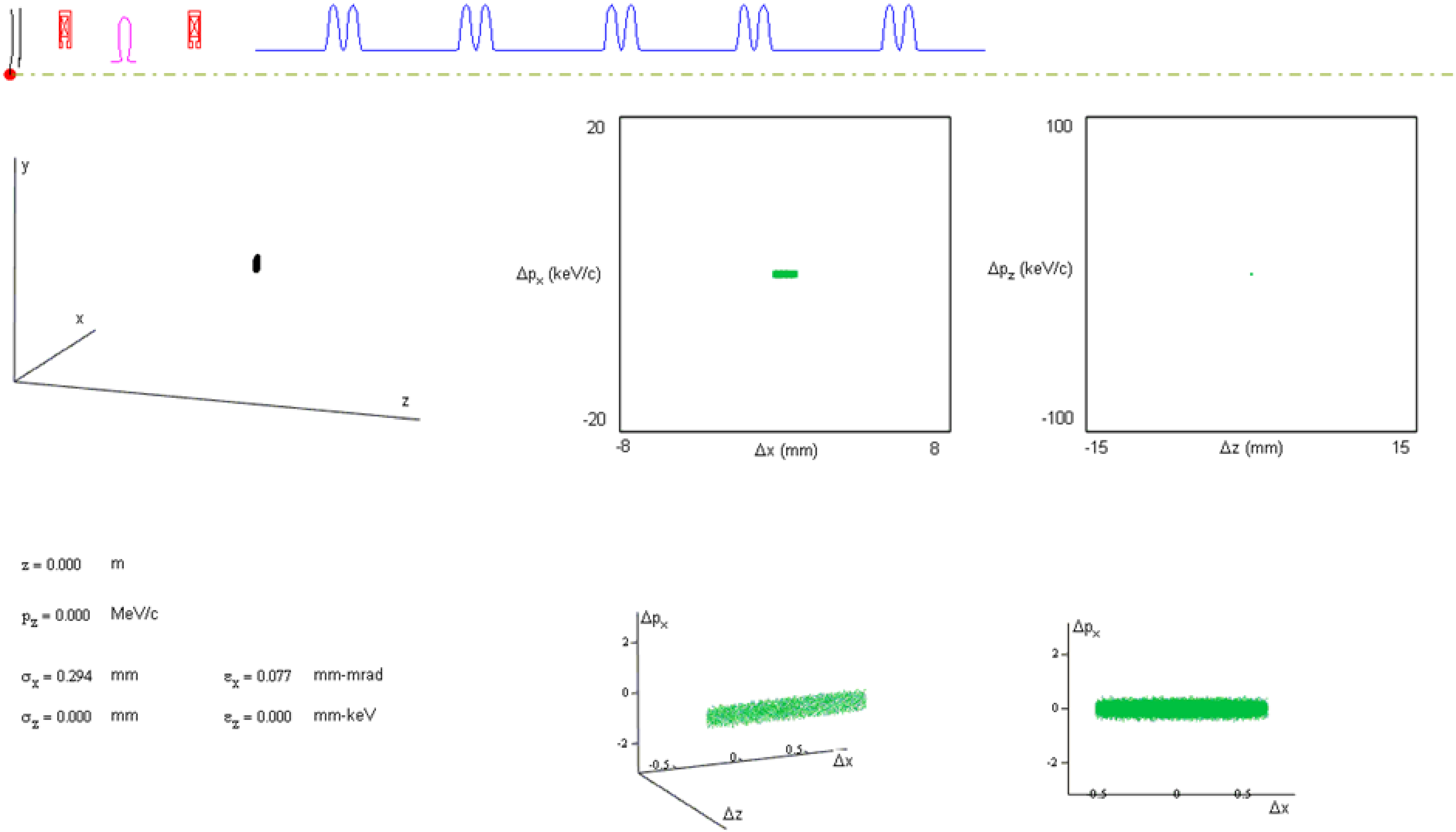
bean



• … erational

– … eV

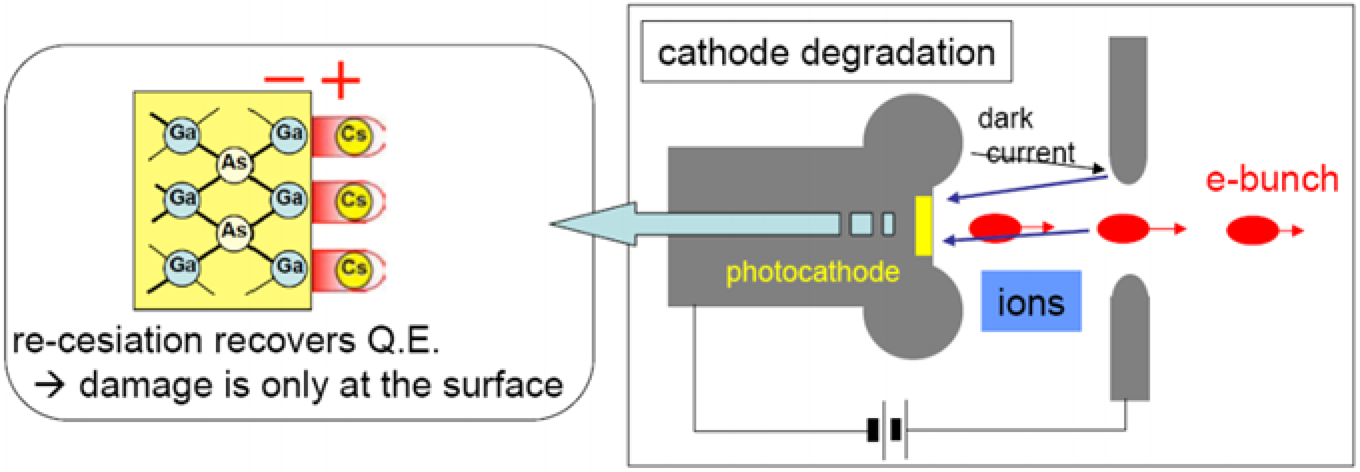
Beam dynamics inside the photoinjector (80 pC/bunch)



Getting high average current

- Must couple ~MW RF power into the beam without disturbing the low emittance

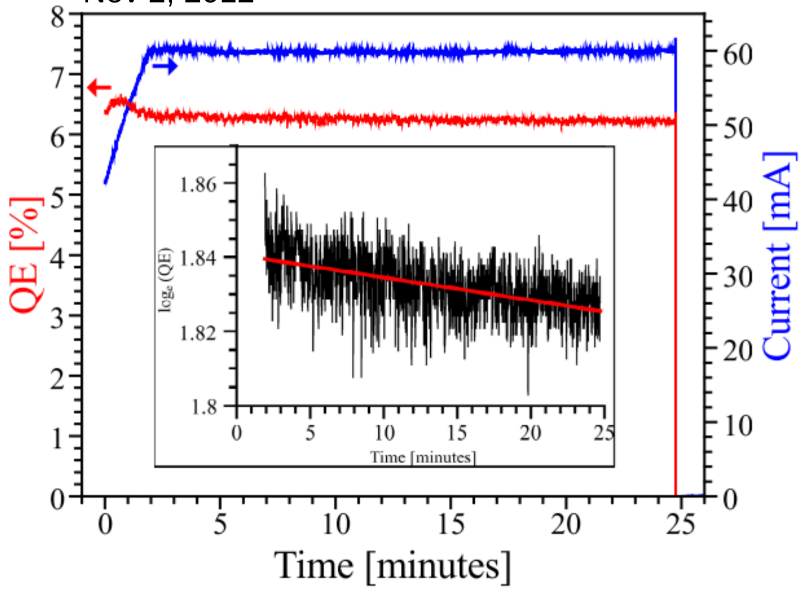
- Ion back-bombardment: a sure killer of sensitive photocathodes



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

- Best prior achievements
  - Boeing FEL RF gun 32 mA avg (25% d.f.)
  - JLAB FEL DC gun 9.1 mA avg (100% d.f.)

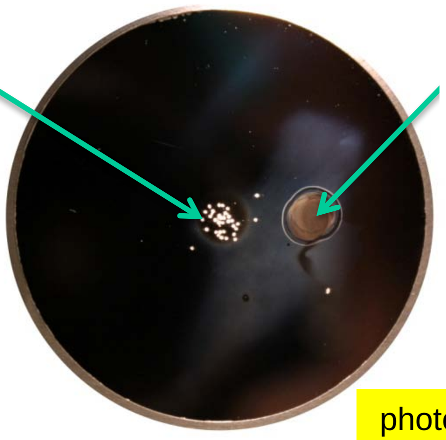
Highest current at Cornell photoinjector with CsK_2Sb



- **60 mA with > 30 hour 1/e lifetime (run the beam offset!)**
- **went as high as 65 mA (limited by RF processing in input couplers)**

