Particle Sources

Luca Serafini *INFN-Milan and University of Milan*

- **Ion Sources** (***plasma physics of gas discharge, potential distribution, ionisation processes, magnetic confinement***)

- **Electron Sources** (***Thermoionic emission vs. Laser driven Photocathodes***)

Emphasys on Beam Physics rather than on Plasma / Solid State Physics

↓

- **Particle Beam Generation and Acceleration (first stage):**

  Space Charge diode saturation in CW / Long Pulse:

  Child-Langmuir Law ***(limitation in beam current density)***

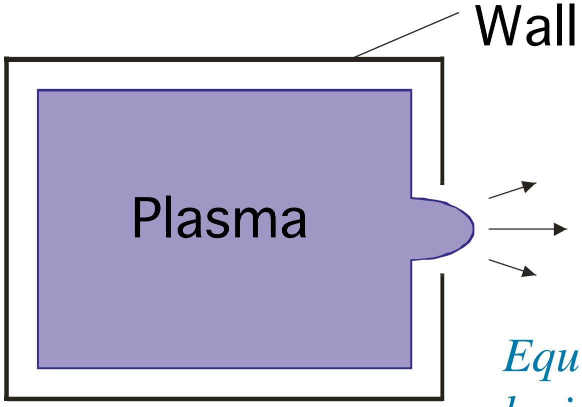
  Beyond Child-Langmuir: emission in short transients

  RF Photo-Injectors ***for High Brightness Beams (X-ray FEL)***

Baden bei Wien (A) - Sept. 23rd 2004 “ **C.A.S. Introduction to Accelerator Physics Course 2004**”

Ion Sources: plasma physics of ion production

Ion generation
inside the plasma
via gas discharge



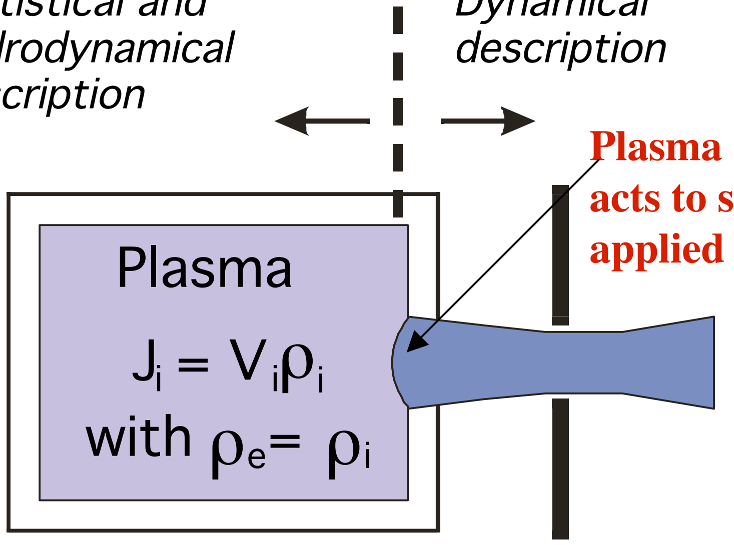
Plasma confinement sets up equilibrium

Equilibrium is locally broken by ion extraction from plasma

- **Plasma** : a hot gas containing free electrons, ions and neutral atoms.
- **Quasineutrality** : plasma (macroscopically) quasineutral if the number of positive charges per unit volume equals the negative charge density (electric field of single charges is screened over distances larger than the Debye length, usually microscopic)

$$\lambda_d = \sqrt{\frac{k_B T_e \varepsilon_o}{e^2 n_i}}$$

Ion Sources: plasma physics of ion production



Statistical and hydrodynamical description

Dynamical description

Ion source : beam generation

Plasma

$J_i = V_i\rho_i$

with $\rho_e = \rho_i$

Plasma sheath or meniscus acts to shield out the externally applied electric field

Ion column

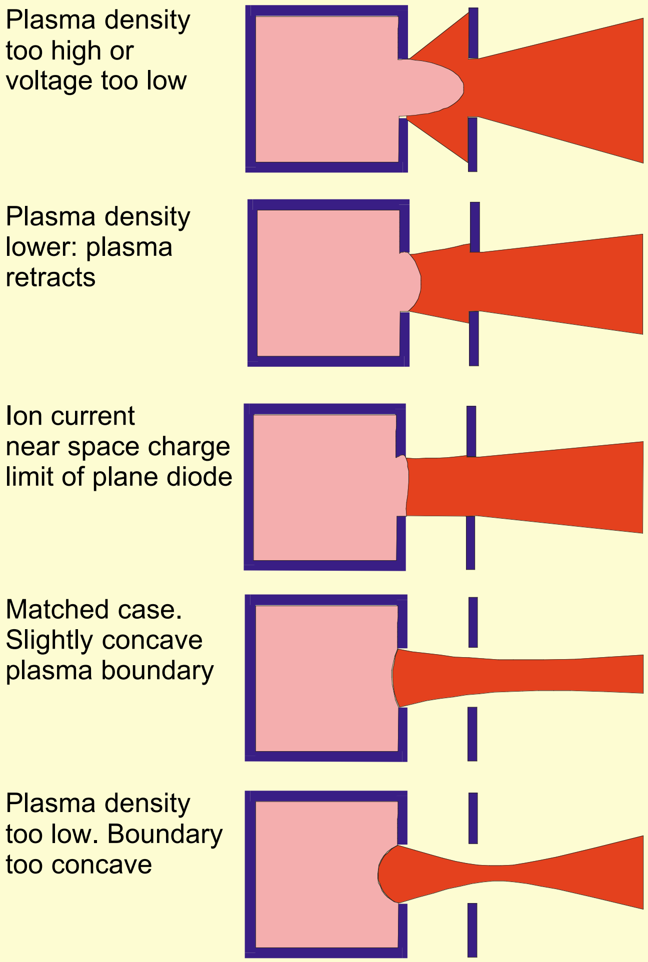
+20 kV

0 kV

- The ion current is determined only by ion temperature, ion density and area of extraction opening

Ion Sources: plasma physics of ion production

Adaptation of plasma boundary according to plasma density and extraction voltage



Plasma density too high or voltage too low

Plasma density lower: plasma retracts

Ion current near space charge limit of plane diode

Matched case. Slightly concave plasma boundary

Plasma density too low. Boundary too concave

Ion Sources: plasma physics of ion production

- ***Collisional processes between plasma particles (inelastic collisions) bring to ionization***

Electron impact ionization

Simple case : $e^- + He \rightarrow He^+ + 2e^-$ with binding energy above 25 eV
then $e^- + He^+ \rightarrow He^{2+} + 3e^-$ with binding energy above 50 eV

More complex : including ionisation of molecule, e/atoms, ion/atoms, ions/molecule … collisions :

$e^- + H_2 \rightarrow H^0 + H^+ + 2e^-$
$e^- + H_2 \rightarrow H^+ + H^+ + 3e^-$
$e^- + H_2 \rightarrow H_2^+ + 2e^-$
$e^- + H_2^+ \rightarrow H^0 + H^+ + e^-$

Table 2 Typical ionisation potential ranges :

Ion Ionisation	Potential (eV)
Oxygen 5+ to 6+	138.1
Oxygen 0+ to 6+	433.1
Oxygen 7+ to 8+	871
Lead 26+ to 27+	874
Lead 0+ to 27+	9200
Lead 81+ to 82+	91400

Ion Sources: magnetic confinement necessary to improve ionization

- The maximum charge state that can be attained is limited by the maximum incident electron energy.

- *Multi-step ionisation is thus the only really feasible route to high-charge-state ions but this process takes time.*

- This time depends on plasma density and ionisation cross section - must be shorter than ion lifetime in the plasma.

Confining electrons and ions by means of a magnetic field improves this process

Ion Sources: magnetic confinement to improve ionization -> magnetic mirror effect

axial confinement due to conservation of magnetic momentum M and total energy E_{tot}

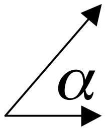
$$M = \frac{mv_{\perp}^2}{2B} = \frac{mv_{\perp\min}^2}{2B_{\min}} \qquad E_{tot} = \frac{1}{2}mv_{\perp}^2 + \frac{1}{2}mv_{//}^2 + E_p$$

$$E_{tot} = \frac{1}{2}mv_{\perp\min}^2 + \frac{1}{2}mv_{//\min}^2 + E_p = MB_{\min} + \frac{1}{2}mv_{//\min}^2 + E_p$$

if $v_{//}(z_{max}) = 0$ we have : $$\frac{1}{2}mv_{//\min}^2 = \frac{1}{2}mv_{\perp}^2(z_{mac}) - MB_{\min}$$

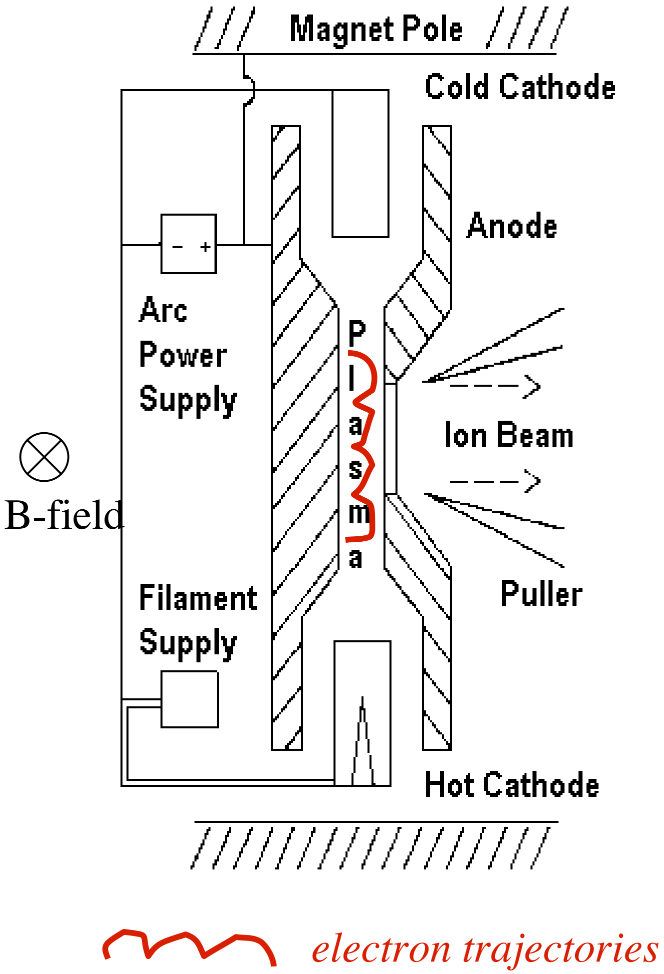
so $$v_{//\min}^2 = v_{\perp\min}^2\left(\frac{B_{\max}}{B_{\min}} - 1\right) \qquad \alpha \equiv \frac{v_{\perp\min}}{v_{//\min}} \geq \sqrt{\frac{B_{\max}}{B_{\min}} - 1}$$

