Energy Recovery Linac (ERL) Science Workshop

Contrasting Machines

- Some Storage Ring Features and Constraints
- Confinement

- 6D emittance ($x, x', y, y,' \Delta t, \Delta E/E$)
- Stay Clear Aperture
- Beam Life (Touschek effect)

- ERL Features and Constraints

- Overall schema
- 6D emittance
- Bunch patterns
- Limitations

Emittance Concept

- Brightness of x-ray beam ⇔ brightness of e-beam
- Brightness of e-beam ⇔ its phase space volume
- The three degrees of freedom (two transverse and one energy) are often decoupled in practice so that they may be considered independently. The areas describing the relevant degrees of freedom are called *emittances*: $\varepsilon_x, \varepsilon_y, \varepsilon_E$ and $V_{6D} \equiv \varepsilon_x \cdot \varepsilon_y \cdot \varepsilon_E$

$$\varepsilon_x \equiv \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

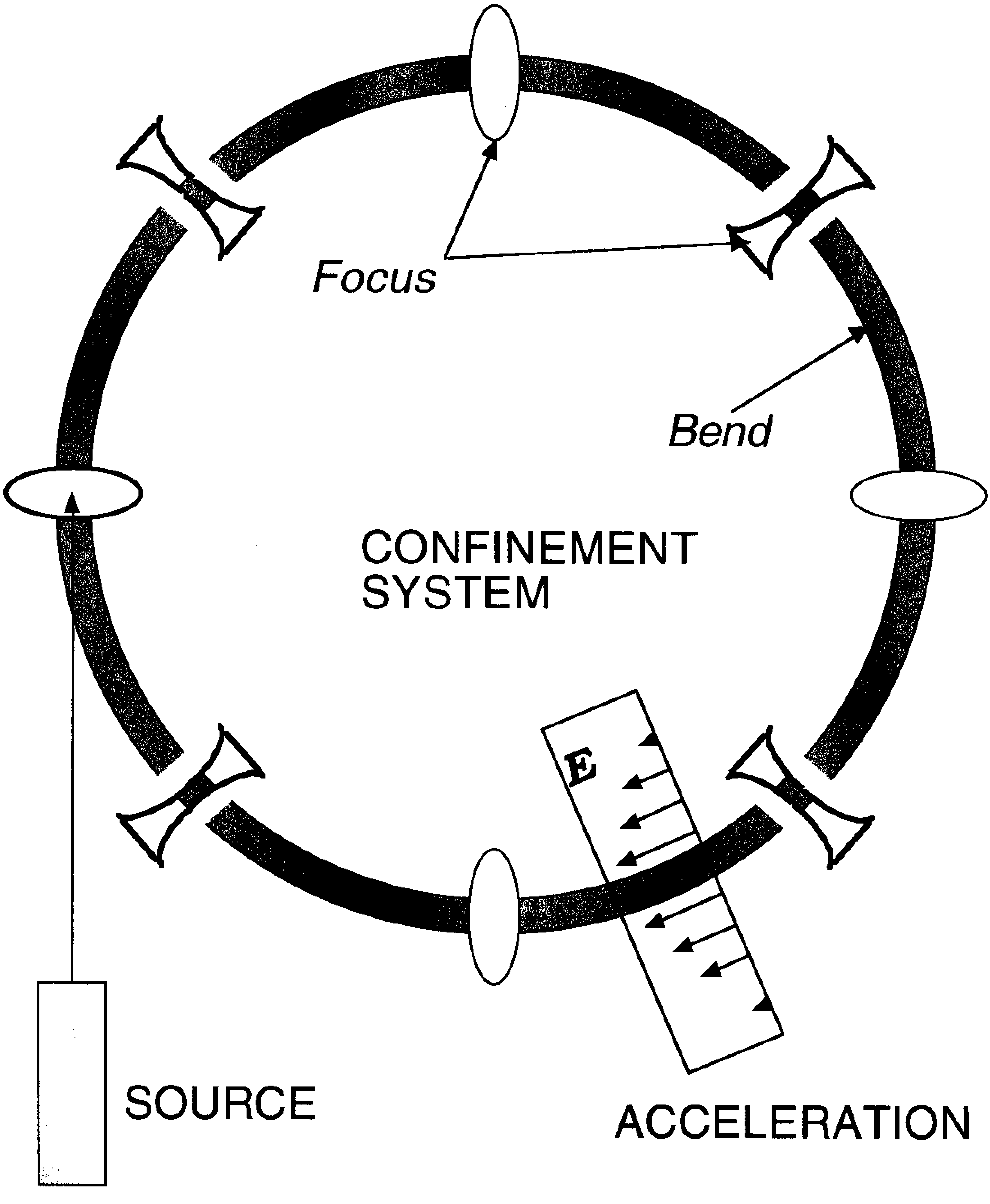
if no correlation (often the case) $\langle xx' \rangle = 0$