Ion damage limited to the central area

Active area is offset from the center

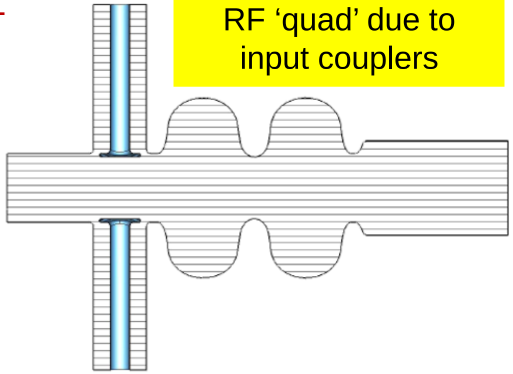


photocathode after use

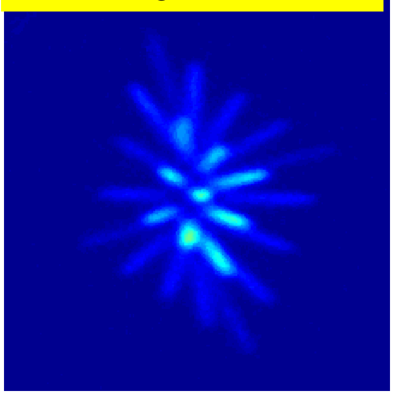
- **Exceeded the 1993 Boeing results by x2!**

Ultralow emittance: many 'tricks' needed to get there

- **6D phase space diagnostics!**
- **'Virtual accelerator': 3D space charge, 3D RF cavity field models, quads, dipoles, etc.**
- **Beam-based alignment via beam response matrices from fieldmaps**
- **Improved 3D laser shaping**
- **And many others…**

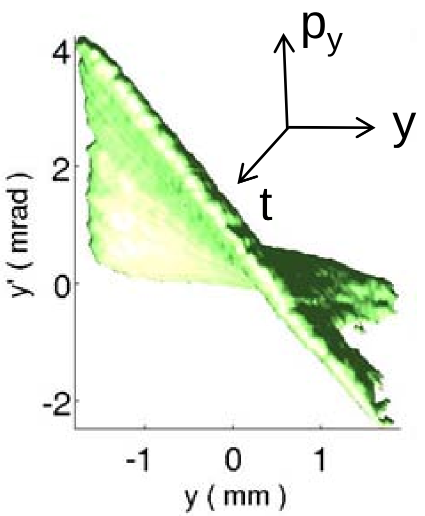


RF 'quad' due to input couplers



beam alignment check

Phys. Rev. ST-AB 15, 024002 (2012)
Phys. Rev. ST-AB 14, 032002 (2011)
Phys. Rev. ST-AB 14, 112802 (2011)
Nucl. Instr. Meth. A 614, 179 (2010)
…



slice emittance with 0.1ps

Emittance results after 'merger'

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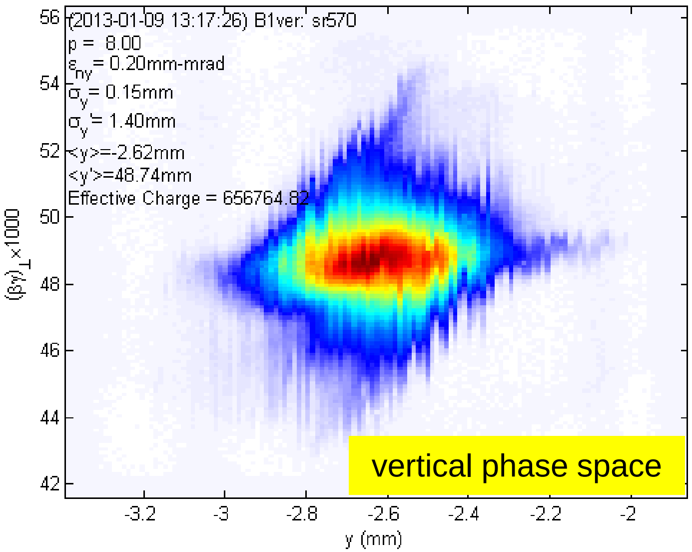
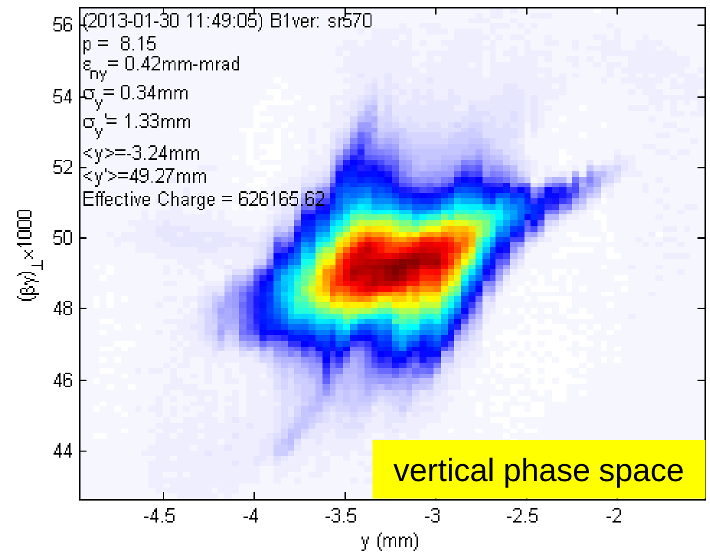
20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps rms