trapping condition



min *max*

Simplest example: the Penning ion source



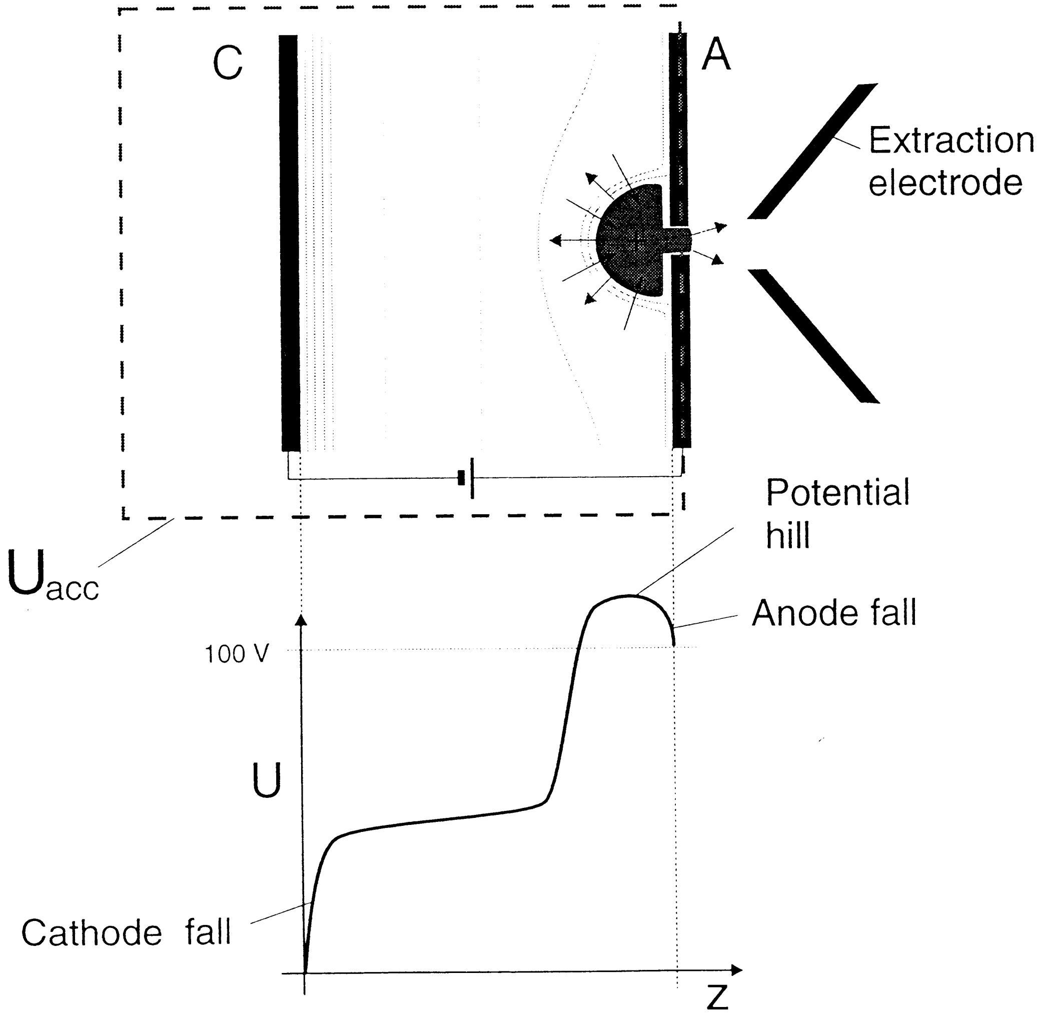
Electrons are emitted by the cathode , usually by thermoionic emission, and accelereted to an anode. Some of these **primary electrons** have collisions with gas atoms and ionize them. **Secondary electrons** from these collisions can be accelerated toward the anode to energies depending on the potential distribution and the starting point of the electron.

If a **ring or cylindrical anode is immersed in an axial magnetic field** with an electron emitter perpendicular to that field, electrons in the discharge plasma are forced into **cycloidal paths** thus increasing their path to the walls and **increasing, thereby, the probability of an ionising collision** with the neutrals.

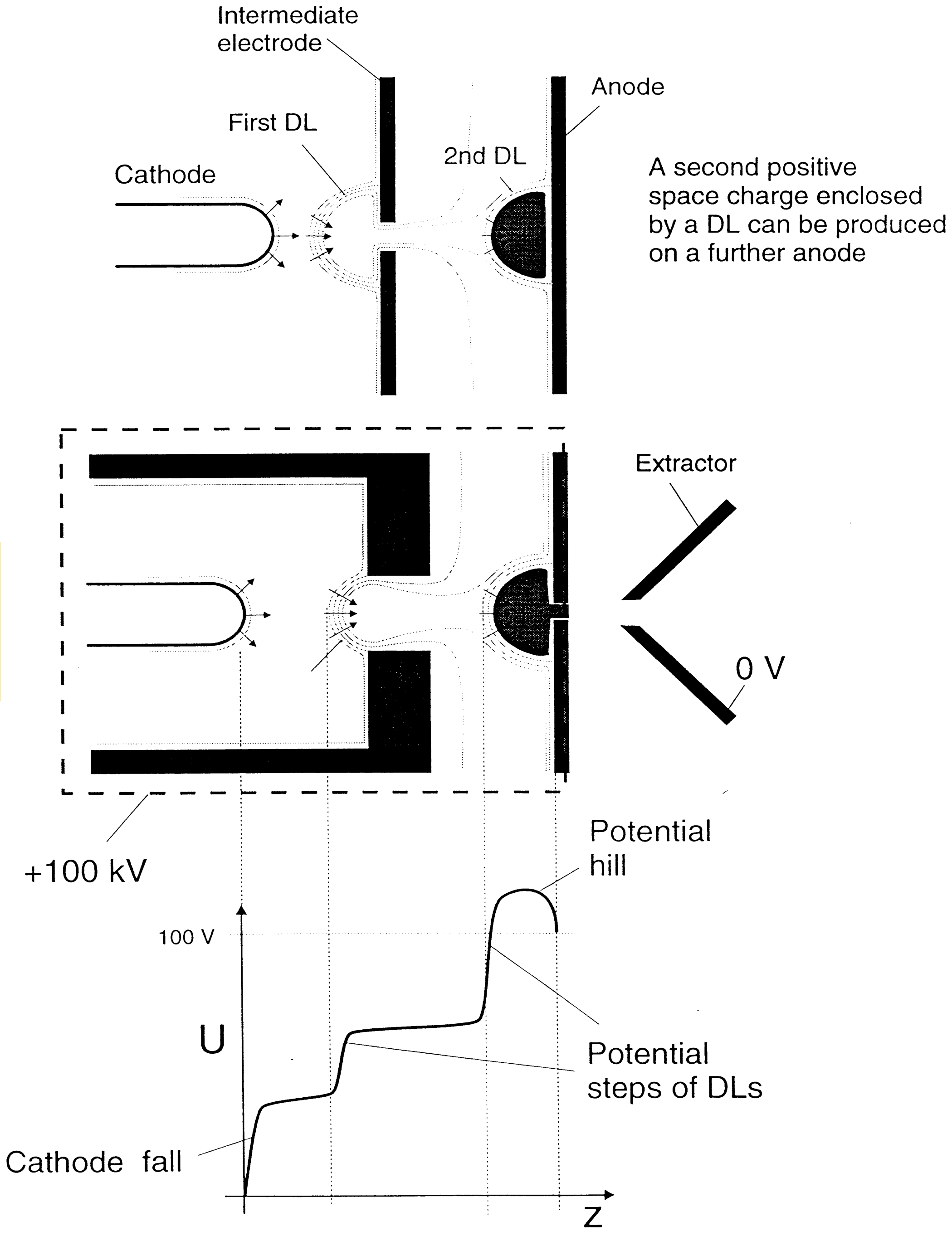
More efficient scheme for high current protons: the Duo-plasmatron

Anode Double Layer As an ion source

Potential distribution



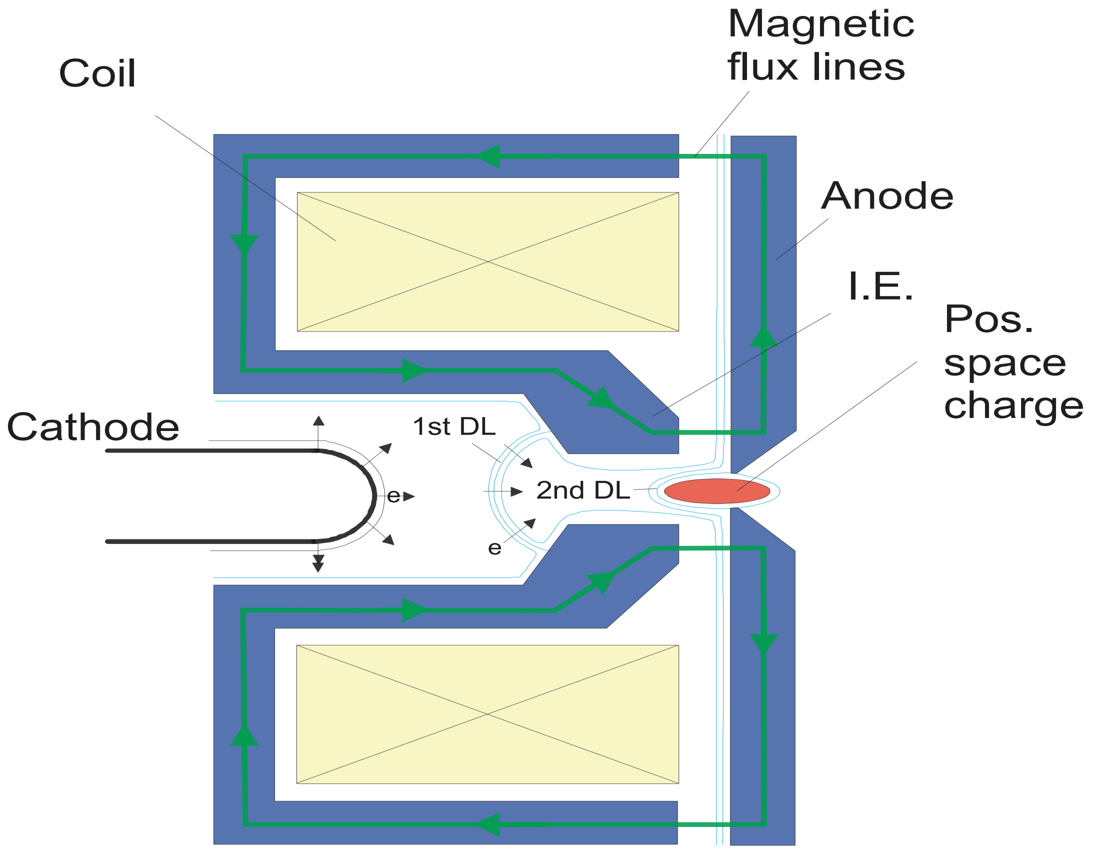
Duo-plasmatron



A second positive space charge enclosed by a DL can be produced on a further anode