- For Gaussian beam distributions (close for e-rings)

$$\varepsilon_x = \frac{\sigma_x^2}{\beta_x}; \;\; \sigma_x = \sqrt{\beta_x \varepsilon_x}\;; \;\; \sigma_{x'} = \sqrt{\frac{\varepsilon_x}{\beta_x}}$$

$$\varepsilon_{x,N} \equiv \gamma \cdot \varepsilon_x$$

$$[\varepsilon_{x,y}] = \mathrm{mm} \cdot \mathrm{mrad} = 1\,\mu\mathrm{m} = 1000\mathrm{nm}$$



ELECTRON STORAGE RING

<u>**Storage Rings**</u>

Dynamical Equilibrium – Transverse
(beam physical cross-section)

<u>Actors</u>

- Transverse focusing (lenses, bends → "betatron" oscillations & dispersion)

+

- Statistically independent photon emissions → diffusion in amplitude space
- Photon emission along direction of electron motion (reduces all momentum components)

+

- Restoration of momentum <u>*along*</u> design orbit → damping of amplitudes

↓

Equilibrium emittance (beam size)

$$\varepsilon_x \propto \gamma^2 \theta^3$$

<u>*Equilibration time is usually about 10^4 turns*</u>

Storage Rings

Dynamic Equilibrium – Longitudinal (energy)

Actors

- phase focusing (acceleration system → "synchrotron" oscillations)

+

- statistically independent photon emissions of varying energies → diffusion in energy space (time of arrival)
- energy dependence of average energy loss $\frac{\Delta E}{\Delta n} \propto \frac{E^4}{\rho}$ →damping