0.22/0.15 mm-mrad | 0.49/0.29 mm-mrad

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

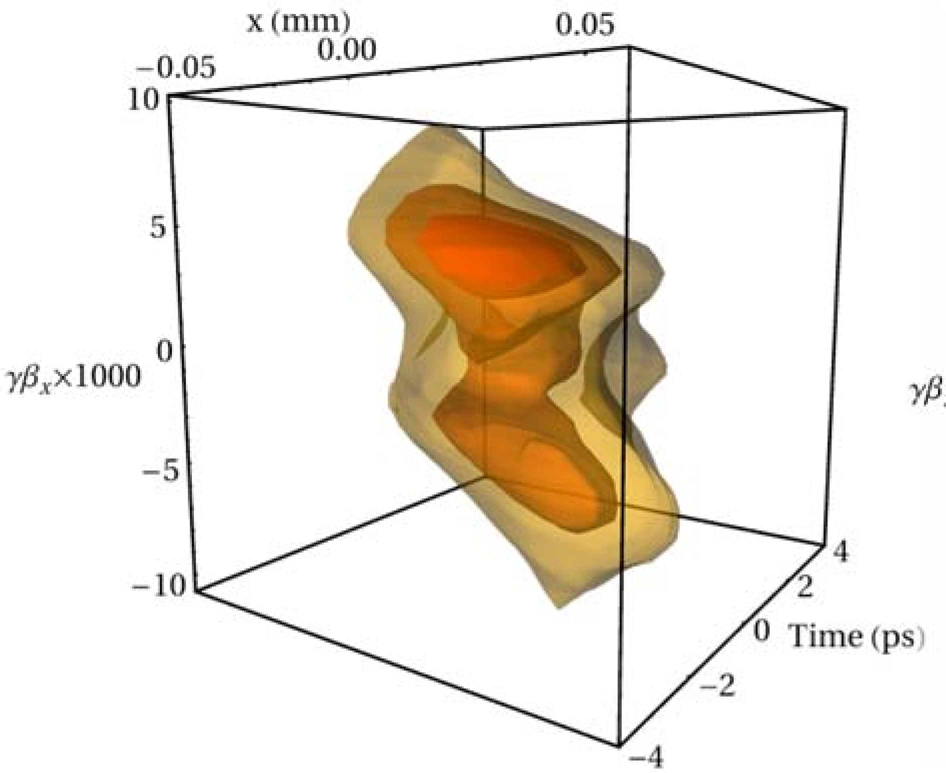
0.14/0.09 mm-mrad @ 68% | 0.24/0.18 mm-mrad @ 61%