Duo-plasmatron for protons

M.v. Ardenne 1955

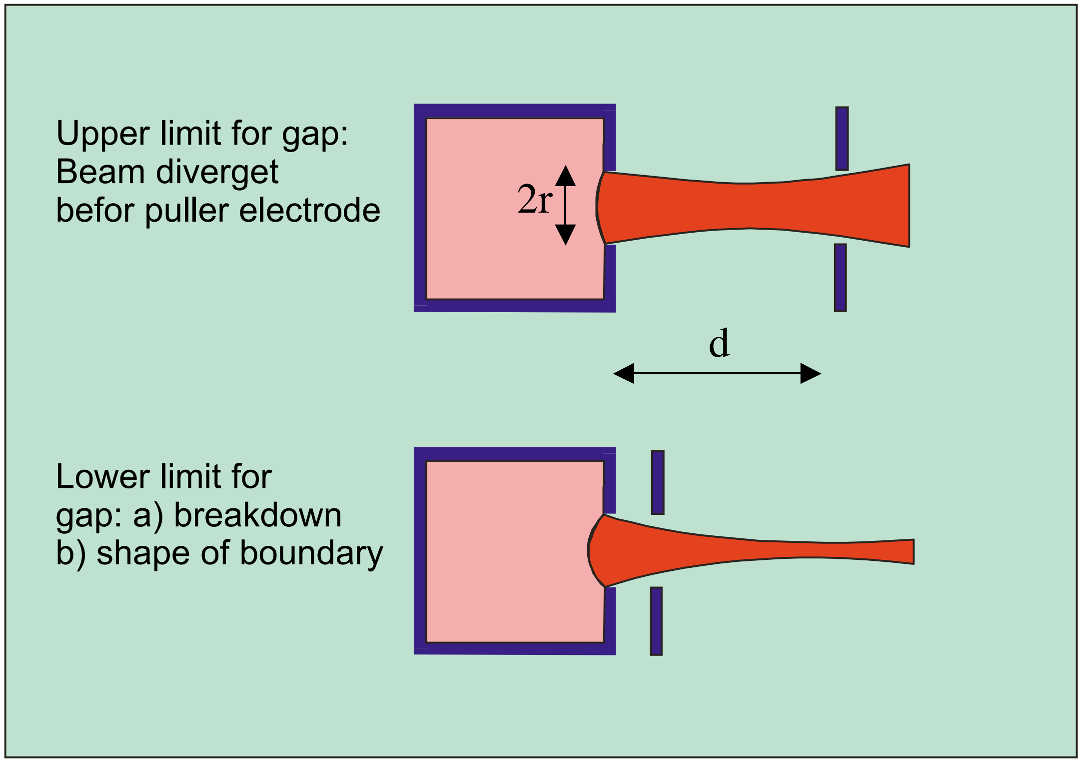


limited to single charge state ions

- "duo"= two times plasma compression i.e. by DLs and mag. field
- Advantages: Simple, robust, cheap high currents, any gas
- Still used at CERN as "workhorse" (300 mA protons)

Beam Formation: Space Charge, Diode Saturation, Child-Langmuir Law

Gap variation to match boundary to given voltage



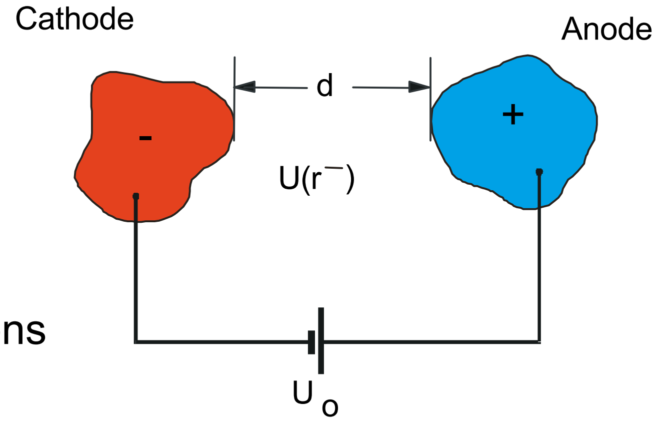
Upper limit for gap: Beam diverget befor puller electrode

Lower limit for gap: a) breakdown b) shape of boundary

Ratio S = r/d must stay in a certain range
Best: S = 0.5 , Possible: 0.3......0.6

Ion current is restricted to a certain range for a given beam energy

Child-Langmuir Law



General case:

Assumptions:

a) Cathode can emitt infinite number of electrons

b) The electric field at the cathode is zero

c) Electrons are emitted with no initial velocity v = 0

$$\frac{d^2\phi}{dx^2} = -\frac{\rho}{\varepsilon_0}$$ Poisson's equation

$$J_x = \rho\dot{x} = const$$ Continuity equation bring to: $$\frac{d^2\phi}{dx^2} = -\frac{J}{\varepsilon_0\sqrt{2e/m}}\frac{1}{\sqrt{\phi}}$$

$$\frac{1}{2}m\dot{x}^2 = e\phi(x)$$ Equation of motion

Child-Langmuir Law for planar diode

A 1st integration of
$$\frac{d^2\phi}{dx^2} = -\frac{J}{\varepsilon_0\sqrt{2e/m}}\frac{1}{\sqrt{\phi}}$$

gives
$$\left(\frac{d\phi}{dx}\right)^2 = -\frac{4J}{\varepsilon_0\sqrt{2e/m}}\sqrt{\phi} + C$$

A 2nd integration:
$$\phi(x) = U_0\left(\frac{x}{d}\right)^{4/3}$$

Substituting back for *J* :
$$J = \frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m}}\frac{U_0^{3/2}}{d^2}$$

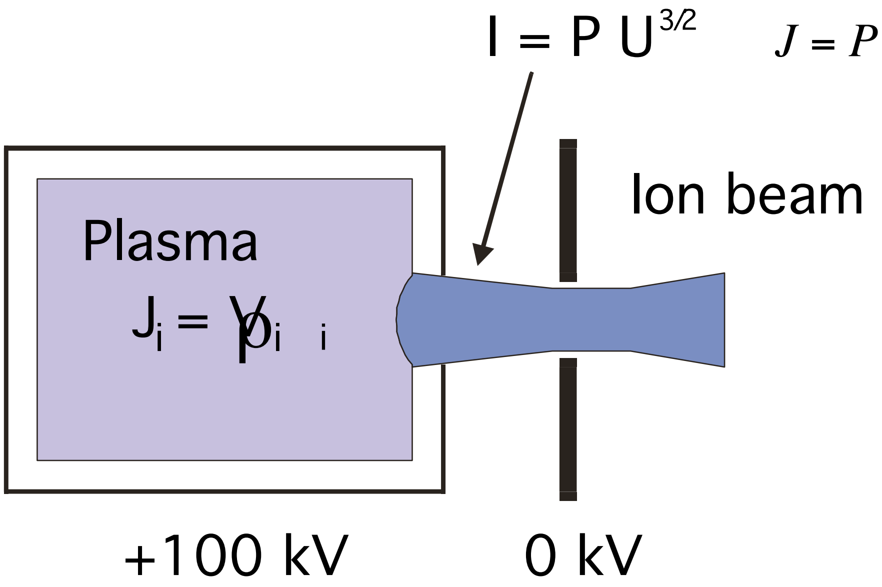
J independent on x

electrons $J = 2.3\cdot 10^{-6}\frac{U_0^{3/2}}{d^2}$ protons $J = 5.4\cdot 10^{-8}\frac{U_0^{3/2}}{d^2}$

100 kV over *d*=1 cm electrons *J*=73 A/cm^2 protons *J*=1.7 A/cm^2

Child-Langmuir Law for real diodes

The ion source current in a "diode" system is space charge limited



$$J = P\frac{U_0^{\,3/2}}{d^2}$$

The ***Perveance P*** is a function of the geometry of electrodes, always smaller than ideal planar diode value

$$\textit{ideal } P_{el} = 2.3\ 10^{-6} \qquad \textit{ideal } P_{prot} = 5.4\ 10^{-8}$$

$$\textit{max-}P_{el} = 7\ 10^{-7} \qquad \textit{max-}P_{prot} = 1.6\ 10^{-8}$$

Three Generations of Electron Sources

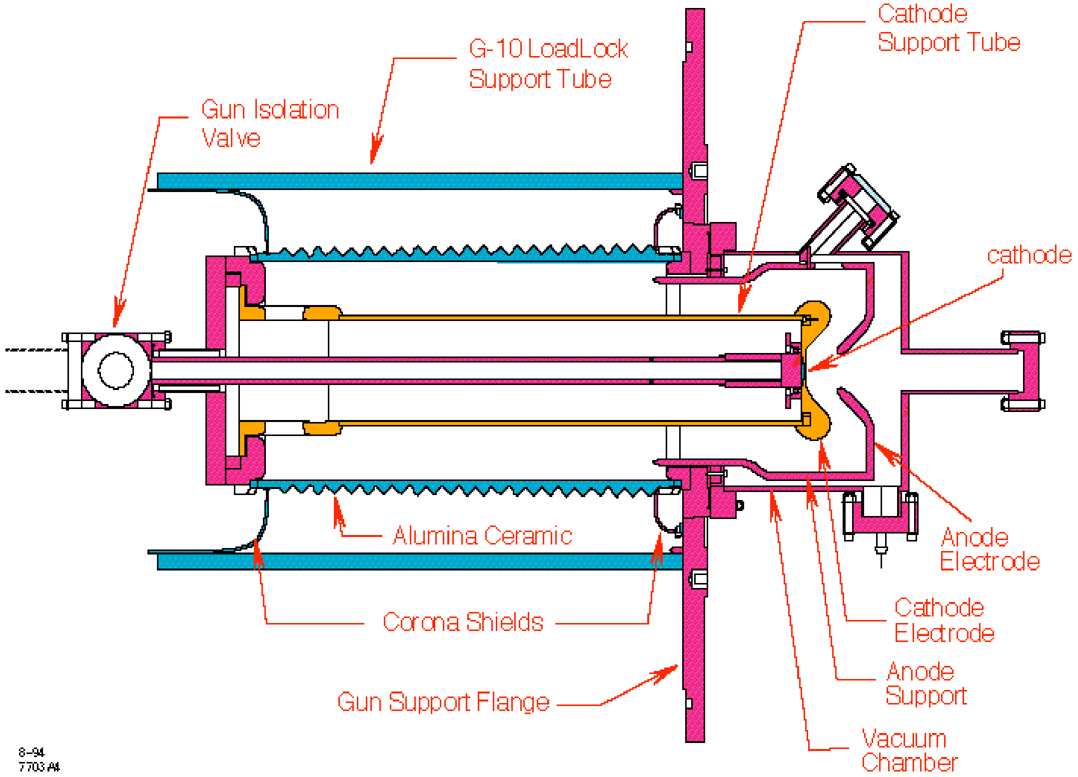
- **Thermo-Ionic** **time-scale** Q_{bunch}=1-100 nC
  $B_n=10^{10}$ A/(m·rad)^2 **μs ⇒ ns** (ps with RF bunchers) I=0.1 ⇒ 10 A
  DC Diode (triode) with thermoionic cathode E ≈10 MV/m