+

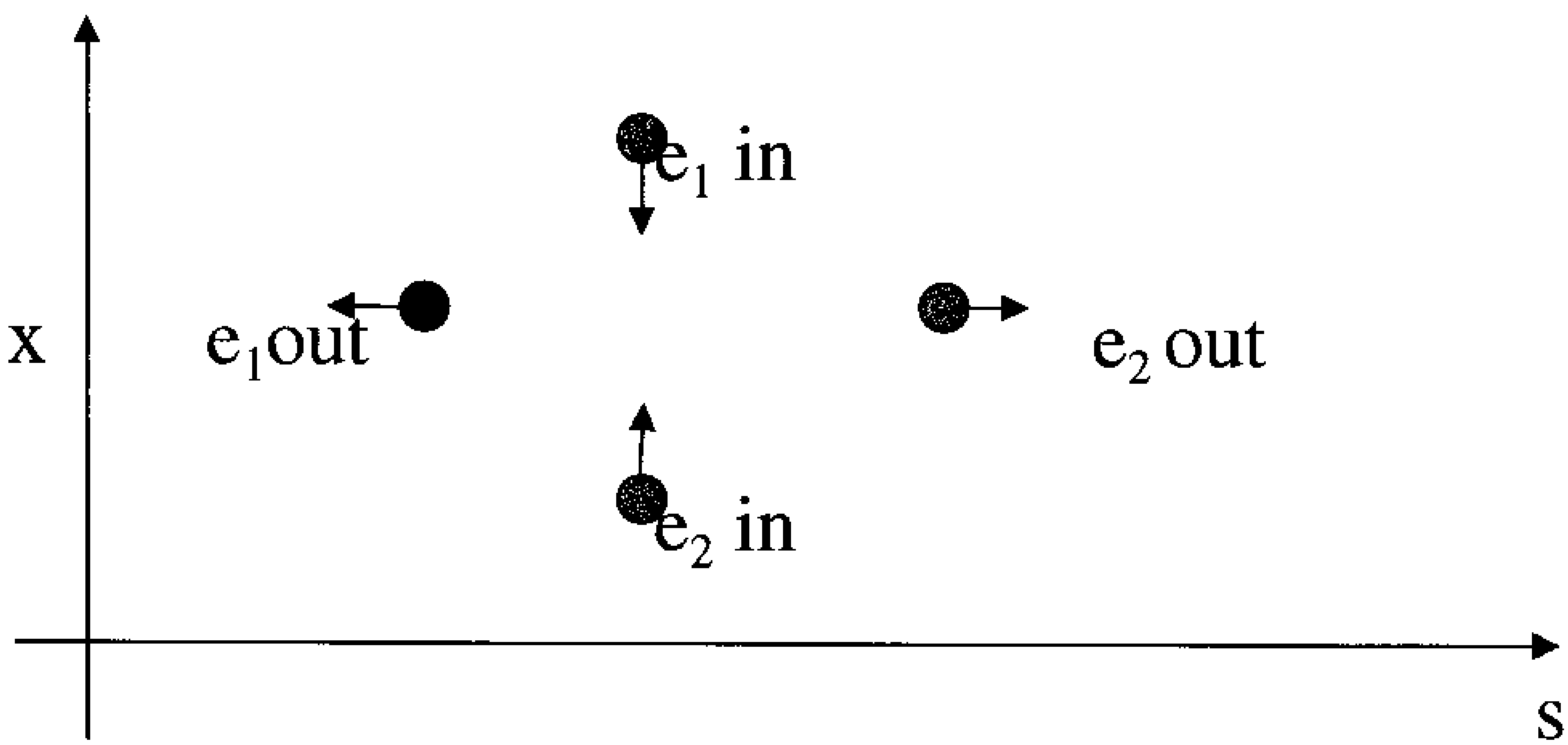
- maintenance of average beam energy by acceleration system

↓

Equilibrium energy spread (bunch length)

$$\sigma_s \propto \frac{\sigma_\varepsilon}{E_{beam}} \propto \frac{\gamma}{\sqrt{\rho}}$$

Touschek Effect



Intrabeam Coulomb scattering converts $p_{x,y}$ into Δp_s if $\Delta p_s \geq \Delta p_{aperture}$ then particles are lost.

$$\frac{1}{T_{life}} \propto \frac{N_B}{\gamma^4 \varepsilon_x \varepsilon_y \varepsilon_E}$$

limits current – gets smaller for each improvement in emittance.

Some (Geometrical) Emittances

Machine	ε_x[nm]*	$\Delta E/E[10^{-3}]$	σ_s[ps]
APS	8	3	20-50
ESRF	4	1	15

$^*\varepsilon_y \leq .01\varepsilon_x$

Stay Clear Aperture

Gaussian beam distribution functions established by radiation equilibrium. Must not clip tails → very short lifetime → minimum gap size for ID's $g \approx 8mm$ in today's practice (Spring 8 has 5mm) we'll see if that g works out OK

Energy Recovery Linac

Many thanks to Jlab collaborators G.Krafft, L. Merminga and C. Sinclair & I. Bazarov, Cornell

Electron beam passes through once and is disposed of but its kinetic energy is saved as field energy in *superconducting** cavities and delivered to the newly accelerating beam