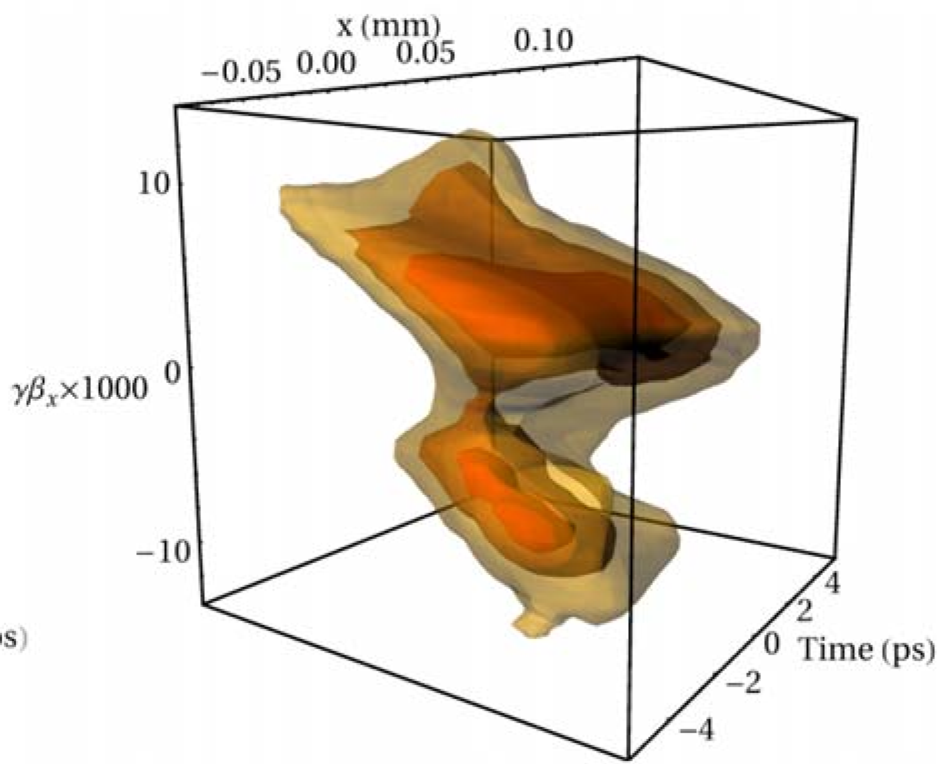
<u>20x the brightness at 5 GeV</u> of the best storage ring (1nm-rad hor. emittance 100 mA)!
<u>Similar to the best NCRF guns emittance</u> but with > 10^6 repetition rate (duty factor = 1)

arXiv:1304.2708 (2013)

Measured time-resolved phase space distribution

20 pC/bunch **80 pC/bunch**



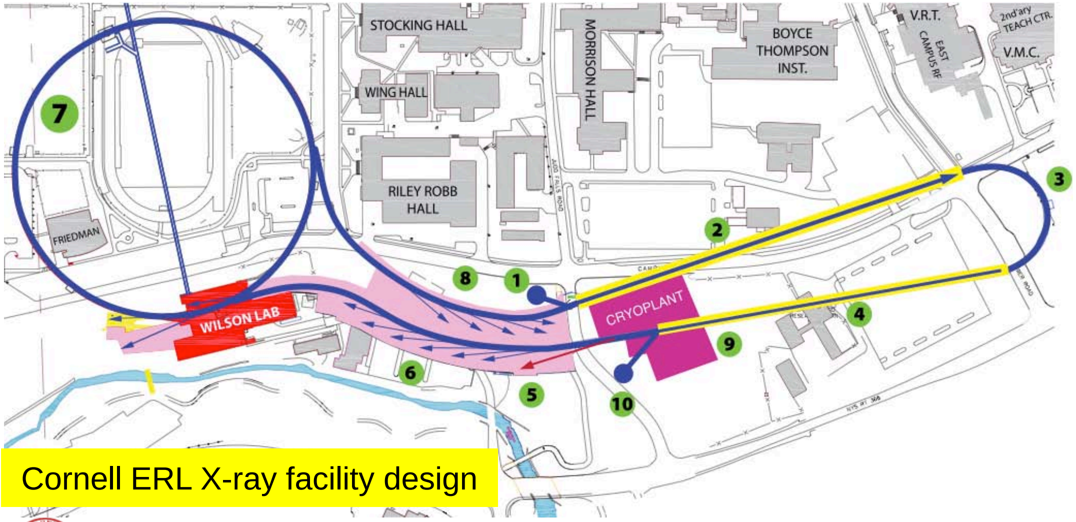


2.1±0.1 ps 3.0±0.2 ps

Energy spread: 0.1-0.2%

Energy Recovery Linac

- If built today, would be the world's brightest source of continuous x-rays (x20 better than Petra-III); another x10 improvement in photoinjector brightness anticipated over the next couple of years
- Superconducting RF cavity tests demonstrated better than spec'ed Q_0 inside the cryomodule (lower LHe refrigeration power)
- An entirely different concept of a new and better x-ray source using ERL configuration has been proven feasible!



Cornell ERL X-ray facility design

Q_0 of SRF cavities exceeds the spec by 50%

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The End