- **Photo-Injectors** **time-scale** Q_{bunch}=0.1-10 nC
  $B_n=10^{15}$ A/(m·rad)^2 **ps** I=10 ⇒ 100 A
  RF Cavity with photo-cathode E ≈50-150 MV/m

- **Plasma Guns** **time-scale** Q_{bunch}=1-10 pC
  $B_n=10^{14}$-10^{15} A/(m·rad)^2 **fs** I≈ 1 kA
  Langmuir waves in cold plasmas +
  local wave-breaking E ≈ 1-10 GV/m

Thermoionic Injectors

SLC Polarized Electron Gun



$$J_{\max}\left[A/cm^2\right] = 120T^2 e^{-W/k_B T}$$

$$W \equiv cathode\ \ work - function$$

$$T \equiv cathode\ \ temperature$$

LIMITATIONS

Cathode Emissivity $J < 20\ A/cm^2$

Diode Saturation

$\Downarrow$

Child-Langmuir Law $I = PV^{3/2}$

V=100 kV I=15 A with $P=5\cdot10^{-7}$

$\Downarrow$

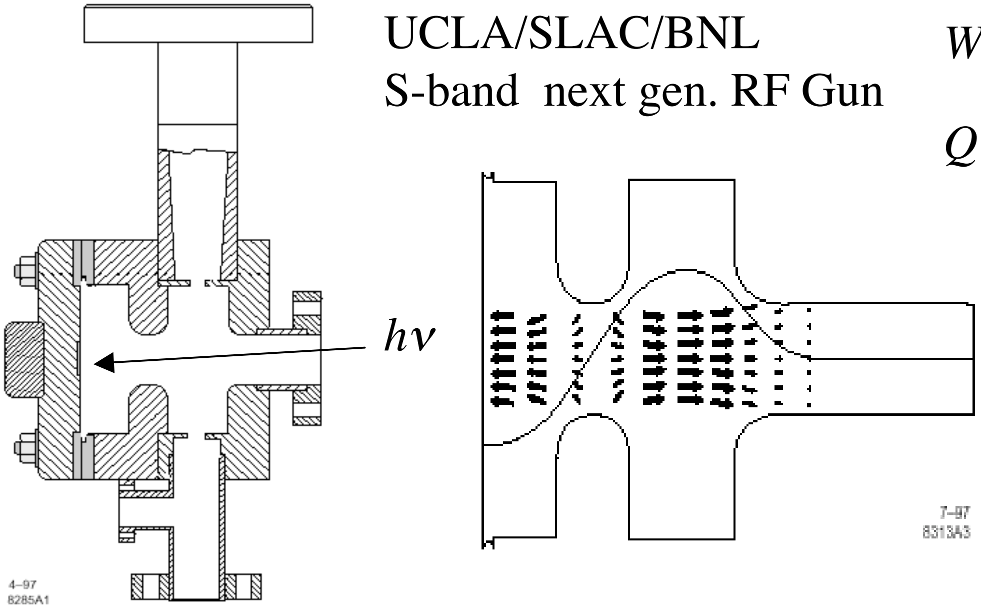
Field limited

MATURE and CONSOLIDATED TECHNOLOGY

Radio-Frequency Photo-Injectors

Photo-Cathode Emissivity **J < 10 kA/cm²**
Prompt emission on a ps time scale

UCLA/SLAC/BNL
S-band next gen. RF Gun



$$Q_{eff} = N_{electrons} / N_{laser-photons}$$

$$Q_{eff}(Cu \quad photo-cathode) \cong 5 \cdot 10^{-5}$$

$$W_{Cu} = 4.2eV, \; h\nu = 4.6eV$$

$$Q = 1 \quad nC \quad needs \quad U_{las} = \frac{h\nu \cdot Q_{bunch}}{Q_{eff}} = 92 \quad \mu J$$

LIMITATIONS

Transverse plasma oscillations
Time dependent space charge effects
dilution of projected emittance

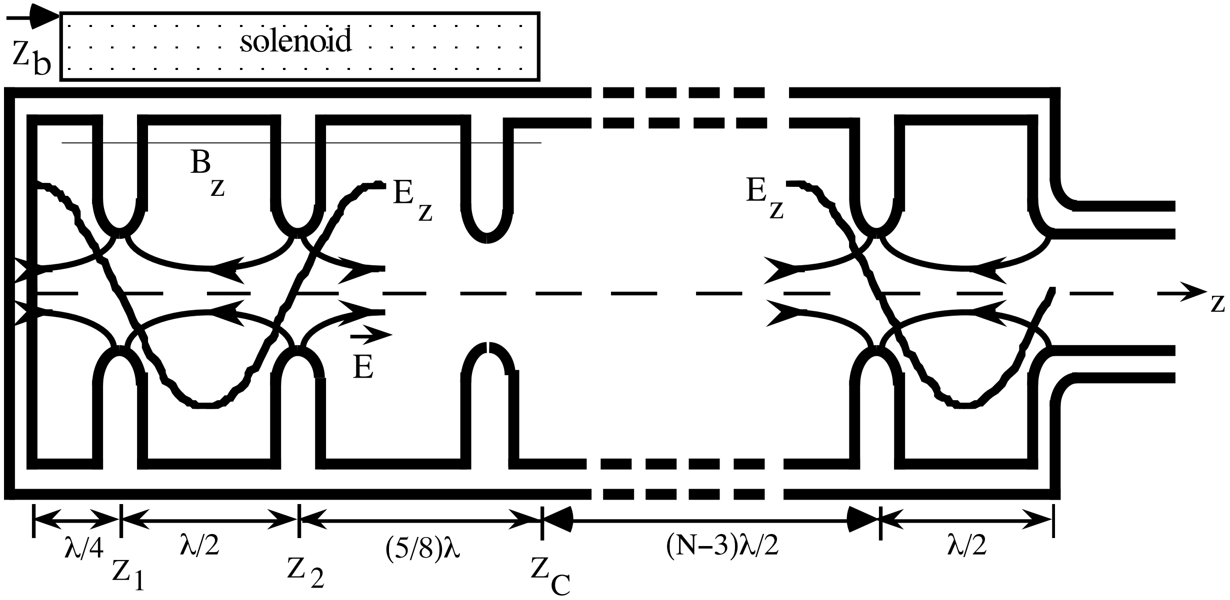
Photocathode and/or laser disuniform.

PROBLEMS

Space and Time Jitters
Laser beam quality
Challenging Diagnostics (sub-ps)

Mature but non Consolidated Technology
Stability , repetibility , ease of tuning

Brief Review of
Beam Dinamycs in Photo-Injectors



On-axis expansion of the $TM_{010\text{-}\pi}$ standing mode

E_0 = the peak field at the cathode
k ≡ 2π/λ = ω/c
a_n = spatial harmonic coefficients functions of cavity geometry

$$\begin{cases} E_z = \varepsilon_z(r,z)\cdot\sin(\omega t+\varphi_0) \quad ; \quad \varepsilon_z(r,z) = E_0 \sum\limits_{n=1,odd}^{\infty} a_n \cos(nkz) \\ E_r = \varepsilon_r(r,z)\cdot\sin(\omega t+\varphi_0) \quad ; \quad \varepsilon_r(r,z) = \dfrac{kr}{2} E_0 \sum\limits_{n=1,odd}^{\infty} n\cdot a_n \sin(nkz) \quad ; \quad a_1 = 1 \\ \mathrm{B}_\theta = B_\theta(r,z)\cdot\cos(\omega t+\varphi_0) \quad ; \quad B_\theta(r,z) = c\,\dfrac{kr}{2}\varepsilon_z(r,z) \end{cases}$$

Beam Dinamycs in Photo-Injectors

Photo-electrons at photo-cathode surface are non relativistic
(laser photon energy just overcomes cathode metal work-function)

$$T_{cat} = h\nu_{las} - W_S = 4.6 - 4.4 = 0.2 \;\; eV \;\; ; \;\; \beta_{cat} \cong 10^{-3} \;\; (for \;\; Cu \;\; cathodes)$$

Define dimensionless vector potential amplitude of RF field $\alpha \equiv \dfrac{eE_0}{2mc^2k}$

$$E_0 = 100 \;\; MV/m \;\; @ \;\; 2.856 \;\; GHz \Rightarrow \;\; \alpha = 1.6$$

Photo-electrons become relativistic in a distance much shorter than λ_{RF}

⇩

RF wave is able to capture electrons from rest if α>1

$$T = 1 \;\; MeV \;\; @ \;\; z = 1 \;\; cm \;\; (first \;\; cell \;\; length \;\; = \;\; 2.5 \;\; cm) \qquad \beta = 0.95$$

Beam Dinamycs in Photo-Injectors

Impulsive approximation
E_{RF} = DC field = E_{cat}

$$E_{cat} \cong \mu E_0 \sin\varphi_0 \;\;;\;\; \mu \equiv \sum_{n=1}^{\infty} a_n$$