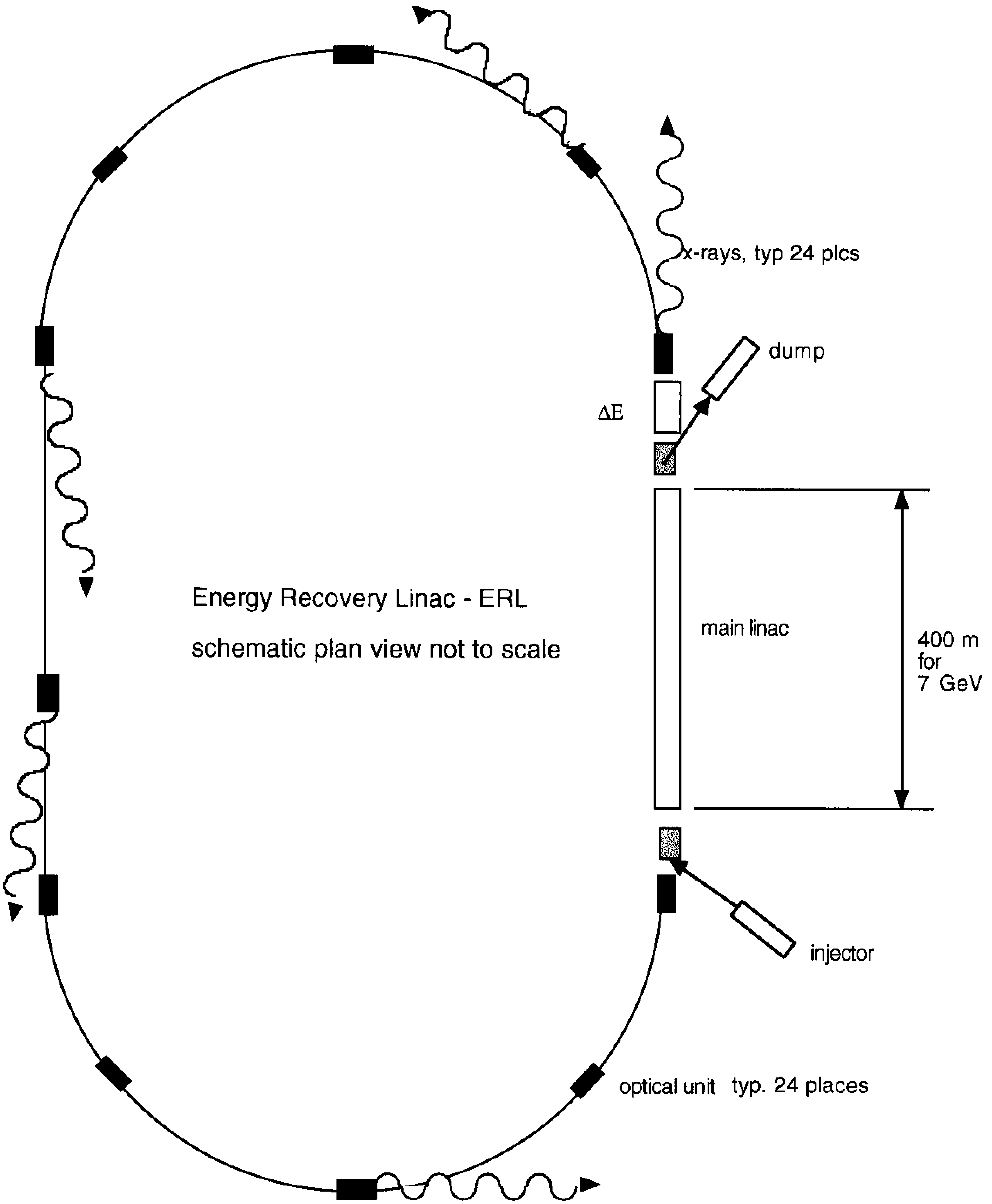
- no Touschek effect
- flexible bunch pattern
- no radiation equilibrium to establish emittance

$\downarrow$

emittance characteristic of the source only i.e. can collimate (small gaps ok)