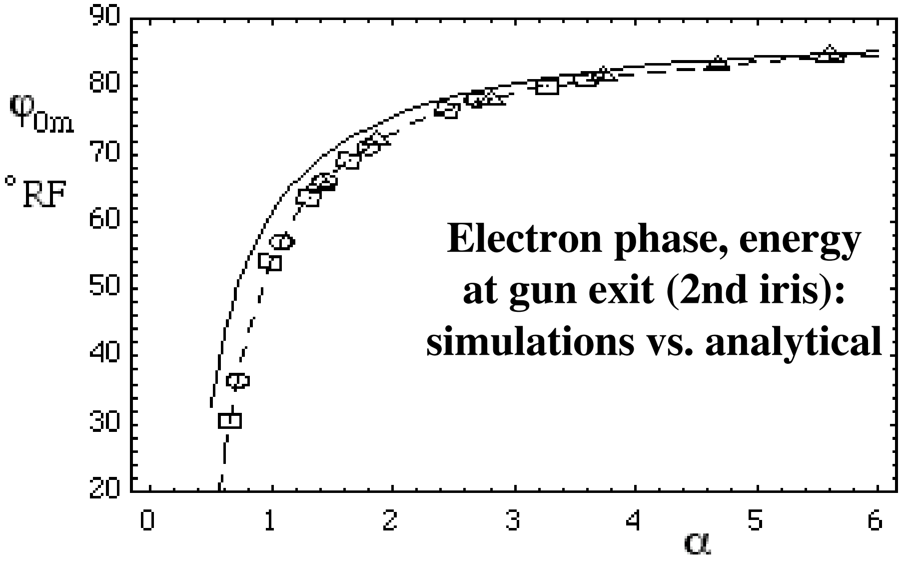
Equivalent relativistic motion with effective phase shift

$$z = ct - \frac{1}{2\,\mu\alpha k \sin\varphi_0}$$

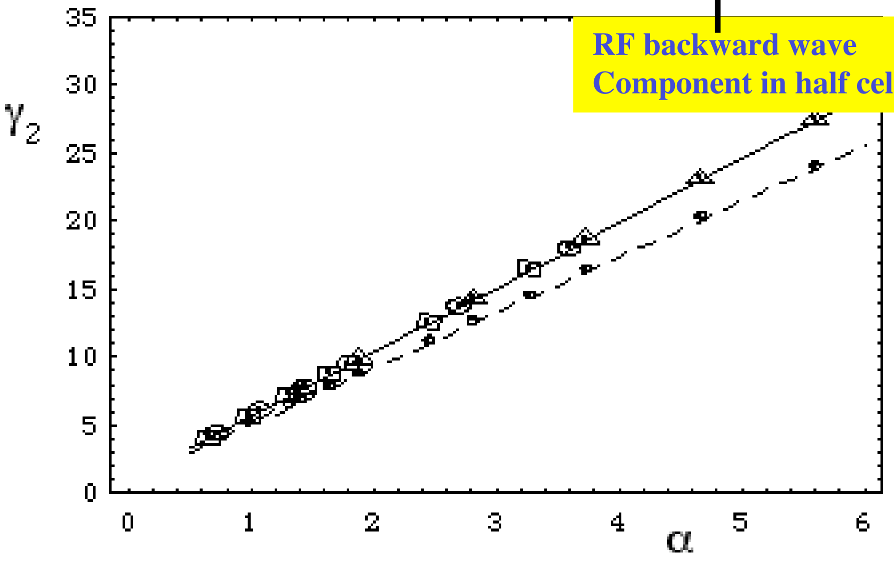
$$\varphi = \varphi_0 - \frac{1}{2\mu\alpha\sin\varphi}$$

$$\gamma_2 = 1 + \frac{3\pi\alpha}{2}\sin\varphi + \alpha\cos\varphi$$

RF backward wave Component in half cell

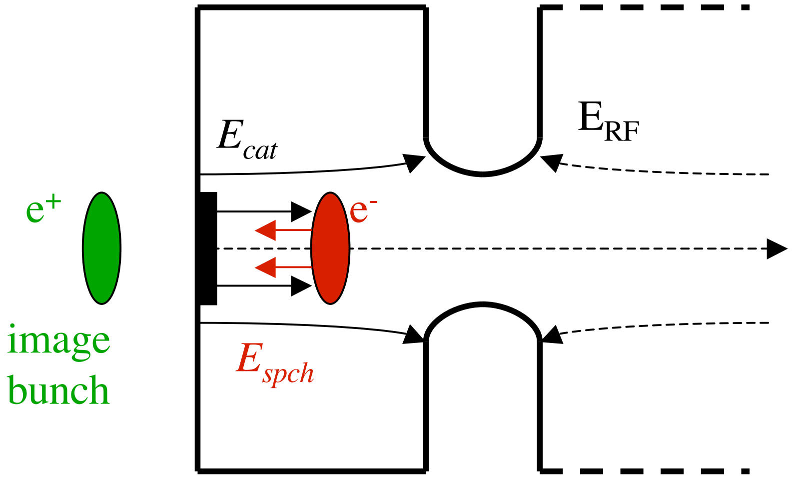


Electron phase, energy at gun exit (2nd iris): simulations vs. analytical



Beam Dinamycs in Photo-Injectors: overcome Child-Langmuir limitation

Laser driven RF Photo-Injectors work far from the (equivalent) diode saturation regime, well into the linear regime



$$E_{spch} << E_{cat} \Rightarrow \frac{Q_{bunch}}{\pi\varepsilon_0 R^2} << E_{cat}$$

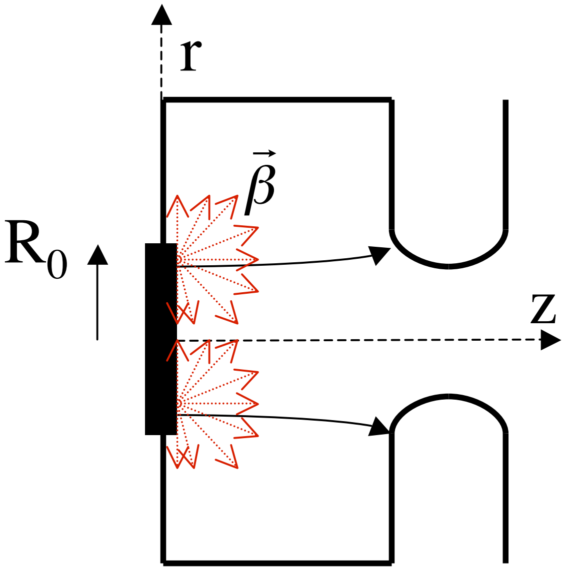
$$Q_{bunch}[nC] << \frac{1}{25} E_{cat}[MV/m] \, (R[mm])^2$$

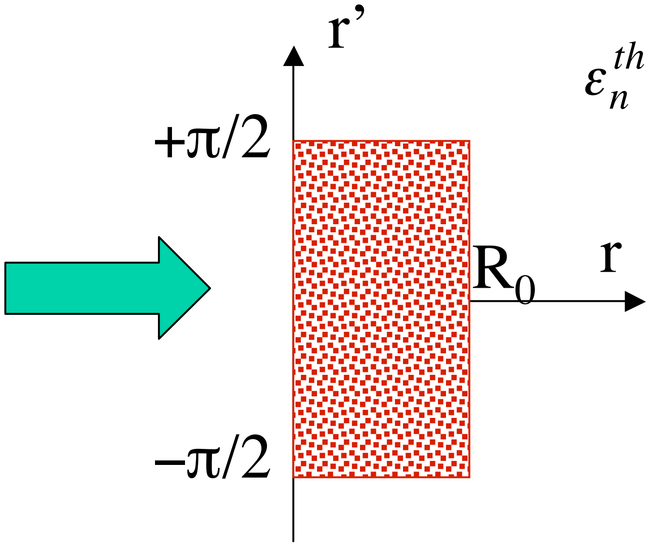
$$I \equiv \frac{Q_{bunch}}{\tau_{bunch}} \Rightarrow I \geq 100 \;\; A \;\; !!$$

$$Q_{bunch} << 5.6 \;@\; (140 \;\; MV/m \;,\; 1 \;\; mm)$$

Beam Dinamycs in Photo-Injectors

themperature emittance @ photo-cathode (real liouvillian emittance)





$$\varepsilon_n^{th} = \frac{\langle \beta\gamma \rangle}{2} \sqrt{\langle r^2 \rangle \langle r'^2 \rangle - \langle r r' \rangle^2}$$

$$\langle r^2 \rangle \equiv \frac{\int_0^{R_0} r^3 dr}{\int_0^{R_0} r dr}$$

$$\langle x^2 \rangle = \frac{\langle r^2 \rangle}{2}$$

$$\langle \beta\gamma \rangle \cong \langle \beta \rangle \cong \sqrt{2T_e / m_e c^2} = 2 \cdot 10^{-3} \sqrt{T_e[eV]} \quad \Longrightarrow \quad \varepsilon_n^{th} = \frac{\pi \langle \beta \rangle R_0}{4\sqrt{6}}$$

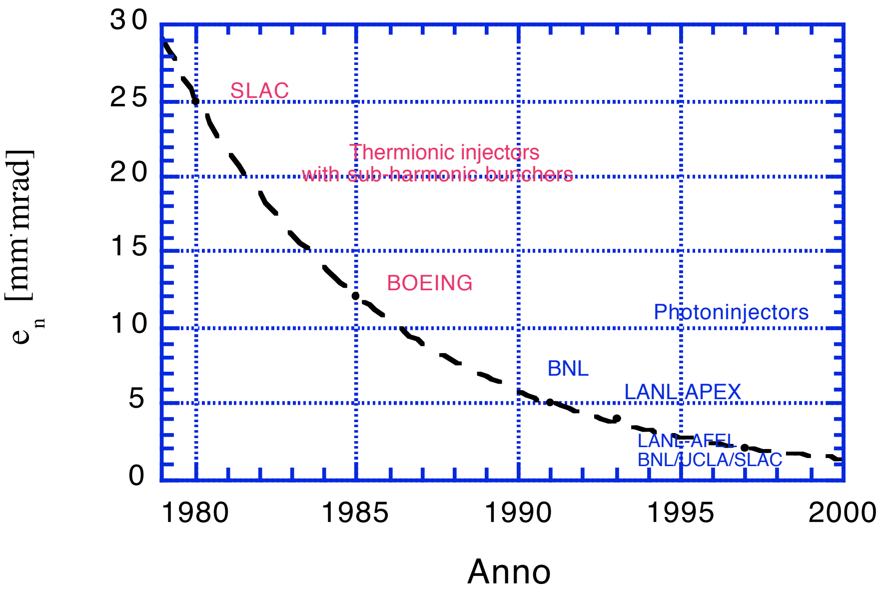
$$\varepsilon_n^{th} \, [mm \cdot mrad] = 0.64 \;\; R_0[mm] \; \sqrt{T_e[eV]}$$

in absence of any channeling mechanism

From Thermoionic Injectors to Laser-Driven RF Photo-Injectors : the Quest for Beam Brightness

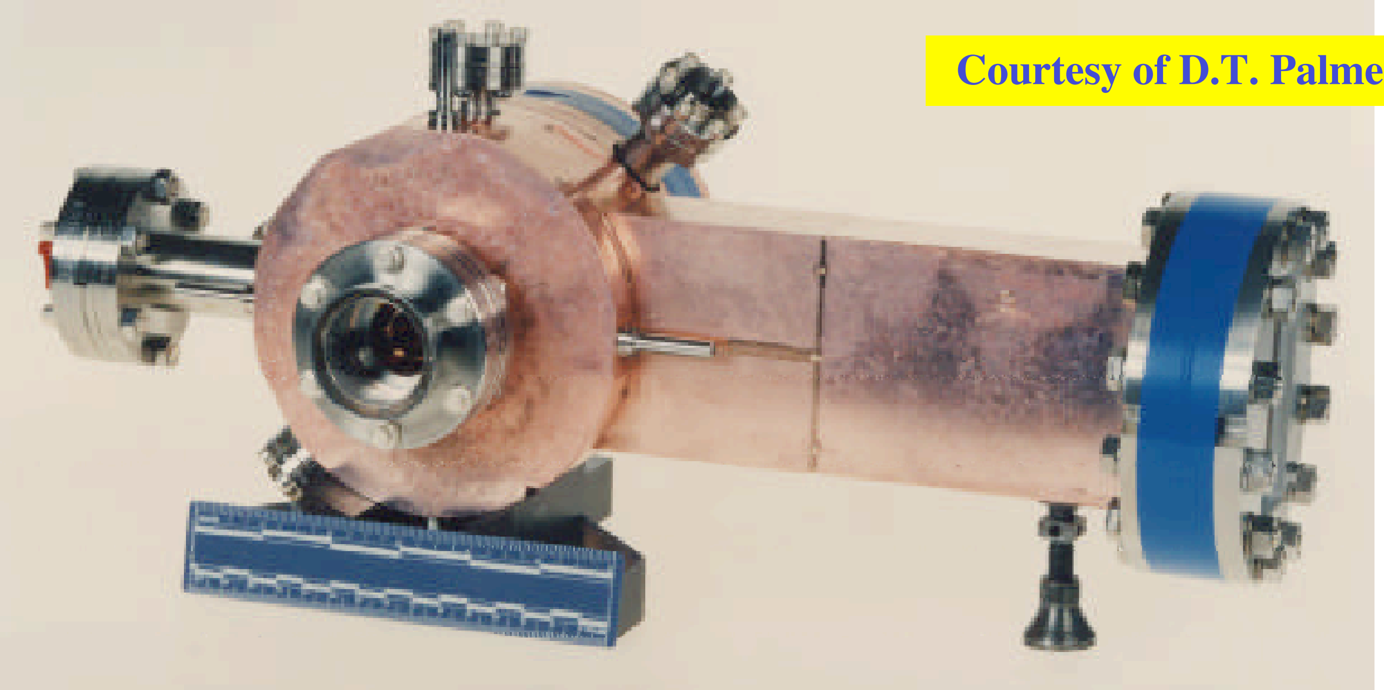
Thermoionic Injectors operate in a quasi-steady state regime at low DC field amplitudes - the beam has to be manipulated by bunchers to get down to the ps time scale - this causes a severe emittance grow ⇒ **Integration of emission process into the bunching action of RF accelerating field**

⇒ ***RF Photo-Injectors Hera***



PhotoInjectors serve nowadays User Facilities, Advanced Accelerator Experiments, and...they make short wavelength SASE-FEL saturate!

BNL/SLAC/UCLA 1.6 cell S-Band RF GUN

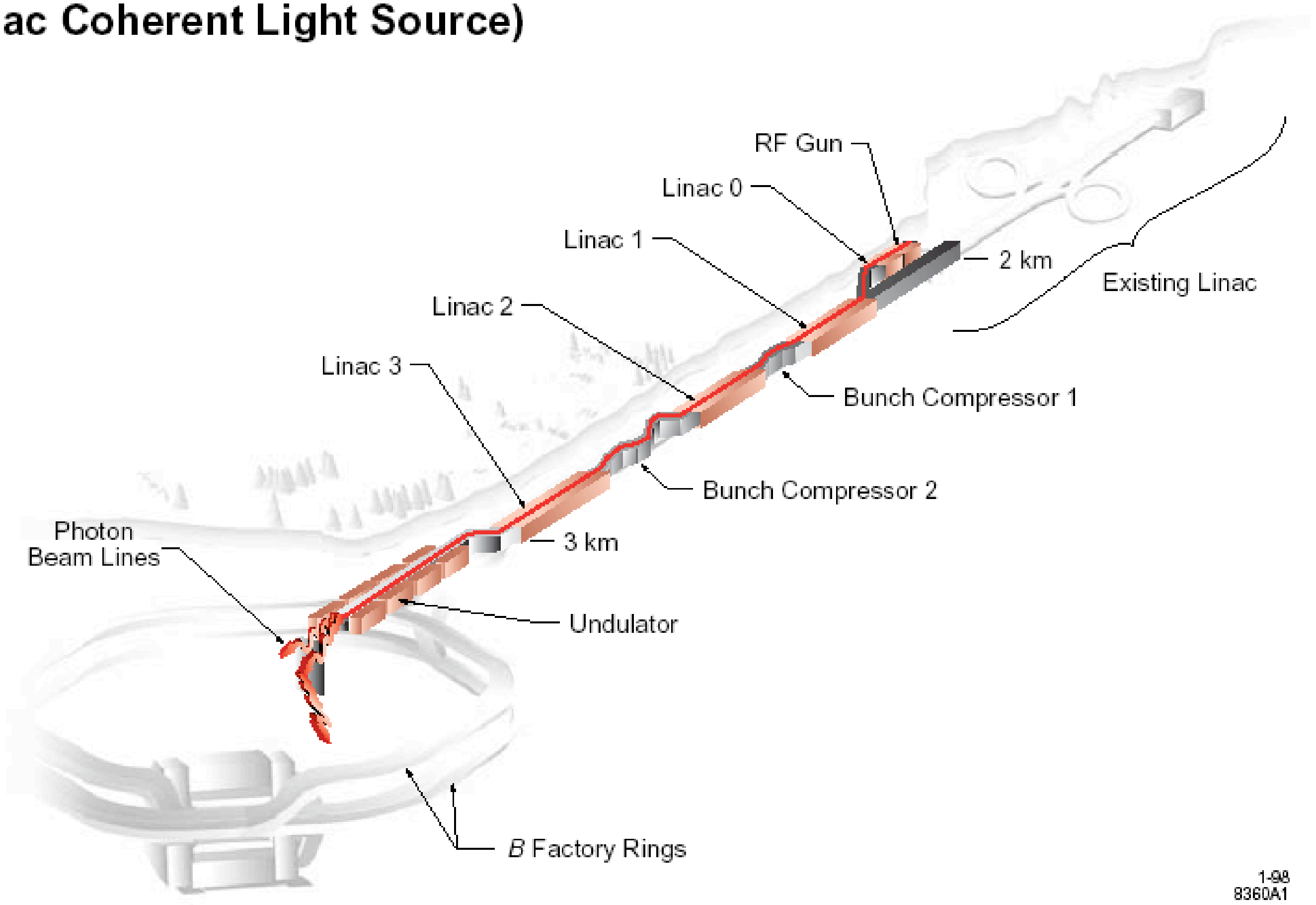


Courtesy of D.T. Palmer / SLAC

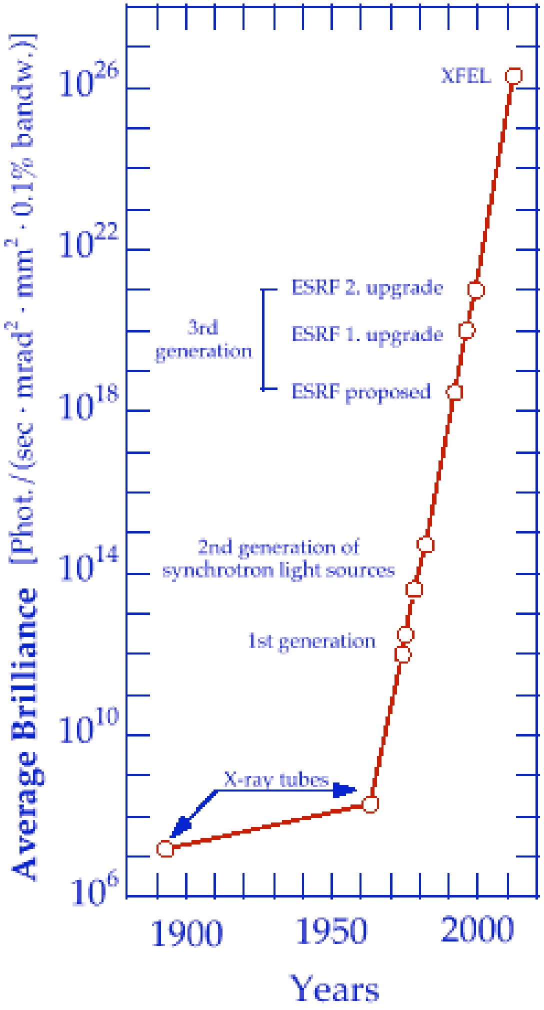
10 copies of this gun operated routinely around the world (USA, Japan) it holds the emittance record

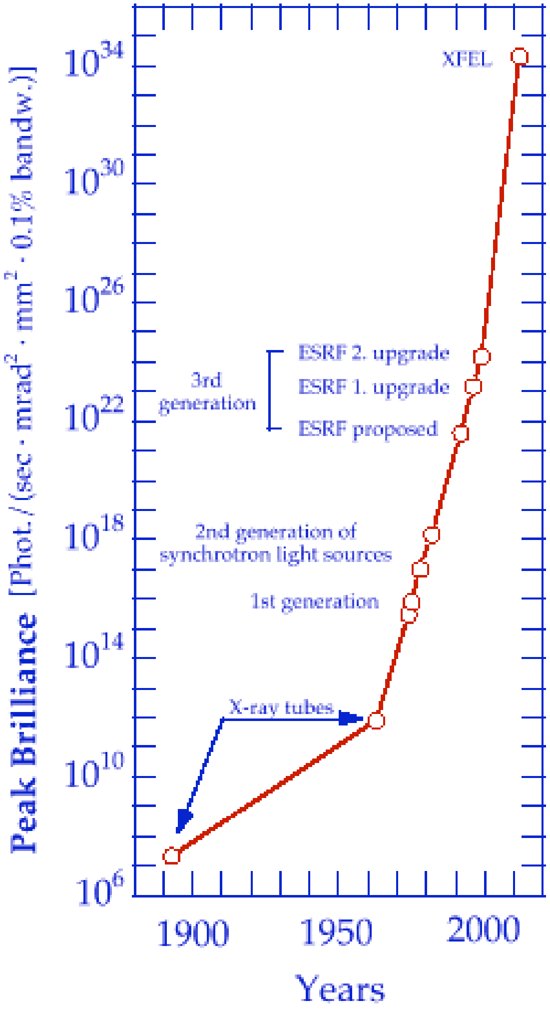
Free Electron Lasers are based on Linear Accelerators
Beam quality needed to operate FEL's is crucially dependent on emittance produced by the injector (unlike circular accelerators)