$\downarrow$

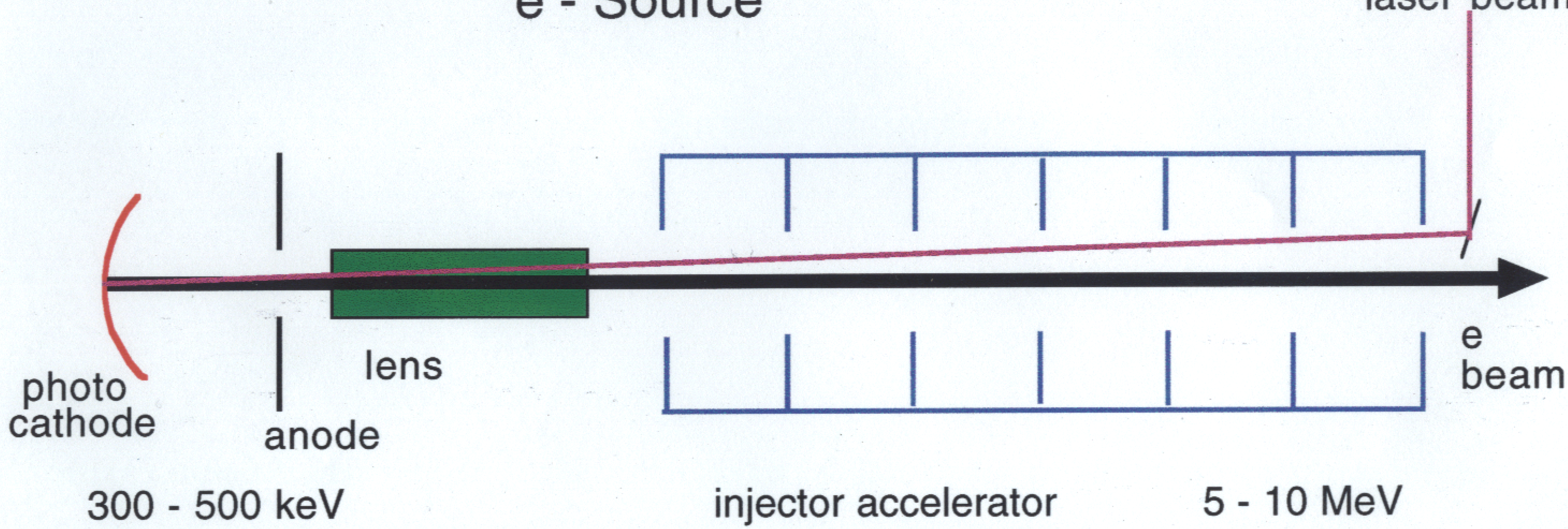
very small emittance, very short bunch lengths possible



Energy Recovery Linac - ERL

schematic plan view not to scale

e - Source



laser beam
photo
cathode
anode
lens
e
beam
300 - 500 keV
injector accelerator
5 - 10 MeV

Emittance Possibilities

- Bright e source R&D very active worldwide
  - linear collider
  - FEL

- Goals of 3 projects

Param./Project	ERL	CLIC	TESLA	NLC/JLC
Q/bunch[nC]	0.08	0.64	3.2	1.5
$\varepsilon_{x,N}$[µm]	2*	2	10	4.5
σ_s[ps]	0.1	0.1	1.3	0.4

*corresponds to a geometric emittance of $1.5 \cdot 10^{-10}$ m at 7 geV

- Some Example Accomplishments
  - Tesla Test Facility $\varepsilon_{x,N}(1nC) \approx 3-4\mu m$, $\varepsilon_{x,N}(8nC) \approx 15-20\mu m$, $\sigma_s(4nC) \approx 1ps$
  - CEBAF $\sigma_s(1pC) \approx 85fs$
- Obviously charge dependent - scaling not sure yet

Limitations

• Space charge effects (beam dynamic and HOM) will ultimately set the relation among peak and average beam current and transverse phase space density. Based on some simulation results one can guess that current technology may be capable of

$$\varepsilon_{x,N} \approx 0.3\mu m,\ \sigma_s \approx 100 fs \text{ at 80pC/bunch (0.1A avg)}$$

• With input from this workshop we will focus on the most important parameters and look to their realization.