The LCLS
(Linac Coherent Light Source)



X-ray sources over the last 100 years: the story of a marriage between electron beams and X-rays

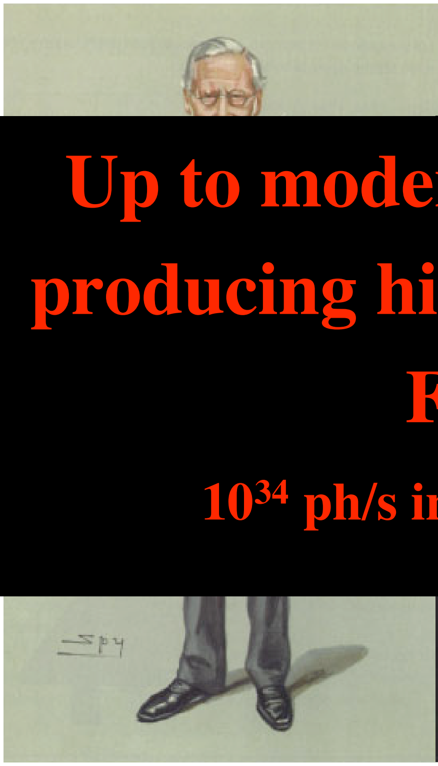


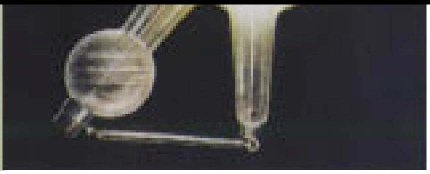


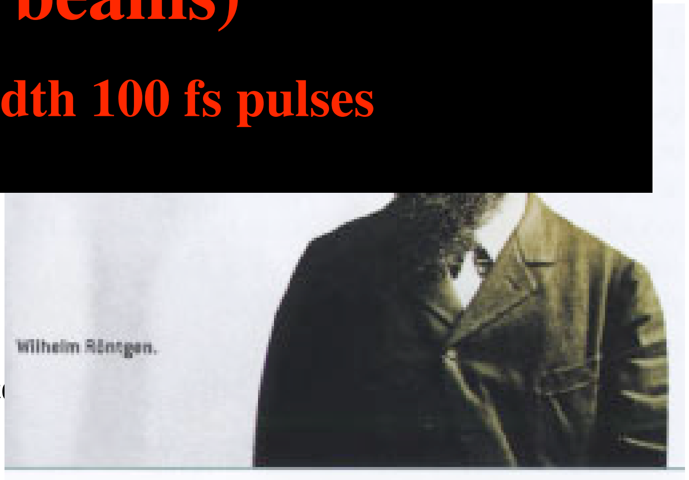
X-Ray beam quality goes along with upgrade of electron beams

Since the invention of Crookes tubes (step! Roengten…)

DC 10^6 photons/s
in 1 (mm·mrad)^2
0.1 % bandwidth
10-50 keV electrons





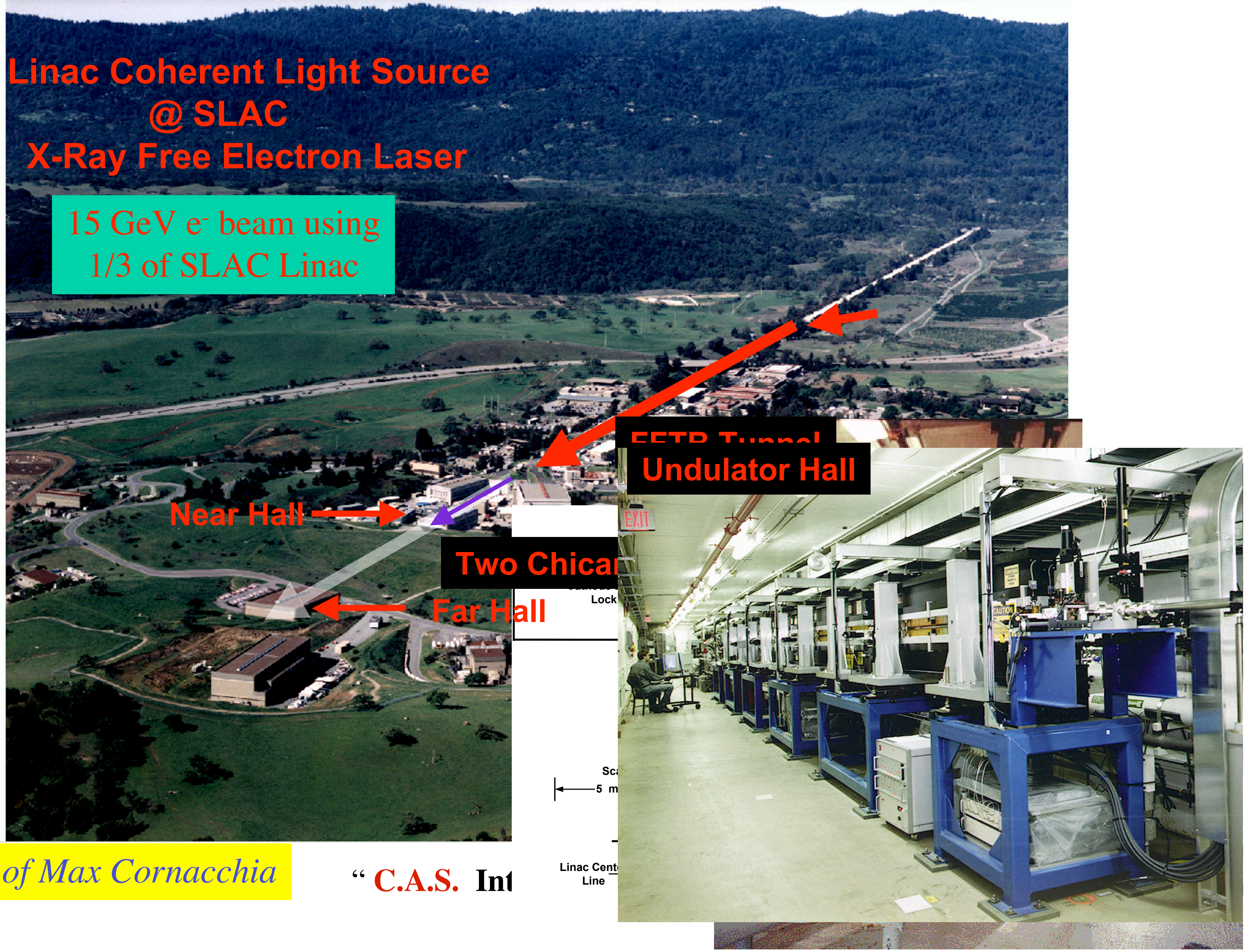


Up to modern (still under design) photo-LINACs producing high brightness electron beams to drive X-FELs (coherent X-ray beams)

10^{34} ph/s in 1 (mm·mrad)^2 0.1 % bandwidth 100 fs pulses

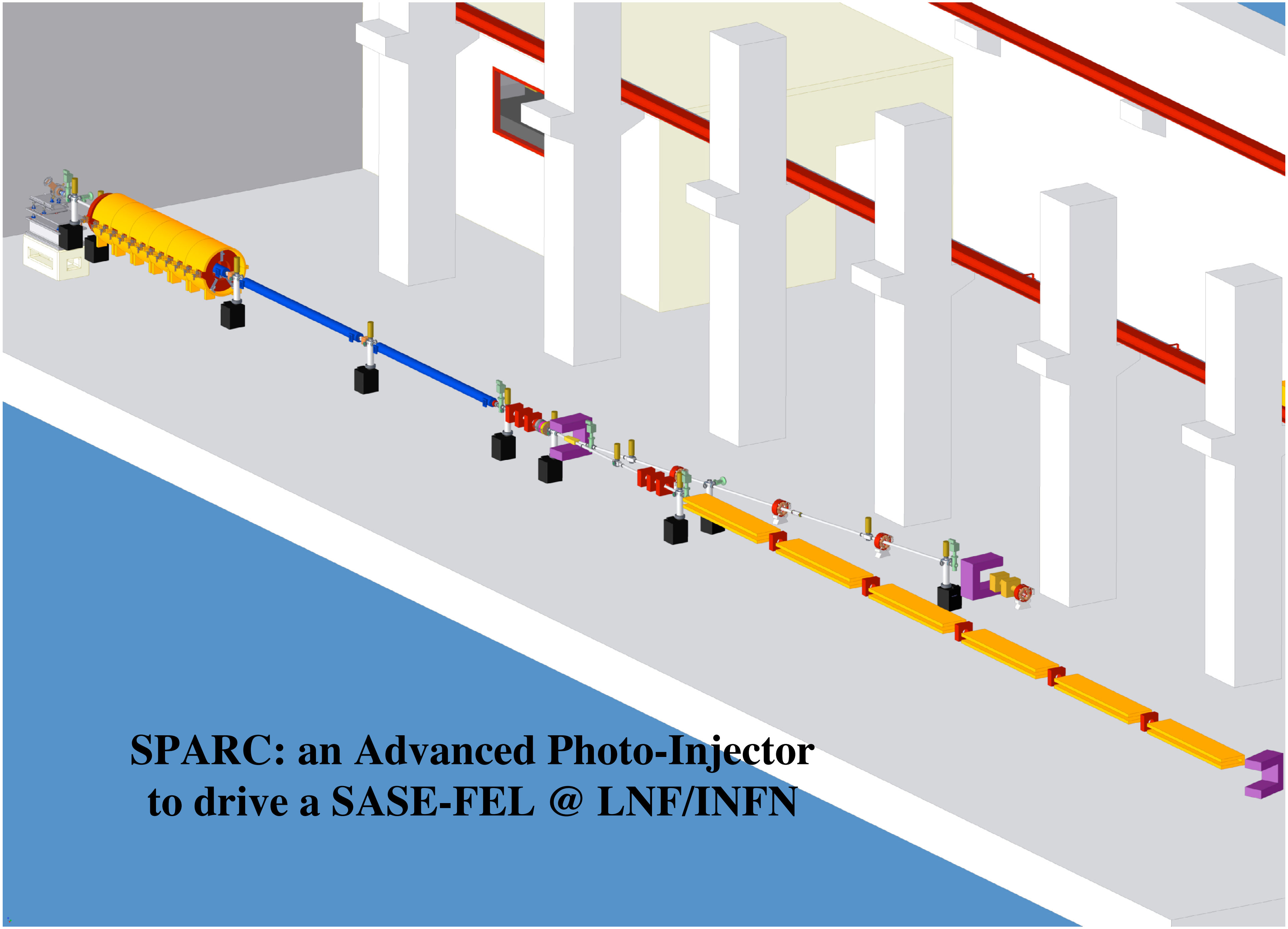
Linac Coherent Light Source
@ SLAC
X-Ray Free Electron Laser

15 GeV e$^-$ beam using
1/3 of SLAC Linac



Courtesy of Max Cornacchia

“ C.A.S. Int



SPARC: an Advanced Photo-Injector to drive a SASE-FEL @ LNF/INFN

Suggested readings

J.S. Fraser et al., IEEE Trans. Nucl. Sci. NS-32 (1985), p.1791

R.L. Sheffield et al., Proc. 1988 Linear Accelerator Conf., Williamsburg, VA, Oct. 1988, CEBAF rep. 89-001 (1989), p.520

C. Travier, Particle Accelerators 36 (1991), p.33

K.J. Kim, NIM A275 (1989), p.201

B.E. Carlsten, IEEE Catalog no. 89CH2669-0 (1989) p.313

B.E. Carlsten et al., Proc. 1988 Linear Accelerator Conf., Williamsburg, VA, Oct. 1988, CEBAF rep. 89-001 (1989), p.365

L. Serafini, AIP Conf. Proc. 279 (1993), p.645 *and* L.Serafini, NIM A340 (1994), p.40

J.B.Rosenzweig and L.Serafini, Phys. Rev. E-**49** (1994), p.1599

S.C. Hartman and J.B.Rosenzweig, Phys. Rev. E-**47** (1993), p.2031

W.K.H. Panofsky and W.A. Wenzel, Rev. Sci. Instr. 27 (1956), p.967

More suggested readings

J.B. Rosenzweig and E. Colby, AIP CP 335 (1995), p.724

L.Serafini, Particle Accelerators 49 (1995), p.253

L. Serafini et al., NIM A387 (1997), p.305

L.Serafini and J.B.Rosenzweig, Phys. Rev. E-**55** (1997), p.7565

Proceedings of the ICFA 1999 Workshop on *The Physics of High Brightness Beams*, Los Angeles, 1999, Published on World Sci. ISBN 981-02-4422-3, June 2000

Proceedings of the ICFA 2002 Workshop on *Physics and Applications of High Brightness Beams*, Chia Laguna, Italy, 2002, in publication, see www.physics.ucla.edu/AABD

S. G. Anderson and J. B. Rosenzweig, PRSTAB **3** (2000), p. 094201-1

F. Zhou et al., PRSTAB **5** (2002), p.094203-1

More suggested readings

F. F. Chen, 1984, Introduction to Plasma physics, New York, Plenum.

J. L. Delcroix, 1980, Introduction to the theorie of ionized gases, New york, Wiley-Intersciences

I. G. Brown, 1989, The Physics and Technology of Ions sources, New york, Wiley-Intersciences

B. Wolf, 1995, Handbook of Ions Sources, London, CRC Press

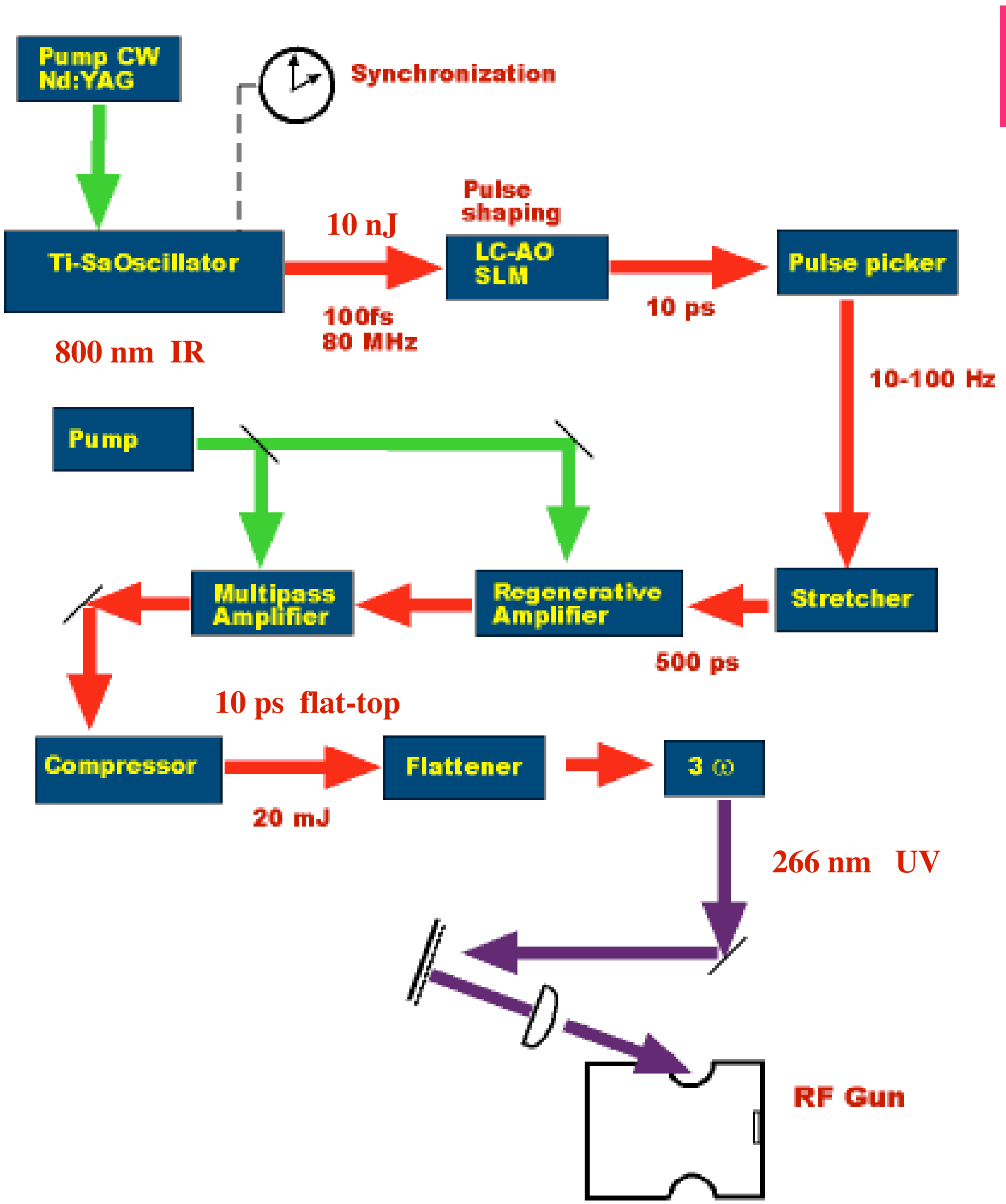
C.E. Hill, Ion and Electron Sources, CERN, at www.cern.ch

Review of Scientific Instrument, Proceeding of International Conference On Ion Sources (since 1989)

H. Zhang, 1999, IonSources, Springer Verlag

Many thanks to Pascal Sortais (ISNG, Grenoble)
for kindly providing various material on Ion Sources

Laser layout


Pump CW
Nd:YAG
Synchronization
Ti-SaOscillator
800 nm IR
10 nJ
100fs
80 MHz
Pulse shaping
LC-AO
SLM
10 ps
Pulse picker
10-100 Hz
Pump
Stretcher
500 ps
Regenerative Amplifier
Multipass Amplifier
10 ps flat-top
Compressor
20 mJ
Flattener
3 ω
266 nm UV
RF Gun

Major Issues in Laser System come from Stability Requirements

Phase jitter

Pointing Stability

Amplitude jitter

Transverse* Brightness of Electron Beams

$$B_n = \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}}\left[\frac{A}{m^2 rad^2}\right]$$

I = peak current

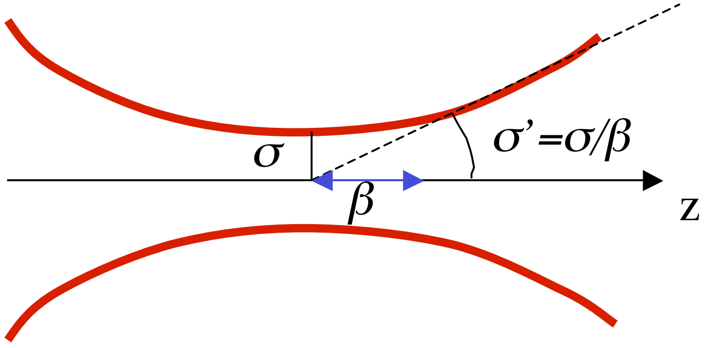
ε_{nx} = rms normalized transverse emittance

Quality Factor : beam peak current density normalized to the rms beam divergence angle

Round Beam : $\varepsilon_{nx} = \varepsilon_{ny}$, $J = I/\sigma^2$ $\Rightarrow$

$$B_n = \frac{2J}{(\sigma'\gamma)^2} = \frac{2J\sigma^2}{\varepsilon_n^2}$$

$$\sigma = \sqrt{\varepsilon_n\beta/\gamma}$$



* 5D Projection of 6D Brilliance used for Photon Beams

$$B'_n = \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}\frac{\sigma_\gamma}{\gamma}}\left[\frac{eN_e/s}{m^2\,rad^2\cdot\%band}\right]$$

Transverse Brightness
RF Photo-Injector Achievements vs. Demands

TTF photo-inj. (achieved) **$6\cdot10^{12}$**
exit of linac (compr.) **$2\cdot10^{13}$**

ATF photo-inj. (achieved) **$5\cdot10^{13}$**
@ photocathode **$1.2\cdot10^{15}$**
Max. achievable without compr. $\varepsilon_{n\text{-}cath} = \varepsilon_{thermal}$

$$B_n \equiv \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}} \quad \left[\frac{A}{m^2 rad^2}\right]$$

I = bunch peak current

LCLS (requested @ 15 GeV) **$4\cdot10^{15}$**
$\varepsilon_{nx} = \varepsilon_{ny} = 1.5\ \mu m$

ESRF (storage ring) **$< 10^{14}$**
$\varepsilon_{nx} = 20\ \mu m \quad \varepsilon_{ny} = 0.07\ \mu m$